RITSUMEIKAN ASIA PACIFIC UNIVERSITY (APU)

GRADUATE SCHOOL OF ASIA PACIFIC STUDIES

DISSERTATION ON

PRECIPITATION-VEGETATION DYNAMICS OVER ZIMBABWE AND THEIR RELATIONSHIP TO THE EL NIÑO SOUTHERN OSCILLATION

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The year is composed of seasonal activities. When the number of seasons is completed, the year is completed. The actual number of days is irrelevant. Therefore one year might have 350 days while another year has 390 days. The years may, and often do, differ in their length according to days, but not in their seasons and other regular events (Concept of year for an ancient African tribe as reported by Mbiti, 1969)

"I think the relationships of world weather are so complex that our only chance of understanding them is to calculate the facts empirically" (Sir Gilbert Walker as cited by Scot, 1904)

Abstract

The El Niño Southern Oscillation (ENSO) is the engine that drives weather extremes in various parts of the globe. Although the impacts of ENSO are global, most attention has been given to the regional impacts of the phenomenon which are often cause death, insecure livelihoods, and loss. Because of the strong teleconnection between Pacific Ocean sea surface temperatures (SSTs), large scale near surface pressure systems, and rainfall around the globe, scientists have been interested in modeling and predicting its regional impacts. Southern Africa is one of the regions whose climate experiences high variability related to the ENSO phenomena. A concerted effort to produce and disseminate consensus seasonal climate forecasts in Southern Africa, known as the Southern African Regional Climate Outlook Forum (SARCOF), to mitigate the negative consequences of ENSO especially in the agricultural sector. The assumption is that once a drought is forecast, agriculturalists can make anticipated adaptation and mitigation decisions. Unfortunately recent research indicates that climate forecasts are not realizing their potential value in Southern Africa. There has been a gap between the information provided by forecasters and that which is useful to smallholder farmers. The present forecasts are given at large spatial resolutions, and their provided in the language of probability terciles, which is very difficult for end users to interpret. There is a need for higher spatial and temporal resolution climatic information that is simple for agriculturalists to understand.

Remote sensing technology permits evaluation with high resolution, the inter-annual and intra-seasonal oscillations of rainfall and its predictability (Matariara and Jury, 1991; Makaudze, 2005). The advantage with remote sensing technology is that it provides repeated measurements at a particular spatial scale that allows dynamic environmental monitored with considerable

accuracy (Makaudze, 2005). Therefore this study investigates, using higher resolution datasets, climatic variability over Zimbabwe and its predictability using the El Niño Southern Oscillation. A preliminary study is also carried out to assess the state of climatic information at the local level because locally captured climatic information can be used to complement seasonal forecasts and scenario maps that can be given at the country level.

At the local level, this study has shown that though abundant climatic information is being captured locally, this information is not effectively accessible to local farmers. Local agricultural extension personnel are also limited in their ability to derive the benefits of the available data and they rely mainly on sensory perceptions. Precipitation analysis results showing inter-annual variability and correlations with the Southern Oscillation Index (SOI) highlight the potential of response farming in this region. A participatory approach is recommended involving university scientists practicing agro-meteorology, farmers, and agricultural extension. Training extension personnel in agro-meteorology is recommended. Locally captured climatic data has the potential to complement regional seasonal forecasts or country level scenario maps.

At the country level, the dominant modes of vegetation variability over Zimbabwe are investigated using principal components analysis (PCA) on NOAA-AVHRR NDVI monthly imagery from 1982 to 2006. Spectral analysis is also used to determine the periodicities of the component loadings. NDVI PCA-1 corresponds to the major vegetation types of Zimbabwe, and we demonstrated that grasslands and dry Savannah have the strongest relationship with mean annual precipitation. Furthermore the March-April loadings showed the highest correlation ($r = 0.73$) to mean annual precipitation. NDVI PCA-1 sheds some light on the land reform challenge in Zimbabwe. NDVI PCA-2 is highly correlated ($r = 0.87$) to the mean annual relative variability of rainfall map indicating a south-east/north mode of anomalies associated with the convectional rainfall bearing systems over Zimbabwe. NDVI PCA-2 is also highly correlated (r = 0.86) to precipitation PCA-2. NDVI PCA-3 shows a south-east/west mode and is highly correlated (r = 0.87) to precipitation PCA-3. A high correlation (r = 0.66) is also noted between NDVI PCA-4 and the elevation map. Spectral analysis of the PCA loadings revealed several periodicities corresponding to those found in tropical SSTs.

The spatio-temporal analysis of dry and wet years revealed new knowledge about the evolution of extreme precipitation seasons over Zimbabwe. Results show a significant ($p<0.01$) inverse relationship between early season and late season precipitation and NDVI for above normal wet seasons and major dry years (r = -0.49). The swing from normal to above normal wet seasons is shown to cause an alternating north-south mode of precipitation anomalies which is also resonated in vegetation. The greatest impacts of extreme precipitation seasons are noted from January to March, and lag 1-2 months later in vegetation. The length of rainfall seasons is shorter for dry years than for above normal wet years. Three distinct temporal patterns of dry years were also noted by considering maximum NDVI level, mid-post season NDVI condition, and nested dry spells. The intra-seasonal patterns observed in the study are shown to be occurring within a broader inter-annual pattern that is influenced by large scale climate forcing factors. The highest correlationship between Zimbabwe's NDVI and the four ENSO indices is obtained with the Southern Oscillation Index (SOI) at lag 6, though the earliest significant correlationship were at lag 4. Lag 4 correlations imply that as from approximately September-October, it may be possible to make forecasts about whether the forthcoming season will likely be dry or wet. These results are encouraging because it may therefore be possible to make forecasts for farmers in Zimbabwe usually start planting crops in October. The findings of this study can help to address the challenges of existing seasonal climate forecasts systems. Though this study was carried out using the case study of Zimbabwe, the methodology can be applied to other countries in Africa and the Asia Pacific that are often terrorized by the negative impacts of the El Niño Southern Oscillation.

Acknowledgements

I would like to express my deepest gratitude to my supervisor Professor Dr. K. Sanga-Ngoie, for helping me to achieve my research goals. I would have been unable to perform this study without his help and support.

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CHAPTER 1

INTRODUCTION

1.1 Background

Since the ground breaking and innovative work of Sir Gilbert Walker in the early 20th century, scientists have begun to think of environmental questions on a global scale, and have been fascinated by the prospect of modeling and forecasting links between the El Niño Southern Oscillation (ENSO) and precipitation patterns in various parts of the globe (Walker 1923; Tyson, 1975; Ropelewski and Halpert, 1987; Fagan, 1999). The El Niño Southern Oscillation is a coupled ocean-atmosphere system over the central-eastern Pacific Ocean that drives inter-annual climatic variability and severe climate extremes around the globe (Flohn and Fleera, 1975, Glantz, 1996; Cane 2000). El Niño is the term used to describe the warming phase and La Niña is the term used to describe the cold phase (Figure 1.1).

Although the impacts of ENSO are global, most attention has been given to the regional impacts of the phenomenon (Figure 1.2) (O'Brien and Vogel, 2003), which are often massive and disastrous. For example the catastrophic 1877/78 ENSO caused millions of farmers to starve in India, while in China grain prices rose sharply and tens of thousands of people migrated to Shanghai in search of food and many died from famine and attendant diseases. In more recent history El Niños have ravaged tropical forests in Borneo, and brought drought to Australia and Hawaii (Scot, 1904; Fagan, 1999). In the Philippines poor harvests due to El Niño raised prices of coconut oil, soaps and detergents while the French Polynesia suffered through unseasonal tropical cyclones destroying thousands of coconut palms. Hundreds of people died in savage floods that hit coastal Ecuador and northern Peru, and grain stocks came to dangerously low levels in Zimbabwe (Kinsey et al., 1998; Fagan, 1999). Civil disorder, food riots and looting have often accompanied El Niño events. In the present day of globalization, the repercussion of El Niño could affect the global economy and international business (Burke et al., 2009; Fagan, 2009).

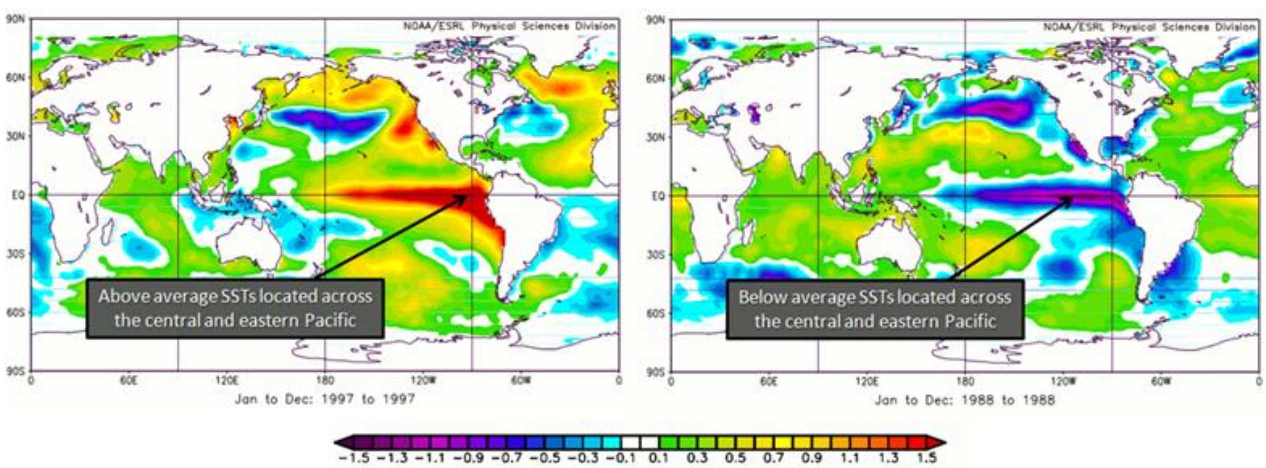


Figure 1.1. Departure of sea surface temperatures (SSTs) from the long-term average during (a) El Niño and (b) La Niña episodes. The El Niño Southern Oscillation is centered in the central eastern Pacific Ocean.
Source: The National Oceanic and Atmospheric Administration Climate Prediction Center (2005). Retrieved April 23, 2013, from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/elninosfc.shtml

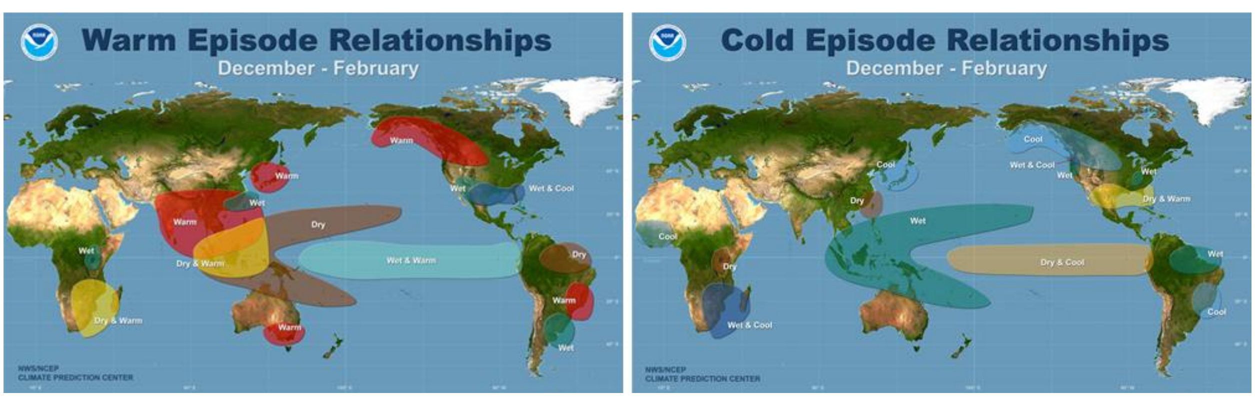


Figure 1.2. The impacts of ENSO on precipitation patterns around the globe. Although the impacts of ENSO are global, most attention has been given to the regional impacts of the phenomenon (O'Brien and Vogel, 2003), which are often disastrous.
Source: The National Oceanic and Atmospheric Administration Climate Prediction Center (2005). Retrieved April 23, 2013, from http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/elninosfc.shtml

As the world's population continues to grow, and as global warming is expected to shift the properties and dynamics of the Southern Oscillation (Phillips et al., 2006), the need to understand the ENSO phenomenon and its impacts has only become greater. Today an enormous army of scientists and an extraordinary array of scientific instrumentation monitor ENSO (Fagan, 1999). Because of the strong teleconnection between Pacific Ocean sea surface temperatures (SSTs), large scale near surface pressure systems, and rainfall around the globe, scientists have been able to develop statistical multivariate models for forecasting droughts and extreme rainfall seasons (Glantz, 1996; Mason and Jury, 1997; Ropelewski and Foland, 2000; Jury, 2002). This knowledge has the potential to guide cost-saving decisions in various economic sectors (O'Brian and Vogel, 2003).

1.2 The Socio-Economic Context for Climate Forecasts in Southern Africa

Southern Africa is one of the regions whose climate experiences high variability related to the ENSO phenomena (Ropelewski and Halpert, 1987; Lindesay, 1988; Glantz, 1996). Important interconnections between ENSO and rainfall in Southern Africa have been reported for Tanzania, Zambia, Mozambique, north-east South Africa and Zimbabwe. Agriculture is the mainstay of most countries in the region. It is estimated that more than one-half of gross domestic product (GDP) and three-quarters of all jobs in the region are attributable to rain-fed agriculture (Hulme 1996; Jury, 2002), see Table 1.1. The population of Southern Africa is growing at a rate of 3% per year. Measures of production such as GDP indicate that many countries of the region are poverty-stricken, with per capita annual incomes of less than US$ 1000 (World Economic Forum 2000; Jury, 2002).

Since the 1950s, major El Niño droughts in Southern Africa have occurred in 1965/66, 1972/73, 1982/83, 1986/87, 1991/92, 1994/95, 1997/98, 2002/03, and 2006/07 though occasionally there have been some dry summers unrelated to El Niño, for example in 1968 and 1970 (Goddard et al., 2001). Jury (2000) points out that droughts over the region often result in rainfall of about 40-50% below normal, temperatures of about 5°C above normal and evaporative losses of more than 10 mm/day, and the percentage of land that can support crop production shrinks by about 25%. Maize yields decline to below 1 t/ha while yields for crops such as sunflower and sugarcane show greater decline (Jury, 2002). Water deficits during the 1982/3 and 1991/92 El Niño events led to malnutrition on a large scale in the region (Glantz et al. 1997; Kinsey et al., 1998; Jury et al. 1999; Manatsa et al., 2010).

The consequences of major droughts affect both individual livelihoods and national economies. For commercial farmers the result is a cash flow crisis and bankruptcy, followed by a vicious circle of higher interest rates and shrinking profit margins, but even more serious is the impact of a failed crop on subsistence farming, which constitutes two-thirds of all jobs in Southern Africa (Hulme, 1996; Jury, 2002). Climate related shocks aggravate and accentuate other conditions and stress factors such as disease burdens (HIV/AIDS) and insecure livelihoods (Vogel and O'Brien, 2006). In Zimbabwe, trends in economic growth have been linked to rainfall variability, which can be attributed to sensitivity in the agricultural sector (Figure 1.3) (Phillips et al., 1998; Richardson, 2007).

Table 1.1. Contribution of agriculture to the economies and labor force of selected Southern African countries. Most of the agricultural production is not irrigated.

Country	Importance of agriculture to economy (%GDP)	Labor force in Agriculture (%)	Irrigated Land (%)
Angola	13	72	2.5
Congo (DRC)	59	63	0.2
Malawi	45	83	1.3
Mozambique	35	81	2.7
South Africa	5	10	10.2
Tanzania	56	80	4
Zimbabwe	28	63	3.6

Source: O'Brien and Vogel (2003)

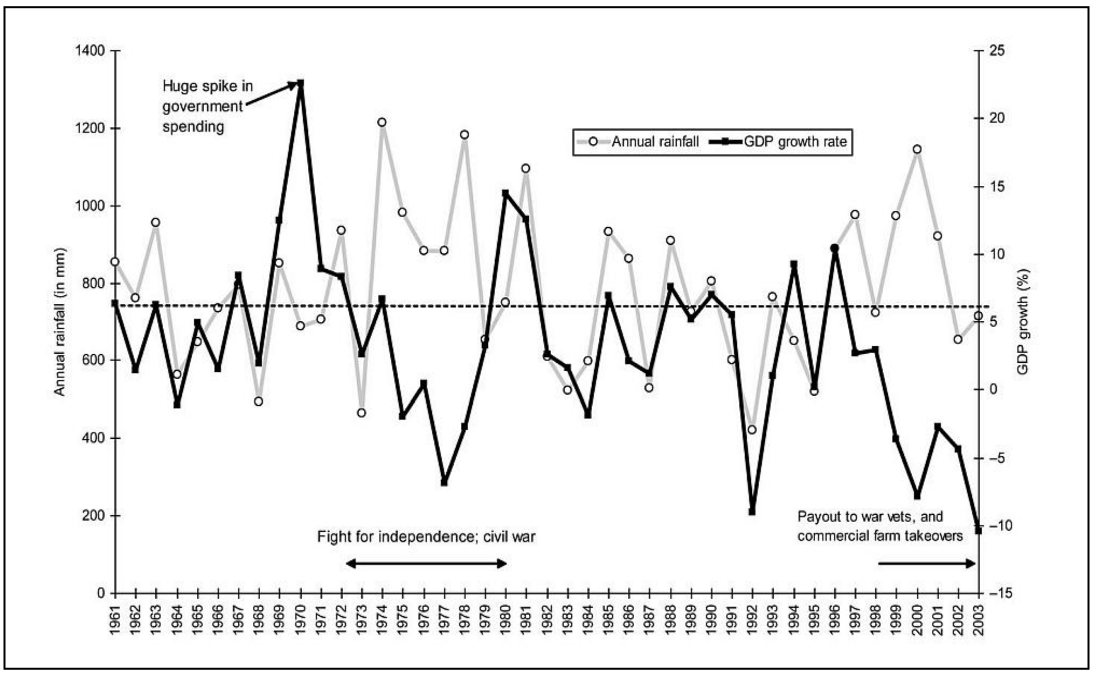


Figure 1.3. Remarkable correlation between GDP and rainfall is evident in Zimbabwe (Richardson, 2007). For example for the period 1980-1996 (r = 0.7). Climatic variability has a strong impact on individual farmers' livelihoods and national economies.
Source: Richardson (2007)

1.3 Framework for ENSO-based Climate Forecasts in Southern Africa

A concerted effort to produce and disseminate consensus seasonal climate forecasts in Southern Africa, known as the Southern African Regional Climate Outlook Forum (SARCOF), was initiated in 1997 in Kadoma, Zimbabwe (O'Brien, 1999). The seasonal climate forecast or climate outlook is produced for the region indicating possible rainfall conditions months prior to the agricultural season (Figure 1.5), thus influencing agricultural production decisions and enabling tactical or logistical decision for food distribution and aid programs (Patt and Gwata, 2002; Vogel and O'Brien, 2006). The forecast is derived from both statistical and structural models relating seasonal rainfall patterns to the El Niño Southern Oscillation (Goddard et al., 2001). Various user groups are represented at SARCOF meetings including international donor agencies, government ministries, farmer organizations, and researchers.

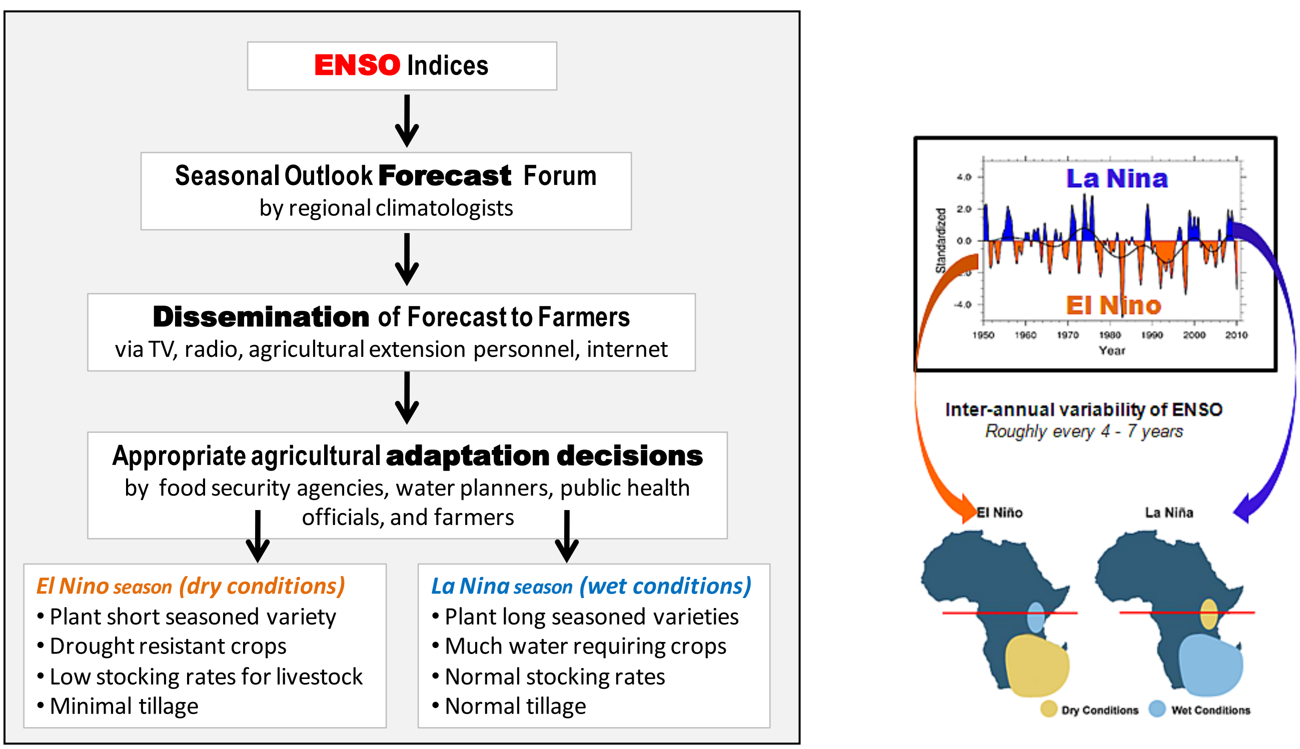


Figure 1.4. Framework for ENSO based Seasonal Forecasts in Southern Africa. Although climatic variability is just one of many factors influencing end-user decision making, seasonal climate forecasts present a potential tool that could assist agriculturalists in better managing risks.
Source: O'Brien and Vogel (2003)

The assumption is that once a drought is forecast, the various user groups can make anticipated adaptation and mitigation decisions. Some agricultural adaptation options have been suggested in the literature and they encompass a wide range of scales (local, regional, global), actors (farmers, firms, government), and types (Mendelsohn and Dinar, 2001; Smit and Skinner, 2002; Gbetibouo, 2007). Dinar et al. (2009) in their extensive World Banks supported study covering 11 African countries including Zimbabwe have reported about farmers' perceptions to climate change adaptation. They showed that in all the studied countries, excluding Cameroon and South Africa, the planting of different varieties of the same crop was considered to be one of the most important adaptation measures. Other key adaptations noted were different planting days, adopting a shorter growing season, using irrigation, and soil conservation techniques. The strategies vary among different end users and the ability to cope and adapt is often constrained by factors such as the ability to gain access to resources that would assist them in their agricultural activities (O'Brien and Vogel, 2003). Moreover there is a widespread perception that seasonal climate forecasts can help societal adaptation to climatic variation (O'Brien et al., 2000).

1.4 Problems and Limitations of Current Climate Forecasts Systems in Southern Africa

Emerging research however indicates that climate forecasts are not realizing their potential value in the Southern Africa (Patt and Gwata, 2002; Vogel and O'Brien, 2006; Ziervogel and Zermoglio, 2009). Despite significant advances in climate research and climate forecasting world-wide, the majority of Southern African countries continue to suffer from the adverse impacts of climate variability (Tarhule, 2010). The World Climate Research Program's White Paper on Seasonal Prediction (Kirtman and Pirani, 2008) shows that Southern Africa is one of the regions in the world where uptake of seasonal climate forecasts by farmers has not been positive (Ziervogel and Zermoglio, 2009). Several factors have been reported as contributing to the low uptake of seasonal forecast:

1.4.1 Uncertainty Factors

The Spatial Scale:

A major problem cited about climate forecasts and local-level agricultural adaptation in Southern Africa is the scale constraint (Tadross et al., 2005). This problem arises because seasonal forecasts are provided at low spatial resolutions over very large areas, with one grid covering thousands of square kilometers (Blench, 2002, Bohn, 2003; Patt, 2007). Yet rainfall in semi-arid Africa can vary substantially over a distance of only a few kilometers. The highest probability for a particular grid will actually occur in some parts of the respective grid. Though Southern Africa's precipitation is influenced by ENSO, other regional and meso-scale factors modify the impacts of ENSO over a single country (Tadross et al., 2005; Mazvimavi, 2008). The present course forecasts may therefore be of negative value to farm enterprises located in patches characterized by variant rainfall patterns (Blench, 2003).

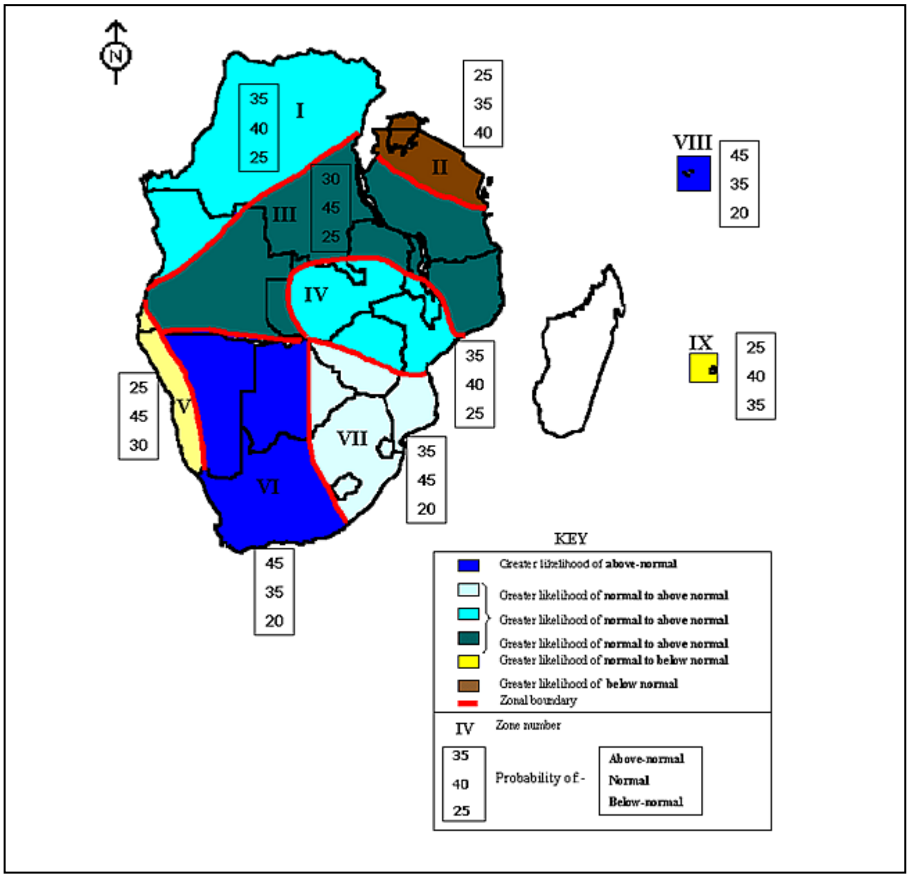


Figure 1.5. ENSO based seasonal rainfall forecast for Southern Africa in the 2006/07 season provided by the Southern African Regional Climate Outlook Forum (SARCOF). These forecasts have low spatial resolution and are characterized by sharp boundaries between different forecast regions. The forecast lacks the precision necessary for guiding local-level response decisions (Patt, 2007).
Source: Southern African Regional Climate Outlook Forum (2006)

Moreover the forecasts are characterized by sharp boundaries between different forecast regions, making it difficult for end users to know which one is applicable to their part of the country (Figure 1.6). Though the SARCOF forum emphasizes that the boundaries between the forecast regions should be considered as transition zones rather than absolute boundaries, regional averaging of precipitation parameters lacks the precision necessary for guiding local-level response decisions of smallholder farmers who are already operating at critical thresholds due to multiple constrains (Blench, 2003).

Temporal Scale:

Another problem is that seasonal forecasts are limited to probabilistic information about total seasonal rainfall. They do not provide information about key characteristics of interest to subsistence farmers, such as the temporal distribution and intensity of the rainfall season (Blench, 2003; Ziervogel and Zermoglio, 2009). Although crops cannot grow without a certain absolute amount of rainfall, the temporal distribution of that rainfall within the season is critical; any crops that experience too long of a gap between rains may die, regardless of the total seasonal precipitation (Scot, 1904). Similarly, rains above certain intensity may cause flooding or otherwise damage crops causing stunting or types of mildew. From farmers' perspective, it is important to consider intra-seasonal rainfall parameters that affect crop growth cycles such as onset of the rainy season, temporal distribution, frequency of dry spells, and length and cessation of the rainy season (Glantz, 2000; Reason, Hachigonta and Phaladi, 2005; Tadross et al., 2005). Hence there is a gap between the information provided by forecasters and that which is useful to smallholder farmers.

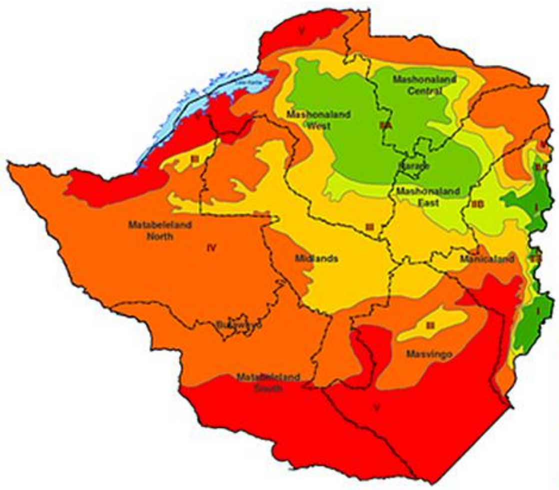
Probabilistic Language:

SARCOF seasonal climate forecasts are expressed using language and jargon that the meteorology community can easily understand, but which other users have a difficult time deciphering. (Cash et al., 2003; O'Brien et al. 2000). The SARCOF forecast, as shown in Figure 1.6, is presented using the tercile method which consists of probability distributions indicating the likelihood of below-normal, normal, or above-normal rainfall for different sub-regions based on the likelihood that each occurs 10 times in a specified 30 year period. For example a specified region a forecast would say: a 35% probability that the total seasonal rainfall will be in the above normal tercile, a 40% probability for the near normal rainfall tercile and a 25% probability for the below normal tercile. The implications of an increase in the probability of below normal rainfall (e.g. from 33% to 45%) are not easy to understand in the absence of explanations or education. Such information could be better interpreted if it were translated into possible rainfall levels. Even then the implications would differ according to whether a farmer normally plants maize or root crops, beans or cabbage (Blench, 2003).

Probabilistic forecasts can result in confusion as what happened in the 1997/98 El Niño forecast as outlined by Glantz (2000) and Dilley (2003). Whilst the failure of widespread severe drought to materialize contrasted with public expectations, the more moderate, probabilistic predictions of the consensus outlook guidance issued prior to and midway through the 1997/98 season exhibited skill levels well above what would be expected by chance (Ward et al., 1998). Yet the drought fears brought by the probabilistic forecast had caused farmers in Zimbabwe to reduce the area planted.

Lack of Climate Scenario Reference Maps

End users need agro-climatic reference information to be able to interpret and use seasonal forecasts that give rather general probabilistic information (Parry et al., 1988). Without such information, farmers have to rely on their memories of past climatic experiences, including narratives and sensory responses, in order to make agricultural decisions. Examples of agro-climatic reference information include derivatives of historical data such as mean precipitation maps/graphs, agro-ecological maps, and drought incidence maps/graphs. An advantage of agro-ecological maps is that they provide information about the cumulative impact of precipitation, temperature and soil factors on vegetation/crop production. Such reference information ought to be available and accessible to the farmers and other end users. Unfortunately in most African countries the available reference maps are of very poor quality. For example the Ministry of Agriculture of Zimbabwe is still using an agro-ecological map that was made in 1961 (Figure 1.7). This map being was created using historical records from the early half of the 20th century and it has not been updated since then. Moreover its spatial resolution is very coarse.



