CLIMATIC TRENDS AND SOIL MOISTURE FEEDBACKS OVER ZIMBABWE

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

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June 2005

Abstract

The research focuses on an objective analysis of austral summer rainfall variability over Zimbabwe as well as characterization of rainfall patterns and frequency analysis over southern Africa region. A statistical analysis of historical trends in climate extreme events is used and lays a foundation of projecting into future climates. A trend analysis done on rainfall patterns attained from SOMs approach compliments the RClimdex statistical approach and strengthens some of the historical trends findings on climate extremes. Thereafter, some exploratory research seeks to explain the trends observed using the land-atmosphere interactions and shows the response of rainfall to anomalous soil moisture conditions during an extreme wet and dry seasons using RegCM3. Finally, some radiation effects results are presented from these soil moisture perturbations experiments.

Results show drying out patterns over the region from the historical records analysed. The trend analysis done with SOM arrays revealed a positive trend towards drier conditions and a negative trend for wet conditions. The climate extremes indices analysis complimented these findings as shown in the decrease in total precipitation and an increase in the number of dry spells. This is supported by the circulation patterns showing an increase in frequency of the 500hPa anticyclones and a decrease of low pressures. However, some high altitude stations showed an intensification of precipitation events. This would exacerbate need for proper planning of future water resource management and farming strategies. Soil moisture rainfall feedback mechanisms were not fully explored. However drier conditions experiments showed a stronger response to soil moisture perturbations than in wetter conditions experiments. No consistent response to soil moisture initialisation over southern Africa was found. The altitude does modulate these feedback mechanisms with low-lying areas depicting a stronger response. A better understanding of the observed rainfall patterns, historical climate trends and soil moisture-rainfall feedback mechanisms are essential for improved short-term and seasonal forecasting and will aid the generation of plausible climate change impact predictions

Acknowledgments

I would like to convey much gratitude to my supervisors Prof. Bruce C. Hewitson and Dr. Mark Tadross for their invaluable support and guidance throughout my MSc course.

My sincere thanks to Prof. Filippo Giorgi and Dr. Jeremy S. Pal who during my scientific visit to the International Centre of Theoretical Physics (ICTP) did magnificent jobs of contributing with brilliant ideas towards my modelling work with RegCM3.

I would like to acknowledge and thank Jeremy Main, Sharon Barnard and Sharon Adams for all the assistance they gave me at University of Cape Town (UCT). Special mention should also be made of Christian Winter and Pandora Pieri at ICTP.

I am grateful to the following for financial assistance throughout the period of this research:
1. BIOTA Southern Africa - an interdisciplinary research programme funded primarily by Germany's Federal Ministry of Education and Resarch (BMBF) and administered through the University of Hamburg.
2. WRC - Water Research Commission on the K5/1154 project "The Dynamical Modelling of present and future climate system variability at inter-annual and inter-decadal time scales.
3. AIACC Project AF07 - Funded through START. Development of Regional Climate Change Scenarios for Sub-Sahara Africa.

I am most appreciative and indebted to my parents, for instilling the thirst for knowledge and pushing me into taking up this opportunity.

Special thanks to my girl friend Stella T. Mavondo for all her patience, encouragement and unwavering love during this whole period of research.

I am also indebted to Sepo Hachigonta for helping with printing out the final corrected copy whilst I was away.

Lastly, I have also received invaluable support, suggestions and encouragement from family, friends and colleagues in CSAG, ZMS and ICTP.

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Chapter 1

Background

1.0 Introduction

Zimbabwe is an agro-based economy where climate extremes, particularly recurrent droughts are a cause for concern. The looming possibility of climatic change is also among the main hurdles facing agricultural and environmental policy management, as well as economic development in southern Africa. Climate extremes such as prolonged dry spells, a shift in the onset, breaks and cessation dates of rainfall have remained unresolved issues for Zimbabwean farmers especially in the wake of the on-going land reform policy. Recent mid-season dry spells have been devastating on agriculture in Zimbabwe and the region at large (Lindesay, 1998; Unganai, 2002; Usman and Reason, 2004).

The study seeks to carry out an objective analysis of austral summer rainfall variability over Zimbabwe as well as characterization of rainfall patterns and frequency analysis over southern Africa region. A statistical analysis of historical trends in climate extreme events is employed with a view to aid understanding of current events as well for purposes of projecting into future climates. A trend analysis is also done on rainfall patterns attained to complement the statistical approach and findings on climate extremes. Thereafter, the research seeks to explain some of the trends observed using the land-atmosphere interactions and shows the response of rainfall to anomalous soil moisture conditions during extreme wet and dry seasons using a regional climate model, RCM. Finally, some radiation effects are also studied during these soil moisture perturbations experiments.

Rainfall being a major climatic element in southern Africa, whose economies are largely based on rain-dependant agriculture, great potential exists to minimize the impacts of adverse inter-annual and intra-seasonal climatic fluctuations by pursuing intensive research or study of the dynamics of droughts and floods. Underpinning any regional climate study is an appreciation of the historical climate information and any observed trends. The ultimate aim is a clearer understanding of regional dynamics contributing to the production of good seasonal forecasts and understanding of the future projected climate changes. Good climate forecasts would better equip farmers to make informed decisions and reduce food insecurity (increasing production) and improve livelihoods.

The majority of rural populations in Zimbabwe are communal farmers or smallholder farmers and their livelihoods depend largely on agriculture. Any climatic extremes such as droughts would impact negatively not only on agriculture, but also on livelihoods as about 70% of the population is from rural areas and dependent on farming. The impacts go beyond large financial losses for the agricultural communities by causing additional hardship and personal loss in urban areas. Other sectors, such as the water management, transport, and communication sectors are also affected within the country. The current droughts have also impacted on the government's land reform policies as new farmers allocated land in Zimbabwe have been left with an insurmountable task due to poor crop yields (FAO reports, 2004).

1.2 Literature Review

Over the years progress has been made in documenting the temporal and spatial variability of Zimbabwe's rainfall. Recurrent droughts over Southern Africa have raised interest, mostly since the most devastating events of 1982/83 and 1991/92 seasons (Matarira, 1989, 1990; Matarira and Jury, 1992; Unganai and Mason, 2001, 2002; Makarau, 1995; Makarau and Jury, 1997; Jury, 1996; Torrance, 1981). The Southern Africa region is characterized by highly variable rainfall patterns on both spatial and temporal scales. These persistent drought events require a deeper understanding of the intraseasonal characteristics of the region's rainfall patterns and the dynamics influencing their frequency, intensity, duration and (spatial and temporal) distribution, (Matarira and Jury, 1992; Makarau and Jury 1997a; Tennant and Hewitson, 2002; Walawege, 2002).

Although this study will focus on Zimbabwe, it is envisaged that some of the results portray the general patterns or trends over other regions of Southern Africa.

Besides the availability of good daily station data, Tenant and Hewitson (2002) point to the fact that there has been limited work to improve the understanding of the nature and characteristics of rainfall on a daily-intraseasonal time scale. They adopted the Self-Organised Maps (SOMs) analysis techniques in delineating the summer rainfall season and demonstrated how daily station rainfall can be processed into regional data. In an earlier study, Washington and Todd (1999) performed an objective analysis of daily austral summer rainfall variability over southern Africa using satellite-derived rainfall estimates and using Empirical Orthogonal Function (EOF) analysis. They showed that the leading mode of variability is characterized by tropical-temperate links. Findings and arguments in the above mentioned studies were augmented by Usman and Reason (2004) in their study employing dry spell frequency (DSF) to assess spatial and temporal patterns in the consistency of rainfall during the mid-summer season and its relationship to drought occurrences in the sub-region.

Over Zimbabwe, some of the intraseasonal studies were carried out and compiled into a rainfall chapter in the Climate Handbook of Zimbabwe (Torrance, 1981). Torrance was of the school of thought that: "A month is too large a unit to show clearly the variations in the incidence of rainfall, and yet the fine detail given by daily falls tend to be excessive." He argued that since rain tends to occur in spells of a few days' duration followed by dry spells lasting a few days, there was merit in using 5-day periods or the pentad as a unit for rainfall incidence. However, state of the art research methods can now easily manipulate the finer details given by daily observations.

Significant work on intraseasonal aspects using daily data was carried out by Matarira (1990b) who studied the frequency and tracks of anticyclones and their effects on rainfall patterns using synoptic charts from the South African Weather Bureau Daily Weather Bulletins. Matarira and Jury (1992) subsequently contrasted the meteorological structure of intraseasonal wet and dry spells in Zimbabwe using daily data from a network of 33

Zimbabwe rainfall stations. They used an area-average weighted index which transforms point precipitation to represent precipitation over a given area. This was a follow up to the work of Matarira and Flocas (1989) in which they compare rainfall variability at different daily rainfall observation stations during extremely wet and dry years and attempted to give some physical explanation of the causative mechanism. An investigation of the short period composition of Zimbabwean rainfall was carried out by considering days with precipitation for those 33 stations, (Matarira, 1990a). In all the above studies records with missing values were completed with estimated precipitation by interpolation from nearby stations following the k method of ratios.

Another study using daily data over Zimbabwe was by Makarau and Jury (1997) where wet spells from pentad area-rainfall time series for the November-March season (1987-1992) were analysed. These were averaged using data from 30 stations distributed evenly over central Zimbabwe. In most of the studies carried out over Zimbabwe, the European Centre for Medium Range Weather Forecasting (ECMWF) reanalysis data was used. This seems to give a good representation of the conditions over Zimbabwe and ECMWF forecast models are used on daily basis for most of the country's short-range weather forecasts. My personal experience as a Zimbabwean weather forecaster and in-house model forecaster indicates high skill for the ECMWF model over Zimbabwe, compared to other models. The most commonly used techniques in most of the past studies over Zimbabwe were Principal Component Analysis (PCA) (Mdoka, 2002; Unganai and Mason, 2002), Empirical orthogonal Functions (EOF) (Unganai, 2002); Fast Fourier Transform (FFT) method (Makarau, 1995; Makarau and Jury, 1997a) and Spectral Analysis (Makarau, 1995; Makarau and Jury, 1997b). Details of these statistical and time-series methods can be found in textbooks such as Johnston (1992) and Stock and Zwiers (1999).

Mulenga (1998) focused on the role of local and remote forcing in controlling southern Africa climate. He mentions that local seasonal heating initiates the formation of the Angola Low, which controls the entire summer circulation in Southern Africa and modulates regional climate at intra-seasonal and interannual time scales. Through composite analysis, the evolution of the Angola Low was shown to modify wet spells and the temporal characteristics depicted major periods ranging from 20-30 days. He concluded that local forcing (internal, 21%) through the Angola Low contribute most of the interannual variations of summer rainfall anomalies and is linked to warm water in the sub-tropics.

Extreme convective activity, in the form of widespread moderate to heavy rainfall (periods of rain days greater than 5 days), occurs in some regions and has been linked to intra-seasonal oscillations. Makarau (1995) using pentad rainfall data showed that the season is characterized by 5 wet spells alternating with 4 dry spells. The dynamics of such wet spells are linked to the intensity of the thermal low. However, no follow-up work has been performed lately to augment these findings. Tadross et al. (2005a) studied the onset of the maize growing season over South Africa and Zimbabwe, assuming a minimum quantity of rainfall that was required for the germination of maize. Early onset was associated with positive geopotential heights to the southeast of the continent, with El-Niño often causing late onset over parts of southern Zimbabwe. The suggested mechanism for this influence was through a change in the storm tracks south of the continent.

Heavy rains and droughts have repeatedly battered Zimbabwe from the last decade of the 20^{th} century into the current century (Matarira and Flocas, 1989; Matarira, 1990a, 1990b, 1990c; Matarira and Jury, 1992; Makarau and Jury 1997a, 1997b; Unganai and Mason, 2002; Unganai, 2002). Limited availability of long-term data sets remains the greatest challenge for climate studies across the country and the region at large. However, the studies of historical climate change over the region, especially examining of shorter time scales extreme events, are still lagging with those data sets that are available. Few of the works published focused on the broad African continent with some sub-regional studies mainly for West Africa. Hulme et al. (2001) and Nicholson et al. (2001) give a good account of the continent's regional climates.

The shortcomings of the southern Africa region, in terms of climatic information, have not gone unnoticed. This was evidenced by a workshop to address some of these issues, which was organized by the World Meteorological Organization/Climate Variability (WMO/CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) in Cape Town, South Africa (2004). The workshop aimed to calculate climate indices for southern and eastern Africa. This workshop was carried out employing techniques of the ETCCDMI. Despite the ever-mentioned complexness of the region's climate and El Niño Southern Oscillation (ENSO) teleconnections, there are many regional forcing processes over the continent itself such as landuse change and the adjoining oceans which factor in on causing extreme dry or wet conditions (Lindesay, 1998; Nicholson, 2001).

At interannual time scales, sea surface temperature (SST) and the related ENSO play an important part in modulating rainfall over southern Africa. Jury and Pathack (1993); Makarau (1995) linked rainfall to spatial anomalies of SST; the ENSO phase (Ropelewski and Halpert, 1987; Matarira, 1990; Rocha, 1992; Mason and Goddard, 2001; Unganai and Mason, 2001); Ogallo et al. (1993) examined linkages to the phase of the Quasi-Biennial Oscillation (QBO); interhemispheric teleconnections (Nicholson, 1986; Makarau and Jury, 1997) and convective anomalies (Jury et al., 1992).

Feedback processes between the soil and the atmosphere are also of major importance for our climate system. Global ecosystems are stabilised by a series of feedbacks between man, animals, soil, vegetation and climate. Land-atmosphere interaction is particularly important to adequately model these features in order to have a complete understanding of the climate variability in the region. The earliest discussions of a possible role for soil moisture in semi-arid climates date back to the 1950s (CLIVAR Africa Report II). Subsequently many modelling studies have explicitly addressed the impact of variations in soil moisture on the atmosphere. These studies have demonstrated the role of soil moisture in influencing the annual cycle and also 5-day weather forecasts in Africa. The timescale of soil moisture retention is also a key issue (Delworth and Manabe, 1993)

A positive soil moisture-rainfall feedback exists when above-normal soil moisture increases the chances of subsequent precipitation whilst the reverse should occur for dry soil moisture conditions. Although there are no documented studies over Southern Africa, numerous studies over the rest of the world have shown that persistence in soil moisture is translated into persistence in near-surface humidity, temperature, and precipitation (Delworth and Manabe, 1993; Eltahir, 1998; Zheng and Eltahir, 1998; Schär et al., 1999; Findell and Eltahir 1999, Pal and Eltahir, 2001). Therefore, it contributes towards enhancing the severity and persistence of droughts and floods.

Several key pathways and mechanisms through which soil moisture conditions affect future rainfall have been investigated using global climate models (GCMs) and regional climate models (RCMs). Eltahir (1998) describes the physical mechanisms and processes resulting in the positive feedback between initial soil moisture and future rainfall and proposes that anomalously high soil moisture conditions yield an increase in moist static energy per unit mass of the boundary layer air and hence more rainfall in convective regimes. The mechanisms responsible for the feedback are directly linked to the surface energy budget. A follow up study over Western Africa, Zheng and Eltahir (1998) pointed to the crucial role of radiative processes in the soil moisture-rainfall feedback. Whilst in Southern Africa some of the related studies focusing on boundary layer processes and causal mechanisms particularly rainfall characteristics near the surface were done by Matarira (1990); Matarira and Jury (1992). Over southern Africa, the configuration of an RCM is important when simulating such changes. Tadross et al. (2005b) demonstrate that the frequency and diurnal nature of rainfall in the Pennsylvania State National Center for Atmospheric Research Mesoscale Model version 5 (MM5) is dependent on which convection scheme is used in the model. Such dependencies alter the surface energy budget, which is further modified by the choice of boundary layer scheme.

According to the positive feedback mechanism, when soil moisture is reduced it should lead to a decrease in precipitation. This mechanism has been confirmed over the United States (Eltahir, 1998; Pal and Eltahir, 2002) and over central Europe (Schär et al., 1999).

Decreased initial soil moisture leads to: (a) decreased latent heat fluxes (decreased evapotranspiration); (b) increased sensible heat fluxes (increased surface temperatures); (c) decreased total heat fluxes (d) increases in incident solar radiation along with decreased cloud cover and precipitation. The converse would be true for an increase in soil moisture. However, these simplified one-dimensional explanations ignore the possibility of horizontal advection and changes in the atmospheric circulation. For instance, the aforementioned increased surface temperatures and sensible heat fluxes may lead to increased convection, drawing moisture from other regions and leading to an increase of both cloud cover and precipitation. Such a situation results in a negative feedback. This different response to soil moisture indicates that drier soil moisture conditions might actually lead to increased precipitation via an increase in convective instability (Seth and Giorgi, 1998).

1.3 Needs for further research

It has been found out that at daily time-scale, studies of climate extremes so far are limited to South Africa, given the lack of sufficient data for other countries in Southern Africa (Fauchereau *et al*, 2003). Work to improve the understanding of the nature and characteristics of rainfall on an intra-seasonal time scale, particularly at the daily scale, is lacking in the region (Tennant and Hewitson, 2002). As the above review demonstrates the influence of ENSO on Zimbabwe's inter-annual rainfall pattern is well documented. However, there is a need for research on other aspects such as ENSO influence on seasonal boundaries (onset/cessation), dry spells, thermal lows and upper-level anticyclones.

Tyson (1986) related rainfall over Southern Africa to variations in pressure and circulation patterns over the oceans surrounding Southern Africa. The studies revealed that distinct relationships exist between pressure anomalies and rainfall over the region. Besides the circulation patterns, moisture sinks and sources need to be reviewed enabling further analysis of moisture transport. In his study of synoptic systems, Matarira (1989) asserts that during drought years, the circulation pattern inhibits formation of active weather systems. In the light of recent advances in computer modelling and understanding it seems logical to revisit the findings and the land-surface contribution.

The steadiness of rainfall supplied by repeated wet spells is more crucial to high crop yields than the total amount of seasonal rainfall (Matarira and Jury, 1992). Current forecasts contain no information about the intra-seasonal character of the rainfall season i.e. the active/break periods, the duration and timing of such periods. Statistical methods alone cannot be used to isolate the relative importance of the different predictors in producing the observed characteristics of inter-annual rainfall variability in Southern Africa (Goddard and Graham, 1999). Predicting the intra-seasonal spells would provide extremely useful information in agricultural management. Thus a comprehensive understanding of the physical reasons for such extreme events or insight into its historical trends will enable research into seasonal climate forecasts of increased utility.

Seasonal and inter-annual predictability requires a solid understanding of the space-time characteristics of the major climatic processes of the region. Large-scale patterns of SST anomalies constitute the majority of statistical predictors. There is also evidence that atmospheric variables such as seasonal 500hPa height patterns and 200hPa winds may be useful (Tyson, 1986; Matarira, 1992; Lindesay, 1998; Cook et al., 2004). Land surface variables such as pre-season rainfall, soil moisture and vegetation may also affect coupled processes in a low frequency capacity similar to SSTs, yet so far studies of their effects over southern Africa are limited.

The study attempts to determine whether the soil moisture conditions of the 1991/92 and 1995/96 seasons played a role in initiating and/or enhancing the extremes in observed rainfall or whether they were just one of the ingredients for extremes. As Pal and Eltahir, (2001), put it "Knowledge of these pathways could potentially have significant implications for water resources management and cropping strategies and also help in reducing human and economic losses".

1.4 Aims and Objectives

The aim of this study was to carry out an objective analysis of the austral summer rainfall variability over Zimbabwe, including a study of historical trends in extreme events, and the land surface-atmosphere interactions that may contribute to this variability. The view is to improve understanding of extreme weather events, especially prolonged dry spells or wet spells, by seeking to delineate between local and synoptic forcing factors. Firstly, the available historical climate data is subjected to a trend analysis to see if there have been any persistent changes in rainfall variability over Zimbabwe. Secondly, a study of rainfall-soil moisture feedbacks attempts to determine whether anomalous soil moisture conditions play a role in initiating or enhancing the extremes in observed rainfall, and seeks to verify the positive soil moisture – rainfall feedback hypothesis using a RCM. This will aid understanding of climate change scenarios for Southern Africa and be valuable in directing research into seasonal climate forecasts.

Specifically the objectives of the study are: -

a) To characterize the rainfall patterns over southern Africa and assess the frequency of occurrence.
b) To analyze trends in the frequencies and study the behaviour of the rainfall patterns with time.
c) To derive historical trends in the extreme events using daily station data over the country.
d) To assess the frequency of occurrence, duration and intensity of extreme events.
e) To address the dominant forcing behind some identified extreme events.
f) To detect the effects of climate change due to changes or trends already evident.
g) To verify soil moisture feedbacks mechanism during extreme dry and wet years.

1.5 Layout of the thesis

Chapter 1 provides a general introduction about Zimbabwe. The aims and objectives of the study are highlighted. Some general literature review is outlined. The motivation and justification behind the research study are discussed. A more detailed description of Zimbabwe and its climate is presented in **chapter 2**. Various parameters closely related to Zimbabwe's rainfall are discussed. **Chapter 3** describes the data and methodology employed in this study. A Kohonen Self-organizing map (SOM) technique utility in capturing the modes of variability in the rainfall patterns and expression of these synoptic types across a two-dimensional continuum is presented in **chapter 4**. It encompasses the characterization of rainfall patterns and frequency analysis. A trend analysis of the SOM arrays is also summarized and presented as lead-on to the trend analysis of climate extremes that follows in the next chapter. **Chapter 5** discusses the trends in extreme events**.** Results attained from statistical analysis for trends in time series of daily data using RClimdex statistical package are presented. Land–atmosphere interaction experiments done using RCM are discussed in **chapter 6**. **Chapter 7** presents discussion and conclusions in which explanations on the tested hypotheses and the findings are highlighted. A way forward or proposals for future research are also discussed.

Chapter 2

Rainfall Characteristics over Zimbabwe

2.0 Introduction

Zimbabwe is a landlocked country situated between 15-22°S and 25-33°E (Figure2.1a), entirely lying in the tropics. The main physical characteristics of the country are the high watershed areas (1200m-1500m) which are the southern and central watershed with the northern watershed basically dividing the country into the southeast and northwest; the Eastern Highlands, a series of mountain ranges lying across the eastern border with the eastern slopes falling to the Mozambique lowlands (2200-2600m); the northern escarpment whose slopes are steep with the altitude falling by about 1 000m over a distance of no more than a kilometer or two in places; and the main river valleys, Zambezi, Limpopo and Sabi which are below 500m with the latter two falling to below 300m in the lower reaches, Figure 2.1b.

In general the land falls away from the watershed and escarpments towards the main river valleys being interrupted by secondary plateaus, ranges and valleys here and there. These may have a localized but considerable effect on the climate. Lake Kariba, covering over 5 000km^2 has created some significant changes to its local climate ((Torrance, 1981).

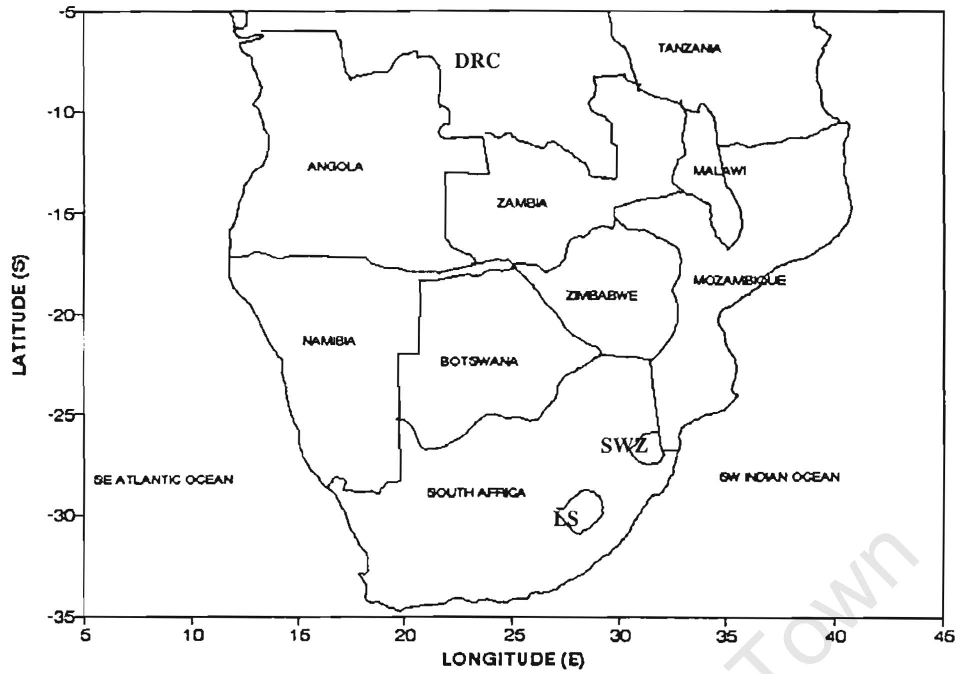
2.1 Atmospheric General Circulation

In tropical latitudes and in all seasons, the general circulation of the atmosphere is dominated by easterlies converging into the near equatorial trough or Inter-Tropical Convergence Zone (ITCZ). The easterly wind, although more limited in extent and strength than the westerlies of middle latitudes, also extends throughout the troposphere in the zonal mean (Tyson, 2000; Lindesay, 1998, Makarau and Jury, 1997; Matarira and Jury, 1992; and Torrance, 1981). The warm waters of the Mozambique Channel and tropical Indian Ocean thus form an important moisture source for the country especially during the austral summer.

Figures 2.2a and 2.2b show the mean sea-level pressure (MSLP) patterns over the region during the months of January and July. The semi-permanent, near surface sub-tropical high pressure belt (Figure 2.2a) is the major feature of the circulation and lies to the south of Zimbabwe throughout the year, centered at about 30°S; the South Indian Ocean (SIO) Anticyclone, and the South Atlantic Ocean (SAO) Anticyclone. The anticyclones translate by about 4° equatorwards during winter when they are slightly stronger. During winter an additional high-pressure cell usually develops over the Northern Province of South Africa, Figure 2.2b.

A second feature associated with being equatorward of the high-pressure belt is the comparative steadiness of the plateau-level pressure distribution patterns. These tend to have little daily change despite changes in the upper-air flow patterns and even marked changes in the weather. The diurnal pressure changes are often greater than the interdiurnal changes at identical times of the day (Torrance, 1981). The seasonal changes follow a predictable pattern, the winter anticyclone giving way to a weak pressure trough near the Zambezi in summer, Figures 2.2a and 2.2b. Fluctuations in the position and intensity of this trough are largely affected by eastward propagating pressure systems further south, which account for much of the rainfall variability. This trough is prevalent over the southeastern parts of Zimbabwe and enhances convergence and rainfall in the northern areas during the austral summer. The presence of lower pressures over the tropical region in January also indicates the southerly extension of the ITCZ (Figure 2.2a). There is a strong meridional pressure gradient in January which deepens in July in association with northward shift of the intensified anticyclones (Joubert, 1997; Engelbrecht et al., 2002).

a.



b

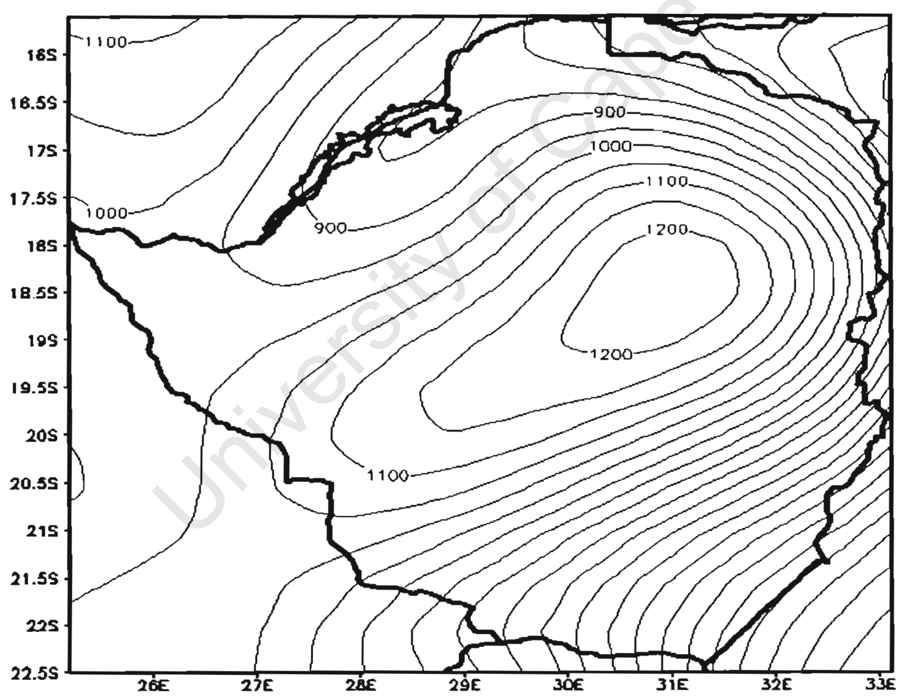
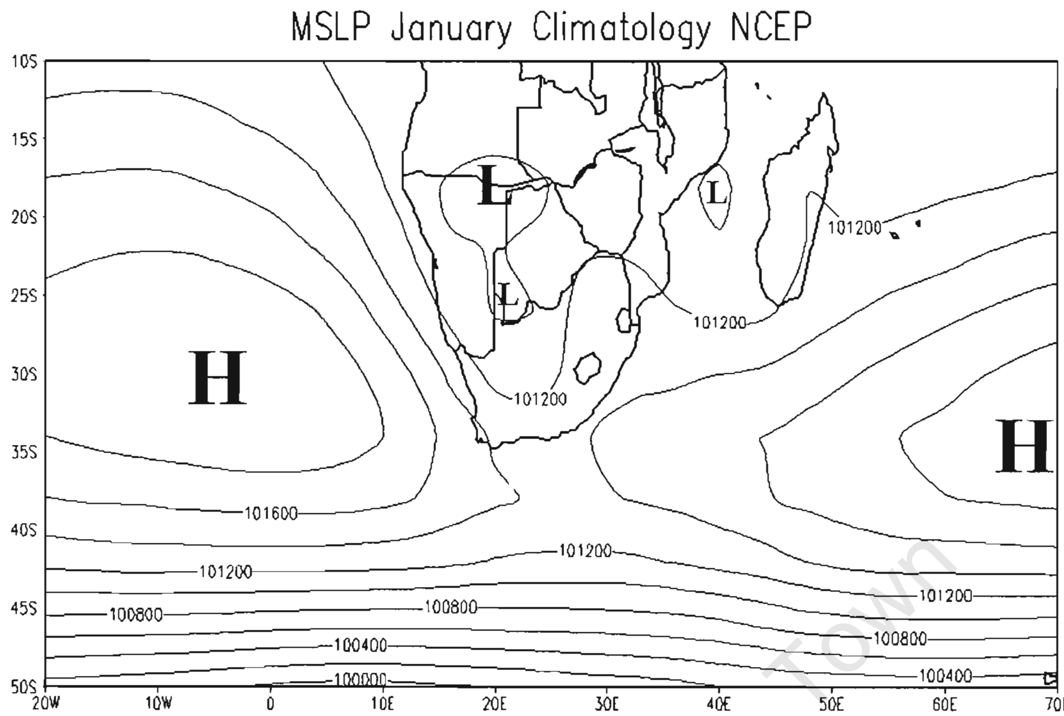


Figure 2.1 (a) Political map of southern African countries. Note Zimbabwe, which lies between latitudes (-15°S; -23°S) and longitudes (25°E; 34°E). LS is Lesotho and SWZ is Swaziland. (b) Terrain map of Zimbabwe derived from RegCM3 model.

a.



