An investigation into dry and wet spell characteristics over Zambia and into the onset of the rainy season

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Declaration

This work has not been previously submitted in whole, or in part, for the award of any degree. I declare that this dissertation is my own original work, produced with normal supervisory assistance from my supervisor. Each significant contribution to, and quotation in this dissertation from the work, or works of other people has been attributed, and has been cited and referenced.

Name: Sepo Promise Hachigonta

Signature: Signed by candidate

Signed this ....day of May 2005

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Abstract

Recurring dry/wet spells and decreased agricultural productivity during the last decade in the southern and northern parts of Zambia point to the need for a clearer understanding of these events, their frequencies and their possible connection to large-scale climate modes. Apart from having a high number of dry spells during the December-February (DJF) core rainy season, the southern part of Zambia is frequently subjected to late onset dates and short durations of the rainy season whereas the northern and northwestern region frequently have high numbers of wet spells which in most cases lead to flooding. Using CMAP and station data, rainfall variability in terms of dry spells, wet spells, onset and cessation dates of the Zambian rainy season and the associated circulation anomalies are investigated. The study also looks at relationship between these extreme events with Niño3.4 SST anomalies.

Low level easterly anomalies over Zambia are enhanced during seasons with high dry spells. As a result, there is reduced moisture penetration into Zambia from the Angola low and reduced low level moisture convergence over the country and hence increased dry spells. During the seasons with high numbers of wet spells, there are low level westerly anomalies over southern Angola and western Zambia implying a strong moisture influx from the tropical South East Atlantic and increased convergence over Zambia. It was shown that El Niño (La Niña) events typically result in above (below) average DJF dry spell frequency in Zambia.

Early onset dates over the northern parts of Zambia were observed to occur during strong El Niño seasons and the strength of the observed relationship with Niño3.4 SSTs seems to be stronger for years during the 1980s than those during the 1990s. Early onset dates tend to occur for years with higher than average dry spell frequency in the following DJF season. This suggests that early onset may be a disadvantage in that it often leads to more dry spells during the subsequent peak growing period of the season.

Late onset seasons (often La Niña seasons) are associated with a cyclonic pattern over southern Africa and south of the continent while early onset seasons are characterised by an anticyclonic anomaly centered over Angola. A Pacific South America-like Rossby wave train teleconnecting the Pacific anomalies with the South Atlantic and southern African circulation anomalies is evident during early and late onset seasons. In addition, a potential link with the strength of the Asian summer monsoon during late boreal summer was noted for anomalously early and late onset seasons.

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Chapter 1

Introduction

1.1 Motivation

Rainfall in Zambia is highly irregular in space and time which makes cultivation of crops like maize difficult. Small differences in the amount and timing of rain received at a particular site may determine the success or failure of critical stages in maize production, which is the nation's main staple food. Understanding how rainfall is distributed and the various circulation anomalies responsible for its variability could be of tremendous help to the subsistence farmers in Zambia.

Over 90% of farmers in Zambia are small-scale and rely on rain fed-agriculture. Agriculture is the leading sector in terms of its contribution to GDP (24.8% in 2000) and employs about 50% of the total labour force (FAO, 2002). The lack of capacity to adapt to appropriate technologies makes most farmers vulnerable to climate variability. For these farmers, reduced crop yield is not a matter of profit but of survival as it is the only source of income. Recent food security concerns across Zambia especially over the southern province, which was once know as the food basket for the country, arise in part from fluctuations in regional climate. Any possibility of developing drought or flood conditions in a particular season needs to be identified well in advance to enable decision makers to take the necessary measures to avoid catastrophe during the farming season.

This study is motivated by the desire to understand Zambian rainfall variability in terms of dry spells, wet spells, onset and cessation dates of the rainy season and their associated regional circulation anomalies. In addition, an attempt will be made towards better understanding the circulation anomalies responsible for extreme dry/wet spells and late/early onset dates of the rainy season. These parameters are more useful to end users (e.g. seasonal forecasters and farmers) than seasonal rainfall totals. Previous work has examined the variability in dry spell frequency and onset dates over Zimbabwe (Matarira and Jury, 1992; Tadross *et al.*, 2005), over southern Africa as a whole (Usman and

Reason, 2004), and over the Limpopo region (Reason *et al*., 2004) but very little work has been done over Zambia. Therefore, one of the objectives of this thesis is to identify global and regional climatic features that influence dry/wet spells and variability in onset dates during the summer rainfall seasons over Zambia.

1.2 Location

Zambia is a land locked country, situated in southern Africa between 22° and 34° east of Greenwich and 8° and 18° south of the Equator. It covers an area of about 752,620 square kilometers and eight countries, namely, Angola, Botswana, Democratic Republic of Congo, Malawi, Mozambique, Namibia, Tanzania and Zimbabwe (Figure 1.1) surround it. The South Indian Ocean is located approximately 800kms to the east while the South Atlantic Ocean is approximately 1100kms to the west.

1.3 Objective

The objective of the thesis is to investigate the spatial-temporal patterns of dry and wet spell occurrence, the start and end dates of the wet season and to establish the major circulation features that influence these parameters. The number and severity of dry spells and extreme onset dates during the study period will be examined and related to Sea Surface Temperatures (SSTs) and atmospheric circulation. The ultimate goal of this study is to help improve rainfall prediction, which is very important for rain fed agriculture. It is well known that an 'above average' rainfall season measured in terms of the amount of rain received may not be any better than a 'below average' season for a farmer if the rains are not properly distributed either in time or space (Usman and Reason, 2004). In order to accomplish the above mentioned objectives, the following research questions will be addressed.

(i) What are the main circulation systems that are responsible for summer rainfall variability over Zambia?

(ii) How are dry/wet spells distributed over the country and what are the associated circulation anomalies during seasons with anomalously high frequency in wet and dry spells?

(iii) How are onset dates distributed across the country and what are the relationships between onset dates and regional circulations?

(iv) How do El Niño and La Niña events impact on dry/wet spells and rainy season onset/cessation dates over Zambia in relation to rainfall predictability?

1.4 Rainfall over Zambia

The year in Zambia can be divided into two distinct halves, a dry half from May to October and a wet half from November to April. The dominant circulation pattern over the country during the summer season is the Intertropical Convergence Zone (ITCZ), which moves across Zambia during this period. The average highest temperatures over Zambia occur in October prior to the start of the rainy season, when the mean daily daytime temperature of most stations lies within the range of 28°C-31°C. Daytime temperatures then drop during the peak rainy season (November to April) to 20°C-26°C. The rainfall patterns over Zambia can be divided into three main regions. Figure 1.2 shows interpolated rainfall distribution across Zambia derived from daily station data. Details of station interpolation are shown in Chapter 3.

Region I

The southern part of the country is located between 15°S-18°S and lies between 300 and 900 meters above sea level. It receives less than 900mm of rainfall annually and temperatures vary from 20°C to 25°C. It is the driest region, most prone to droughts and has limitations in terms of crop production during most summer seasons.

Region II

This region covers the central part of Zambia extending from the east through to the west. It receives medium rainfall of between 900mm and 1100mm, which is evenly distributed throughout the growing season. Temperatures during the rainy season range from 23°C to 25°C and may rise to about 32°C in the hot season. It is regarded as the most productive area in terms of agricultural production. Important crops that are grown here include the staple food maize and sugar cane, which is commercially grown.

Region III

This region receives more than 1100mm of annual rainfall on average and covers the northern part of the country (8°S-12.8°S). This region often experiences more rainfalls than is useful, with severe flooding in many areas especially over the northeastern parts. It is suitable for late maturing varieties of crop, such as cassava and pineapples, although about 65% of the entire region is yet to be exploited.

The northern part of Zambia receives above average rainfall during most of the summer seasons due to the influence of the ITCZ, which is located over this area during this time of the year. In contrast, rainfall in the southern part is very erratic, often below average and poorly distributed. Figure 1.3 shows a comparison of annual rainfall between northern and southern Zambia from 1979-1999 using station rainfall data.

The El Niño-Southern Oscillation (ENSO) impacts significantly on rain-fed agriculture both through alterations to the consistency of rainfall events and to accumulated seasonal totals. The relationship between southern Africa rainfall variability and ENSO has been widely reported (Ropelewski and Halpert, 1987; Lindesay *et al.*, 1986; Nicholson and Kim, 1997; Reason *et al.*, 2000; Usman and Reason, 2004). The warm (cool) phases of ENSO or El Niño (La Niña) are typically characterised by warm (cool) SST anomalies in the tropical Pacific and Indian Oceans and below (above) average summer rainfall over southern Africa. Knowledge of the state of ENSO during the proceeding austral winter may therefore give some indication of the climatic conditions that may be expected over southern Africa during the summer (mature phase of ENSO), thus helping the farmers plan for the growing season. Other regional SST patterns, such as over the south Indian Ocean (Behera and Yamagata, 2001; Reason, 2001) also influence the summer rainfall variability over Zambia but their predictability is yet to be investigated.

1.5 Thesis lay-out

Chapter 1 has given an introduction of the thesis and also considered the motivation, objectives and implications of climate variability across Zambia. Chapter 2 provides a literature review and discusses previous studies that have been done on the rainfall characteristics of southern Africa. Systems that directly affect rainfall over the country are also discussed in this chapter. Chapter 3 is concerned with the methodology, data and software used in the thesis.

Analysis of dry and wet spells over Zambia is performed in chapter 4. This chapter presents characteristics of dry and wet spells during the peak summer (December, January and February) rainy period and considers how the spells are distributed both in space and time based on 22 years of Climate prediction center Merged Analysis of Precipitation (CMAP) and station rainfall data. This chapter also looks at the associated circulation anomalies and correlations between dry spell anomalies and Niño3.4 SST anomalies during the study period. It is illustrated that SST variability is one of the factors influencing the frequency of dry spells over most parts of the country. The implication of dry spells over Zambia is also discussed.

Chapter 5 examines the onset dates of the summer rainfall season and its cessation dates over Zambia as well as the associated circulation anomalies. The time and space structure of onset dates and the duration of the rainy season over the country are analysed. Correlation between onset dates and Niño3.4 SST anomalies are derived. This chapter also shows that the Angola low feature is influential in the early onset over the western regions of the country. Chapter 6 summarises the findings of the thesis and presents the conclusions of the thesis.

Location of Zambia

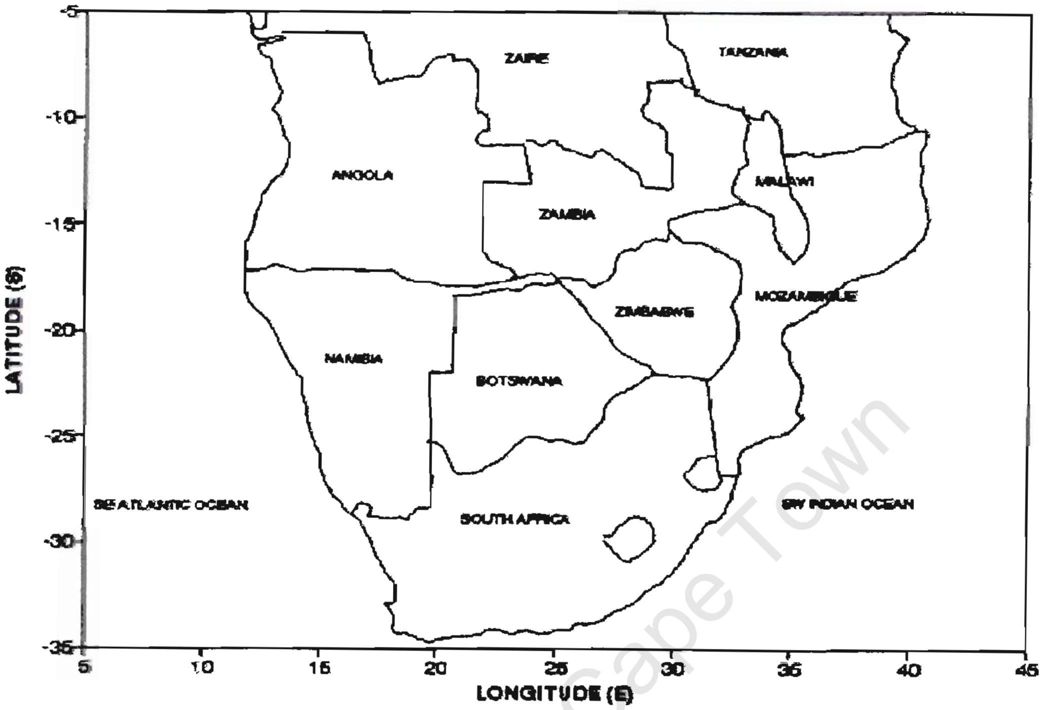


Figure 1.1: Map showing location of Zambia.

Annual total rainfall climatology 1979-1999

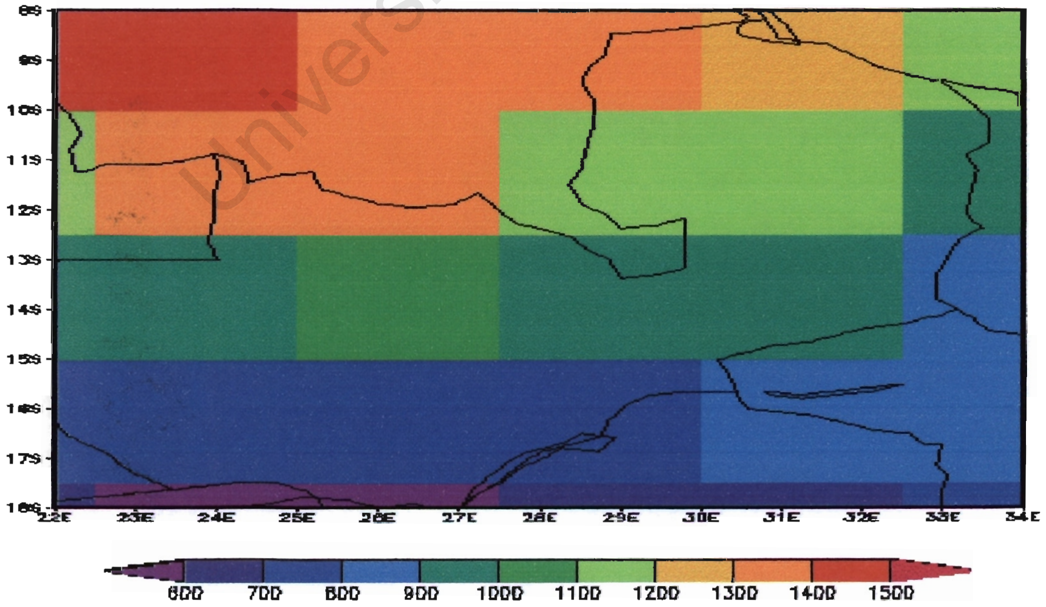


Figure 1.2: Annual rainfall climatology over Zambia (1979-1999, gridded station data)

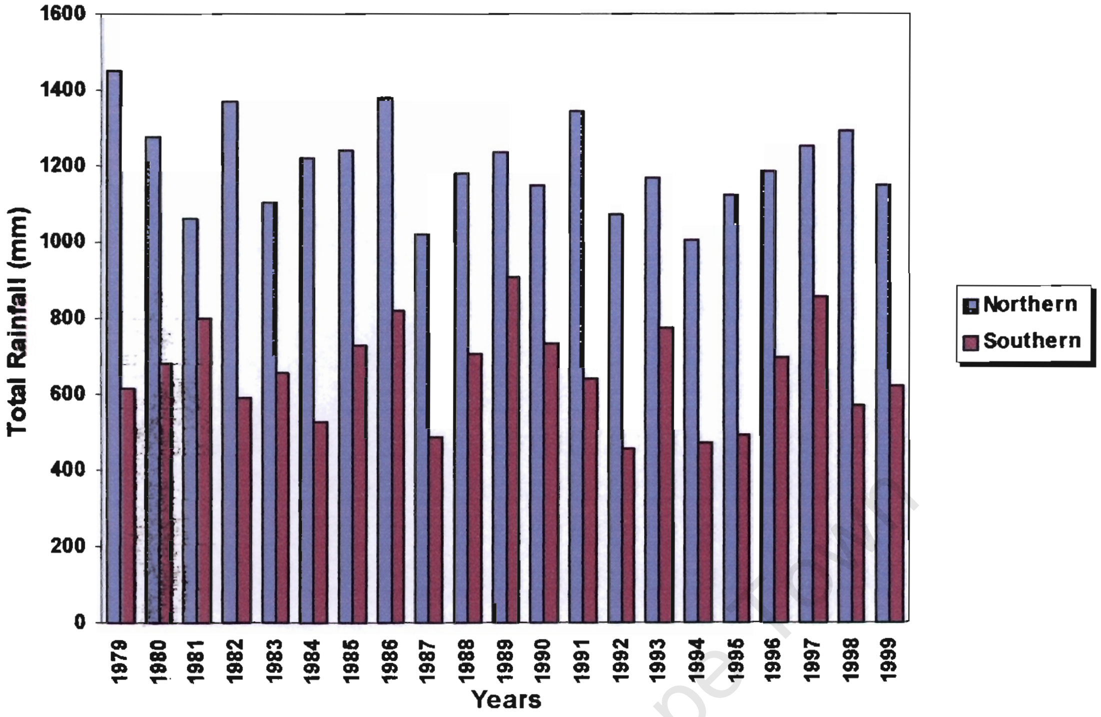


Figure 1.3: Time series of rainfall in the northern and southern parts of the country during the 1979-1999 period (station data)

Chapter 2

Literature Review

2.1 Introduction

The main objective of this chapter is to provide a literature review of the characteristics of the austral summer rainy season, such as onset dates, cessation dates, frequency of dry/wet spells during the season and rainfall producing systems over Zambia. The El Niño Southern Oscillation and regional SST variability will also be reviewed in association with rainfall over Zambia.

As mentioned earlier in chapter one, about 90% of Zambian farmers rely on rain fed-agriculture. The high number of dry spells (or wet spells in the northern parts) is often the most important contributory factor causing acute food insecurity in Zambia. For instance during the 1997-98 El Niño season, aggregate maize production declined by 41 % from the average of the last five years (FAO /WFP, 1998). Little research work has been done on dry spells and onset dates of the rainy season over Zambia to provide the required information to guide farmers and government agencies on how rains are spread over the season and to provide potential early warning indicators of the possibility of significant droughts or floods.

Southern African rainfall is characterized by substantial variability on intraseasonal, interannual and interdecadal time scales (Walker, 1990; Levy and Jury, 1996; Mason and Jury, 1997; Nicholson, 2000, Reason and Mulenga, 1999; Reason and Rouault, 2002). This variability in rainfall affects rain-fed agriculture, which is fundamental to food security and planning in southern African countries (Landman and Klopper, 1998). Impacts of the drought of the early 1980s and of the 1991–1992 droughts illustrate the susceptibility of communities in the southern African region to climatic extremes (Vogel and Drummond, 1993; Vogel, 1994).

A reasonable knowledge of the date of onset of rainfall enables the prediction of the start the growing of crops, which is most useful for the selection of crop varieties, crop matching and cropping sequences (Kowal and Knabe, 1972), and will greatly assist on-time preparation of farmlands. Therefore, in order to ensure maximum and sustainable agricultural productivity, reliable predictions of the dry/wet spell frequency, duration, onset dates, cessation dates and the length of the rainy season are all very important.

2.2 Dry (Wet) Spells and Onsets

Dry and wet spell analysis is crucial for a good crop yield as it is usually not the amount of seasonal rainfall that is important, but how the rains are distributed within a season. Many studies have examined rainfall variability over southern Africa (e.g. Harrison, 1984; Taljaard, 1986; Nicholson and Entekhabi, 1987; Lindesay, 1988; Walker and Shillington, 1990; Walker, 1990; Lindesay and Jury, 1991; Lyons, 1991; Jury, 1992; Mason, 1995; Levey and Jury, 1996; Todd and Washington, 1998; Cook, 1998, 2000; Jury, 1999; Reason and Mulenga, 1999) although little research has been done on the details of dry/wet spells and onset of the rainy season over the region. Most work has focused on interannual, often ENSO related variability with less emphasis on intraseasonal (e.g. Levey and Jury, 1996) or interdecadal variability (e.g. Tyson *et al.*, 1975; Reason and Rouault, 2002). Recently, Usman and Reason (2004) analysed dry spells in the southern African region to find that there is strong relationship between dry spells and Niño3.4 SST. A number of studies have provided strong evidence of links between interannual variability of SST in the Indian Ocean and observed rainfall over southern Africa (e.g. Walker, 1990; Landman and Mason, 1999; Rocha and Simmonds, 1997; Reason, 1999; Reason and Mulenga, 1999; Nicholson, 2003) but little has been done to investigate links between SST and dry spell occurrence. Makarau (1997) noted that the first wet spell is important for crop planting, whereas the third wet spell in January breaks the mid-summer drought and comes at a critical time in the growth of maize, the staple food in the region. Over southern Africa, the historical distribution of summer rainfall is typically composed of five wet spells, occurring at approximately monthly intervals from late November to late March (Makarau, 1995). On seasonal scales, Jury (1996) has pointed out that SSTs in the central Indian Ocean may be significant predictors of southern African rainfall. Mulenga (1998) noted that wetter summers over western Zambia, Angola, northern Botswana, Zimbabwe and southern Mozambique are associated with cold SST anomalies over the Atlantic Ocean.

In terms of the circulation, Tyson (1981) found wet spells to be associated with low pressure anomalies over the interior of the subcontinent. Miron and Tyson (1984) associated wet spells with negative pressure deviations over the central parts of the subcontinent and positive anomalies over the South Atlantic near Gough Island. Cook *et al.*, (2004) observed that some wet spells over southern Africa are characterised by a strong cyclonic anomaly north of the region, which may draw in moisture from the tropical South Atlantic as well as from the South Indian Ocean, if it is located near the Angola low. A conceptual diagram showing the position of the ITCZ and other circulation features over the landmass may be found in Van Heerden and Taljaard (1998).

The understanding of onset dates over southern Africa has been recently given some attention Tadross *et al.*, (2005). Using CMAP and station data, the onset date of the maize growing season over Zimbabwe and some areas of South Africa was calculated and related to global SST anomalies. Mulenga (1998) associated onset dates over Zambia with a deep cold low over the South Indian Ocean, which brings in moisture. Mumba (1998) found that the onset of summer rains is as early as the first and second weeks of October over most of Zambia. It should be noted though that the definition used by Mumba (1998) obtained through operational observations of rainfall events was not for the onsets of the growing season but rather arrived at by observing rainfall in the first few days of the rainy season.

2.3 Rain producing systems over Zambia

The country's rainfall during the rainy season is mainly influenced by the ITCZ, the tropical heat low over southern Angola and northern Namibia, the interaction between the low and the ITCZ and synoptic systems like easterly waves and tropical depressions. The major circulation systems controlling seasonal rainfall are described below. Over southern Africa, the source of moisture for summer convection is largely from the South Indian Ocean (D'Abreton and Tyson 1995; Rouault *et al.*, 2003; Cook *et al.*, 2004) with a secondary source of moisture from the tropical southeast Atlantic.

2.3.1 Inter Tropical Convergence Zone (ITCZ)

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 (Wallace and Hobbs, 1977). 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). Jury *et al.,* (1994) studied the ITCZ evolution and variability over the south-western Indian Ocean and found that the mean position of the ITCZ for the period 1987-1990 was 15°S over south-east Africa and Madagascar. The easterly winds to the south were driven by the South Indian Ocean anticyclone. The ITCZ can be identified on a surface map as a confluence line between airflow with a northerly component and that with a southerly component. Over land, variability in the ITCZ may be influenced by feedbacks with the land surface (Webster, 1983). In the summer (November–March), the ITCZ moves southwards over central Africa to approximately 17°S (Taljaard, 1994) and convective disturbances evolve along it.

As the early summer progresses and the heat low over Angola intensifies, the northwesterly winds from the Congo basin strengthen and move eastward. At the same time, the northeasterly flow from the winter Asian monsoon and the southeast trade winds from the subtropical high belt penetrate into the subcontinent. This airflow is characterized by onshore flow over southeastern Africa from the South Indian Ocean. As a result, these three airstreams converge toward a confluence belt over Zambia and the Congo basin associated with maximum cloudiness and precipitation. The ITCZ is more pronounced over the northern parts of Zambia as evident from the high rainfall received during most seasons.

Rainfall variability in Zambia not only depends on changes in the ITCZ position and strength but also on the strength and distribution of the tropical easterlies, which are enhanced during the summer season and bring in moisture towards the northern parts of Zambia. Other circulation systems of importance include the tropical heat low, which is usually located over Angola or northern Namibia.

2.3.2 Angola low

The Angola low is an inland seasonal heat low centered over southern Angola, northern Namibia and northwestern Botswana associated with high surface temperature in early summer. The low is initiated in September / October as the maximum solar insolation moves south across the equator and it influences the regional summer circulation of southern Africa. It modulates regional climate at both intraseasonal and interannual time scales (Mulenga, 1998; Cook *et al.,* 2004). Land surface boundary conditions play an important part in the formation of the Angolan low and in the creation of available potential energy through land-ocean temperature contrasts (Mulenga, 1998). The heating of the sub-continent and cooling of the neighbouring coastal ocean via upwelling in the Benguela current system favours the formation of high-pressure over oceanic regions and low pressure over the heated areas (Mulenga, 1998). In the second half (January-March) of the rainy season, the tropical low over southeastern Angola becomes quasi-stationary. A trough originating from the tropical low extends into the eastern part of Africa and is associated with the so-called Congo Air Boundary (Mugara, 1997).

The tropical low, which is usually located at the furthest southwestern limit of the ITCZ, provides significant rainfall to Zambia (Jury and Pathack, 1993). When the tropical low is coupled with a westerly temperate trough in the midlatitudes, a north-south oriented trough (so-called tropical temperate trough) identified by cloud bands separating the South Atlantic and the South Indian Ocean high-pressure systems is formed. This pattern usually results in heavy rainfall over Zambia. Quasi-stationary waves in the midlatitudes also play an important part in regulating summer rainfall (Harrison, 1986) since they influence the tropical and temperate climate. The position of the low is very important since it modulates the convergence of water vapour over the subcontinent (Mulenga, 1998). It was also noted by Mulenga (1998) that the combination of the Angolan low with a lower pressure depression located over Mozambique results in diffluent flow over Zambia, Botswana, Zimbabwe and Malawi, which inhibits rain producing system resulting in dry conditions over the region.

Mudenda and Mumba (1996) also linked tropical cyclones with rainfall over Zambia. They observed that heavy rains can occur over Zambia when there is passage of a weakening storm from the southwest Indian Ocean into or near the country, though this can lead to rainfall deficits over the southern parts. Sometimes these storms can travel right across southern Africa to northern Namibia leading to good rains over a broad swath of the subcontinent, e.g. tropical cyclone Eline in February 2000 (Reason and Keibel, 2004). Significant amount of rainfall over the Zambezi valley might be attributed to winds or cut off lows south of South Africa shifting eastwards, reaching Zambia. These winds fetch moist air in the Mozambique channel and probably south of this region in the Agulhas retroflection region.

The next section looks at oceanic conditions responsible for rainfall variability over southern Africa. Harrison (1986) suggested that the roles of the Hadley Circulation, the semi-annual oscillation, ENSO and Walker Circulation across the tropical Indian Ocean play in modulating southern African variability should be emphasized. Higher rainfall over South Africa in summer tends to be associated with an intensified Hadley circulation (Harrison, 1986).

The influence of the Walker Circulation over the southern Africa's rainfall is well established (Mulenga *et al.,* 2003). This circulation responds to sea surface temperature variability in the Pacific and Indian Oceans.

2.4 ENSO influence on rainfall over Zambia

This section will discuss the literature on ENSO and the role it plays in the variability of southern African rainfall and Zambia in particular. ENSO is a fluctuation in the ocean-atmospheric system involving large changes in the Walker and Hadley Cells throughout the tropical Indo-Pacific Ocean region (Philander *et al.*, 1990). This fluctuation arises from the instability of the coupled tropical ocean-atmosphere (Kook, 1989). The Niño 3.4 region (70°E to 90°E, 5°S to 5°N) has been identified as the SST region having strongest concurrent association with mid-latitude and tropical ENSO-forced circulation variations (Barnston *et al.*, 1997). The warm (cool) phases of ENSO or El Niño (La Niña) are characterised by warm (cool) SST anomalies in the tropical Pacific and Indian Ocean and typically below (above) average summer rainfall over southern Africa. ENSO is the dominant mode of interannual climate variability in sub-Saharan Africa (Ropelewski and Halpert, 1987).

The links between ENSO and the prevalent atmospheric circulation over southern Africa are relatively well understood (Lindesay, 1988; Reason *et al.*, 2000). A number of studies have confirmed a relationship between rainfall and ENSO in parts of southern Africa (e.g. Lindesay *et al.*, 1986; Farmer, 1988; Janowiak, 1988; Van Heerden *et al.*, 1988; Reason *et al.*, 2000). Nicholson and Kim (1997) found strong connections between ENSO and rainfall over much of the African continent and suggested a linkage through ENSO induced SST anomalies in the Indian Ocean, which in turn modulate interannual variability of rainfall over Africa. Tourre and White (1997) and Reason *et al.,* (2000) show strong evidence of ENSO signals in the Indian Ocean. Usman and Reason (2004) found a high correlation between Niño3.4 SSTs and southern African dry spells.

Most recent droughts over Zambia have been related to El Niño events. Recent El Niño events occurred in 1982/83, 1986/87, 1991/92, 1994/95, 1997/98 and 2002/03. The droughts during these El Niño years, which were preceded by summer seasons of below-average rainfall, had devastating results on Zambia and resulting in substantial financial losses and major stressful conditions on water resources for agricultural, industrial and other purposes.

The 1982/83 El Niño season had frequent dry spells in January, February and March which led to poor performance of the agricultural sector, especially the southern half of Zambia. During the 1991/92 season, the country was faced with massive food shortages due to the El Niño induced drought. This was the worst drought for many years to hit Zambia at the most critical crop stage. Almost all of Zambia was declared a disaster area. During the 1997/98 event, the southern parts had below normal rainfall whereas the northern half experienced massive rainfall, which led to flooding and crop loss (FAO/WFP, 1998). Vogel and Drummond (1993) pointed out that the impacts of the drought of the early 1980s and of the 1991/92 droughts illustrate the susceptibility of communities in the southern African region to climatic extremes.

As mentioned earlier, interannual variability in summer rainfall over southern Africa correlates strongly with the sea surface temperatures (SSTs) over the South Indian Ocean (e.g. Walker, 1980, Mason, 1995, Reason and Mulenga, 1999, Behera and Yamagata, 2001, Reason, 2001). On interannual time scales, ENSO events are important for SST variability over the Indian Ocean (Reason *et al.*, 2000) but other modes also exist which influence southern African rainfall (Rocha and Simmonds, 1997; Behera and Yamagata, 2001; Reason, 2002). Kiladis (1997) observed that during warm El Niño events, strong convection develops over the central and eastern Pacific which drives a stronger than normal divergent circulation. Based on various atmospheric general circulation model experiments, Goddard and Graham (1999) noted that while the SST variability of the tropical Pacific exerts some influence over the African region, it is the atmospheric response to the Indian Ocean SST variability that is more important for rainfall variability over southern, eastern and central Africa. Nicholson and Kim (1996) showed that ENSO has little influence on the main (March–April) rainy season over East Africa but significantly modulates the ‘short rains’ (October-December). They noted that in many areas, the strongest response to ENSO occurs in the months either before or after the core of the rainy season, suggesting a modulation of the length of the season. Although ENSO produces large, wide scale changes in the tropical circulation and southern African rainfall, these changes are not uniform throughout the region. In some regions, an El Niño event is not always accompanied by reduced rainfall FAO/WFP (1998).

In addition to ENSO, other factors such as the Quasi-Biennial Oscillation, sea surface temperature and monsoon intensity can also influence rainfall over southern Africa.

2.5 Quasi-Biennial Oscillation

The stratospheric Quasi-Biennial Oscillation (QBO) is an east-west oscillation of stratospheric winds that encircle the globe near the equator (Wallace, 1973). Some studies have related stratospheric QBO phase to African rainfall variability. The QBO refers to a zonal wind in the equatorial stratosphere that changes direction from easterly to westerly with a period of ±28 months (Naujokat, 1986). The QBO enhances the likelihood of drought when it is in easterly phase (Mason and Tyson, 1992). Ogallo *et al.*, (1994) and Jury *et al.*, (1994) have reported a significant correlation between African rainfall and the QBO. Mukherjee *et al.*, (1985) indicate that the easterly phase QBO is associated with a weak monsoon over India. However, no clear mechanism has been found to explain the interaction of the QBO, the tropospheric circulation and convection over Africa.

In addition to the effects of ENSO and QBO on southern Africa, there are also other effects that appear to directly impact rainfall variability within individual regions. These include variations in regional SST, tradewind and monsoon circulations. For example on intraseasonal scales, Makarau and Jury (1997) found that over Zimbabwe, the changes in moisture transport from the surrounding oceans, particularly the tropical Indian Ocean occur some 5-15 days in advance of wet and dry spells.

2.6 Regional sea-surface temperature variability

In addition to ENSO induced SST variability in the South Atlantic (Colberg *et al.*, 2004) and South Indian Oceans (Cadet, 1985; Reason *et al.*, 2000), a number of other patterns exist that may influence southern Africa rainfall. SST anomalies of the Indian Ocean have previously been related to southern African seasonal rainfall variability (Nicholson and Entekhabi, 1987; Walker and Lindesay, 1989; Mason 1990, 1995, 1998; Walker, 1990; Jury and Pathack, 1991; Jury *et al.*, 1993; Mason *et al.*, 1994; Makarau and Jury, 1997; Mason and Jury, 1997; Rocha and Simmonds, 1997; Behera and Yamagata 2001; Reason, 1999). This association is confirmed by numerical experiments (Reason and Mulenga, 1999; Reason, 2001, 2002). Regional SST variability may arise through local air-sea interactions, oceanic Rossby wave propagation or remote forcing. Warmer (cooler) than average sea-surface temperatures in the Agulhas system are associated with wetter (drier) than average rainfall over part of the summer rainfall region of South Africa (Jury and Pathack, 1993; Reason, 1999). Mason and Tyson (1992) identified links between warmer SST across the southwest Indian Ocean and rainfall deficits over southern Africa. Correlations between rainfall and SST in the Indian Ocean are linked to the monsoon and ENSO circulations (Mason and Jury, 1997). Sea-surface temperature variations are responsible for a large percentage of the rainfall variability of the austral summer rainfall over southern Africa. Understanding the way SSTs interact with southern Africa can significantly help in the prediction of dry and wet spells and onset dates in the region.

2.7 Summary

This chapter has revised literature on rainfall variability over southern Africa and Zambia in particular. Rainfall over Zambia has been mostly linked to the ITCZ, which has been found to be the most dominant circulation system during the austral summer season over the region. The Angola low has also been noted as another system influencing the regional summer circulation of southern Africa (Mulenga, 1998; Cook *et al.*, 2004). The ENSO phenomenon has been related to southern African rainfall in previous studies. Dry spells over southern Africa were recently studied and related to ENSO (Usman and Reason, 2004) who found a good relationship between the two parameters. Based on previous work, this thesis will study rainfall variability over Zambia particularly in terms of dry and wet spells, onset and cessation dates of the rainy season and the circulation anomalies potentially responsible for this variability.

Chapter 3

Data and Methodology

3.1 Data

3.1.1 Rainfall

Analysis of dry and wet spells will focus on the core DJF period during the austral summer, as it is the peak for maize growing and the time of maximum rainfall. This chapter gives a detailed analysis of the data and methods used in this study. Two rainfall data sets were used for the analysis of dry spells, wet spells, onset dates and cessation dates over Zambia. Pentad data is used in order to assess intra-seasonal/ interannual rainfall variability, and daily station rainfall data were used in order to obtain a more detailed examination of dry and wet spell duration on selected areas spread across Zambia. The network of stations used to examine rainfall over Zambia is shown in Figure 3.1 and indicates that the stations are well spread over the country and therefore represent the three main rainfall regions.

The first data set used was the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP), mean pentad rainfall data (Xie and Arkin, 1997) updated to July (2002). The CMAP rainfall data are global precipitation estimates obtained from the merging of observations from rain gauges and rainfall estimates from satellite. This gridded data has a spatial resolution of 2.5 x 2.5°. The CMAP data set used here extends over 1979 to 2002 and has previously been used in recent southern African studies (e.g. Tadross *et al.,* (2004).

The second rainfall data set used was the daily station data obtained from the Zambian Meteorological Department. Station data are used in this study in order to demonstrate the robustness of the results where the two datasets agree, or caution against drawing firm conclusions where the datasets differ and to fill gaps where one of the sets has missing data. This data was derived from 28 daily weather stations over Zambia and it covers the period between 1979 and 2001. This data range was used because the stations during this period had little or no missing records. Figure 3.2 shows the mean annual cycle of rainfall for various stations over Zambia emphasizing the dominant contribution of the summer rains to the yearly total.

The two data sets are not independent as CMAP data uses station data to fix the magnitude of the precipitation field, with satellite-based estimates providing shape and magnitude where station data are absent (Tadross *et al.,* 2004). An attempt is made to confirm the similarity of patterns produced by CMAP and station data and to ascertain if there are significant differences across the country. The two data sets gave similar patterns of dry and wet spell frequencies over Zambia after a subjective monthly analysis during DJF season, indicating that the use of CMAP data had no significant bias.

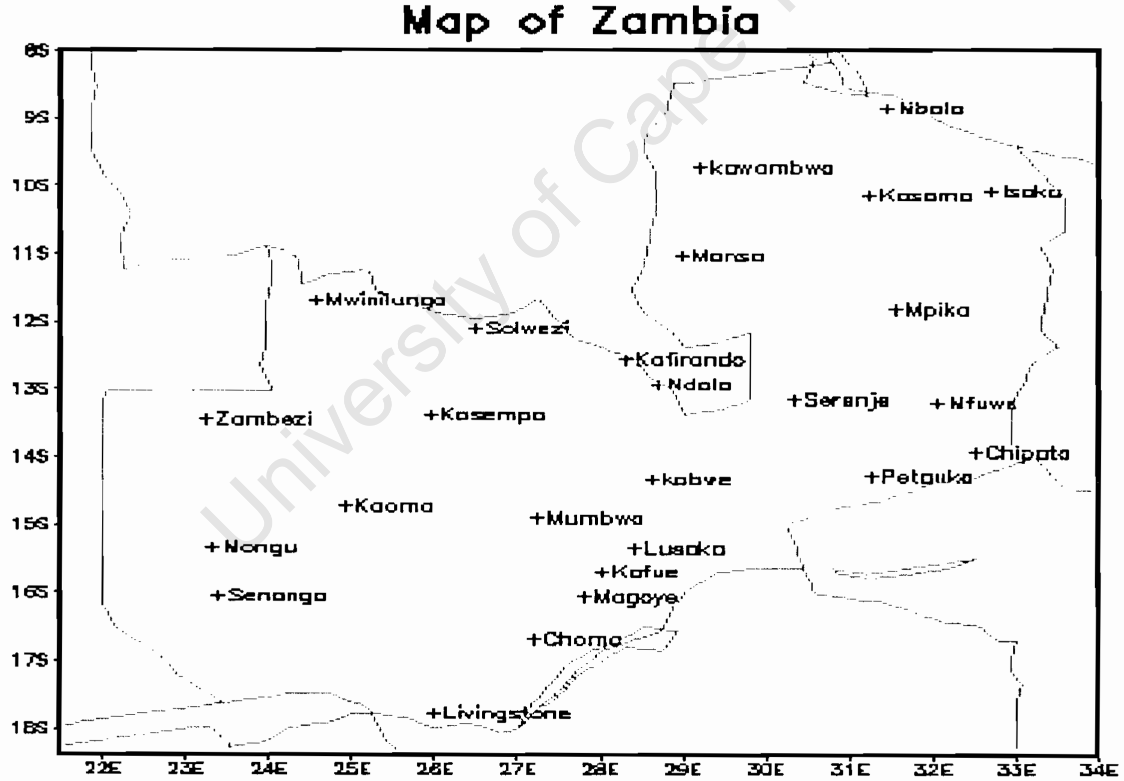


Figure 3.1: Showing the network of stations used

3.1.2 NCEP Reanalyses

The National Center for Environmental Prediction (NCEP) reanalysis data is the outcome of the NCEP Climate Data Assimilation System (CDAS) project, which started in the early 1990s. The NCEP-NCAR Reanalyses encompass all major atmospheric fields at different pressure or isentropic levels. Additionally, the NCEP-NCAR Reanalyses appear to contain useful information when compared with observations and climatologies depending on the category of the output variable (Kalnay *et al.,* 1996). However it should be noted that there are less observations over tropical Africa than many other landmasses and therefore the re-analyses may be less accurate. The NCEP-NCAR reanalyses data used in this study consist of zonal and meridonal wind components, geopotential height, velocity potential, Sea Surface Temperatures (SST) and specific humidity. Some of these parameters anomalies were plotted directly from the CDC Website (http://www.cdc.noaa.gov/).

3.2 Methodology

This section looks at the various methods and techniques used in this study. A detailed account of the each analysis used is discussed in the sections below. Wet and dry spells, onset dates and cessation dates were identified using CMAP and station data. In order to use the daily station data, it was first interpolated to a 2.5 ×2.5 degree grid using Cressman interpolation (Cressman, 1959) and then averaged to produce the gridded pentad (5 day means) data.

3.2.1 Derived parameters

3.2.1.1 Station data interpolation

The interpolation is done with the help of the Grid Analysis Display System (GrADS). Station data was first written to a binary file one report at a time. The groups of station reports are ordered and added within the file according to the time interval and a special header is written to indicate the end of the time group. With the data written out in a binary file, gridded station data sets are created using a C program. Finally, station data descriptor file is written and stnmap utility is run. The stnmap writes out information that allows GrADS to access the station report data more efficiently.

3.2.1.2 Calculation of dry and wet spells

Using equation 3.1, dry spells were calculated in GrADS as a pentad with less than 5mm of rainfall as from the definition of Usman and Reason (2004). Pentads with rainfall above 10mm were defined as wet spells (equation 3.2). An area average was done on the pentad dry and wet spell data over the southern and northern regions of the country to obtain the time series plots.

dry spell=const (const(maskout (p,-(p-1)),1),0,-u) (equation 3.1)

wet spell=const (const (maskout (p,(p-2)),1),0,-u) (equation 3.2)

where: p = precipitation parameter

-u = sets all missing data to 0; non-missing data are unchanged

The const function is used to calculate areas covered by precipitation less than 1mm/day (5mm/pentad). The dry spell variable contains 1 wherever the precipitation value is less than 1mm/day (5mm/pentad), and 0 whenever the precipitation value is greater than 1mm/day. The utility of this threshold is corroborated by the use of 1mm daily rainfall total as a threshold minimum for light rainfall events in the analysis by Tennant and Hewitson (2002). This is done via nested functions by first using maskout which sets all values greater than 1 to missing, then const sets all non-missing values to 1, then the other const is used with the -u flag to set all the missing data values to 0. The same procedure is used to calculate wet spells by redefining the threshold to be above 2mm/day (10mm/pentad).

A time series of area-averaged dry and wet spells over the region is created from the gridded CMAP and station data sets and used to assess the dry and wet spell variability.

The rectangular grid area of 8°S–18°S, 22°E–34°E was found to enclose most of the Zambian summer rainfall region, from inspection of the 22 year DJF rainfall climatology. The DJF 22 year time series of mean area-average rainfall over the southern and northern parts of Zambia (Figure 1.3) shows substantial interannual variability. On the basis of the dry spell time series outline above, extreme dry spells and wet spells were chosen during the study period for both data sets and then further analysed by relating them to the Niño3.4 time series index.

