

**AN ANALYSIS OF RECENT SEVERE CLIMATE EVENTS
OVER TANZANIA**

AGNES LAWRENCE KIJAZI

UNIVERSITY OF CAPE TOWN, OCEANOGRAPHY DEPARTMENT

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OVER TANZANIA**

**SUBMITTED IN FULFILMENT OF THE UNIVERSITY OF CAPE
TOWN DEGREE OF DOCTOR OF PHILOSOPHY**

DEDICATION

The author dedicates this work to her family, husband Mwara Anande, children David, Doreen, Irene and Elizabeth, Parents, mother Christina Lawrence Kijazi, father Lawrence Kijazi, mother in-law Margret Anande, brothers and sisters for their patience, support and encouragement through the years that she was away from home.

Jeremiah 33:3

“Call to Me, and I will answer you, and show you great and mighty things, which you do not know.”

DECLARATION

This is to certify that the dissertation entitled '**An analysis of recent severe climate events over Tanzania**' submitted in fulfilment of the requirements of the degree of Doctor of philosophy of the University of Cape Town is a record of bonafide research work. The subject matter embodied in this report has not been submitted at any other university.

Name; Agnes Lawrence Kijazi

Signature;

Signed this 13th day of January 2009.

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ABSTRACT

This thesis focuses on the analysis of the recent severe climate events over Tanzania. The circulation patterns over the Atlantic and Indian oceans responsible for inter-annual and intra-seasonal rainfall variability in Tanzania were analysed and the skill of Global Circulation Model (GCM) in capturing the inter-annual variability assessed. The results were tailored to the application for agriculture over North-eastern Tanzania to aid decision makers in the formulation of agriculture related policies for sustainable development.

The thesis first touches on an analysis of the mean characteristics of selected meteorological fields comprising both MAM and OND rainfall seasons. Such processes were examined as necessary background information to determine the causes of rainfall variability. Two regions of deep convection were observed: one maritime (over the Indian Ocean), and one continental (over the Congo forests). High values of latent heat flux occurred in the Congo forests during the OND season, suggesting this region to be among the sources of moisture for said season. Generally, the easterly moisture flux dominates the region for both the OND and MAM seasons and this suggests the Indian Ocean to be the main source of moisture for the country's rainfall. The descending branch of the Walker type circulation was located over the Indian Ocean at about 55 °E and longitudinal shifts of this branch may cause rainfall anomalies. Similarly, the departure from any observed mean characteristics may cause climate anomalies over the region.

Inter-annual time scale analysis indicates that the region experienced more dry than wet years during the period of study. However, dry anomalies were much weaker than wet anomalies, and the influence of El Niño on wet anomalies was suggested as one of the causes of this variation. Ascent (descent) over the study region coupled with a strong moisture flux convergence (divergence) was observed to be the dominant feature for wet (dry) years.

On the intra-seasonal time scale that is so important for agricultural planning, wet years were characterised by longer than normal rainfall seasons, while for dry years the seasons were shorter than average. For the dry OND season, an out-of-season peak was evident that could be used to minimize the effect of drought. The circulation features show that the wet years were characterised by a cyclonic moisture flux and wind over the tropical South Indian Ocean east of Madagascar coupled with strong westerly moisture flux emanating from the equatorial Atlantic Ocean and south-easterly moisture flux from the Western Indian Ocean that enhance moisture flux convergence over the country. In contrast, the dry years show more or less the reverse circulation patterns over the Indian Ocean. An anticyclonic circulation occurs east of Madagascar with circulation patterns that divert moisture away from Tanzania.

Comparison of ECHAM 4.5 model with NCEP/NCAR reanalysis over the study region indicated that the model was able to represent the circulation features associated with rainfall during the wet season while for the dry season the model failed to represent the circulation features. This suggests that local features (that are not well captured by the model) contribute significantly to the rainfall variability over the region, especially during dry seasons.

The results obtained from this thesis have contributed to a better understanding of the mechanisms associated with rainfall variability over north eastern Tanzania. The research has addressed the gap that exists in the literature concerning what factors and mechanisms might drive rainfall variability at the sub-regional scale over East Africa. Furthermore, this study is the one of the first to assess the ability of an atmospheric model to replicate the observed circulation and rainfall patterns at this sub-regional scale for Tanzania.

Glossary/Acronyms

Some of the following definitions and acronyms are not universal and serve the purpose of this thesis only. This section has been included to facilitate the reader to view interpretations with author's perspective

North-eastern Tanzania

This is the region of study in this research. It is the region bounded by latitude 2 - 7°S and longitude 35 - 41° E

East Africa

This is the region which encompasses three East African countries i.e. Kenya, Uganda and Tanzania

Northern Coast

The northern part of the Tanzanian coast (north of 7°S)

North eastern highlands

The north eastern part of Tanzania (the region around Mount Kilimanjaro)

Lake Victoria Basin

The northern region of Tanzania (region around Lake Victoria)

Central region

The region located at the centre of Tanzania. It includes two political regions Dodoma and Singida.

Walker circulation

The Walker circulation is a zonal Hadley type circulation assumed to be driven by zonal temperature gradients within the tropics. It is evident over the Atlantic Ocean and more, prominently, the Pacific Ocean, associated with a surface easterly and an upper westerly branch. The reverse cell is less certain, but most research mention the tropical Indian Ocean.

Commonly used abbreviations

MAM	March-April-May rainfall season
OND	October-November-December rainfall season
N-A	November-December-January-February-March-April rainfall season
NEH	North-eastern Highlands
NC	Northern coast
CEN	Central region
GCM	Global Circulation Model
RCM	Regional Circulation Model
ENSO	El Niño - Southern Oscillation
IPCC	Inter-Governmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
EOF	Empirical Orthogonal Function
IOD	Indian Ocean Dipole
SST	Sea-Surface Temperature
WMO	World Meteorological Organization
NCEP	National Center for Environmental Prediction (USA)
NCAR	National Center for Atmospheric Research (USA)
NOAA	National Oceanographic and Atmospheric Administration (USA)
TMA	Tanzania Meteorological Agency
ICPAC	IGAD Climate Prediction and Analysis Centre

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CHAPTER ONE

INTRODUCTION

1. 0 Introduction

Weather forecasting and climate prediction are difficult for Tanzania due to the country's complex topographical patterns, numerous inland water bodies, variation in vegetation types and land-ocean contrasts. Long range forecasts of rainfall in Tanzania can be of considerable economic value to various sectors such as agriculture, water resources, tourism, hydropower, industry and the community at large. However, any such benefits depend essentially on the temporal and spatial scales thereof. Hence, forecasts are desired for a larger spectrum of time and space scales.

In recent years, scientific understanding of the causes of seasonal and inter-annual climate variability has improved substantially. There is also an enhanced ability to provide outlooks of the climatic atmospheric state for one or more seasons into the future. In many respects these advances help to address mankind's natural desire to plan for the future, and to thereby reduce the impact of climatic shocks. Indian Ocean and Atlantic Ocean sea-surface-temperature (SST) form the basis for long – range climate forecasts in many parts of Africa (Barnston et al., 1996; Nicholson, 1996). Nicholson (1996) has noted that East African rainfall is clearly linked to larger-scale features of the general circulation including sea-surface temperatures. Camberlin (1995) and Mutai *et al.*, (1998) have shown significant relationships between rainfall over East Africa and the atmospheric flow pattern over the region.

The chapter is divided into two main sections. The first section provides a summarized review of the literature published on Tanzanian's climatic variability and climate modelling while the second discusses the motivation and outlines the research questions to be answered in this thesis.

1.1 Main systems controlling weather and climate in Tanzania

Convergence zones mainly control weather and climate in tropical areas (Archanya & Bhaskara, 1981). The most important of these is the Inter-tropical Convergence Zone (ITCZ) (Nicholson, 1986), which is a confluence of

several air masses (Torrance, 1981) with different origins. It is important to note that these have to be in phase to produce effective convergence. The ITCZ forms a quasi-continuous belt of unsettled, frequently rainy weather around the tropics, sandwiched between generally fine weather to the equator-ward side and near the subtropical highs (Folland *et al.*, 1991). Over land areas, the ITCZ tends to follow the seasonal march of the sun. According to Jury & Pathack (1991) the convective intensity of the ITCZ, as identified by OLR data, is at its maximum over southern Africa near 10 °S, 20 – 30 °E. In the south-west Indian Ocean, the summer ITCZ is located between 10 and 15 °S.

Janowiack (1988) observed that the ITCZ reaches its southernmost position over Africa at about 12 °S in December - January, the height of the southern hemisphere summer. In addition, during the austral summer, the region of maximum rainfall and the ITCZ are nearly co-located, with the ITCZ being most active in January. Nicholson and Chervin (1983) proposed that the duration of the dry and rainy seasons is determined by oscillation of the ITCZ around the equator. The exact composition, development and role, including characteristic weather sequences of the ITCZ, were documented (Kreft, 1972; Kumar, 1978; Torrance, 1981; Gadgil & Guruprasad, 1990, amongst others).

Over East Africa, the ITCZ may be defined climatologically as a narrow transition belt where the northeast and the southeast trades converge, inducing strong upward motion and heavy rainfall if the air contains sufficient moisture (Okoola, 1999). The associated low pressure that forms as a result of the intense heating of the surface from the sun shifts meridionally with the seasons as the position of maximum insolation shifts (Taljaard, 1986; Tyson, 1986).

Tropical cyclones over the Indian Ocean contribute significantly to weather patterns over East Africa at times. The cyclone season is usually from December to April (Padya, 1989; Matarira, 1990; Jury, 1993; Nassor, 1994). The tracks and associated weather impacts vary significantly from cyclone to cyclone. Tropical cyclones may cause either dry or wet conditions in

Tanzania, depending on their tracks. When cyclones are in the central Mozambique Channel, wet conditions tend to prevail over western Tanzania, mainly due to the eastward shift of the Meridional arm of the ITCZ, while for south-eastern Africa, including south-eastern Tanzania, hot sunny weather prevails. Torrance (1981); Dunn (1985); Diab (1988); Jury & Pathack, (1991); Matarira (1990) and Reason & Keibel (2004) have all examined tropical cyclone activity in the southwest Indian Ocean and associated impacts on southern Africa.

Besides the seasonal migration of the ITCZ over the Indian Ocean and tropical cyclone activity over the southwestern tropics of this basin, other climatic factors known to influence precipitation over East Africa, and in particular Tanzania, result from a complex interaction between SST forcing, larger scale atmospheric patterns (essentially the monsoon) and synoptic scale weather disturbances. These features include the African jet streams (Somali jet, African Easterly jet, Tropical Easterly jet), the sub-tropical anticyclones, easterly/westerly wave perturbations, thermally induced meso-scale circulations and extra-tropical weather systems (Krishnamurti, 1961; Krishnamurti *et al.*, 1973; Cadet & Dehl, 1984; Ogallo, 1988; Okeyo, 1986; Mukabana & Pielke, 1991, Nyenzi 1984; Hills 1979 to mention a few). Some studies (for example, Anyamba, 1992; Kijazi & Reason, 2005, Mapande & Reason, 2005) have related the Intra-seasonal Oscillations over the tropical western Indian Ocean with rainfall variability over East Africa.

1.2 Climate variability in Tanzania

On interannual time scales, much work for example, Ogallo (1988); Beltrando (1990); Indeje *et al.*, (2000) has considered climate variability of East Africa. In the tropics, rainfall is largely organised as deep cumulus convection embedded in a large-scale disturbance, where a confined area receives most of the rainfall. The daily rainfall can vary greatly within a few hundred kilometres (Jackson, 1977; Sharon, 1981) while long term means may be similar throughout an area.

Observational records show that the climate of equatorial Eastern Africa has strong annual and semi-annual cycle components, with precipitation being the parameter with the greatest space-time variability. A larger fraction of this variability arises from processes internal to the atmosphere and is essentially unpredictable. Some of the variability however, arises in response to changes in the oceans (Hastenrath *et al.*, 1993, Goddard & Graham, 1999; Mutai *et al.*, 1998, Indeje *et al.*, 2000). This component may be predictable to some extent and is our focus here. Climate predictability in the tropics is largely due to the slow evolving nature of SST and land surface conditions (Nicholson *et al.*, 1987). It has been suggested that air-sea interaction over the Indian Ocean influences monsoon rainfall over India and some parts of Eastern Africa (Shukla, 1974; Shukla & Misra, 1977; Reverdin *et al.*, 1986, Ogallo *et al.*, 1988).

Much attention for example, Ogallo (1983); Barring (1988); Nicholson (1996), Basalirwa *et al.*, (1999); Indeje *et al.*, (2000) has been given to rainfall variability over Eastern Africa and it has been documented that rainfall in East Africa (Kenya, Uganda and Tanzania) exhibits great spatial and temporal variability. The rainfall seasons are ambiguous and complex with no single month existing during the year when all East Africa is dry (Johnson & Morth, 1961; Asnani & Kinuthia, 1979; Rodhe & Virji, 1976; Nicholson, 1996). Several studies of rainfall variability over East Africa have included inter-annual variations (Ogallo, 1984, 1988, 1989; Beltrando, 1990; Nicholson, 1996), decadal cycles (Ogallo *et al.*, 1994) and more recently intra-seasonal variations (Kijazi & Reason, 2005; Mapande & Reason, 2005).

Tanzania is situated between the latitudes 1 – 12 °S and the longitudes 29 – 41 °E. It covers an area of about 945,000 km² between the great East African lakes, namely Lake Victoria in the North, Tanganyika to the West and Nyasa to the South. To the east lies the Indian Ocean. The country includes Africa's highest point (Mount Kilimanjaro, 5 950 m above sea level) and lowest point (the floor of Lake Tanganyika, 358 m below sea level). However, most of Tanzania, apart from its eastern coastline, lies above 200 m altitude.

The other unique physical characteristics of the region include the North-eastern and South-western highlands. In between these highlands lies the Great Rift Valley that is oriented north/south across central Tanzania. The country also contains many inland water bodies (rivers and lakes). This configuration generates land/sea and land/lake breezes, as a result of water and land temperature contrasts, due to differential solar heating and radiative cooling which greatly modifies the country's climate.

Tanzania, in particular, experiences a variety of climate regimes. Its equatorial location, larger inland lakes and topography plays key roles in determining its climate (Mpeta, 1997). Because the position of the ITCZ follows the position of the maximum surface heating associated with meridional displacement of the overhead position of the sun, the equator-ward part of the country experiences two rainfall seasons while the pole-ward part experiences one distinct rainfall season (Kabanda, 1995; Kijazi, 2003).

The country's interannual variability is determined by several factors as elaborated in section 1.1. However, the El Niño Southern Oscillation (ENSO) is the most dominant perturbation responsible for interannual climate variability (Nicholson & Entekhabi, 1986; Indeje *et al.*, 2000; Kiladis & Diaz, 1989; Ropelewski & Halpert, 1987; Ogallo, 1988; Nicholson & Kim, 1997; Hastenrath *et al.*, 1993; Goddard & Graham, 1999; Janowiak, 1988; Reason *et al.*, 2000; Amissah-Arthur *et al.*, 2002). Ogallo (1988) found that the ENSO explains about 50 percent of the East African coastal rainfall variance, with other factors accounting for the remaining variance. Tanzanian rainfall tends to be increased (decreased) during El Niño (La Niña) except for the southern part of the country where the ENSO impact is mixed (Kijazi & Reason, 2005; Mapande and Reason, 2005). Hastenrath *et al.*, (1993) found that the East African short rain season is related to the Southern Oscillation through zonal pressure gradients produced by SST anomalies in the Indian Ocean. Nicholson & Kim (1997) found a strong connection between ENSO and rainfall over much of the African continent and suggest a linkage through ENSO induced SST anomalies in the Indian Ocean, which in turn modulate interannual rainfall variability over Africa.

SSTs in the Indian and Atlantic oceans have important influence on rainfall variability over Africa (Reason *et al.*, 2000). These SST anomalies in the Indian Ocean may arise in different ways. Reason *et al.*, (2000) focused on the seasonal evolution of the ENSO signal over the Indian Ocean while Saji *et al.*, (1999) and Webster *et al.*, (1999) proposed on east-west SST anomaly patterns, the so-called tropical Indian Ocean dipole or Indian Ocean zonal mode (IOZDM). This mode may sometimes strongly influence OND rainfall over East Africa, for example, in 1997. Saji *et al.*, (1999) found that during a dipole mode event rainfall decreases over the Oceanic Tropical Convergence Zone (OTCZ) and increases over the western tropical Indian Ocean consistent with convergence/divergence shifts associated with the wind field thus suggesting strong empirical evidence for coupling between the SST and wind field through the precipitation field. They further noted that the shift of the convergence zone, manifest the weakening or reversal of the zonal (Walker) circulation across the Indian Ocean, which leads to floods in East Africa and drought in Indonesia. They concluded that during dipole mode events the zonal surface wind over the tropical Indian Ocean experiences large changes resulting in anomalous climatic conditions in eastern Africa and Indonesia. They associated the positive dipole mode with above normal rainfall over Eastern Africa and negative dipole mode with below normal rainfall. The work by Loschnigg *et al.*, (2003) suggested that the dipole mode is infact an inherent component of the ENSO-monsoon interaction over the Indian Ocean and is not an independent mode as originally suggested by (Saji *et al.*, 1999). Zorita & Tilya (2002) analysed the interannual variability of rainfall in the March – May season over northern Tanzania and its relation to larger scale field. Their results indicated that the March to April rainfall is linked with zonal thermal contrast between the Indian Ocean and East African land mass, zonal surface wind anomalies and vertical velocity anomalies. They associated the May rainfall with the Indian Ocean Monsoon. Warmer Indian SSTs give rise to a weaker monsoonal circulation in May that is connected to moisture advection anomalies from the Indian Ocean into the African continent.

Based on the previous research on climate variability over eastern Africa, the forcing mechanisms responsible for climate variability over the region include:

forcing due to local land surface characteristics (Sud & Smith, 1984; Alapaty *et al.*, 1996), radiative forcing (Kiehl & Briegleb, 1993; IPCC 1995) and SST forcing (Webster *et al.*, 1999; Saji *et al.*, 1999; Rasmusson & Carpenter, 1982 among others).

1.3 Intra-seasonal research and heavy rainfall events

1.3.1 Intra-seasonal research

Intra-seasonal oscillations (ISO) in the atmosphere are generally defined as fluctuations with frequencies much shorter than the seasonal cycle. They are mostly in the order of 10 - 60 days. The most studied of these are 30 - 60 day oscillations, sometimes referred to as Madden-Julian Oscillations. Madden and Julian (1971, 1972) first detected them in the zonal wind in the tropics. A 40 -50 day spectral peak has also been observed in coupled fluctuations of the angular momentum of the atmosphere and solid earth (Anderson & Rosen, 1983; Rosen & Salstein, 1983). Anderson & Rosen (1983) showed that the largest coherences between 40 - 50 day fluctuations of zonally averaged zonal winds and global relative angular momentum were found in the tropical latitudes. According to Weickman *et al.*, (1985), certain properties of 40 - 60 ISO have been established and associated with Eastward moving equatorially-trapped Kelvin waves. However, Anyamba (1992) has reported meridional propagation in the Indian Ocean region. Vincent *et al.*, (1991) found that the Madden Julian Oscillation (MJO) was absent during the austral winter and further observed that velocity potential and outgoing long wave radiation (OLR) were the best indicators of the oscillatory convective activity. Rui & Wang (1990) explained the temporal evolution of ISOs in the equatorial region by documenting the development and dynamic structure of tropical intra-seasonal convection anomalies using five day mean anomalous OLR and ECMWF analysed 200 and 850 hPa wind data. A study by Makarau (1994) observed intra-seasonal oscillations with two cycles: 10 - 25 and 40 - 50 days when studying wet and dry spells in the Zimbabwean summer rainfall. Similarly, Levey & Jury (1996) found 20 - 35 day oscillations in precipitation and evaporation pentad time series for central South Africa during its austral summer.

Other intra-seasonal oscillation studies which link tropical Africa and the adjacent oceans include the study by Zhu & Wang (1993) who observed two prominent action centres in the central Indian and Western Pacific Oceans for tropical 30 - 60 day convective variability. Anyamba (1992) has identified the 20 - 30 day oscillation in the tropical OLR spectra in the western Indian Ocean and found that while the 40 -50 day ISO is characterised by an eastward propagating wave in the Indian and West Pacific Oceans, the 20 - 30 day ISO has a much weaker zonal propagation. Kijazi & Reason (2005) found 30 - 50 day oscillations in the Indian Ocean associated with ENSO years. They postulated that the propagating features were absent during strong El Niño years, but present for strong La Niña years. On the other hand, Mapande & Reason (2005) found 30 – 50 day eastward propagating oscillations with origin over the Congo Basin (near 15°E). They concluded that eastward propagating anomalies were slower over Tanzania during wet years. On intra-seasonal time scales, not much work has been undertaken on Tanzanian signals and this study will therefore assist in bridging this knowledge gap. Chapter five of this thesis considers the intra-seasonal oscillations responsible for short-term rainfall variability over North-eastern Tanzania that is beneficial for agricultural activities.

1.3.2 Heavy rainfall

Cases of heavy rainfall that occur in Tanzania include droughts and floods and these have devastating effect on the economy of the country. Rain-fed agriculture is the mainstay of the Tanzanian economy, with plant growth and yield being strongly dependent on weather and climate. Climate is therefore one of the most important factors in determining the agricultural potential of the country. Various researchers have studied drought patterns in East Africa and their potential impacts on the economy (for example, Nieuwolt, 1978; Ogallo & Nassib 1984; Mhita, 1990; Nicholson & Nyenzi, 1990; Ininda, 1987; Ogallo & Ambenje, 1996). Ogallo (1984) reported that East Africa is on average drought-free for only 21 out of 100 years. Extreme rainfall anomalies are common in East Africa and some of these are localised in nature, while

others cover a larger area and persist for several seasons or years (Ogallo & Ambenje, 1996).

The climate forcing that leads to meteorological drought in Tanzania is complex. Several authors have conducted investigations into the various causes of droughts in East Africa. These include Ogallo (1989), Nyenzi (1992) and Kabanda & Jury (1999) who established that the El Niño/Southern Oscillations (ENSO) has an influence on the occurrence of drought in Tanzania. Some extreme rainfall events in East Africa have been significantly associated with ENSO (Ropelewski & Halpert, 1987; Janowiak, 1988; Ogallo, 1988; Kiladiz & Diaz, 1989; Goddard & Graham, 1999; Nicholson & Entekhabi, 1987; Stoeckenius, 1981) among others. Typically, rainfall tends to be enhanced (reduced) over equatorial East Africa during El Niño (La Niña) events (for example, Camberlin, 1995; Nicholson, 1996; Reason *et al.*, 2000; Kijazi & Reason, 2005). Nieuwolt (1978) and Minja (1982) have found droughts to be associated with weak monsoons. Ogallo (1984) attributed the occurrence of droughts over the country to the position of the ITCZ. Recent investigations have provided evidence of anomalous events in the tropical Indian Ocean that clearly point to the existence of coupled modes of interaction between the ocean and the atmosphere over this basin (Anderson, 1999). This Indian Ocean Zonal Dipole Mode (IOZDM) is known to significantly influence the rainfall of eastern Africa during the austral spring / early autumn (Webster *et al.*, 1999; Saji *et al.*, 1999). Hastenrath *et al.*, (2007) associated the 2005 drought that occurred over the Equatorial East Africa with subsidence over the region.

However, little attention has been given to drought events in specific regions in Tanzania and chapter six of this thesis aims to bridge that knowledge gap by analysing the 1998 – 2005 protracted drought over the north – eastern highlands of Tanzania.

A number of researchers such as Ogallo (1988), Kabanda & Jury (1999), Indeje *et al* (2000), Kijazi & Reason (2005) have found evidence that ENSO influences Tanzanian climate and increased (decreased) rainfall occurs during

El Niño (La Niña). Goddard & Graham (1999) associated increased rainfall over East Africa with the occurrence of an anomalous cyclonic circulation over the western Indian Ocean. Camberlin (1995) and Mutai et al., (1998) have shown significant relationships between rainfall over East Africa and the atmospheric flow pattern over the region. The East African short rains (October-December) -OND) are also strongly influenced by the Indian Ocean zonal dipole mode (Saji et al., 1999). A considerable amount of work has been undertaken to study anomalous wet seasons over East African region. However, relatively less attention has been directed towards understanding the large-scale forcing mechanisms responsible for anomalous wet seasons over specific regions in Tanzania. Chapter six of this thesis considers a recent heavy rainfall season (October-December 2006) that occurred over northern Tanzania and its associated large-scale forcing.

1.4 Climate modelling

1.4.1 GCM modelling over Africa

General circulation models are computer simulations of the global atmospheric or oceanic circulation. The success of numerical modelling depends on the quality of the initial and boundary data, the representation of processes that occur below the level of the discretisation, and the accuracy of discrete approximations to the continuous equations. Some GCM applications include the assimilation of observed data which adds an extra component of approximation and hopefully improvement to the simulation. GCMs are used to simulate the evolution of the atmosphere through time from some initial state. The usefulness of GCMs for climate studies is their ability to model the evolution of the atmosphere in response to external forcing mechanisms. These numerical models have been employed in climate studies over parts of Africa with encouraging results (Rowell *et al.*, 1994; Ward *et al.*, 1993; Mason *et al.*, 1994; Rocha & Simmonds 1997; Landman & Mason 1999; Reason and Mulenga, 1999).

Kiker (2000) used three GCMs (Genesis, HadCM2 and CSM) to represent a possible evolution of the global climate system. He identified sectors and areas of highest vulnerability to climate change in Southern Africa. His conclusions were that the performance of the models supports the view that they are capable of capturing the primary dynamical response to the increased radiative forcing from changing concentrations of atmospheric gases. The GCMs were thus found to be skillful in capturing the fundamental dynamics of the atmosphere represented by the synoptic circulation over Southern Africa. On the other hand, Reason & Jagadheesha (2005) found that the UKMO HadAM3 model had difficulty in capturing the impacts of recent ENSO events on southern Africa since its resolution was unable to adequately represent the Angola low. The model was more successful in representing ENSO impacts over East Africa however.

1.4.2 Seasonal forecasts

Predictions of seasonal climate anomalies have been made in certain forms for centuries. One of the earliest scientifically based schemes is that of India's Meteorological Department, which has been issuing predictions for the all-India monsoon rainfall since the late nineteenth century, using various statistical methods (Walker & Bliss, 1932). One of the more recent developments is the regular production of seasonal climate forecasts that are based, at least in part, on global dynamical climate models (GCMs). For example, the U.K. Met Office (UKMO) has used one since 1988 (Ward *et al.*, 1993), as has the Climate Prediction Center (CPC) since 1994, the Canadian Meteorological Center (CMC) since 1995; (Sevranks *et al.*, 1999) and Australia's Bureau of Meteorology (BoM) since 1997, (Frederiksen *et al.*, 2001).

Climate models are fully three dimensional in character, and comprise a series of equations with prescribed initial boundary conditions and physical constraints. A climate model represents a controlled environment, within which the impact of anomalies on the climate system can be studied (Henderson-Sellers & McGuffie, 2005). By comparing an anomaly simulation

to a control simulation, the nature, degree and extent of climatic variability can be identified.

GCMs are a widely used tool for developing climate prognoses and evaluating climate sensitivities. As these models have coarse spatial resolution (typically of order 100-200 km) and as they exhibit varying skill at different spatial-temporal scales, it is necessary to use downscaling tools (either regional climate models (RCMs) for example, Pan *et al.*, 2001, or empirical models for example, Wilby *et al.* 1998) to derive regional climate prognoses. These tools rely on accurate simulation of synoptic and larger scale climate phenomena in GCMs. However, at this time, there are no climate models that have been developed specifically for Tanzania. This situation is possibly due to a lack of expertise in the country and reduced resources compared to elsewhere. GCMs have however, been used to simulate the East African climate and its interannual variability (Indeje *et al.* 2001; Reason & Jagadheesha, 2005).

Because of their high degree of predictability, the October to December East African short rains is a good test bed for seasonal forecast models. Statistical forecasting models usually reproduce about 50% of the total variance of this rain season using global SST fields for the preceding months (Mutai *et al.*, 1998). More recently, Phillipon *et al.*, (2002) increased the explained variance of the short rains up to 64% based on September oceanic-atmospheric regional signals. The high predictability of the East African short rains, coupled (and linked) to their strong spatial coherency, make them suitable to explore rainfall predictability at finer scales.

Given the complex nature of the Tanzanian land surface and the neighbouring oceans, in theory one might expect a RCM to offer considerable advantages in simulating the climate of the region. This expectation results from the fact that RCMs use higher resolution horizontal grids than GCMs so they can simulate finer structures of circulation and precipitation distributions than the coarser resolved global models from which seasonal climate outlooks are more commonly sought. The GCM/high-resolution model nesting approach has been implemented in short-range weather and climate forecasts (Giorgi &

Bates, 1989; Giorgi *et al.* 1993ab; Kida *et al.*, 1991; Giorgi & Marinucci, 1991; Liu *et al.*, 1994). Over East Africa, Sun *et al.*, (1999) demonstrated the ability of the NCAR Regional Climate Model version two (RegCM2) to realistically simulate intra-seasonal and inter-annual climate variability. They further showed how a high resolution GCM/regional scale nested model could be used to resolve the detailed regional features associated with East African climate variability.

As climate predictions produced by several dynamical models are readily available, multi-model ensemble forecasting has become the focus of attention. Krishnamurti *et al.*, (2000) discussed a super-ensemble approach, in which a multi-model linear regression technique is used to improve deterministic forecasts locally.

An ensemble of predictions can be used for deterministic or probability forecasting. Doblas-Reyes *et al.*, (2000) investigated predictions produced by three general circulation models (ECMWF model, ARPEGE model, HADAM3 model) and found that the multi-model approach offers a systematic improvement when using the ensemble to produce probabilistic forecasts. However, they found that the multi-model ensemble improves skill only marginally when verifying the ensemble mean. In contrast, Krishnamurti *et al.*, (2000) found an apparent systematic improvement in mean square error for a multi-model forecast over that of the individual model forecast. Kharin *et al.*, (2001) found that the forecast skill increases monotonically with the ensemble size by using 24 member ensembles to examine the skill of seasonal hindcasts as a function of the ensemble size. As stated earlier, climate modelling is relatively new to Tanzania. Therefore, further validation of numerical models is needed over specific climatic regions of the country. In terms of GCMs, the ECHAM 4.5 model is used and its ability to represent East African climate is assessed. The selection of this model was based on the fact that it is used to provide initial and boundary conditions for the regional high resolution model (RSM) implemented at IGAD Climate Prediction and Applications Centre (ICPAC) for seasonal forecasting over the greater horn of Africa. An important question in this regard is whether this

model is able to represent atmospheric features over Tanzania. If the model is successful, then confidence in its ability to provide robust initial and boundary conditions for downscaling will increase.

1.5 Motivation of the study

Seasonal climate prediction began in the early years of the 20th century with a variety of empirical techniques. Prominent amongst these first efforts were those developed in India following the work of Walker and Bliss (1932, 1937). In other parts of the globe there is also a history of long-range prediction employing empirical techniques (Livezey & Banston, 1988). Today, these empirical statistical methods have the advantage of requiring minimal computing power. However, they have the disadvantage of not incorporating the physics and dynamics of the atmosphere into their forecasting models. An additional problem with these methods is how the appropriate predictors for the models should be chosen; with the danger of over-fitting should the predictors not match the physical processes.

Most numerical modelling centres that produce operational seasonal climate forecasts use atmospheric Global Circulation Models (GCMs) forced with forecast sea surface temperature (SST). In order to improve on the accuracy of forecasts, a multi-model ensemble approach has been adopted for most numerical modelling centres so that the weaknesses of one GCM can be offset by strengths of another. The atmospheric GCMs have been demonstrated to simulate inter-annual rainfall and temperature variability with some skill (for example, Vitart *et al.*, 1997) in many tropical regions when they are forced with the observed time-varying SSTs. These findings lead to a two-tiered forecast method whereby forecasts are made of the expected SST fields, and these are in turn used to force the GCM through the coming season to generate the seasonal climate forecast. This procedure is mainly used over the Pacific Ocean, while over the Indian and Atlantic Oceans, GCMs are mainly forced with persistent observed SSTs (for example, Goddard & Graham, 1999). GCMs have the disadvantage of coarse resolution (typically of order 100 km) and they fail to capture local features over some

regions. It is imperative, therefore, that they are validated at regional level to assess their robustness in providing seasonal forecasts.

A number of studies for example, Rowell (1998) have considered the question of potential long-range predictability of climate variability. They have involved ensembles of multi-decadal simulations using GCMs forced with observed SSTs at different initial conditions. With such an approach it has been possible to separate inter-annual variability into chaotic components (due to sensitivity to initial conditions) and a potential predictable component (based on the ensemble average). Thus it is possible to identify areas where different climate variables are potentially predictable. There results showed high predictability over the tropics in an approximately 30°S - 30°N latitude band. Similarly, the European Union Prediction of climate Variations on seasonal to inter-annual Timescales (PROVOST) project has addressed the question of variations in seasonal-forecasting skill and predictability and indicated that predictability tends to be largest in the Tropics (Graham *et al.*, 2000). It is imperative, therefore, that GCMs are validated over Tanzania at regional level to assess their robustness in providing seasonal forecasts in such a tropical country.

In East Africa, specifically Tanzania, results from GCMs are yet to be tested for their ability to represent climate features at sub-grid scale level. To improve forecasting skills, it is important to direct research into validating GCMs over the region and establish their ability to provide results that realistically represent the observed climate and its variability. Furthermore, the parameterisation and interpolation schemes are not yet universal. The physics and dynamics of the ocean-atmosphere system are not yet fully known and climate variability is therefore not comprehensively represented. There is now considerable evidence concerning the role of orography in shaping local climate (Kasahara, 1966; Semazzi 1980; Semazzi & Sun, 1997). It is imperative therefore, that diagnostic research at regional and local levels is carried out and incorporated into GCMs. This work should extend existing knowledge and provide realistic scenarios of climate, both present and future.

Furthermore, in Tanzania, seasonal forecasts which rely largely on empirical statistical methods have a limited, but useful level of skill (Ntale *et al.*, 2003). The observational stations are sparsely distributed throughout the country's complex topographical features. The level of skill can therefore only be raised by the application of dynamical methods, which provides the motivation for this study.

To date, it has been assumed that the rainfall season over north-eastern Tanzania is nearly normally distributed and bimodal centred in November and April. While this may be true with respect to monthly average rainfall, it does not appear to be so for pentad (five day) data. The season is actually composed of alternating wet and dry spells with duration of 10 - 15 days each as will be shown in this thesis. These wet and dry spells occur during every rainy season and determine the accumulated rainfall. There is also evidence from this thesis that the OND season extends to the month of January of the following year. It is therefore important to understand the climate of a region through the distribution of the rainfall in a particular season.

The research into the intra-seasonal variability of rainfall over north-eastern Tanzania carried out in this thesis may shed light on the role played by local features in climate variability over north-eastern Tanzania. In addition, the part played by large-scale atmospheric circulations in determining the intra-seasonal climate variability can be made clearer as it is currently not adequately represented or accounted for in a mean seasonal time frame. Similarly, the validation of GCMs over the region has not yet been explored. This thesis is intended to contribute towards the filling of that gap by comparing the GCM results with NCEP/NCAR reanalysis and available observations over the Tanzanian region.

A major application of seasonal forecasting is towards agriculture. Most agriculture over Africa is rain-fed and therefore very vulnerable to drought or to unfavourable timing in a given rainy season's wet and dry spells. It is this intra-seasonal variability in rainfall that can strongly impact on food production in many regions of Africa even if the seasonal totals are close to average (for

example, Usman & Reason, 2004; Reason & Jagadeesha, 2005). Thus, crop yield and farm management can be most effective if cognisance is taken of the effects of climatic variability. It is necessary to note however, that considerably more work has been undertaken on the inter-annual variability of seasonal rainfall in various regions of East Africa (for example, Kabanda & Jury, 1999; Indeje *et al.*, 2000) than on the important and applications-oriented intra-seasonal variability. This thesis is aimed at providing results that can be applied to improve our understanding of variability within the season and its application to agriculture over the north-eastern region of Tanzania.

1.6 Objective of the study and research questions

In principle, human societies adapt to climate variability through land-use systems that minimise risk, with agricultural calendars that are closely tuned to long-term climate conditions and by crop choices and animal husbandry that harmonizes with the environment (McCarthy *et al.*, 2001). Tanzania is no exception. The climate impacts on the region and on society are significant but are not yet fully understood. However, recent changes in rainfall variability patterns (including drought and floods) (Dilley & Heyman, 2007) have combined to render a current need for accurate climate forecast. Clearly there is a need to improve the ability of the country, as a whole, to cope with climate variability.

Forecasting rainfall amounts in tropical regions, particularly Tanzania, is potentially of huge benefit due to the strong impact that rainfall variability has on major socio-economic activities (agriculture, energy supply, health etc.). Since the 1980s, the scientific community has performed numerous rainfall predictability studies and currently runs operational statistical forecasting models along with GCMs (Ji *et al.*, 1994).

For many regions, physical dynamical models replicate, and in some cases improve on, the skills realized from empirical statistical models. However, the approach of using numerical models for climate forecast is new in Tanzania, although undertaken extensively elsewhere. Thus, the primary objective of

this study is to provide a better understanding of the circulation features over the Indian and Atlantic Oceans responsible for the country's variable climate system. Specifically the thesis will

- Assess the ability of GCM to represent such circulation features.
- And analyse the inter-annual and intra-seasonal variability in an effort to provide useful information to various bodies concerned with food production and associated policy.

This thesis aims at understanding the mechanisms associated with inter-annual and intra-seasonal climate variability over north-eastern Tanzania. By better understanding the mechanisms associated with inter-annual and intra-seasonal climate variability over north-eastern Tanzania, the groundwork will be provided to potentially improve seasonal climate forecast efforts over Tanzania. The work carried out here may also help in assessing the predictability of Tanzanian rainfall on seasonal and intra-seasonal time scales thereby indicating where climate prediction efforts are most likely to best perform.

Since north-east Tanzania is populous (Figure 2.1) and its marine transportation, industry and tourism make it an important area for the country's natural economy, it provides an appropriate regional focus for this thesis. Furthermore, two important cities of the country are found within this region; namely, the capital city of the country (Dodoma) and the commercial city (Dar es Salaam). This region can be divided into three homogeneous zones that present two main rainfall regimes found in the country. Firstly, the central zone that experiences a unimodal rainfall regime and whose rainfall is mainly controlled by the east – west oscillation of the zonal arm of the Inter Tropical Convergence Zone (ITCZ). Secondly, the coastal zone that experiences a bimodal rainfall regime and whose rainfall is mainly controlled by the north – south movement of the ITCZ. Thirdly, the north – eastern highlands region that experiences a bimodal rainfall regime and whose rainfall is controlled by the north – south movement of the ITCZ. However the rainfall

season over the north eastern highlands is highly modified by topography. Such important characteristics provide a basis for north – east Tanzania as an appropriate regional focus for this thesis. This research specifically assesses the ability of atmospheric models at replicating the observed climate over the north-eastern Tanzania as a test case.

This chapter has reviewed the literature published thus far on Tanzania's climatic variability and climate modelling. The gaps in dynamical modeling and climate variability have been mentioned. This study aims to increase the ability of Tanzania to cope with climate variability and to improve local capacity in climate modelling in the country by addressing the following research questions:

- § What atmospheric circulation features over the Atlantic and Indian Ocean are responsible for inter-annual rainfall variability in Tanzania?
- § Can a GCM represent this variability?
- § What is the nature of the intra-seasonal variability over north-eastern Tanzania?

1.7 Layout of chapters

Chapter one introduces the thesis and gives a literature review of worldwide efforts to understand the application of numerical methods in climate variability. This type of research is relatively new in Tanzania and the available literature on modelling is based on research done outside the country. It also gives a review of previous research related to intra-seasonal variability and heavy rainfall events. The chapter further outline the known knowledge and identify gaps in current knowledge and outline the research questions.

In **Chapter two**, a detailed description of the data used in the study is provided, alongside a discussion of the various methods of analysis employed. The first section introduces the chapter, while the second and third sections outline the data and methods of analysis used respectively.

Chapter three highlights the major features in Tanzanian climate that are of importance. Sections one and two of this chapter use data from 1971 - 2004 climatology to analyse the mean circulations during MAM and OND seasons respectively while section three provides a detailed analysis of the observed inter-annual variability of Tanzanian rainfall. This chapter provides background meteorological information in understanding the evolution of rainfall anomalies during particularly wet and dry years. The main objective is to understand the primary factors that determine Tanzania's climate and circulation features associated with inter-annual variability.

Two case studies have been carried out in this thesis. The first part of **Chapter four** concerns case study of the 1998 - 2005 droughts. A detailed analysis of circulation features associated with the recent 1998 - 2005 protracted drought over the North Eastern Highlands (NEH) of Tanzania is given. In part two of chapter four, the second case study on the analysis of the 2006 (OND season) floods over northern Tanzania is carried out.

Chapter five provides comparisons between the GCM's simulated circulation patterns and NCEP/NCAR reanalysis data. An important question in this chapter is to establish whether the ECHAM 4.5 model is able to realistically capture the mean circulation patterns and inter-annual variability associated with rainfall over north-eastern Tanzania.

In **Chapter six**, the intra-seasonal variability is analysed and its application to agriculture over northeast Tanzania considered. The final chapter, **Chapter seven**, summarises the major findings of this thesis.

The following chapter (chapter two) details the data and methods used in the present study.

CHAPTER TWO

DATA AND METHODS

2.0. Introduction

In chapter one, the objectives and research questions of the thesis were identified. These involve understanding climate variability over north-east Tanzania and the associated forcing mechanisms over the Atlantic and Indian Oceans. A further aim is to investigate the skill of dynamical models in simulating this variability. Such wide-ranging objectives require very different data and analysis techniques to examine the relevant processes properly. This chapter provides a brief explanation of the data used in this study. It also outlines various methods used for the analysis.

Observational data, satellite derived data and ECHAM4.5 global climate model simulations were used in this study to analyse the circulation patterns over the Indian and Atlantic Ocean potentially associated with the rainfall variability in Tanzania and to assess the capabilities of ECHAM4.5 model over the region. The rainfall data provided by the Tanzania Meteorological Agency (TMA) and global climate model outputs were utilised in this research. The gridded data used were from four main sources: NCEP/NCAR reanalysis data (Kalnay *et al.*, 1996; Kanamitsu *et al.*, 2002), output from the Max Planck Institute AGCM ECHAM 4.5 model (Roeckner *et al.*, 1996), CMAP rainfall data (Xie *et al.*, 1997) and GPCP daily rain rates (Huffman *et al.*, 2001). NCEP/NCAR reanalysis data have been widely used by many researchers to study climate variability in many regions throughout the world and also as boundary conditions for regional model simulations including eastern Africa (for example, Hansingo & Reason, 2006). Tennant (2004) has examined the robustness of these re-analyses for the Southern Hemisphere.

Studies by Bengtsson & Shukla (1988) have shown that not all the available model based global data sets are suitable for studying regional climate variability. They cite reasons such as limitations in the early data assimilation system and inconsistencies caused by numerous model changes. However, other authors have used NCEP/NCAR re-analyses to study Tanzania's regional climate and have indicated a significant degree of accuracy (Mapande & Reason, 2005; Kijazi & Reason, 2005). Although NCEP/NCAR

reanalyses now extends back to 1948, data prior to 1968 are not fully reliable for the African continent, as demonstrated in Camberlin *et al.*, (2001). This thesis uses NCEP/NCAR data extending back to 1970 that seem to be reliable and give robust results over Tanzania (Kijazi & Reason, 2005; Mapande & Reason, 2005).

Methods of analysis used in this study include time series analysis, composite analyses, cross sectional analysis, empirical orthogonal function (EOF) analysis, wavelet analysis and numerical model experiments. Following this introduction, section 2.1 gives a brief description of data used for the purposes of this study, while section 2.2 details the methods of analysis employed.

2.1 Data description and sources of data

The data used in this study includes daily and monthly rainfall and atmospheric variables that cover the 1970 – 2005 period of study. Special attention has been given to the bimodal March, April, May (MAM) and October, November, December (OND) rainfall seasons over the North-eastern Highland (NEH) and northern coast (NC) of Tanzania, and the unimodal (November - April) rainfall season over central (CEN) Tanzania (figure 2.1). These data sets were divided into two main sections, namely observational and model data.

2.1.1 Observational and satellite derived data

To understand the spatial and temporal behaviour of rainfall over north-eastern Tanzania, daily and monthly rainfall records for nine stations scattered over the northern part of the country (figure 2.1) were obtained from the Tanzania Meteorological Agency. Daily rainfall data for three stations (Mwanza, Musoma, Bukoba) over the Lake Victoria Basin were used (together with the above mentioned station data) in chapter four for the analysis of the OND 2006 flood. The rainfall data were quality controlled using standard WMO procedures. Thus, all stations obtained their information from

unchanged sites, had a continuous record (no gaps in the data record) and used the same type of rain gauge. A standard 12.9 cm rain gauge has been used in Tanzania since 1921, and is still employed today. Rainfall is measured at a height of 25cm above the surface.

The CMAP precipitation data used in this study were the merged satellite, rain gauge and model precipitation estimates discussed in (Xie *et al.*, 1997). These data are gridded over the globe with a resolution of 2.5 x 2.5 degrees. CMAP data are available from 1979 onwards. Hachigonta & Reason (2007) used CMAP data to investigate the onset and cessation dates of the main summer rainfall season over Zambia. Their results indicated that CMAP data gave robust results over Zambia. Kijazi & Reason (2005) have used CMAP data to analyse the intra-seasonal variability over the coast of Tanzania and the data gave robust results over the region.

The satellite derived (GPCP) daily one degree rain rate data (Huffman *et al.*, 2001), were used in this study to analyse the flooding that occurred in 2006 over northern Tanzania. The GPCP data was used due to its high resolution (1°) as compared to CMAP (2.5°).

The sea surface temperature data used in this study include the National Oceanic and Atmospheric Administration (NOAA) optimum interpolated (OI) SST, produced weekly on a 1° grid (Reynolds *et al.*, 2002). These data are derived from *in situ* and satellites derived SSTs and include data for sea-ice covered regions. Before the optimum interpolation is performed, the satellite data are adjusted for biases. Monthly SST data were used in this study to identify regions of cooling and warming over the Atlantic and Indian Oceans related to rainfall variability over north-eastern Tanzania.

NOAA OLR data, available from June 1974, are used in this study as a proxy for convection (for example, Heddinghaus & Krueger, 1981; Liebmann & Hartmann, 1982). However, between March and December 1978, satellite failure led to missing data in this set.

2.1.2 Model data

The model data used in this study includes the NCEP/NCAR reanalysis and ECHAM 4.5 data sets. The NCEP/NCAR re-analysis data were used to assess the atmospheric circulation patterns over the Indian and Atlantic Oceans potentially associated with rainfall variability over Tanzania. The NCEP/NCAR reanalysis project is a joint undertaking between the National Centre for Environment Prediction (NCEP) and the National Centre for Atmospheric Research (NCAR) (Kalnay *et al.*, 1996). This project has produced atmospheric re-analyses using historical data from 1948. Together they have recovered land surface, ship, rawinsonde, aircraft, satellite and other data sources. They are also responsible for quality control and the assimilation of this data. NCEP re-analysis data are gridded over the globe with a resolution of $2.5^{\circ} \times 2.5^{\circ}$ and contain the horizontal and vertical wind, air temperature, geopotential height, humidity variables and various derived fields such as divergence and relative vorticity on various levels through the troposphere.

Specifically, four different levels of data are available: level A is strongly influenced by observed data and is the most reliable class; level B indicates that although there are observational data that directly affects the value of the variable, the model also has a significant influence on the analysis; level C is the most unreliable class, as the variables are derived solely from the model fields; and level D represents a field that is obtained from climatological values and does not depend on the model. The NCEP data used in this study comprises level A parameters (zonal and meridional wind), level B parameters (specific humidity and omega) and level C (surface latent heat flux). The daily and monthly re-analyses were used for the intra-seasonal and inter-annual variability analyses (Chapters 6, 4) respectively.

The ECHAM 4.5 monthly historical data obtained from the IRI website (<http://iridl.ldeo.columbia>) were used in this study to evaluate the skill of the ECHAM 4.5 GCM in capturing circulation features associated with rainfall variability over north-eastern Tanzania. The simulations were forced with

observed SST and a detailed description of the model is given in Roeckner *et al.*, (1996). Since output from this GCM are used by the IGAD Climate Prediction and Analysis Centre (ICPAC) in Nairobi to provide initial and boundary conditions for the regional high resolution spectral model (RSM) applied to seasonal forecasting over East Africa, there is interest in assessing this model over Tanzania. In particular, it is of interest to see whether this model is able to realistically capture the mean circulation over the region. If the model is reasonably successful in this regard, then confidence in its ability to provide robust initial and boundary conditions for the regional model will increase. The ECHAM4.5 data used were for the period 1970 - 2005. These data sets include monthly rainfall, specific humidity, zonal and meridional wind components at a resolution of $2.8125^{\circ} \times 2.7893^{\circ}$.

2.2 Methods of analysis

This section highlights the various analysis methods used in this study. Different analysis techniques were employed to understand the intra-seasonal and interannual rainfall variability over north-eastern Tanzania and to work towards developing an operational climate prediction capacity over the region. A detailed account of each method employed is discussed in the sections below.

2.2.1 Time series analysis

Monthly and daily rainfall data were subjected to time series analysis to examine the inter-annual and intra-seasonal variability. For inter-annual variability, monthly rainfall data were used to develop standardised rainfall anomaly indices over north-eastern Tanzania for the MAM, OND and November - April (N-A) rainfall seasons. Various indices were used to assess the intensity of the rainfall anomaly in East Africa. These include the standardised rainfall anomaly index (Ogallo & Nasib, 1984; Kabanda, 1995; Kijazi & Reason, 2005), the decile index, the weighted rainfall anomaly index (Ininda, 1987) and numerous others. The standardised rainfall anomaly index

similar to that employed by (Wagner & Da Silva, 1994) was used in the present study.

A rainfall index was computed by averaging a monthly rainfall for each region (north coast, North Eastern Highlands and central) and then computed the normalized departure for each month for each region. These values were computed by subtracting the monthly climatological means based on the 1970 - 2004 climatology from the values, and normalised by dividing each record by the corresponding monthly standard deviation. The normalised seasonal rainfall departures for each region (northern coast, North Eastern Highlands and central region) were obtained by averaging the normalised monthly values for the corresponding region. Based on computed standardised rainfall indices, a dry (wet) year was defined as when the seasonal rainfall was below (above) one standard deviation from the long-term mean (Kijazi & Reason, 2005). Otherwise, the year could be classified as 'normal.' However, for the North Eastern Highlands, an anomaly value of 0.8 was considered significant similar to the observations by (Mapande & Reason, 2005) for the south-western highlands of Tanzania.

For intra-seasonal variability, daily rainfall data were first grouped into five day means (pentads) before being subjected to time series analysis. The grouping was performed on a monthly basis such that the last pentad of a month has six days for a month with 31 days, while for a leap year the last pentad of February has four days (Appendix A). To facilitate comparison, the six – day pentads were multiplied by a factor 5/6 while the four-day pentads were multiplied by 5/4 (Asnani, 2005 chapter 11 p22 and chapter 14 page 48 – 49).

Time series analyses were used to plot five day rainfall time series for climatology and for the anomalously wet/dry years over the central part of the country, the NEH and the north coast. The criteria used in Kijazi & Reason (2005) were used in this study to select the onset, peak, end and major dry spells for each season. These are based on the specific rainfall threshold as defined below;

Short rain season (OND)

Onset: Five day rainfall of ≥ 7.5 mm followed by three consecutive pentads having a rainfall amount of not less than 5mm per pentad

Peak: The pentad with the highest amount of rainfall in the season

End: If three consecutive pentads have a mean rainfall ≤ 2 mm per day, the preceding pentad is considered to be the end of the rainy season

Dry spell: Five day rainfall of less than 7.5mm

Long rain season (MAM).

Onset: Five day rainfall exceeds 10mm followed by three consecutive pentads having a rainfall amount of not less than 10mm per pentad

Peak: The pentad with the highest amount of rainfall in the season

End: If three consecutive pentads have a mean rainfall of ≤ 2 mm per day, the preceding pentad is considered to be the end of rainy season

Dry spell: Five day rainfall of less than 10mm.

November to May season (N-M) for central region.

Onset: Five day rainfall exceeds 10mm followed by three consecutive pentads having a rainfall amount of not less than 10mm per pentad

Peak: The pentad with the highest amount of rainfall in the season

End: If three consecutive pentads have a mean rainfall of ≤ 2 mm per day, the preceding pentad is considered to be the end of the rainy season

The selected dates for each season are given in tables 6.1 – 6.3 in chapter 6 and are consistent with dates observed by (Mhita & Venäläinen , 1992; Kijazi & Reason, 2005) and Camberlin & Okoola, 2003)

2.2.2 Empirical Orthogonal Function analysis

Empirical Orthogonal Function (EOF) analysis is an efficient way of compressing data and identifying groups of inter-correlated variables (Richman *et al*, 1977, North *et al.*, 1982). The EOF analysis will separate noise from meaningful data. The analysis enables fields of highly correlated data to be represented adequately by a small number of orthogonal functions

and the corresponding orthogonal time coefficients, which account for much of the variance in their spatial and temporal variability.

EOF techniques are used to extract the uncorrelated structures that explain the largest variance of the original matrix from the covariance matrix. EOF analysis allows the calculation of orthogonal linear combinations of variables that account for maximum possible amounts of variance in a data set. The technique offers several important advantages (for example, Preisendorfer & Mobley, 1988), namely:

- i) A description of important patterns describing the data variability
- ii) The potential for data sets to be compressed
- iii) The filtering of data using only one significant component
- iv) The orthogonality property of the components is useful for predictor variables

The EOF technique allows the original data to be split into orthogonal spatial patterns (eigenvectors) and corresponding time series coefficients (principal components). An eigenvector pattern that accounts for a larger fraction of the variance (eigen values) is considered to be physically meaningful. Complete details of these methods can be found in statistical textbooks such as (Preisendorfer & Mobley, 1988; Johnston, 1992; William *et al.*, 1997). In addition, Kutzbach (1967) and Storch & Zwiers (1999) have provided an outline of the mathematical procedures necessary to define the functions and their time coefficients.

There are many methods that can be used to determine the number of significant PC components. The Kaiser Criterion considers all PC modes with eigenvalues greater or equal to one significant. North *et al.*, (1982) suggested the use of sampling errors in determining the number of significant eigenvectors. This thesis uses the criteria employed by (North *et al.*, 1982; Kaiser, 1959) to determine the number of dominant EOF modes.

2.2.3 Composite analyses

Composite analysis techniques have been used extensively in the field of meteorology. Rasmusson & Carpenter (1982); Matarira & Jury (1992); Park & Schubert (1993); Makarau (1994); Reason *et al.* (2000); Kijazi & Reason (2005) and others have all used the composite analysis technique to investigate regional climate variability. The advantage of this technique is that common features and patterns are better indicated than in individual cases. This method also reduces the total number of maps and figures associated with each case study.

Various methods are used to select cases to composite. However, it is important to select cases with similar characteristics. For the purposes of this study, cases were selected from the derived rainfall index. The main focus in the said selection is anomalously wet and dry seasons. Individual cases were selected according to the prescribed criteria mentioned above, and sequences of gridded atmospheric parameters were averaged for the specified wet and dry season. The historic mean was then subtracted to produce the anomalies, thereby enabling determination of composite differences and underlying signals.

2.2.4 Cross-sectional analyses

Height-latitude/longitude cross sections were used in this thesis to study moisture flux circulations during anomalously wet and dry years. The chosen longitude height section was for an average over latitude 15 °S and 1 °S, whereas the latitude height sections were for the fixed longitude of 37 °E and 40 °E. These cross-sections were chosen since they adequately represent the greater Tanzanian region and facilitated the analysis of the vertical structure of the regional moisture flux.

2.2.5 Wavelet analysis

Although wavelets were first introduced in the 1980s to process seismic data, they are now widely used in meteorology and oceanography to study a range of phenomena such as ENSO, dispersion of ocean waves etc. (Torrence & Compo, 1998; Emery & Thomson, 1998). Wavelet analysis is particularly well suited to the study of multi-scale, non-stationary processes occurring over finite spatial and temporal domains, in which the amplitudes and phases of the harmonic constituents may be changing rapidly in space or time (Lau & Weng, 1995). This aspect makes wavelets a preferable analysis tool compared to more traditional methods such as Fourier analysis. The latter transforms do not contain any time dependency in the signal and therefore cannot provide any local information regarding the time evolution of its spectral characteristics (Lau & Weng, 1995).

Although there are currently four common non-orthogonal wavelet functions, namely Morlet, Paul, Marr and DOG (Torrence *et al.*, 1998), the Morlet (Morlet, 1983) has been used for the purposes of this study, as its complex nature allows its wavelet power to combine both positive and negative peaks into a single broad peak. In other words, time – dependant amplitude (real) and phase (imaginary) can be detected for different frequencies exhibited in the time series. A Morlet wavelet is one whereby the function has zero mean and is localised both in time and frequency space. It is important to note that before performing a wavelet analysis, the rainfall data in this study was first subjected to PCA analysis and the first principal component for each season for each region was then subjected to wavelet analysis. Equations for the wavelet analysis are given in Torrence *et al.*, 1998.

2.3 Derived parameters

The reason for producing secondary derived parameters is that such values yield results when used in combination with primary parameters, such as winds and temperature, which describe meteorological dynamics and thermodynamic structure (Parker, 1994).

Divergence is defined as the acceleration and diffluence experienced by the air in the local horizontal plane. A region of divergence on an isobaric surface is one from which there is a net outflow of air mass. The component of divergence in the total two-dimensional fields used in this study is given in the following equation (Bluestein, 1992);

$$\text{Divergence} = \partial u / \partial x + \partial v / \partial y$$

where

u = zonal wind component

v = meridional wind component

x = longitudinal distance

y = latitudinal distance

The horizontal moisture flux for a given level can be obtained from the product of specific humidity and horizontal wind vector. In the tropics, the bulk of the horizontal transfer of moisture takes place below 700hPa (Newell *et al.*, 1972). The lower tropospheric wind field can therefore indicate most of the moisture transport. Earlier studies, for example, Goddard & Graham (1999), observed the 850hPa level to be the most representative of the behaviour of the vertically integrated moisture flux over East Africa. Based on this result, the 850hPa level was used in this thesis to analyse moisture flux.

Chen and Chen (1997) have shown that the velocity potential at 200hPa is a useful meteorological parameter in tropical climate studies. Velocity potential and stream function may be more useful than divergence and vorticity since they are components of the horizontal circulation wind vector and give useful representations in the tropics where mean winds are light. The physical properties of the horizontal two-dimensional wind field (V) can be described by considering the rotational and irrotational terms, also known as the non-divergent and divergent wind respectively.

Thus, $V = v_{\psi} + v_{\chi}$; where v_{ψ} is the stream function (rotational) part of the wind, while v_{χ} is the velocity potential (irrotational) part of the wind (Krishnamurti *et*

al., 1973). The velocity potential is useful for inferring changes in the large-scale vertical circulation and the Walker cell and has been used by various researchers for East African problems (for example, Kabanda & Jury, 1999, Mistry & Conway, 2003).

This chapter has provided details of the datasets and the analysis techniques used in this study. The following chapters use these data and techniques to address the research questions set out in chapter one. Chapter three give a description of the inter-annual variability.

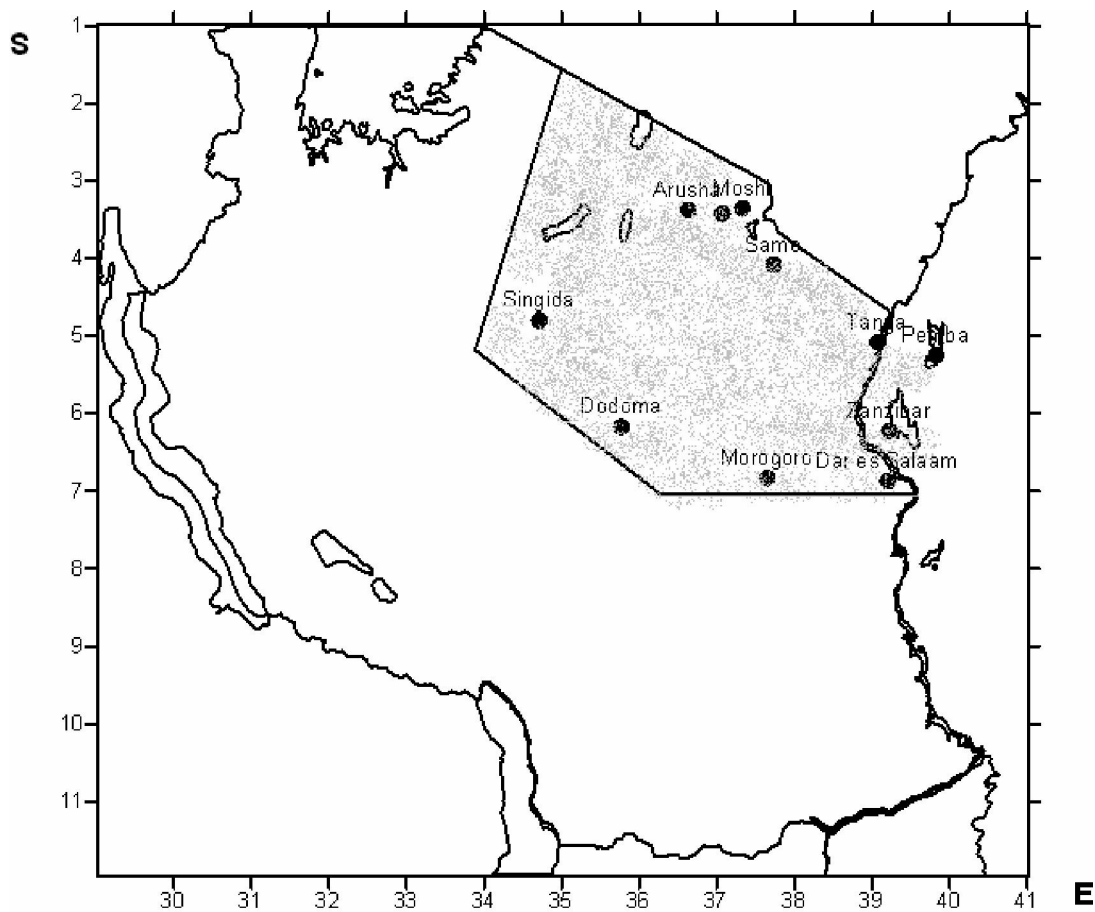


Fig 2.1: Map of Tanzania showing the region of study (shaded). Dodoma and Singida rainfall stations represents Central region; Morogoro, Dar es Salaam, Zanzibar, Pemba and Tanga are rainfall stations in the Northern coast; the North eastern highlands region is represented by Arusha, Moshi, KIA, and Same rainfall stations.

CHAPTER THREE

INTER-ANNUAL VARIABILITY

3.0 Introduction

This chapter deals with inter-annual variability in the climate of the region. However, it is important to understand the climatological fields before undertaking studies of inter-annual or intra-seasonal variability so that the background mean state is well established. Any changes in the intensity or the position of the mean state will influence the local atmospheric circulation and rainfall. This chapter is divided in two main parts. The first part (section 3.1 & 3.2) presents the mean fields for the sub-Saharan Africa and the neighbouring oceanic regions while the second part (section 3.3 to 3.) uses the mean characteristics as a background to examine the causes of inter-annual variability in the region, and specifically the north-eastern Tanzania.

Oceanic and atmospheric circulations over the Indian Ocean have a marked impact on convection over eastern Africa, particularly across the Eastern highlands from Ethiopia to eastern South Africa (Tanzania included). A warmer, tropical Indian Ocean is frequently associated with dry (wet) conditions over southern (equatorial eastern) Africa (Cadet, 1985; Reason and Mulenga, 1999). Observational evidence demonstrates that the strengthening of convection and latent heat release over the warmer central Indian Ocean occurs at the expense of precipitation over Africa (Jury, 1993; Camberlin, 1995). Indian Ocean SST forms the basis for long-range climate forecasts in many parts of Africa (Barnston *et al.*, 1996). Regions with high tropical precipitation have been observed as having a strong correlation with regions that have high SSTs (Bjerknes *et al.*, 1969; Liebmann & Hartmann, 1982; Neelin & Held, 1987).

Several studies have been undertaken to understand climate variability over eastern Africa and its link to global oceanic and atmospheric dynamics (Ropelewski & Halpert, 1987, Ogallo *et al.*, 1988). However, thus far there has not yet been any study that focuses directly on understanding the forcing mechanisms over the Atlantic and the Indian Oceans that are responsible for inter-annual rainfall variability in specific rainfall regions over Tanzania. This study is therefore intended to contribute towards addressing this gap.

In the tropics, OLR values are strongly influenced by cloudiness and vary directly with cloud top temperature and depth (Asnani, 1993). High OLR values are usually associated with the highly radiative temperatures of the Earth's surface and a lack of deep convective clouds in the free atmosphere. Conversely, low values of OLR are associated with the radiation from the tops of cold and high convective clouds (Asnani, 1993). With sufficient moisture in the atmosphere, one mechanism that can initiate convection is wind convergence at low levels and wind divergence at upper levels (Neelin & Held, 1987). As suggested by Chen & Tzeng (1990) the combination of dynamics and moisture fields results in a closer relationship to convection than either wind convergence or moisture alone. For the development of clouds and rainfall, vertical motion and moist air are required.