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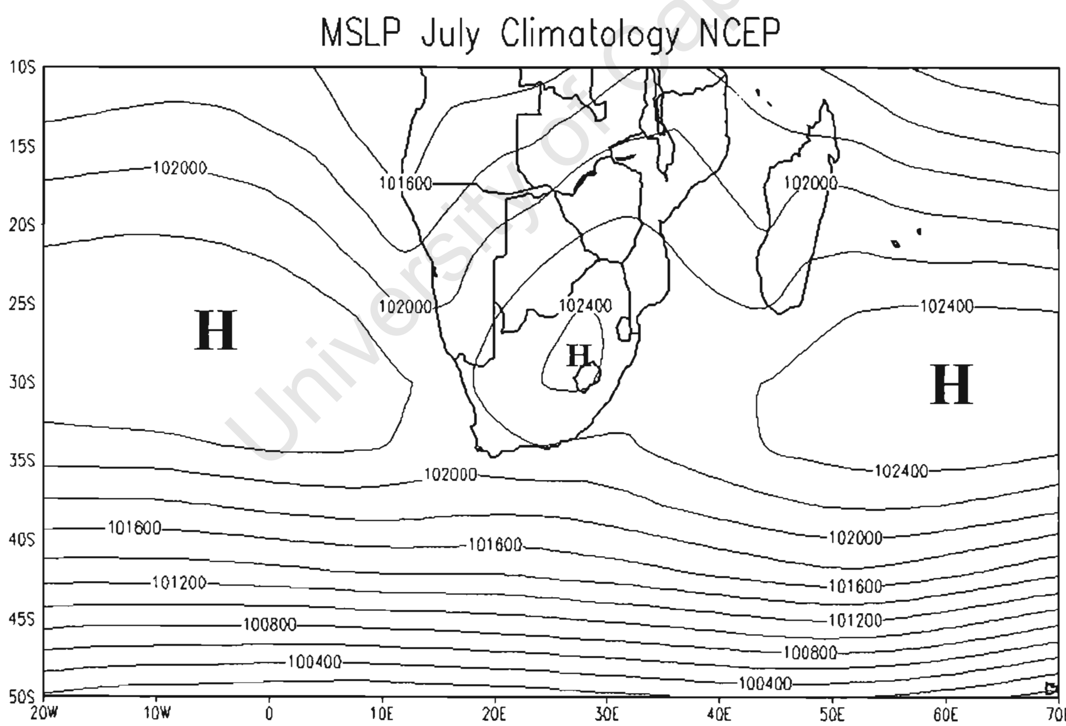

Figure 2.2 MSL pressure over region using ncep data 1970-2000 for (a) January and (b) July.

2.2 Vegetation and soil moisture

Most of Zimbabwe consists of Savanna grasslands, populated by scattered to densely packed bushes or trees (Buckle, 1986; Torrance, 1981). The natural vegetation has often been cleared locally for agricultural use. Recent land reforms have seen some serious deforestation occurring across the country by inexperienced new owners of farms, especially in forestry areas (personal observation, 2003, 2004). Afforestation is a feature of the Eastern Highlands. This can affect local climates as extensive vegetation reduces the temperature of the ground by shielding it from direct solar radiation and warming. Additionally, the presence of vegetation increases transpiration.

If trees come into foliage, during the hot season (the local equivalent of the temperate latitude spring) leaf areas and transpiration increase and ground water is transferred to the atmosphere. In the context of positive feedbacks, the moisture content of the air near the surface increases (as does the convective available potential energy, CAPE) which in turn improve the likelihood of convective rain. Conversely, during the dry cool season, severe black frosts occur and kill most of the remaining foliage on the trees, evapotranspiration is then drastically reduced and demands on ground water are lessened. In such cases, previously dry streams may start to flow again (Torrance, 1981).

2.3 Topography

Figure 2.3 shows the distribution of the mean summer rainfall over the country. Topographic features are of major importance in parts of Zimbabwe. Highest summer rainfall occurs in the Eastern Highlands, which is in excess of 1500mm on the eastern slopes, dropping to about 500mm on the rain shadow side. During the austral summer the northern watershed; especially the north-east facing high ground usually receives high rainfall. Conversely, in the semi-arid Lowveld in the south, annual rainfall is less than 400mm. The relative dryness of southern areas is worsened by the absence of convergent winds during most of the season (Unganai and Mason, 2002; Tyson and Preston-Whyte, 2000; Tyson, 1984; Torrance, 1981).

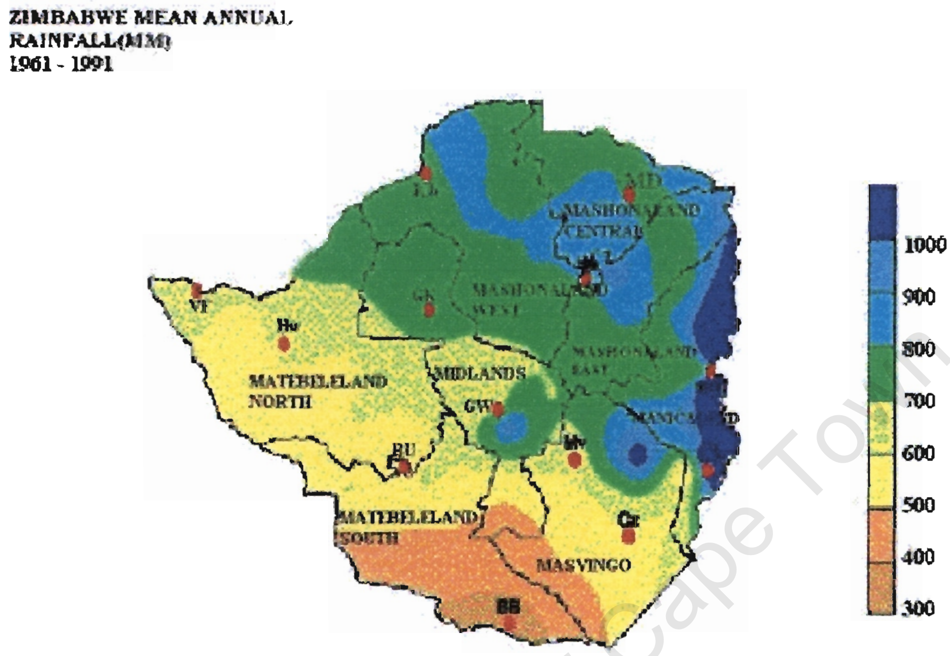

Figure 2.3 Distribution of the mean annual rainfall over Zimbabwe. *(Courtesy of the Zimbabwe Meteorological Services, 2002)*

2.4 Main Rainy season

The main rain season over Zimbabwe stretches from about mid-November to mid-March, though onset or cessation dates vary considerably (Tadross et al., 2005a). A considerable amount of rainfall is concentrated in the December to February (DJF) period. The rainfall season is characterized by intermittent wet spells and dry spells with a very long dry spell often occurring around end of December or in January (Makarau, 1995; Makarau and Jury, 1997; Unganai and Mason, 2002). As mentioned earlier, mid-season dry spells have increased in frequency/length in recent years. Rainfall over the country can be a result of orographic lifting, frontal systems, convergence and convection. The first three methods are mechanical forcing, whereas the fourth depends on the internal structure of the airmass. All these processes cannot produce rain unless the airmass has adequate moisture content and the atmospheric circulation at various levels of the atmosphere is conducive for rainfall. Convection is the dominant rain-inducing process in this country, accounting for almost 90% of the total rainfall (Unganai, 2002). Airmasses suitable for thunderstorm activity need to be moist and not too warm relative to the underlying ground, as cold air can more easily be heated to become unstable (Torrance, 1981). However, many different types of synoptic situations are conducive for thunderstorm formation. A storm can also be fed by moist and unstable air with a northerly component or an air mass can be very warm relative to the underlying ground. These conditions determine the dynamic controls and thermal environment (stability) in which convective systems can grow. All are such that appropriate divergence fields provide the necessary uplift to realize thermal instability and to sustain cloud growth. Common synoptic situations promoting storm formation include a trough in the tropical easterlies or frontal passages (Tyson and Preston-Whyte, 2000). Since most of Zimbabwe's rainfall is produced through convective processes, which depend on the heating of the surface, most rains falls in the warm afternoon hours, which is the peak of its diurnal cycle. The incidence of rainfall decreases from sunset onwards, and the minimum of the diurnal cycle is found to be the first hour or two after sunrise (Torrance, 1981).

2.5 Rain-bearing airmasses

The airmasses of most importance to Zimbabwe rainfall are the Congo Air Boundary (CAB), Northeast (NE) Monsoon and Southeast (SE) Trades, which all contribute to the formation of the ITCZ (Unganai, 2002; Tyson and Preston-Whyte, 2000; Lindesay, 1998; Mulenga, 1998, Makarau, 1995; Buckle 1986; Torrance, 1981). CAB is a recurved south-easterly trade from SAO bringing moisture in from the Congo basin entering Zimbabwe from the northwest when pressure is low to the south or west and its presence is often associated with good rains (Unganai, 2002; Buckle 1986; Torrance, 1981), Figure 2.4. It is nearly saturated, relatively cool and therefore readily becomes unstable. Thunderstorms are common followed by rain from layer clouds. The north of the country receives Congo air more often than the south. The NE Monsoon air mass is rather variable in nature, moist or dry depending on its recent track. With a fairly lengthy land track, this airmass carries only moderate moisture in the lowest 2km with dry air above. Rainfall tends to be light but heavy falls can occur in the northeastern sector when winds blow upslope. The SE Trades also show a low-level moist layer with dry air above and therefore tend to be associated with fair weather. However, in the vicinity of the ITCZ, the layer of moist air is much deeper and rain and thunderstorms occur more freely (Unganai, 2002; Buckle, 1986; Torrance, 1981).

A persistent trough at the northern limit of the trades develops between the Angola low and a low in the Mozambique Channel, separating the moist westerlies over Zambia from the drier easterlies over Zimbabwe. This results in recurrent rain and thunder to about 100km south of the trough (Torrance, 1981) The rain in Zimbabwe is therefore dependent to a large degree on whether the preferred position is at 12°S or 16°S, the latter being more favourable for a good rainfall season. In an extreme year the trough may establish itself or move frequently to the Limpopo Valley resulting in widespread heavy rains over Zimbabwe and further south in the Northern Province of South Africa. Small depressions may develop in the trough and increase local thunderstorm activity.

2.6 Tropical Cyclones

Zimbabwe's rainfall is also affected by Tropical cyclones (TCs) in the southwest Indian Ocean (SWIO). Depending on their proximity and relative position, cyclones may induce an extended dry spell in Zimbabwe or give widespread and heavy rainfall in a short space of time, which can culminate in devastating floods (Matarira, 1990; Unganai and Mason, 2002; Torrance, 1981). A cyclone in the central or eastern Mozambique Channel causes a clearing in the weather over most of Zimbabwe and a break in the rains, which may last from a week to a fortnight. This is mainly due to the development of dry upper southeasterly winds, which could possibly be part of the subsiding outflow from the cyclone which suppresses convection (Matarira, 1990c). On the other hand, the presence of a cyclone in the channel almost invariably sees the generation of an upper anticyclone over the South African interior. The linkage between these two is not yet clear but the trajectories of the dry upper southeasters suggest that they are of continental rather maritime origin (Torrance, 1981). If the cyclone is to move near or crosses the central

Mozambique coast, southeasters strengthen and may produce heavy rainfall and flooding as occurred in February 2002 with tropical cyclone Eline.

Figure 2.4 The airmasses into Zimbabwe are SE Trades, Congo Air and NE Monsoon involved in the ITCZ. *(Adapted from Australian Rainman, 1998).*

2.7 Geopotential Height

Another important feature of Zimbabwe's rainfall season is the middle level (500hPa) anticyclone, which tends to establish a centre about Botswana and is referred to locally as the *Botswana Upper High* (BUH) (Figure 2.5). This has tended out to be a semi-permanent feature fluctuating only in strength and orientation. Subsidence at these levels prevents the formation of cloud in the middle levels and fine weather prevails. Pressure falls more rapidly with height in the warm air and thus strengthens the upper anticyclone. Under this circulation pattern rainfall over Zimbabwe especially in the southwest areas is drastically suppressed. Deviations from these mean conditions are used to separate the dry and wet years. Tyson (1984) inspected the differences in annual geopotential heights at 850hPa and 500hPa levels between 16 stations over southern Africa and adjacent oceans and found that the 500hPa circulation field was more important than its near-surface counterpart as a control of annual rainfall.

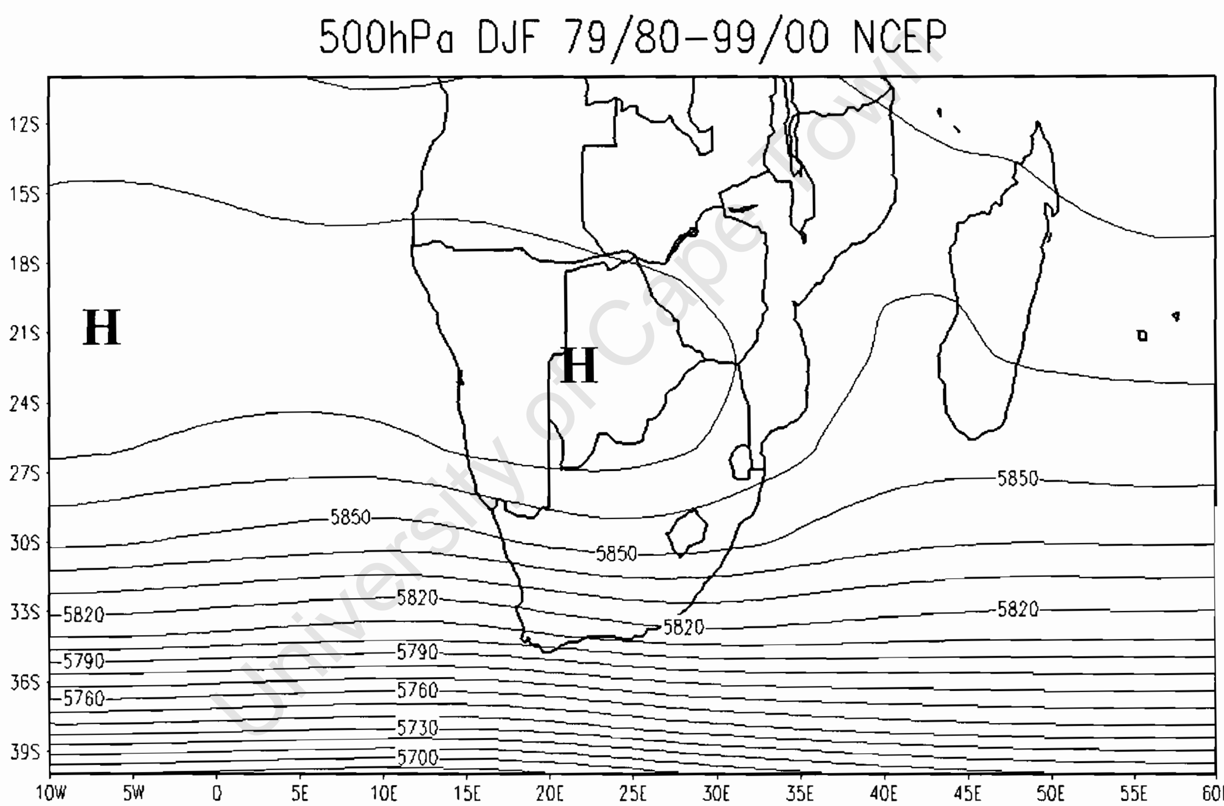

Figure 2.5 Mean 500hPa geopotential heights using NCEP data for the period (1979-2000). An anticyclone stretching from the Atlantic into the sub-continent is shown. This has become a semi-permanent feature.

Figure 2.5 shows the mean 500hPa geopotential height using NCEP/NCAR data for the period 1979-2000. A three-month seasonal (DJF) deviation from the 500hPa geopotential height mean was used to determine circulation anomalies associated with wet and dry conditions within the last 2 decades of the twentieth century. Respectively, five wet years (1981, 1989, 1996,1999 and 2000) and dry years (1983, 1984, 1988, 1992, 1993) were selected from those years that are one standard deviation above and below the long-term mean (1961-1990) derived from Zimbabwe's rainfall data. One standard deviation is a value such that roughly two-thirds of all rainfall years fall within the range from one standard deviation above mean to one standard deviation below mean. This isolates a number of years which can be classified within the wettest and driest years of the records respectively. The most striking feature amongst the dry years is the dominance of the positive anomalies over the continent. Dry season, positive anomalies demonstrate conditions that inhibit development of active systems whilst the wet years portray favourable conditions for rainfall activity. These patterns are similar to those found in an earlier work by Matarira, 1989.

Differencing of the composite fields of December to January dry years from wet years was performed to assess the strength of the anomaly fields at 500hPa geopotential height (Figure 2.6). The differentiation clearly outlines the dominance of the drier-than-normal conditions patterns over the region. The strength of the semi-permanent anticyclone over Namibia/Botswana and its influence on the climatological patterns during the summer season is shown by the very positive geopotential values of up to +25gpms. The system is mostly centred over Namibia/Botswana and has been linked to most of the dry years over Zimbabwe and the bulk of the region.

2.8 Guti

"Guti" is an important weather phenomenon in Zimbabwe and may occur at any time of the year. Guti is defined as type of weather having low overcast stratiform cloud from which drizzle falls, sometimes continuously, but more typically in bursts during which cloud base lowers and visibility is considerably reduced (Hattle, 1979; Torrance, 1981 and Buckle, 86). There is an incursion of moderate to fresh southeasterly wind, which will be cool and gusty. These synoptic conditions are induced by the strengthening surface south-to-north pressure gradient between Durban, KwaZulu-Natal in South Africa and Beira in Mozambique. The steepened gradient is normally caused by the approach of an anticyclone around the South African coast but may be enhanced by a depression north of Beira. When these two occur in conjunction the Guti conditions are severe e.g. during the track of TC Eline in February 2002 (personal experience as a weather forecaster at Zimbabwe Meteorological Services). The process involves orographic uplift from the coastal plains to the plateau and hills of Zimbabwe, with the wind speed contributing to turbulence and a high rate of cooling in the rising air. The drizzle of the plateau and gentle slopes intensifies to rain over the Eastern Highlands. During summer, considerable medium and convective cloud may be present and result in rain or showers from the upper levels (Hattle, 1979; Torrance, 1981 and Matarira, 1990). Increased convergence within the ITCZ is apparent as the subsequent pressure rises over southern Mozambique. Hattle (1979) found that the sequence is often accompanied by a cool westerly wave aloft, which is liable to produce or intensify thunder conditions.

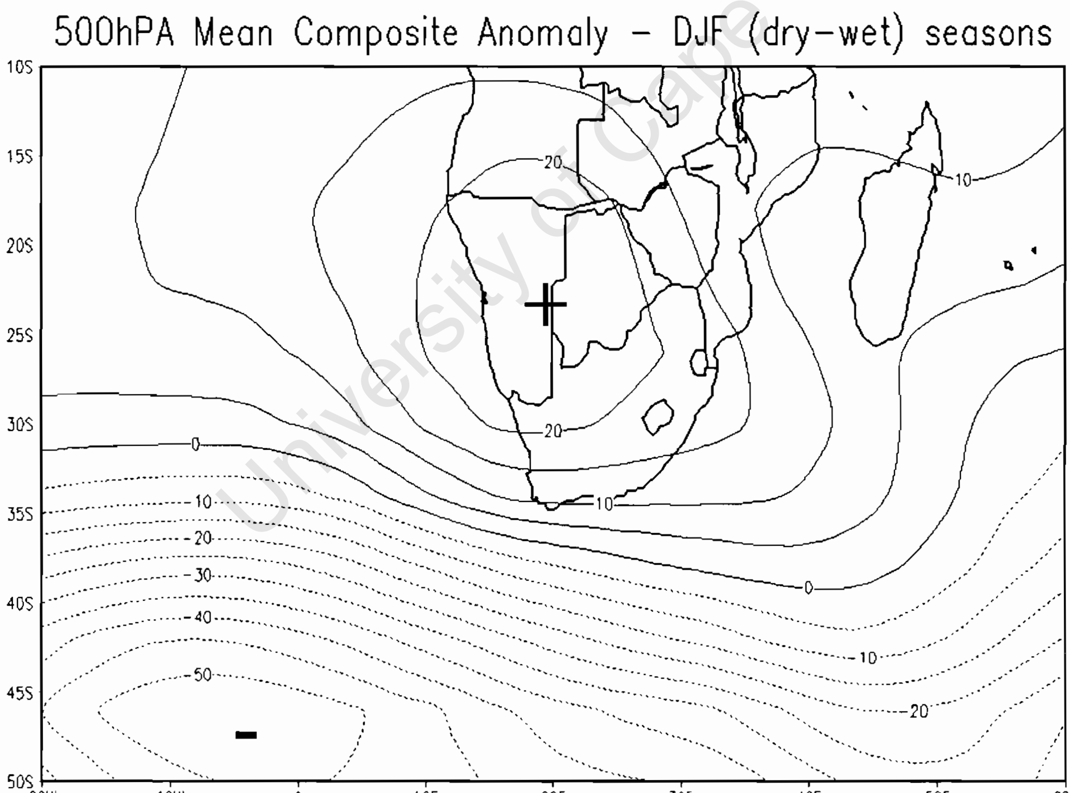

Figure 2.6 500hPa Geopotential Height (m) Composite mean for December to February of dry years differenced from wet years.

2. 9 El Niño Southern Oscillation

As mentioned in chapter 1, there has been much work on ENSO and its connection to southern African rainfall. On the synoptic-scale, many works have attempted to identify the conditions which lead to extreme events over Zimbabwe. Matarira (1990a) carried out some correlation analysis between ENSO and seasonal rainfall over the region and found that the ENSO signal is stronger over the southeast of Zimbabwe and along the coastal areas of Mozambique. El Niño events have generally been associated with below normal rainfall over Zimbabwe. Figure 2.7 shows a time series of seasonal rainfall anomalies and the Southern Oscillation Index (SOI) constructed to show how the variations between the annual rainfall of Zimbabwe is associated with particular ENSO events.

Some correlations between Zimbabwe's rainfall and ENSO exist. Matarira (1990a) found an average of the SOI for the preceding 12 months (January-December) to be positively correlated ($r = 0.42$) to the November-April station rainfall across Zimbabwe and the peak correlations are in the southeast of the country. Makarau and Jury (1997b) found a correlation of 0.40 between national average summer rainfall and monthly SOI at 1-2 months' lag. Relatively strong relationships have also been found between Zimbabwe summer rainfall and global SST's (Rocha and Simmonds, 1997b). Rocha and Simmonds (1997a, 1997b) demonstrated that the SST-rainfall link over the Indian Ocean remains strong after the ENSO effects have been removed, suggesting that the atmospheric circulation anomalies observed over southeastern Africa dry summers, are linked mainly to SST anomalies in the Indian Ocean. Droughts have occurred simultaneously with El Niño in 32% of cases. Up to 16% of the variance in the country's inter-annual rainfall is ascribed to the ENSO influence suggesting that there are also some other forcings, which affect the rainfall of Zimbabwe (Unganai and Mason, 2002).

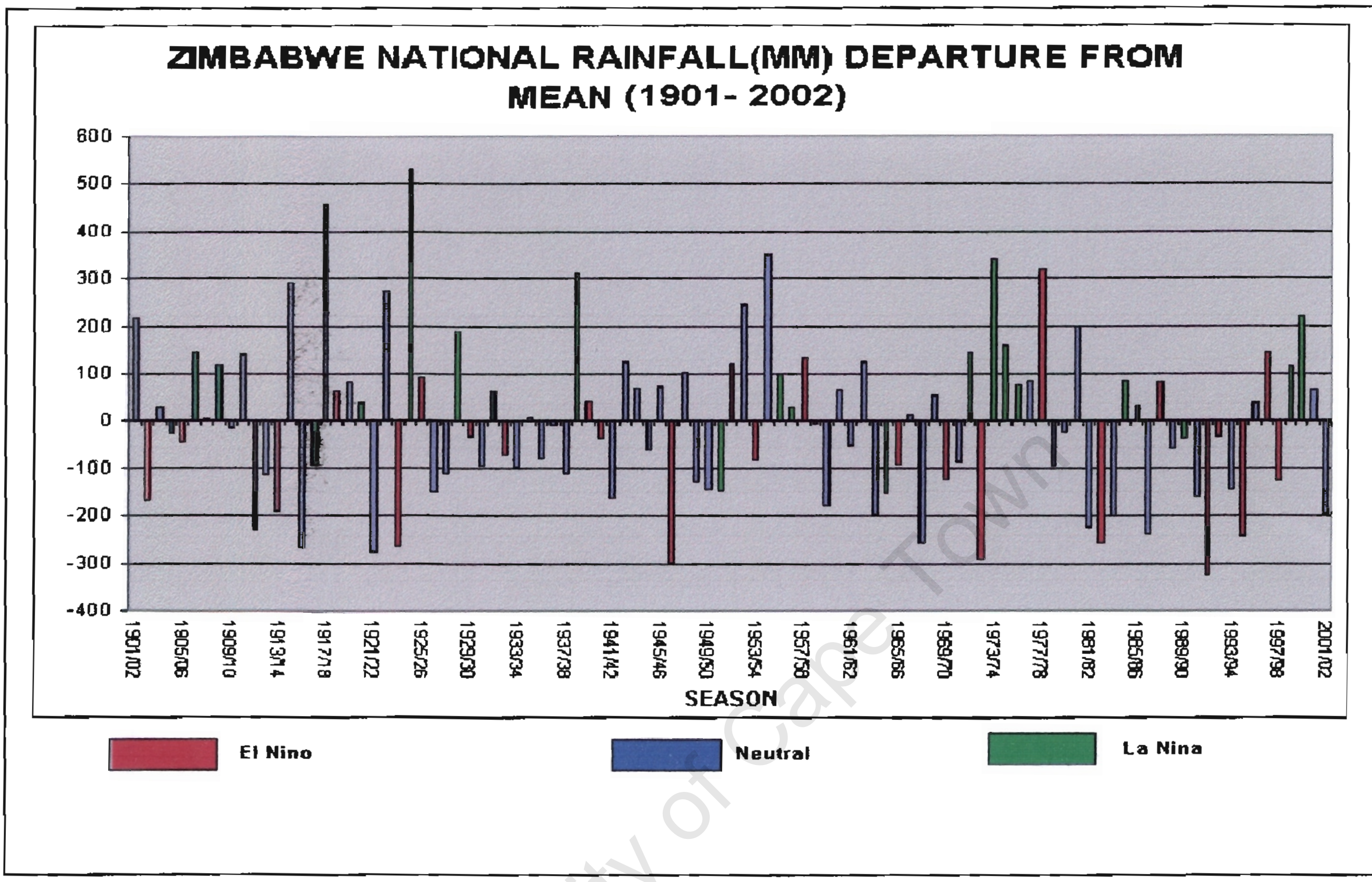

Figure 2.7 Zimbabwe's rainfall departures from the mean and associated ENSO conditions.

Additionally there is evidence that the link between ENSO and southern African rainfall is modulated by the Indian and Atlantic Oceans (Mason et al., 1994; Rocha and Simmonds, 1997a, 1997b; Lindesay, 1998, Landman et al., 2001). The rainfall and circulation patterns responses to below average SSTs in key oceanic areas are similar to those for El-Niño situation in that cooler sea temperatures in much of the southern Indian and Atlantic Oceans are associated with decreased summer rainfall (Mason et al., 1994; Lindesay, 1998, Goddard and Graham, 1999; Reason and Mulenga, 1999; Reason et al., 2003). Mechanisms linking southern African droughts with above–normal SSTs anomalies over central Indian Ocean have also been explored and a temperature dipole was observed which modulates rainfall over the continent (Jury and Pathack, 1993; Jury, 1992, 1996; Tennant, 1996; Rautenbach, 1998; Mason and Goddard, 2001). Using the

Brandon-Marion Index (BMI) which is indicative of changes in the pressure field over the Indian Ocean, Rocha and Simmonds (1997a) showed that BMI correlates with southeastern Africa rainfall better than the SOI (measuring the ENSO influence).

As well as links to mean seasonal rainfall, ENSO has been shown to affect intra-seasonal characteristics of rainfall over Zimbabwe. Usman and Reason (2004) demonstrated that the frequency of mid-summer dry spells over southern Africa increases during El-Niño years. Tadross et al. (2005a) show that the onset of the rains over southern Zimbabwe is often delayed during El-Niño and that this is related to an absence of high pressure anomalies in the southern Mozambique Channel which advect moisture inland.

2.10 Summary

Most of Zimbabwe's rain falls between December and February with an occurrence of a mid-season dry spell at the end of December or in January. The complexity of Zimbabwe's rainfall characteristics at the interannual and intraseasonal variability has been demonstrated. During drought years the circulation pattern inhibits the formation of active weather systems. Composite fields of the recent decades show the dominance of the 500hPa geopotential anticyclone.

Some correlation exists between the ENSO and below normal rainfall especially over southern Zimbabwe. However, there is also influence from the SST anomalies of the adjacent Indian and Atlantic Oceans. Numerous studies have been done on ocean-atmospheric interactions over southern African region, and explain about 20% of the total variance in Zimbabwe's rainfall. Focus should also be made on land-atmosphere interactions over the region to get more insight into the contribution to rainfall variability over Zimbabwe and the region.

Chapter 3

Data and Methodology

3.0 Introduction

Most research studies and analyses of rainfall characteristics over Zimbabwe were carried out for monthly or decadal data sets and thus may not have captured intraseasonal modes, thus substantiating an objective analysis using daily or pentad rainfall data. The main reason for the abundant use of these data sets is that they are readily available and easy to manipulate or use. Most meteorological stations within the region have a good data management system for decadal to monthly or annual totals. However, the quality of a season is based on the evenness of the temporal and spatial distribution of rainfall rather than the seasonal rainfall totals (Matarira and Jury, 1992, Tennant and Hewitson, 2002; Unganai, 2002). This has been a major concern amongst stake holders in agricultural production and water resources management who require a more informative seasonal prediction, incorporating the intraseasonal variations of wet and dry spells; onset and cessation dates; temporal and spatial distribution of the rains (personal communication with stakeholders at Southern Africa Climate Outlook Forums; SARCOFs).