3.2.1.3 Onset date derivation

The onset of growing season was defined as the first dekad with a total rainfall of 25mm and followed by two dekads with a total of at least 20mm of rainfall as from the AGRHYMET (1996) definition. Onset dates were calculated for both data sets. Gridded rainfall data reports for each season were created starting from the 3rd of August of each year. With the data for each season written out in a separate file, a C program (see appendix) was run in order to count the onset dates of a growing season using the above definition during each season across Zambia. Finally, the files were added and a new data file with onset dates was created. An area average time series was created from 1979 to 2001 and correlated with the DJF Niño3.4 SST anomalies.

3.2.2 Intraseasonal / interannual analysis

3.2.2.1 Time series analysis

Both dry and wet spells and onset dates were subjected to time series analysis in order to examine their intraseasonal and interannual variability. Mean values and anomalies of dry and wet spells and onset dates over the southwestern, southeastern, northeastern and northwestern parts were calculated using pentad area average data. Deviations from the 1979-2002 mean are used to identify extreme seasons and for the diagnosis of the impacts of ENSO events over Zambia.

3.2.2.2 Statistical analysis

Statistical analysis was performed on daily data so as to extract the duration of dry spells within each season defined in the months of December, January and February. The range used when processing rainfall data to give dry spells was between 0 to 1mm per day, which defines all days with less than 1mm as dry spells as per Usman and Reason (2004). This threshold is used in all the dry spell analysis in this study although it should be noted that if a higher threshold such as 2 mm is considered, then the number of dry spells will increase substantially. The results give the longest spell length within each period that is specified, as shown in section 4.1. It should be noted that the dry spell duration for each month were treated separately thus slight errors might have occurred for dry spells which crossed the monthly boundary.

3.2.2.3 Composite analyses

Composites of SST and atmospheric parameters associated with seasons showing high dry/wet spell frequency and early/late onset dates were analysed. Composite analysis is useful for indicating pronounced and common features or patterns in the variables and also reduces the total number of maps and figures associated with each case study. Cases with similar characteristics should be selected when doing the composite. However, the analysis of individual cases shows that not all high dry/wet spell years or early/late onset years have the same characteristics and thus some individual cases were also examined.

3.2.2.4 Cross- Section Analysis

Cross section analysis is used to examine the vertical structure of moisture flux associated with dry/wet spell and onset events under study. Cross section analysis of moisture anomalies was used in the thesis to study the source of moisture flux during early and late onset years of Zambia. The longitude height section was averaged over latitude 5°S and 30°S while the latitude height section was fixed at longitude 20°E and 34°E.

3.2.3 Moisture flux

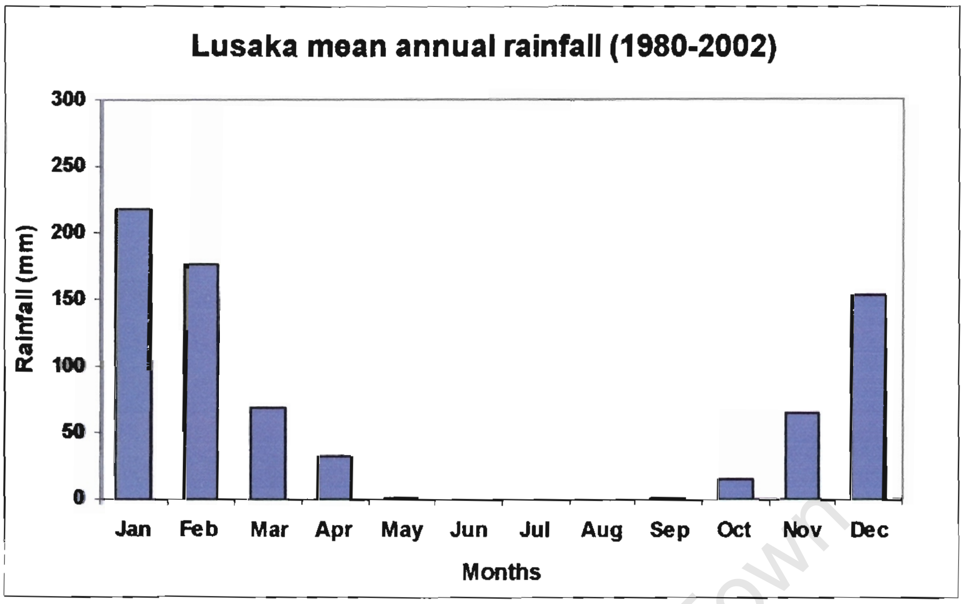
The moisture transport from the NCEP reanalysis data over southern Africa and the adjacent oceans is calculated as the product of specific humidity *(q)* and winds *(u, v)*, giving a vector *(qu, qv)* for 8 pressure levels from 1000hPa to 300hPa. In this study, the 850hPa and 350hPa level data were used to analyse the moisture fluxes during extreme seasons. Anomaly plots were calculated using a 20 year monthly climatology (1979–1999), since the NCEP data is less reliable before 1979 due to a relative lack of observations over the Southern Hemisphere (Kalnay *et al.*, 1996).

3.2.4 Velocity potential

Velocity potential is a measure of divergent flow and is often used to understand the behaviour of the Walker Circulation. Velocity potential anomaly composites during years with high dry/wet spells were plotted at .2101 and .995sigma levels from the Climate Diagnosis Center website (http://www.cdc.noaa.gov/). Negative values indicate rising motion and positive values sinking motion. On average, the Walker Circulation of the Pacific is seen as rising motion over the western Pacific, Indonesia and northern Australia and sinking motion over the Americas and Africa.

3.2.5 Sea Surface Temperatures

The Niño3.4 index is often used as an index of ENSO and is defined as the SST averaged over the tropical Pacific Ocean over the domain 5N-5S, 170W-120W. This index has been previously used in the study of rainfall behaviour over southern Africa (e.g. Usman and Reason, 2004). El Niños are characterised by warmer than average sea surface temperatures (SSTs) in the tropical Pacific and tend to lead to reduced summer rainfall over southern Africa. The Niño3.4 anomalies used were obtained from the CDC web page.



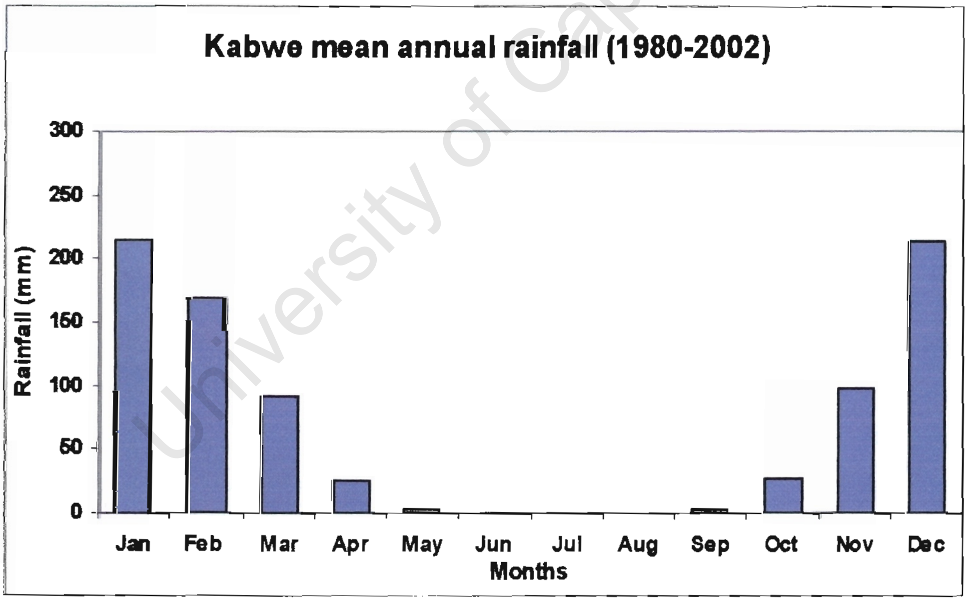
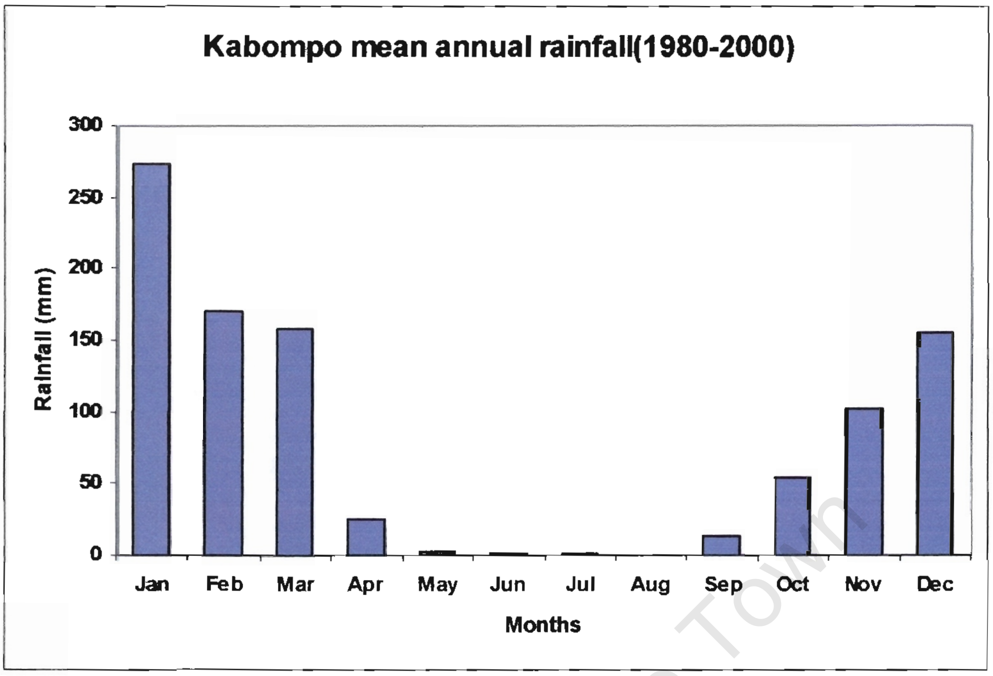


Figure 3.2a: Central region mean annual rainfall



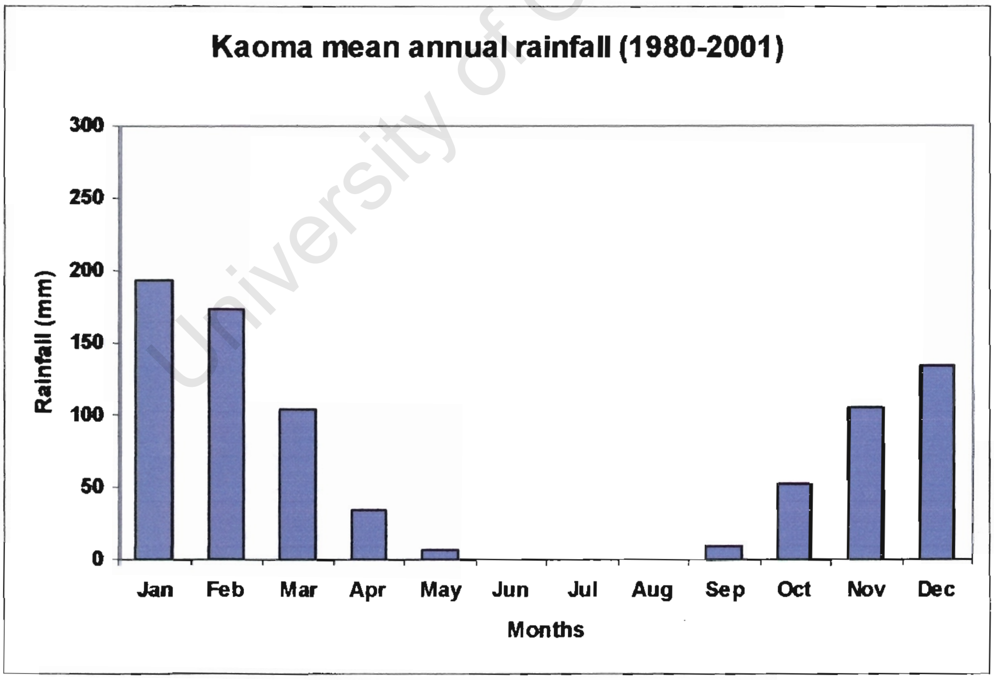
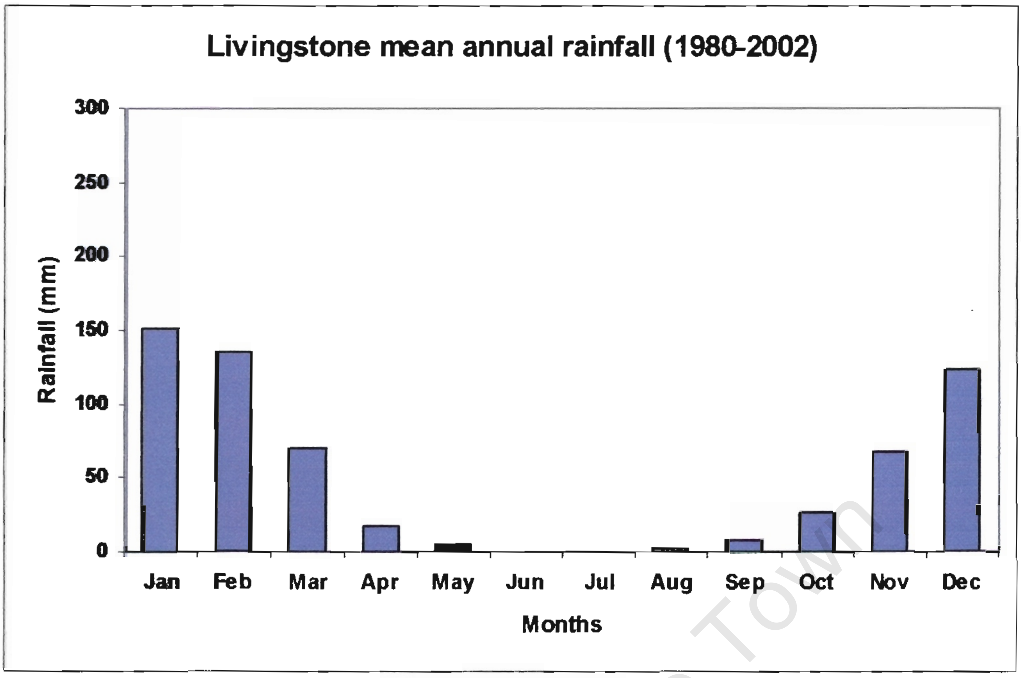


Figure 3.2b: Western region mean annual rainfall



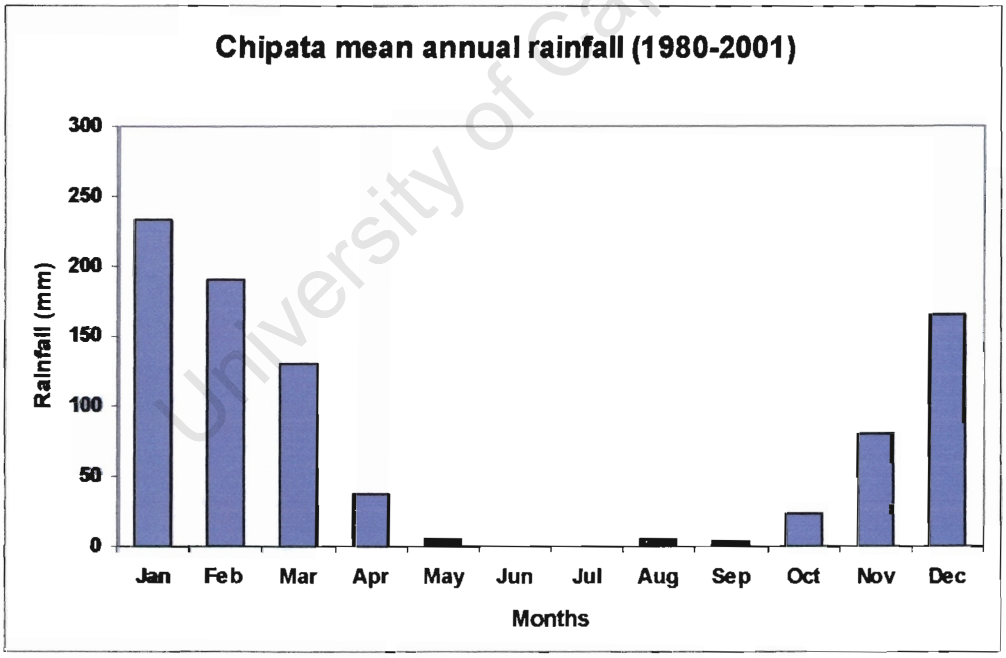


Figure 3.2c: Southern and Eastern region mean annual rainfall

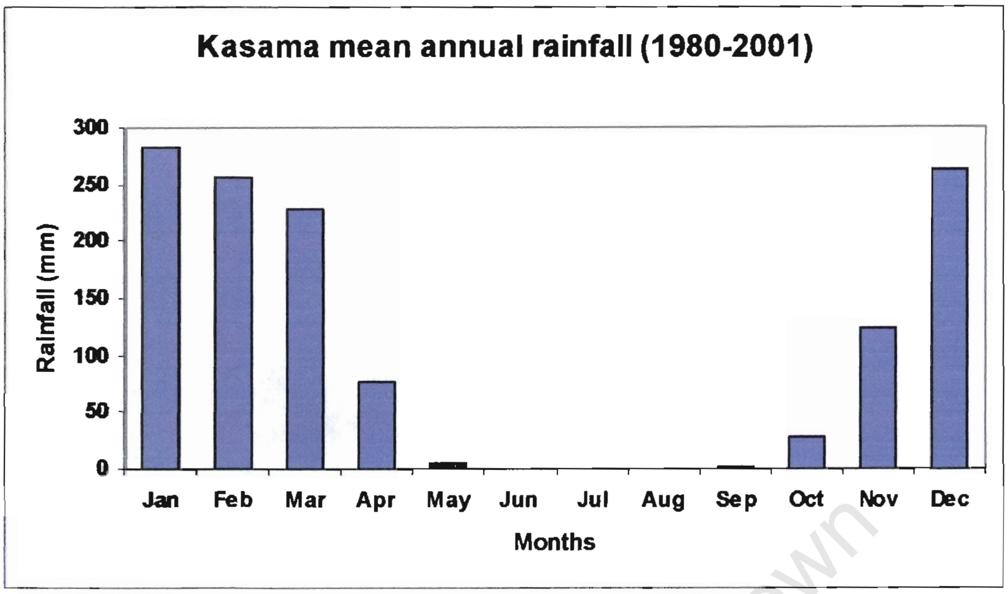


Figure 3.2d: Northern region mean annual rainfall

Chapter 4

Dry and wet spells

4.1 Introduction

This chapter gives a detailed analysis of dry and wet spells over Zambia and examines the circulation anomalies associated with seasons of high occurrence of these spells. The relationship between variability in dry spell frequency and Niño3.4 region sea surface temperatures (SSTs) is also considered. Composite anomalies in wind fields, moisture flux, geopotential height, velocity potential and sea surface temperature are derived for the seasons with high number of dry and wet spells.

A dry spell is not a drought of climatic magnitude but a period of a several days or a few weeks with rainfall below a defined amount. In this thesis, a dry spell is defined as a pentad with less than 5mm of rainfall (Usman and Reason, 2004) and a wet spell as a pentad with more than 10mm of rainfall. Chapter 3 (Data and methodology) gives a detailed account of how these spells have been calculated. The months of December, January and February are focused on in this chapter mainly because of their relevance as the peak of the growing season and because this is when ENSO impacts over southern Africa reach their maximum strength (Usman and Reason, 2004).

Persistent dry spells have historically caused direct and indirect economic, social, and environmental problems over Africa. Crop production in most regions has been very poor and well below average during years with a high number of dry spells during the so-called wet season. In a study over East Africa, Stewart (1988) found that dry spell-induced crop shortages occurred once or twice every 5 years. Persistent wet spells may lead to flooding in areas over southern Africa causing crop failure in most cases (FAO/WFP, 1998). The dry and wet spells that are analysed in this thesis relate directly to agricultural impacts as their frequency and duration indicate the degree of stress plants are exposed to. Rather than looking at rainfall totals, this chapter examines rainfall variability in terms of pentad and daily data because of its significance on rain-fed agriculture. A good crop yield is more likely with uniformly spread light rains than with a few heavy rains interrupted by dry periods.

4.2 Dry spell frequency analysis

4.2.1 Analysis of mean dry spell frequency

The average DJF dry spell frequency during the period 1979-2001 is shown in Figure 4.1. Dry spell frequencies can be categorized into three regions across Zambia depending on the intensity of the spells. The highest frequencies are seen over the southernmost part of the country, between latitudes 17°S – 18°S. A moderate number of dry spells occurs between latitudes 15°S-17°S, whereas the northern part (8°S-15°S) has the lowest dry spell frequencies on average during the study period. In order to obtain insight into how the dry spells are distributed during the summer season, a year to year analysis of dry spell anomalies was done. Both station and CMAP pentad rainfall data are used in parallel to derive dry and wet spell frequencies for the DJF season.

4.2.2 Analysis of episodic dry spell events from 1979/1980 to 2000/2001 season

In this section, dry spells will be analysed on a year to year basis over the 22-year study period using both CMAP and station data. Both data sets show similar trends of dry spells across most parts of the country; however some differences are seen over the south eastern regions, with station data showing high number of dry spells as compared to CMAP. Figure 4.2 shows DJF dry spell frequencies for each season during the study period (1979/80 -2001/02). The southern part of Zambia (15°S-18°S) is clearly marked by a high number of dry spells during the 1979/1980, 1982/83, 1983/84 1986/87, 1991/92, 1994/95 and 1997/98 seasons. Five of these seven seasons correspond to El Niño years. The southern tip (17.5°-18°S) had an average of five pentads of dry spells during DJF with highest frequency being observed during the 1986/87 season in both data sets. However, for 1982, station data showed a high number of dry spells (above six pentads) over the southeastern parts of the country whereas CMAP data only shows two pentads. In addition, the seasons mentioned above share a common feature in the existence of a maximum in the dry spell frequency near the border with Zimbabwe. The lowest number of dry spells over the southern region occurred during 1980/81, 1987/88, 1988/89, 1995/96 and 1996/97 when less than two dry spells occurred.

On the other hand, the northern region of the country (8°S-15°S) is virtually free of dry spells during all seasons under study. An exception is 1999/2000, which had more than five dry spells. As argued later, this increase in dry spells may have occurred as a result of tropical cyclone activity (e.g., Tropical Cyclone Eline) during this season and a southward shift of the main rainy belt over southern Africa. The low number of dry spell incidences during most seasons over this northern region is likely due to the ITCZ which lies across the region in summer and the ongoing input of moist air from the Indian Ocean during the season.

From the discussion in the previous section, it is observed that high dry spell frequencies occur over the southern part of the country between latitude 17.5°S and 18°S while the northern part has a low number of dry spells during the study period. The other part with relatively high but variable frequency of dry spell occurrences exists over the southeast of Zambia. These findings may suggest that the two areas are characterised by two different climate regimes. To get more insight into the intensity and duration of dry spell, the following section discusses dry spell characteristics for selected stations over Zambia using daily rainfall station data.

4.3 Statistical analysis of dry spells

A detailed analysis of dry spells will be done in this section for seasons with a higher than average number of dry spells. This is done in order to have an accurate insight into the intensity and duration of dry spells. The criterion for the selection of stations used in this statistical analysis was subjective mainly due to two considerations; firstly the data sets available at the chosen stations are subjectively robust and hence reliable, and secondly, the intention was to establish the duration of dry spell with high accuracy, which in view of the obtained results was successful. Daily rainfall data for eight stations was used in the study.

The statistical characteristics of each station used in the analysis are given in Table 4 in terms of the number of dry spells, mean dry spells, duration of dry spells and maximum dry spell duration over four regions. The average number of dry spells during the DJF period over the southern tip of the country (17.5°S-18°S) is four pentads (Figure 4.1). Table 4(a-d) gives the dry spell frequency and duration during El Niño years.

4.3.1 Southern region

This region has the lowest rainfall amount over Zambia with mean rainfall totals of less than 600mm during the season. Livingstone had 5 dry spells during the 1982/83 DJF season with the maximum spell lasting 11 days in January (Table 4a). During 1986/87, the longest dry spell was 15 days and it occurred in December while 1991/92 had one of the most severe dry spell seasons with a maximum duration of 23 days over Choma in February. Livingstone had the longest dry spell during the 1994/95 season with a maximum duration of 12 days and 1997/98 had 6 dry spells with the maximum lasting 15 days in Livingstone. In terms of dry spell frequency, the 1997/98 season was the worst at both Livingstone and Choma.

4.3.2 Eastern region

The mean annual rainfall total over this region is between 900mm-1100mm (Figure 1.2) and it experiences between 1 and 3 pentads of dry spells on average during DJF (Figure 4.1). During the 1982/83 season, the longest dry spell over the eastern region was 12 days in Chipata in February (Table 4b) and 2 dry spells were experienced. During 1986/87, the maximum dry spell duration was 10 days in February over Lundazi; however, Chipata experienced more dry spells. The 1991/92 season showed 2 dry spells during DJF with a maximum duration of 16 days over Chipata. The longest dry spells during the 1994/95 and 1997/98 seasons were 14 days and 8 days respectively in Chipata. Long dry spell durations are mostly observed during January and February over this region. In general,

Table 4b suggests that 1991/92 and 1997/98 showed the most severe dry spell characteristics over the eastern region.

4.3.3 Northern region

This region typically has less than 2 dry spells during the summer season. With the exception of the 1982/83 season, which had dry spell duration of 11 days in January at Isoka (Table 4c), the duration of dry spells in all seasons is less than 6 days.

4.3.4 Western region

This region receives more than 1200mm of total rainfall during the year. The mean number of dry spells in DJF is between 1 and 4 pentads. In 1982/83, 4 dry spells were observed in Kaoma and Kabompo with the longest having a maximum duration of 16 days in February at Kaoma. The 1991/92 season showed 3 dry spells at Kaoma but 5 dry spells at Kabompo although the maximum dry spell duration was less than for 1982/83, 1986/87 and 1997/98. No dry spell occurred in Kaoma during 1994/95 season though some were recorded over Kabompo with a maximum duration of 8 days. In the 1997/98 season, 2 dry spells were recorded in Kaoma with duration of 10 days in January.

From the above discussion it can be concluded that the southern region not only has above average dry spell frequency during the El Niño years but also has relatively long dry spell durations. Long dry spells appear to be more frequent during January and February over this region. On the other hand, the northern part of Zambia seems to be rarely affected by severe dry spells. The next section gives an analysis on the relationship between dry spells and Niño3.4 SST anomalies.

4.4 Niño 3.4 SST -Dry spell relationships

Previous studies (e.g. Walker, 1990; Mason, 1995; Behera and Yamagata, 2001; Reason and Mulenga, 1999; Reason, 2001) have shown links between austral summer rainfall and SSTs over the South Indian Ocean. Some regions, particularly the southwest Indian

Ocean and the western tropical Indian Ocean north of Madagascar were found to be important for southern African rainfall variability. Some of this SST variability may be related to ENSO (Hermes and Reason, 2005). Given the strong relationship between Niño3.4 SST and dry spells over southern Africa as a whole, this section looks at the possible relationship between Niño3.4 (SST) anomalies and dry spell anomalies in Zambia for the DJF season during the 1979-2002 period.

A time series of dry spell occurrences for DJF was generated and then analysed in order to identify high dry spell years. Deviations from the 1979-2001 mean are used to identify extreme seasons and for the diagnosis of the impacts of ENSO events. Standardized dry spell frequency time series anomalies and Niño.3.4 SST anomalies were used in this analysis. Figure 4.3 shows the relationship between DJF Niño3.4 SST anomalies and dry spell frequency anomalies averaged over the entire country during the1979-2001 period. Based on their significant departures in the Southern Oscillation Index (SOI) and in central and eastern equatorial Pacific SSTs, El Niño years are considered to be 1982/83, 1986/87, 1991/92, 1994/95 and 1997/98 (Reason *et al.*, 2000). Figure 4.3a shows a strong in phase relationship between anomalies in dry spell frequency and Niño3.4 SSTs. Thus, during El Niño (La Niña) events, increased (decreased) dry spell frequency tends to occur over Zambia. High dry spell years (above 0.5 deviations) are observed during all the El Niño years as well as the non-El Niño seasons of 1979/80 and 1999/2000. The year with the largest number of dry spells in the CMAP time series corresponds to the 1997/98 El Niño season whereas the station time series it is 1982/83. Although some differences exist between the CMAP and station data derived dry spell time series in Figure 4.3, the general relationship with Niño3.4 is coherent and robust in both data sets. Note that the time axis is not the same as the station data only extends to 1999/2000 whereas the CMAP data goes to 2001/02.

Figure 4.4 plots the DJF dry spell anomalies against Niño3.4 SST anomalies for the southern region (15°S to 18°S) and northern region (8°S to 15°S) of Zambia during the period. A better relationship with Niño3.4 SST is observed over the southern parts of the country in both data sets than for the northern regions. This result suggests that the southern region is more prone to ENSO impacts on rainfall.

Although it is evident that most of southern Africa typically receives below-average rainfall during El Niño seasons and La Niña usually brings average or above-average rainfall, this situation does not always apply for the northern part of Zambia. For example, the 1997/98 El Niño was one of the strongest on record, but the northern region received average to above average rainfall. The different climatic conditions over the northern part could be due to the influence of the ITCZ and the fact that the high pressure anomalies that establish themselves over southern Africa during El Niño years (Reason *et al.,* 2000) do not extend deep into the tropics. Thus the relationship between Niño 3.4 SSTs and dry spell frequency anomaly is far weaker for the northern region (Figure 4.4).

The strong relationship apparent in Figure 4.3 suggests that monitoring Niño3.4 SSTs may help in the prediction of dry spells over the southern part of Zambia which is a maize growing area. Since the Niño3.4 SST index can be predicted with improved accuracy several months before the start of a growing season, it may be used as an indication of the likely behaviour of dry spell frequency that will prevail over country during the forth-coming season. This could help farmers plan for the growing season. In addition, Figure 4.3 shows that the statistical links between Niño3.4 SSTs and southern African dry spells derived by Usman and Reason (2004) also holds true for smaller regions such as southern Zambia.

4.5 Wet spell frequency analysis

Apart from having severe dry spells over the southern half of the country, Zambia experiences a high number of wet spells over the northern regions which in most cases lead to flooding e.g. during the 1997/98 season crop production in western province was reduced due to a combination of below average rainfall and flooding on the plains which are the most productive areas (FAO/WFP, 1998). During most of these extreme wet spell seasons, crop production has been significantly reduced due to continuous heavy rains, e.g. crops are washed away or fail due to over saturation of soil. The distribution of wet spells during the DJF austral summer over Zambia will be analysed and then related to Niño3.4 SST anomalies.

Few studies have been done on wet spells over the region. In studying the circulation anomalies associated with synoptic wet spells over South Africa, Cook *et al.,* (2004) found these spells to be associated with increased moisture flux from the tropical or subtropical southwest Indian Ocean (SWIO) together with ridging along the east coast or a deep low over the interior. The characteristics of DJF wet spell frequencies over Zambia are analysed in this section. In this study a threshold of 2mm/day is used for the analysis of wet spells. A wet spell is defined as a pentad with more than 10mm of rainfall. It should however be noted that increasing the threshold of rainfall to above 10mm would reduce the wet spell counts over a given area.

Figure 4.5 shows the number of wet spells for each DJF season during the 1979/80 to 2001/2002 period as derived from CMAP data. The extreme wet spell summers are considered to be 1985/86, 1988/89, 1989/90, 1992/93, 1995/96, 1996/97 and 2000/01. During the extreme wet spell seasons, the highest number of wet spells tends to occur over the northwestern and northeastern region of the country. Figure 4.5 also shows that most of northern Zambia tends to be wet during most DJF seasons since the average wet spell frequency across the region during the season is 15 pentads out of a total of 18. Figure 4.6 shows how the DJF wet spell anomalies change as the definition of wet spell is varied. When the threshold is raised to 15mm/pentad (3mm/day) or 4mm/day, then the number of anomalous wet spell seasons reduces substantially.

4.6 Niño 3.4 -Wet spell relation

Figure 4.7a suggests that an inverse relationship exists between anomalies in the DJF frequency of wet spells averaged over Zambia and Niño3.4 SST anomalies for 1979-2001. A reduced number of wet spells is observed during all El Niño years. An increase in the number of wet spells is observed during the 1985/86, 1988/89, 1989/90, 1992/93, 1995/96 and 1996/97 seasons. Of these, 1988/89 and 1995/96 were La Niña years. Not all seasons of higher wet spell frequency are associated with La Niña events indicting that other factors are also important. The 1998-2001, protracted La Niña only shows an above average number of wet spells during the 2000/01 season. However, the reduced number during the 1999/00 season may be because countries further south (Zimbabwe, Mozambique, northern South Africa) received well above average rainfall, inducing floods during this season (Dyson and Van Heerden, 2000; Reason and Keibel, 2004) and therefore the main rain belt may have shifted south of Zambia. Figure 4.7b shows the relationship between Niño3.4 SST anomalies and DJF wet spell anomalies for various regions over Zambia. A strong inverse relationship is observed over the southwestern (22°E-30°E, 15°S-18°S) and southeastern regions (30°E-34°E, 15°S-18°S) of the country whereas for the northern regions, the link with ENSO is less obvious. All El Niño years are observed to have below average wet spell frequency in the southern regions while the 1995/96 and 1998/99 La Niña years show above average wet spells.

4.7 Circulation Climatology

Before discussing the circulation anomalies associated with seasons of above average wet or dry spells, this section will give a brief analysis of the mean circulation fields responsible for rainfall over Zambia. Figure 4.8(a-b) illustrates monthly and seasonal climatology plots for selected parameters used in the study. The climatology is calculated for the 1979-1999 period. The monthly means are analysed and used in order to help understand the evolution of composite anomalies used during years with above average dry and wet spells. From previous studies it has been shown that during the southern summer (Taljaard, 1994), the ITCZ oscillates over Zambia bringing in rainfall over most parts of the country. It has already been established that the Angola low facilitates the mechanisms that bring substantial amount of rainfall during the austral summer season over the region (Mulenga, 1998; Cook *et al.*, 2004).

At the 850hPa level, the mean DJF moisture flux climatology over southern Africa is characterized by a northeasterly monsoonal flow from the northwest Indian Ocean, a southeasterly flow over Zimbabwe and southern Mozambique from the South West Indian Ocean and a cyclonic flow over southern Angola and northern Namibia emanating from the tropical southeast Atlantic. These three moisture inflows tend to converge over central Zambia and play a significant role in contributing to summer rainfall over the country. The three moisture inflows are noticeably weaker in December than January and February and this helps explain why most of the station rainfall plotted in chapter 3 (Figure 3.2) shows a significant increase in rainfall from December to January. The tropical easterly jet dominates the circulation in the upper levels over low latitude Africa with the subtropical westerly jet apparent south of 25°S.

In December, it is evident (Figure 4.8a) that, compared to the DJF average, the cyclonic flow over southern Angola is weak as is the easterly flow over the South Indian Ocean. The South Indian Ocean anticyclone has not shifted to its southernmost position so some trade wind flow occurs over the northern Mozambique Channel towards Zambia. December rainfall is mostly influenced by the northeasterly monsoonal inflow from the northwest Indian Ocean. In January, the low level cyclonic circulation over Angola strengthens and penetrates into central Zambia while over the South Indian Ocean, the trade wind flow over the northern Mozambique Channel is replaced by monsoonal westerlies. This situation is similar in February when much of the late summer rainfall is due to the location and intensity of the tropical Angola low. The upper level circulation over tropical Africa continues to be dominated by the tropical easterly jet.

The DJF mean wind climatology (Figure 4.8b) is very similar to the moisture flux except that circulation features over cool (warm) ocean areas such as the Benguela upwelling system (tropical western Indian Ocean) stand out more since the wind field is not biased by the humidity field unlike the moisture flux.

The mean velocity potential gives an indication of the vertical overturning in the atmosphere associated with the Walker Circulation. Taken together, the lower and upper level plots (Figure 4.8a) show that the ascending branch of the Walker Circulation is located over northern Australia and Indonesia during DJF with descent over the eastern

Pacific. In the African region, relatively weak ascent occurs over the western Indian Ocean and eastern landmass with subsiding motion over the southeast Atlantic and western landmass.

4.8 Circulation anomaly composites

This section analyses circulation anomaly composites associated with seasons with an above average number of dry/wet spells over Zambia. Wind fields, moisture flux, geopotential height and velocity potential anomaly composites at 850hPa and 350hPa levels are analysed. Anomalously high dry spell years (Figure 4.3c) are considered to be 1982/83, 1986/87, 1991/92, 1994/95, 1997/98 (all El Niño years) and the non-El Niño years of 1979/80 and 1999/2000. Seasons with above average frequency in wet spells are considered to be 1985/86, 1988/89, 1989/90, 1992/93 and 1995/96. It was observed in section 4.3 that the variability in the spells is more significant south of latitude 15°S and therefore the chosen dry spell years refer to southern Zambia. The highest dry spell frequencies occurred during 1982/83 and 1991/92 seasons as seen in Figure 4.3.

4.8.1 Circulation anomalies composites during high dry spell years

Since most of the high dry spell frequency years occur during El Niño, those seasons are composited and the non-El Niño high dry spell frequency seasons of 1979/80 and 1999/00 are considered separately. During DJF seasons with anomalously high dry spells, Figure 4.9a shows southeasterly anomalies in the Mozambique Channel and a strong cyclonic (anticyclonic) anomaly over the subtropical South Indian (central tropical Indian Ocean). The anomalies reflect the high pressure anomaly that extends from Australia during the El Niño mature phase (Reason *et al.*, 2000) and suggest that the ascending branch of the Walker Circulation is shifted offshore. A similar anomaly pattern was also found for El Niño years by Goddard and Graham (1999). Easterly anomalies over Zambia imply reduced moisture penetration from the Angola low and less low level moisture convergence over the country and hence increased dry spells. The upper level flow over tropical Africa is characterised by strong westerly anomalies from the South Atlantic

Ocean and hence a weaker tropical easterly jet. Positive geopotential height anomalies observed at 850hPa over the sub-continent imply relative subsidence and reduced convection. SST anomalies (Figure 4.9; bottom left) are warm in the tropical Indian Ocean, a pattern that is unfavourable for high rainfall over Zambia since it implies more convection over the Indian Ocean and less over southern Africa.

Figures 4.9(b-d) suggest that the circulation anomalies over the South Indian Ocean described above for DJF (Figure 4.9a) are mostly contributed to by those seen in December (Figure 4.9b) and February (Figure 4.9d). In January, the anticyclonic anomaly over the South Indian Ocean extends over the entire basin and well into southern Africa (Figure 4.9c) suppressing convection over the region.

The high dry spell years are characterised by weak low level easterly anomalies in the moisture flux over the northern parts of the country whereas the southern region (15°S-18°S) is characterised by weaker and more variable anomalies. The moisture flux transect at 34°E reflects these easterly anomalies over eastern Zambia whereas that at 20°E suggests a weakening of the Angola low. Taken together, the plots imply less low level convergence over Zambia and increased dry spells. The velocity potential anomalies for DJF (Figure 4.8e) suggest that the main branch of the Walker Circulation shifts east from northern Australia / Indonesia into the central Pacific. In the African region, relative ascent is seen over the western Indian Ocean. Comparing the plots for the individual months suggests that the anomalies in the African region are strongest in December and February.

The non-El Niño seasons with high dry spell frequency (1979/80 and 1999/00) are now considered separately. During 1979/80, the 850hPa geopotential height anomaly (Figure 4.9f) shows strong anticyclonic conditions right across tropical southern Africa with a low pressure anomaly just east of Madagascar. These anomalies suggest that the Angola low and terrestrial ITCZ were weaker whereas the marine ITCZ in the tropical South West Indian Ocean was stronger, implying an offshore shift of the local Walker Circulation. As a result, Zambia experienced increased dry spells during this season.

On the other hand, 1999/2000 shows an area of low pressure anomaly at 850hPa (Figure 4.9f) stretching across southern Africa from southern Angola to Zimbabwe and central Mozambique whereas northern Zambia shows weakly positive height anomalies. Although this cyclonic anomaly might suggest reduced dry spells over Zambia, in fact this did not happen. Most of the DJF seasonal anomaly is contributed to by a few strong tropical depressions (including Tropical Cyclone Eline) that tracked across Mozambique, Zimbabwe into southern Angola and northern Namibia with severe flooding in northern South Africa and southern Mozambique (Dyson and Van Heerden, 2000; Reason and Keibel, 2004). The outflow from these depressions led to relative subsidence over Zambia and an increase in dry spells. Note that the cyclonic conditions were confined to January and February 2000, December 1999 (appendix) showed average or positive height anomalies over Zambia.

4.8.2 Circulation anomalies during years with above average number of wet spells

This section will analyse circulation anomalies during seasons with above average number of wet spells. Composite anomalies of wind, moisture flux, geopotontial height, SST and velocity potential at different pressure levels are analysed.

The DJF composite anomalies (Figure 4.10) highlight the importance of the Angola low and its linkage with the meridional arm of the ITCZ over Zambia for seasons with above average wet spells over Zambia. Positive SST anomalies (Figure 4.10, bottom left) over the tropical South East Atlantic are evident during this period implying increased evaporation of moisture off Angola leading to more moisture import by the Angola low. Strong westerly moisture flux anomalies are evident at 850hPa thereby transporting the moisture over Zambia. These westerly anomalies oppose the mean flow over eastern Zambia, Zimbabwe and Mozambique implying low-level convergence, favourable for increased wet spells. The low level velocity potential anomalies show increased uplift over southern Africa and upper level divergence implying that the ascending limb of the local Walker Circulation is over southern Africa, consistent with the high number of wet spells over Zambia.

To consider how the seasonal anomalies evolve, the monthly plots are now considered. In December, there are easterly anomalies over the tropical western Indian Ocean reducing the export of moisture away from East Africa by the monsoonal westerlies. Westerly anomalies exist over southern Angola and Zambia implying a strong moisture influx from the tropical South East Atlantic and increased convergence over Zambia, consistent with increased wet spells. In addition, cyclonic anomalies are evident in the 850hPa geopotential height field over southern Angola and Namibia implying a stronger Angola low consistent with increased wet spells over Zambia. The moisture flux transect at 20°E shows stronger westerlies over the northern part of the Angola low (near 6°S-15°S). At 34°E, the transect indicates easterly anomalies over Tanzania and westerly anomalies between 16S°-24°S implying low level moisture convergence over Zambia and Zimbabwe.

During January, the Angola low is seen to be substantially stronger and shifted towards western Zambia to join with the ITCZ as evident from the trough at 850hPa located across tropical southern Africa and the Mozambique Channel. As a result, the inflow of tropical moisture from the southeast Atlantic is enhanced over Zambia as evident in the moisture flux transect at 20°E, thereby leading to heavy rainfall over the western regions. This inflow from the Atlantic is further aided by warm SST anomalies off southern Angola and northern Namibia. At 34°E, the moisture flux transect shows low level westerly anomalies over the entire transect north of about 25°S implying deceleration of the easterly flow from the tropical western Indian Ocean, and hence increased convergence over eastern Zambia.