Agro-ecological region	Rainfall (mm)	Farming Systems
I	> 1000	Specialized and diversified farming
IIA*	750 - 1000	Instensive farming
IIB	750 - 800	Intensive farming
III	650 - 800	Semi-intensive farming
IV	450 - 650	Semi-extensive farming
V	< 450	Extensive farming

Figure 1.6. The agro-ecological map for Zimbabwe was created in 1961 (Vincent et al., 1961) using data from the early 20th century and it is still the main reference map offered by the Ministry of Agriculture to agriculturalists in the country.
Source: UNOCHA 2009

The relative influence of other climate forcing factors

Indeed ENSO has been shown to be the most important determinant of year-to-year climatic variability over Southern Africa. However there have been some years when droughts have occurred without co-occurrence of an El-Niño. The roles of the Indian and Atlantic Oceans are an additional consideration. Manasta and Mukwada (2009) have reported the relative influence of the Indian Ocean Dipole Zonal Mode (IODZM) on climatic variability over the region. Other circulation types that play an important role in producing rainfall in Southern Africa include tropical disturbances in the easterlies, temperate disturbance in westerlies, cloud bands that link tropical and westerlies disturbances. Moreover there is still limited understanding about how the annual cycle of the Inter-Tropical Convergence Zone (ITCZ) is influenced by ENSO.

1.4.2. Information Dissemination:

Patt and Gwata (2002) examined credibility, legitimacy and institutional constraints that limit forecast use, suggesting the importance of participatory forecast development and iterated trust building communication between forecasters and users (Patt and Gwata 2002). There is also a lack of serious discussion and debate regarding the type of institutional and organizational design that may be needed to foster better dialogue on climate risk and climate information between these various stakeholders and groups (Vogel, 2000; Ziervogel and Zermoglio, 2009). Access to climate information is also determined by the internal dynamics and 'politics' within organizations such as government ministries or even households. Furthermore for applied agro-meteorology to be effective extension intermediaries with sufficient basic knowledge for training the farmers are necessary (Stigter, 2008).

1.5 Research Questions

Improved rainfall forecasting relies on a better understanding of climatic variability using high resolution data. Assessments of intra-seasonal rainfall characteristics, using both locally captured data and remotely sensed data, are needed to determine what parts of the rainfalls season might have some predictability. Possible relationships between large-scale climate modes and dry and wet characteristics need to be investigated (Hachingota and Reason, 2006). To address these gaps of knowledge, the following scientific research questions are pursued:

At the local level:

- What is the present state of climatic information at the local level?
- How can locally captured climatic information be used to consolidate the interpretation of regional seasonal climate outlook forecasts?

Country level:

- How can high resolution satellite vegetation data be used to improve the understanding of the dominant modes of climatic variability over Zimbabwe?
- What physical processes could be driving the observed dominant modes of precipitation and vegetation variability?
- Which parts of the growing season are vulnerable to droughts and dry spells?
- What kinds of drought scenario maps/plots can be produced using the NDVI?
- Which parts of the rainfall season are predictable?
- How are the observed modes of vegetation variability related to the El Niño Southern Oscillation (ENSO)?
- Which ENSO index is most suitable for predicting vegetation variability over Zimbabwe?
- What are the implications of this knowledge for science and for agricultural adaptation policies?

1.6 Scope of Study

An investigation of precipitation and vegetation dynamics over Zimbabwe and their relationships to ENSO will be carried out as a part of the study. The study will focus on Zimbabwe in Southern Africa. By taking such a country level approach we examine in detail the modes of vegetation variability that have not been given much attention in past continental level or regional scale studies (Eastman and Fulk, 1993; Nonomura et al., 2003). However due to the limited time and resources, the data used in this study is limited to precipitation, remotely sensed vegetation cover imagery, and global sea surface temperatures. Other forms of atmospheric data such as out-going long wave radiation and air pressure data are not used.

1.7 Overview of Chapters

Chapter 2 reviews literature on circulation patterns over Southern Africa and their relationship to the El Niño Southern Oscillation (ENSO). The limitations of solely relying on ground based precipitation observational data in Africa are discussed, and the benefits of using remotely sensed vegetation data are considered. The objectives of this study are also spelled out. Chapter 3 describes the study area and outlines the methodology of this study. The results of this study are presented as from chapter 4. Chapter 4 assesses the state of climatic information at the local level in Africa, using the case study from Makonde district. An extensive discussion on the use of historical climatic information for enhancing agro-meteorology is also given. Chapter 5 investigates the dominant spatial and temporal modes of precipitation and vegetation variability over Zimbabwe and investigates some of the physical processes that could be driving them. The first four principal components of Zimbabwe's vegetation are shown for the first time. Chapter 6 presents for the first time, a detailed analysis of the evolution of all major dry years and above normal wet years over Zimbabwe between 1981 and 2006. A surprising inverse pattern between dry and wet years is revealed which could be a new methodology for climate forecasting in the region. The elusive mid-season dry phenomenon, which farmers often complain about, is captured using monthly NDVI time series. The NDVI long term series is also shown to be correlated to the El Niño Southern Oscillation (ENSO). Finally the skill of 4 ENSO indices is put to the test, and the Southern Oscillation Index (SOI) of Sir Gilbert Walker stands as the best predictor. In Chapter 7 the thesis concludes by outlining the major findings of the study and considering the future use of this methodology for investigating climatic variability in other African and Asian countries that are affected as such by the occasional warming of waters in the Pacific Ocean.

CHAPTER 2

CLIMATIC VARIABILITY OVER SOUTHERN AFRICAN - A REVIEW OF THE UNDERLYING PROCESSES

Though it is well recognized ENSO is a major phenomenon modulating Southern Africa's climate (O'Brien and Vogel, 2003), it should be stated from the onset that climatic variability of the region is a complex phenomenon with several cycles that interact, and wax and wane in their importance on a range of temporal scales (Landman and Mason, 1999; Nicholson, 2000; Reason and Rouault, 2002). These oscillations have been observed in precipitation data (Figure 2.1) and also in tree rings (Figure 2.2). Understanding the predictability of climate in the region entails understanding their relative influence and determining which ones are the dominant factors. Hence this Chapter reviews the circulation patterns over Southern Africa and their relationships to the El Niño Southern Oscillation. The challenges of relying solely on ground based precipitation data in Africa are discussed and the benefits of using remotely sensed data are highlighted. The normalized difference vegetation index (NDVI) is introduced as a useful proxy for investigating precipitation patterns. The objectives of this study are spelled out at the end of the chapter.

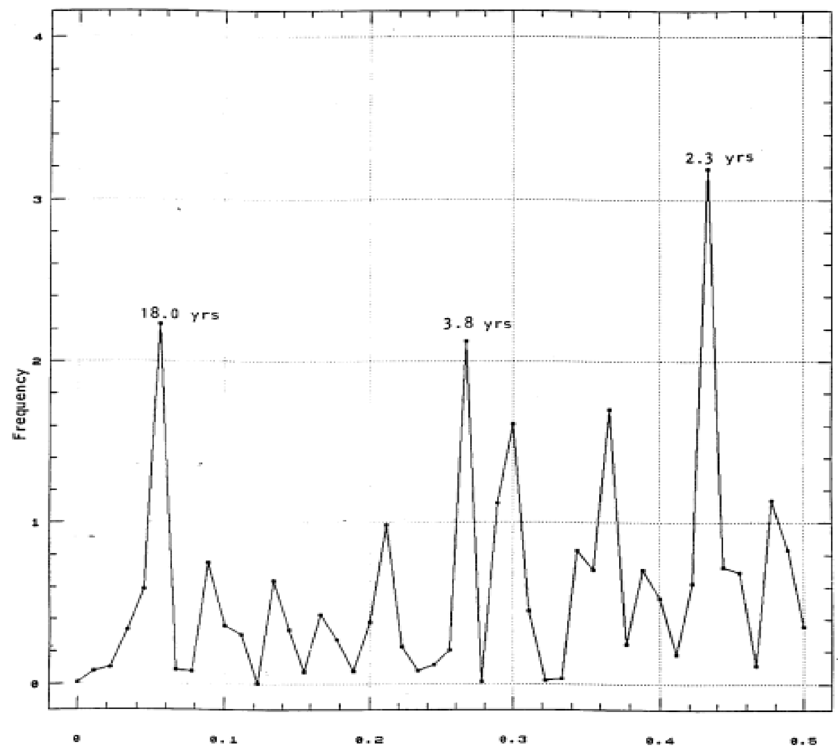


Figure 2.1. Spectral analysis of summer rainfall based on Zimbabwe's 91-year precipitation record showing significant spectral peaks in years.
Source: Makarau and Jury (1997)

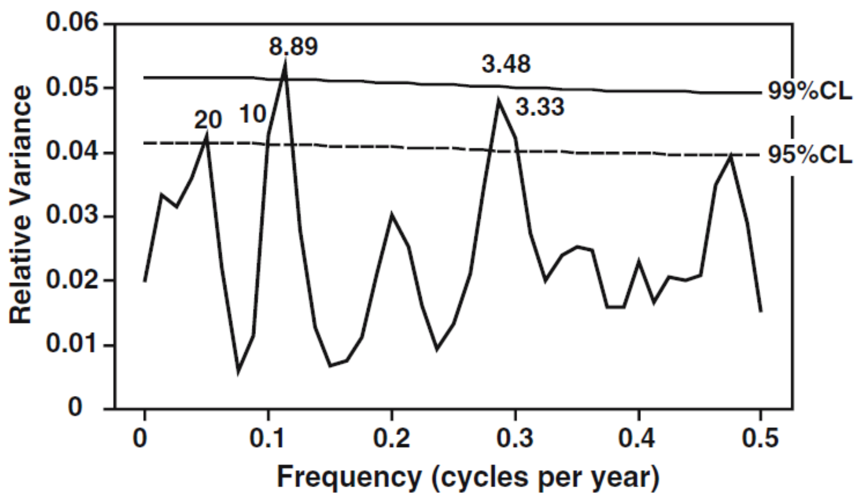


Figure 2.2. Spectral analysis of the tree ring reconstructions of Zimbabwe's rainfall indicates that significant spectral power is concentrated at periods of 20, 8–10 and 3.4 years. The 3.4-year peak may reflect the influence of ENSO.
Source: Therrell et al. (2007)

2.1 Oscillatory Variations of Rainfall in Southern Africa

2.1.1 The Annual Cycle

The annual cycle of Africa's precipitation is the most apparent cycle, forced by solar insolation and corresponding surface fluxes that vary from summer to winter (Jury and Mpeta, 2006). The continent of Africa extends across the equator and its convection is a significant source of atmospheric heat. Energy released over equatorial Africa is exported through tropical/extra-tropical interactions, causing feedback with the global circulation and regional monsoons winds (Jury and Mpeta, 2006). Trade winds from the northern and southern hemispheres meet in the equatorial trough of low pressure linked with the Inter-Tropical Convergence Zone (ITCZ). Annual shifts following the region of maximum solar insolation result in shifts in equatorial trough north and south of the equator as shown in Figure 2.3. From October-January the ITCZ is located south of the equator and in March to June as the sun shifts northward, the ITCZ position lies north of the equator. Heavy rainfall and thunderstorms are associated with the ITCZ (Parry et al., 1988) and vegetation greening respective follows the ITCZ migration (Nicholson and Nyenzi, 1990; Jarlan et al., 2008).

Jury and Mpeta (2005) reported that the amplitude of annual cycle of African rainfall varies coherently at spells lasting 3 to 8 years. Nicholson (2000) also pointed out that in the marginal areas such as parts of Southern Africa, Western Sahara and the Horn of Africa, the patterns of seasonality are even more complicated. This notion is corroborated by Mason and Jury (1997) and D'Abreton and Tyson (1995) who reported that the African ITCZ has a tendency to be strongly developed further away from the equator during La Niña years (10N and 10S) whilst during El Niño events Africa's convection is more equatorial in nature (Figure 2.4). Unganai and Mason (2001) and Love et al. (2010) also suggest that at times the ITCZ advances no further than 12°S and little rainfall is received over Zimbabwe and southern Mozambique, however in other years the convergence system gets further south and above normal rainfall and vegetation cover, and even floods can be expected in the Limpopo Valley.

Understanding the intensity and timing of the annual cycle is crucial for improving the strategic management of climate-impacted resources over the African continent (Reason et al., 200). The location of Zimbabwe, at the southern limits of the ITCZ, provides a vantage point for examining how the annual cycle of Africa's ITCZ varies and how this could be related to the ENSO.

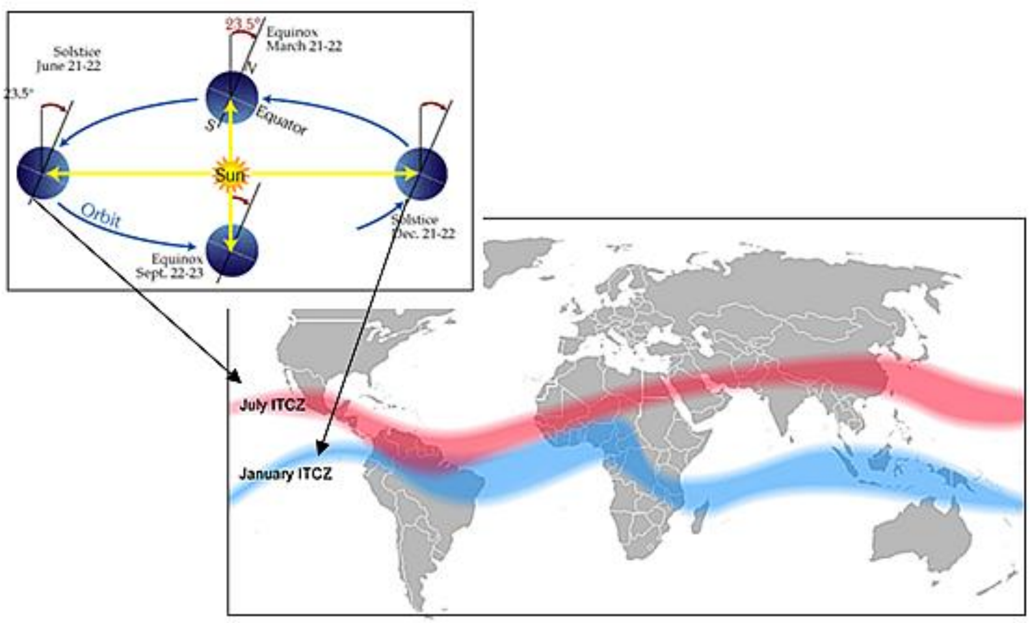


Figure 2.3. Trade winds from the northern and southern hemispheres meet in the equatorial trough zone and this region is known as the Inter-Tropical Convergence Zone (ITCZ). Heavy rainfall and thunderstorms are associated with the ITCZ.
Source: Wikipedia (2013) Retrieved June 12, 2013, from
http://en.wikipedia.org/wiki/Intertropical_Convergence_Zone

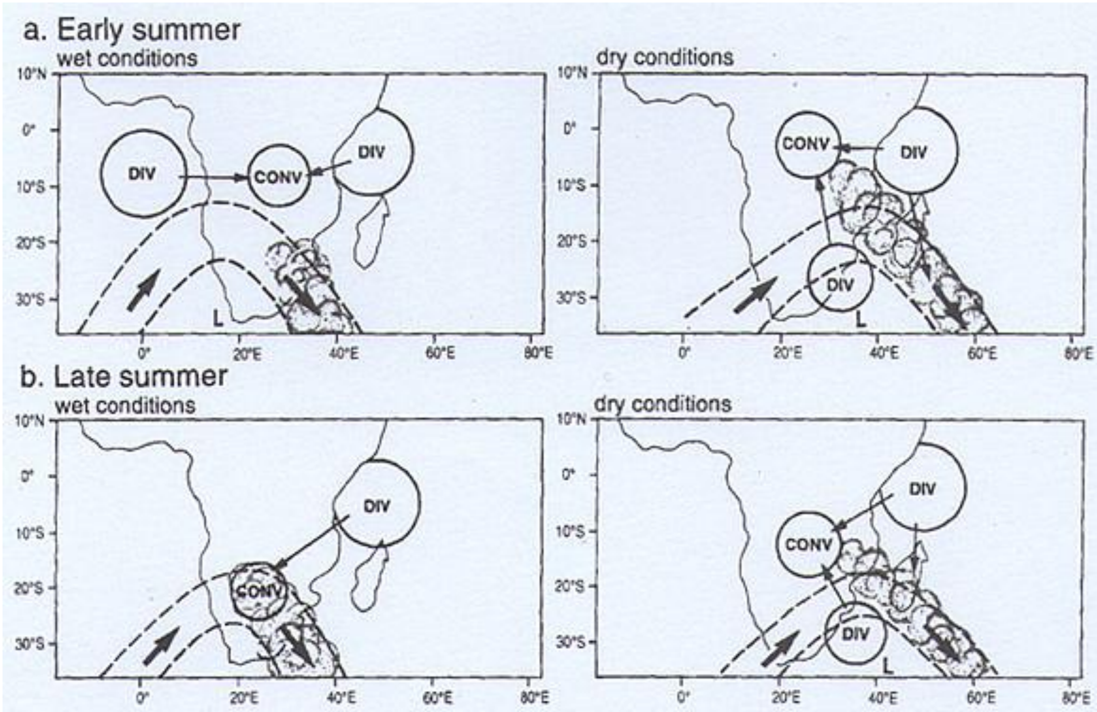


Figure 2.4. Models of the convergence and divergence fields over Southern Africa during wet and dry early and late summers.
Source: D'Abreton and Tyson (1995)

2.1.2 Inter-Annual Variability

The El Niño Southern Oscillation

A number of studies confirm that on interannual time scales, climatic variability over the Southern Africa is dominated by the El Niño Southern Oscillation phenomenon (Nicholson and Entekambi, 1987; Tyson, 1986; Lindesay, 1987; Makarau and Jury, 1998; Nicholson, 2002). ENSO events usually occur periodically, every two to eight years (Tyson, 1986) with a spectral peak at four years. The El Niño Southern Oscillation's teleconnection with rainfall in Southern Africa arises from changes in the regional atmospheric circulation, primarily via the Walker Circulation, and the South Indian Convergence Zone (Reason et al., 2006). The Walker Circulation comprises east–west atmospheric circulation cells along the equatorial belt. The Walker Circulation regulates global exchange of momentum, heat, and water vapor within the tropics via massive overturning motions. It therefore influences the monsoon winds. During the years of El Nino, the Walker Circulation is altered due to the changes in the Pacific Ocean (Figure 2.5). Hence during El Niño years, the precipitation signal is predominantly below normal precipitation, though for some regions of Southern Africa normal precipitation may be realized (Mason and Goddard, 2001). During La Niña years, some seasonality exists in the precipitation signal with more regions experiencing above-normal precipitation (Mason and Goddard, 2001). Since the 1950s major El Niño droughts have occurred in 1965/66, 1972/73, 1982/83, 1986/87, 1991/92, 1994/95, 1997/98, 2002/03, and 2006/07 (Manatsa et al., 2010). However some dry summers unrelated to El Niño have occurred in 1968 and 1970 (Goddard et al., 2001).

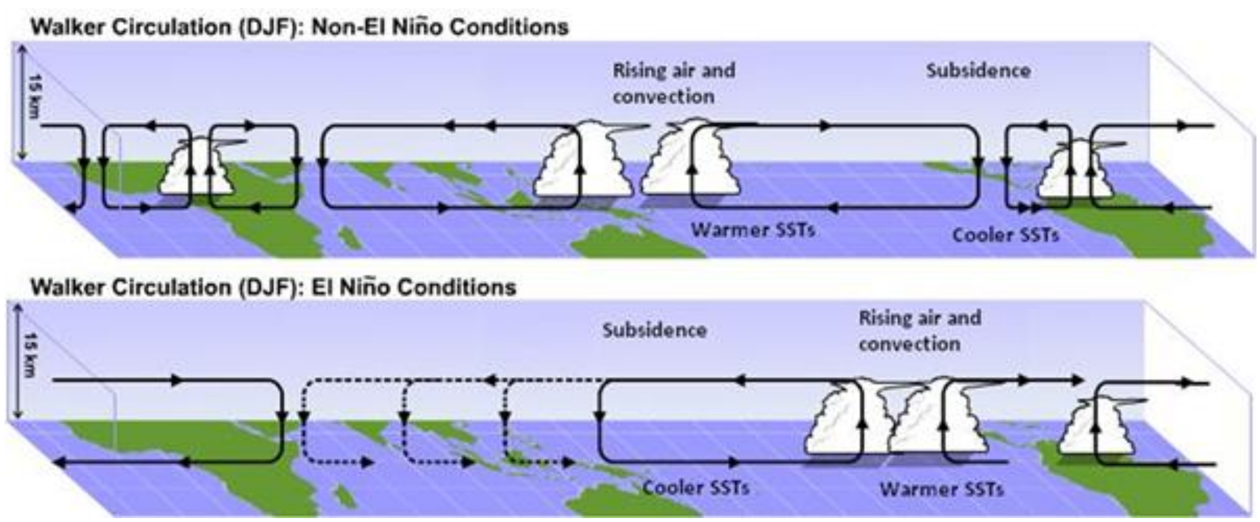


Figure 2.5 Walker Circulation during El Nino and non El Nino years.

Source: Naeyaert (2013)

Retrieved June 12, 2013, from http://www.personal.psu.edu/czn115/blogs/meteo241/2010/10/e-portfolio-2.html

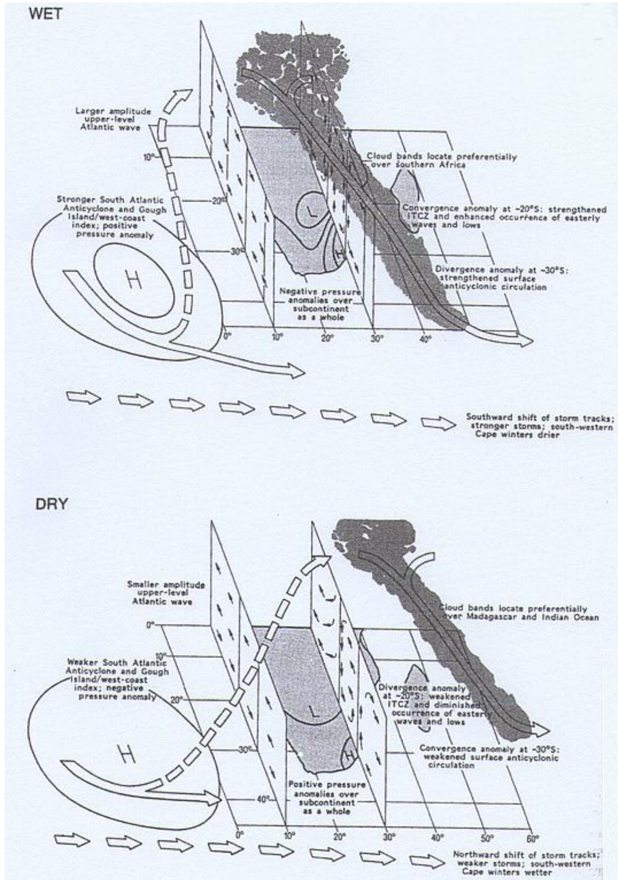


Figure 2.6. Models of anomalous meridonial circulations over Southern Africa during spells of predominantly (a) wet and (b) dry conditions.
Source: Mason and Jury (1997)

Tyson (1986) presented conceptual models of atmospheric circulation during wet and dry conditions (Figure 2.6) (Mason and Jury, 1997). It should be noted that these models are still undergoing review however the essential features are remain valid. Mason and Jury (1997) point out that dry summers are dominated by confluent upper winds which reduce the potential for convection over Southern Africa and often are accompanied by an upsurge of tropical disturbances in the southwest Indian Ocean. The equatorward withdrawal of summer rains during drought years is unclear, but when convergence lies further north and weakened, rainfall over much of the subcontinent decreases. Decreased rainfall over southern Africa is offset by increased rainfall over east Africa due to a reversal of the Walker Cell between wet and dry years.

Hence a convective dipole exists and during El Niño (La Niña) years; East Africa experiences above normal (drought) rainfall South Africa is characterized by drought (above normal rains) (Mason and Jury, 1997) (Figure 2.7).

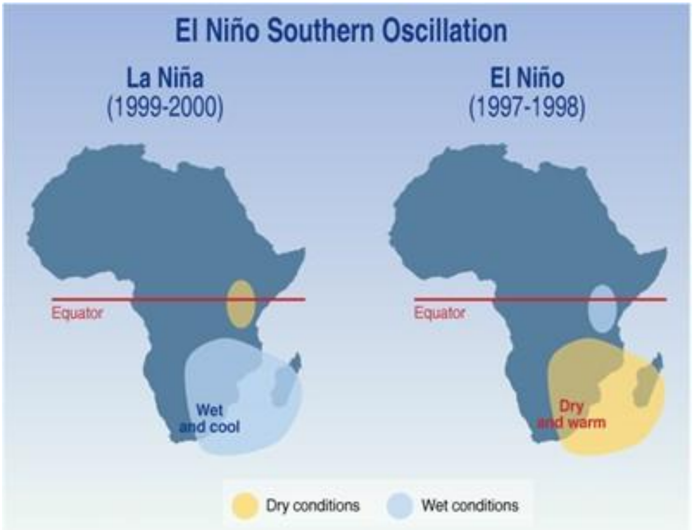


Figure 2.7. Precipitation over Southern Africa and East Africa exhibits a dipole pattern during El Niño and La Niña years.
Source: UNEP/GRID (2005).
Retrieved June 12, 2013, from http://www.grida.no/publications/vg/africa

The Indian Ocean

The Indian Ocean is yet another important forcing factor contributing to inter-annual variability of climate over Southern Africa (Manatsa and Mukwada, 2009). Sea surface temperatures in the Indian Ocean have been shown to vary at periodicities ranging of 2.3years, 5-years, and 10 years (Nicholson and Nyenzi, 1989), see Figure 2.8. When the Indian Ocean experiences higher than average sea-surface temperatures (SSTs), a tendency of dry conditions over Southern Africa has been noted (Jury and Pathack, 1993; Mason and Jury, 1997). Several reports have suggested that the Indian Ocean warming events occur independent of ENSO forcing (Jury and Pathack, 1993; Mason and Jury, 1997; Saji et al., 1999), however it has also been shown that warming in the Indian Ocean could be important in the transmission of the El Niño signal to Southern Africa

(Rocha and Simmonds, 1997).

The relationship between the Indian Ocean sea surface temperatures and Southern Africa's rainfall has however been shown to be changing (Manatsa and Mukwada, 2009). From the 1960s to the mid 1990s the influence of the Indian Ocean Dipole Modal Zone (IODZM) could be attributed to as much as 29% of the rainfall variability in Zimbabwe, however after this period the IODZM seemed to decouple. Manasta and Matarira (2009) suggested that this decoupling could be related to a slower long term evolution of the IODZM or climatic shifts. An implication of the decoupling of the IODZM is that regional forecasting models need to be constantly updated and checked for any longer term variations in inter-annual patterns.

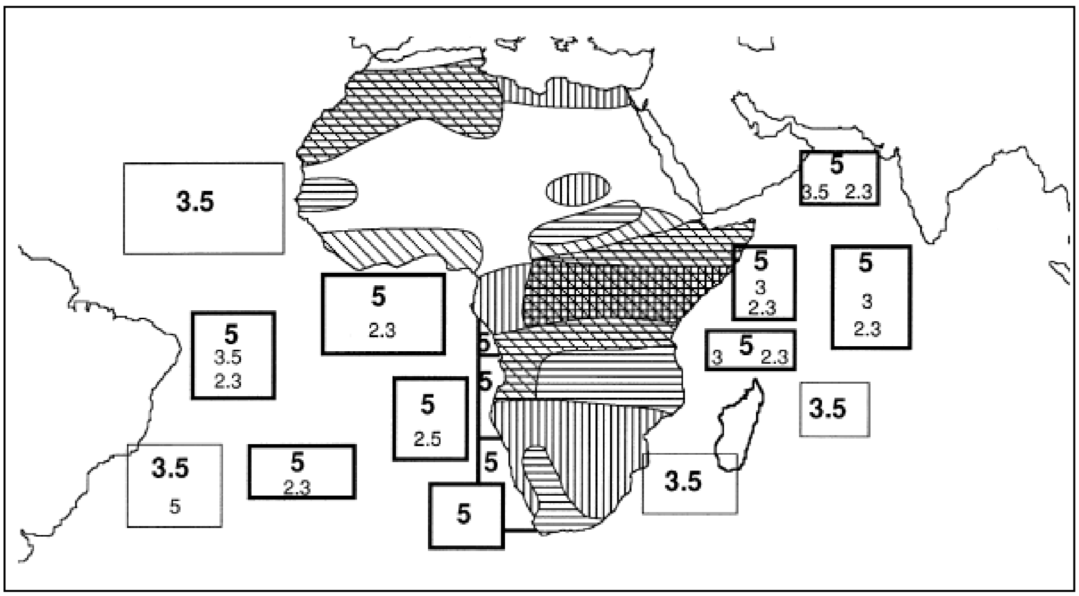


Figure 2.8. Schematic of the distribution of significant spectral peaks for rainfall over the African continent and SSTs over the Atlantic and Indian Oceans based on Nicholson and Entekhabi 1986; Nicholson and Nyenzi,1990). For rainfall, vertical, horizontal and slanted lines indicate, respectively, significant peaks at about 3.5, 5–6 and 2.3 years. For SSTs, the large bold number indicates the most significant peak; smaller numbers indicate secondary spectral peaks. The boldly outlined squares are part of a tropical sector of strongly coherent SST variability on time scales of about 5 to 6 years.

Source: Nicholson and Selato (2000)

The South-east Atlantic Ocean

Reason et al. (2006) note that it is probably fair to say that most climate scientists in the region have tended to consider Atlantic Ocean influences on regional climate to be secondary to those emanating from the Pacific Ocean or the Indian Oceans. This perception has possibly arisen due to the fact that rain bearing weather systems of many parts of Southern Africa tend to come from the east (Reason et al., 2006). Nicholson and Entekhabi (1985) and Nicholson and Nyenzi (1990) reported similar periodicities (5-6 years) in Atlantic Ocean SSTs as those of precipitation over regions of Southern Africa.

The potential influence of the Atlantic on Southern African climate is related to the variability of the Inter-Tropical Convergence Zone (ITCZ), the South Atlantic anticyclone, and to a lesser extern, the mid-latitude westerlies. Evidence exists that modulations of the Angola low, related to tropical southeast Atlantic SST may significantly influence summer rainfall over large areas of Southern Africa. Reason et al. (2006) however acknowledges that knowledge of Atlantic influences on southern African climate is not yet well developed. Though this study will not focus on the south-east Atlantic Ocean, global sea surface temperatures (SSTs) will be employed for correlation analysis and the possible influence of the Atlantic Ocean can be captured, should it be needed.

The Quasi-biennial Oscillation

Another factor influencing Southern Africa's inter-annual variation of precipitation is the stratospheric Quasi-biennial Oscillation (QBO). The oscillation of the QBO equatorial zonal wind between easterlies and westerlies ranges between 2-3 years (Jury et al., 1994; Shiotani, 1992). The QBO is independent of the annual cycle and ENSO. However, Mason and Jury

(1997) report that ENSO's influence on rainfall over Southern Africa may be stronger when the Quasi-biennial Oscillation (QBO) is in its westerly phase (Mason and Jury, 1997). They observe that when the QBO is in its easterly phase (westerly phase) drought (wet) conditions occur during El Niño (La Niña) years, as was the case in the great drought of 1991/92 (Jury, 1995). Mason and Jury (1997) further suggest that the QBO might interact with the Walker Circulation over the Western Indian Ocean. The lower stratospheric easterly zonal winds would provide upper-tropospheric wind stress that would enhance the Walker cell overturning with a descending limb over southern Africa and a rising limb over the ocean to the east (Mason and Jury, 1997). In its westerly phase years, the Walker Cell would be reversed and with a rising limb over Southern Africa, and convection and rainfall over the subcontinent would be enhanced (Mason and Jury 1992).