This chapter describes the different datasets used in this research work. It briefly highlights the limitations of some of these datasets in climate research. The methodologies adopted in the research work are then described. A major focus is the improved knowledge of processes provided by the adopted approaches, which goes beyond methods used in most previous climate studies. This is accomplished through the use of a non-linear pattern-matching technique (SOMs) and experiments using an RCM to highlight potential feedbacks with the land surface. Together, these techniques are able to extract information from the nonlinear climate system which other methodologies may miss, as mentioned in the literature review.

3.1 Data

Daily rainfall data was obtained from the Zimbabwe Department of Meteorological Services' Climate Computing (CLICOM) database or through the WMO Global Telecommunications Systems (GTS) database. The 2.5° x 2.5° Climate Prediction Center Merged Analysis of Precipitation (CMAP) mean pentad and Climate Research Unit (CRU) mean monthly datasets were utilized to supplement the position-specific observed data.

National Center for Environmental Prediction/ National center for Atmospheric Research (NCEP/NCAR, Kalnay et al., 1996) and ECMWF[1] Reanalysis data were used in the RCM experiments as initial conditions and for the analysis of other general circulation features. Variables utilized in the analysis include sea level pressure and geopotential heights

3.1.1 Daily Rainfall Station Data

Daily rainfall data was obtained from the Zimbabwe Department of Meteorological Services' CLICOM database. The stations had a continuous record for the longest possible period of at least 30 years to determine observed rainfall characteristics accurately. Some quality control and homogeneity checks (section 3.2.1) were performed, to eliminate any outliers and fill missing data spots.

Table 3.1 shows the stations used in this study. The information presented in Table 3.1 includes the latitude, longitude, altitude, the atmospheric variables looked at and the period the station has data available. Daily rainfall, maximum and minimum temperature data for a number of stations across the country where utilized, as listed in Table 3.1. The stations selected were those included on the Global Climate Observing System (GCOS) Surface Network (GSN) (Peterson et al., 1997) or the ones being fed into the GTS.

[1] ERA-40 Project Report Series available on http://www.ecmwf.int/reasearch/era/Project

Figure 3.1 shows the spatial network for the stations used in the trend analysis work. The criteria for using a station included the following:

- Stations preferably with digital daily data, extracted from CLICOM database.
- The continuous records were as long as possible, and included the WMO standard reference period of 1961–1990.
- The station, in most cases, had a documented history of changes such as those involving instrumentation, observation practices and the station's immediate environment (metadata). Of the 33 original stations available only 14 had well documented history.
- In most cases, the station had been located at a single site during the period of record.

Although all the stations were subjectively chosen for this study, these criteria were followed for consistency and for the stations to be used in regional analyses of the climate extreme indices. The primary purpose of such stations is to identify long-term climate trends. Therefore, stations need a long, continuous and homogeneous record, minimal influence from urbanization, and a general high-quality of data (Peterson et al., 1998, 2002; Manton et al., 2001).

3.1.2 Climate Prediction Center Merged Analysis of Precipitation

The 2.5° x 2.5° Climate Prediction Center, United States of America (U.S.) Merged Analysis of Precipitation (CMAP) dataset merges satellite and rain gauge data from a number of satellite and rain gauge sources. These data start in January of 1979 and continue through to the present. Xie and Arkin (1996) provide details on the component datasets and the method used to merge these data. Although the data is suitable for climate studies, there are limitations for some climate applications. These include discontinuities in the component data sets, differences in the calibration methods, and the methodology used to weight the individual rain estimates (Xie and Arkin, 1996).

Table 3.1 Stations used in this analysis

Station	Latitude	Longitude	Altitude (m)	Parameters	Period of data
Beitbridge	-22.22	30	457	P,T	1922-2003
Harare Belvedere	-17.83	31.02	1472	P,T	1900-2003
Chipinge	-20.2	32.62	1132	P,T	1960-2003
Bulawayo Goetz	-20.15	28.51	1344	P,T	1900-2003
Kadoma	-18.32	29.88	1157	P,T	1951-2003
Karoi	-16.83	29.62	1344	P,T	1951-2003
Harare Kutsaga	-17.92	31.13	1479	P,T	1959-1997
Kwekwe	-18.93	29.83	1215	P,T	1951-2003
Nyanga	-18.28	32.75	1878	P,T	1951-2003
Rusape	-18.53	32.13	1430	P,T	1904-2003
Masvingo	-20.07	30.87	1095	P	1951-2003
Makoholi	-19.65	30.78	1204	P	1954-1998
Gweru	-19.45	29.85	1429	P,T	1944-2003
West Nicholson	-21.05	29.37	861	P,T	1952-2003

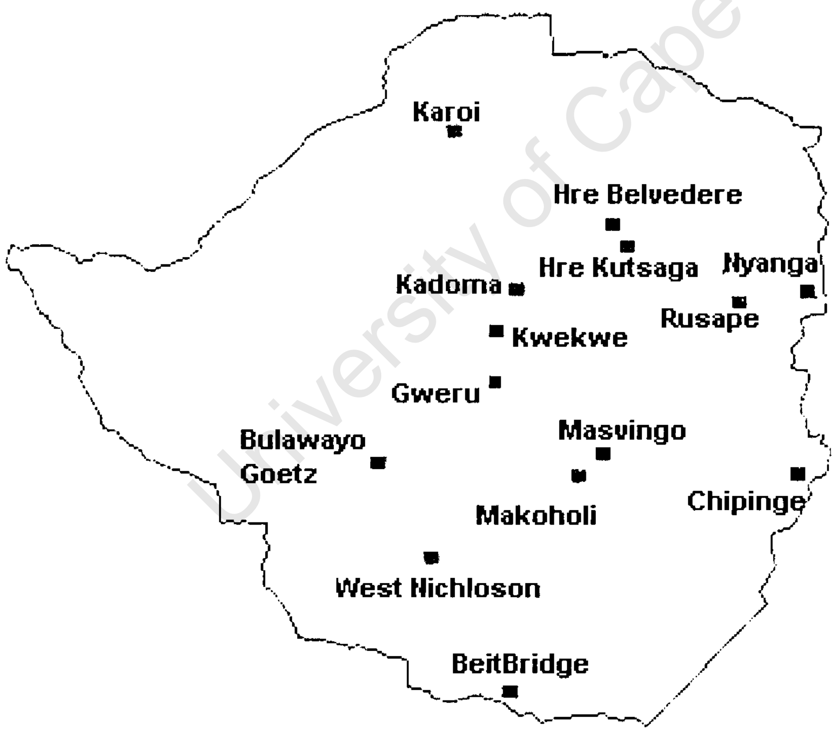

Figure 3.1 Map of Zimbabwe showing the stations used in the climate extremes trend analysis work.

3.1.3 Climate Research Unit 0.5° Dataset

The Climate Research Unit, University of East Anglia, UK (CRU) dataset is a monthly mean data set with a spatial grid resolution of 0.5° x 0.5° (New et al., 2000), using only station observations. CRU rainfall estimates are generally lower than those of CMAP especially over the Democratic Republic of Congo and Angola. A very small number of observation stations with a few records are available in these regions. New et al., (2000) state that where the station density is low, CMAP relies heavily on the satellite estimates whereas CRU data tends to climatology. It is unclear which analysis is a better representation of reality (Tadross et al., 2005b). These discrepancies or uncertainty in the observations complicate the validation of climate models and training of area-average rainfall forecasting methodologies over Southern Africa.

3.1.4 National Centers for Environmental Prediction - National Center for Atmospheric Research Reanalysis Data

The U.S. National Centers for Environmental Prediction (NCEP) - National Center for Atmospheric Research (NCAR) Reanalysis Data (Kalnay et al., 1996) have a spatial resolution of $2.5^{o} \times 2.5^{o}$, with surface variables and free atmosphere variables distributed at 17 pressure levels (8 for humidity), and are available at a time resolution of 6 hours. This global data set describes the state of the global atmosphere and comprises a GCM assimilation of observed values from a number of sources including, land station, ship rawinsonde, pibal aircraft and satellite. It is a retroactive record of more than 50 years of global analyses of atmospheric fields in support of the needs of the research and climate monitoring communities. Kalnay et al. (1996) outline the quality and methods used to generate the reanalysis data[2] .

From the global data set, the study domain for the summer months in the period stretching from 1979 to 2002 was extracted. The data quality prior to 1979 for the southern African region is suspect since the climatology before 1979 (pre-satellite) is

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[2] also available on http://atom.umd.edu/~ekalnay/

dominated by the model climatology in data-sparse areas (Kistler et al., 2001). The reanalysis can be used for daily to seasonal and interannual time scales. However, Kistler et al., (2001) caution that because of the changes in the observing system, estimation of trends with the reanalysis is not recommended. If it is attempted then trends should be computed separately for the periods before and after 1979. Problems and limitations of the NCEP/NCAR reanalysis data are available[3]. However, NCEP/NCAR reanalyses data unlike many of the available analyses, has the positive benefit of a fixed state-of-the-art assimilation scheme (Bromwich and Foot, 2004; Marshall, 2003).

3.1.5 European Centre for Medium Range Weather Forecasting Reanalysis

European Centre for Medium Range Weather Forecasting Reanalysis data (ERA-40) covers the period from mid-1957 to 2002. ERA-40 provides a very high quality reference atmospheric state for a long period at a spatial resolution of $2.5^{\circ} \times 2.5^{\circ}$ and at a time resolution of 6 hours. ERA-40 reanalysis data complements the available NCEP/NCAR 50-year and ECMWF (ERA-15) 15-year reanalyses (Troccoli and Kållberg, 2004).

There were a number of shortcomings in processing the ERA-40 data, namely changes in forecast models, changes in the data assimilation system and unavailability of delayed mode data (Troccoli and Kållberg, 2004). The reanalysis was undertaken using three separate stages, or streams each of which had different data types available and hence required different assimilation techniques. An error was discovered in stream 1 due to among other things, an inadequate algorithm for the assimilation of High Resolution Infrared Sounder (HIRS) radiances leading to a cold bias over sea ice regions in the Polar areas (Marshall, 2003). Concerns have been raised about high precipitation over the Tropics and the imbalance of precipitation to evaporation (P-E), (Kållberg, 1997; Uppala, 1997; Hagemann, *pers. comm.*, 2005)

[3] http://www.cpc.ncep.noaa.gov/gov/products/wesley/reanalysis.html#problem

3.2 Methodology

The rainfall season over Zimbabwe is from mid-November to March although some areas can have an earlier onset with the season commencing in October. It is of utmost importance to determine which part of the season to focus on before calculating and analyzing rainfall characteristics. This research initially incorporated the summer period from October to March and utilized the rainfall departures from the long-term mean to delineate between wet and dry years using daily rainfall station data. A composite analysis was performed by comparing the individual years to the climatologically mean of 30 years to separate into wet and dry categories (the climatological mean value being calculated from 1961-1990 as stipulated by WMO).

Having identified the wet and dry years, the Self-Organised Maps (SOMs, section 3.2.4) are used to capture the modes of variability in the summer rainfall patterns using CMAP pentad data, focusing on the October to November (OND) and January to March (JFM) periods i.e. early and late summer respectively. This separation of the season is based on differences between early summer, in which most rain-producing systems are of a baroclinic westerly wave disturbance in the mid-latitudes, and late summer rains which are mainly of tropical origin (Matarira, 1989; Makarau, 1995, Jury, 1996; Washington and Todd, 1999; Unganai 2002; Tennant and Hewitson, 2002). Further to this separation of early and late summer a SOM (see section 3.2.4) was used to determine how the frequency of archetypal daily low-level atmospheric circulation changes between the early and late seasons. A trend analysis of the frequencies of typical synoptic states was accomplished using the R statistical software package[4].

A composite analysis of the data sets described above contrasts the wet and dry years. The synoptic characteristics of the intra-seasonal wet and dry events are reviewed to verify some of the postulated hypotheses about their occurrence over Zimbabwe. Trends of extreme events in the observed climate record are calculated and the detection of

[4] Freely available from http://www.r-project.org

climate change in the historical database is discussed. The research methods used in this study will now be discussed in greater detail.

3.2.1 Quality Control

The data was subjected to some quality control (QC) tests similar to those described by Peterson et al. (1998). These include assessing the data for physically impossible values, such as negative precipitation and maximum temperature less than minimum temperature, unrealistically long consecutive occurrences of the same value, such as very long zero precipitation indicating that missing data was erroneously set to zero and checks for statistical outliers. Most of these problems were not encountered except for some occasional digitizing errors such as continuous row maximum temperatures like 7.7 instead of 27.7. This was rectified by using knowledge of the station and the climatological mean.

Some studies have shown that even correctly observed and digitized data may be unsuitable for long-term climate analyses. Practical examples include a situation when a thermometer is moved from the shade of a tree to a place out in the grass but near a tarmac, an artificial jump can occur in the time series (Peterson et al. 1998). Inhomogeneities or discontinuities in climate data can be caused by any change to the station or its operation, including site location, exposure, instrumentation, or observational practice (Peterson et al., 1998; Manton et al., 2001; Salinger and Griffiths, 2001). Instead of running specific homogeneity tests, which generally focus on changes in mean values, each station's climate extreme indices time series was visually evaluated for discontinuities such as a big jump in time on the graphical plots. Those with obvious discontinuities were not considered in the analyses that use that concerned variable. This was in view of the fact that a discrepancy in minimum temperature does not necessarily impact the maximum temperature or precipitation observations. However, it should be noted that a more robust method of homogeneity testing was not fully recognized. The objective and subjective methods for homogeneity adjustments of in situ atmospheric climate have been reviewed (Peterson et al.1998)

3.2.2 Trend analysis

The software (RClimdex) used for QC and indices calculation has been developed by Xeubin Wang and colleagues at the Canadian Climate Centre[5]. The program is implemented in the R statistical software package. Daily data (precipitation, maximum temperature and minimum temperature) are read into RClimdex and some basic quality control checks are done as explained in the section 3.2.1.

Some extreme rainfall and temperature indices involving arbitrary thresholds have been used in previous studies e.g. number of days each year with daily rainfall exceeding 25.4mm or 50.8mm (Groisman et al. 1999), or the number of winter days below 0°C (Jones et al., 1999). Manton et al.(2001) point out that these are suitable for regions with little spatial variability in climate, but arbitrary thresholds are inappropriate for regions spanning a broad range of climates e.g. in Zimbabwe there is no single temperature or rainfall threshold that would be considered extreme in all rainfall regions. Thus statistical quantities such as percentiles were used. These upper and lower percentiles are extreme in all regions, but vary in absolute magnitude from site to site and are therefore useful over a wide range of climates.

Percentiles were used to calculate annual extreme indices of maximum and minimum daily temperatures and rainfall. The percentiles were computed using all the non-missing days. For rainfall this included rain days e.g. the 90th percentile and the 10th percentile were chosen, corresponding to the 36th highest daily rainfall and 36th lowest daily rainfall in a 365-day year. The annual indices of extremes were calculated for each year over the WMO reference period 1961-1990. The indices selected for this study are:

- Annual total precipitation in wet days with at least 1mm of rain, PRCPtot (mm).
- Maximum number of consecutive dry days (dry spells), CDD.
- Annual total precipitation exceeding 95th percentile of the rainfall, R95p

[5] See http://ccrp.tor.ec.gc.ca/etccd

- Monthly maximum consecutive 5-day precipitation, RX5day.
- Monthly lowest daily minimum temperature, TNn (°C/century).
- Monthly highest daily maximum temperature, TXx (°C/century).
- Percentage of days when daily minimum temperature is below 10th percentile, TN10P (days).
- Percentage of days when daily maximum temperature is below 10th percentile, TX10P (days).
- Percentage of days when daily minimum temperature exceeds 90th percentile, TN90P (days).
- Percentage of days when daily maximum temperature exceeds 90th percentile, TX90P (days).
- Mean monthly diurnal temperature range, DTR (°C/century).

A dry day was defined as a day where the rainfall total is less than 1 mm, and a rain day as a day with a rainfall total of 1 mm or more. Other useful indices were calculated using the RClimdex software. Although not discussed here the chosen indices were expected to give a good indication of their trends. This was observed with indices like the 95th and 90th percentiles depicting a similar trend pattern. However, not all indices calculated are relevant over Zimbabwe or the southern Africa region at large e.g. the frost detection index (FDI) does not give any trend over Zimbabwe as minimum temperatures are above the threshold value of 0°C.

3.2.3 Cressman Interpolation

A Cressman objective analysis is performed on the station data to arrive at a gridded result that represents the station data. The Cressman Analysis scheme is described in Cressman (1959). Multiple passes are made through the grid with increasingly smaller radii of influence. At each pass, a new value is calculated for each grid point based on a correction factor that is determined by looking at each station within the radius of influence. For each such station, an error is defined as the difference between the station value and a value arrived by interpolation from the grid to the station. The correction factor is based on a distance-weighted formula applied to all such errors within the radius of influence. The correction factors are applied to each grid point before the next pass is made. Any grid boxes that do not have stations/values within the third specified radius are set to the missing data value. The analysis performs three passes by default at three specified numbers. These numbers are proportions of the average minimum station distance calculated in the function. The numbers can be changed when entering the command in Grads. There is also a minimum station number which ensures that a certain number of station data points must be included within the radius of influence for an analysis value to be calculated for that gridpoint. More information on the interpolation technique and on-tutorial is available; e.g. International Research Institute (IRI), US, Statistical Analysis Tutorial[6]. The interpolation commands are available in Grads home page[7] . Therefore, the Cressman analysis uses first guess followed by a correction and weights are an exponential function of distance between grid point and observation.

Advantages are that the scheme is simple and computationally fast. The most limiting factor is that it hugely over-predicts spatial extent of precipitation fields (Hewitson and Crane, 2005). It is not well suited for diverse types of observations because observational error is not accounted for. Also, it does not account for the distribution (density) of observations relative to each other. It is recommended that other, more rigorous objective analysis schemes be used for any specific requirements outside those of which the station data will be used for in this study (Hewitson and Crane, 2005).

3.2.4 Self-Organizing Maps

The Kohonen Self-Organizing Map (SOM) technique is a method for evaluating the distribution of modes of variability within a high-dimensional data set. It is able to capture variability in e.g. rainfall patterns and express these patterns (or nodes) across a non-linear two-dimensional continuum. Additionally it separates patterns where there is more data to warrant such a separation. Once patterns of rainfall have been characterised

[6] Freely available on http://ingrid.ldeo.columbia.edu/dochelp/StatTutorial/Interpolation/
[7] Freely available on http://www.grads.iges.org

the original data may be mapped to these characteristic patterns and a frequency of occurrence of each pattern generated. An analysis of these frequencies and their trends over time will be discussed in chapter 4.

As a powerful utility in capturing the modes of variability in atmospheric patterns and expressing these synoptic types across a two-dimensional continuum, SOM has recently been adopted in synoptic climatology. The SOM has been broadly described as an Artificial Neural Network (ANN) and has an inherent ability for classification, which makes it potentially applicable for use in synoptic climatology (Main, 1997; Hewitson and Crane, 1994, 2002). ANN are currently being used in a number of research fields in Geography (Hewitson and Crane, 1994) and applications have ranged from prediction of precipitation and snowfalls from general circulation fields, to classification of Artic cloud and sea-ice features from satellite data (Hewitson and Crane 1994); forecasting sea surface temperature anomalies (SSTA) for the equatorial Pacific Ocean region (Tangang et al., 1998); empirical down-scaling procedure to derive daily subgrid-scale precipitation from general circulation model (GCM) geopotential and specific humidity data (Crane and Hewitson, 1998); and in predicting the Indian Monsoon rainfall (Cannon and McKendry, 2002). ANNs were initially designed as a mathematical representation of the biological nervous system. Clustering, classification and regression tasks can be performed using different varieties of ANN.

Kohonen Self-Organising Maps is competitive and unsupervised neural network and uses no target data set for training. First developed by Kohonen (1995) at the Helsinki University of Technology, SOMs are now used in a wide variety of applications although there is still limited literature on their use in meteorology or climatology. Main (1997) used SOMs to investigate seasonal cycles in GCMs; Hudson (1998) utilized SOMs to evaluate frequency changes of synoptic events in a GCM perturbation experiment; Tennant and Hewitson (2002) used SOMs to seek particular seasonal modes in the atmospheric circulation. Walawege (2002) used it in examining spatially extensive heavy rainfall events over South Africa. Crane and Hewitson (2003) used SOMs to combine precipitation records of individual stations into a regional data set by extracting the common regional variability from the locally forced variability at each station. Fundamentally, SOMs are a powerful technique to identify dominant modes within the span of a data set and provide a mechanism for visualizing an array of atmospheric states.

SOM technique is a method for mapping a high dimensional input vectors to a two dimensional array of nodes. It can be interpreted as a "nonlinear projection" of the probability density function of the high-dimensional input data onto the two-dimensional display. SOM maintains some measure of the distance between data points in the high dimensional space. The technique is different from traditional cluster algorithms in the way in which groups are defined. Output of SOM analysis is analogous to some form of data clustering; however, unlike clustering algorithms the basic SOM methodology is not primarily concerned with grouping data or identifying clusters (Hewitson and Crane, 2002). SOMs attempt to find nodes or points in the measurement space that are representative of the nearby cloud of observations and when taken together describe the multi-dimensional distribution function of the data set. For this work, the most important attributes of the SOM technique are the ability to classify input data based on non-linear relationships between the input elements and to visualise the continuum of the data space.

SOMs are developed through an iterative training procedure in which elements of the SOM are mapped to representative regions of the input data space (Kohonen, 1995; Hewitson and Crane, 2002; Crane and Hewitson 2003). Training is implemented with one of the two possible neighbourhood kernels which are vital to the SOM algorithm, bubble or Gaussian which relates time and learning rate together to determine how a particular node's weights are updated. Learning rate determines how easily a node's weights may be changed. The user determines the size and shape of this update kernel. Quality of learning is based on initial values and applying different sequences of training vectors and different learning parameters. Thus an appreciable number of random initializations of the initial values ought to be tried and the map with the minimum quantisation error selected. The SOM technique also provides means of knowing how similar or dissimilar nodes are to each other through the Sammon mapping.

The training phase has the effect of adjusting the weight vectors on a node toward the training vectors such that they converge to the dominant variance structure of the data. This phase develops the general ordering of the SOM map. The second phase then develops the finer aspects of the SOM array and allows more local differentiation between nodes. The second phase is usually longer than the first one, the learning rate and neighbourhood radius are smaller. SOM algorithm trains the reference vectors. The topology type and the neighbourhood function that is defined in the initialisation phase are employed throughout the training. The SOM finds the best matching node for each input sample vector and updates those nodes in the neighbourhood of it according to the selected neighbourhood function. The initial value of the learning rate, the measure of how much a node vector is adjusted to a data sample is defined and will decrease linearly to zero by the end of training. The initial value of the neighbourhood radius is also defined and it will become small enough during training that only nearest neighbours are trained. Some of the investigations that can be carried out with the trained SOM are to look at the frequency of occurrence of each archetype and the average error at each node taken as a measure of the coherence around a node (Kohonen, 1995; Main, 1995; Hewitson and Crane, 2002; Crane and Hewitson 2003)

More detailed theoretical discussion on SOMs is well described in the literature especially the techniques by Kohonen, (1995). A practical SOMs software package[8] and its extensive references[9] are freely available.

3.2.5 Regional Climate Model

Tadross et al. (2005b) documents recent climate studies over southern Africa using regional climate models (RCMs). In this study the response of the atmosphere to soil moisture changes is considered through the use of a RCM, RegCM3 (Pal et al.,2005), evaluating in particular, the feedbacks between the atmosphere and land surface as well the effect on precipitation and extreme events.

[8] http://www.cis.hut.fi/research/som-research/
[9] http://www.cis.hut.fi/research/som-bibl/

RCMs simulate the climate by solving the fundamental physical equations of the atmosphere-land-ocean system. However, it is necessary to parameterize certain sub-grid scale processes. Therefore RCMs such as MM5 and RegCM3 contain several options of representing different atmospheric processes such as the planetary boundary layer (PBL) cumulus convection, radiation and cloud microphysical processes. The models are based on the physical laws of fluid dynamics; thermodynamics and the governing equations of conservation of energy, mass and momentum.

The dynamical core of RegCM, originally developed by Dickinson et al. (1989) and Giorgi (1990), is based on the hydrostatic version of the Pennsylvania State University – National Center for Atmospheric Research's Mesoscale Model version 5 (MM5). RegCM3 employs a terrain-following σ-vertical coordinate model, where $\sigma = (p-p_{top})/(p_s-p)$, p is pressure, p_{top} is the pressure specified at the top of the model and p_s is the prognostic surface pressure. The atmospheric radiative-transfer computations are performed using the radiation parameterization from the Community Climate Model version 3 [CCM3; Kiehl et al., 1996] and the planetary boundary layer computations are calculated using the non-local formulation developed by (Holtslag et al., 1990). The vertical eddy flux within the PBL is given by an eddy diffusion term plus a "countergradient" term, which describes nonlocal transport due to deep convective plumes in the PBL. The eddy diffusivity term follows a parabolic profile between the surface and the PBL top.

The resolvable (large-scale) cloud and precipitation processes are computed using a sub-grid explicit moisture scheme (SUBEX) (Pal et al., 2000). The unresolved convective precipitation processes are represented by the Grell scheme (Grell, 1993) with the Fritsch and Chappell (1980) Closure assumption. The scheme considers two steady state circulations comprising of an updraft and a downdraft. No direct mixing occurs between the cloudy air and the environmental air except at the top and bottom of the cloud. The mass flux is constant with height and no entrainment or detrainment occurs along the cloud edges. The levels of maximum and minimum moist static energy give the originating levels of the updraft and downdraft, respectively. The scheme is activated when a lifted parcel attains moist convection and rainfall depends on an efficiency parameter that measures the fraction of the updraft condensate that re-evaporates in the downdraft.

The surface physics calculations are performed using BATS1E (Biosphere-Atmosphere Transfer Scheme), described in detail by (Dickinson et al., 1993). BATS is designed to describe the role of vegetation and interactive soil moisture in modifying the surface-atmosphere exchanges of momentum, energy and moisture. It has a vegetation layer, a snow layer, a surface soil layer (10cm thick), a root zone layer (1-2m thick) and a third deep soil layer (3m thick). A more detailed description of RegCM3 and refereed articles can be found in Pal et al. (2005).

RegCM requires initial conditions and time dependent lateral boundary conditions for wind components, temperature, surface pressure and water vapour. The initial conditions and lateral boundary conditions for each simulation are from National Center for Environmental Prediction, NCEP reanalysis data (Kalnay et al., 1996). The SST is prescribed using data provided by the National Ocean and Atmospheric Administration (NOAA). The vegetation is specified using the Global Land Cover Characterization (GLCC) data (Loveland et al., 1999)

Chapter 4

Observed Patterns of Rainfall over Southern Africa

4.0 Introduction

In this chapter a SOM is used to identify and visualize the dominant patterns within the CMAP rainfall pentad data for the period of 1979 to 2002. The rainfall patterns over southern Africa for the October to December and January to March periods are discussed, with the major focus being on changes observed over Zimbabwe. Frequency maps of the archetypal pentad rainfall patterns are examined to identify the main rainfall patterns occurring during each of the 23 years. A trend analysis of these frequencies is also carried out to study the behaviour of these rainfall patterns with time.

4.1 Application of a SOM

Two SOMs were trained, one using the 18 pentads of CMAP rainfall data for the October to December period and a second for the January to March period, (from 1979 to 2002). In both cases a SOM comprising 35 nodes (5 x 7 nodes) was finally chosen after inspecting all possible groupings from the smallest SOM size of 2 x 3 for significant patterns. The more the nodes, the finer will be the representation of detail of synoptic rainfall variability over the region. The 5 x 7 array is analogous to using 35 clusters in more traditional methodologies, although in the case of SOMs the 35 classes are taken to represent synoptic states spanning the continuum as represented by the data samples (Tennant and Hewitson, 2002; Hewitson and Crane, 2002). The training was accomplished using 2 successive passes of 50 000 iterations each for the CMAP pentad rainfall dataset. Training was defined to take 50 000 steps, but if there are fewer entries in the input file, the file was iterated until only the nearest neighbours are trained. It is important to note that the SOM cannot "overtrain", and extensive iterations will not alter the solution. The initial learning rate was set to 0.05 and the initial radius of the learning "bubble" set at the smaller of the array dimensions (5). This relatively large update radius is used initially in order to develop the broad mapping across the array of nodes. As explained earlier, during successive training passes the update radius is progressively reduced. In the second training stage the initial update radius is set to 3 and the training rate half that of the first pass. This phase develops the finer aspects of the SOM array.

4.2 Observed rainfall patterns

4.2.1 Sammon maps

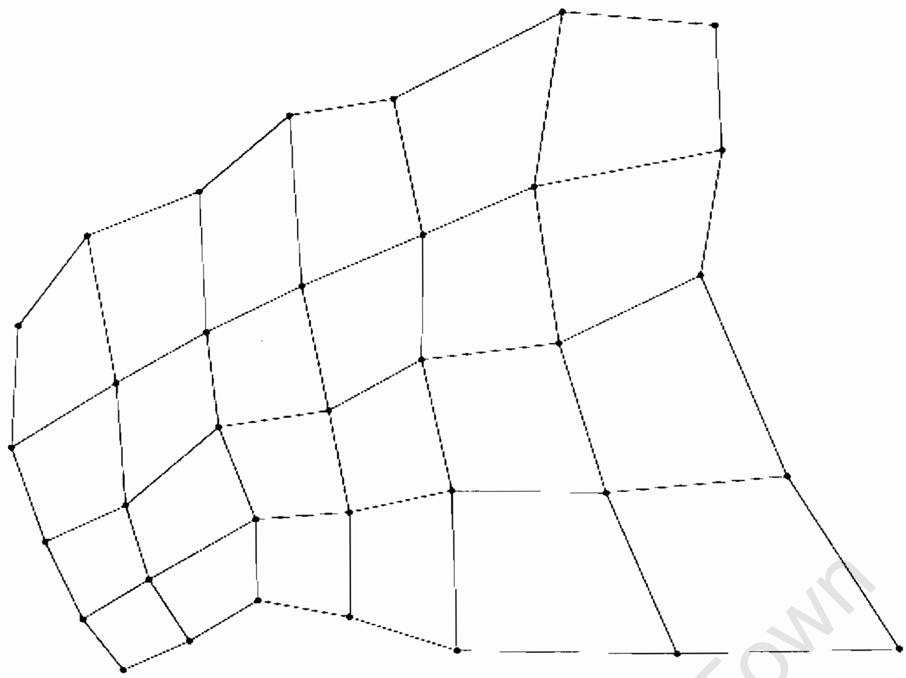
Recall that the SOM technique aims at spanning the continuum of data space rather than trying to cluster groups. SOM mapping will always locate similar nodes close to each other in the SOM space. However, these nodes projected onto a two-dimensional plane are not equidistant from each other in data space as presented in the regular arrays. In the Sammon mapping, a map is generated from an n-dimensional input vectors to two-dimensional points on a plane whereby the distances between the image vectors tend to approximates to Euclidean distances of the input vectors (Kohonen et al. 1996). These node distorted mappings are functional for determining the similarities and continuity across the two-dimensional space and also shed some light onto the interpretations of the data itself.