The stronger Angola low and linkage with the ITCZ continues to be evident during February in both the geopotential height anomalies and circulation fields (Figure 4.10d). The center of the low pressure anomaly is located over the borders between Angola, Namibia and Zambia implying a mode of strong convection here and low level convergence between the enhanced moisture flux from the tropical South East Atlantic and that emanating from the western Indian Ocean. The moisture flux transect at 20°E reflects this strong inflow from the South East Atlantic and is consistent with the enhanced number of wet spells over the western and northern parts of Zambia. Ongoing warm SST anomalies over the South East Atlantic Ocean assist the enhanced moisture flux being imported from this region towards Zambia. The velocity potential anomalies (Fig. 4.10e) show a strengthening of the ascending branch of the local Walker Circulation over southern Africa which is particularly apparent in December and February. The plot for February suggests a relative weakening of the ascent in the Pacific Walker Circulation over northern Australia but a strengthening of the Indian Ocean convection (enhanced uplift over southern Africa) consistent with ongoing wet spell conditions over Zambia.

4.9 Summary

Dry/wet spell characteristics for Zambia and their associated circulation anomalies have been analysed. The southern part of Zambia is frequently subjected to seasons with increased dry spell frequency whereas northern Zambia typically has few dry spells during DJF. This decrease of dry spells over the north could be due to the ITCZ which is located over the area during the DJF season. High dry spells over southern Zambia are observed during all El Niño years signifying the influence of this climate mode over Zambia. The northern and western regions of the country are dominated by high wet spells during the summer season. Seasons with above average number of wet spells tend to be those with an enhanced Angola low importing more moisture off the tropical South East Atlantic into the region. In addition, there is often a link between this feature and the ITCZ as well as a reduction in the export of moisture away from East Africa by weaker than average monsoonal westerlies during seasons with increased wet spell frequency.

Table **Southern Region**

Year	**Livingstone**				**Choma**			
1982-83	**Dec**	**Jan**	**Feb**	**DJF**	**Dec**	**Jan**	**Feb**	**DJF**
Number of dry spells (Pentads)	1	2	2	5	1	1	1	3
Mean dry spell duration (Days)	5	11.5	7	7.8	9	5	15	9.6
Max dry spell duration (Days)	5	11	9	11	9	5	15	15
1986-87								
Number of dry spells (Pentads)	1	2	2	5	1	2	1	4
Mean dry spell duration (Days)	15	10	6	10.3	14	8	13	11.6
Max dry spell duration (Days)	15	13	6	15	14	10	13	14
1991-92								
Number of dry spells (Pentads)	1	2	2	5	1	2	1	4
Mean dry spell duration (Days)	5	8	12.5	8.5	7	11	23	13.7
Max dry spell duration (Days)	5	9	14	14	7	16	23	23
1994-95								
Number of dry spells (Pentads)	2	2	1	5	2	2	1	5
Mean dry spell duration (Days)	9	11.5	7	9.1	6.5	7	5	6.2
Max dry spell duration (Days)	12	12	7	12	7	8	5	7
1997-98								
Number of dry spells (Pentads)	3	1	2	6	3	2	2	7
Mean dry spell duration (Days)	7	9	11.5	9.2	7.5	6.5	8	7.3
Max dry spell duration (Days)	9	9	15	15	11	8	11	11

Table 4b **Eastern Region**

Year	**Chipata**				**Lundazi**			
1982-83	**Dec**	**Jan**	**Feb**	**DJF**	**Dec**	**Jan**	**Feb**	**DJF**
Number of dry spells (Pentads)	1	0	1	2	1	2	1	4
Mean dry spell duration (Days)	6	0	12	6	5	6.5	6	5.8
Max dry spell duration (Days)	6	0	12	12	5	7	6	7
1986-87								
Number of dry spells (Pentads)	1	0	2	3	1	1	0	2
Mean dry spell duration (Days)	5	0	5.5	5.25	5	10	0	5
Max dry spell duration (Days)	5	0	6	6	5	10	0	10
1991-92								
Number of dry spells (Pentads)	1	0	1	2	1	2	2	5
Mean dry spell duration (Days)	8	0	16	8	5	5	6.5	5.5
Max dry spell duration (Days)	8	0	16	16	5	5	8	8
1994-95								
Number of dry spells (Pentads)	2	0	1	3	1	0	0	1
Mean dry spell duration (Days)	10	0	5	5	5	0	0	1.6
Max dry spell duration (Days)	14	0	5	14	5	0	0	5

Table 4b continued

1997-98								
Number of dry spells (Pentads)	1	1	2	4	0	0	1	1
Mean dry spell duration (Days)	6	6	7	6.3	0	0	5	1.6
Max dry spell duration (Days)	6	6	8	8	0	0	5	5

Table 4c **Northern Region**

Year	**Isoka**				**Kasama**			
1982-83	**Dec**	**Jan**	**Feb**	**DJF**	**Dec**	**Jan**	**Feb**	**DJF**
Number of dry spells (Pentads)	0	1	1	2	0	0	0	0
Mean dry spell duration (Days)	0	11	6	5.6	0	0	0	0
Max dry spell duration (Days)	0	11	6	11	0	0	0	0
1986-87								
Number of dry spells (Pentads)	0	0	0	0	0	0	0	0
Mean dry spell duration (Days)	0	0	0	0	0	0	0	0
Max dry spell duration (Days)	0	0	0	0	0	0	0	0
1991-92								
Number of dry spells (Pentads)	1	0	1	2	1	0	0	1
Mean dry spell duration (Days)	5	0	5	3.3	5	0	0	1.6
Max dry spell duration (Days)	5	0	5	5	5	0	0	5
1994-95								
Number of dry spells (Pentads)	0	0	0	0	0	0	0	0
Mean dry spell duration (Days)	0	0	0	0	0	0	0	0
Max dry spell duration (Days)	0	0	0	0	0	0	0	0
1997-98								
Number of dry spells (Pentads)	1	0	0	1	0	0	0	0
Mean dry spell duration (Days)	6	0	0	2	0	0	0	0
Max dry spell duration (Days)	6	0	0	6	0	0	0	0

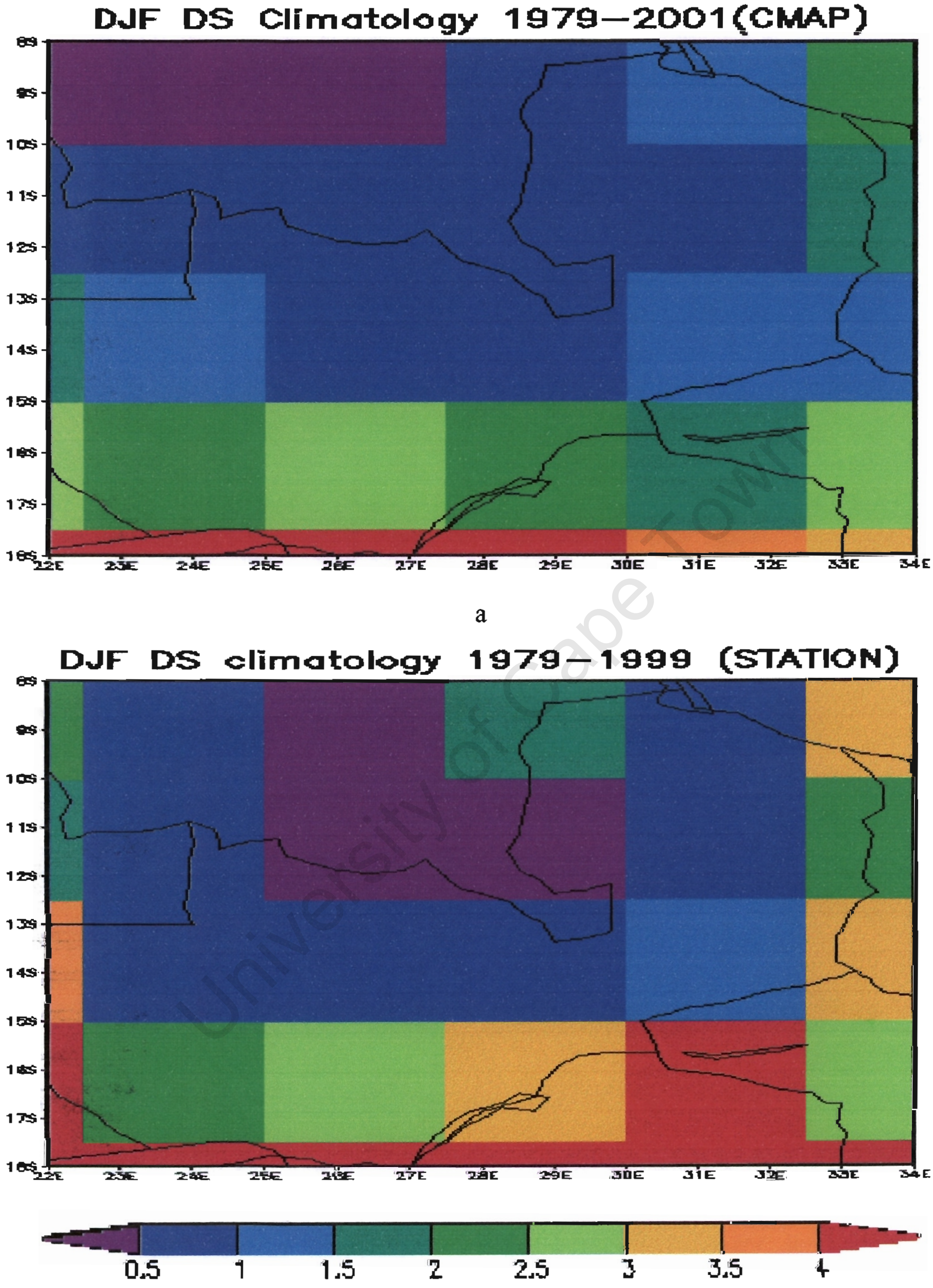
Table 4d **Western Region**

Year	**Kaoma**				**Kabompo**			
1982-83	**Dec**	**Jan**	**Feb**	**DJF**	**Dec**	**Jan**	**Feb**	**DJF**
Number of dry spells (Pentads)	1	1	2	4	2	1	1	4
Mean dry spell duration (Days)	6	6	10.5	7.5	6.5	5	14	8.5
Max dry spell duration (Days)	6	6	16	16	7	5	14	14
1986-87								
Number of dry spells (Pentads)	1	1	0	2	2	0	0	2
Mean dry spell duration (Days)	15	10	0	8.3	6	0	0	3
Max dry spell duration (Days)	15	10	0	15	6	0	0	6
1991-92								
Number of dry spells (Pentads)	0	2	1	3	2	1	2	5
Mean dry spell duration (Days)	0	5.5	5	3.5	5	7	7	6.3
Max dry spell duration (Days)	0	6	5	6	5	7	8	8

Table 4d continued

1994-95								
Number of dry spells (Pentads)	0	0	0	0	1	1	0	2
Mean dry spell duration (Days)	0	0	0	0	7	8	0	5
Max dry spell duration (Days)	0	0	0	0	7	8	0	8
1997-98								
Number of dry spells (Pentads)	0	1	1	2	0	0	1	1
Mean dry spell duration (Days)	0	10	8	6	0	0	7	2.3
Max dry spell duration (Days)	0	10	8	10	0	0	7	7

Table 4(a-d) showing dry spell frequency and duration during El Niño years.



b

Figure 4.1 Mean frequency of dry spells over Zambia averaged over 1979/80 – 1999/00 DJF season; (a) CMAP and (b) Station.

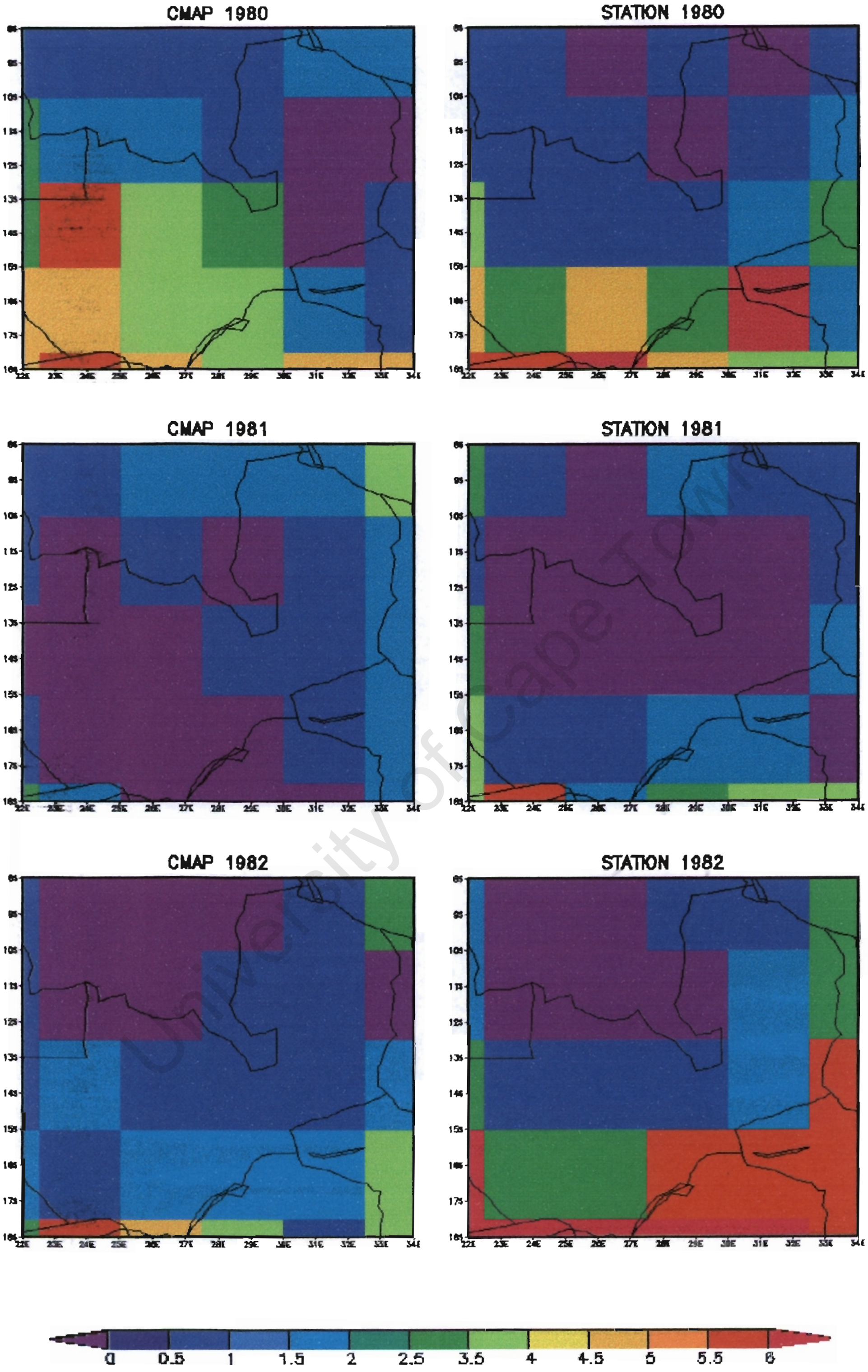


Figure 4.2a: Frequency of dry spell pentads over Zambia; 1980-1982 using both CMAP and Station data.

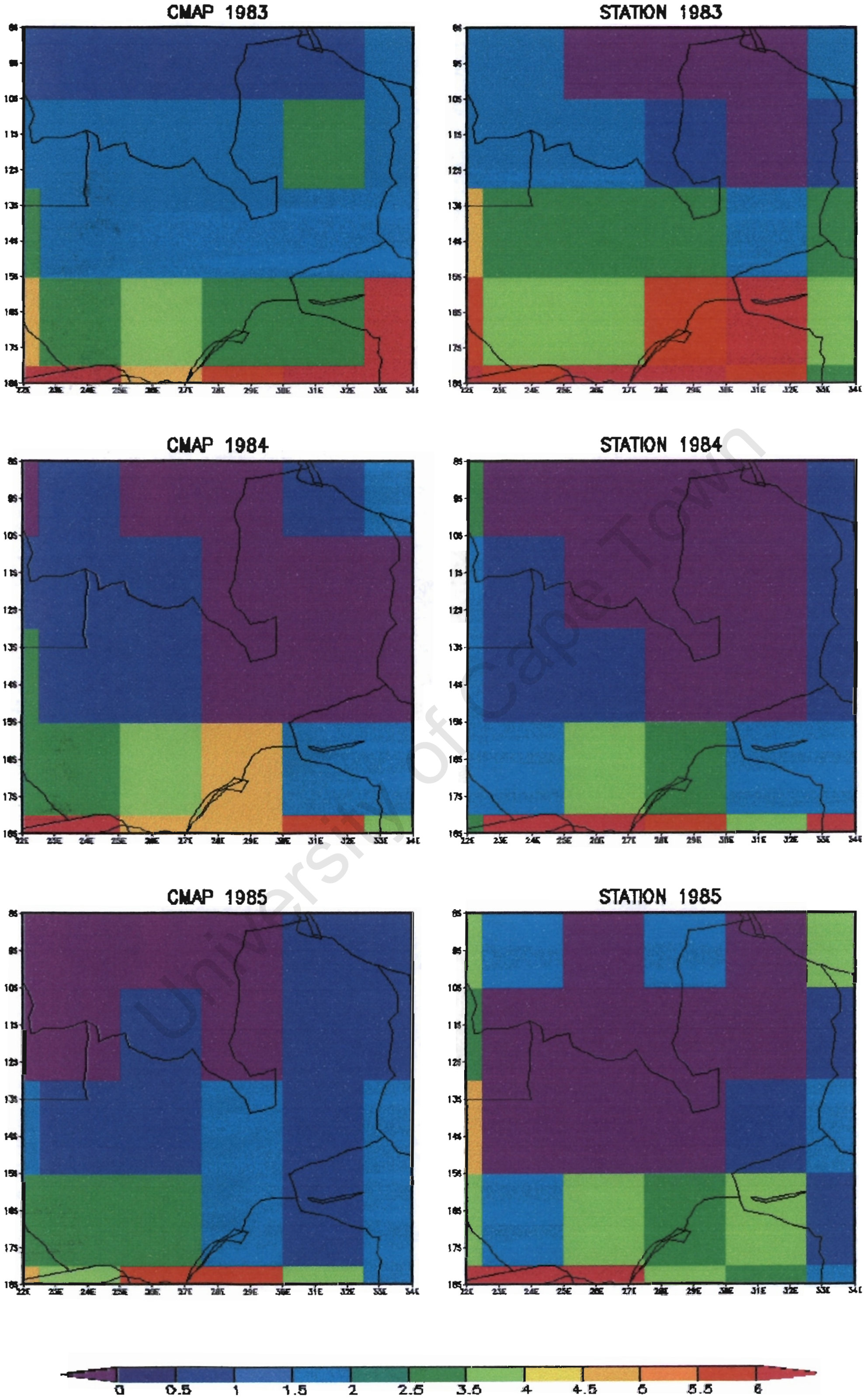


Figure 4.2b: Frequency of dry spell pentads over Zambia; 1983-1985

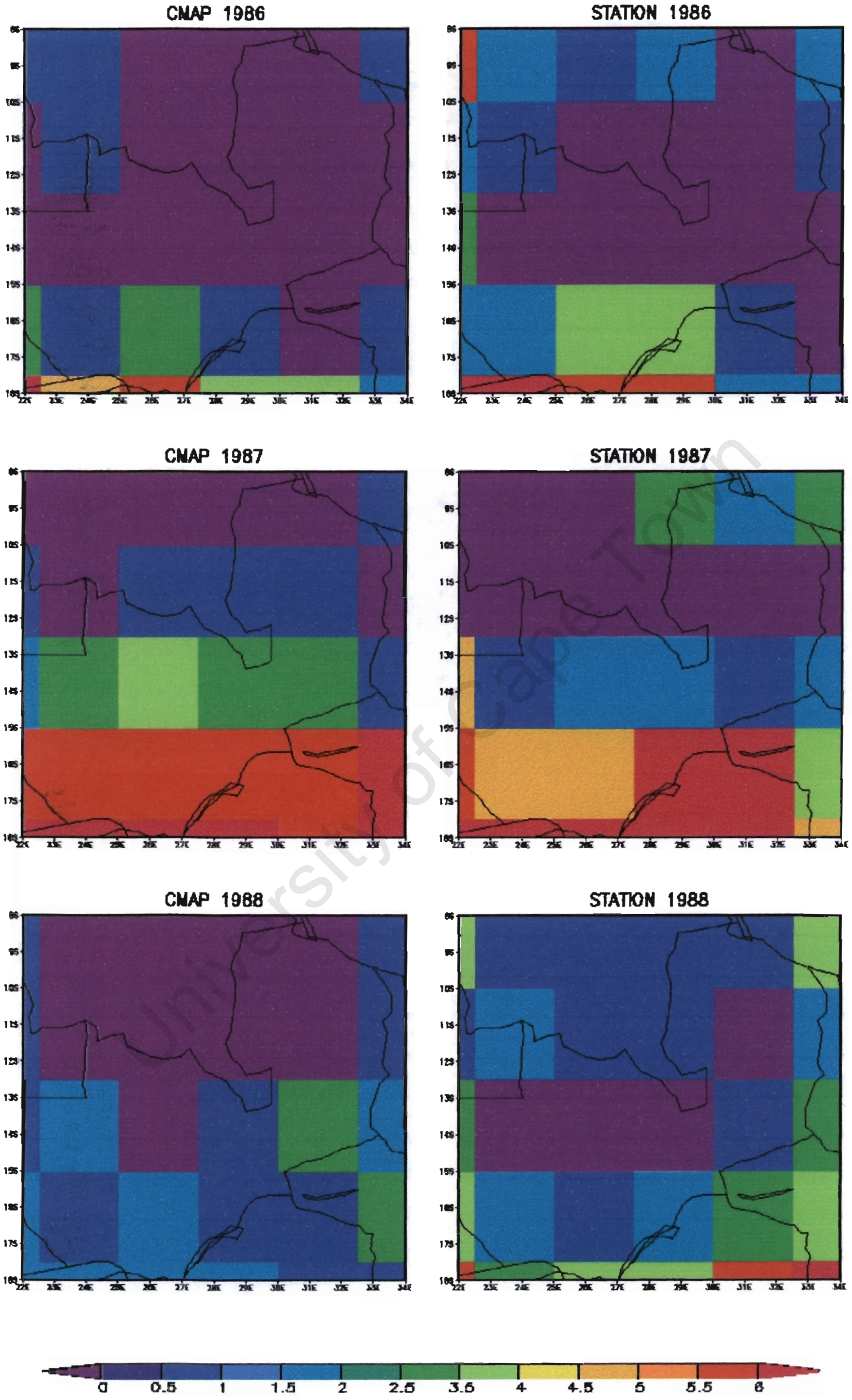


Figure 4.2c: Frequency of dry spell pentads over Zambia: 1986-1988

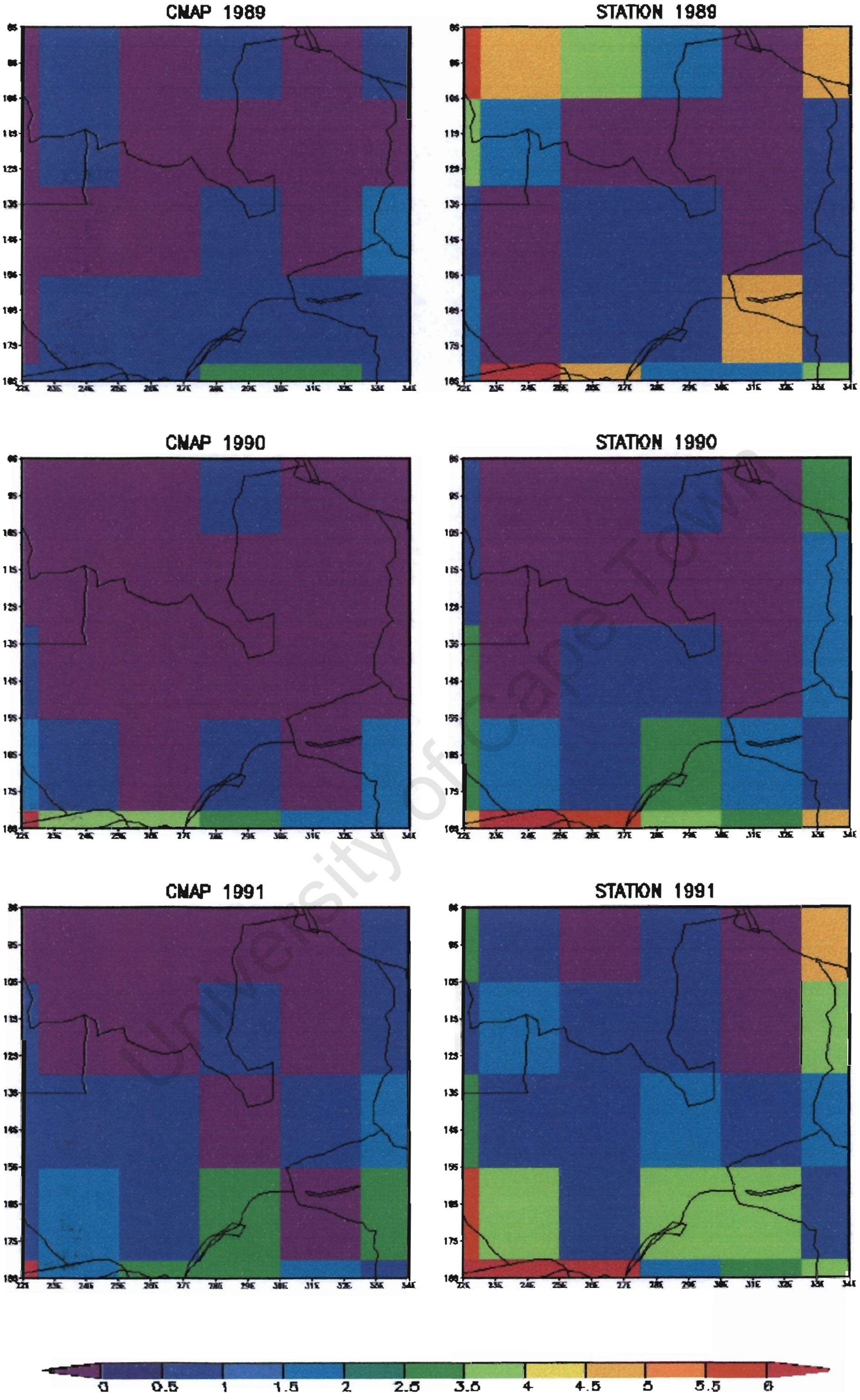


Figure 4.2d: Frequency of dry spell pentads over Zambia: 1989-1991

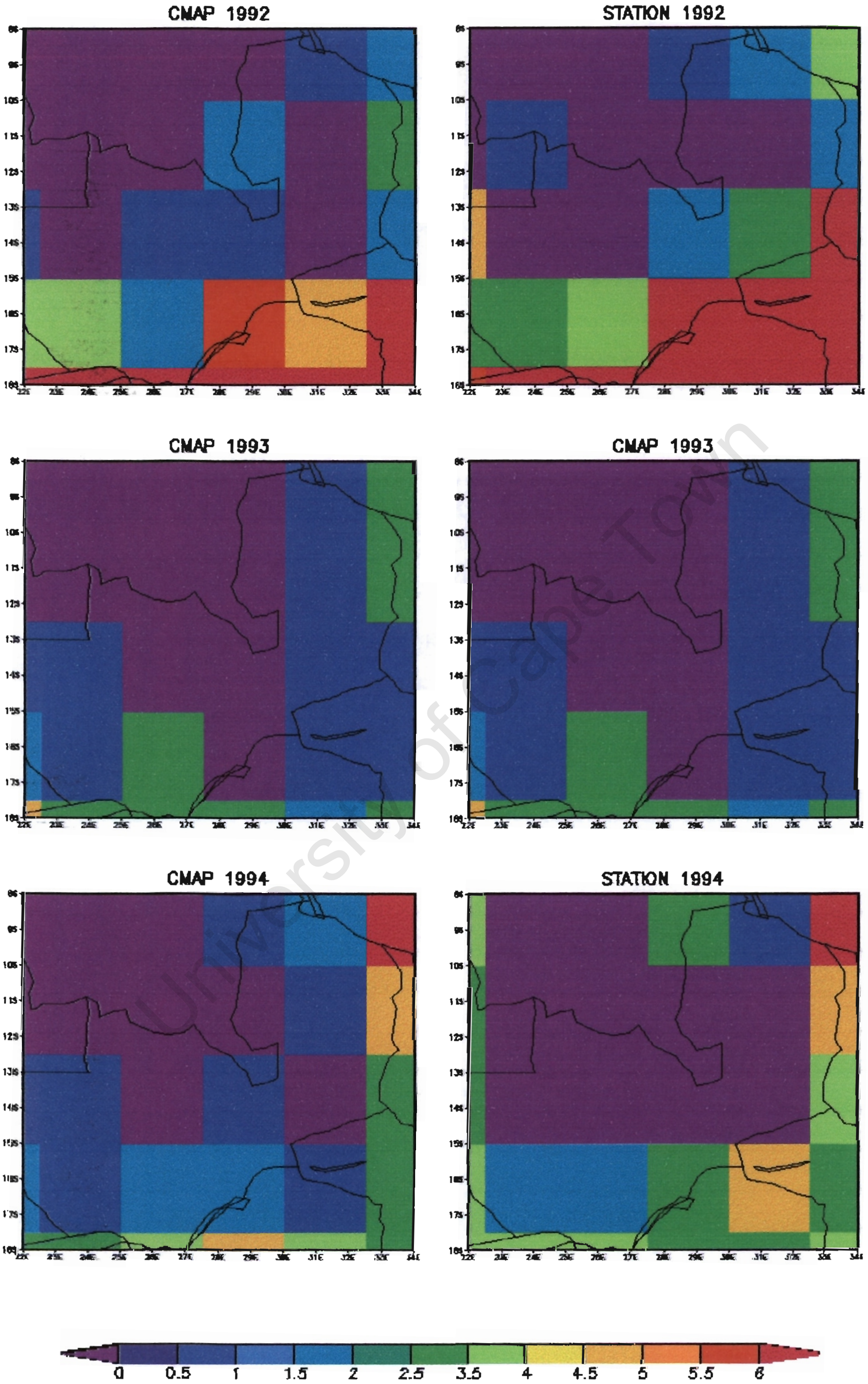


Figure 4.2e: Frequency of dry spell pentads over Zambia: 1992-1994

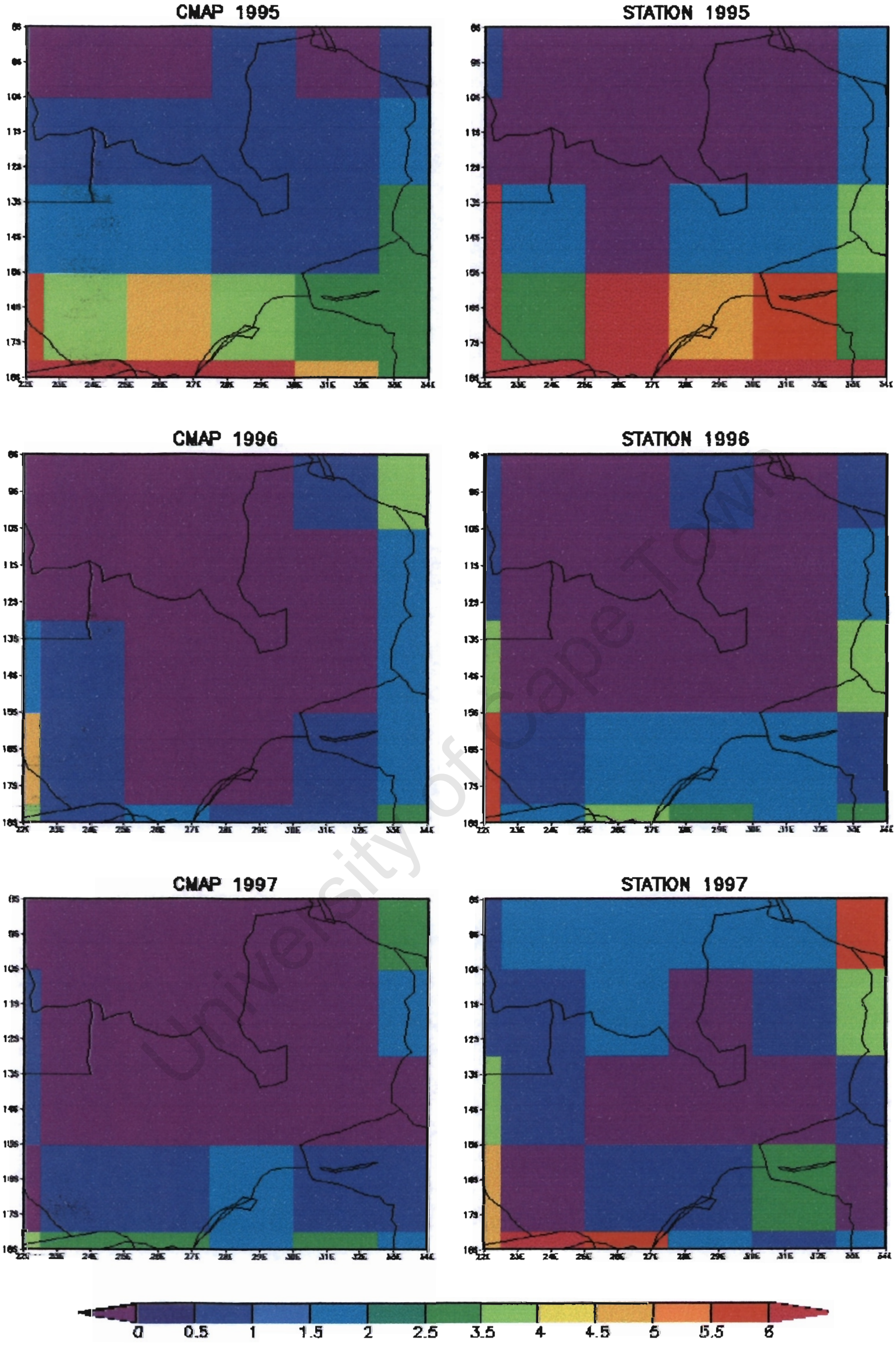


Figure 4.2f: Frequency of dry spell pentads over Zambia: 1995-1997

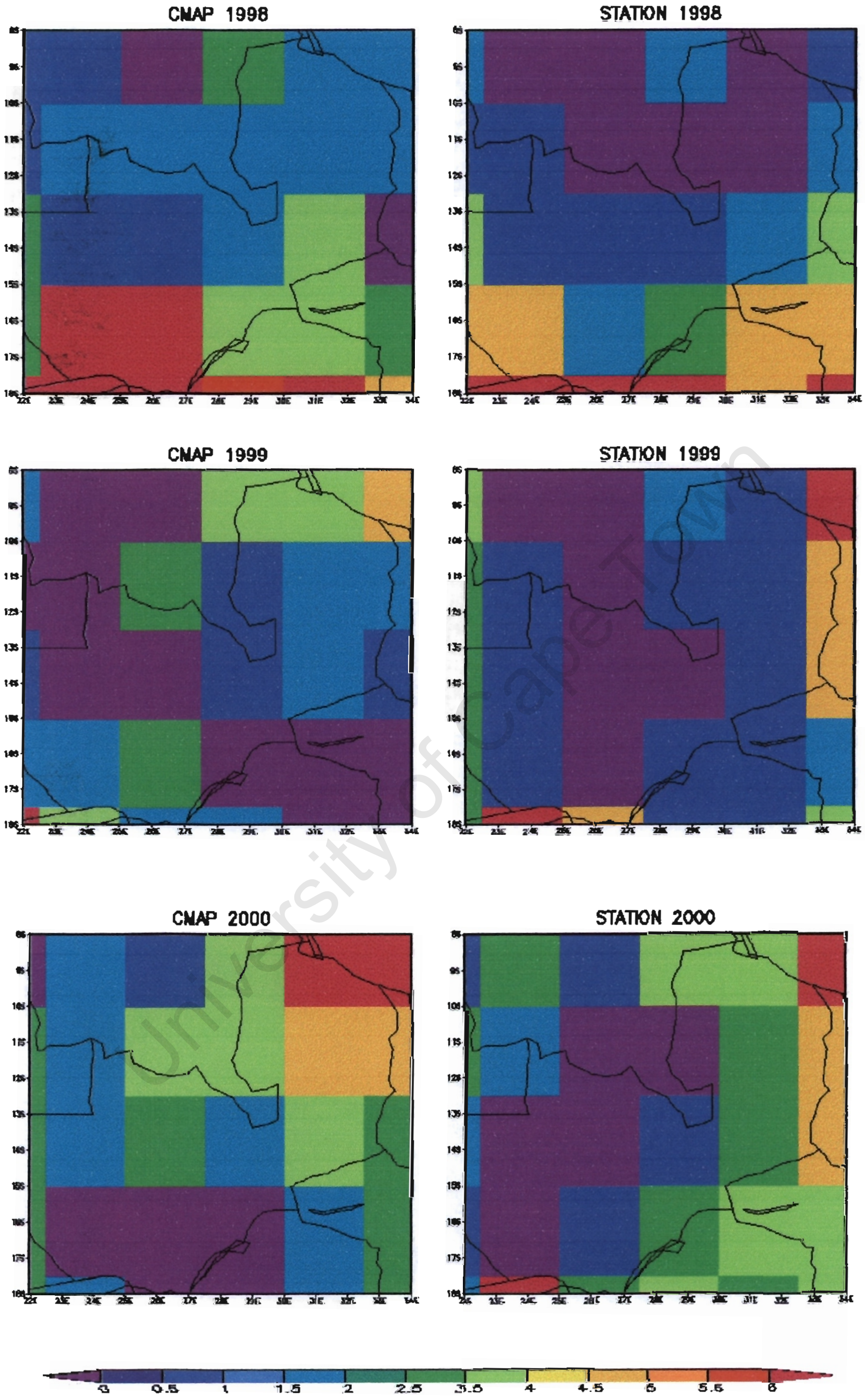


Figure 4.2g: Frequency of dry spell pentads over Zambia: 1998-2000

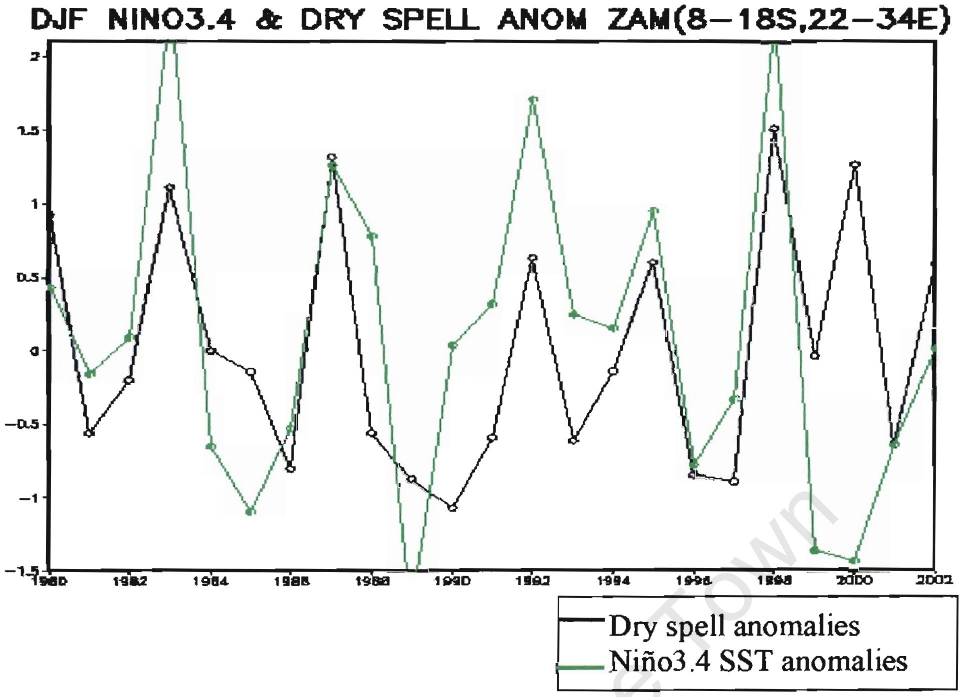


Figure 4.3a: DJF Dry spell anomalies over Zambia (CMAP data) against Niño3.4 SST anomaly time series (1979-2002).

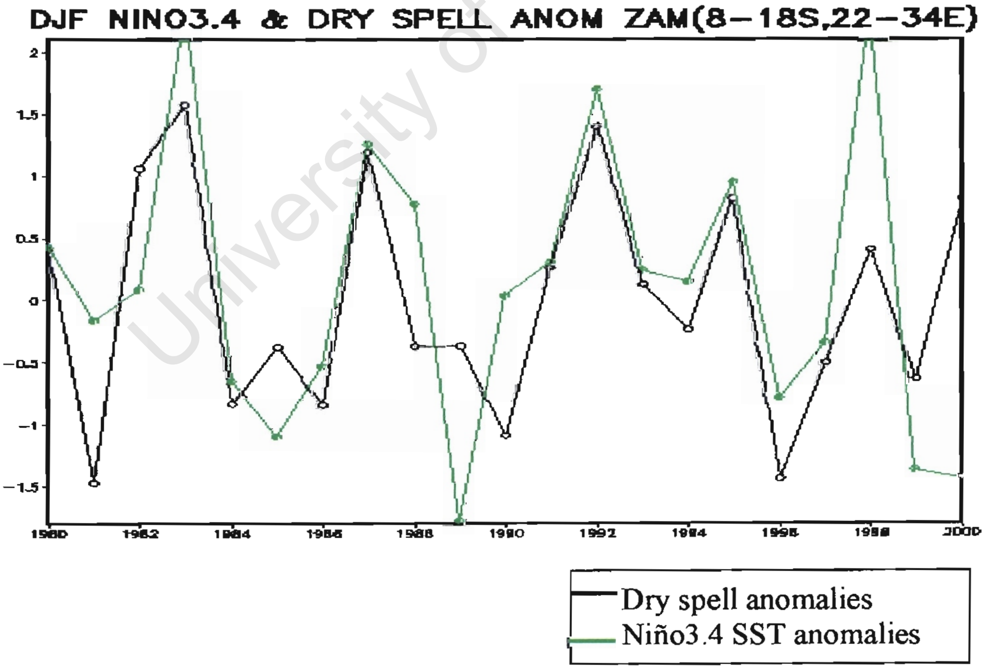


Figure 4.3b: DJF Dry spell anomalies over Zambia (Station data) against Niño3.4 SST anomalies (1979-2000).