Based on the findings cited above, OLR (product of NOAA), SST, latent heat flux, moisture flux, velocity potential and wind (NCEP/NCAR-reanalysis) have been carefully analysed in this thesis to understand the mean circulations over Tanzania and its adjacent oceans (the Indian and South Atlantic Oceans) during the MAM and OND rainy seasons. The seasonal mean structures for wind, moisture flux, velocity potential and vertical velocity (omega) calculated for the period 1971- 2004 have been analysed and used as a background to understand the evolution of anomalies during the anomalously wet and dry years. It is worth noting here that a full discussion of the annual cycle of the various fields over the African region and neighbouring oceans was detailed in Kijazi, 2003.

3.1 Mean circulations during the MAM season

Research results based on statistical and numerical modelling have established SST anomaly forcing as a major climate forcing due to its high memory (Deser *et al.*, 2003). Climate predictability in the tropics is largely due to this slow evolving nature of SST and land surface conditions. Using various numerical model experiments, Goddard & Graham (1999) demonstrated the importance of the atmospheric response to Indian Ocean SST for simulating rainfall over East Africa. They associated warming over the equatorial

Western Indian Ocean with increased rainfall over Eastern Africa and cooling with decreased rainfall. Similarly, Kijazi & Reason (2005) associated positive (negative) SST anomalies over the equatorial Western Indian Ocean with increased (decreased) rainfall over the Tanzanian coast. The results discussed below demonstrate the long term mean SST patterns associated with the MAM seasonal rainfall over north-east Tanzania.

The NOAA optimum interpolated mean sea surface temperature field for the MAM season is shown in Figure 3.1 (a). The tropical Indian Ocean has a larger extent of warm water compared to the Atlantic Ocean. High SST values (over 28 °C) are observed between 15 °N – 15 °S in the Indian Ocean and along the equator over the Atlantic Ocean. In general, SSTs decrease poleward in response to reduced solar radiation. Since deep convection is found over regions of high SST, these play an important role in the diabatic forcing of Tanzanian circulation.

Major zones of convection in the tropics, with their resulting potential precipitation, have long been associated with low OLR (Riehl, 1979, Gadgil & Guruprasad, 1990). Kijazi and Reason (2005) have documented the correlation between seasonal rainfall over Tanzania and OLR. They found that eastward moving negative OLR anomalies over the tropical western Indian Ocean are related to above average rainfall over the Tanzanian coast. Regions of intense and/or frequent convection, such as those associated with the ITCZ, appear as regions of low OLR. At the same time, relatively cloud free subtropical trade wind regions that are characterised mainly by subsidence activity, are associated with relatively high OLR values. However, maritime subtropical regions characterised by stratocumulus clouds, are associated with low OLR values. Vincent *et al.* (1990) confirmed velocity potential and OLR as the best indicators of convective activity. This implies that OLR may be a useful proxy for convection.

The NOAA climatological OLR field for the MAM season is shown in Figure 3.1 (b). Low OLR values are evident over high SST regions, which further substantiate the fact that deep convection is found over regions with high

SST. The warmer Indian Ocean has a larger extent of low OLR values compared to the Atlantic Ocean, which is consistent with the SST field. Over the land areas, a region of continental convection is evident over the Congo basin, characterised by low OLR values of about 208 W/m^2 .

Semazzi *et al.*, (1999) documented the importance of latent heating in maintaining regional climate anomalies over southern Africa.

The latent heat flux data obtained from NCEP were averaged for the MAM season Figure 3.1 (c). Two regions of moisture sources with high latent heat flux values of about 160 W/m^2 can be observed over the South Indian Ocean east of Madagascar and over the Atlantic Ocean between 5°S and 15°S . Another two regions of moisture sources with latent heat flux values of about 140 W/m^2 are observed in the Northern Hemisphere closer to the Somali coast and in the vicinity of the equator over the Congo Basin. Evapo transpirational moisture re-cycling over the Congo forest may contribute to the moisture source in this region

Lower and upper tropospheric fields can help describe the state of the atmosphere. Camberlin & Wairoto (1997) documented the importance of easterly flows in advecting moisture from the Indian Ocean to the East African inland areas. The zonal and meridional wind components used in this section were obtained from the NCEP/NCAR.

MAM mean low level and upper level wind circulations are illustrated in Figure 3.2 (a - c). The subtropical anticyclones are prominent over the South Indian and South Atlantic Oceans as indicated by the 850 hPa plot. An axis of anticyclonic flows separates the westerlies south of 37°S from easterlies to the north. The region between 10°N and 30°S is a general region of easterlies, except for the southerly flow over the Congo basin, monsoonal westerly flow over the Indian Ocean in the neighbourhood of the equator and an anticyclonic circulation over South Africa. The descending branch of the Walker circulation is at about 55°E as indicated by westerlies to the East and easterlies to the West. These fetch moisture from the tropical South Indian

Ocean to Tanzania. The inter-tropical convergence zone (ITCZ) is at about 5 °S as indicated by the north-easterlies and south-westerlies converging near the Tanzanian coast at 700 hPa. The high SST values and low OLR values in this region further confirm the position of the ITCZ. Regions with a strong SST gradient are associated with strong wind (see Figure 3.1(a)). A broad band of easterly flow over the South Indian Ocean transports moisture towards Tanzania from the main region of moisture source, which is east of Madagascar.

At the upper level, strong westerly flow is evident over the subtropics, which indicates the position of the subtropical jet streams. Easterly flow covers much of the tropics reflecting the position of tropical easterly jet. The above outlined mean circulation patterns identify the main primary features responsible for Tanzania's rain in the MAM season. Any changes in the location of these mean features may increase or decrease rainfall over the country. The results suggest that the South Indian Ocean is the country's main source of moisture for the MAM rainfall season.

The MAM long term mean fields of vertical sections of zonal moisture flux averaged between 8 – 2 °S, along 40 °E and along 35 °E are shown in Figure 3.3 (a – c). The east-west vertical section of moisture flux (Figure 3.3(a)) shows an easterly moisture flux over much of the region except for the tongue of westerly moisture flux observed between 850 hPa and 650 hPa over the Indian Ocean. Between 27 °E and 37°E, the moisture flux increases from height, reaching a maximum at about 850 hPa and decreasing thereafter. Another region of high values of the easterly moisture flux is observed over the Indian Ocean between 42 °E and 51 °E, with the highest value at about 950 hPa. Further evidence of the easterly moisture flux over the region is shown by the zonal moisture flux plot along 40 °E and 35 °E (Figure 3.3 (b & c)). The easterly moisture flux over the coast is transported further inland with a high concentration of moisture in the lower levels. Over western Tanzania, between 12 °S to 3 °S, the concentration of the moisture flux seems to increase with movement from the coast further inland as indicated by high values of moisture flux at 35°E. This suggests a contribution from evapo-

transpiration and evaporation from inland lakes and rivers. It can therefore be suggested that local features contribute significantly to rainfall variability over Tanzania.

Regions of vertical motion indicate zones of convergence associated with the interactions between the meso-scale and large-scale flows, which largely determine the distribution of precipitation over Eastern Africa (Okeyo, 1986; Mukabana & Pielke, 1996; Indeje & Anyamba 1998).

The long-term mean velocity potential field at 850 hPa and 200 hPa and vertical velocity (ω) at 500 hPa during the MAM season is illustrated in Figure 3.4. Areas with upward motion are shaded in the ω plot. Subsidence is evident over East Africa as identified by negative (positive) velocity potential anomalies in the lower (upper) levels.

The position of the ITCZ extends over Northern Tanzania and lies north of the equator over Western Africa as indicated by uplift in the 500 hPa level plot (Figure 3.4(c)). The vertical motions, which mainly occur in the vicinity of the ITCZ associated with low-level moisture flux convergence and increase rainfall over Tanzania. Generally, the 500 hPa (Figure 3.4(c)), shows subsidence over much of the country with uplift over the Lake Victoria basin and coastal regions. This suggests that there is relative stability at 500hPa level and to get deep convection intense weather event is required to break through the mid-level stable layer.

3.2 Mean circulations during the OND season

Figure 3.5 (a) shows the mean OND SST field. Again, the tropical Indian Ocean has a larger extent of warm water compared to the Atlantic Ocean. High SST values of over 28 °C cover much of the equatorial Indian Ocean, while over the Atlantic Ocean high SST values extend between 5 °N – 5 °S. The SST values decrease pole-ward over both the Atlantic and the Indian Oceans. Comparison with the MAM plot (Figure 3.1(a)) shows that the water over the tropical oceans is warmer during the MAM season compared to the

OND season. Maximum SST values of about 29 °C are evident over the Indian Ocean during the MAM season, while during the OND season the maximum value is about 28 °C. Similarly, over the Atlantic Ocean the MAM SST values are higher by about 1 °C, compared to the OND SST values.

The climatological OND OLR field is shown in Figure 3.5 (b). One maritime and one continental region of deep convection is evident; namely, over the Indian Ocean east of 70 °E and over the Congo Basin south of the equator. Comparison with the MAM plot (Figure 3.1(b)) indicates that the continental zone of convection seems to deepen with the lower OLR value of about 208 W/m² extended over much of the Congo Basin.

Mean latent heat flux fields for the OND season are shown in Figure 3.5 (c). The region of low OLR values over the Congo Basin coincides with the high values of latent heat flux. This suggests that the Congo Basin may be an important moisture source for Tanzania during the OND season. Another two regions of moisture source with high latent heat flux values of about 140 W/m² are observed; namely, east of Madagascar and in the Arabian Sea.

The lower level and upper level wind fields for the OND season are shown in Figure 3.6 (a – c). The wind configurations are more or less similar to the MAM configuration. However, at 850 hPa over the Congo Basin, westerly winds that fetch moisture from the Congo Basin moisture source towards Tanzania coupled with wind convergence over Lake Victoria suggest that the Congo rain forest moisture source may contribute to OND rainfall over Tanzania. Similarly, over the North Indian Ocean, strong north-easterly flows fetch moisture from the Arabian Sea moisture source. At upper levels, the wind configuration is more or less similar to the MAM configuration.

The vertical section of zonal moisture flux averaged between 8 – 2 °S, along 40 °E and along 35 °E for the OND season is shown in Figure 3.7 (a – c). The east-west vertical section of moisture flux (Figure 3.7(a)) shows an easterly moisture flux over much of the region. The plot also indicates a westward tilt with height of larger easterly moisture flux reaching a maximum at about 850

hPa near 36 °E and at about 700 hPa at 28 °E. A tongue of westerly moisture flux emanating from the Congo rain forest was observed in the lower levels west of 30 °E, which further suggests the contribution of the Congo rain forest moisture source for the OND rainfall season. The zonal moisture flux along 40 °E and 35 °E (Figure 3.7 (b & c)) further shows a strong easterly moisture flux over the region with the highest concentration at 900 hPa over the coast and 850 hPa further inland. This indicates advection of moisture from the South Indian Ocean, which is consistent with the 850 hPa wind plot.

The long-term mean velocity potential at 850 hPa and 200 hPa and vertical velocity (omega) field at 500 hPa during the OND season may be seen in Figure 3.8. Areas with upward motion are shaded in the omega plot. The velocity potential plot (Figure 3.8 (a & b)) suggests the position the descending limb of the Walker type circulation over East Africa as identified by negative (positive) velocity potential anomalies in the lower (upper) levels.

At 500 hPa (Figure 3.8 (c)), the position of the zonal arm of the ITCZ is well defined, with the occurrence of the strong upward motion in the neighbourhood of the equator consistent with the wind and OLR plot. Similarly, the meridional arm of the ITZ is well indicated over western Tanzania, identified by strong upward motion. This position of the meridional arm of the ITCZ is also identified in the moisture flux plot. It is worth noting here that over the Atlantic Ocean, the position of the ITCZ lies north of the equator. Okoola (1999) associated this position with the occurrence of the cold tongue of SST over the region.

3.3 Inter-annual variability

The previous sections highlighted the major features of East African climatology for the MAM and OND seasons as represented on the NCEP/NCAR re-analysis. Some of these mean characteristics (wind, moisture flux, velocity potential and vertical velocity (omega)) are used in this section as a background to examine the causes of inter-annual variability in the region, and specifically the north-eastern Tanzania. Such atmospheric

parameters were selected due to the fact that they give a distinctive difference between wet and dry seasons over north-eastern Tanzania. The central issue is to understand the circulation anomalies over the Atlantic and the Indian Ocean that are responsible for inter-annual rainfall variability in the country as a whole. To further examine this, a detailed analysis of selected wet and dry seasons over Northern Tanzania will be conducted. It is worth noting here that no true composite analysis is carried out in this section and therefore the results obtained below should not be generalized. Specifically, this study looked at anomalous neutral years (that is, no ENSO event in the Pacific and no dipole mode event in the Indian Ocean). Analyses of individual years were considered to be appropriate since each year seems to have its own characteristics; thus, if they were combined in a composite, the results might be distorted. However, some aspects of the circulation anomalies determined below show similarities with previous studies (for example, Kabanda and Jury, 1999; Kijazi and Reason, 2005).

3.3.1 Results of rainfall time series analysis

Monthly rainfall data for nine stations scattered over the study region (Figure 2.1) were first normalized with respect to the standard deviation, and the time series of rainfall anomalies for the period 1970 - 2005 were plotted. Figure 3.9 – 3.11 shows the inter-annual time series analysis for the North Eastern Highlands (NEH), Northern Coast (NC) and Central (CEN). The seasons considered over the bimodal areas that is the NC and the NEH were October to December (commonly referred as “vuli”), and March to May (commonly referred as “masika”). The CEN’s season was divided into two: the early season extending from November to January, and the late season encompassing February to April. These were analysed alongside the long rainfall season, N-A. For wet seasons the years with standardized departure of ≥ 2 were considered to be anomalous wet years while for dry years the standardized departure of ≥ 1 was considered.

Normalised rainfall departures (averaged over the region) for the NEH’s OND and MAM seasons are shown in Figure 3.9 (a – b). During OND 1982 and

1997, the NEH experienced anomalously wet conditions (Figure 3.9(a)). These were El Niño and positive Indian Ocean Dipole Zonal Mode (IODZM) years, while 1975 (La Niña year) and 1996 (La Niña and negative Indian Ocean Dipole Zonal mode year) were anomalously dry years throughout the region. A scrutiny of the time series shows that during the period of study, the region experienced more dry than wet years. However, the dry anomalies are much weaker than the wet anomalies, which might be due to the fact that most of the strongest wet years experienced in the region were associated with El Niño and positive IODZM events (for example, 1972, 1982 and 1997). El Niño and positive IODZM events have been associated with devastating floods over East Africa (Indeje *et al.*, 2000). Two periods of widespread drought in the region include the years 1973 - 1976 and 1998 - 2005 (with the exception of 2002). Protracted strong La Niña events (Allan *et al.*, 2003) and negative IODZM events also occurred in these periods.

Despite 2002 being a wet year with a rainfall anomaly value of about 0.8, the period 1998 - 2005 stands out as one of Tanzania's worst droughts in recent history. Almost the entire country experienced at least two consecutive dry years of this period. However, longer periods of drought occurred in Northern Tanzania, specifically the NEH. This dry season had a significant impact on agriculture and energy, killing livestock by reducing the amount of foliage available for feeding, to name but one example. Farms dried up as well, which caused food rationing throughout the region. Similarly, water and electricity were rationed. Chapter four of this thesis examines a case study experienced during the drought to further illustrate its devastating effects.

During the MAM season (Figure 3.9(b)), 1978 and 1979 were anomalously wet years with a rainfall departure of >2 . Years 1973 and 2004 were anomalously dry with a rainfall anomaly value of about -1.5. Again, more dry than wet years occurred and it is important to note that the dry anomalies tended to be weak compared to the wet anomalies. The recent drought in the region (1998 - 2005) that occurred during the OND season was also observed during the MAM season, although it began in 2000 rather than in 1998 as for the OND season.

During the NC's OND season (Figure 3.10(a)), 1994 (El Niño year) and 1997 (El Niño and positive IODZM year) were anomalously wet years, while 1973 (a La Niña year) and 1974 were anomalously dry. Again, many years were observed to be dry with weaker rainfall anomalies as compared to wet years. The extended periods of drought from 1973 - 1976 and 1998 - 2005 experienced in the NEH were also observed in the NC apart from the near average rainfall that fell in 2002 and 2004. This illustrates the spatial distribution of drought over the northern part of the country during this period. The main impact of the 1998 - 2005 droughts over the NC was on power and water rationing, which caused negative economic growth.

During the NC's MAM season (Figure 3.10(b)), 1979, 1986 and 1994 were anomalously wet years, while 1980 and 2003 were anomalously dry. Four years of protracted drought were observed from 1974 – 1977, and were repeated during the years 1999 - 2004 (apart from average rainfall in 2005 and wet conditions in 2002). Again, this is indicative of the widespread drought that occurred over Northern Tanzania during this period.

The CEN usually experiences one long rainfall season extending from November – April (N – A). As previously mentioned, this season has been divided into an early season (November to January) and a late season (February to April) to study its impact on agriculture, which is significant. During the N - A long rainfall season (Figure 3.11(a)), the CEN experienced more dry years than wet. 1997 and 2000 were anomalously wet years, while 1996 was an anomalously dry year. Five consecutive years of drought were observed throughout the region from 1973 - 1977.

During the early season of November to January (Figure 3.11(b)), the time series shows two anomalously wet years, namely 1997 and 2000, while 1996 was anomalously dry. A drought extending from 1973 - 1977 was also recorded. During the February to April late season (Figure 3.11(c)), 1990 and 1996 were anomalously wet years, while 1997 and 2003 were anomalously dry. Four consecutive dry years were observed from 1975 to 1978.

A comparison of the three time series over the CEN shows that the contribution towards the anomalously wet years during the N - A long rainfall season mainly came from the early season. During the late season, 1997 was dry, while 2000 had near-normal rainfall. Similarly, 1996 was anomalously wet during the late season, while for the long season it was an anomalously dry.

In the next sections, the analysis will concentrate on the selected anomalous wet and dry years over the study region. The focus is on studying atmospheric circulations over the Indian and Atlantic Oceans associated with inter-annual rainfall variability over north-eastern Tanzania.

3.3.2 Circulations associates with anomalous wet and dry OND and MAM seasons over the NEH

This section considers the circulations associated with selected wet and dry OND and MAM season. Based on the rainfall index (Figure 3.9(b)) a few selected wet and dry years during MAM season over the North Eastern Highlands (NEH) were analysed in this section. The analysis of inter-annual variability over the north coast (NC) during El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) years was detailed in Kijazi (2003). This section therefore considers the NEH which is an important agricultural region in the country. Special attention was given to the March to May (MAM) season and non-ENSO years during the OND season. The selection of years was based on the strong wet/dry years having rainfall anomaly value of at least one standard deviation (Figure 3.9(b)). However, for the sake of brevity two years will be considered in each category except for wet OND season where only one non ENSO year (1978) occurred during the study period. The wet years to be considered for MAM season are 1978 and 1979 while 1973 and 1993 are selected dry MAM years. For the OND season 2001 and 2003 were considered as dry non ENSO years while 1978 was the selected wet non ENSO year.

Various atmospheric parameters were analysed with the objective of understanding the circulation features associated with wet and dry MAM and

OND seasons over the NEH. However, only the moisture flux, omega and velocity potential are shown for brevity.

3.3.2.1 Anomalous wet and dry years during the OND season over the NEH

The analysis under this section considered seasonal anomalies for selected meteorological fields during the OND season of the selected anomalous neutral years (that is no ENSO in the Pacific and no dipole mode in the Indian Ocean. As mentioned earlier 1978 was the selected anomalous wet year while 2001 and 2003 were the selected dry years.

The main objective of this section is to understand the atmospheric circulation features that are responsible for the anomalous wet and dry conditions over the NEH during neutral years and to contrast the results with ENSO and IOD years. A detailed analysis of ENSO and IOD years can be found in Kijazi (2003) and Kijazi and Reason (2005). El Niño and positive IOD years were associated with wet conditions while La Niña and negative IOD years were associated with dry condition over Tanzania.

Figure 3.12 and 3.13 illustrate OND anomaly fields for 1978 wet non El Niño and non negative IOD year. The OND moisture flux plot at 850 hPa (Figure 3.12(a)) shows the existence of easterly anomalies of moisture flux over the equatorial Western Indian Ocean between 5°N and 5°S. Kijazi and Reason (2005) have associated easterlies over this region with increased rainfall over Tanzania. Strong westerly moisture flux anomalies emanating from the Congo basin converge with north easterly anomalies over northern Tanzania. Such moisture flux convergence is further shown by the moisture flux convergence plot (Figure 3.12(b)) that shows strong moisture flux convergence over northern and eastern Tanzania consistent with wet conditions observed over the NEH. The omega plot (Figure 3.12(c) shows strong relative uplift over the tropical Western Indian Ocean and much of Tanzania. Again this is consistent with wet conditions observed.

The descending limb of the Indian Ocean Walker cell was located over the equatorial Eastern Africa as revealed by the negative (positive) velocity potential in the lower (upper) levels. The corresponding ascending limb is located over Australia as identified by the positive (negative) velocity potential anomalies in the lower (upper) levels. Kijazi and Reason (2005) associated wet conditions over Tanzania during El Niño years with the ascending limb of the Indian Ocean Walker cell located over the country. In this case, the rainfall is more likely related to regional atmospheric circulation anomalies rather than from any clear influence from larger scale circulation patterns unlike for El Niño.

Figure 3.14 and 3.15 illustrate seasonal anomaly fields for 2001 which was a particularly dry non La Niña and non negative IOD year during the OND season. The moisture flux anomaly plot (Figure 3.14(a)), shows strong westerly flux over the equatorial western Indian Ocean coupled with easterly anomalies over the Congo basin and moisture flux divergence over much of East Africa (Figure 3.14(b)). Such moisture flux circulation features tend to divert moisture away from Tanzania consistent with dry conditions observed.

The omega plot (Figure 3.14(c)) shows strong relative subsidence over the equatorial Western Indian Ocean and much of East Africa including Tanzania. The subsidence over the study region tends to suppress convection consistent with the observed dry conditions. The subsidence over the region is further indicated by the velocity potential plot (Figure 3.15 (a & b)) that show negative (positive) velocity potential in the lower (upper) levels.

It is worth noting here that the Congo basin is an important region that shows a distinctive moisture flux patterns during wet and dry non ENSO years. Kijazi and Reason (2005) have shown a distinctive wind and moisture flux circulation patterns over the equatorial West Indian Ocean between 5°N and 5°S during wet and dry ENSO years. During wet El Niño years easterly anomalies dominate over the region while during dry La Niña years westerly anomalies occur there. However, this study has identified the occurrence of

westerly moisture flux anomalies over the Congo basin during wet non ENSO years and easterly moisture flux anomalies during dry non ENSO years.

Figure 3.16 and 3.17 illustrate seasonal anomaly fields for 2003 which was a dry non La Niña and non negative IOD year during the OND season. During the OND 2003, the moisture flux plot (Figure 3.16(a)), indicate similar features as 2001 except for the strong westerly moisture flux anomalies over much Tanzania. The moisture flux divergence (Figure 3.16(b)) covers much of Uganda, Kenya and the north eastern highlands of Tanzania consistent with the observed dry conditions. The omega plot (Figure 3.16(c)), shows subsidence over the equatorial Western Indian Ocean, Kenya, Uganda and northern Tanzania, again, consistent with the observed dry conditions.

The velocity potential plot (Figure 3.17 (a & b)), shows similar features as 2001 with subsidence over Tanzania as identified by negative (positive) velocity potential in the lower (upper) levels. It is worth noting here that similar atmospheric circulation patterns were observed over the region during the OND 2001 dry non ENSO year suggesting that the circulation patterns presented here are not simply a special case but may have relevance to other dry non ENSO years and thus may have some predictability based on the atmospheric circulation patterns.

3.3.2.2 Anomalous wet and dry years during the MAM season over the NEH

This section considers circulations associated with anomalously wet and dry MAM seasons. The seasonal atmospheric fields for the wet and dry MAM seasons of selected anomalously wet/dry years over the NEH were analysed. The specific intention is to understand the circulation features associated with wet/dry conditions over the NEH during MAM season. Scrutiny of the time series (Figure 3.9 (b)), indicated 1993 and 1973 as anomalously dry years while 1979 and 1978 were anomalously wet years.

Figure 3.18 and 3.19 illustrate seasonal anomaly fields for 1973 dry MAM season over the NEH. During 1973 dry MAM season (Figure 3.18(a)), the moisture flux plot indicate westerly moisture flux anomaly over much of Tanzania and equatorial western Indian Ocean with strong westerly anomalies between the equator and 5°S. The moisture flux divergent plot figure 3.18(b) shows moisture flux divergence over Tanzania. Such moisture flux circulation patterns tend to transport moisture away from Tanzania consistent with dry conditions observed.

The omega plot (Figure 3.18(c)) indicates strong relative ascent centred over the equatorial western Indian Ocean with strong relative subsidence over Tanzania consistent with the observed dry conditions. The subsidence is further shown by the velocity potential plot (Figure 3.19 (a & b)) that shows negative (positive) velocity potential in the lower (upper) levels.

Similar moisture flux circulation patterns as 1973 were observed in 1993 (Figure 3.20 (a & b)) except for strong easterly moisture flux anomaly over the Congo Basin that diverts moisture away from Tanzania consistent with the observed dry conditions. Similarly, the moisture flux divergence plot indicates strong moisture flux divergence over Tanzania. The omega plot (Figure 3.20c), show strong relative subsidence that covers the entire country consistent with dry conditions recorded. This was further indicated by the velocity potential plot (Figure 3.21(a & b)), that show negative (positive) velocity potential in the lower (upper) levels over East Africa.

Figure 3.22 and 3.23 illustrate seasonal anomaly fields for 1978 wet MAM season over the NEH. During 1978 wet MAM season (Figure 3.22(a)), the moisture flux plot indicate a reverse circulation patterns to the OND patterns over the equatorial West Indian Ocean consistent with the seasonal march of the ITCZ. The south easterly moisture flux veers to southerly moisture flux over the NEH. The curvature is associated with convergence as shown in the moisture flux divergence plot (Figure 3.22(b)). The vertical velocity plot (Figure 3.22(c)) show strong relative uplift over the equatorial Western Indian Ocean, Uganda, Kenya and northern Tanzania that is consistent with the

observed wet conditions. The velocity potential plot (Figure 3.23) shows divergence (convergence) in the lower (upper) levels over East Africa indicating subsidence over the region of study. Again as defined earlier, the rainfall over the region is more likely related to regional atmospheric circulation anomalies rather than from any clear influence from larger scale circulation patterns.

Figure 3.24 and 3.25 illustrate seasonal anomaly fields for 1979 wet MAM season over the NEH. Similar moisture flux and velocity potential circulation patterns as 1978 were observed except for the moisture flux convergence that seem to extend much far inland in Figure 3.24(b). This suggests that the circulation patterns presented here are not simply a special case but may have relevance to other wet MAM years and thus may have some predictability based on the atmospheric circulation patterns.

In summary, the dry/wet conditions over the NEH during the OND and MAM seasons were associated with moisture flux divergence/convergence over northern Tanzania coupled with downward/upward motion. The following section gives a summary and conclusion of the chapter.

3.4 SUMMARY AND DISCUSSION

The mean MAM and OND structure of Tanzania and its adjacent oceans has been presented in section one and two of this chapter and the following characteristics could be inferred:

(i) The tropical Indian Ocean has a larger extent of warm water compared to the Atlantic Ocean. The lower values of SST over the Atlantic Ocean may be contributed to the Benguela current upwelling, the equatorial cold tongue and upwelling over the Gulf of Guinea. The water over the oceans was warmer during the MAM season compared to the OND season.

(ii) The OLR field shows one maritime (over the Indian Ocean) and one continental (over the Congo rain forest) region of deep convection. Johnson &

Morth (1961) and Nakamura (1968) associate the region of continental convection over the Congo rain forest with East African rainfall. They indicated that the wet rainfall conditions in the region were associated with the cool, moist and unstable westerly air mass from the Congo rain forest transported into the East African region by the equatorial mid-tropospheric westerly winds. Kijazi (2003) associated the maritime region of deep convection over the Indian Ocean with increased rainfall in Tanzania.

(iii) The latent heat flux field shows high values of latent heat flux over the Congo Basin for the OND season, suggesting the Congo rain forest to be among the sources of moisture for this season. The moisture source over the South Indian Ocean east of Madagascar occurs for both the MAM and OND seasons. Camberlin (1995) related latent heat release over the central Indian Ocean with rainfall over Africa.

(iv) The mean wind circulation plots further confirm the contribution of the Congo rain forest moisture source to the OND season. The westerly flow from the Congo forest converges with the easterly flow over the Lake Victoria basin. The descending branch of the Walker circulation is at about 55 °E over the Indian Ocean. Longitudinal shifts of this branch may cause rainfall anomalies over East Africa (Semazzi & Indeje, 1999).

(v) The mean vertical section of the moisture flux field shows an easterly moisture flux over much of the region for both the OND and MAM seasons. This result suggests the Indian Ocean to be the main source of moisture for Tanzanian rainfall. Okoola (1999) associated the easterly wind over the Indian Ocean with wet spells over the East African region.

(vi) The mean vertical velocity field indicates the mean position of the zonal arm of the ITCZ at about 15 °S and the meridional arm over Western Tanzania. The descending branch of the Walker type circulation was shown to be located over the equatorial western Indian Ocean. Again, the shift of these mean positions may translate into climate anomalies over the Tanzanian region.

Section three of this chapter has examined inter-annual variability of seasonal rainfall over North-eastern Tanzania. Generally, the region experienced more drier rather than wet years during the period of study. However, dry anomalies were much weaker than wet anomalies, and the influence of El Niño on the latter is suggested as one of the causes. The early and late seasons in the CEN indicated contrasting rainfall characteristics (for example, 1997 was wet during the early season and dry during the late season). Similarly, 1996 exhibited the same characteristics. It is therefore important to incorporate such rainfall characteristics into agricultural planning.

Circulation features during the OND and MAM seasons indicate that the dry season over the study region were associated with strong subsidence coupled with a strong moisture flux divergence. However, for the wet seasons these observations reverse and moisture flux convergence coupled with upward motion occurs over much of the country.

This chapter had advanced our understanding of the circulation features responsible for the inter-annual rainfall variability over North-eastern Tanzania. The subsidence and ascent coupled with moisture flux divergence and convergence over the region were suggested to have significant contribution to the rainfall variability over the region. To further understand the circulation features during protracted drought and heavy rainfall events, the next chapter analyse the circulations associated with 1998-2005 drought and 2006 flood.

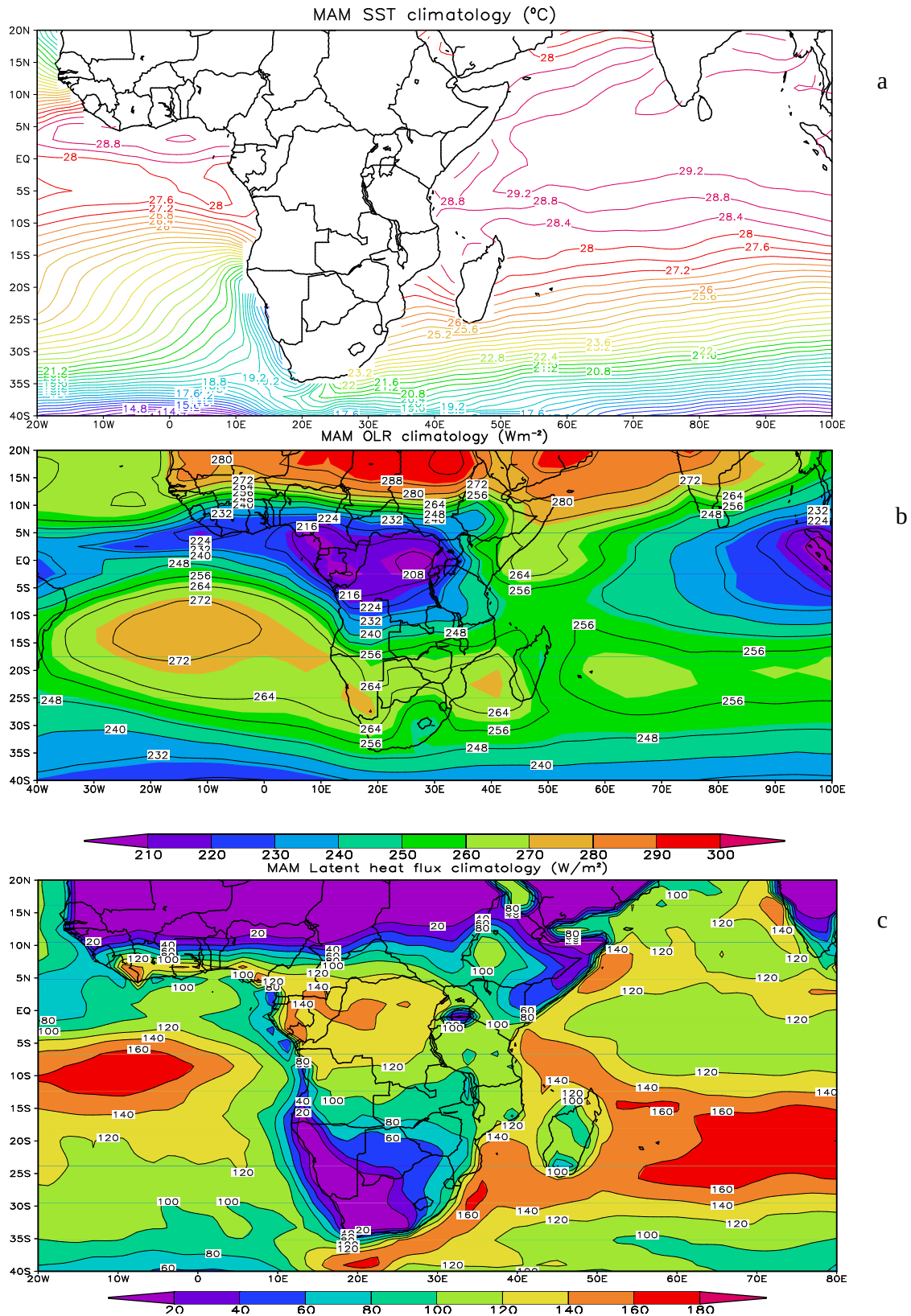


Fig 3.1: MAM long-term mean fields (a) SST in $^{\circ}\text{C}$ (b) OLR in W/m^2 and (c) Latent Heat Flux in W/m^2

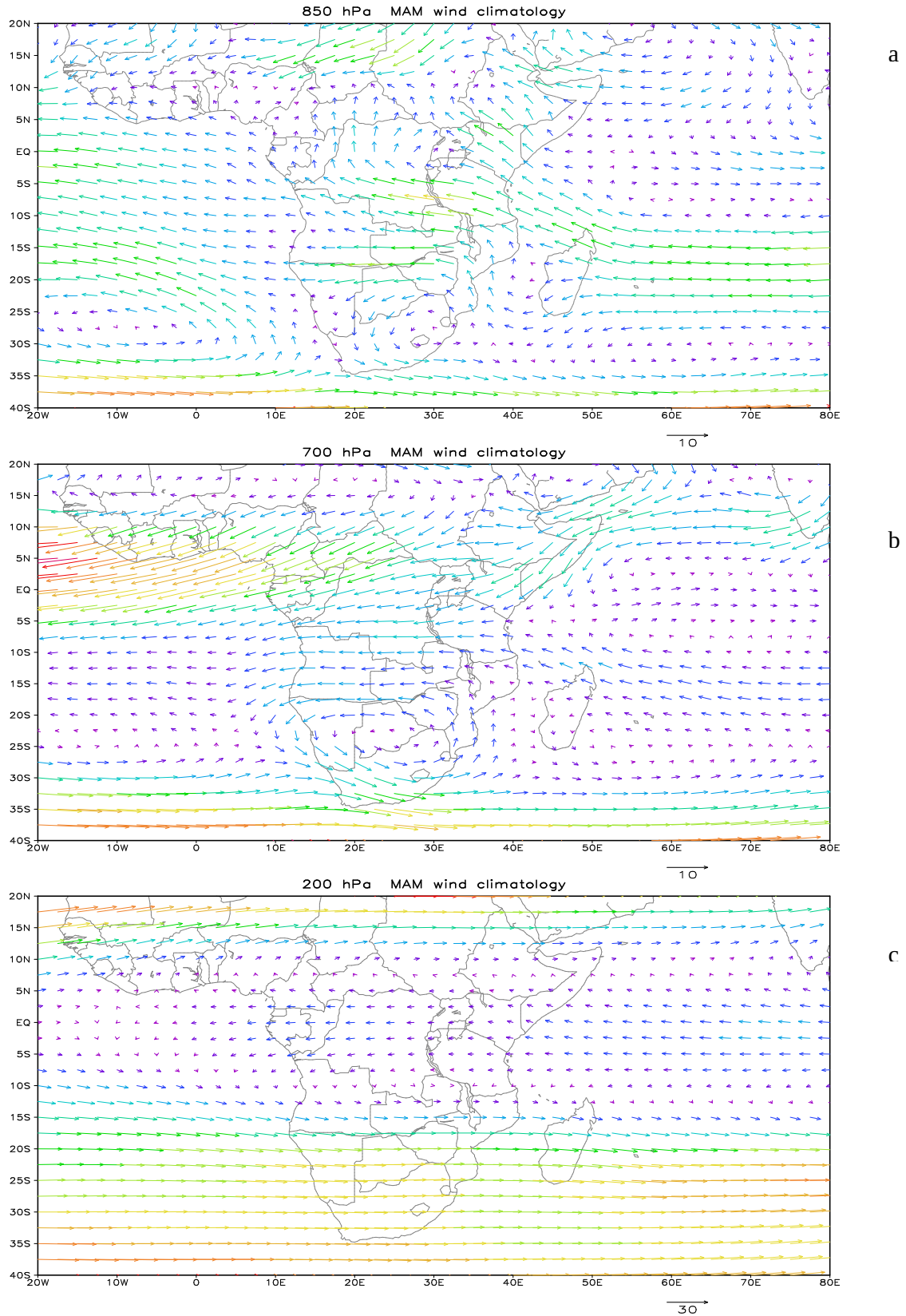


Fig 3.2: MAM long-term mean wind field in m/s (a) 850hPa (b) 700hPa (c) 200hPa

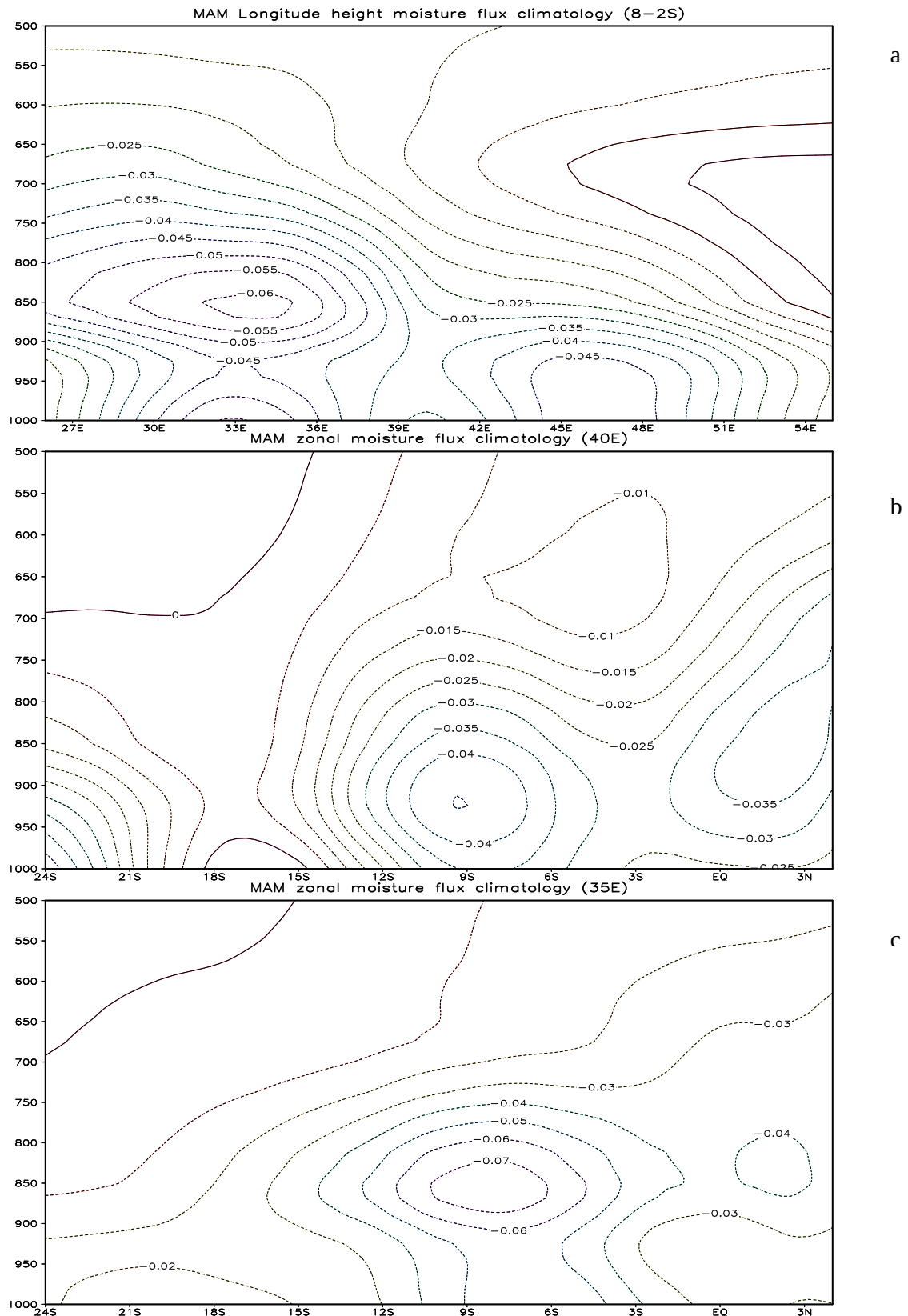
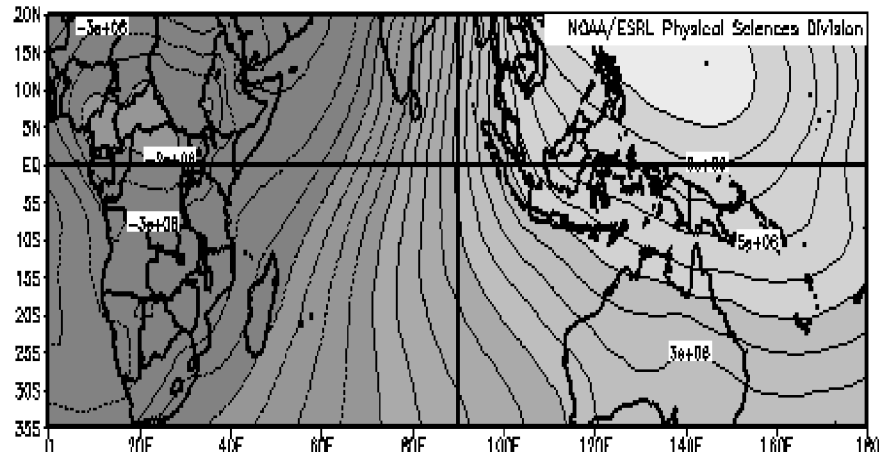


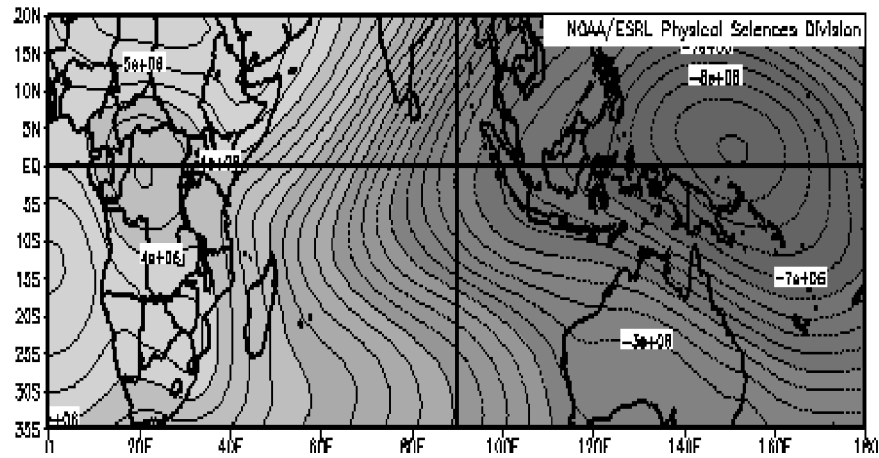
Fig 3.3: MAM long-term mean fields of cross-sectional zonal moisture flux in $\text{gkg}^{-1} \text{ms}^{-1}$ (a) averaged between 8-2°S (b) along 40°E (c) along 35°E

MAM, 850 hPa velocity potential Climatology ($\text{m}^2 \text{s}^{-1}$)



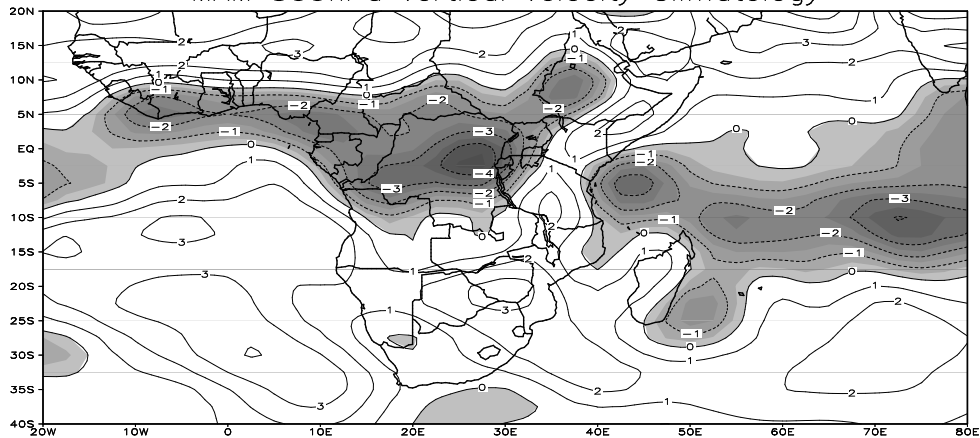
a

MAM, 200 hPa velocity potential Climatology ($\text{m}^2 \text{s}^{-1}$)



b

MAM 500hPa vertical velocity Climatology



c

Fig 3.4: MAM climatological circulations for velocity potential in $\text{m}^2 \text{s}^{-1}$ at (a) 850hPa (b) 200hPa and (c) 500hPa vertical velocity (omega) in Pa s^{-1}

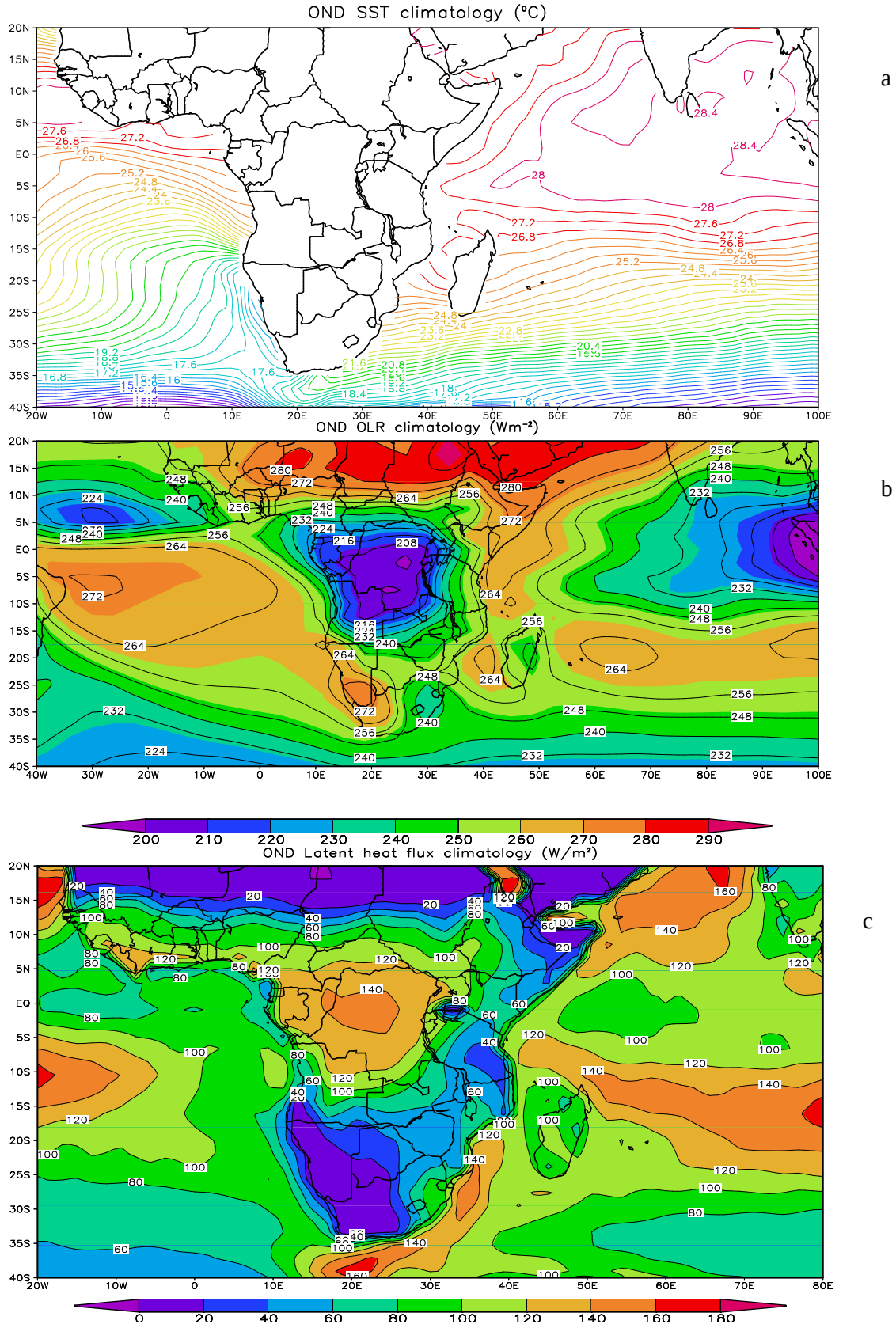


Fig 3.5: As for Figure 3.1 but for OND season

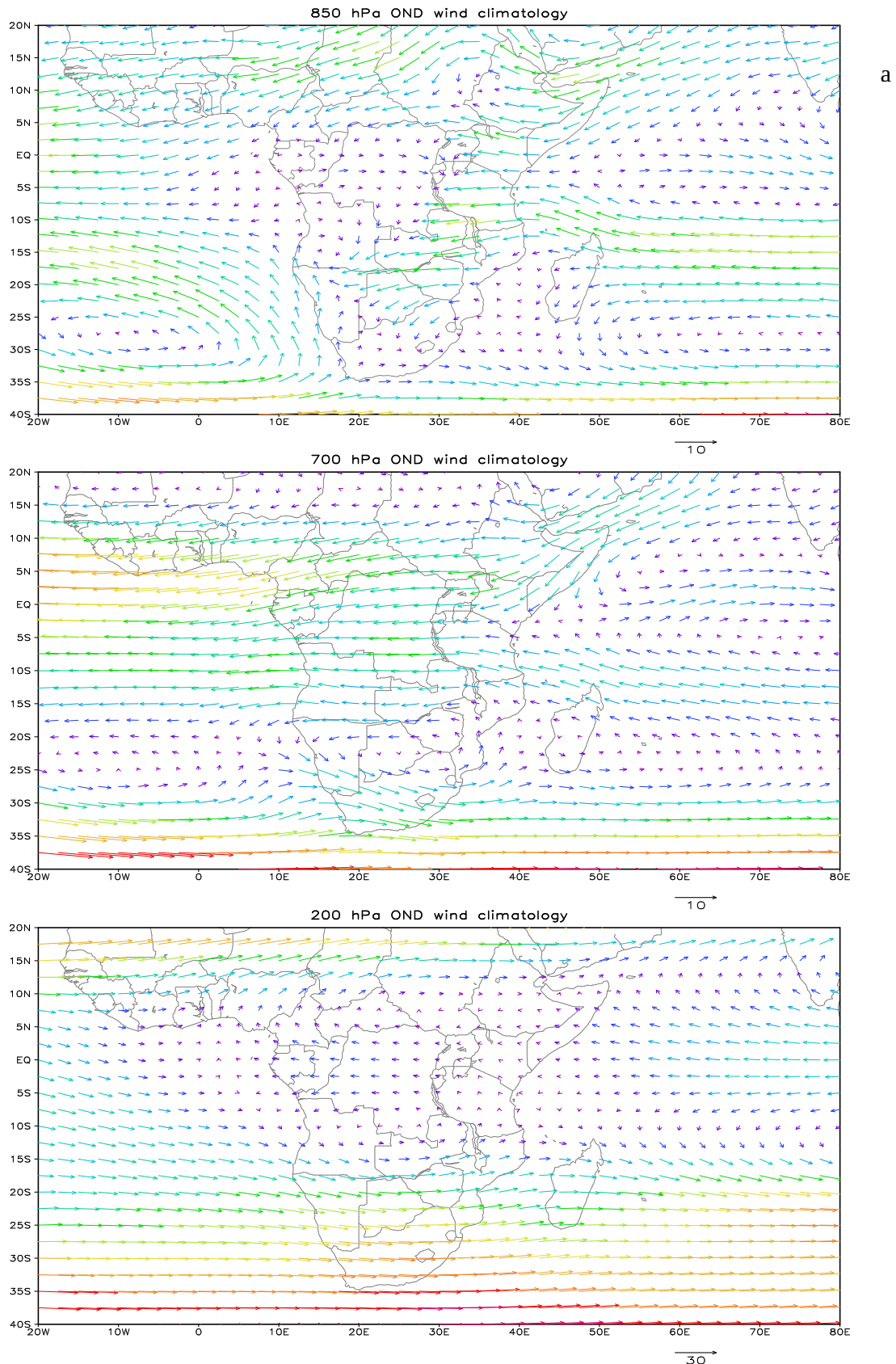


Fig 3.6: As for Figure 3.2 but for OND

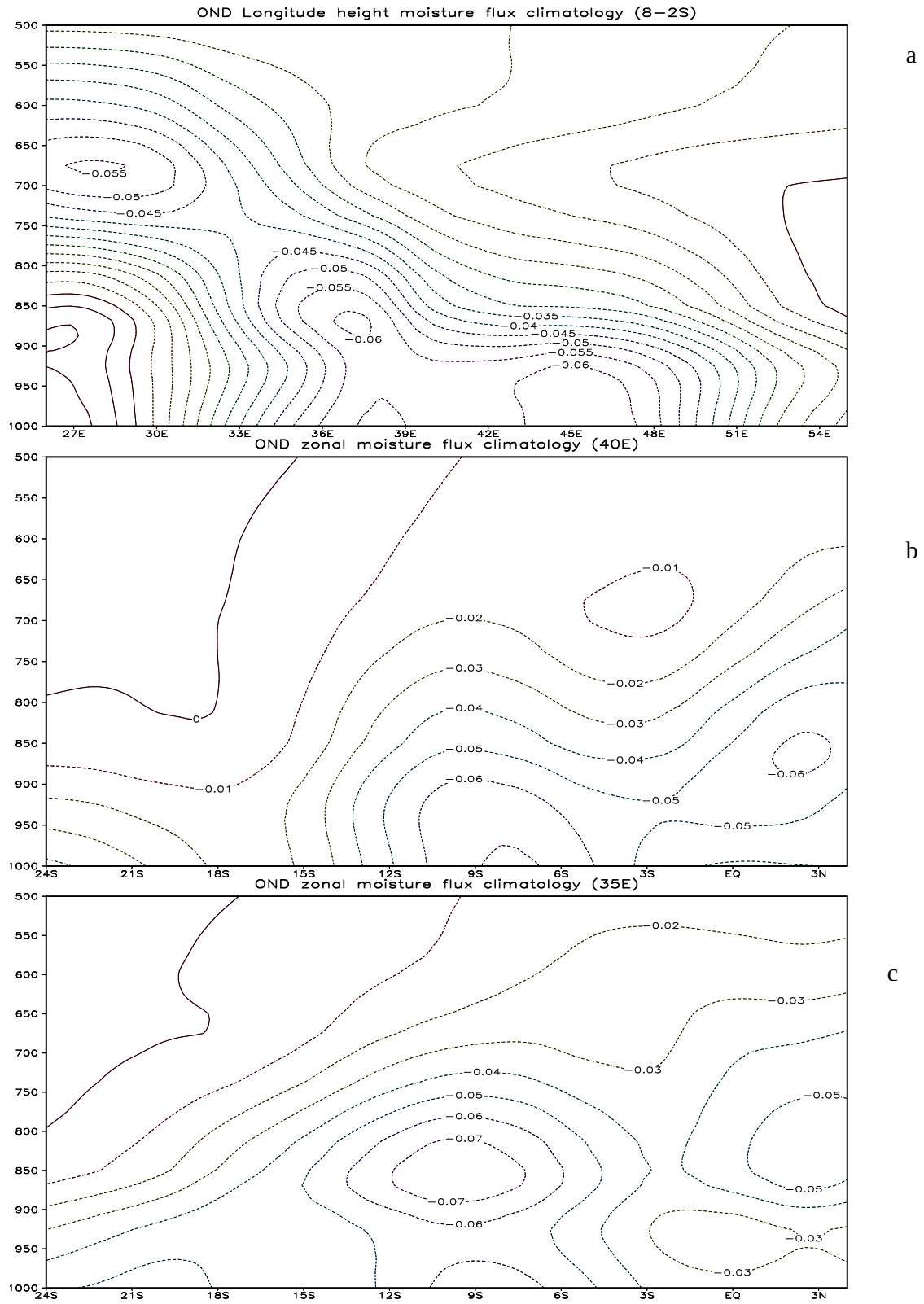
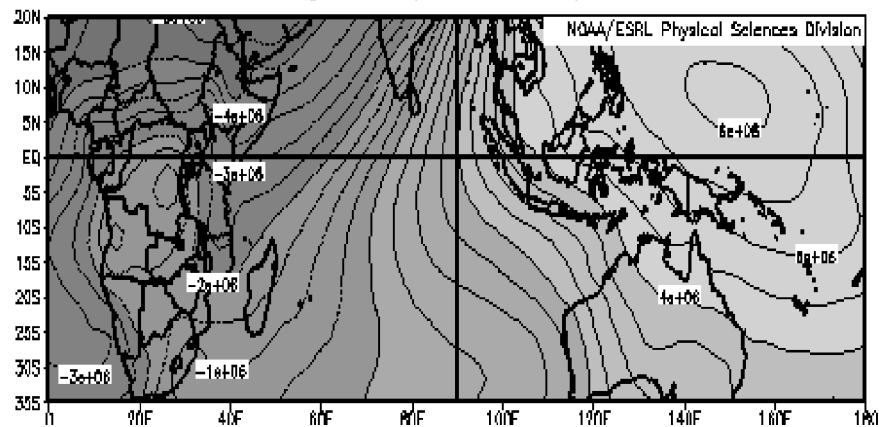


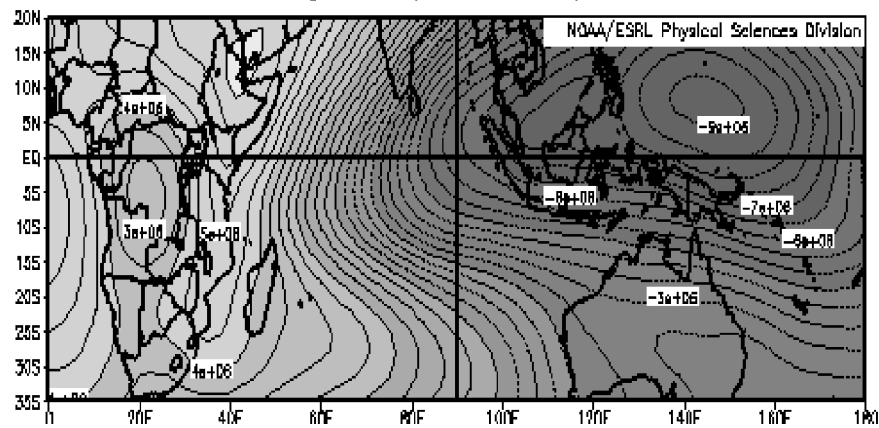
Fig 3.7: As for Figure 3.3 but for OND

OND, 850 hPa velocity potential Climatology ($\text{m}^2 \text{s}^{-1}$)



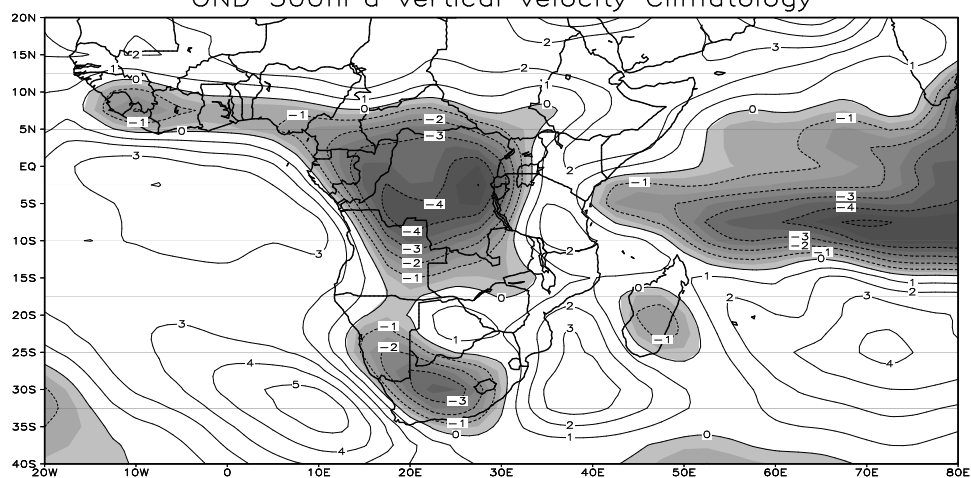
a

OND, 200 hPa velocity potential Climatology ($\text{m}^2 \text{s}^{-1}$)