Sammon maps were inspected to determine the effectiveness of each SOM in mapping the high dimensional data for visualization purposes, and selected those that best facilitate visualization. Note that a poor visualization SOM does not mean the SOM is invalid. The best Sammon maps for the OND and JFM periods showing an even or reasonable spacing of nodes with respect to their characteristic weights are shown in Figure 4.1.a and Figure 4.1b respectively. The OND Sammon mapping exhibits stronger similarities in the nodes of (1,1) ; (2,1); (3,1) ; (1,2) ; (2,2) and (3,2); and less striking similarity features will be to the bottom right-hand and the upper right-hand corners of the SOM array. The nodes are described using an (x,y) convention meaning nodes (2,1) is the second node to the right from the bottom left corner. Conversely, the Sammon mapping for JFM, Figure 4.1.b displays the closer similarity features to the bottom right-hand corner of the array, with distant nodes being on the left-hand side of the array. However, both Sammon maps clearly determine the similarities and continuity across the two-dimensional space and aid the interpretation of the data itself. Sammon mapping could have been rejected due to inconsistent spacing and overlapping or crossover of weight vectors. Such a configuration can be visually misleading and could lead to modes that were not adjacent in the input data being characterized by the same archetype, as represented by the weights. These are some of the precautions to be noted during inspection of the Sammon maps.

4.2.2 SOM arrays

Figure 4.2 shows the October to December (OND) 5 x 7 SOM array from the CMAP pentad data. The bottom left corner, shows the driest patterns in the 5 x 7 SOM array while the wettest of the region are represented in the top right hand corner. The transitional states between the two opposite states are clearly illustrated in the continuum data space as one moves from the bottom left towards the top right hand parts of the array. Nodes (6,4); (6,5); (7,4) and (7,5) capture the wettest patterns during this time of the season with most of the rain falling within a typical ITCZ pattern. Note that there is a meridional spatial distribution of the rainfall pattern over the region. The top-middle nodes of the SOM array represent the pattern of the tropical system linked with the midlatitude systems, commonly known as tropical temperate troughs (TTTs). This is inclined in the northwest to southeast direction stretching from far north of Angola into the southwestern Indian Ocean. Matarira and Jury (1992), Washington and Todd (1999) also found similar patterns. Note that for the wettest rains nodes, Zimbabwe is covered with marked precipitation except for the southwestern and southern areas.

The late summer period JFM SOM array captures some distinct rainfall patterns different from those of the OND period, Figure 4.3. For instance, a greater number of the nodes in a



b.

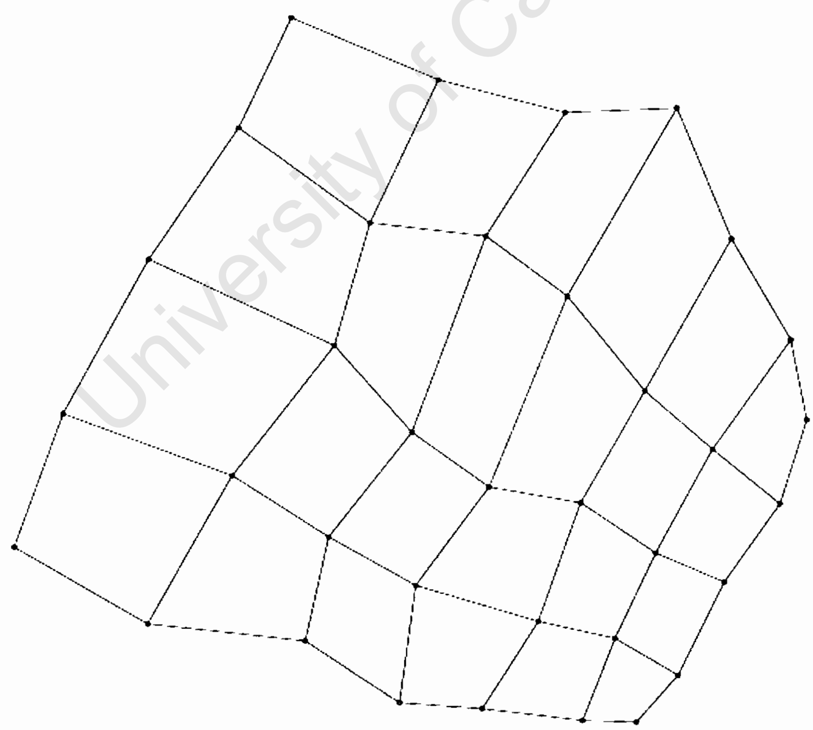


Figure 4.1 Sammon mappings for the SOM array (a) October to November (b) January to March.

Figure 4.3 than in Figure 4.2 indicate a well-developed ITCZ, as would be expected for the later part of the summer season. The driest patterns are found in the bottom left corner of the array, especially nodes (1,1) and (1,2). The other 3 three corners of the JFM SOM array capture different patterns associated with wet maxima and spread well in a continuum across the two-dimensional node space. Tropical cyclone activity in the tropical Indian Ocean is captured on nodes (6,1) and (7,1) and shows the drying out over southwestern Zimbabwe. As mentioned earlier, Torrance (1981) and Matarira (1989) emphasize the position of tropical cyclone in the SWIO causing diffluent flow across that part of the country. The right hand parts of the SOM array have managed to capture the different transient positions of the tropical cyclones and depressions in the SWIO and Mozambique Channel during this part of the summer season. Patterns associated with TTTs are clearly visualised in the nodes (1,5) and (2,5). The node maps also include the cyclones or depressions that make landfall and are associated with the extreme wet conditions that occur over Zimbabwe, Mozambique and northeastern South Africa. These patterns have resulted in devastating floods over that part of the region with losses of human life. Bottom right quadrants and the central node maps outline the horizontal component of the ITCZ. The common feature in most of the node maps is the drying over the southeastern Atlantic Ocean and SWIO. These are associated with regions of the sub-tropical high-pressure systems in these adjacent oceans. It also clearly represents the transitional states and the ITCZ, which is a major rain bearing system over the region during this time of summer.

4.3 Frequency Analysis of a SOM

Figure 4.4 shows the frequency mapping for OND period. The frequency analysis for this period in the study shows most rainfall patterns are mapped towards the nodes (1,3), (1,4) and (3,1) in the OND SOM array. For this period, the most common frequency mapping is on node (1,3) representing a very dry Zimbabwe and most of southern Africa except for the southeastern coastal area and north Angola. The least common nodes of mapping are nodes (4,4), (5,4) and then (5,5). These nodes are associated with rainfall patterns involving the ITCZ and depressions to the northeast of Madagascar. This concurs with the climatology of the region, as these patterns are more prevalent during the late summer period of January to March. It should be noted that the average frequency is 1/35=0.0286. Therefore, low frequency is less than 0.0286 and high frequency is greater. Generally, the frequency of occurrence is for drier rainfall patterns over the 23 years used with fewer occurrences of the rainfall patterns associated with the ITCZ and depressions in the Indian Ocean during the OND period

The frequency of maps for JFM period, Figure 4.5, shows the most common node to be (1,1), the driest corner of the array. This is associated with the whole of southern Africa being dry during this period. Nodes (4,1) and (5,2) are also common in the frequency of occurrence and still represent drier southern Africa although wetter over the northern parts of the region and northeastern Zimbabwe in the latter. The least common node mapping position is (4,4) then (6,2). Node (4,4) represents the transitional state position of depressions moving into the Mozambique Channel before they make landfall or head into the extra-tropical areas. This node mapping, though rare, sustains the rather dry conditions over the southwestern parts of Zimbabwe. Similar to the OND period, frequency of occurrence for the 23 years occurs more in the drier rainfall patterns for JFM period.

4.4 Trend Analysis of the SOM-identified modes

From considering the rainfall patterns and the frequency of occurrence, an examination of the long-term trend in the frequency of the rainfall patterns was done i.e. Using the 5 x 7 SOM array, adjacent nodes with similar patterns were grouped together. The grouping was aided by using some measure of inter-node distance as shown in the Sammon maps (Figure 4.1). The grouping resulted in 3 by 3 grouping of 4 nodes (2 *x* 2) forming a quadrant and represented the whole 5 x 7 SOM array. The groupings aimed to capture dominant mean patterns and assess the average trend across neighbouring nodes. This was done to keep the patterns which are represented by the large 35 nodes mapped into the SOMs. Although with only 18 patterns for each season means it is possible to reduce the degrees of freedom to achieve consistent mapping for each season.

Table 4.1 The 9 quadrants grouping of 2x2 Nodes used in the trend analysis of both the OND and JFM SOM arrays.

Quadrant	**OND SOM Nodes**	**JFM SOM Nodes**
1	(1,1) (1,2) (2,1) (2,2)	(1,1) (1,2) (2,1) (2,2)
2	(3,1) (3,2) (4,1) (4,2)	(4,1) (4,2) (5,1) (5,2)
3	(5,1) (5,2) (6,1) (6,2)	(6,1) (6,2) (7,1) (7,2)
4	(1,2) (2,2) (1,3) (2,3)	(1,2) (2,2) (1,3) (2,3)
5	(3,2) (3,3) (4,3) (4,4)	(3,2) (3,3) (4,3) (4,4)
6	(6,2) (6,3) (7,2) (7,3)	(6,3) (6,4) (7,3) (7,4)
7	(1,4) (2,4) (1,5) (2,5)	(1,4) (2,4) (1,5) (2,5)
8	(3,4) (4,4) (3,5) (4,5)	(3,4) (4,4) (3,5) (4,5)
9	(6,4) (6,5) (7,4) (7,5)	(6,4) (6,5) (7,4) (7,5)

4.4.1 OND SOM Trend analysis

Figure 4.6 displays the trends in each quadrant that represent the entire 5 x 7 OND SOM array as the frequency of occurrence against the number of years (23 years from 1979-2002). The quadrant gives information of the p-value to assess statistical significance at the 5% level and the slope value. The Figure shows a coherent pattern of trend based on the rainfall patterns with increases to the left and top right quadrants; no changes in the centre quadrants and decrease on the right quadrants of the SOM array. Although not statistically significant, there is positive trend in frequency of occurrence for the left quadrants associated with very dry rainfall patterns.

Although not statistically significant, there is positive trend in frequency of occurrence for the left quadrants associated with very dry rainfall patterns. The lower middle quadrants remain unchanged. The right hand quadrants associated with the wettest rainfall patterns show a downward trend in occurrence. Although Null Hypothesis Significant Testing (NHST) is used in atmospheric sciences as a common method for testing trends, some better statistical testing alternatives have been suggested such as confidence intervals, permutation tests and cross-validation (Nicholls, 2000; Mason and Goddard, 1999). However, it is not clear if any significant behaviour can be established using the alternatives. Scatter in the figures suggests that most of the nonzero slopes are insignificant, with some due to one or two outliers.

4.4.2 JFM SOM Trend Analysis

Figure 4.7 shows the trends in each quadrant that represent the entire 5 x 7 JFM SOM array as the frequency of occurrence against the 23 years (1979 to 2002). The quadrant gives information of the p-value to assess statistical significance at the 5% level and the slope value. The Figure displays a coherent pattern of trend based on the rainfall patterns with increases to the left-top and central quadrants and a negative trend for all other quadrants of the SOM array. Left-top and central quadrants show a positive trend although not statistically significant. The rest of the quadrants show a negative trend and are statistically significant on the right bottom for quadrants 3 and 6. As most of the quadrants showing negative trend are associated with the wetter parts of the SOM it implies that there has been a decrease in wet rainfall patterns during the JFM period. The mean precipitation pattern representing this decrease in rainfall for JFM period is then established by averaging the precipitation patterns for the nodes grouped into these quadrants with statistical significant p values.

Figure 4.8 shows the mean precipitation pattern representing the statistically significant p-values for JFM SOM array for quadrants 3 and 6. These mean precipitation patterns for OND (Figure 4.8a) are depicting a depression or TCs to the northeast of Madagascar and continental rainfall being confined to the northeastern parts of the region including northeast Zimbabwe whilst the remainder of the region is dry. The dry patch to the south is associated with the sub-tropical high-pressure belt. As for Figure 4.8b, the rainfall patterns represented in quadrant 6 are associated with depressions or TCs to the northeast of Madagascar and the ITCZ over areas to the north of about 15°S with rest of region dry. The mean precipitation pattern also shows a wet area over the southeastern parts of the region covering Lesotho and Swaziland as well. This area could be associated with a coastal low. This is the mean pattern showing a decrease in trend.

Generally the trends show a drying out rainfall patterns for both OND and JFM periods although not statistically significant for most of the patterns. However, from the statistical significant patterns it can be inferred that the synoptic states reducing precipitation are increasing while the synoptic states leading to enhanced precipitation have been decreasing over time. This can be complemented by the dominance of the 500hPa anticyclonic patterns as discussed in section 3.8.

4.5 Summary

SOM captures well the rainfall patterns within the CMAP pentad data for the period 1979-2002. The important rainfall patterns such as those involving the TTTs, ITCZ, TCs, and depressions/lows over the Angola or in the Mozambique Channel were all captured to various degrees. From the SOM array, the frequency analysis reveals the dominant patterns within the data. A SOM analysis can be complemented with the use of other statistical packages such as R, which was adopted for the trends analysis. There are no statistical significant trends at the 5% level observed in the OND SOM arrays but a couple of quadrants show statistical significance in the JFM SOM arrays. However, more useful insight might have been attained by use of the alternative statistical testing methods to NHST.

The SOM array frequency analysis showed the dominant patterns to be in drier rainfall patterns for both OND and JFM. From the trend analysis it can be inferred that precipitation over time has been decreasing for both OND and JFM SOM arrays. It can be inferred that the synoptic states reducing precipitation are increasing while the synoptic states leading to enhanced precipitation have been decreasing over time.

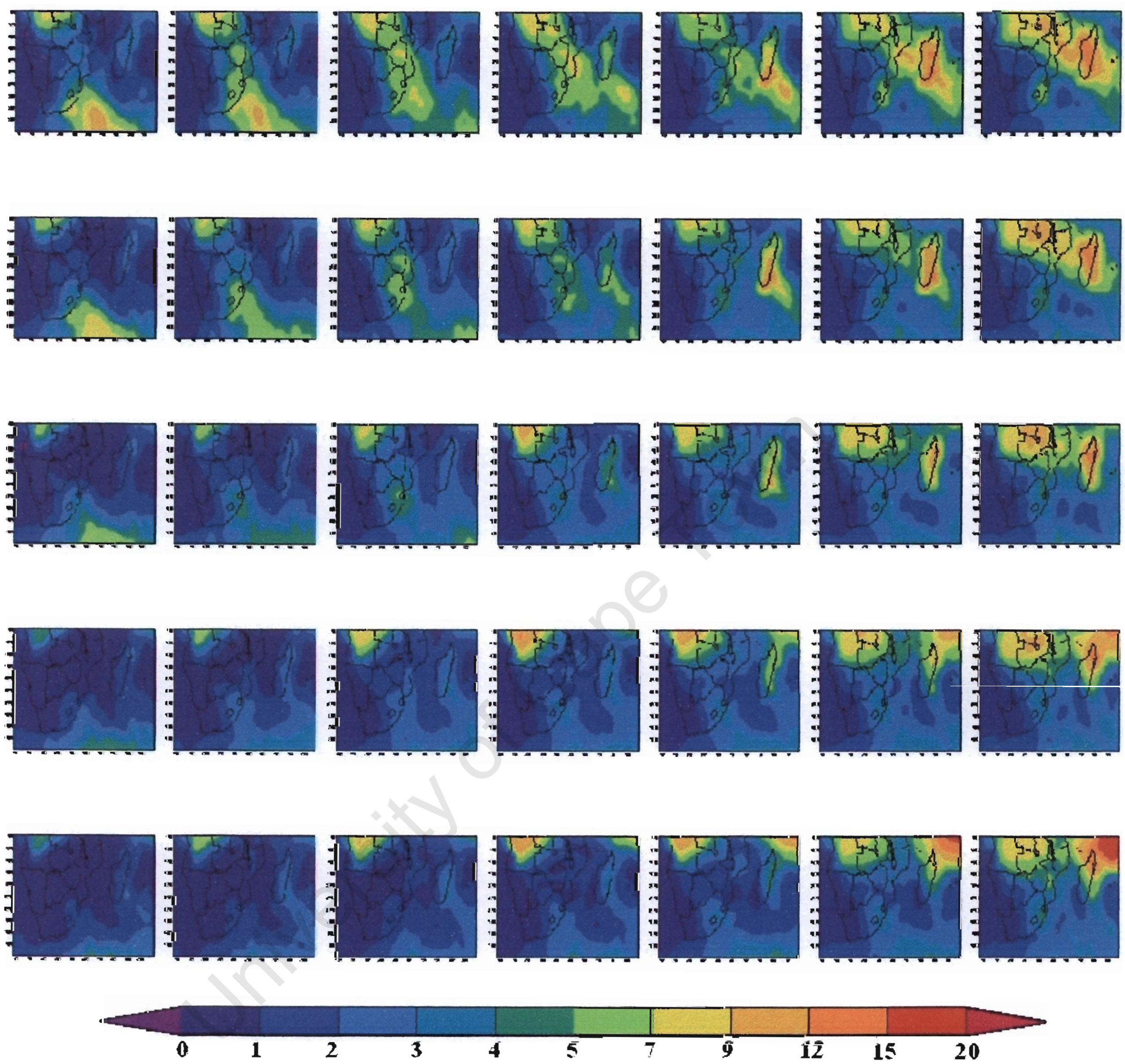


Figure 4.2 A 5 x 7 SOM array of October to December (OND) rainfall distribution pattern for Southern Africa using CMAP pentad data

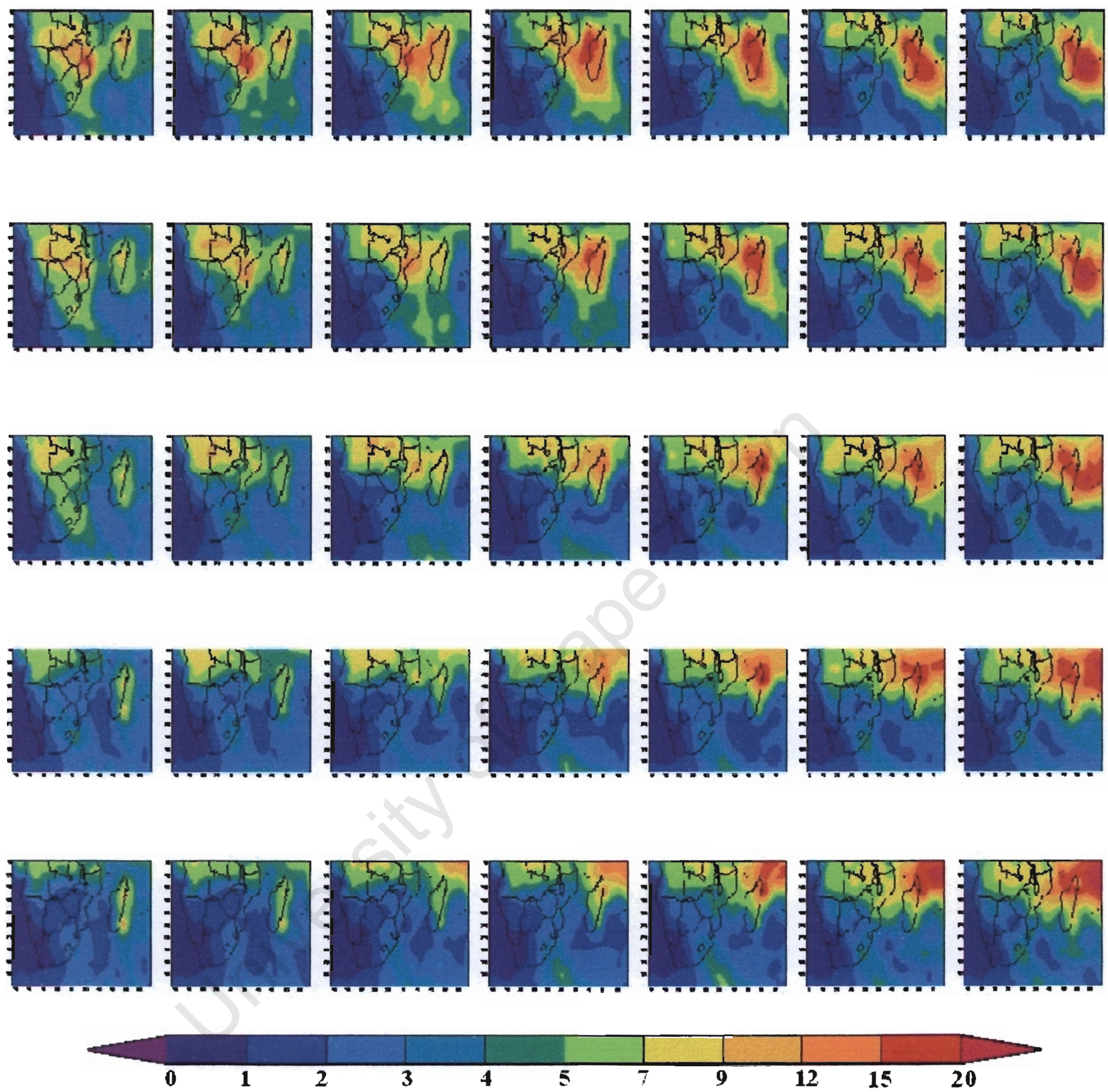


Figure 4.3 A 5 x 7 SOM array of January to March (JFM) rainfall distribution pattern for Southern Africa using CMAP pentad data.

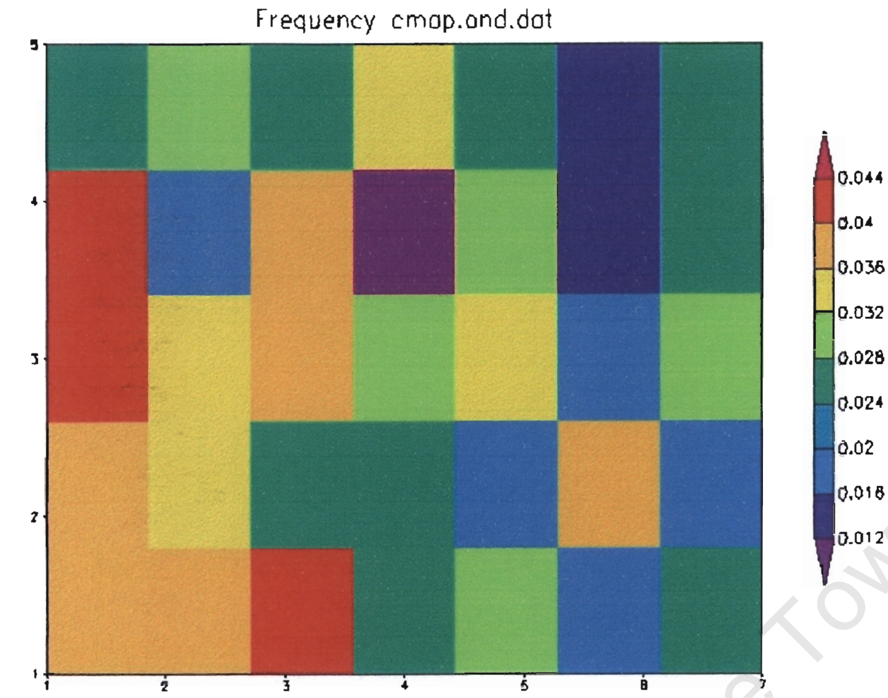


Figure 4.4 Frequency of mapping patterns across the nodes in the 5 x 7 array for the October to November period.

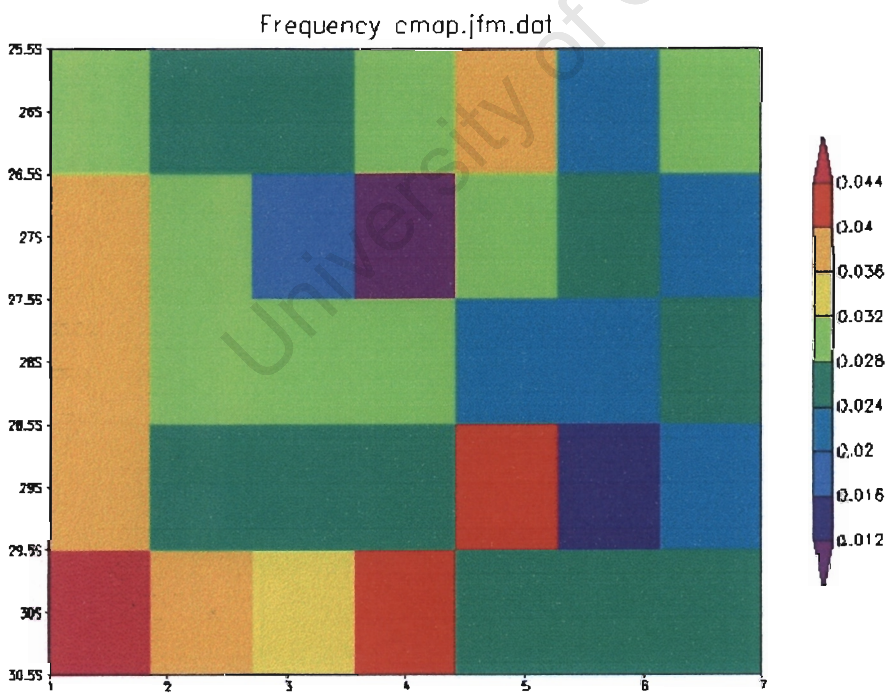


Figure 4.5 Frequency of mapping patterns across the nodes in the 5 x 7array for the January to March period.

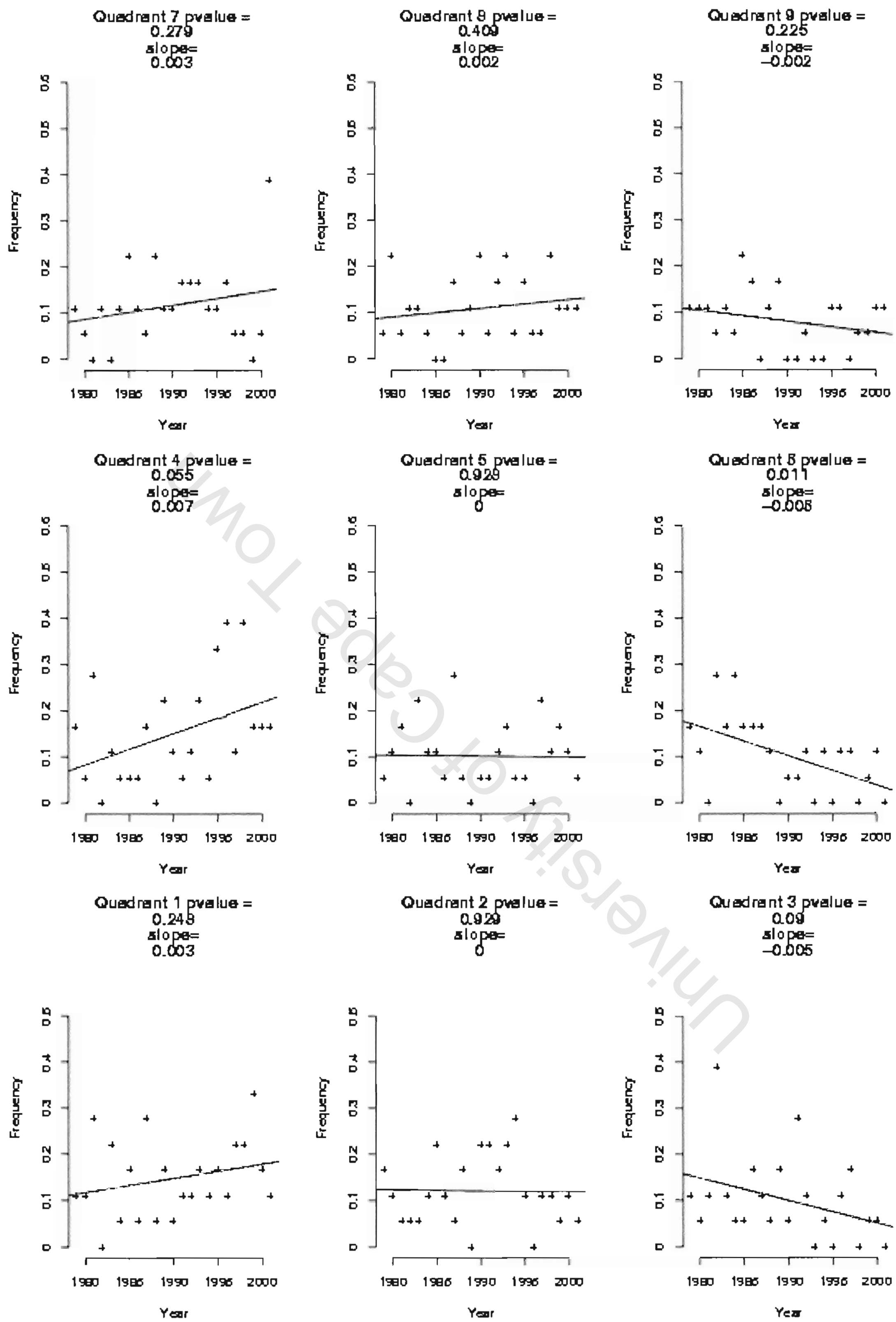


Figure 4.6 Trends in the OND SOM array.