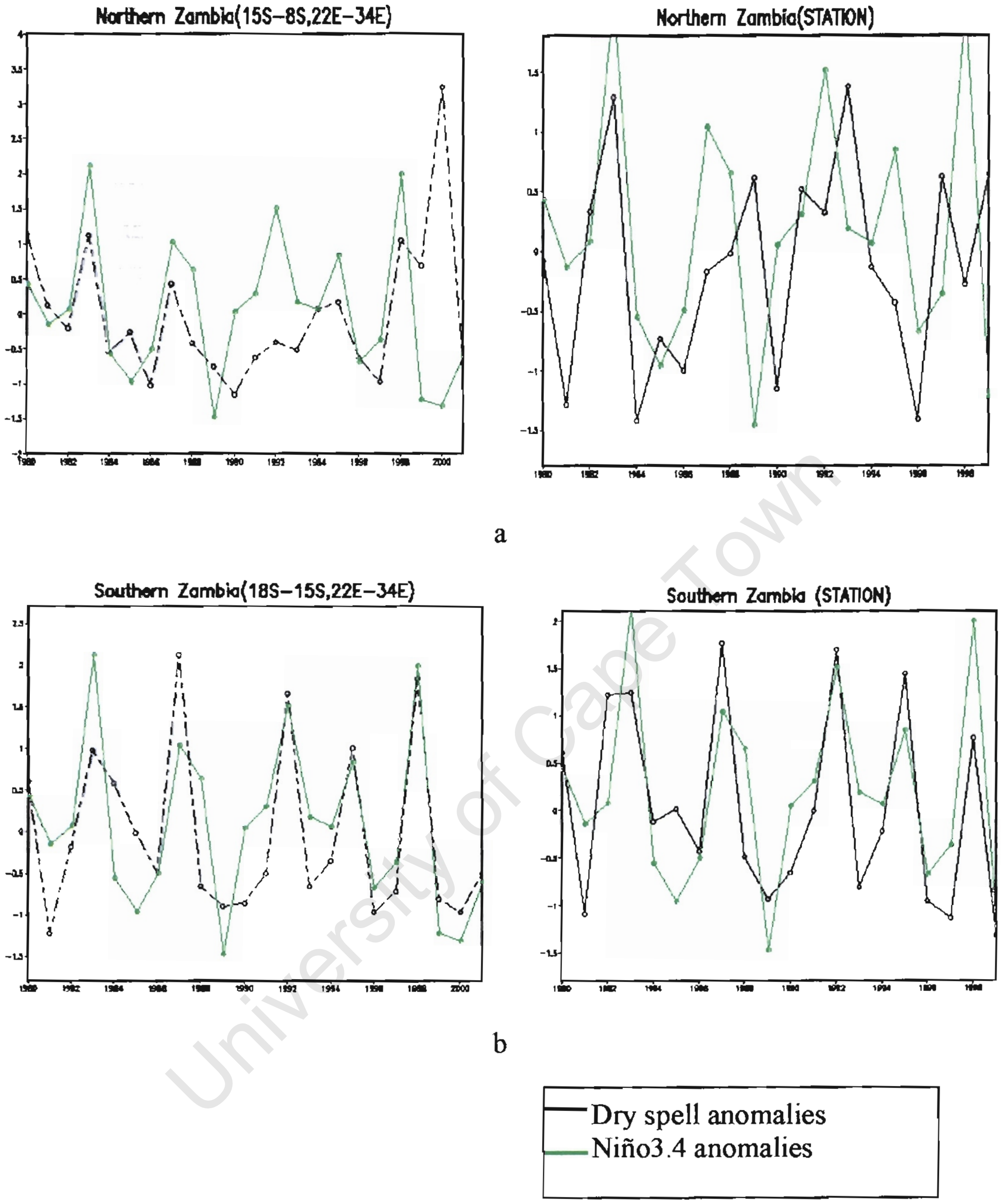


Figure 4.4: a) DJF Dry spell anomalies over northern Zambia (15°S-8°S, 22°E-34°E) against DJF Niño3.4 SST anomalies. b) DJF Dry Spell Anomalies over southern Zambia (18°S-15°S, 22°E-34°E) against DJF Niño3.4 SST anomalies (1979-2000).

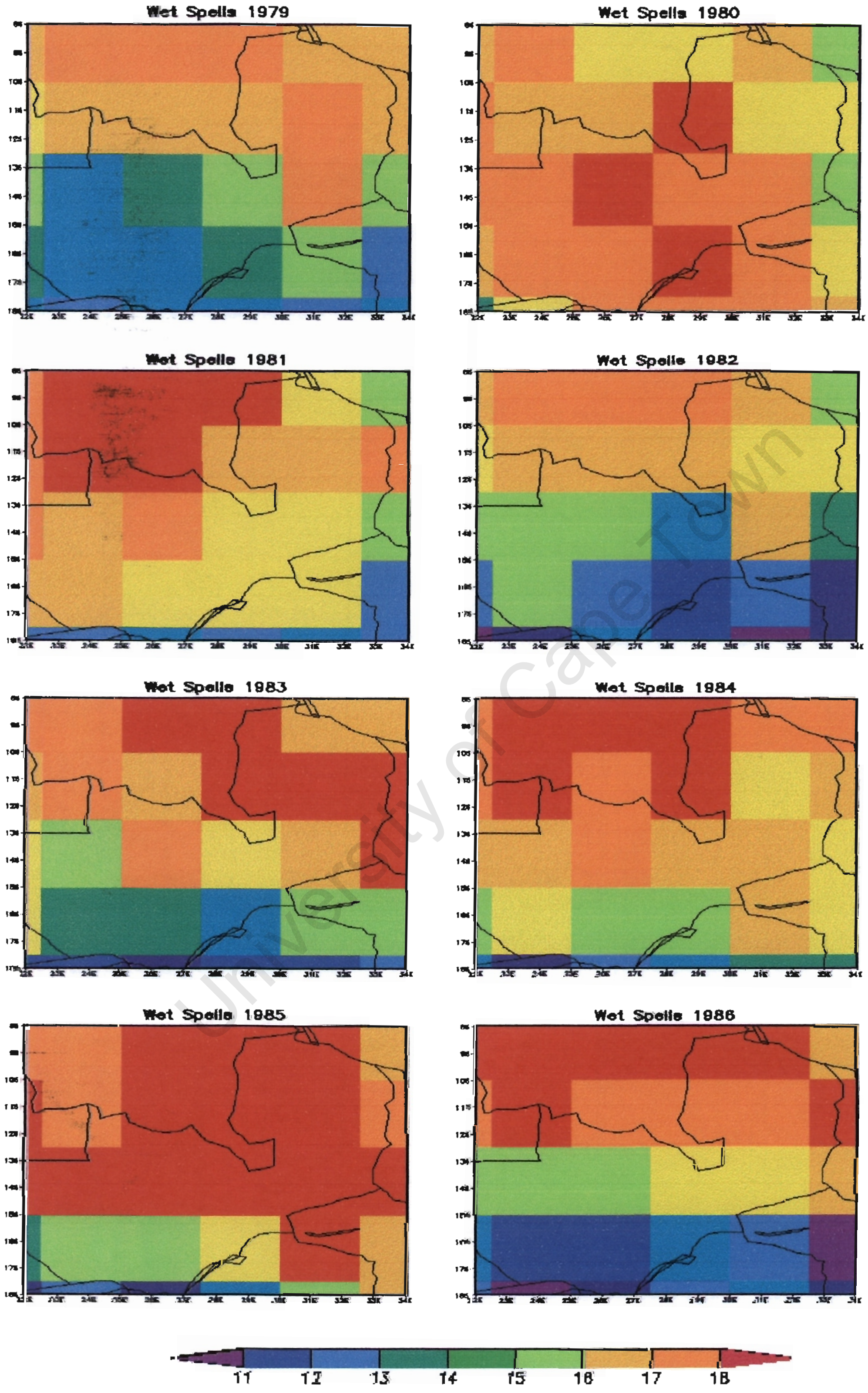


Figure 4.5a: DJF wet spell frequency for each summer from 1979 to 1986 (CMAP)

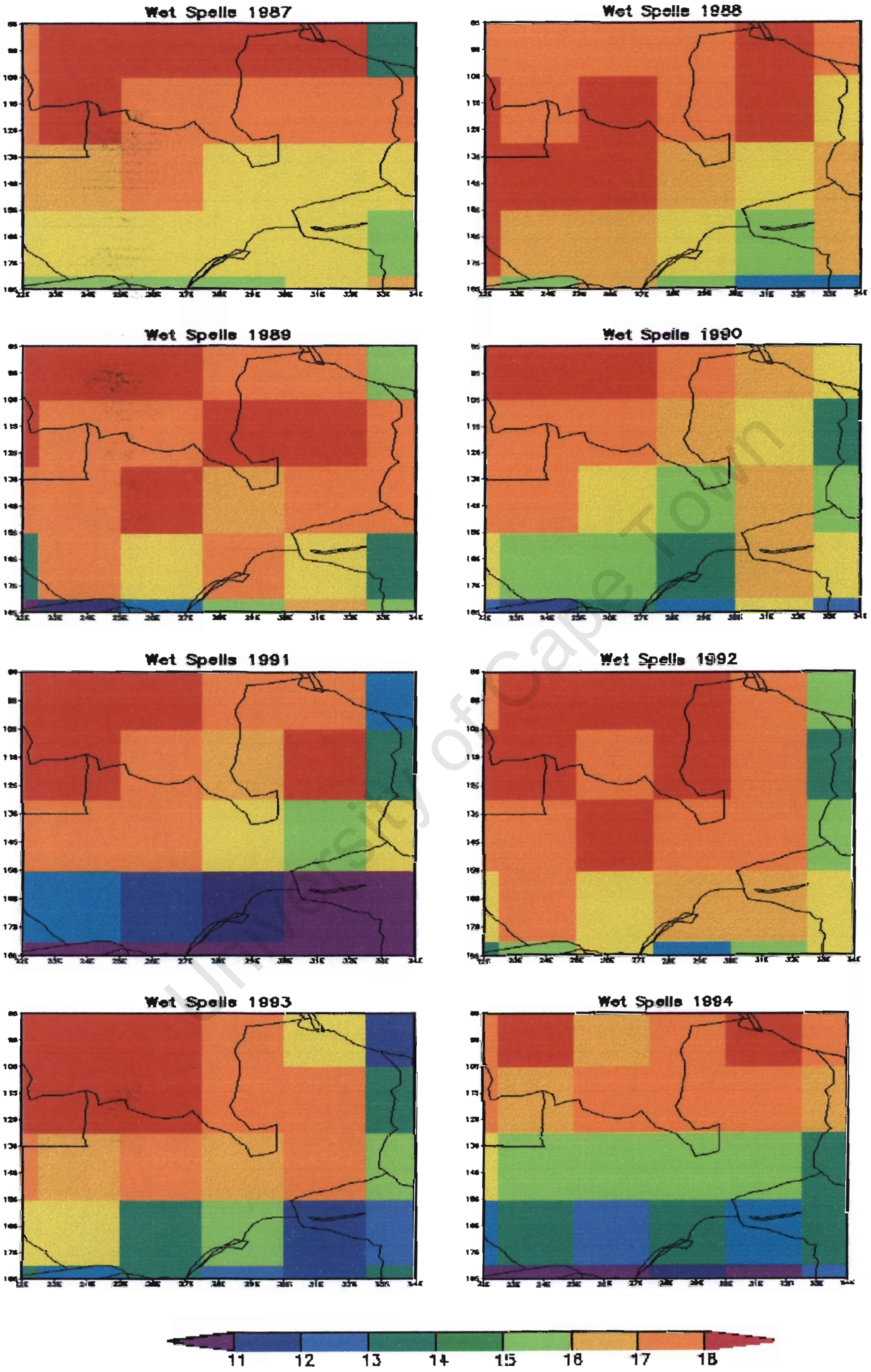
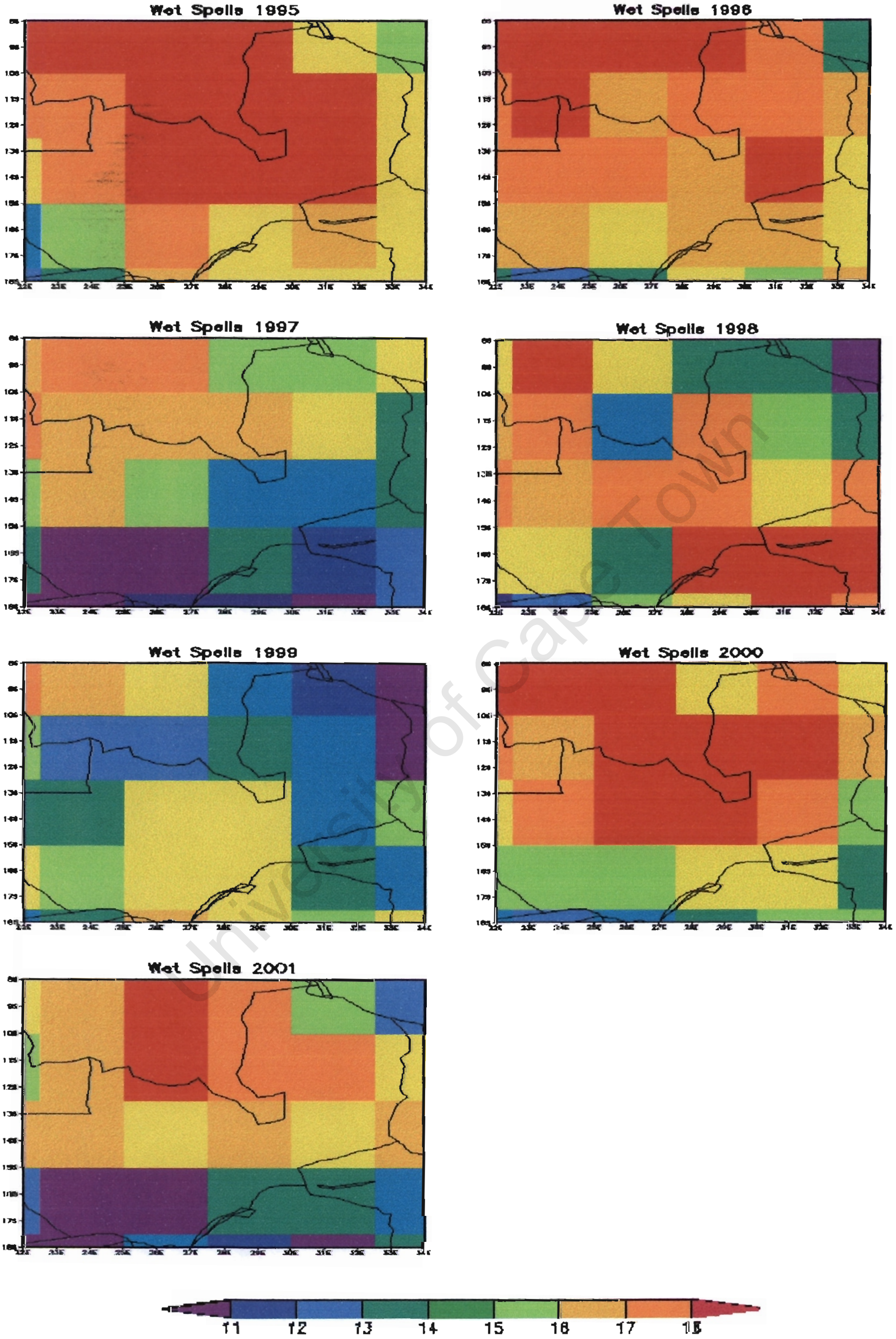


Figure 4.5b: DJF wet spell frequency for each summer from 1987 to 1994 (CMAP)


Wet Spells 1995

Wet Spells 1996

Wet Spells 1997

Wet Spells 1998

Wet Spells 1999

Wet Spells 2000

Wet Spells 2001

Figure 4.5c: DJF wet spell frequency for each summer from 1995 to 2001 (CMAP)

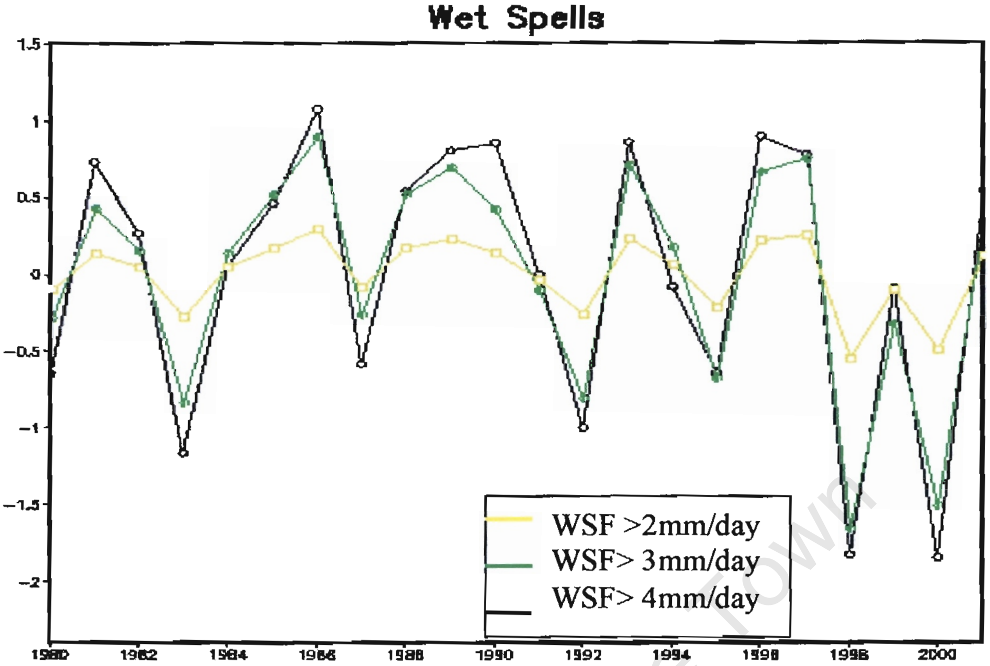


Figure 4.6: DJF wet spell time series at 2mm/day, 3mm/day and 4mm/day (CMAP)

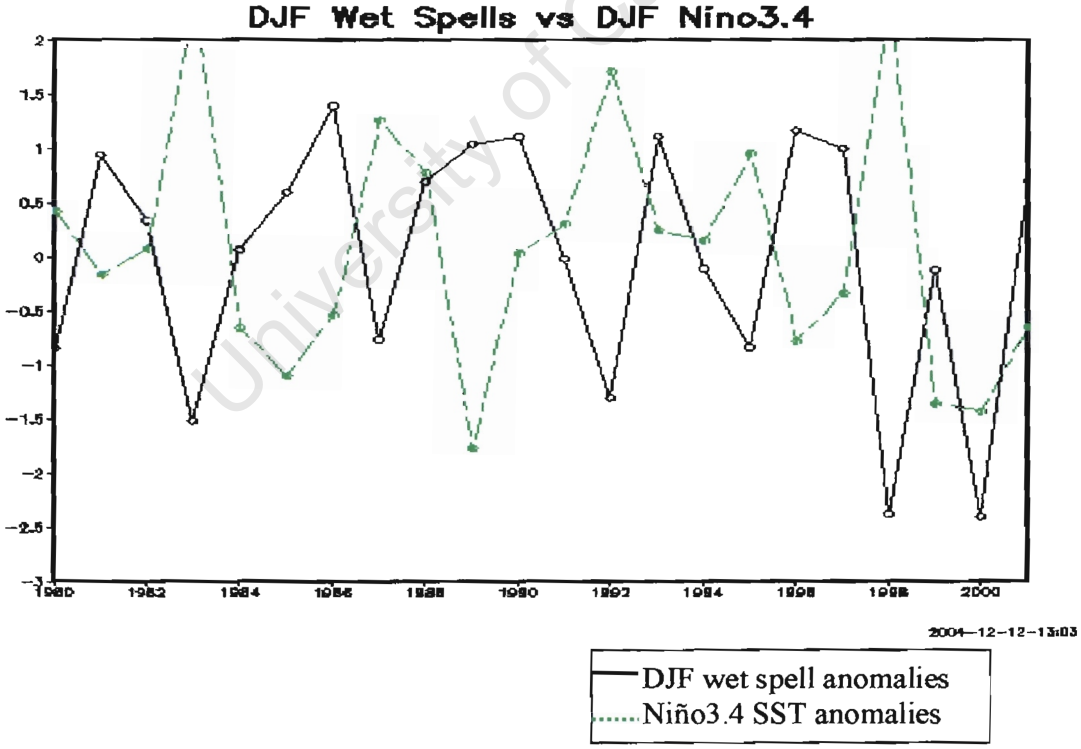
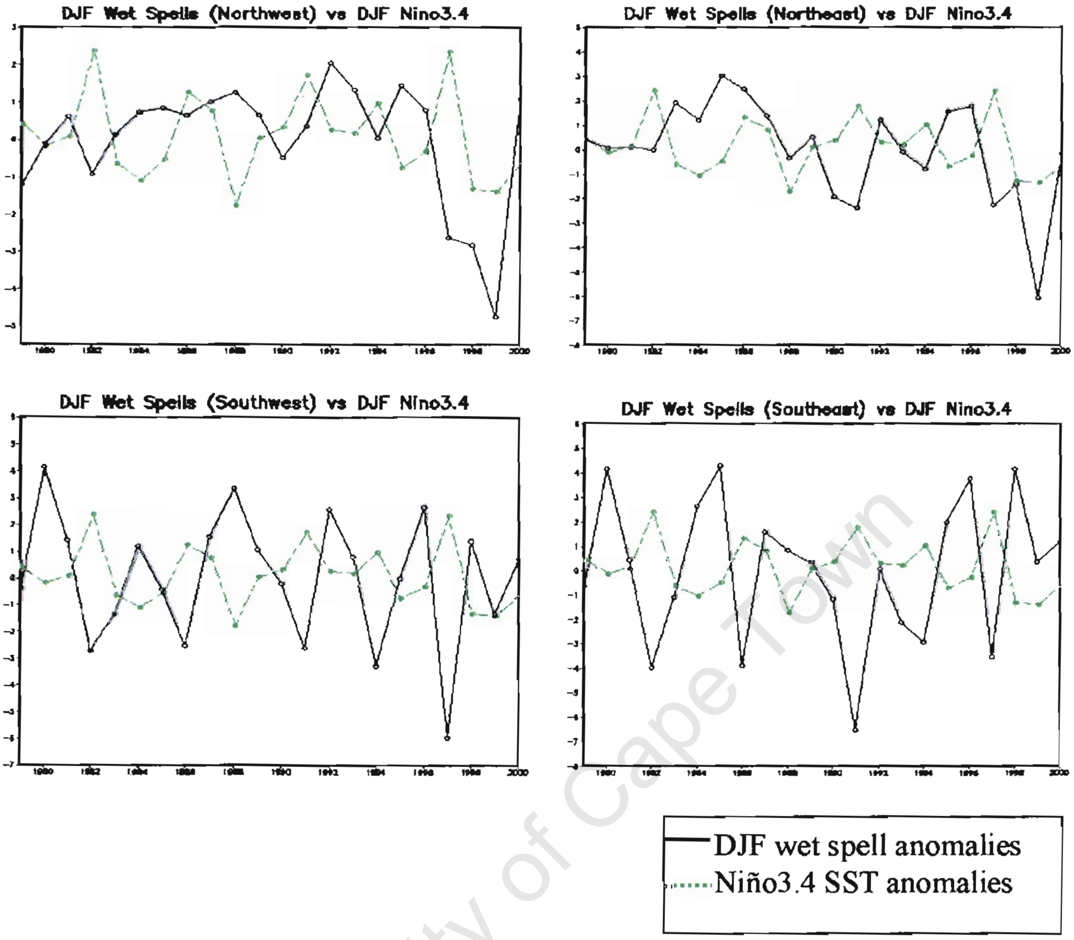


Figure 4.7a: DJF wet spell anomalies over Zambia against DJF Niño3.4 SST anomalies


DJF Wet Spells (Northwest) vs DJF Nino3.4

DJF Wet Spells (Northeast) vs DJF Nino3.4

DJF Wet Spells (Southwest) vs DJF Nino3.4

DJF Wet Spells (Southeast) vs DJF Nino3.4

Figure 4.7b: DJF wet spell anomalies over various regions across Zambia against DJF Niño3.4 SST anomalies

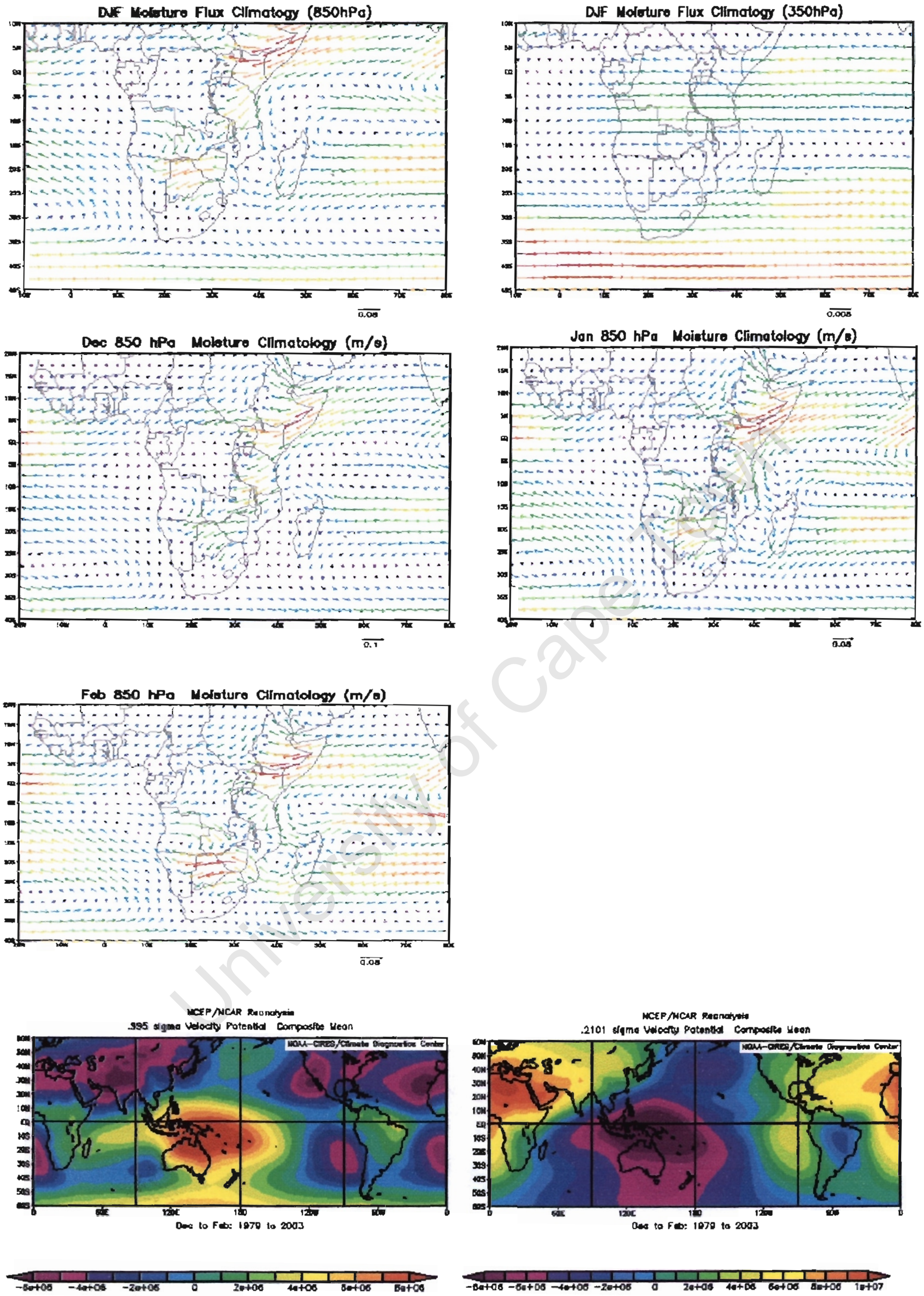


Figure 4.8a: Moisture flux and velocity potential climatology at lower and upper levels (850hPa and 350hPa)

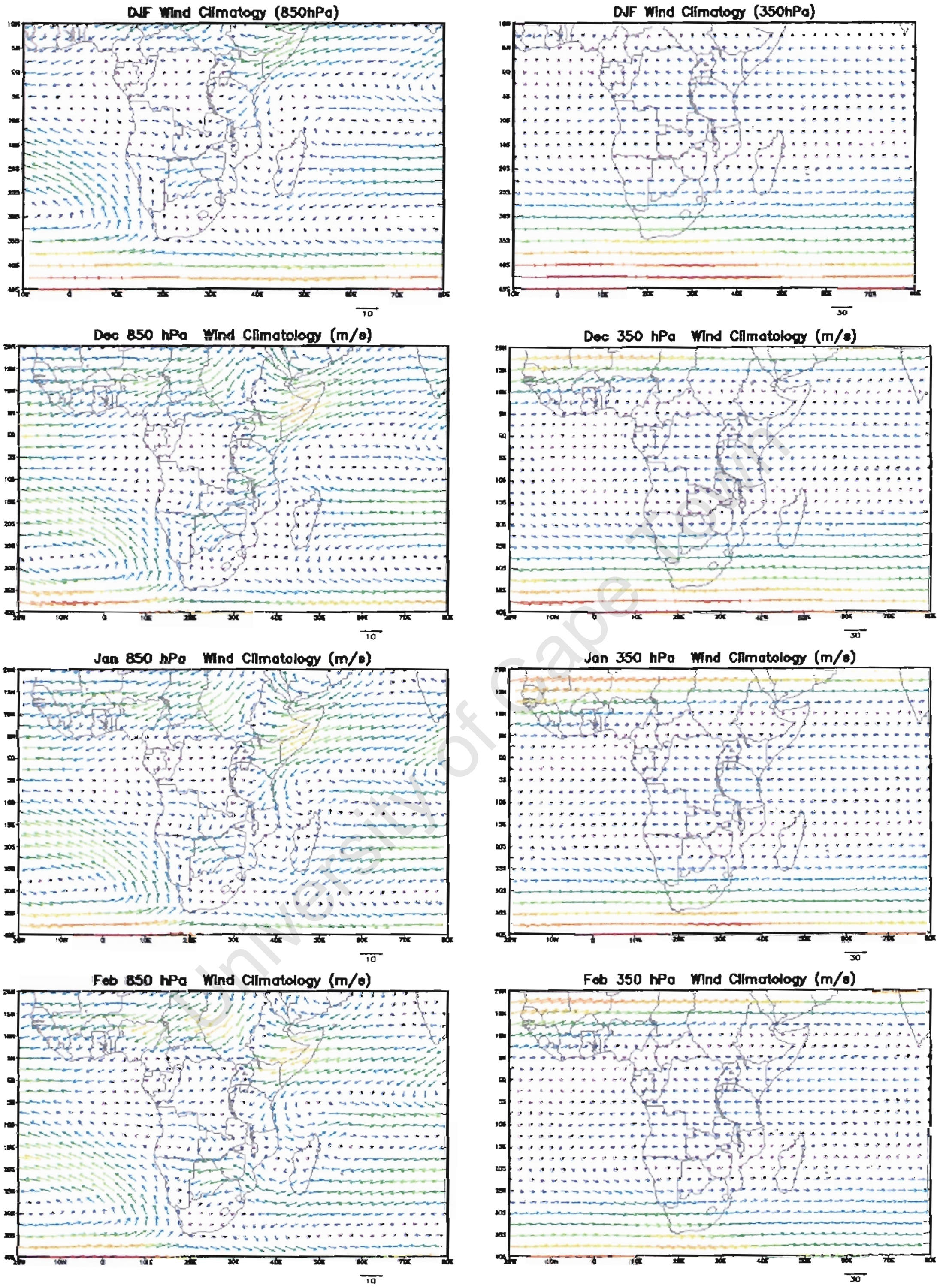
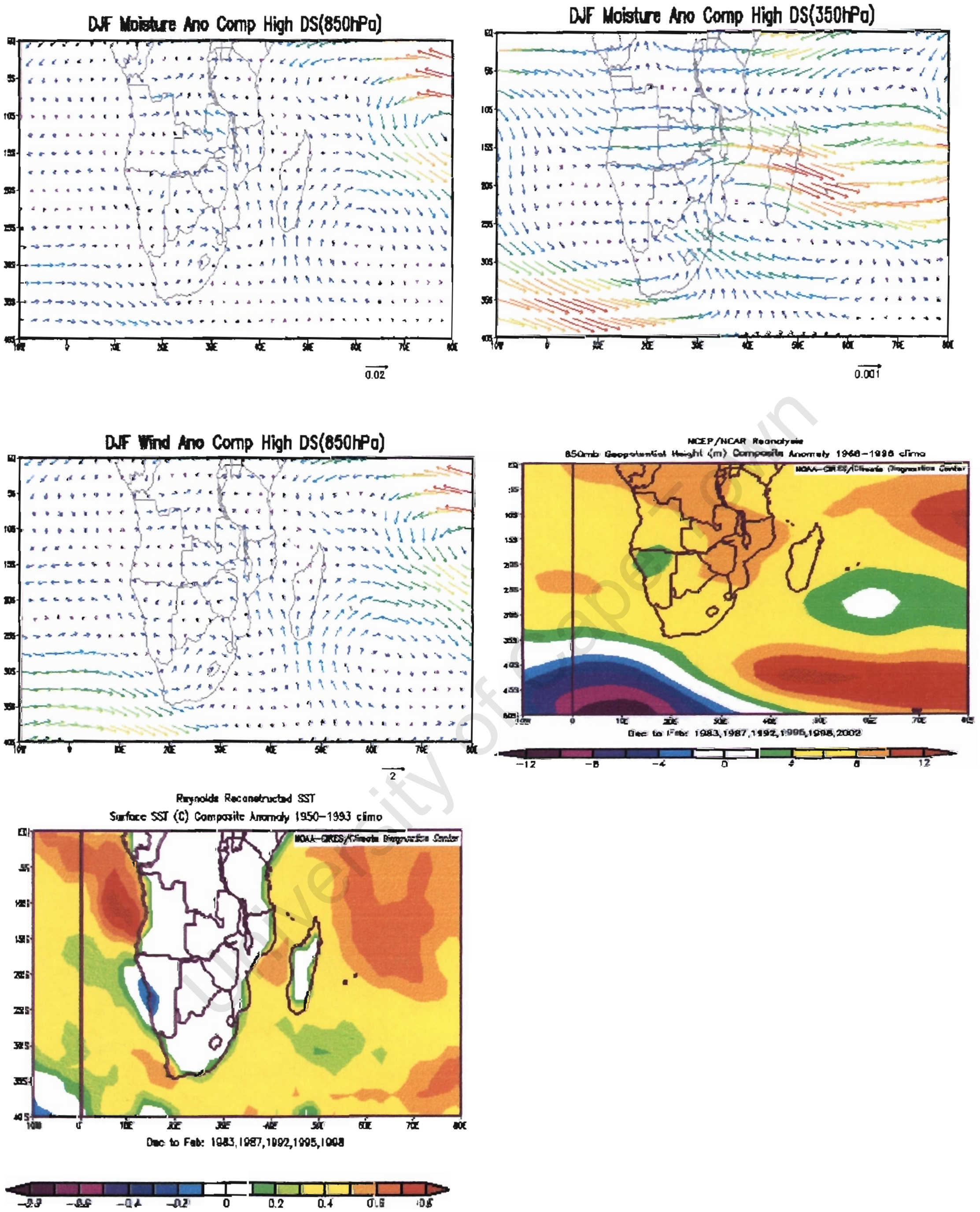


Figure 4.8b: Wind climatology at lower and upper levels (850hPa and 350hPa)

High dry spell years



DJF Moisture Ano Comp High DS(850hPa)

DJF Moisture Ano Comp High DS(350hPa)

DJF Wind Ano Comp High DS(850hPa)

NCEP/NCAR Reanalysis
850mb Geopotential Height (m) Composite Anomaly 1968–1996 climo

Dec to Feb: 1983,1987,1992,1995,1998,2002

Reynolds Reconstructed SST
Surface SST (C) Composite Anomaly 1950–1993 climo

Dec to Feb: 1983,1987,1992,1995,1998

Figure 4.9a: DJF anomaly composite at lower and upper levels (850hPa and 350hPa)

High dry spell years

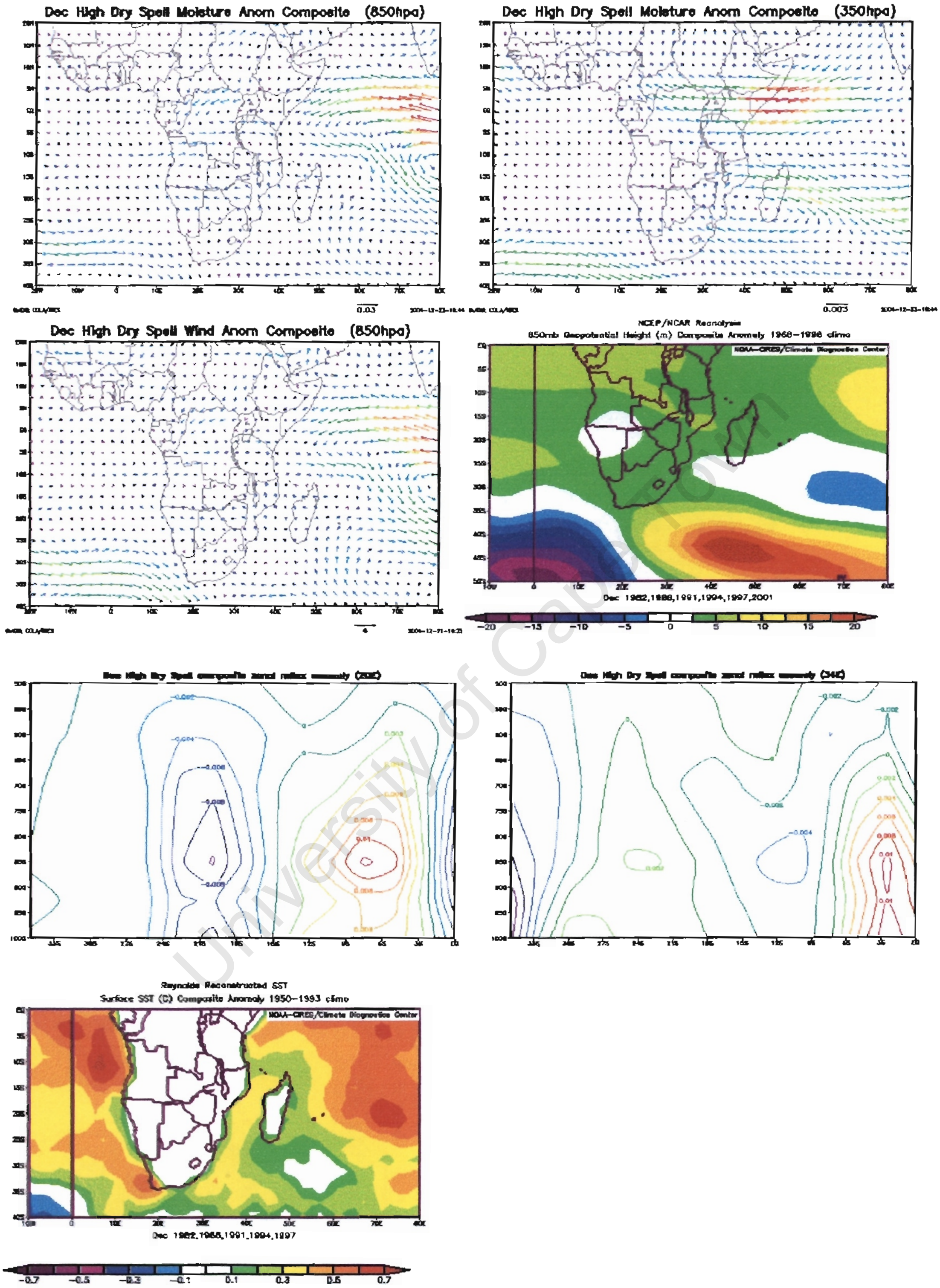


Figure 4.9b: December anomaly composite at lower and upper levels (850hPa and 350hPa). Contour interval for zonal moisture flux transect is 0.002 kg kg^{-1} ms^{-1}

High dry spell years

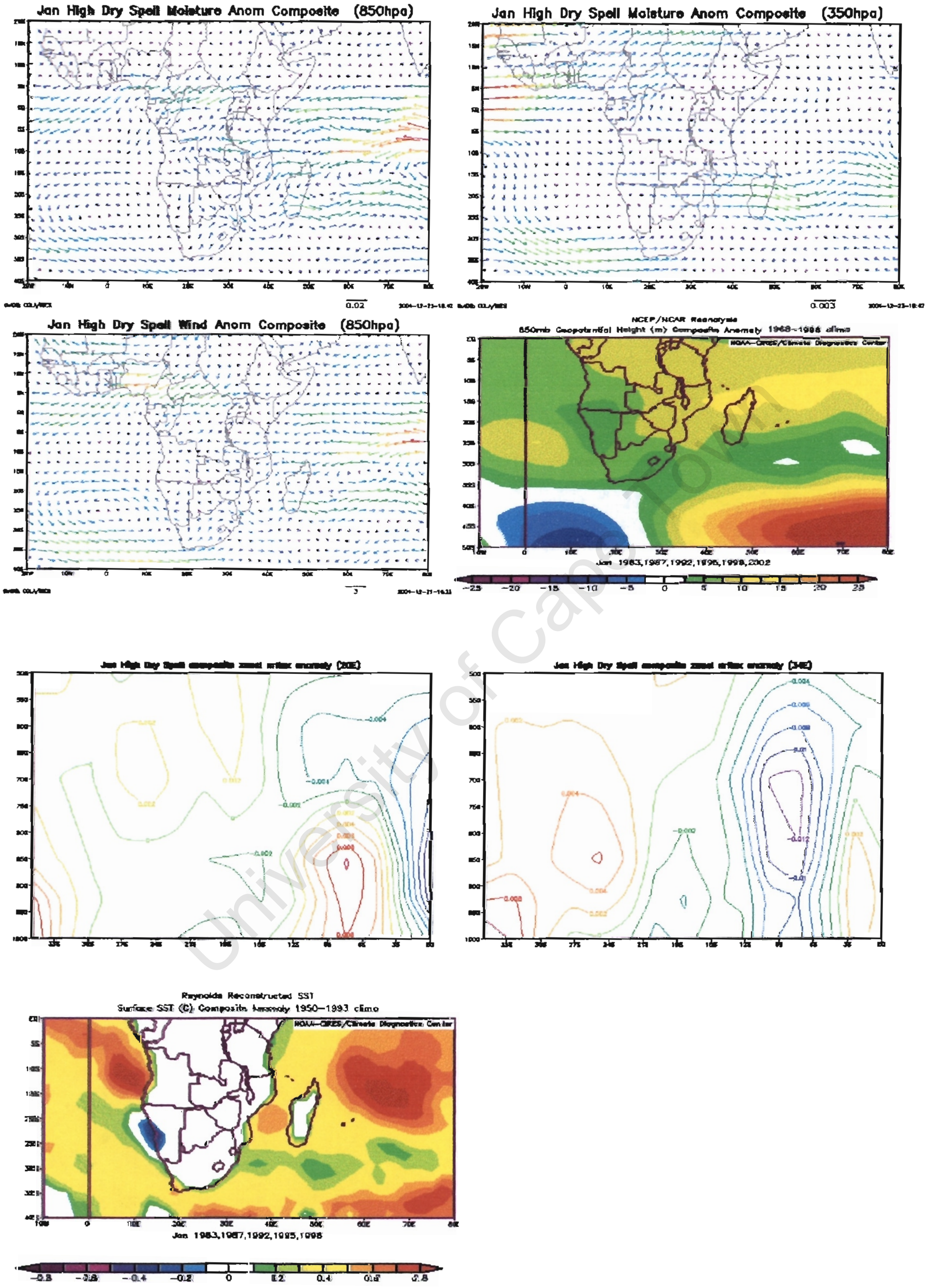


Figure 4.9c: January anomaly composite at lower and upper levels (850hPa and 350hPa) Contour interval for zonal moisture flux transect is 0.002 kg kg^{-1} ms $^{-1}$