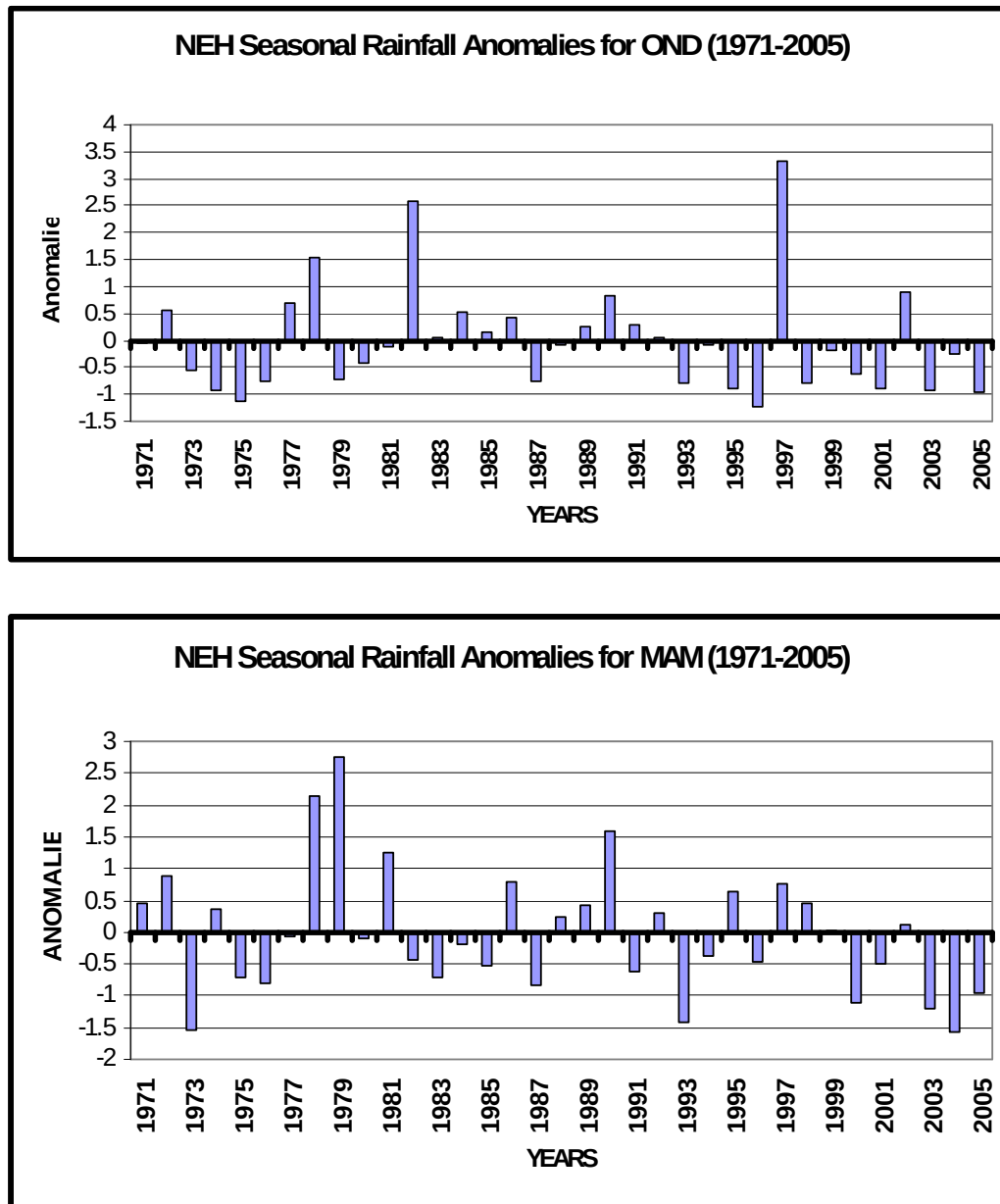
b

OND 500hPa vertical velocity Climatology



c

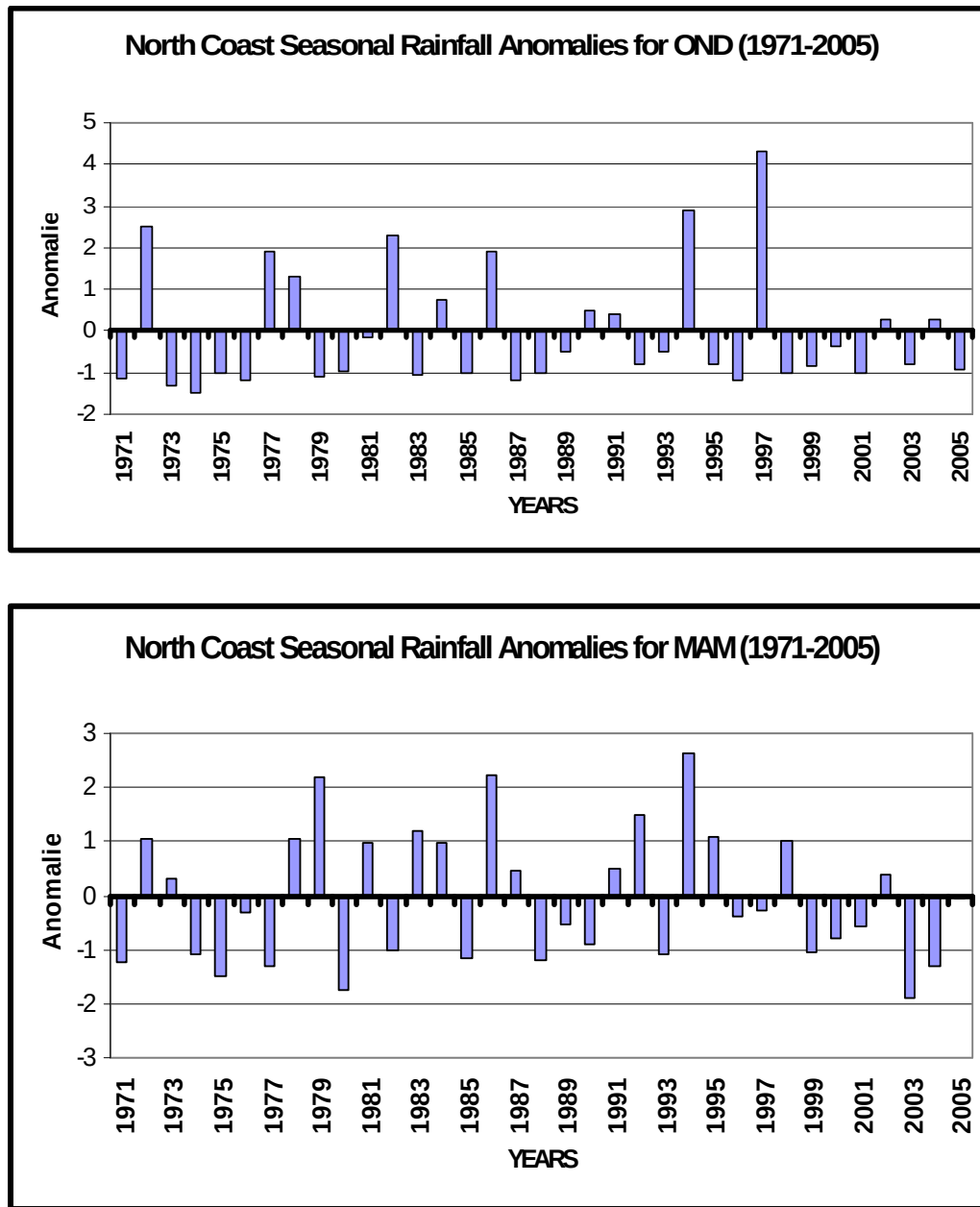
Fig 3.8: As for Figure 3.4 but for OND



a

b

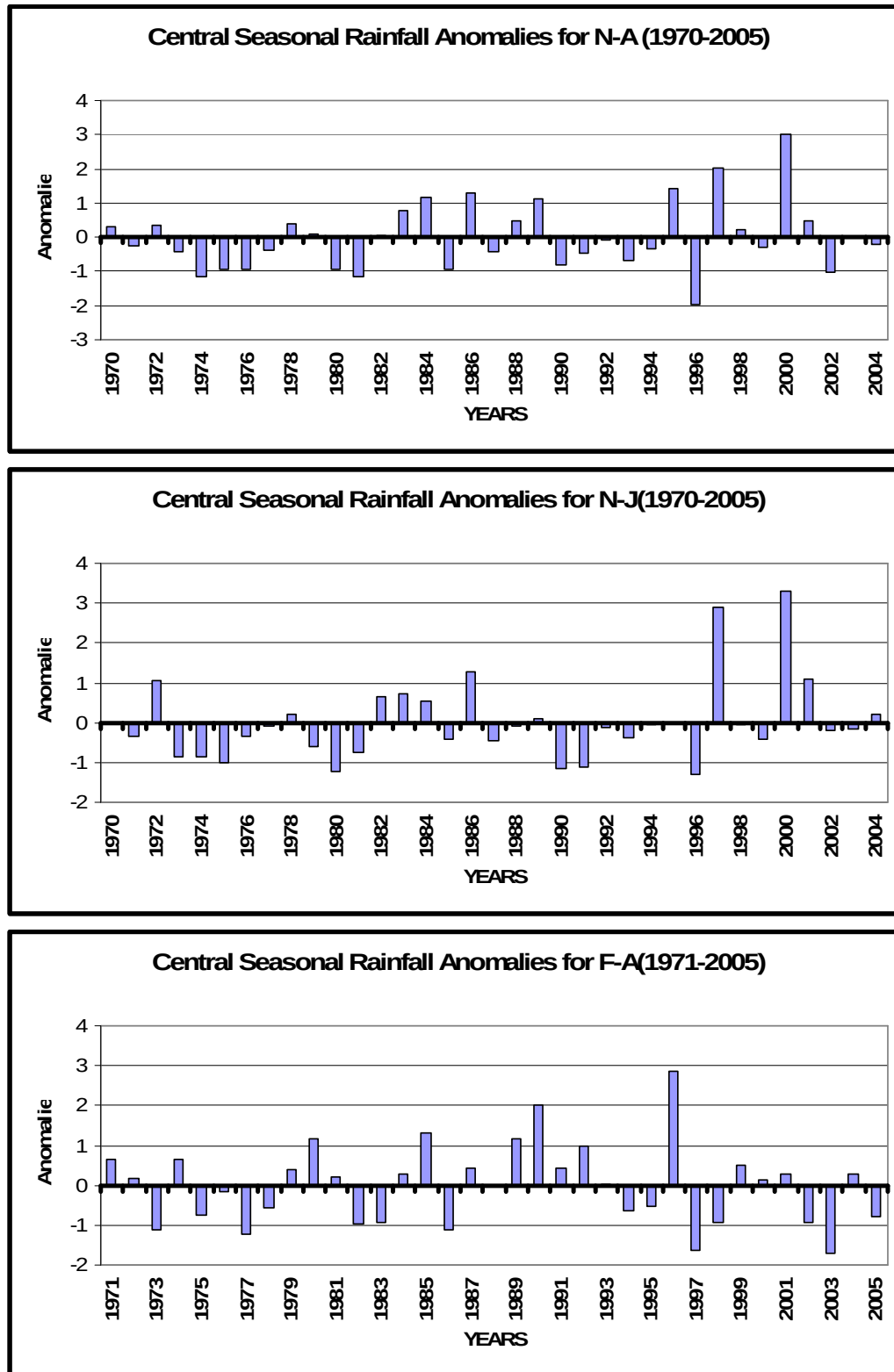
Fig 3.9: Time series of standardized rainfall for North eastern highlands (a) OND (b) MAM



a

b

Fig 3.10: Time series of standardized rainfall for North Coast (a) OND (b) MAM

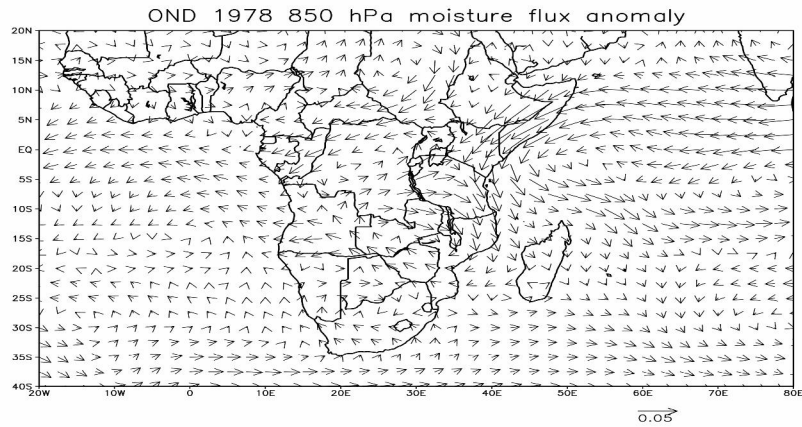


a

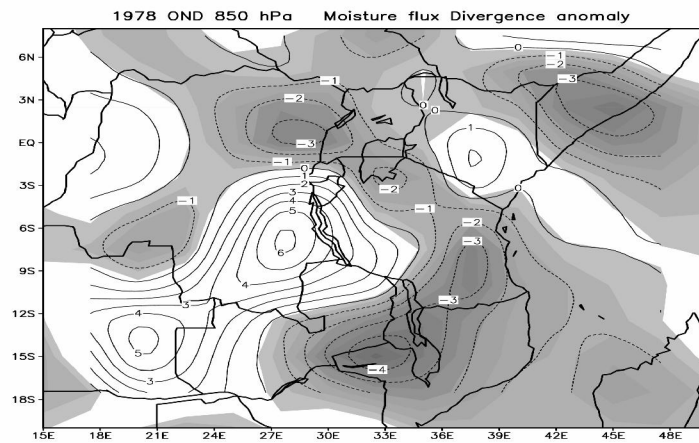
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c

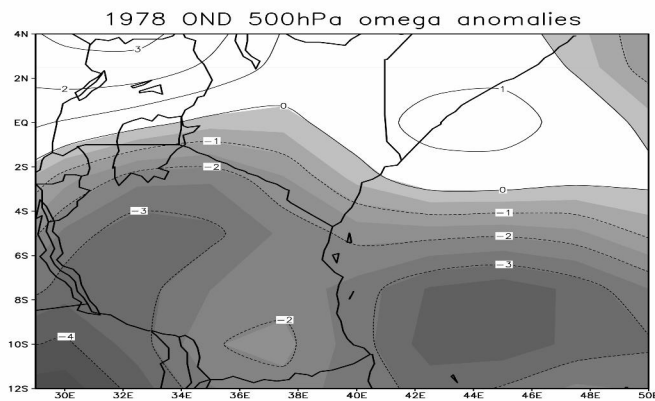
Fig 3.11: Time series of standardized rainfall for Central (a) Nov -Apr (b) Nov – Jan (c) Feb-Apr



a



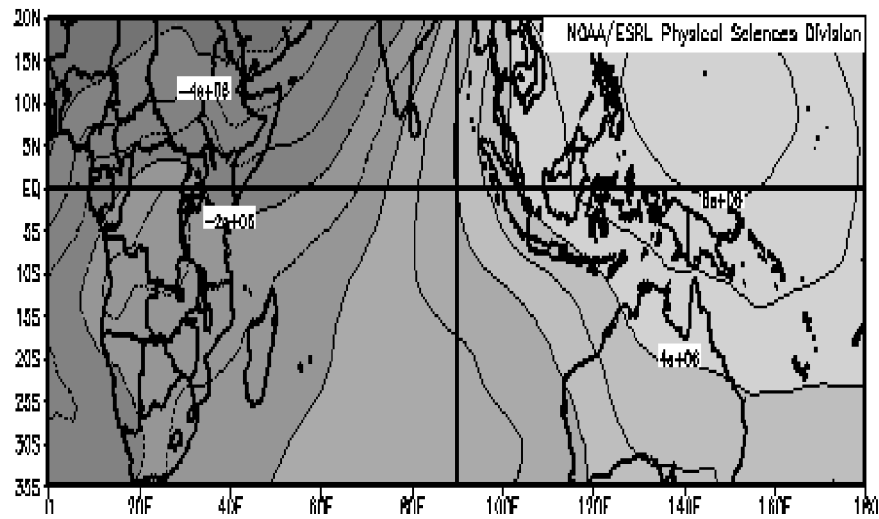
b



c

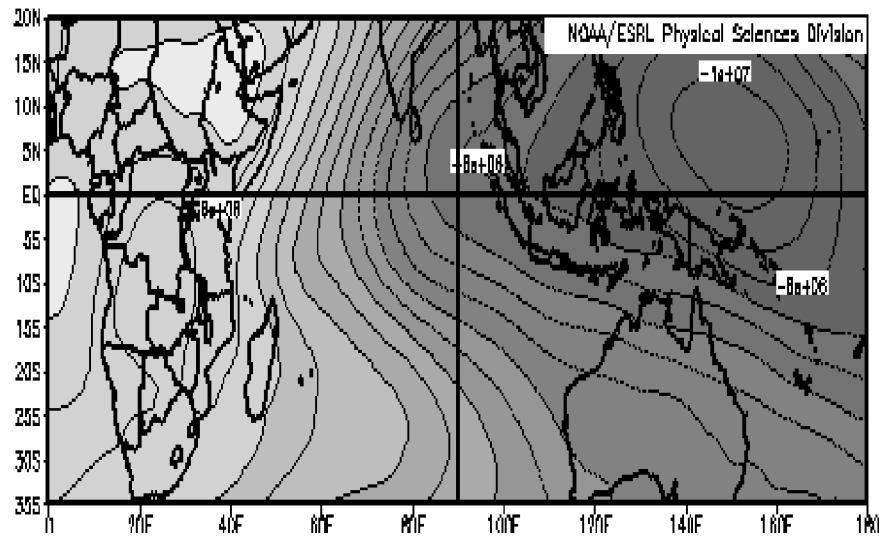
Fig 3.12: 1978 OND wet circulation anomalies for (a) Moisture flux at 850 hPa ($\text{gKg}^{-1} \text{ms}^{-1}$) (b) moisture flux divergence, contour interval $1 \times 10^{-8} (\text{gKg}^{-1} \text{s}^{-1})$ (c) Omega at 500hPa, contour interval is $1 \times 10^{-2} \text{Pa s}^{-1}$. Areas of moisture flux convergence and vertical motion are shaded.

1978 OND wet, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



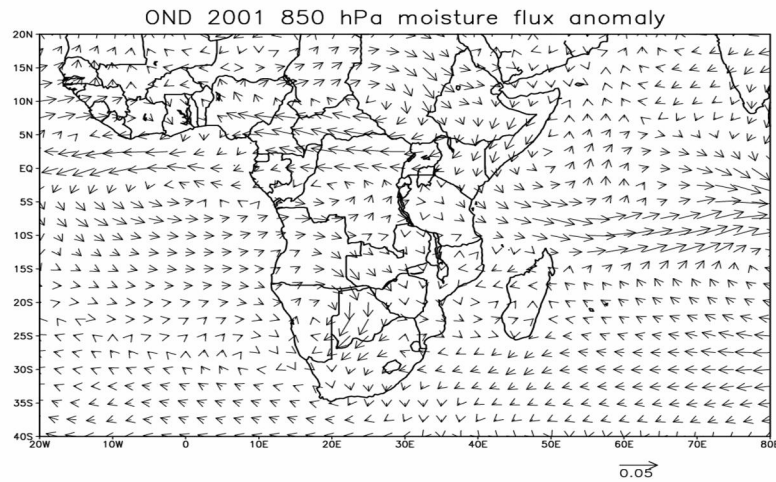
a

1978 OND wet, 200 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)

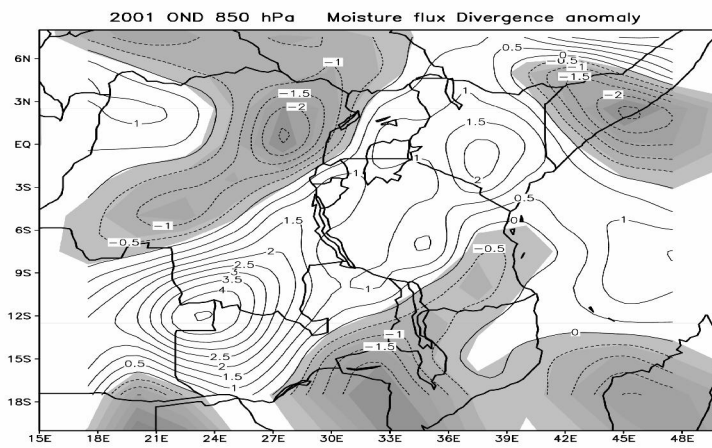


b

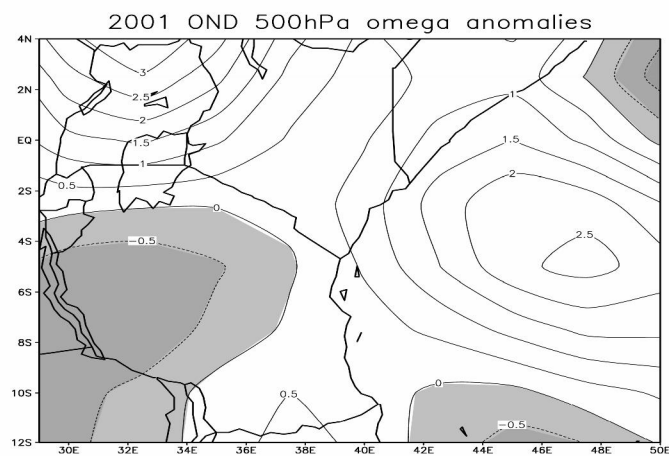
Fig 3.13: 1978 OND velocity potential anomalies at (a) 850 hPa and (b) 200hPa



a



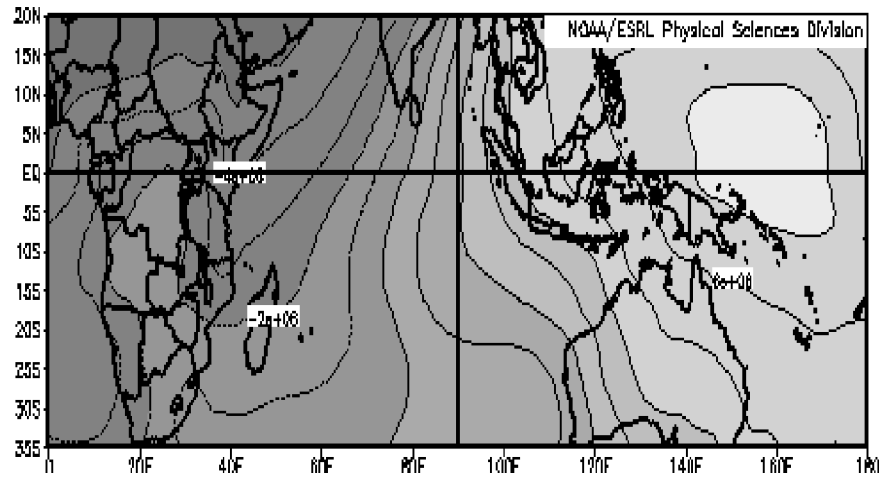
b



c

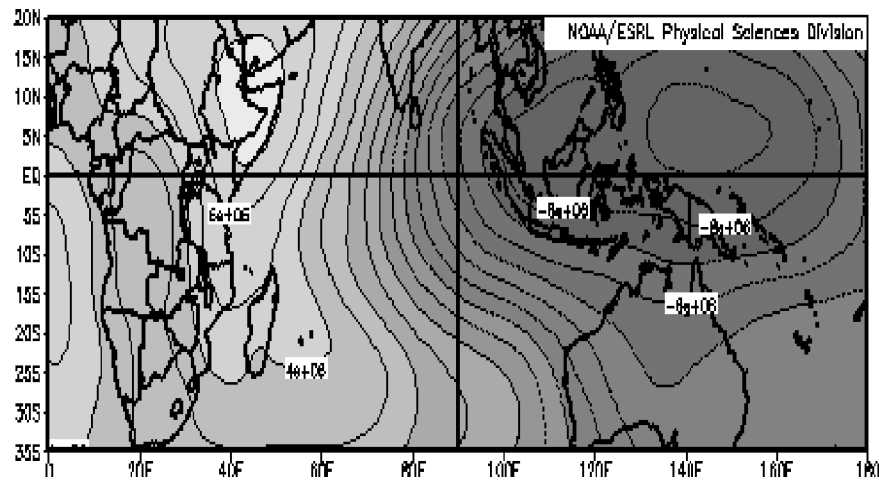
Fig 3.14: As for Figure 3.12 but for 2001 dry OND

2001 OND dry, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



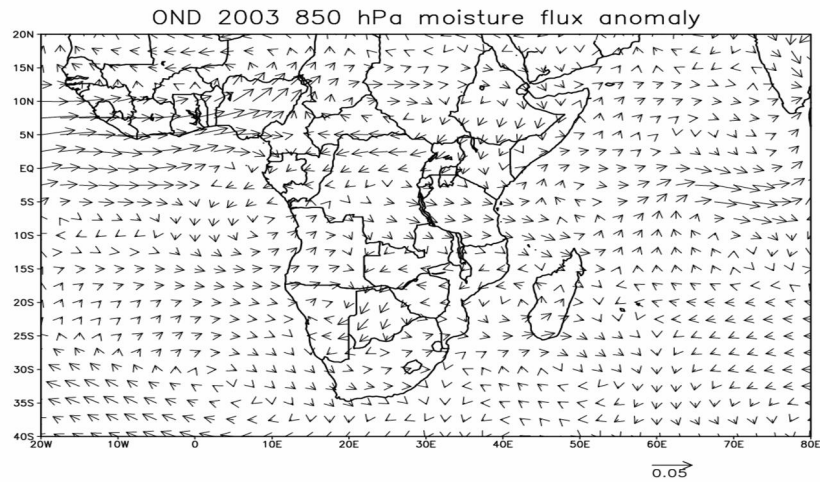
a

2001 OND dry, 200 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)

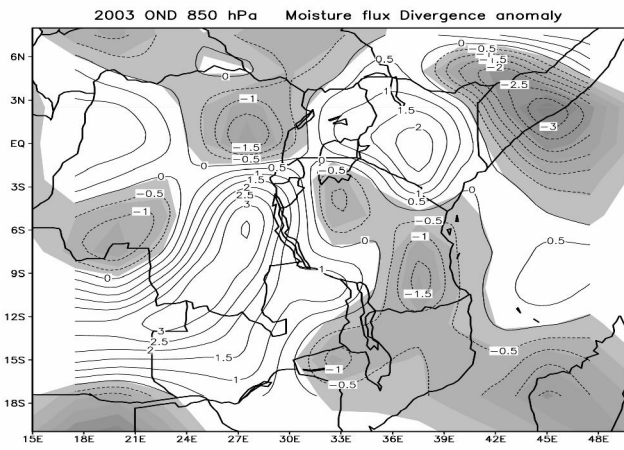


b

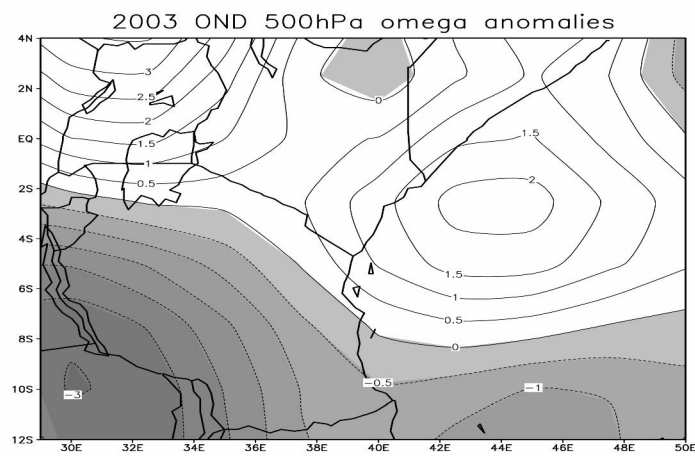
Fig 3.15: As for Figure 3.13 but for 2001 dry OND



a



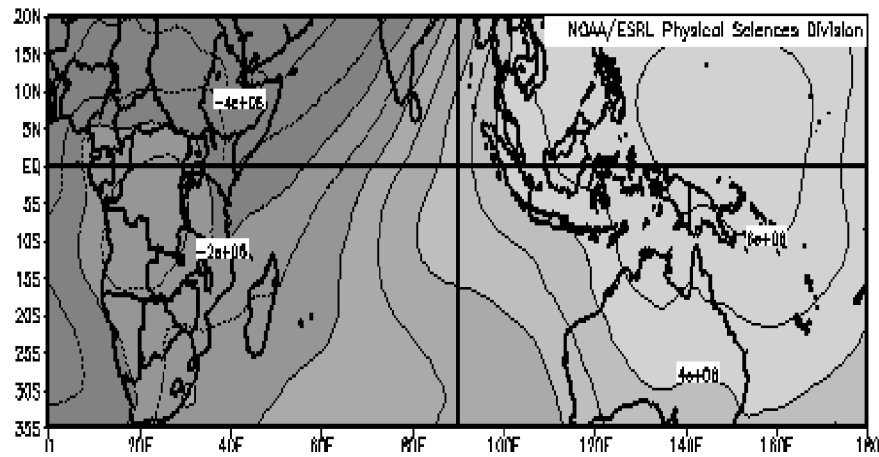
b



c

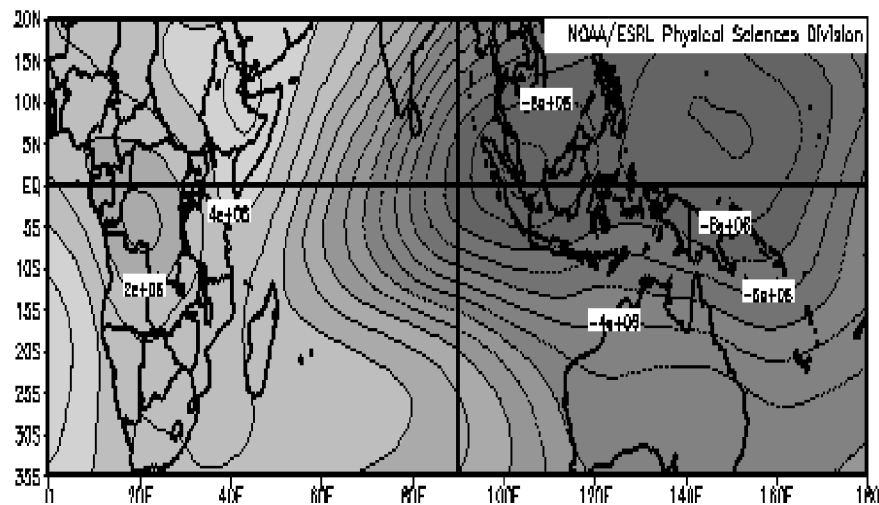
Fig 3.16: As for Figure 3.12 but for 2003 dry OND

2003 OND dry, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



a

2003 OND dry, 200 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



b

Fig 3.17: As for Figure 3.13 but for 2003 dry OND

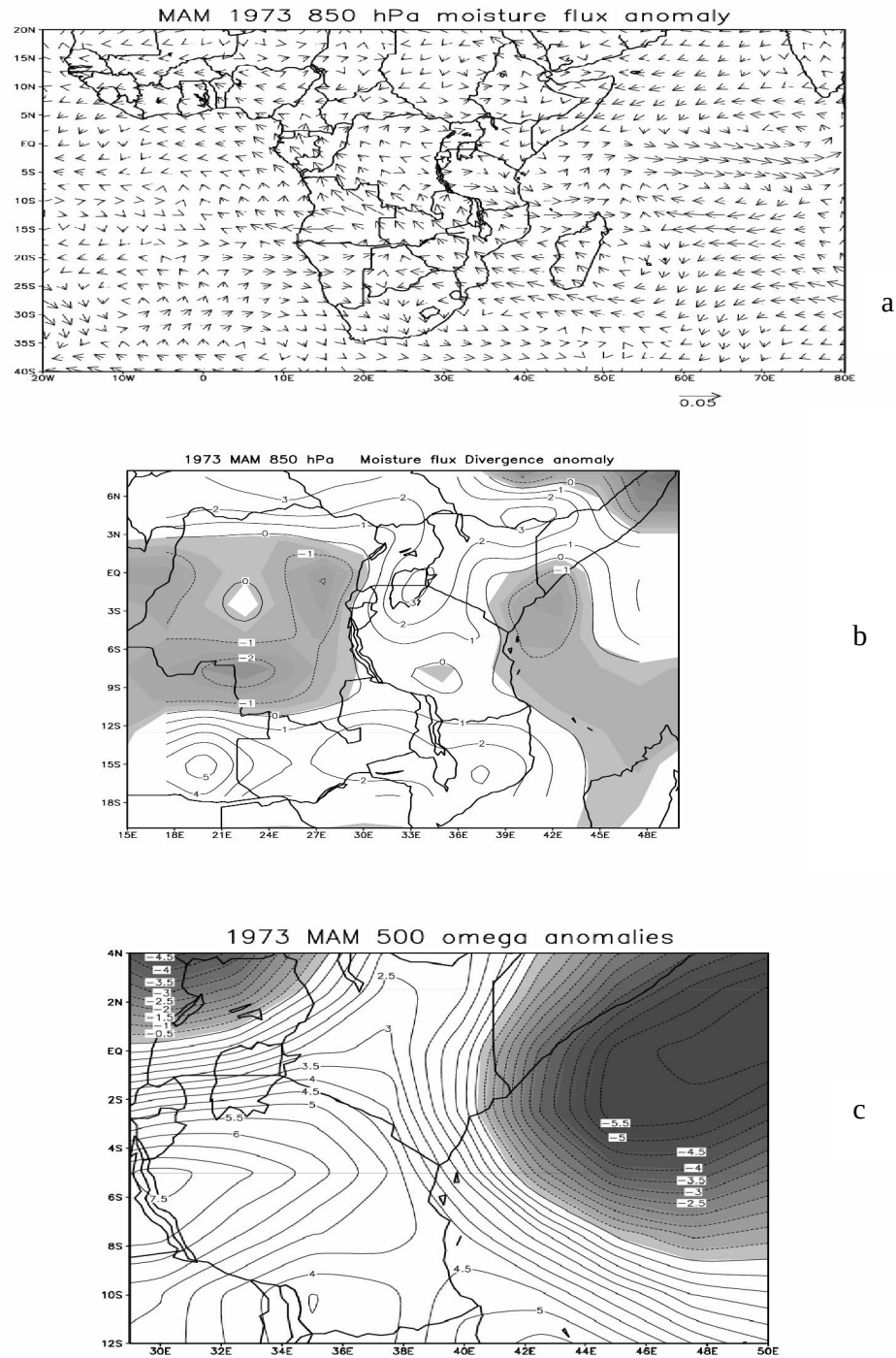
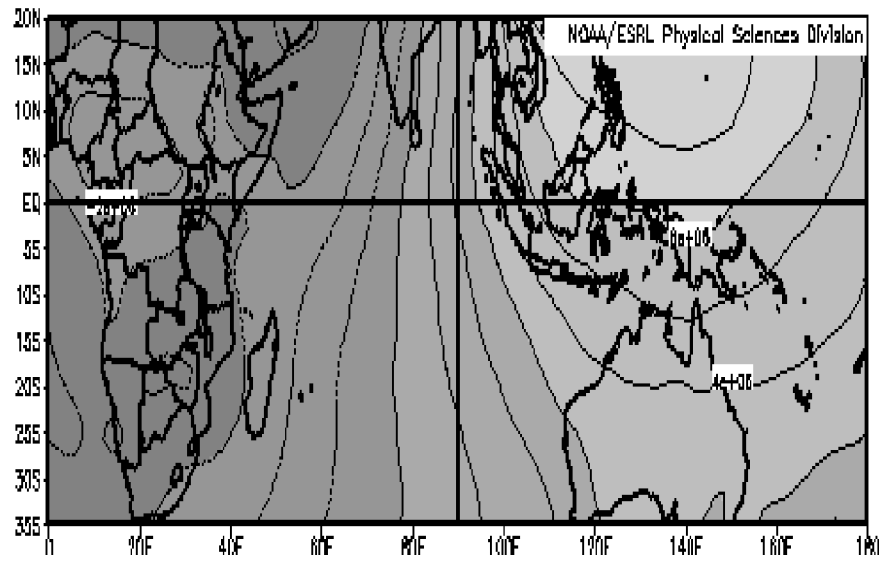


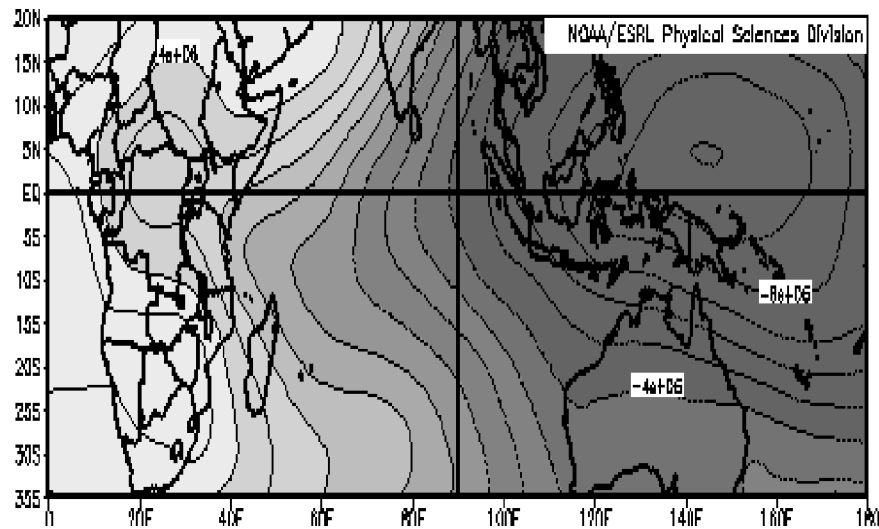
Fig 3.18: 1973 MAM dry circulation anomalies for (a) Moisture flux at 850hPa ($\text{gkg}^{-1} \text{ms}^{-1}$) (b) Moisture flux divergence, contour interval $1 \times 10^{-8} (\text{gkg}^{-1} \text{s}^{-1})$ (c) Omega at 500hPa, contour interval is $1 \times 10^{-2} \text{Pa s}^{-1}$. Areas of moisture flux convergence and vertical motion are shaded.

1973 MAM dry, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



a

1973 MAM dry, 200 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



b

Fig 3.19: 1973 MAM velocity potential anomalies at (a) 850 hPa and (b) 200hPa

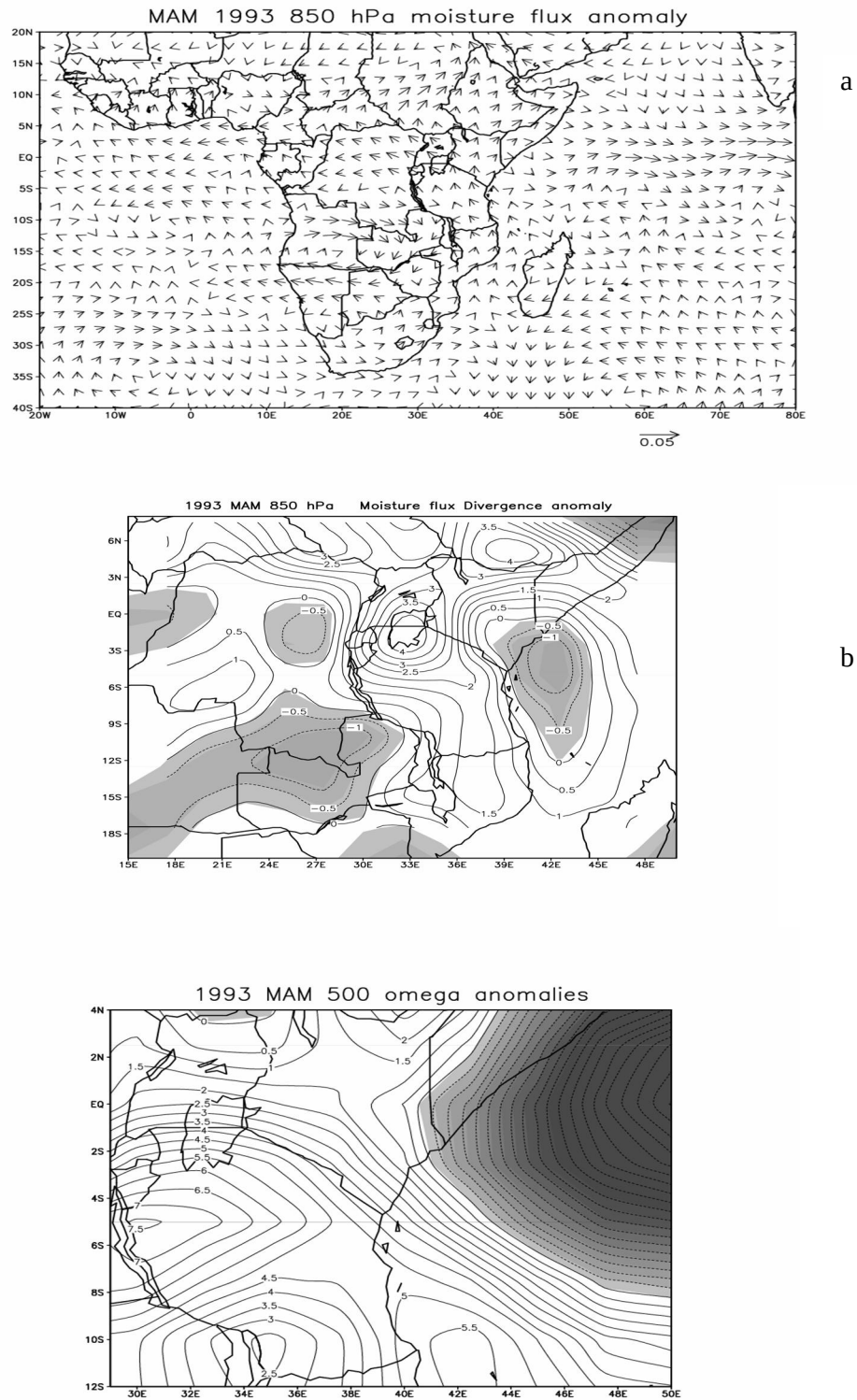
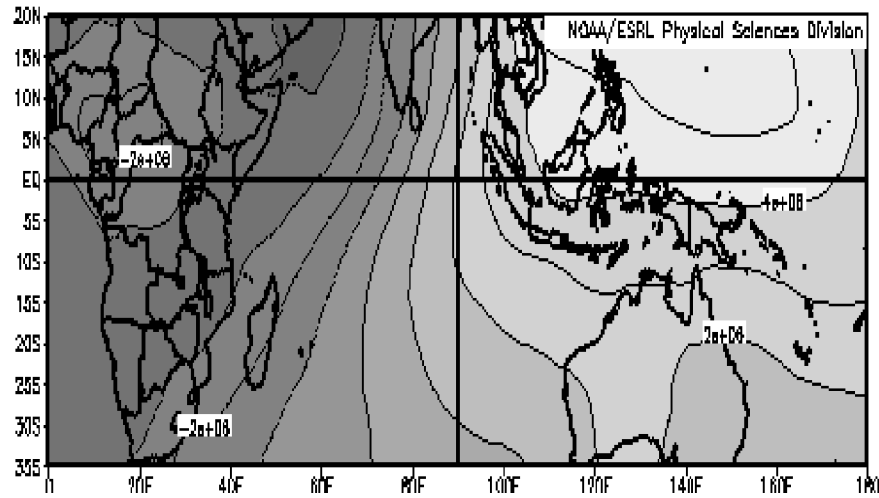
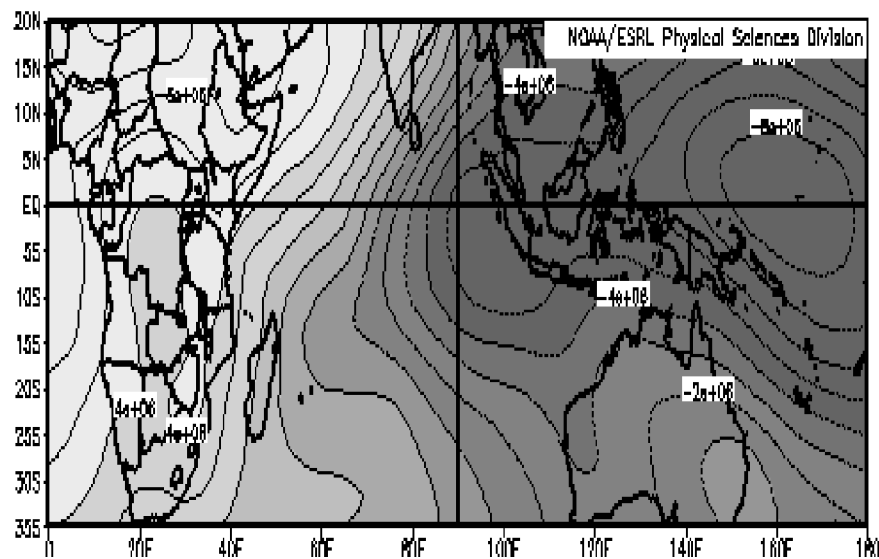


Fig 3.20: As for Figure 3.18 but for 1993 dry MAM
 1993 MAM dry, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



a

1993 MAM dry, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



b

Fig 3.21: As for Figure 3.19 but for 1993 dry MAM

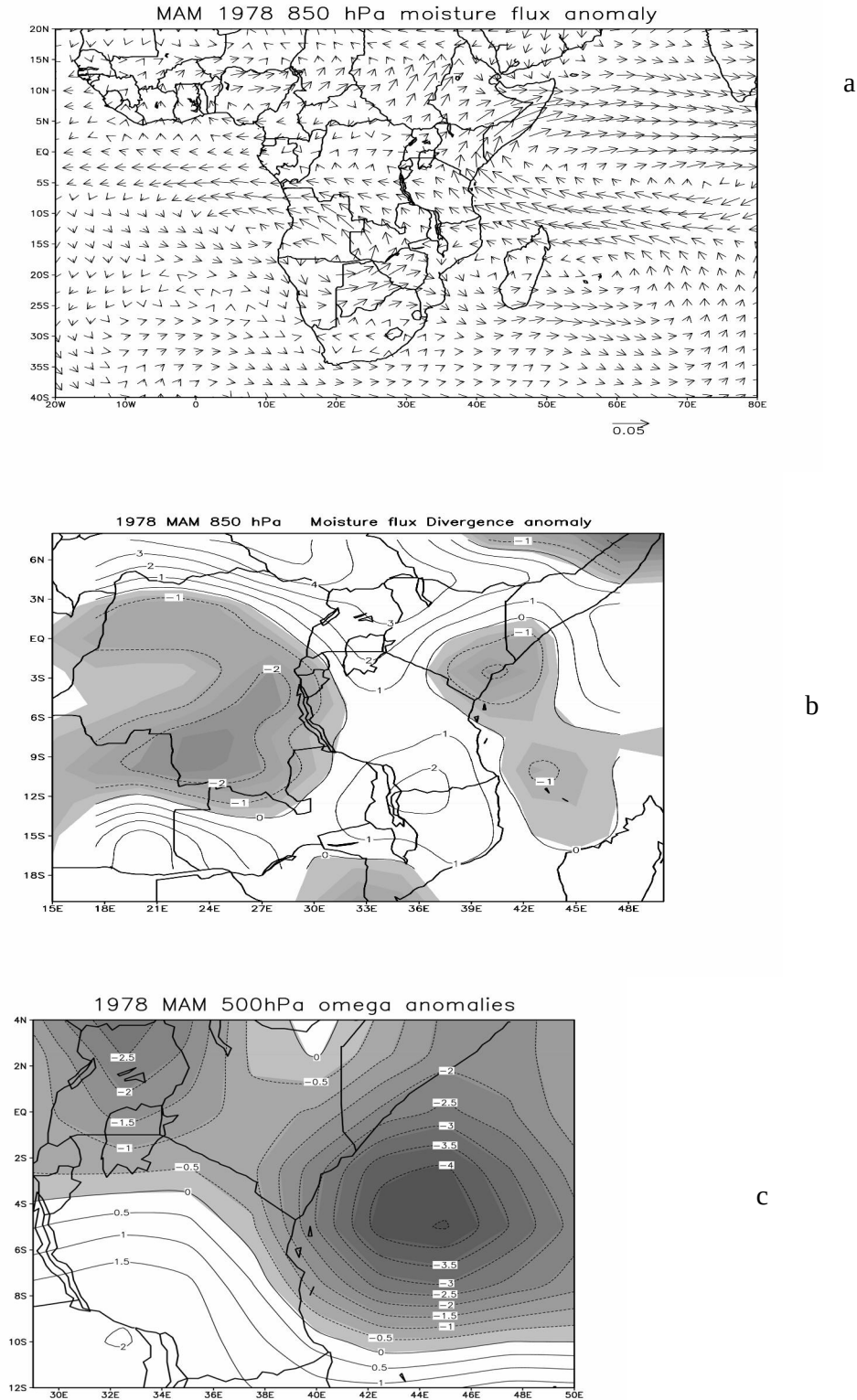
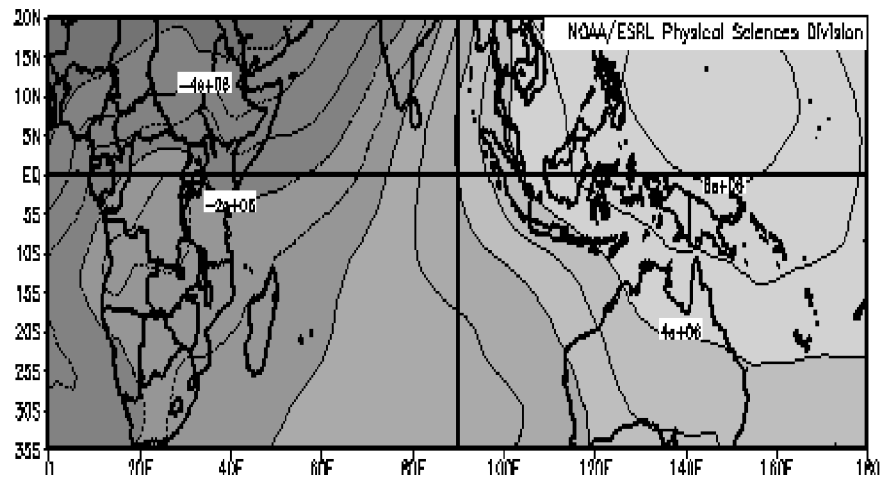


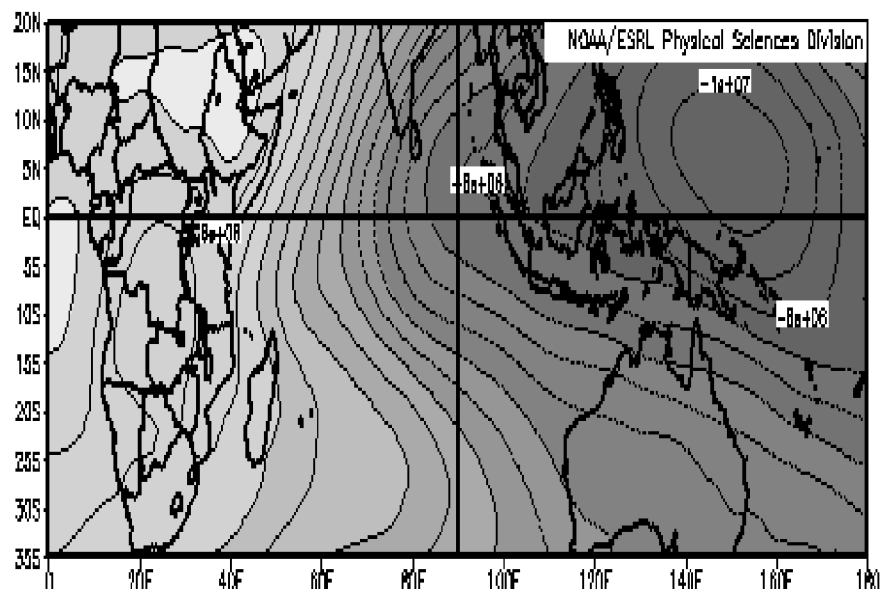
Fig 3.22: As for Figure 3.18 but for 1978 wet MAM

1978 MAM wet, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



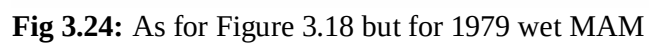
a

1978 MAM wet, 200 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)

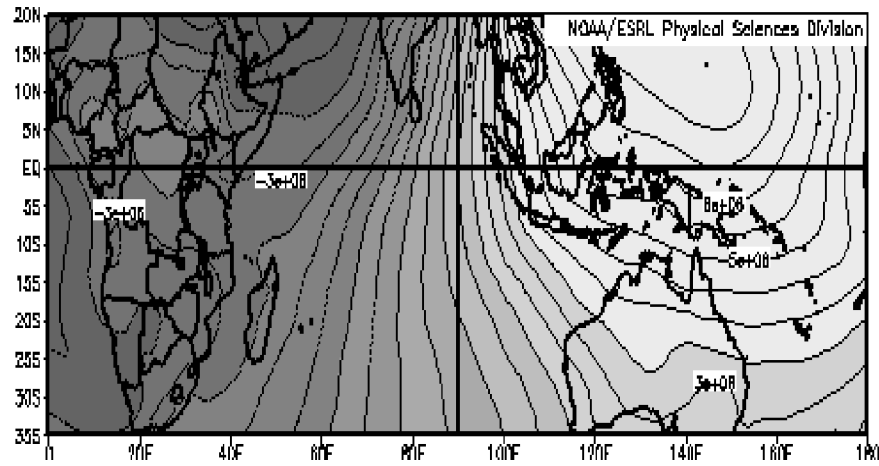


b

Fig 3.23: As for Figure 3.19 but for 1978 wet MAM

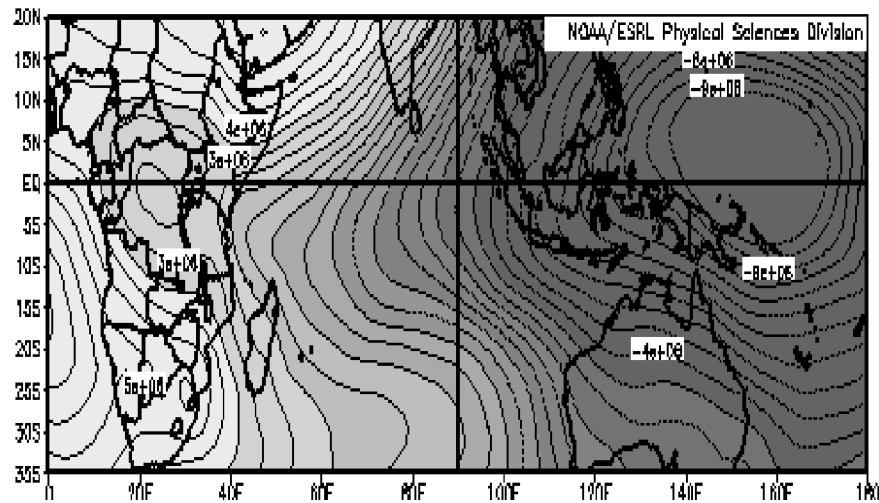


1979 MAM wet, 850 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



a

1979 MAM wet, 200 hPa velocity potential anomalies ($\text{m}^2 \text{s}^{-1}$)



b

Fig 3.25: As for Figure 3.19 but for 1978 wet MAM

CHAPTER FOUR

A CASE STUDY OF THE 1998-2005 DROUGHT AND 2006 FLOODS OVER NORTHERN TANZANIA

4. 0 Introduction

In the recent past, Tanzania has experienced pronounced climate variability that has had major negative impacts on various sectors of the economy, including agriculture, health, food security, energy and other key socio-economic sectors of the country. The most recent cases were the 1997 and 2006 floods and the 1998 - 2005 drought. The 1998 - 2005 drought caused devastating crop failures, livestock losses and reductions in the country's dam levels, which in turn created food shortages, rationing of hydroelectric power and water. On the other hand the 2006 floods caused a devastating loss of life and property, including the destruction of homes and properties, the loss of crops, damaged roads and bridges and the outbreak of diseases

To minimise the adverse impacts of climate variability, it is necessary to understand more fully the mechanisms involved and to improve long range rainfall prediction efforts for the region, hence the motivation for this chapter. Furthermore, to achieve a more sustainable agricultural production, it is important for policy makers and economists to understand and mitigate the variability of climate on both inter-annual and intra-seasonal scales so as to better utilise the natural resources of the country.

Rainfall variability over East Africa is linked to the shift in the location of the ascending and descending branch of the Walker circulation that occurs in association with tropical SST and convection anomalies (Bjerkenes, 1969; Webster, 1983). Regions of vertical motion associated with interaction between meso-scale and larger-scale flows have also been linked to precipitation distribution over Eastern Africa (Okeyo, 1986; Mukabana & Pielke, 1996; Indeje & Anyamba, 1998). Based on the aforementioned research findings, SSTs, moisture flux, vertical velocity, wind and velocity potential are analysed in this chapter to better understand the larger scale climate patterns associated with the 1998 – 2005 prolonged drought and the OND 2006 floods over Northern Tanzania.

Tanzania experiences two main rainfall regimes, with the southern and western parts of the country experiencing one rainfall season from November to April (unimodal) and the northern regions experiencing two rainfall seasons (bimodal). These latter rainfall seasons are the long rains from March to May and the short rains from October to December which are associated with the northward and southward movement of the ITCZ respectively (Nicholson 1986; Okoola, 1999). The Northern Tanzanian bimodal rainfall regions (Figure 4.1) were severely affected by the OND 2006 flooding and the NEH (the area around Mount Kilimanjaro) were severely affected by the 1998 – 2005 drought.

This chapter is divided into two main parts. The first part provides a detailed analysis of the atmospheric circulations associated with the prolonged drought of the 1998 – 2005 period over the NEH and the second part gives a detailed analysis of the OND 2006 floods in Northern Tanzania.

4. 1. Data and Methods

To understand the temporal and spatial behaviour of rainfall over northern Tanzania, daily and monthly totals for twelve stations scattered over the region were obtained from the Tanzania Meteorological Agency for the 1970 - 2006 period. Various authors have divided the East African region into homogeneous zones (for example, Indeje *et al.*, 2000). However, most of these studies combine the northern coast with parts of the North Eastern Highlands (NEH) of Tanzania. Although rainfall over both the NEH and north coast is mainly controlled by moisture advection from the Indian Ocean, the climate of the NEH is also highly modified by topography. Mutoni (2001) has divided Tanzania into ten homogeneous zones, thereby separating the northern coast from the NEH. Tanzania's Meteorological Agency has adopted such zones for various scientific applications over the country. This study considers three of these zones; namely, the north coast (Morogoro, Dar-es-Salaam, Zanzibar and Tanga), the NEH (Same, Moshi, KIA and Arusha) and the Lake Victoria basin (Mwanza, Musoma and Bukoba). A detailed

description of data and methods of analysis is given in chapter two. The analysis of the country's inter-annual variability is provided in chapter three.

4. 2. The 1998 - 2005 drought over the NEH of Tanzania

As previously mentioned, the inter-annual variability has been detailed in chapter three. The normalised rainfall departures for OND and MAM over the NEH of Tanzania are shown in chapter 3 (Figure 3.9). OND 1973 - 1976 and 1998 - 2005 can be identified as two periods of prolonged drought in the region. A scrutiny of the time series shows that despite 2002 being a wet year with a standardised rainfall anomaly value of about 0.8, the period 1998 - 2005 stands out as featuring one of the worst droughts in recent decades over Tanzania. Almost the entire country experienced at least two consecutive dry years during this period. However, longer periods of drought were observed over the northern part of the country, specifically the NEH although these started in 2000 rather than 1998 for MAM.

The strongest OND drought in the region was experienced in 2005 with a standardised rainfall anomaly value of -0.95 followed by 2003 which had an anomaly value of -0.92. However, the 2003 OND dry season was preceded by a MAM 2003 drought (standardised value of about -1.2) and followed by the driest season in MAM 2004 with a standardised anomaly value of -1.57, making the impact of 2003/2004 drought particularly devastating. Based on these results, MAM 2004 will be analysed in this chapter alongside composites for the entire period to understand the forcing mechanisms associated with the drought.

4.2.1 Large scale climate forcing associated with the 1998 - 2005 drought

The analysis in this section considers the seasonal anomalies for moisture flux, wind, vertical velocity and velocity potential fields during the OND and MAM seasons of the composites and the 2004 MAM strong drought year. Since 2002 experienced above-average rainfall, it was excluded from the compositing procedure. The 1998 - 2005 period was composited for the OND

season, while 2000 – 2005 was combined for the MAM season. To ensure that the results were not biased by particular years within the study period, some seasons (e.g. 2005 & 2003 OND, 2004 MAM) were excluded from the compositing procedure and the results were compared. However, it was found that there were no significant differences between the results. This implies that the years considered in the composite have similar seasonal atmospheric circulations despite the fact that in terms of rainfall onset and duration, each year seems to have its own characteristics as discussed in section 4.3.2 of this chapter. The results shown below present the composite anomaly values from the 1971 - 2005 climatology. The low level moisture flux convergence and areas of uplift are shaded in the moisture flux divergence and vertical velocity plot respectively.

The 850hPa level moisture flux will be analysed to identify areas of moisture flux divergence that contributed to the drought. Newell *et al.*, (1972) postulated that the bulk of horizontal transfer of moisture takes place below 700hPa in the tropics. Earlier studies, for example Goddard & Graham (1999), related moisture flux and wind circulation patterns with rainfall over East Africa and remarked that the 850hPa level was the most representative of the vertically integrated moisture flux. Similarly, velocity potential and vertical velocity will be analysed to identify areas of low-level subsidence and possible shifts in the position of the Walker type circulation that were associated with the drought. The shift in the descending and ascending branch of the Walker circulation has also been linked to rainfall variability over East Africa (Bjerknes, 1969; Webster, 1983).

4.2.1.1. The OND season

This section presents the larger scale circulation patterns during the OND 1998 - 2005 composite. Figure 4.2 illustrates rainfall, moisture flux and wind composite anomaly fields for the OND 1998 – 2005 period. Much of the rainfall fell over the western Indian Ocean and southern Tanzania, leaving the northern part of the country under dry conditions. A rainfall anomaly value of about -1.0 mm / day occurred over the Lake Victoria basin with below average

rainfall over the NEH of Tanzania, consistent with the ongoing drought (Figure 4.2(a)). Figure 4.2(b) indicates an anticyclonic moisture flux anomaly over the equatorial western Indian Ocean coupled with strong westerly anomalies between the equator and 10 °S and easterly anomalies over the Congo basin. These moisture flux patterns divert moisture away from Tanzania consistent with the recorded dry conditions.

Camberlin & Wairoto (1997) indicated that during wet conditions over East Africa, the north-easterly monsoonal flow switches to easterly over the region. Consistent with their result, Figure 4.2(c) indicates that dry conditions over Tanzania during 1998-2005 were associated with north-easterly flow backing into northwesterly flow over the country. Further north over the western Indian Ocean, easterly wind anomalies observed over 5-10°N veer into southeasterly anomalies as they approach the Somali coast. The north-easterly anomalies over Kenya and Northern Tanzania originate from Ethiopia and are therefore dry. Westerly wind anomalies from the Atlantic Ocean cover much of western and southern Tanzania. Such wind configuration patterns tends to divert moisture away from Tanzania and are consistent with the observed dry conditions over the NEH.

The low level westerly wind anomalies over North-Eastern Tanzania are identified by the zonal wind transect averaged over the region (Figure 4.3(a)). A westerly anomaly value of about 0.6m/s is evident at 850hPa and opposes the mean easterly winds. At mid-level (700hPa) an easterly anomaly value of about 0.5m/s was evident while at 200hPa, an easterly anomaly value of about 1.0m/s opposes the climatological westerlies and implies upper level convergence. However, in both cases the anomalies and associated upper level convergence are weak consistent with the relatively weak negative rainfall anomalies over the region. Okoola (1999) showed that upper level (200hPa) easterlies were associated with wet conditions over East Africa particularly when there are upper level easterlies aligned with mid-level (700hPa) westerlies. The moisture flux divergence plots (Figure 4.3(b)), shows moisture flux divergence over northern and northeastern Tanzania consistent with the dry conditions observed in this region.

The anomalies in velocity potential and omega for OND 1998 - 2005 can be seen in Figure 4.4. Note that omega indicates the rate of change of pressure with time and therefore negative (positive) values imply relative ascent (descent). The position of the ascending limb of the local Indian Ocean Walker cell and strong ascent is located over the Indian Ocean at about 140 °E as indicated by positive velocity potential and convergent wind in the lower levels (Figure 4.4(a)). This pattern is coupled with negative velocity potential and divergent wind in the upper levels (Figure 4.4(b)). Such lower and upper level atmospheric circulation patterns suggest an eastward shift of the ascending branch of the Walker circulation (Webster, 1983). The position of the strong low level convergence near 30°S suggests changes in the Hadley circulation may be involved. Subsidence covers much of the equatorial western Indian Ocean closer to the East African coast and northern Tanzania as indicated by the omega plot (Figure 4.4(c)), which is consistent with the observed drought. Consistent with our study, Hastenrath *et al*, (2007) found the 2005 drought over equatorial East Africa to be associated with subsidence over the region and westerly wind anomalies.

In summary, the prolonged drought over the North-eastern highlands of Tanzania in OND 1998 - 2005 seems to be related to two main factors: firstly, westerly wind anomaly patterns over the western Indian Ocean and easterly wind anomaly patterns over the Congo Basin that transport moisture away from the country. Secondly, low-level moisture flux divergence and subsidence occurred over Northern Tanzania and acted to suppress convection.

4.2.1.2. The MAM season

Although month to month circulations were analysed, for the sake of brevity, only circulation patterns for the MAM 2000-2005 composite and MAM 2004 (the driest season) are presented here. However, it is worth mentioning here that the month to month circulations were generally similar for each dry season. Figure 4.5 shows rainfall and wind anomaly fields for the MAM 2000 - 2005 composite. All of Tanzania and East Africa experienced dry conditions

(Figure 4.5(a)). At 850 hPa, Figure 4.5(b) shows a zone of easterly moisture flux anomalies over the equatorial western Indian Ocean between 2 – 15 °S veering to southerly anomalies over eastern Tanzania. This pattern is coupled with an easterly anomaly over the Congo Basin that diverts moisture away from Tanzania consistent with the observed drought.

At the 700 hPa levels (Figure 4.5(c)), southerly wind anomalies cover much of Kenya and Eastern Tanzania. These patterns indicate the dominance of southerly anomalies that transport moisture away from the country, by running parallel to the coast, veering to westerly anomalies over Somalia with easterly anomalies over the Congo Basin. These patterns were confirmed by the zonal wind transects averaged over the region (Figure 4.6(a)) that show westerly anomalies over the region in the lower levels, weak easterly anomalies in the middle level and strong easterly anomalies in the upper levels which is consistent with the observed drought. Comparisons with the OND wind transect indicate stronger anomalies during the MAM season, as expected from the stronger negative rainfall anomalies observed in this season. It should be noted here that upper level (200hPa) easterlies are divergent over East Africa. However, heavier rainfall tends to occur over the region when there are easterlies aloft and middle level westerlies (Okoola, 1999). Figure 4.6(b) shows strong moisture flux divergence over much of Tanzania except in the far south-west, which is again consistent with the observed drought.

Velocity potential and vertical velocity for the MAM 2000 - 2005 composite can be seen in Figure 4.7. The position of the descending branch of the Walker type circulation is located over the African region centred at about 30 °E as identified by negative velocity potential and divergent wind in the lower levels (Figure 4.7(a)). This pattern is coupled with positive velocity potential and convergent wind in the upper levels (Figure 4.7(b)). This suggests strong subsidence over the East African region, which is confirmed by the omega plot (Figure 4.7(c)). The occurrence of strong subsidence over the NEH of Tanzania suggests unfavourable conditions for convection consistent with the dry conditions over the region.

Figure 4.8 shows rainfall, moisture flux anomaly and vertical velocity fields for MAM 2004, which was the driest season in the period of study. The rainfall plot (Figure 4.8(a)) shows dry conditions over the entire country during MAM 2004. The moisture flux anomaly fields (Figure 4.8(b)) indicate more or less similar patterns to the composite except for the moisture flux divergent plot (Figure 4.8(c)) which shows moisture flux convergence over much of the southern Tanzania. Similarly, the velocity potential plot at 850hPa and 200hPa (Figure 4.9(a & b)) indicate more or less similar features to the composite. However, for the vertical velocity plot (Figure 4.9(c)), the relative uplift observed over the equatorial western Indian Ocean in the composite plot was not observed in 2004. Instead, subsidence covered the entire domain. Thus, even though there was relative moisture convergence over southern Tanzania, the strong subsidence suppressed convection everywhere. Over the North East Highlands region of the country focussed on in this study, both strong subsidence and relative moisture flux divergence combined to produce the drought.

It should be noted here that the 1973 – 1976 prolonged drought were also analysed and found to display similar atmospheric circulation patterns over the region suggesting that the results presented here are not simply a special case but may have relevance to other multi-year droughts and thus may have some predictability based on the atmospheric circulation patterns. However, the 1973 – 1976 prolonged drought were not discussed here for the sake of brevity.

In summary, the drought over northern Tanzania that occurred during MAM 2000 - 2005 was associated with two main factors: firstly, strong moisture flux divergence over the region; and secondly, strong subsidence associated with occurrence of the descending branch of the Walker type circulation over East Africa.

