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AN ANALYSIS OF RAINY SEASON CHARACTERISTICS OVER
THE LIMPOPO REGION

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A thesis submitted in fulfillment of the degree of Master of Science

Department of Environmental and Geographical Science
University of Cape Town

May 2005
DECLARATION

This is to certify that the dissertation entitled 'An analysis of rainy season characteristics over the Limpopo region' submitted in fulfilment of the requirements of the degree of Master of Science of the University of Cape Town is a record of bonafide research work. The subject matter embodied in this report has not been submitted at any other university.

Name; Raesetje Florina Phaladi

Signature; 

Signed this 03... day of May 2005.
Abstract

This thesis investigates characteristics of the summer rainy season over the Limpopo region that are important to the agricultural sector and other user groups. The Limpopo region supports a large rural population dependent on rain-fed agriculture as well as significant biodiversity, particularly in the Kruger National / Limpopo Transfrontier Park and is vulnerable to severe flood and drought events. Recently, the region has been impacted by severe drought (2002-2004) and flooding in late summer 2000.

The rainy season characteristics investigated are the frequency of wet and dry spells during the rainy season and the onset date of the season. It is found that both the dry spell frequency during summer and the onset date of the rains are related to ENSO via changes in regional circulation. Niño 3.4 sea surface temperature (SST) anomalies, a widely used index for ENSO, appear to show a robust relationship with dry spell frequency during the 1979-2002 period analysed. Anomalies in onset date of the rainy season during 1979-2002 appear to be inversely related to Niño 3.4 SST, with the relationship strengthening after 1986. A weaker relationship appears to exist between Limpopo maize yield and Niño 3.4 SST anomalies than might be expected given the ENSO impacts on rainfall. However, this situation may arise from other factors such as irrigation and fertilization which can impact on agricultural productivity.

In addition to droughts induced by El Niño, the region is also impacted every so often by severe drought associated with other mechanisms. The evolution of the 2002/03 El Niño
induced drought into the 2003/04 non-El Niño drought over Limpopo is examined. By contrast to El Niño induced droughts in which the signals emanate from the tropics and affect the tropical source of cloud bands over low latitude southern Africa, for non-ENSO droughts like 2003/04, midlatitude circulation anomalies south and southwest of South Africa lead to an increase (decrease) in the advection of cool, dry (warm, moist) South Atlantic (South Indian) air masses over South Africa and hence dry conditions. It is shown that a similar situation occurred in OND 2003 to previous severe non-El Niño droughts but that these circulation anomalies started to break down in January 2004 resulting in a transition towards above average rainfall by the end of summer.
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Chapter 1: Introduction

The Limpopo province of South Africa is a summer rainfall region that is prone to flood events (Dyson and van Heerden, 2001; Reason and Keibel, 2004) and to drought, some of which are related to the El Niño Southern Oscillation (ENSO) (Lindesay, 1988; Mulenga et al., 2003). This province also contains important agricultural regions, a relatively large rural subsistence population and considerable biodiversity in the Kruger National and other parks. Extreme weather and climate events can adversely affect agricultural productivity in this region and hence the rural economy and wellbeing of the population. It is very important to better understand the mechanisms that are associated with these extreme weather and climate events to improve seasonal forecasts and the mitigation of adverse impacts. Farmers depend on specific environmental conditions for the production of crops, which makes the management of climatic risk a critical part of agriculture.

Seasonal forecasts tend to be issued in probabilistic format and are not easy to understand by user groups. Farmers desire information about onset, distribution and cessation of rainfall as well the frequency of dry and wet spells in a season, whereas seasonal forecasts tend to focus on seasonal rainfall totals (e.g., Vogel and O’Brien, 2003; Johnston et al., 2004). Although seasonal forecasting skill may improve, the most important issue is whether the predicted quantities are useful to the user groups or not. These seasonal forecasts are issued such that it remains up to the user to interpret them in a way that relates to their specific fields.
Application of climate variability to various fields such as agriculture and water resource management needs specific information about high frequency fluctuations in rainfall, temperature and other parameters. For example, it is known that a season with above average rainfall over an agricultural region may not be any better than a below average season if the rains are not well distributed either in time or space. For crop production, consistent rainfall throughout the season is more important than the total amount by the end of the season because crops are more likely to do well with uniformly spread light rains than with heavy rains interrupted by dry periods. Temperature is also an important factor for agriculture, as crops require a certain amounts of heat units to complete their life cycle. For example, near average rainfall conditions with above average temperatures throughout the season will not improve yield as there will be high evapotranspiration that causes moisture stress in crops.

Floods and droughts often impact livestock production, which directly influence the availability of grazing areas as well as drinking water. High temperatures may lead to disease and require farmers to provide shade especially for young livestock. Successful livestock management requires an understanding of the impacts of climate variability of the region with respect to the potential for extremes in water availability, temperature and severe weather.

With these agricultural impacts in mind, this thesis investigates the rainfall characteristics of the Limpopo region (22-25°S, 27-32°E) of northern South Africa, southwestern Mozambique and eastern Botswana. The Limpopo region falls within the ‘drought
Atlantic air over South Africa. The 2003/04 drought is the most recent non-ENSO
drought of this type and is specifically considered in this thesis. Mulenga et al. (2003)
also showed that out of 10 strong El Niño events during the 1921-2000 period, only the
1957/58 event was not associated with below average rainfall over the Limpopo region.
The results of Mulenga et al. (2003) suggest that the El Niño signal over Limpopo is
relatively robust but that the numerous non-El Niño droughts are more challenging to
understand, let alone to predict.

Knowledge of the onset and cessation of rainfall as well as the frequency of wet and dry
spells in a season is the most important factor for subsistence farmers. The availability of
this information in advance can assist farmers in decisions regarding planting, fertilising,
pesticide application, irrigation demand etc. This information will help these farmers to
use their resources effectively as most of them do not have the resources to afford a
second planting should the first one fail (Tadross, Hewitson and Usman, 2003, 2004).
These farmers might also be misled by few days of light rainfall early in the season and
start planting which will be problematic if this rain is then followed by an extended dry
spell. In order to address these problems, the climate variability of Limpopo and its
implications for agriculture need to be better understood.

Given the foregoing discussion, the main objectives of this thesis are to investigate the
frequency of dry and wet spells over Limpopo as well as variability in the onset date of
the rainy season. In addition, the circulation anomalies that influence these parameters
and their possible connection to ENSO will be investigated. To accomplish these objectives, the following research questions are addressed:

1. What are the potential influences of ENSO events on wet and dry spells over Limpopo?
2. How often do wet and dry spells occur over Limpopo?
3. Is there a relationship between variability in the onset date of the rainy season over Limpopo and ENSO?
4. What circulation anomalies were responsible for the most recent non-ENSO drought in 2003/04?

The long-term goals of studies such as this are to improve understanding of rainfall variability over the region and its seasonal prediction. In turn, this research may help to improve the ability to issue appropriate early warning information to the agricultural and other user sectors (see Appendix). Where possible, and given the data readily available, the implications of the rainfall variability on agriculture are discussed. However, a detailed analysis of agricultural impacts is not within the scope of this thesis.

The thesis lay out is as follows: Chapter 1 has given the introduction of the thesis and also considered the aim and objectives of the study. Chapter 2 provides a literature review and the motivation of the study. It also discusses previous studies on rainfall characteristics of southern Africa. Systems that affect rainfall over South Africa are also discussed in this chapter. Chapter 3 describes the data and methodology used in this thesis. Analysis of wet and dry spells is performed in Chapter 4. This chapter examines
the characteristics of dry and wet spells during the peak summer (DJF) rainy period and considers how the spells are distributed both in space and time based on CMAP data. This chapter also looks at the relationships between anomalies in the frequency of dry spells and those in Nino 3.4 SST. The implication of dry and wet spells on maize yield and vegetation activity is also discussed. The onset dates of the summer rainfall season over the region as well as the associated circulation anomalies are also considered in chapter 4. Chapter 5 examines the circulation anomalies associated with the 2002/03-2003/04 drought and its impacts on maize yield and vegetation activity. This chapter also explains the nature of the early warning information dissemination and the problems experienced during 2003/04 summer season. The summary and conclusions are presented in Chapter 6 while the Appendix discusses aspects of the early warning advisories issued to the agricultural sector based on available climate and seasonal forecast information.
Fig. 1.1. Climatological rainfall over southern Africa for the austral summer (December-February) derived from CMAP data. Contour interval is 0.5 mm / day.
Chapter 2: Literature review

2.1 Agricultural sensitivities to climate variability (drought)

Climate is one of the factors that affect agricultural systems directly or indirectly and is a determining influence on the adaptation of natural ecosystems to their environment. Southern Africa is a region of significant variability in climate (Mason and Jury, 1997) and the vulnerability of agricultural systems to this climate variability is often higher than in many developed countries since most African agricultural systems are precipitation dependent with very low technical adaptation (Ogallo et al., 2000). South Africa is prone to both extreme weather events (particularly in the northern and eastern areas) and large scale flood/drought episodes associated with interannual climate variability. These extreme events often have significant impacts on agriculture and rural life. It has been said that there is no greater challenge to the ingenuity and resilience of farmers around the world than climatic variability (Anderson and Dillon 1992, Wilken 1987). The fact that farmers are dependent on specific environmental conditions for the production of crops has made the management of climatic risk a critical part of agriculture since the first crops were domesticated.

Since changes in extremes in climate at regional or local levels have immediate impacts on nature and human society, such changes are more tangible and immediate than global changes averaged over time and space. Katz and Brown (1992) have shown that changes in variance can have a larger impact on the exceedance frequencies for monthly maxima
than a change in the mean. Well above average values of daily maximum temperature can directly lead to unhealthy development of plant organs, which results in lower yield or poorer quality of plants (Salinger et al., 2000). Understanding the developmental stage of crops is important in evaluating its yield potential. The importance of these various stages is evident when considering that plant requirements are different at different stages of its life cycle. Extreme climate events occurring during critical stage of the crop have a significant impact on yield. For example, drought and flood episodes occurring prior to planting or after the harvest season will generally have less impact than those that take place during the crop season itself (Vogel and O’Brien, 2003; Usman and Reason, 2004). Furthermore, some crops have different moisture requirements at different stages of their development.

The Limpopo region of southern Africa studied in this thesis is prone to drought and flood events (e.g., Dyson and van Heerden, 2001; Mulenga et al., 2003; Reason and Keibel, 2004) and is an important agricultural region with a relatively large rural subsistence population. Extreme weather and climate events impacting on the region can adversely affect agricultural productivity as well as the rural economy and human welfare. Better understanding of extreme events such as significant drought will help with the management of the associated risks associated with this fundamental and frequently occurring feature of southern African climate. Both the intensity and the duration of drought contribute to the adverse impacts it has on agriculture.
Drought may be defined as the shortage of precipitation over an extended period and can be broadly classified as socioeconomic, meteorological, hydrological and agricultural. It is very important to understand these classifications as well as their impacts in a particular area at a given period. An illustration of the differences between these types of drought is provided by Rouault and Richard (2003). Agricultural drought is defined as a shortage of a precipitation resulting in extensive crop damage that leads to yield loss. A good understanding of agricultural drought should be able to account for the variable susceptibility of crops during different crop stages development, from germination to maturity. For example, deficient topsoil moisture at planting may hinder germination, leading to low plant populations per hectare and a reduction of final yield. However, if topsoil moisture is sufficient for early growth requirements, deficiencies in subsoil moisture at this early stage may not affect final yield if subsoil moisture is replenished as the growing season progresses or if rainfall meets plant water needs. Agricultural drought in a particular growing season in Africa may apply to maize but not to millet or sorghum because of the different drought tolerance of these crops.

Hydrological drought is associated with the precipitation shortage on a longer scale and its effect on surface and subsurface water supply (Miegh et al., 1999). Although all droughts originate from a lack of precipitation, hydrologists are interested in how precipitation variability influences components of the hydrological system such as surface run-off, river and lake levels. Meteorologists define drought as a significant departure of precipitation below average over a prolonged period. Due to regional
differences in rainfall totals, what is considered a drought in one location may not be drought somewhere else.

Drought produces a complex web of impacts that spans many sectors of the economy and reaches well beyond the area experiencing physical drought. This complexity exists because water is integral to our ability to produce goods and provide services. Impacts are commonly referred to as direct or indirect. Reduced crop, rangeland, and forest productivity, increased fire hazard, reduced water levels, increased livestock mortality rates are few examples of direct impacts. The consequences of these impacts may lead to indirect impacts. For example, a reduction in crop, rangeland and forest productivity may result in reduced income for farmers and agribusiness, increased prices for food and timber, unemployment, foreclosures on bank loans to farmers and disaster relief programs. Not all impacts of drought are negative. Some agricultural producers outside the drought area or with surpluses benefit from higher prices.

Many economic impacts occur in agriculture and related sectors, including forestry and fisheries because of the reliance of these sectors on surface and subsurface water supplies. In addition to obvious losses in yields in both crop and livestock production, drought is associated with increases in insect infestation, wind erosion and livestock or crop disease. In addition, crops or forest areas impacted by drought become more susceptible to fire damage.
Income loss is another indicator used in assessing the impacts of drought because so many sectors are affected. Reduced income for farmers has a ripple effect. Retailers and others who provide goods and services to farmers face reduced business. Less discretionary income affects the recreation and tourism industries. Prices for food, energy and other products increase as supplies are reduced. Environmental losses are the result of damages to plant and animal species, wildlife habitat, air and water quality and soil erosion. Other environmental effects linger for some time or may even become permanent.

Applications of rainfall variability studies to many fields such as agriculture and water resource management need more detailed information e.g. it is known that a season with above average rainfall over an agricultural region may not be any better than a below average season if the rains are not well distributed either in time and space (Usman and Reason, 2004). For crop cultivation, the consistency with which minimally required rainfall is received is more important than the total received over time because crops are more likely to do well with uniformly spread moderate rains than with a few heavy rains. Thus, the timing of breaks in rainfall (dry spells) relative to the cropping calendar rather than total seasonal rainfall tends to be more important for crop viability.