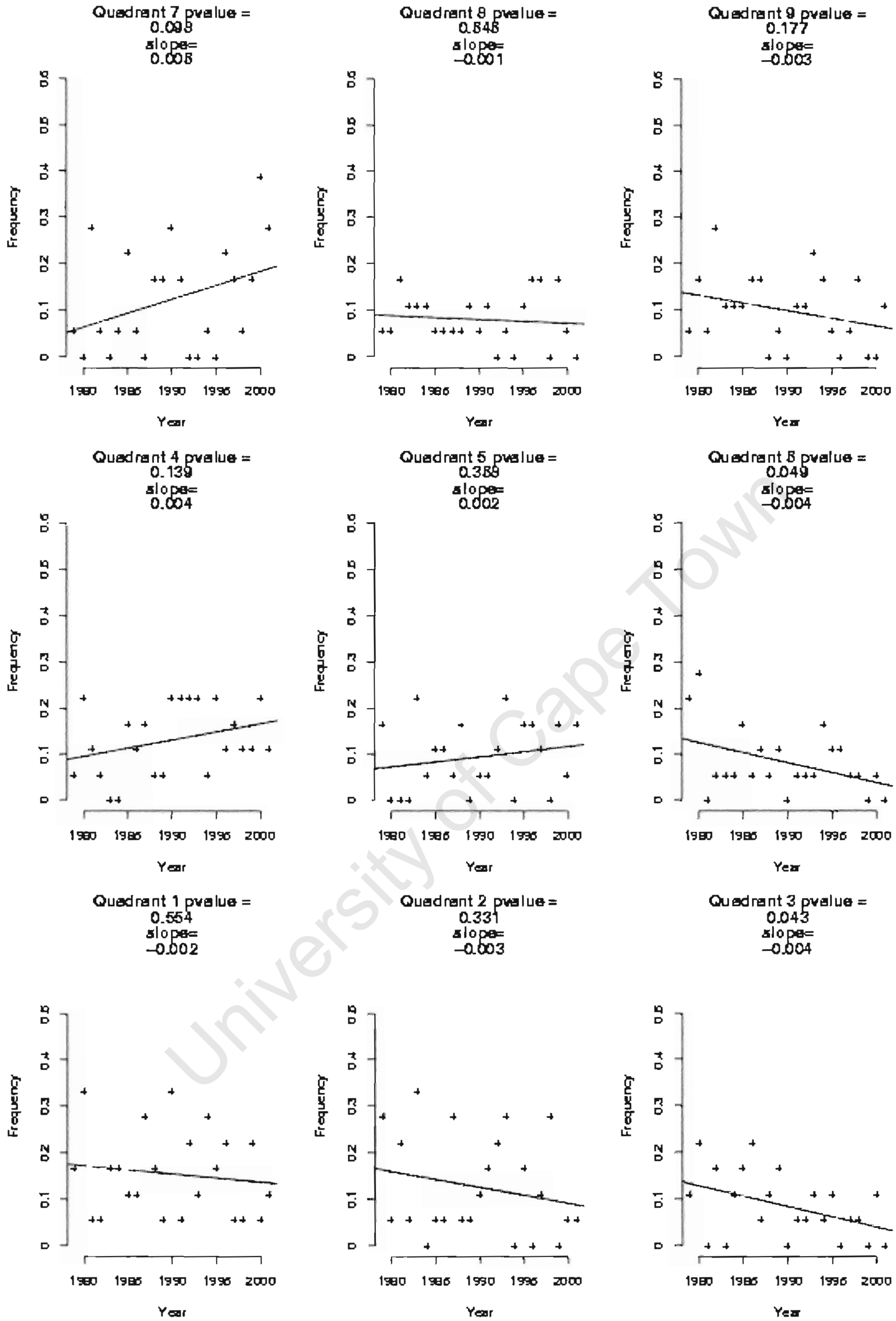


Figure 4.7 Trends in the JFM SOM array.

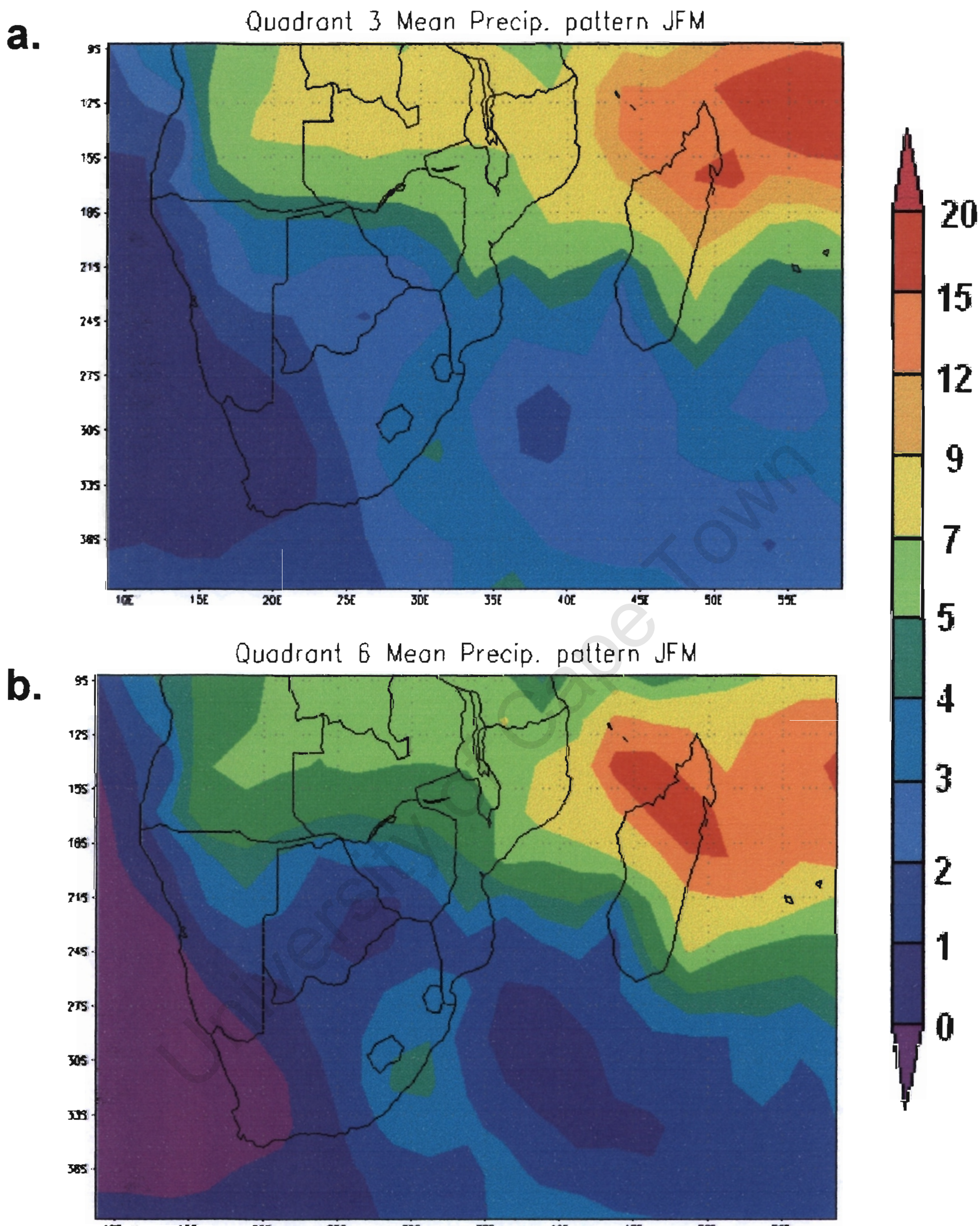


Figure 4.8 Mean precipitation patterns (mm/day) representing the statistically significant pattern at the 5% level from JFM SOM array. (a) Quadrant 3 and (b) Quadrant 6.

Chapter 5

Climate Extremes Trend Analysis

5.0 Introduction

As mentioned in earlier chapters, Zimbabwe's rainfall is already highly variable on the inter-annual time scale, suggesting future climate changes will further exacerbate societal vulnerability. Particularly, for a country that has more than 70% of its population relying on agriculture directly or indirectly, the impact of extreme weather events is critical. The study of the historical and current changes of extreme events is essential to understand before projecting any future changes. This chapter discusses observed trends in extreme events. Results attained from statistical analysis for trends in time series of daily data using RClimdex statistical package are presented. A selection of suitable indices over Zimbabwe are calculated and examined based on percentiles for rainfall, maximum and minimum temperatures. A discussion and summary completes the chapter.

As mentioned earlier, the stations were subjectively chosen for this study, the criteria mentioned in section 3.1.1 were followed for consistency and for the stations to be used in regional analyses of the climate extreme indices. The primary purpose of such stations is to identify long-term climate trends. Therefore, stations need a long, continuous and homogeneous record, minimal influence from urbanization, and a general high quality of data (Peterson et al., 1998, 2002; Manton et al., 2001). Each station's climate extreme indices time series was visually evaluated for discontinuities or outliers such as a big jump in time on the graphical plots. Those with obvious discontinuities or outliers were not considered in the analyses that use that concerned variable.

The indices presented are as defined earlier in section 3.2.2. The annual indices of extremes were calculated for each year over the WMO reference period 1961-1990. The indices selected for this study are: Annual total precipitation in wet days with at least 1mm of rain, PRCPtot (mm); maximum number of consecutive dry days (dry spells), CDD; annual total precipitation exceeding 95th percentile of the rainfall, R95p; monthly maximum consecutive 5-day precipitation, RX5day, monthly lowest daily minimum temperature, TNn; monthly highest daily maximum temperature, TXx; percentage of days when daily minimum temperature is below 10th and above 90th percentiles, TN10P and TN90P respectively; percentage of days when daily maximum temperature is below 10th and 90th percentiles, TX10P and TX90P respectively and Diurnal temperature range, DTR. A complete list of definitions and units of the indices calculated using RClimdex is given in Appendix A-1.

5 .1 Results

5. 1.1 Patterns of trends

Table 5.1 present the results of the selected indices calculated for the chosen stations across the country. As noted in Table 3.1, Masvingo and Makoholi had no temperature observations whilst all the other missing results could not be attained by this analysis. The following overview is on the spatial variation in the direction of trends. The statistical significance is not shown in the maps but trend values noted as significant at 95% confidence level are highlighted in bold, Table 5.1. The station network used in producing the climate extreme indices is shown in Figure 3.1. Thereafter, a description of the direction and magnitude of trends at a selected station with 95% significance are then presented.

5 .1.2 Rainfall

Figure 5.1a shows the annual total precipitation in wet days with at least 1 mm of rainfall, PRCPtot (mm). Annual total precipitation has generally decreased across most of the country although not statistically significant. There is some spatial coherence for decreasing annual total precipitation with the exception of the central watershed and southeastern areas. Figure 5.1b displays the maximum number of consecutive dry days

(CDD). None of these CDD values is statistically significant. However, there is credible spatial cohesion into the northern and southern areas.

Table 5.1 Results of the selected indices calculated for the chosen stations. Note these trends are of the annual values (see appendix A-1).

Index/Station	Beitbridge	Belvedere	Chipinge	Goetz	Kadoma	Karoi	Kwekwe
TXx (°C /century)	**0.02**	0.006	0.002	0.009	-0.007	-0.015	0.014
TNn (°C /century))	**0.026**	0.02	-0.03	**0.027**	0.032	-0.027	**-0.036**
TN10p (days/year)	**-0.141**	**-0.166**	0.06	**-0.159**	**-0.109**	**0.619**	**-0.083**
TX10p (days/year)	**-0.072**	**-0.15**	**-0.071**	**-0.087**	-0.092	**0.495**	**-0.098**
TN90p (days/year)	**0.111**	**0.199**	0.06	**0.248**	**0.136**	-0.065	0.042
TX90p (days/year)	**0.2**	**0.208**	**0.162**	**0.24**	**0.188**	0.169	**0.102**
DTR (°C/century)	0.007	0.005	**0.025**	0.004	0.009	**0.022**	**0.013**
RX1day (mm)	0.147	-0.305	0.558	0.063	0.138	-0.337	0.154
RX5day (mm)	-0.045	**-0.861**	0.597	0.176	0.103	0.224	-0.488
CDD (days/year)	-0.422	0.951	0.081	0.243	-0.36	0.186	0.424
R95p (mm)	1.028	**-2.747**	2.501	-0.125	-1.005	-1.162	-0.339
PRCPtot (mm)	0.781	-3.732	0.772	-0.942	-2.414	-3.816	-3.117

Index/Station	Nyanga	Rusape	Kutsaga	Gweru	West Nicholson	Makoholi	Masvingo
TXx (°C /century)	-0.003	0.019	-0.011	-0.003	**0.045**		
TNn (°C /century)	0.02	-0.009	**-0.054**	0.003			
TN10p (days/year)	**-0.324**	-0.112	0.108	**-0.219**	**-0.238**		
TX10p (days/year)	-0.028	0.019	-0.04	-0.131	-0.101		
TN90p (days/year)	**0.277**	0.039	**0.102**	**0.222**	**0.278**		
TX90p (days/year)	**0.274**	0.052	0.052	0.368	**0.423**		
DTR (°C/century))	-0.008	-0.008	0.008	0.006	0.008	0.017	
RX1day (mm)	0.222	0.39	**0.484**	0.184	-0.83	0.07	0.232
RX5day (mm)	-0.368	-0.252	-0.066	0.227	-1.289	0.084	
CDD (days/year)	0.51	0.356	0.259	0.184	-0.863	-0.826	-0.75
R95p (mm)	-0.396	1.022	2.410	2.594	-2.299	1.721	-1.374
PRCPtot (mm)	-5.198	-0.246	3.401	0.6	-2.467	-0.739	-0.362

Figure 5.1c shows the annual total precipitation exceeding 95th percentile of the rainfall, R95p.. One station, Harare Belvedere exhibits a statistical significant decrease of 2.7mm in the annual total precipitation exceeding 95th percentile of rainfall. However, there is some semblance of spatial coherence into the southeastern areas showing an increase in trend whilst a decrease in trend occurs over the rest of the country. Figure 5.1d shows the monthly maximum consecutive 5-day precipitation, RX5day. All stations except Harare Belvedere are not statistically significant. The station shows a 0.86mm decrease in the monthly consecutive 5 day precipitation. However, the use of statistical significance alone can be misleading (Nicholls, 2000). The spatial cohesion of the trends provides credible information to the detected trends.

Trends in the total precipitation, dry spells and maximum consecutive 5-day are more spatial coherent than those for the annual total precipitation exceeding the 95th percentile. The southeastern areas around Chipinge show an increase in all four variables. Although not statistically significant (95% level) it shows that an increase in total rainfall with more dry spells (CDD) implies a rise in extreme events with higher rainfall intensity.

5.1.3 Temperature

Figure 5.2a shows the monthly lowest daily minimum temperature, TNn.. Beitbridge and Bulawayo Goetz stations are exhibiting a significant increase with Kwekwe and Harare Kutsaga showing a significant marked decrease. Generally, the high magnitudes of the stations showing a significant decrease would imply a decrease in coldest days over the country. Figure 5.2b shows the monthly highest daily maximum temperature, TXx. Based on Beitbridge and West Nicholson stations which are showing statistical significance at 5% level, there is an increase in the hottest days.

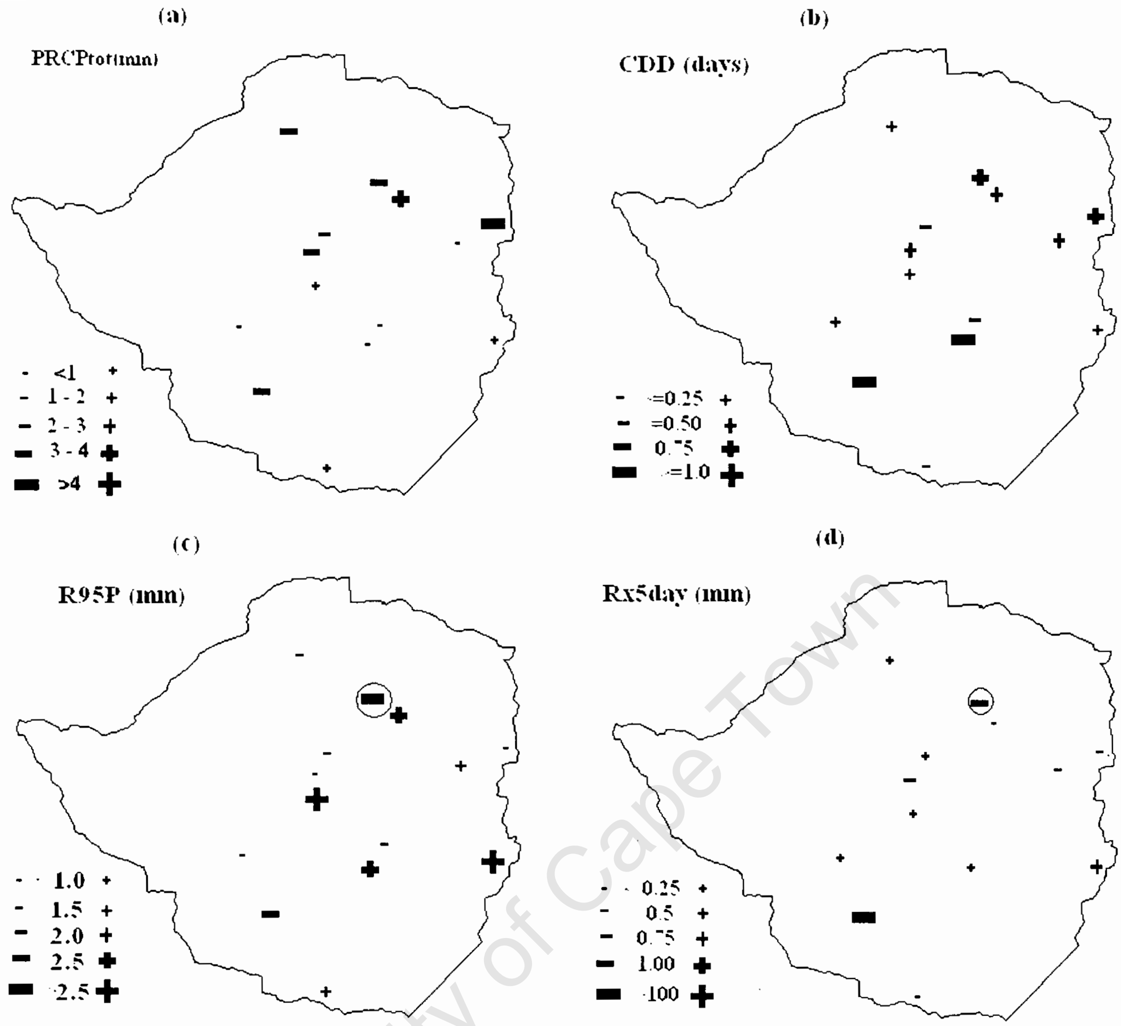


Figure 5.1(a) Annual total precipitation in wet days with at least 1mm of rain, PRCPtot (mm). (b) Maximum number of consecutive dry days (dry spells), CDD. (c) Annual total precipitation exceeding 95th percentile of the rainfall, R95p and (d) Monthly maximum consecutive 5-day precipitation, RX5day. The plus signs depict an increase whilst the minus sign is for a reduction. Trends that are significant at the 90% level are circled.

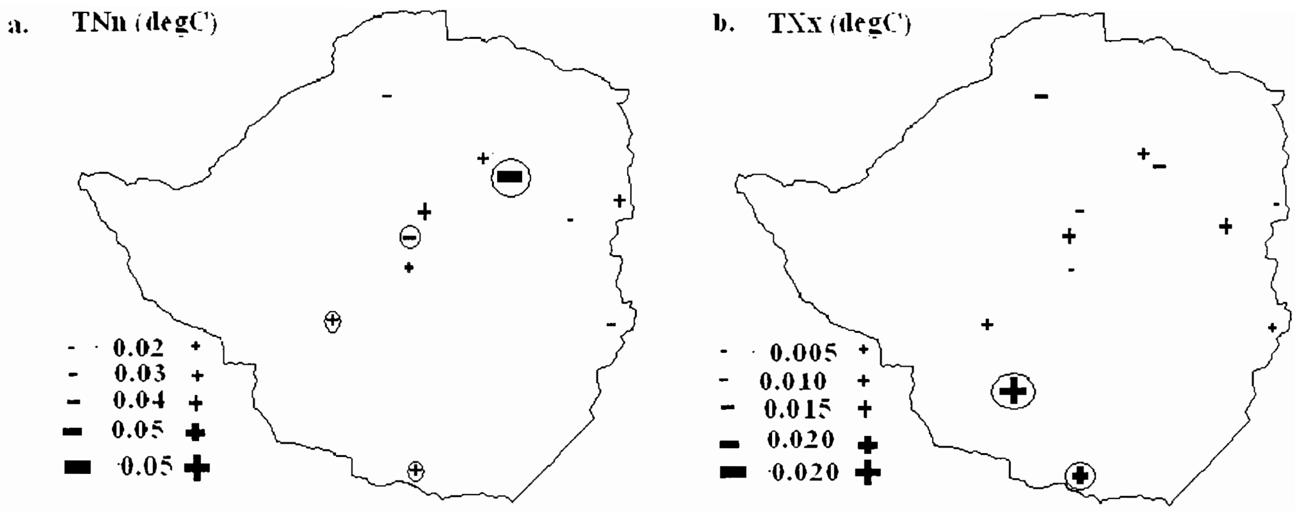


Figure 5.2 (a) Monthly lowest daily minimum temperature, TNn. (°C/century) (b) Monthly highest daily maximum temperature, TXx. (°C/century). The plus sign depicts an increase whilst the minus sign is for a reduction. Trends that are significant at the 90% level are circled.

Figure 5.3a shows the percentage of days when daily minimum temperature is below 10th percentile, TN10P. The number of cold nights has decreased at most stations (significantly at several stations) as depicted by the reduction in percentage of days when daily minimum temperature is below 10th percentile. Figure 5.3b displays percentage of days when daily maximum temperature is below 10th percentile, TX10P. Cool days have also significantly declined at most stations as shown by percentage of days when daily maximum temperature is below 10th percentile. The exception to these spatially consistent trends is Karoi in the north, which indicates a statistically significant and large increase in the percentage of days below the 10th percentile for both minimum and maximum temperatures. However, there is lack of nearby stations such as Kariba or Gokwe to validate the indices. Thus strengthening the approach of using spatial cohesitivity approach to infer than considering the significant testing alone (Nicholls, 2000).

Figure 5.3c shows percentage of days when daily minimum temperature exceeds 90th percentile, TN90P. Warm nights increased across most of the country, as depicted by the percentage of days when daily minimum temperatures exceeded the 90th percentile and most of these stations are statistically significant. As for Percentage of days when daily minimum temperature exceeds 90th percentile, TN90P (Figure 5.3d) shows that the number of hot days has increased at all stations (significantly at several stations) as is being exhibited by percentage of days when daily maximum temperature exceeds 90th percentile. Karoi station does not exhibit as significant a change in days crossing both the minimum and maximum 90th percentile, as was seen with the 10th percentiles of minimum and maximum temperature.

Figure 5.4 shows the diurnal temperature range, DTR measured at an annual rate. DTR has increased over most of the stations, with Chipinge, Karoi and Kwekwe exhibiting a significant increase, but reduced over the eastern Highlands. There is some spatial coherence with most stations depicting an increase in DTR. Generally, there is more spatial coherence to the temperature trends of the 10th and 90th percentiles of the minimum and maximum temperatures than can be seen in the minimum and maximum mean values.

The trends in the number of cold nights and cool days for each station (Figure 5.5) shows that generally there has been a larger decrease in the number of cold nights than cool days, except for Karoi which indicates a larger increase of cold nights than cool days. The three other exceptions include Harare Kutsaga, Kwekwe and Chipinge with rather a larger increase in cold nights as compared to either the increase or decrease of the cool days. Comparison of the country average trends calculated showed there was a larger decrease in the number of cold nights than cool days.

Figure 5.6 shows the trends in the number of warm nights and hot days for each station. Most stations had a stronger increase in the number of hot days than warm nights except Harare Kutsaga, Nyanga and Bulawayo Goetz. Nyanga and Bulawayo Goetz trends were almost similar although the bias was towards the warm nights. The country average trends exhibited a stronger increase of hot days than warm nights.

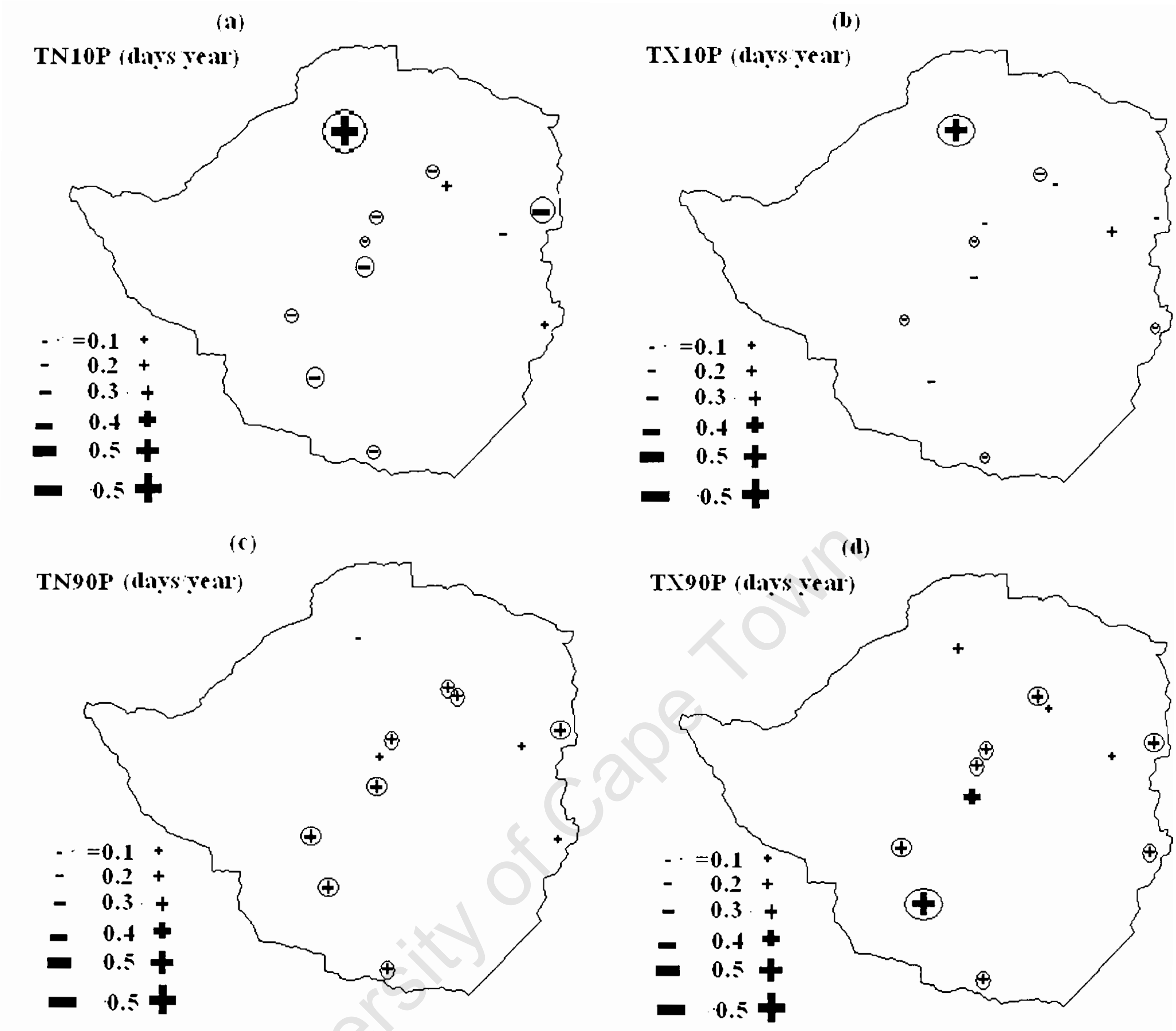


Figure 5.3 (a) Percentage of days when daily minimum temperature is below 10th percentile, TN10P. (b) Percentage of days when daily maximum temperature is below 10th percentile, TX10P. (c) Percentage of days when daily minimum temperature exceeds 90th percentile, TN90P. (d) Percentage of days when daily maximum temperature exceeds 90th percentile, TX90P. The plus sign depicts an increase whilst the minus sign is for a reduction. Trends that are significant at the 90% level are circled.

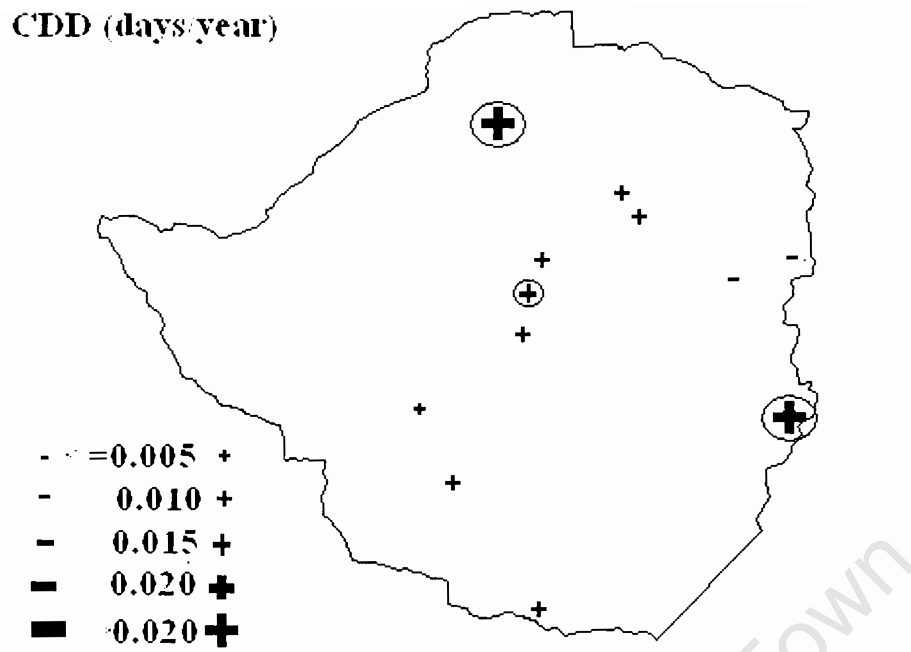


Figure 5.4 The Diurnal Temperature Range (DTR) (°C/century) trends measured at an annual rate. The plus sign depicts an increase whilst the minus sign is for a reduction. There is some spatial coherence with most of Zimbabwe showing an increase in DTR. Trends that are significant at the 90% level are circled.