Comparison between the circulation patterns during OND and MAM rainfall seasons indicate that the rainfall anomalies were stronger during the MAM season. Such stronger rainfall anomalies were associated with strong easterly

wind anomalies in the upper level coupled with strong subsidence over the region of study while for the OND the upper level wind anomalies were weaker. Both the OND and the MAM seasons were characterized by westerly wind anomalies over the western Indian Ocean at 850hPa level. However, such westerly anomalies were located north of the equator during the MAM season and south of the equator during the OND season. Low level moisture flux divergence and subsidence over northern Tanzania were the common features for both the OND and MAM droughts. Both the moisture flux divergence and the subsidence over the region were unfavourable for convection.

4.3. Intra-seasonal variability

Most studies of rainfall variability over East Africa thus far have concentrated on seasonal to inter-annual scales. This study investigates the intra-seasonal spells of drier conditions recorded over the NEH of Tanzania during the 1998-2005 drought. A detailed analysis of the intra-seasonal variability during wet and dry years is provided in chapter six.

4.3.1. Pentad rainfall time series during the 1998 – 2005 drought

This section considers year to year intra-seasonal variability during the 1998 – 2005 drought. An analysis for each year during the OND and MAM seasons of the 1998 - 2005 droughts was undertaken. As mentioned earlier a detailed analysis of the climatological series is presented in chapter six. The criteria for rainfall onset, peak and cessation dates used in Kijazi & Reason, 2005 were adopted for this study and is defined in chapter three.

Figures 4.10 and 4.11 illustrate the pentad rainfall time series for each year during the 1998 – 2005 OND drought and Table 4.1 shows the onset, peak and end dates as derived from the time series. The scrutiny of yearly time series indicate that the onset of OND rainfall were undefined for all years except for year 2000 where the onset was at the 64th pentad (16th - 20th November). In 1998, 1999 and 2000 the peak and end of the OND rainfall season coincides at pentad 66th (Table 4.1). However, the amount of rainfall

received varies for each year and the rainfall season were much shorter than climatology consistent with the prolonged drought. In 2001, 2003, and 2004 each year has its own rainfall characteristics, especially in terms of the duration of the rainfall season and the amount of rainfall received (Table 4.1). Generally during the 1999 – 2005 drought, the rainfall season completely failed in most of the years. The criteria for the onset and cessation of the rainfall season were not met and the rainfall peak coincides with its end resulting in shorter than average rainfall season and below average rainfall was recorded.

In some years, the out of season peak seems to be significant and may have helped to minimise the impact of the drought (e.g. year 2000 (Table 4.1)). About 164 mm of rainfall was observed in January 2001, which was near the OND average. During 2000/2001, the total amount of rainfall received from NDJ was 292 mm, which was above the OND average. Such shifts of the rainfall season could have helped to minimise the impact of the drought.

The pentad rainfall time series for each year during the MAM 2000 – 2005 drought is illustrated in Figure 4.12. Table 4.2 show the onset, peak and end dates as derived from the time series. Scrutiny of the time series indicates that in most years the rainfall season was much shorter than average. Similarly the total amount of rainfall received was below average. Furthermore, the seasons were characterised by frequent dry spells while climatologically (Figure 6.2(b)); there are no dry spells during this season.

Table 4.1: Onset, peak and cessation dates for each year during the OND season. The amount received during January out of season peak is shown in the brackets

Year	1998	1999	2000	2001	2003	2004	Climatology
Onset (Pentad)	Undi fined	Undi fined	64 th 16 - 20 Nov	Undi fined	Undi fined	Undi fined	60 th 26 – 31 Oct
Peak (Pentad)	66 th 26 – 30 Nov	66 th 26– 30 Nov	66 th 26 – 30 Nov	61 st 1 – 5 Nov	69 th 11 – 15 Dec	72 nd 26 - 31 Dec	66 th 26 – 30 Nov
End (Pentad)	66 th 26 – 30 Nov	66 th 26– 30 Nov	66 th 26 – 30 Nov	61 st 1 – 5 Nov	69 th 11 – 15 Dec	72 nd 26 – 31 Dec	3 rd 11 – 15 Jan
Amount Received (mm)	40	105	77 (164)	36.7 (123)	47 (74)	131.7	180mm

Table 4.2: Onset, peak and cessation dates for each year during the MAM season

Year	2000	2001	2003	2004	Climatology
Onset (Pentad)	16 th 16 – 20 March	Undi fined	Undi fined	14 th 6 – 10 March	15 th 11 – 15 March
Peak (Pentad)	21 st 11 – 15 Apr	23 rd 21 – 25 Apr	25 th 1 – 5 May	21 st 11 – 15 April	22 nd 16 th -20 th April
End (Pentad)	26 th 6 – 10 May	30 th 26 – 31 May	30 th 26 – 31 May	24 th 26 – 30 April	29 th 21 st – 25 th May
Amount Received (mm)	175.7	303	248.5	169	388

4.4. Summary of the findings

The characteristics of the inter-annual and intra-seasonal rainfall variability over the north-eastern highlands of Tanzania and their associated circulation anomaly patterns during the prolonged 1998 - 2005 drought have been analysed. It is evident that the 1998 - 2005 drought was characterised by a complete failure of both MAM and OND rainfall seasons (Table 4.1 and 4.2). The rainfall onset was undefined in most of the years with unevenly distributed rains associated with prolonged periods of dry spells within the shorter-than-average seasons. Such drought had devastating effects, most notably crop failures and livestock losses that resulted in a food shortage. Another major effect was the reduction in the level of the country's dams, which resulted in hydroelectric power and water rationing. The Drought Impact Assessment (TMA bulletin, 2006) reported widespread death of animals over the region associated with the prolonged drought. This run of consecutive years of below average rainfall during 1998-2005 was very problematic; in fact, since 1970, only 1973-1976 seems to be comparable in terms of the duration of the drought and magnitude.

During the short rainy season, a displacement of the rains from October, November, and December to November, December, and January was observed with sometimes strong wet spells in January or even February (e.g., Figure 4.10(c)). In fact, most of the years (2000, 2001 and 2003) indicated an out-of-season rainfall peak that occurred in January (Table 4.1). This section found that the out-of-season peak received a significant amount of rainfall, thus suggesting an important application for agriculture. It is therefore worth suggesting here that the January out-of-season peak may be used to mitigate the impact of drought over the country. The circulation anomalies indicate that the observed drought over northern Tanzania was associated with three main factors: firstly, wind circulation patterns that diverted moisture away from the country; secondly, strong moisture flux divergence over the region; thirdly, strong subsidence associated with an eastward shift of the ascending limb of the Walker type circulation.

4.5 The OND 2006 floods over northern Tanzania

This section of the chapter is divided into two main sections. The first part provides a detailed analysis of the rainfall observed during the OND 2006 floods in Northern Tanzania, using daily and monthly rainfall data. The second part examines the atmospheric circulation associated with the floods. Monthly NCEP/NCAR reanalyses (Kalnay *et al.*, 1996) are used in this section to understand the mechanisms related to the floods. The main objective of the section is to show that the OND 2006 season was anomalously wet and to advance our understanding of the circulation features associated with the heavy rainfall that was observed. The atmospheric circulation features for another recent very severe flooding episode over Tanzania that occurred in OND 1997 is also analysed for comparison purposes. This season was chosen since, like 2006, it was also a year when a positive phase Indian Ocean dipole event and an El Niño event occurred at the same time (Figure 4.15(iii)).

4.5.1. Station rainfall over northern Tanzania

This section discusses the results obtained from the time series of station observed rainfall. It also compares the rainfall observed with satellite derived rainfall and the climatological monthly and seasonal averages. For these purposes, a rainfall amount of >25mm per day is considered to be a heavy event. The 25mm threshold was chosen based on the fact that 25mm (that falls in a single day) contributed about 4% to the seasonal total over the North coast and the Lake Victoria basin and about 5% over the NEH and significantly contributed to the ongoing flooding over the study region.

Area averaged time series for the NC, the NEH and the LAKE are shown in Figure 4.13 (i - iii). Note that different vertical scales are used in the plots. On the 1st October (Figure 4.13(i)), the Lake Victoria Basin received about 19 mm of rainfall, followed by a dry spell of two weeks that was interrupted by 14 mm of rainfall on the 9th. On the 20th and 22nd October, 9 mm and 19 mm fell over the same area, and the last week of the month recorded ≤ 5 mm per day

(except for the 28th in which 7 mm was recorded). The NC recorded about 25 mm on the 14th October and 20 mm on the 20th, interspersed by dry spells before a heavy rainfall of about 30 mm per day (1/3 of the October average) on the 31st. The NEH recorded 27 mm of rain on the 16th October (which was almost the monthly average) followed by another wet spell of almost the same amount on the 20th and 21st. Little rain fell over the NEH during the other days of this month.

During November, the Lake Victoria basin recorded rainfall throughout the month with a maximum of 30 mm on the 26th November and again on the 28th (Figure 4.13(ii)). The north coast had two significant wet spells (20 mm on 5th and 6th and 25 mm on the 29th). The NEH recorded 38 mm (about half the monthly average) on the 6th November. On the 29th November, the highest rainfall event of the season (75 mm per day, note that the November average is 63 mm) was recorded over the NEH. This resulted in wide-spread floods in the region as the soil was already saturated. The 29th November event will be used for further analysis in this chapter to understand the circulation features associated with heavy rainfall event. Throughout December (Figure 4.13(iii)), rainfall was more consistent over each region. On the 12th December, 30 mm per day (about 1/3 December average) was recorded over the Lake Victoria Basin.

The rainfall events per region for selected heavy rainfall events are summarised in table 4.3 below:

Table 4.3: Northern Tanzania rainfall total for selected events during the OND 2006 season. The percentage contributions to the seasonal total for each event and the percentage of the climatological total for the OND 2006 season are shown inside the brackets

EVENTS PER REGION	NEH <i>mm</i>	NC <i>mm</i>	LAKE <i>mm</i>
October - December Climatological Total	173.8	378.9	396.2
October - December, 2006 Total	378.8 (218%)	602.7 (159%)	620.3 (157%)
16 October, 2006	27 (7%)		
31 October, 2006		30 mm (5%)	
28 November, 2006			28 (4.5%)
29 November, 2006	75 (20%)		
12 December, 2006			30 (5.8%)
23 December, 2006	29 (7.7%)		
30 December, 2006	32 (8.4)		

During OND 2006, Table 4.3 indicates that there were more days (four) with heavy rainfall in the NEH than for the other two regions. These falls contributed about 43% of the seasonal total over the NEH. On 29th November alone, about 20% of the seasonal total fell. Over the Lake Victoria basin, about 10% of the seasonal total fell on November 28th and December 12th, while over the north coast, the largest event on 31st October contributed about 5 % of the seasonal total.

Rainfall time series for the GPCP rainfall data are illustrated in Figure 4.14 (i-iii). Comparison of the station data series (Figure 4.13) and GPCP data series reveal the consistency of the two series for most (but not all) days and showed most of the rainfall peaks illustrated in the station data series. However, the GPCP time series seems to show lower values than the station data series. In particular, GPCP appeared to underestimate the heaviest rainfall day (29th November over the NEH). This difference may result from the fact that few stations were available for averaging over each region and the GPCP data were not interpolated to the station locations.

To get a better idea of how wet OND 2006 was relative to other years, Figure 4.15 plots the time series of OND rainfall over northern Tanzania for 1971-

2006 determined from the 11 stations scattered throughout the region (Figure 4.1). Thus, 2006 was the third wettest season over the last 35 years for the region as a whole with 1997 being by far the wettest. If only the stations for the NEH and Lake Victoria basin are included, then OND 2006 becomes the second wettest season on record since 1971. Compared to climatology (Table 4.3), OND 2006 resulted in over twice the seasonal mean rainfall for the NEH and about 1.5 times this mean for the other two regions.

4.5.2. Larger scale climate patterns associated with the OND 2006 floods over northern Tanzania

Numerous studies have observed that regions with high tropical precipitation correlate well with regions exhibiting high SST (Bjerkenes *et al.*, 1969; Liebmann & Hartmann, 1982; Neelin & Held, 1987). Empirical studies by Cadet & Beltrando (1987) and Latif *et al.*, (1999) demonstrated the existence of an association between rainfall variability in East Africa and SST patterns. Nicholson & Kim (1997) found a strong connection between ENSO induced SST anomalies in the Indian Ocean, which in turn modulate inter-annual variability of rainfall over East Africa. Goddard & Graham (1999) related SSTs, moisture flux and wind circulation patterns with rainfall over East Africa. Okoola (1999) and Hills (1979) found an association between wind circulation patterns and rainfall over East Africa. Hills (1979) indicated that divergence in upper levels (200 – 300 hPa) was present during the short rains although there was definite convergence in long rains over Eastern Africa.

Moisture flux, vertical velocity, SSTs, wind and velocity potential are analysed in this section of the chapter so as to gain greater insight into the climate patterns associated with the OND 2006 floods over northern Tanzania. The SST and moisture flux circulation features for the 1997 floods are also analysed for comparison since this season had similar large scale climatic conditions to 2006 (i.e. El Nino plus a positive phase Indian Ocean zonal dipole mode event). Focus is placed on November, the peak of the rainfall season when most of the heavy events occurred in OND 2006 (6th, 28th and 29th November) and August. The latter month is considered to see whether

any pre-conditioning features might be identified prior to the onset of the rainy season.

Two months before the onset of the short rainfall season in August (Figure 4.16 (i)), warm SST anomalies of about 0.5°C are evident over much of the western Indian Ocean coupled with an easterly moisture flux over the equatorial western Indian Ocean between 5°N and 10°S . These SST and moisture flux anomalies are consistent with El Niño conditions (Reason *et al.*, 2000). The presence of this easterly moisture flux near the equator is important for Tanzanian rainfall since it indicates moisture availability two months before the onset of the rainfall season. However, the convergence of this moisture (not shown) is mainly over the ocean at this stage.

In November 2006, a contrasting warm (cool) SST anomaly pattern was evident in the western (eastern) Indian Ocean, reflecting a positive Indian Ocean Zonal Dipole Mode event (Saji *et al.*, 1999) occurring at the same time as the El Niño. The largest SST anomalies (about 1°C) occurred at about 70°E near the Somali coast (Figure 4.16 (ii)). This pool of warm water over the equatorial western Indian Ocean coupled with cooling over the equatorial eastern Indian Ocean is often associated with enhanced convection and increased rainfall over East Africa (Saji *et al.*, 1999; Webster *et al.*, 1999).

Figure 4.16 (ii) also shows a strong easterly moisture flux anomaly over the equatorial western Indian Ocean with a northeasterly anomaly over Somalia and Kenya that backs into a northerly anomaly over Tanzania. The resulting broad zone of moisture flux convergence across Tanzania (Figure 4.17 (i)) led to anomalous rainfall over northern Tanzania during this period. In general, the western tropical Indian Ocean is the major source of moisture for Tanzania's short rains (Kijazi, 2003). During wet years, a larger proportion of moisture is advected from the Indian Ocean, apparently by the stronger and more easterly winds which result in a high moisture flux convergence over Tanzania (Kijazi & Reason, 2005; Okoola *et al.*, 2008). As a result, enhanced convection, and increased rainfall occurs.

Comparison with the 1997 conditions (Figure 4.16 (iii & iv)) shows more or less similar features to 2006 except for larger SST anomalies in August 1997 near the Somali coast of 0.5°C to 1.0°C and cool SST anomalies over the Atlantic Ocean south of the equator (in August 2006, SST anomalies here were mainly positive). Similar features to November 2006 were also observed in November 1997 (Figure 4.16(iv)) except for greater warming over the Atlantic Ocean between 15°S and 25°S , and cooling over the Indian Ocean south of Madagascar in 1997 compared to November 2006. The moisture flux divergence plot (Figure 4.17 (ii)) shows similar features to the November 2006 plot except for a larger moisture flux convergence over western Tanzania / northern Zambia than in 2006 and a moisture flux divergence over the south coast (convergence here in 2006).

The velocity potential and divergent wind anomalies for November 2006 are shown in Figure 4.18. At the 850 hPa level, positive velocity potential and wind convergence occurs across the East African region coupled with negative velocity potential and wind divergence at the 200 hPa level, thereby reflecting the position of the ascending limb of the local Indian Ocean Walker type circulation. The descending limb of the Walker circulation is apparent at about 130°E , and is indicated by negative velocity potential and wind divergence at 850 hPa coupled with positive velocity potential and wind convergence at 200 hPa. Such velocity potential and divergent wind patterns suggest an eastward shift of the ascending branch of the Walker circulation (Webster, 1983). The occurrence of the rising branch of the Walker circulation over the western Indian Ocean and East Africa region enhances convection there, consistent with the floods observed over the region. The vertical velocity (ω) anomaly field at the 500 hPa level over East Africa during November 2006 is shown in Figure 4.19. Upward motion is evident over the entire region and adjoining ocean, with the strongest uplift being over northern Tanzania where the heaviest rainfall was experienced.

In summary, it has been shown that the northern Tanzania OND 2006 floods were related to warm SSTs in the western Indian Ocean with enhanced low level moisture convergence and uplift over Tanzania. These SST anomalies

were associated with a positive phase Indian Ocean Dipole and an El Niño occurring during this season. The extreme flooding in Tanzania seems to be preceded by warming near the Somali coast and an easterly moisture flux anomaly over the eastern equatorial Indian Ocean. Generally, the OND 2006 floods anomalies is roughly the opposite of the 1998 – 2005 drought anomalies. However, the OND 2006 flood circulation anomalies seem to be stronger than the 1998 – 2005 drought circulation anomalies consistent with the larger positive rainfall anomalies observed.

4.5.3. Circulation features for the heavy precipitation event on the 29th November, 2006.

About 75 mm of rain was recorded over NEH of Tanzania on 29 November 2006, significantly more than the long term monthly average of 63 mm. This event stands out very prominently in the OND 2006 rainfall record (Figure 4.13). This section of the chapter examines the wind circulation patterns in an effort to enhance our understanding of the atmospheric circulation patterns over the Indian Ocean associated with the heavy rainfall event.

The vertical velocity (ω) anomaly at 500 hPa for 29 November 2006 can be seen in Figure 4.19(ii), while Figure 4.20 shows wind streamlines for that day. Strong relative uplift at 500 hPa is evident over Tanzania on 29 November 2006. At the 850 hPa level (Figure 4.20(i)), the wind streamlines show an omega shape over the equatorial western Indian Ocean with cyclonic circulation over the Tanzanian coast, which implies local cyclogenesis there. This circulation is coupled with a north-easterly wind flow over northern Tanzania and enhanced low level moisture flux convergence (Figure 4.21 (i)). An easterly wave is evident over the Indian Ocean south of 10°S. These circulation features enhance the moisture flux convergence over much of Tanzania (Figure 4.21 (i)) and are thus consistent with the devastating floods that occurred.

At 700 hPa (Figure 4.20(ii)), the streamlines indicate a strong cyclonic circulation centred over the equatorial West Indian Ocean closer to the Tanzanian coast associated with weak south easterly and north easterly flow converging over Tanzania. This in turn reflects a strong moisture flux

convergence over the region. Johnson & Morth (1961) indicated that the prevailing easterlies typically contain more moisture in November, while Camberlin & Wairoto (1997) suggested that, at the 700 hPa level, the easterlies advect moisture from the Indian Ocean to the inland areas. The advected moisture over northern Tanzania interacts with meso-scale circulations over the region (lake and topographic effects) and, in particular, enhances the orographically induced precipitation over the highlands (Mukabana & Pielke, 1996).

The streamlines show the well located position of the zonal arm of the ITCZ over the equatorial western Indian Ocean and Tanzania between two ridges; namely the Northern Hemisphere high pressure cell located over the Somali coast and the Southern Hemisphere subtropical high pressure cell. A series of cyclonic circulations, favourable for rainfall, is evident within the ITCZ over the western Indian Ocean and the East African coastal region.

At 200 hPa (Figure 4.20(iii)), the streamlines indicate a centre of strong upper level divergence over the western Indian Ocean and southern Africa, coupled with easterly circulation over much of Tanzania. This may be associated with the Tropical Easterly Jet, and implies a strong upper level divergence, which in turn enhances moisture convergence in the lower levels, consistent with the heavy rainfall event observed.

The velocity potential anomalies for 29th November 2006 are shown in Figure 4.21 (ii - iii). At the lower levels (Figure 4.21(ii)), positive velocity potential occurs across the East African region with the largest value centred over Tanzania. At the upper levels (Figure 4.21(iii)), negative velocity potential covers much of the Indian Ocean and East African region. The occurrence of positive velocity potential in the lower levels coupled with negative velocity potential in the upper levels reflects the position of the ascending limb of the local Indian Ocean Walker type circulation, which is consistent with heavy rainfall observed over the NEH. The vertical velocity anomaly field at 500 hPa for 29 November 2006 (Figure 4.19(ii) further confirms the strong relative uplift over northern Tanzania during this heavy rainfall event. Low level negative anomalies in velocity potential over the south-eastern Indian Ocean (Figure

4.21(ii)) together with positive anomalies in this field at the upper levels indicates that the descending limb of the Walker circulation was located between 100°E and 120°E while convergence occurs over much of the country. Such eastward shift of the descending limb of the Walker circulation is consistent with the observed flood.

4.6. Summary of the findings

This section has examined the circulation patterns associated with the strong wet spells that Tanzania experienced during the OND period of 2006. Attention has been focused on the northern part of Tanzania as this region was significantly affected by the devastating floods that occurred. OND 2006 was the third wettest season in this region since 1971.

Scrutiny of the observed station rainfall data indicates that short spells of heavy rainfall experienced within a short duration in OND 2006 exacerbated the flood. A pertinent example was the rainfall on 29 November, 2006, in which the NEH received about 75 mm of rainfall in a single day, well above the November average of 63 mm. The station data was found to agree with satellite derived rainfall estimates, and thus provides increased confidence in the results.

The observed circulation features during OND 2006 indicate that the northern Tanzania OND 2006 floods were related to warm SSTs in the western Indian Ocean with enhanced low level moisture convergence and uplift over Tanzania. These SST anomalies were associated with a positive phase Indian Ocean Dipole and an El Niño occurring during this season. Consistent with this feature, the velocity potential plot indicated the position of the ascending limb of Walker type circulation to be centred over Tanzania as expected for a season of well above average rainfall. The extreme flooding in Tanzania seems to be preceded by warming near the Somali coast and an easterly moisture flux anomaly over the eastern equatorial Indian Ocean.

Examination of the patterns for the 29th November heavy rainfall event showed that, the lower levels were characterized by easterly flow with a long

ocean track towards Tanzania coupled with strong upper level divergence. Positive velocity potential at the lower levels coupled with negative velocity potential at the upper levels and relative uplift at 500 hPa were evident. It is worth noting here that the 18th October 1997 heavy rainfall event were also analysed (not discussed here for the sake of brevity) and found to have similar atmospheric patterns suggesting that broadly similar patterns can be identified for the extreme rainfall day of each season, thus providing more confidence in the robustness of the results.

Two months prior to the onset of the rainy season (i.e. August), warming occurs over the tropical western Indian Ocean with easterly moisture flux anomalies towards East Africa, thus suggesting that, for forecasting purposes, monitoring in this region is crucial. Timely implementation of the Research Moored Array for African-Asian-Austrarian Monsoon Analysis and Prediction (RAMA) (McPhaden *et al.*, 2008) in the tropical western Indian Ocean is therefore of great importance for East African climate monitoring and prediction efforts.

This chapter has examined the mechanisms associated with the 1998 – 2005 drought and 2006 floods over Northern Tanzania. Chapter 5 gives a detailed analysis of the ability of ECHAM4.5 GCM to represent atmospheric circulations associated with the inter-annual variability over the region. The chapter will further examine the ability of the model to represent the circulation patterns associated with 1998 – 2005 drought.

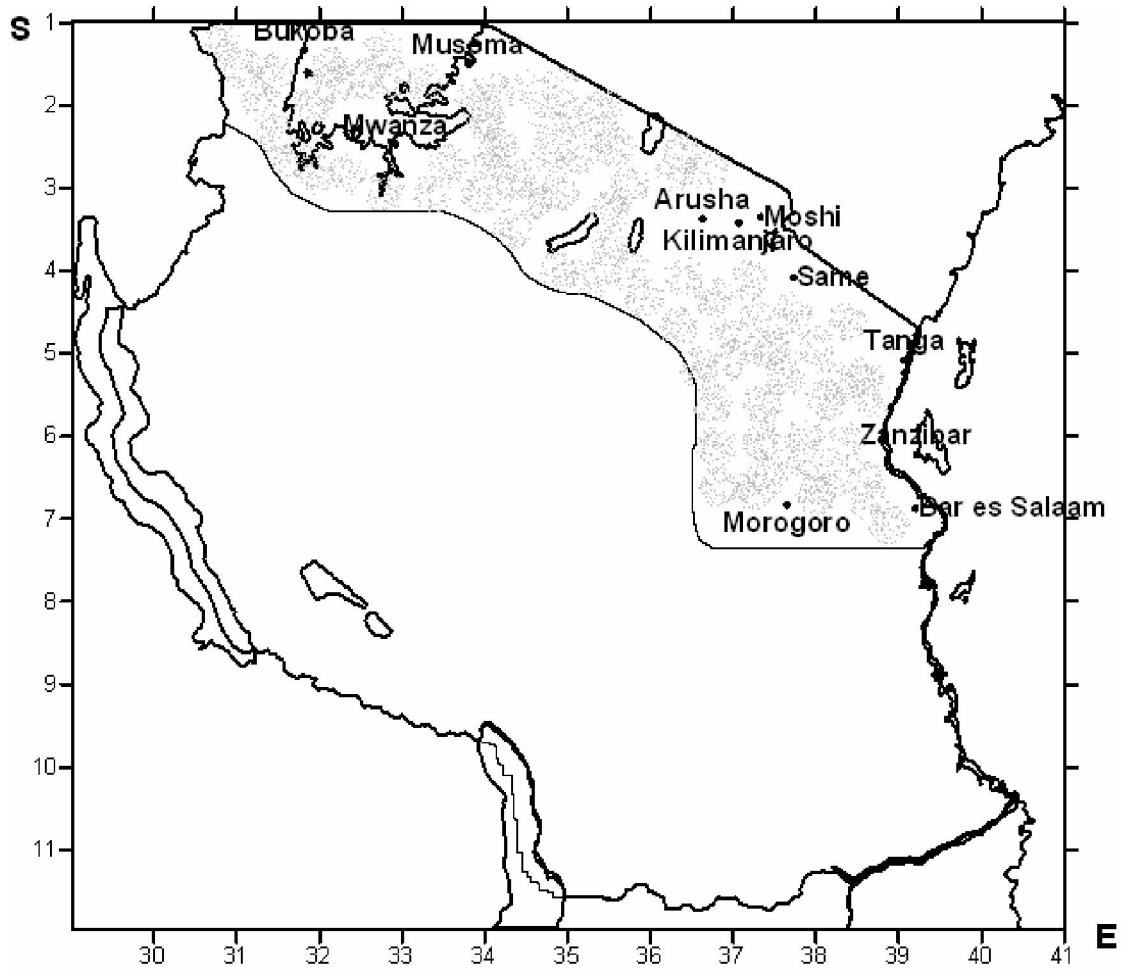
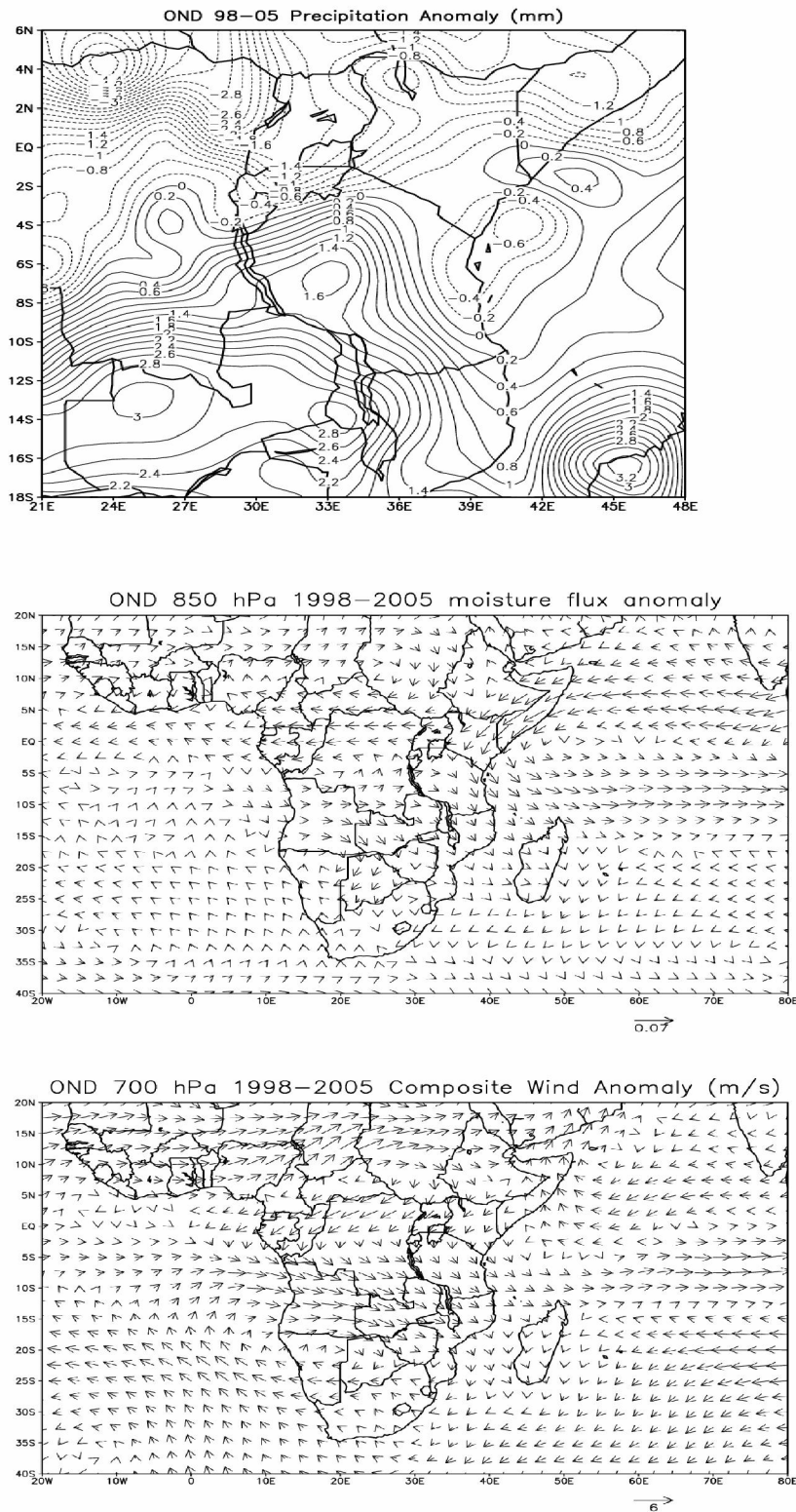


Fig 4.1: Map of Tanzania showing the region of study (shaded) and rainfall stations used in this study

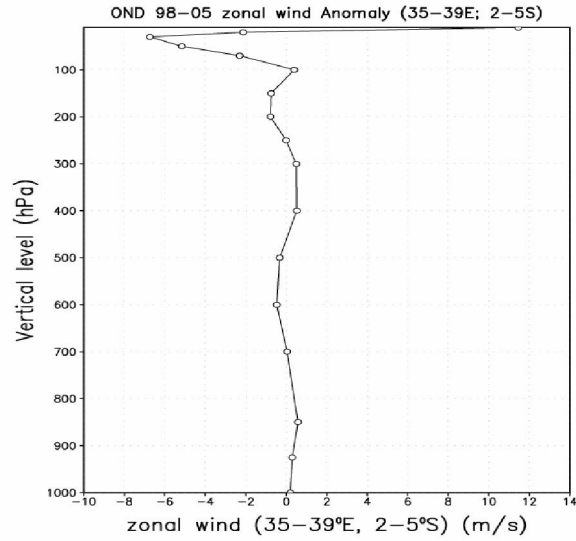


a

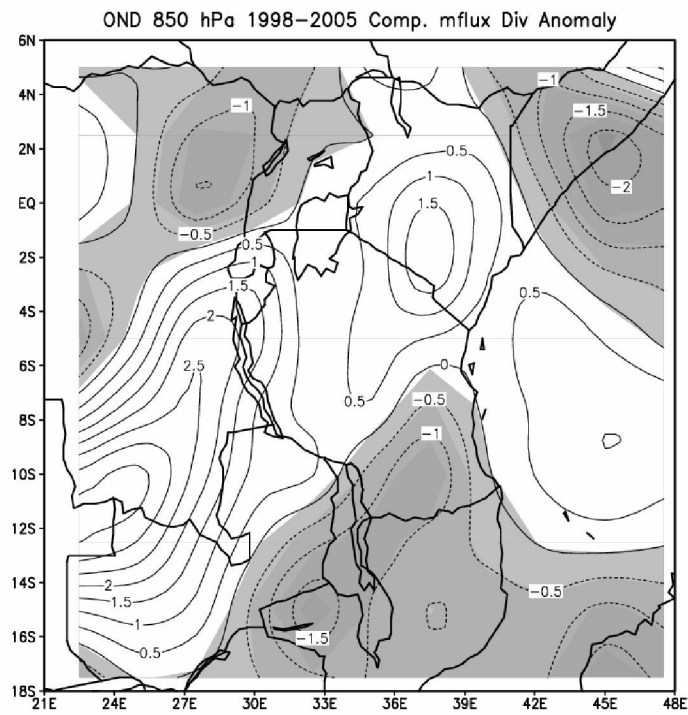
b

c

Fig 4.2: OND 1998–2005 composite anomalies of (a) CMAP rainfall (negative anomalies in dashed contours) (b) 850hPa moisture flux ($\text{KgKg}^{-1} \cdot \text{ms}^{-1}$) (c) wind at 700hPa



a



b

Fig 4.3: OND 1998-2005 composite anomalies of (a) zonal wind transect (b) moisture flux divergence ($10^{-8}(\text{KgKg}^{-1}\text{s}^{-1})$). Areas of convergence are shaded.

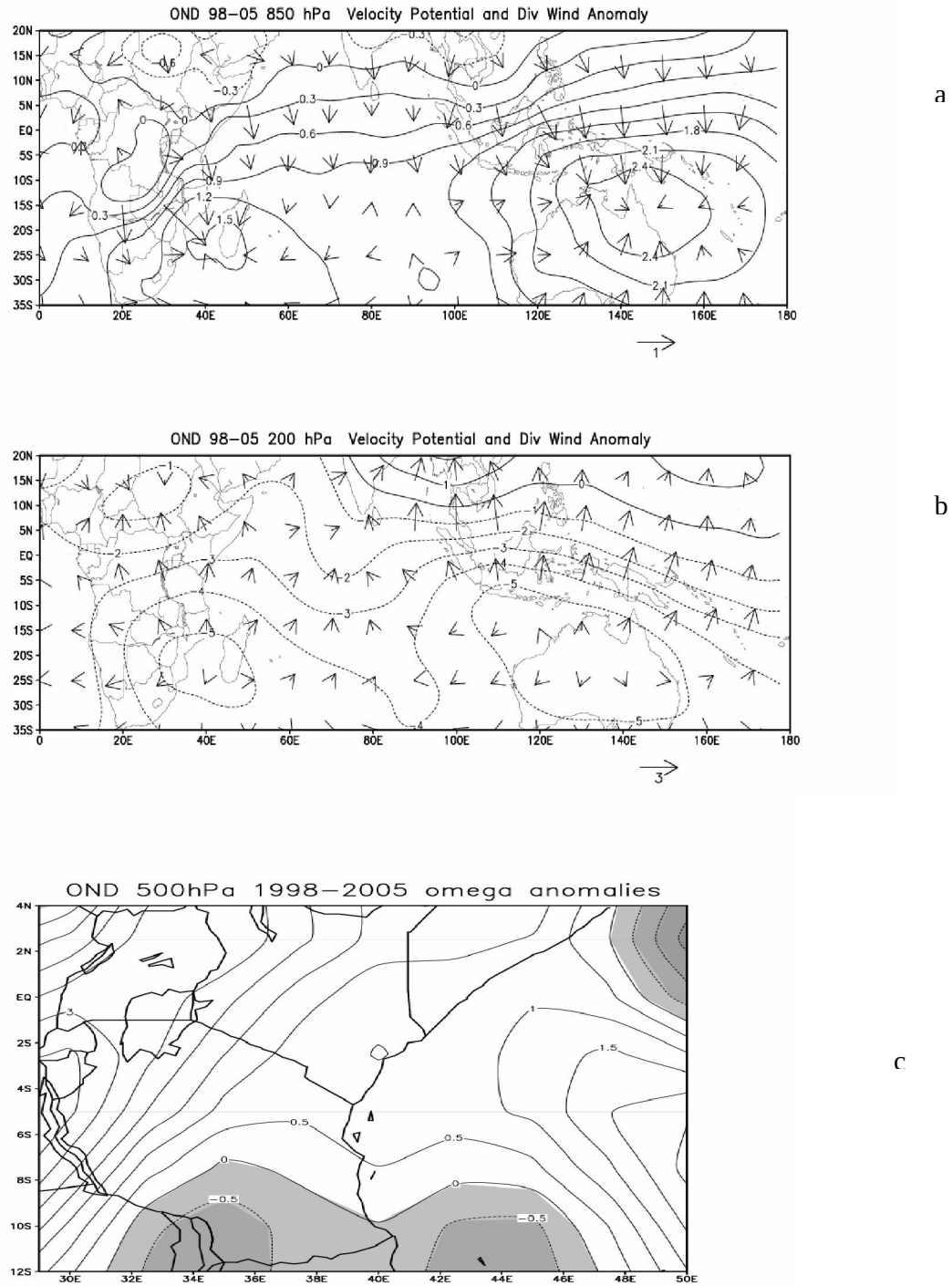


Fig 4.4: OND 1998-2005 composite velocity potential and divergent wind anomalies at (a) 850hPa (b) 200hPa and (c) 500hPa omega anomalies. Velocity potential in $\text{m}^2 \text{s}^{-1}$ and omega contour intervals is $0.5 \times 10^{-2} \text{ Pa s}^{-1}$. Shaded are areas of relative uplift.

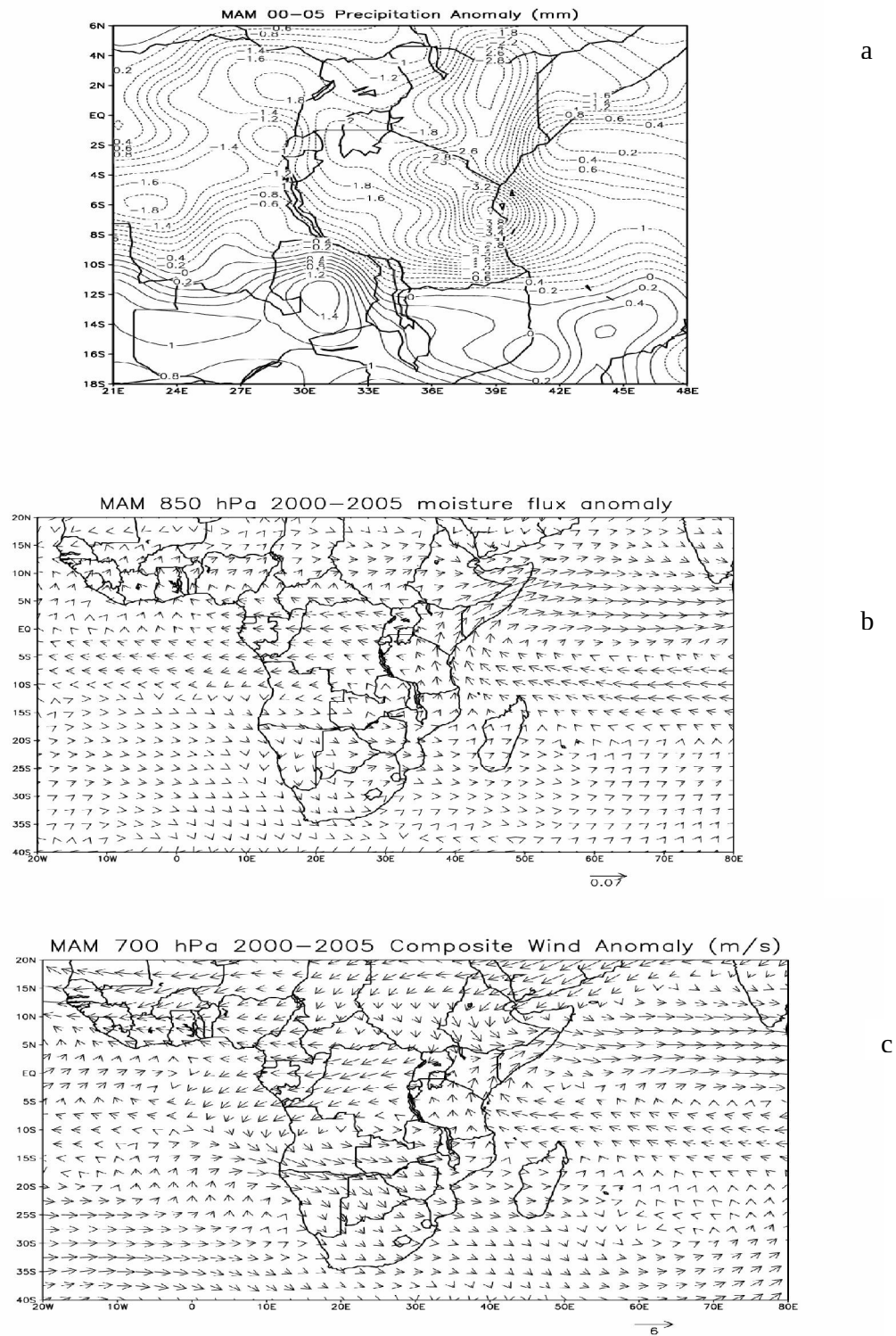
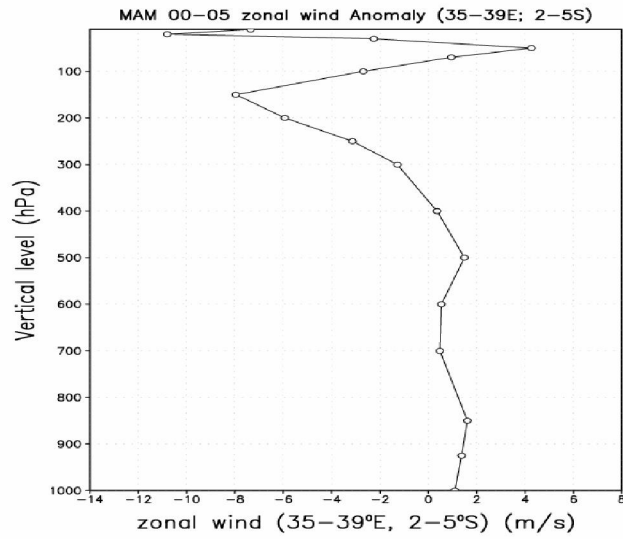
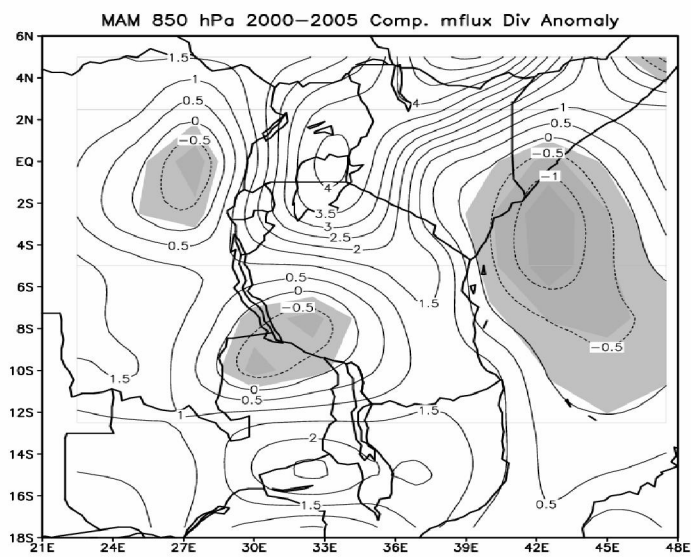


Fig 4.5: As for Figure 4.2 but for MAM 2000-2005 composite

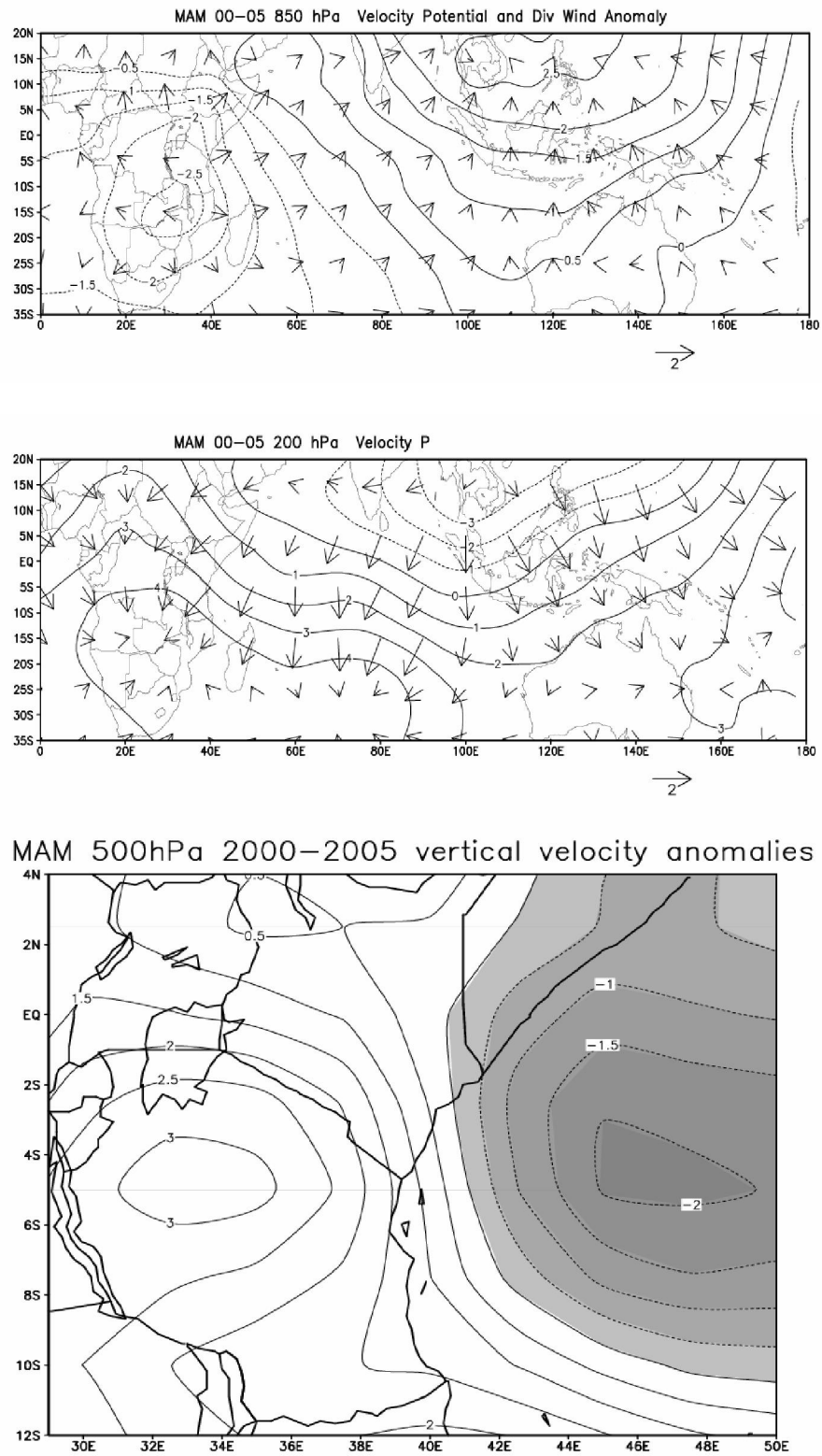


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Fig 4.6: As for Figure 4.3 but for MAM 2000-2005 composite

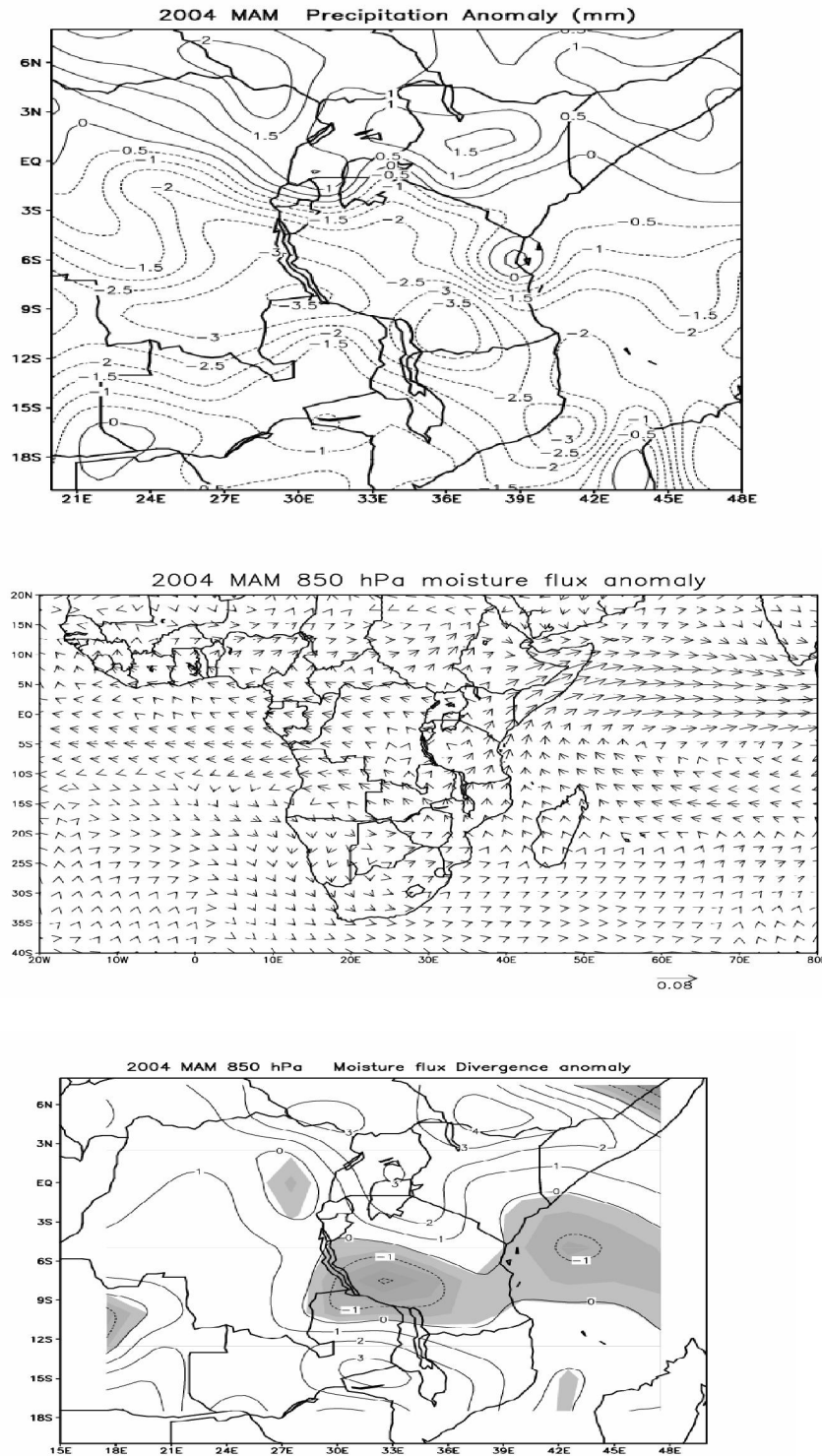


a

b

c

Fig 4.7: As for Figure 4.4 but for MAM 2000-2005 composite



a

b

c

Fig 4.8: MAM 2004 composite anomalies of (a) CMAP rainfall (negative anomalies in dashed contours) (b) 850hPa moisture flux ($\text{KgKg}^{-1} \cdot \text{ms}^{-1}$) (c) 850hPa moisture flux divergence ($10^{-8}(\text{Kg/Kg}) \cdot \text{S}^{-1}$).

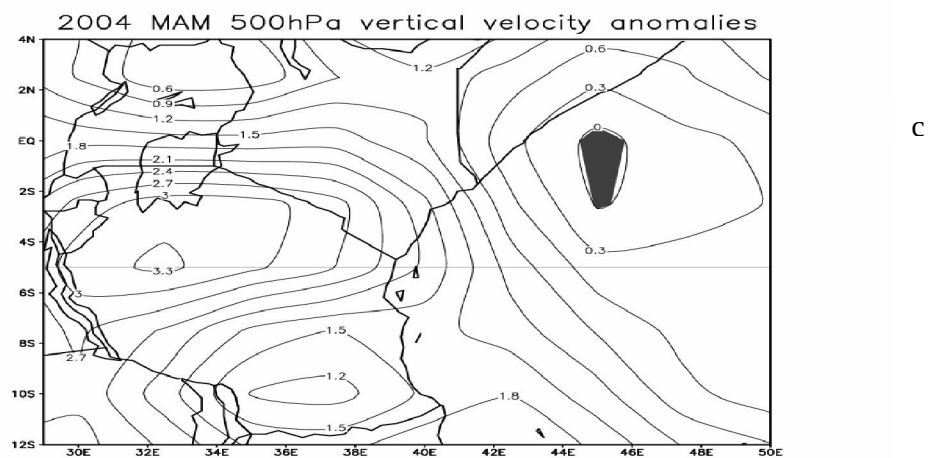
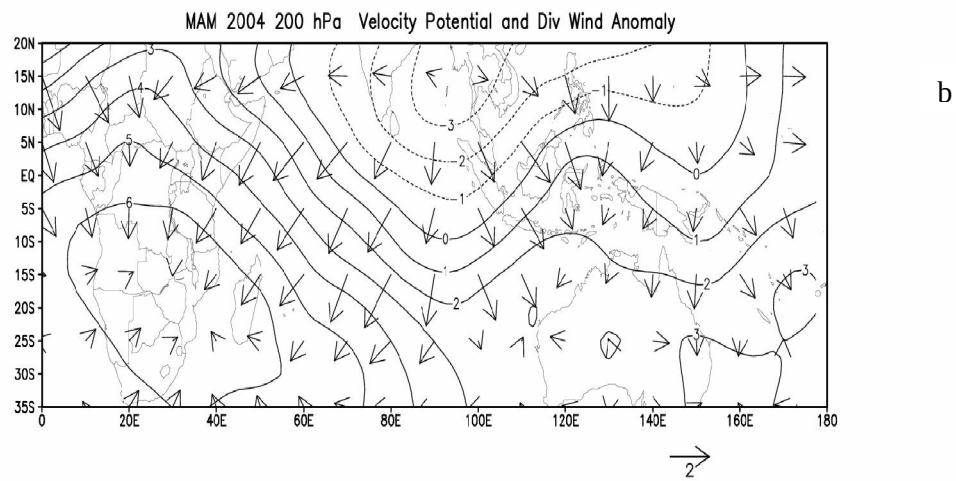
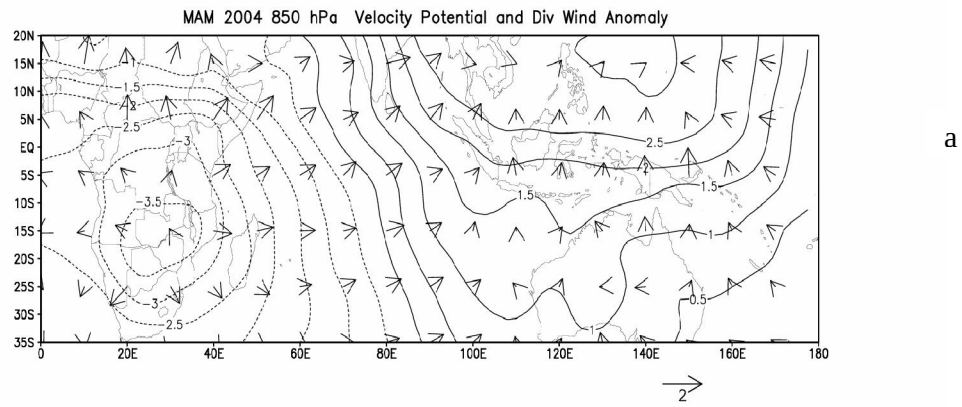
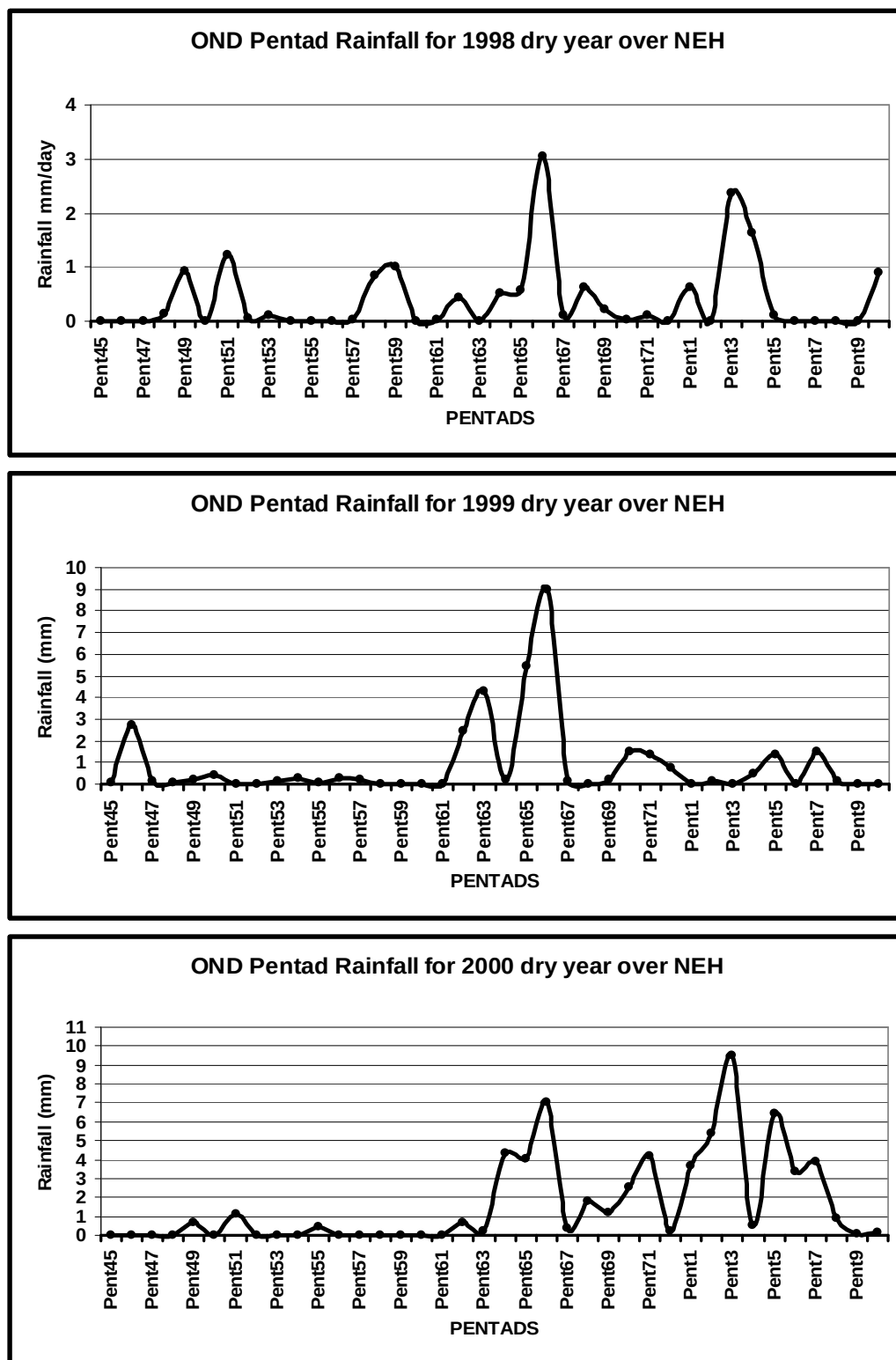


Fig 4.9: As for Fig 4.4 but for MAM 2004

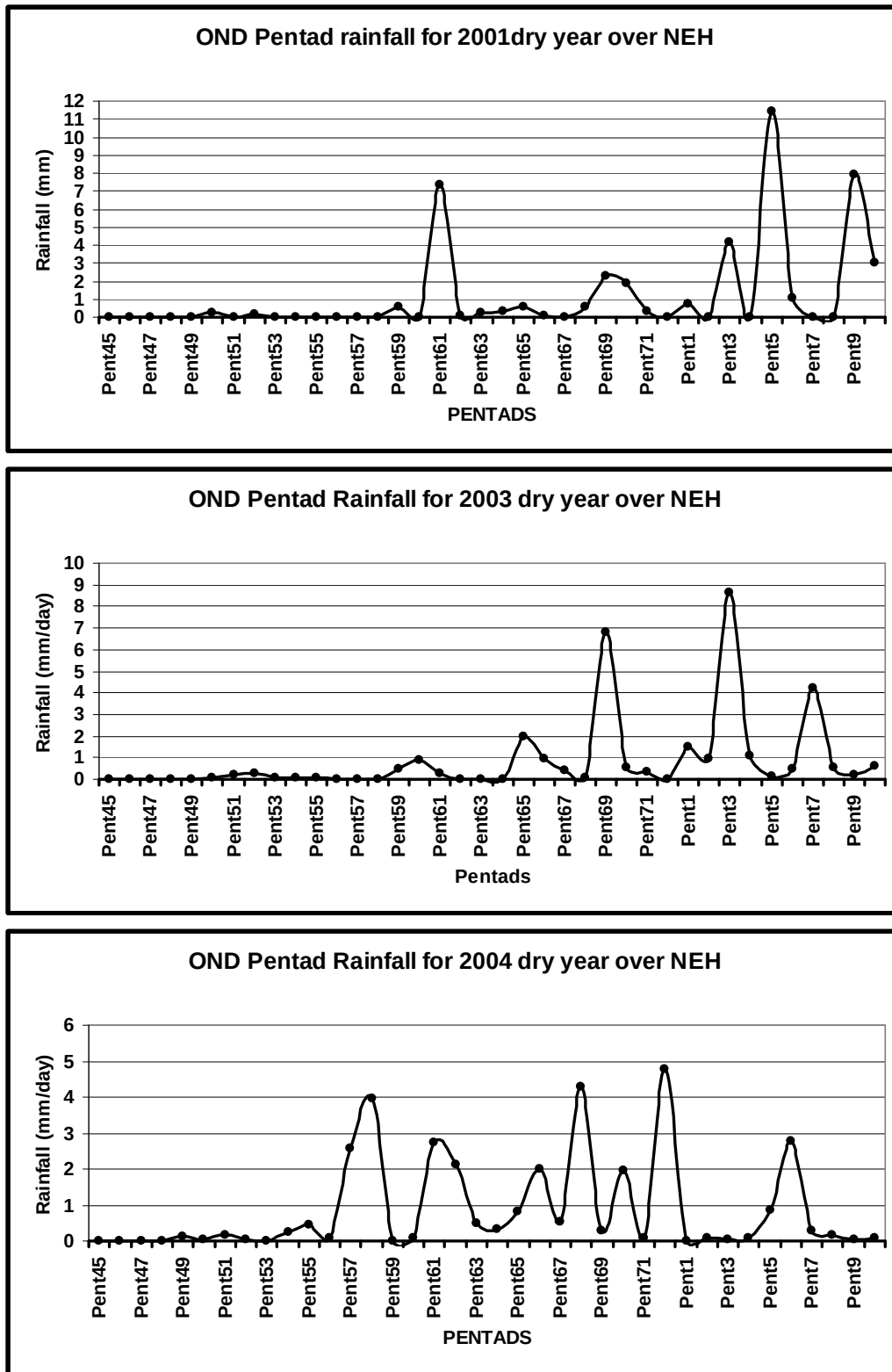


a

b

c

Fig 4.10: Pentad rainfall time series for NEH (a) OND 1998 (b) OND 1999 (c) OND 2000

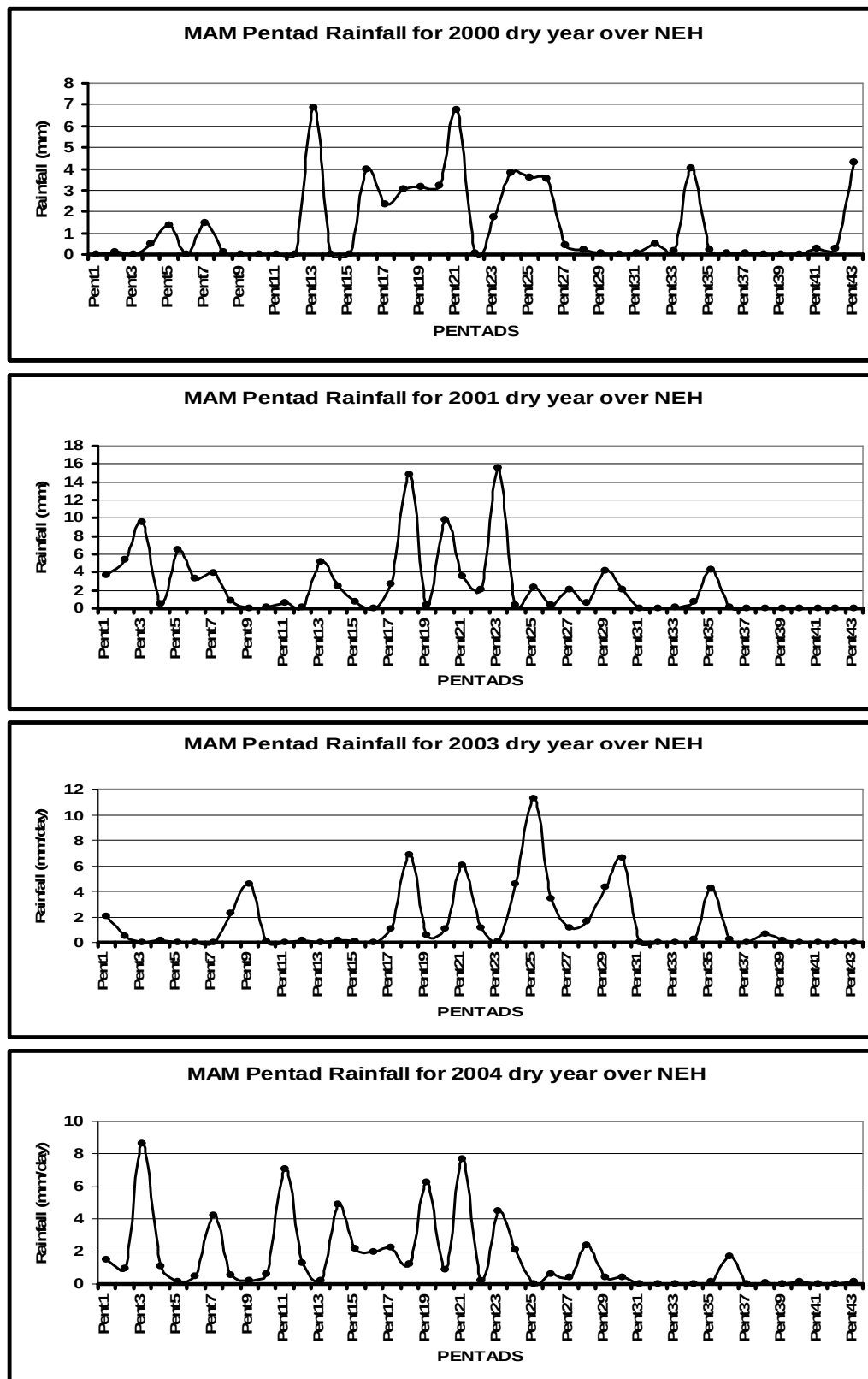


a

b

c

Fig 4.11: Pentad rainfall time series for NEH (a) OND 2001 (b) OND 2003 (c) OND 2004



a

b

c

d

Fig 4.12: Pentad rainfall time series for NEH (a) MAM 2000 (b) MAM 2001 (c) MAM 2003 (d) MAM 2004

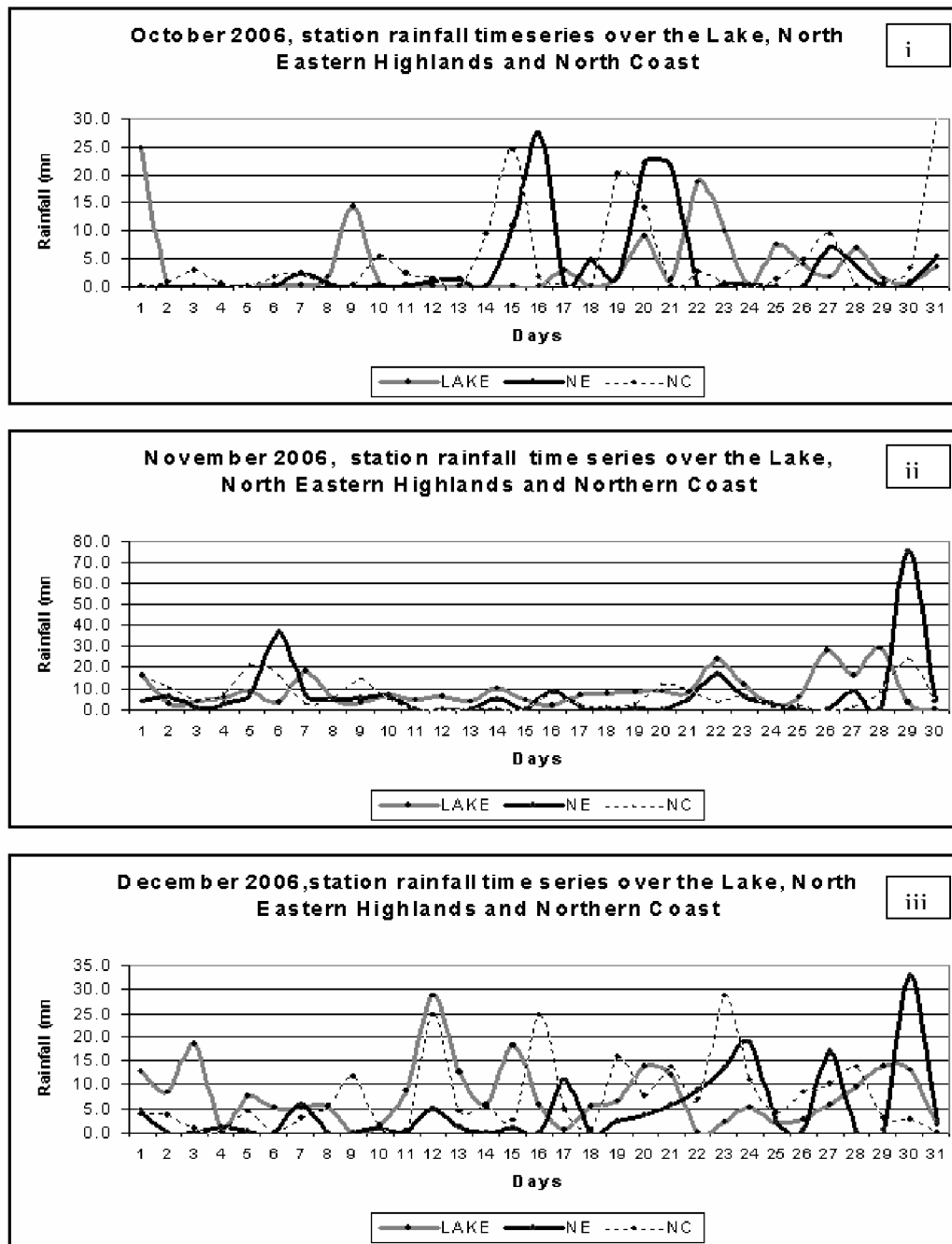


Fig 4.13: Station rainfall time series for 2006 (i) October (ii) November and (iii) December over northern coast, north-eastern highlands and Lake Regions. Rainfall in mm. Note different vertical scales.

