Variability and long-term trends of climate extremes over the Limpopo, South Africa

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Declaration

I, Thendo Sikhwari, hereby declare that the dissertation for the Master of Environmental Sciences (Geography) degree at the University of Venda, hereby submitted by me, has not previously been submitted for a degree at this or any other university, and that it is my own work in design and execution and that all reference material contained therein has been duly acknowledged.

Signature……………………… Date……………………………..

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I would like to thank God for being my guide and providing me with the strength, ability and health I needed to complete this research project. He was my pillar of strength and my daily dose of encouragement. I would also like to extend my gratitude to my supervisors: Dr N.S Nethengwe, Dr H. Chikoore and Dr C. Sigauke for their invaluable motivation, input, support, and encouragement throughout the duration of this study and preparation of this project.

Several data sources are recognized for making this study possible. South African Weather Service provided rainfall data while other climatological data were obtained from the National Centers for Environmental Prediction (NCEP). The Southern Oscillation Index (SOI) and Temperature from National Oceanic-Atmospheric Administration (NOAA) Climate Prediction Center (CPC) were obtained via Royal Netherlands Meteorological Institute (KNMI) Climate Explorer. This study was supported by a generous funding from the National Research Foundation (NRF).

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NRF
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Abstract

Climate change has a crucial impact on livelihoods, economy, and water resources due to the occurrence of weather and climate extreme events such as floods, droughts and heat waves. Extreme weather has been increasing worldwide, hence the need to understand their nature and trends. The aim of this study was to analyse the spatial variability and long-term trends of climate extremes over the Limpopo in South Africa from 1960 to 2014. Rainfall, temperature, and circulation fields were analysed to understand the extent, nature of climate extremes over the Limpopo. Extreme value theory (EVT) is a powerful method that was also employed in this study to provide statistical models for events rarely observed. R statistical software was used for clustering analysis which has a variety of functions for cluster analysis. Any station whose value is larger than 95th for any day of the season was considered as a widespread extreme event. The results show that the study area is highly vulnerable to extreme events due to its latitudinal location and low altitude. Anomalous cut-off lows, tropical cyclones and tropical storms are the major extreme producing systems affecting the Limpopo province whilst the Botswana High becomes dominant during heat waves and drought. Extreme weather events are common in Limpopo during summertime and often coincide with mature phases of the El Nino Southern Oscillation. In this study, after the suitable model for data was chosen, the interest was in deriving return levels of extreme maximum rainfall. The computed data for return levels predicted that the 5-year return period’s return level is approximately 223.89 mm, which suggests that rainfall of 223.89 mm or more per month should occur at that station or location on the average of once every five years.

Key words: Droughts, Extreme events, Extreme Value Theory, Floods, Heat waves,

Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

COLs	Cut-off lows
CSIR	Council for Scientific and Industrial Research
DJF	December-January-February
ENSO	El Niño-Southern Oscillation
EVT	Extreme Value Theory
GEV	Generalised Extreme Value
GEVD	Generalised Extreme Value Distribution
GPCP	Global Precipitation Climatology Project
hPa	Hectopascal
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
JJA	June-July-August
RNMI	Royal Netherlands Meteorological Institute
MAM	March-April-May
MLE	Maximum Likelihood Estimation
NASA	National Aeronautics and Space Administration
NCEP/NCAR	National Centres for Environmental Prediction-National Centre for Atmospheric Research
NOAA	National Oceanic-Atmospheric Administration
OND	October-November-December
OLR	Outgoing longwave radiation
QBO	Quasi Biennial Oscillation
SAWS	South African Weather Service
SOI	Southern Oscillation Index

SST	Sea surface temperature
TTT	Tropical Temperate Troughs
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

Chapter 1

Introduction

1.1 Background of the study

Southern Africa is a predominantly semi-arid region with a high degree of inter-annual rainfall variability (Washington & Preston, 2006; Tyson, 1986; Mason & Jury, 1997). Climate extremes such as floods, droughts and heat waves have become topical issues since they have triggered most natural disasters in recent decades that can potentially affect humans and the natural environment (Shongwe *et al.,* 2009). The crucial effects of climate change are intensified by high sensitivity of ecological social systems in the region with limited resources to respond properly to these rising threats. The populace around the world are threatened by a wide variability of geographical hazards, including floods, tropical cyclones and drought (Doswell, 2005).

South Africa is recognised as one of the vulnerable countries worldwide in terms of high rate of poverty, limited coping strategies during disasters and a highly variable climate. In southern Africa, more than 90% of natural disasters are related to weather, climate and water. Thus, the region is particularly vulnerable to climate extremes events such as heatwaves, floods and drought, which threaten the lives and livelihoods of rural communities (Doswell, 2003). Climate extreme events (e.g. floods) contribute to an average of USD 4 billion annually in terms of property damage around the world (Wardsworth, 1999).

In February 2000, about 700 people lost their lives and over a million residents were displaced due to flooding which was associated with tropical cyclone Eline (William *et al.*, 2008; Layberry *et al*., 2006). Therefore, climate variability causes risks to lives and livelihoods of the South African society (Hellmuth *et al*., 2007). South Africa has a high vulnerability to extreme climate events due to its geographical location and socio-economic factors. Several tropical cyclones have distressed various countries such as Madagascar, Mozambique and South Africa (Malherbe *et al.,* 2012).

Rainfall is highly variable over southern Africa on several spatio-temporal scales (Mdoka, 2005). Rainfall characteristics are changing, and may persist to change, characterized by severe and recurrent dry spells (Simonovic, 2009). This results in regular and severe water-associated extremes such as floods and drought (Edossa, 2013). Climate extreme events are regular across the globe and have impacts on society in various ways: leading to loss of lives, shortage of food, failure of crops, famine, mass migration and health issues (Masih *et al*., 2014). Some analysis on extreme events have mainly focused on changes in mean values due to unavailability of high quality daily resolution data required for attributing, detecting and monitoring changes in climate extremes (Jones, 1999). Daily climate data are essential for societally-sensitive extremes.

Information gained from historical extreme climate analysis provides a huge possibility for good management, forecasting and mitigation of climate extremes (Serrano *et al*., 2012). A complete science-based analysis of historical floods, heatwaves and droughts, and their sources can improve preparation strategies and building resilience. The majority of rural populations of South Africa are communal or smallholder farmers and their livelihoods depend mostly on rain-fed agriculture or livestock production. The main climate component in southern Africa is rainfall, with economies mainly based on rain-fed agriculture. The regional climate is characterized by wet summers from November to March (Richard *et al.,* 2000).

1.2 Problem statement and motivation

The Limpopo Lowveld is a semi-arid region which is predominantly rural and with limited capacity to cope with natural hazards and subsequent disasters. The lowveld is highly vulnerable to extreme climate events as the region exhibits a high coefficient of rainfall variability (Maposa *et al.,* 2014). Extreme climate events have been increasing in South Africa. Whilst it is complex to quantify variability and long-term trends and their impacts, climate extremes are known to cause human mortality affecting livelihoods and causing widespread damage to property and infrastructure as well as destruction of fauna and flora.

Socio-economic activities including agricultural production and tourism are also significantly affected by climate extremes. The Kruger National Park is a major tourist attraction in the Limpopo and often loses wildlife and revenue from tourists due to such climate extremes as droughts and floods. These extreme events also result in the transmission and spread of respiratory, diarrheal and malaria diseases to humans.

Malaria is endemic to the Limpopo and peaks in malaria outbreaks and epidemics often follow flood events. During drought, there is an increased risk for wildfires and dust storms. Particulate matter suspended in the air from these events can irritate the bronchial passages and lungs.

1.3 Research aim and specific objectives

The main aim of the study was to analyse the spatial variability and long-term trends of climate extremes over the Limpopo Lowveld from 1960 to 2014.

The specific objectives of the study were to:

I. identify and analyse trends of extreme weather and climate events over the study area;
II. determine the dominant weather systems and remote phenomena associated with extreme events;
III. examine the link between extreme events and the tropical ocean hotspots; and
IV. employ Extreme Value Theory to model future climate extreme events in Limpopo.

1.4 Research questions

I. Where have major changes of extreme weather and climate events occurred over the period from 1960-2014?
II. What are the dominant weather systems and their associated remote phenomena in the study area?
III. What is the relationship between observed extreme events and tropical ocean hotspots? and
IV. To what extent can Extreme Value Theory model future climatic extreme events in Limpopo?

1.5 Justification of the study

Extreme climate events including droughts, floods and heat waves are expected to increase in South Africa (IPCC, 2007). The aim of this study is to increase knowledge on variability and long-term trends of climate extremes over the Limpopo Lowveld.

There are many impacts associated with climate change that would lead to crucial changes in climate extremes events, biodiversity, human mortality, freshwater resources and food production. Climate extremes have a crucial impact on livelihoods, infrastructure destruction and loss of lives. Therefore, it is important to determine, analyse and quantify those impacts. The effects of weather shocks in the form of floods, drought and heatwaves have crucial impacts on the environment, health sector, economy and the ecosystem (Matebane, 2011). An understanding of the occurrence of extreme climate events will help in the preparation and formulation of mitigation strategies to cope with events associated with climate change.

1.6 Description of the study area

South Africa is a semi-arid country, receiving about 464 mm of rainfall on average yearly, compared to about 860 mm of rainfall world average. South Africa receives rainfall in winter and summer seasons, especially the western part which includes the Western Cape Province. The study area is Limpopo province which is located on the north east part of South Africa which neighbors Zimbabwe, Mozambique and Botswana. The province falls within a summer-rainfall region (October to March) and thunderstorms are common during the day. During winter (May to August), nights are cold and mostly frost-free, with chilly mornings and dry and sunny days. The lowveld (eastern part) can be very hot in summer.

The southern part of Limpopo lies on the African plateau whilst the north eastern Lowveld is well below 1000m in the Limpopo River valley (see Figure 1.2). The elevated interior, the low-altitude coastal plain and mountain systems are the three basic landforms of southern Africa. The terrain enhances rainfall by causing orographic uplift of warm moist air.

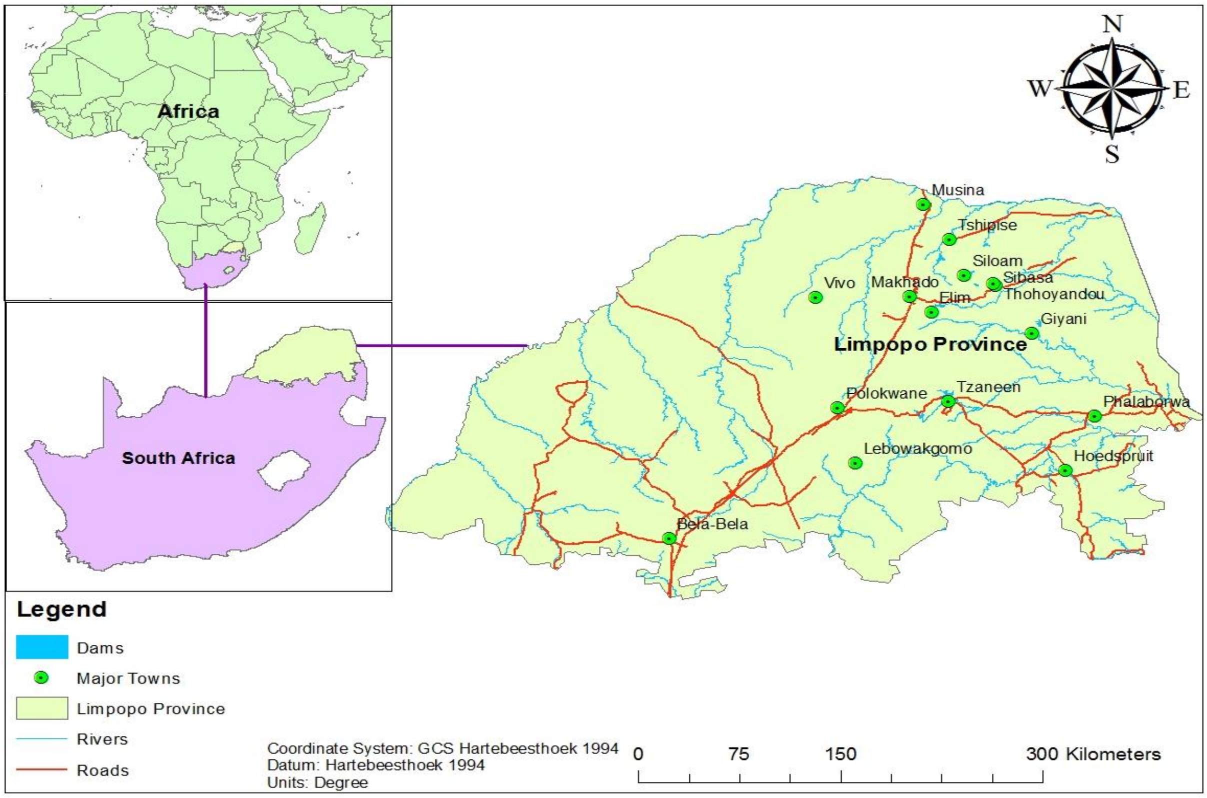


Figure 1.1 Study area map of Limpopo Province

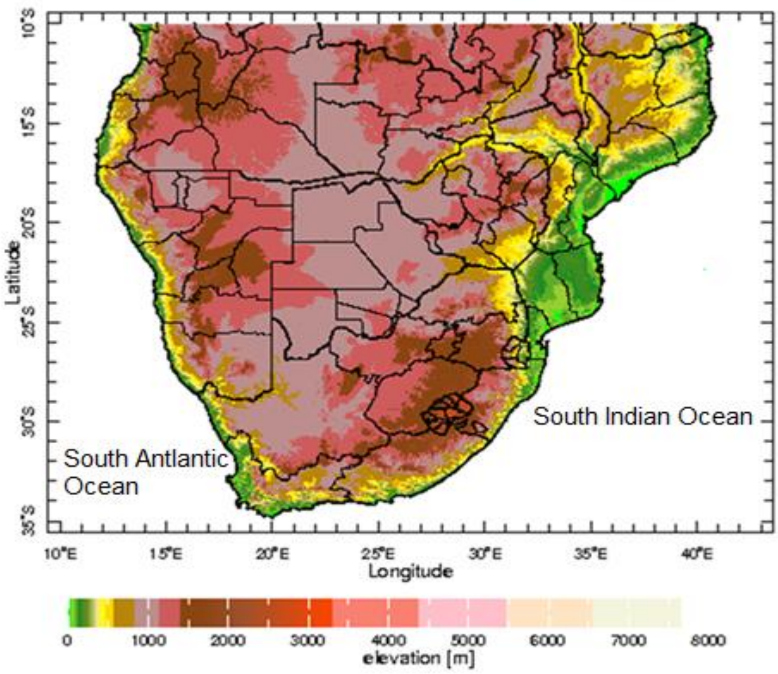


Figure 1.2: Elevation over southern Africa

1.7 Definition of key terms

- *Climate*

  Climate refers to statistical average weather over a period of 30 years in a particular area (IPCC, 2012a).

- *Climate extreme*

  Climate extremes are defined as events that take longer periods over a particular environment and their timescales vary with extreme weather events (IPCC, 2011).

- *Climate variability*

  Climate variability is defined as the deviations in the mean state and statistics such as standard deviation and the occurrence of extremes (UNISDR, 2009).

- *Drought*

  Drought is the scarcity or lack of precipitation over a long period of time and its effects on people rely on its severity and period (Rouault & Richard, 2003).

- *Flood*

  Flood is the overflowing of the normal confines of a river or other body of water, or the accumulation of water over areas not normally submerged (Ward, 1978).

1.9 Dissertation structure

The study consists of six chapters. Chapter 1 has provided the introduction, background, problem statement, aim, specific objectives and justification of the research. The description of the study area is also done in this section.

Chapter 2 provides literature review which is relevant to this study, and the literature review presents weather systems inducing extreme events, causes and their impacts. Application of extreme value theory is also provided in this chapter. Extreme heat wave events and their impacts on livelihood are also presented in the chapter.

Chapter 3: The datasets used in this work are described in detail, together with the methods and approaches used to analyse them. The chapter also presents different sources of the data employed and methods of analysis applied to achieve the objectives outlined in the first chapter. Rainfall data which is a major dataset of this study was obtained from South African Weather Service station observations. This chapter also provides the methods involved in obtaining the data.

Chapter 4: Rainfall variability over the study area such as mean spatial patterns, annual cycle of rainfall and inter-annual rainfall variability are presented in this chapter. Local drivers of climate extreme in Limpopo, South Africa, are also discussed here. Trends of climate extremes, their frequency and duration are discussed in this chapter. Seasonal variability of climate extremes is also discussed here. The influence of oceans on extreme events such tropical Pacific and tropical Atlantic is presented in this chapter.

Chapter 5: Detailed application of Extreme Value Theory is provided in this chapter focusing mainly on the block maxima approach. Maximum annual rainfall analysis is presented in this chapter from 1960-2014 over Limpopo province, South Africa for Thabazimbi, Pietersburg and Tsianda stations. Long term trends of maximum rainfall, and return levels are also provided in this chapter. The generalized extreme value distribution which is a flexible family distribution which include classes of distributions such as Frechet, Gumbel and Weibull are also discussed in the chapter.

Chapter 6 provides discussion and general conclusions of the study. Summary of key findings are also presented here. Finally, the chapter provides recommendations for further studies to analyse climate extreme events for the improvement of the quality of results and continue to protect property and save more lives.

Chapter 2

Literature Review

2.1 Introduction

The aim of this chapter is to conduct a literature survey and synthesize application of long-term trends of climate extremes, their extent and nature over Limpopo, South Africa. This chapter also seeks to provide an understanding of variability, trends, meteorological structure and impacts of climate extremes. Several studies (e.g. Meehl & Tebaldi 2004; Cowan *et al.* 2014) suggest that extreme events are projected to last longer, become more frequent and more intense on a global scale. Climate extremes are often threatening water resources management and food systems in several regions globally. Understanding historical nature of climate extremes over Limpopo, South Africa, can assist in formulating mitigation strategies which seek to minimize the negative impacts resulting from these events in the region.

2.2 Climate extremes in a changing climate

Climate extreme is an aggregate term encompassing both 'climate extreme' and 'extreme weather' events. In this study, climate extreme is defined as the occurrence of weather or climate variable exceeding (or below) a threshold value near the upper (or lower) ends of the extent of observed values of the variable within a certain climate period. There are various definitions of climate extreme events such as extreme monthly rainfall amounts and large areas experiencing unusual storm events such as tropical cyclones or warm monthly temperatures (Easterling, 2000). In southern Africa, floods and drought are expected to increase and occur more regularly in a warmer future climate (IPCC, 2013). These events have crucial impacts on health, social life, food intake and economy for poor people in South Africa. Human activities such as burning of fossil fuel, land-use changes or excess demand for water could intensify climate extremes controlled by normal variability and could result in frequent drought occurrence (Sheffield & Wood, 2008; Glantz *et al.,* 1997).