Rainfall over South Africa is influenced by many different weather systems that originate from the tropics and subtropics as well as from the midlatitudes to the south of the subcontinent (Joubert 1998; Hobbs et al 1998; Tyson and Preston-Whyte, 2000). Interactions between these different weather systems are the source of summer rainfall
background environment within which extreme events may evolve. For example, evidence exists that Tropical Cyclone Eline which contributed significantly to the flooding over northeastern South Africa and southern Mozambique in early 2000 was related to the La Niña conditions at the time (Reason and Keibel, 2004).

2.2 ENSO

The term "El Niño" has evolved in its meaning over the years, leading to confusion in its use (Trenberth, 1997). There is a need to understand a more definitive meaning of the El Niño Southern Oscillation (ENSO) phenomenon as it is the dominant source of interannual climate variability around the world. The Southern Oscillation, a "seesaw of atmospheric pressure between the eastern equatorial Pacific and Indo-Australian areas" (Glantz et al., 1991), is closely linked with El Niño. During an ENSO event, the Southern Oscillation is reversed and warm sea surface temperature (SST) anomalies occur in the tropical central and eastern Pacific Ocean. Generally, when pressure is high over the Pacific Ocean, it tends to be low in the eastern Indian Ocean, and vice versa (Allan et al., 1996). ENSO events are those in which both a significant anomaly in the Southern Oscillation and an El Niño occur together. El Niño and a deviation in the Southern Oscillation often occur together, but may also happen separately. La Niña events are characterized by the opposite SST and pressure anomalies (i.e., cool SST anomalies in the tropical Pacific and low pressure anomalies centred over northern Australia and Indonesia).
ENSO occurrences are global climate events that are manifest as various climatic anomalies. Not all anomalies, even in ENSO years, are due to ENSO. Statistically, evidence shows that ENSO can account at most for about 50% of the interannual rainfall variance in eastern and southern Africa (Ogallo, 1994), but many severe droughts, flooding and tropical cyclone events in the region appear to have strong teleconnection to ENSO events. Teleconnections are defined as atmospheric interactions between widely separated regions (e.g., Ropelewski and Halpert, 1987).

Drought can occur virtually anywhere in the world during an ENSO event, though researchers have found the strongest connections between ENSO and intense drought in Australia, India, Indonesia, the Philippines, Brazil, parts of eastern and southern Africa, the western Pacific basin islands, Central America, and various parts of the United States. Drought occurs in each of the above regions at different times (seasons) during an event and in varying degrees of magnitude. For southern Africa, rainfall over areas of almost all African countries south of 15°S is influenced by ENSO events (Ropelewski and Halpert, 1987, 1989; Mason and Jury, 1997). These events bring warmer than normal conditions during the rainfall season from November to May and in turn result in drier conditions. The association with southern African rainfall is evident also in the Southern Oscillation; the high-phase of the Southern Oscillation is associated with an increase in rainfall, while the low-phase is associated with decreased rainfall (Mason and Jury, 1997; Lindesay, 1988; Van Heerden et al., 1988). Lindesay (1988) showed that the strongest association occurs in a north-west to south-east line across the South African central summer rainfall region. The global and regional precipitation and circulation patterns
during strong ENSO events have been studied previously (Ropelewski & Halpert 1987, 1989, 1996, Kiladis & Diaz 1989, Reason et al. 2000, Cook 2001). El Niño events tend to be associated with dry conditions over much of southeastern Africa (Ropelewski & Halpert 1987, Janowiak 1988, Nicholson & Kim 1997). Southern Africa tends to undergo dry conditions during the mature phase (January to March) whereas equatorial eastern Africa tends to have a wetter than average short rains during the previous October-December (Ropelewski and Halpert, 1987).

Typically, an El Niño event develops every 3 to 7 years and is one of the most important influences on South African rainfall variability (Tyson, 1986, Kruger 1999, Joubert 1998; Reason et al., 2000). The widely reported severe droughts of 1982/83 and 1991/92, which were preceded by seasons of below average rainfall, resulted in substantial financial loss and major stressful conditions on water resources for agricultural, industrial and other metropolitan use (Joubert 1998, Kruger 1999). Cane et al., (1994), Vogel (1994) and Lecomte and Thiao (1995) also indicated that ENSO related droughts have major impacts in the agricultural sector in the region at both national and household levels. Some of the droughts that affect South Africa in particular are related to ENSO (e.g. Lindesay et al. 1986, Mason & Jury 1997), although the country also experiences droughts that are not related to ENSO (Mulenga et al., 2003).

Previous studies have shown that ENSO related SST anomalies may affect rainfall over southeastern Africa through modification of the Walker and Hadley circulations and mid-latitude storm tracks (e.g. Lindesay 1988; Reason et al., 2000). The greater importance of
ENSO to South African rainfall variations in the late rather than in the early-summer season is in accordance with changes in the atmospheric circulation over southern Africa (Lindesay, 1988). Comparison of the circulation over the central interior with rainfall, suggests that tropical systems dominate the rain-producing systems during January and February (i.e., mature phase of ENSO). Early summer rainfall may be more influenced by midlatitude features but, during December, a shift from baroclinic systems occurs (Van Heerden et al., 1988).

Previous work has found evidence for an offshore shift of the ascending branch of the local Walker Circulation so that it lies over the western Indian Ocean rather than over southern Africa during ENSO (e.g. Lindesay 1988, Jury 1992, Cook 2000, Reason et al. 2000). That kind of a shift is favourable for the offshore location of tropical-extratropical cloud bands that are important for summer rainfall over South Africa and therefore results in dry conditions (Harrison 1984, Preston Whyte and Tyson 1988). These studies have shown that when the local Walker circulation ascends over tropical southern Africa, the significant rains occur over northern and eastern South Africa because the cloud bands extend south east from southern Angola and out over the southern coast of South Africa.

During strong El Niño summers, a large area of positive pressure anomalies extends out across the Indian Ocean-southern Africa-Southeast Atlantic region from its centre over tropical Australasia (Allan et al., 1996). These anomalies lead to local subsidence and suppression of convection over southern Africa and weakening of the tropical low over
southern Angola which is the source region for cloudbands (Reason et al., 2000; Mulenga et al., 2003). In addition, these high pressure anomalies lead to an equatorward expansion of the westerlies over the southeast Atlantic and South Africa, again unfavourable for cloud-band occurrence over South Africa.

Northern South Africa, including the Limpopo province, tends to be strongly impacted by El Niño events. According to Mulenga et al. (2003), the only strong El Niño event during the 1921-2001 period that did not produce below-average rain over the region was 1957/58. The lack of a significant drought during 1957/58 may have occurred because this strong ENSO season was unusual in that high-pressure anomalies did not extend over southern Africa from the Indian Ocean-Australasia region as is more typical. Instead, there were cyclonic anomalies over southern Africa, favourable for above-average rainfall that occurred during this season.

In summary, the anomalous circulation patterns during ENSO dry summers which act to discourage convection and cloud band formation across southern Africa are outlined by Mulenga et al.(2003) as follows:

- Anticyclonic conditions centered over Namibia and southern Angola with associated stable conditions and regional subsidence.
- Low level divergence and upper-level convergence along a northwest-southeast-oriented band across southern Africa associated with an eastward shift of the
ascending branch of the Walker Circulation and cloud-band occurrence over the
Indian Ocean.

- Increased westerly flow in the mid-latitudes favoring more frontal systems over
southwestern South Africa and advection of dry South Atlantic air over northern
South Africa.

- Increased upper-level westerlies and the jet core positioned further west to the
south of Africa than average.

- Reduced upper-level easterlies over low-latitude southern Africa which decrease
the frequency and growth rate of tropical disturbances that are needed to promote
the source of the cloud bands over the region.

2.3 Non-ENSO droughts over northern South Africa

Mulenga et al., (2003) studied the driest non-ENSO summers for 1950-2000 over
northern South Africa, namely, 1951/52, 1967/68 and 1981/82. By contrast to the
droughts associated with El Niño events, it is important to look at these non-ENSO
droughts individually. Although each case is associated with an increased (decreased)
advection of cool, dry South Atlantic (warm moist South Indian) Ocean airmasses over
the country, the midlatitude circulation anomalies that lead to this situation is somewhat
different in each case. Thus, a simple compositing technique obscures these midlatitude
features of interest since the cyclonic anomaly that leads to the increased advection of
cool, dry South Atlantic air is located either to the south of South Africa, or further to the
southwest or west.
In addition to these circulation anomalies, Mulenga et al. (2003) showed that the maximum wind shear in the midlatitude westerlies is shifted west from its average position, thereby discouraging the mid-latitude component of the tropical extratropical cloud-bands from lying across South Africa. Relative divergence at the 850 hpa level across a northwest-southeast band extending from Angola to eastern South Africa with a weakened or absent tropical low over Angola-northern Botswana was also noted. The occurrences of these anomalies in the region are unfavourable for convection and cloud band occurrence across northern South Africa leading to the observed dry conditions (Mulenga et al., 2003).

While the ENSO dry summers result from significant changes in the tropical circulation and SST, the mid-latitude influences play a much greater role in the non-ENSO dry seasons (Mulenga et al., 2003). This greater influence of midlatitude anomalies in the non-ENSO droughts suggests that they will be harder to forecast than the ENSO droughts.

2.4. Other influences on northern South African rainfall

The essential feature of summer rainfall over South Africa is its high variability on a wide range of temporal and spatial scales (Joubert, 1998). Situated in the subtropics, South Africa is generally dry with an arid climate found along the western parts of the continent. It is also exposed to ocean influences from the South Atlantic and South Indian Oceans as well as the tropical Pacific. It has been shown that rainfall variability over
addition, these shifts are likely to affect the passage of fronts to the south of the country and therefore the location and intensity of the cloud bands that bring much of the summer rainfall.

2.5. Time scales of rainfall variability

Previous studies on rainfall variability in South Africa have tended to focus on the interannual or interdecadal scale (e.g., Tyson et al., 1975; Mason, 1995; Mason and Jury, 1997; Reason and Mulenga, 1999; Mulenga et al., 2003). Far less work has been done on intraseasonal rainfall variability. Recently, Washington and Todd (1999) examined the intraseasonal to interannual variability of tropical-temperate troughs using daily rainfall data. Tennant and Hewitson (2002) further emphasized the importance of intraseasonal variability over the region to southern African seasonal prediction. The circulation characteristics associated with wet and dry synoptic spells during anomalously wet and dry South African summers was examined by Cook et al. (2004). They found that modulations in the strength and position of the Angola low as well as ridging to the south and southeast of South Africa were important features of these wet and dry spells.

In addition to previous work devoting less attention to intraseasonal or higher frequency rainfall variability, this research has also tended to concentrate on seasonal anomalies. Recently, Usman and Reason (2004) investigated a more applicable measure of rainfall variability for user groups, namely, dry spell frequency during the core summer months of the rainy season, for the southern African region as a whole. Following on from that work, in this study, the frequency of wet and dry spells and the mechanisms behind their
occurrences will be investigated. The relationship between the ENSO and the onset of the rainy season is also investigated. The recent 2003/04 non-ENSO drought is also investigated in this study to examine whether the mechanisms associated with this drought are the same as the non-ENSO droughts documented in Mulenga et al., 2003. Better knowledge of wet and dry spells and onset date variability, may help with planning for agricultural purposes, particularly with respect to maize, the staple crop for most of southern Africa. Such knowledge would also help with assessing whether it is possible to forecast these parameters a season ahead.

2.5. Seasonal forecasting

Skillful climate forecasts are valuable to society to the extent that they provide knowledge that can be used to cope better with climate variations. In agriculture, a forecast is useful to the extent that it permits more advantageous actions, such as altered choice of crop species and cultivars and timing of tillage (Mjelde et al., 1998) or altered composition or allocation of herds (Smith and Foran, 1992). For example, a skillful forecast may allow a farmer to diversify less and to match cropping decisions more closely to expected climatic events. A farmer who can anticipate that rainfall is likely to be anomalous can plant seeds that are sensitive to water availability to improve profits; conversely a farmer who knows that there is a high probability that rainfall will be unusually low can use less water-sensitive practices.

Forecasts of growing season length or degree-days may be useful in various ways. However, forecasts are only helpful if they arrive before planting or stocking decisions
are made and if the producer is capable of responding. Some responses such as changing stock species may require resources available only to the most successful producers. Forecasts may benefit the 10-15% of farmers in the semiarid areas who would lose money by planting in bad-climate years (Rosenzweig and Binswanger, 1993) - given appropriate information, these farmers could decide not to plant at all thereby reducing losses.

According to Stern and Easterling (1999), climate forecast information should have the following characteristics for it to be useful:

1. A matching of the disseminated information to the characteristics and situation of the target audience is needed. Seasonal forecasts are useful only to the extent that they provide information that people can use to improve their outcomes beyond what they would otherwise have been. Different kinds of forecasts information are useful for different climate-sensitive activities, regions and coping systems. The dissemination of forecasts is most likely to be effective if it addresses the specific needs of the recipients.

A forecast can be of great use for decisions especially when it is available before key decisions are made. For example, crop yield forecasts are much more useful to the farmers if they are made before the crop is planted. The usefulness of a forecast may also depend on how frequently it is updated and how well users understand the implications.
Seasonal forecasts typically provide estimates of average temperature and rainfall for a future month or season. However, these estimates are not always the most decision-relevant parameters for farmers. More specific parameters such as the frequency of wet and dry spells may be more relevant to the needs of farmers (e.g., Vogel and O'Brien, 2003; Johnston et al., 2004). In addition, seasonal forecasts tend to be for large regions, and it is unlikely that a forecast will be of similar accuracy for all areas within the region. Therefore, some downscaling of the regional forecast to smaller areas is generally needed. For example, Landman and Tennant (2000) and Landman and Goddard (2002) have applied a monthly downscaling system from global model output for seasonal forecasts over South Africa. This, and other seasonal forecasting work (e.g., Landman et al., 2001; Goddard and Mason 2002; Jury, 2002; Landman and Goddard 2002) suggests that anomalies in rainfall totals during the DJF summer season over South Africa may have some predictability.

A forecast that provides any measurable skill beyond historical averages or persistence of currently observed anomalies is likely to be valuable. Small scale farmers who are particularly vulnerable to the impacts of climate variability and who lack resources to mitigate their impacts, may be unwilling to change their practices on the basis of a forecast of uncertain or unproved accuracy.