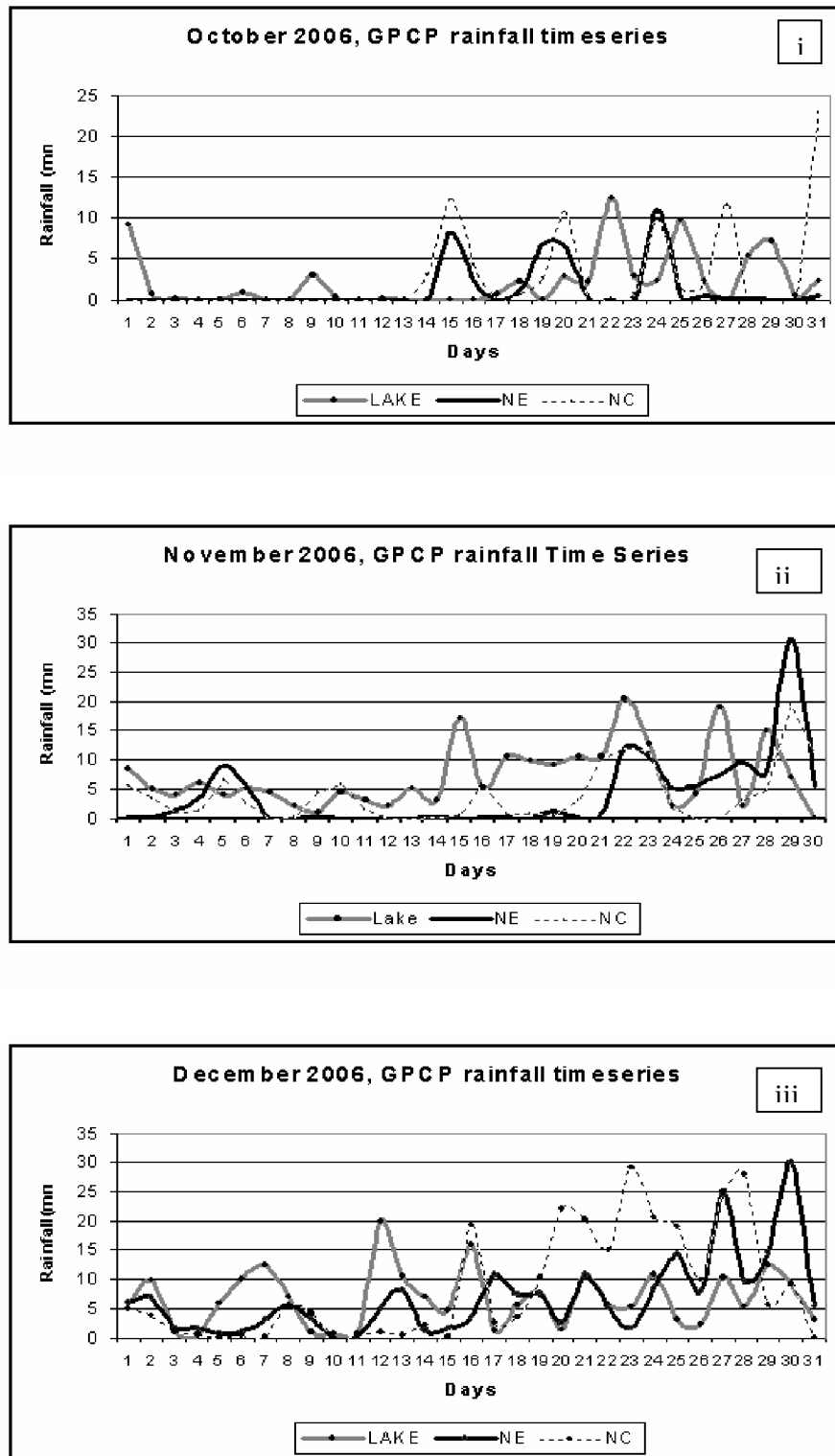
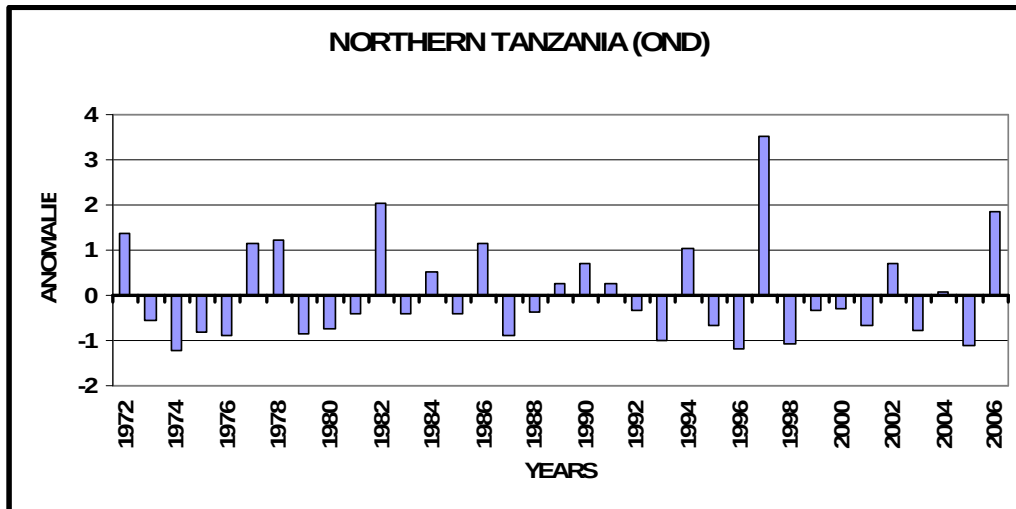
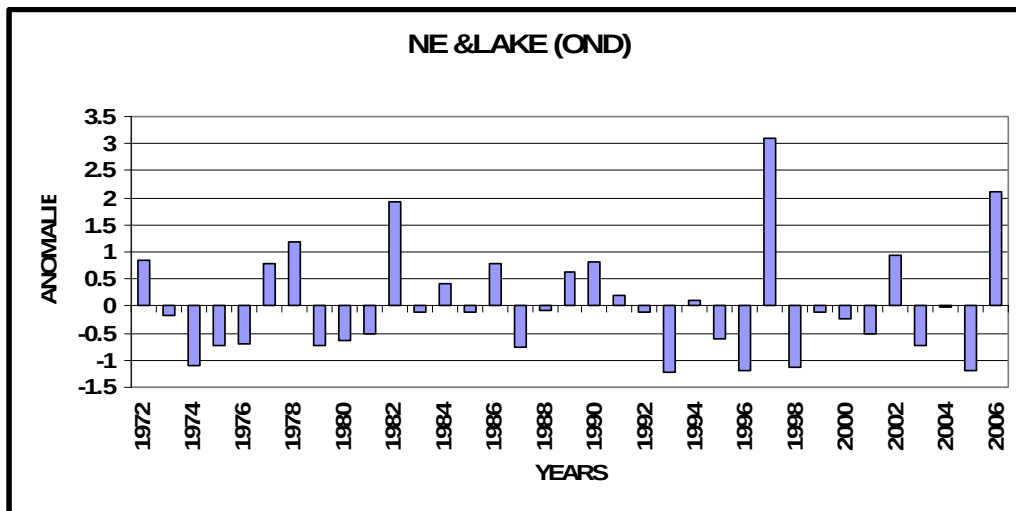


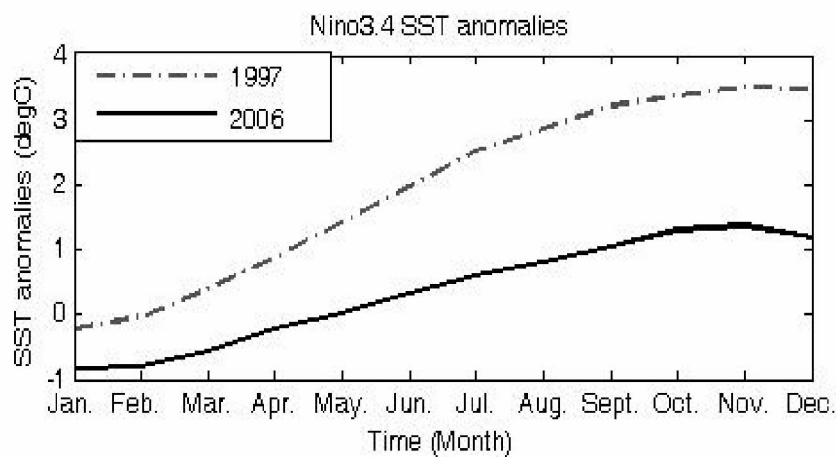
Fig 4.14: As for Figure 4.13 but for GPCP rainfall. Note different vertical scales.



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iii

Fig 4.15: Time series of rainfall anomalies for (i) Northern Tanzania (ii) North-eastern highlands and Lake Victoria basin and (iii) NINO 3.4 SST anomalies for 1997 and 2006

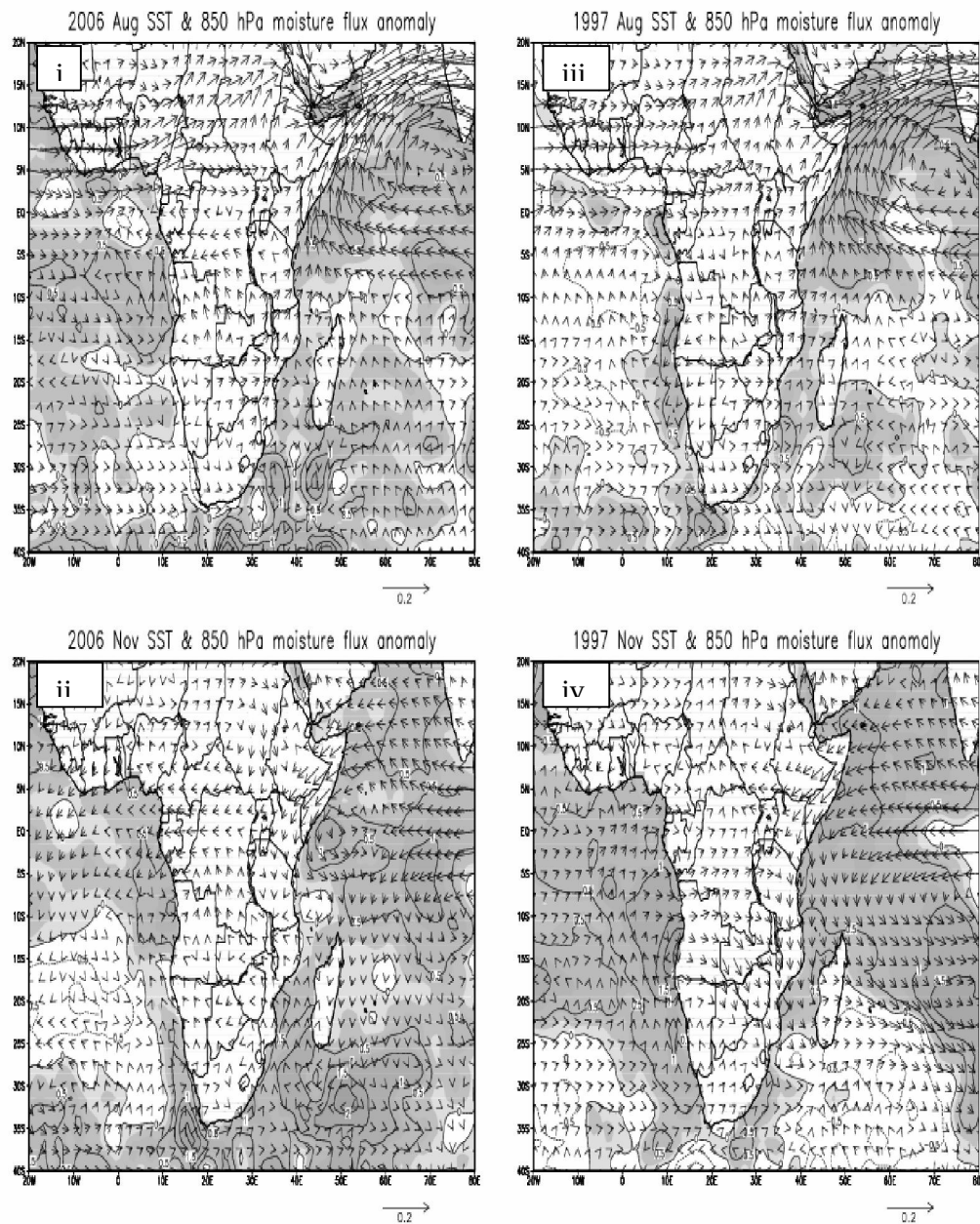
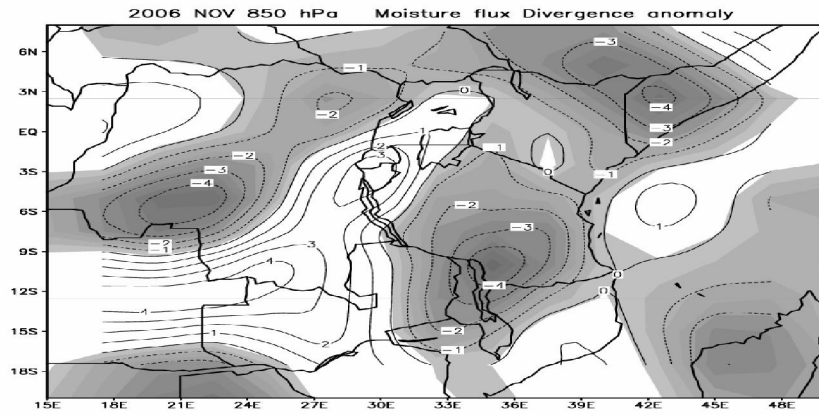
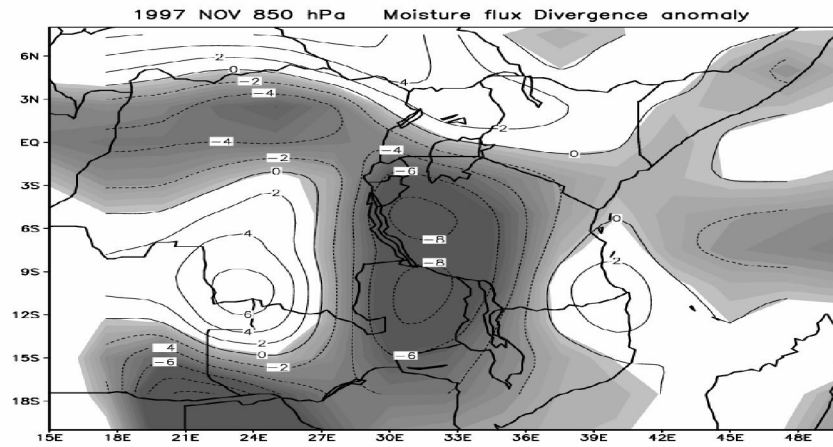


Fig 4.16: 2006 and 1997 SST and Moisture flux anomaly for August (upper panel) and November (lower panel). Positive SST anomalies are shaded. The scale vector corresponds to moisture flux 0.2g/kg m/s. SST contour interval 0.5°C.

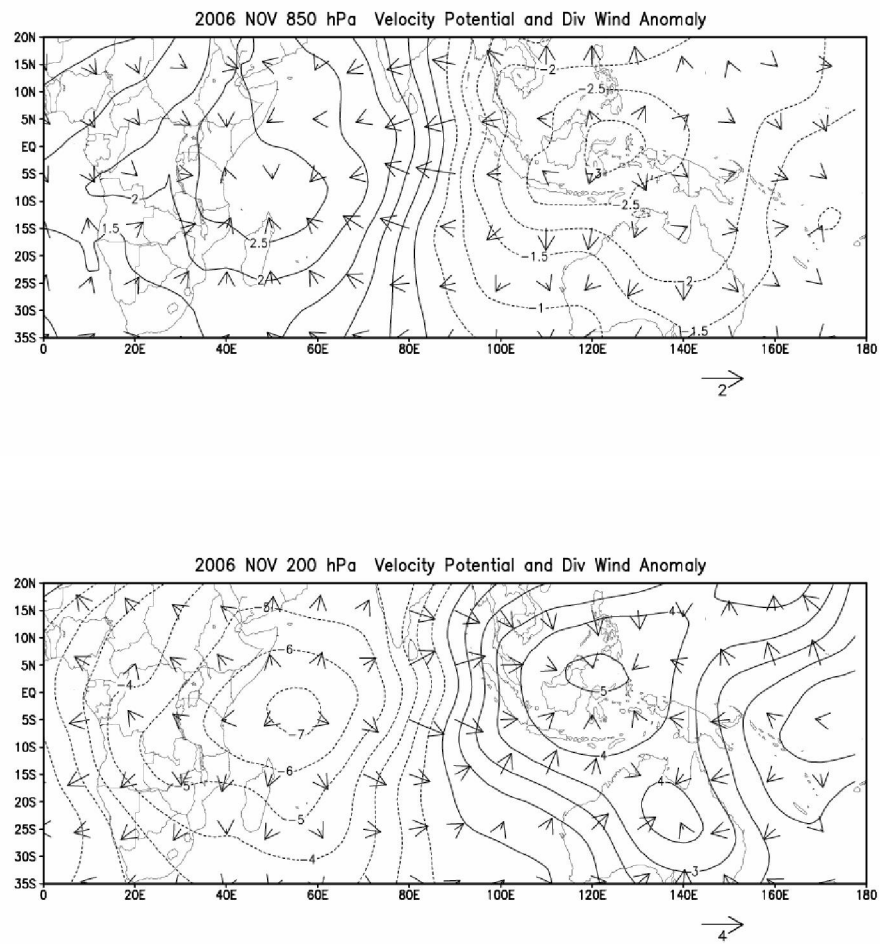


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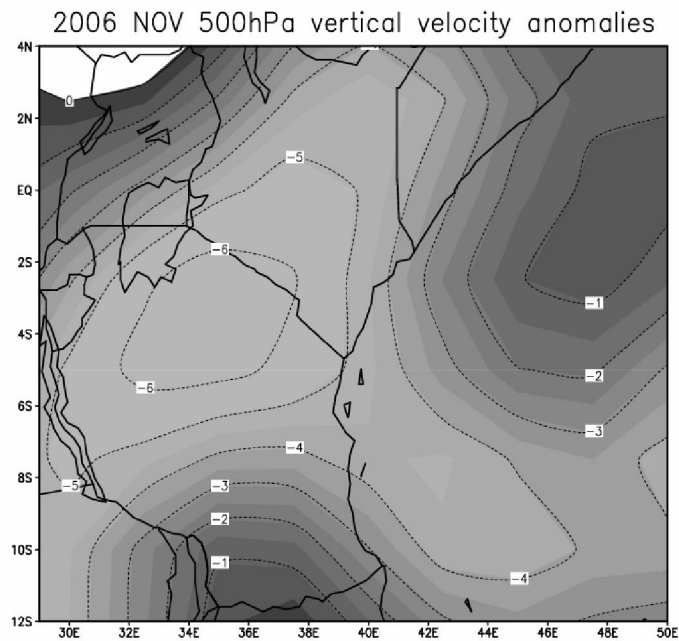
Fig 4.17: Moisture flux divergence for November 2006(i) and 1997(ii). Moisture flux divergence contour interval is $1 \times 10^{-8} \text{ g/kg/s}$ for 2006 and $2 \times 10^{-8} \text{ g/kg/s}$ for 1997.



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Fig 4.18: November 2006 velocity potential and divergent wind at 850hPa (i) and 200hPa (ii). Velocity potential in m^2/s .



29th Nov 2006 vertical velocity (omega) anomalies

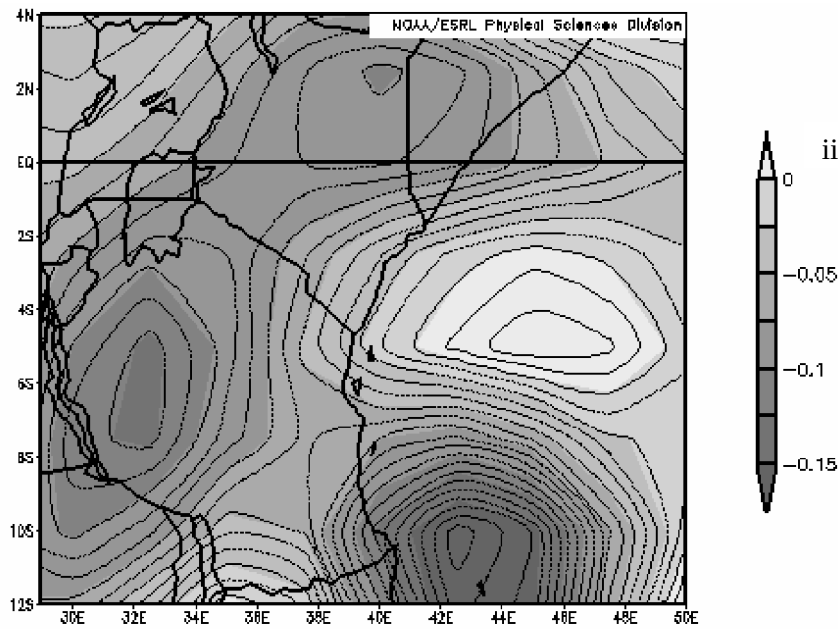
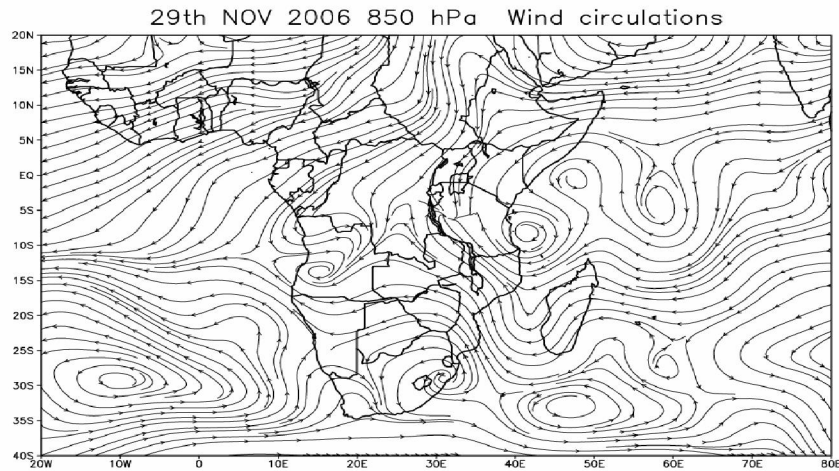
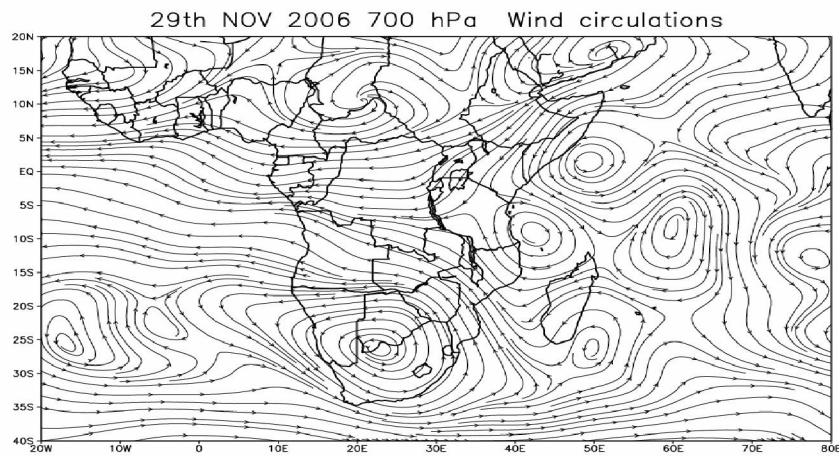


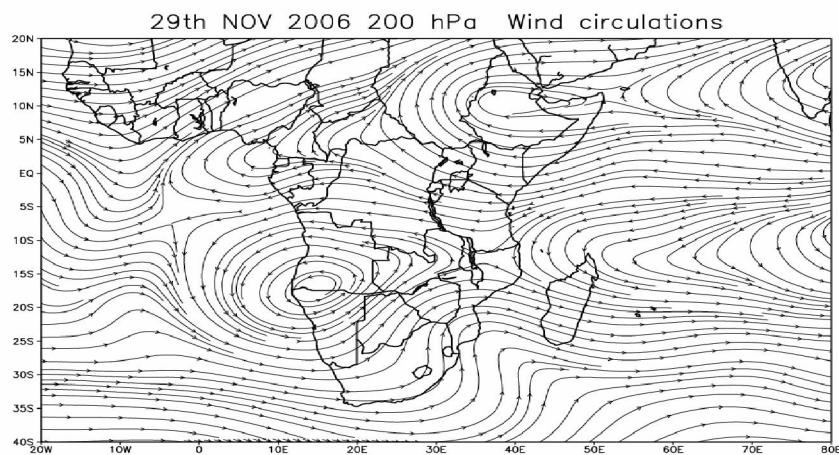
Fig 4.19: Vertical velocity (omega) anomalies for (i) Nov 2006 and (ii) 29th Nov 2006. Contour intervals for November (i) is 1/100 Pa/s



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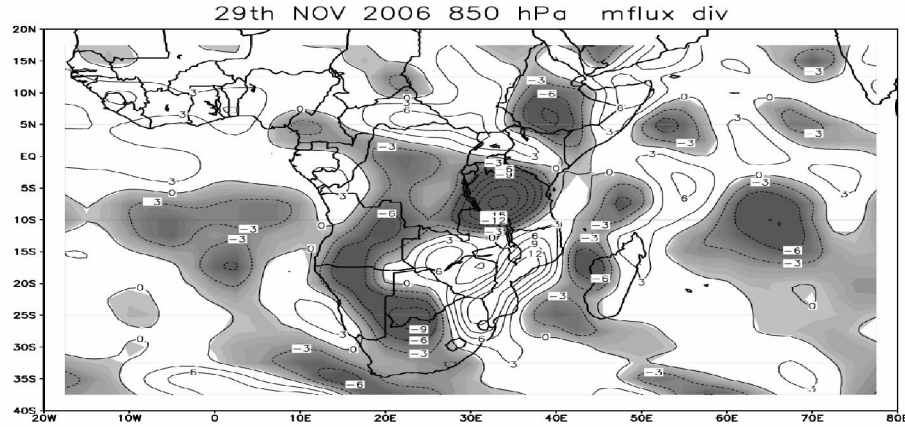


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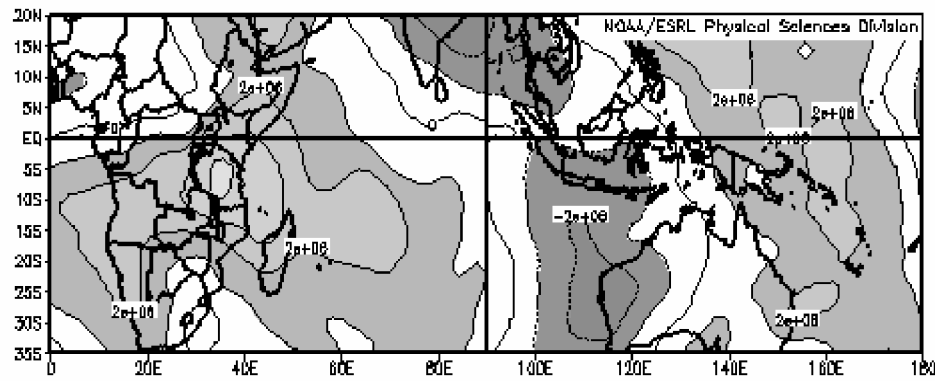
iii

Fig 4.20: Wind circulations for 29th Nov 2006 at 850hPa (i) 700hPa (ii) and 200hPa (iii) Wind in m/s



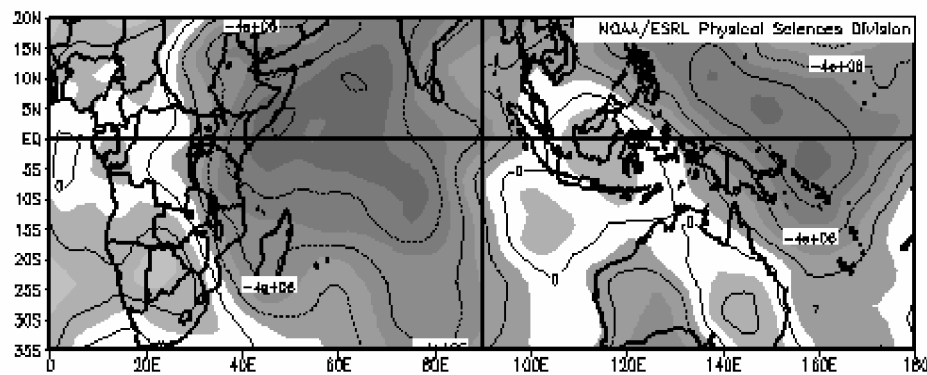
i

2006 Nov 29th, 850hPa velocity potential anomalies



ii

2006 Nov 29th, 200hPa velocity potential anomalies



iii

Fig 4.21: 29th November 2006 (i) Moisture flux divergence (ii) velocity potential anomalies at 850hPa and (iii) velocity potential anomalies at 200hPa. Velocity potential contour interval is $1 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ at 850 hPa and $2 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ at 200 hPa, and moisture flux divergence contour interval is $3 \times 10^{-8} \text{ g/kg/s}$.

CHAPTER FIVE

THE ABILITY OF ECHAM 4.5 GCM TO REPRESENT THE ATMOSPHERIC FIELDS FOR THE OND AND MAM RAINFALL SEASONS

5. 0 Introduction

A number of Atmospheric General circulation Models (AGCMs) and Regional Climate Models (RCMs) have been developed by different institutions around the world in an attempt to simulate the behaviour of the atmosphere (Dabberdt & Schlatter, 1996). The ultimate goal of these models is to represent the atmosphere in a realistic manner. However, each model is different from the other as they each employ varying physics, parameterisations and interpolation methods. Some represent certain regions better than others and it is therefore necessary to validate them. There are various methods to do this, such as model versus observation, or model versus model. However, the former is usually found to be more reliable. In terms of this method, the model output results are compared with observations, either via simple visual comparison of various simulated atmospheric fields or with more sophisticated statistical methods.

This chapter evaluates the ability of the ECHAM 4.5 GCM to realistically represent the atmospheric features associated with the country's climatology and inter-annual rainfall variability. Current perceptions and scenarios of GCM simulation of the tropical eastern African climate are largely based upon regional analyses (Goddard & Graham, 1999, for example). The results of these have not been assessed or verified for specific regions at national levels. As they are not country specific, they have not been used for operational forecasting in the countries comprising the Eastern African region including Tanzania. To address this concern, this study examines the north-east region of Tanzania.

As mentioned earlier several studies have been undertaken to understand climate variability over eastern Africa and its link to global oceanic and atmospheric dynamics. However, there have been no attempts to validate the use of GCMs over Tanzania. This study is therefore intended to contribute towards addressing this gap. The results discussed herein are based on the ECHAM 4.5 model, which was used with a global resolution of $2.81^{\circ} \times 2.79^{\circ}$ and 24 ensemble simulations runs nine vertical levels. The ECHAM climate model has been developed from the ECMWF atmospheric model and the

ECHAM4 is a current generation version (Roeckner, *et al.*, 1996). A summary of developments regarding model physics in the ECHAM4 and a description of the simulated climate with the uncoupled ECHAM4 model is available in Roeckner *et al.*, (1996). The initial sea surface temperature and sea-ice data is the COLA/CAC AMIP SST and sea-ice data (Gates W.L., 1992). The mean terrain heights are computed from a high resolution US Navy data set. The fraction of grid area covered by vegetation is based on the Wilson & Handerson-Sellers (1985) data set. Historical monthly data obtained from the IRI website (<http://iridl.ldeo.columbia.edu>) is used in this chapter. The evaluation is conducted for the period from 1971 - 2005.

The NCEP data with a resolution $2.5^{\circ} \times 2.5^{\circ}$ (Kalnay *et al.*, 1996) were linearly interpolated to the ECHAM 4.5 grid using a regrid bilinear interpolation method. The results from this data were compared with GCM results to evaluate the simulation of atmospheric circulations over north-east Tanzania. It is imperative to understand the atmospheric circulations over the Atlantic and Indian Ocean associated with seasonal rainfall over Tanzania. It is specifically necessary to establish whether the ECHAM 4.5 GCM is able to capture the mean and inter-annual circulations associated with rainfall over north-eastern Tanzania realistically. Despite the fact that there is not much data available to assimilate into the NCEP/NCAR data over the region, previous research has shown that NCEP/NCAR data represents the regional climate reasonably well (Kabanda & Jury, 1999; Kijazi & Reason, 2005; Mapande & Reason, 2005) and is used here for comparison with the ECHAM 4.5 model. Moisture flux, velocity potential and divergent winds are also used to evaluate the GCM's ability to represent areas of moisture convergence and vertical motion. The moisture flux is calculated by multiplying the zonal wind with specific humidity as defined in chapter two. Moisture flux convergence regions are shaded.

This chapter is divided into two main sections; section 5.1 discusses the ability of the ECHAM 4.5 model to represent climatological atmospheric circulations while section 5.2 discusses the ability of the GCM to represent inter-annual variability. Station rainfall data, CMAP data and NCEP/NCAR

reanalysis were used in this chapter for comparison with ECHAM 4.5 GCM output.

5.1 Ability of ECHAM 4.5 model to represent mean atmospheric circulation features

This section compares the mean ECHAM 4.5 atmospheric circulation features with NCEP/NCAR reanalysis and CMAP rainfall data. However, it should be mentioned that the low-level divergence field may be significantly influenced by the coastal topography, which varies greatly with movement inland from the Indian Ocean. About a hundred kilometres inland from the coast, the ground rises rapidly westwards, attaining a height of 1.5 km or more above mean sea level (Asnani, 1993). The lower tropospheric winds near the coast are observed to have an easterly component. These rise over the slopes of high grounds, which run roughly north south parallel to the coast a few hundred kilometers inland. When the rising air has sufficient moisture, clouds develop. Therefore, most of the rainfall observed over eastern Tanzania may result from the interaction between the moist easterly trades and orography. Mulenga (1999) also found that the rainy spells over the eastern coast of the Republic of Southern Africa (RSA) could be associated with low-level divergence and concluded that these were due to the interaction between moist trades and orography. As the GCM's resolution is coarse, these regional topographic features are not evident and divergence therefore persists over the coast throughout the rainfall season.

5.1.1 Moisture flux and velocity potential circulation features

The ECHAM 4.5 simulated and NCEP reanalysis moisture flux circulation features for the OND season are indicated in Figure 5.1 (a & b). The NCEP moisture flux plot (Figure 5.1(a)) indicates a strong easterly moisture flux advected from the Ocean and a westerly moisture flux advected from the Congo basin that converges over western Tanzania. Strong moisture flux convergence is evident over the region covered by latitude 5 °N – 10 °S and longitude 25 °E and 35 °E. This band of north-south oriented moisture flux

convergence arising from the confluence of two air-masses with different origins defines the position of the meridional arm of the ITCZ, as suggested by (Torrence, 1981). The meridional arm of the ITCZ is an important phenomenon influencing weather patterns over western Tanzania. Its east-west fluctuation determines the spatial extent of its influence. Eastward shifts result in increased rainfall over Tanzania, while westward shifts are mainly associated with dry conditions. The mean position of the ITCZ will therefore be used as a background to understand the anomalous rainfall events throughout the region.

A deceleration of the easterly moisture flux is evident over the equatorial Indian Ocean closer to the Tanzanian coast, suggesting a strong convergence of the easterly moisture flux advected from the Ocean, consistent with Camberlin & Waioto (1997). The eastern parts of Tanzania experience easterly moisture flux divergence, which suggests the influence of the coastal topography. Over the eastern tropical Atlantic Ocean, easterly moisture flux convergence is observed between 5 ° and 10 °S. The ECHAM 4.5 model (Figure 5.1(b)) is able to capture the moisture flux convergence over western Tanzania and the Indian Ocean. However, over the Atlantic Ocean, a westerly moisture flux dominates north of the equator while the NCEP plot shows an easterly moisture flux over the same region. This may infer that upwelling is not properly resolved in the ECHAM4.5 model.

The velocity potential and divergent wind for the OND seasons is shown in Figure 5.2. Scrutiny of the plots indicates the region of continental and maritime convection observed with OLR plots (Figure 3.5(b)) to be associated with strong low level and upper level wind divergence. The ECHAM 4.5 model seems to reproduce these features during the OND season.

The ECHAM 4.5 simulated and NCEP reanalysis moisture flux circulation features for the MAM season are indicated in Figure 5.3 (a & b). The moisture flux convergence over the Indian Ocean observed during the OND season seems to shift southward in the NCEP/NCAR plot (Figure 5.3(a)) consistent with the movement of the zonal arm of the ITCZ, leaving a strong easterly

moisture flux between the equator and 5 °N which converges further inland. The convergence over western Tanzania seems to be weak compared to the OND season. Southerly moisture flux divergence dominates the northern Congo Basin, which suggests that the Indian Ocean is the main source of moisture during the MAM season. The ECHAM 4.5 model (Figure 5.3(b)) simulates the easterly moisture flux convergence well over the Indian Ocean and western Tanzania. However, it fails to do the same for the southerly moisture flux divergence over the northern Congo Basin. These results partly explain the deficiency of the low resolution model to capture circulation patterns associated with local features over equatorial Eastern Africa. This suggests a need for the application of a high resolution model to accurately simulate the regional climate of equatorial Eastern Africa, specifically Tanzania.

The velocity potential and divergent wind for the MAM seasons is shown in Figure 5.4. Again scrutiny of the plots indicates the region of continental and maritime convection observed with OLR plots to be associated with strong low level wind convergence and upper level wind divergence. However, the ECHAM4.5 fails to reproduce the upper level features and the model fields seem to be too weak.

Generally, the ECHAM 4.5 model seems to simulate the climatological moisture flux features associated with rainfall over the region reasonably well. Furthermore, a statistical test for the hypothesis that there is no difference between simulated and NCEP reanalysis climatology at a 95 percent level is accepted for the ECHAM4.5 model. The next section examines the annual cycle and spatial distribution of rainfall over the region and assesses the capability of the ECHAM 4.5 model to simulate the patterns that have been observed.

5.1.2 Rainfall distribution

Rainfall information has great value in Tanzania, especially for the socio-economic benefit of farmers, water managers, energy suppliers and public

policy makers. In this section, the annual cycle and seasonal spatial distribution of rainfall over Northern Tanzania is illustrated. The ability of the ECHAM 4.5 model to simulate the observed features is assessed using visual comparison and simple correlation methods. The rainfall spatially averaged over the region (4 S - 7.5 S, 35 E – 40 E) is used for correlation with station-averaged data. However, the coarse resolution of the GCM does not allow detailed comparison with the station data and the CMAP data is therefore used instead.

The time series of the ECHAM 4.5 model versus CMAP and station observed rainfall over north-eastern Tanzania is indicated in Figure 5.5 (a – c). It is evident from these Figures that the region exhibits two rainfall seasons: March to May and October to December. However the ECHAM 4.5 model seems to indicate a unimodal rainfall season extending from October to April with a maximum in January. The ECHAM 4.5 series indicates a high correlation with both CMAP and station data. The correlation co-efficient between ECHAM 4.5 and station data was 0.6, whereas with CMAP, it was 0.72. Both correlation values were significant at a 95 percent level using the student's t-test. Lower values of correlation with station data as compared to CMAP data may be caused by the coarse resolution of the model that does not allow detailed comparison with station data as stated earlier. However, the CMAP data series indicates high correlation with station data ($r = 0.97$). This suggests that CMAP data can be used to represent station data over Tanzania and it has therefore been used in this study to investigate the spatial distribution of rainfall.

The spatial distribution of rainfall over Tanzania is indicated in Figure 5.6. For the MAM season (Figure 5.6 (a)), high values of rainfall (over 450 mm) were evident over the coast and Lake Victoria basin. The lowest values of about 300 mm were located over central Tanzania. The ECHAM 4.5 model overestimated the observed rainfall over the Lake Victoria basin and underestimated the observed value over the coast. In general then, the ECHAM 4.5 model seems to underestimate the rainfall value observed over Tanzania.

For the OND season (Figure 5.6 (b)), the highest rainfall values of about 300 mm were again observed over the coast, with the lowest value of about 200 mm seen over central Tanzania. Western Tanzania and the Lake Victoria basin received the highest levels of rainfall (about 350 mm). The ECHAM 4.5 model again overestimated the rainfall observed over the Lake Victoria basin. About 450 mm of rainfall were simulated over the Lake with an eastward decrease of rainfall reaching the lowest value of about 100 mm over the coast. The model fails to represent the lower rainfall values over central Tanzania. Generally then, the model does not capture the spatial distribution of rainfall over the country.

Generally, the comparison between GCM and NCEP reanalyses indicated that the ECHAM 4.5 model represented some of the climatological circulation features related to rainfall over the region. This section has provided the mean characteristics that will be used as a background for the analysis of anomalies in the next section.

5.2 Ability of ECHAM 4.5 model to simulate circulation features related to inter-annual variability

This section attempts to compare the ECHAM4.5 model over North-eastern Tanzania with CMAP rainfall data. Simulated moisture flux circulation patterns were compared with NCEP/NCAR reanalysis. These data sets represent the main Tanzanian circulation features reasonably well (Kijazi & Reason, 2005; Mapande & Reason, 2005). Station rainfall time series were also compared with CMAP and GCM rainfall time series. The central issue is to understand the ability of the GCM in capturing the inter-annual variability of rainfall over the north-eastern part of the country. Specifically, there is an interest in understanding how well the GCM is able to simulate the deep convection associated with extreme rainfall events over the region. As previously mentioned, there is currently very little experience with dynamical modelling in Tanzania, and the ability of GCM in representing atmospheric circulations

over the country is therefore completely unknown. This study accordingly aims to contribute towards bridging this knowledge gap.

5.2.1 Results of rainfall time series

Inter-annual variability of the ECHAM 4.5 simulated and observed rainfall for the OND and MAM seasons is shown in Figure 5.7 & 5.8. Both station and CMAP rainfall data were used for correlation with the GCM data. The OND results (Figure 5.7(a)), indicate a correlation of 0.63 between the ECHAM 4.5 series and the station data series. The model reproduces most of the rainfall peaks, for example, 1972, 1977, 1982 and 1986. For the 1994 and 1997 peak, the model seems to strongly under-estimate the observed rainfall value. A correlation value of 0.63 that was significant at the 95 percent level using a student t-test was evident between these two series. For the CMAP data during the OND season (Figure 5.7(b)), the model seems to represent the 1982 peak, while under-estimating the 1986 and 1997 peaks. A correlation value of 0.4 that was again significant at the 95 percent level was calculated.

During the MAM season (Figure 5.8 (a & b)), the model performs poorly in comparison to the station and CMAP rainfall time series. A correlation value of -0.03 and 0.15 were evident with model data for the station and the CMAP series respectively. The model series were out of phase with the observed series for most rainfall peaks. The low correlation between the ECHAM 4.5 series and the observed rainfall series may be attributed to the fact that the ECHAM 4.5, being a GCM, only captures larger scale forcing, thereby omitting the effect of local factors such as topography, land-lake interactions, and local soil moisture or vegetation contrasts that might be influencing individual stations. Other possible factor is weaker SST forcing in MAM as suggested by (Quan *et al.*, 2004). The significant correlation with the OND time series suggests that larger scale features such as El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD)) are significant in modulating the OND rainfall season as suggested by Indeje *et al.* (2000). These results suggest that use of the ECHAM 4.5 during the OND season rather than the MAM season is likely to produce better results. These may be

contributed to the fact that the ENSO and IOD modes are very influential in OND but not in MAM as suggested by (Kijazi, 2003).

5.2.2 Results of wavelet analysis

To understand the temporal characteristics and assess the ability of the ECHAM 4.5 model to represent this variability, the principal component analysis (as described in chapter two) was applied to the standardised rainfall data. To estimate the dominant periods, a wavelet analysis was applied to the first (PC1) and second (PC2) principal components that explained the highest percentage of variance for the ECHAM 4.5 and CMAP data.

PC1 and PC2 time series and power spectrum for the MAM season are shown in Figure 5.9 – 5.12. For PC1 (Figure 5.9(a)), the CMAP data indicated strong positive anomalies for 1979, 1983, 1989, 1991, 1999 and 2006 with negative anomalies recorded in 1988, 1994, 2001 and 2003. The power spectrum (Figure 5.9(b)), indicates strong power at two to four year period with two of the highest peaks centred around 1987 and 1999. These were separated by low power between 1991 and 1996. A PC2 time series (Figure 5.10(a)) indicate strong positive anomalies for 1989, 1997 and 2003 with negative anomalies for 1982, 1991 and 1999. The power spectrum (Figure 5.10(b)) indicates strong power of between 3 and 7 years with highest peaks centred around 1983 and 1993.

The ECHAM 4.5 model (Figure 5.11(a)), indicates strong positive anomalies in 1982, 1987, 1992, 1999 and 2004 with negative anomalies in 1984, 1993 and 1998 for PC1 time series. The power spectrum (Figure 5.11(b)) indicates strong power at two to four year period with the strongest values extending from 1991 – 1999 for the period. For PC2 time series (Figure 5.12(a)), the ECHAM 4.5 data indicates strong positive anomalies in 1982, 1993, 1998 and 2005 and negative anomalies in 1983, 1986, 1989, 2000 and 2006. The power spectrum (Figure 5.12(b)) indicates strong power between 2 and 4 years with highest peaks centred at 1980 and 2003.

PC1 and PC2 time series and power spectrum for the OND season are shown in Figure 5.13 - 5.16. For PC1 (Figure 5.13(a)), the CMAP data indicates strong positive anomalies for 1982, 1989, 1997, 2000 and 2004 and negative anomalies in 1981, 1987, 1993, 1995, 1998 and 2005. The power spectrum (Figure 5.13(b)) shows a strong power at two to four years with peaks centred around 1982 and 1997. For PC2 time series (Figure 5.14(a)), the CMAP data shows positive anomalies for 1989, 1997 and 2003 with negative anomalies for 1982, 1991 and 1999. The power spectrum (Figure 5.14(b)) shows a strong power at eight years with highest peak extending from 1991 – 1999.

For the ECHAM 4.5 data (Figure 5.15(a)), PC1 indicates strong positive anomalies in 1991 and 1995. The power spectrum (Figure 5.15(b)) shows strong power at two to four years and extends from 1987 - 1999 with relatively strong power at four to eight years centred in 1987. For PC2 (Figure 5.16(a)), the time series indicate positive anomalies in 1982, 1987 and 1997 with negative anomalies in 1984, 1999 and 2005. The power spectrum (Figure 5.16(b)) indicates strong power between 2 and 4 years with highest power centred in year 2004.

Generally, the ECHAM4.5 model represented the 2 - 4 years' variability but has problems with capturing the periods of strongest power. The spatial maps for EOF 1 during the OND season (Figure 5.17(a)) indicates negative values over Tanzania with highest concentration over central Tanzania and southern Kenya for CMAP data while for ECHAM 4.5 (Figure 5.17(b)) positive values extends over the entire country with highest values over the Lake Victoria Basin and central Tanzania. This was further confirmed by the correlation between CMAP and ECHAM PCs. Significant negative correlation (-0.3) was found for PC1 during the OND season while for MAM season the correlation was very low.

5.2.3 Results of circulation features for the 1998 – 2005 drought

This section considers the OND season of the 1998 – 2005 protracted drought over the NEH of Tanzania. A detailed analysis of this event is given in

chapter 4. The aim of this section is to assess the ability of ECHAM 4.5 model in representing the circulation features associated with the protracted drought. Figure 5.18 (a and b) show the OND 850hPa moisture flux and OND 700hPa wind anomalies respectively for ECHAM 4.5 model. Comparison with Figure 4.2 (b and c) indicate that the ECHAM 4.5 model well represented the moisture flux and wind circulation features associated with the protracted drought except for the cyclonic wind circulation pattern centred over Madagascar that is not evident in the NCEP/NCAR plot. Figure 5.19 (a and b) show the 850hPa moisture flux divergence and OND rainfall circulations respectively for ECHAM4.5. Comparison with Figure 4.3 (b) and Figure 4.2 (a) indicate that the ECHAM 4.5 model fails to represent the moisture flux divergence and rainfall circulation features associated with the 1998 – 2005 protracted drought over the NEH. This might be contributed by the coarse resolution of the model. However, despite some deficiencies in the model, it seems to capture some features related to rainfall over the region.

To understand the ability of the model to represent the circulation features associated with heavy rainfall events the next section of this chapter discusses the circulation features for selected heavy rainfall seasons.

5.3 Circulation features for the selected heavy rainfall events

This section considers the OND season of the selected wet and dry season over the region of study. Year 1997 was an El Niño year and Positive Indian Ocean Dipole zonal mode year with devastating floods over much of East Africa while 1996 was a negative Indian Ocean zonal mode year with dry conditions over the region of study. For the purpose of this section these two years were considered to examine the ability of the ECHAM 4.5 model to simulate the vertical velocity (ω) circulation patterns associated with dry and wet conditions over the region. Only the OND season that indicated significant correlation between ECHAM 4.5 and CMAP data was considered here. A detailed analysis of ω circulations at 500hPa was carried out and discussed below. The vertical velocity (ω) is chosen since is an important atmospheric parameter that determine rainfall in the region (Kabanda, 1995). However, other atmospheric parameters (for example, wind,

moisture flux) were also analysed but the model fails to capture important atmospheric features related to rainfall over the region (as shown in section 5.2.3). For the sake of brevity this section only considers the vertical velocity (ω).

ECHAM 4.5 and NCEP/NCAR ω circulations for the wet year 1997 and the dry year 1996 during the OND season are illustrated in Figure 5.20 & 5.21, areas with relative uplift are shaded. The NCEP/NCAR reanalysis plot (Figure 5.20(a)) shows negative ω anomalies over the equatorial western Indian Ocean and Tanzania with larger ω values located over the northern coast and north-eastern highlands. The occurrence of larger negative ω anomalies over the study region implies strong uplift over the region consistent with the observed heavy rainfall. The ECHAM 4.5 ω plot (Figure 5.20(b)) shows similar ω circulation patterns except that the model underestimates higher values. Generally the model well represented the ω circulation features over the region.

Year 1996 was a negative Indian Ocean zonal mode year but the 1995/96 La Niña event had decayed by OND 1996. Figure 6.21(a) indicates the ω circulation patterns for OND 1996. At 500hPa the NCEP/NCAR reanalysis plot indicates strong down ward motion over the Indian Ocean that extends to parts of Tanzanian coast and northern Tanzania. Areas of uplift were confined to the central, southern and western parts of the country. The occurrence of positive ω anomalies over the study region is consistent with the observed dry conditions. The ECHAM 4.5 ω plot (Figure 5.21(b)), shows slightly different features from the NCEP/NCAR plot with relative uplift extending from the Indian Ocean to western Tanzania south of 4°S leaving the northern part of the country under strong subsidence.

Comparison between ECHAM 4.5 and NCEP/NCAR reanalysis plots indicate that the GCM represents the ω circulation features associated with rainfall during the wet season while for the dry season it fails to represent the NCEP/NCAR reanalysis features. This may be partly caused by the coarse resolution of the model, as it is not able to capture local features associated

with rainfall in the region. A high resolution model therefore needs to be used to capture such local features as they contribute significantly to the rainfall over the region.

5.4 Summary of the findings

Comparison of ECHAM 4.5 model with NCEP/NCAR reanalysis over the study region indicated that the model was able to represent the circulation features associated with rainfall during the wet season while for the dry season the model failed to represent the circulation features. This suggests that local features (that are not well captured by the model) contribute significantly to the rainfall variability over the region, especially during dry seasons. It is worth noting here that although there is some deficiencies in the model it seems to capture the major features related to climate over the region of study.

The next chapter provides a detailed analysis of the intra-seasonal variability.

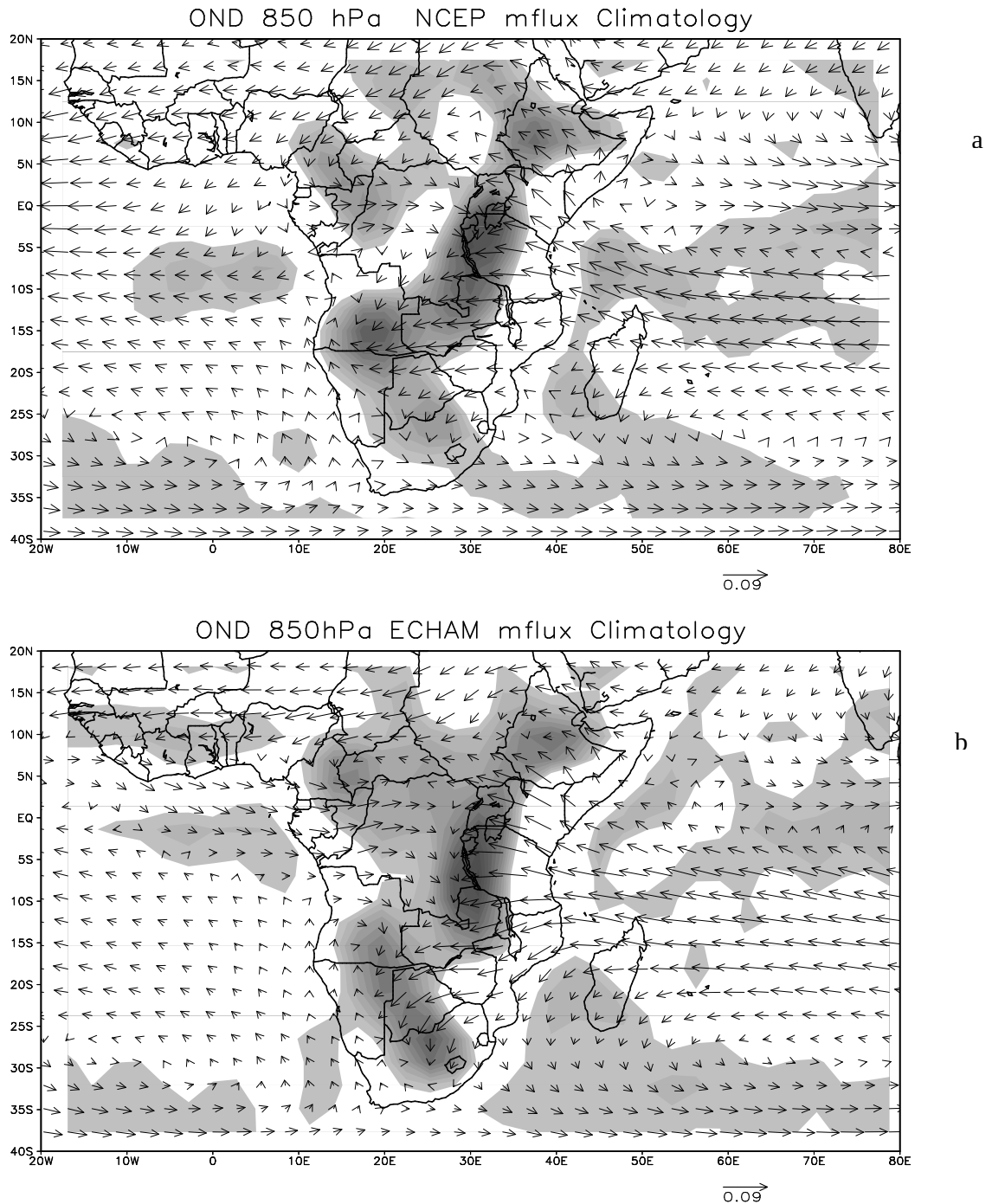


Fig 5.1: OND moisture flux climatology for (a) NCEP/NCAR reanalysis and (b) ECHAM 4.5 simulated; shading indicates regions of moisture flux convergence.

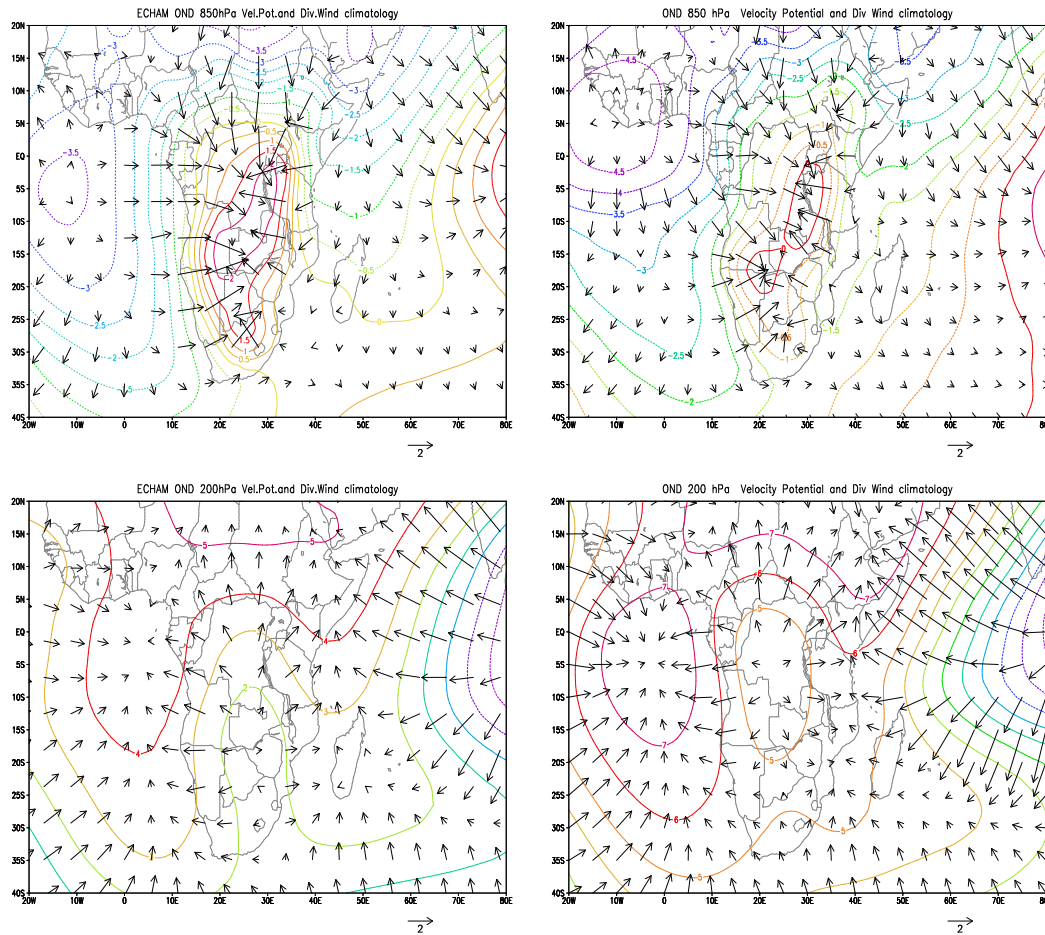


Fig 5.2: ECHAM 4.5 simulated and NCEP/NCAR reanalysis climatological average velocity potential and divergent wind at 850 hPa and 200 hPa for OND

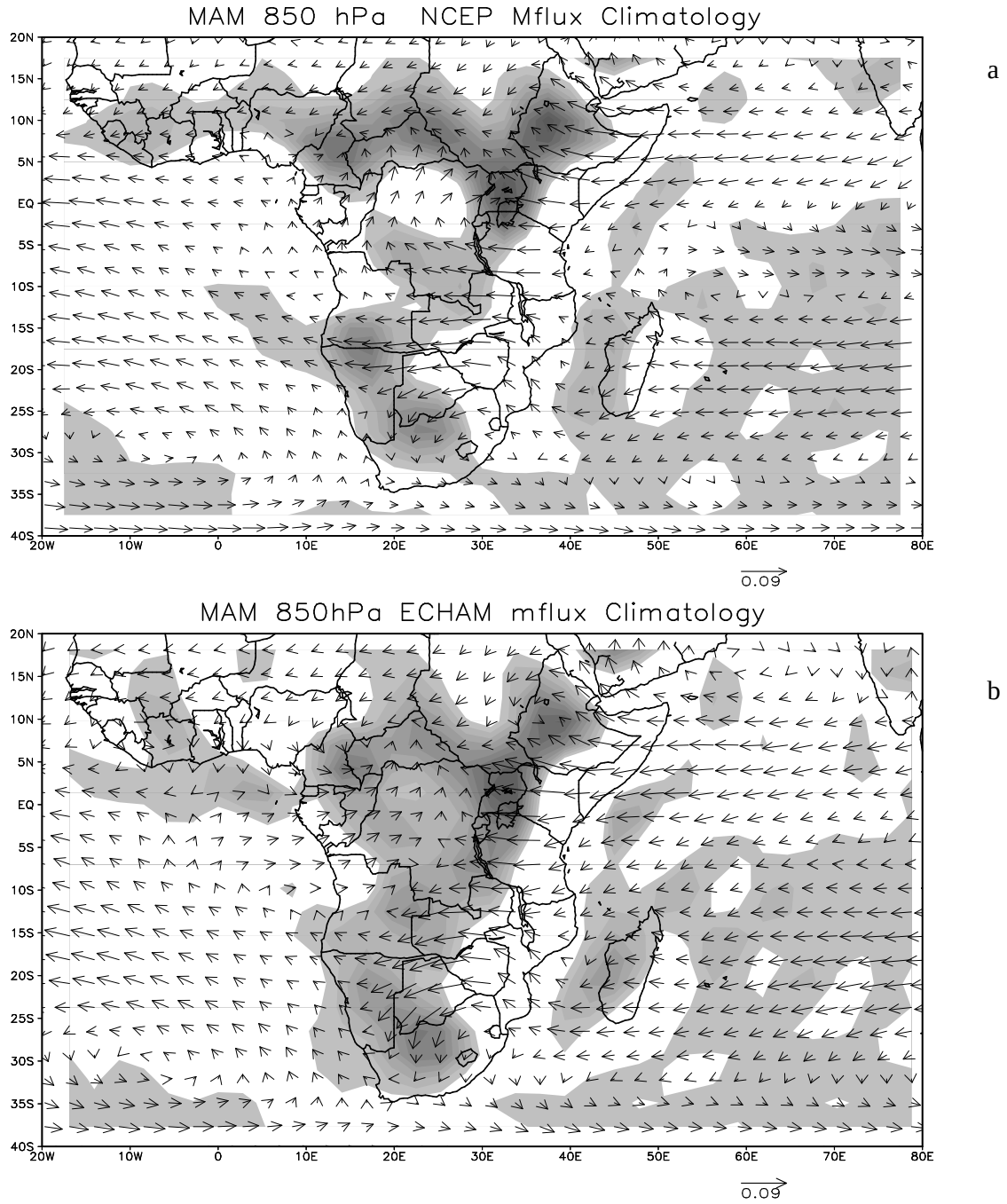


Fig 5.3: MAM moisture flux climatology for (a) NCEP/NCAR reanalysis and (b) ECHAM 4.5 simulated; shading indicates regions of moisture flux convergence.