2.3 Drought

Drought is the scarcity or lack of precipitation over a long period of time and its effects on people rely on its severity and period (Rouault & Richard, 2003). There is no universal definition of drought as several definitions exist in the literature (Kim *et al*., 2002), but several studies (e.g. Mckee *et al.,*1993; vanZyl, 2006; Sheffield and Wood, 2007) suggest that droughts are associated with declines in water supply and soil moisture compared to the normal conditions that the environment sustains. Hydrological variables such as channel runoff, soil moisture, groundwater volume, basin volume and meteorological variables such as precipitation and evaporation are common indicators of droughts (Shahid, 2007).

Drought may be classified into such different categories as meteorological, agricultural and hydrological droughts (WMO, 2012). Drought classification can be done by using the following definitions: meteorological (anomaly short-term dryness from normal precipitation); hydrological (associated with abnormal water resources); agricultural (abnormal soil moisture conditions) (UNEP, 2012). In southern Africa, drought could occur for several years in one region, for example, droughts of the 1960s, 1980s and 1990s (Hayes *et al*., 2012). In tropical and subtropical regions, the intensity of drought and duration has gradually increased since the 1970s (IPCC, 2007). Duration is one of the important features of drought. About two to three months are required for the establishment of drought, however, droughts can last for long periods. The extent of drought is linked to the onset of the rainfall or precipitation in that region.

Prolonged drought periods have a major effect on the society particularly depending on subsistence farming. According to WMO (2006), nearly all climatic regions have experienced drought and it is categorised as one of the main environmental hazards damaging the environment and the economy of various countries widely. Damages of drought are well-marked in regions where livelihoods are under threat. There is still a gap in understanding the threats related to extreme drought events, so it is challenging for the drought management to move from crisis to risk management to make significant change (Palchaudhuri & Biswas, 2013). Drought is caused by shortage of precipitation over a prolonged period in a particular environment.

Droughts originate from absence of precipitation over large areas and periods. Meteorological drought has a crucial effect on hydrology and agriculture. Droughts cause more damage on water resources and food production. The effects of drought are intensified by the climatological features such as atmospheric moisture, temperature and wind.

Extreme drought events are also caused by large-scale or regional spatio-temporal anomalies in the climate system (Tallaksen *et al.,* 2011). In addition, slow development enables land-atmosphere feedbacks that might intensify and enlarge the area affected by drought (Seneviratne *et al.,* 2006). Projection of drought has been frequently based on a limited regional climate models (RCMs), emission scenarios and General Circulation Models (GCMs) (Yu, 2013). Changes in drought using great ensemble simulations under disturbed climate have been measured by few studies, for example (Burke, 2011).

2.4 Heat waves

The availability of high quality climate and weather data in southern Africa gives an opportunity to develop a good understanding of the hazards caused by high temperatures. Globally, heat waves can claim more lives than any natural hazard including tropical cyclone, floods and bush fires. In Limpopo province, the occurrence of heat waves is one of the most common natural hazards.

Heat waves may be defined as periods of unusual or exceptional hot weather in a particular environment. Although heat waves are meteorological events, they cannot be assessed without reference to human impacts. There is no agreed definition of heat waves, therefore such events can occur for several days or more with temperatures sufficiently enough above normal resulting in increased human mortality rate (Robinson, 2001). These extreme events typically occur in summer in South Africa, although they are less in spring and early autumn. The impact and characteristics of a heat wave vary considerably from region to region. Greenhouse effects create problems in determining characteristics of heat waves (Hunt, 2006). The most commonly experienced types of heat waves are those that occur over a number of consecutive days (e.g Khaliq *et al.,* 2005; Huth *et al.,* 2000 & Burt, 2004).

Soil moisture is a key contributor to the relationship between heat wave occurrences and droughts (Mbokodo, 2017; Albright *et al.,* 2010). Negative soil moisture anomalies are associated with droughts (Trenberth & Shea 2005). The negative soil moisture anomalies increase Bowen ratio, resulting in hotter land surfaces which then increase atmospheric temperatures (Fischer *et al.,* 2007). As a direct result of the joint occurrence between heat waves and droughts, there are negative anomalies of soil moisture reducing surface evaporation (Hunt, 2007), but increases the atmospheric demand.

Droughts can also occur during extremely cold periods, even though it is not usual (Trenberth & Shea, 2005). However, there are cases where heat waves and droughts do not coincide. Heat waves can also be observed during either normal or above-normal rainfall (Gershunov *et al.,* 2009).

2.5 Floods

Floods are catastrophic events which claim more human lives than other natural disasters (Drogue *et al.,* 2004). A flood may be defined as the increase of water in rivers and streams which lead to overflowing of the usual limits of a river (Ward, 1978). Extreme floods events were rare in South Africa, but the rate of occurrence of floods has been increasing every year, which has resulted in loss of human lives, damage to properties and infrastructure as well as the destruction of the natural environment. The communities are threatened by a wide variability of geographical hazards including floods, tropical cyclone and drought (Doswell, 2005). A prolonged period of precipitation is the most common cause of flooding globally. The areas that are often affected by floods are those situated in low lying parts of hydrological floods plains (Mwape, 2009). The vulnerable areas for floods are low-lying parts of flood plans, low-lying coasts and deltas (Mwape, 2009). Extreme floods events over South Africa can be caused by various phenomena.

Extreme floods that occurred in the year 2000/2001 were related to La Nina event which was more severe than any floods over southern Africa (Reason & Keibel, 2004). Rainfall in South Africa is influenced by various weather systems that originate from tropics and subtropics as well as from the mid-latitudes to south of the subcontinent (Raesetje 2005; Joubert 1998; Hobbs *et al.,* 1998; Tyson & Preston-Whyte, 2000). The interactions between weather systems are the source of summer rainfall background environment within which extreme events may evolve.

The East African region, including Tanzania, Kenya, and the White Nile basin experiences long precipitation from March to May, often wetter than normal conditions. In 1995, and leading up to 2009, El Niño was the major factor triggering floods in East Africa. In essence, El Nino triggers floods in East Africa and drought in southern Africa.

However, floods can occur in the absence of La Nina (Manatsa *et al.,* 2008), suggesting that there are other phenomena that trigger floods.

2.5.1 Riverine Flooding

Riverine flooding occurs when surface water enters the streams and rivers and exceeds the capacity of the natural or constructed channels to accommodate the flow, water overflows the stream banks, spilling out into adjacent low-lying areas (Matebane, 2011). This results in riverine flooding. Flood magnitude is determined by the amount of rainfall that has fallen in the catchment, its duration and its spatial distribution.

Between 1996 and 2005, there were 290 flood-disasters in Africa alone, which left 8,183 people dead and 23 million people affected, and caused economic losses of $1.9 billion (Musungu *et al.,* 2014). Studies on the changing weather patterns in South Africa predict increased intensity of extreme rainfall events (Mason *et al.,* 1999), which is one of the causes of riverine flooding. Communities are still exposed and vulnerable to floods hazards.

2.5.2 Ground Failure

Ground failure affects the community socially, economically as people stay in areas which are not surveyed or approved to be settled. Ground failure can lower the ground surface, thereby causing or increasing flood damage in areas of high ground water levels, areas that are shallowly underlain up to 100m (meters) by dolomite (Matebane, 2011.; CGS, 2007). Ground failure can result in several types of flooding and soil erosion. Sinking and dissolution of soil may result in immediate flooding in some areas (National Weather Services, 2005). Ground failure is the cause of both human activities and natural processes.

Natural causes incorporate solution (karsts topography), consolidation of subsurface materials (such as wetlands soils), and movements in the earth's crust. Human activities which trigger the natural processes steering to subsidence include mining, inadequate compaction of fill material during construction, and withdrawal of oil or water from subsurface deposits (Matebane, 2005). On 22 February 2000, Limpopo residents in Vhembe District areas around Nzhelele, Muledane, Nesengani, Musina and Sinthumule experienced a ground failure which tends to damage infrastructures and agricultural plantation. However, these types of extreme events do not occur all seasons (SAWS, 2011). Ground failure due to subsidence can result in increased flood damages for two main reasons (Matebane, 2011). If the land surface is lowered, it may be more frequently (or more deeply) flooded. In addition, subsidence can block drainage ways, heading to deeper or unexpected flooding. The increase in damage can be related to the rise in population and construction of roads, passes, railways and housing developments.

2.5.3 Flash floods

The most frequent cause of flash flooding is slow-moving thunderstorms. The high rate of flash flood is expected to occur in urban areas where plants have been cleared, with paved environment and poor drainage systems (Matebane, 2011). Flash floods can be essential more than ordinary riverine floods because of the speed with which flooding occurs, the high speed of water and debris load. Flash floods occur in a very short time as a result of storm (Norbiato, 2008). Flash floods are fuelled by heavy rainfall events (Loczy, 2012). Extreme flash flood events that occur in the Limpopo Lowveld are most common in steep sloping valleys in mountainous areas, but can also occur along rivers in urban environments.

2.6 Weather systems inducing floods

2.6.1 Cut-off lows

Extreme rainfall is the primary cause of floods even though there are many natural triggers. Communities are vulnerable to the effects of climate extremes such as flooding. Different studies suggest that there have been various cases of extreme rainfall events related to cut-off lows over South Africa (Singleton & Reason, 2007). Cut-off lows tend to result in persistent heavy rainfall since the cold air aloft promotes deep convection. Cut-off lows also bring a range of extreme weather events, including winds, and extreme cold conditions on the mountainous areas and torrential rainfall. Cut-off lows are one of the main drivers of damaging floods in South Africa and can also trigger thunderstorms (SAWDOS, 2012).

Over subtropical southern Africa, the most common month for cut-off lows is April although other months such as March, and May also show high occurrence (Tyson & Preston-Whyte, 2000; Singleton & Reason, 2007; Ndarana & Waugh, 2010). Conversely, some of the strongest and most catastrophic events occurred during December and February although frequency of occurrence is least during these months (Tyson & Preston-Whyte, 2000; Singleton & Reason, 2007; Ndarana & Waugh, 2010). Cut-off lows are easily recognized in isobaric maps as geo-potential contours with a cold core, due to the fact that air within its origin at a higher latitude. Cut-off lows are linked with several forecasting problems, essentially to various characteristics of the terrain and to the presence or absence of Warm Ocean that allows/hinders convection. Globally, it is known that COLs are responsible for extreme rainfall events (Molekwa, 2013; Muller et al., 2007; Zhao & Son, 2007).

The anti-cyclone ridges eastward along the coast promoting upslope flow, low level convergence encouraged by strong heat lows and upper level divergence provided by westerly waves propagating into the subtropics (Hart, 2012; Mason & Jury, 1997). A ridging anti-cyclone associated with a westerly wave frequently produces widespread heavy rainfall over the eastern parts of southern Africa (Tyson & Preston-Whyte, 2000). This is due to the strong advection of moist unstable air from the Indian Ocean over land which is promoted by the steep pressure gradient at the surface of the Indian Ocean and adjacent inland areas (Mason & Jury, 1997; Tyson & Preston-Whyte, 2000).

Over subtropical southern Africa, the most common month for COLs is April though other months such as MMJ also show high occurrence. Conversely, some of the strongest and most catastrophic events occurred during December and February although frequency of occurrence is least during these months (Tyson & Preston-Whyte, 2000; Singleton & Reason, 2007; Ndarana & Waugh, 2010). Also, a semi-annual cycle in COLs frequencies with relative peaks in March to May and September to October appears to be evident (Tyson & Preston-Whyte 2000; Singleton & Reason, 2007). Preston –Whyte and Tyson (1988) define a cut-off low as a feature that is defined by cold core of depression formed by westerly trough which starts in the upper westerlies as a trough and depends on a closed circulation that extends downwards to the surface (Figure 2.1).

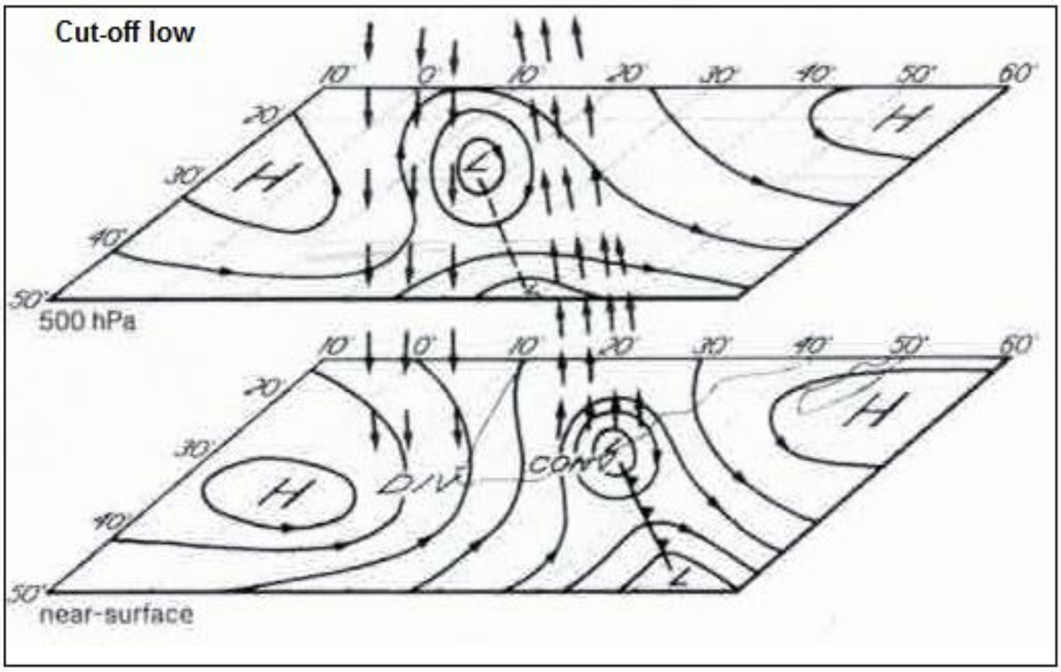


Figure 2.1: Cut-off low at 500hPa and the near-surface circulation as well as vertical flow (Source: Preston-Whyte & Tyson, 1988).

2.6.2 Tropical cyclones

The Limpopo River basin experiences rainfall which is more than 85% during summertime in the eastern interior part of the basin (Malherbe *et al.,* 2012). According to Mavume (2008), the south West Indian Ocean and the Mozambique Channel TCs are major hazards to the central and northern coasts. The high incidence of flooding is caused by tropical cyclones that are formed in the Mozambique Channel. Tropical cyclones generally develop only over seawater surface temperature which is greater than 26°C (Narita *et al.,* 2008). Tropical cyclone activity occurs most during summertime in the Southwest Indian Ocean from November to April (Holland, 1993).

Approximately 80% of all tropical cyclones form in or just pole ward of the inter Tropical Convergence Zone (ITCZ) monsoon trough (Gray, 1968). Several tropical cyclones which hit South Africa, Mozambique and Madagascar such as tropical cyclone Dera, and Favio have affected various countries (Malherbe *et al.,* 2012). The frequency with which floods occur is on the increase in many regions of the world (Drogue *et al.,* 2004). From a number of studies conducted and undertaken within the field of natural hazard, it is apparent that extreme flood events have become the most considered natural hazards which are destructive in nature and their intensity have increased.

2.6.3 Cloud bands

Tropical temperate troughs (TTTs) are regarded as the primary rainfall producing system over subtropical southern Africa (Hart et al., 2013; Washington & Preston, 2006). Tyson and Preston-Whyte (2000) argue that the ideal conditions for the development of upward vertical motion and the formation of extended cloud bands that link tropical and middle latitudes over southern Africa are an appropriate conjunction of a tropical disturbance in a form of an easterly wave or low. Generally, the bands line up from north west to south east across subtropical southern Africa, these events typically involve the export of moisture and heat from the tropics pole ward (Hart *et al.*, 2012). Usman and Reason (2004) maintain that in some seasons, when the tropical source is over the eastern margins of the subcontinent or even Madagascar, the tropical temperate trough tend to be located further east, then significantly reduce rainfall over most of southern Africa under such conditions. Clouds bands may produce heavy rainfall if there are slow propagating.

2.7 Ocean-Atmosphere Interactions

2.7.1 El Nino Southern Oscillation

The dominant source phenomenon of inter-annual climate variability around the globe is the El Niño Southern Oscillation (ENSO) (Raesetje, 2005). During an ENSO event, the Southern Oscillation is retained as warm sea surface temperature (SST) anomalies occur in the central tropical and eastern Pacific Ocean. Mostly, when pressure is high over the Pacific Ocean, it tends to be low in the eastern Indian Ocean and vice versa (Allan *et al*., 1996). El Niño and a deviation in the South Oscillation often occur jointly, but may also happen independently (Raesetje, 2005). Rainfall variability of a region can be influenced by the variation in SSTs of the oceans (i.e. the Indian Ocean, Atlantic Ocean and Pacific Ocean). In general, the Pacific Ocean and South Atlantic Ocean basins have been identified as regions responsible for the variation in rainfall. Various studies about the Pacific Ocean suggest that the equatorial Pacific Ocean seems to have larger effect on climate and weather of southern Africa, particularly rainfall which is by far the most important meteorological parameter.

Richards *et al.* (2000) conducted a study about the relationship between rainfall variability over southern Africa and ENSO. Monthly rainfall data were used from about 149 stations (rain gauge) from 1949 to 1988 in various regions: Namibia, Zimbabwe and South Africa and these are countries within southern Africa. The study shows that the southern oscillation index (SOI) between January and March is weak and accounts for less than 10% of year-to-year rainfall variability over southern Africa. El Niño events are more frequent than La Niña events and that recent ENSO events are embedded in different global scales climate conditions (Richards *et al.*, 2000).

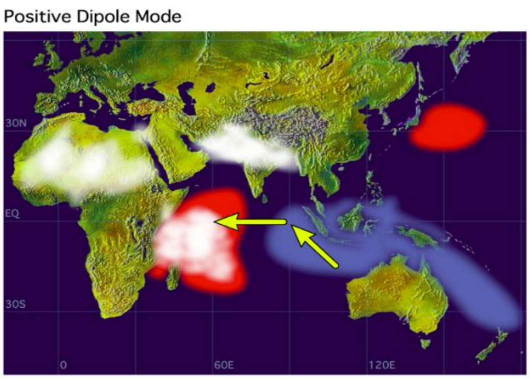
The eastern Africa rainfall variability is driven by the Indian Ocean shifting the native Walker circulation (Dutra *et al*., 2013). In most cases, rainfall over the eastern part of South Africa decreases during El Niño seasons (Nicholson & Kim, 1997; Phillips *et al.,* 1998). In southern Africa, the occurrence of droughts usually coincides with El Nino years (Rouault & Richard, 2005). In addition to a warm ENSO phase, droughts over the area may also be influenced by various local and global factors such as SSTs, negative Indian Ocean Dipole (IOD) (Ngomane, 2014). Some of the extreme events may be due to drought.