2. Responses to previous seasonal forecasts – the responses to previous seasonal forecasts are an essential source of information for understanding responses to future ones. Previous studies (Hudson 2002) suggest that before 1997, few farmers in southern
Africa were using the seasonal forecast information. However, the few cases that exist suggest the value of carefully examined experience (Hudson, 2002). The 1997-1998 El Niño event provided a valuable opportunity for building knowledge from experience that may be critical for improving the use of future seasonal forecasts since the rainfall impacts over the region were not as expected given the magnitude of this event (Usman and Reason, 2004).

The science of short and medium range weather forecasting with computer models of the global atmosphere is now quite advanced. Operational short to medium range weather forecast products are now available in many climate centres world-wide. More recently, statistical and dynamical based seasonal predictions of regional rainfall and temperature for example are being provided. Growing understanding of the ocean-atmosphere system, and substantial investments in monitoring the tropical oceans now provide some degree of predictability of climate fluctuations several months in advance for particular seasons in many parts of the world (Barnett et al., 1994; Palmer and Anderson, 1994; Latif et al., 1998). However, for such seasonal forecast products to be useful in agricultural applications, they have to be downscaled, not only to national and regional levels but also to farm levels. Although most short and medium range weather forecast products are readily available to all National Meteorological and Hydrological services world-wide through efforts of the WMO and other organisations, it seems as if downscaling to specific farm level is unrealistic in the foreseeable future as most of the techniques will at best only incorporate regional characteristics (Ogallo et al., 2000).
There is a need to address the climate needs of the specific sectoral agricultural users in order to enable the customer tailored climate prediction products to be developed by the climate prediction centers (Ogallo et al., 2000). It is crucial that agricultural users have adequate knowledge of the skill and limitations of any climate prediction products in order to provide implement any early warning or other advisories appropriately.

Prospects exist for seasonal forecasts to modify the management of crops and livestock so as to minimize some of the negative impacts of climate variability over southern Africa (Mason 2001, Hansen 2002, and O'Brien & Vogel 2003). Previous studies have also shown that predicting the onset date of the rainy season will be of great help in the preparation of farmlands, mobilization of seeds/crops. Prior knowledge of the likely date of the onset of the rainy season should reduce risks of planting too early or late (Makarau and Jury, 1997; Omotosho et al 2000; Dodd and Jolliffe (2001).

Research into the ENSO phenomenon has opened a discussion on how climatic risk in agriculture might be minimized through the use of long-lead climate forecasts and agro-climatic information (Battisti and Sarachik 1995, Glantz et al., 1991). The global models permit ENSO events to be predicted with increasing skill as well as the regional climatic implications of these events are also to some extent predictable (Trenberth 1996). These predictions could play a central role in adaptation and risk management for agricultural producers in ENSO affected regions, particularly for small scale, low input farmers whose rain fed production is often considered to be most vulnerable to climatic variability.
More efforts have been designed to actively try and alleviate the impacts of droughts on the southern Africa region through the use of consolidated seasonal rainfall and temperature forecasts (e.g. Southern African Regional Climate and Outlook Forum, SARCOF) (NOAA-OGP, 1999; International Federation of Red Cross and Red Crescent Societies, 1999). Although recognizing that the climate forecasting efforts are improving, Vogel (2000) suggested more research is needed into whether these forecasts are being used appropriately by the agricultural community. The emerging ability to provide timely, skillful climate forecasts offers the potential to reduce human vulnerability to the agricultural impacts of climate variability through improved agricultural decision making, either by preparing for expected adverse conditions or taking advantage of expected favourable conditions.

The focus amongst the forecasting community has widened to include efforts to improve and serve end users of such forecasts (NOAA-OGP, 1999). The use of seasonal forecast information among various sectors (e.g. water, industry and agriculture) is limited to broad assessments of ENSO in the wider SADC region (e.g. Hulme, 1990; Hulme et al., 1992; Gibberd et al., 1995/96; Glantz et al., 1997; Thomson et al., 1998; Phillips et al., 1999). Few detailed assessments exist of how such information is accessed, used and to what extent it adds value to various agricultural activities in South Africa (e.g. Sear, 1998; Klopper, 1999; Patt and Gwata, 2003; Ziervogel and Calder, 2003).
It is important to emphasize that there are other influences on South African rainfall variability than ENSO. Regional SST variability and atmospheric circulation anomalies may influence rainfall over South Africa and neighbouring countries (e.g., Reason and Mulenga, 1999; Behera and Yamagata, 2001; Mulenga et al., 2003) unrelated to ENSO, and these influences may be more difficult to monitor or predict in advance.

Another important factor is the communication gap between the agricultural sector, farmers and the operational agencies producing the seasonal forecasts (e.g., Ziervogel and Downing, 2004). During the meetings with farmers organized by the South African Department of Agriculture (Agricultural Risk and Disaster Directorate), farmers indicate that seasonal climate forecasts will be easier to understand if they are less probabilistic in nature, and will be more useful if they address parameters such as the onset, distribution and the cessation of rainfall as well as the frequencies of dry spell and wet spell during the season.

2.6 Mitigation of disasters caused by climate variability

Disaster mitigation as outlined in the Disaster Management Act (Act No. 57 of 2002) refers to measures that can be taken to minimize destructive and disruptive effects of hazard and thus lessen the scale of a possible disaster. In South Africa, millions of rand, which could support ongoing development initiatives, are diverted to provide relief for those affected by natural and man-made disasters (White Paper on Disaster Management, 1998). Disaster Management has become a focus area for scientific endeavors to achieve a better understanding of hazards that shape our natural and built environments and to set
standards to bring about a safer world. It encompasses, for example, interpreting the early warning signals of natural phenomena, such as too little or too much rainfall that might cause drought or flood respectively, (White Paper on Disaster Management, 1998). Similarly, it involves contingency planning and response to emergency events triggered by extreme climate events.

Studies of the value of climate information can have important implications for decisions made by a variety of individuals, including program managers, researchers and users of such information as many critical agricultural decisions that interact with climatic conditions must be made several months before the potential impacts of climate materialize. Climatic risks need decision makers to be always prepared by putting conservative risk management strategies that reduce negative impacts of disasters.

The ability of farmers to mitigate climatic risks depends not only on their field-level knowledge and experience, but also on market conditions, price structures and production costs they face as well as the economic security of their households (Eakin, 2000). Since the Disaster Management Act (Act No. 57 of 2002) among others is aimed at binding the government to issue the early warning information that is timely and freely available, it is very important to first address the gap that exists between knowledge of the climate variability and its implication thereof.
2.7. Summary

Agricultural systems are more vulnerable to the climate variability in developing countries where agriculture is more dependent on rainfall with less emphasis on irrigation or other intensive agricultural practices. The Limpopo region studied in this thesis is an important agricultural area with a relatively large rural subsistence population and contains significant biodiversity in the various national parks. It is also a region that is prone to significant drought and flood events (e.g., Dyson and Heerden, 2001; Mulenga et al., 2003; Reason and Keibel, 2004). These events often lead to adverse impacts on agriculture, the rural economy and human welfare.

In this thesis, attention is given to drought over Limpopo, the variability of wet and dry spells during the rainy season and the relationships with ENSO. The evolution of the most recent El Niño-induced drought (2002/03) into the 2003/04 non-El Niño drought is considered. In addition, interannual variability in the onset date of the summer rainy season over Limpopo and potential relationships with ENSO and regional circulation anomalies are considered.

Seasonal forecasting for southern Africa is gradually improving in skill but an important issue is whether these forecasts are issued in ways, and contain information, that are useful to the user groups such as farmers. In agriculture, a useful forecast is one that facilitates more advantageous actions such as altered choice of crop species and cultivars as well as the timing of tillage or altered composition or allocation of herds. A skillful forecast may allow a farmer to match cropping decisions more closely to expected
seasonal rainfall or temperature conditions. Issues remain concerning the probabilistic format of seasonal forecasts and how these forecasts are interpreted by user groups.

Farmers desire forecasts about specific quantities such as frequency of wet and dry spells and the likely date that the rains will start. These quantities are not yet forecast as more research is needed into their variability, potential relationships with large-scale modes such as ENSO, and possible predictability. Thus, this study aims to assess the variability in wet and dry spells during the rainy season, the variability in onset date, possible relationships with ENSO and also with regional circulation anomalies.
Chapter 3: Data and Methodology

3.1. Introduction

The purpose of this chapter is to give a brief description of the various datasets used in this thesis, their limitations and potential caveats, and the methods of analysis employed.

3.2. Rainfall Data

Two rainfall gridded datasets are used to analyse rainfall variability over the Limpopo region. These comprise the 0.5° resolution global land surface precipitation data of New et al. (2000) available as monthly values for 1900-1998 and the 2.5° resolution CMAP global (i.e., including the oceans) data set (Xie and Arkin, 1997) available from 1979-present. The latter is a merge of rain gauge, satellite and model-based precipitation estimates and has been extensively used in previous studies of rainfall variability in the region (e.g., Behera and Yamagata, 2001; Reason et al., 2003). In this thesis, pentad (5 day) rainfall data from CMAP are used. Previous work has compared the CMAP product over southern Africa with station data (Tadross et al., 2002) and found that, although there are discrepancies between the two datasets for some southern African countries where gauge networks are sparse, for South Africa and Zimbabwe there is generally good agreement. As a result, it seems justifiable to use CMAP data for the purposes of this thesis.

Previous studies that use CMAP pentad data to investigate the intraseasonal and interannual rainfall variability over various regions of southern Africa include Usman and
Reason (2004) and Kijazi and Reason (2004). The use of pentad data helps to remove diurnal and synoptic effects and allows focus on the intraseasonal and interannual scales of interest here. Consideration was given to potentially using the daily 0.5° resolution dataset of the Computing Centre for Water Research. However, this data only extends from 1950-1997 which precludes analysis of this data during recent severe ENSO events, and therefore this data set was not used to derive any of the results presented in the thesis.

3.3. Atmospheric circulation

The NCEP-NCAR re-analysis data set (Kalnay et al., 1986) which consists of primary variables such as wind, geopotential height, air temperature, specific humidity at 2.5° horizontal resolution at various pressure levels throughout the global atmosphere was used to assess circulation patterns associated with various anomalous seasons. Although this data extends back to 1948, emphasis is placed on the post-1979 period after which the pentad CMAP rainfall data are available and after which the NCEP re-analyses are considered to be more reliable due to the availability of satellite data for assimilation into the NCEP model. The NCEP re-analysis dataset has been widely used in studies concerned with the interannual variability of rainfall over various regions of southern Africa, recent examples being Mulenga et al. (2003) for northeastern South Africa and Cook et al. (2004) for the summer rainfall region of South Africa.

3.4. Sea surface temperature

To investigate possible relationships between regional oceanic variability and anomalous rainy seasons in the Limpopo region, the extended NOAA sea surface temperature (SST)
data set (Smith and Reynolds, 2003) was used. This data set is available as monthly values back to 1871 and at a horizontal resolution of 1°. Various statistical techniques have been used to construct missing data for regions outside major shipping lanes for the pre-satellite period. Relationships of various rainfall parameters with anomalies in Nino 3.4 SST, a widely used measure of ENSO, are investigated using time series analysis.

3.5. Analysis methods

Since this thesis is mainly concerned with the interannual variability of characteristics of the rainy season important for agriculture and other user groups, most of the results derive from analyses of pentad CMAP rainfall post-1979. The major parameters considered are dry spell frequency during the core months (December-February) of the summer rainy season, wet spells during this period, and the onset date of rainy season. Following Usman and Reason (2004), a dry spell is defined as a pentad with rainfall of less than 5 mm (i.e., less than 1 mm per day on average). A wet spell is defined as a pentad with rainfall of 10 mm or more. Since the data used to calculate wet and dry spells in this way is based on pentad rather than daily totals, it is possible that a dry or wet spell could straddle two pentads rather than be counted as falling within either one of them. As a result, the dry and wet statistics derived in this way later in the thesis should be regarded as lower bounds.

Based on the moisture requirements of maize, the major staple crop of the region, the onset date of the rainy season is defined as the date of the first pentad following August 3 such that 25 mm occurs in the first two pentads with at least 20 mm total rainfall over the
following four pentads (AGHRYMET, 1996). This definition has also been applied in previous studies of the variability in onset over South Africa and Zimbabwe (Tadross et al., 2004) and seems appropriate since it is based on the dominant crop of the region. A potential drawback of this definition is that it is based purely on rainfall received in a defined period of time with no consideration of the synoptic system bringing the rainfall. Most of Limpopo’s summer rainfall is related either to easterly waves and depressions, or to tropical-extratropical cloudbands that link a tropical disturbance over low latitude southern Africa to a midlatitude system passing south of the country. However, significant late winter or early spring rainfall results on occasion from midlatitude weather such as a cut-off low or a severe cold front and it is possible that this situation may bias the calculation of the onset date.

Time series of anomalies in December – February dry spell frequency standardized using the mean and standard deviation are plotted against those for Nino 3.4 SST. Similar plots are constructed of anomalies in Nino 3.4 SST and onset date. These plots allow anomalous seasons to be identified and potential relationships with ENSO to be investigated.

To study potential relationships between regional atmospheric circulation anomalies and dry spell frequency, or onset date, composite analyses for the anomalous seasons are derived. An anomalous season in dry spell frequency is considered to be as season whose standardized departure is more than 0.5 deviations from the mean. For onset data, a criterion of 0.8 standard deviations was used. These criteria are based on inspection of the
relevant data sets and lead to 5 or 6 positive or negative anomaly seasons being defined to be included in each composite. Many other studies of southern African climate variability have used composite analysis (e.g., Rasmusson and Carpenter, 1982; Matarira and Jury, 1992; Reason et al., 2000; Mulenga et al., 2003). The advantage of composite analysis is that it tends to highlight the most important and common features between the individual cases and suppress noise. However, it is possible that a composite may be biased by one or two events showing much stronger features than for the other members. To check this possibility, plots of circulation anomalies for individual seasons were also inspected.