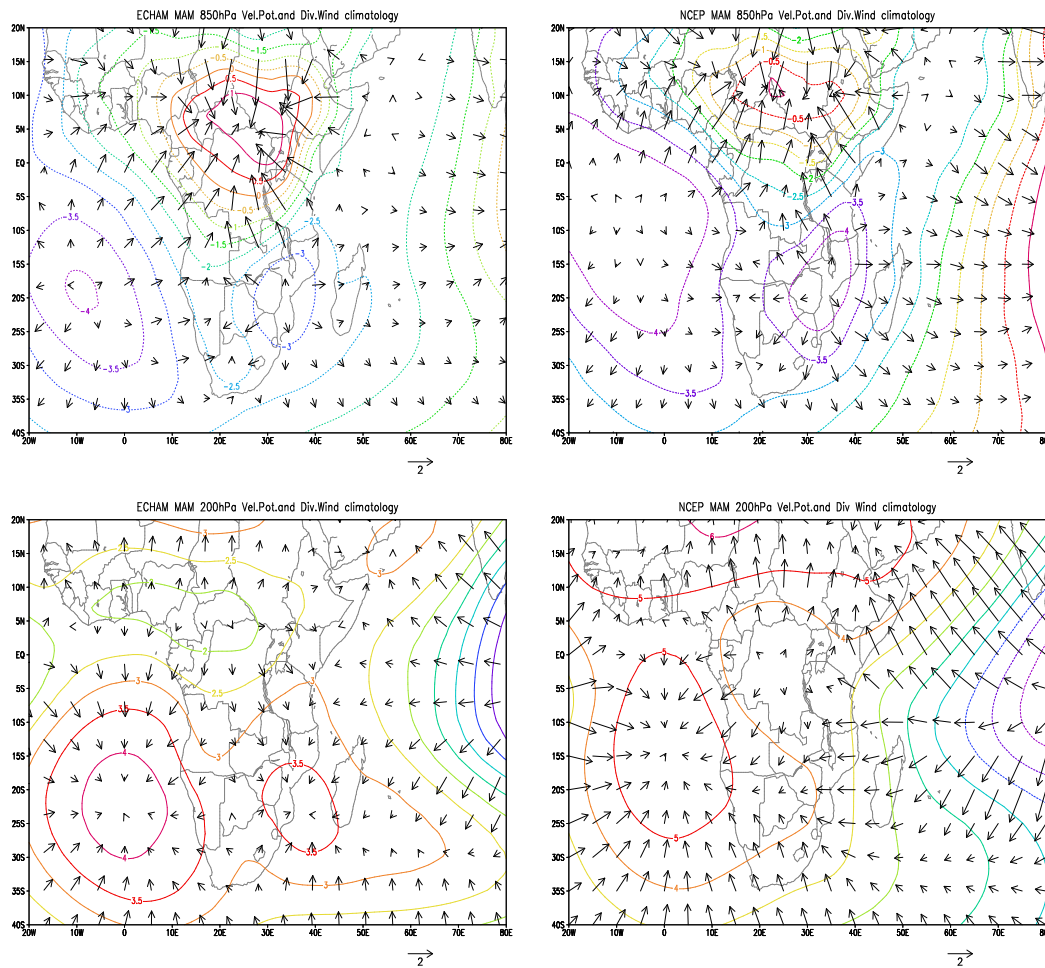
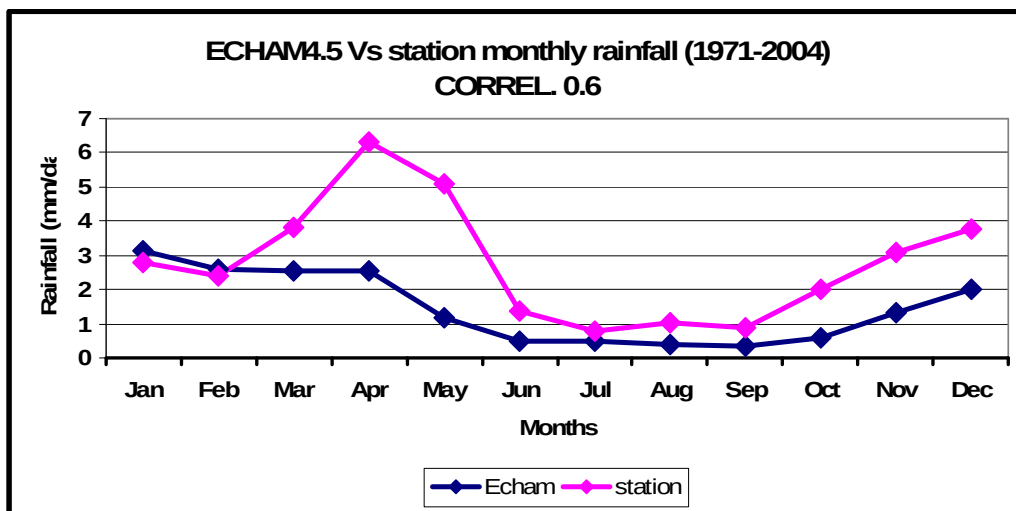
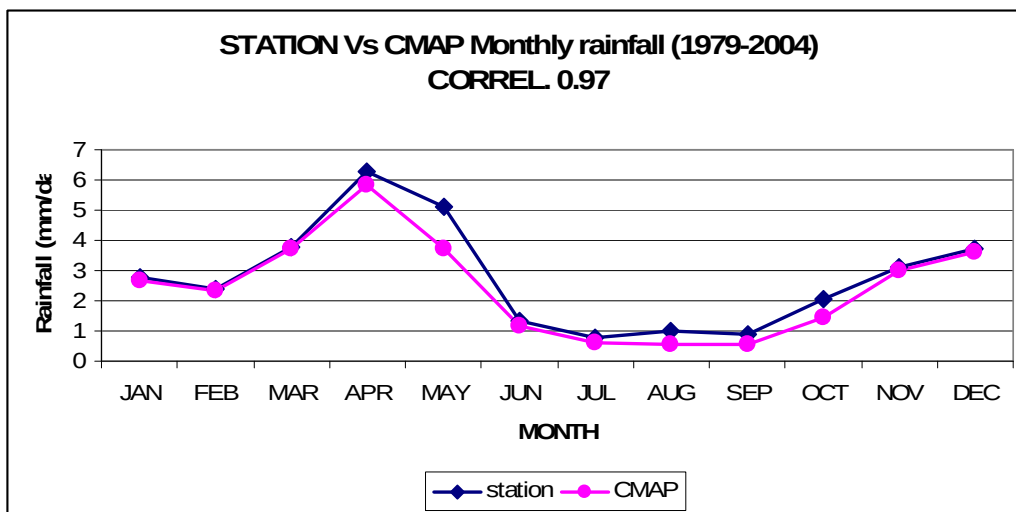


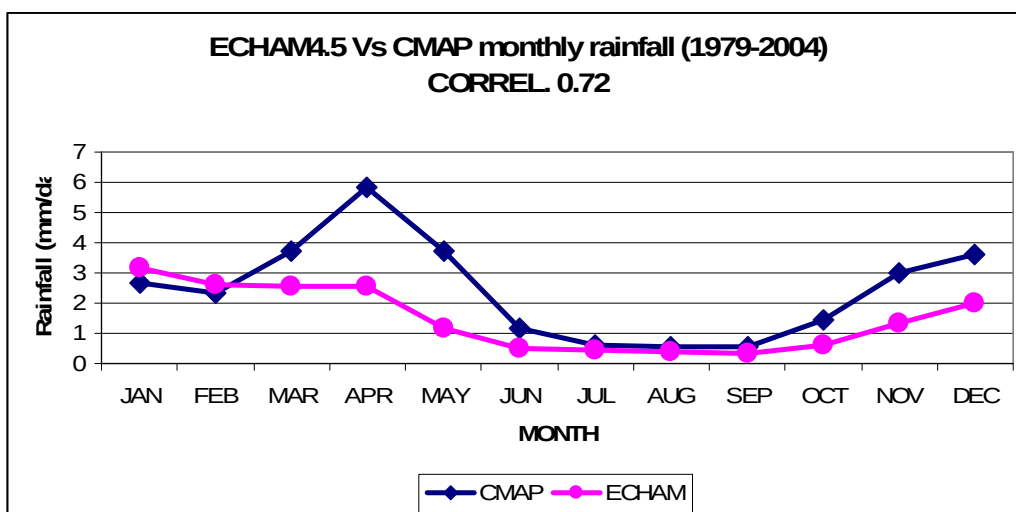
Fig 5.4: ECHAM 4.5 simulated and NCEP/NCAR reanalysis climatological average velocity potential and divergent wind at 850 hPa and 200 hPa for MAM



a



b



c

Fig 5.5: Rainfall climatology for North-eastern Tanzania (a) ECHAM4.5 Vs station (b) CMAP Vs station (c) ECHAM 4.5 Vs CMAP. Correlation values are shown.

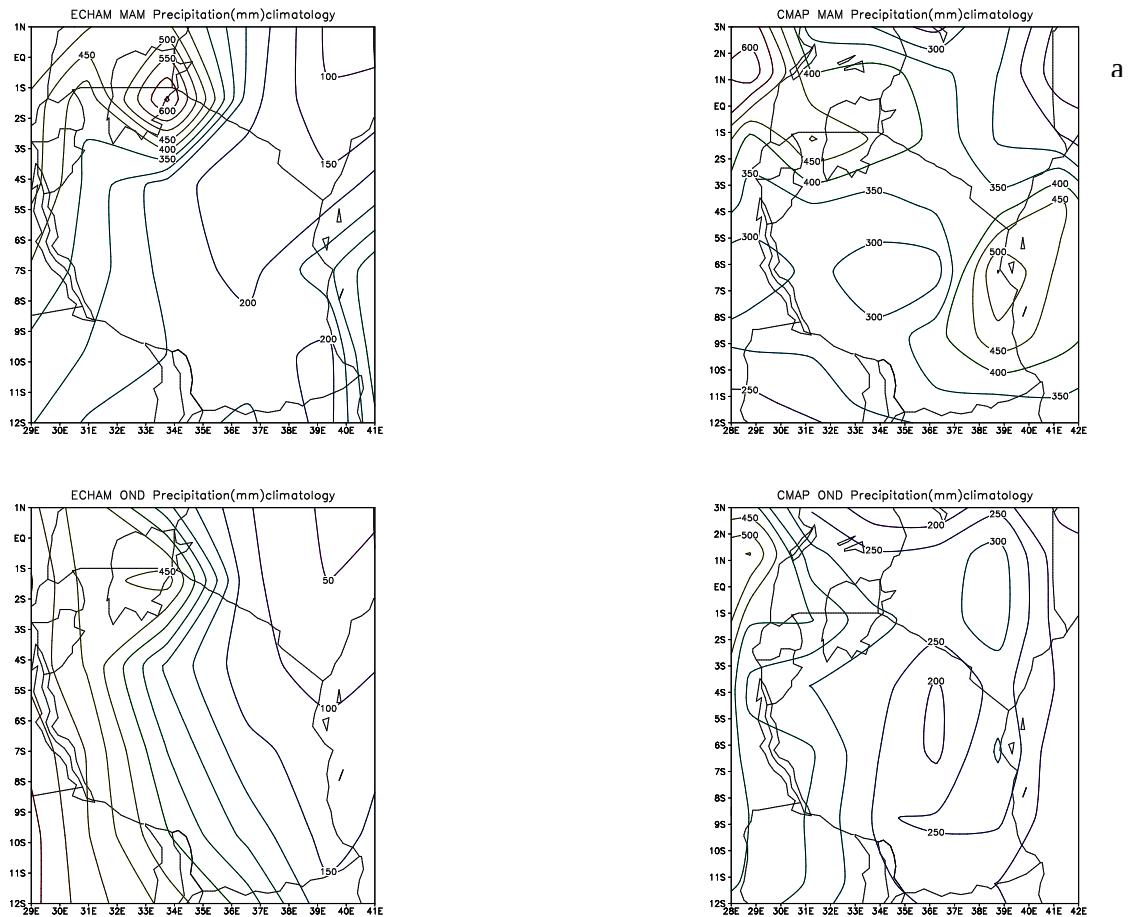
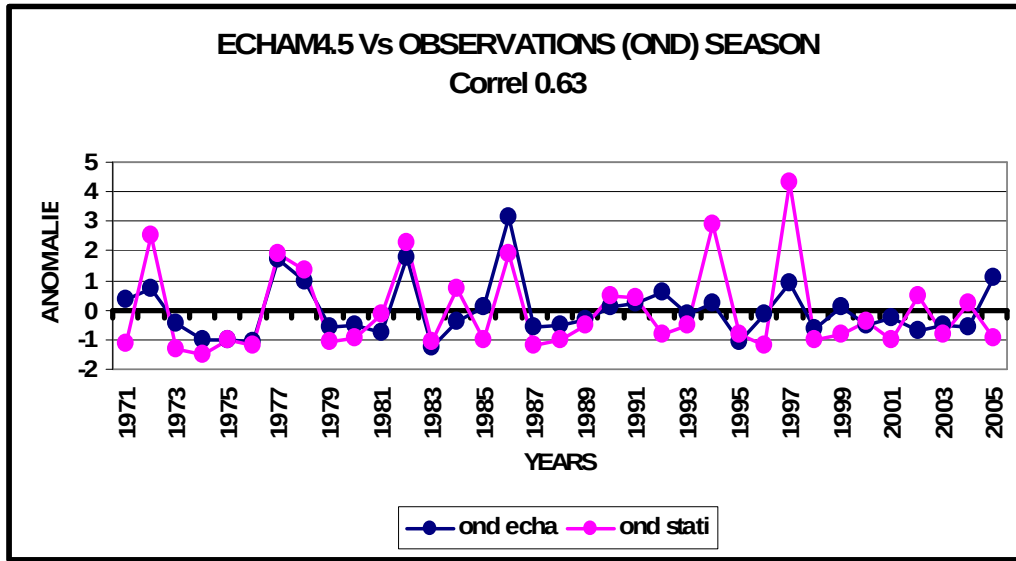
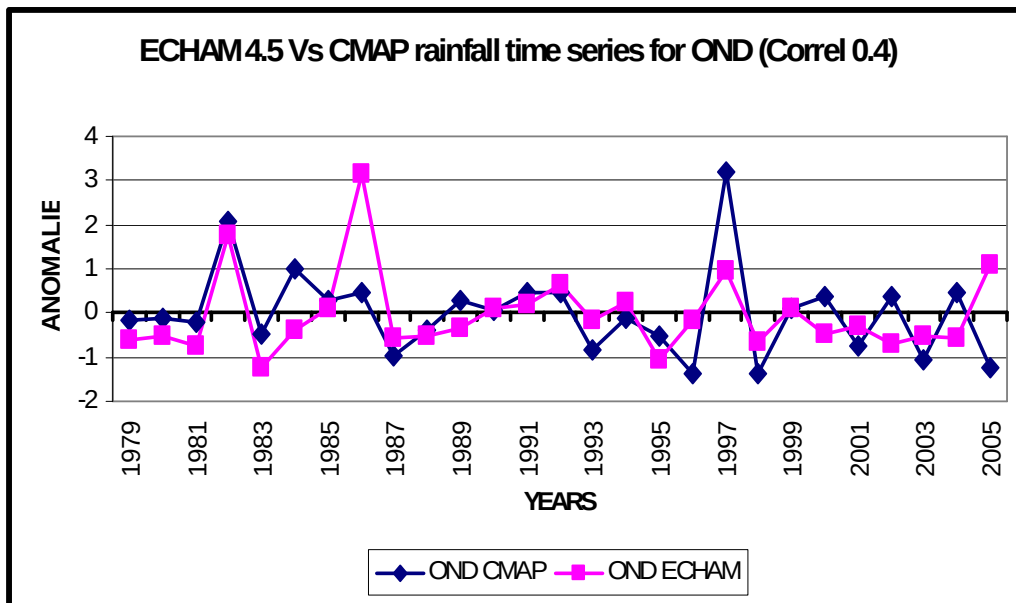


Fig 5.6: ECHAM simulated and CMAP spatial distribution of seasonal rainfall for (a) MAM and (b) OND seasons

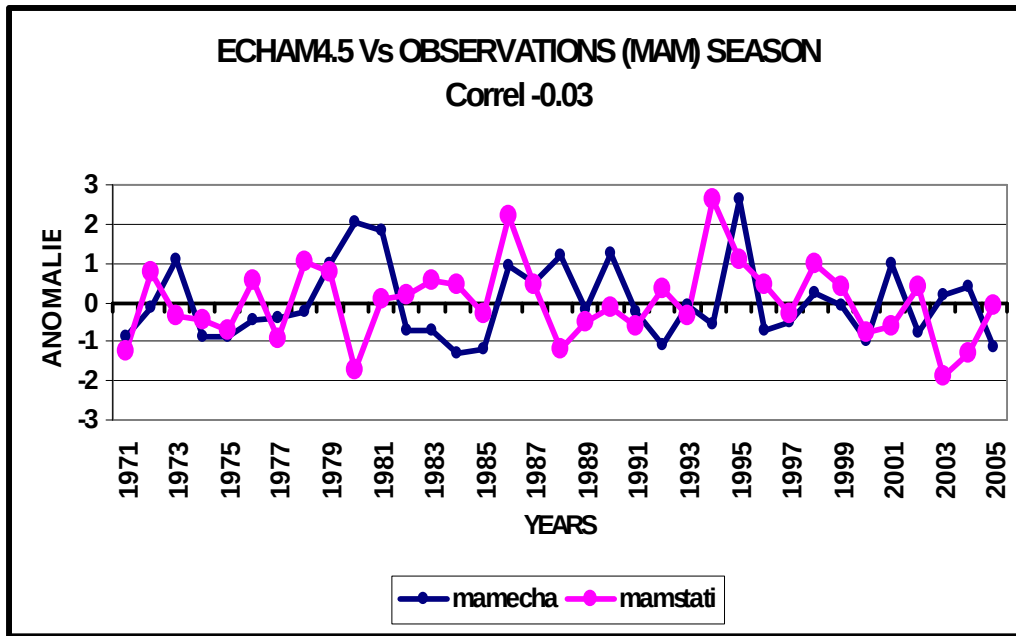


a

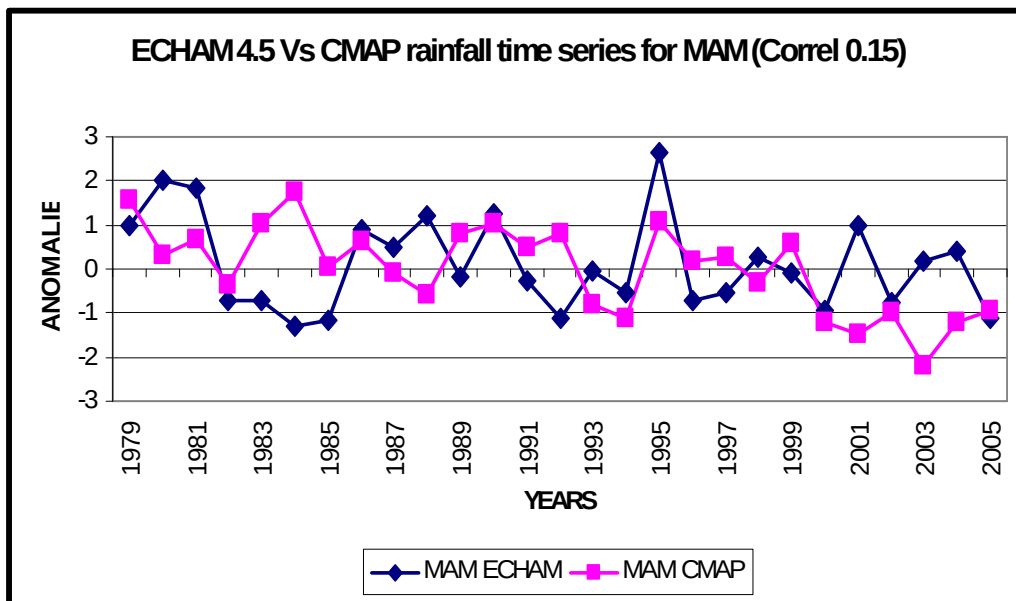


b

Fig 5.7: OND rainfall time series for (a) ECHAM 4.5 Vs Station (b) ECHAM 4.5 Vs CMAP



a



b

Fig 5.8: MAM rainfall time series for (a) ECHAM 4.5 Vs Station (b) ECHAM 4.5 Vs CMAP

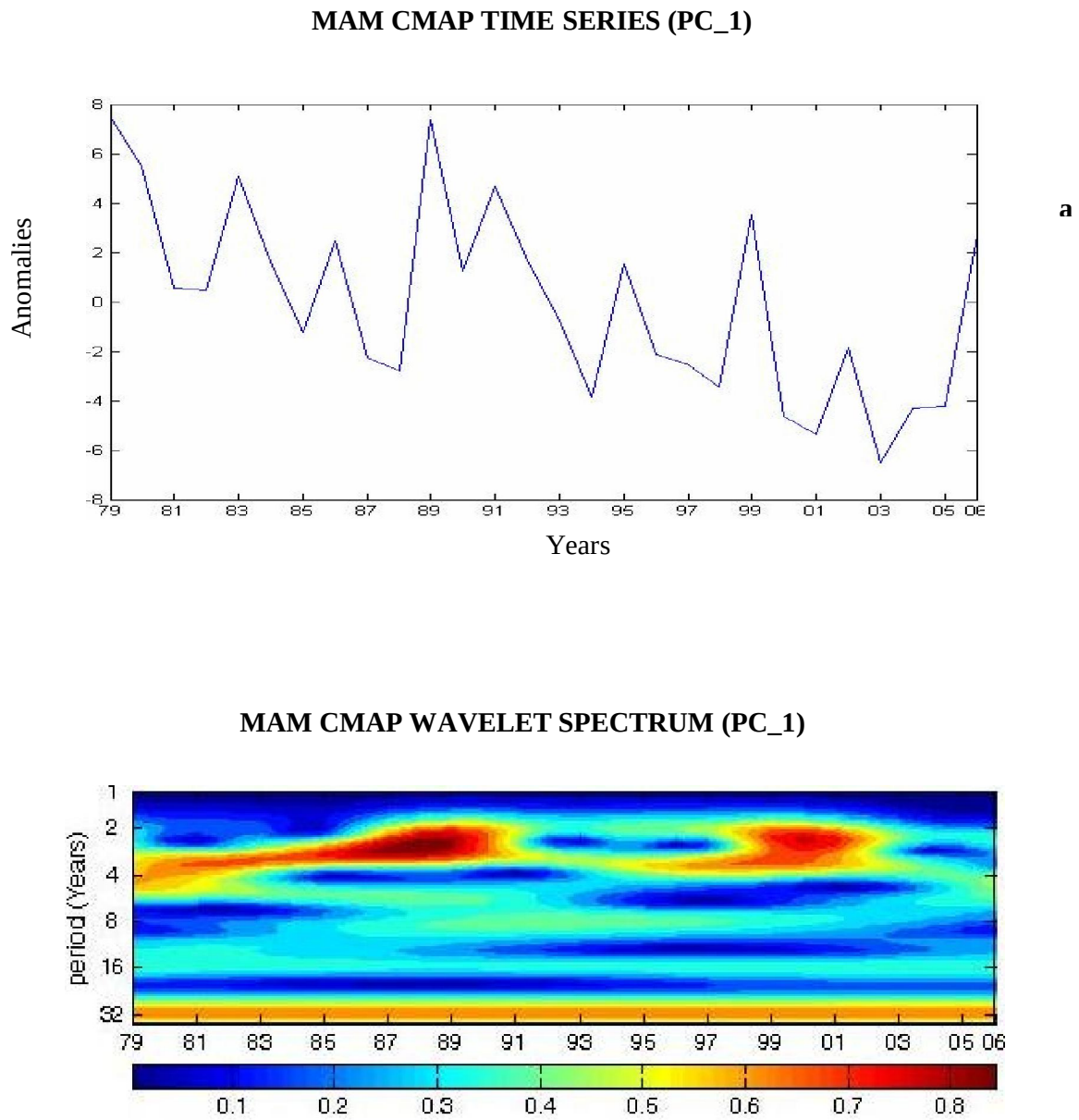


**Fig 5.9: MAM CMAP RAINFALL PC_1 (a) TIME SERIES
(b) WAVELET SPECTRUM**

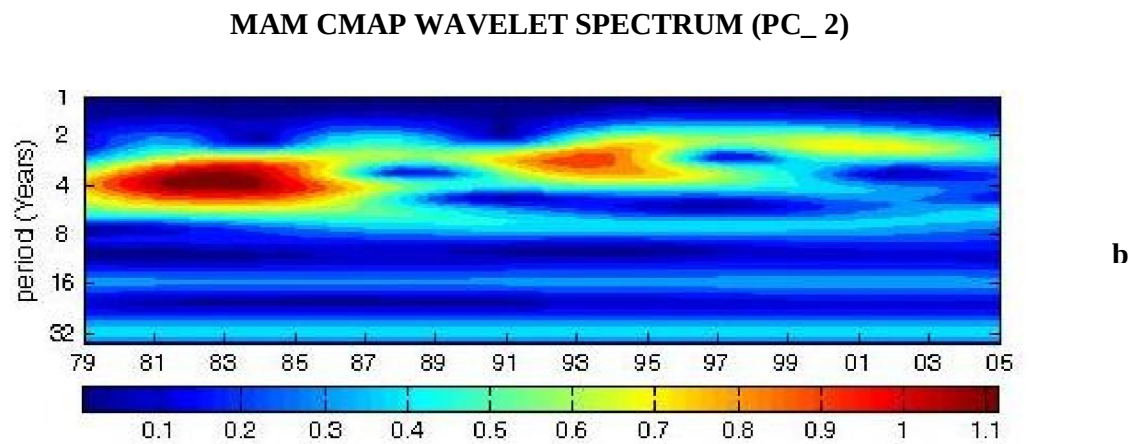
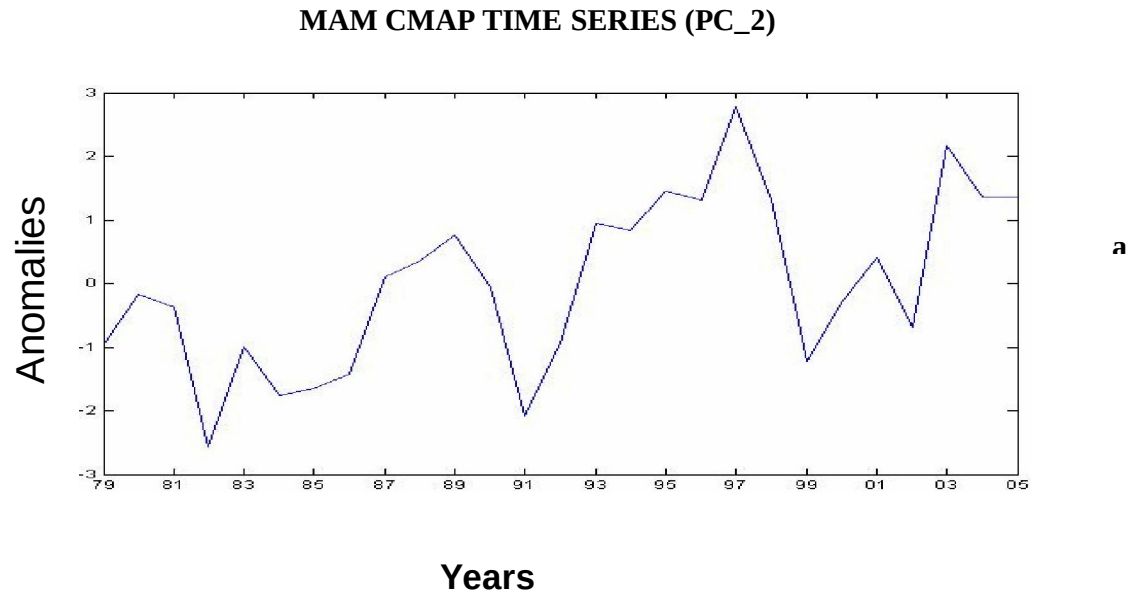
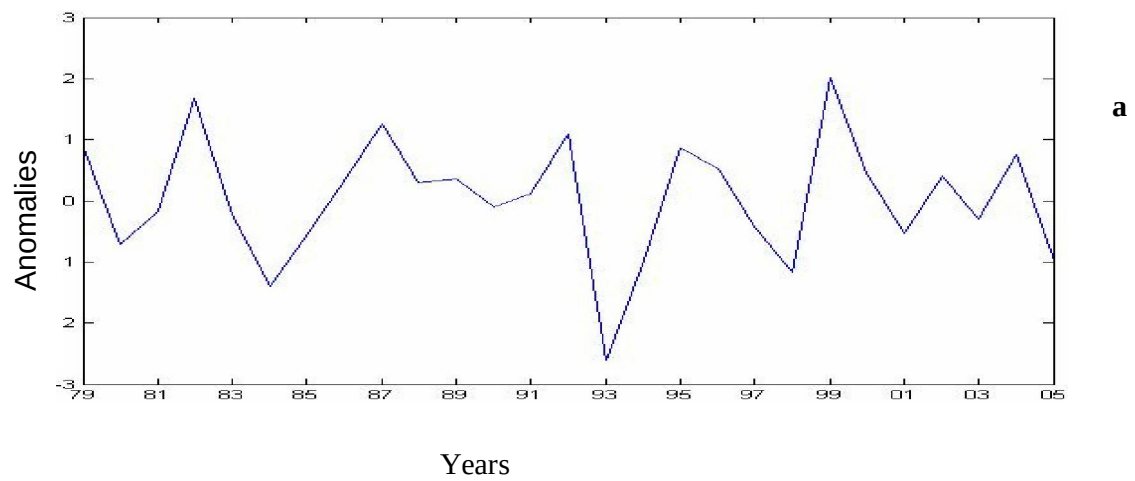


**Fig 5.10: MAM CMAP RAINFALL PC_2 (a) TIME SERIES
(b) WAVELET SPECTRUM**

MAM ECHAM 4.5 TIME SERIES PC_1



MAM ECHAM 4.5 WAVELET SPECTRUM (PC_1)

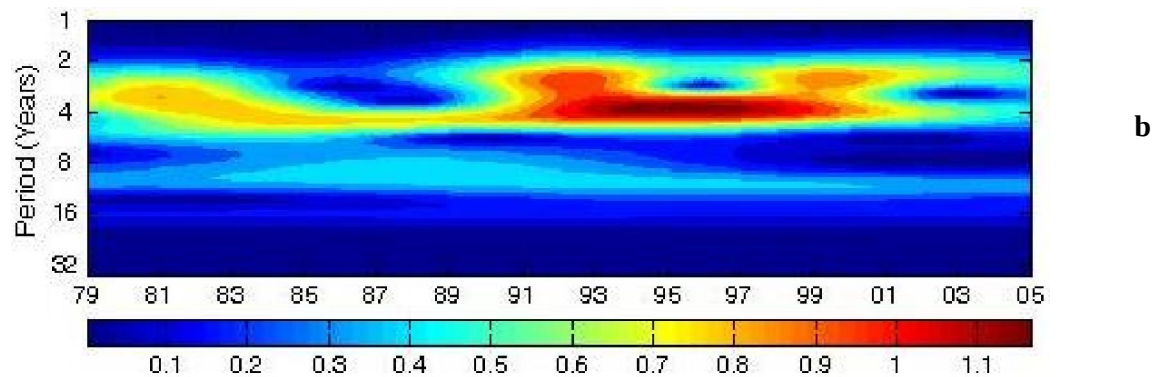


**Fig 5.11: MAM ECHAM 4.5 RAINFALL PC_1 (a) TIME SERIES
(b) WAVELET SPECTRUM**

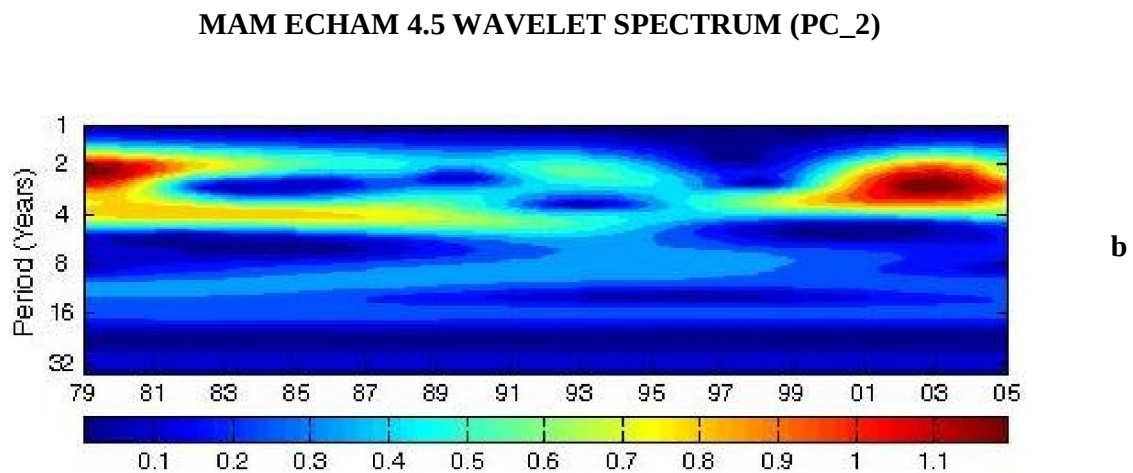
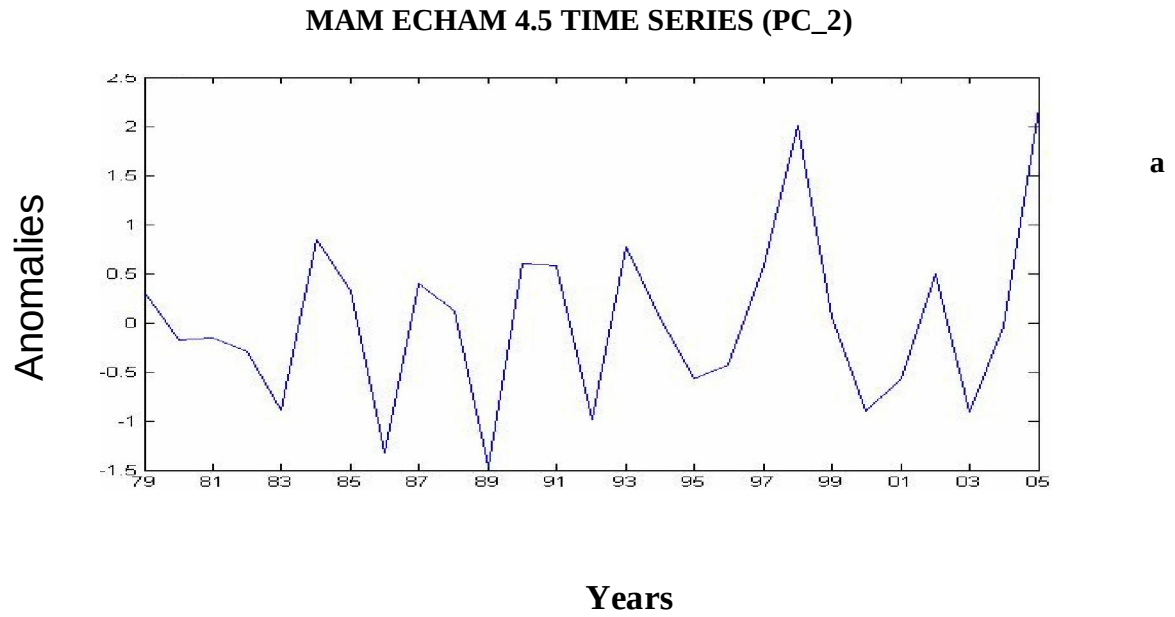


**Fig 5.12: MAM ECHAM 4.5 RAINFALL PC_2 (a) TIME SERIES
(b) WAVELET SPECTRUM**

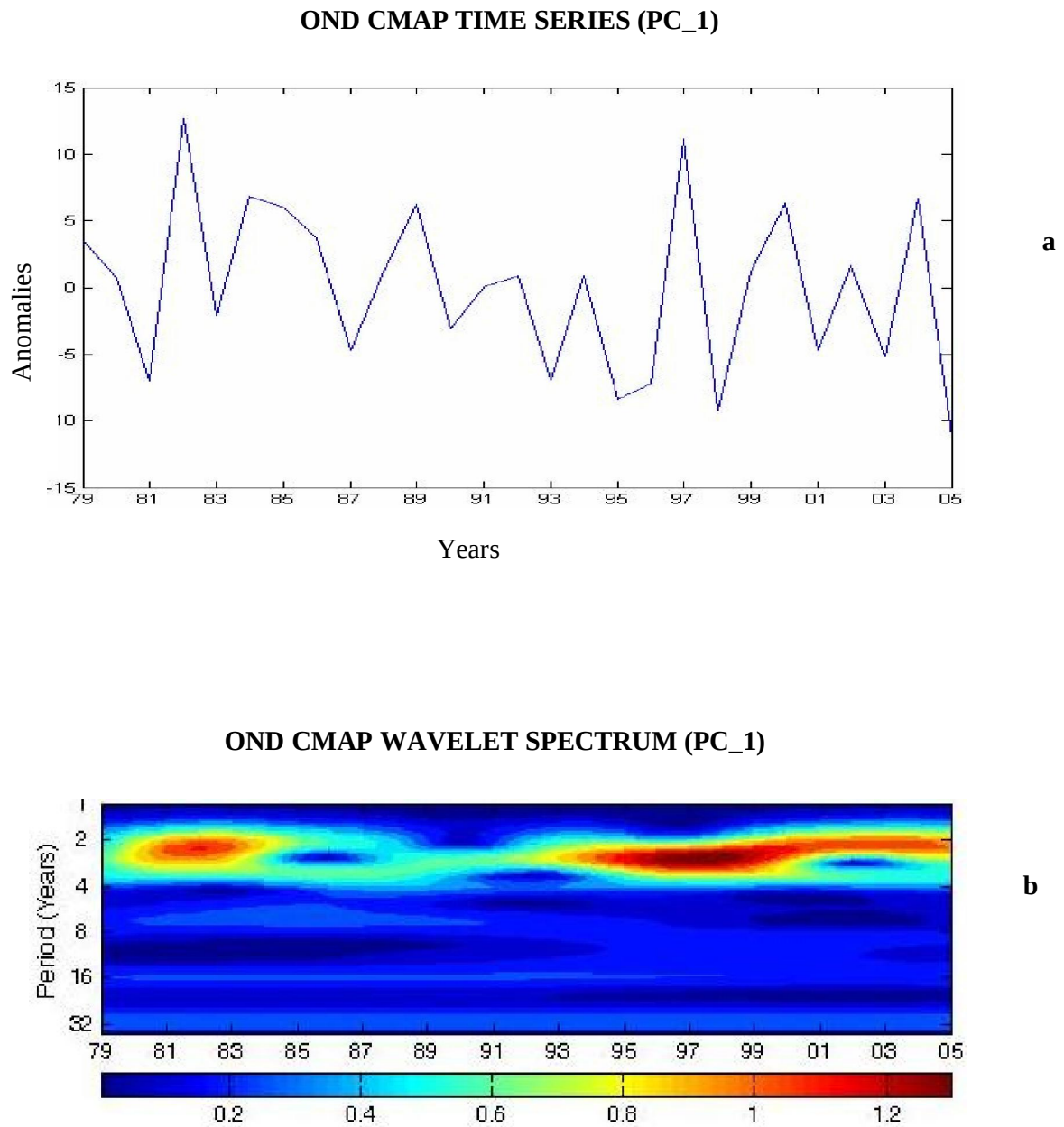


Fig 5.13: As for Figure 5.9 but for OND

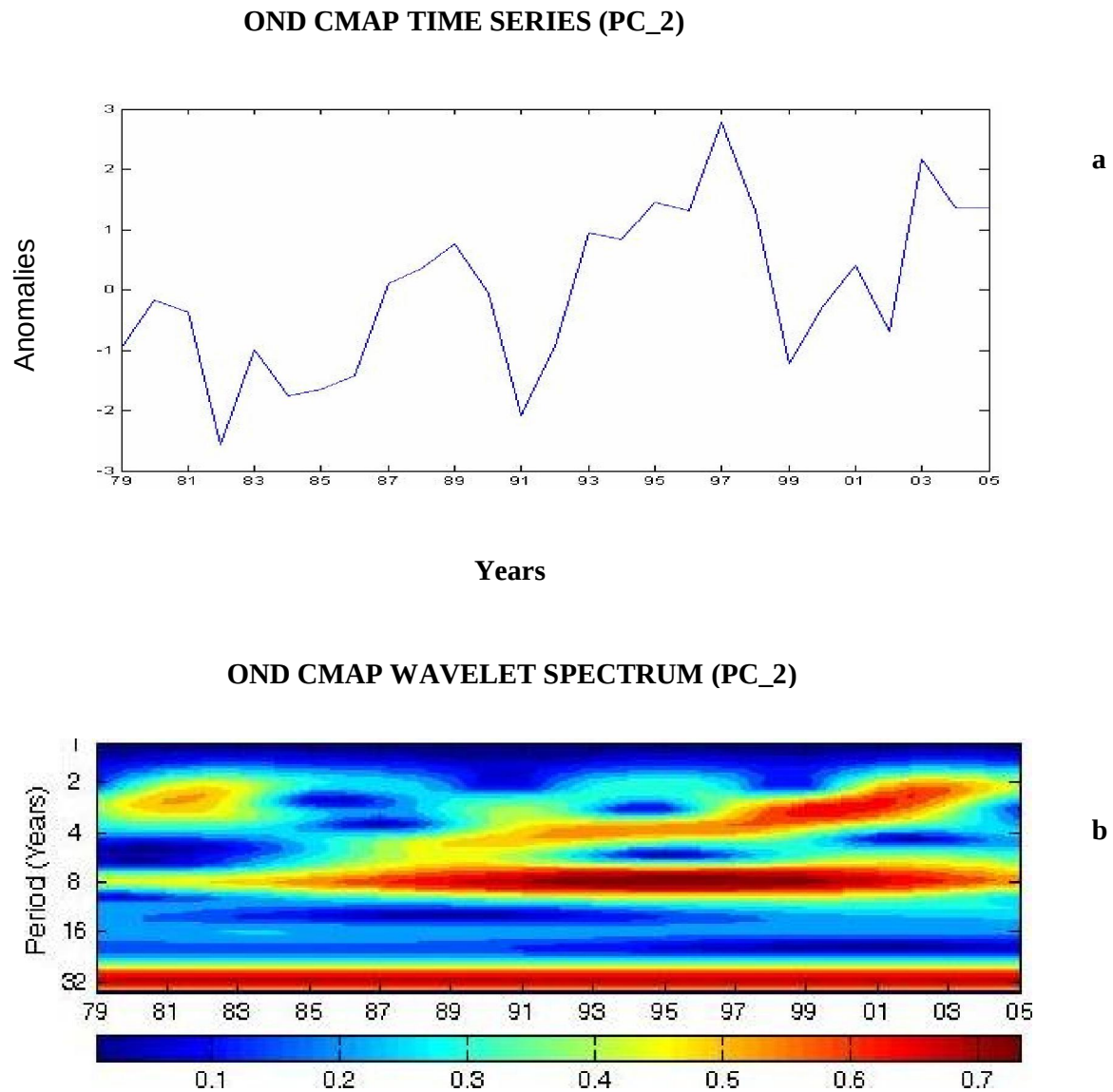
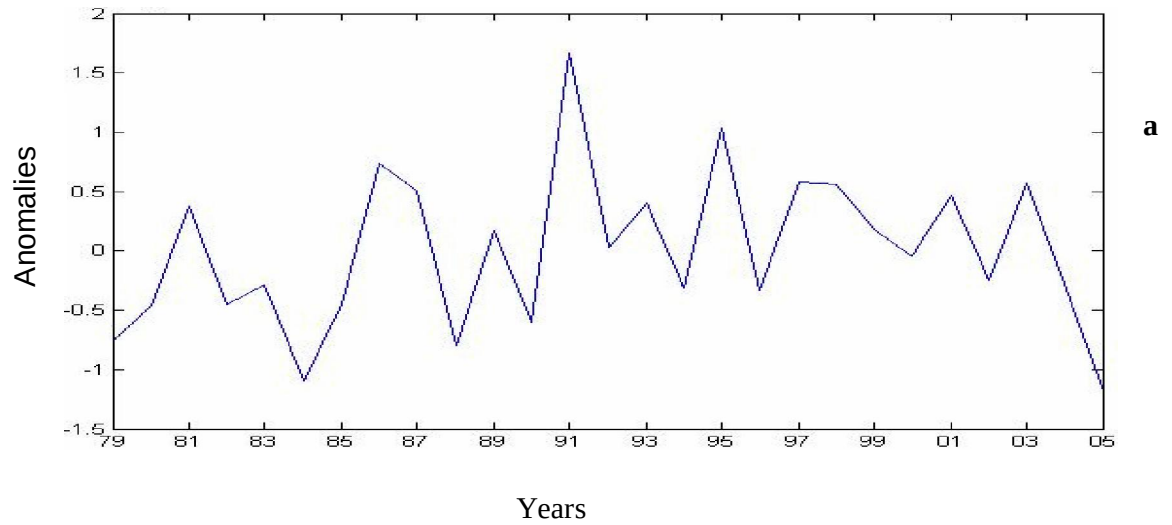


Fig 5.14: As for Figure 5.10 but for OND season

OND ECHAM 4.5 TIME SERIES (PC_1)



OND ECHAM 4.5 WAVELET SPECTRUM (PC_1)

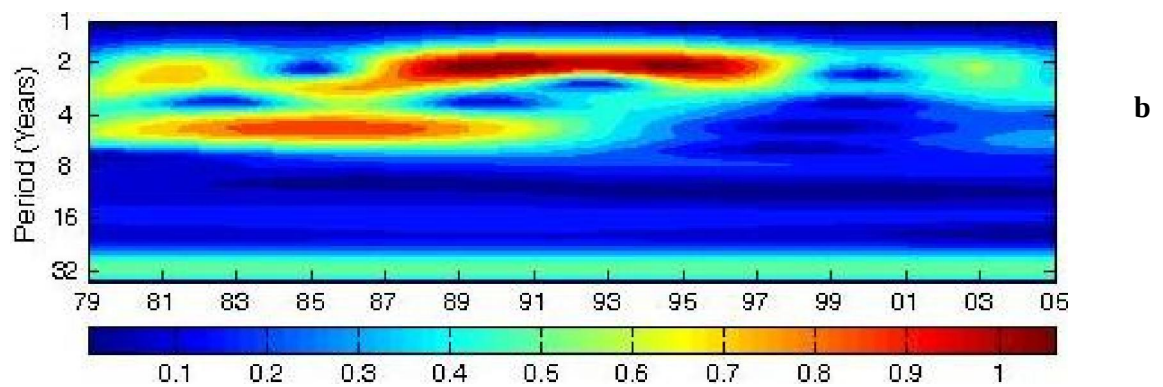
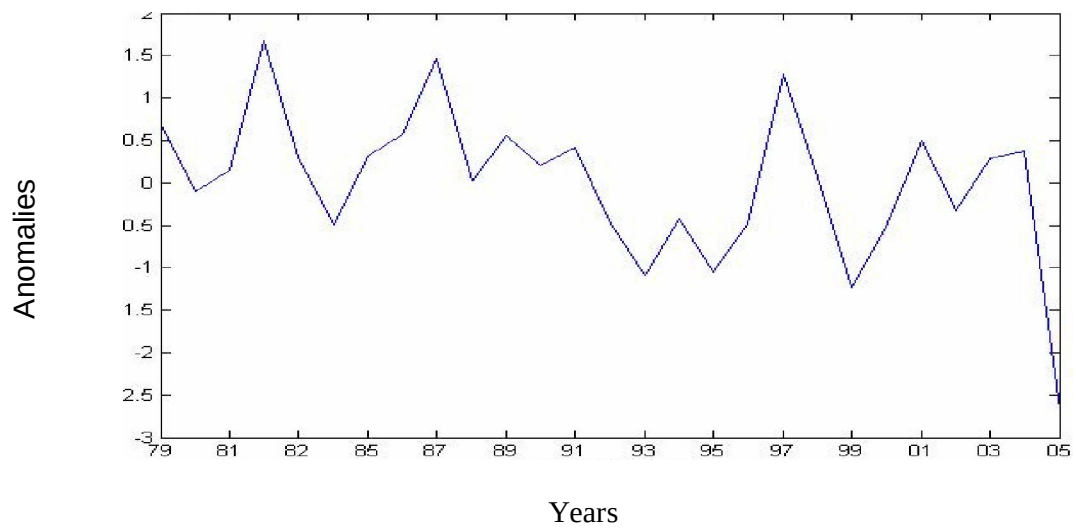


Fig 5.15: As for Figure 5.11 but for OND season

OND ECHAM 4.5 TIME SERIES (PC_2)



OND ECHAM 4.5 WAVELET SPECTRUM (PC_2)

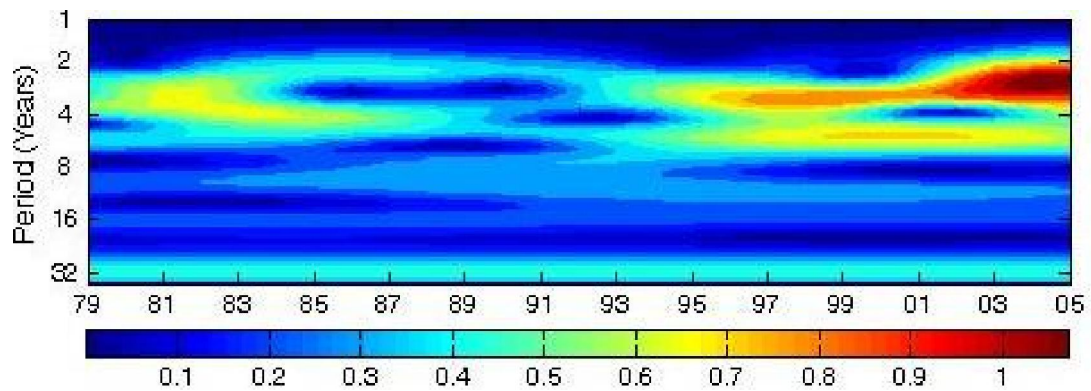


Fig 5.16: As for Figure 5.12 but for OND season

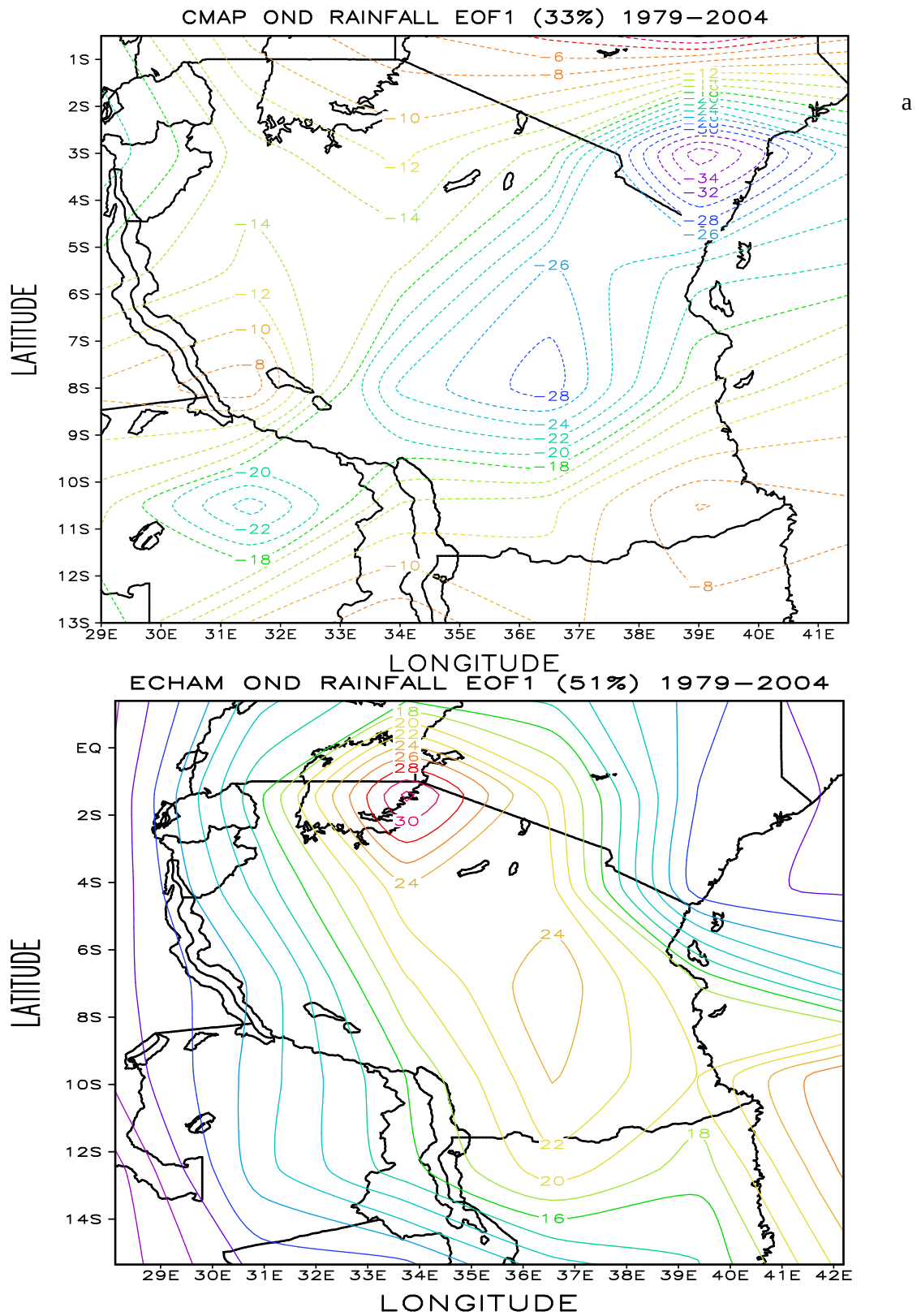


Figure 5.17: Spatial map of EOF 1 for the OND season for (a) CMAP and (b) ECHAM 4.5

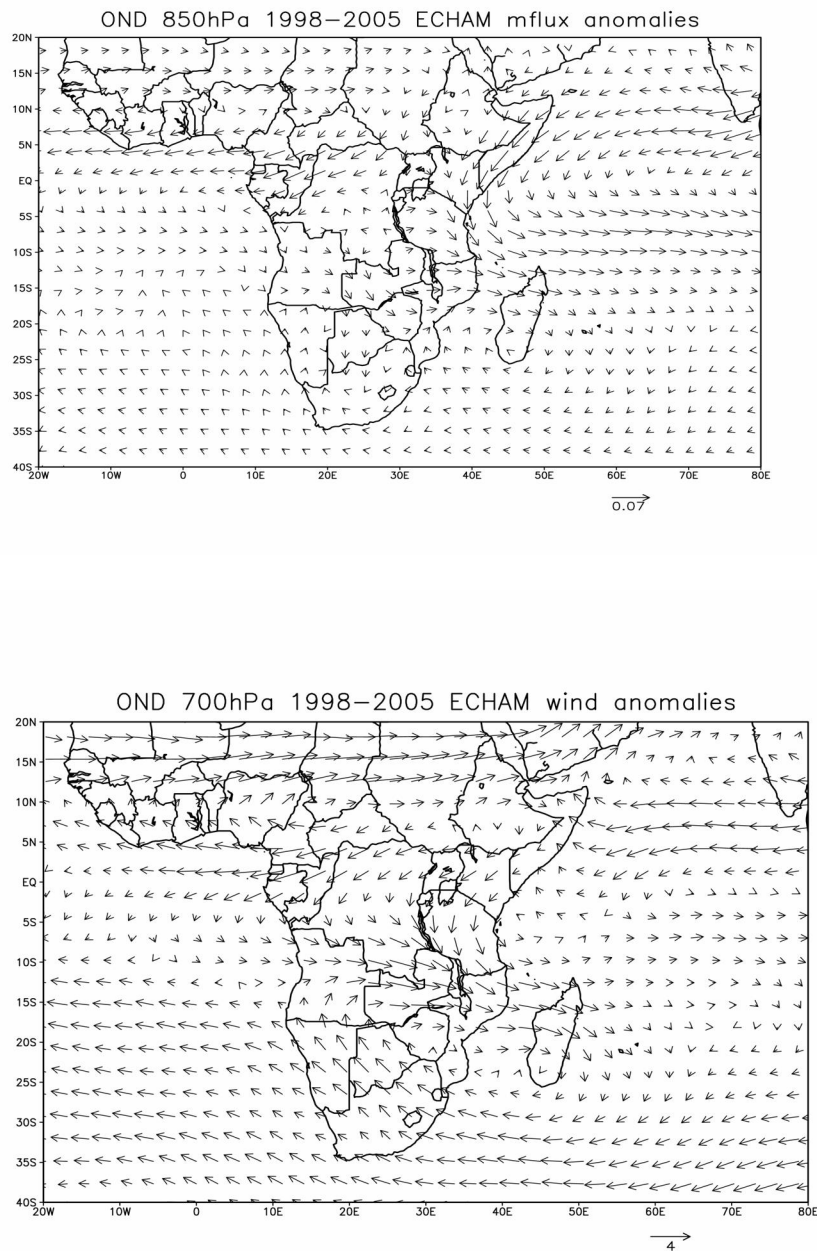
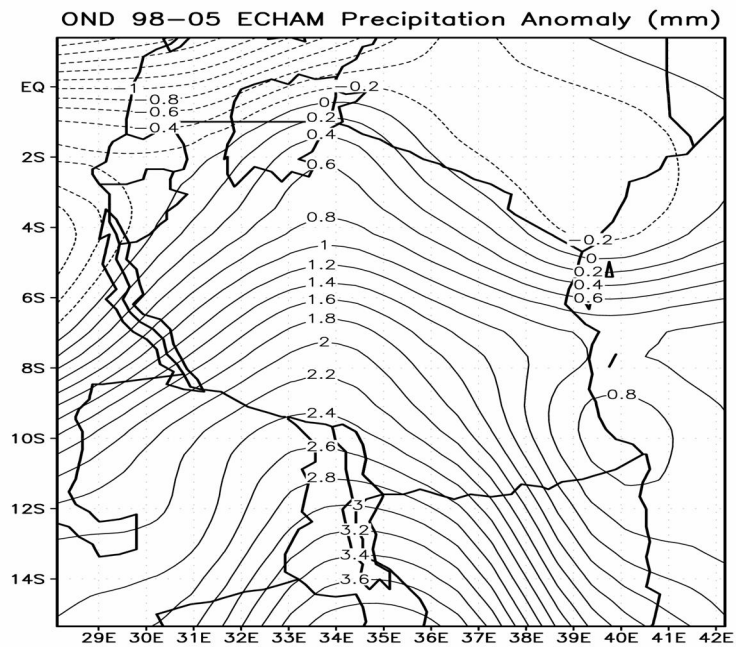
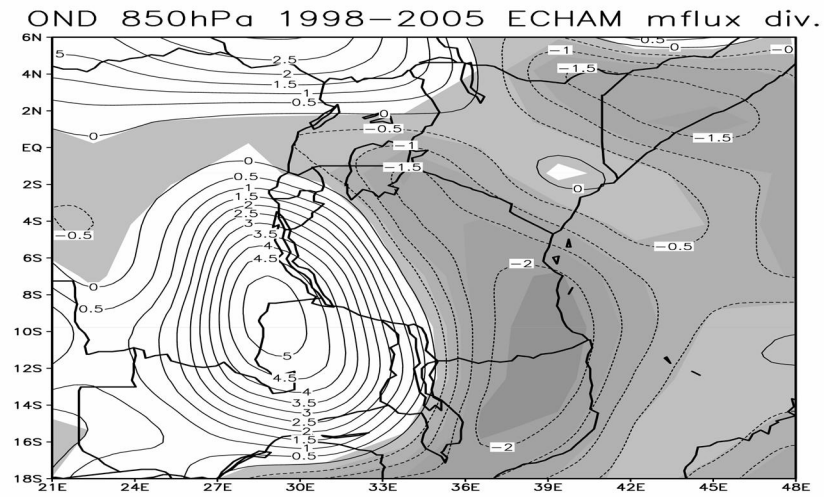


Fig 5.18: OND 1998 – 2005 composite ECHAM 4.5 anomalies for (a) 850 hPa moisture flux (b) 700hPa wind



b

Fig 5.19: As for Figure 5 18 but for (a) moisture flux divergence (b) Precipitation

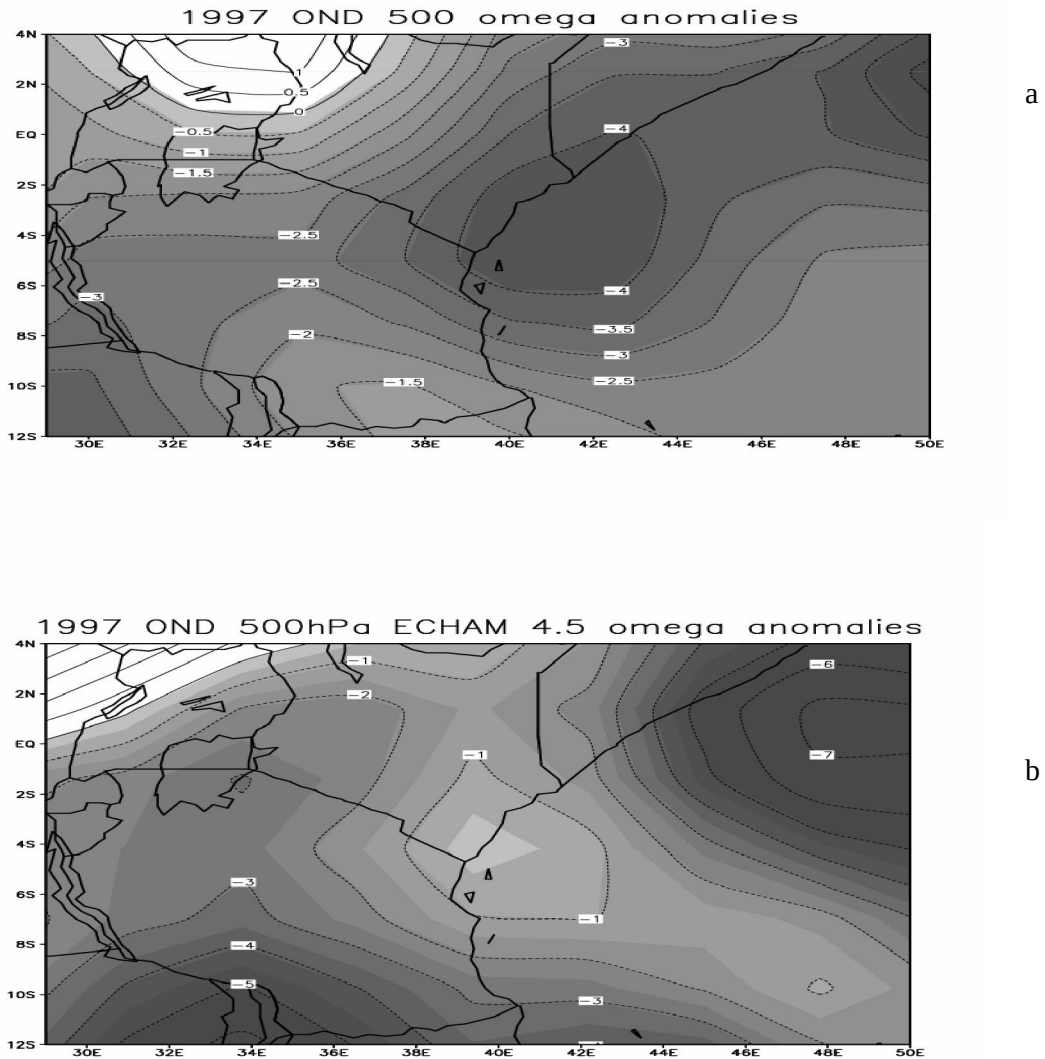


Fig 5.20: OND 1997 omega anomalies (a) NCEP/NCAR reanalysis (b) ECHAM 4.5. Contour interval $0.5 \times 10^{-2} \text{ Pa s}^{-1}$ for NCEP and $1.0 \times 10^{-2} \text{ Pa s}^{-1}$ for ECHAM 4.5. Shaded are areas of relative uplift.