Inter-Decadal Variability

A prominent 18-20 year cycle is found in Zimbabwe's summer rainfall over the past century of metrological records (Matarira and Jury, 1991). Principal component analysis (PCA) followed by spectral analysis of rainfall series confirms the presence of this ubiquitous temporal variation of rainfall in other Southern African countries (Tyson, 1986; Mason and Jury, 1997). Evidence pointing to the reality of the 18-year oscillation also emanates from variations in other parameters such as temperature, river run-off and tree ring reconstructions (Tyson, 1975; Tyson, 1986; Therrell et al., 2006). Various mechanisms have been proposed including regional SST forcing modulations of the Southern Hemisphere circulation and the projection of ENSO like decadal modes (Reason et. al., 2006).

The 10-12 year cycle is also a significant periodicity in Southern African rainfall. However it is not as strong as the ENSO signal or the 18-year cycle. Nicholson and Entekhabi

(1986) also reported the 10-12-year cycle in various parts of Africa, not limited to southern Africa. The 11-year cycle is one of the most widely reported and discussed in meteorological literature, and some researchers have attributed it to the 11-year cycle of solar irradiance or sunspot activity. To improve the understanding of factors affecting Southern African precipitation and vegetation variability at different time scales, this study will employ the method of spectral analysis.

All the cycles reviewed thus far are likely to influence Zimbabwe's vegetation variability through precipitation. Hence in this study the Fourier Transformation methodology of spectral analysis will be used to investigate embedded periodicities in Zimbabwe's rainfall and NDVI. Though spectral analysis does not give cause and effect relationship, it hints the possibility of relationships that may be hidden with the data distribution. A detailed explanation of spectral analysis is presented in the methodology chapter.

2.2 Atmospheric Circulation during Wet and Dry Conditions

The mean circulation over Southern Africa is anti-cyclonic throughout the year above the surface boundary layer (Tyson 1986; Matarira, 1990). The semi-permanent Angola Low is of importance since it generally acts as the tropical source region for the tropical-extra tropical cloud bands the extend NW-SE across Southern Africa and bring much of the rainfall (Reason et al, 2005). Synoptic perturbations cause daily weather changes and ultimately are responsible for rain bearing systems (Tyson 1986).

Tropical–Temperate Trough

A significant proportion of austral summer (wet season) rainfall over much of Southern Africa, and in particular Zimbabwe, is derived from synoptic-scale tropical–temperate trough (TTT) systems that extend across the continent into the adjacent southwest Indian Ocean (Figure 2.9.) (Todd et al., 2004). The semi-permanent Angola Low is of importance since it generally acts as the tropical source region for the tropical-extra tropical cloud bands/troughs the extend NW-SE across Southern Africa and bring much of the rainfall (Reason and Jagadheesha, 2005). Mason and Jury (1997) point out that total rainfall volume from individual trough events depends upon the availability of atmospheric moisture, atmospheric stability, strength of upper-level divergence, and the speed of movement of the trough (Mason and Jury, 1997). The tropical troughs are generally short lived in the early part of the rainfall season, but are responsible for much rainfall and sometimes floods during the second half of the rainfall season. The tropical low is usually located over southeast Angola or southwest Zambia forming preferentially during the period of December-March at the furthest southwestern limit of the Inter-Tropical Convergence Zone (ITCZ).

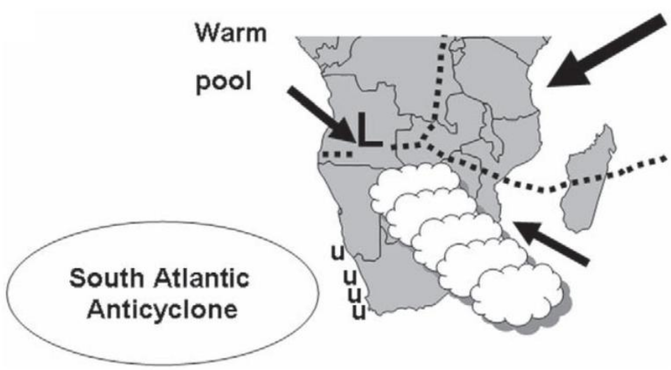


Figure 2.9. Schematic showing the important circulation and other features in Southern Africa during the austral summer. The Angola low is denoted by L, the ITCZ and confluence regions by the thick dotted lines. The arrows denote important directions of low-level moisture fluxes with their thicknesses giving an indication of relative strengths. The cloud symbols refer to the tropical temperature troughs or tropical–extratropical cloudbands that typically extend from the Angola low during summers with average or above-average rainfall and that are the most important summer rain–producing weather systems over subtropical southern Africa.
Source: Reason, Landman, and Tennant, (2006)

Cut-Off Lows

Although subtropical troughs contribute to widespread rainfall over much of Southern Africa, the heaviest rainfalls are usually associated with cut-off lows. Cut-offs are unstable, baroclinic systems which slope to the west with increasing height and are associated with strong convergence and vertical motion (Tyson, 1986). These systems have been responsible for a number of severe flooding events such as in September 1987 and March 1988. The frequency of cut-off lows producing rains shows a semi-annual variation with peaks in September-November and March-May, hence are important contributors of early and late season rainfall. The lowest frequency of cut-off lows occurs in December and February (Taljard, 1982). The high interannual variability of the frequency of cut-off lows is largely responsible for the high variability of rainfall during the transition season (Mason and Jury, 1997).

Tropical Cyclones

Mason and Jury (1997) point out that some of the heaviest rains over Southern Africa are associated with the infrequent passage of tropical cyclones across the coastal margins of Mozambique (Mason and Jury, 1997). They usually curve to the south before reaching land (Tyson, 1986). Hence they are more frequently associated with dry conditions over southern Africa, when the tropical cyclone remains in the Mozambique Channel. Occasionally tropical cyclones fail to recurve seaward and penetrate inland causing devastating effects, as was the case with the flooding produced by cyclones Domoina and Imbaoa in 1983/84 or Cyclone Elene in early 2000.

2.3 Remote Sensing and Climate Monitoring

A major problem that has impeded accurately monitoring drought and above normal wet seasons, and quantifying their spatial extent, severity and duration is the availability of data. Rainfall data come from sparse meteorological network. When available the data are often incomplete and often not always available on time. Moreover the discrete nature of convective rainfall in the region renders the sparsely distributed rain gauge network of limited use for accurate spatial analysis (Martiny et al., 2006). Worse more, there are fewer meteorological stations now in Africa than there were 20 or 30 years ago (Washington, 2006). Remote sensing technology permits evaluation with high resolution, the inter-annual and intra-seasonal oscillations of rainfall and its predictability (Matariara and Jury, 1991; Makaudze, 2005).

The advantage with remote sensing technology is that it provides repeated measurements at a particular spatial scale that allows dynamic environmental monitored with considerable accuracy (Makaudze, 2005). Moreover remote sensing offers a unique vantage point and offers extra visual information and is usually cost-effective (Lillesand et al. 2000). High resolution precipitation estimates are now available from satellites such as the Tropical Rainfall Measuring Mission (TRMM) or the Meteosat series of satellites. Unfortunately these satellites do not have a long times series yet. Meteosat came into operation only at the start of 2004, and TRIMM was launched in 1997. This study requires a longer time series data set for a more comprehensive analysis of the dominant modes of climatic variability and their relationship to ENSO. Hence the normalized difference vegetation index (NDVI) is used together with ground based precipitation data.

The normalized difference vegetation index (NDVI) is used to investigate vegetation dynamics over Zimbabwe. The NDVI is a spectral vegetation index defined as the difference between near infrared and red reflectance’s divided by their sum (Curran and Steven, 1983). It is strongly correlated with vegetation biophysical parameters such as leaf area index (LAI), green leaf biomass, and the leaf photosynthetic activity (Barbosa et al., 2006). NDVI measurements theoretically range between -1 and +1 (Bellone, 2009), but in practice NDVI measurements for vegetation generally range between -0.1 and + 0.7 (Goward et al., 1985). The higher the NDVI value, the higher the green vegetation density. The foundation of using NDVI is based on a number of studies that have demonstrated a close relationship between NDVI and seasonal precipitation in semi arid regions (Tucker and Nicholson, 1999; Anyamba and Eastman, 1996). We used NDVI imagines obtained from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) because it provides the longest available representation of biosphere dynamics for studies of climate vegetation interactions (Anyamba et al., 2001).

2.4. The Role of Climatic Information and Advisory Services

Olufayo, Walker, and Twomlow (1998) stress that African applied climatology or agro-meteorology needs to concentrate on the problem of changing local farming and agro-businesses from their present state of relative ignorance to a more knowledgeable condition about climatic issues. Regional averaging of precipitation parameters as in the SARCOF forecasts lacks the precision necessary for guiding local-level response decisions of smallholder farmers who are already operating at critical thresholds due to multiple constrains. An ideal methodology would be the end-to-end forecasting systems and user applications as demonstrated by Coelho and Costa (2010), which incorporate knowledge from global climate models through to stochastic modeling of crop yields at small spatial scales. However, as we develop such technologies, historical data available from the existing local meteorological stations may also be used to guide local agriculturalists in interpreting the rather coarse climatic information.

In fact, making locally captured agro-meteorological information accessible to local agriculturalists could contribute to the maintenance of rain gauge measuring spots, thereby contributing also to the interests of global networks such as the World Weather Watch. There are fewer meteorological stations now in Africa than there were 20 or 30 years ago (Washington, 2006). In the past when Africa's meteorological stations were more, it was because many mission schools, hospitals and police stations were also involved in diligent capturing climatic data. We suggest that by providing local communities with locally based climatic information collected through the response farming network and advisory services, it is likely to bring local interest and participation in maintaining, and possibly even establishing, a wider network of rain gauges in existing government schools and hospitals as it used to be the case during colonial times. At the same time it is likely to bring local interest and participation in initiatives to formulating strategies for dealing with phenomena of global-scale influence.

The use of local data also harbors risks, as well as other professional and quality issues of concern. It is therefore important to consider carefully arguments for the challenges and risks, in order to avoid false expectations and also to guide further research.

2.5 On the risks of disseminating local climatic data and their by-products

When dealing with local climatic data agro-meteorologists choose from among the following: they can either present historical observational data in their raw format only, or present the derivatives or by-products of these historical data. In the case they choose to present the raw data alone, they leave it up to farmers to analyze and interpret the data. Unfortunately most smallholder farmers lack the knowledge and hardware necessary to analyze raw data. Therefore, this option is not much different from making agro-meteorological information inaccessible. If the agro-meteorologists take the latter choice, then to maintain credibility, they would need to emphasize also on the uncertainty inherent in the statistical derivatives of historical data. Literature from seasonal outlook forecasts sheds some light about this issue. Patt (2000) quotes O'Brian (1999) who suggests that forecasters should provide users with the raw forecast, and avoid just communicating the most likely option. In fact, by communicating only the most likely option, forecasters fail to understand the weaknesses of the risk estimates, which in the case of a wrong forecast, could do significant damage to the public credibility of science and technology. Glantz (2000) has also highlighted using the example of El Niño that, even though there remains considerable uncertainty with regards to seasonal forecasts, people must be educated about the El Niño phenomenon and how best to cope with it. The forecast skill needs to be always be provided (Davis, 2011) and hence scientists should be involved together with agricultural extension service in helping farmers understand both the usefulness and limitations of climatic information.

The potential for distributing agro-meteorological information for local farmers makes it important to ask questions about which among the climatic parameters are most relevant for farmers. Kingamkono and Kaihura (2003) point out that rainfall is the aspect of the biophysical environment that most farmers mention when they talk about difficulties in managing their farms and maintaining production. However even for precipitation alone there are many indices to consider. For example, for start of rains there are several definitions, some based on minimal moisture required to sow and seeds to grow, and others which take into account the problem of long dry spells soon after planting. Therefore it will be essential for agro-meteorologists to address climatic parameters that have been jointly identified with farmers, driven by the needs of poor people (Stigner, 2008; Olufayo et. al, 1998).Since this work is an explorative case study, we focus only on daily precipitation data and we adopt definitions of precipitation parameters from the Southern African Regional Expert Meeting as described by Tadross et al. (2005).

Another challenge pertaining to climatic parameters is the possible concurrence of both the linear and the cyclic trends. This is an important issue in Southern Africa where inter-annual cycles of precipitation have been well documented through spectral analysis (Tyson, 1986, Sanga-Ngoie and Fukuyama, 1996; Makarau and Jury, 1997; Therrell et al., 2006), and where global warming may result in significant changes in long term precipitation means (Hulme, 2001; Unganai, 1996). Parry et al's (1998) methodology of visualizing shifts of climatic zones for different seasons could be useful for this purpose.

2.6 Study Objectives

This study aims to investigate, using high resolution data, climatic variability over Zimbabwe and its relationships to the El Niño Southern Oscillation for the purpose of enhancing the quality of seasonal climate forecast for agricultural adaptation. To attain this main objective, four objectives are considered.

Objective 1

The first objective is to assess the possibility of using locally captured climatic information for consolidating the use of seasonal climatic forecasts. Agro-meteorological information captured at the local level, if made accessible to local people, can complement and sustain the use of seasonal climate forecasts that are given at the regional level (Mberego and Sanga-Ngoie, 2013).

Objective 2

The second objective which is country level approach is to investigate the dominant spatial and temporal modes of vegetation variability over Zimbabwe and the physical processes that could be driving them. By taking such a country level approach this study is able to examine in detail the modes of vegetation variability that have not been given much attention in past continental level or regional scale studies (Eastman and Fulk, 1993; Nonomura and Sanga-Ngoie, 2003).

Objective 3

The third objective is to investigate the intra-seasonal trends of major dry years and above normal wet years over Zimbabwe. This objective determines the parts of the growing season that are most vulnerable to drought or above too much rain. This objective seeks to provide drought and above normal rain scenario maps that can be useful for guiding farmers in interpreting seasonal climate outlook forecasts.

Objective 4

The fourth objective is to investigate the relationships between the observed modes of vegetation variability over Zimbabwe and the El Niño Southern Oscillation. Four ENSO indices are tested to determine their predictive skill.

CHAPTER 3
METHODLOGY

3.1 Study Area

Zimbabwe is a landlocked country located between latitude 15^{o}30'S and 22^{o}30'S and longitude 25^{o}00'E and 33^{o}00'E (Figure 3.1). The main topographical feature of the country is the central plateau which ranges from 1000 to 1500m above sea level, and which decreases northwards towards the Zambezi River and southwards towards the Limpopo River (Torrence, 1981; Unganai, 1996). The most pronounced mountains lie in the eastern highlands located along the eastern boarder of Zimbabwe with Mozambique. Mean annual precipitation ranges from 337mm year^{-1} in the extreme southern part of the country to 1110mm year^{-1} on the Eastern Highlands. Mean annual temperature ranges from 15^{o}C in the high altitude areas to above 25^{o}C in low altitude areas (Mazvimavi, 2010). Drought is a common phenomenon frequently reported in Zimbabwe's climate (Kinsey, 1998; Manatsa et al., 2010).

Zimbabwe's vegetation cover consists of moist savannah woodlands, or Miombo woodlands, and dry savannah interspersed with grassland plains (Figure 3.1). Most maps showing the vegetation of Zimbabwe are based on estimates of the expected climax vegetation (Nyamapfene, 1991). The country is divided into five agro-ecological zones (Vincent et al., 1961). Agricultural productivity decreases from AEZ-1 to AEZ-5 based on rainfall and soil factors.

Makonde district, where the preliminary study was carried out is in the agro-ecological region IIA. This region is part of the main cropping area of Zimbabwe with 75-80 percent of farming area planted with crops, which are mainly maize, tobacco, cotton, wheat, soybeans, sorghum and groundnuts (Rukuni and Eicher, 1994). The total population of the district is approximately 30 000 people, of which more than seventy-five percent are farmers (CSO, 2002).

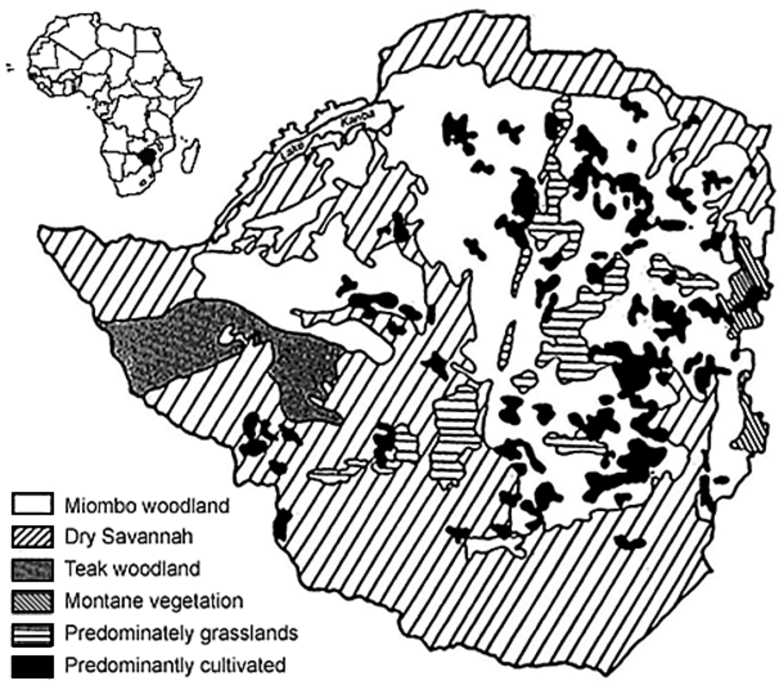


Figure 3.1. Natural vegetation of Zimbabwe (adapted from Witlow, 1987). Insert showing the geographic location of Zimbabwe in Africa.

3.2 The Role of Locally Captured Climatic Information and Advisory Services

Locally captured precipitation data can be used to interpret seasonal outlook forecasts provided by the SARCOF, which are published as probabilities of normal, near normal, and below normal rainfall seasons and covering several hundred square kilometers. This study assesses the existing state of climatic information and agro-meteorological information at the local level using the case study of Makonde District in Zimbabwe. Several district level studies in Africa have analyzed spatial and temporal characteristics of rainfall (Kingamkono and Kaihura, 2003, O'Brien and Vogel, 2003). Ziervogel and Zermoglio (2009) highlight a case in Machakos district in Kenya where pastoralists blamed climate change and decreasing rainfall for decreasing crop yields, opting to downplay the detrimental effects of overgrazing on pasture resources. The meteorological records, however, indicated that rainfall had been increasing rather than decreasing. Using another comprehensive case study in Kenya, Parry, Carter, and Konijn (1988) present the potential of using district-level climatological data for revealing local temporal and spatial precipitation trends that are relevant to local agriculture. However we lack studies that assess whether locally captured climatological data are actually being made accessible to local farmers. Though this is case study focuses on Makonde District in Zimbabwe, it may be generalizable to other locations in Africa. The conceptual framework of the study is shown in Figure 3.2.

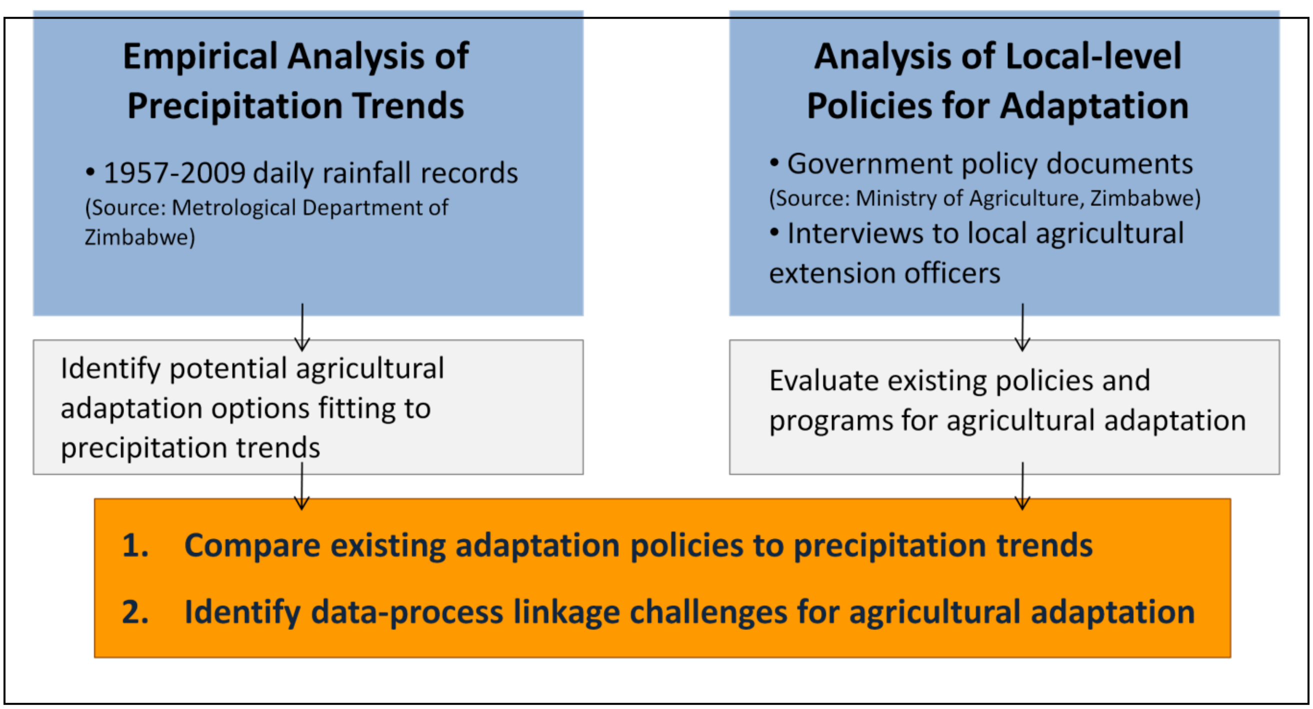


Figure 3.2. Conceptual framework of preliminary study to investigate the state of climatic information at the local level in Zimbabwe.

Interviews and policy analysis

Semi-structured interviews were undertaken from a sample of 20 agricultural extension officers and front-line extension members of the Makonde District Agricultural Extension personnel during the February-March 2010 period. The interviews were designed to extract knowledge about the actual extension programs being run in the district. All interviewees were selected from Makonde District to enable comparison of their perceptions to empirically measured climatic data in the area. Secondary information sources about existing policies and programs related to climate change adaptation in Zimbabwe were reviewed.

Statistical analysis of precipitation data

Daily precipitation data for the district, from 1957 to 2009, were collected from the Makonde Meteorological Station, the main station in Makonde District. The database was quality checked for any records that seemed extremely unusual. Even though it is acknowledged that a period of 52 years of rainfall data is extremely short within the context of climate change, this detailed precipitation database gave us a strong opportunity for a detailed statistical investigation of possible trends.

The definitions for wet and dry days were adopted from The Southern African Regional Expert Meeting report (Tadross et al., 2005). A wet day is one with more than 2 mm of rain and a dry day as one with less than 2 mm of rainfall. This definition takes into account the fact that trace precipitation, i.e., daily rainfall less than 2mm, is agronomically insignificant for most crops. The Southern Africa Regional Expert Meeting report also uses two criteria to define the onset of the planting season. Criteria "A" refers to a planting based on minimal moisture required to sow and for the seeds to grow: more than 25 mm of cumulative rainfall in 10 consecutive days.

Criteria "B" reflects a definition adopted to take into account a common problem associated with early planting: the risk of a long dry spell soon after planting characterized by a total of more than 25 mm in 10 days, but not followed by a period of 10 consecutive dry days during the following 20 days. Cessation of the rains is defined as a 3 consecutive dekads each with less than 20mm of rain. The length of the growing season is the time elapsed between the dates of the onset and cessation of rains.

3.3 Investigating the Dominant Modes of Precipitation and Vegetation Variability over Zimbabwe Using NOAA-AVHRR NDVI

NDVI data from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) for the period 1982–2006 were used for this study. Monthly maximum NDVI composites were downloaded for the whole of Africa from the Global Inventory Modeling and Mapping Studies (GIMMS) group at NASA's Goddard Space Flight Center. The data were already processed to take into account various factors including pre-launch calibration, intra-sensor degradation, changes in solar zenith angle, and correction for Rayleigh scattering and ozone absorption, details of which can be found in Tucker et al. (2005). Prior to analysis, the NDVI imagery was geo-referenced over the geographical study area and pixels corresponding to water bodies based on vector maps of major lakes and rivers in Zimbabwe were removed.

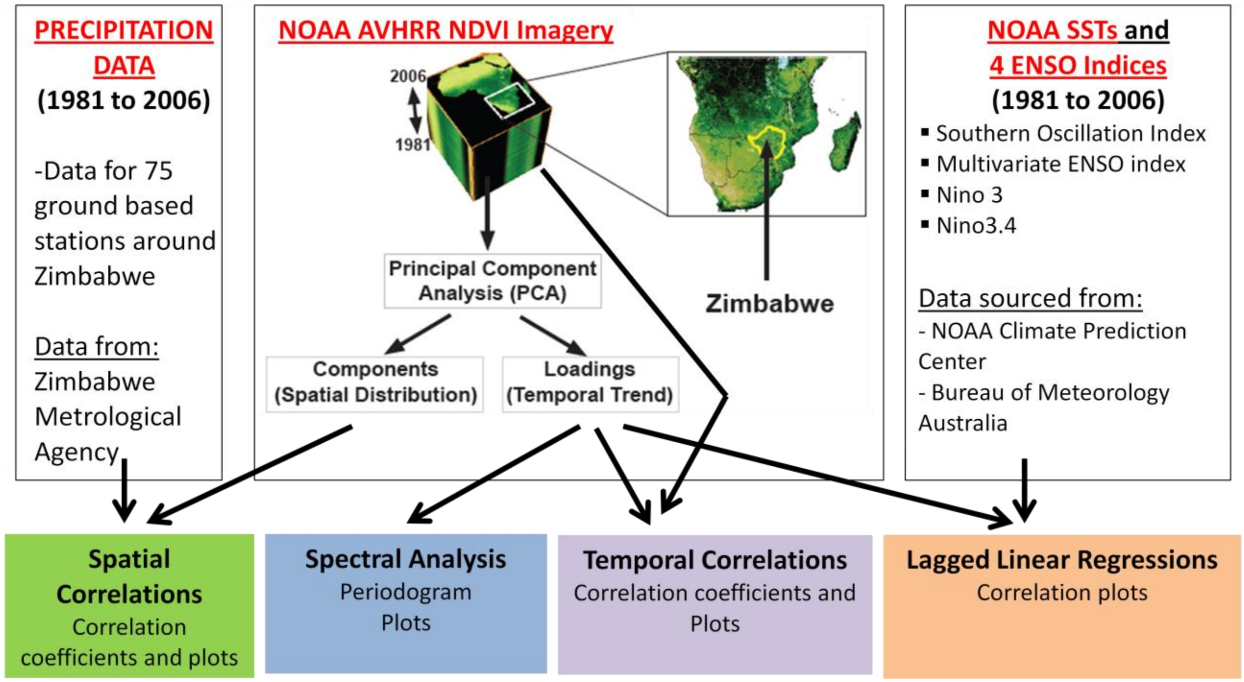


Figure 3.3. Conceptual framework for investigation of Precipitation-NDVI dynamics and their relationships to ENSO.

In order to isolate the dominant spatial and temporal modes of vegetation variability for Zimbabwe, the standardized principal component analysis was performed using the Earth Trends Modeler of IDRISI Selva GIS and Image Processing Software (Eastman, 2012). Principal component analysis (PCA) has widely been used to describe the spatial and temporal variability of vegetation cover. PCA has the advantage that it can describe the most important modes of variability both in time and space. The principal components algorithm produces a set of principal components which are orthogonal to each other and taken together they account for all the variance of the original data (Li and Kafatos, 2000). The first principal component accounts for the largest variance and subsequent components account for smaller and smaller proportions of variance and the associated anomaly or residual spatial patterns are more regionalized or localized. Therefore it is usually possible to only consider a few principal components. The significance of the components was assessed using the Scree Test (D’agostino and Russell, 2005), and we have chosen to evaluate and describe the first four PCA components (PCA 1-4) as the most relevant to assess the vegetation dynamics in Zimbabwe.

To assess whether the principal components are physically meaningful a variety of criteria can be considered. These include stability or robustness of the solutions, the interpretability, and the temporal characteristics or the variability (Nicholson and Nyenzi, 1990). Hence we employed image-to-image correlations analysis to determine relationships between our NDVI-PCA spatial images and the images/maps of some related factors such as precipitation principal components, mean annual precipitation, relative variability of mean annual precipitation, and digital elevation maps (ASTER-DEM). Hence precipitation principal component analysis of Zimbabwe's mean annual precipitation had to be performed using data from 73 observational stations distributed across Zimbabwe for the same time period as the NDVI time series (Figure 3.4). The precipitation data were sourced from the Meteorological Department of Zimbabwe. The map of mean annual relative variability of precipitation was also created based on Tyson (1986) defined as the mean deviation expressed as a percentage of the mean. For the main PCA, correlation analysis between the time series of monthly loadings and the temporal profiles of respective spatial zones in the original standardized NDVI time series was also performed. Temporal profile time series were extracted from the original NDVI dataset using the Earth Trends Modeler of IDRISI Selva GIS and Image Processing Software (Eastman, 2012). Additionally, linear-series to spatial-series regressions were performed to investigate the presence of teleconnections associations between NDVI PCA-1 loadings and tropical sea surface temperature (SSTs). Here the time series for each pixel in the spatial series (global SSTs) is correlated to the PCA-1 series, to produce a correlation map.

A unique feature of the NDVI-PCA analysis was the method of interpreting the relationship between temporal pattern of loadings and the rotation of their respective spatial pattern. In the loadings of the PCAs the time points that had extreme loading values (>1.5 standard deviations and < -1.5 standard deviations) were identified. Then the images corresponding to those specific months with extreme anomalies were manually selected from the original standardized NDVI time series, and composite images were made. Two composite images of extreme loading images were thus created for each PCA, one for greater than 1.5 standard deviations and another less than -1.5 standard deviations. Thereafter we correlated the extreme loading composites with their respective NDVI-PCA images. By performing this procedure it was possible to interpret the rotation of the PCA spatial images in relation to the loadings time series. It should be noted that numerous past studies employing PCA, not limited to NDVI-PCA studies, have omitted this cumbersome yet important step in the interpretation process of principal components and their loadings.

In order to decipher more information from the PCA loading time series, the spectra of the PCA loadings were examined (Jenkins and Watts, 1968) and those which had discrete significant peaks were identified and compared to frequencies commonly found in the tropics. Similarities in spectral peaks among various principal components were noted. Possible dynamical linkages were discussed.

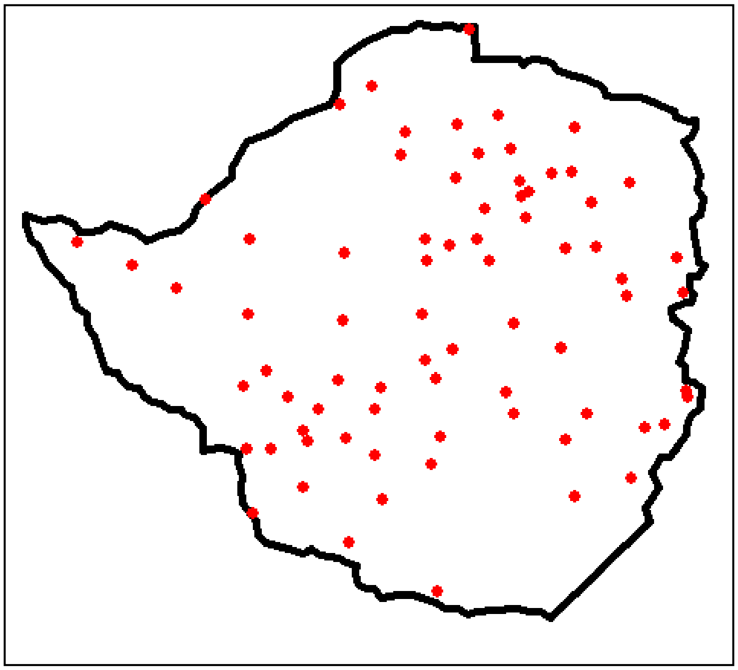


Figure 3.4 Map showing the location of the 73 rainfall stations used in this study.