3.6. Summary

This chapter has discussed the various data sets and analysis techniques used in the thesis as well as some of their limitations and potential drawbacks. Data constraints mean that caution must be used in the interpretation of the results particularly with respect to their potential application to seasonal forecasting or agriculture. The following chapter analyses wet and dry spells over Limpopo and variability in the onset of the rainy season over this province whereas chapter 5 considers the evolution of the 2003/04 severe drought.
Chapter 4

Variability in dry and wet spells during the rainy season over Limpopo and in the onset date of this season

4.1 Introduction

Rainfall variability often hampers agriculture and tourism in Limpopo, activities important to the national economy. Given its poor and large rural population, great biodiversity and importance for tourism and agriculture, better understanding of the nature of individual anomalously wet and dry seasons and their associated mechanisms is needed. In addition, improved understanding may assist with increasing the skill of seasonal forecasting over the region. It should be noted that these forecasts will always have considerable uncertainty and are best interpreted in probabilistic format as a result of the nonlinearities inherent in the atmospheric and ocean circulation and their interaction with rainfall processes. If the skill of the forecasts can be improved then there is the potential to reduce the agricultural impacts of climate variability through improved advisories issued by the extension officers and better decisions made by farmers. Most important agricultural decisions that are influenced by climate variability should be made several months in advance before the climatic impacts take place. Thus, both issuers and users of advisories should prepare for the range of possibilities leading to conservative risk management strategies that reduce negative impacts of climatic conditions in advance.

Information about the likely onset, distribution and cessation of rainfall as well as the frequency of dry and wet spells during the forthcoming rainy season is of importance to the farmer as most staple crops like maize will do better in a season with evenly distributed rainfall than in one where there is more rain at the beginning of the season and less during the season or at the end. Makarau and Jury (1997) over southern Africa and recently Omotosho et al (2000), Dodd and Jollife (2001) in studies over the western
Africa region have illustrated that the reliable prediction of the onset date is of great help in preparing lands for crops on time and in the mobilization of seeds. This will also reduce risks, as planting too early might lead to a crop failure, while the growing season might be reduced as a result of planting too late. Omotosho et al. (2000) also noted that even after seeds have been planted, they still need favourable rainfall during the early stages to avoid crop failure. Omotosho et al. (2000) also pointed out that appropriate decisions with regard to irrigation timings and their needs, as well as other related water conservation strategies, are all dependent on reliable estimates of monthly and seasonal precipitation amounts.

Makarau and Jury (1997), Tennant and Hewitson (2002), and Cook et al. (2004) focussed on intra-seasonal rainfall variability which is of great importance for agriculture, water resources and other activities. Many of these user groups also need information about quantities such as the onset and end dates of the rainy season, or the number of dry and wet spells within it. This is particularly true for the predominantly rain-fed subsistence agriculture practiced over much of Africa. A crucial decision these subsistence farmers face is when to plant staple crops such as maize, sorghum or millet, which depends critically on the onset date of the rainy season. Too early a planting, when the rains are more erratic and frequent dry spells may occur, will likely lead to insufficient soil moisture for proper germination of the seed. On the other hand, if planting occurs too late, and the rains are too intense, the seed may be washed away. Furthermore rain-fed crops are more likely to do well with more uniformly spread light rains than with a few heavy falls interrupted by dry periods. The timing of breaks in rainfall (dry spells) relative to the cropping or plant physiological calendar is of great importance to the eventual yield. Thus, any information provided in advance by agricultural extension officers about the likely onset of the rains or the characteristics of subsequent wet and dry spells can have a substantial impact on crop yields as well as on the well being of the rural population.
Makarau and Jury (1997) suggested that changes in moisture transport from surrounding oceans, particularly the tropical Indian Ocean is important for rainfall variability over South Africa, especially that occurring some 10-15 days in advance of the rainfall. Makarau and Jury (1997) and Omotosho et al (2000) further noted that changes in moisture transport may result in changes to the onset of the rainy season from one region to another and that these variations could range between 40 and 60 more days from one year to another. In addition, these moisture transport changes may influence the cessation and length of the rainy season. For South Africa, Cook et al (2004) showed that the main source of low-level moisture for the summer rainfall region is the southwest Indian Ocean. Wet spells tended to be associated with a stronger Angola low, the source region for tropical-extratropical cloud bands and ridging south and southeast of South Africa, thereby transporting more moisture onto the landmass for southwest Indian Ocean.

Rainfall over the Limpopo region is strongly seasonal with most occurring during the austral summer (DJF) via easterly waves and lows, or tropical-extratropical cloud bands and associated thunderstorms (Taljaard and van Heerden, 1998; Tyson and Preston-Whyte, 2000). Relatively few rainfall events occur during a particular rainy season. Recently, the Limpopo region has been severely impacted by drought (2001-2004) and was also affected to some extent by heavy rains in February 2000 that led to severe flooding over many areas in northeastern South Africa and southern Mozambique (Dyson & van Heerden, 2001; Reason and Keibel, 2004). The 2002/03 summer rainfall season was an El Niño season and most of the areas in the country experienced dry conditions with very dry conditions over the northern part of Limpopo. Most farmers suffered livestock and crop losses during this season. The 2003/04 summer rainfall season was dry in the first part of the season and wet in the later part of the season. These conditions affected most farmers who had planted their crops in the first part of the season as they lost their crops due to poor rainfall and favoured those who planted in the second part as they had better rains.
Focus in this chapter is placed on investigating the interannual variability of, firstly, dry spells within the rainy season over Limpopo and, secondly, in the onset dates of the season rather than on seasonal rainfall anomalies. Attention is also paid to the impacts of the variability on maize yield and vegetation activity. The possible relationships of these parameters with ENSO and with regional circulation anomalies is considered as a first step towards assessing whether it may be possible to seasonally forecast these parameters that are more useful to agriculture than seasonal rainfall totals. Dry spells are analysed for the core DJF period of austral summer since this is typically the period when ENSO impacts most strongly over the region (Lindesay, 1988; Reason et al., 2000) and because December is the beginning of the critical period for maize when significant rainfall variability can have a major impact on the viability of the crop. Maize flowers within December to February, after germinating in late October or November, and typically needs about 120 growing days from planting to harvesting. Thus, the DJF period is fundamental for both regional ENSO impacts and for the growth and yield of the major staple crop of the large rural population.

4.2 Rainfall variability over Limpopo

Fig. 4.1 shows a time series of anomalies in austral summer rainfall for the Limpopo region for DJF during 1979/80 to 2001/2 using CMAP (Xie and Arkin, 1997) pentad data. The mean rainfall rate for DJF is 3 mm / day with a gradient from about 3.5 mm / day in the east to around 2.5 mm / day in the west (Fig. 1.1). Anomalous wet and dry summers during this period agree with those derived by Mulenga et al (2003) for a slightly larger region of northern South Africa using monthly gridded data from the South African Weather Service. These authors pointed out that the only strong El Niño event during 1921-2001 that did not produce below-average rain over the region was 1957/58. During this season, the circulation anomalies over southern Africa and the neighbouring Indian Ocean were atypical compared to the ENSO composite (Reason et al., 2000) because low pressure anomalies existed over southern Africa and the South West Indian Ocean with a reduced high pressure anomaly over Australia.
Based on the more recent pentad data plotted in Fig. 4.1, the most pronounced dry summers occurred during the 1982/3, 1991/2 and 1997/8 El Niños, closely followed by the neutral 2001/2 summer. Of these three El Ninos, it will be shown in section 4.6 that maize yields were significantly reduced in 1982/3 and 1991/2 but not in 1997/98 or 2002/03. As pointed out by Mulenga et al. (2003), it needs to be appreciated that not all significantly dry summers over the region correspond to El Niño events. Of the five La Niña summers during the period, only 1995/6 and 1999/2000 correspond to very wet conditions over Limpopo with 1980/81 (a neutral year) being the third wettest summer, and another neutral season, 1987/88, the fourth wettest. Rainfall over the Limpopo region during the 1988/89 and 2000/01 La Niña summers (DJF) was slightly below average whereas that for 1998/99 was slightly above average. The latter season also showed below average temperatures and this may have impacted on maize yields (Section 4.6). As a result, the impression one gets from Fig. 4.1 is that the ENSO impact over the Limpopo region is nonlinear since the dry summer / El Niño relationship appears to be more reliable and stronger than the wet summer / La Niña relationship. Although Fig. 4.1 only extends from 1979/80 until 2001/02, Reason et al. (2000) found a similar more consistent El Niño rainfall impact than for La Niña over a larger southeastern African region for 14 strong events during the 1900-1993 period using CRU rainfall data (Hulme and New, 1997).

4.3 Dry spell frequencies and rainy season characteristics

Recently, Usman and Reason (2004) showed that a strong relationship exists between DJF dry spell frequency averaged over southern Africa from 5-30°S and the Niño 3.4 SST index. These authors defined a dry spell to exist within DJF for any pentad where the rainfall was less than 5 mm. Using the same definition as Usman and Reason (2004), the Limpopo region experiences about 5 pentads of dry spells on average during the 18 pentad long season, although there is considerable interannual variability in this number (Table 4.1 and Fig. 4.2). If one defines a wet spell as a pentad with at least 10 mm of rain, then on average about 10 pentads are wet (Table 4.1), again with substantial interannual
variability. However, increasing the minimum rainfall to 15 or more mm per pentad markedly decreases the number of wet spells.

Fig. 4.2 indicates that increased (decreased) dry spell frequencies during DJF 1979-2002 over Limpopo tend to coincide with El Niño (La Niña) events and that for much of the time, the series tracks the Niño 3.4 SST anomaly. The correlation coefficient between the two series is 0.5 over the period, but this increases to 0.76 for 1989/90-2001/02 which simple inspection of Fig. 2 indicates as the time when the two series are more strongly related to each other. Of the 10 ENSO summers during 1979/80-2001/02, only the 1986/87 El Niño and the weak 2000/01 La Niña are exceptions, with the 1988/89 La Niña close to zero anomaly. During the mature phase of ENSO events, there is an offshore shift of the ascending branch of the local Walker Circulation so that it lies over the western Indian Ocean rather than over southern Africa (Lindesay 1988, Jury 1992, Cook 2000, Reason et al., 2000). This shift is favourable for the offshore (onshore) location of tropical-extratropical cloud-bands that are important for South African summer rainfall and therefore results in drier (wetter) conditions (Harrison 1984, Preston Whyte and Tyson 1998). These studies also showed that when the local Walker circulation ascends over tropical southern Africa, significant rains occur over the northern and eastern South Africa because the cloud bands extend south east from southern Angola and out over the southern coast of South Africa. This behaviour is associated with the increase (decrease) in the number of dry spells during El Niño (La Niña) phase shown in Figure 4.2.

For neutral DJF seasons, the tendency in dry spell frequency sometimes tracks that in Niño 3.4 (e.g., 1979/80-1981/82, 1989/90, 2001/02) and sometimes not (e.g., 1984/85-1985/86). After closely tracking each other over the 90s, a relatively large deviation in magnitude between the Niño 3.4 and dry spell frequency series occurred during the 2000/01 season. This season lies at the end of the protracted 1998/2001 La Niña, and prior to the 2002/03 El Niño, with Niño 3.4 anomalies being relatively weak. This situation suggests that some other forcing may have been responsible for the dry conditions (Fig. 4.1) and increased dry spell frequency in 2000/01 (Fig. 4.2). Indeed,
during DJF 2001 a low-level circulation cyclonic anomaly existed south of South Africa, which together with low level relative divergence and anticyclonic conditions (not shown) over the region, were unfavourable for rainfall. These 2000/01 anomalies are reminiscent of the circulation patterns analysed by Mulenga et al. (2003) for northern South Africa for the severe non-ENSO droughts of 1951/52, 1967/68 and 1981/82. During each of these summers, midlatitude influences emanating from the South Atlantic dominated and tropical influences were weak. As will be shown in chapter 5, the recent 2003/04 drought over much of South Africa was also associated with midlatitude and a significant advection of relatively dry and cool South Atlantic air over the country.

4.3.1 ENSO summers

The relationship between dry spell frequency and seasonal rainfall anomaly during DJF for Limpopo is not linear. For example, Fig. 4.2 has shown that 1997/8 is the season which had largest number of dry spells; however, Fig. 4.1 showed that it is not the driest summer, being surpassed by 1982/3 and 1991/2. Similarly, the neutral 2001/02 summer is almost as dry as 1997/8 and has a dry spell frequency close to that experienced during 1982/3. Tables 4.1-4.2 display some characteristics of dry and wet spells recorded during seasons of both anomalously high and low dry spell frequency whereas Fig. 4.3 plots the pentad rainfall recorded during each of them. Note that, in addition to DJF rainfall, Fig. 4.3 also plots that falling during the onset months of October and November. On average, each dry spell during DJF 1979/80-2001/02 lasts just over 1 pentad but only the 1986/87, 1994/5 and 1997/98 El Niños exceed this dry spell duration. However the very dry 1982/83 and 1991/92 strong El Niño cases show shorter lasting dry spells.

Although 1997/8 stands out prominently in terms of number of dry spells during DJF and as having the longest lasting dry spell, this El Niño event had less impact on South Africa than might have been expected given the size of the anomaly in the Southern Oscillation Index or the Niño 3.4 SST. The long lasting dry spell occurred in late January / early February and the early part of the season had relatively good rains, including long lasting wet spells of at least two pentads in early October, much of November and also late
December (Fig. 4.3a). NDVI images for October and November 1997 (Fig. 4.4) indicate that much of the region had average to above average vegetation activity in stark contrast to images for October and November 1982, 1991, 1994 and 2002. These images suggest that a dramatic reduction in vegetation activity occurred in December 1997 and January 1998 although the reduction was not as severe as in 1982/83 or 1991/92. The reduction in vegetation activity is problematic for livestock farmers, as they will experience shortage of grazing and may require additional feed for livestock survival. Furthermore, Fig. 4.5 indicates that commercial maize yields over the Limpopo province of South Africa were substantially higher in 1997/98 than for the other El Niño seasons. Thus, the good rains in the early part of the 1997/98 El Niño relative to other El Niño summers may have then led to improved agricultural output, or at least significantly less severe impact on agriculture than might have been expected given the magnitude of the SST anomaly in the tropical Pacific and previous work on ENSO impacts on southern Africa (Lindesay, 1988; Reason et al., 2000).

The 1994/5 El Niño also showed a large number of dry spells and longer than average mean dry spell duration (Table 4.1). However, the dry spell behaviour in DJF was offset by a close to average number of wet spells, several of which were relatively intense, and thus the impacts of the below average seasonal total rainfall was far less severe than for 1982/83 or 1991/2 (Fig. 4.1).