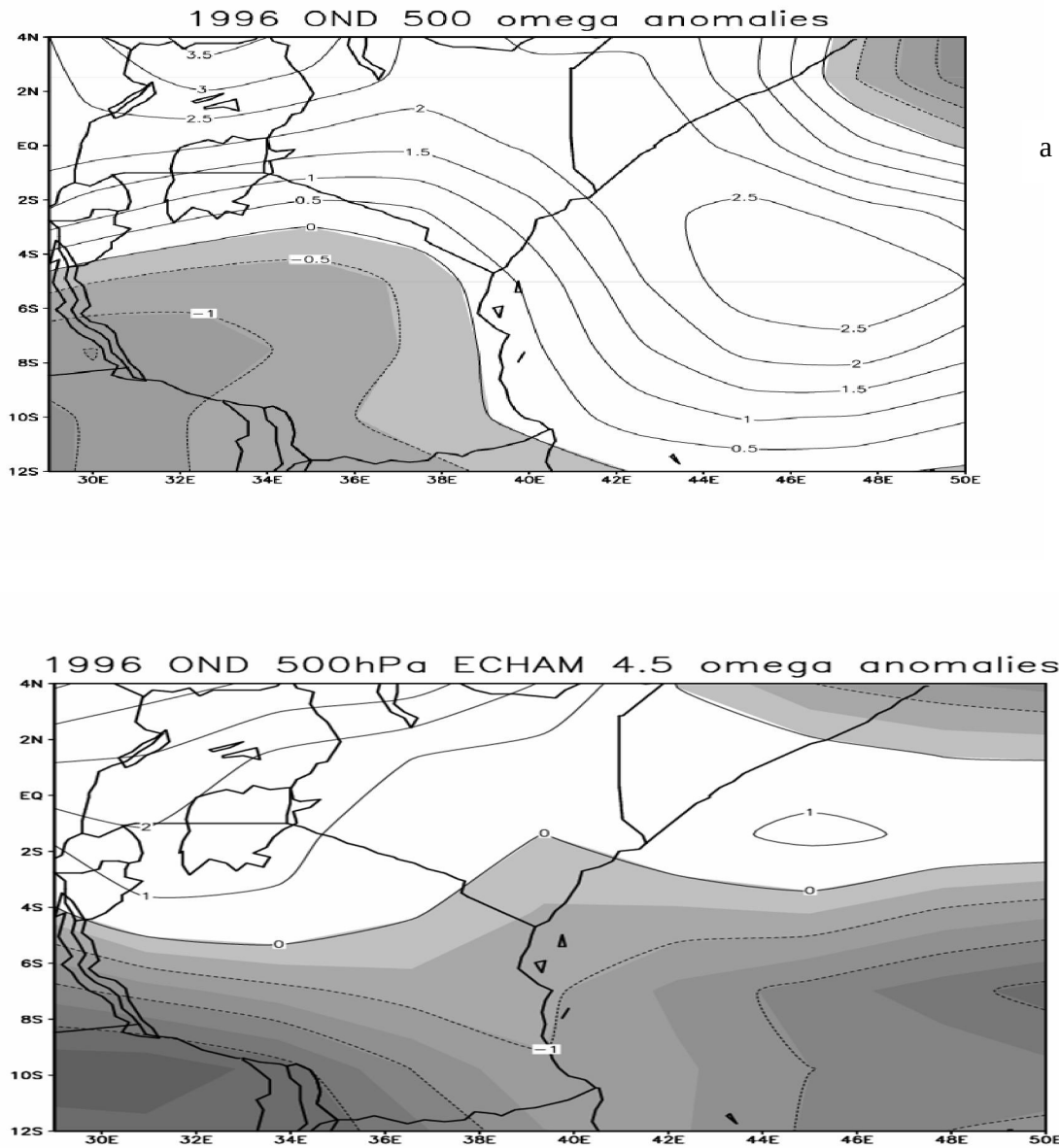


Fig 5.21: As for Figure 5.20 but for 1996

CHAPTER SIX

INTRA-SEASONAL VARIABILITY OVER NORTH-EAST TANZANIA

6.0. Introduction

In chapter five the ability of the ECHAM 4.5 model to represent atmospheric circulations associated with rainfall over north-eastern Tanzania was discussed. The NCEP/NCAR reanalysis and CMAP data were used for comparison with ECHAM 4.5 data obtained from IRI website. Both climatological and inter-annual variability was examined, with special attention given to the extreme events that occurred over the NEH during the study period 1970 - 2005. The ECHAM 4.5 model represented some of the circulation patterns reasonably well. This chapter deals with intra-seasonal variability over north east Tanzania. The country's farmers, whose crops need timely and plentiful watering in the growing season, are often highly affected by extreme weather events. To date, these have included an increase in successive years of droughts (for example, the 1998 - 2005 droughts) or floods (for example, the 2006 floods). A farmer can survive a less productive year if it is followed by a year of normal output, but at least two successive less productive years make this extremely difficult. To illustrate this, chapter four has considered a case study of the 1998 - 2005 droughts and 2006 floods. The intra-seasonal variability during these case studies was discussed there.

Prolonged droughts affect agricultural output and can decimate livestock populations, leading to malnutrition and dehydration, and sometimes, human starvation. By contrast, floods can ruin food stocks, remove fertile topsoil and impair food production for many seasons afterwards. They can also contribute significantly to the severity and extent of water-borne diseases such as malaria. Most studies of rainfall variability over East Africa thus far have concentrated on seasonal to inter-annual scales (for example, Ogallo, 1988; Nicholson, 1996). However, more recently, Kijazi & Reason (2005) have examined the intra-seasonal oscillations responsible for short-term rainfall variability along the Tanzanian coast during the ENSO years. Mapande & Reason (2005) have analysed the link between rainfall variability on intra-seasonal scales over western Tanzania and regional circulations. These authors have suggested that during the wet years the rainfall seasons tend to

end considerably later than the dry years, that is, wet years tend to have longer than average rainfall seasons and vice versa for dry years.

This particular chapter investigates one important research issue which has not hitherto been studied over north-east Tanzania; namely, addressing the region's intra-seasonal variability, paying special attention to rainfall onset, peak and cessation. The important questions to answer in such an endeavour include understanding the nature of intra-seasonal variability in the region, giving special attention to the derivation of the rainfall onset and cessation dates that have important application to agriculture. The main aim of this chapter is thus to provide research results that will aid decision makers in the formulation of agriculture related policies for sustainable development.

6.1 Intra-seasonal variability

The inter-annual variability of seasonal rainfall over Tanzania is primarily expressed as intra-seasonal wet and dry events with varying characteristics. However, much of the available knowledge about this phenomenon is scanty and needs to be explored. To date, rainfall forecasting in Tanzania has been based on a seasonal understanding of the mechanisms involved and is mainly provided in a probabilistic manner that is a percentage occurrence of above, below and normal conditions for a season. Such forecasts are not of much use to the agricultural sector as the application of rainfall variability studies needs more detailed information than a simple departure from the long-term average. For example, a season with above-average rainfall over an agricultural region may not be any better than a below-average season if the rains are not well distributed in either time or space. For crop cultivation, the consistency with which minimally required rainfall is received is more important than the total received over time. Crops are more likely to do well with uniformly spread 'light' rains than with a few 'heavy' rains interrupted by dry periods (Hachigonta & Reason, 2007). The timing of rainfall onset, duration and cessation relative to the cropping calendar is more fundamental to crop viability than focussing on total seasonal rainfall alone. With this in mind, the analysis in this section aims to identify the characteristics of in-

season variability, such as rainfall onset, cessation and dry spells. To this end, the NCEP/NCAR reanalysis was used to analyse the circulation features associated with the in-season variability.

6.1.1 Results of time series analysis

Daily rainfall data from ten stations scattered over the study region (Fig 2.1) was first grouped into five day means (pentads). The grouping was done on a monthly basis, so that the last pentad of a month has six days for a month with 31 days, while for a leap year, the last pentad of February has four days (Appendix A).

The climatological pentad rainfall time series plots for the central part of the country, the NEH and the NC can be seen in Figure 6.1. Station rainfall data is averaged over each region and a long-term mean pentad rainfall time series has been plotted. The criteria used in the previous study of teleconnections between seasonal rainfall in coastal Tanzania and ENSO (Kijazi & Reason, 2005) has been used in this study to select the onset, peak, end and major dry spells for each season. A detailed explanation of the methodology is given in (Kijazi & Reason, 2005). Based on the rainfall seasons' similarities, the NC criterion was used over the NEH, and the South Coast criterion was applied over the CEN as defined in chapter two. The climatological rainfall onset, peak, end (withdrawal) and total amount received were extracted from each time series and are presented in Table 6.1.

Based on the rainfall index (Fig 3.9(b)) a few selected wet and dry years during MAM season over NEH were analysed in this chapter. As mentioned earlier the analysis of intra-seasonal variability over the north coast ((NC) during ENSO, non- ENSO and IOD years was detailed in (Kijazi, 2003). This chapter therefore considers the NEH which is an important agricultural region in the country. Special attention was given to the March to May (MAM) season since the OND season was detailed in (Kabanda, 1995). The selection of years was based on the strong wet/dry years having rainfall anomaly value of at least one standard deviation (Fig 3.9(b)). The wet years to be considered

are 1978, 1979, 1981 and 1990. The dry years to be considered are 1973 and 1993. Time series for dry and wet years were plotted in Figure 6.3 and 6.4. The rainfall onset, peak, end (withdrawal) and total amount received were extracted from each time series and are presented in Tables 6.2 and 6.3.

Table 6.1: Rainfall onset, peak, end and total rainfall received for the NC, NEH and CEN (Climatology)

Event	NC (OND)	NC (MAM)	NEH (OND)	NEH (MAM)	CEN (N– A)
ONSET (P0)	58 th Pentad 16 - 20 Oct	14 th Pentad 6-10 th March	60 th Pentad 26- 31 st Oct	15 th Pentad 11-15 th March	67 th Pentad (1 - 5 th Dec)
PEAK (P1)	65 th Pentad 21 – 25 Nov	24 th Pentad 26-30 th April	66 th Pentad 26-30 th Nov	22 nd Pentad 16-20 th April	3 rd Pentad 11-15 th Jan
END (P+1)	4 th Pentad 16- 20 Jan	31 st Pentad 1 - 5 th June	3 rd Pentad 11- 15 th Jan	29 th Pentad 21- 25 th May	20 th Pentad 6 - 10 th Apr
TOTAL RAINFALL	348 (mm)	600 (mm)	180 (mm)	388 (mm)	518 (mm)

Table 6.2: Rainfall onset, peak, end and Total amount received for the NEH (MAM) wet seasons (In bracket the percentage of seasonal total)

Event	1978	1979	1981	1990
ONSET (P0)	10 th Pentad 16-20Feb	15 th Pentad 11-15 Mar	16 th Pentad 16-20 Mar	10 th Pentad 16-20 Feb
PEAK (P1)	17 th Pentad 21-25 Mar	20 th Pentad 6-10Apr	25 th Pentad 1-5 May	23 rd Pentad 21-25 Apr
END (P+1)	30 th Pentad 26-31 May	32 nd Pentad 6-10 Jun	28 th Pentad 16-20 May	26 th Pentad 6-10 May
TOTAL RAINFALL	729 mm (188%)	780 mm (201%)	529 mm (136%)	696 mm (179%)

Table 6.3 Rainfall onset, peak, end and total amount received for the NEH (MAM) dry seasons (In bracket the percentage of seasonal total)

Event	1973	1993
ONSET (P0)	21 st Pentad 11-15 Feb	20 th Pentad 6-10 Apr
PEAK (P1)	24 th Pentad 26-30 Apr	29 th Pentad 21-25 May
END (P+1)	25 th Pentad 1-5 May	29 th Pentad 21-25 May
TOTAL RAINFALL	165 (mm) (42.5%)	175 (mm) (45%)

It is evident from Table 6.1 that rainfall for the NC OND season starts about two pentads earlier than the NEH. It is similarly evident that the OND rainfall season is about three pentads longer over the NC than NEH. For MAM season the rainfall starts about one pentad earlier over the NC than NEH. For the central region the unimodal rainfall season seems to start in December, peak in January and end in April. Comparison with the southern coast unimodal rainfall season (Kijazi, 2003) indicates that the rainfall starts earlier over the southern coast (November). These results suggest that despite the fact that the rainfall seasons over Tanzania is controlled by the north-south seasonal migration of the Inter-Tropical Convergence Zone (ITCZ), coastal regions seem to have earlier onset of rainfall as compared to the inland regions.

For the selected wet years over the NEH during MAM season (Table 6.2), each year seems to have its own characteristics in-terms of rainfall onset, peak, end and total amount received except for the 1978 and 1990 where the rainfall started at the same time (16 – 20 February). 1979 was an anomalous wet year during the period of study with a standardised rainfall anomaly value of about 2.7 (Fig 3.9b). It is evident from Table 6.2 and 6.1 that the rainfall season was longer than average by about three pentads and the amount of rainfall received was about 201% of climatology. For 1978, the rainfall season was much longer than climatology and the amount received was about 188%

of climatology. For 1981 the rainfall season was shorter than climatology but the amount of rainfall received was much higher than the climatology (about 136%) with the peak of about 15mm/day. 1990 MAM season over the NEH was about two pentads longer than climatology. The amount of rainfall received was about 179% of the climatological total.

Generally, the wet years over the NEH during the MAM season were characterised by longer than average rainfall seasons with heavy rainfall of about 1.5 to 2 times the average.

During the selected dry years (Table 6.3) again each year seems to have its own characteristics in-terms of rainfall onset, peak, end and total amount received. In 1973, the onset of rainfall was late by about six pentads and the rain itself ended at about four pentads earlier. The rainfall season was much shorter (about five pentads) and the amount received was below average. Similarly in 1993 the onset of the rainfall season was about five pentads late and the amount received was much lower than the average.

6.2 Circulations associated with intra-seasonal variability

This section examines NCEP/NCAR reanalysis moisture flux circulations related to the rainfall over the country. Attention has been given to the lower level moisture flux circulations to understand the evolution of moisture transport during the onset, peak and end pentads of selected wet and dry seasons. Goddard & Graham (1999) observed the 850hPa level to be the most representative of the behaviour of the vertically integrated moisture flux over East Africa. Based on this result, 850hPa level was used in this section to study the intra-seasonal moisture flux circulations during selected wet and dry MAM seasons over the NEH. Newell *et al.*, (1972) postulated that in the tropics, the bulk of horizontal transfer of moisture takes place below 700hPa. Wind circulations at 850hPa and 700hPa during the onset, peak and end of the rainfall season were analysed. However, both levels seem to show similar patterns and only the 700hPa level is shown.

6.2.1 Results of moisture flux and wind for climatology

The long rain season (MAM) is associated with the northward movement of the ITCZ. Figures 6.5 – 6.7 represent long term mean patterns of moisture flux at 850 hPa and wind at 700 hPa for onset, peak and end pentads of MAM rainfall season over the NEH.

At the onset of the rainfall season (Figure 6.5a), most of Tanzania is covered by easterly moisture flux. Between 5°S and 10°S over the Indian Ocean there is a zonal band of westerly moisture flux with north easterly moisture flux closer to the Tanzanian coast. To the north and south of this westerly band, easterly moisture flux dominates.

At 700hPa (Figure 6.5b), easterly wind anomalies cover much of the Indian Ocean and Tanzania. The position of the ITCZ is clearly indicated by the converging south easterly and north easterly wind near northern Madagascar with strong westerly wind anomalies in the Indian Ocean between 5° - 10°S. The occurrence of the ITCZ over the region results in increased rainfall marking the onset of the rainfall season.

At the peak of the rainfall season (Figure 6.6a&b), strong south-easterly moisture flux exists over the central equatorial Indian Ocean with easterly moisture flux over much of Tanzania. The descending limb of the Walker type circulation lies over the Western Indian Ocean as indicated by the origin of the easterly and westerly moisture flux and wind. Strong easterly wind anomalies cover much of the Indian Ocean and Tanzania suggesting strong moisture fetch from the Indian Ocean. Such wind and moisture flux circulation patterns result in enhanced easterly moisture flux convergence over Tanzania and increased rainfall during this peak pentad of the rainfall season.

Towards the withdrawal of the rainfall season (Figure 6.7), easterly moisture flux emanating from the Indian Ocean veer to south easterly anomalies near the Tanzanian coast, thus it starts to transport moisture away from the NEH. The equatorial Indian Ocean between the equator and 10°N is covered by

westerly moisture flux transporting moisture away from Tanzania that marks the end of the rainfall season.

6.2.2 Results of moisture flux and wind for selected dry years.

This section discusses results obtained from the analysis of 850 hPa moisture flux and 700hPa wind for dry MAM seasons over the NEH. The analysis for each year was completed and generally all years seem to show similar patterns related to rainfall onset, peak and end. However, for the sake of brevity the 1973 anomalous dry season with rainfall anomaly value of about -1.6 is discussed here. The moisture flux and wind anomalies for onset, peak and end pentad are shown in Figures 6.8 – 6.10.

Moisture flux and wind circulation features for the onset pentad of 1973 dry MAM season is shown in Figure 6.8 (a & b). During the onset of the MAM rainfall season (Figure 6.8(a)), an anticyclonic moisture flux circulation occurs over the Indian Ocean east of Madagascar with westerly anomalies over the equatorial Indian Ocean between 5°N and 5°S. The position of the descending limb of the Walker type circulation was over the equatorial Western Indian Ocean closer to the East African coast as identified by westerly anomalies over the ocean and easterly anomalies over the land. Over the lake Victoria Basin, there are convergence of westerly anomalies emanating from the Congo Basin and easterly anomalies. The occurrence of the descending limb of Walker type circulation closer to the East African coast tends to suppress convection over the NEH consistent with the observed dry conditions.

At 700 hPa (Figure 6.8(b)) an anticyclonic wind anomaly exists south – east of Madagascar coupled with westerly anomalies over the equatorial West Indian Ocean between 5°N and 5°S and weak easterly anomalies over the NEH that converge with westerly anomalies over the Lake Victoria Basin. The occurrence of westerly anomalies over the Indian Ocean tends to transport moisture away from Tanzania as suggested by (Kijazi & Reason, 2005). It is worth noting here that strong easterly moisture flux and wind circulations over

the equatorial western Indian Ocean between 5°N and 5°S is an important feature for increased rainfall over Tanzania as indicated in section 6.2.1 of this chapter and Kijazi & Reason, 2005. During this onset pentad this area is covered by westerly moisture flux and wind anomalies consistent with the observed dry conditions.

During the peak of the rainfall season (Figure 6.9(a)), a cyclonic moisture flux anomaly occurs near the Somali coast. The easterly moisture flux over the South Western Indian Ocean veers to southerly moisture flux over the East African coast denying inland penetration of moisture consistent with below average rainfall received over the NEH. Over the Congo Basin the easterly moisture flux anomalies divert moisture away from the country, again consistent with the observed dry conditions. At 700 hPa (Figure 6.9(b)), an anticyclonic circulation occurs south of Madagascar coupled with a cyclonic circulation over the Somali coast. These circulations cause the easterly wind anomalies over the South Western Indian Ocean to veer to south-easterly and back to north easterly as they approach the Tanzanian coast. Such circulations deny inland penetration of moisture consistent with dry conditions observed. Over the Congo Basin, the south-easterly anomalies accelerate the background flow (Figure 6.6(b)), thus, fetching moisture away from the country consistent with below average rainfall received.

At the end of the rainfall season (Figure 6.10(a & b)), westerly moisture flux and wind anomalies occurs over much of the Indian Ocean transporting moisture away from the country, thus marking the end of the rainfall season.

6.2.3 Results of moisture flux and wind for selected wet years.

This section discusses results obtained from the analysis of 850 hPa moisture flux and 700hPa wind for wet MAM seasons over the NEH. As mentioned earlier, the analysis for each year was completed and all years seem to show similar patterns related to rainfall onset, peak and end. However, for the sake of brevity the 1979 anomalous wet season with rainfall anomaly value of

about 2.8 is discussed here. The moisture flux and wind anomalies for onset, peak and end pentad are shown in Figures 6.11 – 6.13.

During the onset of the MAM rainfall season (Figure 6.11(a)), a cyclonic moisture flux circulation occurs south east of Madagascar between 50° and 60°E coupled with strong easterly moisture flux anomaly over the equatorial western Indian Ocean between 5° and 15°S. Such moisture flux circulation features enhance moisture flux convergence over Tanzania as suggested by Goddard and Graham, 1999 and thus marking the onset of the rainfall season. At 700 hPa (Figure 6.11(b)), strong easterly wind anomalies with long Ocean track converges with westerly wind anomalies emanating from the Congo Basin over Tanzania. Such wind circulation patterns enhances moisture convergence over Tanzania during this onset pentad of rainfall season.

During the peak of the MAM rainfall season (Figure 6.12(a)), a cyclonic moisture flux circulation occur over the tropical South Indian Ocean east of Madagascar coupled with strong westerly moisture flux emanating from the equatorial Atlantic Ocean and south-easterly moisture flux from the western Indian Ocean. Such moisture flux circulation patterns fetch moisture from the Indian and Atlantic Ocean towards Tanzania consistent with above average rainfall during this peak pentad of rainfall season. At 700 hPa (Figure 6.12(b)), the cyclonic circulation over the Indian Ocean observed at 850 hPa level was also observed at 700hPa level and 500 hPa (not shown). This shows the vertical extent of the cyclonic circulation pattern over the region consistent with wet conditions observed. Strong westerly wind anomalies emanating from the Indian Ocean cover much of Tanzania. Again, such wind circulation patterns fetch moisture from the neighbouring oceans during this peak pentad of above average rainfall season.

Toward the end of the rainfall season ((Figure 6.13(a & b)), the cyclonic circulation over the India Ocean weaken and show a slight southward shift. The westerly anomalies emanating from the Indian Ocean veer to northerly

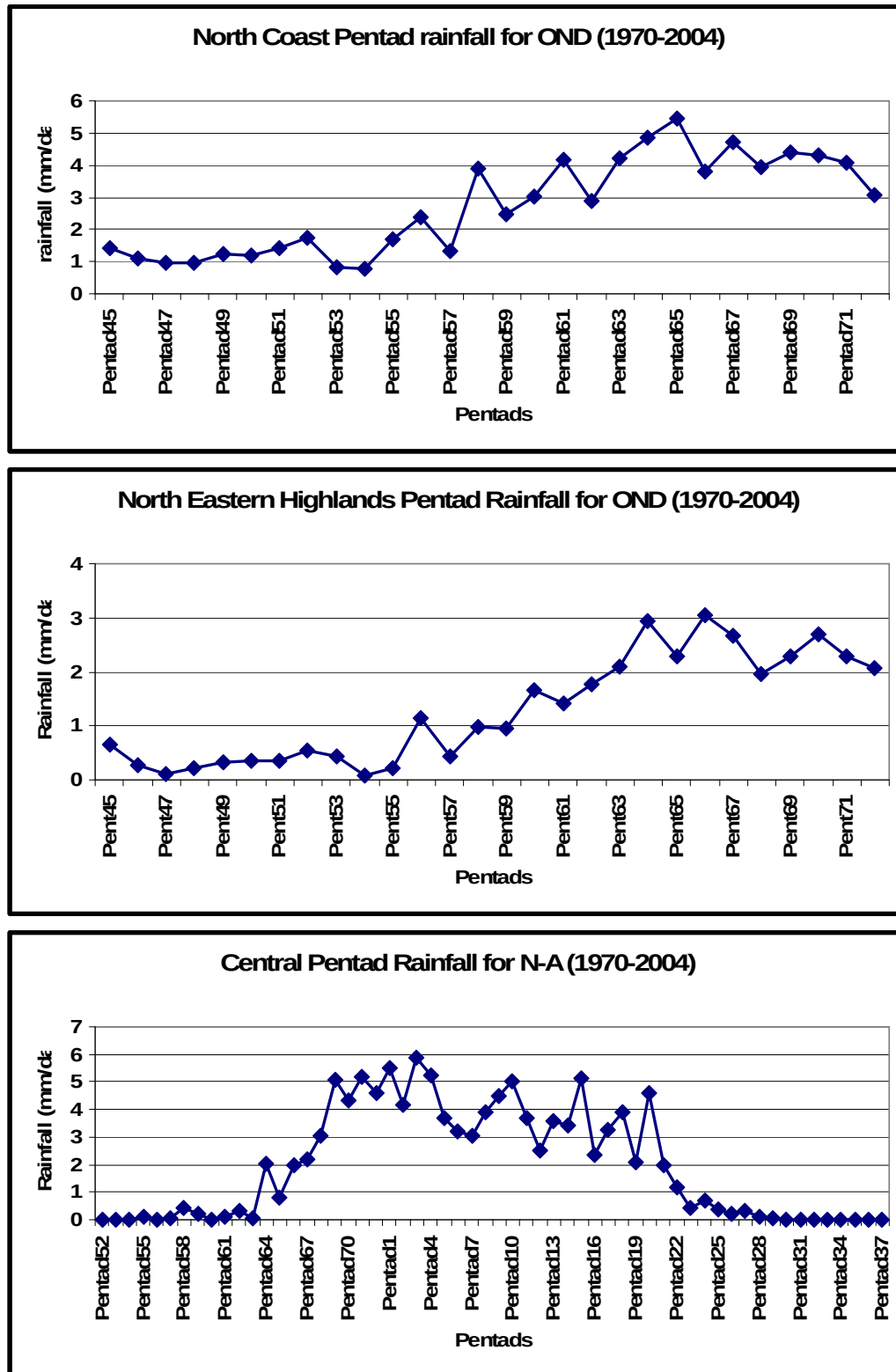
anomalies over the continent. Such moisture flux and wind circulation patterns divert moisture away from the country marking the end of the rainfall season.

6.4 Summary of the findings

In summary, it must be noted that the wet years were characterised by a cyclonic moisture flux and wind over the tropical South Indian Ocean east of Madagascar coupled with strong westerly moisture flux emanating from the equatorial Atlantic Ocean and south-easterly moisture flux from the western Indian Ocean that enhance moisture flux convergence over the country. In contrast, the dry years show more or less the reverse circulation patterns over the Indian Ocean. An anticyclonic circulation occurs east of Madagascar with circulation patterns that divert moisture away from Tanzania.

This chapter has provided an insight into understanding the intra-seasonal climatic patterns related to extreme events, which is particularly important for the agricultural sector. It was shown that wet years were characterised by longer than normal rainfall seasons, while for dry years the seasons were shorter than average. An out-of-season peak was evident six pentads after cessation of the rainfall season. This can be used to minimize the effect of drought in dry years.

Chapter seven will give the summary and conclusion of the thesis.

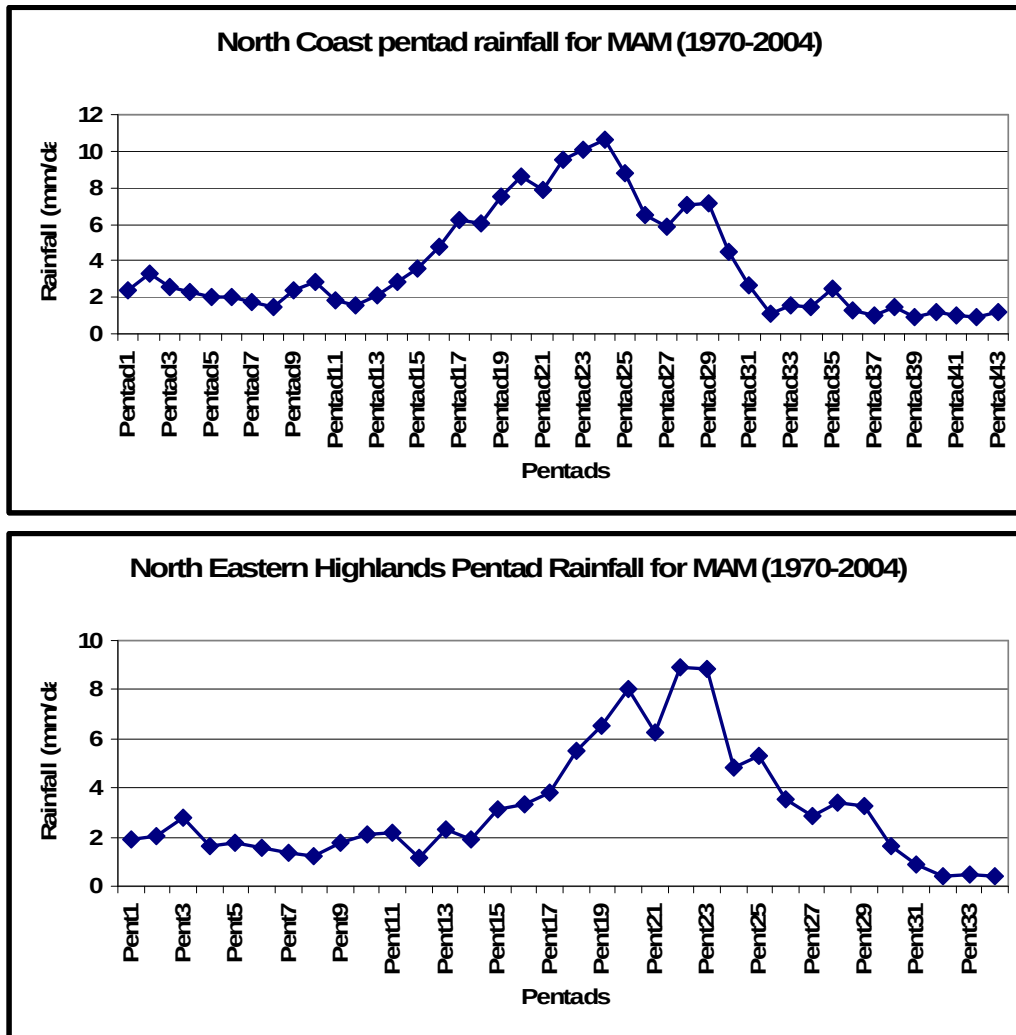


a

b

c

Fig 6.1: Climatological Pentad Time series for (a) North coast, OND (b) North eastern highlands, OND and (c) Central, N-A.



a

b

Fig 6.2: Climatological Pentad Time series for (a) North coast, MAM (b) North eastern highlands, MAM

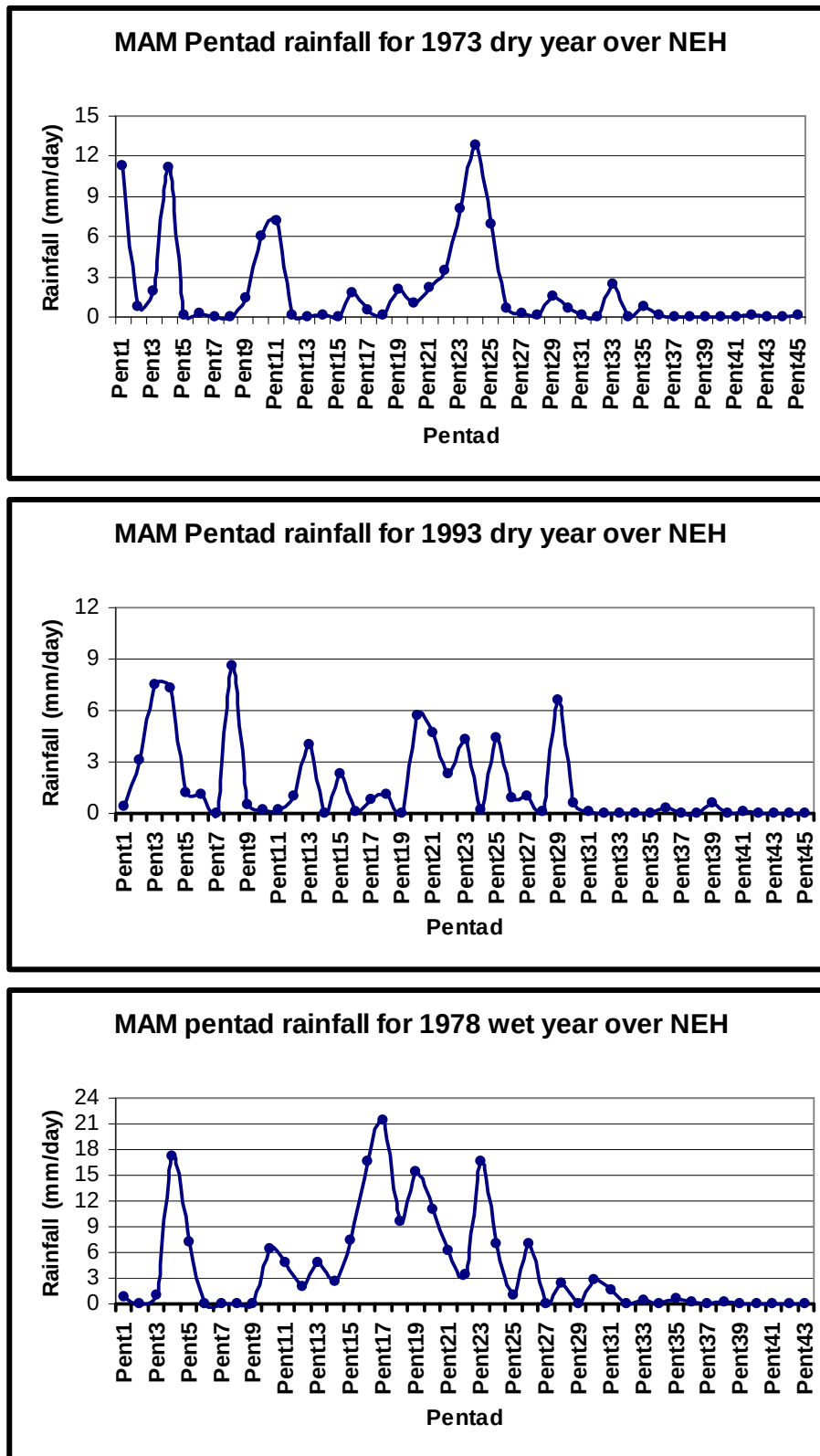
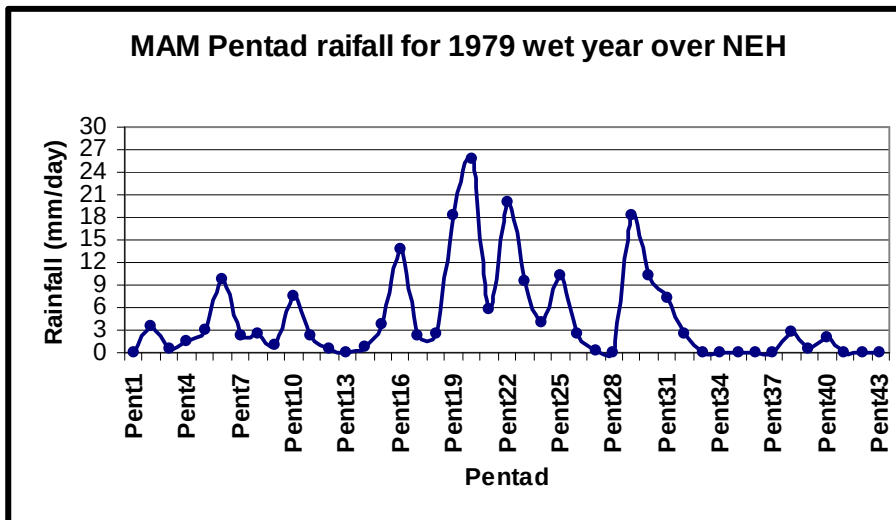
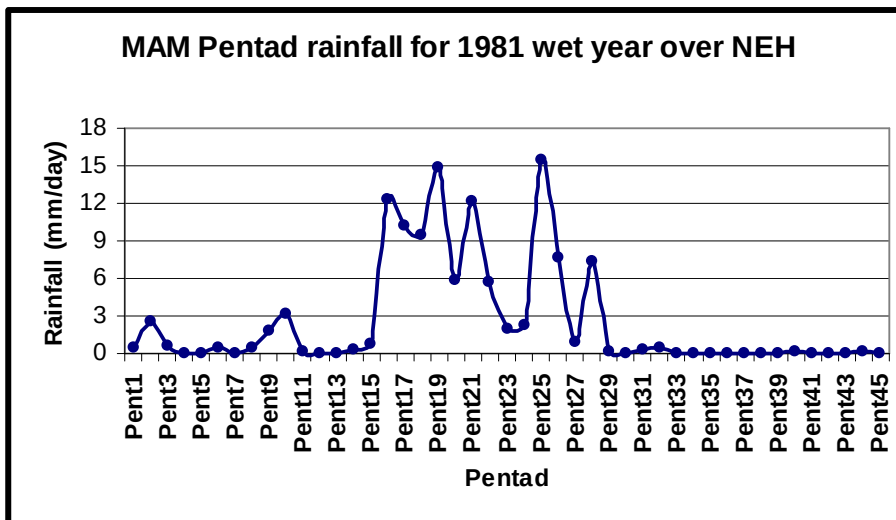


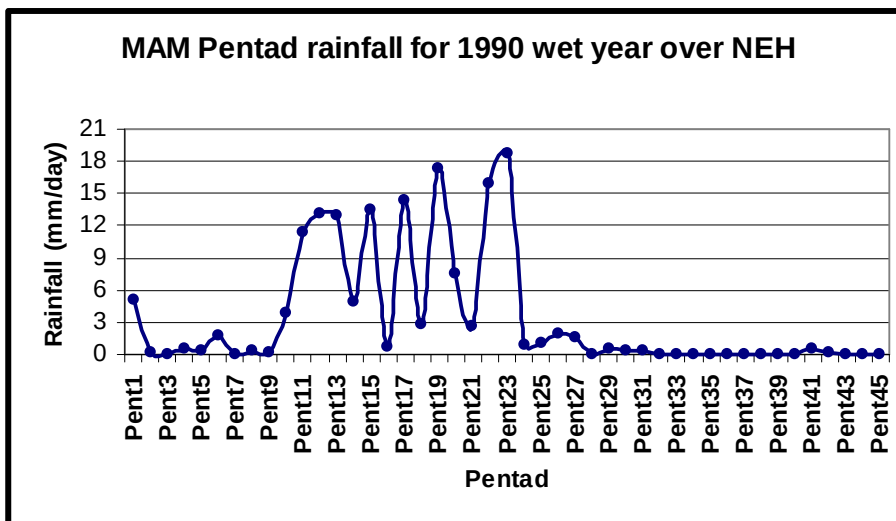
Fig 6.3: Time series of pentad rainfall for NEH during MAM season
(a) 1973 dry year (b) 1993 dry year and (c) 1978 wet year



a



b



c

Fig 6.4: Time series of pentad rainfall for NEH during wet MAM season
(a) 1979 (b) 1981 and (c) 1990

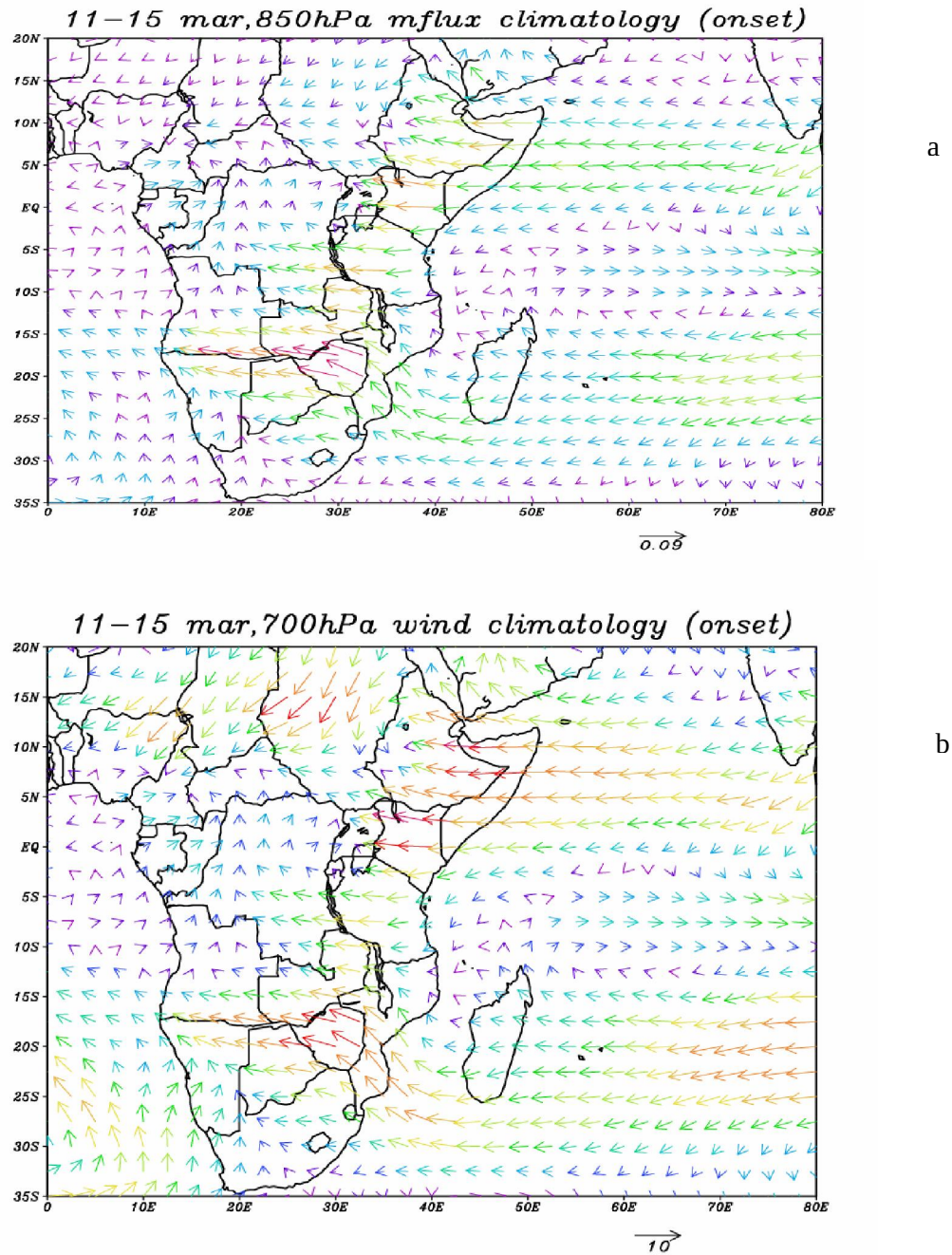


Fig 6.5: MAM climatological circulations for onset pentad over NEH (a) Moisture flux ($\text{gkg}^{-1}\text{ms}^{-1}$) (b) Wind in ms^{-1}

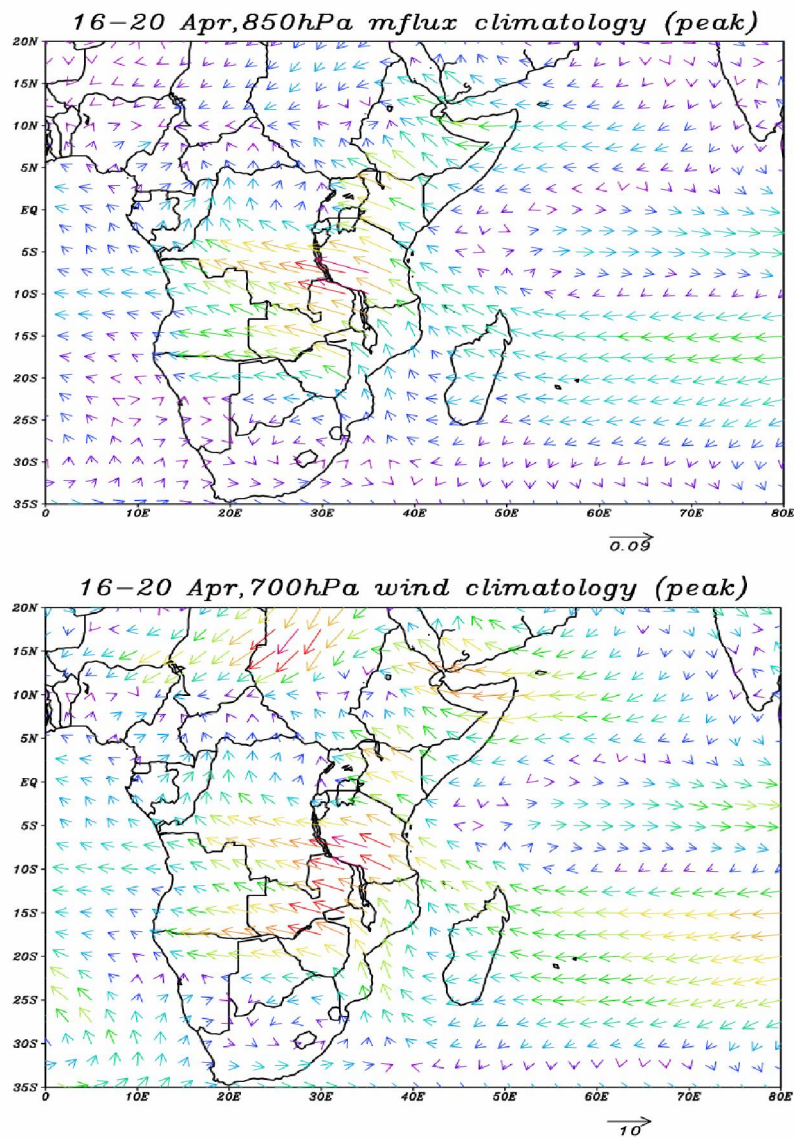
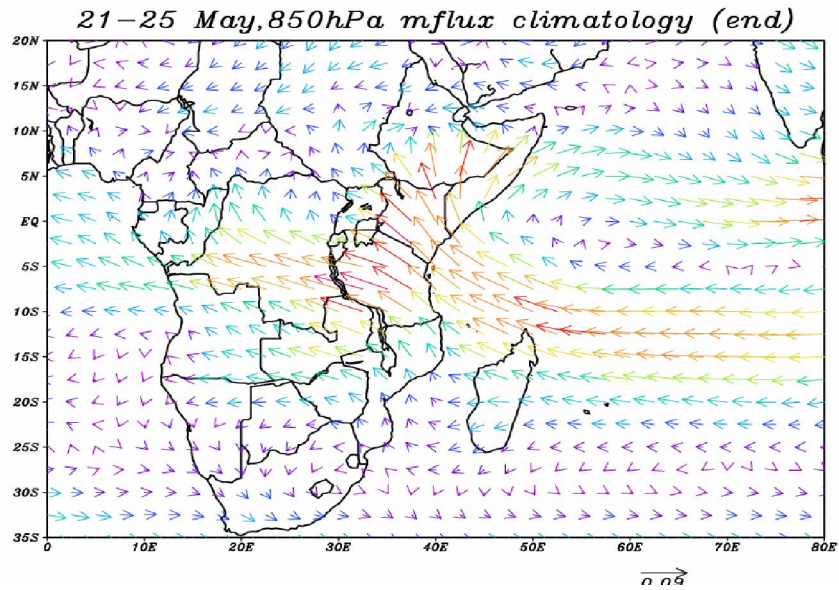
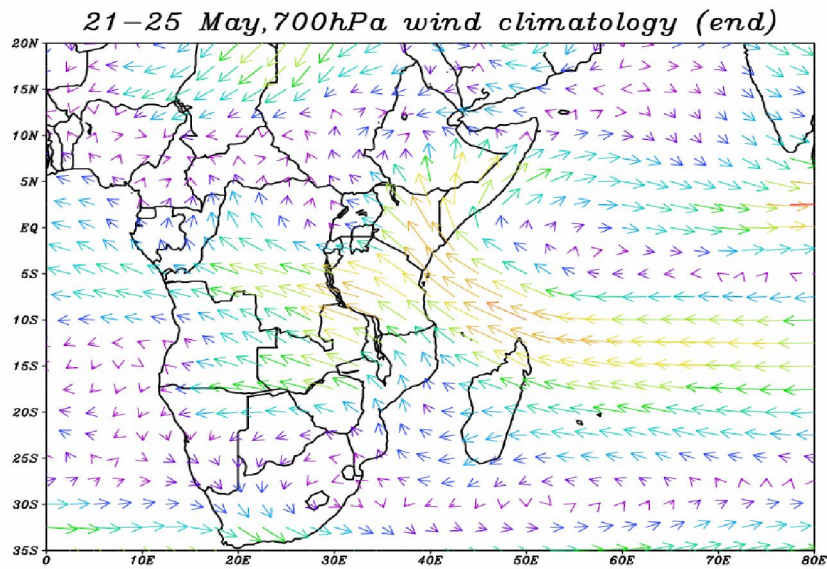


Fig 6.6: As for Figure 6.5 but for peak pentad



a



b

Fig 6.7: As for Figure 6.5 but for end pentad

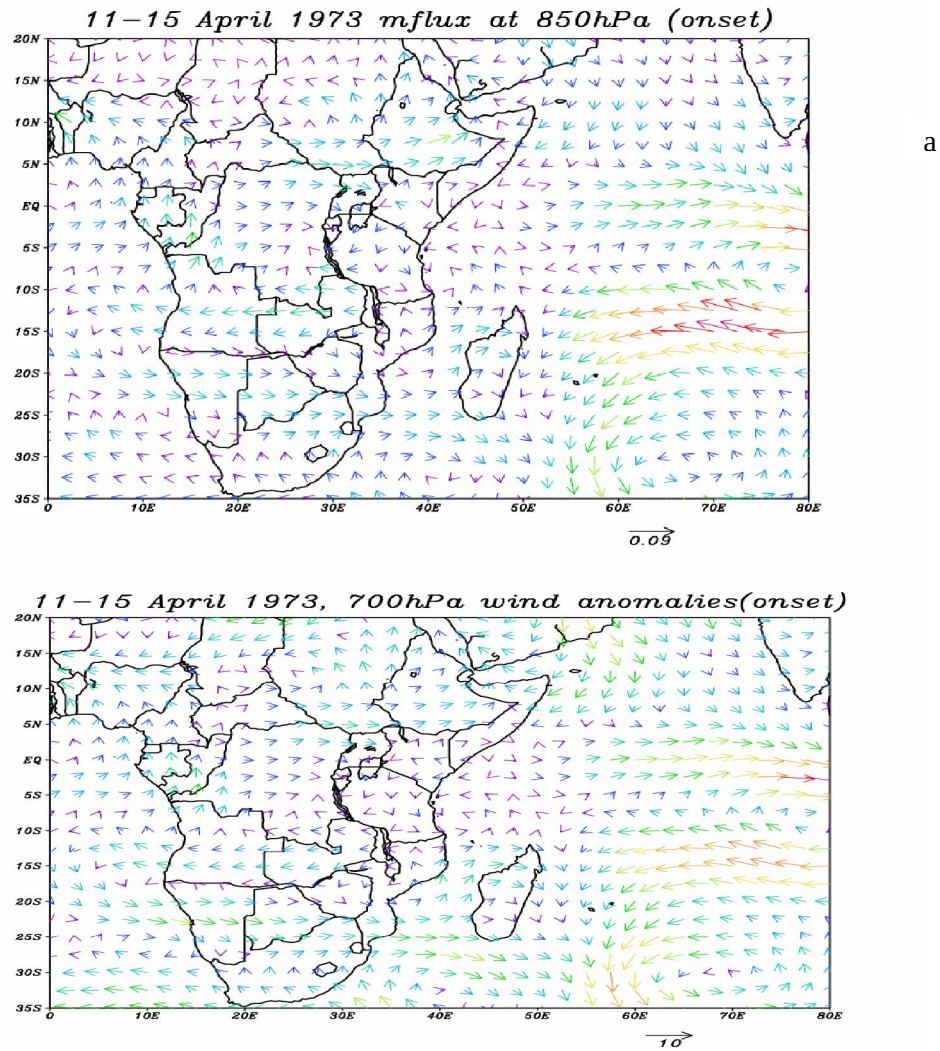


Fig 6.8: 1973 MAM dry season circulations for onset pentad over NEH (a) Moisture flux ($\text{gkg}^{-1}\text{ms}^{-1}$) (b) Wind in ms^{-1}

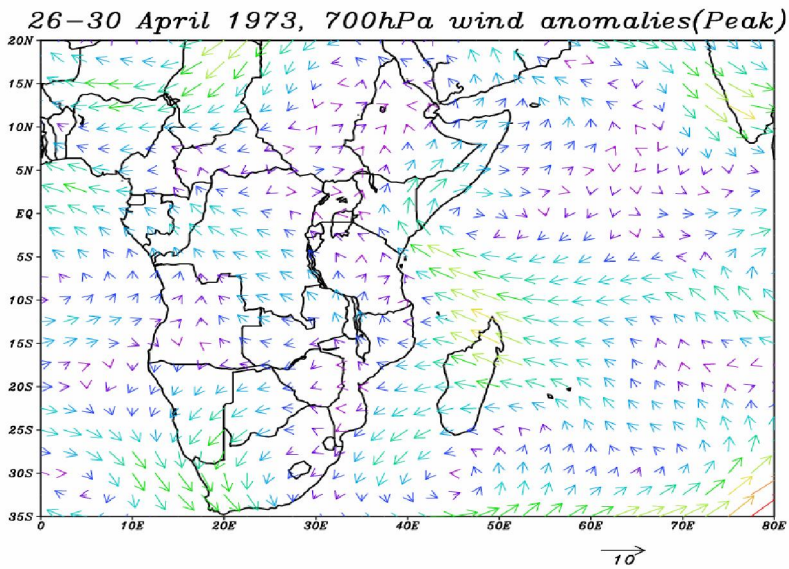
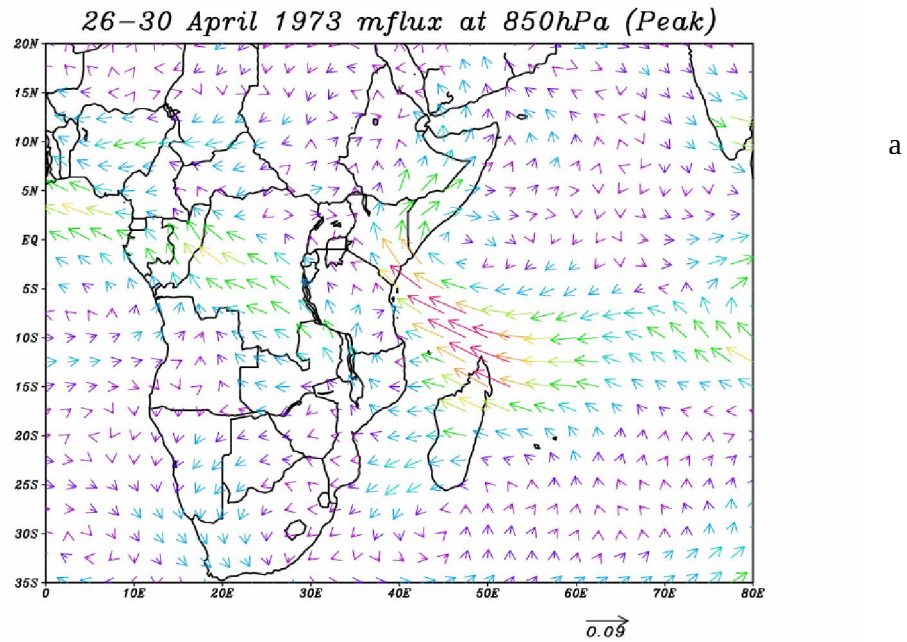
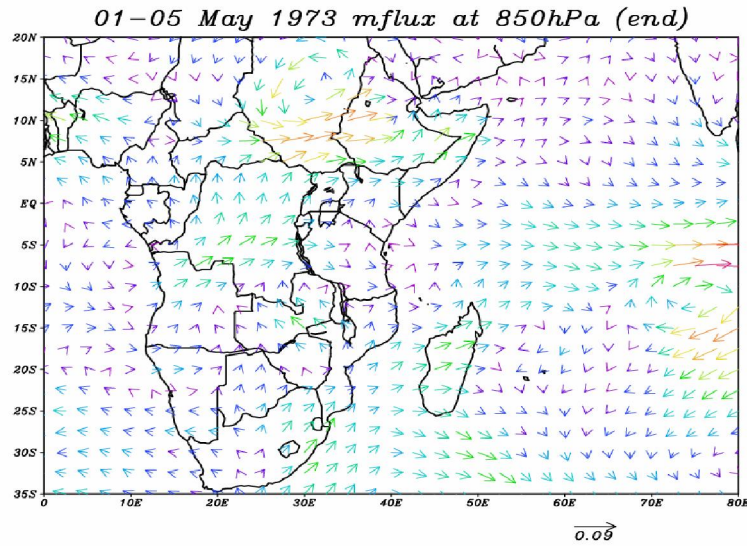
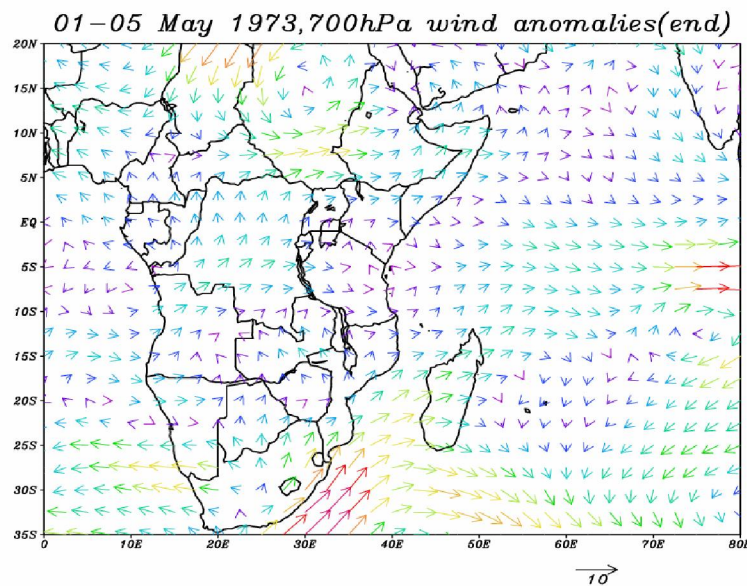


Fig 6.9: As for Figure 6.8 but for peak pentad

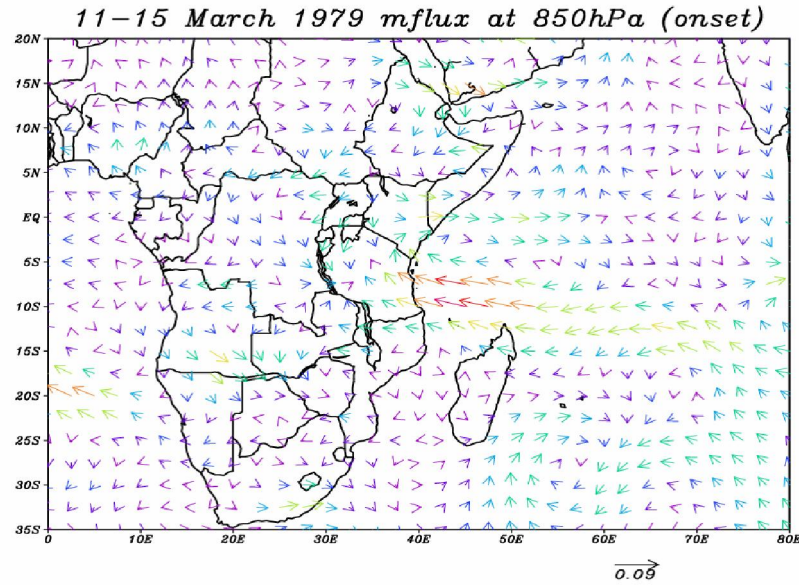


a

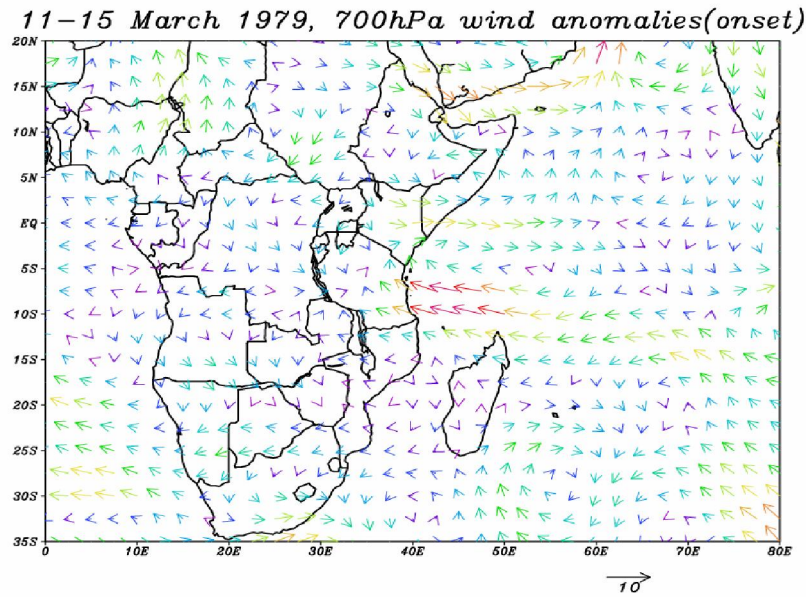


b

Fig 6.10: As for Figure 6.8 but for end pentad



a



b

Fig 6.11: 1979 MAM wet season circulations for onset pentad over NEH
 (a) Moisture flux ($\text{gkg}^{-1}\text{ms}^{-1}$) (b) Wind in ms^{-1}

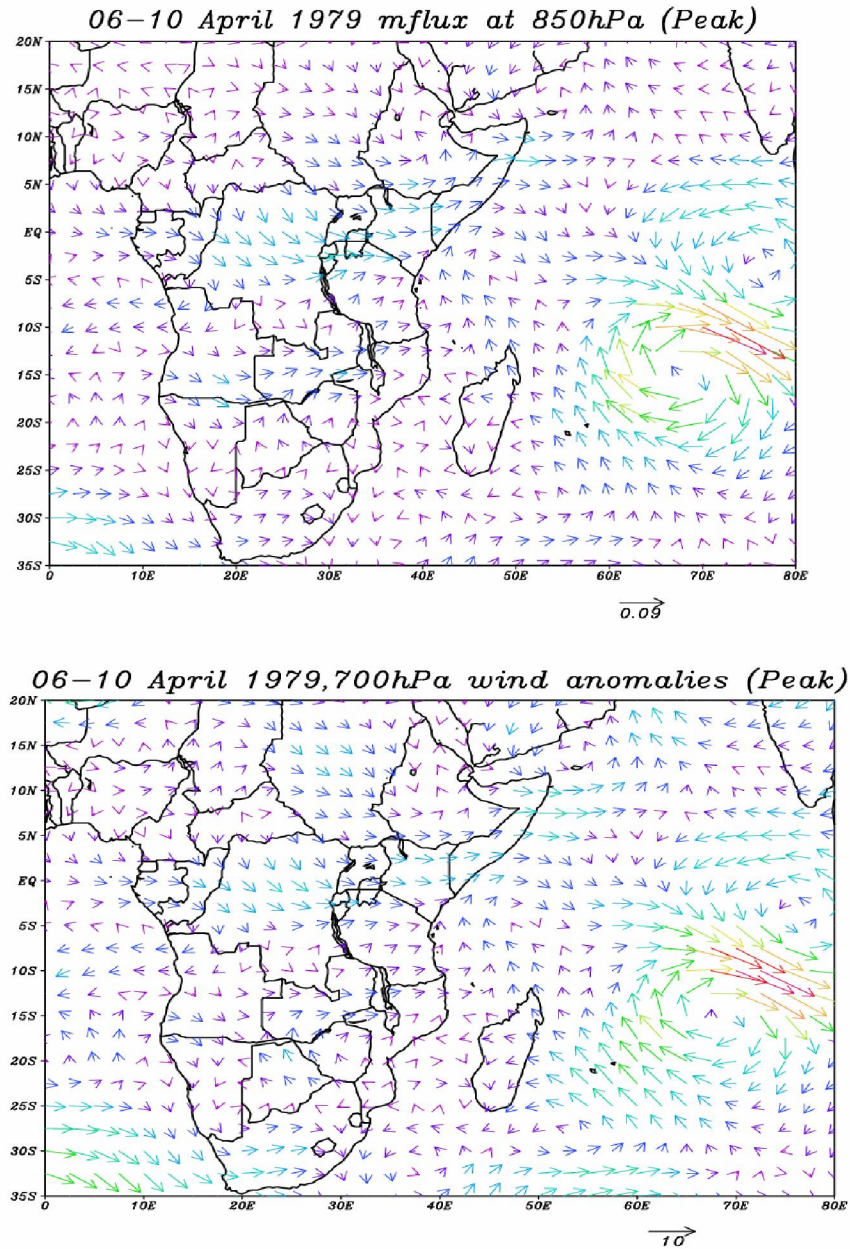


Fig 6.12: As for Figure 6.11 but for peak pentad

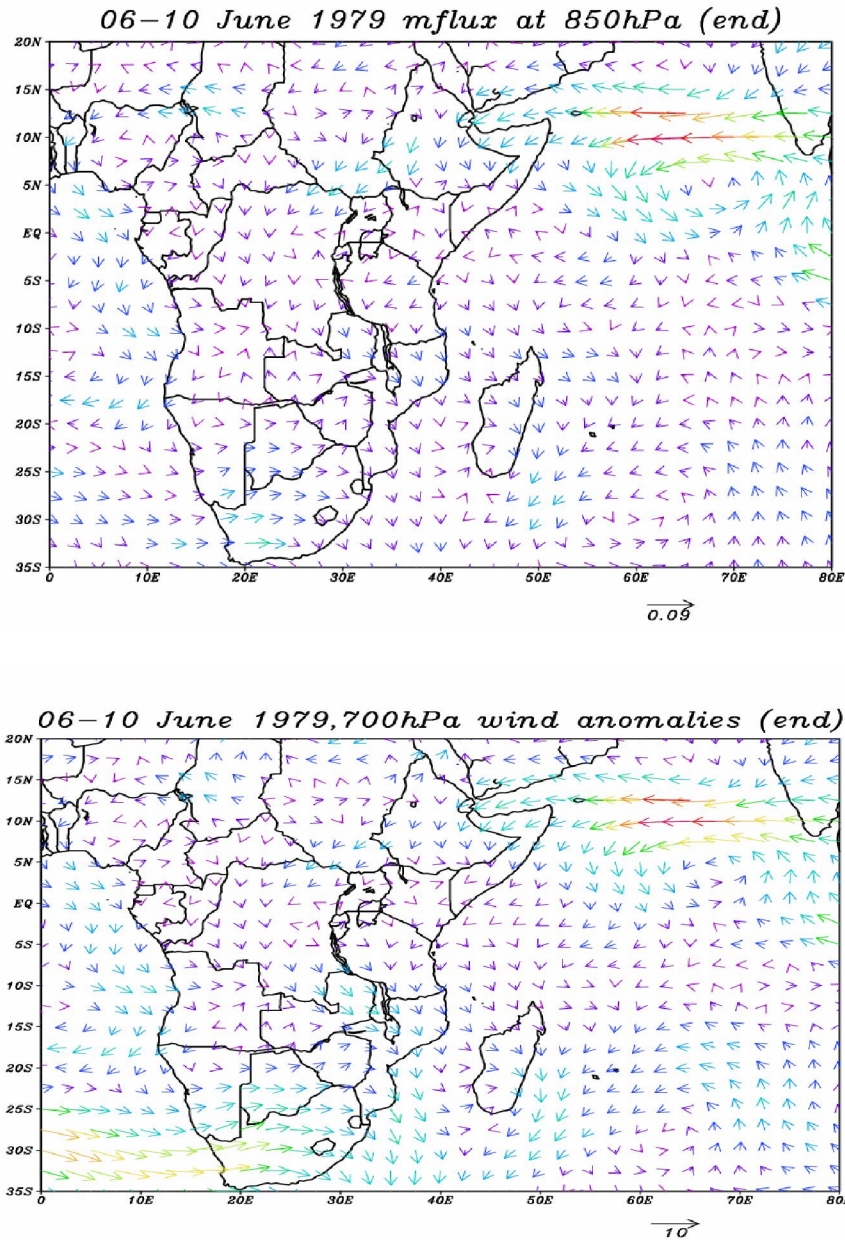


Fig 6.13: As for Figure 6.11 but for end pentad

CHAPTER SEVEN

CONCLUSION

7.0. Summary

This thesis has presented an examination of the analysis of recent severe climate events over Tanzania. Attention has been directed to the understanding of climate variability over Northern Tanzania and the circulation features over the Atlantic and Indian Oceans responsible for said climate variability. Furthermore, the ability of ECHAM4.5 model in representing this variability was investigated. In East Africa, specifically Tanzania, results from GCMs are yet to be validated for their ability to represent climate patterns related to climate variability and dynamical modelling is a new study in the country. It is therefore important that research is directed into the validation of GCMs over the region and their ability to provide results which can improve forecasting skills. A detailed analysis of the intra-seasonal analysis over north-eastern Tanzania was conducted to understand the nature of intra-seasonal variability over the region.