High dry spell years

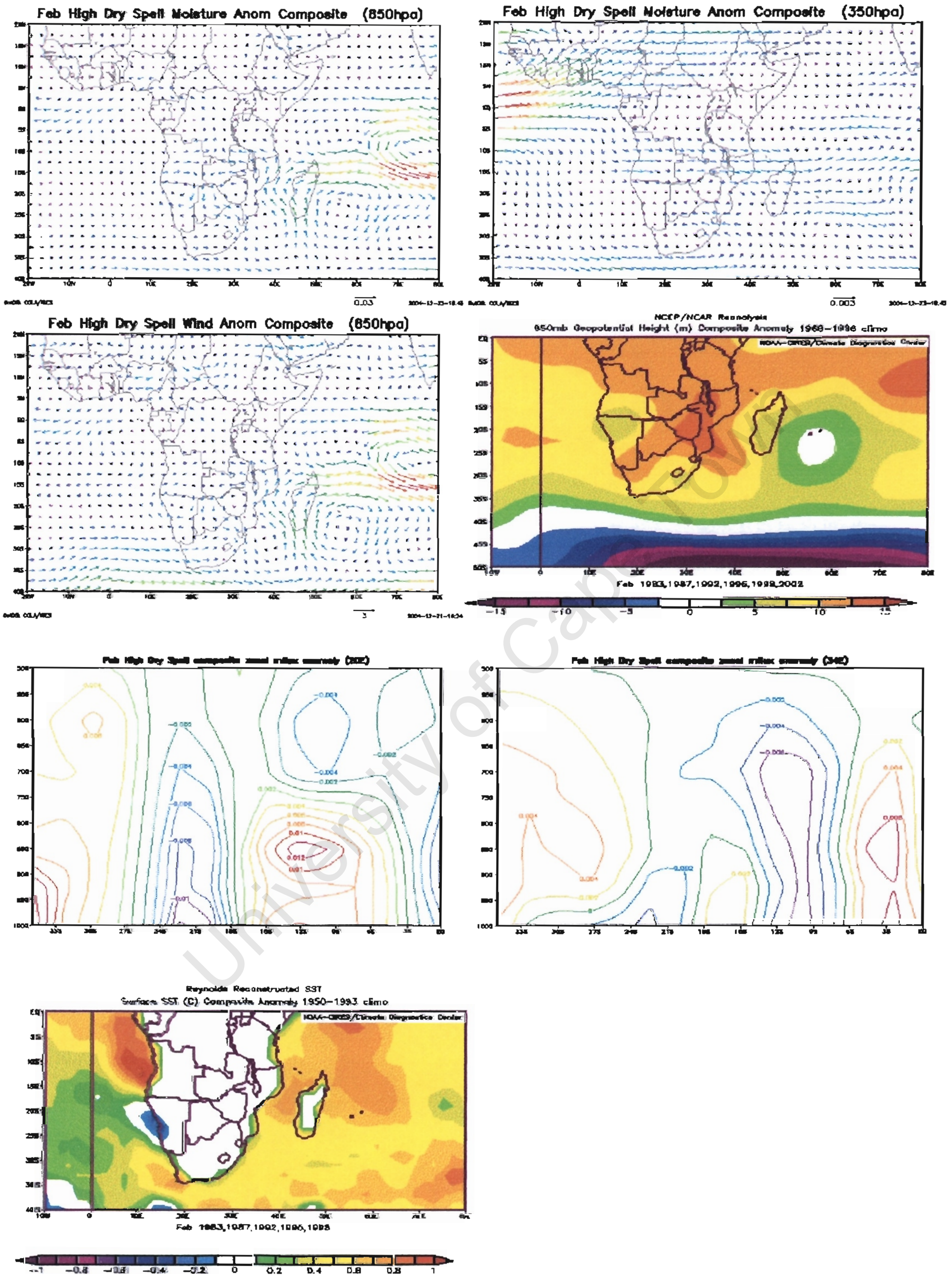
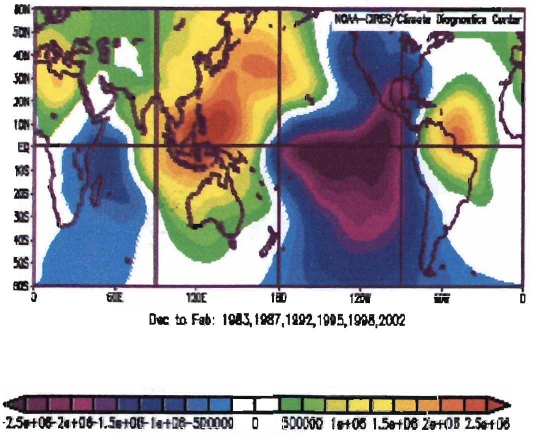


Figure 4.9d: February anomaly composite at lower and upper levels (850hPa and 350hPa). Contour interval for zonal moisture flux transect is 0.002 kg kg^{-1} ms $^{-1}$

High dry spell years

NCEP/NCAR Reanalysis

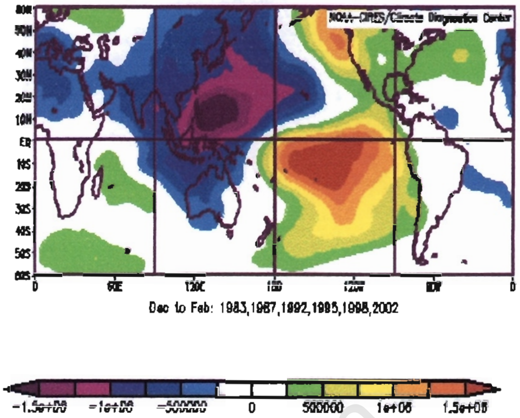
.2101 sigma Velocity Potential Composite Anomaly 1968–1996 climo



Dec to Feb: 1983,1987,1992,1995,1998,2002

NCEP/NCAR Reanalysis

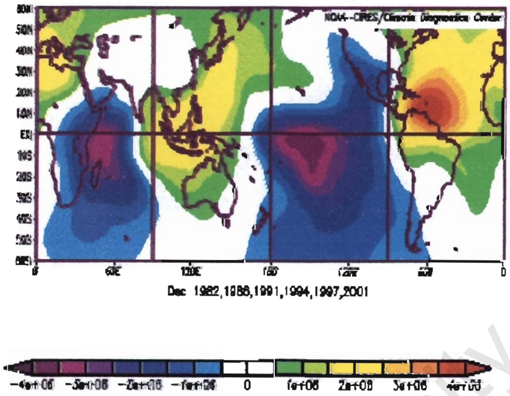
.995 sigma Velocity Potential Composite Anomaly 1968–1996 climo



Dec to Feb: 1983,1987,1992,1995,1998,2002

NCEP/NCAR Reanalysis

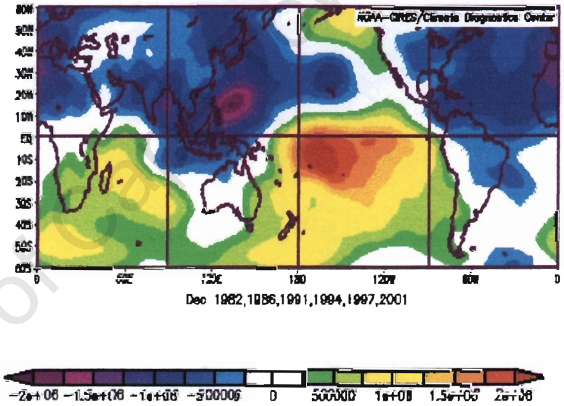
.2101 sigma Velocity Potential Composite Anomaly 1968–1996 climo



Dec 1982,1986,1991,1994,1997,2001

NCEP/NCAR Reanalysis

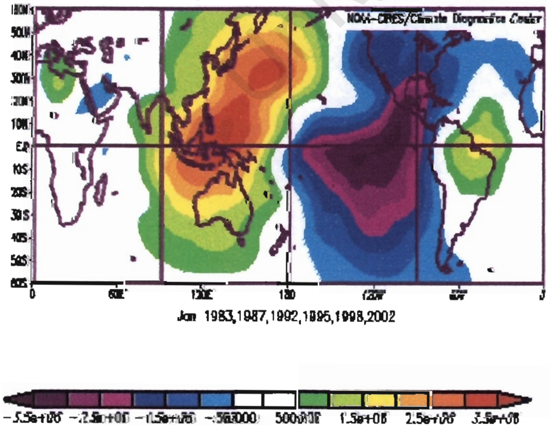
.995 sigma Velocity Potential Composite Anomaly 1968–1996 climo



Dec 1982,1986,1991,1994,1997,2001

NCEP/NCAR Reanalysis

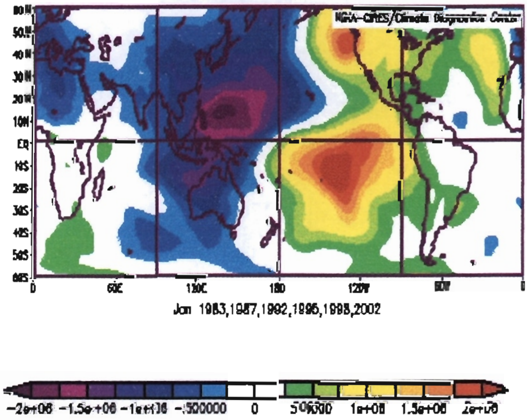
.2101 sigma Velocity Potential Composite Anomaly 1968–1996 climo



Jan 1983,1987,1992,1995,1998,2002

NCEP/NCAR Reanalysis

.995 sigma Velocity Potential Composite Anomaly 1968–1996 climo



Jan 1983,1987,1992,1995,1998,2002

Continued, next page...

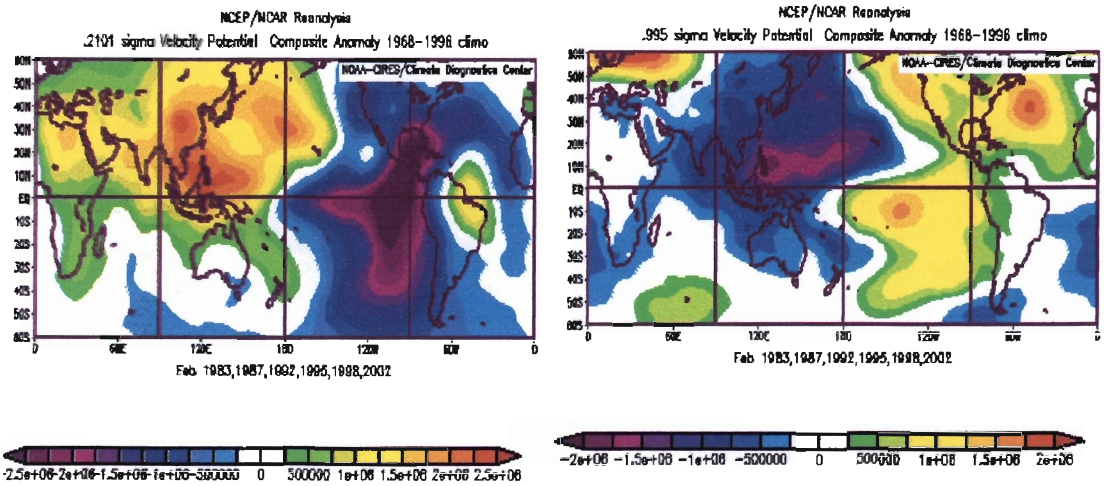


Figure 4.9e: upper and lower level velocity potential anomaly composite

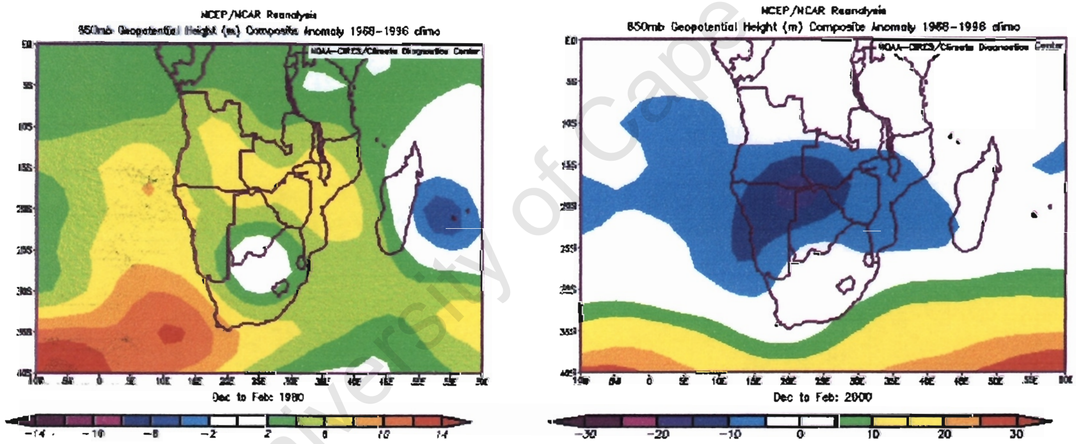


Figure 4.9f: Anomalies in 850hPa geopotential height for 1979/80 (left) and 1999/00 (right)

High wet spell years

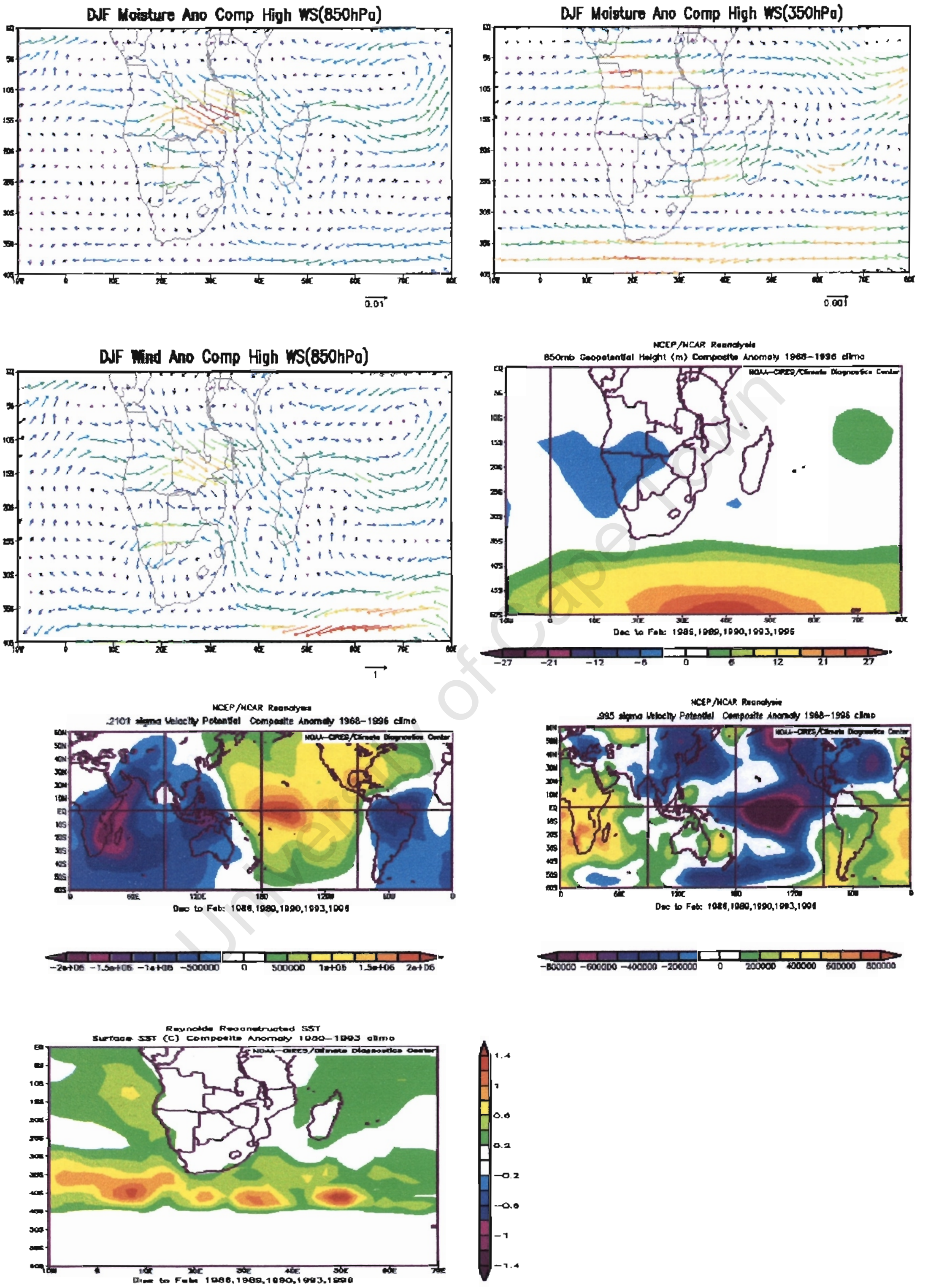


Figure 4.10a: DJF anomaly composite at lower and upper levels (850hPa and 350hPa)

High wet spell years

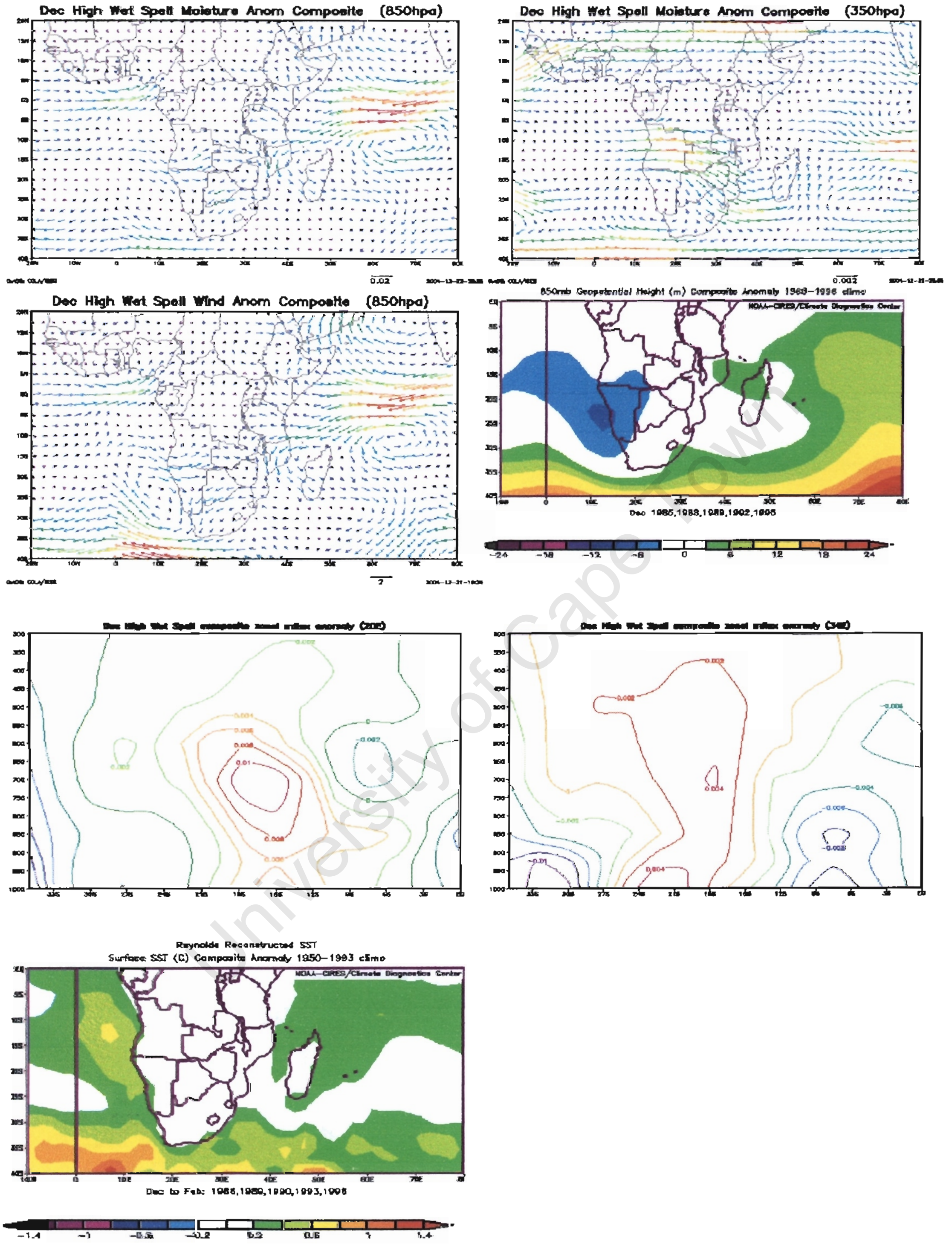


Figure 4.10b: December anomaly composite at lower and upper levels (850hPa and 350hPa). Contour interval for zonal moisture flux transect is 0.002 kg kg^{-1} ms $^{-1}$

High wet spell years

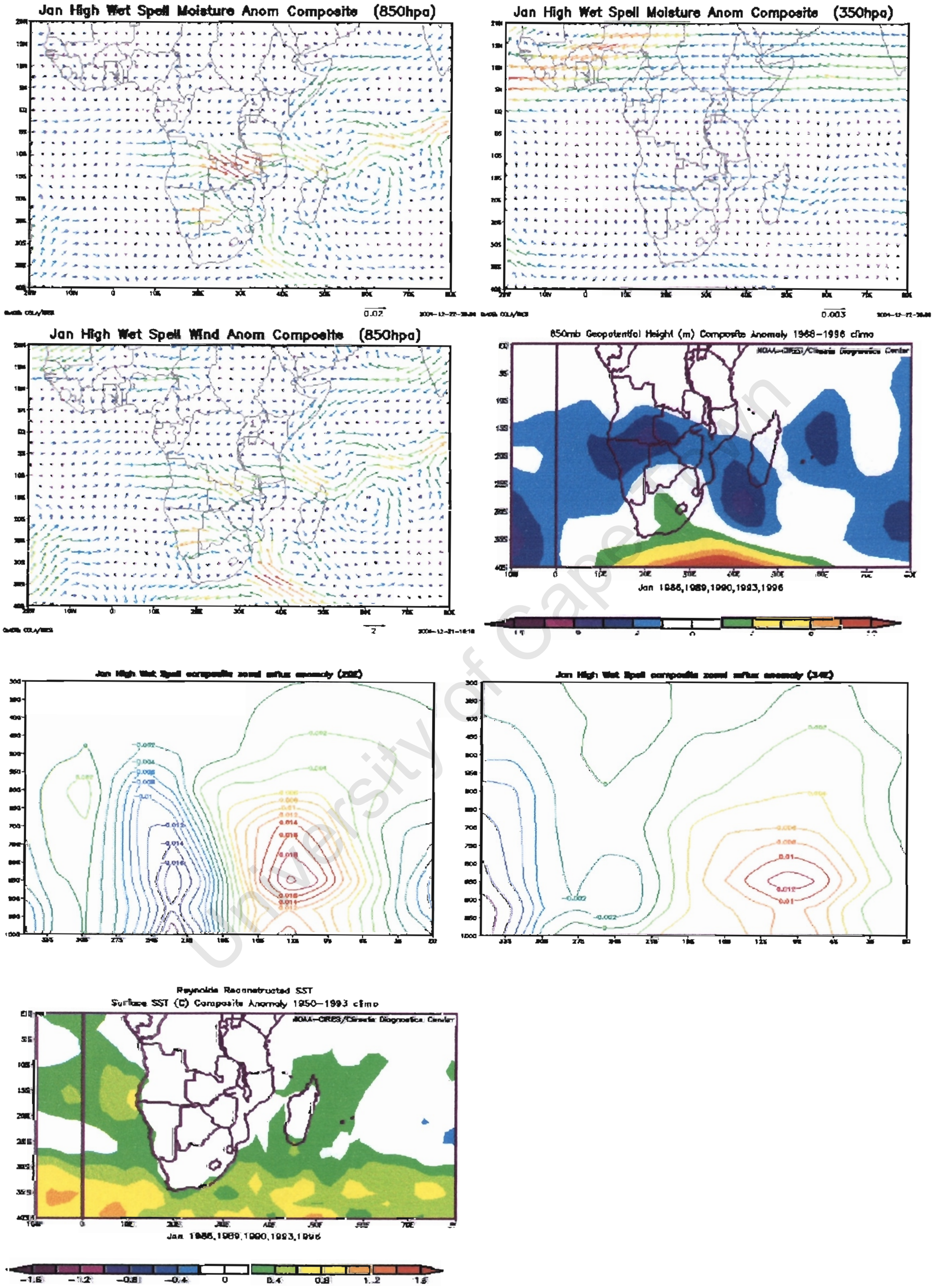


Figure 4.10c: January anomaly composite at lower and upper levels (850hPa and 350hPa). Contour interval for zonal moisture flux transect is 0.002 kg kg^{-1} ms^{-1}

High wet spell years

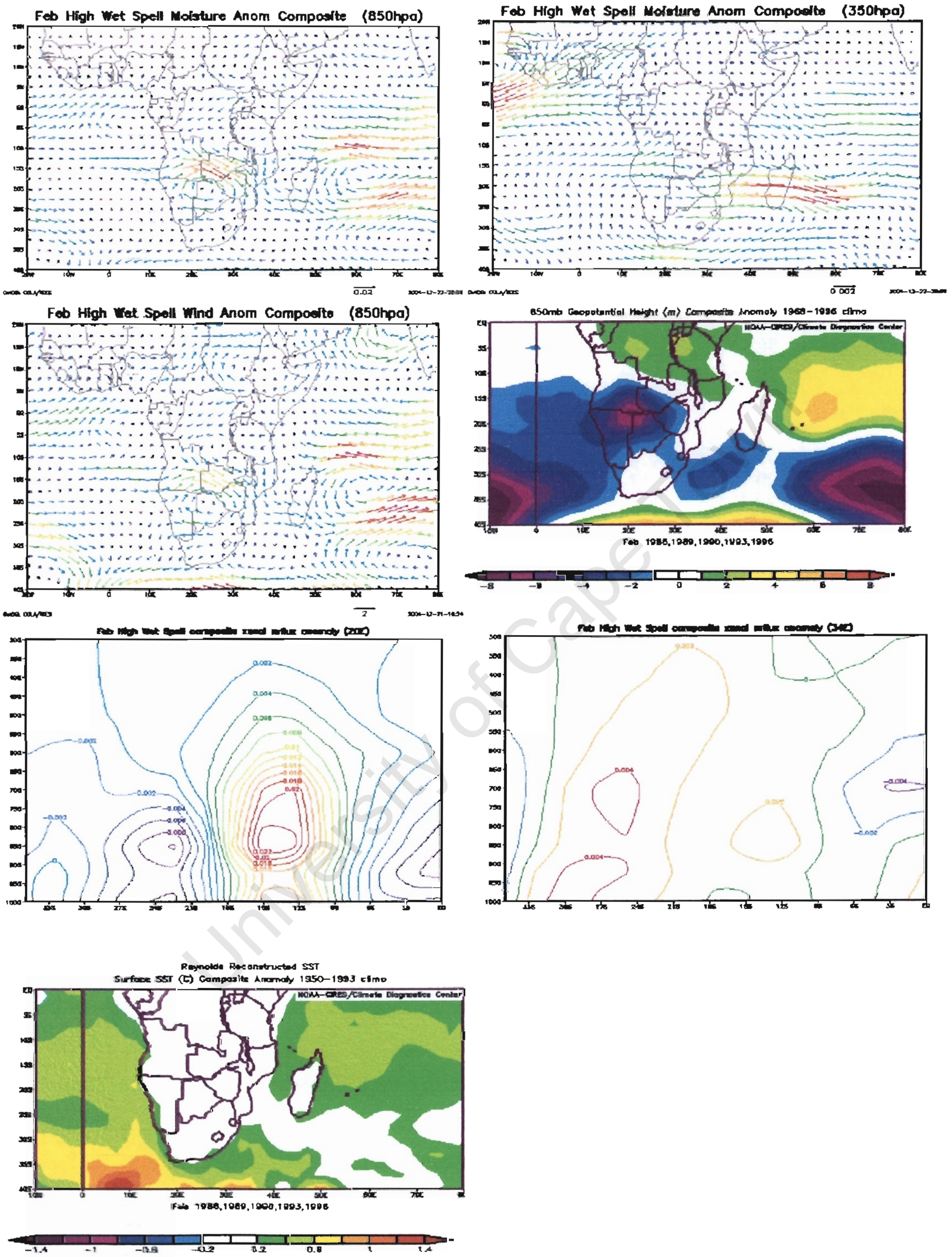


Figure 4.10d: February anomaly composite at lower and upper levels (850hPa and 350hPa). Contour interval for zonal moisture flux transect is 0.002 kg kg^{-1} ms $^{-1}$

High wet spell years

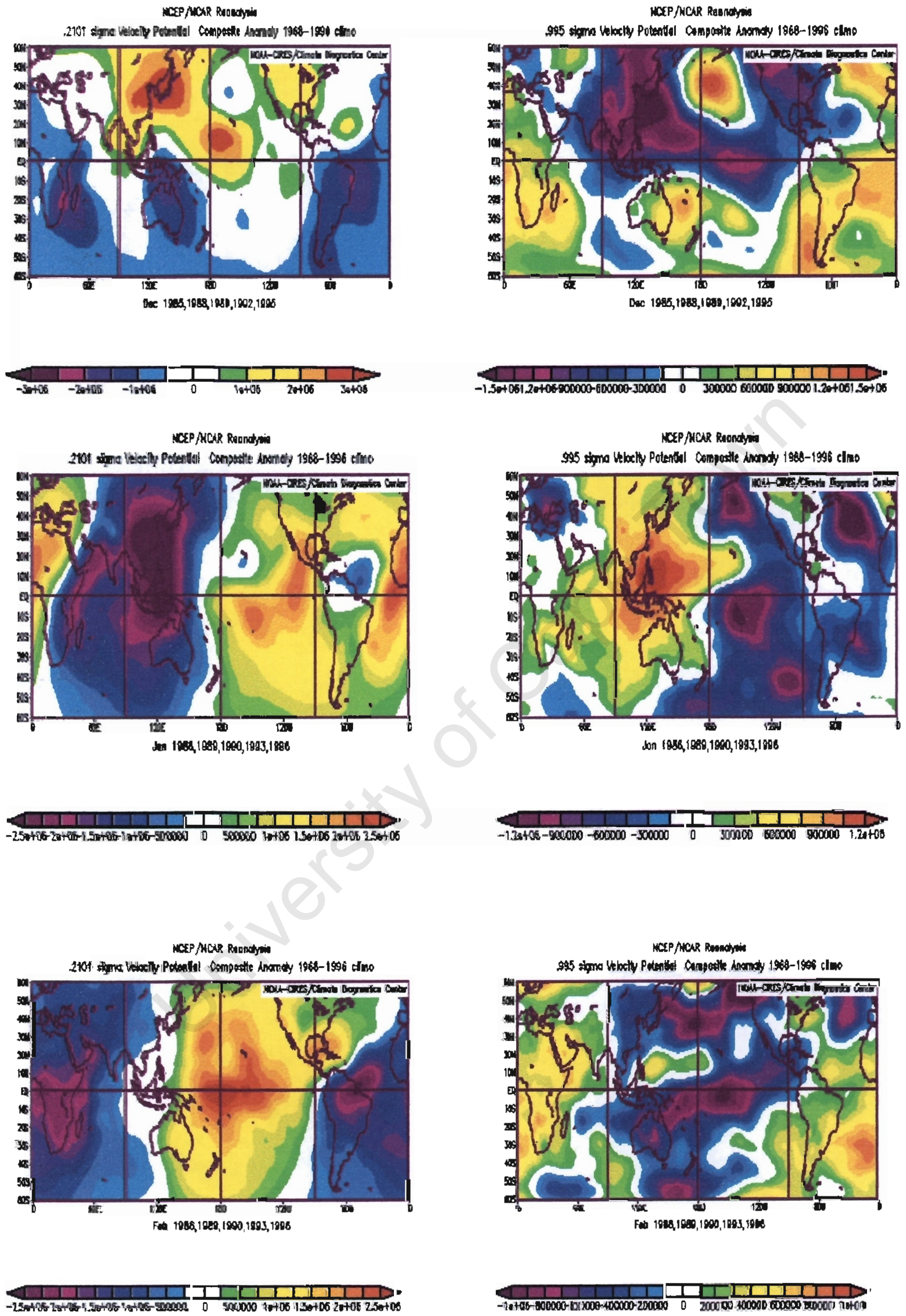


Figure 4.10e: Upper level and lower level velocity potential anomaly composites

Chapter 5

Variability in onset and cessation dates of rainy season

5.1 Introduction

This chapter investigates the variability in onset dates of the summer rainy season as well as the cessation or withdrawal of the rains over Zambia. It also examines anomalies in circulation related parameters such as wind field, moisture flux, geopotential height, SSTs, moisture divergence and velocity potential during seasons with extreme onset dates. The period considered for onset calculation was early August to late December. Monthly and composite anomalies discussed in this chapter were calculated by subtracting individual monthly/composite means for a given seasons/composite from the long term monthly/composite average.

To most subsistence farmers, having prior information about when the first rains are likely to occur has strong implications for their agricultural activities and subsequently on crop yields later in the season. During the first few weeks of sowing, enough soil moisture is required to meet the needs of a particular crop at a particular time. The information on onset dates of the rainy season becomes critical for planning purposes for the majority of the farmers especially if it is made available before the growing season. This will greatly assist on-time preparation of farmlands, mobilisation of seeds and also reduce the risks involved in planting too early or too late (Omotosho *et. al.,* 1999). Planting too early may lead to crop failure, whereas planting too late may reduce the growing season and hence the crop yield reduction. Dry spells (discussed in chapter 4) during the early days of the season tend to increase the risk of seedling failure since most farmers start growing their crops immediately after a few days of rainfall. Farmers would benefit greatly and avoid rainfall related risk if adequate and timely information on cropping conditions is given in advance and thus there is a strong need to understand the inherent variability in onset and cessation dates.

This investigation of onset and cessation dates focuses on the amount of rainfall needed for the proper growth of maize, which is the staple food for the country. The seasonal maize crop flowers within the summer season after being planted in late October or November. It is also known that maize requires on average 120 growing days from planting to harvesting, thus December marks the beginning of the critical 4-month (December – March) period outside which the chances of a good harvest are considerably reduced (Usman and Reason, 2004).

A number of studies have used different approaches in the determination and forecasting of the onset of the growing season in various parts of the world. For example, Mumba and Chipeta (1984) used precipitation to study the onsets dates of the rainy season over Zambia. They observed that over the central and southern parts of Zambia, the effects of the continental high pressure over the southeastern subcontinent (i.e., southern Mozambique/Kwazulu Natal coast) may take time to erode and hence lead to delays in the onset of the seasonal rains the central parts of Zambia. Precipitation has also been used in the Sahel region of West Africa to assess onset of the rains (e.g. Omotosho *et al.*, 1999; Ati *et al.*, 2002). Dodd and Jolliffe (2000) used linear discriminant function analysis (LDF) to distinguish between 'Real' and 'False' starts to the onset of the rainy season in Burkina Faso and Mali. Camberlin and Okoola (2002) used Principal Component Analysis (PCA) to calculate the onset of the rainy season over Eest Africa. They found that during late onset, patterns develop in the sea level pressure field with positive and negative values in the tropical Indian and Atlantic Oceans respectively, which they suggested is partly related to temperature anomalies, the South Atlantic Ocean and the African continent being warm and the western Indian Ocean being cool in late onset years. Using upper-wind data, onset and cessation dates were predicted over Sahel region of West Africa more than 2 months ahead (Omotosho, 1990, 1992). It was observed that the rainy season starts between 49 and 81 days after the first sudden changes in wind direction at specified atmospheric levels. Recently, Tadross *et al.*, (2004) analysed the inter-annual variability of the onset of the growing season over southern Africa.

The criterion for defining onset dates used in this thesis is based on rainfall and is that used by the Famine and Early Warning System (FEWS) and given in AGRHYMET (1996). It is calculated as the amount of rain needed in the first month when planting maize, the first dekad (10 days) must have a total rainfall of 25mm and this must be followed by two dekads with a total of at least 20mm of rain. The onset date will then be taken as the first day of the first dekad. The algorithm used to identify the onset based on this criterion started at the pentad centered on 1st August in each year, which is before the summer growing season in the region.

The above conditions for onset dates are more stringent than some methods used in the previous studies (e.g. Camberlin and Okoola, 2002) and take care of the initial moisture requirement for maize seed germination and crop establishment as well as the need to avoid false starts by ensuring that soil moisture levels are high enough to sustain initial crop development.

5.2 Onset analysis

Although the general climate variability (particularly drought) over southern Africa has been given some attention (e.g. reviewed in Mason and Jury, 1997; Tyson and Preston-Whyte, 2000), not much is known about interannual variability in the patterns of onset dates over southern regions, which have important implications for the agriculture sector in Zambia and other countries. Knowledge of the year to year variability can help in understanding the various circulation systems that may play a role in influencing the onset dates over Zambia and help in its potential prediction. The data analysed in this section consist of pentad rainfall records covering a period of 22 years over Zambia from 1979-2001. To confirm the similarity of patterns produced by station data and to improve on the accuracy, comparison was made with onset dates derived from CMAP data.

Nkomoki (1998) observed that the year in Zambia can be divided into two distinct halves, a dry half from May to October and a wet half from November to April. The onset of the rainy season is normally between October and November but is characterised by substantial interannual variability. Figure 5.1 shows pentad rainfall climatologies for the September, October and November (SON) season calculated for the 1979-2002 (CMAP data) period over the western (22°E-30°E, 8°S-15°S), eastern (30°E-34°E, 15°S-18°S), southern (22°E-30°E, 15°S-18°S) and northern (30°E-34°E, 8°S-15°S) regions of Zambia. The four plots show that, on average, rainfall is earliest over the western region, which sometimes experiences significant rainfall in September. The early rains in this region could be due to the Angola low, which develops during this period and helps bring in moisture from the tropical southeast Atlantic Ocean. Over the other three regions, significant early rains frequently occur in October.

The mean onset dates for the period 1979-2001 derived from both data sets are shown in Figure 5.2. Slight differences between the two data sets occur over the southwestern parts (22°E-25°E, 15°S-18°S) with station showing average dates for onset to be in early November while CMAP data shows mid-November. Some differences are also observed over the northeastern parts (30°E-32.5°E, 10°S-12.5°S) with CMAP data showing average dates to be in early November while stations data shows late November. Elsewhere, the two data sets generally agree over most areas. On average, onset dates over the southern region (15°S-18°S) occur in November in both data sets. Over the central region (15°S-13°S), onset dates are in mid October while the northwestern parts have the earliest onset dates in early October.

Following this estimation of the observed mean onset dates and how they vary over the country, Figure 5.3(a-e) shows the onset dates for the 21 seasons under analysis. The years 1982, 1983, 1986, 1989 and 1991 are characterized by early onset dates over the central and northwestern parts of the country with onset dates in early October. The earliest onset dates during the study period was observed during the 1982 and 1986 seasons, with the entire country having onset between late September and early October although Livingstone station data had onset in mid November in 1982. For 1983, the onset dates showed a strong contrast with the southern, eastern and northeastern parts of Zambia experiencing late onset dates (late November-early December) whereas the western and north western parts had onsets as early as October. The northwestern region had early onset dates in 1982 and 1986 with a tendency for late onset in the 1990s. Figure 5.4 shows time series plots of onset dates over the northwest, northeast, southeast and southwest parts of Zambia derived from CMAP data.

The two data sets seem to show the same common features in the interannual onset variability for most years though 1980, 1996 and 1998 showed differences between them. Inconsistencies were mostly observed over the northeastern region. The southern and eastern provinces showed consistency in onset during the 1980 to 1994 period with slight differences between the two data sets afterwards. The two data sets also showed consistency over the western region, which was characterized by early onset during most seasons as compared to other regions in Zambia. Except for few instances mentioned above, the onset dates obtained from the two data sets are identical, or differ by no more than five days over most regions.

It is evident from the above discussion that the southern and eastern parts of Zambia are more prone to a later onset in summer rainfall than the other regions. In addition these regions are characterised by high number of dry spells as noted in chapter 4. The western and northwestern regions experience earlier onset than other regions especially along the border with Angola where growing can start as early as September in some seasons. This could be due to the influence of the Angola low which usually starts to develop to the west of this area in September.

Figure 5.5 suggests that there is an inverse relationship between onset dates over the northern region (22°E-34°E, 8°S-15°S) and dry spell frequency for the DJF period over Zambia during the 1979-2001 period. For most of the record, anomalously early onset dates tend to occur for years with higher than average dry spell frequency in the following DJF season and vice versa. In general therefore, early onset in the northern region is disadvantage in that it often leads to more dry spells during the subsequent core period (DJF) of the season. Seasons with late onset dates tend to show below average numbers of dry spells in DJF for 1979/80-1996/97 but the late onset seasons of 1997/98, 1998/99 and 1999/00 show average or above average dry spells. A suggestion of a tendency towards later onset after the mid-1990s may account for this behaviour. The inverse relationship in Figure 5.5 suggests that the same circulation anomalies might be responsible for the variability in both onset of the rainy season and dry spells.

5.3 End/Duration of the growing season

As mentioned previously, cessation dates are important for appropriate decision making with regard to irrigation needs, likely harvest times and the prediction of the length of the growing season. In this thesis, if three consecutive pentads have rainfall less than or equal to 2mm/day, then the preceding pentad is considered the end of a rainy season. This definition for the end of the rainy season has been used previously by Kijazi and Reason (2004) for Tanzania.

Figure 5.6 shows cessation dates for selected stations over the central, northern, eastern, northwestern, northern and southern parts of Zambia using daily station rainfall data. Over the central parts of the country (Lusaka), cessation dates during the study period are typically observed between late March and late April with the exception of 1993 and 2000 which had cessation dates in early May. In the eastern, northwestern and northern region, the cessation dates usually extend till late May during some seasons though generally it is in April (Figure 5.7). The southern (Livingstone) region typically experiences cessation dates between late March and mid April (Figure 5.7). This implies that the southern region has the shortest rainy season, as this part of the country is also prone to late onset of rains. The shorter season here could be due to early withdrawal of moisture from the Indian Ocean and the subtropical anticyclone shifting to the northwest as autumn progresses and the fact that this region is further away from the meridional arm of the ITCZ compared to other regions over the country. Over the northern and western regions, the influence of the ITCZ and Angola low may be responsible for the general later cessation dates during most of the seasons. Table 5 below shows the duration of the rainy season calculated for station data representation of the over various regions across Zambia for each year between 1979/80 and 2001/02.
(Note 1980=1979/80 season)

(i) Lusaka (central)

Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)
1980	150	1985	180	1990	142	1995	122	2000	177
1981	169	1986	207	1991	200	1996	140	2001	173
1982	137	1987	134	1992	161	1997	128		
1983	167	1988	193	1993	192	1998	--		
1984	194	1989	182	1994	166	1999	168		

(ii) Livingstone (southern)

Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)
1980	202	1985	179	1990	200	1995	137	2000	135
1981	179	1986	143	1991	174	1996	152	2001	183
1982	167	1987	223	1992	178	1997	153	2002	175
1983	194	1988	132	1993	190	1998	163		
1984	111	1989	208	1994	175	1999	152		

(iii) Chipata (eastern)

Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)
1980	214	1985	191	1990	190	1995	152	2000	188
1981	174	1986	204	1991	169	1996	128	2001	184
1982	203	1987	197	1992	206	1997	204	2002	123
1983	125	1988	183	1993	193	1998	181		
1984	159	1989	217	1994	214	1999	188		

(iv) Kasama (northern)

Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)
1980	224	1986	221	1991	174	1996	155	2001	208
1981	296	1987	235	1992	234	1997	169	2002	173
1982	184	1988	164	1993	182	1998	192		
1983	214	1989	184	1994	216	1999	193		
1985	186	1990	214	1995	254	2000	192		

(v) Kabompo (northwestern)

Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)	Year	Duration (days)
1980	225	1985	222	1990	186	1995	187	2000	157
1981	193	1986	192	1991	289	1996	234	2001	152
1982	169	1987	223	1992	224	1997	171	2002	211
1983	228	1988	290	1993	180	1998	173		
1984	204	1989	252	1994	153	1999	193		

Table 5.1: Showing rainfall season duration over various regions in Zambia.