5 .2 Discussion

The climatic indices analysed and reviewed in the previous section have presented some useful insights into the changes occurring to the climate of Zimbabwe. Patterns of the temperature trends clearly show spatial cohesion of warming trends across the country. It should be noted that most of these trends were statistically significant with the exception of the DTR. More than half the stations show an increase in the monthly highest daily maximum temperature (TXx) though inconclusive on the monthly lowest daily minimum temperature (TNn). New et al., (2005) show that the number of cold days and nights (TX10P and TN10P) has decreased. However, nearly all the stations (with the exception of Karoi in the north) are accompanied by a decrease of the number of days below the 10^{th} percentile (implying a decrease in cold extremes), an increase in the number of days exceeding the 90^{th} percentile (implying an increase in hot extremes) indicating that both

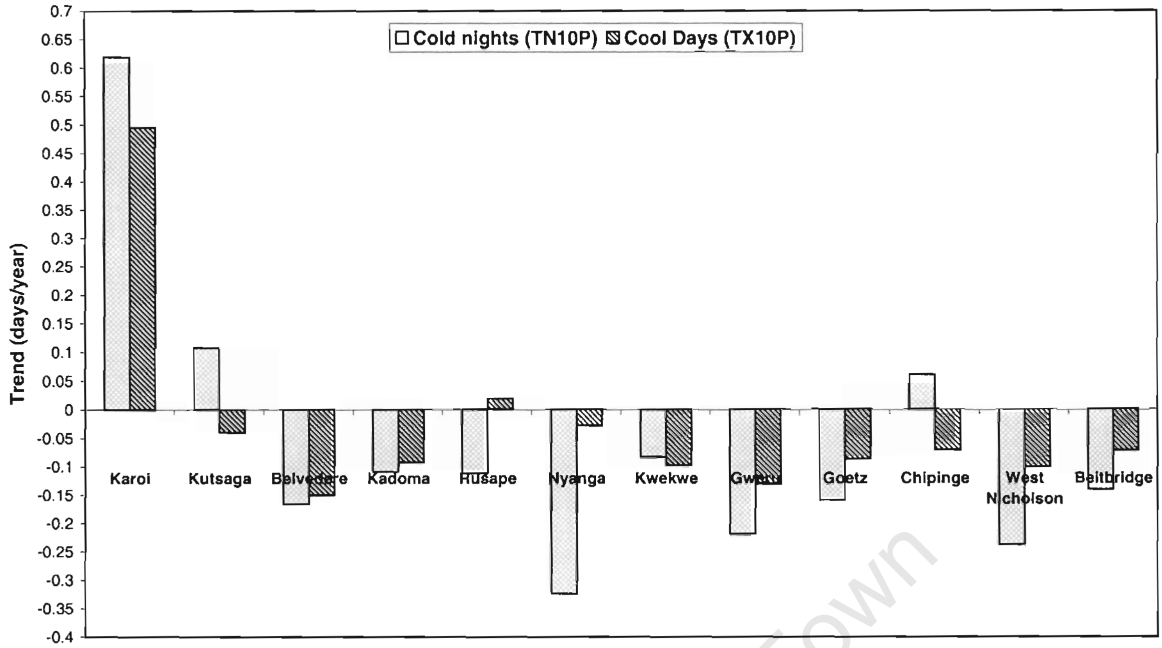


Figure 5.5.Bar graph showing the trends in the number of cold nights and cool days for each station. The stations are arranged in a north-south and west-east orientation, so that the results can be compared with neighbouring stations.

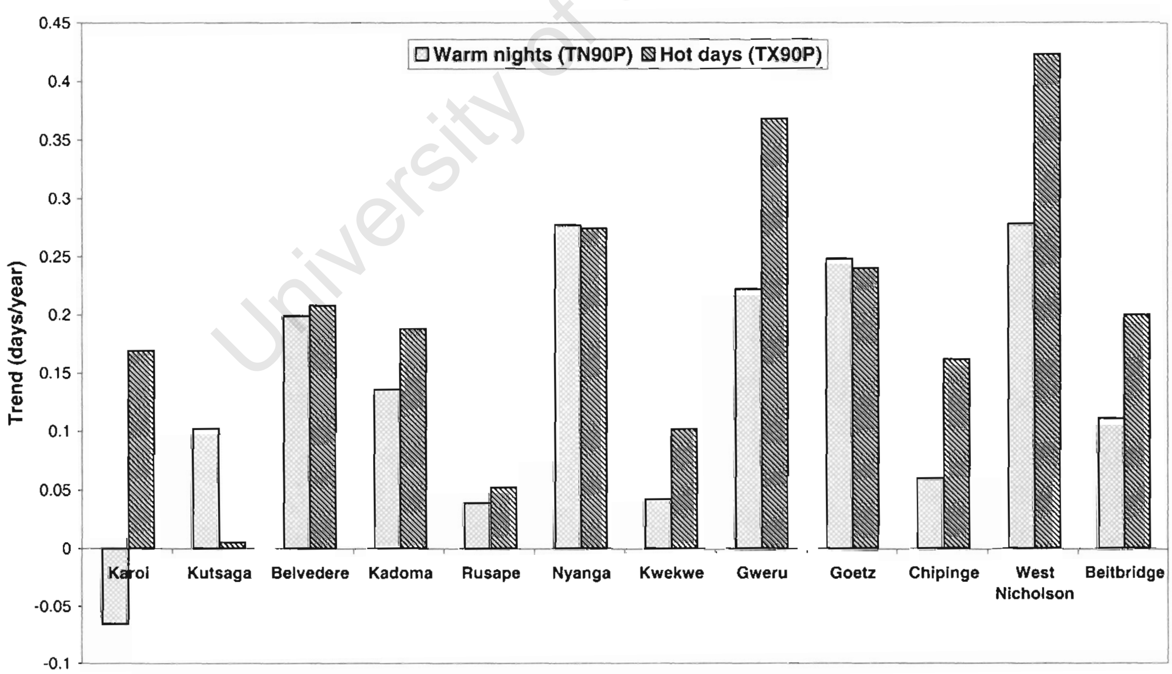


Figure 5.6 As in Figure 7 but for warm nights and hot days.

maximum and minimum temperature extremes are increasing. There is an increase in the diurnal temperature range, DTR. The DTR increases would be suggestive of an increase in cloud-free days for their occurrence and influence of systems such as the 500hPa anticyclone. On the contrary, New et al., show that approximately 60% of regional stations show a decrease in DTR.

Similar positive trends in temperature have been identified in earlier studies. Hulme et al., (2001) obtained positive mean linear trends from the New et al., (1999, 2000) data set and found temperatures over the southern Africa region to be between 0.2 and 0.3°C warmer than the 1961-90 average. These results were also supported by the regional analysis of the ETCCDMI workshop (2004), which clearly shows a spatial cohesion of warming trends across southern Africa (New et al., 2005). Figure 5.7 shows that change in the number of days where daily maximum temperature rose above the 90th percentile from the preliminary results of the ETCCDMI workshop.

There has been an increase in the global mean temperature of about 0.6°C since the start of the 20th century and that this increase is associated with a stronger warming in daily minimum temperatures than in maximums, leading to a reduction in the diurnal temperature range (Easterling et al. 2000). This agrees with the observations made here except for the DTR. Most climate model results with increased Greenhouse Gases (GHGs) produce increased surface heating with warmer surface temperatures. Most of the findings in the simulations such as warmer mean temperatures associated with increased extreme warm days and decreases extreme cold days as well as increased intensity of rainfall events are in agreement with the regional and global observations (IPCC 2nd Assessment Report, Shongwe, 2005, New et al. 2005, Hewitson 2004, Hulme et al. 2001 and Easterling 2000).

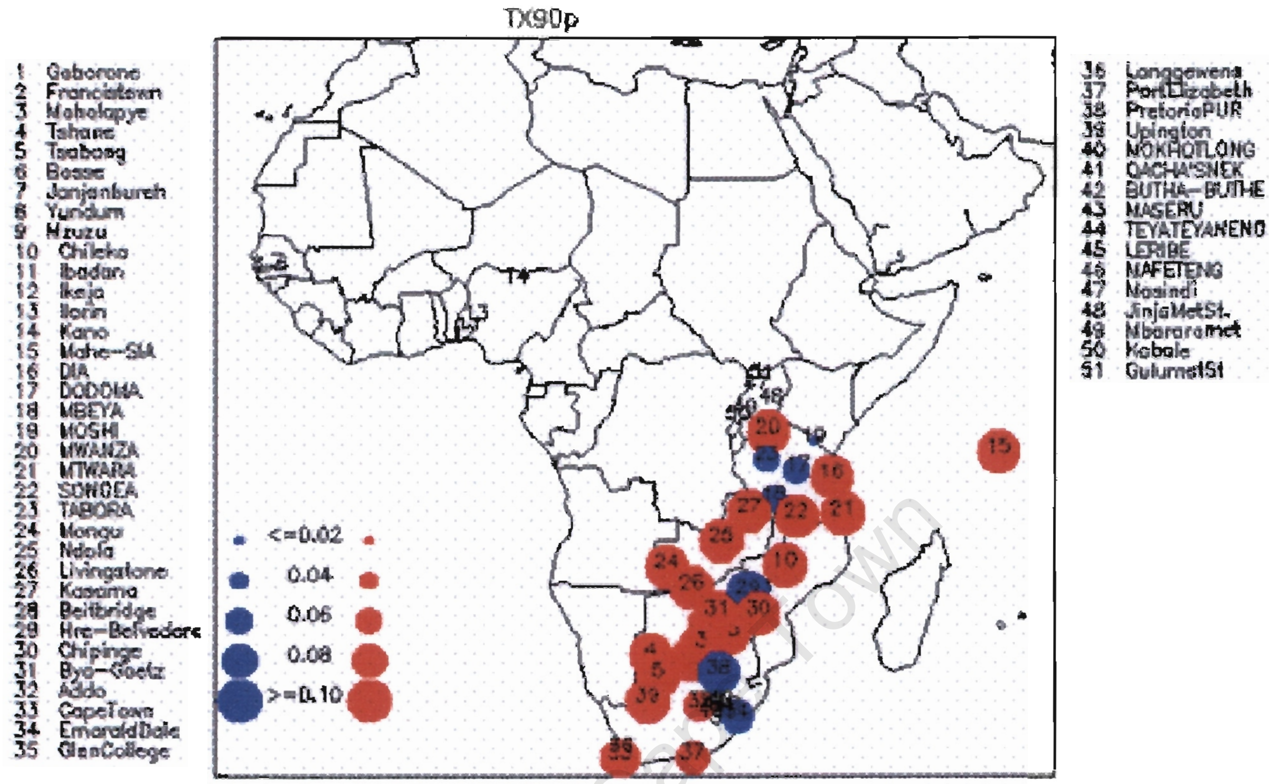


Figure 5.7 Change in the number of days where daily maximum temperature rose above the 90th percentile. These trends are from the preliminary results of the ETCCDMI workshop, 2004.

Precipitation has decreased over much of the country, with the spatial patterns less consistent than those for temperature. However there does appear to be some intriguing and spatially cohesive patterns in the trends for consecutive dry days, CDD. Although not statistically significant, the CDD shows an increase over the northern parts of the country where there is a decrease in precipitation. The spatial cohesion thus lends credibility to the trends. Comparing Fig 5.2b with Fig 3.1b also indicates that trends for increasing CDD are generally associated with higher altitudes over the central watershed whilst the decrease in dry days is over the low lying areas to the south. To a first approximation, examination of extreme precipitation indicates that heavy rainfall is increasing where precipitation is increasing and decreasing when precipitation is decreasing (Groisman et al., 1999). This seems to be the case for the R95p, which is showing decrease/increase over most areas where the total precipitation has decreased/increased except for Rusape and Makoholi (Figure 5.1a and Figure 5.1c). Harare Kutsaga, Gweru and Chipinge show an increase in PRCPtot are all associated with an increase in CDD and R95P, demonstrating that the increase in total precipitation is due to an increase in rainfall intensity ((Figure 5.1a, Figure 5.1b and Figure 5.1c).

Some of the features which can be attributed to the drying trends include the dominance of the semi-permanent anticyclonic circulation over the southern Africa region as was shown in chapter 2 and the strong influence of ENSO during the last two decades. Hulme et al. (2001) and Fauchereau et al (2003) suggest that ENSO may have caused the regional changes. Some daily data show that the frequency of positive heights has increased during DJF period over the last 25 years (Tadross et al., 2005c). Nicholson et al. (2001) emphasized the influence of the adjacent oceans rather than the ENSO and a significant role of the feedback between the land and atmosphere especially over the semi-arid regions. These feedback processes are treated in the next chapter. The rainfall data presented here also suggests the influence of local geographical effects due to altitude over the central high ground areas and the eastern highlands. Most of the trends in these areas have not been consistent with the rest of the other stations.

Generally the patterns of rainfall trends presented in this study are in harmony with some earlier findings over the region. Hulme et al. (2001) point to a moderate drying pattern of rainfall trends over Zimbabwe. Mason et al. (1999) observed an increase in the frequency of the most intense daily precipitation over South Africa, even though there was little long-term trend in total annual rainfall amount. Similar findings were attained by Richard et al. (2001) and in the follow-up work by Fauchereau et al., (2003). Their study also revealed some shifts in the southern Africa rainfall variability and pointed to the occurrence of more intense and widespread droughts in the last two decades. A decrease in total precipitation (PRCPtot) over most of Zimbabwe is also supported by New et al., (2001) findings of a decrease in precipitation over southern Africa. Recent results by Hewitson (2004) noted some strong trends of increased dry spell duration over much of the southern African region, especially during late austral summer. This is in unison with the result of increased maximum number of dry days over parts of Zimbabwe.

This study still has unresolved issues besides the lack of sufficient data. Problems related to inhomogeneities in the time-series makes detection of trends difficult and should be removed using recently developed methods. These require a well-documented history of changes such as those involving instrumentation, observation practices and the station's immediate environment (metadata), [Peterson et al., 1998, 2002; Manton et al., 2001, Fauchereau et al., 2003]. Most of the indices except for some temperature trends were not statistically significant. However, general spatial consistency and similarity of trends between is suggestive to the credibility of the final results. Application of this trend analysis to a larger number of stations would provide a more detailed analysis of the country and elevate confidence in the trends calculated here. These results are averaged over a year and might obscure the seasonal changes or time of year when these changes are more or less significant.

5.3 Summary

There is much less confidence in the rainfall trends than the temperature trends. A limitation to the studies is the low spatial density of stations with homogeneous data. However some useful insights into changes in climate extremes over Zimbabwe were observed. The country clearly shows a spatially coherent warming trend in temperature. The number of warm days and warm nights is increasing while the number of cool days and cold nights is decreasing. Precipitation indices are less spatial coherent than temperature indices. Nevertheless, the rainfall patterns show evidence of drying, dry spells duration is increasing over most of the country except the southern parts and an increase in rainfall intensity is evident over the southeastern areas.

Chapter 6

Soil Moisture Feedback using RegCM3

6.0 Introduction

This chapter describes the results from experiments done to investigate soil moisture-rainfall feedbacks using a regional climate model, RegCM3. As discussed in the previous chapter some of the observed drying trends over Zimbabwe were attributed to the ENSO effect (Hulme et al., 2001; Fauchereau et al., 2003) and the intensification of the upper level anticyclones (Tadross et al., 2005c). However, Nicholson et al. (2001) suggested the influence of the adjacent oceans rather than the ENSO and a significant role of the feedback between the land and atmosphere especially over the semi-arid regions. The latter proposal of land-atmosphere interaction prompted this exploratory work seeking some confirmation of the regional changes that might be attributed to this feedback. The work aims at seeking out the role of soil moisture perturbations to rainfall changes especially during extreme dry or wet years. This is an exploratory experiment to appreciate the contribution of land-atmosphere feedback mechanism to the observed trends over the region, influence on changing climate and lay ground for further research.

First, the choice of domain and the topography overlaid with the landuse classification is presented. A description of the experimental setup for modeling follows. Changes to the parameterizations and fine-tuning of the convection scheme are highlighted. Caveats regarding the observations, reanalysis data and model physics are discussed. Following this, the response of the model to changes in soil moisture is described using various model surface parameters which show how the surface energy and moisture budget changes. The basic theory of the highlighted feedbacks is explained as part of a general discussion and particular regions of Zimbabwe are highlighted where these feedbacks are potentially important to the local climate.

6.1 The model domain

As mentioned in section 3.2.5, RegCM requires initial conditions and time dependent lateral boundary conditions. The RegCM3 initial conditions and lateral boundary conditions for each simulation are forced from National Center for Environmental Prediction, NCEP reanalysis data (Kalnay et al. 1996). The SST is prescribed using data provided by the National Ocean and Atmospheric Administration (NOAA). The vegetation is specified using the Global Land Cover Characterization (GLCC) data (Loveland et al.1999). The model domain is centered near northeastern South Africa at 17.5S and 35.0E and the grid is defined on a normal mercator projection. In the horizontal the grid is 109 points in the east-west direction and 102 in the north-south with a resolution of 60km. Figure 6.1 shows the domain choice with the (a) surface elevation and (b) various landuses over southern Africa. This resolution captures the main topographic features of the domain, such as the mountainous Lesotho and the main central watershed over Zimbabwe (Figure 6.1a). The vegetation or land cover types in Figure 6.1b represent various landuses over the region. Table 6.1 show the vegetation classes as defined within GLCC dataset.

Table 6.1: Land Cover or Vegetation classes as defined within GLCC dataset.

1	Crop/mixed farming	11	Semi-desert
2	Short grass	12	Ice cap/glacier
3	Evergreen needleleaf tree	13	Bog or marsh
4	Deciduous needleleaf tree	14	Inland water
5	Deciduous broadleaf tree	15	Ocean
6	Evergreen broadleaf tree	16	Evergreen shrub
7	Tall grass	17	Deciduous shrub
8	Desert	18	Mixed Woodland
9	Tundra		
10	Irrigated crop		

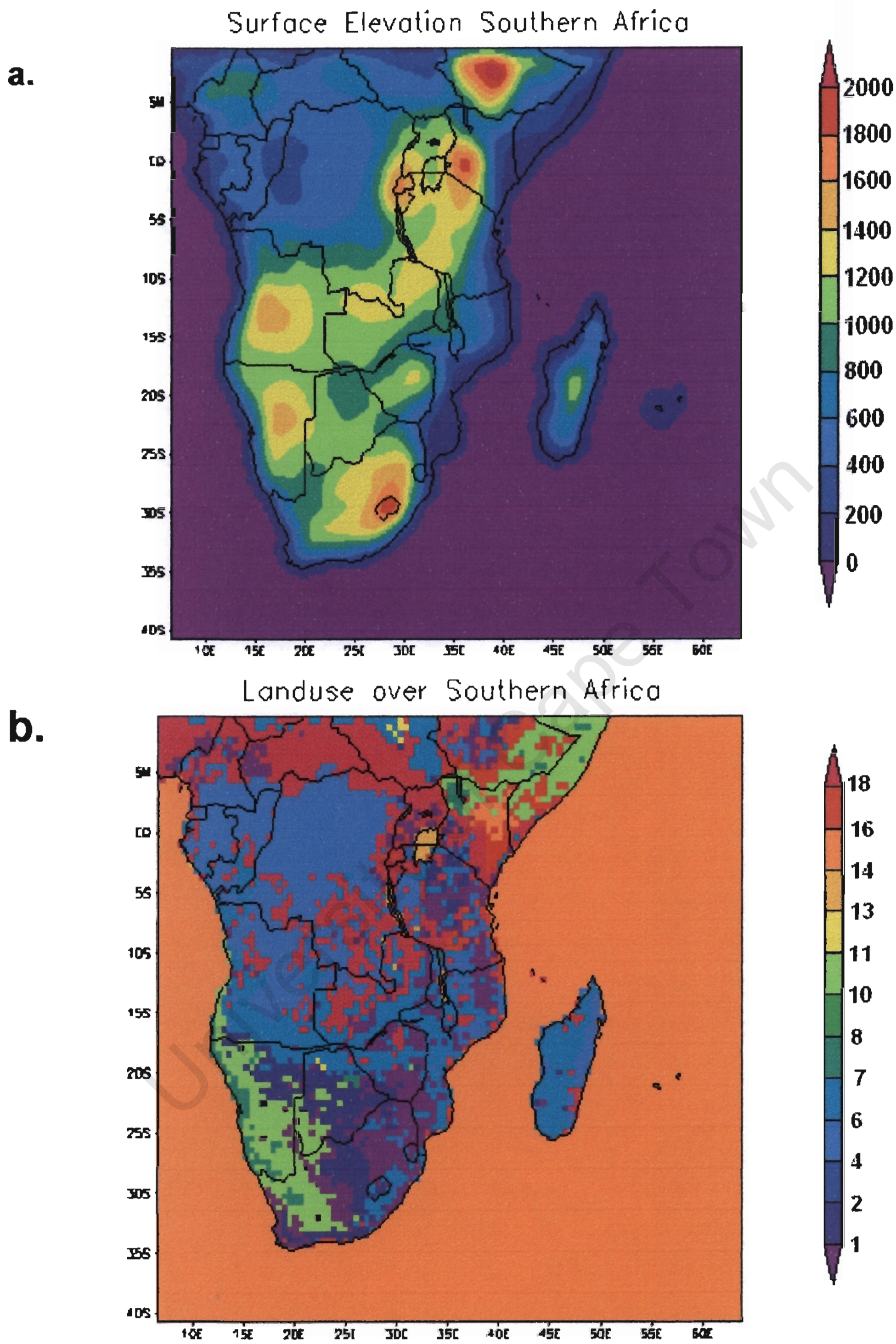


Figure 6.1 Domain choice showing the (a) elevation of the topography and (b) various landuses over southern Africa.

6.2 Modeling Experiments

The default RegCM3 model settings resulted in too much precipitation over the region as compared to the available daily rainfall data as well as the CRU and CMAP data. Several experiments were then carried out to try and fine-tune the model physics by altering parameters in the convection scheme. The models experiments were done for January 1992 and January 1996 allowing a spin up of 15 days. To improve on the model's simulation of real climatology, some attempts to alter parameters included the threshold values at which rain forms in the cloud, reduction of the CAPE within the Fritsch Chappell closure system, increasing the raindrop re-evaporation rate, changing the cooling rate of convection and reducing the rate at which precipitation forms within clouds.

The earlier simple fine tunings such as

- by change of convection schemes had so many point storms over the northern parts of southern Africa even in semi-arid zones of Namibia, drying of the wet portions of the regions including northern Mozambique channel and equatorial Indian Ocean and simulating a rather wet western South Africa, Namibia and south Botswana.
- Alterations of individual parameters mentioned earlier gave some better simulation in one zone but being erratic over the rest. Citing a few, increasing the level at which cloud forms or removing some CAPE resulted in the central parts of the region being dry and very deep convections occurring in central Indian Ocean;
- using the Kuo scheme underestimated precipitation over most of the region and removed all the point storms;
- increasing the threshold at which rain forms within the cloud maintained some point storms over the region and overprecipitated over the western areas.

Combining the various conditions in simulating the real climatology had to be adopted with some parameters being increased or decreased and others being maintained at default settings of the model's schemes. Finally, only a few parameters where altered to come up with a simulation to use for the next stage of the experiments.

In general, the results from modifying the model physics had regionally specific effects on the spatial distribution of precipitation, drying some areas whilst increasing precipitation elsewhere. There were also boundary problems which varied with the alterations of the parameters. The selected option was for an increase in reevaporation rate of the raindrops to $0.25(kgm^{-2}s^{-1})^{-1/2}$ from $0.10(kgm^{-2}s^{-1})^{-1/2}$ with the total CAPE removal time reduced from 45 minutes to 30 minutes and everything else being under the default settings within the Grell scheme (Giorgi F and J. Pal, *pers. comm..*, 2004). The reevaporation rate was more effective considering the fact that a rain drop falling over dry area will reevaporate faster. The control simulations for January 1992 and January 1996 were done with the soil moisture being initialised and allowed to be interactive with the model.

Once the tuning of the model had been finalised a series of soil moisture perturbation experiments were performed. The aim of the soil moisture experiments was to use the RegCM3 model to determine how soil moisture and surface fluxes affect the boundary layer climate of Southern Africa. The state of soil moisture, as described by the level of saturation in the soil upper-levels, is regulated by rainfall and potential evaporation. Both of these atmospheric forcings exert significant control on the evolution of the soil moisture state. To investigate these underlying processes a series of experiments utilizing wet, dry and normal soil moisture conditions were designed. The simulations experiments were designed such that the model was initialised and fixed with 75% and 25% soil moisture field capacity which are prescribed as the saturating and wilting threshold values within the (BATS) model scheme (Seth and Giorgi, 1998; Pal and Eltahir, 2000). For these fixed simulations, the surface impacts the atmosphere, but the soil moisture does not respond to the atmosphere (Pal and Eltahir, 2002).

6.3 Results

6.3.1 Model comparison to observed precipitation

Figures 6.2 and Figure 6.3 compares the model-simulated total precipitation averaged over January for both 1992 and 1996 with the observed rainfall over Zimbabwe's stations (produced using Cressman interpolation) and CRU datasets for the region. January 1992 and January 1996 are selected to represent extremes years in precipitation and hence soil moisture. Note that the simulation figures have been cut from the original domain to focus on contiguous Africa which is the main area of study. Due to computational demands and constraints, only one month was chosen to represent the extremes situations. Some grid point storms were observed in the simulations for tropical areas especially near lakes and high terrain, Figures 6.2 (a) and 6.3(a). This can possibly be associated with some local effects or the lake model scheme (Giorgi F, *pers. comm.,* 2004).

For January 1992, the model performs well in capturing the spatial distribution of the rainfall over the southern Africa region, Figure 6.2. However, the model overestimates by more than 8mm/day over most portions of the region as compared to the CRU data (Figure 6.2b) and Zimbabwe's observed rainfall station data (Figure 6.2c). There are small isolated regions where there is a considerable overestimation of rainfall such as in northern Zimbabwe and the point storms between 12°S and 14°S. However, the model captures well the rainfall peaks over southeastern South Africa, northern Mozambique as well as over the west and northeast of Zimbabwe. The model does well in capturing the spatial extent of the dry portion over the southwestern parts of the region.

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For January 1996, the model overestimated precipitation over much of the region as compared to the observed daily station data and CRU, Figure 6.3. The peaks of the precipitation are simulated too far to the north of the observed peak. The peak of observed rainfall over the Eastern Highlands (Figures 6.3b and 6.3c) is not present in the simulated precipitation and underestimates by about 13mm/day as compared to the Zimbabwe observations. However, the spatial distribution over mid-latitudes and over the northwestern Zimbabwe was acceptable. There was a underestimation in some zones especially over northeastern South Africa and Swaziland. Again, the model does well in capturing the portion over the southwestern part of the region.

The model clearly distinguishes between the two extreme years. This is very important as it shows the model's ability to capture interannual variability. However, some limitations still exist in the model's simulation of the precise location and magnitude of precipitation peaks. There is also limited observed station data for validation of the model simulations.

6.3.2 Model response to initial soil moisture

(a) Total Precipitation

Figure 6.4 show the sensitivity of the model to total rainfall at different initial soil moisture conditions. The control simulation is initialized using the conditions selected in section 6.2 and the remaining simulations are initialized uniformly in the horizontal and vertical at soil moisture percentages of 25% and 75% (Pal and Eltahir, 2001; J Pal, *pers. comm.*, 2004). The comparisons are made using the monthly averages of the resultant precipitation from these different soil moisture conditions expressed as an anomaly from the precipitation of the control simulation. Note that the total precipitation was presented and no convective precipitation outputs shown as they were very similar to the responses shown hereafter.

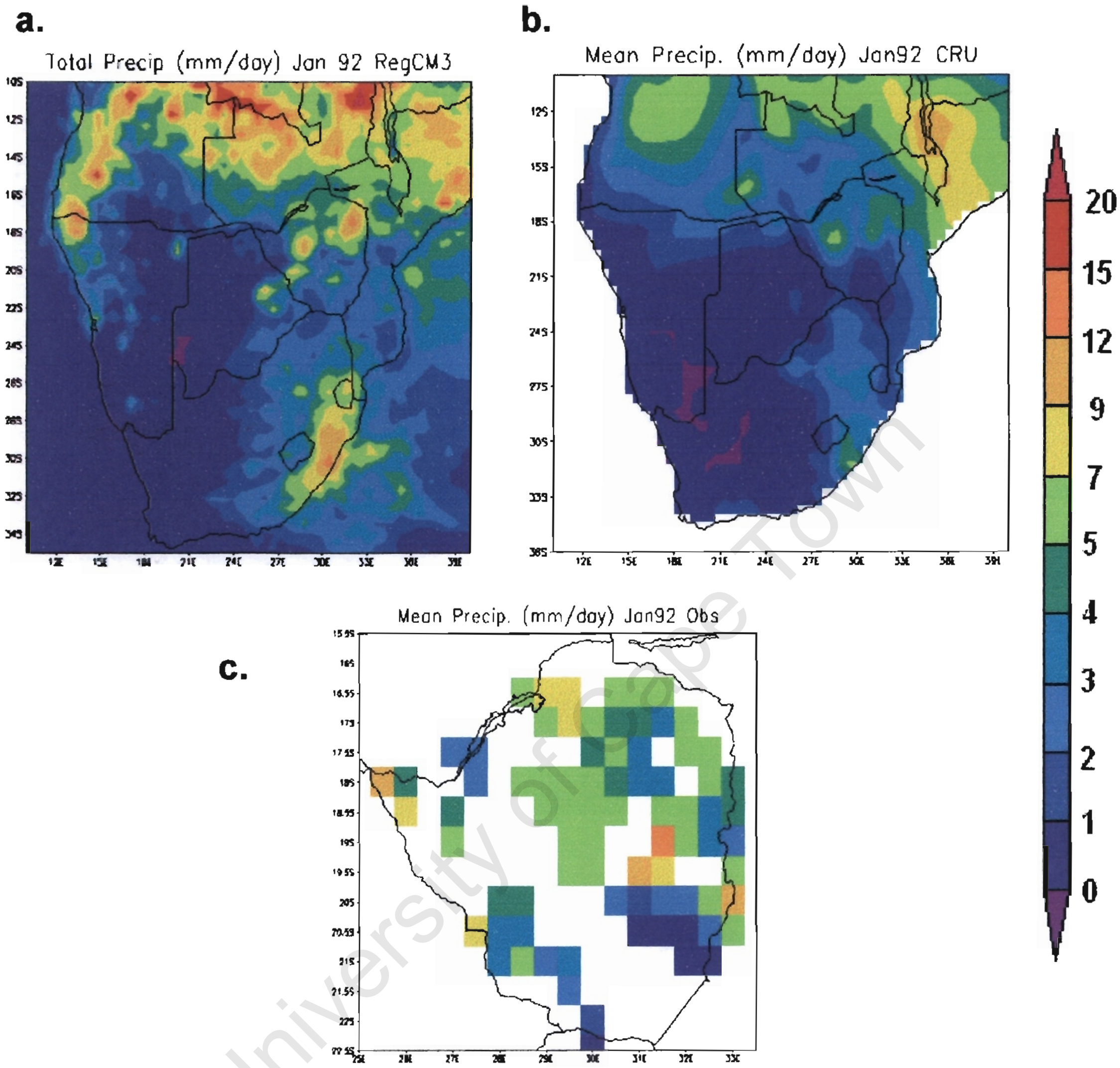

Figure 6.2 Total precipitation (mm/day) for January 1992 over the Southern Africa (a) RegCM3 , (b) CRU and (c) Zimbabwe's observed rainfall.