The 1991/92 season, which is considered to be one of the most severe droughts in the last few decades and which had the lowest commercial maize yield over Limpopo (Fig. 4.5), shows little rainfall from mid-November until a significant wet spell in mid January (Fig. 4.3a). Thus, the number of dry (wet) spells was considerably greater (less) than average (Table 4.1), and those wet spells that did occur were of shorter than average duration. The NDVI maps also support this statement as the province experienced well below average vegetation activity in December 1991. A slight improvement occurred from January to February 1992 and then conditions deteriorated again in March 1992 (Fig. 4.4). This situation not only affected planted crops but also livestock production, as the grazing area...
alone could not have sustained the animals. Seasons like these require farmers to buy additional feed to sustain their livestock to avoid mortalities.

For the 1982/83 severe drought, it was more a case of reduced quantity through most of the season rather than extended dry spells that were responsible for the dry conditions (Figure 4.3, Table 4.1). However, the mid-October to mid-November 1982 period corresponds to an extended dry spell. In addition, DJF 1982/83 contained significantly fewer wet spells than average and these were short lasting (Table 4.1). Finally, the 1986/87 El Niño season, which was anomalous in terms of its dry spell frequency during DJF (Fig. 4.2), also stands out as a season of relatively good rains throughout most of the October-February period (Fig. 4.3a) (total rainfall was above average in 1986/87). This season also showed a larger number of wet spells than average, although these were relatively short in duration (Table 4.1) and, as a result the maize yield was slightly below average (Fig. 4.5). Thus, the reductions in maize yield were less severe than for the 1991/2 or 1994/95 El Niño.

In summary, Fig. 4.3 and Table 4.1 show that there are substantial differences between the five El Niño seasons in terms of DJF rainfall total, number of dry and wet spells, and intensity.

All the La Niña seasons, except 2000/01 (which falls towards the end of the 1998/01 protracted event) correspond to ones of average or reduced dry spell frequency. However, similar to the El Niño cases, there is considerable variability in the timing and duration of wet and dry spells between each La Niña event. Of these, the very wet 1995/96 and 1999/00 seasons are noteworthy in displaying a number of intense wet spells, and with the exception of early in the season, no long lasting dry spells (Fig. 4.3a). These two seasons had the highest commercial maize yields over Limpopo province of the La Niña cases (Fig. 4.5). By contrast, 1988/89 only experienced two strong wet spells separated by a long period with both significant dry spells and relatively weak wet spells.
(only one of these strong wet spells occurred after December 1st) (Figure 4.3a) and as a result the maize yield was near average, (Fig. 4.5). The number of wet spells in this season was less than average (Table 4.1).

Rainfall during 1998/99 tended to be more consistent than for the other seasons with a number of moderate wet spells occurring throughout the season. As shown by Fig. 4.5, these rains did not appear to have a significant impact on yield which was below average. The 2000/01 La Niña season was unusual in having an above average number of dry spells and a below average number of wet spells during DJF (Table 4.1). The maize yield reflects that since it was much reduced compared to the previous 1999/00 season (Fig. 4.5). A relatively strong wet spell occurred both at the beginning and at the end of DJF 2000/01 (Fig. 4.3). Overall, DJF 2000/01 received slightly below average rainfall totals, whereas the preceding October/November onset was close to average in terms of totals. Taken together, Figs. 4.2-4.3 and Table 4.1 emphasize the differences in rainfall timing and intensity between the various La Niña seasons.

4.3.2. Neutral seasons

The neutral years of high DJF dry spell frequency in Fig. 4.2 (i.e., 1983/84, 1984/85, 2001/02) all tend to show wet spells of greater magnitude than the 1982/83, 1991/92, 1994/95, 1997/98 El Niño seasons, and except for 2001/02, more regularly spaced rainfall throughout the entire October-February period (Fig. 4.3b). The 2001/02 season experienced wet spells in early to mid-November and followed by increasingly dry conditions that intensify after mid-December. This neutral season is not like any neutral or El Niño summers in that a wet early to mid-November is followed by increasingly dry conditions that intensify dramatically after mid-December as shown in figure 4.3a-4.3 b. Although the number of dry and wet spells during DJF 2001/02 is similar to 1983/84 and 1984/85, the mean dry spell duration is shorter than either 1983/84 or 1984/85 (Table 4.2). This might give the impression that the overall seasonal total is expected to be greater. Fig. 4.3b shows that DJF 2001/02 had no wet spell with rainfall above 6 mm / day and its generally reduced intensities led to a reduced seasonal total (Fig. 4.1). Indeed,
December 2001 marked the beginning of the intense 2001-2004 drought experienced over Limpopo and neighbouring regions. The dry conditions during 2001/02 resulted in the livestock being more dependent on additional feed which then had to be subsidised by government who also had to fund the drilling of extra boreholes to supplement the depleted dam levels.

Neutral years with low dry spell frequency during the core summer period include 1979/80, 1980/81, and 1981/82 with 1980/81. From the perspective of agriculture and other applications, 1980/81 is preferable to either 1979/80 or 1981/82 since both of the latter two seasons experienced lower and more variable rainfall (Figs. 4.1, 4.3 and Table 4.2). For all three seasons, the tendency in dry spell frequency followed that in Niño 3.4 reasonably closely. This behaviour suggests that a forecast scheme based on Niño 3.4 SST or other ENSO indicator may also perform to some extent during some neutral years. However, the high dry spell frequency season of 1984/85 reinforces the fact that the relationship with Niño 3.4 SST is not always strong for neutral seasons. This is one of the seasons with the largest discrepancies between the two variables. It is also unusual in that the frequent dry spells tend to be separated by relatively intense wet spells (Fig. 4.3b); thus, overall, the DJF rainfall total was close to average for 1984/85.

As emphasized above, the number and timing of dry spell occurrences during the rainy season are two parameters of great interest to farmers and water resource managers. Another characteristic of great significance is the onset or starting date of the rainy season, and this parameter is considered in the next section.

4.4. Onset dates of the rainy season

Onset of the rainy season over Limpopo has been defined as the date of the first two pentads with at least 25 mm of rainfall. This has to be followed by four pentads within which at least 20 mm of rainfall occurs. This definition is the same as that used by AGRHYMET (1996) and is based on the rainfall needed for successful germination of
maize in the first month after planting. Using this definition, the mean onset date for the Limpopo region calculated over the 1979/80-2001/02 summers is the pentad of 23-27 October. Fig. 4.6 shows the anomalies for the onset of each rainy season from this date. This suggests that for much of the record, the tendency in onset date is opposite to that of Niño 3.4 SST. When considering the individual seasons, three out of five El Niño seasons (1986/87, 1994/95, 1997/98) had substantially early onset. However, the strong 1982/83 and 1991/92 El Niños (both of which also produced severely reduced rainfall totals as well as significantly increased dry spell frequency during DJF) showed an anomalously late onset. Similar to the rainfall totals, the onset relationship with La Niña appears less strong than for El Niño since only two out of five La Niña seasons (1995/6, 1999/00) had a notably late onset (1988/89 was slightly late). On the other hand, both 1998/99 and 1999/00 were substantially early.

In general, the inverse relationship with Niño 3.4 SST seems to work better after about 1985, and is noticeably poorer for the 1983/84 to 1985/86 seasons. The definition of onset used here is based purely on rainfall amount in a certain period with no consideration of the type of circulation system that produces the rainfall. In simple terms, a season in which the tropical influences become established early (i.e. the ITCZ shifting south earlier than average) so that pronounced easterly waves and tropical-extratropical cloud bands occur relatively early is likely to be more advantageous in terms of significant and regular rainfall over Limpopo during DJF. However, early onset, as defined here, may occur via one or two midlatitude systems penetrating anomalously north over South Africa such as an intense cold front, or a cut-off low. ENSO influences on the regional circulation and weather system development is complex; thus, it is not surprising that the Niño 3.4 SST relationship is weaker than that found for dry spell frequency. However, it should be recognised that a different definition of onset might produce a different relationship with ENSO.

In some cases, an anomalously early start to the rainy season in Limpopo may not be associated with favourable rainfall conditions over the season as a whole. For example,
the neutral 1983/4 season started early but had a larger than average number of dry spells (Fig. 4.3, Table 4.2) and the DJF totals were below average. Such a result could prevail if early onset occurs through strong ridging from the south, a cut-off low or some other midlatitude feature rather than the greater tropical influence that is needed for a favourable rainy season as a whole. Indeed, during SON 1983 a large anticyclonic anomaly was present south and southeast of South Africa suggesting strong ridging from these ocean areas towards eastern South Africa. Weak cyclonic anomalies were present over the Limpopo region, favourable for rainfall. In DJF 1983/84, this anticyclonic anomaly persisted but extended over South Africa and Botswana thereby discouraging rainfall over the Limpopo region during the summer. The next section considers the regional circulation associated with early onset to see whether in general this may be associated with a greater influence of midlatitude than tropical circulation patterns.

4.5. Circulation anomalies associated with early onset

Fig. 4.6 has indicated that seasons with substantially early onset are 1979/80, 1983/84, 1987/88, 1989/90, 1994/95, 1997/98 and 1998/99. In this section, composite anomaly circulation plots have been constructed for the onset season of September-November. Fig. 4.7 suggests that early onset over Limpopo is associated with an anticyclonic (cyclonic) anomaly to the southeast of South Africa (in the southwest Atlantic). This figure also suggests a Rossby wave train that extends from the tropical central Pacific across the South East Pacific and midlatitude South Atlantic Oceans and into the South West Indian Ocean. This wave train is reminiscent of the Pacific South America (PSA) pattern associated with ENSO (Mo and Paegle, 2001; Colberg et al., 2004). Indeed the SST anomalies show El Niño characteristics in the tropical Pacific with the east-west zonal SST anomaly contrast across the tropical Indian Ocean that usually occurs during the austral spring of an El Niño event (Reason et al., 2000). The sensitivity of the composite to the very strong 1997/98 El Niño and the 1998/99 La Niña events was checked by re-calculating with these seasons removed. It was found that the same patterns were evident although the magnitude of the SST anomalies in the Pacific and Indian Oceans were reduced and the cyclonic circulation anomalies in the South West Atlantic were slightly weaker.
The 500 hPa height (Fig. 4.7) and MSLP (not shown) anomalies imply that early onset may be associated with a strengthening and southward shift of the South Atlantic and South Indian anticyclones and increased ridging southeast of South Africa. Using a self-organising map approach, Tadross et al. (2004) found a similar result for early onset seasons calculated for Zimbabwe. Relative convergence (divergence) (Fig. 4.8) is seen over the central interior, the eastern seaboard of South Africa and Limpopo (large areas of the South West Indian Ocean). This is consistent with increased ridging southeast of South Africa. The relative convergence over the central interior and eastern seaboard suggests favourable conditions for convective rainfall. Upstream of South Africa, Fig. 4.9 suggests that the subtropical jet is shifted slightly further south and strengthened, consistent with the southeastward shift of the anticyclone. An increased tendency for ridging may also enhance the chances of cut-off low activity over South Africa (van Heerden and Taljaard, 1998), and hence increases the possibility of significant early season rainfall.

The increased ridging south and southeast of South Africa implies increased easterly flow of moist marine air from the subtropical SW Indian Ocean towards eastern South Africa. Fig. 4.10 shows that easterly anomalies occurred over the ocean areas east of KwaZulu Natal. Further north over the Mozambique Channel, the mean easterlies (Cook et al., 2004) are weakened implying more (less) low level moisture flux convergence over eastern South Africa (central and northern Mozambique). Increased precipitable water is evident over Limpopo and most of subtropical southern Africa (not shown) with anomalous uplift present in the lower and middle troposphere (Fig. 4.11) over Limpopo and neighbouring regions. Together with the enhanced easterly flow of moist marine air over eastern South Africa near the surface, and relative convergence (Fig. 4.8) over Limpopo and neighbouring areas, these plots imply favourable conditions for convective rainfall over eastern South Africa, and Limpopo as observed (Fig. 4.12).

Plots of velocity potential anomaly can be used to assess changes in the vertical overturning in the atmosphere associated with the Walker circulation. Fig. 4.13 implies
an eastward shifted Walker circulation in the Pacific and enhanced uplift in the lower
atmosphere over subtropical southern Africa and the neighbouring South West Indian
Ocean. As a result, conditions for convection are further promoted over the Limpopo
region. In addition to these large scale circulation anomalies, Fig. 4.14 suggests that early
onset may also be associated with anomalous pre-season enhanced soil moisture over
eastern and northern South Africa. This enhanced soil moisture appears to arise from
anomalous winter rains over most of the country, but particularly over the eastern
seaboard (Fig. 4.15). This situation could improve agricultural yields provided it remains
reasonably wet throughout the season.

Another way of assessing the pre-season moisture availability is to calculate the
standardised precipitation index (McKee et al., 1993; Hayes et al., 1999). This index
measures the relative wetness or dryness over an area over various time scales on a range
from -3 to 3 to give an indication of the severity of flood or drought conditions. This
range represents the number of standard deviations that the observed value would deviate
from the long-term mean, assuming a normally distributed variable. Since rainfall is not
normally distributed, a transformation is first applied so that the resulting data is normally
distributed. In practice, values of below -2 or greater than 2 represent extremely dry and
wet conditions respectively which should occur about 2 % of the time while values
between -1 and -1.5 or between 1 and 1.5 represent moderately dry and wet conditions
that should occur about 10 % of the time. When calculated over a three month period
centred on August (i.e., for the season immediately prior to the early summer rainy
season), each of the anomalously early onset years shows anomalously wet conditions
over Limpopo and neighbouring regions to the south. The numerical values for August
ranged from 0.5 in 1979 and 1987 (slightly wet) to over 2 in 1983 and 1989 (extremely
wet). Thus, pre-season conditions indicate above average rainfall and moisture
availability over Limpopo, consistent with an anomalously early start to the summer
rainy season.
4.6. Impacts on maize yield

Section 4.3 has already noted some seasons where maize yields were well above or below average and connected these with rainfall conditions. It should be noted that there are a number of factors affecting maize yield besides rainfall. However, using data for 1970-1993, Cane et al. (1994) showed a strong relationship between SST anomalies in the Niño 3 region and Zimbabwean maize yield which was even stronger than that between Zimbabwean rainfall and Niño 3 SST. The inference in this study was that rainfall is affected by ENSO and that the maize yield was an integrated measure of the ENSO-rainfall impact over Zimbabwe. Given the close proximity of northern South Africa to Zimbabwe and similarities in climate, one might expect a similar relationship to exist for Limpopo. Fig. 4.5 shows that for the 1986/87 to 2003/04 period that data are available, only 3 out of the 5 El Niño seasons had reduced yields of maize in Limpopo whereas 4 out of the 5 La Niña seasons had above average yields. However, the 1998/99 La Niña had well below average yield and the strong 1997/98 and moderate 2002/03 El Niño seasons had above average yields. Inspection of the rainfall time series and totals for 1998/99 suggests that factors other than rainfall may explain the poor yields obtained in this season. Two possibilities are the lower than average near-surface air temperatures recorded during this season and the drier than average pre-season soil moisture suggested by the NCEP re-analyses for these fields. For example, it has been shown that during the vegetative growth phase of maize, the maximum response to temperatures occurs for the range 25-30°C (Stewart et al., 1998) with a marked decrease in growth for cooler temperatures. During summer 1998/99, the mean air temperature over Limpopo was 1-2°C below average suggesting that this factor may have contributed to the poor yield.