The duration of the rainy season was derived by subtracting the end dates of the rainy season from the onset dates. From Table 5.1, regions with short rainy season are located in the southern and central parts of the country. At Livingstone, the duration of the rainy season varies between 134 -207 days whereas the northern and northwestern regions experience a longer rainy season (155-290 days) with the maximum of 290 days observed in Kabompo during the 1988 season. In almost all seasons, the rains start first over the north and progress to the south. The growing season is shorter further to the south and there is greater variability in the start and duration of the season. The main harvest takes place from April to June for all rain fed crops (FEWS, 2004).

5.4 Niño 3.4 SSTs – Onset relation

ENSO is one of the major contributors to the interannual variability observed over southern Africa. With increased understanding of ENSO in recent decades has come a renewed interest in ENSO teleconnections and impacts. This section considers the possible relationships between ENSO parameters and onset dates over Zambia as a first step towards assessing whether it may be possible to seasonally forecast these parameters that are more useful to farmers. The relationship between onset dates and Niño 3.4 SSTs anomalies will be investigated for the 22-year period (1979/80-2001/02). Several studies have documented the large-scale patterns of southern Africa rainfall anomalies associated with ENSO based on observed data (e.g. Lindesay *et al.*, 1986; Nicholson and Kim 1997; Reason *et al.*, 2000). They highlighted broad regions over southern Africa which show significant precipitation anomalies associated with ENSO. Usman and Reason (2004) analysed anomalies in dry spell frequency averaged over the southern African region and found a strong relation with Niño3.4 SST. Rocha and Simmonds (1997), Reason and Mulenga (1999) and Goddard and Graham (1999) used atmospheric GCM experiments to show that warm SST anomalies in the western Indian Ocean region may lead to anomalous rainfall over South Africa. Whether or not these Indian Ocean SST anomalies are also related to anomalies of the onset of the rainy season is yet to be established.

In the previous chapter, it was found that virtually all El Niño years during the period (1982/83, 1986/87, 1991/92, 1994/95 and 1997/98) were associated with a relatively high number of dry spells during DJF while most La Niña years were characterised by a relatively low number of dry spells. Given these apparent associations with ENSO, we investigate possible relationship between onset dates and Niño3.4 SST anomalies. Given that SST prediction in the tropical Pacific is relatively successful, any relationship could help in obtaining useful information about likely onset date of the forthcoming rainy season.

To investigate the relationship of onset dates with Niño3.4 SSTs, a time series (CMAP data) was used to analyse the relationship for five area averaged regions across the country (Figure 5.8). The DJF period was used for the analysis of Niño3.4 SST anomalies. The five regions of southwestern, northwestern, southeastern, northeastern and northern Zambia were analysed in order to understand how the relationship with Niño3.4 SSTs may vary for different regions across the country.

The northern (22°E-34°E, 8°S-15°S) and northwestern (22°E-30°E, 8°S-15°S) regions showed the strongest relationship between anomalies in onset date anomalies and Niño3.4 SST anomalies [Figure 5.8(a-b)]. Thus the northern region will be analysed in detail (section 5.5) in order to extract extreme onset dates and their associated circulation anomalies. Seasons with early onset dates (below -1.7 standard deviation) and those with late onset dates (above +2 standard deviation) were extracted from the CMAP time series. The early onset seasons are 1980/81, 1982/83, 1986/87 and 1991/92 whereas late onset seasons are 1981/82, 1995/96, 1996/97 and 1998/99. Early onset dates occur during the strong El Niño seasons of 1982, 1986 and 1991 (Figure 5.8a). La Niña seasons (1995 and 1998) show late onset. Important exceptions are the 1994 and 1997 El Niño and the 1988 La Niña. The 1981/82 neutral season shows anomalously late onset.

In the northwestern region (22°E-30°E, 8°S-15°S), early onset is observed in 1982, 1986 and 1987 (Figure 5.5b). The late onset dates are observed in 1989, 1995, 1996 and 1998. The El Niño years of 1982 and 1986 showed early onset over this region while 1991 and

1994 show the same pattern although slightly weaker in magnitude compared to the northern region. Over the southwestern region (22°E-30°E, 15°S-18°S), early onset is observed in 1979, 1980, 1982 and 1986. All El Niño years during the 1980s show early onset dates while the La Niña years of 1995 and 1999 show late onset dates over this region. The relationship between onset dates and Niño3.4 anomalies is not well defined over the southeastern parts of Zambia as evident from Figure 5.8(c-e).

The strength of the observed relationship with Niño3.4 SST seems to be stronger for most years during the 1980s than for the 1990s. Figure 5.8 also shows that the relationship is much stronger over the northern (Figure 5.8a) region. The analysis of onset variability presented so far tends to suggest that ENSO may influence the onset dates of the rainy season over some regions over Zambia (e.g. northern region). Onset dates can to some extent be predictable from the knowledge of Niño 3.4 SSTs, which is commonly predicted with some degree of accuracy. However ENSO is not the only primary mode of influence on onset dates over Zambia, other patterns of variability may be important. Hence, the following section will analyse the circulation anomalies that tend to be associated with early and late onset over Zambia.

5.5 Circulation patterns associated with early and late onset

This section looks at the circulation anomalies related to seasons with anomalously early or late onset dates of the rainy season over the northern parts of the country (22°E-34°E, 8°S-15°S). The objective is to investigate characteristics associated with early and late onset seasons over Zambia. The August, September, October (ASO) period was used in order to analyse the behaviour of the circulation potentially responsible for early or late onset dates. Moisture flux anomalies were analysed to examine the source of water vapour during seasons with early or late onset of rains. Composite wind anomaly field and geopotential heights anomalies at upper and lower levels were analysed in order to diagnose the large-scale circulation associated with onset dates over the study area. Velocity potential, which is a measure respectively of the non-divergent and divergent component of the wind were also examined at both lower and upper levels.

5.5.1 Composite circulation anomalies during early onset years

The moisture flux composites anomalies at 850hPa associated with early and late onset dates over northern Zambia are shown in Figure 5.9a and Figure 5.9b respectively. Based on the northern region, the years chosen are 1980, 1982, 1986 and 1991 for early onset and 1981, 1995, 1996 and 1998 for late onset. Circulation plots were constructed from the months (ASO) prior to the mean onset date in mid October. This is intended to show sources of moisture prior to the onset of the rainy season. During the early onset years, the ASO low level moisture flux composite anomalies are characterised by an anticyclonic feature with its centre located over Angola at approximately (15°S, 17°E). A weakening of the trades is evident over the southeast Indian Ocean together with some ridging south of South Africa similar to that found for early onset over Zimbabwe and South Africa (Tadross *et al.*, 2004; Reason *et al.*, 2004). At 350hPa there are westerly anomalies over Angola, western Zambia and Zimbabwe suggesting a weaker tropical easterly jet. The middle level anomalies (not shown) suggest the possibility of moisture input from the Congo basin.

The above discussion suggests that an anticyclonic anomaly centered over Angola is present during early onset over the northern region of the country. However caution is required when interpreting the moisture and wind anomaly composites as they may not be the only sources of variability in the onset signal.

Figure 5.9a (bottom right) also shows geopotential anomaly composites over the Southern Hemisphere during early onset seasons. Positive anomalies are present over southern Africa consistent with the ridging south of Africa and the anticyclonic feature over Angola. The train of alternating high and low pressure anomalies to the southwest over the South Atlantic and South Pacific suggests that the southern African anomalies may arise via a Pacific South American (PSA) Rossby wave pattern generated by anomalously convection in the Pacific (Kiladis and Mo, 1988; Mo and Peagle, 2001). The Rossby wave train across the Pacific and South Atlantic to South Africa is still present at 350hPa (not shown).

To examine the connection between onset dates over Zambia and vertical cells in the global atmosphere, velocity potential anomaly composites were computed during early onset seasons. Figure 5.9a shows the velocity potential associated with early onset seasons over Zambia at .995sigma (lower) and .2101sigma (upper) levels for ASO. Taken together, these plots imply a weakening of the mean anticyclonic winter/spring subsidence over southeastern Africa and a strengthening of early wet season convection over northern Tanzania and southwestern Kenya (the OND season represent the 'short rains' over this region). Over the North Indian Ocean / South Asian region, the plots imply a weakening of the uplift associated with the boreal summer monsoon. A weaker Asian monsoon suggests less outflow to the Southern Hemisphere at upper levels and therefore less subsidence over southern Africa and Australia, as observed. The link between early season convection over Tanzania / Kenya and early onset over Zambia is evident in Figure 5.9a which shows anomalous uplift at 500hPa (i.e., negative pressure tendencies) over Angola, the southern Congo, Zambia and Tanzania / Kenya. Further south over the South West Indian Ocean and eastern South Africa, there is subsidence (positive pressure tendencies) consistent with the high pressure anomaly to the south and southeast of South Africa. In addition, a band of low level convergence exists across Zambia, Tanzania and northern Mozambique facilitating the connection between early season convection over East Africa and rainfall over Zambia. In summary, both a Southern Hemisphere (PSA wave train) and Asian monsoon link seems to play a role in the early onset over Zambia.

5.5.2 Composite circulation anomalies during late onset years

In this section, the composite anomalies associated with late onset seasons (1989, 1995, 1996 and 1998) are discussed Figure 5.9b. At the 850hPa level, a cyclonic moisture flux anomaly is evident over Angola, Congo and Zambia, with another cyclonic feature over and south of South Africa. The latter implies less advection of moisture from the subtropical South West Indian Ocean over southern Africa and reduced rainfall. Further north, the westerly anomalies over southern Kenya, Tanzania and northern Mozambique imply less moisture advected towards eastern Zambia from the tropical western Indian Ocean.

Over the Southern Hemisphere as a whole, Figure 5.9b also shows a PSA-like wave train stretching across the South Pacific, southern South America and into the South Atlantic. However, the sign is opposite to that seen for the early onset years such that for the late onset composite, the train starts off as positive anomalies in the South Pacific and a cyclonic anomaly is seen over and south of South Africa. In addition to this wave train, a negative phase Antarctic oscillation (Kidson, 1988) pattern is evident with positive (negative) height anomalies apparent over Antarctic (southern midlatitudes).

The velocity potential anomalies suggest a weaker Asian monsoon as did the early onset plots (Figure 5.9b); however, the difference from the early onset case is that the weakened outflow to the Southern Hemisphere and reduced subsidence now seems to be more over northern Australia rather than over southern Africa as was found for the early onset case. In addition, the anomalies in the 500hPa pressure tendency (Figure 5.9b) do not show a link between Zambia and East Africa as was the case for the early onset composite. Although there is weak anomalous uplift over western Zambia (weak negative anomalies), eastern and northern Zambia does not show any obvious anomaly in uplift.

In summary, late onset seasons seem to be associated with strong low level westerly anomalies over Zambia and East Africa which reduces the moisture flux from the western Indian Ocean and implies reduced low level convergence over Zambia. A cyclonic anomaly is present over and south of South Africa which is connected to a PSA-like wave train emanating from the South Pacific. This cyclonic feature also reduces the moisture flux from the subtropical South West Indian Ocean towards southeastern Africa, and this reduction together with a weakening of the trade wind moisture flux north of Madagascar towards East Africa weakens the low level moisture convergence over Zambia leading to a delay in the rains.

5.6 Summary

This study has investigated one of the most important impacts of climate variability on rain-fed agriculture over Zambia. Farmers depend entirely on the start of the rains, which is highly variable, to plant crops like maize for subsistence agriculture. The CMAP and station pentad rainfall datasets from 1979-2002 were used to calculate onset dates of the rainfall season across Zambia and to distinguish circulation anomalies related to early and late onset events.

The onset of the austral summer rainy season for various regions of the country was analyzed and determined. It was found that the northwest and western regions of Zambia often experience early onset of rains, which in some cases is as early as late September whereas the southern, eastern and northeastern regions are more vulnerable to late onsets. A high degree of interannual variability in onset dates of the rainy season was found over different parts of the country.

An interesting feature noted during the study was the relationship between onset dates and Niño3.4 SST anomalies. During the strong El Niño years of 1982, 1986 and 1991, northern Zambia tends to show early onset and during the strong La Niña years of 1995, 1999 and 2000 showed late onset. Thus, some teleconnection between ENSO and onset dates exists although there are exceptions such as 1997/98. Niño3.4 SSTs may be possibly used for potential prediction of onset dates over the region. It appears that the ENSO teleconnection is contributed to by a PSA-like Rossby wave train across the South Pacific and South Atlantic which helps set up an anticyclonic (cyclonic) anomaly over and south of South Africa during early (late) onset seasons. A possible connection with the strength of the Asian monsoon was also noted.

Another important relationship found was that between DJF dry spells and onset dates over Zambia. The early onset dates over the northern regions tend to be associated with high dry spells whereas late onset seasons tend to be associated with low dry spell frequencies although the relationship over the southern region is poor. Thus, an early onset to the rains over the northern region usually does not mean a favourable rainfall season. The definition of the onset dates in this study was purely based on the rainfall amount needed for germination of the maize seed over the first few pentads. This definition does not take into account the variability in the weather systems bringing the rainfall, or the relative influence of tropical circulation patterns that are needed for a season with good rains or adverse mid- latitude influence over the south that may disrupt the rain.

The study further demonstrates that there is large interannual variability of the onset, ranging mostly from 8th October to 30th November over the 22 year period. The withdrawal date which is associated with the northward shift of the ITCZ is also variable, ranging from 20th March to 5th May.

An important issue that needs attention is how rainfall variability interacts with the farmers' choices of planting dates. To address this, one would need to develop an understanding of farmer responses to climate variability and their decision making processes. Locally, there is a common understanding amongst farmers to plant their crops as per traditional ways rather than follow advice based on scientific results. In cases, where traditional methods lead to good outcomes it then becomes more difficult to convince subsistence farmers of the need to follow more scientific methods in their operations.

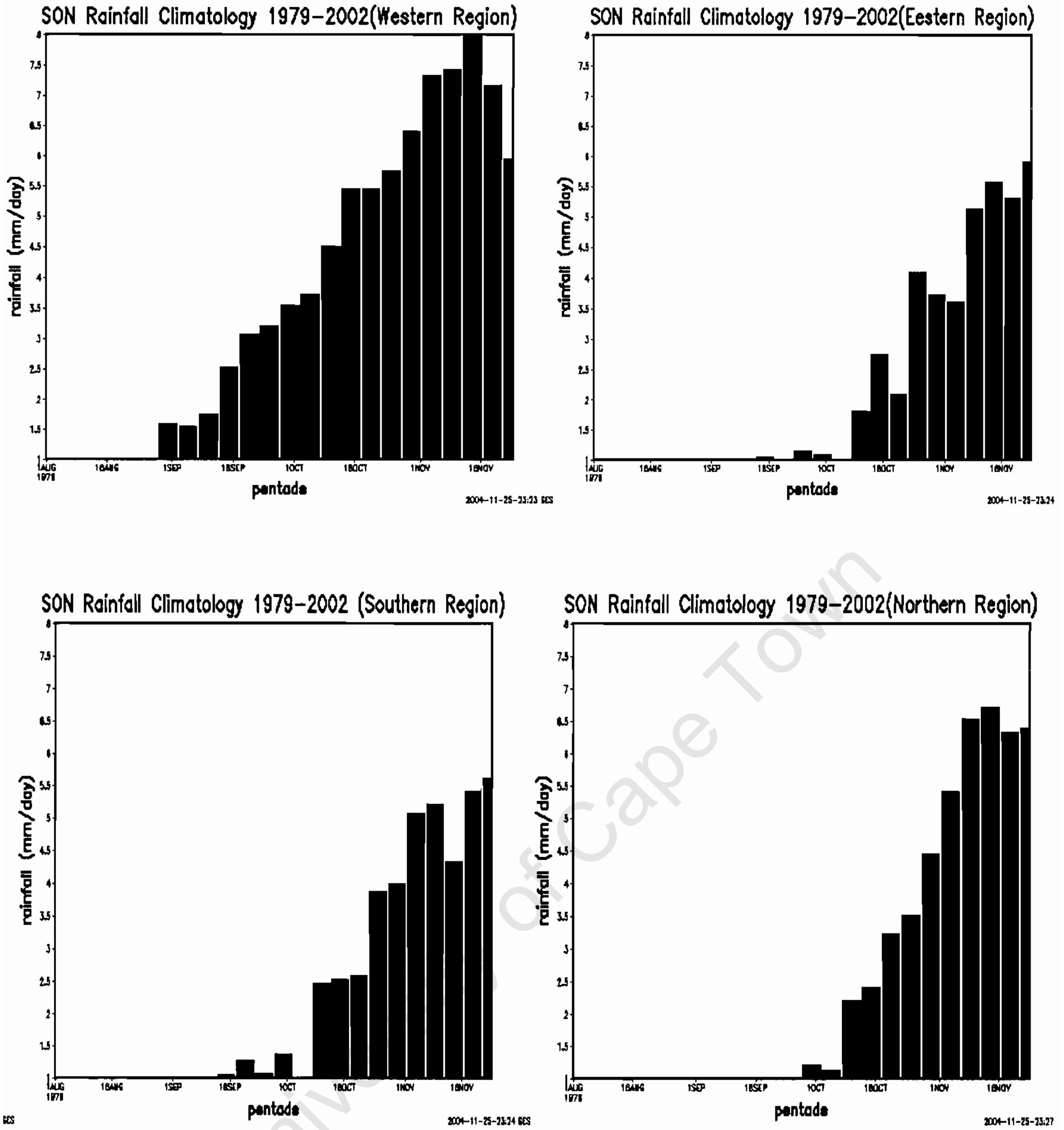


Figure 5.1: Rainfall climatology during the early summer season over Zambia

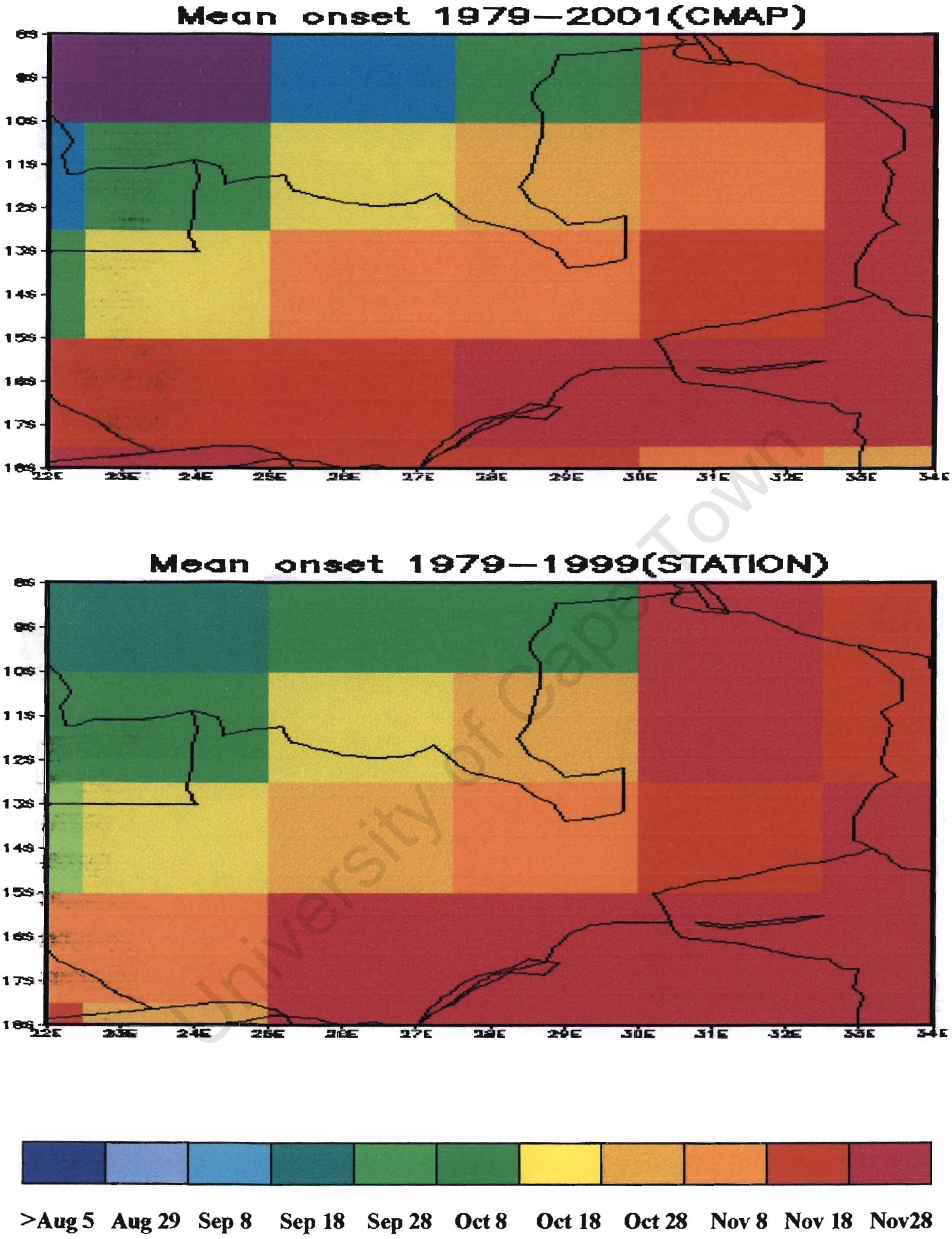


Figure 5.2: Mean onset dates over Zambia (CMAP and Station)

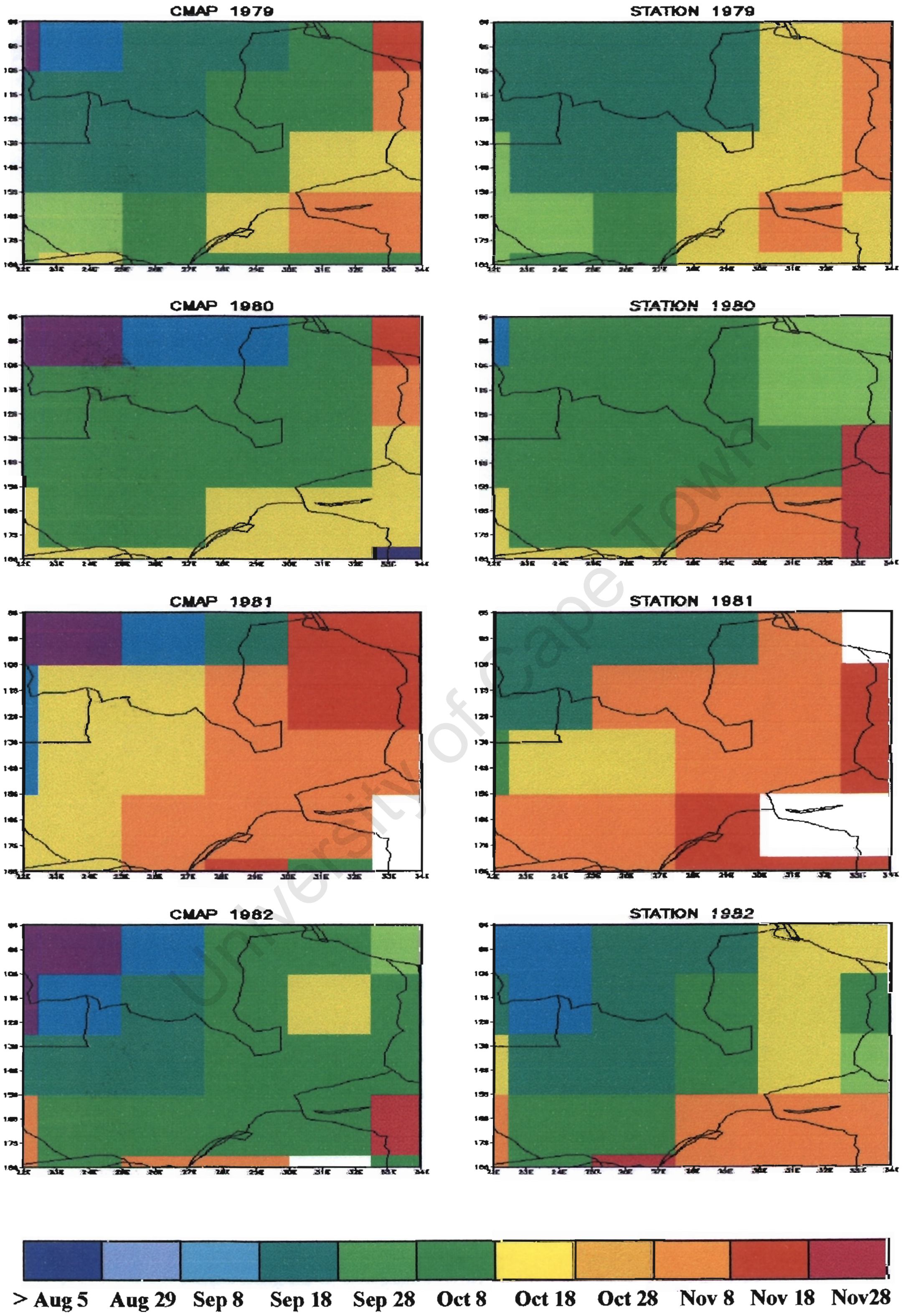


Figure 5.3a: Onset dates over Zambia (CMAP and Station)

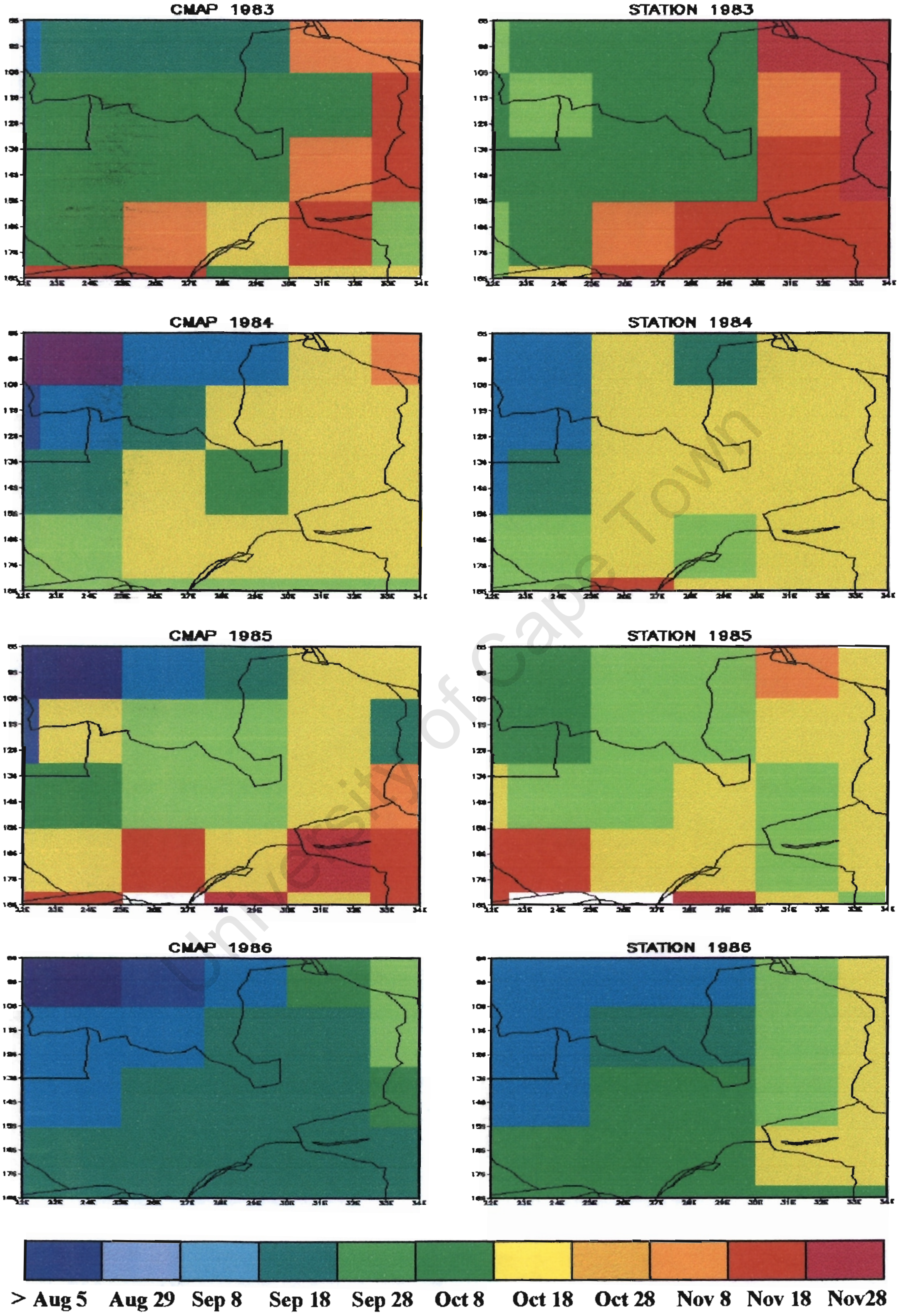


Figure 5.3b: Onset dates over Zambia (CMAP and Station)

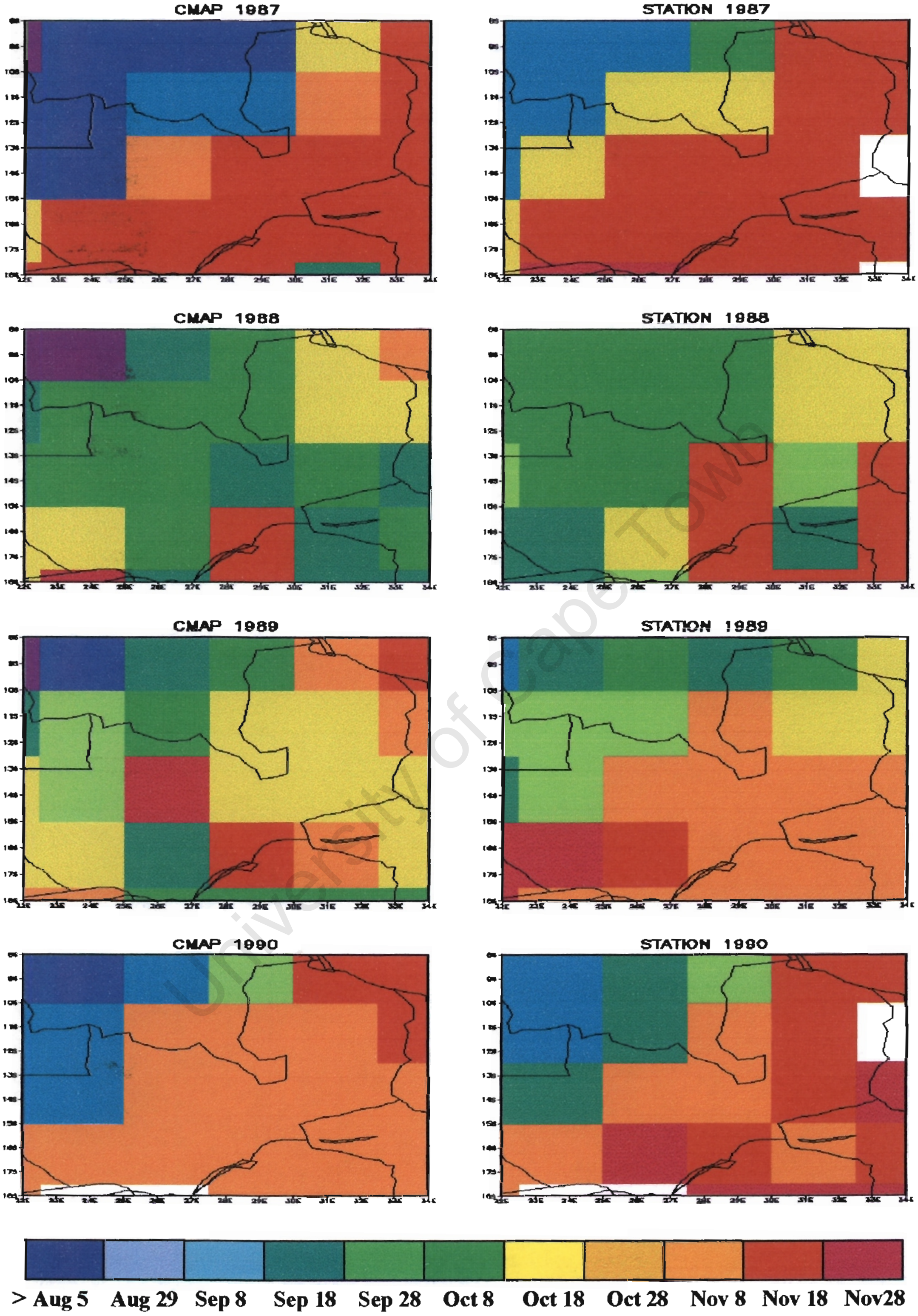


Figure 5.3c: Onset dates over Zambia (CMAP and Station)

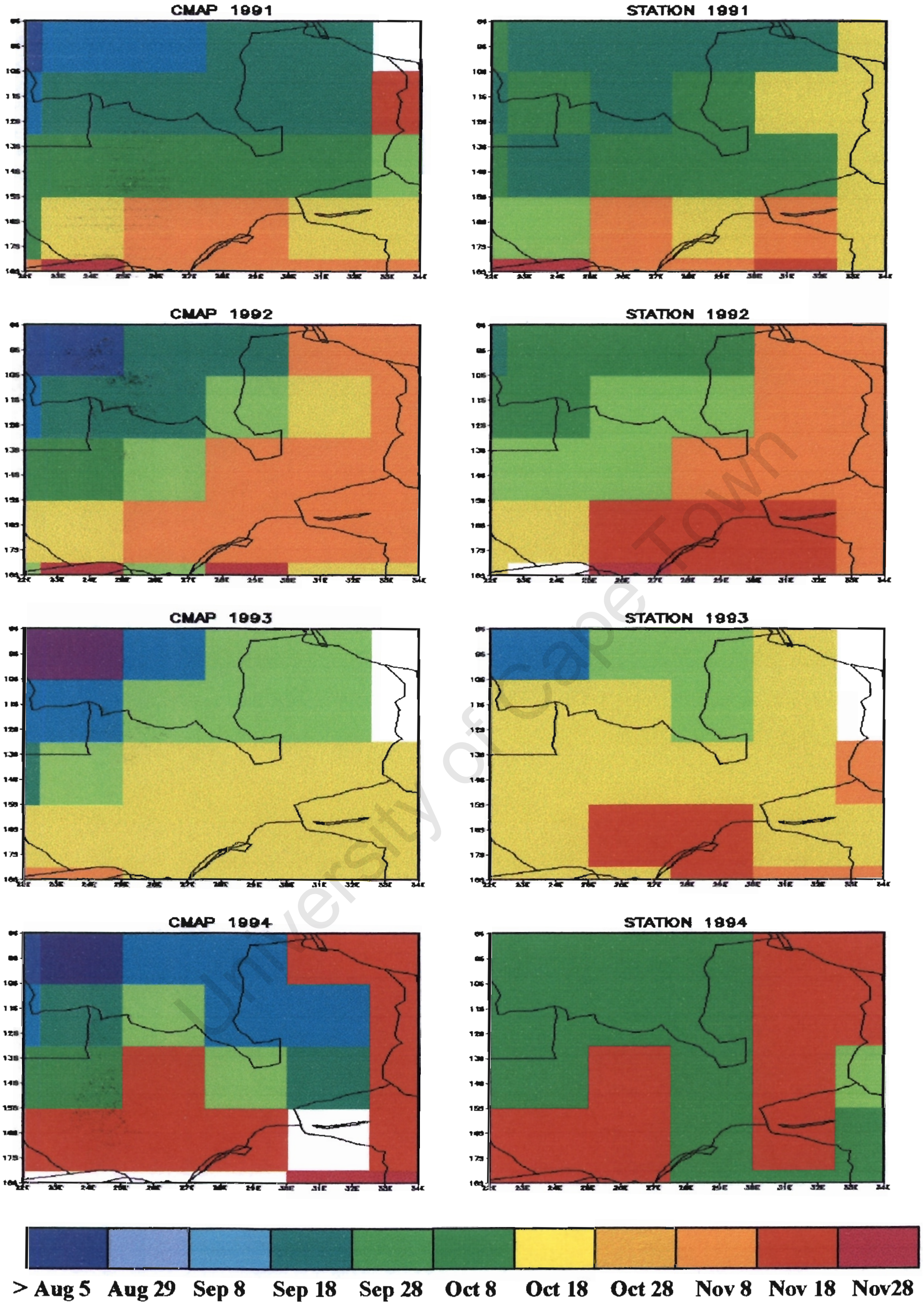


Figure 5.3d: Onset dates over Zambia (CMAP and Station)

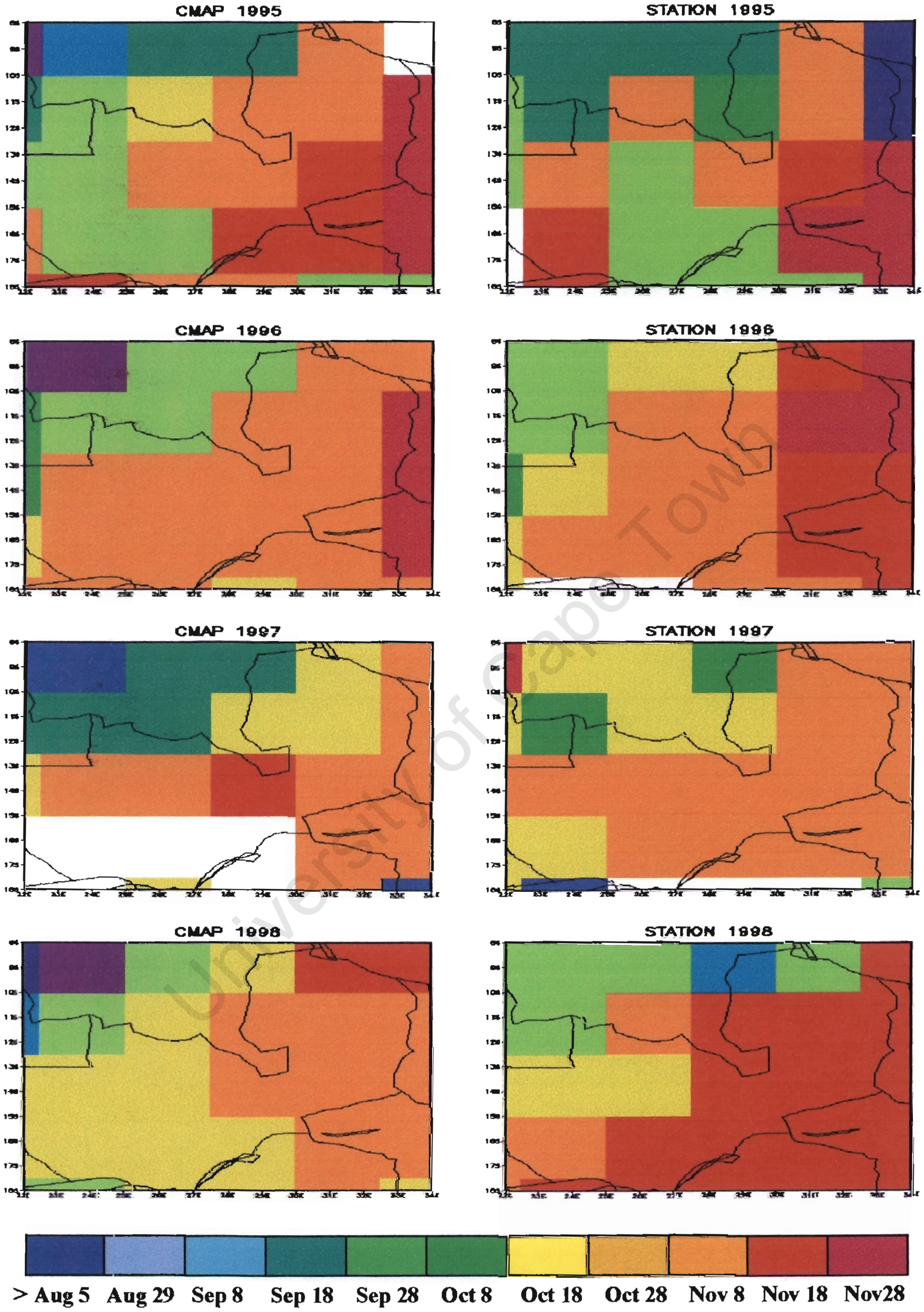


Figure 5.3e: Onset dates over Zambia (CMAP and Station)

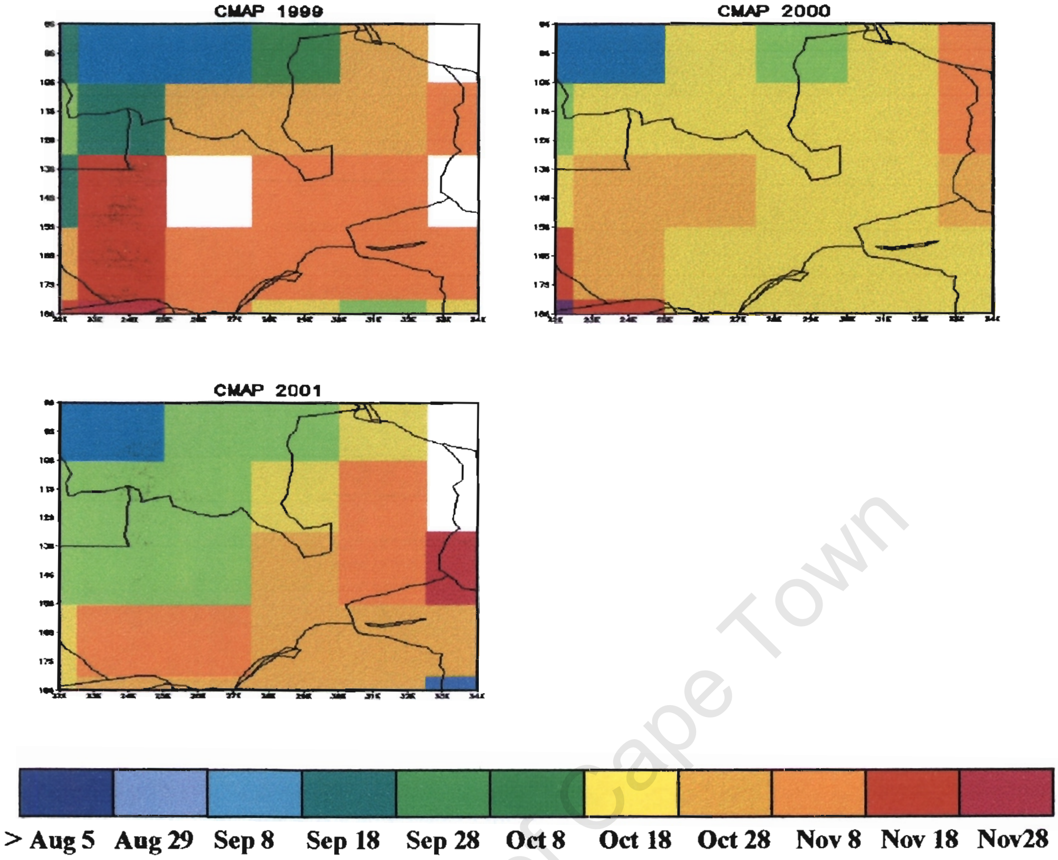


Figure 5.3f: Onset dates over Zambia (CMAP)