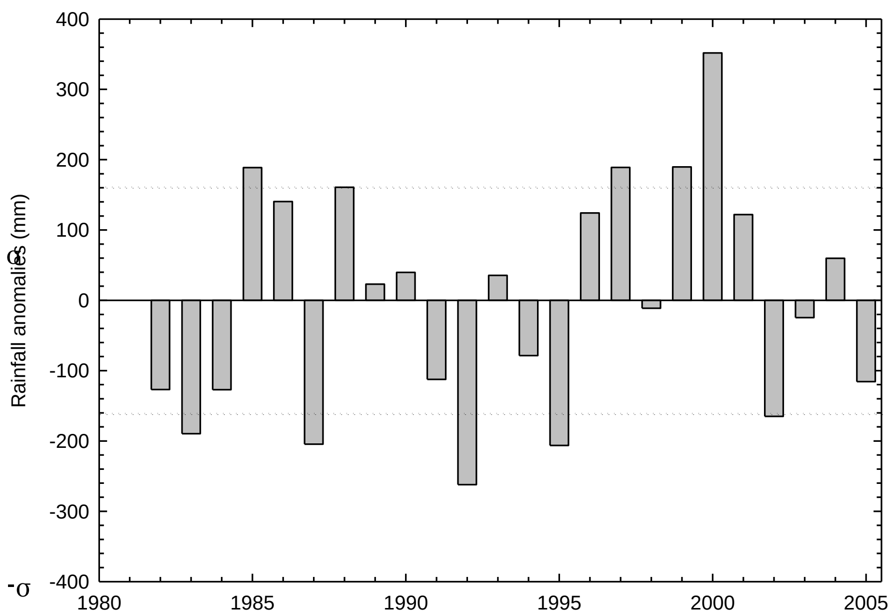


Figure 3.5. Zimbabwe's mean annual rainfall anomalies from the 1981/82 to 2004/05, based on rainfall observational data of 75 stations distributed around the country. Mean annual rainfall was calculated from July to June the proceeding year to capture without breaking the full rainfall season. Years with a standard deviation greater than 1 and below -1 were selected as major wet and dry years respectively.

3.4 Temporal Patterns of Vegetation Variability over Zimbabwe during Drought and Above Normal Wet Climatic Conditions

A major aspect of this analysis was to compare the patterns of extreme dry and wet seasons. Categorization of major dry years and above normal wet years was based on mean annual precipitation anomalies as shown in Figure 3.5. Each year was defined as beginning in July and ending in June of the following year to capture without breaking the austral growing season months. Idrisi Selva GIS and Image Processing Software (Eastman, 2012) and XLSTAT software were used for the analysis. Descriptive statistics, such as means, standard deviations and coefficient of variation, and also t-tests and correlations, were used to characterize the temporal patterns.

In order to distinguish the different influences of the varying influences of ENSO, the Indian Ocean and also the Atlantic Ocean, the method of partial correlations shall be used. This will involve a linear-spatial time series correlation between Zimbabwe's NDVI and global sea surface temperatures (SSTs). Thereafter the prediction skill of four ENSO indices is investigated. The four indices to be compared are: the Southern Oscillation Index (SOI), the Multivariate ENSO Index (MEI), Niño-3 and Niño-3.4 (Figure 3.6) (Hong Kong Observatory, 2013). The main differences between these four indices are the positions on the Pacific Ocean where the measurements are taken and also the parameters used. Measurements of the four ENSO indices from 1981 to 2006 at monthly time-steps were sourced from the National Oceanic and Atmospheric Administration (NOAA) (NOAA, 2013), Australia's Bureau of Meteorology (2013), and the National Center for Atmospheric Research (NCAR) (2013).

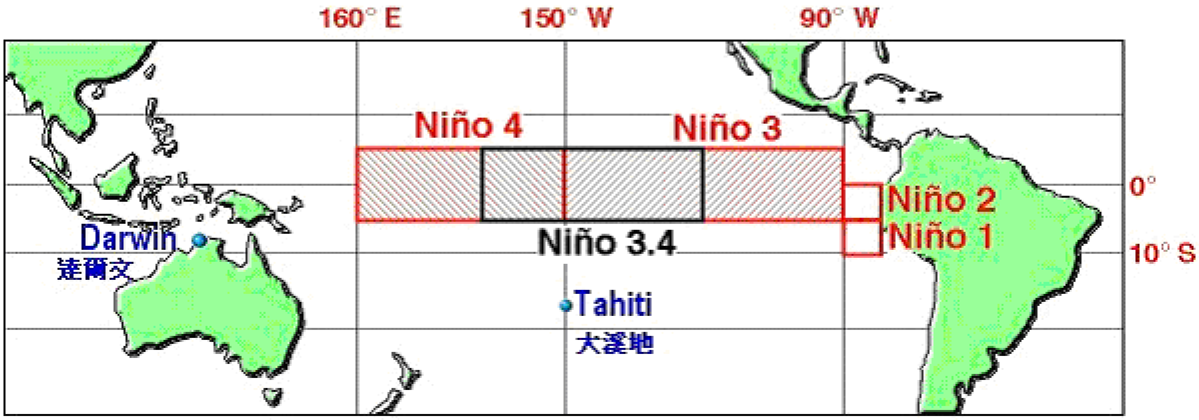


Figure 3.6 Four regions of the tropical Pacific Ocean that have been highlighted as being important for monitoring and identifying El Niño and La Niña.
Source: Hong Kong Observatory (2013).
Retrieved June 12, 2013, from http://www.hko.gov.hk/privacy/policy.htm

CHAPTER 4
THE ROLE OF LOCALLY CAPTURED CLIMATIC INFORMATION AND ADVISORY SERVICES - CASE STUDY OF MAKONDE DISTRICT IN ZIMBABWE

This chapter investigates how empirical climatic information captured at a local weather station is made accessible to local agriculturalists in the same region. Regional averaging of precipitation parameters as in the SARCOF forecasts may lack the precision necessary for guiding local-level response decisions of smallholder farmers who are already operating at critical thresholds due to multiple constrains. Local-level agricultural decision making during the growing season can be promoted by agro-meteorological applications such as response farming (Stigter, 2010). Response farming utilizes localized daily rainfall records to evolve forecast criteria for rainfall in the pending growing season in time to influence decisions that set yield ceilings as well as a set of alternative recommendations for all forecast contingencies (Stewart and Faught, 1984). However, for applied climatology or agro-meteorology to be effective extension intermediaries with sufficient basic knowledge for training the farmers are necessary (Stigter, 2008).

4.1. State of agro-meteorological information and services in Makonde

At the national level, the major institutions involved with agro-meteorological information and services are the Department of Meteorology and the Ministry of Lands, Agriculture and Rural Development. At the district level, it is principally the Department of Agricultural Extension that has direct contact with farmers. Each district in Zimbabwe has a district agricultural extension office with agricultural extension officers who are assisted by a team of front-line extension workers. The main role of the district agricultural extension personnel is to provide agricultural advisory services to farmers and to organize and supervise farmers' training programs. In the present study area, all the interviewed district agricultural extension officers were noted to have up to university-level agricultural training and all front-line extension staff had at least college level of agricultural education. However, none of them was with special training in applied meteorology.

The district agricultural extension office does not yet have any specific programs for applied agro-meteorology or climate change adaptation. Existing farmer training and advisory programs that seem to relate to climatic variability such as the irrigation program and the soil and water conservation program were incepted well before global climate change and variability became an issue of concern. For example, soon after independence in 1980, the government invested in smallholder irrigation to assist indigenous farmers who during colonial times had received little government assistance for improving their agricultural production. Soil and water conservation has traditionally been a key land-use management component of public agricultural extension package in Africa.

No observational climatic records or summarized handouts or visualizations showing historical climatic trends and growing season characteristics for the district were available at the district agricultural extension office. The only form of empirical agro-climatic information that was noted was a copy of the national agro-ecological map (Figure 1.7), which itself was created in 1961 (Vincent et al., 1961). This is a static map; it does not show scenarios for wet and drought seasons or any growing season dynamics. Moreover, due to its coarse resolution, it does not show any district-level spatial variations.

Based upon their sensory perceptions, all agricultural extension personnel reported that total seasonal rainfall was declining, and that the onset of the rainfall season delayed, causing the length of the rainy season to get shorter. They all highlighted and complained about mid-season dry spells in recent years, which affect crops during critical growth stages. With the exception of one officer who suggested that a severe drought did occur every 10 years, all other interviewees did not indicate any knowledge about inter-annual cycles of precipitation. Only one out of the 20 agricultural extension personnel interviewed showed some relative knowledge about the El-Niño and linked it to drought, and that, notwithstanding the rich documentation available on this subject.

Agricultural adaptations that were cited to deal with the perceived precipitation changes include: shifting planting dates to fit the perceived delay in onset of the planting season, using short-seasoned, fast-growing varieties of maize that fit in with the reduced length of season and soil and water conservation to make maximum utilization of precipitation. Asked about the idea of changing crops from maize to other crops that resist long periods of water stress such as sorghum and millet, the officers highlighted that these two crops despite their advantage with regard to drought resistance, do not fetch a good market price and they are also susceptible to bird pests. It was also noted that none of the officers were aware of the seasonal outlook forecasts issued annually by the SARCOF. At the district meteorological office, which is located about 5 km from the agricultural extension office, climatic information could be accessed but only in raw format. No visualizations or summarized handouts exist to inform local farmers about historical climatic trends in the district.

4.2. Analysis of precipitation data

This section analyzes precipitation data obtained from Makonde District Meteorological Office to determine the potential agro-meteorological information that can be obtained from the data but is presently being unused by local agriculturalists.

4.2.1. Spectral analysis of total rainfall

Average seasonal precipitation is 785 ± 184 mm, and total seasonal precipitation does not show any significant linear change (Figure 4.1). The most recent decade experienced a high number of low rainfall seasons and just one above normal rainfall season. This recent experience is probably what influenced the extension personnel to perceive that total seasonal rainfall is declining. It is apparent that the district's seasonal precipitation often falls below the minimum level of 750 mm as defined for Region II in the agro-ecological map that is still being used to date. A visual inspection of 4-year moving averages shown in Figure 4.2 indicates cycles with troughs in the 1960s, early 1980s, early 1990s, and 2000s, and peaks in the early 1960s, mid 1970s, and late 1990s. These results are consistent with the findings reported by other researchers for national precipitation trends (Makarau and Jury, 1997; Unganai, 1996).

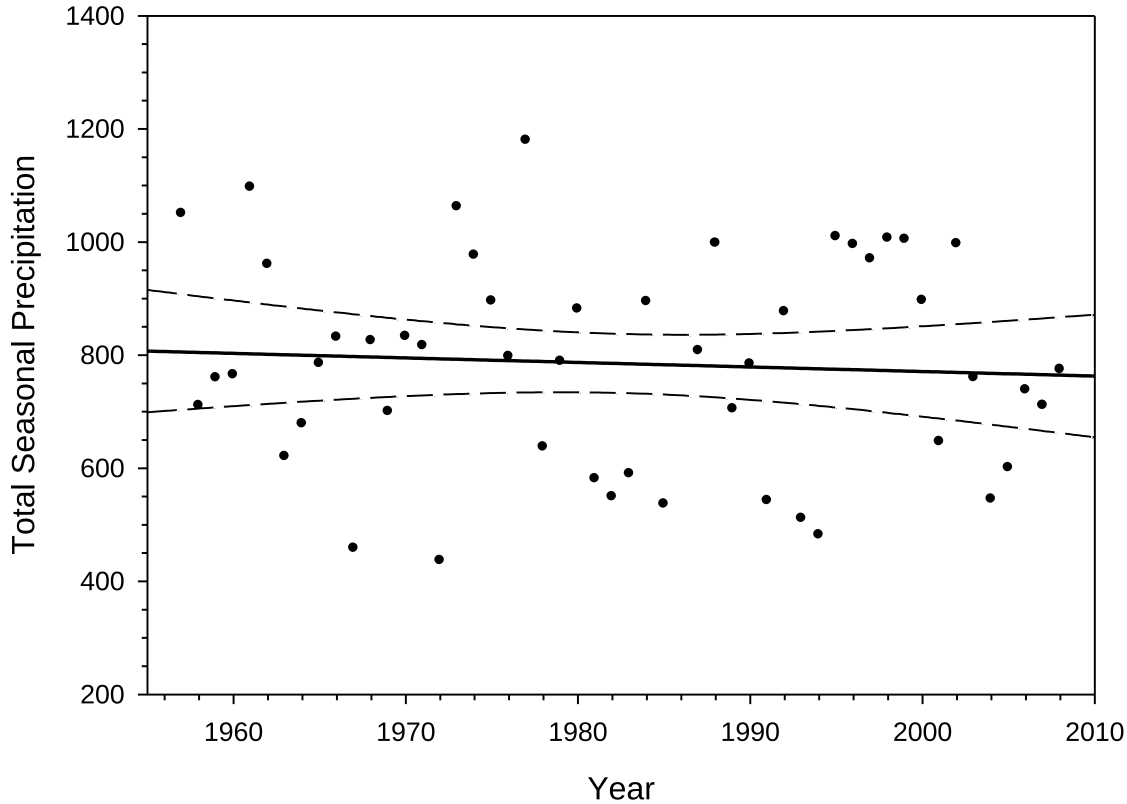


Figure 4.1. Total seasonal precipitation (dots) with a superimposed linear regression (solid line) and 95% confidence intervals of the mean (dotted lines) showing no significant long term trend in Makonde District's rainfall. The most recent decade experienced a high number of below normal rainfall seasons and just 1 above normal rainfall seasons. This recent experience is probably what influenced extension personnel to perceive that total seasonal rainfall is declining. It is apparent that the district's seasonal precipitation often falls below the minimum level of 750 mm as defined for Region II in Vincent's 1961 agro-ecological map being used.

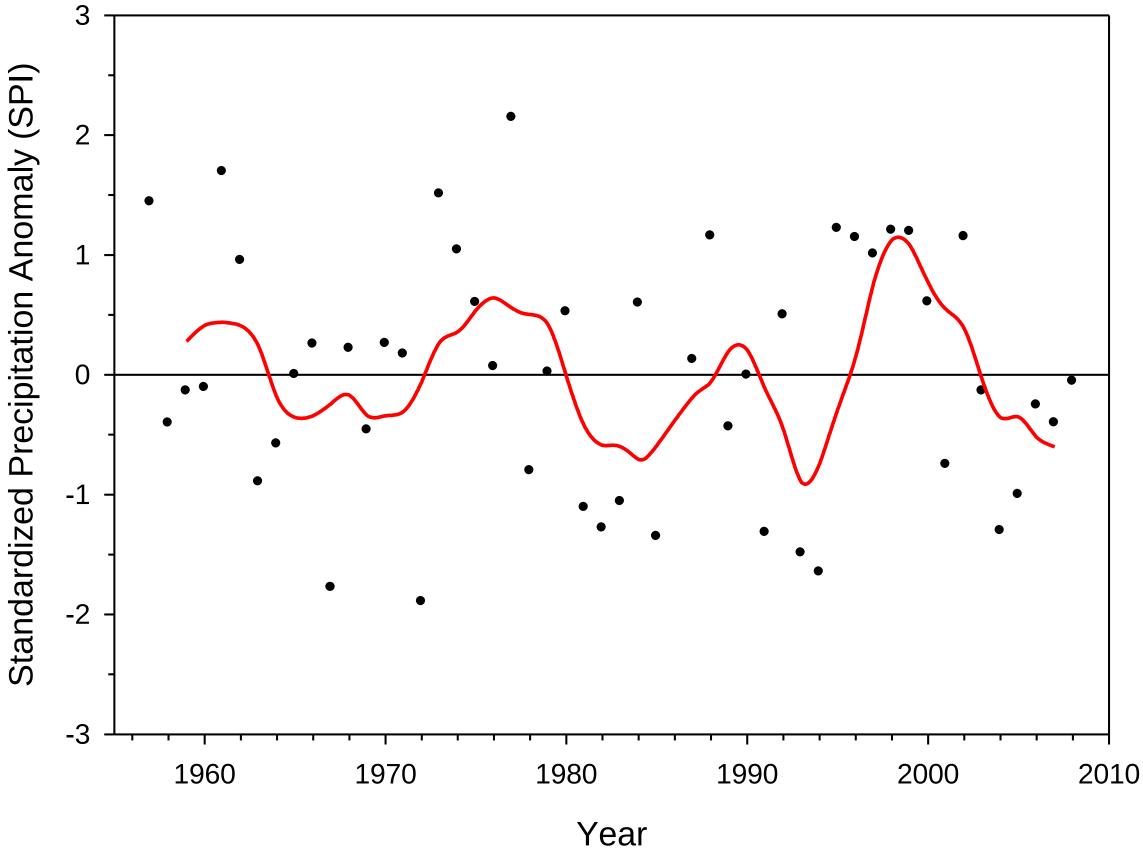


Figure 4.2. Standardized seasonal precipitation anomaly (dots) with a superimposed 4-year running mean (solid line) showing the cyclic trend. The cyclic trend gives support for the adoption of response farming approaches to enable farmers to tactfully adapt to both periods of high rainfall and below normal rainfall.

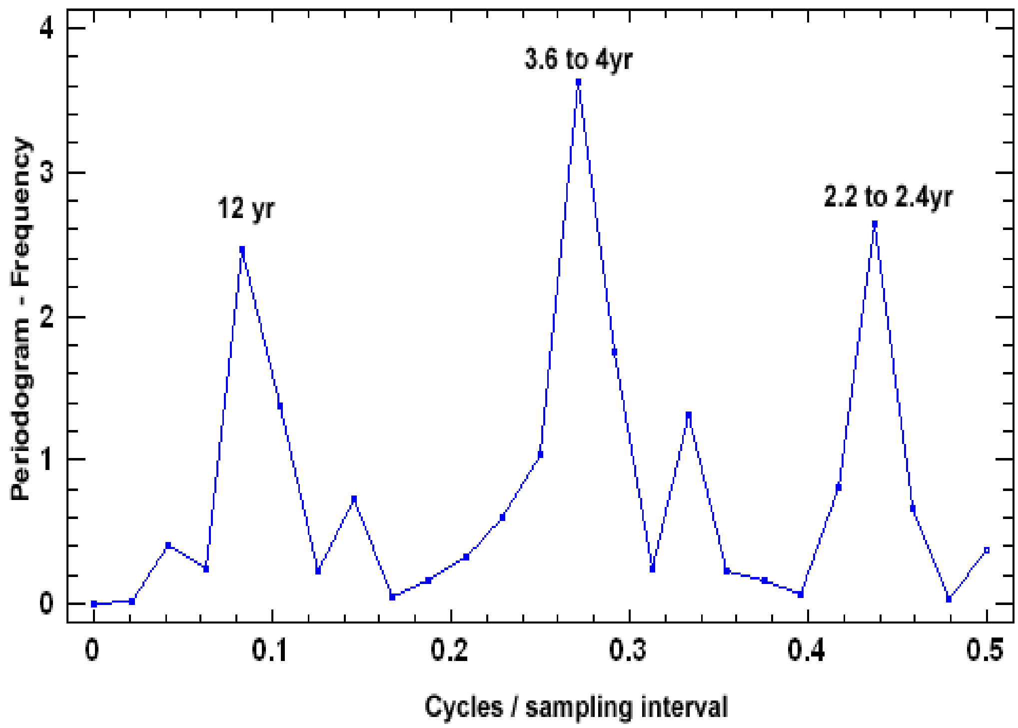


Figure 4.3. Spectral analysis of total seasonal rainfall based upon the 52-year record. The 3.6–4 year periodicity which is most dominant shows similar spectral peaks with the El Niño Southern Oscillation index.

Spectral analysis of total seasonal precipitation (Figure 4.3) showed cycles with periodicities in an order of decreasing significance; 3.6–4 years, 12 years, and 2.3–2.4 years. The 12-year cycle and 2.3- to 2.4-year cycle are subordinate to the 3.6- to 4-year cycle. Upon viewing the 3.6- to 4–year cycle and 2.3- to 2.4-year cycles, whose literature relate to the ENSO Phenomenon (Makarau and Jury, 1997; Sanga-Ngoie and Fukuyama, 1996; Tyson, 1986), a correlation analysis of total seasonal rainfall and Southern Oscillation index (SOI) was performed. Significant correlations were obtained for August–October Southern Oscillation indices (Table 4.1). Correlations of SOI with total seasonal precipitation were lower than those of SOI with total number of rainy days. These results support the literature that emphasizes the predictability of Zimbabwe's rainfall trends and the use of seasonal climate forecasts (Makarau and Jury, 1997;

Manatsa, Mukwada, Siziba, and Chinyanganya, 2010), thereby highlighting the potential of adopting response farming in this district.

Table 4.1. Pearson correlation coefficients between Southern Oscillation index (SOI), total seasonal precipitation, and total number of days.

Month	Total seasonal precipitation	Total number of days > 2mm
August SOI	0.3142	0.5201
September SOI	0.4475	0.6789
October SOI	0.3236	0.4424
Aug – Oct SOI	0.3938	0.5944

4.2.2. Trends in rainfall

A significant decline ($P < 0.05$) in the number of rainy days is seen in Figure 4.4. This decline in number of rainy days is occurring without a corresponding decline in total seasonal precipitation, thereby suggesting an increase in rainfall intensity along the temporal scale. From the 4-year moving averages (Figure 4.5), inter-annual cycles were noted similar yet more pronounced compared to the total seasonal rainfall cycles. A decrease in the number of rainy days implies an increase in the dry spell length somewhere along the rainfall distribution. The position of the decrease in number of rainy days within the seasonal distribution is therefore important as it informs about crop growth stages that may be affected. Figure 4.6 shows that the greatest decrease is occurring in the December–February period.

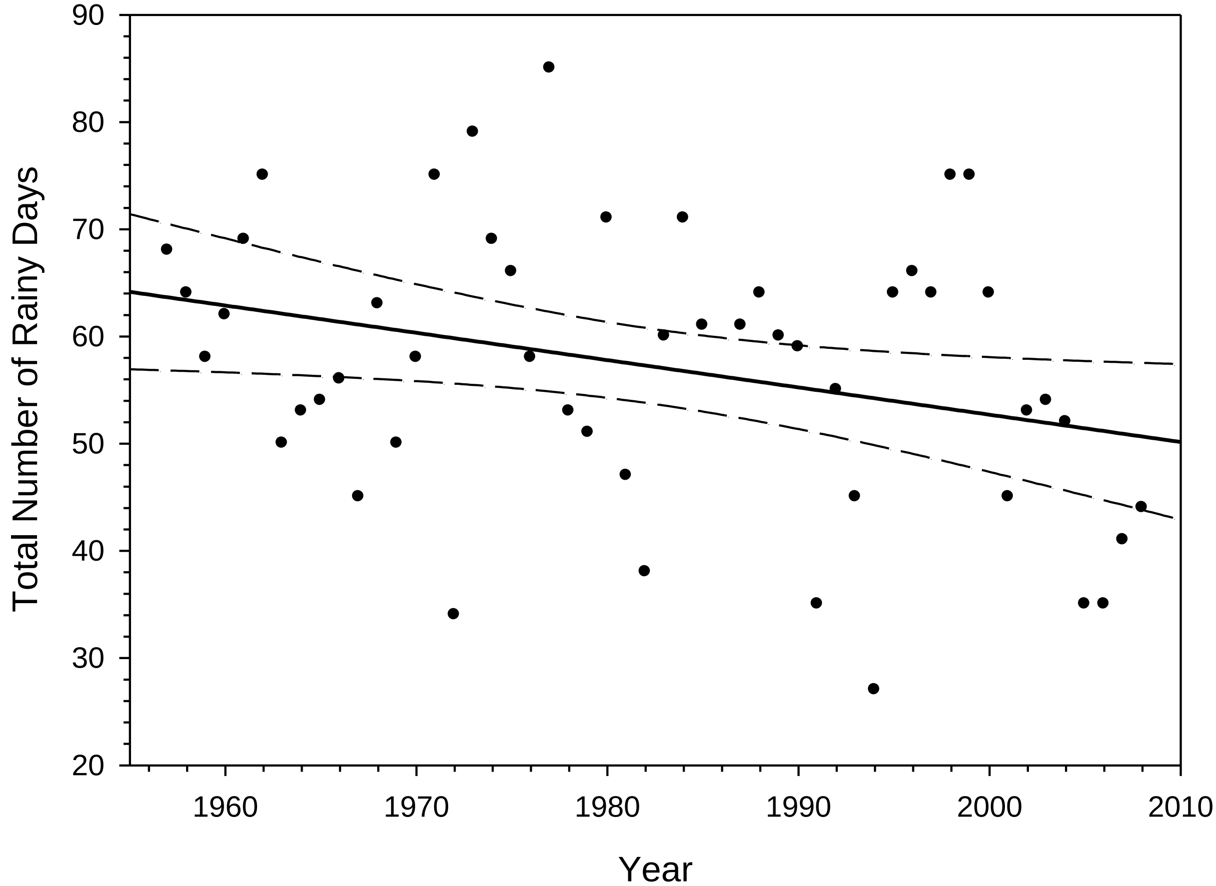


Figure 4.4. The total number of rain days per year (dots) showing a significant declining trend (solid line), and the 95% confidence intervals (dotted lines) for the linear trend. This decline in number of rainy days is occurring without a corresponding declining in total seasonal precipitation thereby suggesting an increase in rainfall intensity along the temporal scale.

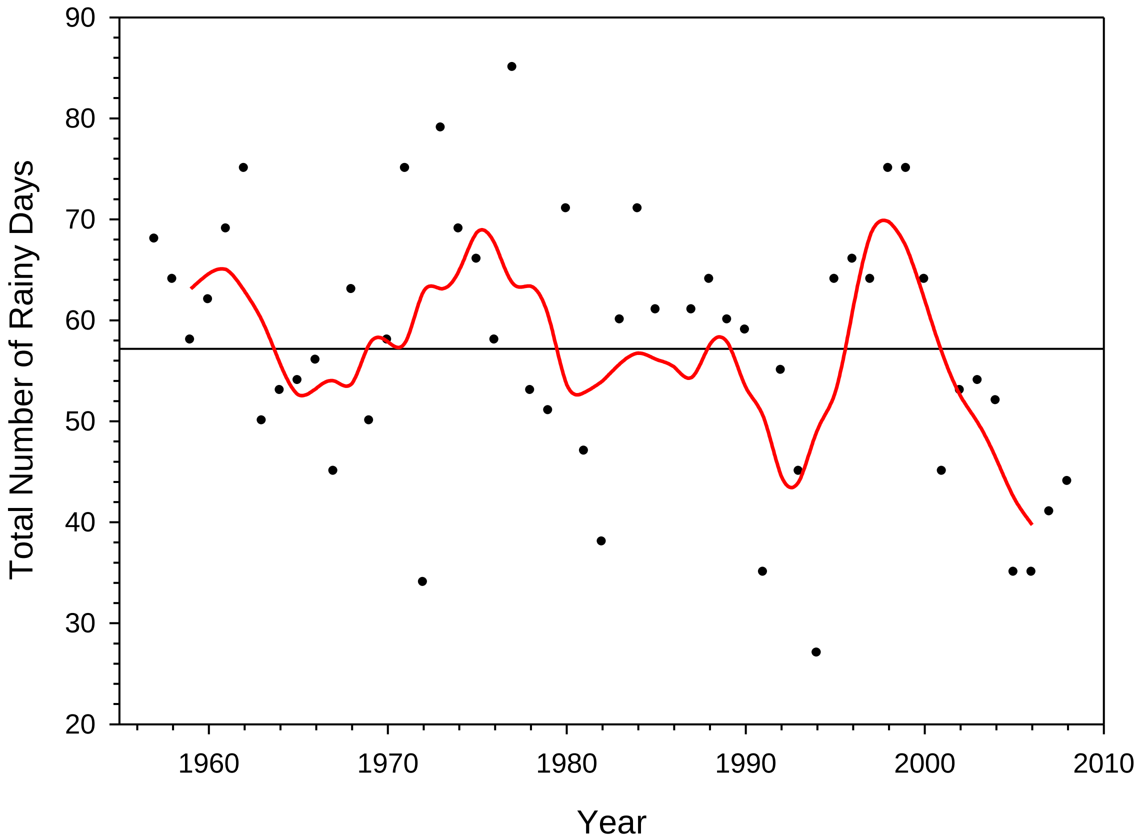


Figure 4.5. The total number of rainy days (dots) with a superimposed 4-year running mean (solid thick line) showing a cyclic trend and the long-term mean (thin solid line). This cyclic trend follows an almost similar trend to that of total seasonal precipitation, thereby reinforcing the need for response farming approaches to survive the inter-annual climatic variability.

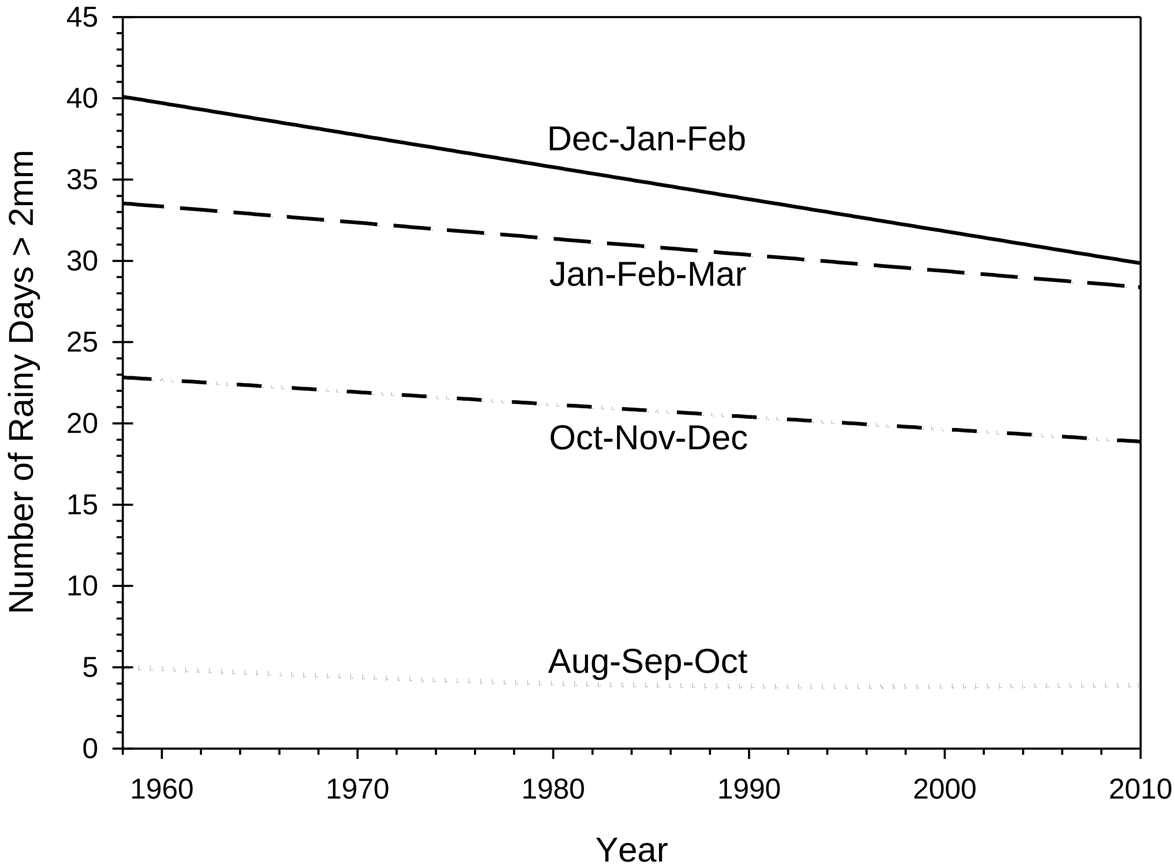


Figure 4.6. Linear regression plots of total number of rain days showing that the greatest decline is occurring during the middle of the rainy season (December–February). This time period is a critical stage when most crops that are grown in this region, including maize, are maturing.