The correlation between the standardised maize anomalies and maize yield for the 1986/87-2003/04 period is -0.22 whereas for 1970-1993 period, Cane et al. (1994) obtained a correlation with Zimbabwe maize yields of -0.78. Although the two periods do not overlap for long, the much weaker correlation for Limpopo is surprising. If a correlation is performed between Limpopo maize yields and Niño 3.4 SST anomalies, then the value improves from -0.22 to -0.31. One significant difference between the two regions concerns the amount of irrigation. Cane et al. (1994) note that much of the
Zimbabwe maize crop from 1980 to 1993 was rain-fed rather than irrigated whereas over 80% of the maize areas in Limpopo are irrigated which will weaken any relationship with ENSO.

Another potential difference between Limpopo and Zimbabwe concerns the varieties of maize grown as some are more drought tolerant than others. In addition, Limpopo farmers may use different management strategies to those in Zimbabwe which may involve pesticide applications, timing of plantings, harvestings and any irrigation etc. It is beyond the scope of this thesis to determine the potential contribution of these various factors to the apparently weaker ENSO relationship on Limpopo maize yield than for Zimbabwe. However, it is noted that there are several factors besides rainfall timing and amount that are important and that the weaker ENSO relationship suggests that these factors are likely to be important for Limpopo. A good example concerns farm management as per the 2003/04 drought. As discussed further in the next chapter, the early summer (OND) was much drier than the late summer (JFM). Thus, maize yields were significantly higher for those farmers who planted late in the season as rainfall and temperature conditions were better in JFM 2004. Additionally, some farmers employed a second late planting to improve yields. Unfortunately, many emerging farmers cannot always afford to plant for the second time later in the season should conditions for the first planting be unfavourable.

4.7. NDVI

In this section, plots of NDVI anomaly for the recent El Niño seasons of 1991/2, 1997/8 and 2002/3 are examined. The focus in this section is to discuss the potential relationship between rainfall and vegetation activity in Limpopo. It was found that in 1991, the vegetation activity was near average in October and deteriorated slightly in November and worsened in December. In January 1992, the northern part remained very dry whereas the western part had patches of near average conditions. February 1992 experienced a mixture of lower than average and average vegetation conditions which deteriorated in March (Figure 4.4). Note that the 1991/2 season was the strongest drought
in terms of DJF totals after 1982/83 with well above (below) average frequencies in dry (wet) spells (Figure 4.2, Table 4.1). These wet spells were of shorter than average duration. These adverse conditions are suggested to be at least partly responsible for the much reduced maize yields for the province (Figure 4.5). In agricultural terms, lower vegetation activity means additional feed for livestock production or else livestock reduction.

In terms of the Southern Oscillation Index and Niño 3.4 SST, another very strong El Niño season is 1997/98. This season showed the largest number of dry spells over Limpopo, however as indicated earlier in the chapter, the impacts were less severe than might have been expected. In October 1997, NDVI plots show average vegetation activity which extended into November which also indicated some patches of above average vegetation activity. In December 1997, average vegetation conditions are mainly evident with below average activity in the northern part of the province. These conditions also prevailed in January 1998 while the situation improved in February 1998 and then deteriorated again in March.

By contrast, October to November 2002 experienced average vegetation activity with November having patches of below average vegetation activity in the southwestern and northern parts. In December 2002, the province experienced below average vegetation activity with average conditions in the western part of the province. Conditions improved slightly from January 2003 to March 2003 with reduced patches of below average vegetation activity. The NDVI images for this season suggest that this El Niño event did not affect agricultural production over Limpopo to the same extent as 1991/92 as also suggested by the maize yields in Figure 4.5.
4.8. Summary

To date, much research in rainfall variability has tended to use anomalies in seasonal totals as the base unit for study; likewise, seasonal forecasting efforts tend to revolve around trying to predict the probability that a particular season will experience above average, average, or below average rainfall totals. For many applications and user groups, more specific information such as the onset date of the rainy season, or the number of wet and dry spells within it are more useful. The synoptic to intraseasonal variability of wet / dry spells within a given rainy season has significant implications not only for agriculture but also for health and water resources beyond what can be determined simply by assessing seasonal or even monthly, rainfall anomalies.

In this chapter, evidence has been presented of a relationship between ENSO (as measured via the Niño 3.4 SST index) and the dry spell frequency within the core summer (DJF) period over the Limpopo region (22-25°S, 27-32°E) of southern Africa. A slightly less strong (and also inverse) relationship appears to exist with Niño 3.4 and the onset date of the rains. As a result, one might expect these two parameters to also be inversely related to each other. Fig. 4.16 suggests that this is true since from 1990 but that for the 80s, the relationship between onset date and dry spell frequency is more complex. Of the 11 (7) seasons with anomalously early (late) onset, 6 (4) also experienced above (below) average dry spell frequency although clearly the numbers improve after 1990. Thus, this result suggests that once the onset date has been determined some time in October-November, a 50 % chance of skillfully predicting whether the number of dry spells will be above or below average during DJF may exist. Although Niño 3.4 SST anomalies have some predictability, it seems that the dry spell / onset date relationship is of more useful for diagnosing why a season may have been anomalous rather than predicting ahead.

It should be emphasized however that the results are based on data extending back to 1979 and have used pentads (i.e. 5 day totals). Daily data for part of the Limpopo region do extend further back than 1979 but only go up to 1997 and hence, following Usman and Reason (2004), the decision was made to use CMAP rainfall. Note that the
consistency of CMAP and the higher resolution gridded data was checked to 1997 and found to be comparable. A potential limitation of using pentad data is that it is possible that a dry spell may fall between two pentads and, thus, not be counted when assessed using pentad amounts. As a result, the dry spell numbers derived herein should be regarded as a lower bound. However, since this study focusses on standardised anomalies from the mean in assessing potential ENSO relationships, the possibility of undercounting is unlikely to significantly modify the general result of higher (lower) frequency of DJF dry spells during strong El Niño (La Niña) events.

Analysis of onset variability suggested that seasons with anomalously early onset tend to be associated with an anticyclonic (cyclonic) circulation anomaly to the southeast of South Africa (in the southwest South Atlantic). It was suggested that these features may be part of the Pacific South America (PSA) pattern associated with ENSO. In addition, it was argued that they help promote increased ridging in the South West Indian Ocean and hence enhance the advection of moist low-level marine air over eastern South Africa from this ocean region. Previous work (Lindesay, 1988; Kiladis and Mo, 1988; Reason et al., 2000) has shown that increased ridging east of South Africa occurs during El Niño. Anomalies in vertical overturning in the atmosphere were also noted as being favourable for uplift and convection over the Limpopo region. Although not presented here, analysis of circulation anomalies associated with late onset seasons (1981/82, 1982/83, 1990/91, 1991/92, 1993/94, 1995/96, 1999/00) did not show a clear pattern, in contrast to the early onset seasons. Given that the late onset seasons include a mixture of an El Niño and La Niña seasons, this result is not surprising.

It was also found that early onset tended to be associated with anomalous pre-season soil moisture and rainfall over the region. This tendency, together with the observation that some early onset seasons show a relatively large number of DJF dry spells or below average seasonal totals, re-inforces the suggestion that an early onset to the rains does not mean a favourable season overall. Onset in this study has been defined purely in terms of the rainfall amount over the first few pentads that is needed for germination of the maize seed. This definition does not take into account the relative influence of tropical
circulation patterns that are needed for a season with good rains, or the type of weather systems producing the rainfall. Given that significant early season rainfall can result from midlatitude systems such as a cut-off low or unusually strong cold front, one needs to view the onset results with a certain amount of caution. Testing the sensitivity of these results to different definitions of onset, to regional Atlantic and Indian Ocean SST influences, and to local land surface influences (e.g., pre-season soil moisture content and vegetation state) is a high priority for future research.
Table 4.1. Rainy season characteristics during ENSO summers (DJF). P refers to pentads and D to days.

<table>
<thead>
<tr>
<th>Variable</th>
<th>1979-2002</th>
<th>El Niño summers (DJF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of dry spells (P&lt;5mm)</td>
<td>4.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Mean dry spell duration (D)</td>
<td>6.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Max dry spell duration (D)</td>
<td>9.8</td>
<td>4.1</td>
</tr>
<tr>
<td>No. of wet spells(P&gt;10mm)</td>
<td>9.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Mean wet spell duration (D)</td>
<td>14.7</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Table 4.2. Rainy season characteristics during neutral summers (DJF). P refers to pentads and D to days.

<table>
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<tr>
<th>Variable</th>
<th>1979-2002</th>
<th>La Niña summers (DJF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of wet spells (P&gt;10mm)</td>
<td>9.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Mean wet spell duration (D)</td>
<td>14.7</td>
<td>8.1</td>
</tr>
<tr>
<td>Max wet spell duration (D)</td>
<td>25.6</td>
<td>12.4</td>
</tr>
<tr>
<td>No. of dry spells (P&lt;5mm)</td>
<td>4.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Mean dry spell duration (D)</td>
<td>6.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 4.3. Rainy season characteristics during dry spell summers (DJF).

<table>
<thead>
<tr>
<th>Variable</th>
<th>1979-2002</th>
<th>High dry spell summers (DJF)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>STD</td>
</tr>
<tr>
<td>No. of dry spells (P&lt;5mm)</td>
<td>4.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Mean dry spell duration (D)</td>
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<tr>
<td>Max dry spell duration (D)</td>
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<td>4.1</td>
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<tr>
<td>No. of wet spells (P&gt;10mm)</td>
<td>9.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Mean wet spell duration (D)</td>
<td>14.7</td>
<td>8.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>1979-2002</th>
<th>Low dry spell summers (DJF)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>STD</td>
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<tr>
<td>No. of wet spells (P&gt;10mm)</td>
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<td>2.8</td>
</tr>
<tr>
<td>Mean wet spell duration (D)</td>
<td>14.7</td>
<td>8.1</td>
</tr>
<tr>
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<td>12.4</td>
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<tr>
<td>No. of dry spells (P&lt;5mm)</td>
<td>4.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Mean dry spell duration (D)</td>
<td>6.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>
**Fig 4.1.** Rainfall anomalies (mm/day) over the Limpopo region. The year on the axis refers to the January – February of the given summer.

**Fig. 4.2.** Standardised anomalies in DJF dry spell frequency (black) and Nino 3.4 SST (green). The year on the axis refers to the January – February of the given summer.
Fig. 4.3a Time series of Oct-Feb pentad rainfall (mm / day) for ENSO seasons
Neutral seasons

Fig. 4.3b Time series of pentad rainfall (mm/day) for Oct-Feb for neutral seasons
Fig. 4.4 Monthly NDVI images for October-March inclusive for a) 1991/92, b) 1997/98, c) 2002/03. Green indicates above average vegetation activity, yellow near average, and red below average activity.
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Fig. 4.12. Composite rainfall anomalies (mm / day) for onset season
Fig. 4.13 Composite lower (left) and upper (right) level velocity potential anomalies for onset season

Fig. 4.14. Composite soil moisture fraction for the pre-onset season
Fig. 4.15. Composite winter rainfall anomalies

Fig. 4.16. Time series of standardised anomalies in onset date (green) versus DJF dry spell frequency. The year on the axis refers to the January – February of the given summer.
5.1. Introduction

Circulation anomalies associated with summer droughts in Limpopo are of importance to understand as they affect agricultural production. With its large and poor rural population, many of whom are dependent on rain-fed agriculture, it is a region that is particularly vulnerable to extremes in weather and climate. In a study of droughts over northeastern South Africa, including Limpopo, Mulenga et al. (2003) suggested that those droughts that occur during non-El Niño years tend to be associated with significant midlatitude circulation anomalies south or southwest of South Africa that result in the advection of relatively cool and dry South Atlantic air over South Africa. In this chapter, the recent 2003/2004 non-El Niño drought over Limpopo is considered.

It should be noted that the 2003/2004 season was preceded by the 2002/2003 El Niño induced drought. Therefore, the focus in this chapter is to investigate the evolution of this 2002/2003 drought into that occurring during the non-El Niño 2003/2004 season, and the subsequent improvement of conditions in February / March 2004. The regional circulation anomalies associated with the evolution of this drought will be examined. Such information has the potential to aid seasonal forecasting efforts over South Africa.

The 2002/03 summer drought coincided with an El Niño event when one expects dry conditions over most of the summer rainfall region, particularly in the north and east (Lindesay, 1988; Reason et al., 2000; Mulenga et al., 2003). Conditions continued to be very dry in early summer (October-December) 2003 but these then improved slightly in
January 2004 (Fig. 5.1). In February, the northern half of the province remained dry whereas the southern half recorded average or above average rainfall. During March 2004, most of Limpopo received above average rains (particularly the north east) (Fig. 5.1).