The main objective of this research is to advance our understanding of atmospheric circulation patterns associated with seasonal, intra-seasonal and inter-annual climate variability over north eastern Tanzania and address the gap of dynamical modelling in Tanzania. Beyond the expected improvement in the understanding of atmospheric circulations associated with inter-annual variability this thesis also investigated the intra-seasonal variability over north-eastern Tanzania in an effort to provide useful information to various bodies concerned with food production and associated policy.

To achieve the above mentioned objective, different data and analysis techniques were used to examine the relevant processes. The data used include the rainfall station data provided by the Tanzania Meteorological Agency (TMA) and global climate model simulations. Methods of analysis used include time series analysis, composite analyses, cross sectional analysis, Empirical Orthogonal Function analysis and wavelet analysis.

7.1 Major conclusions

7.1.1 Mean characteristics, inter-annual and intra-seasonal variability

Mean characteristics processes were examined as necessary background information for the causes of rainfall variability. The main objective was to understand the primary factors that determine Tanzania's climate and circulation features associated with inter-annual and intra-seasonal variability. The results obtained from climatological analysis showed the occurrence of high SSTs in equatorial regions and a low SST in midlatitudes. However, the water over the oceans was warmer during the MAM season compared to the OND season, which suggest strong upwelling during the OND season. Two regions of deep convection were observed one maritime (over the Indian Ocean) and one continental (over the Congo rain forests). High values of latent heat flux occurred at the Congo forests during the OND season, suggesting the Congo forest to be among the sources of moisture for the OND season. The mean wind circulation that showed westerly flow from the Congo rain forest converging with the easterly flow from the Indian Ocean over the Lake Victoria basin confirmed this. However, the easterly moisture flux dominates the region for both the OND and MAM seasons and this suggests the Indian Ocean to be the main source of moisture for Tanzanian rainfall.

These mean characteristics were used to understand the region's climate variability through analysis of the departure from the observed mean characteristics. On an inter-annual time scale the North-east Tanzania study region experienced more dry than wet years during the period of study. However, dry anomalies were much weaker than their wet counterparts, and the influence of El Niño on the latter was suggested as one of the causes. For the CEN, the early and late seasons indicated contrasting rainfall characteristics (for example, 1997 was wet during the early season and dry during the late season). Similarly, 1996 exhibited the same characteristics. It is therefore important to incorporate such rainfall characteristics into agricultural planning.

Circulation features during the wet non ENSO years suggests the equatorial Western Indian Ocean and the Congo basin to be the source of moisture for the OND season. The existence of low level easterly moisture flux and wind anomalies over the equatorial Western Indian Ocean between 5°N and 5°S fetch moisture toward Tanzania contributing to the observed wet conditions. Similarly, strong westerly moisture flux and wind anomalies emanating from the Congo basin fetch moisture from the Congo basin towards the study region. Such moisture flux and wind circulation patterns were coupled with strong moisture flux convergence and strong relative ascent that occurs over the north eastern Tanzania consistent with wet conditions observed over the region. However, for the dry seasons these observations reverse (except over the equatorial West Indian Ocean) and moisture flux divergence coupled with downward motion occurs over much of the country. In terms of moisture flux and wind circulation pattern the Congo basin is an important region that shows a distinctive pattern during wet and dry non ENSO years.

Similarly during the dry MAM season moisture flux divergence and down ward motion occur over north eastern Tanzania and such moisture flux and omega circulation patterns reverse during wet MAM season. In summary, the dry/wet conditions over the NEH during the OND and MAM seasons were associated with moisture flux divergence/convergence over northern Tanzania coupled with downward/upward motion over the region.

On the intra-seasonal time scale, wet years were characterised by longer than normal rainfall season, while for dry years the seasons were shorter than average. For the dry OND season, an out-of-season peak was evident, that can be used to minimize the effects of drought. The circulation patterns show that the wet years were characterised by a cyclonic moisture flux and wind over the tropical South Indian Ocean east of Madagascar coupled with strong westerly moisture flux emanating from the equatorial Atlantic Ocean and south-easterly moisture flux from the western Indian Ocean that enhance moisture flux convergence over the country. In contrast, the dry years show more or less the reverse circulation patterns over the Indian Ocean. An

anticyclonic circulation occurs east of Madagascar with circulation patterns that divert moisture away from Tanzania.

7.1.2 Comparison with ECHAM 4.5 model

Comparison of ECHAM 4.5 model with NCEP/NCAR reanalysis over the study region indicated that the model was able to represent the circulation features associated with rainfall during the wet season while for the dry season the model failed to represent the circulation features. This suggests that local features (that are not well captured by the model) contribute significantly to the rainfall variability over the region, especially during dry seasons. It is worth noting here that although there are some deficiencies in the model it seems to capture the major features related to climate over the region of study. Thus, confidence in the ability of the ECHAM 4.5 model to provide robust initial and boundary conditions for the regional high resolution spectral model (RSM) that is being applied by the IGAD Climate Prediction and Application centre (ICPAC) to seasonal forecasting over East Africa may be increased.

7.1.3 Case studies of the 1998 – 2005 drought and the 2006 flood

Two case studies have been performed in this thesis. The first concerned the 1998 - 2005 droughts over the NEH and the second centred on the 2006 OND floods over the northern part of the country. The characteristics of the inter-annual and intra-seasonal rainfall variability over the north-eastern highlands of Tanzania and their associated circulation anomaly patterns during the prolonged 1998 - 2005 drought have been analysed. It is evident that the 1998 - 2005 drought was characterised by a complete failure of both rainfall seasons (Table 4.1 and 4.2). The rainfall onset was undefined in most of the years with unevenly distributed rains associated with prolonged periods of dry spells within the shorter-than-average seasons. Such drought had devastating effects, most notably crop failures and livestock losses that resulted in a food shortage. Another major effect was the reduction in the level of the country's dams, which resulted in hydroelectric power and water rationing. The Drought

Impact Assessment TMA bulletin (2006) reported widespread death of animals over the region associated with the prolonged drought. This run of consecutive years of below average rainfall during 1998-2005 was very problematic; in fact, since 1970, only 1973-1976 seems to be comparable in terms of the duration of the drought and magnitude.

During the short rainy season, a displacement of the rains from October, November, December to November, December, January was observed with sometimes strong wet spells in January or even February. In fact, most of the years (2000, 2001 and 2003) indicated an out-of-season rainfall peak that occurred in January (Table 4.1). This thesis found that the out-of-season peak received a significant amount of rainfall, thus suggesting an important application for agriculture. It is therefore worth suggesting here that the January out-of-season peak may be used to mitigate the impact of drought over the country. The circulation anomalies indicate that the observed drought over northern Tanzania was associated with three main factors: firstly, wind circulation patterns that diverted moisture away from the country; secondly, strong moisture flux divergence over the region; thirdly, strong subsidence associated with an eastward shift of the ascending limb of the Walker type circulation.

The observed circulation features during OND 2006 indicate that the northern Tanzania OND 2006 floods were related to warm SSTs in the western Indian Ocean with enhanced low level moisture convergence and uplift over Tanzania. These SST anomalies were associated with a positive phase Indian Ocean Dipole and an El Niño occurring during this season. The extreme flooding in Tanzania seems to be preceded by warming near the Somali coast and an easterly moisture flux anomaly over the eastern equatorial Indian Ocean. Generally, the OND 2006 floods anomalies is roughly the opposite of the 1998 – 2005 drought anomalies. However, the OND 2006 flood circulation anomalies seem to be stronger than the 1998 – 2005 drought circulation anomalies consistent with the larger positive rainfall anomalies observed.

Examination of the patterns for the heaviest rainfall day (29 November 2006) showed that, the lower levels were characterized by easterly flow with a long ocean track towards Tanzania coupled with strong upper level divergence. Also the cyclonic conditions near the Tanzanian coast were evident during this day of heavy rainfall event. Positive velocity potential at the lower levels coupled with negative velocity potential at the upper levels and relative uplift at 500 hPa were evident. Two months prior to the onset of the rainy season (that is, August), warming was evident over the tropical western Indian Ocean and easterly moisture flux anomalies towards East Africa, thus suggesting that, for forecasting purposes, monitoring in this region is crucial. Timely implementation of the Research Moored Array for African – Asian – Australian Monsoon Analysis and Prediction (RAMA) in the tropical western Indian Ocean (McPhaden *et al.*, 2009) is therefore of great importance for East African climate monitoring and prediction efforts.

7.2 Concluding remarks and suggested future work

The composites mean and consequent anomalies used in this thesis are based on a limited set of data in the 1970 - 2005 period. The meteorological inferences in the thesis lay not so much in the absolute magnitudes of the basic parameters, but in their relative structure and temporal variability. Hence, reference to magnitudes has been kept to a minimum. It is hoped that as quality data for a longer period becomes available, the understanding and prediction of climate variability over Tanzania will become more objective.

This thesis has shown the circulation patterns over the Atlantic and Indian oceans that were responsible for inter-annual and intra-seasonal rainfall variability over Tanzania. The study has shown that not all wet years over the NC are wet over the NEH. However, the study concentrated on the analysis of wet and dry years over each region. The study on years with contrasting characteristic over NC and NEH, that is, wet over the NC and dry over the NEH and vice versa is required to advance our understanding of the circulation patterns for such contrasting rainfall characteristics.

Furthermore, recent studies have indicated that the use of ensemble projections from more than one model is superior to the forecasts from individual models (Latif *et al.*, 2001). The suggestion is that the use of another GCM alongside the ECHAM4.5 may contribute towards an improved prediction. On the other hand, our study was conducted using GCM at low resolution and further study using Regional Model at a higher resolution is therefore required to assess the role of the horizontal grid spacing on the accuracy of the simulated climatic features.

This study has compared the GCM (ECHAM 4.5) with NCEP/NCAR reanalysis over northern Tanzania. This has contributed towards advancing our understanding of the ability of the GCMs in representing the circulation features related to rainfall over the country. Specifically it has contributed towards bridging the gap of dynamical modelling in Tanzania. However, in order to improve forecasting skills, validation of other numerical models is recommended.

This thesis has also analysed the inter-annual and intra-seasonal variability of rainfall over Tanzania and outlined the circulation features over the Atlantic and Indian oceans responsible for the variability. The nature of intra-seasonal variability over the north-eastern Tanzania was also detailed in this thesis. It is worth noting here that the results obtained from this thesis have contributed to a better understanding of the mechanisms associated with rainfall variability over north eastern Tanzania. The research has addressed the gap that exists in the literature concerning what factors and mechanisms might drive rainfall variability at the sub-regional scale over East Africa. Furthermore, this study is the one of the first to assess the ability of an atmospheric model to replicate the observed circulation and rainfall patterns at this sub-regional scale for Tanzania. Generally this thesis has answered the three research questions outlined in chapter one and has advanced our understanding of the inter-annual and intra-seasonal variability. The findings of this thesis may therefore be used to improve the seasonal forecasts.

REFERENCES

- Acharya, U.R., and N.S. Bhaskara, 1981:** Meteorology of Zambia: Part II. Govt. Printers, Lusaka, Zambia. 49pp
- Anderson, J. R., and R. D. Rosen, 1983:** The latitude height structure of the 40 – 50 – day variations in atmospheric angular momentum. *J. Atmos. Sci.*, **40**, 1584 – 1591
- Anderson, D., 1999:** Extremes in the Indian Ocean. *Nature*, **401**, 327 -328
- Anyamba E.K. 1992:** Some properties of a 20-30 day oscillation in tropical convection. *J. Afr. Met. Soc.* **1**, 1-19.
- Alapaty, K., J. E. Pleim, S. Raman, D.S. Niyogi and D.W. Byun, 1996:** Simulation of atmospheric boundary layer processes using local and nonlocal-closure schemes. *J. Appl. Meteorol.* **36**, 214-233
- Allan, R.J, C.J.C. Reason, J.A. Lindesay and T. J. Ansell, 2003:** Protracted ENSO episodides and their impacts in the Indian Ocean region. *Tropical Studies in Oceanography*, Volume **50**, Issues12-13, 2331-2347
- Amissah-Arthur A, S. Jagtap, C. Rosenzweig, 2002:** Spatio-Temporal effects of El Niño events on rainfall and maize yield in Kenya. *Int.J. Climatol.*, **22**, 1849-1860 (2002)
- Anyah R.O., and F. H. Semazzi, 2006:** Climate variability over the Greater Horn of Africa based on NCAR AGCM ensemble. *Theor.Appl. Climatol.* **86**, 39 - 62
- Anyamba, E.K., 1984:** Some aspects of the origin of rainfall deficiency in East Africa. *Proc. of the WMO Regional Scientific Conference on GATE, WAMEX and Tropical Meteorology*, Dakar, Senegal, pp.110-112
- Asnani G.C, Kinuthia J. H.1979:** Diurnal variation of precipitation over East Africa. *East African Meteorological Department Research Report No. 8/79*.
- Asnani, G.C., 1993:** *Tropical Meteorology*. Published by Prof. G.C. Asnani, Noble Printers, Pune-India.
- Asnani, G.C., 2005:** *Tropical Meteorology*. Published by Prof. G.C. Asnani, Noble Printers, Pune-India.
- Barnett, T.P., and R. E. Davies, 1975:** Eigenvector analysis and prediction of sea surface temperature fluctuation in the northern Pacific Ocean. *Proc. WMO/IAMAP Symposium on Long-term Climatic fluctuations*, Norwich, England, 439-450

Barnston, A. G., and T. M. Smith, 1996: Specification and prediction of global surface temperature and precipitation from global SST using CCA. *J. Climate*, **9**, 2660 - 2697

Barring, L. 1988: Regionalization of daily rainfall in Kenya by means of common factor analysis. *J. Climatol.* **8**, 371 – 389.

Basalirwa C.P.K, J.O. Odiyo, R.J. Mngodo, E.J. Mpeta, 1999: The climatological regions of Tanzania based on the rainfall characteristics *Int. J. Climatol.* **19**, Issue 1 , Pages 69 – 80.

Beltrando, G., 1990: Space – time variability in April and October-November over East Africa during the period 1932 – 1983. *J. Climatol.*, **10**, 691 – 702.

Bengtsson L, J. Shukla 1988: Integration of Space and In situ Observations to study Global climate change, *Bul. Amer. Met. Soc.*, Vol. **69**, 10, 1130-1143.

Bjerknes, J., L.J. Allison, E.R. Kreins, F.A.Godshall, and G. Warnecke, 1969: Satellite mapping of the Pacific tropical cloudiness. *Bull.Amer. Meteor. Soc.*, **50**, 313-322

Bjerknes J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, **97**, 163 - 172

Bluestein, H.B., 1992: Synoptic-dynamic Meteorology in midlatitudes vol.1, *Oxford University Press* pp 82-152

Cadet , D.L. and B. Diehl, 1984: Interannual variability of the surface field over Indian Ocean during recent decades. *Mon. Wea. Rev.* **112**, 1921-1935

Camberlin, P., 1995: June-September rainfall in north-astern Africa and atmospheric signals over the tropics: A zonal perspective. *Int. J. Climatol.* **15**, 773-783.

Camberlin, P., and J. G. Wairoto, 1997: Intraseasonal wind anomalies related to wet and dry spells during the long and short rainy seasons in Kenya. *Theor. Appl. Climatol.*, **58**, 57-69

Camberlin, P., S. Janicot and I. Poccard, 2001: Seasonality and atmospheric dynamics of teleconnection between African rainfall and tropical sea surface temperature: Atlantic vs ENSO. *Int. J. Geophys. Res.*, **104 (C2)**, 3035-3047

Camberlin, P., and R. E. Okoola, 2003: The onset and cessation of the "Long Rains" in Eastern Africa and their interannual variability. *Theor. and Appl.Climatol.*, **75**, 43 - 54.

Chen, T-C., and R-Y. Tzeng, 1990: Global scale Intra-seasonal and annual variation of divergent water vapour flux. *Meteor. Atmos. Phys.*, **44**, 133-151

Chen, T.C and J-M Chen, 1997: On the relationship between the Streamfunction and velocity Potential of the Madden Jullian Oscillation. *J. Atmos. Sci.* **54** no 5, 679 - 685

Chen M., P. Xie, J. E. Janowiak, and P. A. Arkin, 2002: Global land precipitation: A 50-yr monthly analysis based on gauge observations, *J. Hydrometeo.*, **3**, 249 - 266.

Christina O.C., P.J. Webster and J.E. Cole, 2002: Interdecadal Variability of the Relationship between the Indian Ocean Zonal Mode and East African Coastal Rainfall Anomalies. *J. climate*, **16**, 548-554

Collins, M., S. Tett, and C. Cooper, 2001: The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments. *Climate Dyn.*, **17**, 61-81

Cressman, G.P., 1979. An operational objective analysis system. *Mon. Wea. Rev.* **87**, 367-381.

Dabberdt, W.F., and T.W. Schlatter, 1996: Research opportunities from emerging atmospheric observing and modelling capabilities. *Bull. Amer. Meteor. Soc.*, **77**, 305-323

Das, P.K., 1986: *Monsoons*, Fifth IMO lecture, WMO-No-613, World Meteorological Organisation, **155pp**.

Deser C., M. Alexander and M.S.Timlin, 2003: Understanding the persistence of sea surface temperature anomalies in mid latitudes. *J. Climate* **16**: 58-72

Diab, R.D., 1988: Rainfall producing systems in Natal. *Final Report to FRD*, CSIR, Pretoria, 126pp.

Dilley M. and B.N. Heyman, 2007: Possible influence of ENSO on annual maximum streamflow of the Yangtze River. *J. Hydrolo.* **333**, 265 - 274

Doblas-Reyes, F.J., M.Déqué and J. -P. Pielikevire, 2000: Model and Multi-model spread and probabilistic seasonal forecasts in PROVOST. *Quart. J. Roy. Meteor. Soc.*, **126**, 2069-2088

Doswell, C.A. III, H.E Brooks and R.A Maddox, 1996: Flash flood forecasting: An ingredient based methodology. *Wea. Forecast.*, **11**, 560-581.

Drakeley, C.J., I. Carneiro, H. Reyburn, R. Malima, P.A. John, Lusungu, J. Cox, G. T. Theander, W.M.Nkya, M.M. Lemnge and E.M. Riley, 2005: Altitude-dependent and Indepent variations in Plasmodium falciparum prevalence in Northern Tanzania. *J. Infect. Disea.* **2005**, 1589-98

Drought Impact Assessment: An experience over north eastern highlands and central areas of Tanzania: *Tanzania Meteorological Agency (TMA) bulletin* Issue **no.6**, January - March, 2006

Dunn, P., 1985: An investigation into tropical cyclones in the SW Indian Ocean, Flood studies. *Tech. Note 1, Dept. Water affairs, Pretoria, South Africa*. 33pp.

Dyer, T.G.J., 1977: The assignment of rainfall stations into homogeneous groups: An application of principal component analysis. *Quart. J. Roy. Meteor. Soc.*, **101**, 1005-1013

Eliassen, A., 1949: The quasi-static equations of motion with pressure as independent variable. *Geophys. Publ.* **17**, No.3, 44pp

Emery, W.J., and R. E. Thomson, 1998: Data Analysis Methods in Physical Oceanography. *Pergamo, Oxford*, 500pp

Findlater, J., 1969: A major low-level air current near the Indian Ocean during the Northern summer. *Quart. J. Roy. Meteor. Soc.*, **95**, 362-380

Findlater, J., 1971: Mean monthly airflow at low levels over the western Indian Ocean. *Geophys. Mem.*, **115**, H.M.S.O., London, 53pp

Folland, C.K., J.A. Owen, M.N.Ward, and A.W. Colman, 1991: Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods. *J. Forecasting*, **10**, 21-56.

Frederiksen, C.S., H. Zhang, R.C. Balgovind, N. Nicholls, W. Drosowsky, and L. Chambers, 2001. Dynamical seasonal forecasts during the 1997/98 ENSO using persisted SST anomalies. *J. Climate*, **14**, 2675-2695.

Freedman D., R. Pisani , R. Purves , 1978: Statistics. Published by George J. Mcleod Limited, Toronto Canada., pp 409-415

Gadgil, S., and A. Guruprasad, 1990: An objective method for the identification of the ITCZ. *J. climatol.* **3**, 558-567

Gates, W.L. 1992, AMIP: The atmospheric model Intercomparison Project. *Bulletin of the American meteorological Society*, **73** no.12, 1962 - 1970

Gill, A. E., 1982: Atmosphere-Ocean Dynamics. Academic Press, New York.

Giorgi, F., and G.T. Bates, 1989: The climatological skill of a regional model over complex terrain. *Mon. Wea. Rev.* **117**, 2325-2347

Giorgi, F., and M.R. Marinucci, 1991: Validation of regional atmospheric model over Europe : Sensitivity of wintertime and summertime simulations to selected physics parameterizations and lower boundary conditions. *Quart. J. Roy. Meteor. Soc.* **117**, 1171-1206

Giorgi, F., and L.O. Mearns, 1991: Approaches to the simulation of regional climate change: A review. *Rev. Geophys.* **29**, 2, 191-216

Giorgi, F., and M.R. Marinucci, and G.T Bates, 1993a: Development of second-generation regional climate model (RegCM2). Part I: Boundary-layer and radiative transfer processes. *Mon. Wea. Rev.* **121**, 2794-2813.

Giorgi, F., and M.R. Marinucci, and G.T Bates, 1993b: Development of second-generation regional climate model (RegCM2). Part II: Convective processes and assimilation of lateral boundary conditions. *Mon. Wea. Rev.* **121**, 2814-2832

Giorgi F., and M.R. Marinucci, 1996: An investigation of the sensitivity of simulated precipitation to model resolution and its implications for climate studies. *Mon. Wea. Rev.* **124**, 148-166

Goddard L, N.E.Graham, 1999: Importance of the Indian Ocean for simulating rainfall anomalies over eastern and southern Africa. *J. Geophys. Res.*, **104**, D16, 19099-19116.

Graham, R.J., A.D.L Evans, K.R. Mylne, M.S.J. Harrison and K.B. Robertson, 2000: An assessment of seasonal predictability using atmospheric general circulation models. *Quart. J. Roy. Meteor. Soc.*, **126**, 2211- 2240

Grell, G.A., 1993: Prognostic evaluation of assumptions used by cumulus parameterizations. *Mon. Weather. Rev.* **121**, 764-787.

Hansingo, K. and C.J.C Reason, 2006: Sensitivity of the atmospheric response to sea-surface temperature forcing in the South West Indian Ocean: a regional climate modeling study. *South African J. Sci.* **102**: 137 – 143.

Hachigonta, S. and C.J.C. Reason, 2006: Interannual variability in dry and wet spell characteristics over Zambia. *Climate Res.*, **32**, 49 – 62

Hastenrath, S., A. Nicklis, L. Greischar, 1993: Atmospheric hydrospheric mechanisms of climate anomalies in the western equatorial Indian Ocean. *J Geophys. Res* **98** (C 11), 20219-20235

Hastenrath S, D. Polzin, C. Mutai, 2007: Diagnosing the 2005 Drought in Equatorial East Africa. *J. Climate* 20(18): 4628-4637

Heddinghaus, T.R., and A. F. Krueger, 1981: Annual and interannual variations of outgoing longwave radiation over the tropics. *Mon. Wea. Rev.*, **109**, 1208-1218

- Henderson- Sellers A. and K. McGuffie, 2005:** A climate Modelling Primer third edition.
- Hewitson, B.C., 1999:** Deriving Regional Precipitation Scenarios from General Circulation Models. *Water Research Commission Reports*, **751/1/99**
- Hewitson, B.C. and R.G. Crane, 1996:** Climate downscaling: techniques and application. *Climate res.*, **7**, 85-95.
- Hills, R. 1979.** The structure of the Inter-Tropical Convergence zone in the Equatorial African rainfall. *Transaction of the Institute of British geographers*. **4**, 329-352
- Hong, S.-Y., and H.-L. Pan, 1996:** Non local boundary layer vertical diffusion in a medium-range forecast model. *Mon. Wea. Rev.*, **124**, 2322-2339
- Hsie, E.Y., R. A. Anthes and D. Keyser, 1984:** Numerical simulation of frontogenesis in a moist atmosphere. *J. Atmos. Sci.*, **41**, 2581-2594.
- Hudson, D.A. 1998:** Antarctic sea-ice Extent, Southern Hemisphere Circulation and South African Rainfall. *PhD thesis, University of Cape Town, South Africa.*
- Huffman G.J., R.F. Adler, M. Morrissey, D.T Bolvin, S. Curtis, R. Joyce, B. McGavock, J. Susskind, 2001:** Global Precipitation at one-Degree Daily Resolution from multi Satellite observations. *J. Hydrometeor.*, **2**, 36-50
- Indeje, M., and E.K. Anyamba, 1998:** Sensitivity of mesoscale systems over Kenya to changes in roughness length. *J. African Met. Soc.* **3**, 19-33
- Indeje M., F.H.M. Semazzi, and L. J. Ogallo, 2000:** ENSO signals in East African rainfall seasons. *Int. J. Climatol.*, **20**, 19-46
- Indeje M., F.H.M. Semazzi, L. Xie and L. J. Ogallo, 2001:** Mechanistic Model Simulations of the East African Climate using NCAR Regional Climate Model: Influence of larger-scale Orography on the Turkana Low-level Jet. *J. climate* **14**, issue 12, 2710 - 2724
- Indeje M. 2000:** Prediction and Numerical simulation of the regional climate of equatorial Eastern Africa. *PhD thesis*, North Carolina state University.
- Ininda J.M. 1987:** Spatial and temporal characteristics of drought in Eastern and Southern Africa. MSc Thesis, University of Nairobi.
- Intergovernmental Panel on Climate Change (IPCC), 1995:** World Meteorological Office, United Nations Environmental Programme, Radiative Forcing of climate change. *The 1994 Report of Scientific Assessment Working Group of IPCC. Summary for Policymakers.*

- Jackson, I. J. 1977:** Climate, Water and Agriculture in the Tropics. *Longman*, 249pp
- Janowiak, J.E., 1988:** An investigation of interannual rainfall variability in Africa. *J. Climatol.*, **1**, 240-255
- Johnson D.H., and H.T. Morth, 1961:** Forecasting research in East Africa, in Tropical Meteorology in Africa. Edited by D.J. Bargman, pp 56-137, Munitatalp, Nairobi, 1960.
- Johnston, R. J., 1992:** Multivariate Statistical Analysis in Geography. Longman Scientific Technical. *John Wiley and Sons, Inc.* New York, 280pp
- Ji M., A. Kumar and A. Leetmaa, 1994:** A Multiseason Climate Forecast System at the National Meteorological Center. *Bull. Amer. Meteor. Soc.*, **75**, no 4, 569 - 577
- Jury, M.R., and B. Pathack, 1991:** A study of climate and weather variability over the tropical southwest Indian Ocean . *Meteorol. Atmos. Phys.*, **47**, 37-48
- Jury, M.R., and B. Pathack, 1992:** Climatic patterns associated with the 1992 drought over southern Africa : Observations and GCM results. *Proc. 1st conf. African Met. Soc., Nairobi, Kenya*.
- Jury, M.R., 1993:** A preliminary study of climatological associations and characteristics of tropical cyclones in SW Indian Ocean. *Meteor. Atmos. Phys.*, **51**, 101-115
- Jury, M. R. 1996:** Regional teleconnection patterns associated with summer rainfall over South Africa, Namibia and Zambabwe. *Int. J. Climatol.* **16**, 135 – 153.
- Kabanda T. A. 1995.** Seasonal and intraseasonal dynamics and precursors of rainfall over northern Tanzania. *Msc thesis University of Cape Town*.
- Kabanda T. A, and M.R. Jury, 1999.** Inter-annual variability of short rains over northern Tanzania, *Climate Res.* , Vol.**13**, 231-241
- Kaiser, H.F., 1959:** Computer program for varimax rotation in factors analysis. *Educ. Psychol. Meas.* **19**, 413-420
- Kalnay E, M. Kanamitsu, R. Kistler, W.Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, Roy Jenne and D. Joseph, 1996:** The NCEP/NCAR 40-year Reanalysis Project, *Bull. Amer. Meteor. Soc.*, **77**, 437-471.
- Kanamitsu M., W. Ebisuzaki., J. Woollen, S. Yang, J. Hnilo, M. Fiorino, and G. Potter, 2002:** NCEP–DOE AMIP-II Reanalysis (R-2), *Bull. Amer. Meteor. Soc.*, **83**, 1631 - 1643

Kapala A, K. Born , H. Flohn, 1994: Monsoon anomaly or an El Niño event in the Equatorial Indian Ocean? Catastrophic rains 1961/62 in East Africa and their teleconnections. *WMO/TD 619*: 119-126

Kasahara, A. 1966: The dynamical influence of orography on the large-scale motion of the atmosphere. *J. Atmos. Sci.* **23**, 259-270

Kharin V.V and F.W. Zwiers , 2003: Improved seasonal probability forecasts. *J. Climate* vol **16**, No. **11**, 1684-1701

Kharin V.V and F.W. Zwiers , 2002: Climate Predictions with Multimodel Ensembles. *J. Climate* Vol.**15**, No.**7**, 793-799

Kharin V.V., F.W. Zwiers and N. Gagnon., 2001: skill of seasonal hindcasts as a function of the ensemble size. *Climate Dyn.*, **17**, 835-843.

Kida, H., T. Koide, H. Sasaki, and M.Chiba, 1991: A new approach for coupling a limited area model to a GCM for regional climate simulations. *J. Meteor. Soc. Japan.* **69**, No. **6**, 723-728

Kijazi A.L., 2003: Teleconnections between seasonal rainfall in coastal Tanzania and ENSO. *MSc thesis*, University of Cape Town; South Africa.

Kijazi A. L. and C.J.C. Reason, 2005: Relationships between intraseasonal rainfall variability of coastal Tanzania and ENSO. *Theor. Appl. Climatol.* **82**, 153 - 176

Kiehl, J.T., and B.P. Briegleb, 1993: The relative roles of surface aerosols and greenhouse gases in climate forcing. *Science*, **260**, 311-314

Kiker, G.A., 2000: South African Study on Climate Change: Synthesis report for the vulnerability and adaptation assessment section- Draft report for the Department of Environmental Affairs and Tourism, South Africa.

Kiladiz G. N and H. F. Diaz, 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. *J. climate*, **2**, 1069-1090.

Koteswarran, P., 1958: The easterly jetstreams in the tropics. *Tellus.* **10**, 43-57

Kreft, J., 1972: Composition of Rhodesian (Zimbabwean) rainfall. Meteorological series A. no. 34, Department of Meteorological services, Harare, Zimbabwe.

Krishnamurti, T.N., C.M Kishtawal, Z. Zhang, T.E. LaRow, D.R. Bachiochi, C.E. Willifor, S.Gadgil and S. Surendran, 2000: Multimodel ensemble forecasts for weather and seasonal climate. *J. Climate* **13**, 4196-4216.

- Krishnamurti, T.N., 1961:** The subtropical jet-stream of winter. *J. Meteor.* **18**, 172-191
- Krishnamurti, T.N., M. Kanamitsu, W.J. Koss, and J .D. Lee, 1973:** Tropical east-west circulations during the northern winter. *J. Atmos. Sci.*, **30**, 780 - 787
- Krishnamurti, T.N., J. Xue, H.S. Bedi, K. Ingles and D. Oosterhof, 1991:** Physical initialization for numerical weather prediction over the Tropics. *Tellus*, **43AB**, 53-81.
- Krishnamurti, T.N., J. Molinari, and H.L. Pan, 1976:** Numerical simulation of the Somali jet. *J. Atmos. Sci.* **33**, 2350-2362
- Krishnamurti, T.N., R.J. Pasch and P. Ardanuy, 1980:** Prediction of African waves and specification of squall lines. *Tellus*. **32**, 215-231
- Kumar, S., 1978:** Interaction of upper westerly waves with the ITCZ and their effect on the weather over Zambia during the rain season. *Govt.Printer, Lusaka, Zambia*.
- Kutzbach, J.E., 1967:** Empirical eigenvectors of sea level pressure, surface temperature and precipitation complexes over North America. *J. Appl. Meteor.* **6**, 791-802
- Landman, W.A and S.J. Mason, 1999:** Change in the association between Indian Ocean sea-surface temperatures and summer and summer rainfall over South Africa and Namibia. *Int. J. Climatol.*, **19**, 1477-1492.
- Latif, M., D. Dommenges, M. Dima and A. Grötzner, 1999:** The role of Indian Ocean sea surface temperature in forcing East African rainfall anomalies during December – January 1997/98. *J. Climate* **12**, 3497 - 3504
- Latif M. and co-authors (2001):** ENSIP: The El Niño Simulation Intercomparison Project. *Climate Dyn.*, **18**, 255-276.
- Lau, K. –M. and H. –Y. Weng, 1995:** Climate signal detection using wavelet transform: How to make a time series sing. *Bull. Amer. Meteor. Soc.*, **76** (12), 61-78
- Leonard M. Druyan and Matthew Fulakeza, 2002:** Dynamic Downscaling of seasonal climate predictions over Brazil. *J. Climate*, **23**. 3411-3426
- Levey K. M, 1993:** Intra-seasonal oscillations of convection over Southern Africa. *MSc. Thesis*, University of Cape town.
- Levey, K.M., and M.R. Jury, 1996:** Composite Intraseasonal oscillations of convection over Southern Africa. *J. climate* **9** no 8, 1910 - 1920

Liebmann, B., and D.L. Hartmann, 1982: Interannual variations of outgoing IR associated with tropical circulation changes during 1974-78. *J. Atmos. Sci.*, **39**, 1153-1162

Linthicum K. J., C.L. Bailey, C.J. Tucker, K.D. Mitchell, T.M. Logan, F.G. Davis, C.W. Kamau, P.C. Thande, and J.N. Wagateh, 1990: Application of polar-orbiting, meteorological satellite data to detect flooding of Rift Valley Fever virus vector mosquito habitats in Kenya. *Med. Vet. Entomol.* **4**: 433-438.

Liu, Y., F.Giorgi, and W.M. Washington, 1994: Simulations of summer monsoon climate over East Asia with an NCAR regional climate model. *Mon. Wea. Rev.* **122**, 2331-2348

Livezey, R.E. and A.G. Barnston, 1988: Operational multifield analog prediction system for United States seasonal temperature. Part 1: System design and winter experiments. *J. Geophys. Res.* **93**, 10953 - 10974

Lorenz, E.N., 1982: Atmospheric predictability with a larger numerical model. *Tellus*, **34**, 505-513

Loschinigg J., G.A. Meehl, P.J. Webster, J.M. Arblaster, G.P.Compo, 2003: The Asian Monsoon, the Tropospheric Biennial Oscillation and the Indian Ocean Zonal Mode in the NCAR CSM. *J. Climate*, **16**, no 11, 1617 – 1642.

McPhaden, M.J., G. Meyers, K. Ando,Y. Masumoto, V.S.N. Murty, M. Ravichandran, F. Syamsudin, J. Vialard, L. Yu, and W. Yu, 2009: RAMA: The Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. *Bull. Amer. Meteor. Soc.*, Vol **90**, issue **4**, pp. 459–480

Madden R. A., and P.R. Julian, 1971: Detection of a 40 – 50 day oscillation circulation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702 - 708

Madden R. A., and P.R. Julian, 1972: Description of global- scale circulation cell in the tropics with a 40 – 50 day period. *J. Atmos. Sci.*, **29**, 1109 - 1123

Makarau A. 1994: Intra-seasonal oscillatory modes of the Southern Africa summer circulations. PhD. Thesis, University of Cape Town.

Mapande A.T. and C.J.C Reason 2005: Links between rainfall variability on intraseasonal and interannual scales over western Tanzania and regional circulation and SST patterns. *Meteorol Atmos Phys* **89**, 215-234

Mason, S.J., J.A Lindsay, and P.D. Tyson, 1994: Simulating drought in the southern Africa using ses-surface temperature variations. *Water SA.* **20**, 15-22

Matarira C. H., M.R. Jury, 1992: Contrasting Meteorological structure of Intra seasonal wet and dry spells in Zimbabwe. *Int. J. of Climatol.*, **12**, 165-176

Matarira, C.H., 1990a: Drought over Zimbabwe in a regional and global context. *Int. J. Climatol.*, **10**, 609-625.

Matarira, C.H., 1990b: Frequency and tracks of anticyclones and their effect on rainfall patterns over Zimbabwe. *Theor. Appl. Climatol.*, **42**, 53-66

McCarthy, J.J., O.F.Canzian, N.A. Leary, D.J. Dokken and K.S. White, Eds, 2001: *Climate change 2001: Impacts, Adaptation and Vulnerability*. Intergovernmental Pannel on Climate change, Cambridge University Press, 1032pp.

Mhita, M.S., 1990: The analysis of rainfall Data for agriculture in Tanzania. TMRP Research Report No.2/90: Directorate of Meteorology Tanzania

Mhita, M.S and A. Venäläinen, 1992: The variability of rainfall in Tanzania. FINNIDA/SATCC/WMO– meteorology project Helsinki. Finnish Meteorological Institute.

Minja, W.S.M., 1982: The weather anomalies during Northern Summers of 1972 and 1978 over Africa. Tech. Conf. on Climate of Africa, Arusha Tanzania, 195-208pp

Morlet, J., 1983: *Sampling theory and wave propagation*. NATO ASI series, Fi, Springer, 233 -261

Mpeta E. J. 1997: Intra-seasonal convection dynamics over southwest and northeast Tanzania: An observational study. MSc thesis, University of Cape Town.

Mukabana J. R and R.A Pielke, 1991: Numerical simulation of the effects of monsoon winds on the weather patterns over Kenya: A case study during the 'long rains 'season. *9th Conference on Numerical Weather Prediction*. October 14-18, 1991, American Meteorological Society, Denver, CO.

Mukabana, J.R. and R.A. Pielke, 1996: Investigating the influence of synoptic-scale monsoonal winds and mesoscale circulations and diurnal weather patterns over Kenya using a mesoscale numerical model. *Mon. Wea. Rev.* **124**. 224-243

Mulenga H.M. 1999: Southern Africa Climatic anomaly, Summer rainfall and the Angola low. PhD thesis University of Cape Town 232pp

Mulenga , H. M., M. Rouault and C. J. C. Reason, 2003: Dry summers over northeastern South Africa and associated circulation anomalies. *Climate Res.*, **25**, 29-41

- Murphy, A. H and E.S Epstein, 1989:** Skill scores and correlation coefficients in model verification. *Mon. Wea. Rev.* **117**, 572-581
- Mutai, C. C., M.N. Ward and A.W Coleman, 1998:** Towards the prediction of the East Africa short rains based on sea-surface temperature-atmosphere coupling. *Int. J. Climatol.* **18**, 975-997
- Mutoni, E.J. 2001:** Seasonal rainfall outlook for Tanzania. *Tanzania Meteorological Agency research report*, September, 2001.
- Nakamura K., 1968:** Equatorial westerlies over East Africa and their climatological significance. *Jpn. Prog. Climatol.* **29**, 9-27
- Nassor, A., 1994:** Monsoon surges, tropical cyclones and extreme rainfall in NW Madagascar. MSc thesis, University of Cape Town, 183pp.
- Neelin, J.D. and L.M. Held 1987a:** Modelling tropical convergence based on the moist static energy budget. *Mon. Wea. Rev.*, **115**, 3-12
- Newell R.E, J.W. Kidson, D.G.Vincent and G.J. Boer, 1972:** The general circulation of tropical atmosphere and interaction with extra tropical latitudes. **Vol 1**, MIT press, Cambridge, MA, 256pp
- Nicholson, S.E., and R.M. Chervin, 1983:** Recent rainfall fluctuations in Africa-interhemispheric teleconnections. Variations in the global water budget, street parrot et al, EDS., Reidel, 221-238.
- Nicholson, S.E., 1986:** The nature of rainfall variability in Africa south of the equator. *J. climatol.*, **6**, 515-530
- Nicholson S.E, D. Entekhabi, 1986:** The quasi periodic behavior of rainfall variability in Africa and its relationship to the Southern Oscillation. *Archiv für Meteorologie, Geophysik und Bioklimatologie* **A34**, 311 - 348
- Nicholson S.E, D. Entekhabi 1987:** Rainfall variability in equatorial and southern Africa: relationships with sea surface temperatures along the southwestern coast of Africa. *J. Clim. Appl. Meteorol.* **26**, 561-578
- Nicholson, S.E. and B.S. Nyenzi, 1990:** Temporal and spatial variability of SSTs in the tropical Atlantic and Indian Oceans. *Meteorol. Atmos. Phys.*, **42**, 1-17
- Nicholson, S.E. 1996:** A review of Climate Dynamics and Climate Variability in Eastern Africa. The Limnology, Climatology and Paleoclimatology of the East African Lakes. *Gordon and Breach*, New York, 57pp.
- Nicholson S.E, Kim J. 1997:** The relationship of the El Nino-Southern Oscillation to African Rainfall. *Int. J. Climatol*, **17**, 117-135

Nieuwolt, S., 1978: Rainfall and drought frequencies in East Africa, *Erkunde* **32**: 81-88

North G.R., T.L.Bell and R.F.Cahalan, 1982: Sampling errors in estimation of empirical orthogonal functions. *Bull. Amer. Meteor. Soc* **110**, 699-706

Ntale, H.K., T. Y. Gan and D. Mwale, 2003: Prediction of East African Seasonal Rainfall Using Simplex Canonical Correlation Analysis. *J. Climate*, **16**, 2105–2112.

Nyenzi B. S. 1984: equatorial zonally moving disturbances which contribute to East African long rains March to May 1979, Msc. Thesis, Florida state University 73pp.

Nyenzi, B.S., 1992: El Niño/Southern Oscillation (ENSO) Fluctuations and its influence to Southern Africa Climate. Proceedings of First SADC Conference on Climate Change, Windhoek, Namibia, March 2-6, 1992.

Ogallo L. J., 1983: Quasi-periodic patterns in East African rainfall records. *Kenya J. Sci. and Techn.* **A3**, pp. 43-54

Ogallo L.J, 1984: Temporal Fluctuations of Seasonal Rainfall Patterns in East Africa , *Mausam* , Vol. **35**, No. **2**, pp 175-180

Ogallo L.J, I.R. Nassib, 1984: drought patterns and famines in East Africa during 1922-1983. The second WMO symposium on meteorological aspects of Tropical droughts. *Fu.* 1984, 41-44

Ogallo, L.J., Janowiak, J.E. and Halpert, M.S., 1988: Teleconnections between seasonal rainfall over East Africa and Global Sea surface temperature anomalies. *J. Met. Soc. Jpn.* **66**, 807-822

Ogallo L.J. 1988: Relationship between seasonal rainfall in East Africa and Southern Oscillation. *J.Climatol*, **8**, 34-43.

Ogallo L.J. 1989: The spatial and temporal patterns of the East African seasonal rainfall derived from principal component analysis. *Int. J. Climatol.* , **9**, 145-167

Ogallo L.J. , R. E. Okoola and D. N. Wanjohi, 1994: Characteristics of quasi-Biennial Oscillation over Kenya and their predictability potential for seasonal rainfall. *Mausam*, **45**, No. 1, 57 – 62.

Ogallo, L.J., and P. G. Ambenje, 1996: Monitoring Drought in Eastern Africa. WMO/TD NO.753.

Okeyo, A. E. 1986: The influence of Lake Victoria on the convective systems over the Kenya highlands. Proc. International conference on short, medium range weather forecasting. Tokyo, Japan, August 1986.

Okoola, R.E., 1999: A diagnostic study of the eastern Africa monsoon circulation during the Northern Hemisphere spring season. *Int. J. Climatol.* **19**, 143-168

Okoola R.E., P. Camberlin and J. M. Ininda, 2008: Wet periods along the East Africa Coast and the extreme wet spell event of October 1997. *Journal of the Kenya Meteorological Society*, 2008, **2**, 1, p. 67-83

Padya, B.M., 1989: Weather and climate of Mauritius. *Mauritius: M. Ghandi Institute*. 283pp

Pan, Z., J. Christensen, R.W. Arritt, W.Gutowski, E.S. Takle, F. Otieno, 2001: Evaluation of uncertainties in regional climate change simulations. *J.Geophys Res-Atmos* **106**: 17735-17751.

Park, C. and S.D. Schubert, 1993: Remotely forced intraseasonal oscillations over the tropical Atlantic, *Journal of Atmospheric Science*, **Vol. 1**, 89-103.

Parker D.E, 1994: Maximum and minimum temperatures: a backward and a forward look. *Atmos. Res.* **37**, 3-9

Patwardhan, S.K., and G.C. Asnani, 1999: Meso-scale distribution of summer monsoon rainfall near the Western Ghats (India). *Int. J. Climatol.* **20**, 575-581.

Patz J. A, S. Lindsay, 1999: New challenges, new tools: the impact of climate change on infectious diseases. *Curr. Opin. Microbiol.* **2**(4):445–451.

Patz, J.A., 2002: A human disease indicator for the effects of recent global climate change, *Proc. National Academy of Science. USA*, **99**, No. 20, 12506 – 12508

Philippon N., P. Camberlin and N. Fauchereau, 2002: Empirical predictability study of October-December East African rainfall, *Quart. J. Roy. Meteor. Soc.*, **128**, 2239-2256.

Pope, V., M. Gallani, P. Rowntree, and R.Stratton, 2000: The impact of new physical parameterization in the Hadley centre climate model HadAM3. *Climate Dyn.*, **16**, 123-143

Preisendorfer, R.W. and Mobley, C.D., 1988: Principal component analysis in meteorology and oceanography. Elsevier Science Publishers, New York USA 455pp

Preston-Whyte, R.A. and Tyson, P.D., 1993: The Atmosphere and Weather of Southern Africa. *Oxford University Press*, Cape Town, pp375.

Quan X. W., P.J. Webster, A.M. Moore and H.R. Chang, 2004: Seasonality in SST-forced atmospheric short-term climate predictability. *J. Climate* **17**, 3090 - 3108

Rasmusson E. M, T .H. Carpenter 1982: Variations in tropical sea surface temperature and surface wind fields associated with Southern Oscillation/ El Nino. *Mon. Wea. Rev.*, **110**, 354-384

Reason, C.J.C., R.J. Allan, J.A. Lindesay and G.C.R. Spenning, 1997: Mechanism associated with low frequency climate variability in the south Indian Ocean region, Fifth International Conference on southern hemisphere Meteorology and Oceanography, *American Meteorological Society*, 7-11 April, 1997, Pretoria, South Africa, 3-4.

Reason C.J.C and H. Mulenga, 1999: Relationship between South African rainfall and SST anomalies in the southwest Indian Ocean. *Int. J. Climatol.* **19**, 1651 - 1673

Reason C.J.C, R.J. Allan, J.A. Lindesay, and T.A. Ansell 2000: ENSO and Climatic signals across the Indian Ocean basin in the global context. *Int. J. Climatol.*, **20**, 1285-1327

Reason C.J.C, Keibel A, 2004: Tropical cyclone Eline and its unusual penetration and impacts over the southern African mainland. *Wea. Forecast.* **19**: 789-805

Reason C.J.C, D. Jagadheesha, 2005: A model investigation of recent ENSO impacts over southern Africa, *Meteorology and Atmospheric Physics* **89**, 181-205.

Reiter, P. 2001: Climate change and Mosquito-Borne Disease. *Environmental Health Perspectives* **109(1)**, February.

Reverdin, G., D. L. Cadet and Gutzler, D., 1986: Interannual displacements of convection and surface circulation over the equatorial Indian Ocean. *Quart. J. Roy. Meteor. Soc.*, **112**, 46-67

Richman, M.D., 1981: Obliquely rotated principal components. An improved meteorological map typing technique. *J. Appl. Met.* **20**, 1145-1159

Richman, J.G., C. Wunsch and N.G. Hogg, 1977: Space and time scales and meso-scale motion in the sea. *Rev. Geophys. Space Phys.*, **15**, 385 – 420.

Riehl, H., 1979: Climate and Weather in Tropics. Academic press, London, 611pp

Rocha, A., and I.T. Simmonds, 1997: Interannual variability of southeastern Africa summer rainfall. Part I: relationships with air-sea interaction processes. *Int. J. Climatol.* **17**, 235-266

Rodhe H, Virji H, 1976: Trends and periodicities in East African rainfall data. *Mon. Wea. Rev.***104:** 307-315

Rodwell, M., and C. Folland, 2002: Atlantic air-sea interaction and seasonal predictability. *Quart. J. Roy. Meteor. Soc.*, **128**, 1413-1443

Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dümenil, L., Esch, M., Giorgetta, M., Schelese, U. and Schulzweida, U. 1996: The atmospheric general circulation model ECHAM – 4: model description and simulation of present – day climate *Max – Planck Institute for Meteorology*, Report No. **218**, Hamburg, Germany, 90pp

Romero, R., C.A. Doswell III, and C.Ramis, 2000: Mesoscale numerical study of two cases of long-lived quasi-stationary convective systems over eastern Spain. *Mon. Wea. Rev.*, **128**, 3731-3751.

Ropelewski C. F, M.S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation, *Mon. Wea. Rev.*,**115**,1606-1626.

Rosen, R. D., and D. A . Salstein, 1983: Variation in atmospheric angular momentum on global and regional scales and length of day. *J. Geophys. Res.*, **88**, 5451 - 5470

Rowell, D.P., C.K. Folland, K. Maskell, J.A. Owen, and M.N. Ward, 1994: Causes and predictability of Sahel rainfall variability. Climate Research Technical Note No. 12, Hadley Center, Bracknell, 15pp

Rowell D.P, 1998: Assessing Potential Seasonal Predictability with an ensemble of Multidecadal GCM simulations. *J. Climate* **11** no. **2**, 109 - 120

Rui H, Wang B. 1990: Development characteristics and dynamic structure of tropical intra seasonal convection anomalies. *J. Atmos. Sci.*, **47**, 357-379.

Saha, K. R, 1974: Zonal anomaly of sea-surface temperature in equatorial Indian Ocean and its possible effect upon monsoon circulation. *Tellus.* **22**, 403-409

Saji N. H, B.N. Goswami, P.N. Vinayachandran and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature.* **401**, 360-363

Semazzi H.F.M., 1980: Stationary barotropic flow induced by a mountain over a tropical belt. *Mon. Wea. Rev.* **108**, 922-930

Semazzi H.F.M, N.H. Lin, Y.L. Lin and F. Giorgi, 1993: A GCM nested model study of the influence of sea surface temperature anomalies on Sahelian Climate, *Geophys. Res. Lett.*, **20**, 2897-2900

Semazzi H.F.M, B. Burns N.H. Lin and J.E Shem, 1996: A GCM study of the teleconnections between the continental climate of Africa and global sea-surface temperature anomalies. *J. Climate*, **9**, 2480-2497.

Semazzi H.F.M and L. Sun, 1997: The role of orography in determining the Sahelian climate. *Int. J. Climatol.* **17**, 581-596.

Semazzi H.F.M. and M. Indeje, 1999: Inter-seasonal variability of ENSO rainfall signal over Africa. *J. Afr. Meteorol. Soc.* **4**, 81-94

Servranckx R. , Gagnon N, Lefaivre L., and Plante A., 1999: Environment Canada Seasonal forecasts: products, methods, procedures and verification. *Canadian Meteorological Centre*, Dorval, Québec

Sharon, D (1981): The distribution in space of local rainfall in the Namib Desert. *J. Climatol.*, **1**, 69-75

Shukla, J., 1974: Effects of Arabian Sea-Surface Temperature Anomaly on Indian Summer Monsoon. A numerical study with the GFDL Model. *J. Atmos. Sci.* **32**, 501-511

Shukla, J. and B.M. Misra, 1977: Relationships between Sea-Surface Temperature and windspeed over central Arabia and monsoon rainfall over India. *Mon. Wea. Rev.* **105**, 998-1002

Shukla, J., 1998: Predictability in the midst of chaos: A scientific basis for climate forecasting. *Science*, **282**, 728-731

Stoeckenius T., 1981: Interannual variations of tropical precipitation patterns. *Mon. Weather Rev.*, **109**, 1233-1247

Storch, H.V., and F.W.Zwiers, 1999: Statistical analysis in climate research. The press Syndicate of the University of Cambridge. UK. 400pp

Sud, Y.C and W.E.Smith, 1984: Ensemble formation of surface fluxes and improvement in evapotranspiration and cloud parameterization in a GCM. *Bound Layer Meteor.* **29**, 185-210

Sun, L., F.H.M.Semazzi, F. Giorgi, and L.J.Ogallo 1999a: Application of the NCAR Regional climate model to Eastern Africa. Part I. Simulations of Autumn Rains of 1988. *J. Geophys. Res.* **104**, No. D6, 6529-6548

Sun, L., F.H.M.Semazzi, F. Giorgi, and L.J.Ogallo 1999b: Application of the NCAR Regional climate model to Eastern Africa. Part II. Simulations of Interannual Variability. *J. Geophys. Res.* **104**, No. D6, 6549-6562

Taljaard, J.J., 1986a: Change in rainfall distribution and circulation patterns over southern Africa in summer. *J. Climatol.*, **6**, 579 -592

Taljaard, J.J., 1986b: Contrasting atmospheric circulation during dry and wet summers in south. *S. Afr. Wea. Bureau Newsletter*, **445**, 1 - 5

Tennant, W. J., 2004: Considerations when using pre-1979 NCEP/NCAR re-analyses in the Southern Hemisphere. *Geophysical Research Letters*, **31**, L11112, doi: 10.1029/2004GL019751

Thiaw, W., A.G. Barnston and V. Kumar,1999: Predictions of African rainfall on the seasonal timescale, *J. Geophys Res.*, **104**, D24, 31589-31597.

Torrance, J. D., 1981: Climate Handbook of Zimbabwe. *Zimbabwe Met. Services Harare, Zimbabwe*. 222pp

Torrence, C. and G. P Compo, 1998: A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society*, **79 (1)**, 61-78

Trenberth, K.E., 1974: A quasi-biennial standing wave in the southern hemisphere and inter-relations with sea surface temperature. *Quart. J. Roy. Meteor.Soc.*, **101**, 55-74.

Trenberth, K.E., 1997: The definition of El Niño. *Bull. Amer. Meteor. Soc.* **78**, 2771-2777

Trenberth, K.E., 1998: Forecasts of the development of the 1997-98 El Niño events. *Clivar Scientific Issues*. Based in part on presentations made at the Seventh session of the CLIVAR SSG in Santiago, Chile (**April 1998**).

Trenberth, K.E. and C. J. Guillemont, 1998: Evaluation of the atmospheric moisture and hydrological cycle in the NCEP/NCAR re-analyses. *Climate Dyn.*, **14**, 213-231

Tyson, P.D., 1986: Climate Change and variability in southern Africa. *Oxford University Press*, Cape Town, 220pp

Usman, M. and Reason, C.J.C. 2004: Dry spell frequencies and their variability over southern Africa. *Climate Res.*, **26**: 199 - 211

Vincent, D., T.Sperling, A. Fink, S. Zube, and P. Speth, 1991: Intraseasonal Oscillation of convective activity in the tropical Southern Hemisphere: May 1984-April 1986. *J. Climate*, **4**, 40-53

Vitart F. J.L. Anderson, W.F.Stern, 1997: Simulation of Interannual Variability of Tropical Storm Frequency in an Ensemble of GCM Intergrations. *J. Climate* **10** no **4**, 745 - 760

Wagner R.G. and A.M. DA Silva, 1994: Surface conditions associated with the anomalous rainfall in the Guinea Coastal region. *Int. J. Climatol.* **14**, 179-199

Walker, G.T, E.W. Bliss 1932: World weather V.*mem.Roy.Met.Soc.*, **4**, 53-84.

Walker, G.T, E.W. Bliss 1937: World weather V1. *mem.Roy.Met.Soc.*, **4**, 119-139.

Ward M.N., C.K. Folland, K. Maskell, A.W. Colman, D.P. Rowell, and K.P. Lane, 1993: Experimental seasonal forecasting of tropical rainfall at the UK Meteorological Office. In *prediction of interannual variations*, volume **16**, pp 197-216. NATO, Springer-Verlag.

Weare, B.C., A.R. Navato and R.E.Newell, 1975: Empirical orthogonal analysis of Pacific sea surface temperatures. *Proc. WMO/IAMAP Symposium on long-term Climatic fluctuations*, Norwich, England, pp 167-174

Webster, P.J., A.M. Moore, J. P. Loschnigg and R. R. Leben, 1999: Coupled ocean-atmosphere dynamics of the Indian Ocean during 1997-98. *Nature*. **401**, 356-360

Weickmann, K. M., G. R. Lussky, and J . E. Kutzbach, 1985: Intraseasonal (30 – 60) fluctuations of outgoing longwave radiation and 250 mb streamfuction during northern winter. *Mon. Wea. Rev.*, **113**, 941 - 960

Wilby, R. L., T. M. L. Wigley, D.Conway, P.D. Jones, B.C.Hewitson, J. Main, D.S.Wilks, (1998): Statistical downscaling of general circulation model output: a comparison of methods, *Water Resour.* **34**: 2995-3008

Wilby, R. L., T. M. L. Wigley, 2000: Precipitation predictors for downscaling: Observed and general circulation model relationships. *Int. J. Climatol.*, **20**, 641-661

William, J.E and R.E Thomson, 1997: Data Analysis Methods in Physical Oceanography, Gray Publishing, Tunbridge Wells, Kent, 634pp

Wilson, M. F. and A. Henderson-Sellers, 1985: A global archive of land cover and soils data for use in general circulation climate models, *J. Climatol.*, **5**, 119–143.

Xie P., and P.A Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates and numerical model outputs. *Bul.l Amer. Meteor. Soc.*, **78**: 2539-2558

Xue, Y and A.J Thorpe. 1990: A mesoscale numerical model using the nonhydrostatic pressure-based sigma-coordinate equations. Model experiments with dry mountain flow. *Mon. Wea. Rev.*, **119**, 1168-1185

Yeh, H.-C., and Y.-L. Chen, 2002: The role of offshore convergence on coastal rainfall during TAMEX IOP 3. *Mon. Wea. Rev.*, **130**, 2709-2730.

Zheng X., H. Nakamura and J. A. Renwick, 2000: Potential predictability of seasonal means based on monthly time series of meteorological variables. *J. Climate* vol. **13**, NO. **14**, 2591-2604.

Zhu, B., and B. Wang, 1993: The 30-60 day convective seesaw between the Tropical Indian and Western Pacific Oceans *J. Atmos. Sci.*, **50**, 184-199.

Zorita E., and F. Tilya, 2002: Rainfall variability in Northern Tanzania in the March–May season (long rains) and its links to large-scale climate forcing. *J. Climate Res.* **20**, 31–40

Zou, X., Y.H. Kuo, and S. Low-Nam, 1998: Medium-Range prediction of an extratropical oceanic cyclone: Impact of initial state. *Mon. Wea. Rev.*, **126**, 2737-63

APPENDIX

PENTAD DATES

AND

PUBLICATIONS

APPENDIX A: TABLE OF PENTAD DATES USED IN THIS THESIS

PENTAD	MONTH	DATE	PENTAD	MONTH	DATE
01	JAN	1-5	37	JULY	1-5
02	JAN	6-10	38	JULY	5-10
03	JAN	11-15	39	JULY	11-15
04	JAN	16-20	40	JULY	16-20
05	JAN	21-25	41	JULY	21-25
06	JAN	26-31	42	JULY	26-31
07	FEB	1-5	43	AUG	1-5
08	FEB	6-10	44	AUG	6-10
09	FEB	11-15	45	AUG	11-15
10	FEB	16-20	46	AUG	16-20
11	FEB	21-25	47	AUG	21-25
12	FEB	26-29	48	AUG	26-31
13	MAR	1-5	49	SEP	1-5
14	MAR	6-10	50	SEP	6-10
15	MAR	11-15	51	SEP	11-15
16	MAR	16-20	52	SEP	16-20
17	MAR	21-25	53	SEP	21-25
18	MAR	26-31	54	SEP	26-30
19	APRIL	1-5	55	OCT	1-5
20	APRIL	6-10	56	OCT	6-10
21	APRIL	11-15	57	OCT	11-15
22	APRIL	16-20	58	OCT	16-20
23	APRIL	21-25	59	OCT	21-25
24	APRIL	26-30	60	OCT	26-31
25	MAY	1-5	61	NOV	1-5
26	MAY	6-10	62	NOV	6-10
27	MAY	11-15	63	NOV	11-15
28	MAY	16-20	64	NOV	16-20
29	MAY	21-25	65	NOV	21-25
30	MAY	26-31	66	NOV	26-30
31	JUNE	1-5	67	DEC	1-5
32	JUNE	6-10	68	DEC	6-10
33	JUNE	11-15	69	DEC	11-15
34	JUNE	16-20	70	DEC	16-20
35	JUNE	21-25	71	DEC	21-25
36	JUNE	26-30	72	DEC	26-31

APPENDIX B: PAPERS PUBLISHED FROM THIS THESIS

Two papers were published at the peer review journals.

1. Kijazi A. L. and C.J. C. Reason., 2009: Analysis of the 2006 floods over northern Tanzania. *Int. J. Clim.* **29**, No 7, 955 - 970
2. Kijazi A. L. and C.J. C. Reason., 2009: Analysis of the 1998 – 2005 drought over the north-eastern highlands of Tanzania; an observational study. *Clim. Res.***38**,209 - 223