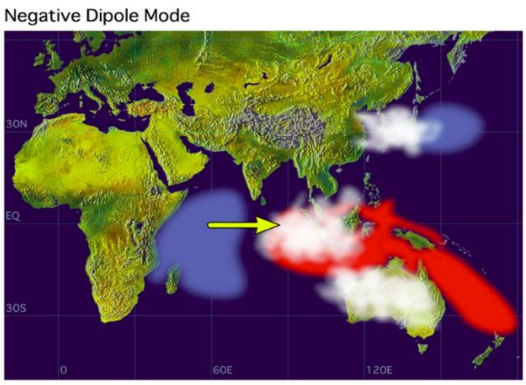
ENSO, SSTs in the Indian Ocean, and land-atmospheric feedback are the main factors governing the variability of precipitation in the African continent. Regarding the ENSO phenomenon, it has been found that the SSTs in the Indian Ocean and tropical Atlantic have a significant influence on rainfall over southern Africa (Reason & Mulenga 1999). In 1970-1988, El Niño was the major feature for drought occurrences in southern Africa (Masih *et al.,* 2014). Drought of the year 1925/26 occurred in the absence of El Niño (Manatsa *et al.,* 2008), proving that there are other phenomena triggering droughts, therefore, El Niño on its own is not suitable for drought prediction in southern Africa.

2.7.2 Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon which behaves like ENSO in the Indian Ocean (McIntosh *et al*., 2007). Similarly to ENSO, the tropical Indian Ocean Dipole (IOD) influences the climate of several regions in the world through the walker circulation though it develops in the Indian Ocean (Yamagata *et al*., 2004; Ashok *et al*., 2007). An important mechanism that plays a vital role in the formation of IOD is a wind evaporation-SST feedback that exists over the southeast tropical Indian Ocean. This occurrence is considered as another air-sea coupled process, enhancing the growth of IOD (Hilary *et al.* 2005). The dipole is one of the most dominant modes of inter-annual variability in the Indian Ocean sea surface temperatures (Saji, 2005; Hong *et al.,* 2008; Mahala *et al*., 2015). The dipole in sea surface temperatures in the tropical Indian Ocean is primarily caused by the change in wind direction (Lan, 2013).

Hong *et al*., (2008) suggest that approximately 40% of IOD events occur with ENSO, La Nina associated with the negative IOD while El Niño is associated with the positive IOD, for example, the 1997 strong El Niño, though Ashok et al., (2003) regarded it as a coincidence. Consequently, there are some years when the El Niño co-occurs with the negative IOD. Saji *et al*. (1999) discovered that the dipole mode accounts for about 12% of the sea surface temperatures in the Indian Ocean during its active years. The negative IOD event intensifies extreme TC activities as does during La Nina (Currie *et al.,* 2013; Mahala *et al.,* 2015). The positive IOD event results in decreased rainfall over the eastern Indian Ocean which results in extreme drought (Ashok *et al.,* 2007). The SST anomalies (Figure 2.2) are shaded (red colour is for warm anomalies and blue is for cold). During the IOD events, the white patches indicate increased convective activities and arrows indicate anomalous wind directions.





a) b)

Figure 2.2a) Schematic of positive IOD event and b) Schematic of negative IOD event (JAMSTEC, 2015).

2.8 Other Climate modes

2.8.1 Quasi-Biennial Oscillation

The Quasi-Biennial Oscillation (QBO) has been found to influence climate variability in various regions over the tropics and subtropics. QBO is a quasi-periodic oscillation of equatorial zonal wind between easterlies and easterlies in the tropical stratosphere with a mean period of 28 to 29 months. QBO is known to affect the temperature field and the transport of atmospheric constituents such as water vapour, aerosols, ozone, N2O, and CH4 (Gray & Dunkerton, 1990; Lait *et al.,* 1989, Zawodny & McCormick, 1991; Trepte & Hitchman, 1992; Randel *et al.,* 1998).

The QBO circulation requires that a westerlies' shear zone be accompanied by a warm temperature anomaly created by convergence aloft, subsidence and warming at the equator. A study conducted by Huesmann and Hitchman (2001) shows that QBO affects tropical convection by modulating the cloud top environment (Collimore *et al.,* 1998). In southern Africa, the El Nino Southern Oscillation appears to be modulated by the Quasi-Biennial Oscillation (Mason & Tyson 1992, Richard *et al.,* 2000; Lindesay, 1988).

2.8.2 Southern Annular Mode

The Southern Annular Mode (SAM) or the Antarctic Oscillation (AAO) is a mode of variability in the circulation where pressure anomalies over the Antarctica are opposite to pressure anomalies in the region of the coast from 40-50ºS (Reason, 2005). The SAM was found to be linked to wettest and driest winter over the Western Cape. Reason (2005) found the SAM to shift low level moisture flux, vorticity and convergence fields and also the location of the upper subtropical jet. The SAM has also been found to correlate positivity with rainfall in some subtropical locations of southern Africa including the Limpopo (Malherbe *et al.,* 2014).

2.9 Impacts of climate extremes

Climate extremes can have devastating consequences which can affect the society and all living things on the environment. In the extreme floods that occurred between 1967 and 2003, about 18 floods were recorded, killing at least 570 people, rendering 130, 000 homeless, and affecting a total of 1.8 million. In developing countries, floods cause a multiplicity of both negative and positive impacts to economies relying on rain-fed agriculture and physical infrastructure. Climate extreme events link to different issues related to human livelihood. They have significant negative impacts on health, water quality, energy demand, infrastructure performance, agriculture and economy (Zou *et al.,* 2015).

One extreme event can affect a considerable number of people, as it was the case in Australia where about one million people were affected in some way by one heat wave event in 2009 (Kiem *et al.,* 2010). The negative impact from this climate extreme include casualties due to high heat stress, and power cuts resulting in huge amount of financial losses and public transport (Kiem *et al.,* 2010). Factors which may play an important role in the mitigation of climate extremes related impact include policies and plans, building design, and cultural change (Kiem *et al.,* 2010). However, a detailed understanding of climate extremes characteristics is required first. The subsections below provide an insight of climate extreme impacts on agriculture, human health, and economy.

2.9.1 Agriculture

In the agriculture sector, floods can remove top fertile soil which affects agricultural production (Merz *et al.;* 2010). An imbalance in terms of floods damage may cause the Limpopo farmers to suffer with their agricultural production. This may also affect the economy of the country as South Africa depends on primary production. Extreme flooding has significant financial crucial implications for individuals, businesses, local communities, and regions. It is not easy to mitigate all floods, but to reduce the effects of floods. The vast majority of African countries depend on subsistence agriculture for survival (Ruth & Ruth, 2013). Agriculture is a backbone for most African countries (Hussein *et al.,* 2008), and between 70 and 90% of Africa people are employed in this sector (FAO, 2007). The agricultural sector is highly affected by climate extremes and climate variability (Thornton *et al.,* 2007; Easterling *et al.,* 2007).

Climate extreme events such as heat waves are projected to increase in the warming climate (Cubasch *et al.,* 2013), and this can minimize crop production since it is known that environmental factors such as temperature and soil moisture are determinant factors of yields (Waggoner, 1983). Changes of short-term temperature extremes such as heat waves can be critical and can drastically reduce agricultural production in most regions across the country (Wheeler *et al.,* 2000). However, establishing a relationship between agricultural production and climate change is very complicated because there are other non-climate factors such as change in livestock, overgrazing and migration (Rust & Rust 2013) which also influence agricultural changes.

The volume of water in streams or rivers, lakes, and dam increases and results in stress to water catchment. Floods trigger some industries to close or relocate to regions which are not prone to floods events (World Bank, 2000). Climate change also discourages tourism development as it results in catastrophic natural events such as floods and drought (Viner & Agnew, 1999). Tourism is the single largest industry in the world that has become a significant contributing sector of the global economy (South Africa, 1998).

The society's well-being is affected in the beginning of every extreme drought event. The effects of most extreme droughts are deaths of livestocks, failure of crops, famine, and loss of income. Droughts cause some industries to close or relocate to regions with better water supply (Africa-Asia Drought Adaptation Forum, 2011). Drought results in higher costs for supplemental or new development water resource (National Disaster Management Centre, 2006). Extreme droughts may also affect the quality of water in addition to quantity (Tallaksen & van Lanen, 2004).

In developing countries, droughts can trigger diseases, severe famine and loss of human lives (Hayes *et al*., 2012). Droughts of the 1980s and 1990s had wide ranging impacts on economies of southern Africa (Vogel, 2000). High rate of unemployment and retrenchments often led to increased crime levels and poverty (Vogel 2000). Maize yields were significantly reduced during the droughts of the 1980s declining to 10% during 1982 to 1984 (Makarau, 1995). In most circumstances, droughts result in degradation of the environment. This situation or difficulty is more noticeable and is usually observed in cases where the land is not used appropriately.

2.9.2 Environment

Long-term extreme drought events result in reduced streamflow, lower groundwater and dam levels (Tallaksen & van Lanen, 2004). During the 1991/92 drought in southern Africa, about 90% of small dams dried up in Namibia, South Africa, Botswana and Zimbabwe (Jury & Mwafulirwa 2002). The population growth and human activities in rural areas such as overgrazing, drought impacts may lead to environmental degradation and desertification (Msangi 2004; Tallaksen & van Lanen, 2004). This situation or difficulty is more noticeable and is usually observed in cases were the land is not used appropriately. The soils are left and restoration for their production possibility is very expensive (Africa-Asia Drought Adaptation Forum, 2011).

2.9.3 Economy

Climate extreme events such as drought could lead to economic costs and major losses to agricultural production such as the damage to quality crops and reduced crop yield, resulting in income loss for farmers. Productivity of crop land reduced (i.e. long-term loss of organic matter and wind erosion) plant diseases, insect infestation, and increased irrigation costs result in low production. Extreme drought results in higher costs for supplemental or new development water resource (National Disaster Management Centre, 2006). This drives the government to shift economic resources from projects developments to import foodstuff (Africa-Asia Drought Adaptation Forum, 2011).

Availability of water is a crucial problem during drought events, high mortality rate of livestock is observed, and reproduction cycles are disrupted. More veld fires are predominant during droughts. The droughts of the 1980s and 1990s had wide ranging impacts on economies of southern Africa (Vogel, 2000). Unemployment and retrenchments often led to increased crime levels (Vogel, 2000) and social unrest. There are direct and indirect impacts of heat waves to the economy (Zuo *et al.,* 201; Mbokodo, 2017). Extreme heat waves can affect the economy of a region through extensive usage of air conditioners as a mitigation strategy to avoid heat-related diseases resulting from high atmospheric temperatures (Maller & Strengers, 2011).

2.9.4 Human Health

Extreme heat waves affect human health through air pollution (Fischer, 2007). Extreme heat waves have serious effects on human health, often referred to as “silent killer”. In Australia, heat waves have caused more deaths over the past 100 years compared to any other natural event (Steffen *et al.,* 2014). In health services, heat waves increase pressure on service delivery such as ambulance and emergency services, and also hospital admissions (Schaffer *et al.,* 2012; Turner *et al.,* 2013; Xu *et al.,* 2013; Toloo *et al.,* 2014). A typical example is the 1995 heat wave in Chicago which lasted for 3 days and killed 700 people more than the expected number (Karl & Knight 1997). In Health, floods pose serious risks and emerging evidence from around the world show that they can increase human exposure to toxins and pathogens, which may have problems to mental health and disrupt the capacity of health care (McMichael *et al.,* 2000).

2.10 Extreme Value Theory

Extreme value theory (EVT) has been widely used in various fields such as atmospheric science (e.g., Maposa *et al.,* 2014; Buishand, 2008), hydrology (e.g., Katz *et al.,* 2002), finance industry (Embrechs *et al.,* 1997) and many other fields of applications. The observational and statistical modelling results of the above mentioned studies have shown that there are remarkable increases in intensity of precipitation extremes. In the last decades, EVT has been regarded as one of the most quickly developing areas (Li *et al,* 2005). Nicolaus Bernoulli was one the first researchers who studied statistics of extremes in 1709; Bernoulli answered the question: if n men of equal age die within t years, what is the mean duration of life of the last survivor? A rigorous mathematical framework provided by L. de Hann in 1970 played a crucial role in EVT, a theory of regular variation.

On the subject of EVT, there are various books including Embrechts *et al.,* (1997) which give a comprehensive mathematical background of the theory, Beirlant *et al.,* (2004), and Coles (2001b) focus on applications and data analysis which are mainly followed in this dissertation. EVT is mainly interested in describing the behaviour in the upper (or lower) tail of a distribution. In extreme value analysis, the outliers are of interest, and the data which describe the typical behaviour of the random variable is discarded. For one to describe the tail of the distribution, various statistical methods are needed. The extreme value theory originates to find up methods to model and measure events which occur with very small probability (Faranda, 2012).

EVT is divided into three main broad areas which are:

- The block maxima approach: the distribution of a series of maxima (minima) converges to the so-called extreme value laws for extremes taken by dividing the data series into an asymptotically infinite number of bins (blocks) each containing an asymptotically infinite number of observations.
- The generalized extreme value distribution, which is a flexible family of distribution is then used to model the upper or lower tail of the distribution of the maxima or minima data.
- The peak over threshold approach: the distribution of excesses over a given threshold coverage. The excesses are then modelled by the generalized Pareto distribution.

2.11 Summary

This chapter discussed the nature of extreme events and long-term trends over South Africa compared to global long-term trends and provided different definitions of climate extremes previously used in different studies. This chapter has provided a general background on the extreme value theory and the application in the different studies across the world. It also discussed how these extreme events are associated with other phenomena such as floods, drought and heat waves and the negative impacts of such extreme events.

From the literature, it is noted that:

a) Extreme events negatively impact on human livelihoods by reducing agricultural productions and affecting human health.
b) In most parts of the world, extreme flood events are characterized by wet atmospheric condition.
c) Extreme Value Theory has been used in various studies such as Hydrology and Atmospheric science.
d) There is no universal definition of an extreme event because it varies across the world from one place to another. An extreme event definition may depend on the nature, extent and time.
e) The vast majority of African countries depend on subsistence agriculture for survival.
f) Many studies of climate extremes in southern Africa have focused on provinces of South Africa. These localized extreme events appear to be caused by localized perturbations within the large scale.
g) The occurrences of extreme floods over Southern Africa usually coincide with El Niño years.

Regardless this progress in understanding long-term trends of climate extremes, it is also known that extreme events and their impacts are evolving with time due to climate change, environmental degradation and population growth. The next chapter provides a description of all datasets used in this work and methods of analysis adopted to analyse the datasets in order to achieve the aim and objectives outlined in chapter one.

Chapter 3

Research Methodology

3.1 Introduction

Climate extremes are complex events which differ from period to period in relation to their extent, onset, severity and geographic scale. Re-analysis datasets are acquired from the National Centers for Environmental Prediction (NCEP). Attributing, detecting and monitoring changes in climate extremes require long-term, high quality and continuous data (e.g. ECA&D, ETCCDMI) (Politano, 2008; Jones, 1999). The homogeneity, quality and data availability of climate series are prerequisites for reliable and detailed climate studies. The homogeneity adjustments of climate data make it possible to consider temporal variations caused by climate processes (e.g. Della-Marta & Wanner, 2006). If inhomogeneity is not accounted for properly, results of climate analyses can be inaccurate (Peterson *et al.,* 1998).

However, most long-term time series are altered by inhomogeneity caused by changes in site displacement, instrumentation, and changes in environmental expansion such as urbanization or the establishment of distinctive observing practices (Politano, 2008; Wijngaard, 2003). To improve predicting models, it is vital to have a trustworthy set of observations. The detection of long-term trends in weather extremes remains a challenge because of rare occurrence of extreme events. The aim of this chapter is to present and describe data used in this study and their sources. It also presents the methods adopted and applied to analyse the data in order to achieve the specific objectives of the study outlined in chapter 1. The primary data sets that were used include daily and monthly rainfall, temperature, circulation fields, and outgoing long wave radiation.

3.2 Description of data sets

3.2.1 Rainfall

In this study, daily rain gauge observations from several stations in Limpopo were obtained from the South African Weather Service (SAWS) for the period 1960-2014. The observations are made once every 24 hours at 6.00Z (8:00 am South Africa Standard Time). This study selected stations of different altitudes including the lowveld and the plateau (Table 3.1) that have at least 95% data available from 1960 to 2014 over Limpopo province, South Africa (Figure 3.1). The data is recorded at a uniform time in all stations as per the World Meteorological Organization (WMO) guidelines. The observations are made at the same time across the southern African region in order to allow for inter comparisons.

However, since rain gauges are often sparse and rainfall variability is high, satellite Global Precipitation Climatological Project (GPCP) rainfall data is also used to map the spatial patterns of rainfall. The GPCP dataset (Hoffman *et al*., 2009) combines rain gauges' data with microwave sensed data from polar-orbiting meteorological satellites and infrared estimation from geostationary satellites. GPCP rainfall datasets are gridded at 2.5º x 2.5º resolution and are appropriate for the study area. The GPCP dataset has been used in several studies (e.g New *et al*., 2008; Jury, 2009; Chikoore, 2016).