This is the middle of the season when maize crop is maturing and flowering. The median planting and end of season dates for above normal, normal, and drought rainfall seasons are shown in Table 4.2. The significant difference between the two criteria of planting dates is to be noted. Criterion A of planting dates are approximately 15 days earlier than criterion B of planting dates in all three types of seasons (above normal, normal, and drought rainfall seasons). There are no significant ($P > 0.05$) long-term changes in the start and the end of growing season and no significant correlations ($P > 0.05$) between the start and the end of growing season. Furthermore, no significant correlation (P > 0.05) was observed between growing season characteristics and total seasonal precipitation. Planting dates and end of season dates do not follow cyclical or inter-annual trends as noted in total rainfalls. This lack of significant long-term changes suggests that the characteristics of planting and end of season dates are influenced by factors other than the total seasonal rainfall. Detailed examination of trends in intra-seasonal rainfall characteristics is presented in Chapter 6.

Table 4.2. Growing season characteristics for above normal, normal, and drought seasons. Based on Tadross et al. (2005), planting criterion A refers to a planting based on minimal moisture required to sow and for the seeds to grow (>25 mm of cumulative rainfall in 10 consecutive days). Criterion B takes into account the risk of a long dry spell soon after planting (>25 mm in 10 days but not followed by a period of 10 consecutive dry days during the following 20 days). Cessation of the rains is defined as three consecutive decades each less than 20 mm.

Season Type	Statistic	Planting criteria A	Planting criteria B	End of Season
High rainfall season	Median	30 October	15 November	1 April
	Standard dev. (days)	12	10	22
Average rainfall season	Median	31 October	14 November	1 April
	Standard dev. (days)	17	15	26
Low rainfall season	Median	5 November	16 November	2 April
	Standard dev. (days)	16	15	19
All seasons	Median	31 October	15 November	29 March
	Standard dev. (days)	16	13	29**

End of season dates have high correlation (r = 0.86) with season length, but planting dates do not show a significant correlation with season length. End of season dates have significantly higher (P < 0.05) standard deviation than planting dates in all three types of seasons (above normal, normal, and drought rainfall seasons). This variation in end of season (±29 days) is large enough to influence the success or failure of crop yields in rainfed agriculture. If variances of both planting date and end of season are combined, then it can be seen that growing season characteristics play a very important role in determining the success or failure of crop in this rain-fed area.

4.3. Discussion

This study has exemplified the poor state of agro-meteorological information at the local level in Southern Africa. Although it may be argued that raw climatic data are available at the District Meteorological Station, the majority of smallholder farmers do not have the ability to acquire or analyze them. Therefore, these local data are essentially inaccessible. Olufayo et al. (1998) also highlighted that the majority of African farmers are likely to be unaware of the local scientific knowledge of agricultural meteorology in their immediate environment, and the same may also apply in the poorer parts of Asia as well. The agricultural extension office has no summarized handouts or brochures of climatic trends, and the national agro-ecological map (Vincent et al., 1961) being used so far is too old because it is based on observational data from the first half of the twentieth century. Moreover, it does not show shifting boundaries or scenarios for the above normal, average, and drought seasons, and because of its coarse resolution, districts are simply categorized as homogeneous regions. This map has high risks of influencing farmers to maladaptation instead of helping them to adapt to climatic change and variability.

By not using observational climatic information, the accuracy and effectiveness of agricultural extension advisory services in the district is negatively affected. For example, the perceptions of extension personnel about long-term precipitation trends are not consistent with observational records. Furthermore, the extension personnel cited shifting planting days as the most important agricultural adaptation; however, the question is if they do not have empirical records to show the historical ranges of onset of season dates, how can they objectively advise about appropriate planting days? Some possible reasons for this lack of use of climate observational data by the local extension office could be ineffective institutional structures for data exchange between the meteorological and extension departments or precautionary measures by the departments to avoid the credibility risks associated with interpreting and translating the derivatives of observational data. However, an important point that emerged from the discussions with the agricultural extension officers is that they have limited knowledge about how to derive the benefits of locally available climate observational data for response farming. It is therefore evident that university scientists practicing agro-meteorology and agro-climatology need to be involved in interpreting the raw data and forecasts and deriving response farming approaches with the extension office and farmers participating. Moreover, extension personnel need to be trained in agro-meteorology so that they can better articulate the needs of the farmers and farming communities for weather services (Stigter, 2010).

The precipitation analysis results indicating high inter-annual variability and correlations with the SOI underscore the significance of adopting response farming in this area where the majority of farmers do not have irrigation facilities. Every season, farmers have to make tactical decisions either to survive prolonged dry periods or drought or to take advantage of ample soil moisture when sustained rainfall arrives. For example, short-seasoned varieties of maize would be best in the case of late season or drought years, but, during the average and above average rainfall years, medium or long-seasoned maize varieties would be better because they are high-yielding varieties. Therefore, local precipitation data can be used to interpret seasonal outlook forecasts provided by the SARCOF, which are published as probabilities of normal, near normal, and below normal rainfall seasons and covering several hundred square kilometers. In this analysis, no significant long-term changes in total annual precipitation were noted in agreement with Mazvimavi (2008) and New et al. (2006); however, long-term changes in total number of rainy days were noted that could be associated with changes in rainfall intensities since they do not correspond to any long-term changes in total rainfall. Projections have also been made about future changes in rainfall extremes in Southern Africa (Davis, 2011). Therefore, the validity of present response farming approaches needs to be tested frequently.

One of the most important climate information inputs for farmers is the forecasting of the start of the rainy season. Extension personnel cited shifting planting days as the most important adaptation strategy, in agreement with Mano and Nhemachena (2007) and Dinar, Hassan, Mendelsohn, and Benhin (2008), who reported shifting planting dates as one of the major climate change adaptation strategies by farmers in Zimbabwe. The study noted, however, that onset dates computed in this study area were different from those reported by Mupangwa, Walker, and Twomlow (2011) in the southern districts of Zimbabwe. This difference could be attributed to the differences in definitions of the onset of seasons and also differences in rainfall producing systems such as the Inter-Tropical Convergence Zone (ITCZ), which brings rainfall first to the northern parts of Zimbabwe in its southward movement. Since these dates may vary across the country, it becomes clearer that local historical records have to be available at respective agricultural extension offices where local farmers can access this important information and get advisory services. This is also important as current SARCOF forecasts say little about onset or cessation of rainfall (O'Brien and Vogel, 2003).

It is interesting to note that the difference between the criteria A and B is shorter for low rainfall seasons (11 days) than for medium and high rainfall seasons (14 or 16 days, respectively). The planting criterion A is also earlier in high rainfall seasons than in low rainfall seasons. Although these planting criteria and end of season data have interesting averages, they also have large standard deviations. There is a need for more research investigating the variability of onset and length of season and the uncertainties involved. Moreover, there is need for a participatory approach involving farmers, agricultural extension, and scientists each year. Farmers noting what is happening over the years will more likely get involved in response actions, supported by agricultural extension and scientists.

In order to address the problem of the poor state of agro-meteorological information and services at the local level, a participatory approach involving farmers, university scientists, and agricultural extension is suggested. Instead of relying on observational measurements from a single station for the whole district, farmers or farmer groups should be involved in measuring daily rainfall in their plots and recording other observations relevant to yield determination such as pest outbreaks, crop diseases, droughts, and floods. Such a practical involvement of farmers will make them experience the increasing climatic variability and the consequences of climate change, and at the same time, this will give a more useful density of rainfall observations than that obtainable at a district meteorological station. Scientists practicing agro-meteorology and agro-climatology would be involved in the interpretation of the raw data and forecasts into a message the farmers can use assisted by the extension services. At the extension office, summarized tables and graphs for the district can be visualized on posters or handouts so that farmers can easily see and learn from them. The success of such a participatory approach in response farming has been demonstrated in pilot projects set up by the National Meteorological and Hydrological Service in Mali (Stigter, 2010) and the Climate Field Schools (CFSs) in Indonesia (Stigter et al. 2008; Winarto et al. 2008) where groups of farmers meet once a month to discuss their data and observations with scientists and extension officers. In addition to a package of recommendations derived by scientists, on the basis of experiments in the field station and theoretical studies, a participatory approach will help the farmer choose rationally among the various available options on the basis of scientifically grounded advisory services (Stigter, 2010).

4.4. Discussion

Agro-climatic information and advisory services play a big role in enhancing smallholder farmers' resilience to climatic variability. This study, using a case study of Makonde in Zimbabwe, has shown that although an abundant amount of climatic information is being captured at the local meteorological station, this information is not effectively accessible to local farmers. At the local agricultural extension office, no summarized visualizations or handouts were found to inform local farmers about climatic trends with the exception of an old national agro-ecological map which is likely to influence farmers to maladaptation as it is based on pre-1960 observational data. It was noted that extension personnel have limited knowledge about how to derive the benefits of locally available climate observational data and their advisory services are mainly guided by sensory perceptions. The study therefore recommends that university scientists practicing agro-meteorology and agro-climatology be involved in deriving response farming approaches.

On the other hand, the results of the precipitation analysis showing inter-annual variability and correlations with the SOI highlight the potential of adopting response farming in this region where the majority of farmers rely on rain-fed agriculture. Local precipitation data can be used to interpret SARCOF's seasonal outlook forecasts that are often given in probability estimates of above, below, or normal conditions and covering hundreds of kilometers. This study also demonstrated the use of local daily precipitation data in determining the variability of onset, length, and cessation of rainfall season. Apart from relying on rainfall measurements from just one station in the district, it is recommended that farmers and farmer groups be involved in making observational measurements from their fields as this will make them to practically experience climatic variability, and will also give a useful density of rainfall observations.

A participatory approach is therefore recommended involving farmers, scientists, and agricultural extension in Zimbabwe, following the success of case studies from Mali and Indonesia. Moreover, training of extension personnel in agro-meteorology should be emphasized so that they can better articulate the needs of the farming communities for weather services and also be able to bring response farming approach advisory services to farmers for participatory applications in their fields. At the state level, it is strongly recommend that the agro-ecological map of Zimbabwe be updated at the earliest for it to be useful and other updated climate scenario maps be produced.

CHAPTER 5
THE DOMINANT MODES OF PRECIPITATION AND VEGETATION VARIABILITY OVER ZIMBABWE

This chapter investigates the dominant spatial and temporal modes of vegetation variability over Zimbabwe and the physical processes that could be driving them. By taking such a country level approach this study examines in detail the modes of variability that have not been given much attention in past continental level or regional scale studies (Eastman and Fulk, 1993; Nonomura, Sanga-Ngoie and Fukuyama, 2003).

5.1 Principal Component 1 (PCA-1)

Figure 5.1a shows the spatial distribution of the NDVI PCA-1 which explains 35.6% of the total variance in the 300 image time series. The lowest anomalies in this image are distributed in the eastern strip of the country corresponding to agro-ecological zone 1 (AEZ-1) (Figure 1.7). This zone is unique in Zimbabwe for its dense vegetation cover consisting of evergreen montane forests, plantation estates, and year round intensive agriculture. Low anomalies (<0.5) are also observed over the region corresponding to AEZ-2, where intensive agricultural activities are practiced and savannah woodlands dominate non-cultivated areas (Ministry of Education, 1985; Nyamapfene, 1991). Scattered spots of low anomalies that can be observed outside of AEZ-1 and 2 correspond mainly to specific well-vegetated sites such as gazetted forests and irrigated estates. The high anomalies (>0.5) distributed over AEZs 3, 4 and 5 where dry savannah dominates the natural vegetation cover and land-use activities include semi-intensive, extensive farming and wildlife parks. The highest anomalies in NDVI PCA-1 correspond to the grassland plains.

The total area with low anomalies (<0.5) in the NDVI PCA-1 is 19%, in agreement with the Ministry of Education (1985) reporting that AEZ 1 and 2 comprise 1.5% and 18.7% of the total area of Zimbabwe. These two zones follow a similar spatial pattern to the area circumscribed by the +700mm isohyet in the mean annual precipitation map (Figure 5.1c). However over the vast area (81%) of Zimbabwe the anomaly distribution does not show correspondence to the mean annual precipitation distribution, and there is an overall lack of correlation (r = -0.28) between the NDVI PCA-1 and mean annual precipitation images. No correlation was noted (r = -0.01) between the NDVI PCA-1 and precipitation PCA-1 image (Figure 5.1b). Instead an interesting association between the NDVI PCA-1 and precipitation is revealed through the temporal pattern of PCA-1 loadings.

Figure 5.2a shows the temporal pattern of NDVI PCA-1 monthly loadings. The superimposed 12-month running mean reveals an inter-annual pattern which has valleys in 1982/83, 1986/87, 1992, 1994, 1995, 2002-2003, and 2005-06, and peaks in 1985, 1987/88, 1990-91, 1996/97, and 1999/2000. It is interesting to note that the valleys in this 12-month running mean correspond to years when Zimbabwe experienced major drought seasons and the peaks correspond to high rainfall seasons (Richardson, 2007; Manatsa et al. 2010). The peaks in the 12-month moving average line have lesser magnitude compared to the valleys possibly related to the fact that after a certain level, additional rains are associated with diminishing returns in vegetation growth (Funk and Budde, 2009). The correlation between the monthly NDVI PCA-1 loadings and mean annual precipitation is greatest (r = 0.73) with March-April NDVI PCA-1 loadings (Figure 5.3) in agreement with (Funk and Budde, 2009) that the mid-end of season NDVI provides a better estimate of the cumulative effect of seasonal precipitation on vegetation.

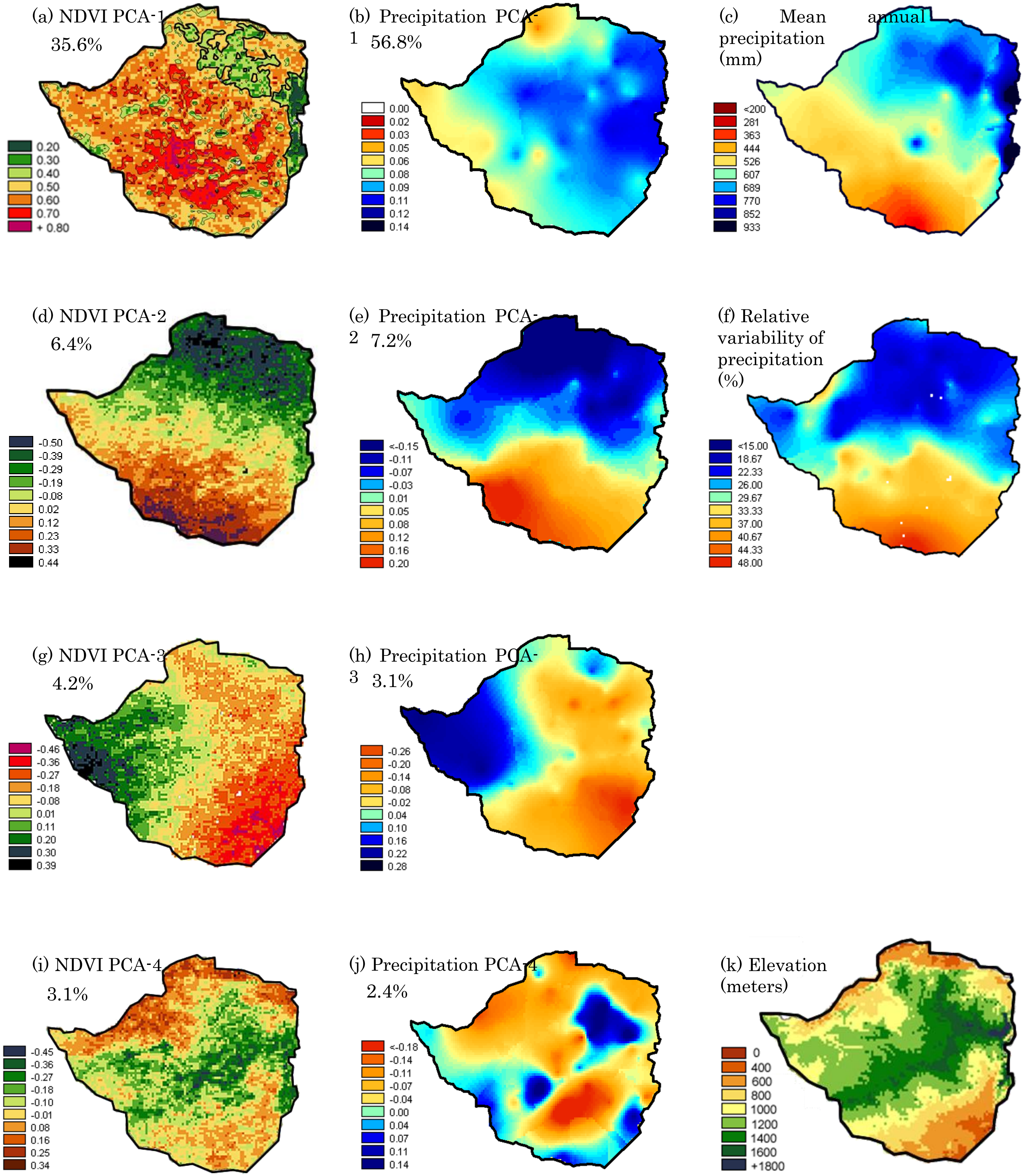


Figure 5.1. NDVI PCA images (left column) and precipitation PCA images (middle column) and their associated images (right column).

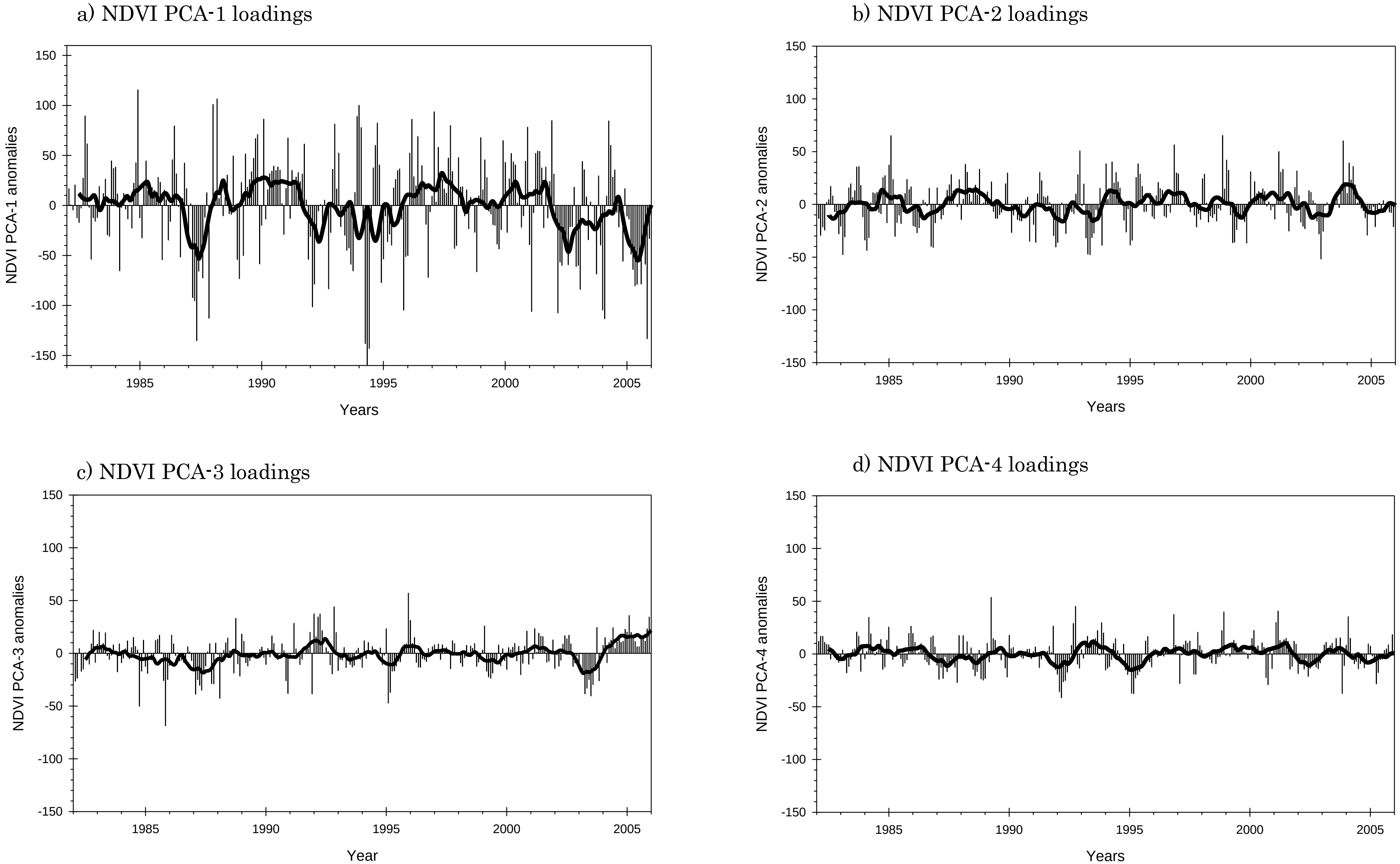


Figure 5.2. Temporal patterns of monthly loadings for NDVI PCA 1 to 4 (bars) with superimposed 12-month running mean (thick line)

On the other hand, since this is the main principal component, the study examines how raw NDVI temporal profiles of the different spatial regions of NDVI PCA-1 image are related to the loadings of PCA-1. A gradual increase in correlationship between monthly NDVI temporal profiles and monthly loadings is noted as we move from the ever-green forest region (r = 0.34) to the grassland plains (r = 0.83). These findings therefore indicate that all vegetation types across Zimbabwe experience variability that is related to mean annual precipitation. However it is on the grasslands and dry savannahs that the strongest relationship with mean annual precipitation is observed. Dye and Walker (1987), using limited field observations, also concluded that the grasslands of Zimbabwe show marked year to year variation in response to droughts and high rainfall seasons. Drought is a creeping disaster (Tannehill, 1947) and it can be difficult to detect when it begins, but these grasslands, with their high anomalies in PCA-1, could serve as early signal points for detecting a drought or dry spell. It is also interesting to note that the low anomaly region in NDVI-PCA-1 is also the area that was predominantly owned by European farmers before the country's recent controversial land reform program. Hence the spatial distribution of NDVI PCA-1 may underline some implications for the social-economic demographics of the country.

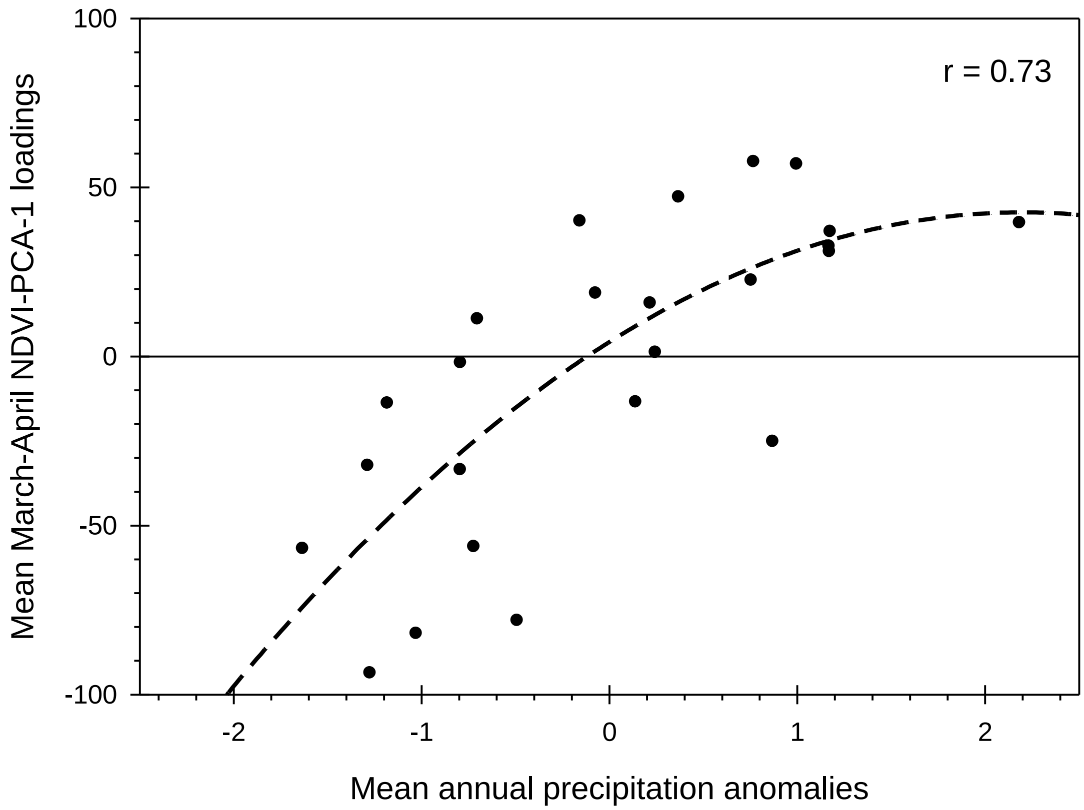


Figure 5.3. The highest correlation between NDVI PCA-1 monthly anomalies and the national mean annual precipitation is obtained with mean March-April NDVI PCA-1 anomalies (r = 0.73). The relationship between precipitation and NDVI seems to decline after a certain level of precipitation (dotted line) in agreement with Funk and Budde (2009) that vegetation response to precipitation diminishes after a given level of precipitation.

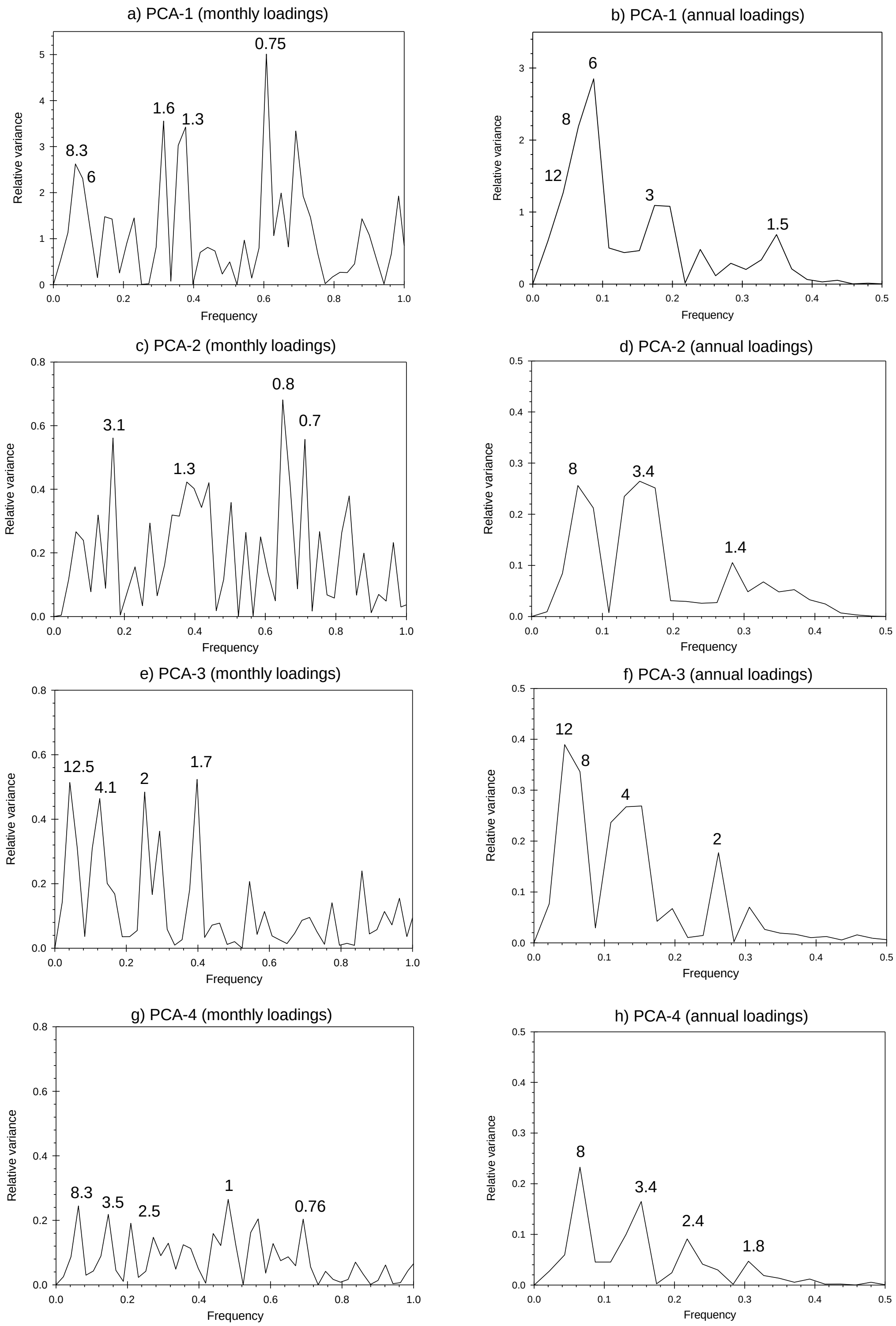


Figure 5.4. The spectral frequencies of the monthly and annual loadings of NDVI PCA 1-4. The spectral peaks are shown in years.

Spectral analysis of the NDVI PCA-1 monthly loadings (Figure 5.4a) reveals dominant peaks at 0.75 and 1.3 years which could be related to the two major changes of vegetation cover in the annual cycle; greening up at rainfall season onset and drying up at the end of the rainfall season. Spectral analysis of the NDVI PCA-1 annual loadings (Figure 5.4b) reveals a dominant broad peak ranging from 6 to 12 years. Therrel et al. (2006) also identified a dominant 8.89 year peak in their 200-year tree ring reconstructions of Zimbabwe's precipitation, and a 10-12 year cycle was reported in regional precipitation (Tyson, 1986; Nicholson and Nyenzi, 1990). The subordinate 3-year peak could be associated with the 2.9 year peak that was identified in Zimbabwe's precipitation (Makarau and Jury, 1997). These spectral analysis results concur with Jury and Mpeta (2005) who reported that the annual cycle of African climate varies coherently over periods of 3 to 8 years, attributed to atmospheric interactions of the Hadley cell over the tropical South Atlantic, standing waves in the southern subtropical jet and the global ENSO.

5.2 Principal Component 2 (PCA-2)

Figure 5.1d shows the spatial distribution of the NDVI PCA-2, which accounts for 6.4% of the total variance in the time series. The most significant pattern in this image is a south-west/northeast mode of anomalies. The highest anomalies are distributed in the low lying Limpopo River basin in the south-west and the lowest anomalies are in the north. This image is highly correlated ($r = 0.86$) to the precipitation PCA-2 (Figure 5.1e) which also exhibits a south-west/north-east mode of anomalies. A similar south-west/north-east mode was observed in outgoing longwave radiation (OLR) over Zimbabwe extending into neighboring countries (Jury and Pathack, 1991; Matarira and Jury, 1992). Since this south-west/north-east mode is observed in both precipitation and vegetation cover, it is likely to be reflecting a climatic phenomenon of significant importance.

The NDVI PCA-2 image is highly correlated (r = 0.87) (Figure 5.5) to the annual relative variability of rainfall map of Zimbabwe (Figure 5.1f). It should be pointed out that to our knowledge this is the first time that the annual relative variability of rainfall map of Zimbabwe is published. The highest rainfall variability is in the south-west of the country and the least rainfall variability is in the north. The northern region experiences the least rainfall variability possibly due to its closer proximity to the preferred location of the ITCZ during the austral summer months. Northern winds in the convergence have higher moisture than the southern winds, leading to less frequent rainfall in the southern areas than the northern for a given air-moisture level (Love et al., 2010). In-fact it is for this reason that the northern provinces of Zimbabwe are the main farming regions of the country (Torrance, 1981). In some years the ITCZ advances no further than 12^{o}S resulting in little rainfall and reduced vegetation cover across much of the country especially in the south. However in the years that the convergence system gets further south then above normal rainfall and vegetation cover, and even floods can be expected in the Limpopo Valley (Unganai and Mason, 2001; Love et al. 2010).