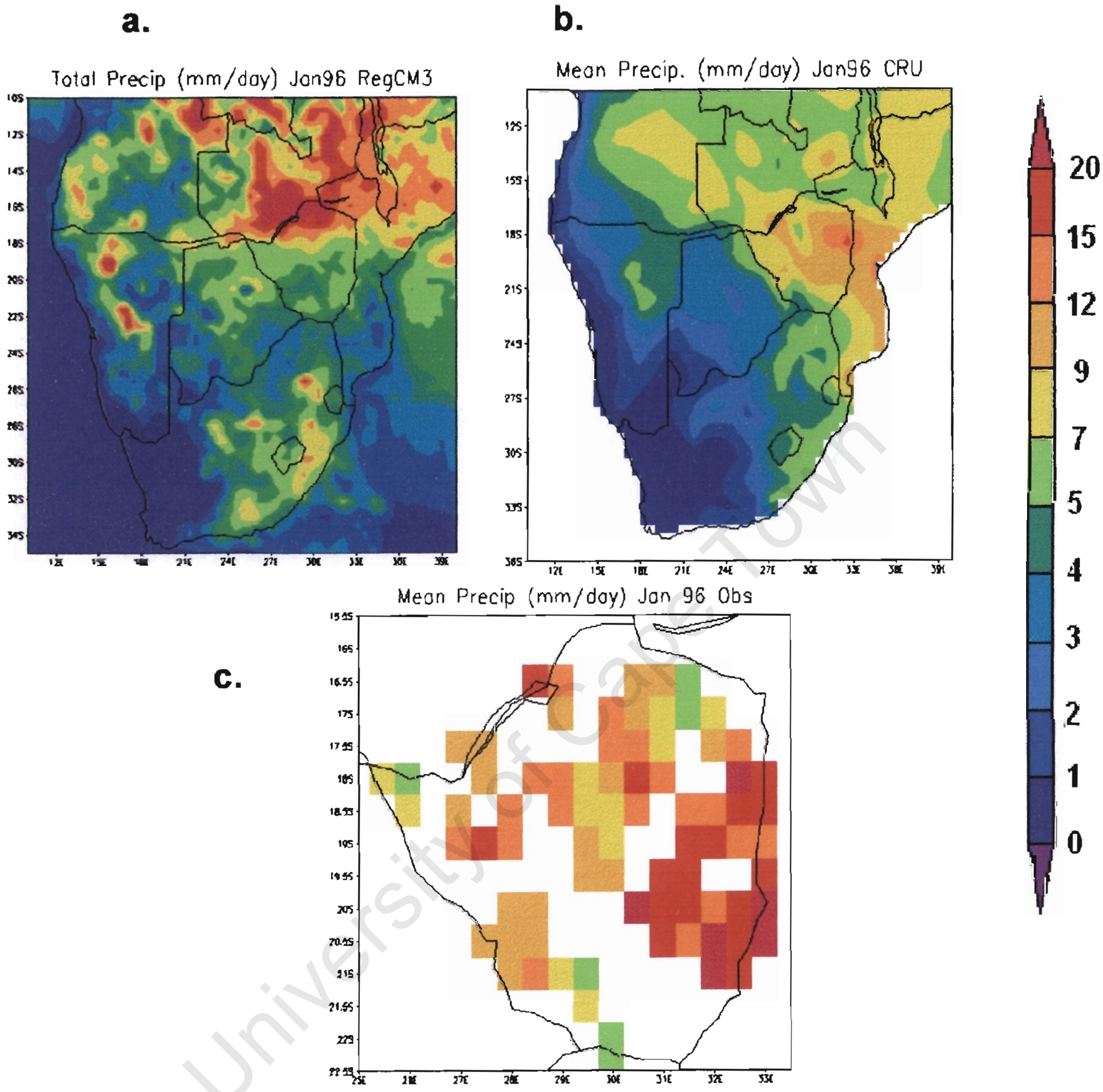

Figure 6.3 Total precipitation (mm/day) for January 1996 over the Southern Africa (a) RegCM3, (b) CRU and (c) Zimbabwe's observed rainfall.

For January 1992, the dry run i.e. soil moisture fixed at 25%, Figure 6.4(a) shows a decrease in precipitation over most of southern Africa. Exceptions are over the southern Angola, southeastern and northwestern South Africa, most of Botswana and Namibia where there is an increase in precipitation. Zimbabwe has a decrease in precipitation although there are a few localized places with an increase in precipitation. There is a marked decrease in precipitation over northwestern Zimbabwe and low-lying areas of the Zambezi valley. As for soil moisture fixed at 75%, Figure 6.4 (b), the region as a whole has no clear response. The greater part of the region has an increase in precipitation as would be expected of the positive feedback mechanism. The response to the wet simulation is not consistent as the remainder of the region has a decrease in precipitation. Generally, there is a decrease in precipitation over Zimbabwe, except for the northwestern and southeastern areas. The central and eastern areas are generally at a higher altitude (Figure 6.1) and it appears that the low-lying areas of the Zambezi and Limpopo valleys are more responsive to the change in soil moisture.

January 1996, the dry run (Figure 6.4c) shows a decrease in precipitation over Zimbabwe except for an increase in precipitation over the western areas. The bulk of region is also showing a decrease in precipitation in response to the dry soil moisture conditions. However, there are some areas with a marked increase in precipitation such as coast of Angola, Swaziland, eastern Lesotho as well as northern and southeastern areas of South Africa. The wet run, Figure 6.4 (d) shows a a marked decrease in precipitation over the northern and southern parts of Zimbabwe.. The greater portion of southern Africa region shows an increase in response to the soil moisture conditions, especially over the western areas.

Generally a decrease/increase in soil moisture results in a decrease/increase in precipitation over much of the region. However, in some areas the converse is true. This different response to soil moisture indicates that drier soil moisture conditions might actually lead to increased precipitation via an increase in convective instability (Seth and Giorgi, 1998). This could be the mechanism behind the increase in precipitation under drier conditions over the southeastern parts of South Africa. The increased convective instability over the continent draws in moist air from the surrounding oceans which lead to increased rainfall along the steep coastal escarpment of South Africa. For the two years analysed, precipitation is more responsive to drier than wetter conditions, e.g. Figure 6.4a and Figure 6.4c show a decrease in precipitation with a decrease in soil moisture. Figure 6.4b and Figure 6.4d are not so consistent as most eastern areas are showing an increase in precipitation with increase in soil moisture and conversely, a decrease in precipitation with an increase in soil moisture in a sizeable portion of the eastern areas. Pal and Eltahir (2001) suggested that soil moisture-rainfall feedbacks would tend to favour more persistent drought conditions in comparison to flood conditions.

(b) Surface Temperature

Figure 6.5 shows surface temperature differences for fixed soil moisture values of 75%, 25% and the control simulation. For January 1992, the surface temperature difference between the soil moisture fixed at 25% and the control simulation (Figure 6.5a), positive anomalies result over the whole region except for coastal and southern Namibia, parts of southern Botswana and western South Africa . The anomalously dry condition results in an increase in surface temperature. In Zimbabwe, the low-lying areas of Zambezi and Limpopo valleys also show this marked positive response. The anomalously wet soil moisture condition (Figure 6.5b) shows the whole region has a decrease in surface temperature except for the some isolated small portions. Marked decreases occur over the western areas where a marked increase in precipitation was observed (Figure 6.4b).

For January 1996 with dry soil moisture conditions, the surface temperatures show a warming everywhere except for some western parts of southern Africa, Figure 6.5c. Notable increases are over the Zambezi and Lowveld areas of Zimbabwe as well as the northern Mozambique, southeastern Botswana and northwestern South Africa. These large increases are mostly found around the Zambezi and Limpopo river valleys. Some useful positive and statistically significant trends have been found in these areas as discussed in chapter 5 e.g. percentage of days when daily maximum temperature exceeds 90^{th} percentile. Figure 6.5d shows a decrease in temperature over most of the region for anomalously wet soil moisture conditions. The largest decreases occur over the western, more arid parts of the region, with a less marked change over the wetter regions to the east. Northern Zimbabwe and southern Zambia indicate a slight increase in temperature. However, the western areas showing a decrease in surface temperature are in the dry region with very little or no precipitation during January as shown in Figure 6.2 and Figure 6.3. The 25% soil moisture initialization into these drier areas thus brings in unavailable moisture resulting in an increase in precipitation (Figure 6.4a and Figure 6.5a) and the decreases in temperature.

Therefore, drier conditions simulations are often associated with warming of the surface and the converse is true for wetter conditions. The effects of soil moisture changes are clearer on surface temperature than total precipitation as also seen in trends in the observed records (chapter 5). The largest surface temperature differences are experienced when dry soil is combined with dry synoptics (positive anomaly). The largest differences occur over the arid western regions. The Limpopo and Zambezi valleys show clear positive anomalies for dry soils regardless of the prevailing synoptics, indicating the Eltahir (1998) finding for feedback mechanism to be stronger for the dry soil moisture perturbations.

(c) Evapotranspiration

Figure 6.6 shows evapotranspiration differences (mm/day) for 25% and 75% fixed soil moisture values and the control simulation. For the evapotranspiration rate differences, January 1992 shows a decrease in response to the fixed 25% soil moisture conditions. The Evapotranspiration rates show a decrease over the most of southern Africa region except for some parts of the western areas, Figure 6.6 (a). There is a marked decrease in the rates over northern and southeastern Zimbabwe. As for Figure 6.6b, there is an increase in evapotranspiration rates over most of the region which are gradually reducing from west to east. The rates are decreasing over the northeastern parts of the region including northern and southeastern Zimbabwe. The Eastern Highlands and central parts of Zimbabwe show a positive evapotranspiration anomaly.

Figure 6.6c indicates there is mostly a decrease in evapotranspiration rates over southern Africa when dry soil moisture conditions are forced for a wet January 1996. Marked decreases occur over southeastern Zimbabwe (Lowveld area), northeastern South Africa as well as southern and coastal Mozambique. There is also an increase of evapotranspiration over most of the region for the wet soil moisture perturbation experiment in January 1996, Figure 6.6d. Decreases are occurring over the eastern areas including the northern and southeastern Zimbabwe. Very high increases are shown over the west coasts. This is typically a dry area during this time of the year and thus any moisture infiltration enhances the evaporation rates. Under dry conditions, the evapotranspiration rates decrease, as there is less moisture, resulting in an increase in surface temperatures. This is observed over the western areas of the region especially for January 1996.

(d) Sensible Heat

Figure 6.7 displays the sensible heat differences of the fixed soil moisture (25% and 75%) from the control simulations. In January 1992 under the dry soil moisture perturbation, Figure 6.7a, there is an increase in sensible heat over the sub-continent except for parts of the western areas where there is a decrease. The low-lying areas of Zimbabwe (i.e. Zambezi and Limpopo valleys) show a marked increase in the sensible heat. However, under the wet soil moisture condition (Figure 6.7b) there is a decrease in sensible heat for most areas except for the northern parts of the region. Zimbabwe show negative anomalies with marked decrease over the western and central parts.

In Figure 6.7c, the anomaly is positive for most of the region except for some portions of the western areas for January 1996 in dry soil moisture experiment. Marked positive anomalies in sensible heat are noted over southeastern Zimbabwe, northeastern South Africa and southern Mozambique. Figure 6.7d, most notably shows a marked decrease in sensible heat over the arid western parts of southern Africa region and an increase over northeastern parts of the region, including eastern Zimbabwe. This mixed response can be attributed to the control simulation for January 1996 having more soil moisture than the fixed 75% soil moisture simulation in some parts of the region especially towards the tropics. The area showing an increase is inclined in a typical manner associated with the ITCZ position during a wet January.

(e) Incident Solar Radiation

Figure 6.8 shows the incident solar radiation differences for the soil moisture fixed at 25% and 75% value from the control simulations for January 1992 and January 1996. January 1992 (Figure 6.8a), for the 25% fixed value under dry conditions the incident solar radiation is showing some mixed responses. There are positive anomalies, notably especially over the northern and southeastern Zimbabwe, northern and southern Mozambique as well as central Zambia. Some decreases occur along the west coast, over Angola, Botswana, Swaziland , northeastern South Africa, eastern Lesotho, and western Zimbabwe. For the wet soil conditions, Figure 6.8b, there is a decrease in incident solar radiation over most of southern Africa. Marked decreases are over the semi-arid and dry areas to the west of the region. Some coastal areas, central Zambia and northern Angola are showing a positive anomaly to the solar radiation.

Increases occur in the incident solar radiation for January 1996 under dry soil moisture conditions (Figure 6.8c), although there are some islands of decrease in the radiation. Notably, is the sensitive area to the southeast of Zimbabwe, southern Mozambique, northeastern and southern South Africa where very high increases are attained. In addition, central Mozambique and northeastern Zimbabwe do show some positive anomalies as well. Again these regions mostly correspond to the low-lying areas. Lesotho shows a conspicuous decrease in incident solar radiation. Figure 6.8d, shows the decrease in incident solar radiation over the bulk of the region with a similar pattern to Figure 6.8b. However, a notable difference is the increase in solar radiation over central parts and eastern highlands of Zimbabwe. A major decrease occurs over Botswana and the arid inland regions, depicting the responsiveness of incident solar radiation in that area to soil-moisture conditions. The radiation is increased over the ITCZ region, physically consistent with the positive surface temperature anomalies and decreased evapotranspiration.

The incident solar radiation is expected to decrease in the wet experiments as a result of increased cloud cover and the converse being true for the dry experiment. However, cloud cover may also change due to circulation changes and may not necessarily change in this expected manner. In this respect, it is noteworthy that dry soil moisture conditions, regardless of the season simulate the same positive radiation anomalies (though slightly damped during the wet season) over the low-lying river valleys of Zimbabwe. However,

in some areas the response is different because the effect can be overpowered by the decrease in net longwave emission as a result of increased cloud backscatter, decreased emission and increased water vapour greenhouse effect (Schär et al., 1999)

6.4 Discussion

The RegCM3 precipitates more rainfall than observed over Southern Africa although it is able to capture aspects of the inter-annual variability. The model was able to simulate the January 1992 and January 1996 associated dry and wet conditions respectively. There are some boundary problems and this requires a good choice of domain for better representation of the simulations. Simulated precipitation and moisture transport are affected by the choice of the limited area domain (Seth and Giorgi, 1998).

For sensitivity studies to internal forcings, domains much larger than the area of interest should be utilized (Seth and Giorgi, 1998). A large domain should be selected to include the large-scale responses to the soil moisture (Pal and Eltahir 2002). Longer period simulations are required for a critical study of the radiative processes in the soil moisture-rainfall feedback and to check if the model can simulate closer to the real climatology. Without the radiative feedback processes the initial soil moisture anomaly has little effect on the rainfall (Zheng and Eltahir, 1998; Schär et al., 1999; Pal and Eltahir, 2001). The soil moisture- rainfall feedback is also dependent on the convective parameterization and varies from one region to another. In this regard Tadross et al (2005a) show that the diurnal cycle and frequency of rainfall over southern Africa are dependent on the choice of convection scheme. Further, they show that the choice of planetary boundary layer is also important for simulating the diurnal cycle of incident solar radiation, all of which are important for correctly simulating the hydrological cycle. Schär et al. (1999), proposes a detailed analysis including an investigation of the mean diurnal cycle should be performed to isolate the physical mechanism underlying the soil moisture-rainfall feedback.

The role of circulation changes should be underpinned in order to yield a better understanding of the feedback mechanism. One of the difficulties of evaluating changes that may be linked to circulation changes is the nonlinearity of the regional climate system, which can generate unforced changes that one might view as noise. This noise may be the cause of some of the localized changes that are opposite to simple expectations. This noise may be the cause of some of the localized changes that are opposite to simple expectations. In this study, it is difficult to separate the noise from the signal because the simulations are fairly short. There is need to find ways of increasing the size of the dataset to analyse by continuous multi-year simulation, by simulating more Januaries or by ensemble simulation (not recommended for midlatitude regional climate simulation). In this kind of modeling study, use of convective precipitation output is very important. The models's convective precipitation outputs (not shown here) were not included as they are quite similar to the total precipitation results shown. There are slight differences due to the stable component within the total precipitation which results in a few higher rainfall peaks in some isolated areas.

The model depicts that when fixed at 25% soil moisture field capacity, surface temperatures are increased for most of the region except for the coastal and western regions. The evapotranspiration is thus reduced in response to the drier conditions. The northeastern portion of the region where the surface temperatures are higher has a significant drop in the evapotranspiration rate. The western semi-arid and dry lands show strong responses to soil moisture perturbations for all the variable analysed. The surface temperature changes are significantly higher in the low-lying regions of the Zambezi and Limpopo valleys, during wet and dry seasons. This concurs well with the Eltahir's (1999) feedback mechanism that anomalously dry soil moisture conditions are typically associated with anomalously warm temperatures and low humidities at or near the surface via an increase in sensible heat flux and a decrease in latent heat flux. Pal and Eltahir, 2002 concur and also highlight that anomalously dry surface conditions are associated with less clouds and hence, more net surface solar radiation. This is clearly reflected in the drier soil moisture conditions experiments, with the anomalous changes being higher during the already dry January of 1992. Therefore, drier conditions experiments are likely to have a stronger response than in a wetter conditions set-up. The Limpopo valley area shows a very sensitive climatic response to soil moisture when a dry anomaly is applied. This might induce and maintain drought–like conditions over that area. This mechanism appears to play an important role in both the persistence and intensity of precipitation events (Pal and Eltahir, 2002; Nicholson, 2001).

Some high ground areas of the region like the central watershed and Eastern Highlands of Zimbabwe as well as the Drakensberg Mountains (Lesotho incorporated) seem to have a different response to the soil moisture. The response over these regions substantiates the Giorgi et al. (1996) finding that local recycling effects were not important in the development of extreme climatic regimes and that a dry soil initial condition provides for increased sensible heat flux, which contributes greater buoyancy to the air, enhancing convective systems and producing more precipitation. This cycle supports a negative feedback mechanism between initial soil condition and precipitation. However, none of these studies focused on southern Africa and are mostly applicable in northern hemisphere.

6.5. Summary

Parameters analysed Drier conditions experiments show stronger responses to the soil moisture under both experimental conditions and seasons. However, no consistent response to soil moisture initialisation over southern Africa was found. In general, the response to initial soil moisture condition is not projecting the proposed positive feedback mechanism (Eltahir, 1998) theory. However, the response is mostly positive to the dry soil moisture perturbations for the variables investigated. Under dry conditions experiments, temperatures increased for most of the region except for the coastal and western regions. The evapotranspiration is thus reduced in response to the drier conditions. The results might be different if the factors mentioned above such as in-depth knowledge of the physical mechanism of the feedback process, domain choice, large-scale dynamics, diurnal cycles and period of simulations are incorporated well. The role of convective precipitation and circulation changes should be underpinned in order to yield a better understanding of the feedback mechanism. Powerful knowledge of the simulated soil moisture-rainfall feedback over southern Africa can have far reaching conclusions such as in weather forecasting models, seasonal forecasting, climate change and water resource management.

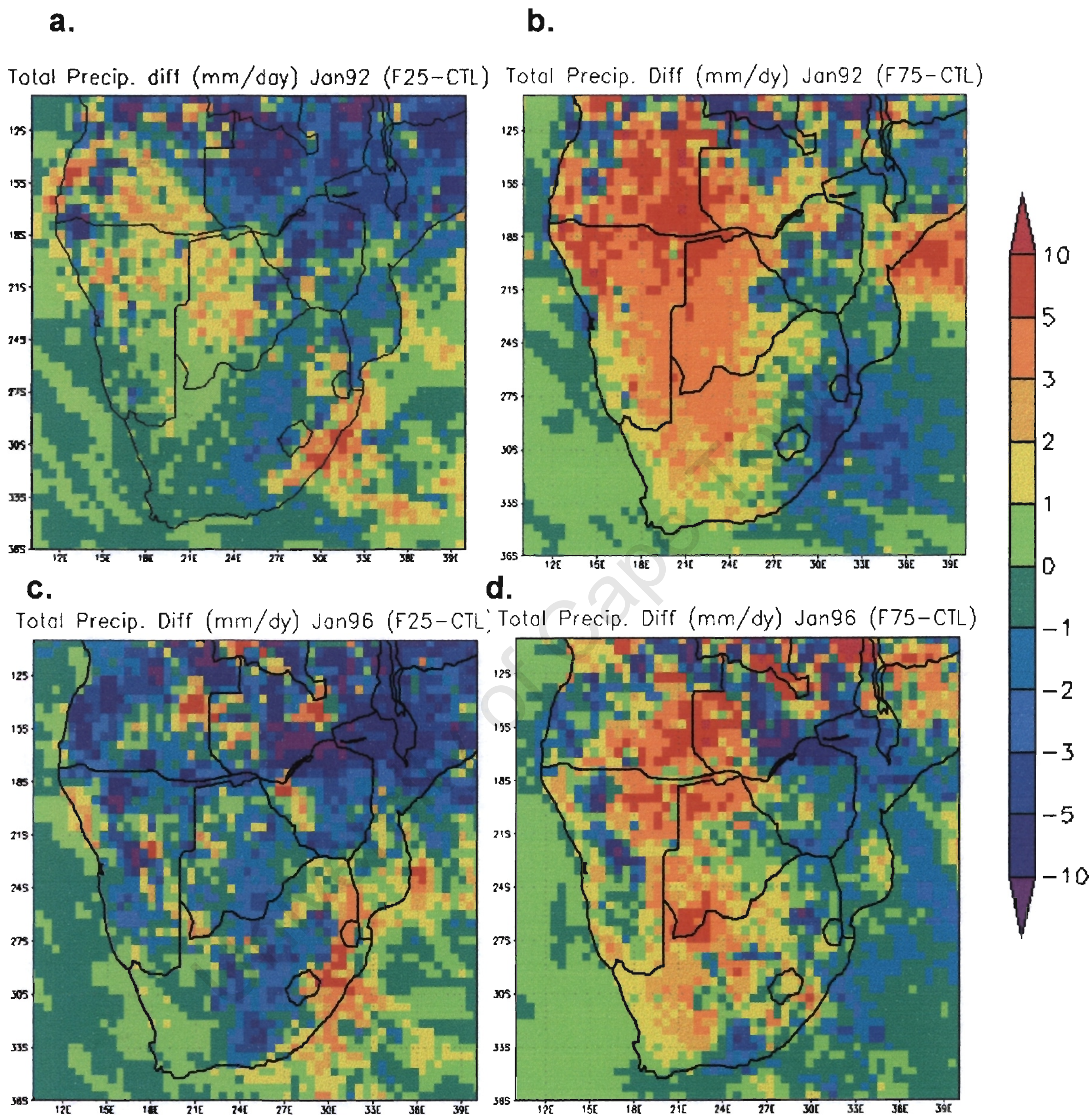

Figure 6.4 Precipitation differences for fixed soil moisture values of 75%, 25% and the control run. (a) Fixed-Control at 25% for January 1992, (b) Fixed-Control at 75% for January 1992, (c) Fixed-Control at 25% for January 1996 and (d) Fixed-Control at 75% for January 1996.

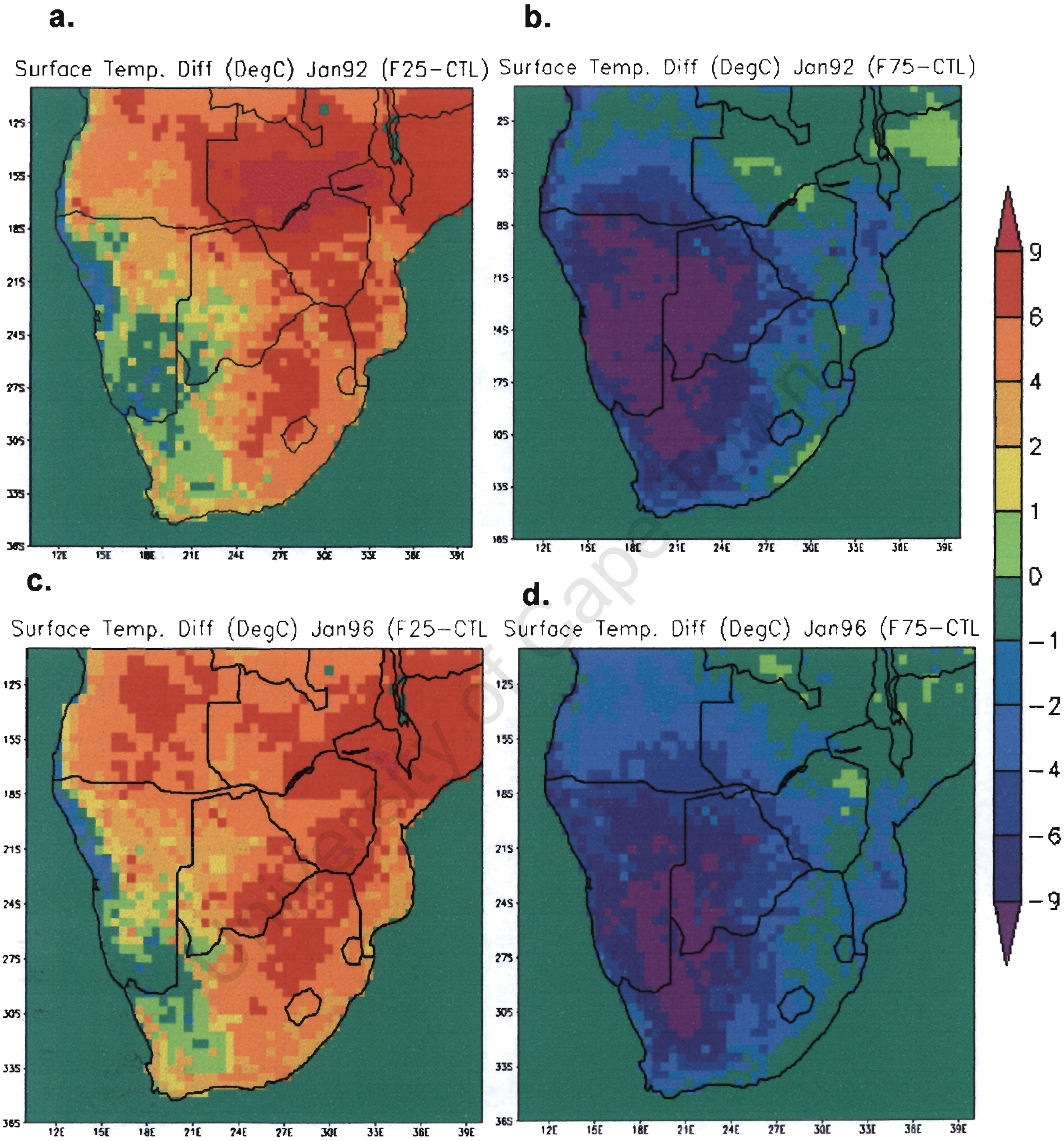

Figure 6.5 Surface temperature differences (˚C) for fixed soil moisture values of 75%, 25% and the control simulation. (a) Fixed-Control at 25% for January 1992, (b) Fixed-Control at 75% for January 1992, (c) Fixed-Control at 25% for January 1996 and (d) Fixed-Control at 75% for January 1996.

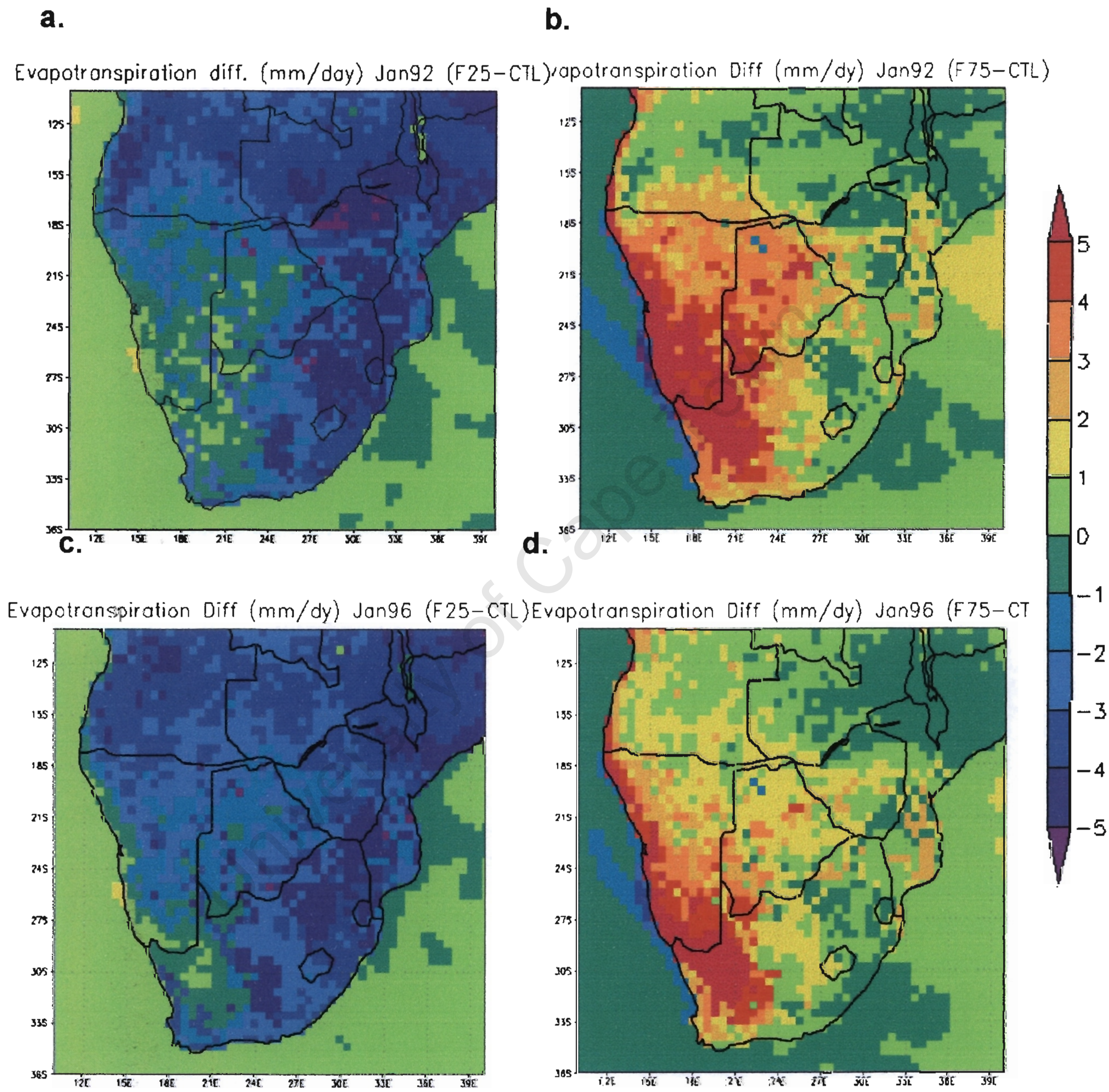
a.
Evapotranspiration diff. (mm/day) Jan92 (F25-CTL)
b.
Evapotranspiration Diff (mm/dy) Jan92 (F75-CTL)
c.
Evapotranspiration Diff (mm/dy) Jan96 (F25-CTL)
d.
Evapotranspiration Diff (mm/dy) Jan96 (F75-CT
5
4
3
2
1
0
-1
-2
-3
-4
-5

Figure 6.6 Evapotranspiration differences (mm/day) for 25% and 75% fixed soil moisture values and the control simulation. (a) Fixed-Control at 25% for January 1992, (b) Fixed-Control at 75% for January 1992, (c) Fixed-Control at 25% for January 1996 and (d) Fixed-Control at 75% for January 1996.