Table: 3.1 SAWS weather stations used in this study

Station Name	Climate Number	Latitude	Longitude	Altitude (m)	Rainfall data availability
Thabazimbi	0587697 2	-24.6170	27.4000	1026	1960-2014
Pietersburg	0677834 6	-23.8930	29.4600	1297	1960-2014
Tsianda	0723603 0	-23.0500	30.3500	671	1960-2014
New Agatha Bos	0679267 7	-23.9460	30.1330	1151	1960-2014
Entabeni Bos	0766480 2	-23.0000	30.2700	1376	1960-2014
Matiwa	0766509 9	-22.9800	30.2800	1311	1960-2014
Mara-Pol	0721665 5	-23.1440	29.5570	894	1960-2014

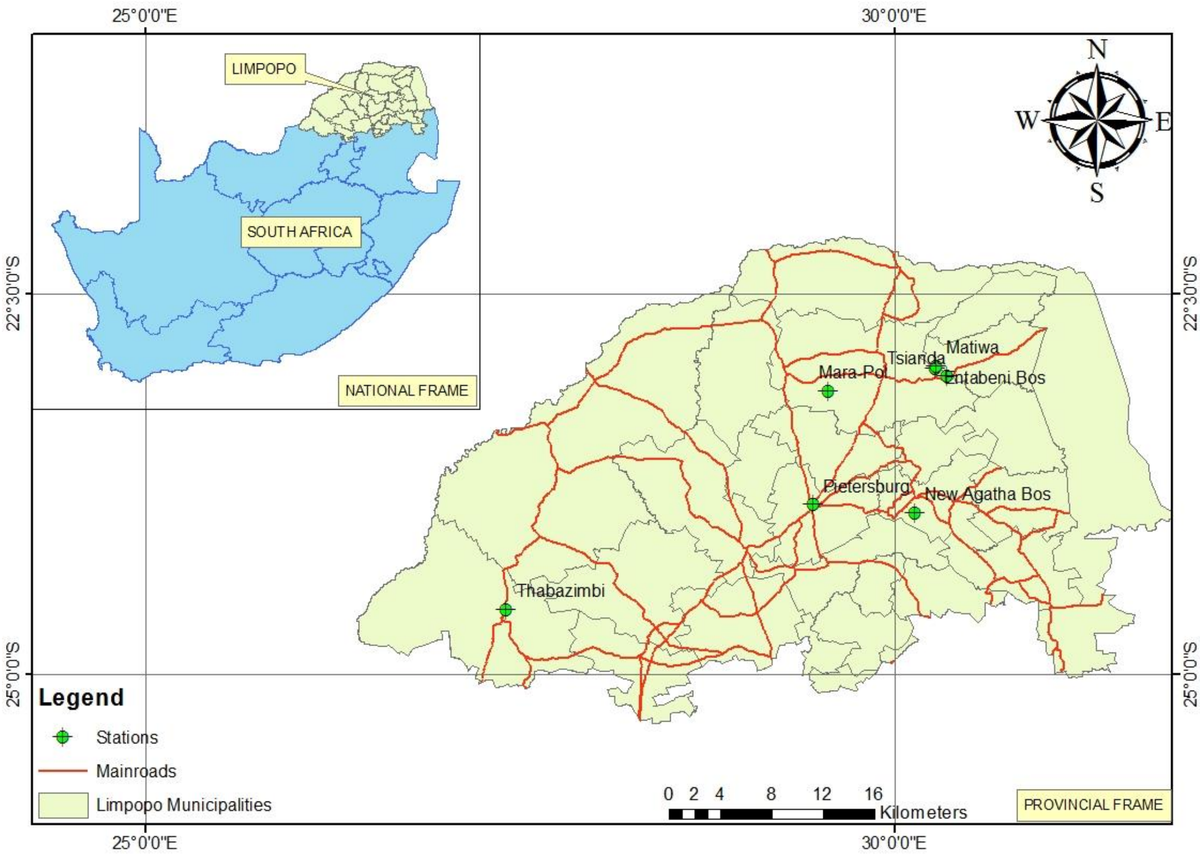


Figure 3.1 SAWS meteorological stations used in this study

3.2.2 Maximum and Minimum temperatures

Daily maximum (Tx) and minimum (Tx) temperatures were obtained from station data from SAWS. The highest temperature of the day is measured at 13.00Z in this region and the minimum is measured at 06.00Z. In manual stations, alcohol in tube thermometers is used to measure minimum temperatures as alcohol has low freezing point. Mercury is used in thermometers to measure maximum temperatures as mercury has a high boiling point. Automatic weather stations have temperate sectors (WMO, 1982). In this study, extreme temperature is defined to be daily maximum temperature to values Tx $\geq 40°$ C and minimum temperature Tx ≤ 10° C. Extreme Value Theory was applied for modelling extreme temperature over a particular period. According to SAWS (2008), Table 3.2 shows how minimum and maximum temperatures are classified.

Table 3.2 Daily temperature forecast terms used, SAWS (2008)

Highest day temperature (Maximum)	
Extremely hot	40°C ≤ T_X
Very hot	36°C ≤ T_X < 40°C
Hot	32°C ≤ T_X < 36°C
Warm	25°C ≤ T_X < 32°C
Cool	18°C ≤ T_X < 25°C
Cold	10°C < T_X < 18°C
Very cold	T_X ≤10°C
Lowest day temperature (Minimum)	
Extremely cold	T_N ≤ -10°C

3.2.3 Circulation parameters

Circulation parameters such as sea-level pressure, geopotential height and vertical velocity (omega) were analysed. These derived variables are obtained from the NCEP Reanalysis 2 (Kalnay *et al.,* 1996).

a) Sea level pressure

Atmospheric pressure and mean sea level (MSL) are analysed in this study to depict the synoptic-scale circulation patterns associated with extreme weather and climate events in the Limpopo. The NCEP reanalysis and MSLP analysis in this study have been detailed by Kanamitsu *et al.,* (2002). The SLP data model data which are available at 2.5x 2, 5º resolution. As much of southern Africa lies on the African plateau (Chikoore, 2016), it is often important to analyse the circulation on a pressure surface above the sea-level using geopotential heights.

b) Geopotential height

Geopotential height (values in meters) mainly represents the height of a pressure surface in the free atmosphere. Geopotential height can show highs and lows in the upper air and may help to identify weather systems that trigger extreme events. The data were obtained via the Internet data portal on the KNMI Climate Explorer. The circulation parameters were used to identify the typical weather systems associated with extreme weather events. Circulation parameters were used to relate particular features of the atmospheric circulation with local weather by statistical methods (Gofa & Tzeferi, 2013).

c) Winds

Wind vectors were mapped using the selected extreme events to observe the wind circulation patterns since wind systems transport atmospheric moisture. In the study, wind is used to investigate circulation over the South Indian Ocean. Omega is the vertical velocity in pressure coordinates. Vertical velocity is a useful parameter to determine uplift or subsidence of air. Vertical velocity is given by

$$\omega = \frac{Dp}{Dt}$$

where Dp is the change in pressure and Dt is the change in time. Since pressure decreases monotonically with height in the earth's atmosphere, ω is negative for rising motion and positive for subsidence. The data obtained from vertical velocity are used in this study to show the subsidence during extreme events. Sea level pressure anomalies were analysed over the Southwest Indian Ocean to identify pressure patterns and strength of tropical cyclones. The study mapped Omega at 500 hPa during wet season with extreme rainfall occurrences. Hence, tropical cyclones cut-off lows and cloud bands that bring heavy rainfall over east southeast Africa would be associated with negative omega values

3.2.4 Outgoing Longwave Radiation

Outgoing Longwave Radiation is defined as the energy which is radiating from the earth and its atmosphere as infrared radiation at low energy to space, and is controlled by temperature of the earth and its atmosphere including the presence of clouds and water vapour (Sapra *et al.,* 2011; Mbokodo, 2014). The National Oceanic and Atmospheric Administration (NOAA) interpolated Outgoing Long Wave Radiation (OLR) used as a proxy for convection. In the tropics, areas of low OLR are regions of deep convection and high rainfall. Thus, OLR has been widely used as a proxy for cloud, convection and precipitation in several studies (e.g. Jury & Pathack, 1993; Jury, 1996; Levey & Jury, 1996; Jury & Levey, 1997).

3.2.5 Sea-surface temperature

To determine the role of ocean-atmosphere interaction on the occurrence of extreme events over the Limpopo, Sea-surface temperatures are analysed. The Optical Interpolated SST data are obtained as a combination of observations satellite, ships and drifting buoys (Branzon *et al.,* 2014). SST anomalies in the Indian Ocean and tropical Atlantic are also analysed for correspondence with seasonal rainfall and drought events.

Droughts that occurred in South Africa during 1950 to 1969 were mainly caused by atmospheric anomalies and regional oceanic phenomena such as spatial variation of Sea Surface Temperature (SSTs) (Masih *et al.,* 2014). In the western tropical Pacific, the SSTs are generally warmer with high rainfall and low sea-level pressure, while the eastern Pacific is the opposite (Dube, 1998). In the equatorial eastern Pacific, cold water perseveres the whole year. Westward winds are related to the standard gradient SSTs along the equator (Dube, 1998).

3.2.6 El Niño Southern Oscillation Indices

Seasonal rainfall over southern Africa has been related to phases of El Niño Southern Oscillation (ENSO). The phase and strength of El Niño and La Nina events may be measured using the Southern Oscillation Index (SOI) or Niño 3.4 Index. The SOI measures the standardized pressure difference between Tahiti in the central Pacific and Darwin in the northern Australia (Mwafulirwa, 1999). The Niño 3.4 Index is the sea surface temperature anomaly in the eastern equatorial Pacific. The two indices were obtained from the archives of NCEP and were correlated with extreme seasonal rainfall over the Limpopo province.

3.3 Methods of Analysis

3.3.1 Annual cycles and anomalies

Annual cycles of monthly mean rainfall and temperature were analysed and provide a description of temporal variability of hydro meteorological variables in the Limpopo Lowveld. The leads and lags between the rainfall peak and the temperature peak were also investigated. Anomalies are also important descriptors in climate research. They represent the difference between a variable and its climatological average. It is therefore an exaggeration of the annual cycle. Monthly anomalies of rainfall and temperature were investigated. The climatology of 1981-2010 was used to determine the anomaly.

3.3.2 Cluster analysis

Daily precipitation and temperature were tagged in stations whereby the value is larger than 95^{th} percentile for each day of the chosen season (e.g DJF). Cluster analysis is a technique or method of dividing data into groups (Jan *et al.,* 2001). Cluster analysis for all the tagged stations was performed based on their geographical coordinates (latitude and longitude) for any potential day. The purpose of clustering is to identify extreme events at higher resolution. R statistical software was used for clustering analysis and it has a variety of functions for cluster analysis. Any station whose value is larger than 95th for any day of the DJF season was considered as a widespread extreme event.

3.3.3 Trend Analysis

Trends of rainfall and temperature were determined using trend analysis. A trend is defined as a significant change over a particular period exhibited by a random variable, detectable by statistical parametric and non-parametric procedures (Longobardi & Villani, 2009). Linear trends and polynomial trends were determined using regression. This helped to analyse rainfall time series over a wide area to detect potential trends and assess their significance. For rainfall, different stations with at least 90% data available were selected in the study area and analysed.

3.3.4 Composite Analysis

The study used composite analysis which is a method widely used in the geophysical sciences to study collective patterns and features. Composite analysis seeks to identify common characteristics between common events. This method of analysis makes interpretation to be easy, because it eliminates the number of maps (Mwafulirwa, 1999). Several climate extreme events were studied as composites to identify common weather systems and circulation patterns causing the extreme rainfall or extreme dryness. Composite analysis has been widely used in climate research (e.g. Jury & Pathack, 1993; Jury, 1996; Levey & Jury, 1996; Jury & Levey, 1997). This study used composite analysis to map GPCP precipitation, temperature and other variables during extreme events.

3.3.5 Correlation Analysis

Correlation analysis is a measure of a relationship between two variables. It indicates how or to what extent variables are linked with each other. Correlation coefficient measures only the degree of linear relationship between two variables. This method does not distinguish between cause and effect, so it should be used wisely to prevent incorrect analyses (Mwafulirwa, 1999). Zero value relationship between variables does not certainly mean that there is no relationship. Correlation analysis between precipitation anomalies and SOI over southern Africa was performed. Significance of the correlation was determined using P values. Low correlations or correlation for small samples need to be put to the test.

3.3.6 NCEP ESRL Plots

The online and interactive Global Forecast System (GFS) model from the National Centres for Environmental Prediction (NCEP) was used in this study to plot mean season precipitation and anomalies associated with extreme rainfall events over the Limpopo. The GFS is a climate model from National Centres for Environmental Prediction and National Centre for Atmospheric Research. The NCEP/NCAR re-analysis dataset is a continually updating gridded data set representing the state of the earth's atmosphere, incorporating observations and numerical weather prediction (NWP) model output dating back to 1948.

3.4 Extreme Value Theory

Extreme Value Theory (EVT) is unique as a statistical discipline in that it develops techniques and models for describing the unusual rather than the usual (Coles, 2001). EVT was used in the modelling of extreme rainfall. The analysis of extremes for a given data, representing extremes was selected. EVT provides a tool for modelling the asymptotic distribution of a sequence of observations (Fisher & Tippett 1928; Trophonia *et al.,* 2016). The best way to describe the behaviour of climate extreme events for a particular environment is to identify the distribution(s) which was suitable to fit the data. In this study, the generalised extreme value (GEV) distribution was applied using historical monthly rainfall data from 1960 to 2014. R package was used for extremes events (Gilleland *et al.,* 2013; Christopher, 2016) that are able to perform parametric inferential analysis of the GEV distributions for Thabazimbi station over the study area. Climate and weather applications are the intended focus of the package, although the functions could be used in other applications.

R is the statistical software that contains the most utilities for modelling extreme values (Katz, 2016). The software packages are available for free, open-source statistical software language and environment called R (R Development Core Team, 2012) because this has become the software language most used by academic statisticians (Gilleland *et al.,* 2013). The previous versions of the package provided graphical user interfaces predominantly to R package ‘ismev’, whereas the new version is to be used from the command line and implements various methods from (predominantly univariate) extreme value theory (Heffernan & Stephenson, 2012).

3.4.1 Block Maxima approach

Block Maxima approach is the most classical model for extreme events. This model is appropriate when the maximum observations of each period or block with a predefined and fixed length are assembled from a large number of identically and independently distributed (iid) variables (McNeil, 1999). For example, there may be a seasonal periodicity in case of yearly maxima, or there may be short range dependence that plays a role within blocks but not between blocks (Katz, Parlange & Naveau 2002; Madsen, Rasmussen & Rosbjerg, 1997). In this study, block maxima and peaks-over-threshold approaches were applied. With the block maxima approach, only the maxima of equally-sized disjoint blocks of data were used (e.g annual maxima). In this work, extreme rainfall events are considered to occur when 24-hour rainfall exceeds 50 mm. Daily rainfall data were ranked from highest to lowest and events exceeding 50 mm/ day were identified. ERA-interim daily rainfall and monthly GPCP rainfall were analysed over the Limpopo province.

3.4.2 The Generalized Extreme Value Distribution

The chapter focuses on the EVT in modelling climate extreme events in future by fitting historical weather data to the GEV distribution to determine if there is any trend in precipitation or temperature. This study uses approximately 54 years of daily, monthly precipitation and temperature, including minimum daily precipitation over Limpopo province (1960 to 2014). The GEV in particular is characterized by a location, scale and shape parameter. The GEV distribution is regarded as an approximate distribution to model the maximum of sufficiently long sequence of random variables. GEV model is suitable when the maximum observations of each period or block with a predefined and fixed length are assembled from a large number of identically and independently distributed variables (Coles, 2001).

Here, we let $X_1, X_2, \dots, X_n$ to be a sequence of daily rainfall measurements. Then $M_n = \max(X_1, X_2, \dots, X_n)$ is the maximum daily rainfall over an $n-$observation period where $n \geq 2$. We divide our daily data into b blocks. Each block consists of 365 days, which is a year. The maximum of n observations in block i is then defined as $\{M_{ni} = \max(X_{i1}, X_{i2}, \dots, X_{in})\}_i$, $i = 1,2, \dots, b$ and $n \geq 2$, with $X_{i1}, X_{i2}, \dots, X_{in}$ the data in the i-th block. The selection of block size, n is crucial. A value of n which is too small is likely to lead to a poor approximation by the limit model. This would lead to bias in the estimation of parameters and, consequently, in extrapolation. If n is too large, however, too few block maxima were obtained, resulting in large estimation variances. A trade-off needs to be found between the bias and the size of variances. Normally, the blocks relate to a time period of one year (i.e. n is the number of observations in a year) resulting in a series of annual maxima data.

In order to extract upper extreme values, an extreme value distribution is then fitted to the block maxima data $\{M_{ni}\}_i, i = 1, \dots, b$. The probability of M_{ni} not exceeding a value x_i is then given as

$$\begin{aligned} P\{M_{ni} \leq x_i\} &= P\left\{\max_{i \leq n} X_{in} \leq x_i\right\} = P\{X_{i1} \leq x_i , X_{i2} \leq x_i , \dots, X_{in} \leq x_i\} \\ &= \{F(x_i)\}^{ni} \end{aligned} \qquad (1)$$

The GEV distribution consists of the Gumbel, Frechet and Weibull classes which are also known as the type I, II and III extreme value classes respectively. The unified model is given by

$$G(x) = \exp\left\{-\left[1 + \left(\frac{x-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\}, \text{if } 1 + \xi\left(\frac{x-\mu}{\sigma}\right) > 0 \text{ and } \xi \neq 0 \qquad (2)$$

where ξ is the extreme value index (EVI). For $\xi = 0$ equation (2) is the Gumbel class of distributions which is given by

$$G(x) = \exp\left\{-\exp - \left[\frac{x-\mu}{\sigma}\right]\right\}, \qquad \text{if } \xi = 0. \qquad (3)$$

When $\xi > 0$, we have the Frechet class of distributions and when $\xi < 0$, we have the Weibull class of distributions. The three parameters ξ, μ and σ are estimated for the given dataset through the maximum likelihood method.

3.4.3 The Generalized Pareto Distribution

The Generalized Pareto Distribution (GPD) is a Peaks-over-threshold (POT) distribution which can be used to model the observations above a sufficiently high threshold (De Haan & Ferreira, 2006; Pickands, 1975; De Haan, 1970). The GPD has two parameters ξ, the shape parameter, and σ, the scale parameter. The survival function of the GPD is given in equation (4).

$$P(X > x|\tau) = \begin{cases} \left(1 + \frac{\xi(x-\tau)}{\sigma}\right)^{-\frac{1}{\xi}}, & \text{if } \xi > 0, x-\tau > 0 \\ \exp\left(-\frac{x-\tau}{\sigma}\right), & \text{if } \xi = 0, x-\tau > 0 \\ \left(1 + \frac{\xi(x-\tau)}{\sigma}\right)^{-\frac{1}{\xi}}, & \text{if } \xi < 0, 0 < x-\tau < -\frac{\sigma}{\xi} \end{cases} \quad (4)$$

3.4.4 Estimation of parameters

There are different methods to estimate the GEV parameters. The three parameters are estimated by method of maximum likelihood, method of moments, method of and equivalent L-moments, including Bayesian estimation among others. Hosking (1985) showed that the probability weighted moments estimator for the GEV distribution is more appropriate than the maximum likelihood method for small samples ($n < 50$). The method of moments estimators is suitable or perform well when the sample size is modest (Madsen *et al*., 1997). In this study, the maximum likelihood method was used because $n > 50$.

3.5 Summary

This chapter described data sets and data sources used and the methods of analysis applied to achieve the objectives of this study. The NCEP ESRL Laboratory was used to map various fields whilst annual cycles, trends, composites and correlations were also employed. Extreme Value Theory (EVT) is the main statistical method which was used in this study to determine the probability of extreme events. These methods assist in analysing the spatial variability and long-term trends of climate extremes over the Limpopo Province, South Africa. Maximum rainfall is the major dataset used to identify long-term extreme events over the study.

Chapter 4

Extreme Events, Weather Systems and Teleconnections

4.1 Introduction

The Limpopo Province is highly vulnerable to climate weather extreme events (Pinto, 2015; Washington *et al.,* 2004) which are known to have negative impacts on food production water resources, and affect livelihoods and food security, particularly in rural communities. The trends in disaster losses have been increasing (Pinto, 2015; WMO, 2014; Seneviratne *et al.,* 2012), and whilst some of these increases are due to increased exposure of assets and populations, increases in weather and climate extreme also play a role.