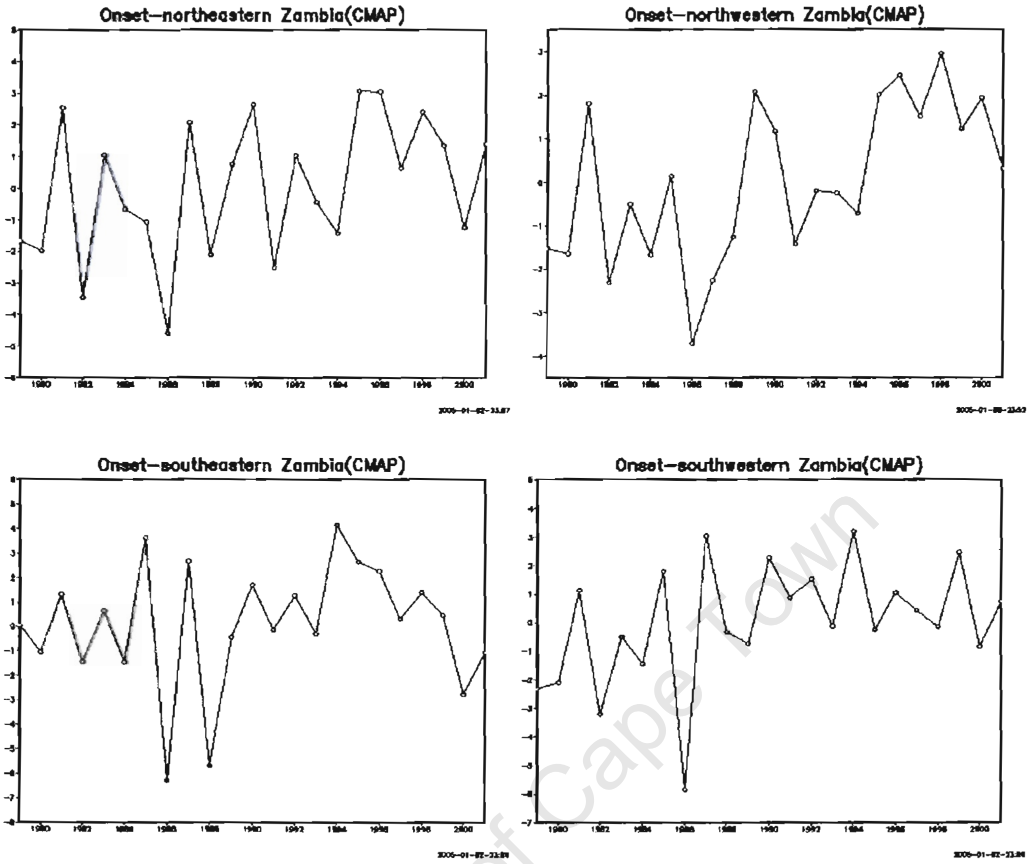


Figure 5.4: Onset anomalies

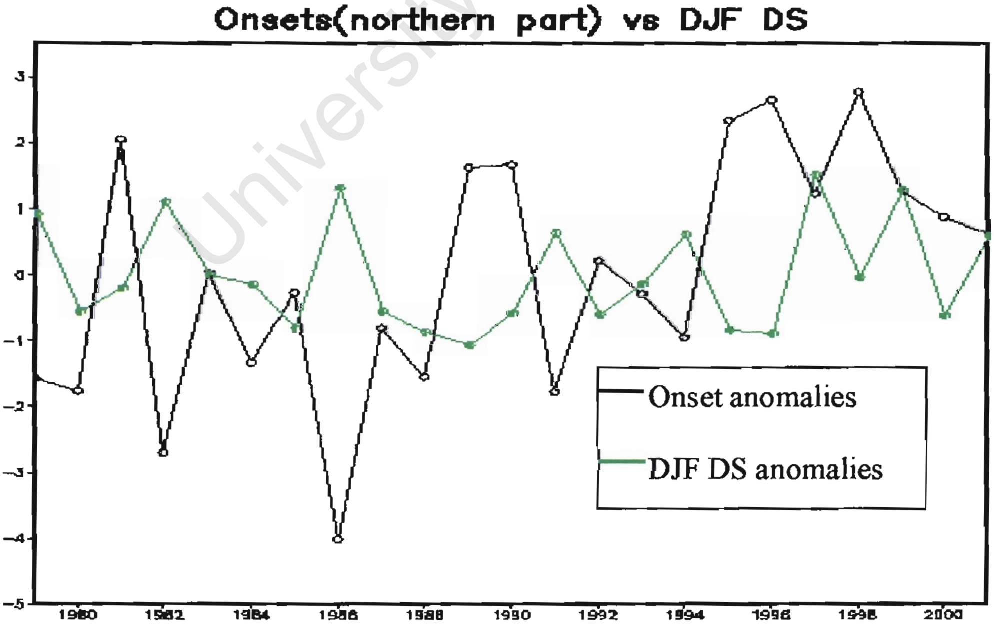


Figure 5.5: Onset anomalies against DJF dry spell anomalies

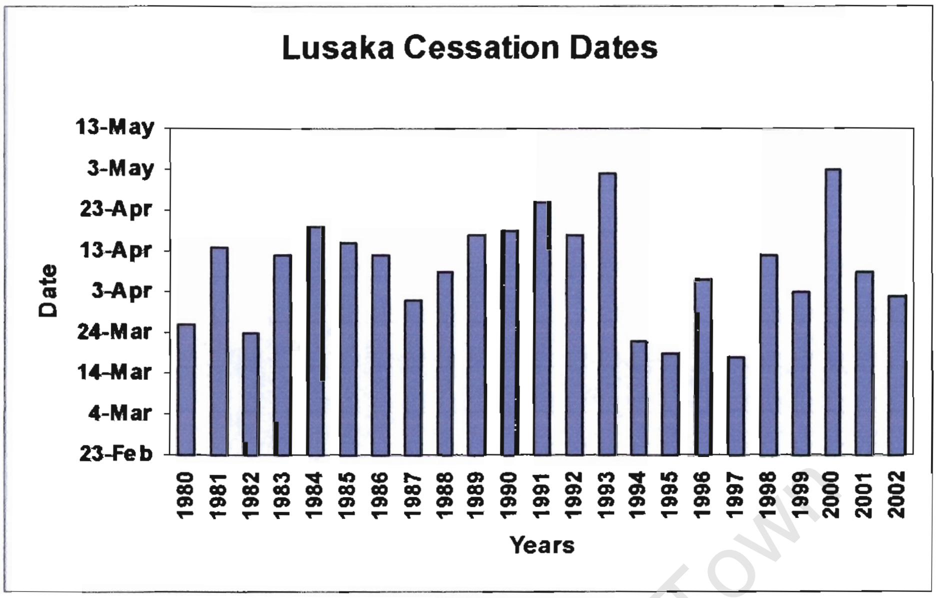


Figure 5.6a: Cessation dates over the central region.

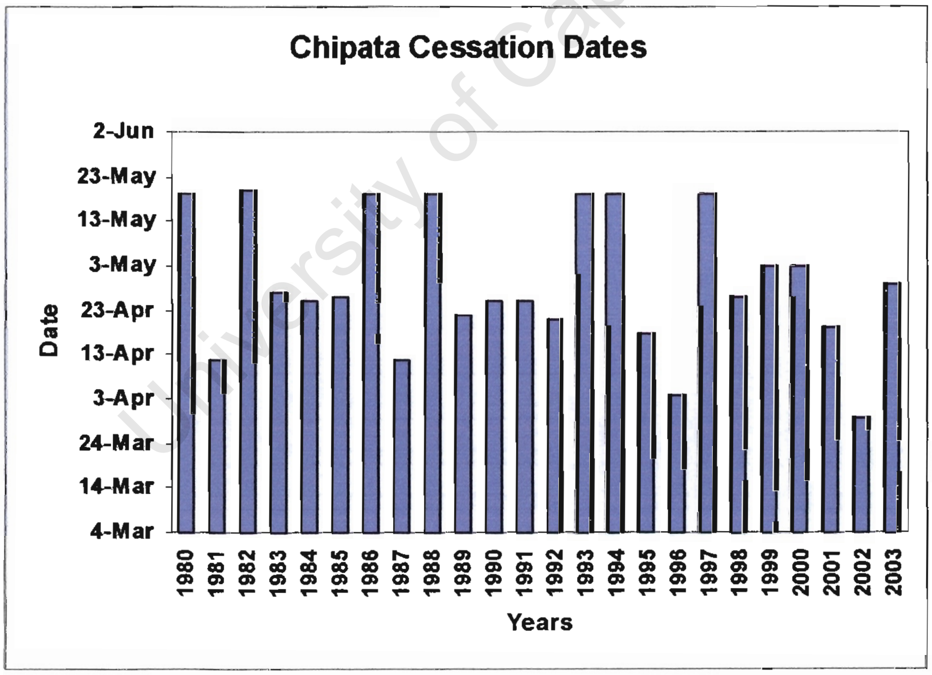


Figure 5.6b: Cessation dates over the Eastern region.

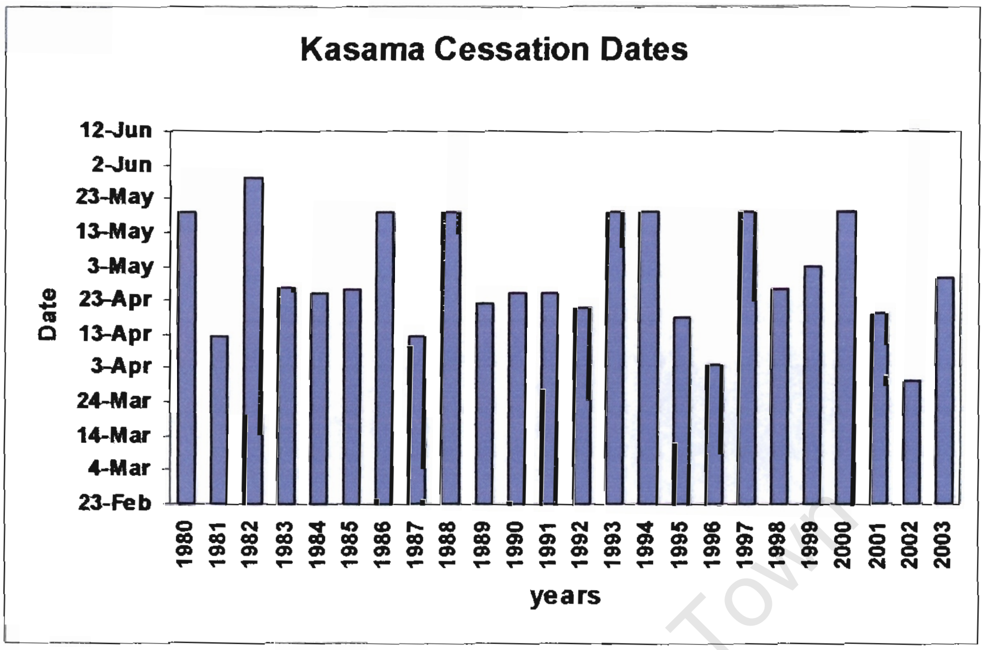


Figure 5.6c: Cessation dates over the northern region.

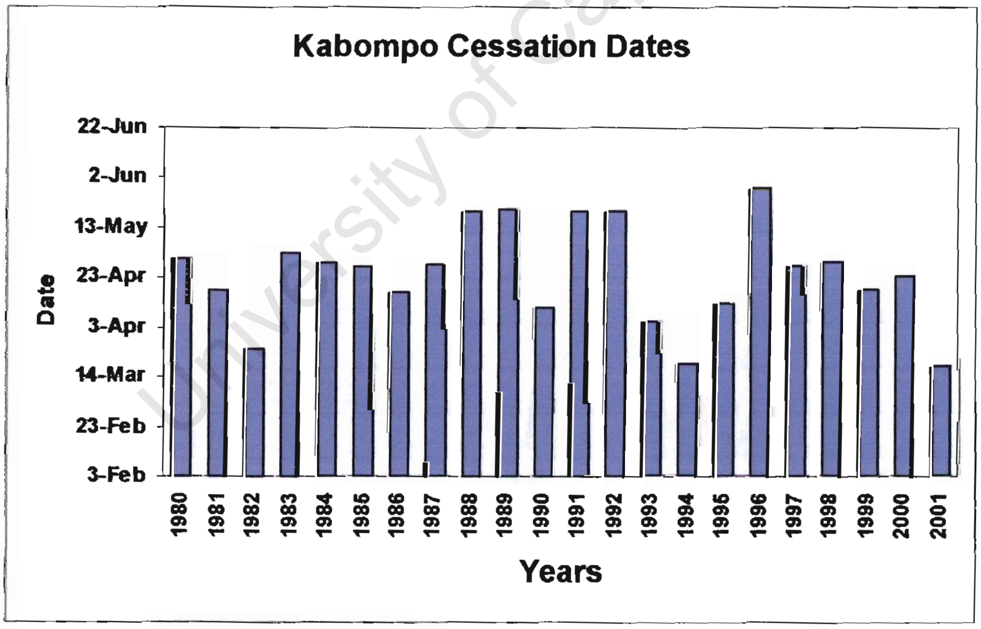


Figure 5.6d: Cessation dates over the northwestern region.

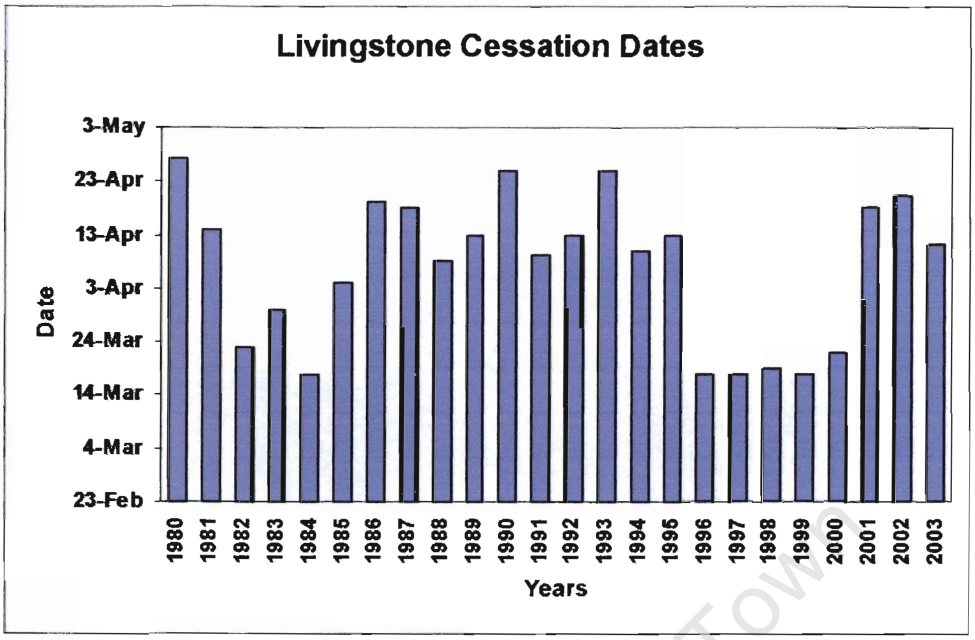


Figure 5.6e: Cessation dates over the southern region.

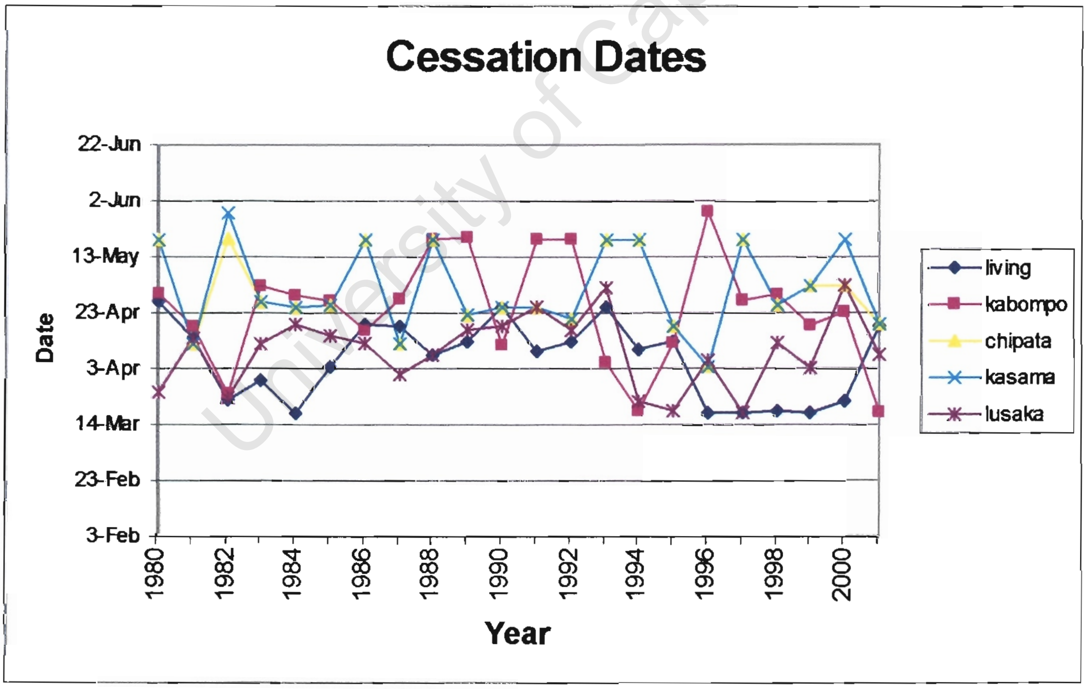
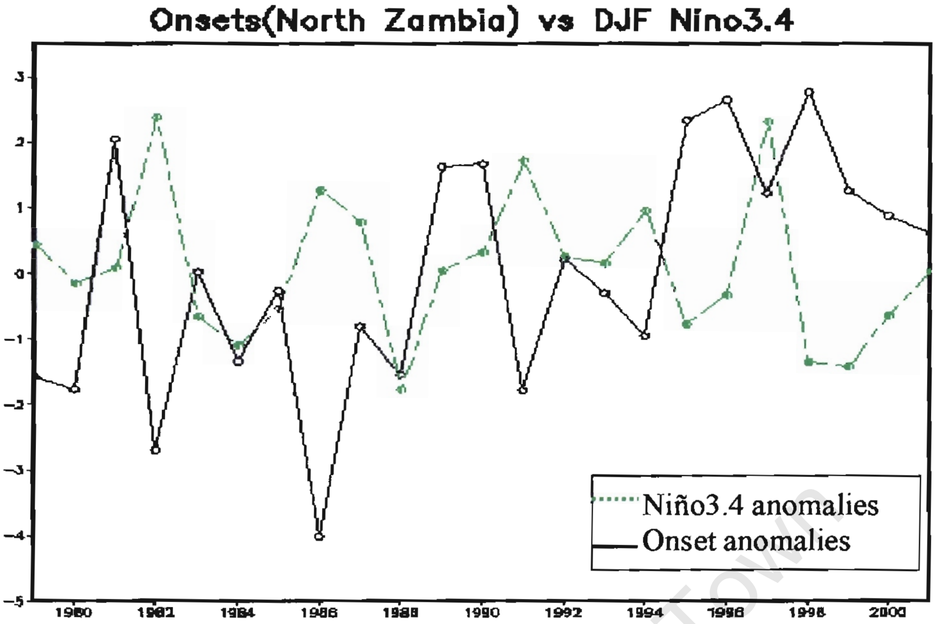
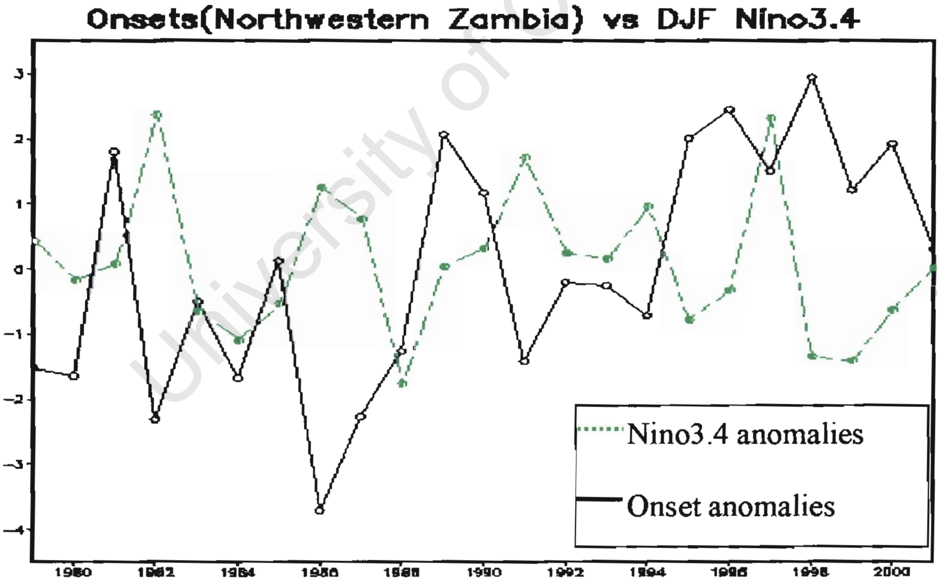


Figure 5.7: Cessation dates over various regions across Zambia.



Onsets(North Zambia) vs DJF Nino3.4

Figure 5.8a: Onset anomalies for north Zambia (22°E-34°E, 8°S-15°S) against Niño3.4 anomalies



Onsets(Northwestern Zambia) vs DJF Nino3.4

Figure 5.8b: Onset anomalies for northwestern Zambia (22°E-30°E, 8°S-15°S) against DJF Niño3.4 SST anomalies

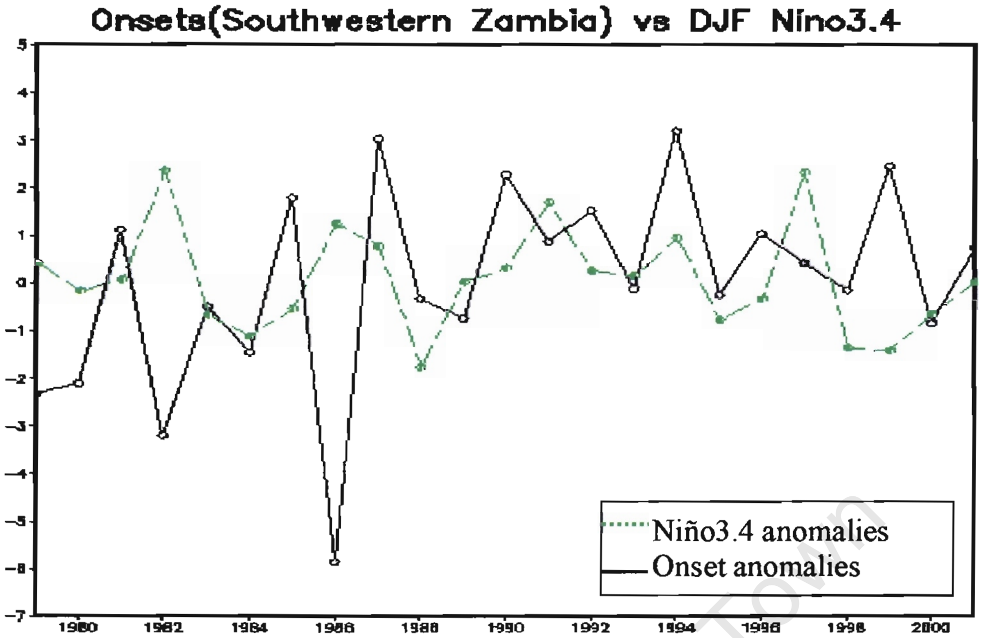


Figure 5.8c: Onset anomalies for southwestern Zambia (22°E-30°E, 15°S-18°S) against DJF Niño3.4 SST anomalies

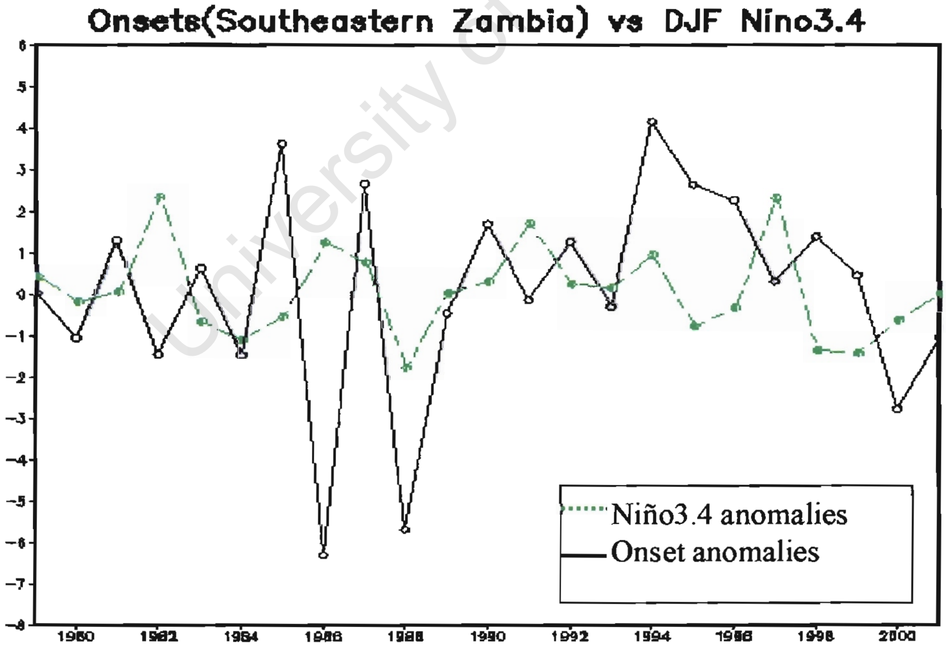


Figure 5.8d: Onset anomalies for southeastern Zambia (30°E-34°E, 15°S-18°S) against DJF Niño3.4 SST anomalies

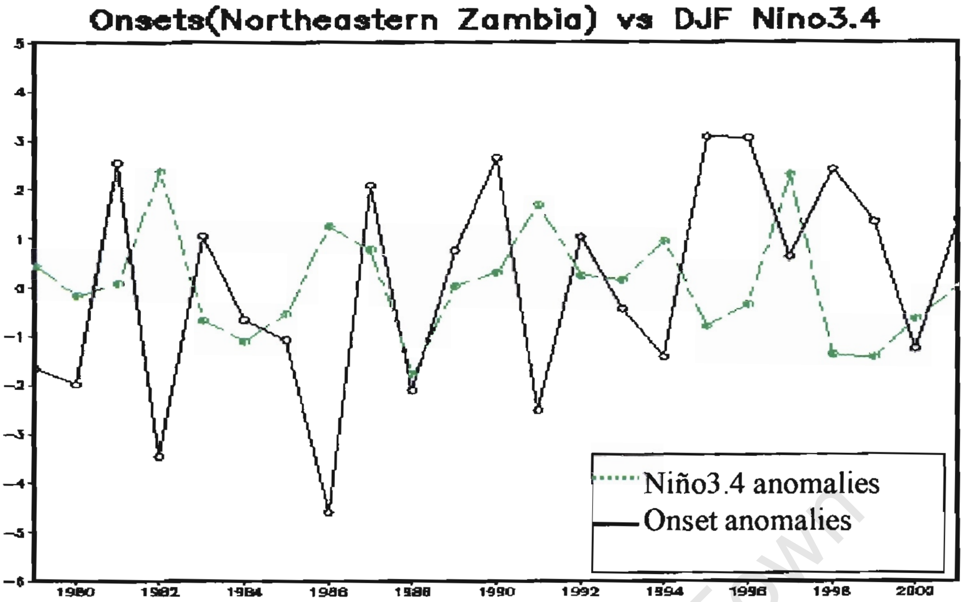


Figure 5.8e: Onset anomalies for northeastern Zambia (30°E-34°E, 8°S-15°S) against DJF Niño3.4SST anomalies

Early Onsets

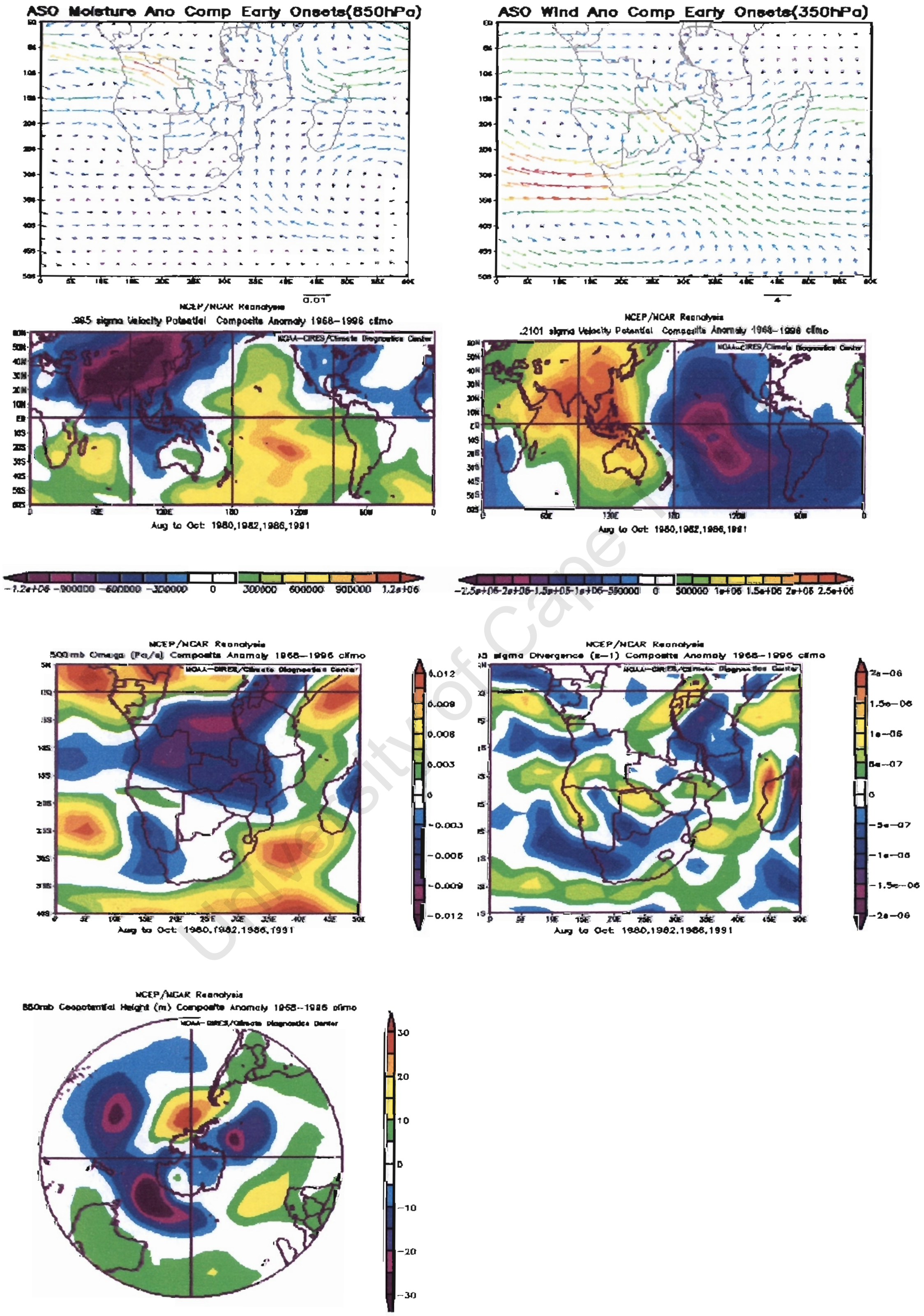


Figure 5.9a: ASO composite anomalies for early onset seasons at lower and upper levels

Late Onset

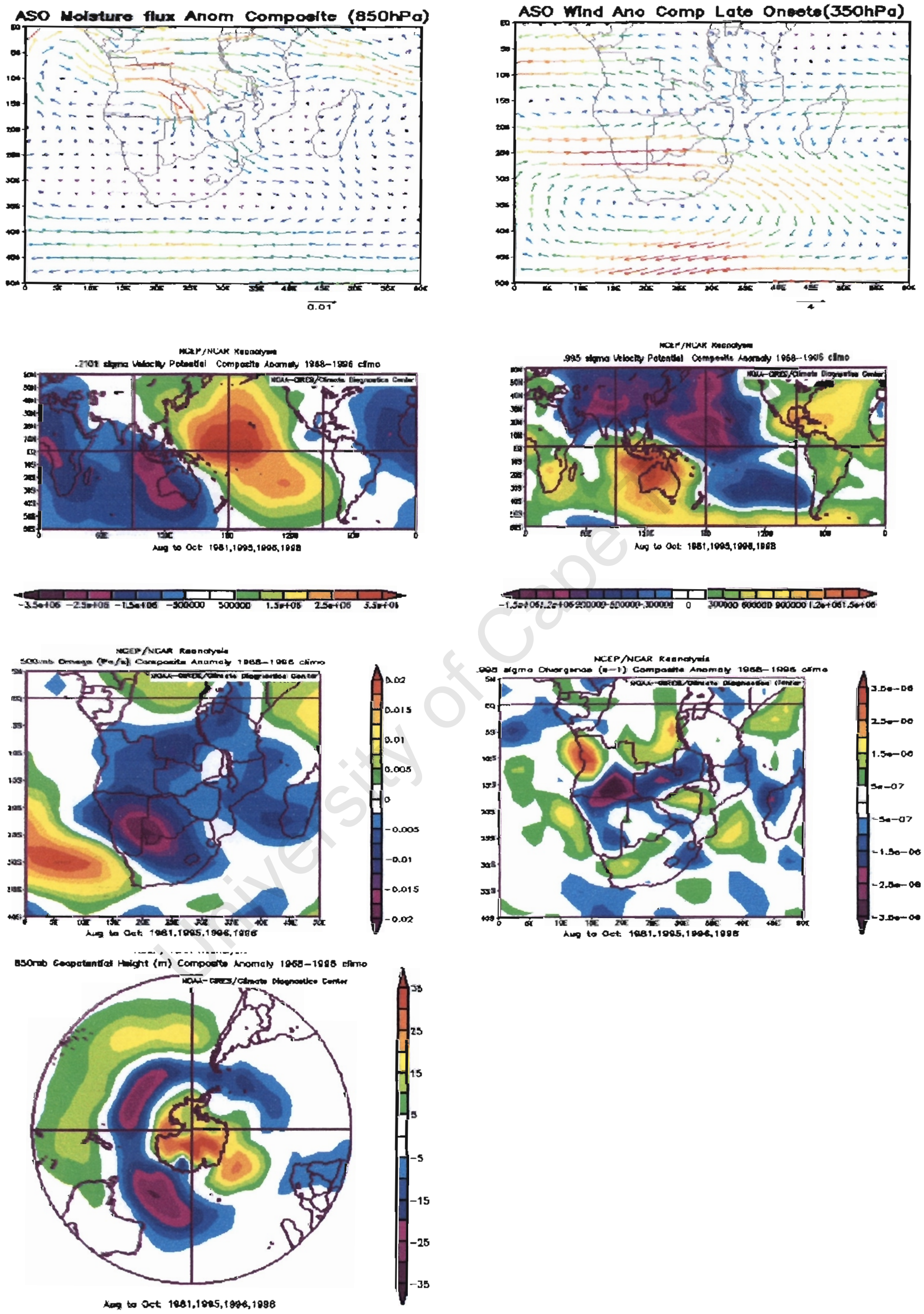


Figure 5.9b: ASO composite anomalies for early onset seasons at lower and upper levels

Chapter 6

Summary and Conclusion

Characteristics which describe rainfall variability over Zambia in terms of dry spells, wet spells, onset and cessation dates were investigated in this thesis. These characteristics are important for peasant farmers who make up the majority of farmers over Zambia and who rely on rain-fed agriculture. The intraseasonal and inter-annual circulation anomalies during seasons with extreme dry/wet spell frequencies and onset/cessation dates over Zambia were investigated as well as potential relationships with sea surface temperatures (SSTs). Very little research has previously considered dry/wet and onset/cessation dates analysis over the region.

Previous work as described in chapter 2, reveals that the main rainfall bearing systems over Zambia are the Inter Tropical Convergence Zone (ITCZ), the tropical heat low over southern Angola and northern Namibia, the interaction between the low and the ITCZ and synoptic systems like easterly waves and tropical depressions. It was noted that on average, the northern parts of the country experiences higher rainfall than the southern half since it tends to lie beneath the meridional arm of the ITCZ. Previous work on the El Niño-Southern Oscillation (ENSO) and the role it plays in southern African rainfall are also reviewed. It was observed that warm (cool) phases of ENSO or El Niño (La Niña) are characterised by warm (cool) SST anomalies in the tropical Pacific and Indian Ocean and typically result in below (above) average summer rainfall in Zambia. During the 1991/92 El Niño event, southern Africa was faced with severe food shortages due to reduced rainfall. The seasonal rainfall behaviour during the 1997/98 El Niño appears to show mixed signals over Zambia with two extreme events being observed. The southern regions had below normal rainfall whereas the northern half experienced massive rainfall, which led to flooding and crop loss. This behaviour illustrates firstly the complexity of the relationship between the investigated rainfall characteristics and their interaction with circulation anomalies, and secondly, it shows the importance of understanding these relationships for the benefit of farmers in Zambia.

The results show that a high number of dry spells occurs more often over the southern parts of the country between latitude 15°S and 18°S while the northern part has a low number of dry spells during the study period. The highest number of dry spells occurred during the 1979/1980, 1982/83, 1983/84 1986/87, 1991/92, 1994/95 and 1997/98 seasons whereas low dry spell frequency is observed during 1980/81, 1987/88, 1988/89, 1995/96 and 1996/97 with less than two dry spells being observed during each season. A common feature of dry spell occurrence is the location of maximum frequency in areas near the southern border with Zimbabwe. The dry spell frequency plots (Figure 4.2) show that over this region, more than 6 dry spells typically occur during El Niño seasons. This region also has the longest dry spell duration with a maximum length of 23 days being observed during 1991/92, one of the worst droughts over southern Africa. The northern and northwestern regions are observed to have low dry spells during the summer season and high number of wet spell due to the location of the ITCZ and the Angola low near these regions.

Figure 4.3 shows that recent occurrences of high dry spell frequencies over Zambia have been associated with El Niño events. It is found that El Niño events have a strong impact over the southern part of the country (22ºE-34ºE, 15ºS-18ºS) as compared to the north as already been observed in some previous works over southern Africa (e.g. Usman and Reason 2004). During El Niño (La Niña) events, increased (decreased) dry spell frequency was observed over southern Zambia.

Wet spells (pentad>10mm) are a common phenomenon over the northern regions of the country and these frequently lead to flooding. The highest number of wet spells during the DJF season tends to occur over the northwestern and northeastern regions of the country. Figure 4.5 shows that most of Zambia is generally wet during most DJF seasons since the average wet spell frequency across the country is 15 pentads out of a total of 18 pentads. All El Niño seasons are observed to have below average wet spell frequency while the 1995/96 and 1998/99 La Niña seasons experienced above average wet spells.

The mean DJF moisture flux climatology over southern Africa and Zambia is characterized by a northeasterly monsoonal flow from the northeast Indian Ocean, a southeasterly flow over Zimbabwe and southern Mozambique from the South West Indian Ocean and a cyclonic flow over southern Angola and northern Namibia emanating from the tropical southeast. These three moisture inflows tend to converge over central Zambia and play a significant role in contributing to producing of summer rainfall over the country.

Composite circulation anomalies associated with high dry and wet spell seasons are investigated in chapter 4. During seasons with a high number of dry spells, low level easterly anomalies exist over Zambia implying a reduced moisture penetration from the Angola low and reduced low level moisture convergence over the country, and hence increased dry spells. The strong upper level westerly anomaly from the South Atlantic Ocean implies that the tropical easterly jet is weakened. Cool SST anomalies exist off the coast of Namibia with warm SST anomalies further north off Angola; however, the generally weaker Angola low means that there is less westerly moisture flux from the tropical South East Atlantic towards Zambia, resulting in the high number of dry spells.

During seasons with a high number of wet spells, low level westerly anomalies exist over southern Angola and western Zambia, implying a strong moisture influx from the tropical South East Atlantic and increased convergence over Zambia. This situation and the warm SST anomalies near the Angolan coast imply more evaporation in the source region of the moisture imported by the Angola low. Cyclonic anomalies in the geopotential height field over southern Angola and Namibia imply a stronger Angola low consistent with increased rainfall over Zambia and more wet spells than average.

In chapter 5, the analysis of onset and cessation dates of maize growing areas within Zambia was calculated. A high degree of variability over the country during the seasons under study was observed. The onset of the rainy season over Zambia was observed to generally lie between October and November and is characterised by substantial interannual variability. The results reveal that the northern and northwestern regions experience earlier onset dates as compared to other regions especially along the border with Angola. The latter arises from the influence of the Angola low, which usually starts to develop to the west of this area in September. Over the northern region (22Eº-34ºE, 8ºS-15ºS), early onset seasons were observed during the years 1980/81, 1982/83, 1986/87 and 1991/92. During the study period, the 1982 and 1986 seasons had the earliest onset dates, with the entire country having onset between late September and early October. Another interesting observation was the relationship between onset dates and DJF dry spells. Anomalously early onset dates tend to occur for years with higher than average dry spell frequency in the following DJF season. Thus in general, early onset is a disadvantage in that it often leads to more dry spells during the subsequent peak growing period of the season.

A strong relationship between onset dates over the northern regions and Niño3.4 SSTs was the most notable feature. Early onset dates over this region were observed to occur during the strong El Niño seasons of 1982, 1986 and 1991. The La Niña seasons of 1995 and 1998 showed late onset characteristics. The strength of the observed relationship with Niño3.4 SSTs seems to be stronger for years during the 1980s than those during the 1990s.

During early onset seasons, an anticyclonic anomaly centered over Angola is present over the northern region of the country and a wave train of high and low pressure anomalies exists to the southwest over the South Atlantic and South Pacific. This wave train pattern suggests that the southern African anomalies may arise via a Pacific South American Rossby wave pattern generated by anomalous convection in the Pacific. A high pressure anomaly was evident south of South Africa implying increased advection of moist marine air over southeastern Africa. Late onset seasons tend to show the reverse anomaly patterns with a cyclonic anomaly over the sub-continent and south of South Africa. Over the Southern Hemisphere as a whole, an Antarctic Oscillation type pattern was evident.

This thesis has attempted to examine rainfall variability over Zambia and the systems responsible for this variability. It is hoped that this work will contribute towards the better understanding of rainfall variability and help the forecasting community to consider the value of observing SSTs anomalies and other parameters that are related to rainfall over Zambia. In turn, better understanding may assist decision making within the farming community in their preparation for the growing season. It should be noted that other factors such as pre-season soil moisture and land surface – atmosphere interactions may also be important for variability in dry/wet spells and onset dates over Zambia. These factors have not been investigated in this thesis but future work should consider them in order to improve understanding of Zambian rainfall variability and its potential predictability. Future research should also consider how farmers respond to extreme weather and climate events and the impacts of these events on the yields of various crops across the country.

References

AGRHYMET, 1996: Methodologie de suivi des zones a risque. AGRHYMET FLASH, Bulletin de Suivi de la Campagne Agricole au Sahel, Centre Regional AGRHYMET, B.P. 11011, Niamey, Niger, Vol. **2**: No. 0/96, 2 pages.

Allan, R.J., C.J.C. Reason, J.A. Lindesay, T.J. Ansell, 2003: Protracted ENSO episodes over the Indian Ocean region. Deep-Sea Res. II, Special Issue on Physical Oceanography of the Indian Ocean: From WOCE to CLIVAR, **50**: 2331-2347.