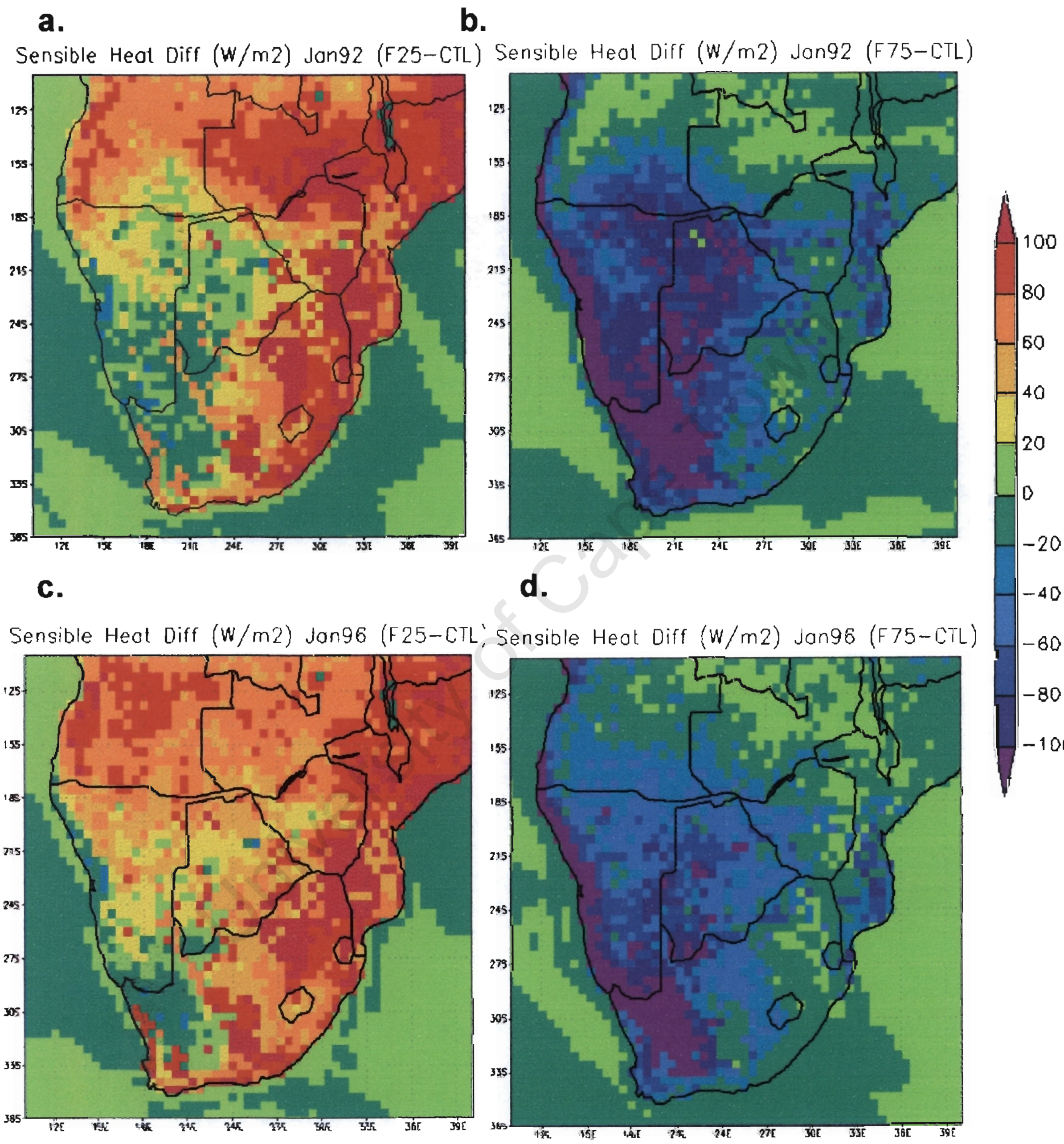

Figure 6.7 Sensible heat differences (W/m^{-2}) for 25% and 75% fixed soil moisture values and the control simulation. (a) Fixed-Control at 25% for January 1992, (b) Fixed-Control at 75% for January 1992, (c) Fixed-Control at 25% for January 1996 and (d) Fixed-Control at 75% for January 1996.

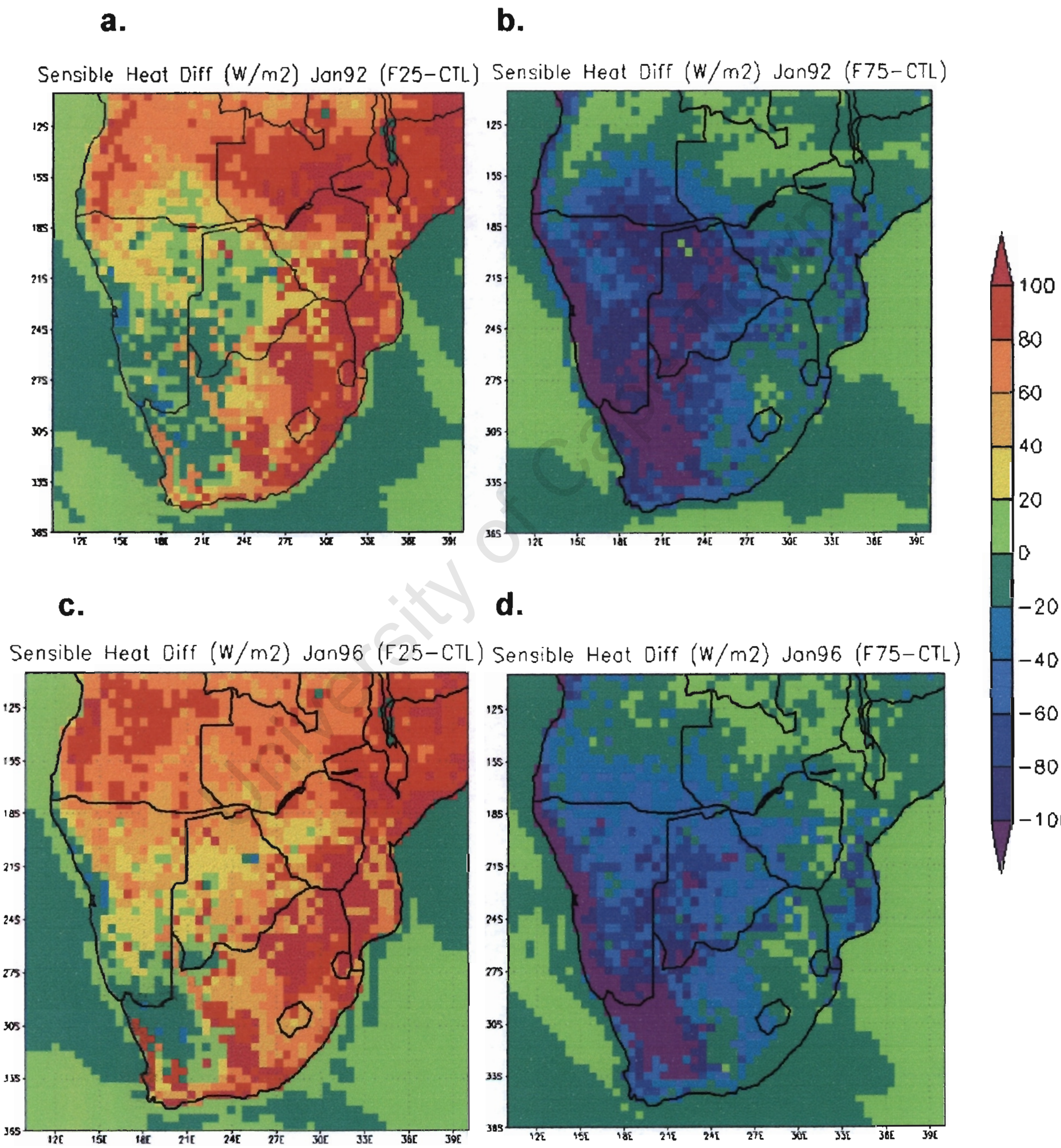

Figure 6.8 Incident solar radiation (W/m^{-2}) for 25% and 75% fixed soil moisture values and the control simulation. (a) Fixed-Control at 25% for January 1992, (b) Fixed-Control at 75% for January 1992, (c) Fixed-Control at 25% for January 1996 and (d) Fixed-Control at 75% for January 1996.

Chapter 7

Discussion and Conclusion

7.0 Introduction

This chapter seeks to synthesize the thesis foci and highlight some of its important findings, limitations, lessons learnt and recommendations for future work. A summary of the results found in the preceding three chapters is presented and discussed. Caveats or limitations are then discussed in which explanations on the methodologies, tested hypotheses and the findings are highlighted. Implications and proposals for future research are then presented with some concluding statements wrapping up the chapter.

7.1 Summary of results

7.1.1 Observed Rainfall Patterns over southern Africa

The SOM captures well the rainfall patterns within the CMAP pentad data for the period 1979-2002. The late summer period JFM SOM array shows some distinct rainfall patterns different from those of the OND period. From the SOM array the frequency of occurrence is for drier rainfall patterns for both OND and JFM over the 23 years used with fewer occurrences of the rainfall patterns associated with the ITCZ and depressions in the Indian Ocean during the OND period. The rainfall patterns associated with depressions or tropical cyclones to the northeast of Madagascar and the ITCZ are prevalent during the JFM period. As for the trend analysis, there is positive trend in frequency of occurrence for the left quadrants associated with very dry rainfall patterns.

7.1.2 Climate Extremes Trend Analysis

There is much less confidence in the rainfall trends than the temperature trends. The country clearly shows a spatially coherent warming trend in temperature. Most of the indices, except for some temperature trends, were not statistically significant. However, general spatial consistency and similarity of trends between stations suggests credible trends that have a real spatially cohesive component. The number of warm days and warm nights is increasing while the number of cool days and cold nights is decreasing. Precipitation indices are less spatially coherent than temperature indices. Nevertheless, the rainfall patterns show evidence of drying; decrease in total precipitation and dry spells duration are increasing over most of the country except the southern parts. An increase in rainfall intensity is evident over some high altitudes stations.

7.1.3 Soil moisture-rainfall simulations

The greater portion of the southern Africa region shows that a decrease/increase in soil moisture results in a decrease/increase in precipitation. However, in some areas such as the high altitudes areas of central watershed and Eastern Highlands of Zimbabwe as well as the Drakensberg Mountains the converse is true. This different response to soil moisture indicates that drier soil moisture conditions might actually lead to increased precipitation via an increase in convective instability. The surface temperature differences to soil moisture perturbations show the anomalously dry conditions result in an increase in surface temperature while for the anomalously wet soil moisture condition, a decrease in temperature over most of the region is observed. The RegCM3 model depicts that under dry conditions experiments, temperatures increased for most of the region except for the coastal and western regions. The evapotranspiration is thus reduced in response to the drier conditions. The northeastern portion of the region where the surface temperatures are higher has a significant drop in the evapotranspiration rate. The altitude does modulate these feedback mechanisms with low-lying areas and the semi-arid or dry lands depicting a stronger response. The surface temperature changes are significantly higher in the low-lying regions of the Zambezi and Limpopo valleys, for both wet and dry seasons. However, the dynamics of the feedback mechanism was not fully explored in this study.

7.2 Discussion

SOM has broadened the techniques by which synoptic climatology may be approached and classifies data on a non-linear basis. Generally the trends show drying out rainfall patterns during the OND and JFM period, implying that the synoptic states reducing precipitation are increasing while the synoptic states leading to enhanced precipitation have been decreasing over time. Thus, from the frequency analysis complemented by the trend analysis it can be inferred that precipitation over time has been decreasing for both OND and JFM SOM arrays.

As mentioned in the results in section 7.1.2, there is evidence of positive trends in temperature over the country, although precipitation is less cohesive. The confidence levels were higher for temperature trends than for precipitation trends. Empirical studies do not provide information on the causal factors of detected trends. However, it can be inferred that the mean monthly diurnal temperature range (DTR) increases would be suggestive of an increase in cloud-free days for their occurrence and influence of systems such as the 500hPa anticyclone. There does appear to be some intriguing and spatially cohesive patterns in the trends for consecutive dry days, CDD. Although not statistically significant, the CDD shows an increase over the northern parts of the country where there is a decrease in precipitation. The spatial cohesion thus lends credibility to the trends. Trends for increasing CDD are generally associated with higher altitudes over the central watershed and eastern highlands whilst the decrease in dry days is over the low-lying areas to the south. Some stations showing an increase in total precipitation are all associated with an increase in CDD and 95^{th} percentile of the rainfall (R95P). There is a behaviour suggesting a relationship between changes in total precipitation is due to an increase in rainfall intensity.

This research did not establish whether the detected temperature trends are the result of global warming (in which case it might be expected to persist in the future) or of short-term variability (Luís, 2000). From the agreement between the observed trends and GCM predictions (Hulme et al., 2001), it may be inferred that the trend in temperature is linked to global warming. Future climate change projects a warming and is inconclusive for rainfall for most of Africa. However, Hulme et al. (2001) relate the reason for the rather ambiguous case in GCMs of ENSO-type climate variability in the tropics (a key determinant of African variability) and the omission in all current GCMs of any representation of dynamic land cover-atmosphere interactions. Such interactions have been suggested to be important in determining the region's climate variability (Nicholson, 2001; IPCC, 2001).

The results summarized in section 7.2.3 concur well with the feedback mechanism that anomalously dry soil moisture conditions are typically associated with anomalously warm temperatures and low humidities at or near the surface via an increase in sensible heat flux and a decrease in latent heat flux. These anomalously dry surface conditions are associated with less cloud and hence, more net surface solar radiation. This is clearly reflected in the drier soil moisture conditions experiments, with the anomalous changes being higher during the already dry January of 1992. Therefore, drier conditions experiments are likely to have a stronger response than in a wetter conditions set-up. The Limpopo valley area shows a very sensitive climatic response to soil moisture when a dry anomaly is applied. This might induce and maintain drought –like conditions over that area. This mechanism appears to play an important role in both the persistence and intensity of precipitation events.

There are so many other climatic variables that need to be considered in the soil moisture-rainfall feedback mechanisms. Some responses, such as decreases in precipitation, not only occur over the anomalous source region but may also occur in a remote area. An understanding of the feedback in relation to the large-scale dynamics would be useful in explaining the impacts of soil moisture. Western parts of southern

Africa and the area around southeastern Zimbabwe, northeastern South Africa and southern Mozambique (Limpopo valley area) are typical good examples of areas where more investigation should be done. Similar, though slightly weaker responses were also noted over the Zambezi valley areas to the north. These results therefore suggest the possible role of altitude in modulating these feedback mechanisms over the eastern regions of southern Africa. In the western areas, the soil saturation might be near the wilting point of the soils within the BATS scheme used in the RegCM3 model.

The significance of altitude has been expressed through the difference in trends of dry spells over the north (high altitude areas) and south (low-lying areas) of Zimbabwe, rainfall intensification over high altitude stations, stronger response to soil moisture perturbations in low-lying areas than the high altitude areas e.g. increase in surface temperatures, decrease in evapotranspiration and reduction in rainfall. It can be inferred that the high altitude areas are more influenced by synoptic forcings whereas the low-lying areas are due to land surface interactions. There is a need for better understanding of the soil moisture feedbacks, associated circulation dynamics and links to the predicted changes in climate.

7.3 Issues Requiring Further Investigation

Some of the important issues that have not been fully explored in this study due to time constraints, computer demands and complexity include:

Data, Quality Control and Homogeneity testing: Availability of sufficient or good record of observation data to work with has come out as one of the obvious limiting factors. However, even in areas where the data is available there are issues such as the quality control, homogeneity process that had to be dealt with. The data was subjected to some quality control (QC) tests such as assessing the data for physically impossible values, unrealistically long consecutive occurrences of the same value and checks for statistical outliers. Some studies have shown that even correctly observed and digitized data may be unsuitable for long-term climate analyses e.g. a thermometer moved from the shade of a tree to a place out in the grass but near a tarmac, an artificial jump can occur in the time series (Peterson et al. 1998). As discussed earlier, inhomogeneities or discontinuities in climate data can be caused by any change to the station or its operation, including site location, exposure, instrumentation, or observational practice (Peterson et al., 1998; Manton et al., 2001). Thus a quality dataset would require a more robust quality control and homogeneity testing than the visual approach adopted at times in this work. Further improvements of the homogeneity testing and use of more stations would be worthwhile. However, some of the best approaches require considerable resources that may not be available within the constraints of a given project.

The Cressman interpolation: Although adequate for the present study in coming up with an observational precipitation dataset, it takes no account of the synoptic dependence and the bounded nature of the precipitation function (Hewitson and Crane, 2005). Thus the Zimbabwe's observed (Cressman interpolated) precipitation is overestimated because it takes no account of the synoptic dependence especially over the low-lying areas but remains lower in some places than the RegCM3 model's precipitation simulations. Accuracy will still be low in using conditional interpolation proposed by Hewitson and Crane (2005), as there is a very low density of observing stations over Zimbabwe. This further highlights the limitations of sparse data in the atmospheric science research work, particularly in Africa.

SOM approach: The technique has expanded into a useful computer-based technique by which scientific research can be approached. However, it remains subjective with still some decisions being made by the user pertaining to training of a SOM. This can be limiting in that it changes the degree of generalization although the identified patterns remain stable.

Trends: Despite the caveats of data discussed above, arbitrary threshold values to come up with climate extreme indices are inappropriate for regions spanning a broad range of climates e.g. in Zimbabwe there is no single temperature or rainfall threshold value that would be considered extreme in all rainfall regions. Null hypothesis statistical testing was ineffective for some of the climate extreme indices. Thus credibility of the results had to be based on the spatial cohesiveness of the indices. No vigorous attempt was made to consider the possible causes of the observed trends in extremes. However, they fit in with the pattern change in the large-scale circulation depicting an increase in 500hPa anticyclones (section 2.7) and a decrease in frequency of low pressures (Tadross et al, 2005c). This would be helpful in accepting or rejecting the historical climate trends findings. There are also regional issues of desertification, land degradation, sea level rise and variability in the strength of teleconnection couplings such as ENSO, Indian Ocean Dipole Mode, Brandon Marion Index.

Regional climate model simulations: In the feedback mechanism experiments, the RegCM3 model was unable to capture well the observed dynamics and thermodynamics of the atmosphere. Some of the strong or weak responses to the exploration experiments include possible errors in the simulation model that could be due to boundary conditions. The aim should be for improved model physics and parameterization that could modify and improve results (Tadross et al., 2005b). Longer period with a sufficient spin-up time simulations are required for a critical study of the radiative processes in the soil moisture-rainfall feedback and to check if the model can simulate closer to the real climatology. There is need to find ways of increasing the size of the dataset to analyse by continuous multi-year simulation; by simulating more Januaries or by ensemble simulation (not recommended for midlatitude regional climate simulation).

Soil moisture-rainfall feedbacks: For sensitivity studies to internal forcings, domains much larger than the area of interest should be utilized to include the large-scale responses to the soil moisture. It is worth noting that a too wet model may interfere with the way the feedback process actually operates possibly due to too much remnants of moisture available and might require a longer period to equilibrate the moisture within the model's atmosphere. In a non-linear system, bias towards wet soil moisture conditions can result in an erroneous solution such as the weak response observed with the wet soil moisture perturbation experiments. Analysis of moisture transport within the vertical columns could give more insight into the changes taking place when model results are erratic. There was also little evaluation of the mechanism due to varied soil moisture levels. Due to the short period simulated within only two extreme years, the findings cannot be conclusive for other seasons and years. More robust experiments still need to be undertaken before any conclusions can be made. No attempt was made to include the direct effects of vegetation on changing soil moisture. Experiments are been carried out to examine the vegetation-atmosphere effects over southern Africa and include sensitivity test of the MM5 regional climate model (Drew, 2004, Hewitson and Tadross, *pers. comm.*).

7.4 Recommendations for Future Work

SOM technique has the capability to characterizing frequencies of daily resolution synoptic events (Main, 1997; Hewitson and Crane, 2002). This renders SOM a useful tool for evaluation and validation of climate model performance and global climate change scenarios on the basis of synoptic circulation. The method can be adopted in the future to compare any experimental simulations to the control runs. Due to its varying range of uses in synoptic climatology and its robustness, the SOM approach is recommended for use in any follow-up or similar research.

A more detailed investigation to the climate extreme trend analysis is required to assess fully the impacts of changes in these events. Empirical studies do not provide possible causes of the observed trends in extremes. In particular from this study it is not possible to establish whether the detected trends are the result of global warming or regional variability. Further work should initially utilize a dense and homogeneous daily data to substantiate the results. To evaluate the findings other test methods should be adopted such as confidence intervals, permutation test, cross-validation or simulation of extreme events using a stochastic weather generator,

Land surface-atmosphere interactions over southern Africa emerge as an area that is essential for future studies. A bottom-to–top approach should be adopted starting from attaining close to the real climatology of southern Africa in the RegCM3 model. Thus more fine-tuning process of model's physics and sensitivity experiments of the model to soil moisture conditions should be done. Increasing the number of studies with different RCMs would aid in determining if the models are producing the most realistic response.

Similar experiments to the present study (which assumed a homogeneous soil layer) but with varying soil moisture within the model's three layers of top soil, root soil and deep soil can be helpful in assessing each layer's contribution to the model's atmosphere response. The change in the soil moisture perturbations (e.g. 10%, 25%. 50%, 75%, 90%) should also be done to check the model's sensitivity especially towards the wetter soil moisture perturbation where the response was weaker as compared to the drier one. To help resolve the variability of model's atmosphere, experiments should not only be for selected extreme dry and wet years but also for normal, El Niño and La Niña years (assuming stability of the ENSO teleconnections in the future i.e. if ENSO phases do not become locked into one state). Soil moisture retention or memory experiments could be useful in assessing the model's response as well as for forecasting purposes i.e. how an initial soil moisture perturbation persists and affects rainfall during a seasonal forecast. The knowledge of the antecedent conditions would be very important during the seasonal forecasting process.

An approach of analyzing the diurnal cycles can also be adopted to try and improve on model's precipitation simulations (Tadross et al., 2005a). There is a need to look at large-scale dynamics such as circulation patterns and moisture trajectories to aid in the feedbacks analysis. This acknowledges that the response might not be a local effect but an effect translated from a remote area. Further research could also assess the sensitivity within a window of interest whilst maintaining default conditions elsewhere. This can aid in better understanding of the local effects and assess on the capabilities of the model at finer resolutions. Thus improve in better identifying the significant processes responsible for the soil moisture-rainfall feedback i.e. separate the local forcings such as the instability in the vertical distribution of atmospheric temperature and humidity (characterized by CAPE) and the increase of the moist static energy in the PBL from large-scale atmospheric forcings such as those generated by monsoon circulations within the tropics, frontal systems in midlatitudes or orographic lifting. The soil moisture-rainfall feedbacks over southern Africa should be reviewed in an inter-comparison analysis of the regional climate models such as MM5, RegCM3 and PRECIS (Providing Regional Climates for Impacts Studies) which are being used at CSAG.

There is also need for research into impacts of climate change on soil moisture and its feedback to the atmosphere for southern Africa. Sensitivities to temperature, precipitation, evaporation, radiation effects and to climate change scenarios should be tested. Incorporation of realistic soil moisture dynamics over the region into climate change predictions would be useful. This would lead to more plausible regional-scale future climate change predictions for southern Africa. Thus, the necessity for more investigation of the couplings in the regional climate system is imperative if we are to understand the dynamics of the regional climate.

7.5 Conclusions

Making proper homogeneity adjustments, selection of the best station data prior to analyses, meaningful statistical testing techniques, plausible RCM simulations and effective sensitivity testing or adjustments are crucial prior to any climate analyses in this study. Without proper adjustments, erroneous conclusions or inferences may be inevitable. Results from the preceding three chapters point towards the drying out patterns over the region from the historical records analysed. The trend analysis done with SOM arrays revealed a positive trend towards drier conditions and a negative trend for wet conditions. The climate extremes indices analysis complemented these findings as shown in the decrease in total precipitation and a general increase in the number of dry spells. This is supported by the circulation patterns showing an increase in frequency of the 500hPa anticyclones and a decrease of low pressures. This would exacerbate need for proper planning of future water resource management and farming strategies.

Soil moisture rainfall feedback mechanisms were not fully explored. However drier conditions experiments showed a stronger response to soil moisture perturbations than in wetter conditions experiments No consistent response to soil moisture initialisation over southern Africa was found. The altitude does modulate these feedback mechanisms with low-lying areas depicting a stronger response. A better understanding of the observed rainfall patterns, historical climate trends and soil moisture-rainfall feedback mechanisms are essential for improved short-term and seasonal forecasting and will aid the generation of plausible climate change impact predictions.

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Appendices

Appendix A-1: List of Climate Indices

After QC, RClimDex calculates 27 indices from the daily data. Table A-1 shows some of the indices that can be useful over the country whilst those used in this study are highlighted in bold. Not all indices calculated by the RClimdex are relevant over Zimbabwe or the region at large.

Table A-1 Definitions of Indices calculated for the region using RClimdex.

ID	Definitions	UNITS
FD	Annual count when Tn(daily minimum)<2ºC	Days
SU	Annual count when Tx (daily maximum)>25ºC	Days
ID	Annual count when Tx (daily maximum)<0ºC	days
TR	Annual count when Tn (daily minimum)>20ºC	days
GSL	Annual (1st Jan to 31st Dec in NH, 1st July to 30th June in SH) count between first span of at least 6 days with TG>5ºC and first span after July 1 (January 1 in SH) of 6 days with TG<5ºC	days
TXx	**Monthly highest daily maximum temp**	**ºC**
TNx	Monthly highest daily minimum temp	ºC
TXn	Monthly lowest daily maximum temp	ºC
TNn	**Monthly lowest daily minimum temp**	**ºC**
TN10p	**Percentage of days when TN<10th percentile**	**days**
TX10p	**Percentage of days when TX<10th percentile**	**days**
TN90p	**Percentage of days when TN>90th percentile**	**days**
TX90p	**Percentage of days when TX>90th percentile**	**days**
WSDI	Annual count of days with at least 6 consecutive days when TX>90th percentile	days
CSDI	Annual count of days with at least 6 consecutive days when TN<10th percentile	days
DTR	**Monthly mean difference between TX and TN**	**ºC**

RX1day	Monthly maximum 1-day precipitation	mm
Rx5day	Monthly maximum consecutive 5-day precipitation	mm
SDII	Annual mean prcp when PRCP>=1.0mm	mm
R10mm	Annual count of days when PRCP>=10mm	Days
R20mm	Annual count of days when PRCP>=20mm	Days
Rnnmm	Annual count of days when PRCP>=nnmm, nn is user defined threshold	Days
CDD	Maximum number of consecutive days with RR<1mm	Days
CWD	Maximum number of consecutive days with RR>=1mm	Days
R95p	**Annual total PRCP when RR>95p**	**mm**
R99p	Annual total PRCP when RR>99p	mm
PRCPTOT	**Annual total PRCP in wet days (RR>=1mm)**	**mm**

Appendix A-2: List of Acronyms

Here are the acronyms with the exception of those already defined in Appendix A-1:

ANN	Artificial Neural Network
BATS	Biosphere-Atmosphere Transfer Scheme
BATS1E	Biosphere-Atmosphere Transfer Scheme version 1E
BMI	Brandon-Marion Index
BUH	Botswana Upper High
CAB	Congo Air Boundary
CAPE	Convective Available Potential Energy
CCM3	Community Climate Model version 3
CLICOM	Climate Computing Project
CLIVAR	CLIimate VARariability and Predictability
CMAP	Climate Prediction Center Merged Analysis of Precipitation
CRU	Climate Research Unit
CSAG	Climate System Analysis Group
DJF	December January February
DSF	Dry Spell Frequency
ECMWF	European Centre for Medium Range Weather Forecasting
EOF	Empirical Orthogonal Function
ENSO	El Niño Southern Oscillation
ETCCDMI	WMO/CLIVAR Expert Team on Climate Change Detection, Monitoring and Indices
ERA-15	ECMWF 15-year Reanalysis data
ERA-40	ECMWF 40-year Reanalysis data
FFT	Fast Fourier Transform
FAO	Food Agriculture Organization
GCM	Global Climate Model/ General Circulation Model
GCOS	Global Climate Observing System
GHGs	Greenhouse Gases
GLCC	Global Land Cover Characterization

GTS	Global Telecommunications Systems
GSN	GCOS Surface Network
HIRS	High Resolution Infrared Sounder
ITCZ	Inter-Tropical Convergence Zone
ICTP	International Centre of Theoretical Physics
LS	Lesotho
MM5	Mesoscale Model version 5
MSLP	Mean Sea-Level Pressure
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NE	Northeast
NHST	Null Hypothesis Significant Testing
NOAA	National Ocean and Atmospheric Administration
OND	October November December
P-E	Precipitation to Evaporation
PBL	Planetary Boundary Layer
PCA	Principal Component Analysis
PRECIS	Providing Regional Climates for Impacts Studies
QBO	Quasi-Biennial Oscillation
QC	Quality Control
RCM	Regional Climate Model
RegCM3	Regional Climate Model version 3
SARCOF	Southern Africa Climate Outlook Forum
SAO	South Atlantic Ocean
SE	Southeast
SIO	South Indian Ocean
SOI	Southern Oscillation Index
SOM	Self-Organised Maps
SST	Sea Surface Temperature
SSTA	Sea Surface Temperature Anomaly
SUBEX	SUB-grid EXplicit moisture scheme

SWIO	Southwest Indian Ocean
SWZ	Swaziland
TC	Tropical Cyclone
TTT	T tropical Temperate Trough
UK	United Kingdom
US	United States of Ameirca
WMO	World Meteorological Organization
ZMS	Zimbabwe Meteorological Services