Extreme weather and climate phenomena such as droughts, floods, and high temperatures are very sensitive to human activity, especially when they occur over a long period. Extreme events such as floods are often accompanied by damages and losses. For instance, Limpopo province experienced extreme rainfall associated with tropical cyclone Eline in 2000, whereby 700 lives were lost while over a million people were displaced by extreme rainfall (William *et al.,* 2008; Layberry *et al.,* 2006). Some key characteristics of climate extremes phenomenon are their intensity, spatial extent and temporal evolution. Spatial and temporal characteristics of extreme events may vary from one place to another and from time to time, particularly as a result of climate change.

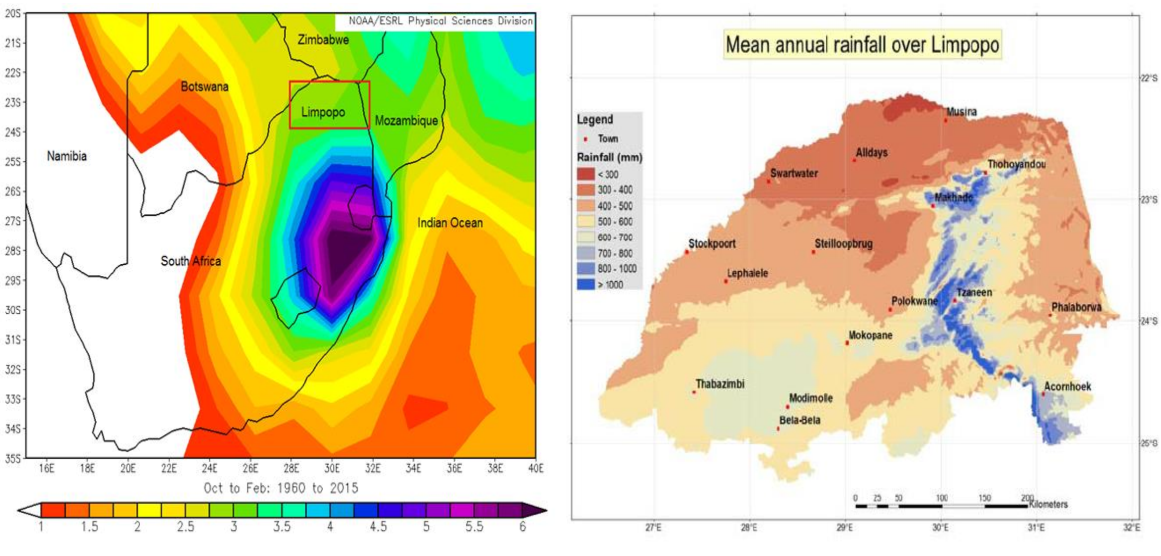
The aim of this chapter is to identify and analyse trends of extreme weather and climate events over the study area; determine the dominant weather systems and remote phenomenon associated with extreme events and examine the link between extreme events and the tropical ocean hotspots. Circulation patterns (seasonal mean and composite mean) are analysed and discussed in this chapter. The Botswana High induces extreme events such as droughts over the southern Africa. The influence of the Botswana High and how it is enhanced by remote phenomena such as the ENSO is also analysed.

4.2 Rainfall variability over Limpopo

4.2.1 Mean spatial patterns of rainfall

The climate of southern Africa has been well documented in the literature (Nicholson, 2000; Tyson & Preston-White, 2000). The north eastern Lowveld is humid and hot in summer whilst prevailing winds are north-easterly. Sometimes, intrusions of cool south easterlies affect the Lowveld following the passage of a cold front. During the summer months, west to east spatial gradients of rainfall are distinct over the Limpopo (Figure 4.1). Over the western part of the study area, less than 3 to 3.5 mm of rainfall per day is received whilst the eastern part receives an average of about 4 to 4.5 mm per day whilst below normal rainfall is found in the Limpopo River valley. It is also evident from the map that southern Africa has a strong west- east mean rainfall gradient (i.e. rainfall decreases westward).

The mean annual rainfall over the region is affected by a variety of forcing mechanisms including tropical and subtropical weather systems, topography and contrasting oceanic surroundings (Pinto, 2015; Tyson & Preston-White, 2000; Taljaatd, 1986). The north-eastern escarpment areas receive some of the highest annual rainfalls in South Africa, in excess of 1500 mm annually (Malherbe *et al* 2012; Hart *et al*., 2013).



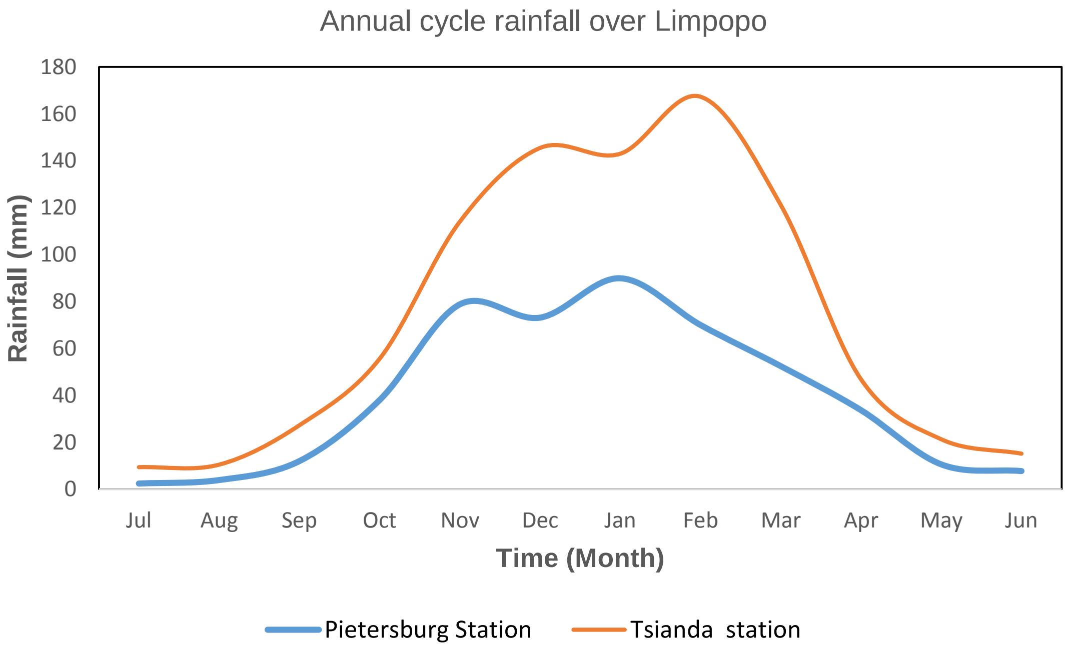
a) b)

Figure 4.1a) Mean summer GPCP precipitation patterns over southern Africa Oct to Mar 1960-2014, b) Mean annual rainfall over Limpopo (source: ARC-Institute for Soil, Climate and Water).

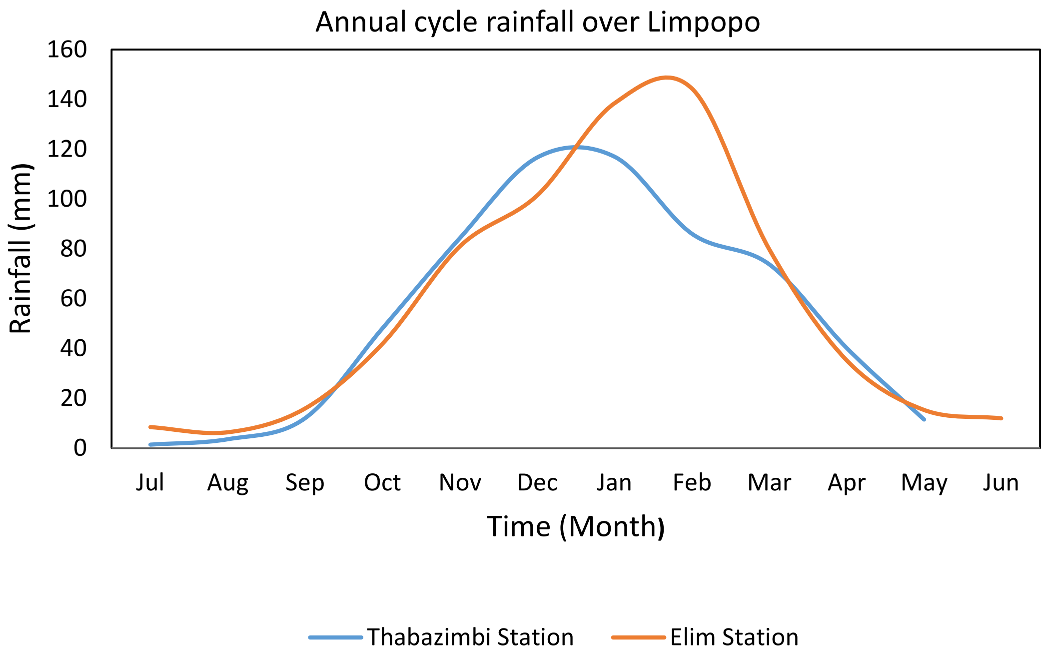
4.2.2 Annual cycle of rainfall over Limpopo

The mean annual cycle of rainfall in Limpopo shows a distinct peak during the austral summer from October to March (Figure 4.2). Limpopo was found to be a region where the difference between summer and winter rainfall are greatest in South Africa (Rouault *et al.,* 2005). Six other regions experience summer rainfall in South Africa, but the amounts and timing of maximum precipitation are different (Rouault *et al.,* 2005). This may also be due to the different synoptic forces affecting the rainfall regions. The Western Cape and Northern Cape receive predominantly winter rainfall whilst the Cape South Coast receives rainfall throughout the year (Pinto, 2015; Taljaard, 1986; D'Abreton & Lindesay, 1993; Tyson *et al.,* 2002). There are significant changes in the annual cycle, but much of this area receives its rainfall during the austral summer season (DJF) which differs with the Western Cape Province which receives much of its rainfall in the austral winter (JJA). Both stations have mid-summer dry spells although they are located in different location (Figure 4.2). Thabazimbi and Pietersburg station earlier peak rainfall in January, the other station such as Tsianda and Elim earlier peak in February.

Peak rainfalls of up to 89,8mm per month occur in January at Pietersburg station (Figure 4.2). During the dry season, the area receives less than 10. 5 mm (Figure 4.2).



a)



b)

Figure 4.2 Mean annual cycle rainfall over Limpopo from 1960-2014 a) Pietersburg, Tsianda and b) Thabazimbi and Elim stations.

4.2.3 Inter-annual rainfall variability

Figure 4.3 showed distinct peak in the year 2000 which resulted in floods which were due to an active tropical cyclone season over the southwest Indian Ocean. The most significant was the landfall of tropical cyclone Eline which made landfall over southern Mozambique and affected much of the subcontinent (The 2000 floods and evolutions, TCs Eline was detailed by Reason and Keibel 2004). Extreme rainfall events due to tropical cyclones have also occurred over southern Africa during the late summers 1966/67, 1983/84, 1999/00, 1996/97, 2007/08 and 2011/12 (Chikoore, 2016).

Limpopo province receives less rainfall compared to other provinces of South Africa excluding Northern Cape Province. Inter-annual rainfall variability is often linked to global and regional anomalies, as atmospheric circulation responds to changes in SSTs (Nicholson, 2003). Lowest rainfall in this province received in 1982 was about 273.1 mm. Other droughts have also occurred during 1983/84, 1986/87, 1991/92 and 1994/95, 2002/3. From the analysis, it is evident that extreme drought events have become more frequent and tend to cluster. During 1982/83 and 1991/92, major droughts occurred in South Africa (Limpopo), but the 1991/92 remains the most severe drought.

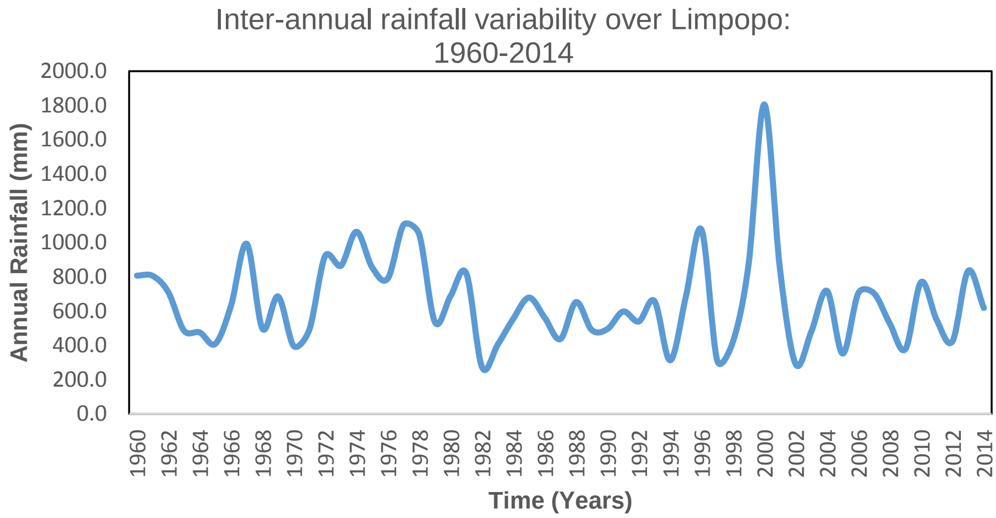


Figure 4.3 Inter-annual rainfall variability over Limpopo (Elim station)

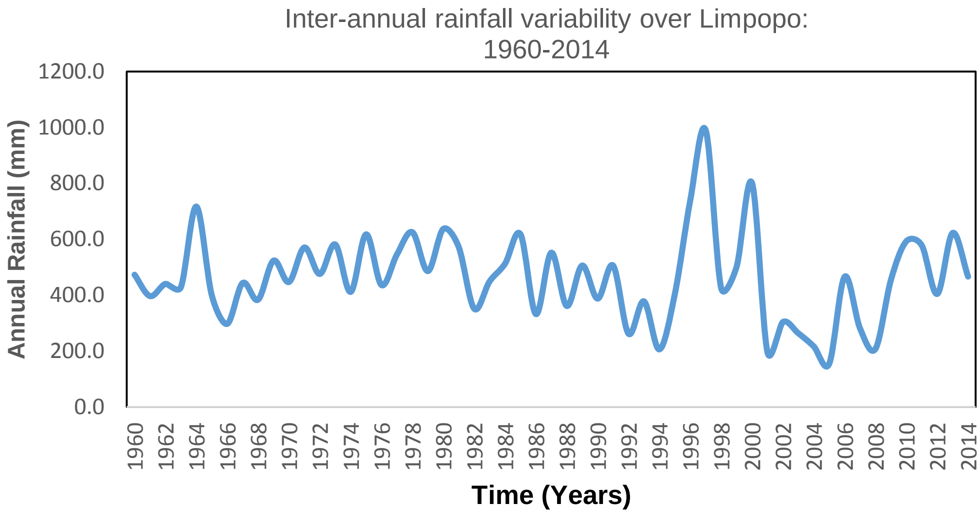


Figure 4.4: Inter-annual rainfall variability over Limpopo from 1960-2014 (Pietersburg station)

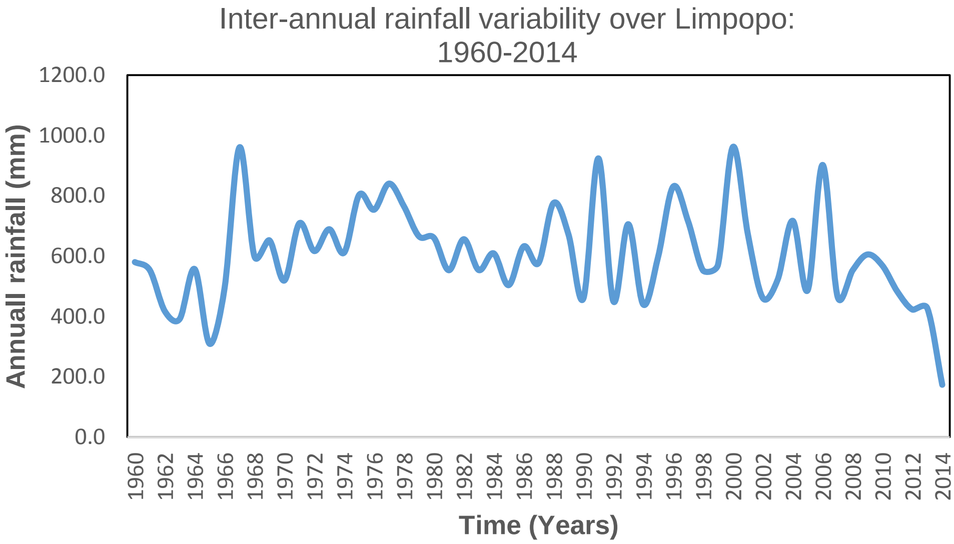


Figure 4.5: Inter-annual rainfall variability over Limpopo from 1960-2014 (Thabazimbi station)

Thabazimbi station seems to have higher rainfall compared to Pietersburg and Elim, whilst Elim is the most variable, indicating that the study area is characterized by high variability of rainfall. Some of the interannual variability and the occurrence of extremes including floods, droughts and heat waves may be linked to ocean-atmosphere interactions which will be discussed later in this chapter.

4.3 Outgoing Longwave radiation

Outgoing Longwave radiation (OLR) is a measure of convection in the tropics. Deep convective clouds act to block and decrease OLR escaping to space. During extreme events such as drought, positive or high OLR anomalies are dominant in South Africa. High OLR indicates the absence of deep convective (non-convective) clouds in the upper level, while low OLR indicates the frequent of deep convection clouds and precipitation (Mwafulirwa, 1999). Strong positive OLR anomalies is showing dry season in this case (Figure 4.6). The dry season was observed on inter-annual rainfall time series (Figure 4.3) and analysis performed for JFM 1960 to 2014.

Strong negative OLR anomalies may therefore indicate persistence of heavy rainfall which may lead to flood conditions. Positive anomalies of OLR in South Africa were observed during 1966, 1970, 1973, 1979, 1983, 1987, 1992, 1995, and 2003 in late summer (JFM) (Figure 4.6). In January-February-March, high OLR anomalies were observed over the northern part of South Africa. The positive anomalies over Limpopo support the focus of this study of extreme events on this region.