5.2. Circulation anomalies associated with the summer 2002/03 drought and evolution towards the 2003/04 drought

Fig. 5.2a shows that high pressure anomalies are evident during JFM 2003 over Australia, most of the South Indian Ocean and southern Africa, as expected for the mature phase of an El Niño event (Lindersay, 1988; Kiladis and Mo, 1998; Reason et al., 2000). These high pressure anomalies act to suppress convective rainfall over Limpopo and neighbouring regions. On the hemispheric scale, a Rossby wave train is evident across the South Pacific and into the South Atlantic, the so-called Pacific South America (PSA) pattern (Kiladis and Mo, 1988), again as expected for El Niño (Mo and Paegle, 2001; Colberg et al., 2004). During AMJ 2003, the high pressure anomalies over South Africa strengthen, consistent with the ongoing dry conditions and, on the hemispheric scale, the PSA pattern starts to weaken with a transition towards a wavenumber 3 pattern in the southern midlatitudes. The latter is characterized by three high and three low pressure anomalies evident around the hemisphere (Fig. 5.2b).

By the following winter (JAS), a strong wavenumber 3 pattern is evident over the midlatitudes of the Southern Hemisphere with a large cyclonic anomaly situated over
South Africa and adjoining ocean areas to the south (Fig. 5.2c). When it occurs during the summer half of the year, this type of anomaly is a characteristic of dry conditions over the summer rainfall region of South Africa since it indicates increased advection of cool, dry South Atlantic air across the country (Mulenga et al., 2003). Thus, if OND 2003 anomalies were to show such a cyclonic anomaly feature, then the observed dry conditions (Fig. 5.1) would be entirely consistent with the hypothesis that non-El Niño droughts over the region are associated with large-scale midlatitude circulation anomalies rather than a tropical influence as occurs during El Niño droughts. This midlatitude influence is indeed the case for OND2003, and the following section discusses how these evolve from the dry early summer of OND 2003 to the improved rainfall conditions in JFM 2004.

5.3. Circulation anomalies associated with the OND 2003 drought

Fig. 5.3 shows 500 hPa geopotential height anomalies for each month of the OND 2003 period. For each month, a cyclonic anomaly is evident south or southwest of South Africa with a high pressure anomaly extending over the country from the South Indian Ocean. These anomaly patterns have some similarities to circulation anomalies documented during the severe non-El Niño summer droughts over northeastern South Africa (1951/52, 1967/68, 1981/82) by Mulenga et al. (2003) in which a combination of a low pressure anomaly to the south or southwest together with high pressure anomalies over the land lead to enhanced (reduced) advection of cool, dry (warm, moist) airmasses from the South East Atlantic (South West Indian) Oceans. In a sense, the patterns displayed in Fig. 5.3 correspond to a circulation pattern that is more typical of winter with little
opportunity for the development of easterly waves and lows over northern South Africa and neighbouring regions that are needed for good summer rains, either via organised tropical-extratropical cloudbands (Harrison, 1984) or less organised thunderstorm systems. Consistent with the suggestion of a more winter-like circulation pattern over the South African region in OND 2003, Fig. 5.4 indicates that the subtropical jet was displaced northwards and strengthened during OND 2003.

On the hemispheric scale, Fig. 5.3 shows a wave 3 or 4 anomaly pattern for each month but with the ridges and troughs arranged such that they discourage the frontal activity needed to the south east of South Africa for rain-producing cloudbands to form across the country. Compared to the JAS 2003 anomaly pattern, October and November 2003 suggest a slow westward planetary wave propagation of the main positive and negative height anomalies in the midlatitudes.

The enhanced (weakened) advection of low-level airmasses from the South East Atlantic (South West Indian) Oceans is confirmed in Fig. 5.5 which plots the zonal wind anomalies at the 850 hPa level, or just above the height of the interior plateau. With the exception of the KZN coast and nearby ocean, positive (or westerly) anomalies are seen throughout South Africa and these extend into the Mozambique Channel and ocean east of Madagascar. Based on analysis of the low-level moisture flux, Cook et al. (2004) showed that these ocean areas are the major source of moisture for South Africa during the OND season. Thus, Fig. 5.5 implies that there is a significant reduction in this mean flux during OND 2003. Furthermore, the SST anomalies in the southern Mozambique
Channel and northern Agulhas Current region near where this flux enters northern South Africa were cooler than average, as well as over much of the greater Agulhas Current region (Fig. 5.6). Cool SST anomalies imply less evaporation of moisture into the lower atmosphere and more stable conditions, thereby reducing the possibility of convective rainfall. Both observational and numerical modelling analyses suggest that cooler SST in the latter region is associated with below average summer rainfall (e.g., Walker, 1990; Mason, 1995; Reason, 1998; Reason and Mulenga, 1999) via changes in local evaporation and the advection of moist marine air towards South Africa.

The velocity potential can be used to assess the vertical overturning in the atmosphere and the existence or otherwise of a local Walker circulation in the southern African / western Indian Ocean region. Low level velocity potential anomalies for OND 2003 (Fig. 5.7) suggest that convection during this season was more likely to occur over the ocean south and southeast of Madagascar rather than over southern Africa, a situation supported to some extent by CMAP rainfall anomalies (not shown). This suggestion is further supported by Fig. 5.8 which indicates relative ascent in the lower atmosphere over these ocean areas and southeastern South Africa but relative subsidence over Limpopo and most of tropical southern Africa and hence unfavourable conditions for convective rainfall or thunderstorms there.

In addition to these regional circulation and SST anomalies, all of which are consistent with reduced rainfall, NCEP soil moisture (not shown) indicates below average moisture over Limpopo and adjacent regions during the preceding JAS season. These dry pre-
season conditions are supported by the NDVI map for October 2003 which indicates average to below average vegetation activity over the province (Fig. 5.9a).

5.4. Evolution from below average to near or above average rainfall over Limpopo in February/March 2004

Figs. 5.9b-f suggest that the vegetation over most of Limpopo continued to be impacted by the drought during November 2003 with the most severe impacts occurring in December 2003 and January 2004 followed by a partial recovery in February. By March 2004, most of the province showed above average vegetation activity. The NDVI images suggest that vegetation response more or less follows the rainfall recovery but with a lag of about a month. In addition, Figure 4.5 indicated that the maize yield over Limpopo was somewhat larger in the 2003/04 season compared to the previous 2002/2003 summer.

In terms of rainfall, December 2003/ January 2004 seems to be the transition period when the dry conditions start to recover and it is of interest to see how the circulation anomalies change during these months.

The most obvious circulation difference during these months is that the cyclonic feature south of South Africa disappears between December and January, and the high pressure anomaly over South Africa weakens (not shown). By March 2004, a NW – SE low pressure anomaly extends across southern Africa thereby promoting a link between frontal activity south and southeast of South Africa and convection over Namibia, and
hence tropical-extratropical cloudbands (Fig. 5.10). Relative ascent (Fig. 5.10) is evident in the middle levels of the atmosphere over a NW SE swath across subtropical southern Africa, consistent with increased cloud band activity. The low level zonal wind shows a weakening of the features evident in OND with increased easterlies over the eastern seaboard of South Africa and much of the South West Indian Ocean, a situation more favourable for rainfall (Fig. 5.1). Similarly, the enhanced westerlies over the Benguela region seen in Fig. 5.5 have largely been replaced by easterly anomalies indicating reduced advection of cool, dry Atlantic air over the country. The low level velocity potential anomaly (not shown) suggests a breaking down of the conditions that supported offshore convection during the previous OND season (Fig. 5.7) while the SST field (Fig. 5.12) has now evolved in JFM 2004 to mainly positive anomalies over the South West Indian Ocean and Agulhas Current regions. Then SST anomalies support increased rainfall in this season by increased evaporation of moisture into the lower atmosphere and increased instability (Walker, 1990; Mason, 1995; Reason and Mulenga, 1999).

In summary, regional circulation and SST anomalies evolved during mid-summer 2003/04 from unfavourable to more favourable for rainfall over northern and eastern South Africa. These anomalies then led to the transition from below average rainfall and vegetation activity (Fig. 5.1, 5.9) over Limpopo in the early summer to the reverse by February and March 2004.
5.5. Summary

Previous work has shown that almost all strong El Niño events lead to below average summer rainfall over Limpopo, with 1957/58 being the only exception since 1921 (Mulenga et al., 2003). Although this result suggests that the existing predictability of El Niño might offer considerable assistance towards seasonally forecasting Limpopo drought, the difficulty is that a number of severe droughts in the region also occur during non-El Niño summers. Prominent examples include 1951/52, 1967/68, 1981/82 and most recently, the drought investigated herein, 2003/04. Consistent with the earlier work of Mulenga et al. (2003), the results presented here show that the OND 2003 drought was associated with significant midlatitude circulation anomalies that led to an increase (decrease) in the advection of cool, dry (warm, moist) South East Atlantic (South West Indian) ocean airmasses over South Africa. These circulation anomalies broke down in January 2004 leading to an increase in the advection of South West Indian airmasses towards South Africa and relative uplift, thereby leading to significantly improved rainfall over the region in February and especially March 2004.

Although these non El Nino droughts have a common feature of enhancing (reducing the advection of cool, dry South East Atlantic (warm, moist South West Indian) Ocean air over South Africa, the midlatitude circulation anomalies that lead to this situation in the most severe droughts (1951/52, 1967/68, 1981/82, 2003/04) varies quite substantially. In 1951/52, a strong negative phase Southern Annular Mode (positive height anomalies over Antartica, negative over the midlatitudes) (Kidson, 1988) was present whereas in
1981/82, a positive phase Southern Annular Mode together with a strong wavenumber 3 structure was in existence. The 1967/68 case was different again with some hints of a negative phase Southern Annular Mode and a very strong and different wave number 3 pattern whereas OND 2003 shows little evidence of a Southern Annular Mode influence. These varied midlatitude circulation features suggest that non-El Niño droughts over Limpopo are more challenging to forecast than those associated with El Niño. In addition, the differences on large scale with between the 1951/52, 1967/68, 1981/82 and 2003/04 droughts indicate that these events need to be considered.
Fig. 5.1 Percentage of average rainfall recorded over South Africa for each month during the 2003/04 summer. Each map shows the same legend (i.e., light blue and browns are below average, medium and dark blue is above average).
Fig. 5.2 a) Geopotential height anomalies (contour interval 5 m) for JFM 2003

Fig. 5.2 b) Geopotential height anomalies (contour interval 5 m) for AMJ 2003

Fig. 5.2 c) Geopotential height anomalies (contour interval 5 m) for 2003
Fig. 5.3. Geopotential height anomalies (contour interval 5 m) for October, November, December 2003
Fig. 5.4. Zonal wind anomaly transect along 10°E upstream of South Africa for OND 2003. Contour interval is 0.5 m/s. Positive values indicate westerly flow anomalies.

Fig. 5.5. Zonal wind anomalies at the 850 hPa level for OND 2003. Contour interval is 0.25 m/s. Positive values indicate westerly flow anomalies.
Fig. 5.6 SST anomalies (contour interval 0.1°C) for OND 2003.

Fig. 5.7. Low-level velocity potential anomalies for OND 2003.
Fig. 5.8. Pressure tendency in the lower atmosphere for OND 2003. Positive values indicate relative subsidence.

Fig. 5.9. NDVI anomaly maps indicating anomalous vegetation activity for each month (Oct-Mar) during summer 2003/04 (red indicates below average vegetation activity, yellow near average, and green above average activity).
Fig. 5.10. Pressure tendency at the 500 hPa level for JFM 2004. Negative values indicate relative ascent.

Fig. 5.11. Zonal wind anomalies at the 850 hPa level for JFM 2004. Negative values indicate easterly anomalies. Contour interval is 0.25 m/s.
Fig. 5.12. SST anomalies (contour interval 0.1°C) for JFM 2004.
Chapter 6: Summary and Conclusions

This thesis has investigated the variability of characteristics of the summer rainy season over the Limpopo region that is important to the agricultural sector and to other user groups. These characteristics are the frequency of wet and dry spells during the core summer rainfall months of December, January and February and the onset date of the rainy season itself. Better understanding of these aspects will not only improve our knowledge of the rainfall variability of the region but is a necessary pre-requisite to assess their potential predictability. Based on rainfall totals and dry spell frequency, the most severe dry summers in the Limpopo region occurred during the 1982/3, 1991/2 and 1997/8 El Niño events and the neutral 2001/2 summer.

A robust relationship between anomalies in the frequency of summer dry spells over the Limpopo region and Niño 3.4 sea surface temperature (SST) anomalies was found for the 1979-2002 period focused on in this thesis. Niño 3.4 SST is often used as an index for ENSO and is predicted with reasonable accuracy months in advance. This relationship suggests that it may be possible to get some prior indication of dry spell behaviour ahead of the season at least for strong ENSO years. For neutral seasons, it was found that the anomalies in dry spell behaviour sometimes tracked the tendency in Niño 3.4 SST and sometimes not. Thus, it appears that more work is necessary before a reliable forecasting scheme of dry spell behaviour based on Niño 3.4 SST could be realized.
The importance of assessing wet and dry spell behaviour was evident from examination of the temporal distribution of rainfall over the Limpopo region for strong ENSO events. In several cases, the impact of ENSO on the characteristics of the dry and wet spells differed from what one might expect given the magnitude of the SST forcing, or the seasonal total rainfall received. It should be emphasized however that the results are based on data extending back to 1979 and have used pentads (i.e. 5 day totals). Daily data do extend further back than 1979 but only go up to 1997 and hence, following Usman and Reason (2004), the decision was made to use CMAP rainfall. Note that the consistency of CMAP and the higher resolution gridded data was checked to 1997 and found to be comparable. A potential limitation of using pentad data is that it is possible that a dry or wet spell may fall between two pentads and, thus, not be counted when assessed using pentad amounts. As a result, the dry and wet spell numbers derived in this thesis should be regarded as a lower bound. However, since this thesis has focused on standardised anomalies from the mean in our assessment of potential ENSO relationships, the possibility of undercounting is unlikely to significantly modify the general result of higher (lower) frequency of DIF dry spells during strong El Niño (La Niña) events.

Some attention was also paid to the potential linkages between ENSO and maize yield and vegetation activity. The correlation between Niño3.4 SST and maize yield over Limpopo is evident but is noticeably weaker than that found previously over Zimbabwe (Cane et al., 2004), just to the north. Although this result may seem surprising, it should be emphasized that the Zimbabwe yield is mainly rain-fed whereas the Limpopo data contain significant irrigated areas (around 80%). Irrigation will damp the impact of
ENSO-induced drought conditions. There are also other factors like different agricultural practices, seed drought tolerances etc that may vary between Limpopo and Zimbabwe and hence influence the results. In terms of NDVI, there appeared to be a roughly one month lag between the rainfall changes during the dry seasons investigated and the vegetation response.