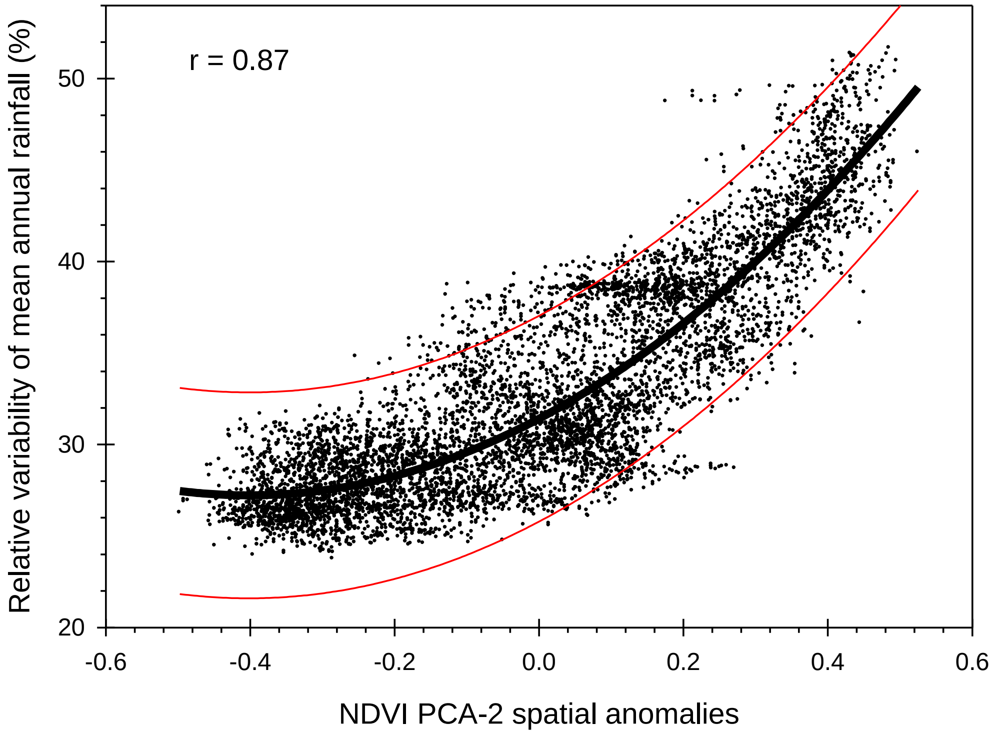


Figure 5.5. Correlation between NDVI PCA-2 and the relative variability of mean annual precipitation (r = 0.87) using approximately 7000 pixels from each image. The red thin lines indicate the 95% prediction range. A sharp increase in rainfall variability is noted from the low anomaly region of NDVI PCA-2 (northern region) to the high anomaly region of NDVI PCA-2 (southern region).

It is important to note in both NDVI PCA-2 and precipitation PCA-2 that the Eastern Highlands, where the highest precipitation is recorded in Zimbabwe, is not exclusively distinguished. Most of the rainfall experienced over Zimbabwe is of convectional type, yet the Eastern Highlands receive contributions from orographic rainfall at various times of the year in addition to convectional type (Torrance, 1981; Nyamapfene, 1991). Therefore PCA-2 is likely to be mainly related to the spatially wider system associated with convectional rainfall.

The temporal pattern of NDVI PCA-2 loadings is shown in Figure 5.2b. In order to understand the relationship between the loadings and NDVI spatial distribution, we created composites from the raw NDVI anomaly imagery for only those months with extreme anomalies

(±1.5 standard deviations (s.d.)) in PCA-2 loadings. The resultant composites for extreme positive anomalies (>1.5s.d.) and extreme negative anomalies (< -1.5s.d.) are strongly correlated to the spatial image of NDVI PCA-2 (r = 0.95) and (r = -0.91) respectively. This indicates that when PCA-2 loadings are positive, the south-west region of Zimbabwe is characterized by above normal NDVI while the north-east experiences below normal NDVI. The pattern is rotated when PCA-2 loadings are negative indicating below normal NDVI in the south-west and above normal NDVI in the northeast. This finding supports literature (Matarira, 1988; Matarira, 1990, Jury and Pathack, 1991; Matarira and Jury, 1992) based on outgoing long wave radiation (OLR) emphasizing that the south-west/north-east mode across Zimbabwe is to be understood as an alternating dipole structure.

Spectral analysis of NDVI PCA-2 monthly loadings (Figure 5.4c) reveals a range of spectral peaks between 1.3 and 0.7 years thereby indicating the significance of the annual cycle in this PCA. At inter-annual times scales (Figure 5.4d) we find dominant spectral peaks at 3.4 – 4 years, and at 8 years. The 4-year cycle has been observed in regional precipitation and has been attributed to the ENSO phenomenon which exhibits a similar spectral peak (Tyson, 1986; Nicholson and Entekhabi, 1986). A dominant 8-year peak was also observed our in PCA-1 and also reported in tree ring reconstructions of Zimbabwe's precipitation (Therrell et al., 2006). Furthermore Jury and Pathack (1991) reported an 8-year cycle in zonal wind index over NE Madagascar and they reported that these zonal winds were negatively correlated to Zimbabwe's rainfall. By showing the presence of these spectra in the northeast/southwest mode, our results provide more evidence supporting Unganai and Mason (2001) who suggested that the fundamental controls of the main rainfall bearing systems of Zimbabwe are more likely to be global or hemispherical rather than regional or local in nature. These findings could contribute to a better understanding of the inter-annual variability of the ITCZ over southern Africa.

5.3 Principal Component 3 (PCA-3)

Figure 5.1g shows the spatial distribution of the NDVI PCA-3. The most distinctive pattern in this image is a south-east/west mode of anomalies with the highest anomalies in the south-east region of the country and the lowest anomalies in the west. The northern part of the country is characterized by anomalies that more or less close to the middle range of anomalies. The NDVI PCA-3 is highly correlated (r = 0.87) to the precipitation PCA-3 (Figure 5.4h). Therefore even though it explains a low amount of the total variability (4.2%), this mode is likely to be reflecting an important climatic phenomenon. Unganai and Mason (2001) who also observed this mode in precipitation using rotated principal component analysis referred to as robust because it was present in all parts of the rainfall season (early, peak, and mid-late season).

Figure 5.2c shows the temporal pattern of NDVI PCA-3 loadings. Composite images made from the raw NDVI anomaly images for months with extreme positive anomalies (>1.5 s.d.) and extreme negative anomalies (<-1.5 s.d.) in PCA-3 loadings are strongly correlated to spatial image of PCA-3 (r = 0.93) and (r = -0.92) respectively. This indicates that when PCA-3 loadings are positive, the south-east region of Zimbabwe is characterized by above normal NDVI while the west experiences below normal NDVI. The pattern is rotated when PCA-3 loadings are negative indicating below normal NDVI in the south-east and above normal NDVI in the west.

Spectral analysis of NDVI PCA-3 monthly loadings (Figure 5.4e) does not indicate a dominant annual cycle as was noted in preceding PCAs. Instead dominant peaks were observed only at inter-annual time-scales suggesting that this mode represents an inter-annual phenomenon. Manatsa and Mukwada (2012), who also observed this spatial mode in precipitation did not examine its loadings and simply basing their comments on its low explained variance they concluded that it is not significant. We argue that the significance of PCA-3 mode is to be evaluated from its presence in both precipitation and vegetation cover. Moreover in any long term time series, such as this 24-year monthly series it is expected that inter-annual phenomenon may show statistically low explained variance, but that does not necessarily imply that the inter-annual phenomenon are not physically important. Spectral analysis of annual loadings (Figure 5.4f) shows a broad dominant 8-12 year peak and a subordinate 4-year peak. These spectral peaks have also been identified in the proceeding PCAs and related to tropical climatic phenomenon. It may therefore be possible that this mode, when it occurs, is exhibited in similar years as the preceding PCA modes but probably in different parts of a single rainfall season. The origin of this south-east/west mode is not clear. Usman and Reason (2004) in their study of intra-seasonal rainfall characteristics over Southern Africa reported that the range of variability in dry spell frequency regime is greater over south-east Zimbabwe and less in the west, and they also identified south-east Zimbabwe as one of the main areas in southern Africa with the largest uncertainty for intra-seasonal rainfall characteristics over any given summer in agreement with the relative variability of precipitation (Fig 5.1f). This could be an interesting topic for further detailed inquiry.

5.4 Principal Component 4 (PCA-4)

Figure 5.1i shows the spatial pattern of NDVI PCA-4, accounting for 3.1% of the total variance. This image is correlated (r = 0.66) to the elevation map of Zimbabwe (Figure 5.1k). The highest anomalies are distributed across the High Veldt and lowest anomalies are distributed across the

Low Veldt. Three broad regions are recognized in Zimbabwe on the basis of elevation: High Veldt (above 1200m), Middle Veldt (900-1200m), and Low Veldt (below 900m). It is interesting to note in the correlation plot (Figure 5.6) that the middle point (50% point) of NDVI PCA-4 anomalies corresponds to an altitude of 968m ± 331m, in agreement with past studies based on aerial surveys reported that the dominant vegetation on the central plateau of Zimbabwe (over 1200m) is savanna woodland and below 900m is more of deciduous tree savanna. Temperature in Zimbabwe is related to altitude, and also follows a similar spatial distribution to that of NDVI PCA-4. A weak negative correlation (r = -0.30) is noted between NDVI PCA-4 and precipitation PCA-4 thereby suggesting an interaction of precipitation, altitude and vegetation cover.

The loadings of NDVI PCA-4 are shown in Figure 5.2d. Composite images of raw NDVI anomaly images for all months with extreme positive anomalies (>1.5 s.d.) and extreme negative anomalies (< -1.5 s.d.) in PCA-4 loadings are strongly correlated to spatial image of PCA-4 (r = 0.88) and (r = -0.87) respectively. This indicates that when PCA-4 loadings are positive, the high elevation areas have above normal NDVI while the low elevation areas have below normal NDVI. The pattern is rotated when PCA-4 loadings are negative indicating below normal NDVI in the high elevation areas and near normal NDVI in the low elevation areas. Since this PCA shows spatial rotation, it may be suggested that it is related to a dynamic climatic phenomenon and not just simply altitude alone.

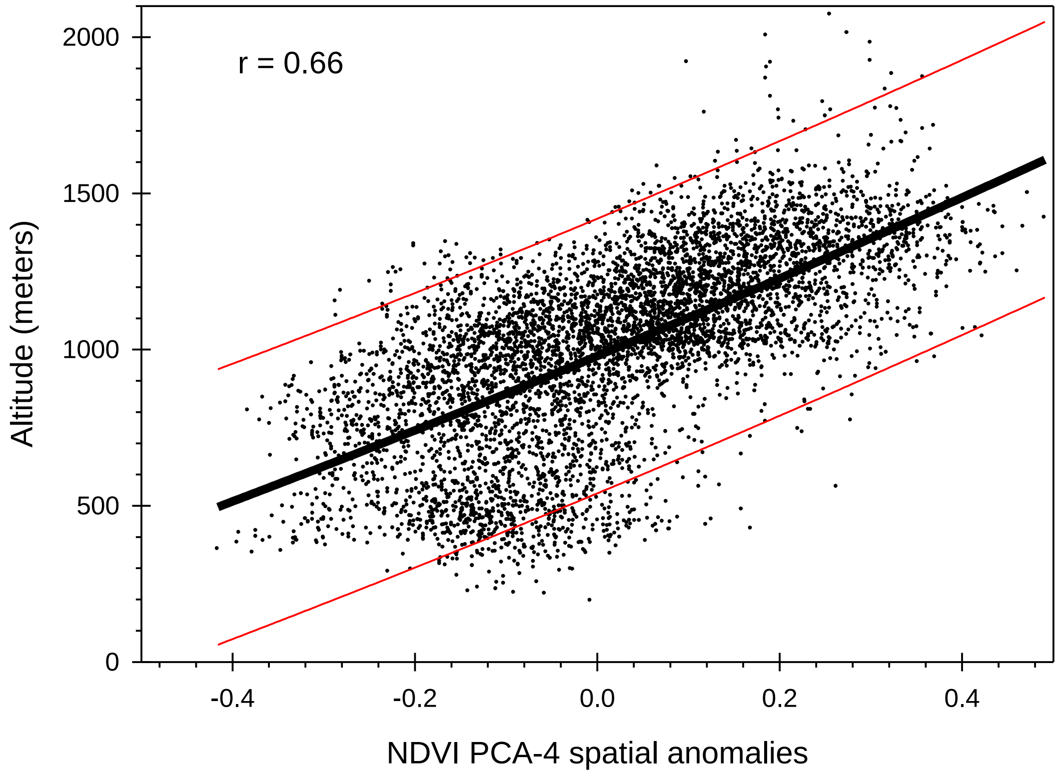


Figure 5.6. Correlation between NDVI PCA-4 and the digital elevation map of Zimbabwe (r = 0.66) using approximately 7000 pixels from each image. The red thin lines indicate the 95% prediction range. A linear increase in NDVI-PCA-4 anomalies is observed from the low altitude regions to the higher altitude regions.

Spectral analysis of NDVI PCA-4 monthly loadings (Figure 5.4g) indicates a dominant 1-year peak which could be associated with the annual cycle of rainfall. Other peaks also noted in the annual loadings (Figure 5.4h) are the 8, 3.4, and 2.4 years, and these were also identified in preceding PCAs. These results suggest that PCA-4 may be exhibited in the same years and seasons that the other preceding PCAs occur.

5.5. Discussion

This study has identified four dominant modes of vegetation variability over Zimbabwe using the 24 year long monthly NDVI time series of NOAA-AVHRR. The first PCA was found to be related to the major vegetation types of the country. These results concur with Nonomura et al. (2003) who also used the first principal component of the NOAA multi-spectral data (the visible channels 1 and 2, and the thermal channel 4) for Africa to produce a macro-scale seven-category African digital vegetation map. Though Nonomura et al. (2003) focused on the continental level, this study has shown that even at the country level the first PCA relates to the dominant vegetation distribution. To enhance the accuracy of any digital vegetation map however, further classification techniques over the PCA-1 image would need to be employed (Nonomura et al., 2003).

Unlike Nonomura et al. (2003) who used non-supervised and supervised classification techniques, this study has demonstrated the possibility of using extracting temporal profile samplings of the different regions of dominant vegetation, and comparing the temporal profiles to the PCA loadings. Extraction of temporal profiles for specific regions of PCA-1 spatial image was made possible by using the Earth Trends Modeler of IDRISI software. It was therefore possible to determine which regions of PCA-1 spatial image are more correlated to the loadings of PCA-1, and in this case it was noted that PCA-1 loadings were more correlated to dry grasslands temporal profiles than to evergreen forest region temporal profiles. By further related the loadings of NDVI PCA-1 to precipitation, it could be concluded that dry grasslands show marked response to precipitation variability than evergreen forests. Many past studies that employed principal components analysis have tended not to make use of the component loadings (Unganai and Mason, 2002). However the technique demonstrated here can be recommended for other area studies to decipher the meaning of the first PCA loadings.

Among the four NDVI PCAs spatial images it was noted that only PCA-1 did not have negative anomalies while PCA 2, 3 and 4 spatial images had both negative and positive anomalies. A question is why only PCA-1 did not have any negative anomalies? Was it just by chance? It was also noted that precipitation PCA-1 did not have any negative anomalies while precipitation PCA 2, 3 and 4 had both negative and positive anomalies. Manatsa and Mukwada (2012) who also performed PCA analysis on Zimbabwe's standardized precipitation index also reported the fact that only PCA-1 did not have negative anomalies but they could not provide a reason for such a trend. The lack of rotation for NDVI PCA-1 could be related to the observation that all vegetation types over Zimbabwe are positively correlated to the loadings of PCA-1, and also to precipitation, though the dry grasslands experience greater response to precipitation than evergreen forests. A possible interpretation of the rotation of PCA-2 is presented in Chapter 6. However more work is still needed to understand the meaning of the possible rotation of PCA 3, and 4. Such knowledge could be useful for determining applications for the agricultural and water resources sectors.

This study has demonstrated that spectral analysis can be a useful technique to obtain useful information from NDVI PCA loadings. The spectral analysis method which was used to decompose the NDVI PCA loadings revealed several periodicities including the annual cycle which corresponds to the summer rainfall season and inter-annual cycles which correspond to those found in tropical sea surface temperatures as reported in literature (Nicholson and Nyenzi, 1990). To the authors knowledge this is the first time that spectral peaks similar to those of SSTs and precipitation are revealed in the vegetation cycles across Zimbabwe. Though Therrell et al., (2006) determined spectral peaks in Zimbabwean tree-rings, their study sampled only 21 trees from four sites in Zimbabwe. In the case of NDVI PCA-3, the annual cycle was not observed and only inter-annual dominant peaks were noted. Here it is suggested that PCA-3 is an inter-annual mode, and care ought to be taken not to underestimate its significance simply based on its statistically low explained variance. Since PCA-3 mode was observed in both precipitation and NDVI, it is likely to be showing an important climatic phenomenon which occurs at inter-annual time scales.

The analysis has also illustrated that NDVI-precipitation relationships are not limited to mean annual/seasonal precipitation, but can also be related to other aspects of precipitation. For example high correlation between NDVI PCA-2 and annual relative variability of rainfall were noted. Zimbabwe's map of mean annual relative variability of precipitation was presented here for the first time, and it is suggested that such crucial maps be created for other African countries which may still lack of it. Since NDVI PCA-2 and the mean annual relative variability map do not highlight the Eastern Highlands of Zimbabwe where the highest rainfall is received, we have thus associated PCA-2 to the influence of a spatially wider system associated with convectional rainfall, not the orographic rainfall effects that are localized in the Eastern Highlands. Rainfall variability decreases with rainfall increase.

The study has identified the major spatial and temporal modes of vegetation variability over Zimbabwe. Though some possible dynamical linkages have been discussed for all NDVI PCAs, there is a need for further inquiry into the mechanisms of these modes especially NDVI PCA-3 and 4. Since the principal components are orthogonal to each other, it could be expected that after PCA-1 showed correlation to mean annual precipitation, the other components would not show any correlation to the same precipitation parameter. It is possible that the loadings of PCA 2-4 could be correlated to other precipitation parameters or other parts of the seasonal distribution of precipitation. This could be an interesting subject for future studies. The unique methodology of relating the PCA-loading patterns to the spatial pattern has contributed to the description of the rotation of the PCAs.

CHAPTER 6
TEMPORAL PATTERNS OF DRY AND ABOVE NORMAL WET YEARS, AND RELATIONSHIPS TO THE EL NIÑO SOUTHERN OSCILLATION (ENSO)

This Chapter investigates the intra-seasonal trends of major dry years and above normal wet years over Zimbabwe. The Chapter begins with an investigation of the spatio-temporal evolution of major dry years and above normal wet years over Zimbabwe using both precipitation and the normalized difference vegetation index (NDVI) data. The investigation also identifies the months of the growing season that are vulnerable to drought and mid-season dry spell effects, and also to explore the implications of this knowledge for agricultural adaptation policies. Thereafter a rigorous correlation analysis is performed to determine the predictability of Zimbabwe's NDVI variability using four El Niño indices. The four indices are: The Southern Oscillation Index (SOI), Niño 3.4, Niño 3, and the Multivariate ENSO index.

6.1 Rainfall Patterns

Mean Conditions

Figure 6.1a shows the mean monthly rainfall maps of Zimbabwe. Rainfall over Zimbabwe is a seasonal phenomena occurring mainly in the austral summer months (October to April). The highest rainfall is received in the Eastern Highlands region and the lowest rainfall is received in the south in all months of the rainfall season. It is interesting to note that in November, when the rainfall season has just begun, more rainfall is received over the central plateau stretching from the north-east to south-west which is the high elevation area of Zimbabwe. In the peak rainfall season months there is a north-south gradient of precipitation with higher rainfall in the north than in the south. It should be noted that this north-south mode is similar to the precipitation PCA-2 and NDVI PCA-2. This north-south mode is consistent with higher moisture content of air-streams that approach Zimbabwe from the northwest and northeast (Unganai and Mason, 2002). Therefore topography and the direction of moisture bringing air currents play an important role in influencing the spatial distribution of precipitation.

Box-plots of the national mean monthly rainfall are shown in Figure 6.2a. Peak rainfall is received from December to February. However the large inter-quartile ranges, indicating the highest precipitation variability are in January and February. Moreover the month of February has the greatest dispersion of upper and lower quartiles and outliers. These months with high precipitation variability are likely to be the key months when distinctive impacts of extreme dry and wet seasons are to be most expected as shown in Figure 6.2b.

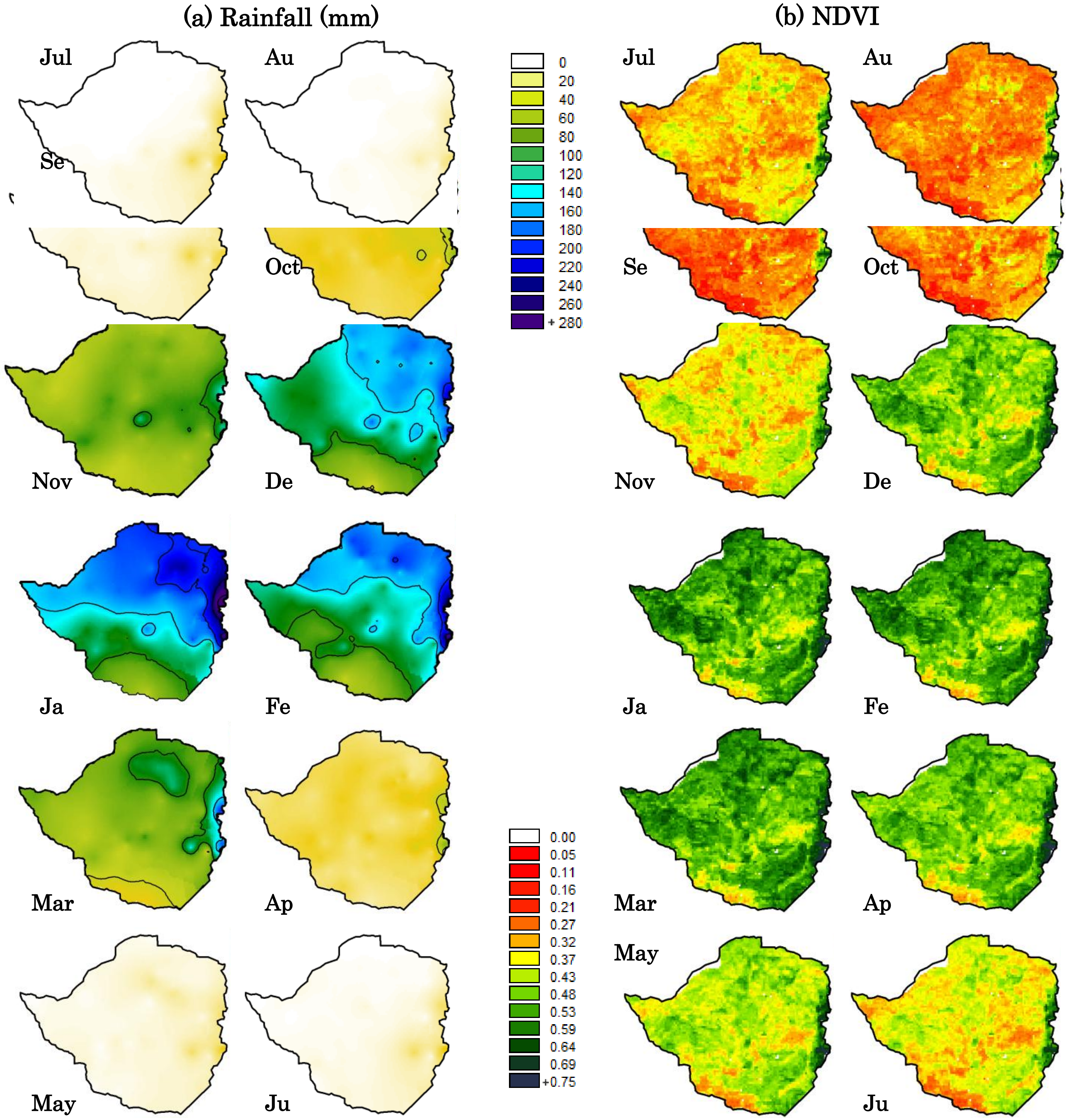


Figure 6.1. (a) Mean monthly rainfall (left two columns) with 50mm contour lines. Soon after rainfall season (November) more rainfall is received across the central plateau and during peak rainfall months (December-February) a north-east/south-west gradient is noted. (b) Mean monthly NDVI (right two columns) showing vegetation seasonality across most of the country with the exception of the Eastern Highlands where highest rainfall is received.

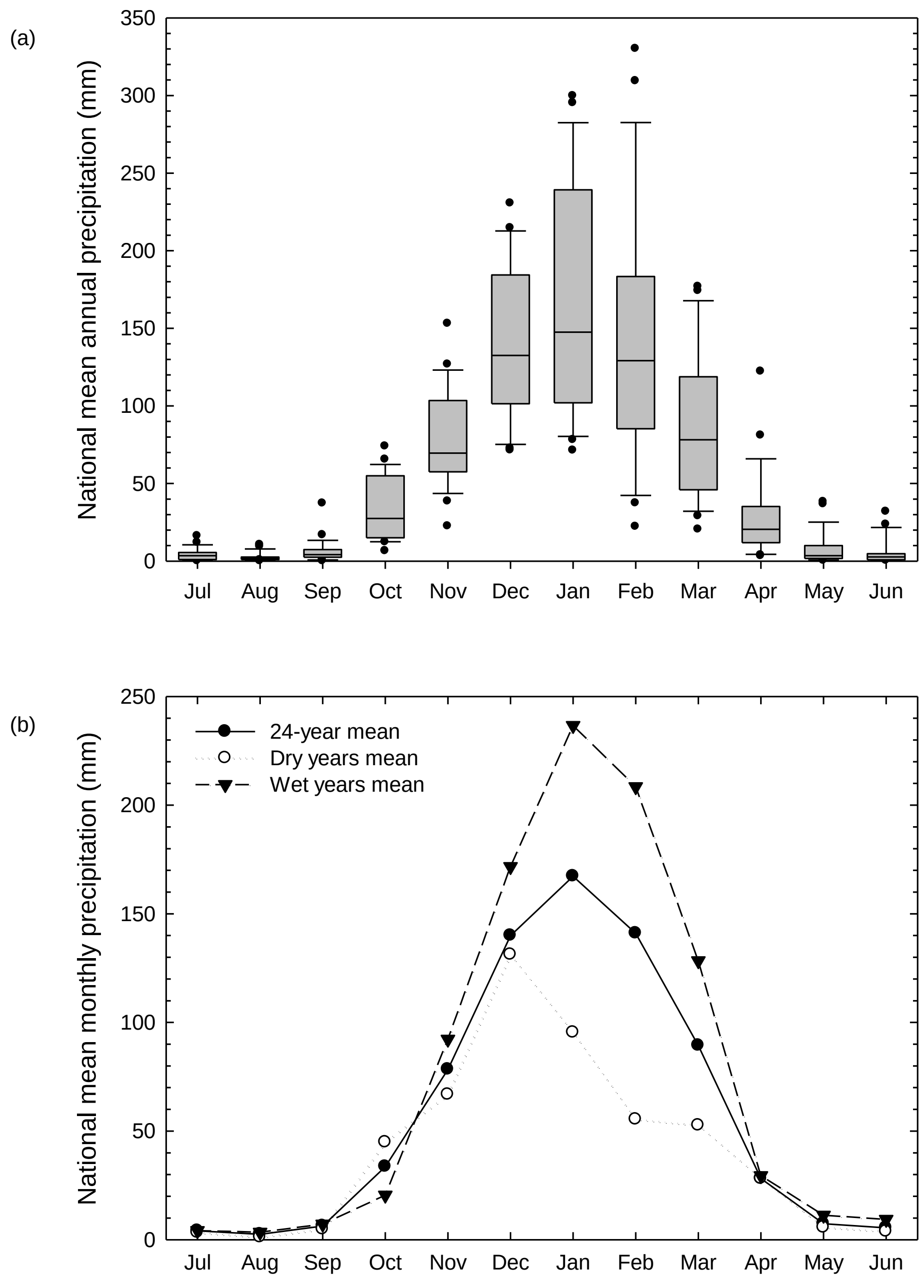


Figure 6.2. (a) Box plots of Zimbabwe's mean monthly rainfall. The top and bottom of the boxes show the upper and lower quartiles respectively and the middle line represents the median. Upper and lower fences show extreme values and dots show outliers. Though peak rainfall is received from December to February, these months also exhibit high rainfall variability. (b) Mean monthly rainfall for normal, dry and wet years. The length of rainfall season is shorter for in dry years than in above normal wet years.

Above Normal Wet Years and Major Dry Years - Extreme Anomalies

Figure 6.3a shows the mean monthly precipitation anomaly maps for above normal wet years. In October, when the mean rainfall season is expected to begin, we find negative precipitation anomalies in the north-western part of the country while the southern part experiences near normal precipitation anomalies. The southern part of the country continues to exhibit higher precipitation anomalies than the north in November and December. This finding is very interesting because in mean rainfall seasons more rainfall was noted in the northern parts. Country-wide positive precipitation anomalies in above normal rainfall seasons are observed in January and February. Then in March when the rainfall season approaches cessation, positive precipitation anomalies are mainly distributed in the north-east.

Figure 6.3b shows the mean monthly precipitation anomaly maps for major dry years. When the rainfall season begins in October, the north-western region is characterized by positive rainfall anomalies while the southern region exhibits near normal precipitation. As the first half of the rainfall season progresses, scattered areas of negative rainfall anomalies are observed across the country. There are country-wide negative rainfall anomalies in January and February, indicating that these are the months when the negative consequences of drought are experienced. As the rainfall season approaches cessation (March), persistent negative precipitation anomalies are noted in the north-east and south-east.

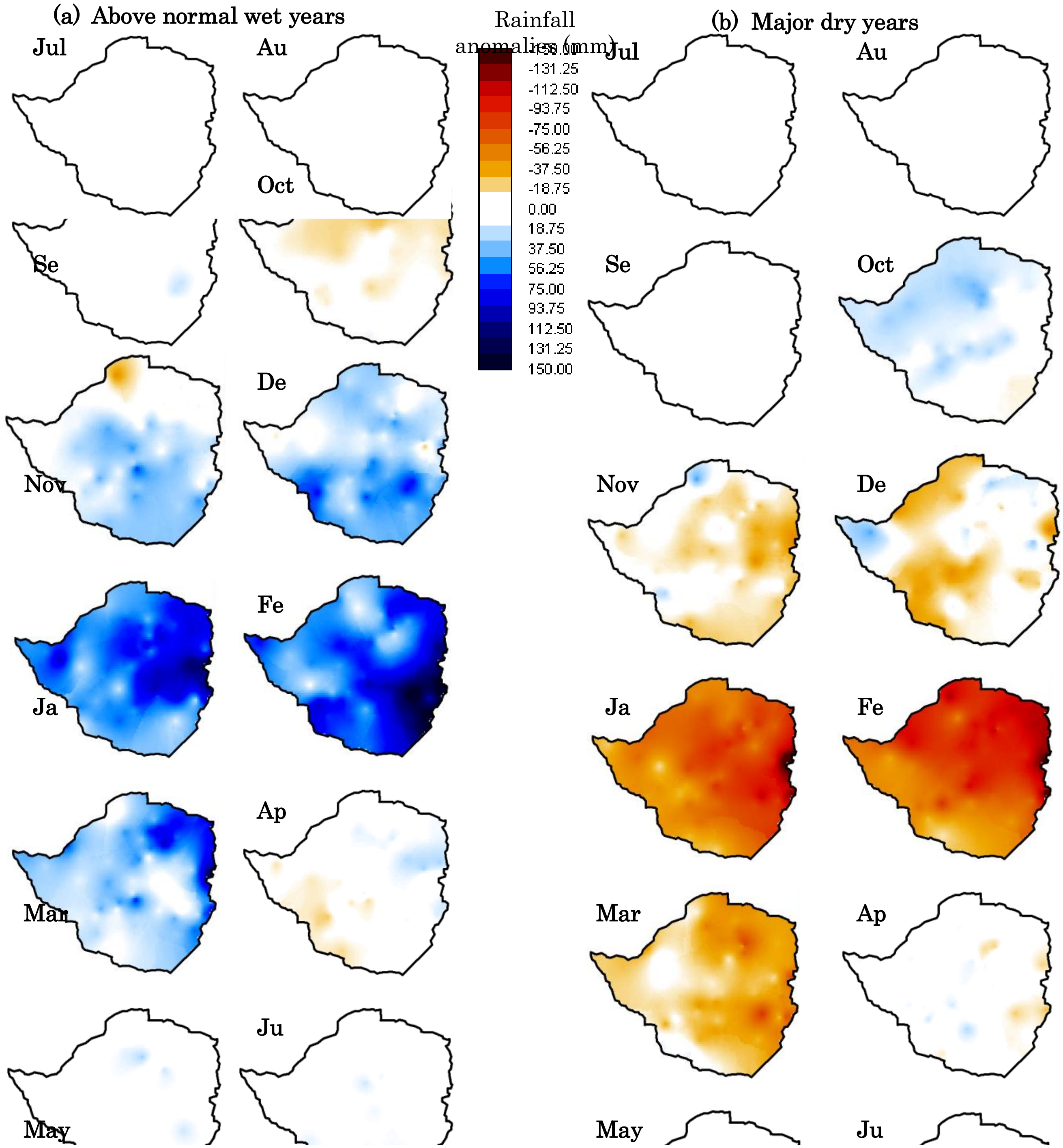


Figure 6.3. Anomalies of mean monthly precipitation for (a) above normal wet years (left two columns) and (b) major dry years (right two columns) over Zimbabwe. The onset of rainfall season (October) in the north-west is characterized by an inverse pattern of rainfall for above normal wet seasons and dry years. Soon after season onset in above normal wet years (November-December), the south part of the country is characterized by above normal rainfall. The largest positive and negative anomalies are in the south-east and least in the west.