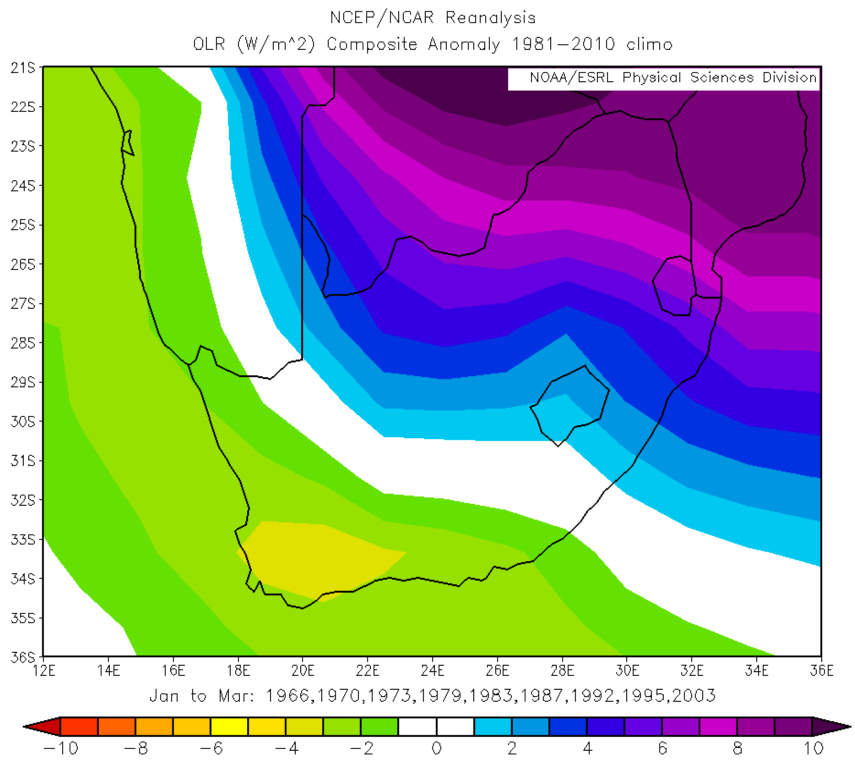


Figure 4.6: OLR anomalies at 200 hPa during JFM IN 1966, 1970, 1973, 1979, 1983, 1987, 1992, 1995 and 2003

4.4 Mean circulation

The mean circulation over southern Africa is predominantly anticyclonic and largely driven by the semi-permanent subtropical highs (Tyson & Preston-Whyte, 2000). The seasonality of rainfall can best be understood in the context of the wind and pressure systems (Nicholson *et al.*, 1988). The thermodynamic characteristics of the underlying subcontinent are responsible for influencing the mean circulation patterns over southern Africa (Theron & Harrison, 1990). During the austral summer, a low in the Mozambique Channel forms part of the equatorial trough extending from the Angola Low in the west to a low over the Mozambique channel (ITCZ) (Figure 4.7).

The ITCZ is the main rain bearing system of the subcontinent which marks the converging point of south easterly trade winds of the Southern Hemisphere and the north easterly monsoon of the Northern Hemisphere (Mwafulirwa, 1999). In South Africa, during summer, the ITCZ may oscillate over the southern tropical areas with pressure changes to the south. The south Indian anticyclone drives onshore trade winds onto the subcontinent which advect moisture from the Indian Ocean. The South Indian Ocean anticyclone is a region of high atmospheric pressure over the Indian Ocean between 20°S and 35°S. In the Southern Hemisphere, the subtropical belt is the centre of anticyclone activity. In some other parts of southern Africa, an anomalously strong South Atlantic Anticyclone is correlated with wet conditions (Driver, 2014; Walker, 1990; Tyson, 1986).

The South Atlantic anticyclone is a semi-permanent high-pressure system in the southern part of the Atlantic Ocean that shifts 6° latitudinally between seasons and has a zonal shift of approximately 13°. These seasonal fluctuations drive changes in surface winds which impact on SSTs particularly in the upwelling zones along the western coast of southern Africa and the Atlantic cold tongue (Reason *et al*., 2006b). Southern Africa weather changes daily as a result of dislocation of westerly or easterly waves to the south or north. The main difference during summer inland is dominated by low pressure system and in winter, high pressure system is over the land and sea.

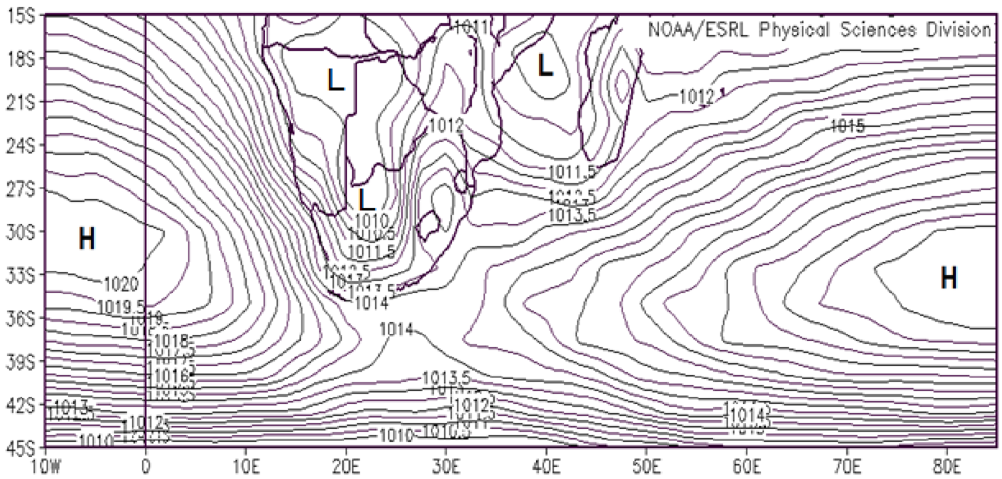


Figure 4.7a) Composite mean SLP (hPa): Dec-Feb 1960-2014 over South Africa and the adjacent oceans

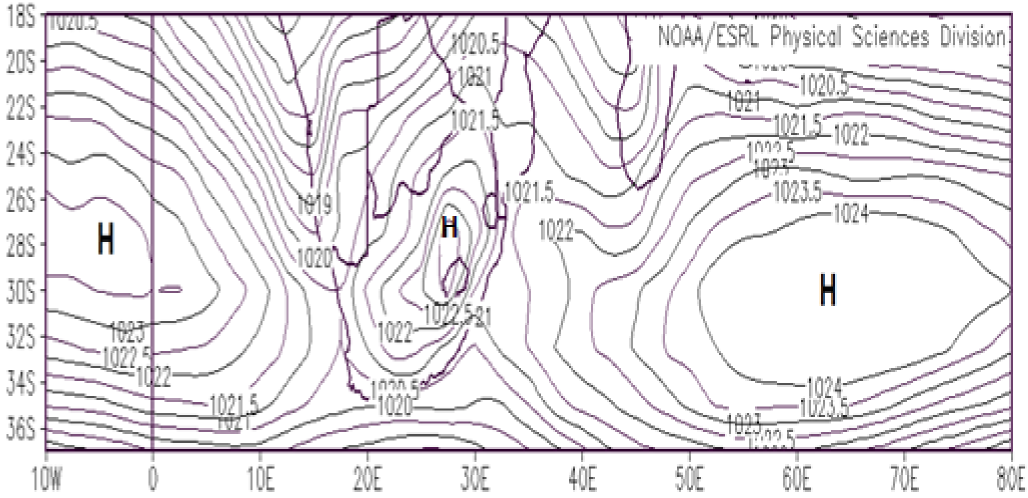


Figure 4.7b) Composite mean SLP (hPa): June-Aug 1960-2014 over South Africa and the adjacent oceans

4.5 Circulation anomalies inducing extreme events

Extreme events such as drought are mainly caused by atmospheric anomalies which may be linked to regional oceanic phenomena such as spatial variation of Sea Surface Temperature (SSTs) (Masih *et al*., 2014). The SSTs are generally warmer in the western tropical Pacific, with high rainfall and low sea-level pressure, while the eastern Pacific is the opposite (Dube, 1998). In this section, composite analysis is used to analyse the anomalies in the mean circulation which are typically associated with extreme events over Limpopo (South Africa).

4.5.1 Type 1: Tropical cyclone

Tropical cyclones (TCs) are tropical revolving systems characterized by a low pressure centre, strong winds and a spiral arrangement of thunderstorms that produce extreme wind and rainfall. TCs form over the warm Southwest Indian Ocean (SWIO) and Mozambique Channel every year during the late austral summer. Whilst TC landfalls are rare, they bring extreme rainfall, flooding and devastation to the vulnerable communities of southeast Africa. For TCs to occur the SSTs must be greater than 27°C (McBride 1995; Tyson and Preston-Whyte 2000; Palmén, 1948). Fewer TCs occur in the SWIO during El Niño years (Jury, 1993).

On average eleven tropical disturbance reach tropical depression intensity over the SWIO per year with a peak in February (Malherbe, 2013; Tyson and Preston-Whyte, 2000; Reason and Kiebel, 2004; Reason, 2007, Mavume *et al*., 2009). TCs produce extremely strong winds and huge waves and generate abnormally high tides (Tyson and Preston-Whyte 2000) causing severe impacts on the low lying areas near the coast. Extreme floods during 1996 over parts Limpopo region were caused by westward moving tropical depression (Malherbe, 2013; Crimp and Mason, 1999) which was ex-tropical cyclone Bonita. In February 2000, tropical cyclone Eline moved westward over the southern Africa mainland causing the extreme floods over Mozambique and heavy rainfall deeper into the interior (Malherbe, 2013; Reason and Keibel, 2004).

Table 4.1: Dominant Tropical Cyclones that have affected the Limpopo province

Year	Name
1977/78	Emilie
1983/84	Domoina
1995/96	Bonita
1999/00	Eline
2007/08	Favio
2011/12	Dando

TC Eline and TC Dando had the greatest impact and therefore discussed here.

4.6 Case Study 1: Tropical Cyclone Eline 1999/2000

4.6.1 Daily mean rainfall

The case of heavy rainfall and extreme floods caused by tropical cyclone Eline in February 2000 is investigated in this study. Extreme floods were created by a succession of tropical storms, starting with depression Connie from 4-7 February 2000. These extreme floods were caused by tropical cyclone Eline, which persisted about 29 days (1 -29 February) and flooded around South Africa. About 14 days before Eline cause landfall over subcontinent there was a tropical low situated over Namibia and Botswana border and its secondary low sitting over the interior of South Africa (Reason and Keibel, 2004). In this case only Six days was investigated (Figure 4.8) focusing on heavy rainfall during that period. It is evident on as depicted in Figure 4.8 that on 22 February, there was less rainfall over the Limpopo (mean surface precipitation).

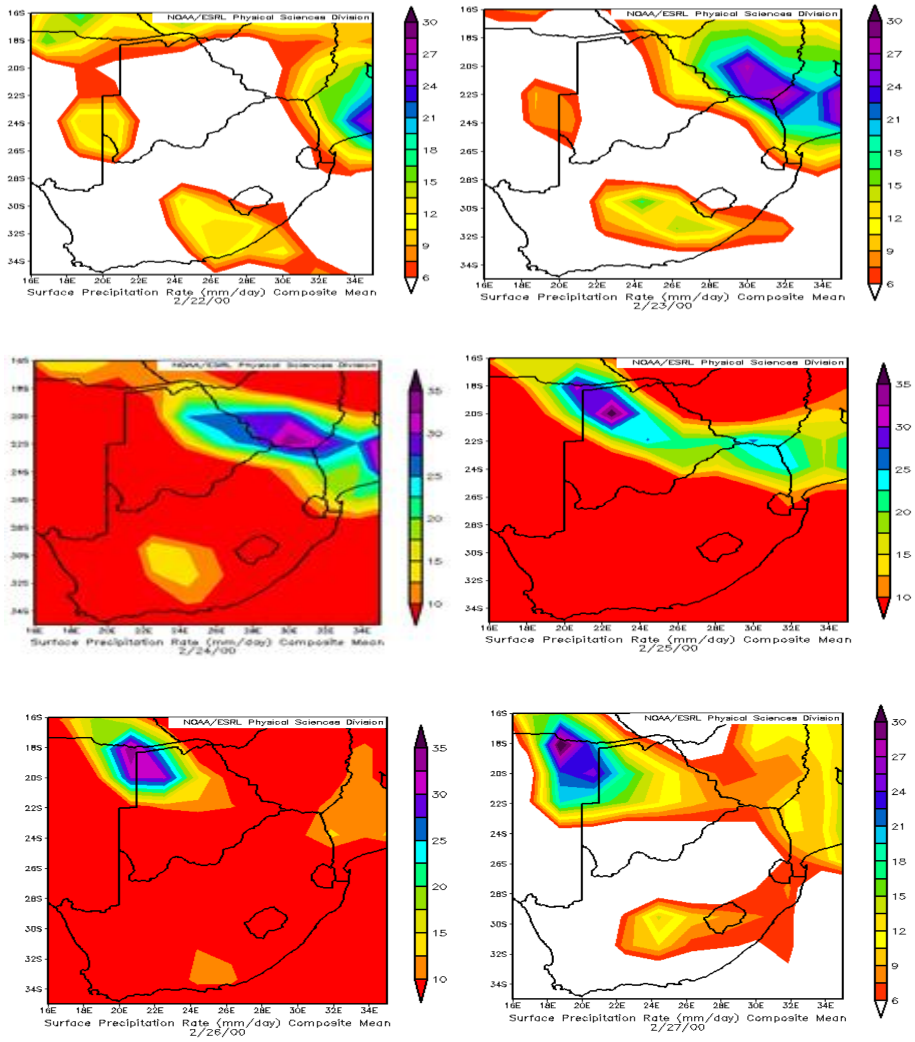


Figure 4.8 Daily mean precipitation from 22-27 February 2000.

4.6.2 Mean Sea Level Pressure

Tropical Cyclone Eline (Figure 4.9) of the season 1999-00 lasted nearly 30 days and penetrated further inland over Zimbabwe towards Nambia, which was quite unusual for this type of weather system. Its formation took place around February 1, 2000 and dissipation on February 29, 2000. This TC caused the worst flooding over Zimbabwe and Mozambique during the month of February (Zimbabwe Meteorological Services, 2008). On this case, we focus on daily mean sea level of TC Eline propagating inland starting from day 22-29. As depicted in (Figure 4.9), TC Eline was moving from south Indian Ocean penetrating to inland Mozambique. On 23 February 2000 (Figure 4.9), it was on far north Zimbabwe and covering Limpopo province in South Africa. Tropical

Cyclone Eline was projecting into the interior of Botswana and Zimbabwe causing extreme rainfall (Figure 4.9).

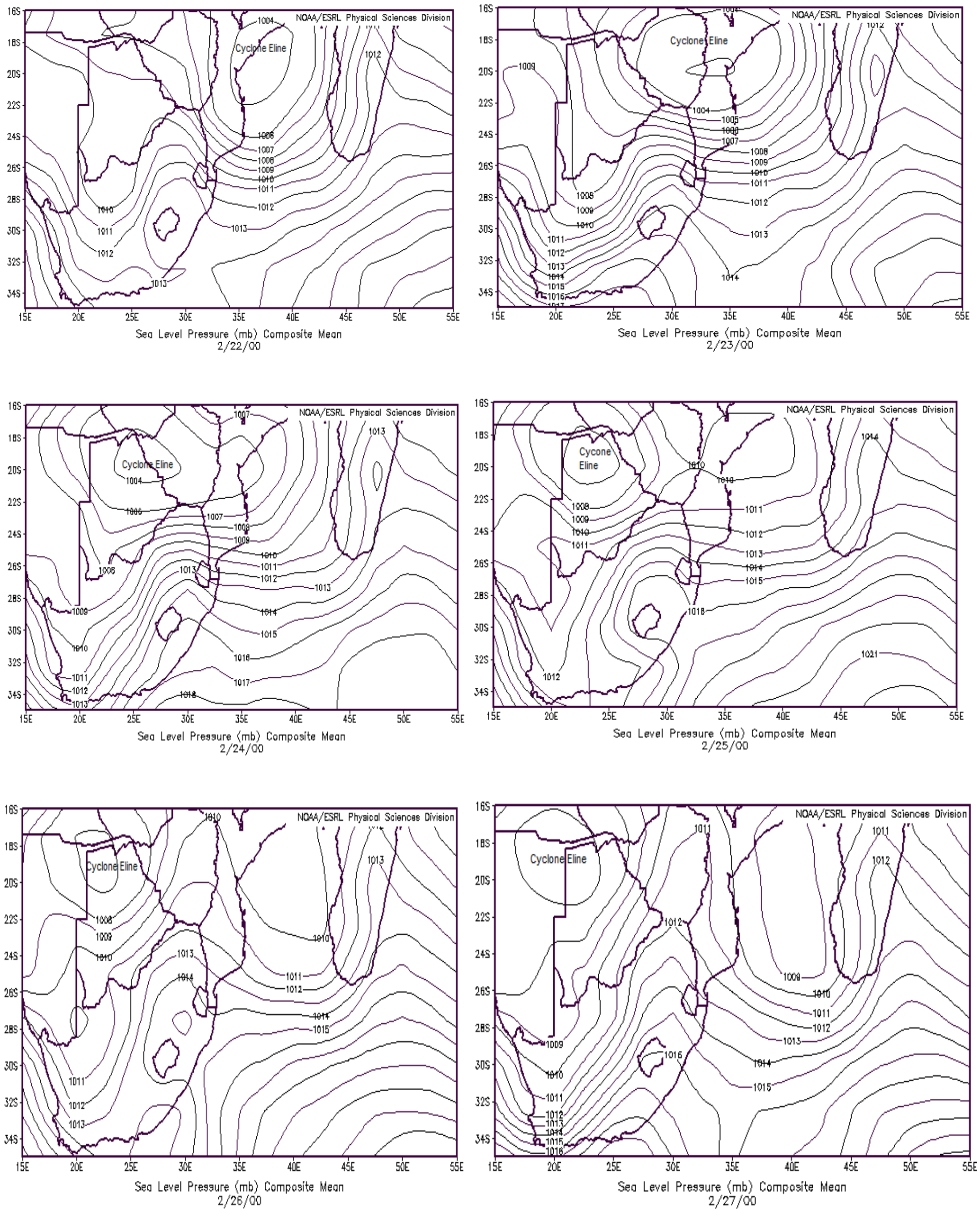


Figure 4.9 Daily sea level pressures over Limpopo from 22-27 February 2000

4.6.3 Sea Level Composite Anomaly, 22-27 February 2000

The SWIO and the Mozambique Channel are conducive for cyclogenesis of tropical revolving storms during mid to late austral summer (Chikoore *et al.,* 2015). In the year 2000, TC Eline moved inland over South Africa, Zimbabwe, Botswana and Zambia. The anomalous TC Eline lasted for long and was coupled with uncommon characteristics. For this case, daily anomalies sea level pressure of TC Eline circulating inland from 22-27 February 2000 are analysed. As illustrated in (Figure 4.10), the tropical cyclone Eline was progressing from SWIO and entering the inland of Mozambique. It moved far north of Zimbabwe and Limpopo covering the large area (Figure 4.10).