Anomalies in onset date of the rainy season during 1979-2002 appear to be inversely related to Niño 3.4 SST, with the relationship strengthening after 1986. Analysis of the regional circulation suggested that seasons with anomalously early onset tend to be associated with an anticyclonic (cyclonic) circulation anomaly to the southeast of South Africa (in the southwest South Atlantic). It was suggested that these features may be part of the Pacific South America (PSA) pattern associated with ENSO. In addition, it was argued that they help promote increased ridging of the South Atlantic anticyclone into the South West Indian Ocean and hence enhance the advection of moist low-level marine air over eastern South Africa from this ocean region. Previous work (Lindesay, 1988; Kiladis and Mo, 1988; Reason et al., 2000) has shown that increased ridging of the South Atlantic anticyclone occurs during El Niño. Anomalies in vertical overturning in the atmosphere were also noted as being favourable for uplift and convection over the Limpopo region. Although not presented here, analysis of circulation anomalies associated with late onset seasons (1981/82, 1982/83, 1988/89, 1990/91, 1993/94, 1995/96, 1999/00) did not show a clear pattern, in contrast to the early onset seasons. Given that the late onset seasons include a mix of El Niño and La Niña seasons, this result is not surprising.
It was also found that early onset tended to be associated with anomalous pre-season soil moisture and rainfall over the region. This tendency, together with the observation that some early onset seasons show a relatively large number of DJF dry spells or below average seasonal totals, re-inforces the suggestion that an early onset to the rains does not mean a favourable season overall. Onset in this study has been defined purely in terms of the rainfall amount over the first few pentads that is needed for germination of the maize seed, maize being the staple crop of the region. This definition does not take into account the relative influence of tropical circulation patterns that are needed for a season with good rains, or the type of weather systems producing the rainfall. Given that significant early season rainfall can result from midlatitude systems such as a cut-off low or unusually strong cold front, one needs to view the onset results with caution. Testing the sensitivity of these results to different definitions of onset, to regional Atlantic and Indian Ocean SST influences, and to local land surface influences (e.g., pre-season soil moisture content and vegetation state) is a high priority for future research.

It should be noted that the dry spell and onset relationships with ENSO analysed in this thesis are based only on events back to 1979. It is therefore possible that this relationship may differ if daily rainfall data where available over the 1900-2002 period for example. However, the circulation relationships derived for the 1979-2002 period are entirely consistent with those derived for the 1878-1993 period by Reason et al. (2000) using historical sea level pressure data and hence it seems likely that these relationships could also hold for strong ENSO events prior to 1979.
Finally, the evolution of the 2002/03 El Niño induced drought into the 2003/04 non-El Niño drought was investigated. The first part of the 2003/04 season was anomalously dry but conditions improved by February and March 2004. It was suggested that the mechanisms associated with this drought involved the increased (decreased) advection of cool, dry (warm, moist) air from the South Atlantic (South West Indian) Ocean over South Africa. Although this general feature is the same for other severe non-El Niño droughts (1951/52, 1967/68, 1981/82) over the region investigated by Mulenga et al. (2003), the large-scale circulation anomaly in the Southern Hemisphere midlatitudes that brings it about differs in each case. As a result, identifying and predicting these non-El Niño droughts over Limpopo ahead of time is likely to be more challenging than for those associated with El Niño.

In summary, this thesis has attempted to provide details of the variability of important parameters that determine the effectiveness or otherwise of the rains over the Limpopo region for user groups such as agriculture. There are of course a number of limitations to the study as well as other factors that should be considered in future work. These include investigating the parameters for smaller sub-regions using daily station data, assessing the potential contributions of soil moisture and vegetation feedbacks and the interactions between climate variability and changes in agricultural practice.
Appendix: Early warnings issued to the agricultural sector

Early warning is defined as the issuing of accurate and timely information from an identified institution that is aimed at alerting the individuals at risk to avoid or minimize the impact of the disaster. Early warning is divided into three categories namely: forecasting and processing of the information, disseminating the information to the relevant individuals, and lastly, the application of the information by the individuals at risk. Farmers need early warning of possible variations in expected rainfall and other climate parameters as well as of severe events in order to adapt their agricultural practices to mitigate against the impacts of increased variability or other unfavourable conditions.

It is in that light that the Department of Agriculture established the National Agro-meteorological Committee (NAC) that is tasked with issuing agro-meteorological advisories to the agricultural sector (Annual Report for the Department of Agriculture, 2004). The NAC is formed by the Provincial Departments of Agriculture, the Agricultural Research Council, the South African Weather Service, CSIR and Universities.

For agricultural purposes, early warning can be any information pertaining to any risk that might hamper agricultural production e.g. weather conditions, pests and diseases, market prices etc. Agro-meteorological advisories include climate information, crop and livestock production information and strategies that could be followed given the current climatic state and its seasonal outlook. Irrespective of how regularly the department
issues the information to the farming community, the most important thing is whether the information is arrives in time and whether is useful or not. Hansen (2002) indicated that the broad distribution and operational use of forecasts beyond the life of a project should be supported by appropriate institutional dissemination channels, with safeguards to ensure quality, accessibility and timeliness of the information. Equitable access is a particular concern for remote regions in less developed counties (Stern and Easterling, 1999).

It is clear that a major factor affecting yields and production in developing countries is intraseasonal and inter-annual climate variability (Weiss et al., 2000). There is a need to assist subsistence farmers in supplying information in order to adapt the agricultural systems to increased climate variability. Important contributions to improve agricultural production and food security in developing countries can be achieved by more efficient agrometeorological services to farmers to stabilize their yields through management of agro climatic resources as well as other inputs (Gommes, 1997). By agro-meteorology, it is meant the science concerned with processes that occur from the soil layer near the ground in which crops grow and animals live to the upper levels of the atmosphere insofar as the circulation here affects climate variability that may then impact on agriculture. In addition, the field of aerobiology is of relevance since it is concerned with the effective transport of seeds, spores, pollen and insects (WMO, 1981). The primary aim of agricultural meteorology is to extend and fully utilize atmospheric knowledge and related processes to optimize agricultural production, thus increasing profitability and decreasing climatic risks. The proper application of this knowledge can lead to improved
animal and plant production as well as food security as a whole. A secondary aim of agricultural meteorology is to help conserve natural resources and protect the environment from detrimental usage. Sustainable human activity is strongly influenced by climatic conditions and variability because climate often places constraints upon particular form of land use at a given place and time. Therefore agricultural meteorology has an important role to play in land use planning and in increasing agricultural yield and food security.

Communicating agro-meteorological advisories

The NAC meets only four times per year i.e. February, May, September and December to check the farming status in the Provinces. The agrometeorological advisory is issued to the extension officers in the provinces on monthly basis irrespective of the NAC meetings by the Department of Agriculture. The extension officers are expected to interpret the information in a more summarized and relevant way to suit their particular provinces. For example, farmers in the Western Cape do not need the same information as those in Limpopo, and similarly, livestock farmers have different needs to those involved in crop production. A significant problem is that most extension officers have not yet received the training in the interpretation and understanding of climate information for agricultural applications, or even understand the causes of climate variability. Agrometeorological information must be disseminated in an optimum way based on the type of advice required and the needs of the end user (Weiss et al., 2000).
For the early warning team in the DoA to compile agro-meteorological advisories, the information on the current farming status needs to be received from each province. These agro-meteorological advisories should not only include the climatic information for the current season and the outlook for the next season but should also include plant and animal production advisories. The need to include all this information often causes delays in the date by which the information can be disseminated back to the extension officers. Significant delays are problematic as if the information is received too late by the user, it becomes useless.

Timely availability, and the appropriate use, of agro-meteorological information is vital to successful farming operations (Weiss et al., 2000). In order for this information to be considered useful, it must be shown to have value to the farmers as well as the people who are involved in the dissemination process. The advisories that are issued by NAC are standardized in a way that the very same document is issued to all the farmers irrespective of their field of interest and location. However, according to Weiss et al., (2000) the content of agro-meteorological information cannot be standardized because of the diverse nature of the user community. This situation arises because the early warning team at the DoA believes that the provincial officers will modify the document appropriately for regional applications. However, in so doing, the original meaning or intent of the advisory may end up being distorted or even lost. These problems emphasize the importance of appropriate training of the people issuing advisories because for this information to be useful it needs to in the right hands at the right time for dissemination purposes.
Experiences and problems

A problem experienced by farmers is that seasonal forecasts are not always reliable, a recent example concerns the 2003/2004 summer rainfall season. During the first half of the season the one-month lead forecast for the OND season indicated that over most of Limpopo there was a 40% probability of near average rainfall and a 35% chance of below average rainfall. With the exception of some central areas, most of the province experienced well below average rainfall in OND 2003 with some areas receiving less than 25% of average rainfall. For the second half of the season, a 40% chance of below average rainfall was forecast in December 2003 for the entire country except for the southwestern Cape and the far northeast whereas large areas of the country received average to above average rainfall during JFM 2004. These differences between forecast and observed rainfall caused tension between the extension officers and farmers as the information that was issued confused the farmers. The producers of the seasonal forecast at the South African Weather Service provide seasonal forecasts in a probabilistic format using three categories (probability of below average, near average, or above average rainfall totals occurring during a particular season). Although care must be taken in the appropriate interpretation of these probabilistic forecasts, problems may arise when forecasts are inaccurate, or perceived to be inaccurate by user groups, since farmers and other users will gradually lose trust in the forecast process. It should be noted that non-ENSO droughts such as 2003/04 may be more difficult to forecast than those associated with El Nino and that the accuracy of forecasts for many other summer seasons has been substantially better. As discussed in Chapter 6, other prominent non-ENSO droughts over northern South Africa include 1951/52, 1967/68 and 1981/82.
Given that the 2003/04 drought was more severe in the early than in the late summer, farmers who planted early were affected more than those who planted later in the season. This motivates the need for the forecasters to be able to forecast not only the seasonal rainfall anomaly but also other important parameters such as the onset and the cessation of rainfall as well as the frequencies of dry spells and wet spells during the season. These reinforce the need for proper training of extension officers and farmers in interpreting and understanding the climate information, its application to agriculture and the impacts of climate modes such as ENSO. In chapter 5, the circulation anomalies associated with the 2003/04 drought were examined to better understand the mechanisms potentially behind this non-ENSO drought.

**Training requirements of extension officers**

Extension officers need to be trained in the understanding and interpretation of climate information for agricultural applications and this knowledge needs to be effectively communicated to the farmers. A reality and a significant challenge to the process is that extension officers will always change jobs, whereas farmers will always need information in a changing environment subjected to substantial climate variability on a range of spatial and temporal scales. New developments by government to formalize the farmer to farmer mentorship program need to be assessed with this reality in mind. Trained farmers may be able to transfer their skills to the emerging commercial farmers. AS a result, the impacts of extreme weather and climate events may be be minimised or avoided all together which is a major objective of government. Appropriate transfer of
knowledge will not only be effective for risk and disaster management but may also lead to improvements in farming practice.

A further challenge to appropriate uptake of seasonal forecasts by farmers is that probabilistic forecasts are difficult to interpret especially for users without statistical knowledge or much understanding of climate and weather issues. If a forecast is issued as the probability of above, near or below average rainfall, then one essentially needs to know what the average rainfall is for a region and over what period it has been computed. The possibility of decadal to multidecadal variability in South African rainfall (e.g., Tyson et al., 1975; Reason and Rouault, 2002) is not completed accounted for in this process unless the averages are shown to be stationary over a sufficiently long period. In addition, forecasts need to be presented in simple and unambiguous language that the farmers can understand with jargon eliminated. In an ideal world, farmers would like forecasters to give accurate information about the onset, distribution and cessation of rainfall as well as the occurrence of wet and dry spells during the forthcoming rainy season. Such information would enable them to effectively plan ahead. However, at present, seasonal forecasts tend to be given as probabilistic expectations of above, near and below average rainfall totals for large regions. Although recent research suggests that there may be some predictability of dry spell frequency and onset date for certain southern African regions (Usman and Reason, 2004; Tadross et al., 2004; Reason et al., 2004), much more research needs to be done before progress is made towards implementing operational forecasts of these other quantities. The communication gap between farmers' desires or expectations of forecasts of specific quantities over particular
regions and what is possible for the forecasters to achieve with reasonable confidence given the constraints of data, resources and state of knowledge needs to be addressed.

Summary and conclusions

For an early warning system of disaster impacts (including droughts and flood impacts) to be implemented and effective in South Africa, all relevant stakeholders should participate in order to achieve this objective e.g. government, universities, research institutes, parastatals and farmers unions etc. The government has made an initiative in 2002 by establishing the NAC that will assist in establishing the early warning system. However, this needs a commitment from all the stakeholders to be successful.

The advisories that are issued on a monthly basis to the farmers will only be useful if they are sent to the right people at the right time. The advice will only be useful if it is received by the relevant person, for example, the farmer who is interested in livestock production should not receive any information that is more biased to crop production and vice versa. Inappropriate information will cause farmers and other user groups to lose interest in the forecast process as they may feel that the advisories issued by the extension officers are irrelevant.

The DoA has various directorates that are aimed at enhancing and supporting sustainable agriculture and rural development, and all are involved in the compiling of these advisories. For example, the plant and animal production specialists as well as the hydrologists and resource economists should be able to collectively interpret the forecasts.
and analyze their impacts on agricultural production. In addition, consultation with the producers of the forecasts should occur so that they are presented appropriately and in a format that is accessible and easy to understand.

Relevant training of agricultural officials and extension officers is crucial so that the application of the seasonal forecasts to agriculture and other applications is appropriate and optimal. As mentioned earlier, it will also be useful to extend this training to the farmers themselves since extensions officers are often transient and replaced from one year to the next. In addition, attention needs to be given towards improving the dissemination of agricultural advisories from the extension officers to the farmers’ organizations and subsequently to the emerging farmers.

Research into the predictability of parameters such as the onset, distribution and cessation of rainfall as well as the frequency of dry spells and wet spells during the rainy season is a pressing need. These parameters directly affect agricultural yields and any prior information about their variation during the season ahead will allow farmers to plan their operations effectively as well as to minimize the impact of adverse conditions.
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