6.2 NDVI Patterns

Mean Conditions

Figure 6.1b shows the mean monthly NDVI patterns over Zimbabwe. A seasonal cycle of vegetation variability with distinct dry and vegetative periods is observed over most of the country corresponding to the rainfall season cycle. An exception to this vegetation cycle is noted in the Eastern Highlands where evergreen montane forests and plantation estates are sustained by the high rainfall which is characteristic of this unique geographical region. However over the large proportion of the country there is vegetation greening up in October-November corresponding to onset of the rainfall season, and vegetation decline in April-May after rainfall cessation.

Figure 6.4 shows the temporal patterns of national mean monthly NDVI. Despite all 24 curves in the time series following a sinusoidal pattern corresponding to the seasonal precipitation cycle, they all exhibit some variability indicative of the cumulative effects of different precipitation regimes on the vegetation cycles. Two peaks of coefficient of variation (CV) are noted; a sharp early growing season peak (November) and a wide peak at the end of the growing season (May). The early growing season peak could be attributed to variations in the onset of rainfall season dates. Dry savannahs and grasslands that dominate much of Zimbabwe's natural vegetation respond remarkably to rainfall season onset (Dye, 1987) hence seasons with early rainfall onset will experience remarkably higher NDVI in the early growing season than those seasons with late rainfall onset. The second peak which is in the late growing season months could be associated with the variability of cessation of rainfall season that has also been reported in literature (Tadross et al., 2005). The lowest coefficient of variation is noted after the peak rainfall season when vegetation biomass production is expected to be peaking and further increases in rainfall are associated with diminished biomass production (Funk and Budde, 2009).

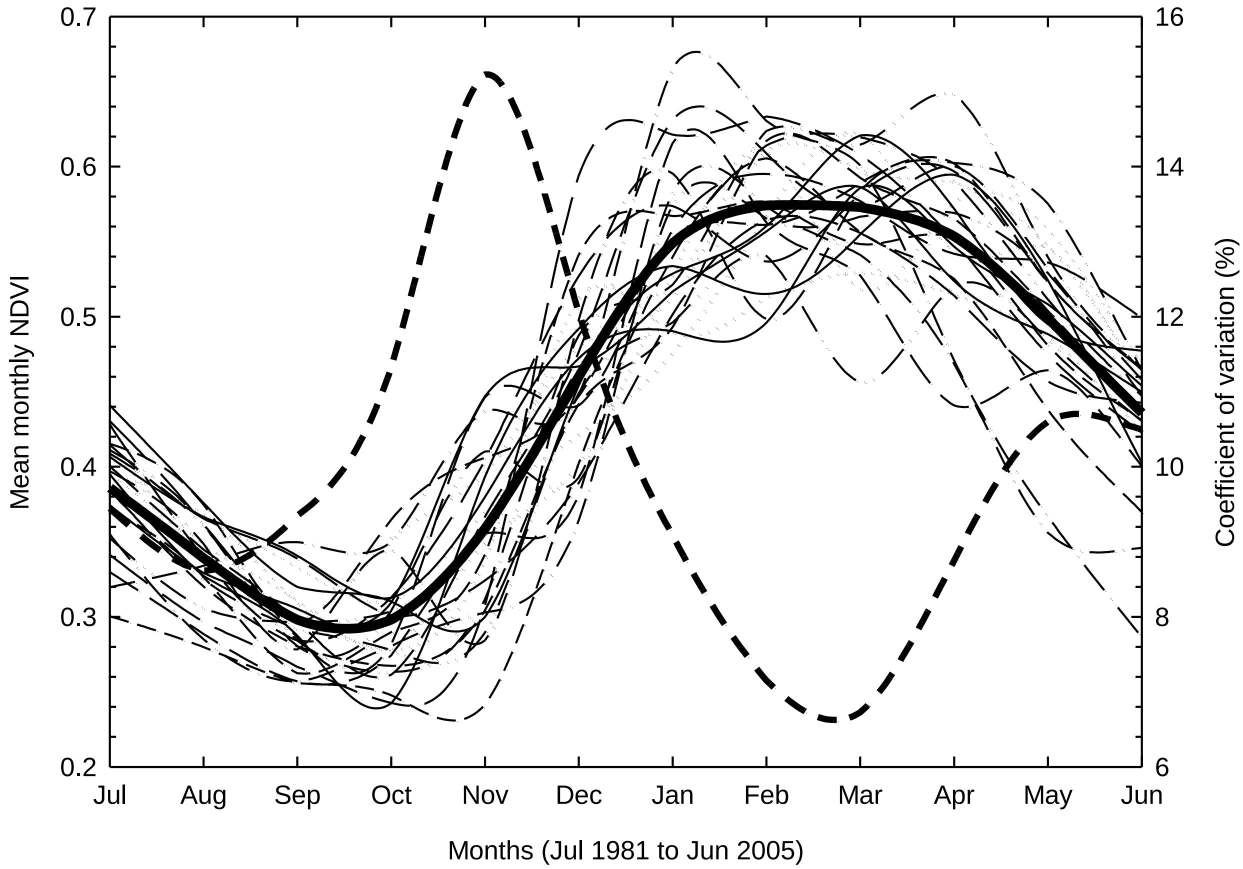


Figure 6.4. Mean monthly NDVI patterns for the 24 years (thin lines) showing the cumulative effects of different precipitation regimes on the vegetation cycles. The thick line represents the mean monthly NDVI for all 24 years. Months of decreased NDVI correspond to the dry season and months of increased NDVI correspond to the rainy season. The two peaks of coefficient of variation (CV), one in the early growing season (November) and another at the end of the growing season (May), can be related to variations in the onset and cessation of the rainfall season respectively. The lowest coefficient of variation is after the peak rainfall season when vegetation biomass production is peaking.

Over the 24 years in the time series, minimum NDVI is noted mainly in two months, September (40%) and October (48%), in contrast to maximum NDVI which is noted over four months with the following frequencies; January (20%), February (36%), March (24%), and April (20%). Maximum NDVI or peak NDVI is often analyzed in terms of its magnitude, however here it is noted that it also has a wide temporal variability. Maximum NDVI represents peak biomass production and the wide temporal variability observed here further hints on the intra-seasonal variability of precipitation distributions.

Above Normal Wet Years and Major Dry Years

Figure 6.5a shows the mean monthly NDVI anomaly images over Zimbabwe for above normal wet years. In October and November negative NDVI anomalies are observed in the north-west, while the south-eastern regions exhibit near normal to positive NDVI anomalies, corresponding to observations for precipitation. As the growing season progresses (December-March) positive NDVI anomalies are noted mostly concentrated in the south-western region also similar to the spatial pattern observed in precipitation. It is interesting to note that in February, the northern regions experience some negative NDVI anomalies that can be related to mid-season dry spells. At the end of the growing season (April) we find positive NDVI anomalies in the north-east. On the contrary, the early season months of major dry years (October-November) are characterized by above normal NDVI in the north-west (Figure 6.5b). Scattered patches of below normal NDVI are noted as from December, and country-wide negative anomalies are noted as from March.

An inverse pattern therefore emerges between the early season and late season NDVI for major dry seasons and above normal wet seasons (Figure 6.6a-c). Summary statistics comparing mean monthly NDVI for major dry years and above normal wet years are shown in Table 6.1. Student's t-tests confirm that the NDVI means in November (early growing season) for major dry years are significantly greater ($p < 0.05$) than those for above normal wet years, and that the NDVI means in March and April (mid-late season) for the major dry years are significantly lower ($p < 0.05$) than those for above normal wet years. Furthermore significant ($p < 0.05$) negative correlations between November NDVI anomalies, and the NDVI anomalies for February ($r = -0.49$) and March ($r = -0.46$) indicate the inverse relationship. To our knowledge this is the first time that this inverse pattern is shown in both precipitation and NDVI over Zimbabwe, though some literature for other parts of Africa have also noted such an inverse pattern (Nicholson and Etkembi, 1986; Hachigonta and Reason, 2005; Reason et al., 2005; Reason et al. 2006; Tadross et al., 2006). It is also interesting to note that this inverse pattern seems to fit in with some of the indigenous traditional seasonal forecasting methods that have been outlined by Kihupi et al. (2003) including, but not limited to: rapid drying up of springs and wells in August-September indicating good rains.

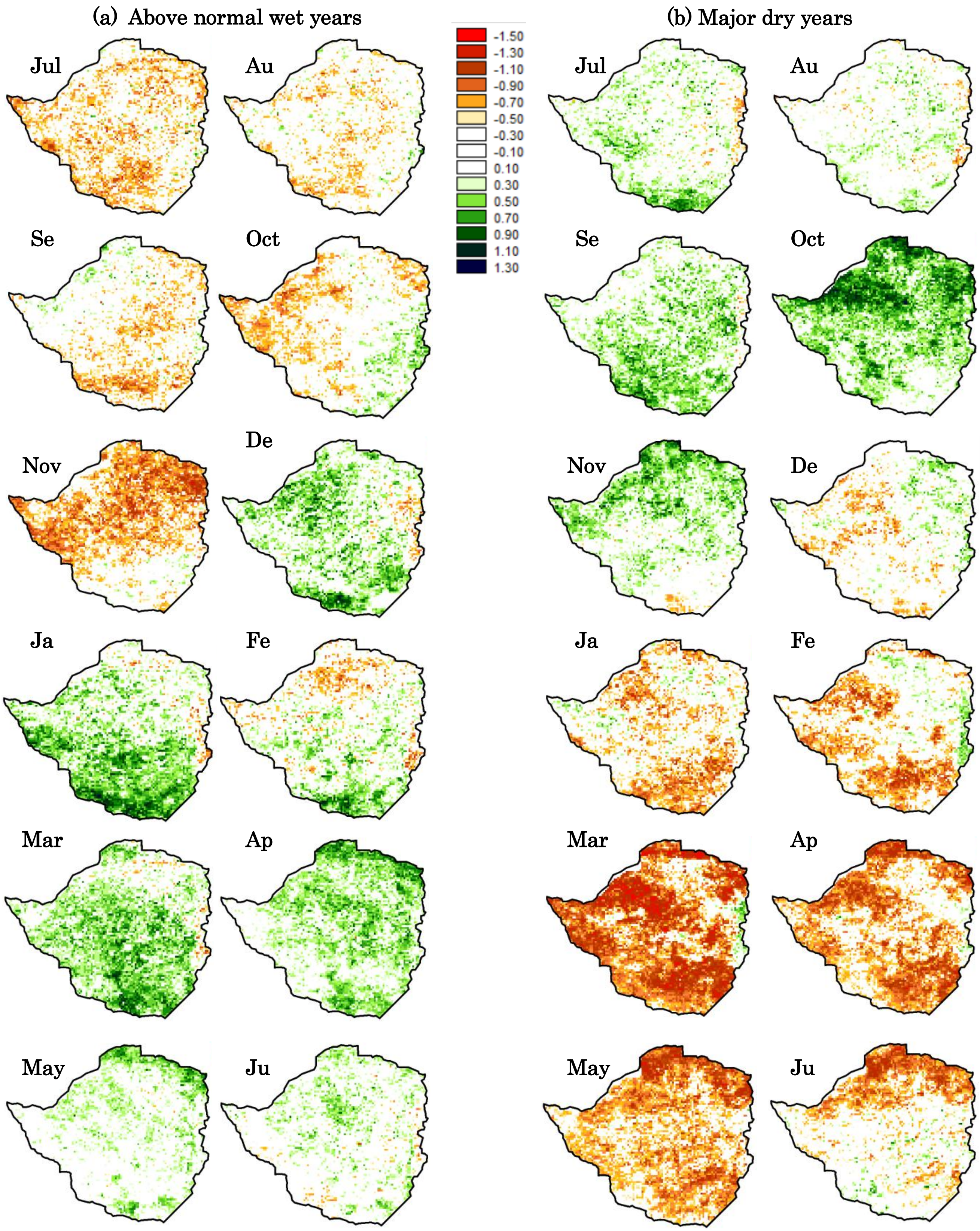


Figure 6.5. NDVI anomalies for (a) above normal wet years (left two columns) and (b) major dry years (right two columns) over Zimbabwe. These NDVI results corroborate the precipitation analysis showing an inverse pattern during months of season onset (October and November) for wet and dry years, and also an inverted north-east/south-west mode of anomalies after season onset in above normal wet years (December-March).

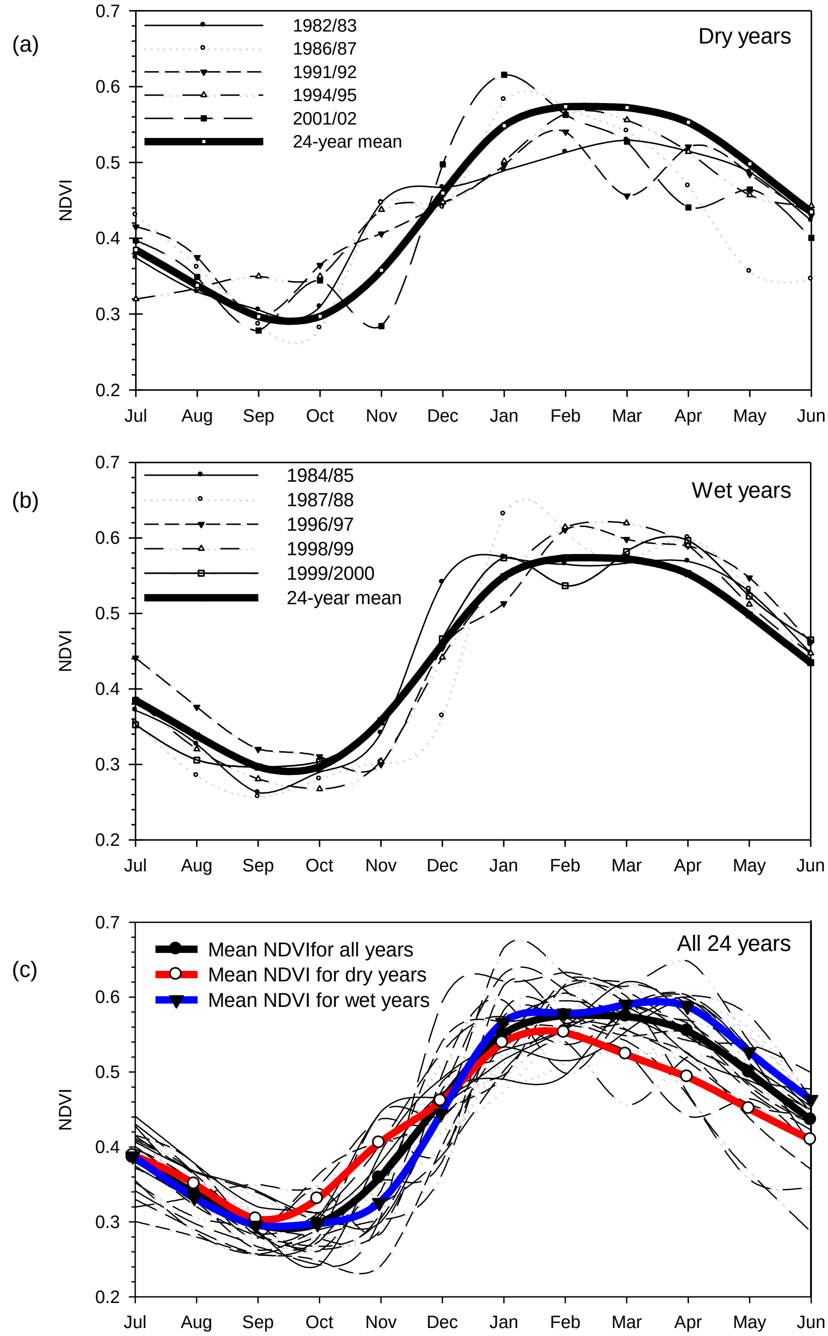


Figure 6.6. NDVI temporal profiles for (a) five major dry years and (b) five above normal wet years. (c) An inverse pattern emerges between early season and late season NDVI for major dry years and above normal wet years.

Table 6.1. Summary statistics of monthly NDVI for major dry years and above normal wet years. Months with significant differences between drought and wet years NDVI means are marked (*).

Month	Mean ± SD for Major Dry Years	Mean ± SD for Wet Years
Oct	0.325 ± 0.033	0.297 ± 0.019
Nov *	0.426 ± 0.025	0.341 ± 0.043
Dec	0.465 ± 0.035	0.486 ± 0.045
Jan	0.517 ± 0.038	0.561 ± 0.032
Feb	0.550 ± 0.024	0.565 ± 0.049
Mar *	0.534 ± 0.048	0.590 ± 0.020
Apr *	0.508 ± 0.023	0.590 ± 0.013

6.3 In-depth Analysis of the Temporal Patterns of Dry and Wet Years

Despite the above noted inverse pattern, some important variations in the temporal patterns of major dry years are also observed. Three different temporal patterns for major dry years were distinguished. The first pattern (Figure 6.7a) observed in the extreme agricultural drought of 1991/92, is characterized by sustained below normal NDVI starting from December-January (mid-season) until end of the growing season with peak NDVI that is below the mean NDVI curve. This drought was particularly catastrophic because additionally it nested a temporary NDVI decline with a magnitude of -0.1 units of NDVI which was a 1 month lag response by vegetation to a rainfall decline in February. Our NDVI findings are supported by Kinsey et al. (1998) reporting that exceptionally dry conditions in January and February of 1992 crippled agriculture as crops withered and livestock perished in their thousands. The second temporal pattern of major droughts (Figure 6.7b) observed in 1986/87 season is characterized by near normal NDVI from season onset until February - March (mid season) thereafter followed by a sharp NDVI decline which persists through the post season months. Post season NDVI condition is very important for smallholder farmers who rely on natural vegetation all year round for livestock feed and other goods and services yet most studies of NDVI variability in Southern Africa have limited themselves to the rainfall season months focusing only on crop-yield forecasts (Funk and Budde, 2009). The third temporal pattern (Figure 6.7c) impacting both the early season and mid-late season is observed in 1994/95. These distinctive variations in the temporal patterns of major dry years suggest that different approaches to adaptation and mitigation may be necessary in the agricultural and water security sectors to deal with different low rainfall/drought regimes.

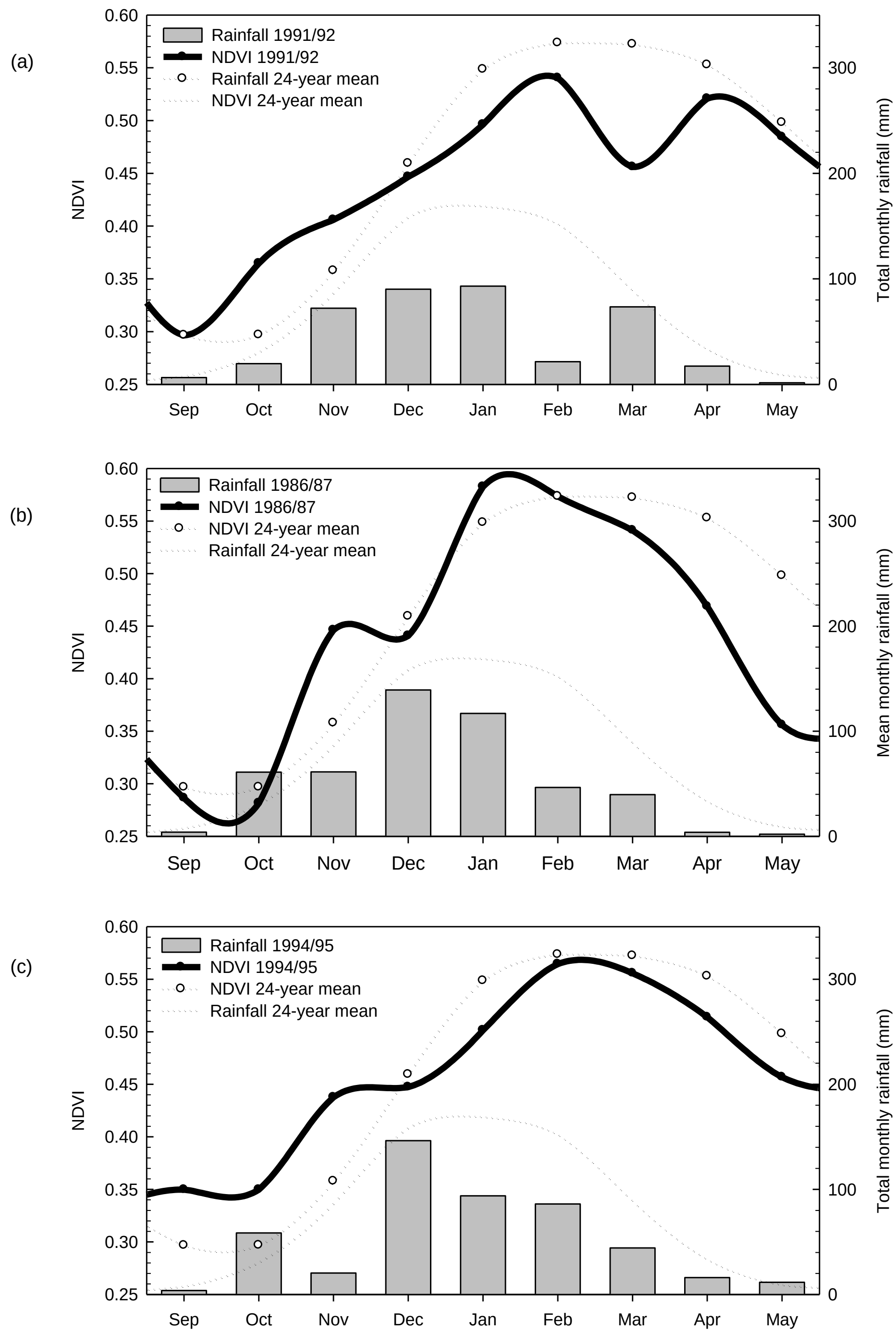


Figure 6.7. In depth analysis showing three distinct temporal patterns for major dry years. (a) The 1991/92 drought experienced below normal maximum NDVI and a nested mid-season dry spell. (b) The 1986/87 drought was characterized by a sharp decline of NDVI from mid-season and extending into post-season months. (c) The 1994/95 drought experienced a temporal dry spell in the early season months.

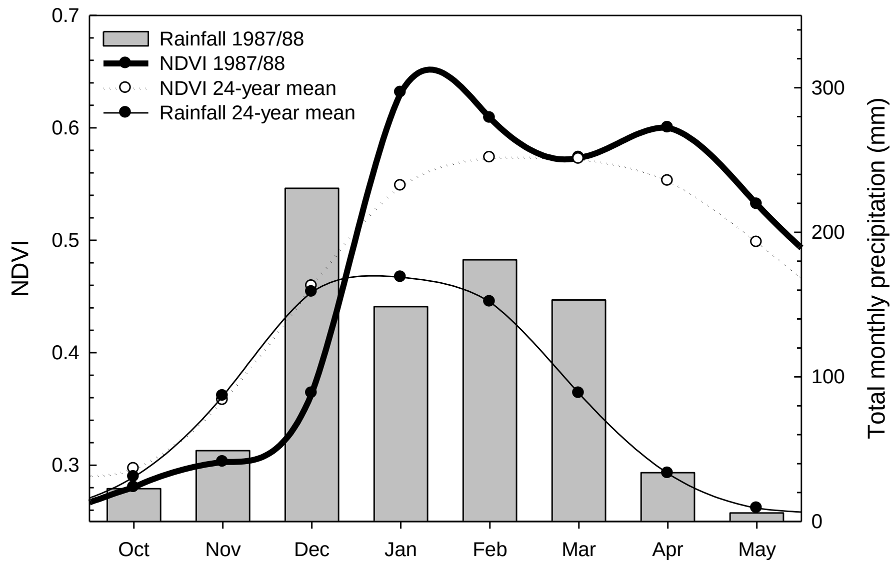


Figure 6.8. A close examination of the 1997/88 indicates that even above normal rainfall seasons may experience temporary shortfalls of rainfall in the middle of the season, that are significant enough to be reflected in the national mean NDVI series.

In the NDVI curves of above normal rainfall seasons (Figure 6.6b) a tendency of double peaks of NDVI maxima is noted. In some years the maximum NDVI occurs in the first peak whereas in other seasons it is observed in the second peak. The months of February and March seem to be prone to temporary declines of NDVI. A close assessment of this double peak pattern using the 1987/88 season (Figure 6.8) demonstrates that the temporary NDVI decline is a lagged response by vegetation to a preceding mid-season dry spell. Makarau and Jury (1997) also reported the possibility of two major wet spells per season influenced by the baroclinic westerly shear-influenced early summer and the barotropic easterly dominated later summer. The second major wet spell, which results in a delayed cessation of the rainfall season, may sometimes hamper drying of seeds and harvesting activities, particularly for farmers who may have planted short seasoned crop varieties while expecting a drought.

6.4 Long-term patterns

Figure 6.9 shows the continuous monthly NDVI time-series from July 1981 to June 2006. It should be emphasize that each point on this curve represents the mean of approximately 7000 pixels of monthly NDVI composites. The peaks in the graph represent rainy season months (October–March) while troughs represent dry (winter) season months. A distinctive feature in this plot is the presence/absence troughs (‘V’ shapes) during peaks of the growing seasons indicating temporary declines in NDVI. It was shown earlier using the case study of 1991/92 and 1987/88 that these temporary NDVI declines are associated with mid-season shortfalls of precipitation. It is interesting that both dry years and major wet years can experience some mid-season dry spells. However the temporary NDVI declines in wet years are still higher than the peak NDVI of some of the dry years. It is interesting to note that there are epochs when mid-season dry spells seem to be mild (e.g. 1982-1986), almost absent (e.g. 1996-1998), and very strong (e.g. 2000-2004). Mid-season dry spells are a big problem for agriculturalists in Southern Africa and there is still limited information about their occurrence and trends. These results suggest that NDVI could be a useful proxy for investigating the variability of mid-season dry spell phenomenon.

Figure 6.10 shows the z-scores of monthly NDVI from 1981 to 2005. Unlike the national mean NDVI time series, the anomaly (z-scores) time series shows the position of each monthly NDVI value relative to the mean value for that particular month in the 24-year time series. This z-score time series is not limited to rainfall season months, but rather shows all months of the year. In the superimposed 12-month running mean an inter-annual pattern emerges with troughs in 1983, 1987, 1992, 1994, 1995, 2002-03, and 2005, and peaks in 1986-87, 1996-98, and 2000.

These troughs and peaks correspond to the major dry years and wet years that have been discussed in greater detail in the earlier part of this study. It is important to note that the 1991/92 season which was earlier described as the most extreme drought is not the most prolonged period of negative NDVI anomalies. Instead 2001 to 2003 emerges as the longest period of continuous negative NDVI anomalies extending through the post growing season months and into the proceeding growing seasons. Correlation analysis between the NDVI z-scores and total annual precipitation shows the highest correlation coefficient (r = 0.74) with mid-end of season NDVI (March-April) as shown in Figure 6.11. This agrees with the earlier results (Table 1) showing significant differences between the NDVI means of March and April for drought and wet years, associated with core rainfall season precipitation.

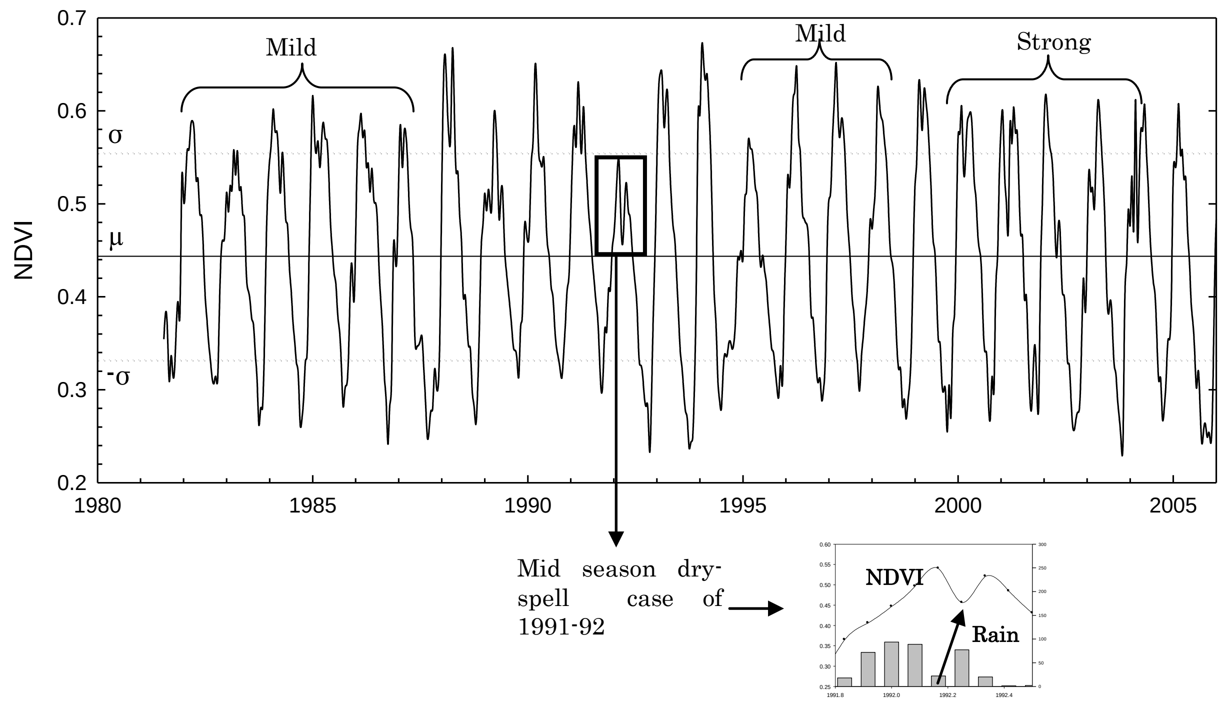


Figure 6.9. The time series of mean national NDVI for Zimbabwe. The peaks represent rainy seasons months and troughs represent dry season months. A distinctive feature of this plot is the presence/absence of troughs 'V' shapes in the middle of the peaks. The insert showing the case of 1991/92 suggests that these 'V' shapes can be associated with mid-season dry spells of precipitation. There are epochs when mid-season dry spells seem to be mild (e.g. 1982-1986), almost absent (e.g. 1996-1998), and very strong (e.g. 2000-2004).