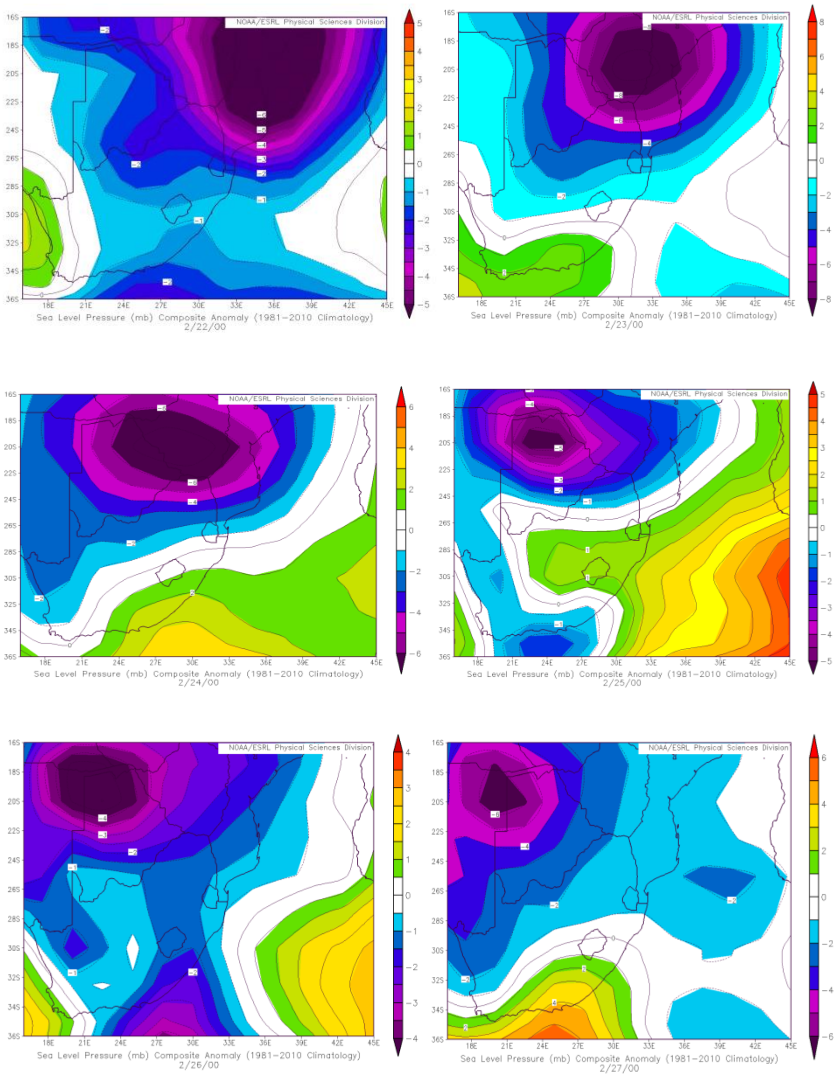


Figure 4.10 Sea Level Pressures, 22-27 February 2000

4.6.4 Outgoing Longwave Radiation

In the northern part of Limpopo province (Figure 4.11), negative values of OLR were observed in 1999/00. Outgoing Longwave Radiation was modelled for December-January-February in 1999/00 over the study. During extreme floods event in Limpopo province, negative or low OLR anomalies are dominant. In this study, areas that were mostly affected by extreme floods than others are denoted by low OLR (Figure 4.11). Limpopo and its neighbouring countries experience extreme floods during December January February (Figure 4.12).

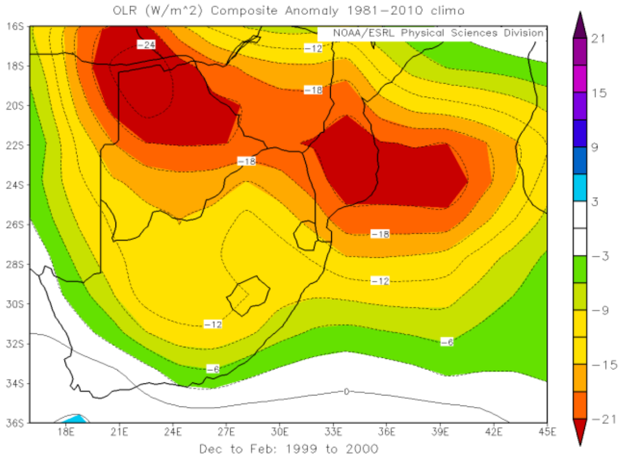


Figure 4.11 Outgoing Longwave Radiation (w/mˆ2) from DJF 1999/2000 over southern Africa

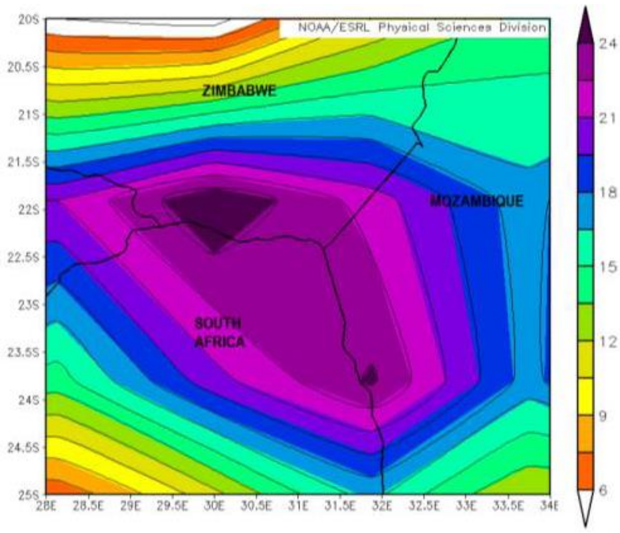


Figure 4.12 Mean rainfall (mm) over southern Africa DJF 1999/2000

4.6.5 Wind anomalies over southern Africa 1999/00

Severe summertime flooding over southern Africa is triggered by wind anomalies and occurs mutually at the surface and 500 hPa levels (Figure 4.13). The vector wind anomaly in February tends to be easterly, transporting moisture inland to east southern Africa and being favourable to produce heavy rainfall in some cases. It is clear that easterly wind vector anomaly has a significant role in the transportation of moisture which results to heavy rainfall over the mainland. The selected wind anomalies with heavy rainfall over Limpopo Province are illustrated in (Figure 4.13).

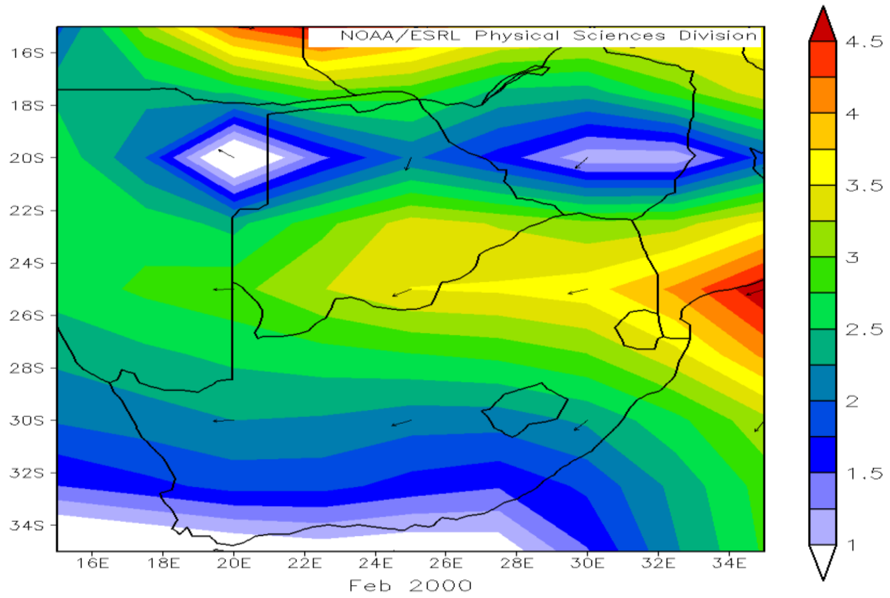


Figure 4.13 Vectors wind at 500hPa (m/s) over southern Africa transporting moisture, February 2000

4.7 Case study 2: Tropical Cyclone Dando 2011/12

4.7.1 Daily mean rainfall

TC Dando (Figure 4.14) of the season 2011/12 formed over the SWIO on January 10, 2012 and made landfall over the mainland over South Africa and the east of Mozambique, and dissipated on January 16. Extreme floods event in January 2012 were created by a succession of severe storms and strong winds between 10 and 16 January over Limpopo province. Heavy rainfall, strong winds, severe storms and hail were experienced over Limpopo province which resulted into extreme flooding (Figure 4.14). Roads, houses and bridges were destroyed, interrupting electricity and water supply. On 13 and14 January as depicted in Figure 4.14, heavy rainfall experienced in this region resulted to flooding. On January, 10 there was lower rainfall over the Northern Zimbabwe and some parts of South Africa in Limpopo province, as illustrated in Figure 4.14. However, dry conditions persisted across Zimbabwe, Botswana and northern sections of South Africa from 16 January 2012 (Figure 4.14).

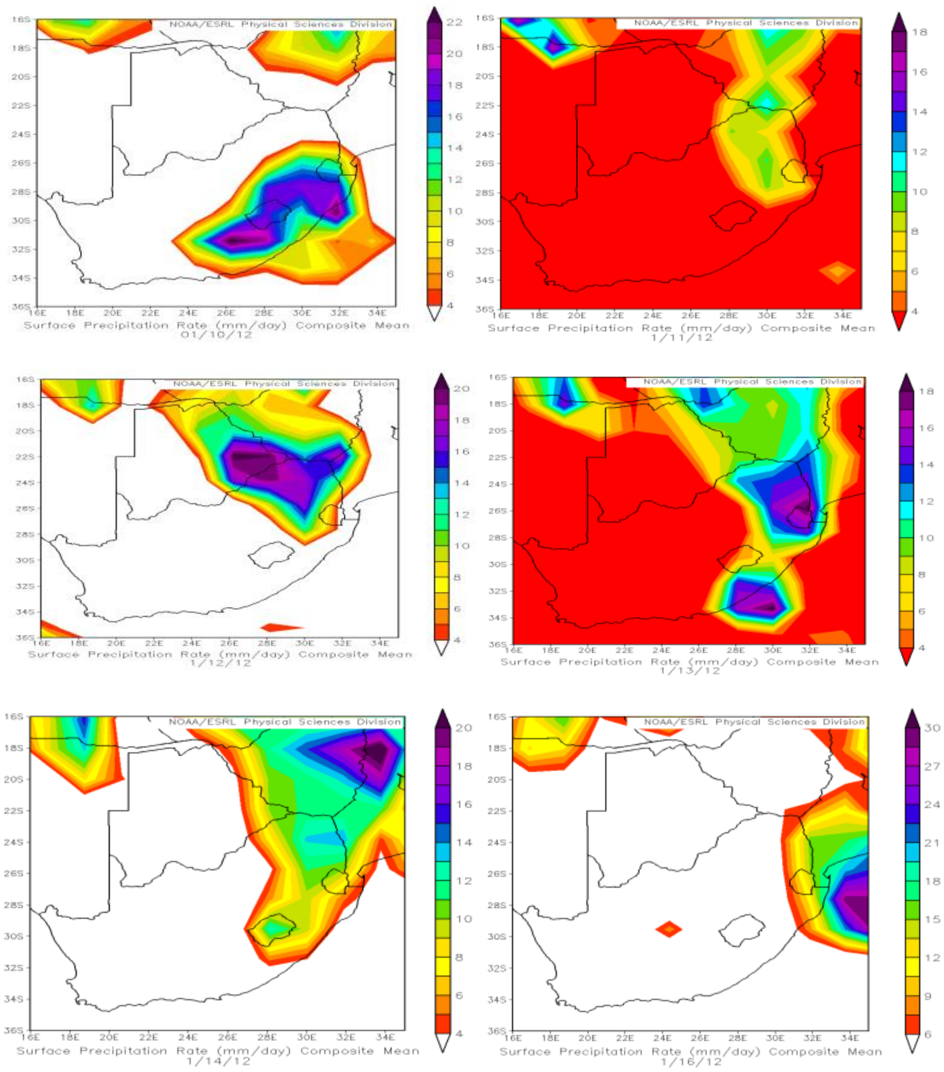


Figure 4.14 Daily mean rainfall (mm/day) from 01/10/12 to 01/16/12 over southern Africa

4.7.2 Sea Level Composite Anomaly

In this case, daily anomalies sea level pressure from 10 to 16 January was observed. Unusual sea level pressure which is influenced by La Nina event (Figure 4:16) of the year 2012 is associated with intense rainfall and rigorous storms. On Figure 4.16, weather systems were moving from south Indian Ocean invading South Africa. On 10 January (Figure 4.15), severe precipitation covered the entire region. On January 11, clouds cover in Figure 4.15 was dissipating and resulting into clear skies in far north of Limpopo province.

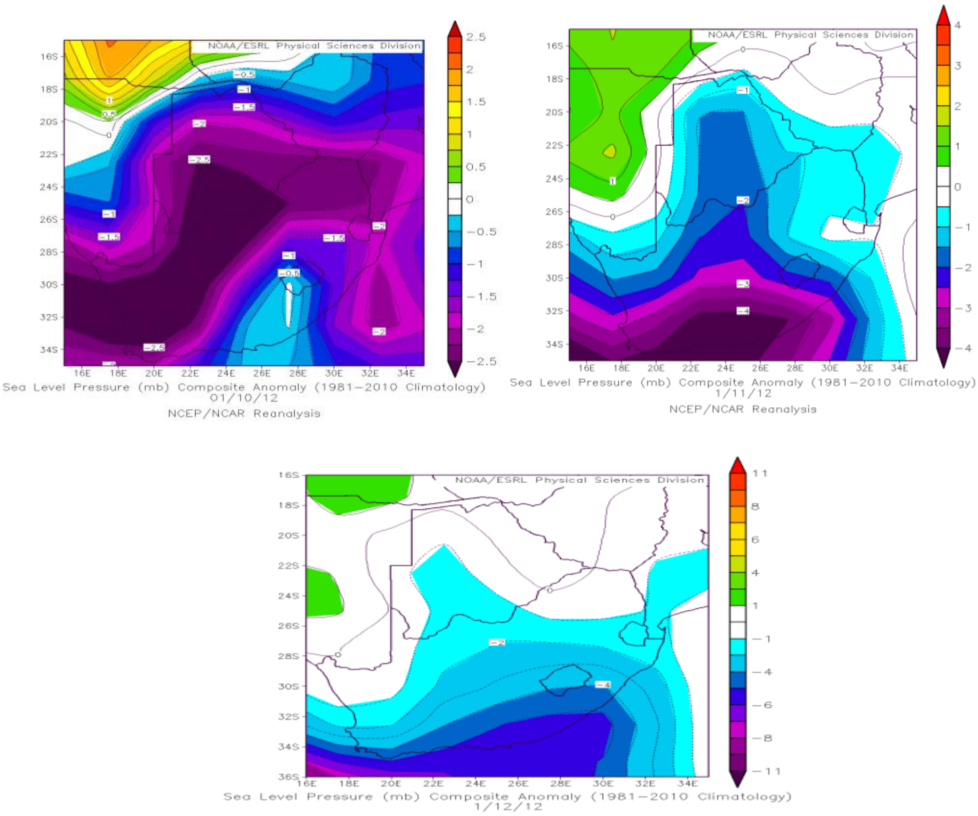


Figure 4.15 Sea Level anomalies (mb) over southern Africa from 10 January 2012 to 12 January 2012

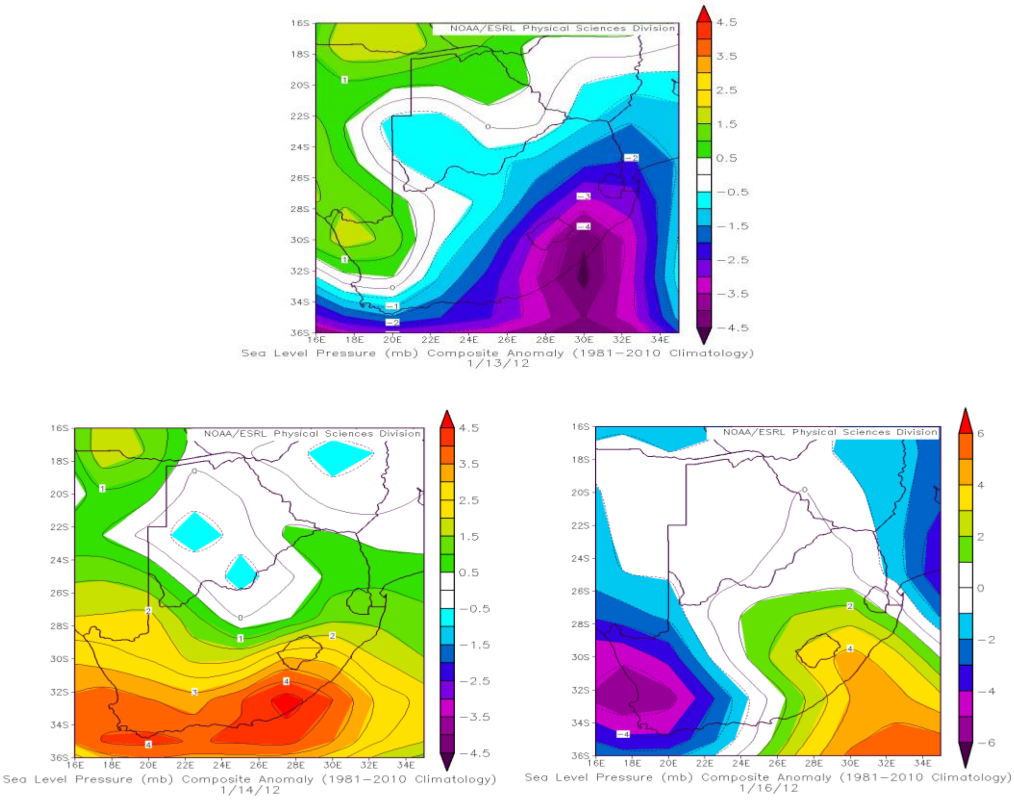
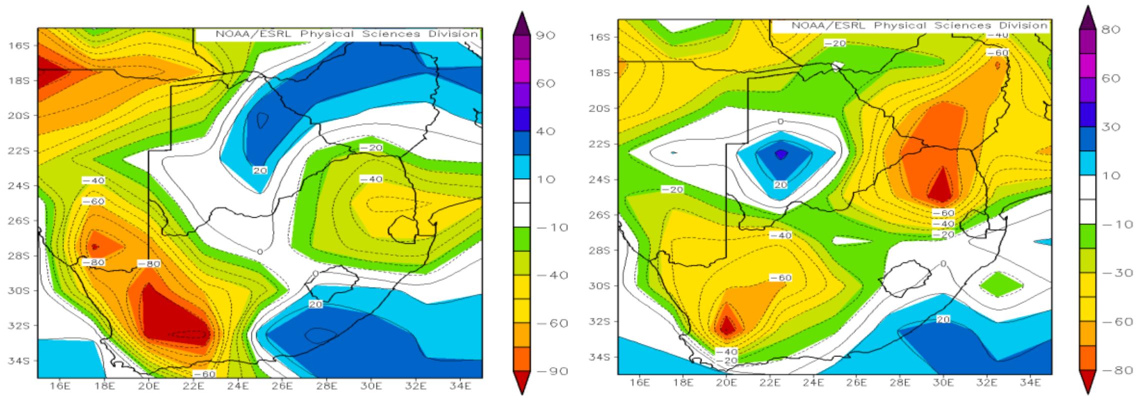


Figure 4.16: Sea Level Pressure (mb) anomalies over southern Africa from 13 January 2012 to 16 January 2012

4.7.3 Outgoing Longwave Radiation

In analysis, low OLR was observed over the southern part of the Limpopo province. During 17-18 January 2012, negative anomaly OLR in Limpopo province was observed (Figure 4.17). During extreme flood events in Limpopo province, negative or low OLR anomalies are dominant. The negative anomalies over Limpopo province support the focus of this study on extreme events.



a) b)

Figure 4.17: a) Outgoing Longwave Radiation (w/mˆ2) from 17 January 2012 and b) 18 January 2012 over southern Africa

4.7.5 Wind anomalies over southern Africa 2011/12

Easterlies were predominant at 500 hPa over the study area in 2011/12 summer season (Figure 4.18). Easterly wind vector anomaly has a significant role in the transportation of moisture which results to extreme rainfall over the mainland and leads to flooding. The vector wind anomaly between December and January tends to be easterly, transporting moisture inland, east southern Africa and being favourable to make extreme rainfall in some cases (Fig.4.18). Vector wind anomalies of the 2011/12 season were investigated in this study. Heavy rains were promoted by onshore winds between the TC and ridging mid-latitude anticyclones (Chikoore *et al.,* 2015). During wet years, easterlies anomalies are predominately over the study area. In Limpopo province, extreme rainfall events are triggered by the vector wind anomalies which occur mutually at the surface and 500 hPa levels.