Ati F.O., Stitger C.J. and Oladipo E.O., 2002: A comparison of methods to determine the onset of the growing season in northern Nigeria, Int. Journal of Climatology, **22**: 731-742

Barnston, A. G., Chelliah M. and Goldenberg S.B., 1997: Documentation of a highly ENSO related SST region in the equatorial Pacific. Atmos. Ocean, **35**: 367383

Behera, S.K., and Yamagata T., 2001: Subtropical SST dipole events in the southern Indian Ocean. Geophysical Research Letter, **28**: 327-330.

Cadet, D. L., 1985: The Southern Oscillation over the Indian Ocean. Journal of Climatology, **5**: 189–212.

Camberlin P. and Okoola R.E., 2002: The onset and cessation of the ''long rains'' in eastern Africa and their interannual variability. Theoretical and Applied Climatology, **75**: 43–54 (2003).

Colberg, F., C.J.C. Reason, and K. Rodgers, 2004: South Atlantic response to ENSO induced climate variability in an OGCM. Journal of Geophysical Research, **109**: C12015,10.1029/2004JC002301

Cook K.H., 1998: On the response of the Southern Hemisphere to ENSO. Proceedings of the 23rd Climate Diagnostics and Prediction Workshop, Miami, FL, American Meteorological Society 323-326.

Cook K.H., 2000: The south Indian convergence zone and interannual rainfall variability over southern Africa. Journal of Climate, **13**: 3789-3804

Cook C, Reason C.J.C and Hewitson H., 2004: Wet and dry spells within particularly wet and dry summers in the South African summer rainfall region, Climate Research,Vol **26**:17-31,2004

Cressman, G. P., 1959: An Operational Objective Analysis System. Mon. Wea. Rev., **87**: 367-374.

D'Abreton P.C and Tyson P.D., 1995: Divergent and non-divergent water vapour transport over southern Africa during wet and dry conditions. Meteorol. Atmos. Phys., **55:** 47–5.

Dodd D.E.S and Jolliffe I.T., 2000: Early detection of start of wet season in Semiarid tropical climate of western Africa Int. Journal of climatology, **21:** 1251–1262 (2001).

Dyson, L.L and van Heerden, J. 2000: The heavy rainfall and floods over the northeastern interior of South Africa during February 2000. South African Journal of Science, **97**: 80-86.

Farmer G., 1988: Seasonal forecasting of the Kenya coast Short Rains, 1901-84. Journal of Climatology, **8**: 489-497.

Food and Agriculture Organization/ World Food Program (FAO/WFP), 1998: Crop and Food Supply Assessment Mission to Zambia. Special report.

Food and Agriculture Organization/ World Food Program (FAO/WFP), 2002: Crop and Food Supply Assessment Mission to Zambia. Special report.

Goddard, L. and Graham N.E., 1999: The importance of the Indian Ocean for simulating rainfall anomalies over eastern and southern Africa. Journal of Geophysical Research, **104**: 19099-19116.

Harrison M.S.J., 1984: A generalized classification of South African summer rain-bearing synoptic systems. Journal of Climatology, **4**: 547-560.

Harrison M.S.J., 1986: A synoptic climatology of South African rainfall variability. Unpublished PhD Thesis, University of the Witwatersrand, 341pp.

Hermes J.C. and Reason C.J.C., 2005: Ocean model diagnosis of interannual co-evolving SST variability in the South Indian and South Atlantic Oceans. Journal of Climate, accepted.

Institute of Economic and Social Research (INESOR), 2003: Zambia Micro Report. University of Zambia.

Janowiak J.E., 1988: An investigation of interannual rainfall variability in Africa. Journal of Climate, **1**: 240-255.

Jury M.R., 1992: A climatic dipole governing the interannual variability of convection over the south west Indian Ocean and southeast Africa region. Trends in Geophysical Research, **1**:165-172.

Jury M.R. and Pathack B.M.R., 1993: Composite climatic patterns associated with extreme modes of summer rainfall over southern Africa: 1975-1984. Theoretical and Applied Climatology, **47**: 137-145.

Jury M.R., McQueen C.A and Levey K.M., 1994: SOI and QBO signals in the African region. Theoretical and Applied Climatology, **8**: 17-30.

Jury, M.R., 1996: Regional teleconnection patterns associated with summer rainfall over South Africa, Namibia and Zimbabwe. Int. Journal of Climatology, **16:** 135-153.

Jury M.R., 1999: Intra-seasonal variability over southern Africa: principal component analysis of pentad outgoing-longwave radiation departures 1976-1994. Theoretical and Applied Climatology, **62**: 133-146.

Jury, M. R., H. M. Mulenga, and S. J. Mason, 1999: Development of statistical long-range models to predict summer climate variability over southern Africa. Journal of Climate, **12**: 1892-1899.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woolen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetma, R. Reynolds, R. Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-year reanalysis project. Bullet. Amer. Meteorol. Soc**.**, **77**: 437-471

Kidson, J. W., 1988: Indices of the Southern Hemisphere zonal wind. Journal of Climate, **1**: 183–194

Kijazi L. and Reason C.J.C., 2005: Relationships between intraseasonal rainfall variability of coastal Tanzania and ENSO. Theoretical and Applied Climatology, doi: 10.1007/s00704-005-0129-0, in press.

Kiladis, G. N., 1997: Interannual variability of the South Pacific circulation related to the Southern Oscillation. Harry van LoonSymp. Studies in Climate II, NCAR Tech. Note TN- 4331PROC, 300 pp.

Kiladis, G.N., and K. C. Mo, 1998: Interannual and Intraseasonal Variability in the Southern Hemisphere. Meteorology of the Southern Hemisphere, Boston, USA, 307-336.

Kowal J.M. and Knabe D.T., 1972: An Agroclimatological Atlas of the Northern States of Nigeria. Ahmadu Bello University Press: Zaria, Nigeria. 15pp.

Kuo, H.L., 1989: Long-term oscillation in coupled atmosphere-ocean system and El-Niño phenomenon, Journal of Climate, **12**: 1421-1437

Landman, W. A. and Klopper, E., 1998. '15-year simulation of the December to March rainfall season of the 1980s and 1990s using canonical correlation analysis (CCA)', WaterSA, **24**: 281̄ 285.

Landman W.A. and Mason S.J., 1999. Operational long-lead prediction of South African rainfall using Canonical Correlation Analysis, Int. Journal of Climatology, **19**: 1073-1090.

Levey K.E. and Jury M.R 1996: Composite intra-seasonal oscillations of convection over southern Africa. Journal of Climatology, **9**: 1910-1920.

Lindesay J., Harrison M. and Haffner T., 1986: The Southern Oscillation and South African rainfall. South African Journal of Science, **82**: 196–98.

Lindesay J.A., 1988: South African rainfall, the Southern Oscillation and a southern hemisphere semi-annual cycle, Journal of Climatology, **8**: 17-30.

Lyons, S. W., 1991: Origins of convective variability over equatorial southern Africa during austral summer. Journal of Climate, **4**: 23–39.

Makarau A., 1995: Intra-Seasonal Oscillatory Modes of the Southern Africa Summer Circulation. Ph.D. Thesis, Oceanography. Dept., University of Cape Town, 324 pp.

Makarau A, Jury M.R., 1996: Prediction of Zimbabwe summer rainfall. Int. Journal of Climatology, **17**: 1421-1432.

Makarau A, Jury M.R., 1997: Seasonal cycle of convective spells over southern Africa during austral summer. Int. Journal of Climatology, **17**: 1317-1332.

Mason S. J., 1990: Temporal variability of sea surface temperatures around southern Africa: a possible forcing mechanism for the eighteen-year rainfall oscillation? South African Journal of Science, **86**: 243-252.

Mason S. J., and Tyson P.D., 1992: The modulation of sea surface temperature and rainfall associations over southern Africa with solar activity and the Quasi-biennial Oscillation. Journal of Geophysical Research, **97 (D5)**: 5847-5856.

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

Mason S.J., 1995: Sea surface temperatures-South African rainfall associations, 1910-1989. Int. Journal of Climatology, **15**: 119-135.

Mason, S. J. and Jury M.R., 1997: Climatic change and inter-annual variability over southern Africa: a reflection on underlying processes. Progress in Physical Geography, **21**: 23-50.

Mason, S. J., 1998: Seasonal forecasting of South African rainfall using a non-linear discriminant analysis model. Int. Journal of Climatology, **18**: 147-164.

Matarira C.H. and Jury M.R., 1992: Contrasting meteorological structure of intra-seasonal wet and dry spells in Zimbabwe, Int. Journal of Climatology, **12**: 165-176.

Miron O. and Tyson., P.D., 1984: Wet and Dry Conditions and Pressure Anomaly Fields over South Africa and the Adjacent Oceans, 1963–79. Climatology Research Group, University of the Witwatersrand, Johannesburg.

Mo K.C., and Paegle J.N., 2001: The Pacific-South American modes and their downstream Effects. Int. Journal of Climatology, **21**: 1211-1229.

Mudenda O.S and Mumba Z.L.S., 1996: The unusual tropical storm of January 1996. Zambia Meteorological Department.

Mugara, R. K., 1997: Intraseasonal variation of convection over southern Africa. Ph.D Dissertation, University of Reading, Department of Meteorology.

Mulenga H.M., 1998: Southern Africa Climate anomaly, Summer rainfall and the Angola low. PhD thesis University of Cape Town.

Mukherjee, B. K., K. Indira, R. S. Reddy, and Bh. V. Ramana Murty, 1985, Mon. Wea. Rev., **113:** 1421-1424.

Mulenga H.M, Rouault M. and Reason C.J.C., 2003: Dry summers over northeastern South Africa and associated circulation anomalies. Climate Research, **25**: 29-4.

Mumba, Z.L.S., and Chipeta, G.B.,1984: Synoptic Aspects of Rainfall in Zambia, with Special Reference to the Migratory Westerly Systems of the Southern Middle Latitudes. Meteorological Notes, Series A No. **20**. Zambia Meteorological Dept., 20pp.

Mumba, 1998: The Occurrence of Dry Spells in Zambia. (Unpublished). Zambia Meteorological Dept.

Naujokat B., 1986: An update of the observed quasi-biennial oscillation of stratospheric winds over the tropics. Journal of Atmospheric Science, **43**: 1873–1877.

Nicholson S.E. and Kim J.Y., 1997: The Relationship of the El-Niño Southern Oscillation to African Rainfall. Int. Journal of Climatology, **17**: 117-135.

Nicholson S.E. and Entekhabi D., 1987: Rainfall variability in equatorial and southern Africa: relationships with sea surface temperatures along southwestern coast of Africa. Journal of Climate and Applied Meteorology, **26**: 561-578

Nicholson S.E., 2000: The nature of rainfall variability over southern Africa on time-scale of Decades to Mellenia. Global and Planetary change, **26**: 137-158.

Nicholson S.E., 2003: Comments on "The South Indian Convergence Zone and Interannual Rainfall Variability over Southern Africa" and the Question of ENSO's Influence on Southern Africa. Journal of Climate, Vol **16**, No. 3, pp 555-562.

Nkomoki J. 1998: Drought research and drought related activities in Zambia. UNESCO, Paris 2-4 December.

Ogallo L., Okoola R. and Wanjoh D., 1994: Characteristics of Quasi-biennial Oscillation over Kenya and their predictability potential for the seasonal rainfall. Masusam **45,** (1) 57-62. 8 577-597.

Omotosho JB. 1990. Onset of thunderstorms and precipitation over Northern Nigeria. Int. Journal of Climatology, **10**: 849–860.

Omotosho JB. 1992. Long-range prediction of the onset and end of the rainy season in the West African Sahel. Int. Journal of Climatology, **12**: 369–382.

Omotosho J.B., Balogun A.A. and Ogunjobi K, 1999: Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data, Int. Journal of Climatology, **20**: 865-880.

Philander, George S., 1990: El Nino, La Niña, and the Southern Oscillation, Academic Press, INC., 289 pp.

Reason, C.J.C., 1999: Interannual warm and cool events in the subtropical / mid-latitude South Indian Ocean region. Geophysical Research Letters: **26**, 215-218.

Reason, C.J.C. and Mulenga H.M., 1999: Relationships between South African rainfall and SST anomalies in the South West Indian Ocean. Int. Journal of Climatology, **19**: 1651-1673.

Reason C.J.C., 2000: Multidecadal climate variability in the subtropics / midlatitudes of the Southern Hemisphere oceans. Tellus, **52A**: 203-223.

Reason C.J.C., 2001: Subtropical Indian Ocean SST dipole events and southern African rainfall. Geophysical Research Letters, **28**: 2225-2227

Reason, C.J.C., Allan R.J., Lindesay J.A and Ansell T.J., 2000: ENSO and climatic signals across the Indian Ocean basin in the global context: Part I, interannual composite patterns. Int. Journal of Climatology, **20**: 1285-1327.

Reason, C.J.C., 2002: Sensitivity of the southern African circulation to dipole SST patterns in the South Indian Ocean. Int. Journal of Climatology, **22**: 377-393.

Reason C.J.C. and Rouault M., 2002: ENSO-like decadal patterns and South African rainfall. Geophysical Research Letters, **29 (13)**: 16-1 – 16-4.

Reason C.J.C. and Keibel A., 2004: Tropical Cyclone Eline and its unusual penetration and impacts over southern Africa. Weather and Forecasting, **19 (5)**: 789-805.

Reason C.J.C., Hachigonta S.P. and Phaladi R.F., 2005: Interannual variability in rainy season characteristics over Limpopo. Int. Journal of Climatology, submitted

Rocha A. and Simmonds I., 1997: Interannual variability of south-eastern African summer rainfall. Part II. Modelling the impact of sea-surface temperatures on rainfall and circulation. Int. Journal of Climatology, **17**: 267-290.

Ropelewski C.F, Helpert M.S., 1987: Global and regional scale precipitation patterns associated with the ENSO, Monthly Weather Review, **104**:3007-315

Rouault, M., Florenchie P., Fauchereau N, and Reason C.J.C., 2003: South East Atlantic Warm Events And Southern African Rainfall. Geophysical Research Letters, **30(5)**: 9-1-9-4.

Sivakumar M.V.K., 1992: Empirical analysis of dry spells for agricultural applications in West Africa. Journal of Climate, **5**:532-539

Stewart J.I., 1988: Response farming in rain fed agriculture. The Wharf Foundation Press, Davis, California, USA, 103.

Tadross M.A., Hewitson B.C. and Usman M.T., 2005: The inter-annual variability of the onset of the growing season over southern Africa and Zimbabwe, Journal of Climate, in press.

Taljaard J.J., 1986: Change of rainfall distribution and circulation patterns over South Africa in summer. Journal of Climatology, **6**:579-592

Taljaard J.J., 1994: Atmospheric Circulation Systems, Synoptic Climatology and Weather phenomena of South Africa. Part 1: Controls of the weather and climate of South Africa. S. Afr. Weath. Serv. Tech.Pap. 27, S. Afr. Weath. Serv., Private Bag X097, Pretoria, 0001. 45pp

Tennant W.J., Hewitson B.C., 2002: Intra-seasonal rainfall characteristics and their importance to the seasonal prediction problem. Int. Journal of Climatology, **22**: 1033-1048.

Todd M.C. and Washington R., 1998: Extreme daily rainfall in southern African and southwest Indian Ocean tropical-temperate links. South African Journal of Science, **94**: 64-70

Tourre Y. M., and White W.B., 1995: ENSO signals in global upper-ocean temperature. J. Phys. Oceanogr., **25**: 1317–1332

Tyson, P.D., Dyer T.J and Mametse M.N., 1975: Secular changes in South African rainfall: 1880-1972. Quart. J. Roy. Meteorol. Soc., **101**: 817-833.

Tyson P.D., 1986: Climatic change and variability in southern Africa. Oxford University Press, Cape Town.

Tyson P.D and Preston-Whyte R.A., 2000: The weather and climate of southern Africa. Oxford University Press, Oxford.

Van Heerden, J. and J. J. Taljaard (1998). Africa and surrounding waters. In Meteorology of the Southern Hemisphere, editors D. J. Karoly and D. G. Vincent, Meteorological Monographs, **27(49)**: 141-174.

Van Heerden J., Terblanche D. and Schulze G., 1988: The Southern Oscillation and South African summer rainfall. Journal of Climatology, **8**: 577-597.

Vogel C.H. and Drummond J., 1993: Dimensions of Droughts, South African case studies, GeoJournal, **30**: 93-98

Vogel C.H., 1994: (Mis) management of droughts in South Africa: past, present, future, South African Journal of Science, **86**: 382-386.

Wallace, J.M., 1973: The general circulation of the tropical lower stratosphere. Rev. Geophys. Space Phys., **11**: 191-222.

Wallace J. M. and Hobbs P.V., 1977: Atmospheric Science: An Introductory Survey. Academic Press, 467 pp.

Walker, N.D. and Lindesay, J.A. 1989. Preliminary observations of oceanic influences on the February–March 1988 floods in central South Africa. Int. Journal of Climatology, **11**: 609–627.

Walker N.D., 1990: Links between South Africa summer rainfall and temperature variability of the Agulhus and Benguela Current system. Journal of Geophysical Research, **95**: 3297-319.

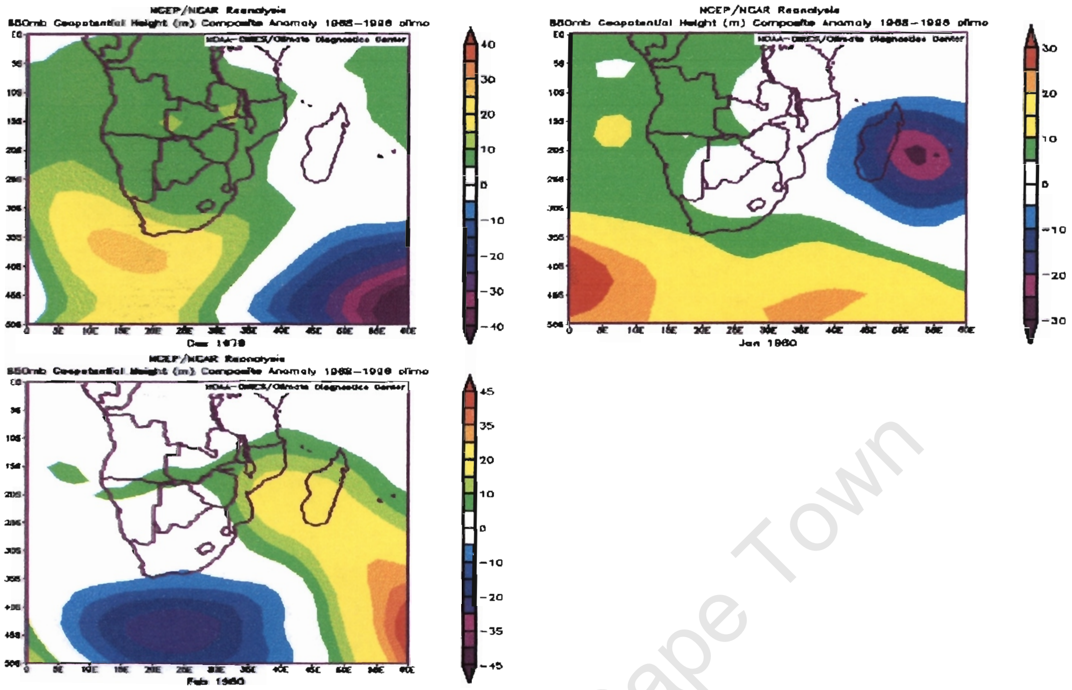
Walker N.D. and Shillington F.A., 1990: The effect of oceanographic variability on South African weather and climate. South African Journal of Science, **86**: 382-386.

Webster P. J., 1983: The large scale structure of the tropical atmosphere. In General Circulation of the Atmosphere, eds. Hoskins and Pearce. New York: Academic Press, pp. 235—275.

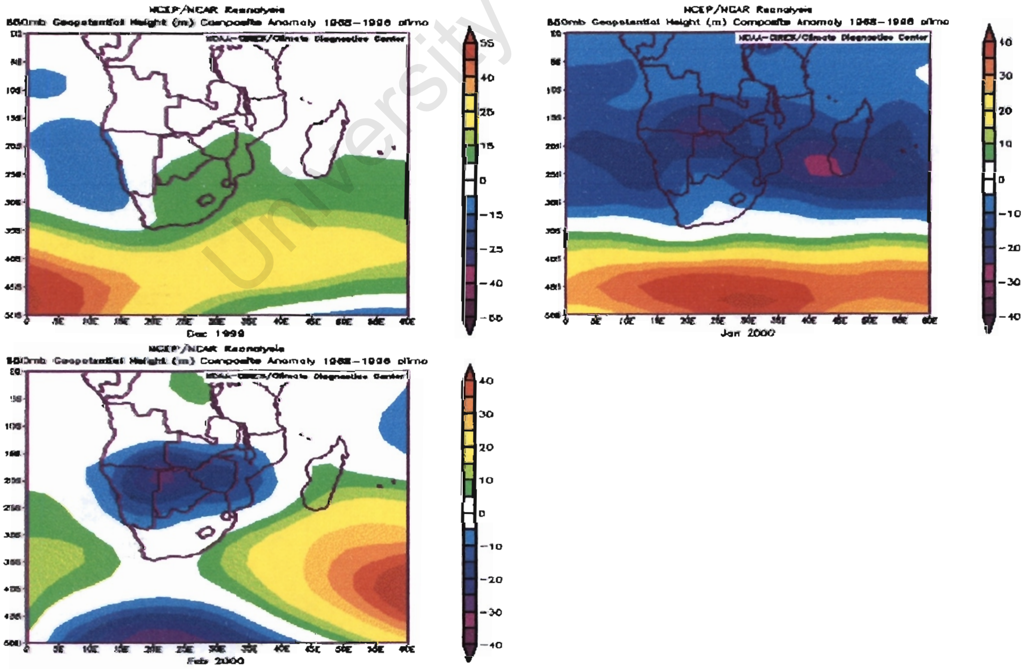
Usman, M.T. and C.J.C. Reason, 2004: Dry spell frequencies and their variability over southern Africa. Climate Research, **26**: 199-211.

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

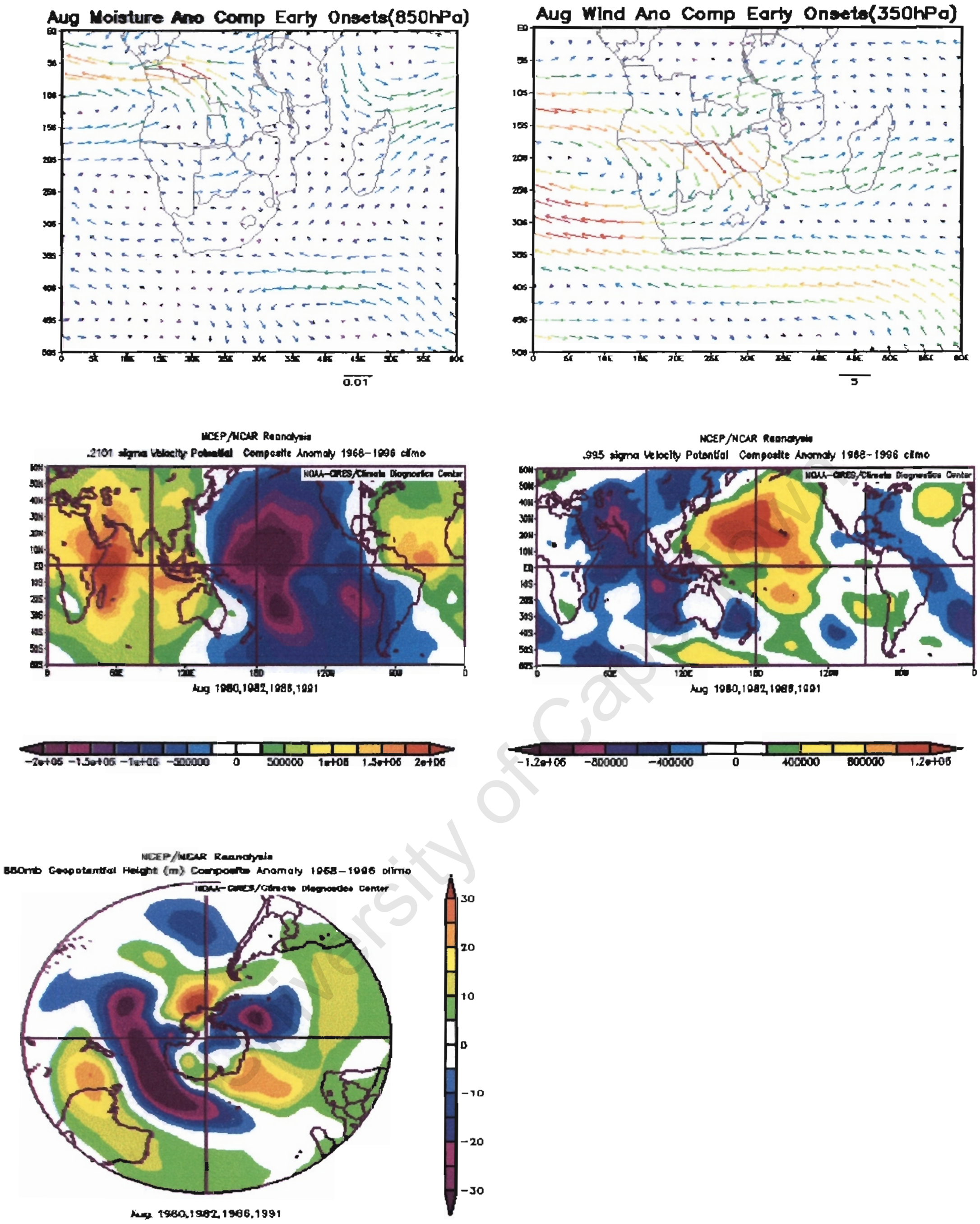
Appendix



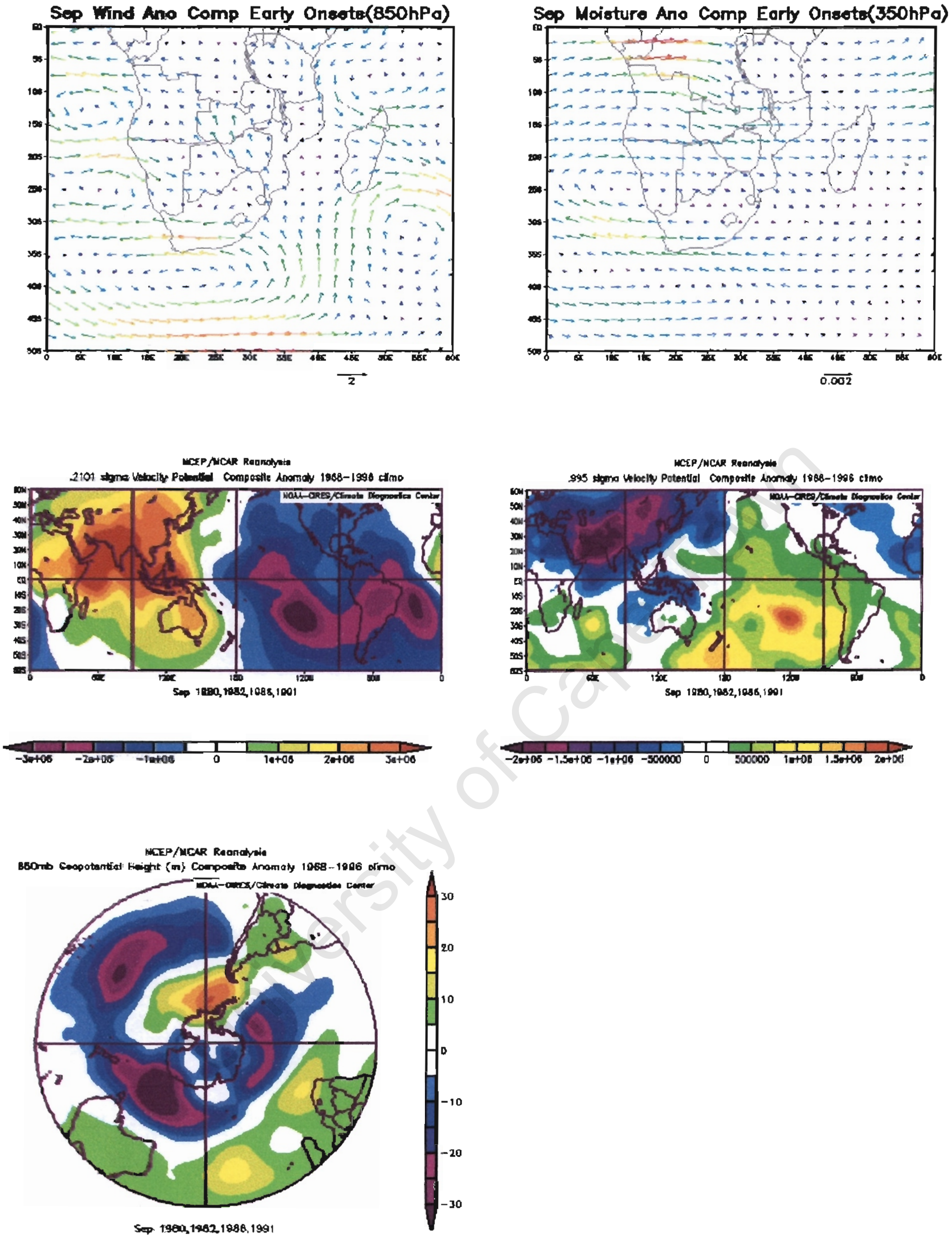
December, January and February anomalies height for 1979/80 (850hPa)



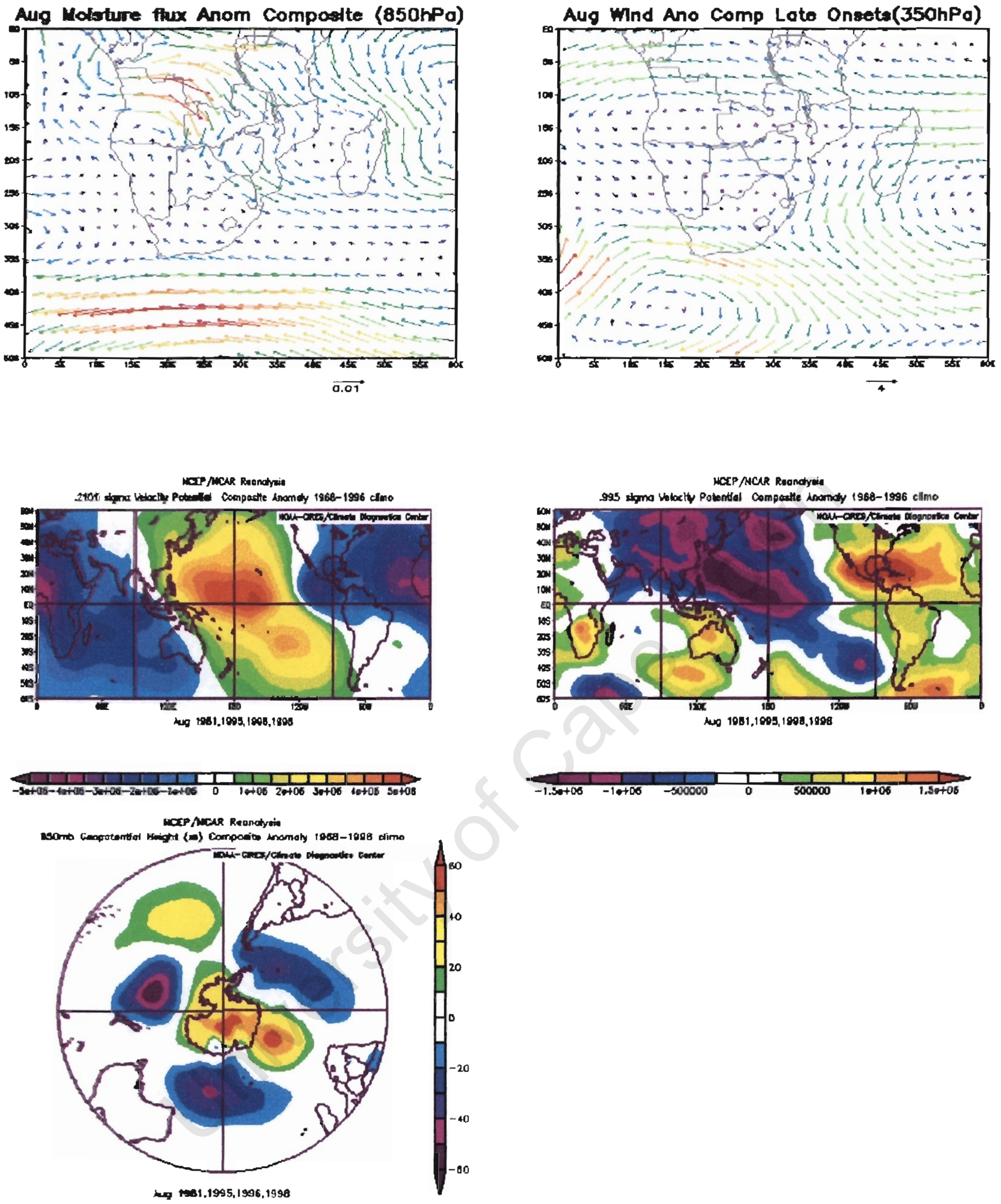
December, January and February anomalies height for 1999/00 (850hPa)



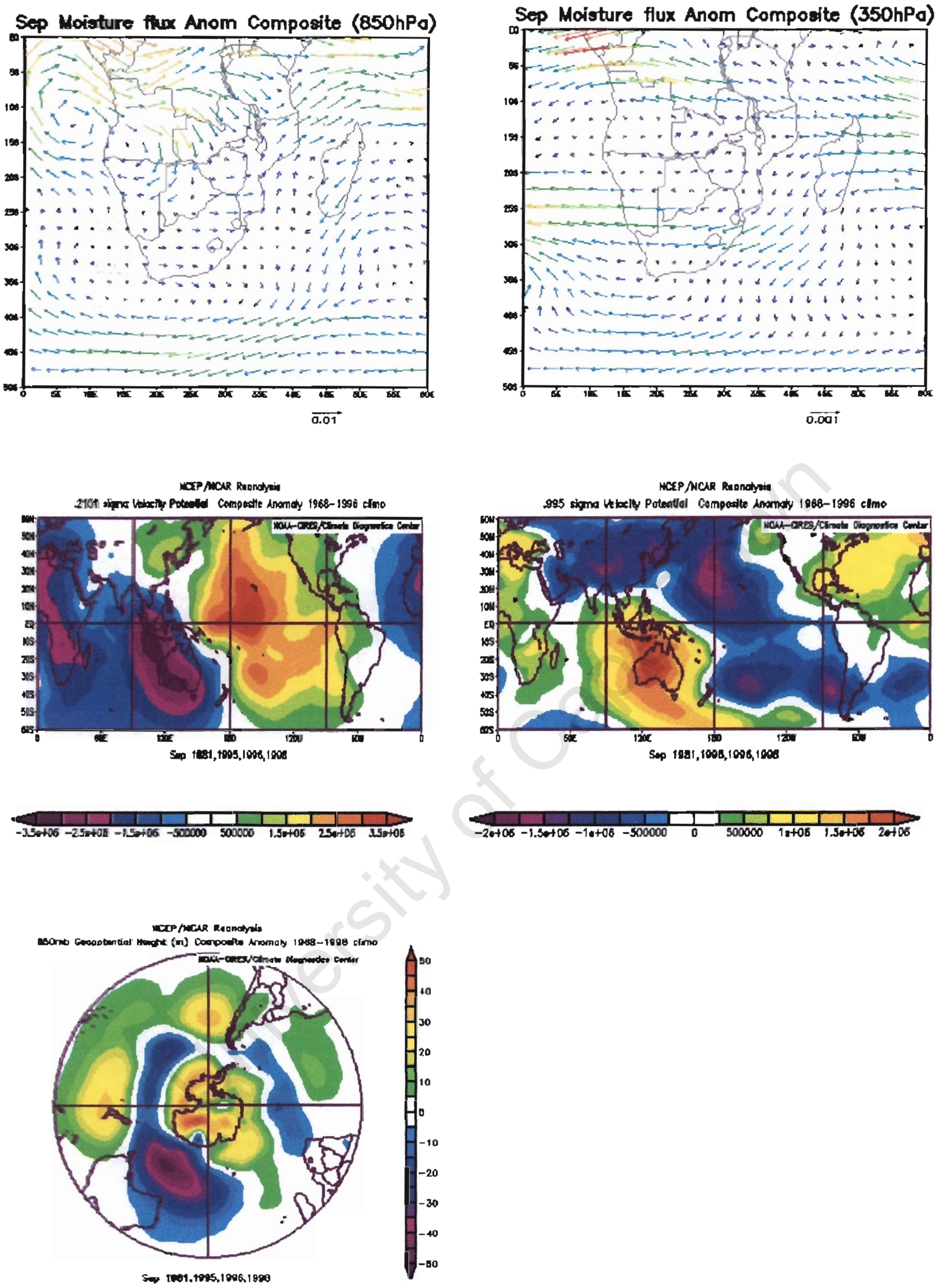
August composite anomalies during early onset seasons



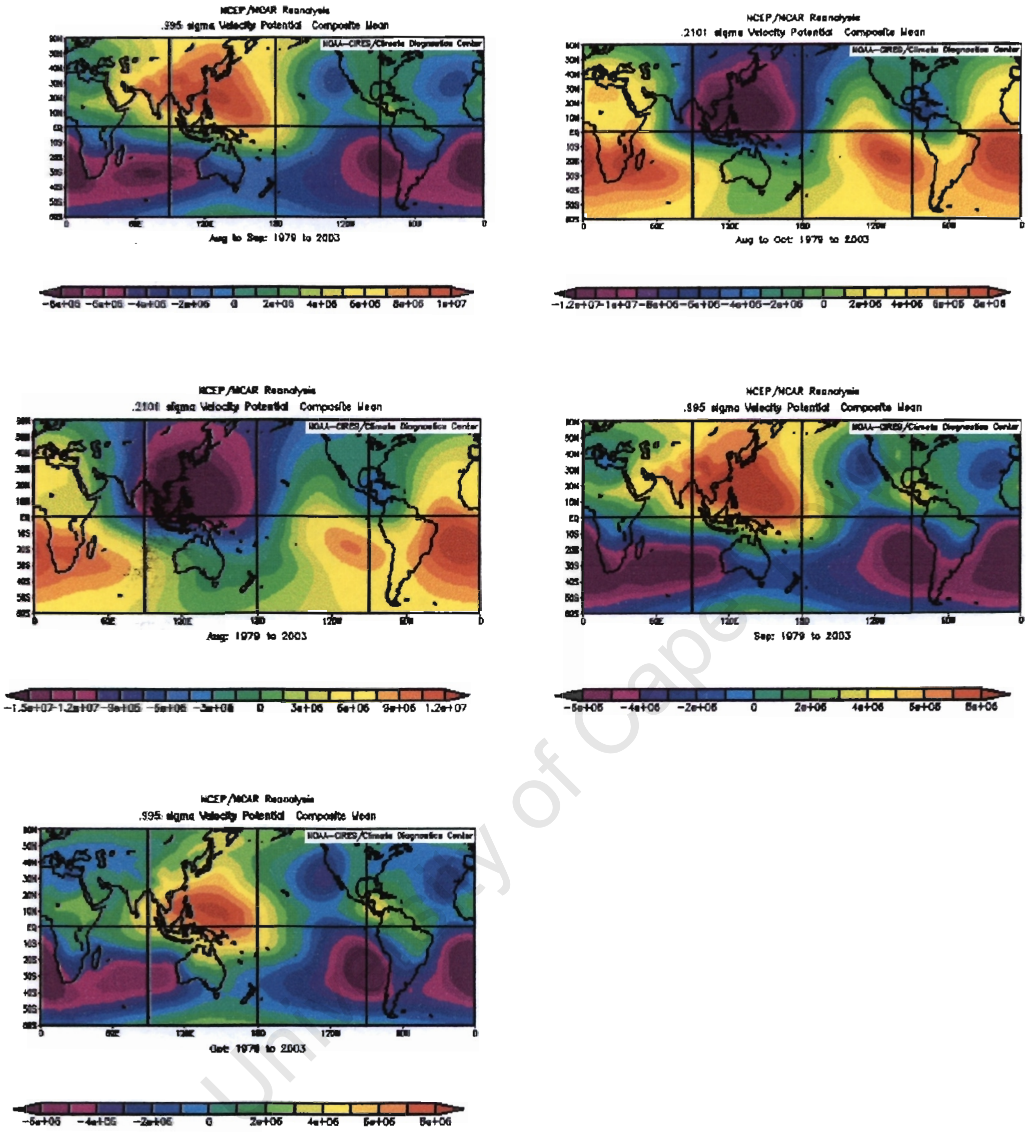
September composite anomalies during early onset seasons



August composite anomalies during late onset seasons



September composite anomalies during late onset seasons



Velocity potential climatology (ASO)

C program used for onset derivation

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>

#define ntimes 31
#define undef1 -1073741824.0
#define undef2 -999.0
#define undef3 1e10

int main(int argc, char *argv[])
{
  FILE *outfile, *infile;
  char inname[50], outname[50];
  int j, i, k, nrows, ncols;
  float *outdata;
  float *indata;

  if (argc != 5) {
        fprintf(stderr, "Usage: onset -rNrows -cNcols -oOnsetfile -iSummerpentadsfile\n");
        exit(-1);
  }
  else {
        while (--argc > 0 && argv[argc][0] == '-') {
           switch(argv[argc][1]) {
             case 'o':
                strcpy(outname,&argv[argc][2]);
                printf("outname = %s\n", outname);
                break;
             case 'i':
                strcpy(inname,&argv[argc][2]);
                printf("inname = %s\n", inname);
                break;
             case 'r':
                nrows=atoi(&argv[argc][2]);
                break;
             case 'c':
                ncols=atoi(&argv[argc][2]);
                break;
             default:
                printf("Illegal option: -%c\n",argv[argc][1]);
                exit(-1);
           }
        }
   }


/* OPEN DATA FILES */

  if (!(infile = fopen(inname, "rb")))
  {
    printf("ERROR opening infile\n");
    return -2;
  }
```

```
 outdata=malloc(sizeof(float)*nrows*ncols);
 indata=malloc(sizeof(float)*ntimes*nrows*ncols);

 printf("Reading infile\n");
        fread(indata,sizeof(float),ntimes*nrows*ncols,infile);

 for(j=0; j<ncols*nrows; j++) {
    outdata[j] = undef1;
    for(k=0; k<(ntimes-2); k++) {
      for(i=0; i<2; i++) {
        if ((indata[((k+i)*ncols*nrows)+j] == undef1) ||
            (indata[((k+i)*ncols*nrows)+j] == undef2) ||
            (indata[((k+i)*ncols*nrows)+j] == undef3))
                          indata[((k+i)*ncols*nrows)+j] = 0.0;
      }

           if (((5*(indata[(k*ncols*nrows)+j]+indata[((k+1)*ncols*nrows)+j]) >=25.0))&&
          ((5*(indata[((k+3)*ncols*nrows)+j]+indata[((k+4)*ncols*nrows)+j]+
              indata[((k+5)*ncols*nrows)+j]+indata[((k+6)*ncols*nrows)+j])>=20)))

            {
          outdata[j] = (float) k+1;
          printf("j=%d,onset = %f\n",j,outdata[j]);
          break;
      }
    }
 }


 if (!(outfile = fopen(outname, "wb")))
 {
   printf("ERROR opening outfile\n");
   return -2;
 }

 printf("Writing outfile \n\n");
        fwrite(outdata, sizeof(float), ncols*nrows, outfile);


 fclose(infile);
 fclose(outfile);

}
```