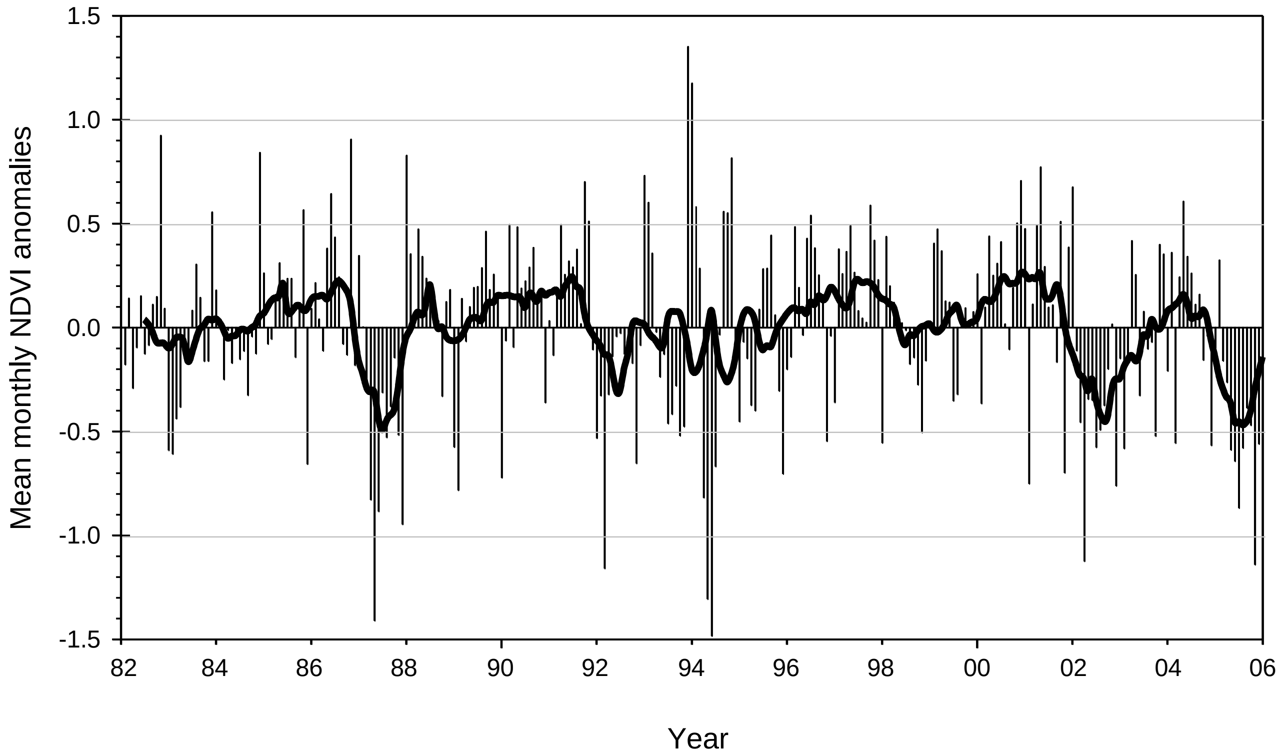


Figure 6.10. Z-scores of Zimbabwe's monthly NDVI (bars). The superimposed 12-month running mean (thick line) shows an inter-annual pattern with troughs and peaks corresponding to major drought and wets seasons respectively. 2001-2003 emerges as the longest period with negative NDVI anomalies spanning through the post-rainfall season months and into the preceding season.

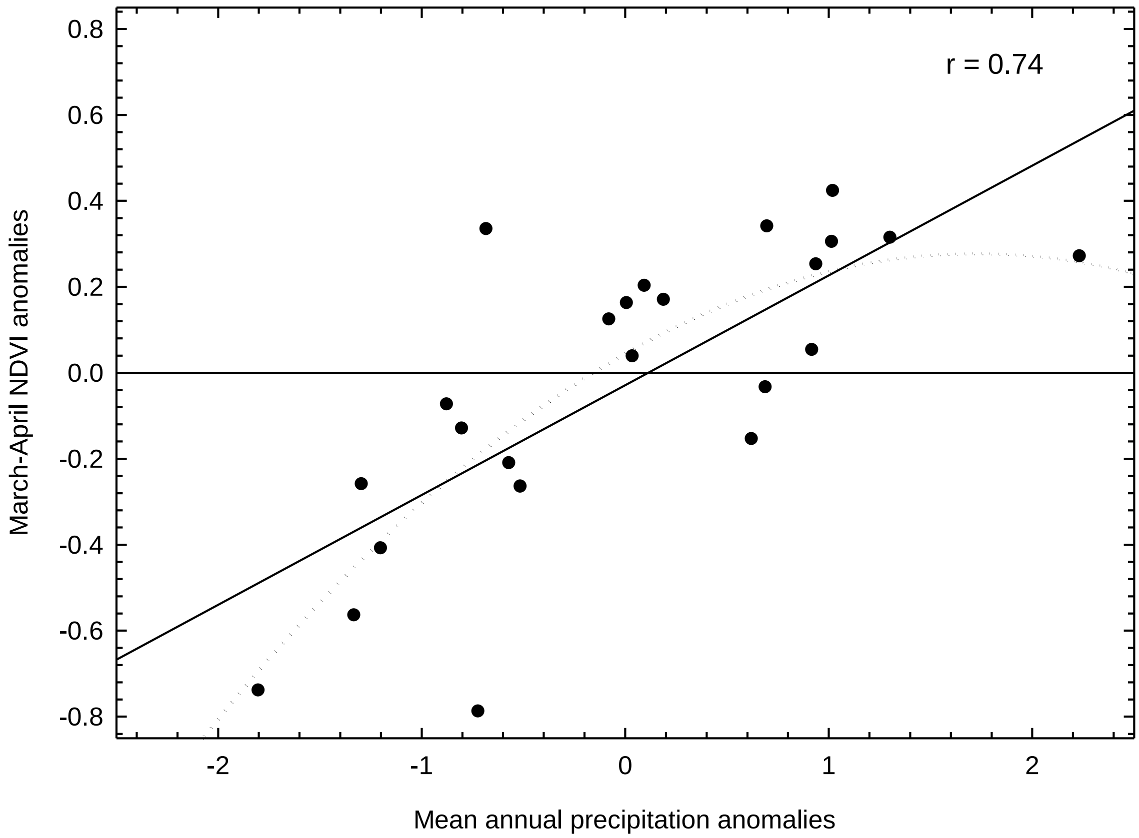


Figure 6.11. The highest correlation (r = 0.74) between NDVI anomalies and total annual precipitation anomalies is obtained with the March-April NDVI anomalies. The relationship between precipitation and NDVI (dotted line) seems to diminish after a certain level of precipitation.

6.5 Correlation Analysis between NDVI–z-scores (PCA-1 loadings) with Global Sea Surface Temperatures (SSTs)

In light of the strong relationship between NDVI anomalies and precipitation, further investigations to determine the long range predictability of Zimbabwe's vegetation cover condition were made. Significant correlations were noted with the Pacific Niño 3.4 region, the Indian Ocean Dipole region and the South-East Atlantic Ocean (Figure 6.12) with peak correlation coefficients of r = -0.30. The largest area of correlationship is noted in the central to eastern Pacific Ocean. This region corresponds to the Niño-3 to Niño 4 region. This is the first time the correlationship between Zimbabwe's NDVI and global SSTs is shown. These results are also very important because they verify the notion that sea surface temperatures of the Indian Ocean and the South-east Atlantic can also be associated with climatic variation in Zimbabwe. However as literature has shown, ENSO sometimes evokes SST changes in Indian Ocean and Atlantic Ocean. Hence a more accurate or direct correlation relationship could be that of the ENSO in the Pacific Ocean. The relationship between the ENSO and Zimbabwe's vegetation cover should be understood however as happening through the effect of precipitation which also has correlation coefficients ranging from 0.30 to above 0.45 (Matarira, 1990; Makararu and Jury, 1997; Lindesay, 1998; Manatsa et al., 2011). Therefore the spatio-temporal variations of precipitation and NDVI that we have discussed in this study could be understood as occurring within a broader inter-annual pattern that is influenced by large scale climatic forcing factors.

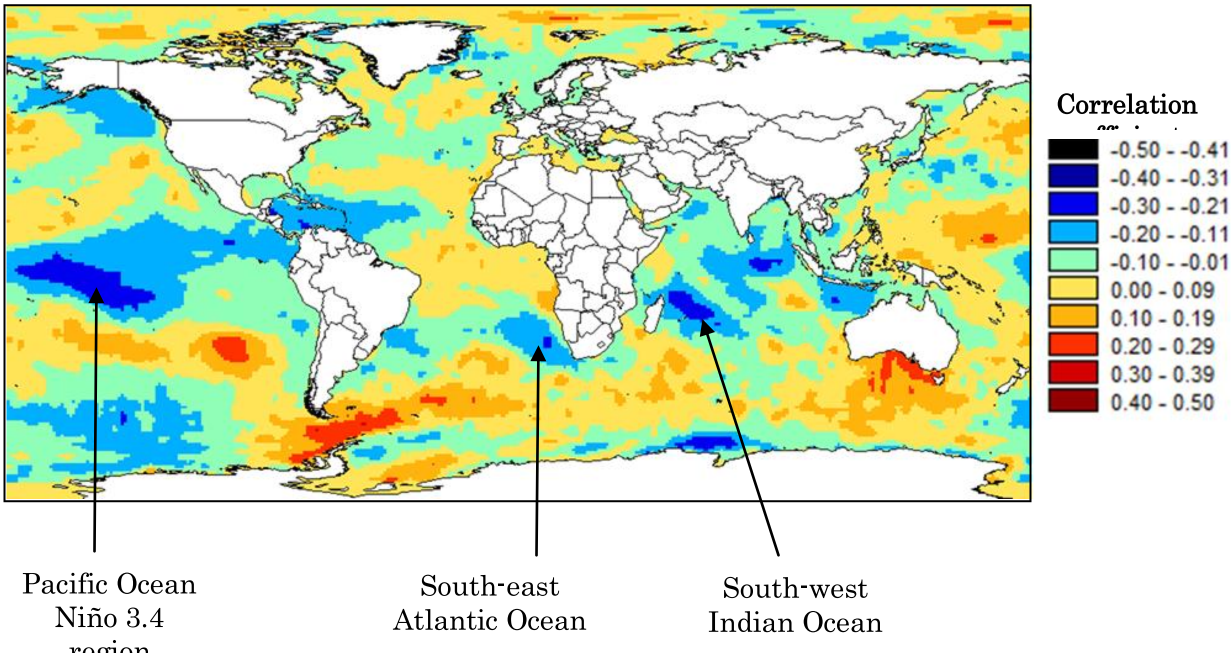


Figure 6.12. Correlation between the 12-month running mean of NDVI z-scores and global sea surface temperatures (SSTs) shows negative correlations in the Pacific Ocean (Niño 3.4 region), Indian Ocean, and South-east Atlantic with peak correlations coefficients of r = -0.3. Therefore SST teleconnections through precipitation influence vegetation variability over Zimbabwe.

6.6. Comparative analysis of the prediction skill of 4 El Niño indices: the Southern Oscillation Index (SOI), Niño 3.4, Niño 3, and the Multivariate ENSO index.

Table 6.2 shows the correlation coefficients between Zimbabwe's NDVI z-scores and four ENSO indices. It should also be recalled the Zimbabwe's NDVI z-scores are also highly correlated to PCA-1 loadings (r = 0.94). The highest correlationship between Zimbabwe's NDVI and the four ENSO indices is obtained with the Southern Oscillation Index (SOI) at lag 6. The earliest significant correlationship is also obtained with the SOI at lag 4. Lag 4 correlations imply that as from approximately September-October, it may be possible to make forecasts about whether the forthcoming season will likely be a dry or wet. Farmers in Zimbabwe usually start planting crops in October therefore this could be a good timing for the forecasts. The association between NDVI and the SOI is also visualized linearly in Figure 6.13. It can be observed that the relationship between NDVI and SOI is rather lower during years of near normal climate. The scatter plot of only the years of extreme SOI anomalies and NDVI confirms this trend (Figure 6.14).

A further investigation was performed to understand the probability distributions of the four ENSO indices with Zimbabwe's NDVI (Figure 6.15). The results show that with regards to negative anomalies (El Niño years) a better relationship to be found between Niño-3 and NDVI, whereas during La Niña years the association is diminished. This differential correlationship between El Niño and La Niña correlationship can be associated with the fact that after a certain amount of rainfall, water is no longer the limiting factor for vegetation growth. This could be an interesting subject for further investigation.

Table 6.2. Correlationship analysis between Zimbabwe's NDVI z-scores, The Southern Oscillation Index (SOI), Niño 3.4, Niño 3, and the Multivariate ENSO INDEX. The highest correlationship is noted with SOI at Lag 6.

ENSO Index	**Correlation Coefficients**			
	Lag 0	**Lag 2**	**Lag 4**	**Lag 6**
MEI	-0.257	-0.326	-0.373	-0.397
Niño3	-0.197	-0.272	-0.322	-0.352
Niño34	-0.259	-0.339	-0.396	**-0.427**
SOI	0.294	0.377	**0.424**	**0.44**

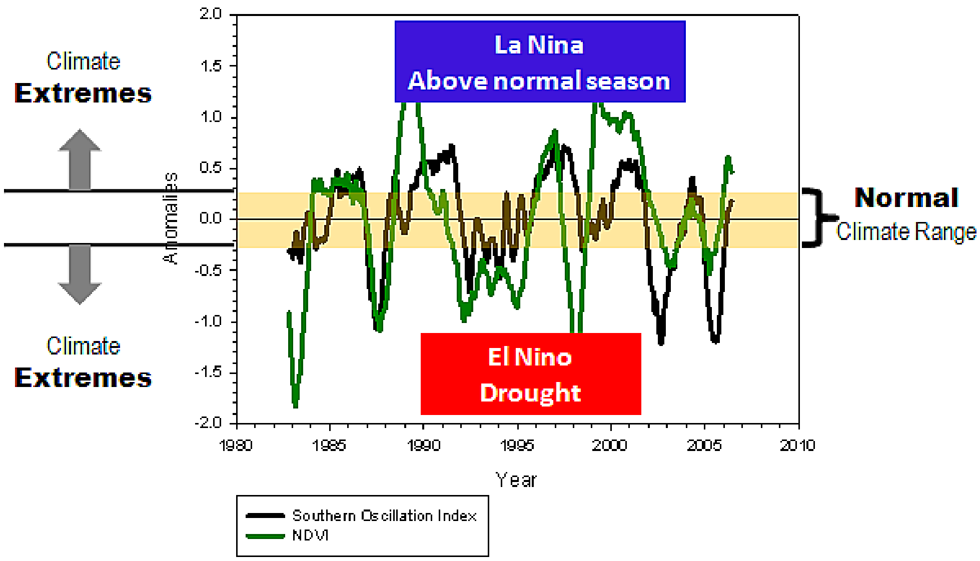


Figure 6.13 Plot of Zimbabwe's NDVI-z scores with the Southern Oscillation Index (SOI). A remarkable association can be seen especially in the extreme anomalies both positive and negative.

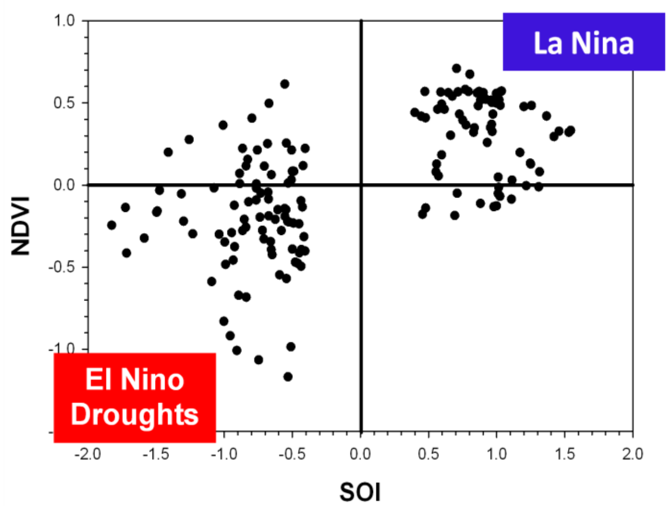


Figure 6.14. Scatter plot showing the relationship between Zimbabwe's NDVI z-scores and the Southern Oscillation Index, for only the extreme anomalies.

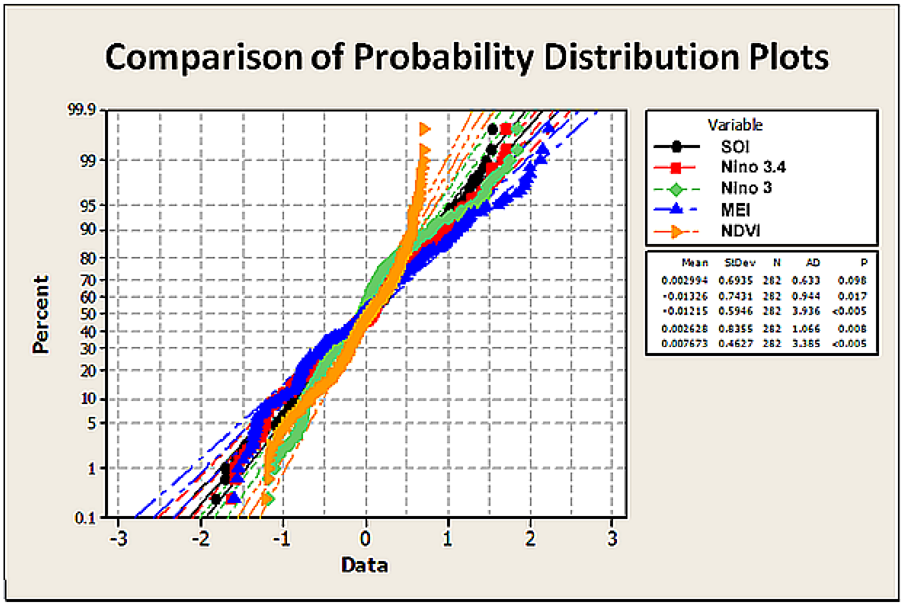


Figure 6.15. Comparison of Probability Distribution Plots for Zimbabwe's NDVI z-scores, The Southern Oscillation Index (SOI), Niño 3.4, Niño 3, and the Multivariate ENSO INDEX. It can be observed that for extreme positive anomalies (La Niña) the NDVI anomalies are less fitted to the ENSO indices. A closer fit is observed for negative anomalies (El Niño years).

6.7. Discussion

The spatio-temporal analysis at monthly time steps employed in this study has revealed new knowledge about the evolution of extreme precipitation seasons over Zimbabwe. In the onset of rainfall season an inverse pattern was noted between above normal wet seasons and major dry years. Rainfall season onset in dry years is characterized by above normal rainfall while onset of season in wet years is characterized by below normal rainfall. This inverse pattern was also resonated in vegetation. This is the first time that this inverse pattern is shown over Zimbabwe though literature based on precipitation data and ingenious knowledge has reported such an inverse pattern in other parts of Africa. Since the inverse pattern is spatially concentrated in the north-western part of the country, it would be interesting to investigate its spatial extend particularly in the countries where the southern limits of the Inter-Tropical Convergences reach. Hachigonta and Reason (2006) reported that during dry years, stations in the southern part of

Zambia had a tendency to receive unusually higher rain in season onset. Their findings therefore can be related to this study because the southern part of Zambia boarders with the north-western part of Zimbabwe. Therefore it would be beneficial to have this intra-seasonal analysis at a region level. It is also strongly suggest that this inverse pattern could have potential to be used to support existing drought early warning systems.

A rather subtle yet very important observation soon after season onset in above normal wet years, is the concentration of positive rainfall anomalies in the south. This is very important because during normal years the northern region receives more rainfall than the south. However in above normal wet years the north-south mode is inverted and the southern region has higher rainfall anomalies than the north. These results concur with the findings from PCA-2. Therefore the north-south mode of precipitation and NDVI over Zimbabwe is in-fact an alternating dipole mode. Rainfall in Zimbabwe is mainly connected to the Inter Tropical Convergence Zone (ITCZ) whose preferred location in a normal year is over the northern part of Zimbabwe. Northern winds in the convergence have more moisture than the southern winds, leading to less rainfall in the southern areas in normal years. However in the years that the convergence system gets further south, then above normal rainfall and vegetation cover and even floods can be expected in the south (Unganai and Mason, 2002; Love et al. 2010). The idea that the north-south mode could be an alternating dipole has been proposed in literature using out-going longwave radiation (Matarira, 1990) and precipitation and NDVI PCA. However this study has clearly shown for the first time how the north-south alternating dipole evolves. This knowledge may also be useful for water security and agricultural planners in the Limpopo River basin in the south of the country.

An important question in the study of precipitation extremes is which months are most vulnerable to the negative consequences of extreme seasons. The study has also shown that for precipitation, the greatest impacts occur from January to March covering the whole country, and consequently the length of rainfall seasons for major dry years is shorter than for above normal wet years. The extreme impacts on vegetation lag 1-2 months later. These results are in agreement with Funk and Budde (2009) who used crop performance based on time series of Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) imagery for just 5 years from 2001 to 2006. In addition this study has shown that expected negative impacts are not limited to drought only, but also delayed cessation of the rainfall season in above normal wet years which may hamper drying of seeds and harvesting activities for farmers who may have planted short seasoned crop varieties while expecting a drought. Therefore appropriate approaches are necessary to adapt and mitigate the negative consequences in these months of extreme rainfall seasons. It should be noted that projections have been made about future changes in rainfall extremes over southern Africa (Davis, 2011), hence continuous assessment is necessary to test the variability of the observed intra-seasonal patterns.

The in-depth analysis of temporal patterns for major dry years has revealed some important intra-seasonal variations. Parameters that we found useful for identifying distinctions in major dry years included maximum NDVI level, mid-post season NDVI condition, and nested dry spells. These results therefore more evidence for Anderson (2007) who suggested using only the basic graph of 2001/02 monthly rainfall that droughts and rainfall extremes ought not to be understood simply in terms of total seasonal precipitation, because within them may be nested significant distribution patterns that may have strong influence on primary production, and therefore the livelihood of thousands of rural people that reply upon it in the semi-arid Southern African region.

The use of both precipitation and NDVI has helped to clarify the occurrence of mid-season dry spells. The NDVI, which estimates the cumulative effect of rainfall on vegetation, has shown that both major dry years and above normal wet years may experience mid-season dry spells. The mid season dry spells were noted approximately one month after being observed in precipitation. It was also noted that there may be inter-annual trends or epochs in the occurrence of mid-season dry spells. Mid-season dry spells are a big problem for agriculturalists in Southern Africa and there is still limited information about their occurrence and trends. It could be an interesting subject for further in-depth inquiry.

The long term trends of NDVI were shown to be highly correlated to mean annual precipitation, and also influenced by large-scale tropical sea surface temperatures. Therefore the various precipitation and NDVI patterns discussed in this study could be understood as occurring within a broader inter-annual pattern that is influenced by large scale climatic forcing factors.

CHAPTER 7
CONCLUDING REMARKS

From Chapter 2 this study has four objectives. The first objective is a local level approach assessing the possibility of using locally captured climatic information for consolidating the use of seasonal climatic forecasts. The second objective taking a country level approach investigates the possibility of using high resolution satellite data for understanding the dominant spatial and temporal modes of climatic variability over Zimbabwe, and the physical processes that could be driving them. The third objective investigates the intra-seasonal scenarios of major dry and above normal wet years. The fourth objective tests the predictability of vegetation variability over Zimbabwe. This chapter presents a summary and conclusion of each objective, and also presents recommendations for policy and for further research. Concise outlines of the results and policy recommendations are presented in Table 7.1 and Table 7.2 respectively.

7.1. Discussion

At the local level, this study has shown that an abundant amount of climatic information can be and is being captured. A problem however is that this information is not effectively accessible to local agriculturalists. It was noted that with the exception of an old national agro-ecological map (Vincent et al., 1961), no summarized visualizations or handouts of local climatic information are available at local agricultural extension offices to inform farmers about local climatic trends. Moreover extension personnel were found to have limited knowledge about how to derive the benefits of locally available climate observational data. On the other hand, this study's precipitation analysis

Table 7.1. Summary of major findings from this research study.

A.	**Local Level**
1.	Abundant climatic information is being captured at limited local meteorological stations.
2.	The locally captured data is not effectively accessible to local agriculturalists.
3.	Extension personnel have limited knowledge about how to derive the benefits of locally available climate observational data.
4.	Precipitation data analysis showing inter-annual variability and correlations to the Southern Oscillation Index (SOI) highlight the potential of adopting response farming.
5.	Locally captured data can be used to consolidate the use of regional seasonal outlook forecasts that are given at spatial scales covering hundreds of square kilometers.

B.	**National Level**
1.	Satellite vegetation data is a useful proxy for understanding modes of rainfall variability.
2.	The problematic land reform challenge in Zimbabwe could be related to climatic variability over the country as shown by NDVI PCA-1.
3.	Vegetation variability over Zimbabwe exhibits inter-annual spectral peaks similar to those of tropical sea surface temperatures (SST).
4.	The Pacific Ocean has the largest SST spatial zone that is correlated to Zimbabwe's vegetation variability.
5.	In overall the Southern Oscillation Index (SOI) performed better at predicting Zimbabwe's vegetation variability than 3 other indices.
6.	The surprising inverse pattern observed between early and late season climate conditions can be a new way of forecasting seasonal climate.

C.	**Other Important Scientific Findings**
1.	Long term changes in climate may not be seen in total seasonal precipitation but in other parts of the rainfall distribution, as was observed in Makonde.
2.	NDVI-PCA-2 loadings could be useful in understanding the variability of the convectional rainfall system (possibly the ITCZ) over Southern Africa.
3.	The north-west/south-east mode over Zimbabwe is not insignificant as had been suggested in past precipitation literature.
4.	NDVI effectively captured the elusive mid-season dry spell phenomenon.
5.	Mid-season dry spells seem to experience inter-annual variability.
6.	Two peaks of NDVI were noted in above normal rainfall years thereby providing new evidence to support the idea of separate baroclinic and barotropic systems in a single season over the country.
7.	The prediction skill of ENSO indices is relative to warm or cold events i.e. some ENSO indices are better at predicting effects of El Niño but poor at predicting effects of La Niña.

showing inter-annual variability and correlations with the Southern Oscillation Index (SOI) highlighted the potential of using locally captured precipitation data for interpreting SARCOF's seasonal outlook forecasts that are often given in probability estimates of above, below, or normal conditions and covering hundreds of square kilometers.

In the second stage of the study four dominant modes of vegetation variability over Zimbabwe were noted and the first four modes were shown to be related to different parameters of Zimbabwe's precipitation. The study has contributed to a better understanding of the physical effects of the dominant modes of precipitation variability over Zimbabwe that had been identified by (Unaganai and Mason 2002 and Manatsa and Mukwada 2012). It was shown that the low anomaly region in NDVI PCA-1 corresponds to the area previously predominantly owned by European farmers, and that a large proportion of the country's area is in the high anomaly region. Hence NDVI PCA-1 could be useful in explaining the land reform challenge in Zimbabwe. The analysis also illustrated that NDVI-precipitation relationships are not limited to mean annual precipitation, but can also be related to other aspects of precipitation. For example a high correlation between NDVI PCA-2 and the annual relative variability of rainfall was obtained. Zimbabwe's map of mean annual relative variability of precipitation was presented here for the first time, and it is recommended that such crucial maps be created for other African countries which may still lack of it. Moreover NDVI PCA-2 and its loadings may also serve the important role of helping to understand the movement of the ITCZ in its southern limits. NDVI-PCA-3 and NDVI-PCA-4 though having smaller explanatory variance were also found to have interesting associations with precipitation patterns in the country.

The analysis of dry and wet years revealed new knowledge about the intra-seasonal patterns of extreme seasons over Zimbabwe that had not been determined in past studies

(Unganai and Kogan, 1998; Funk and Budde, 2009). An inverse pattern was shown to occur between early season and late season precipitation. This surprising inverse pattern was resonated in vegetation thereby confirming its robustness. Dry years experience above normal rainfall and vegetation condition during the onset of season months, and this could confuse farmers into thinking that the oncoming season will be a good. This inverse pattern can be a useful method to support existing drought early warning systems.

An important question in the study of precipitation extremes is which months are most vulnerable to the negative consequences of extreme seasons. This study showed that for precipitation, the greatest impacts occur from January to March covering the whole country, and consequently the length of rainfall seasons for major dry years is shorter than for above normal wet years. The impacts on vegetation lag 1-2 months later in agreement with (Funk and Budde, 2009). Expected negative impacts are not limited to drought only, but also delayed cessation of the rainfall season in above normal wet years which may hamper drying of seeds and harvesting activities for farmers who may have planted short seasoned crop varieties while expecting a drought. Therefore appropriate approaches are necessary to adapt and mitigate the negative consequences in these months of extreme rainfall seasons.

In the last part of the study rigorous correlation analyses were performed to investigate the relationships between Zimbabwe's vegetation variability and ENSO. It was shown that the Pacific Ocean SSTs especially in the Nino 3-4 region is the largest spatial SST zone correlated to Zimbabwe NDVI. The comparative test of four ENSO indices revealed the highest correlationship using the Southern Oscillation Index (SOI) at lag 6, though the earliest significant correlationship was at lag 4. Therefore NDVI imagery can be useful for enhanced early seasonal outlook forecasts.

7.2 Policy Recommendations

At the local level, the agricultural extension department and the department of meteorology need to address the problem of changing local farming and agro-businesses from their present state of relative ignorance to a more knowledgeable condition about climatic issues that affect them. Good coordination and collaboration between the departments is needed for effective information exchange. Financial and technical support for training of extension personnel in agro-meteorology should be emphasized so that they can better articulate the needs of the farming communities for weather services and also be able to bring response farming approach advisory services to farmers for participatory applications in their fields. Moreover university scientists need to be involved in a participatory approach following the success of case studies from Indramayu and Gunung Kidul, Indonesia.

At the state level, it is strongly recommended that the agro-ecological map of Zimbabwe be updated at the earliest for it to be useful. Other relevant climate scenario maps as demonstrated in this study need to be published and made accessible to departments that are involved in food security, water planning, and disaster management. A climate change policy for the country is needed. In addition a national climate down-scaling center needs to be established. International cooperation and sharing of case studies, particularly between South Asian countries and African countries is recommended.

Table 7.2. Strategic policy recommendations for enhancing agricultural adaptation to climatic variability

A. LOCAL LEVEL

Key Actions	Responsible Departments
➢ Publish locally captured climate information	Meteorological Department Agricultural Extension Department
➢ Train extension personnel in agro-meteorology	Agricultural Extension Department Local universities
➢ Establish more rainfall measuring points	Meteorological Department Agricultural Extension Department Universities Local farmers
➢ Strengthen data-information linkages	Meteorological Department, Agricultural Extension Department
➢ Establish climate field schools for farmers	Local universities, Agricultural Extension Department

B. NATIONAL LEVEL

Key Actions	Responsible Departments
➢ Upgrade the "1961" agro-ecological map	Meteorological Department Ministry of Agriculture
➢ Employ the NDVI for making high resolution climate outlook scenario maps	Meteorological Department Ministry of Agriculture
➢ Publish mean annual relative variability map	Meteorological Department Ministry of Agriculture
➢ Support for agro-meteorology studies	Ministry of Finance, Local universities

C. REGIONAL AND INTERNATIONAL NATIONAL LEVELS

Key Actions	Responsible Departments
➢ Sharing of experiences and case studies	Universities, NGOs, Regional organizations
➢ International cooperation in technical assistance and consultancy.	Meteorological Department, Universities and NGOs

7.3 Recommendations for Further Study

The following research should be done in the future to improve the climate forecasting in Southern Africa.

1) Similar detailed research for other Southern African countries (especially Botswana, Congo, Malawi, Mozambique, and Zambia).
2) Interviews to determine to what extent farmers on the ground know or are even using the surprising inverse pattern observed between early season and late season climate conditions.
3) Detailed investigation to understand the inverse pattern and possibly develop a scale for quantifying this inverse pattern as a disaster warning signal.
4) Detailed investigation into the inter-annual variability and predictability of mid-season dry spells that were observed using NDVI.
5) Detailed investigation into the physical significance of NDVI PCA-3 and NDVI-PCA-4.
6) Detailed investigation into the surprising relative nature of the prediction skill of ENSO indices in predicting the effects of El Nino versus La Nina.
7) Climatological studies employing in addition precipitation data, out-going long wave radiation, pressure and wind data to aid in understanding the inter-annual variability of the annual excursions of the ITCZ in its southern limits.

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