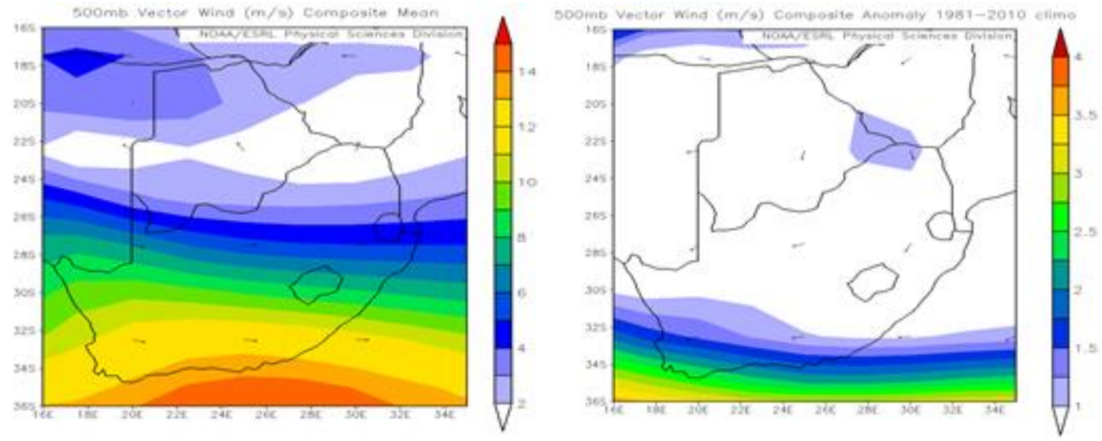


Figure 4.18 Left mean vector wind (m/s) and right anomalous vector wind (m/s) DJF 2011/12

4.8 Type 2: Cut-off lows

In December 1997, (Figure 4.19) more than 112 mm of precipitation fell over Limpopo, (Thabazimbi) area in 24 hours (compared to the monthly average for December of 96.8mm) when the cut-off low was situated over the northern part of Namibia and Botswana. The duration of COLs over South Africa and Limpopo province are categorised into 1-2 days, 3-4 days and >4 days (Figure 4.19). In this study, Limpopo COLs event is called an extreme rainfall event if at least one station reports >50mm rainfall per day. According to Taljaard (1985), COLs lasting only for one to two days are regarded as short-lived systems and are mostly quick-moving and weak. JFM are the most common months for cut-off lows over the region (Figure 4.19). December and April also show high occurrence, while cut-off lows are more common in December and January (Singleton & Reason, 2007) (Figure 4.19). These findings are consistent with Taljaard (1985) for seasonality evidence. Cut-off low pressure system is closed circulations in the upper troposphere which is usually formed from a deep trough in the westerlies (Palmén & Newton 1969; Winkler *et al*. 2000). Rainfall associated with cut-off lows is a challenge to predict; especially due to convection over a warm ocean. Daily rainfall exceeding >50mm per day was selected from January to December 1960 to 2014. Analysis was performed from the selected months (Figure 4.19). Anomalies sea level pressure on 20 February 2001 was observed over southern Africa (Figure 4.22). Unusual sea level pressure is influenced by cut-off low (Figure 4:22) associated with intense rainfall. The air temperature at 200hPa is displayed at Figure 4.24. The position of low at 200hPa air temperature fulfils the requirement of COL according to Taljaard (1985).

Cut-off low is associated with extreme rainfall over large areas. In South Africa, cut-off lows are most crucial weather systems in terms of precipitation rate. Limpopo province experiences summer rainfall, especially via extra tropical clouds bands, specifically the north of the country, easterly lows (Singleton & Reason, 2006). The extreme weather conditions can be identified in this atmospheric patterns (Figure 4. 20), the cut-off low system sitting over the Limpopo, Zimbabwe and Mozambique results to extreme flooding over the area. Anomalous rainfall spreading over Limpopo province results to extreme flood events (Figure 4.21). The vector wind anomaly in 20 February 2001 tends to be easterly, transporting moisture inland, and is favourable to produce heavy rainfall in this case (Figure 4.23).

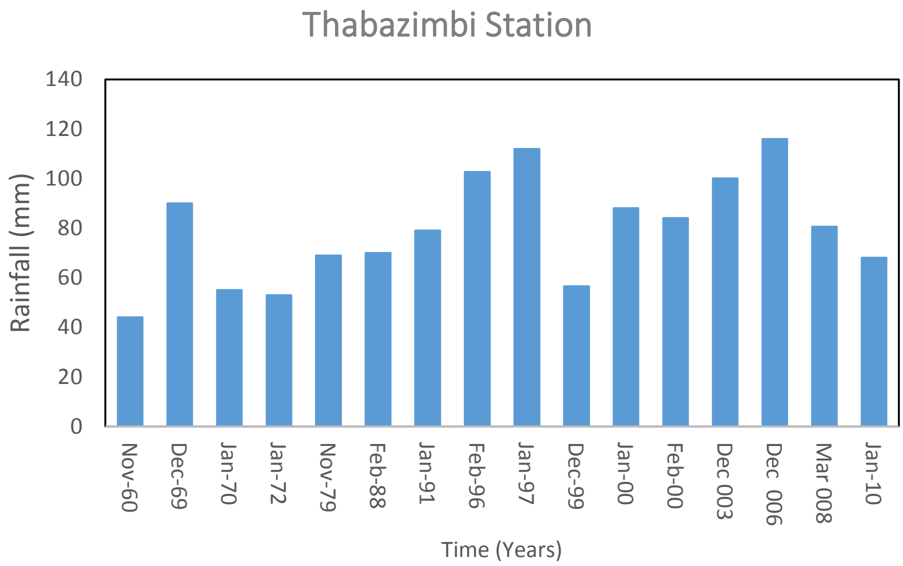


Figure 4.19: Identified Cut-off low from 1960 to 2014, over South Africa (Limpopo)

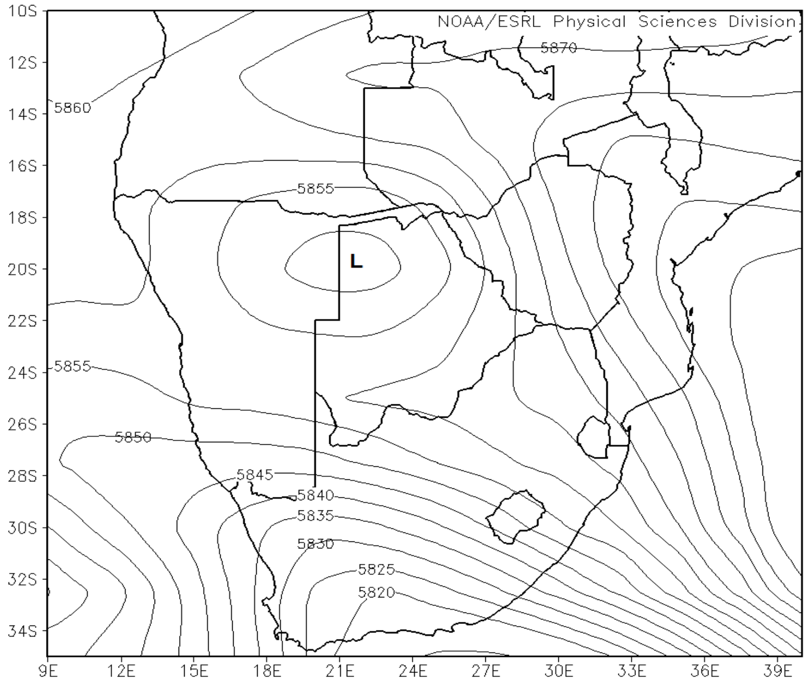


Figure 4.20 Cut-off low identified on 20 February 2001 over Southern Africa, a) Geopotential heights of the 500 hPa pressure level

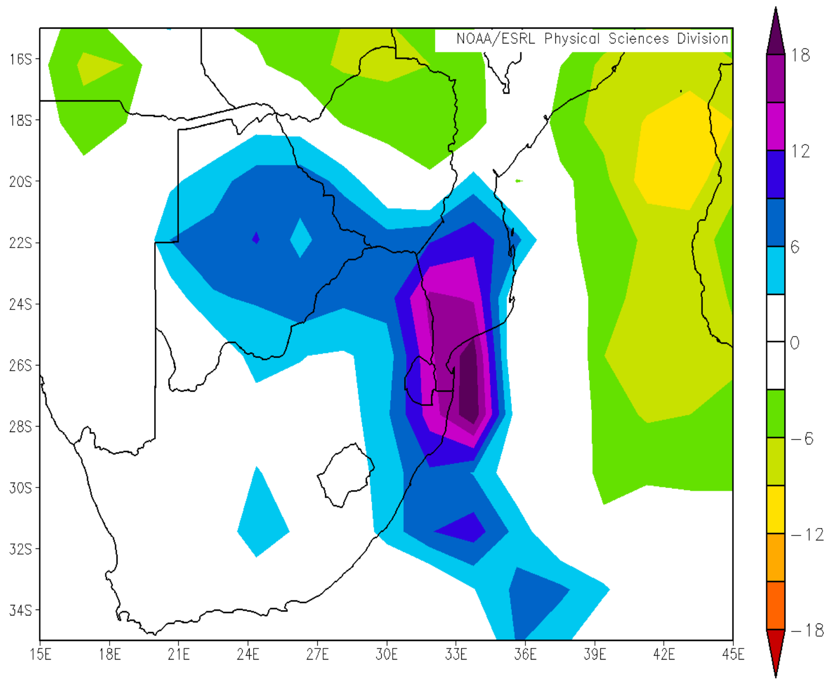


Figure 4.21 Identified anomalous rainfall (mm) on 20 February 2001 over southern Africa

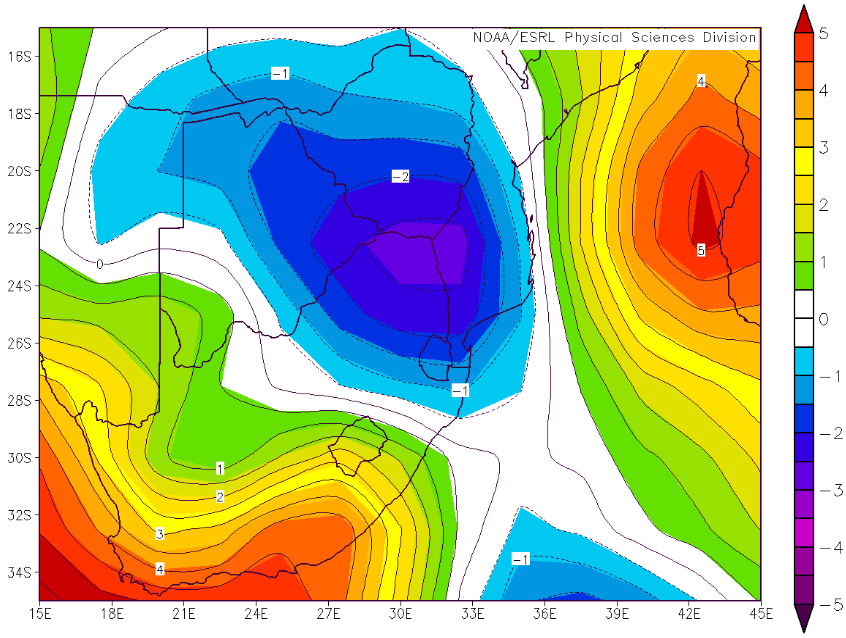


Figure 4.22 Sea Level Composite Anomaly (mb) on 20 February 2001, over southern Africa

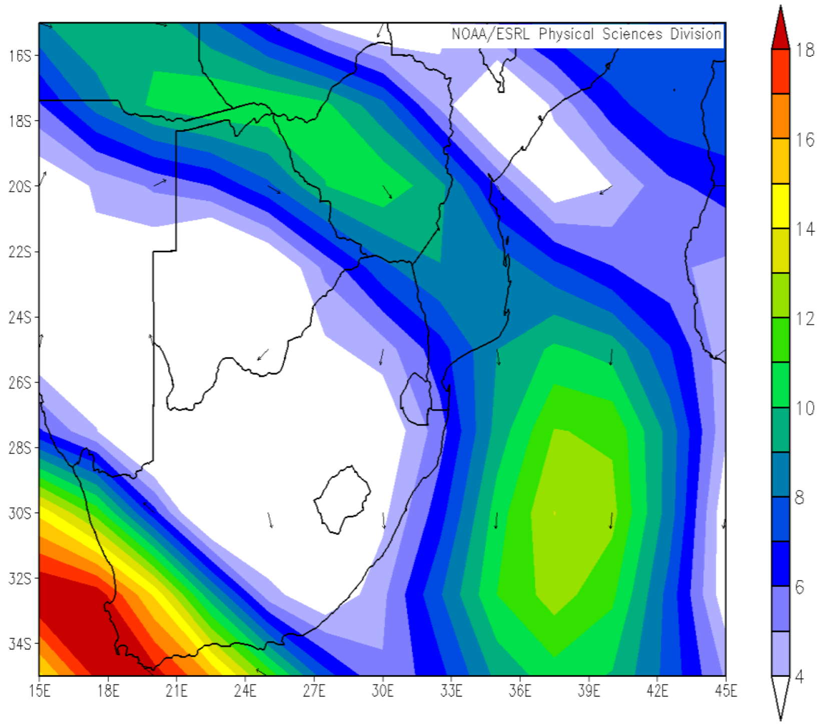


Figure 4.23 Wind anomalies (m/s) on 20 February 2001 at 500hPa, over southern Africa transporting moisture

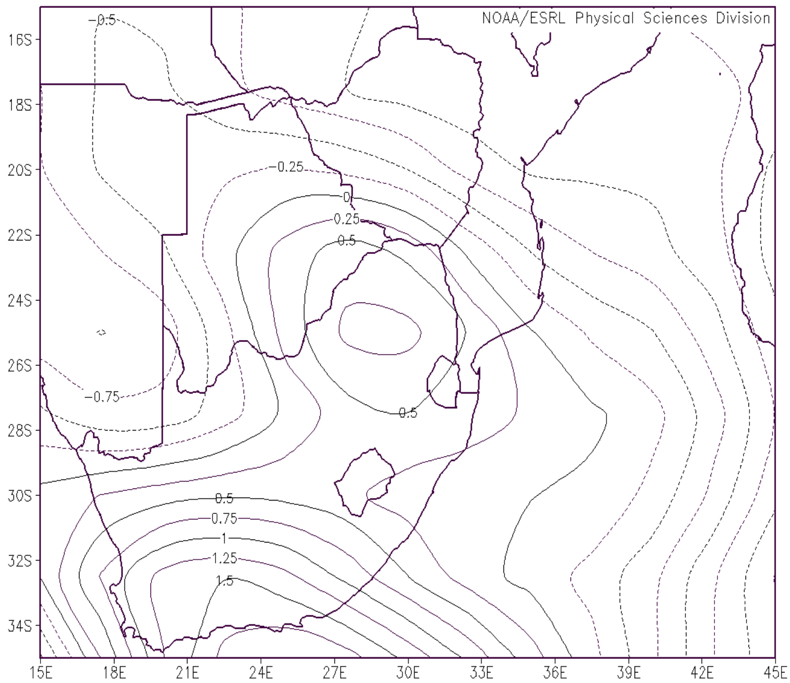


Figure 4.24 Air temperature (C) at 200 hPa, over southern Africa, 20 February 2001

4.9 Type 3: Botswana High

The Botswana high is referred as a high pressure cell which exists at the 500 hPa level and is centred over western Botswana and central Namibia during late austral summer. Over Zimbabwe, the position and strength of the Botswana high is normally known to impact rainfall and is usually associated with below average rainfall (Ratna *et al.,* 2013).

This study focuses on late summer January to March (JFM) season as connections between the Botswana High and regional precipitation appear to be strongest over Limpopo province during those months. Regions that experience high yield of agricultural production are those which lie on the extremity of the ITCZ whereby the level of rainfall depends on the southward movement of the ITCZ (Magadza, 1994). The analysis also indicated that periods of extreme drought events are associated with the dominance of Botswana High, and periods of high precipitation are characterized by a persistence of the ITCZ.

An intense Botswana high occurred during JFM 2002 (Figure 4.26), and during 2001 to 2002 austral summer, there was no ENSO event. During October-November-December (OND) 2001 season, the Botswana high was not much stronger than average (Figure.4.27) and South Africa experienced below- average rainfall. This is a good example of non-ENSO year wherein South Africa received below average precipitation and a strong Botswana high occurred. In South Africa, extreme droughts are consistently associated with the formation and intensification of the mid-tropospheric Botswana high.

The Botswana high is coupled with subsidence over much of the subcontinent. During JFM 1983, the Botswana high was very strong and Limpopo province experienced one of the most widespread extreme droughts ever recorded. The strong Botswana high is generally associated with El Nino years and below average precipitation (Figure 4.28 and 4.29) while a weak Botswana high is associated with above precipitation (Figure 4.28b).

The Madagascan and Mozambique westerly wind anomalies (Figure 4.31a) at 850 hPa expand across the offshore and landmass of Namibia indicate reduced transport of Indian Ocean moist air on the source area of cloud bands by the easterlies. Across southern Africa (Figure 4.28b), anomalous subsidence is present and extending to the mid-latitude South Indian Ocean consistent with the dry conditions and unfavourable for cloud band formation.

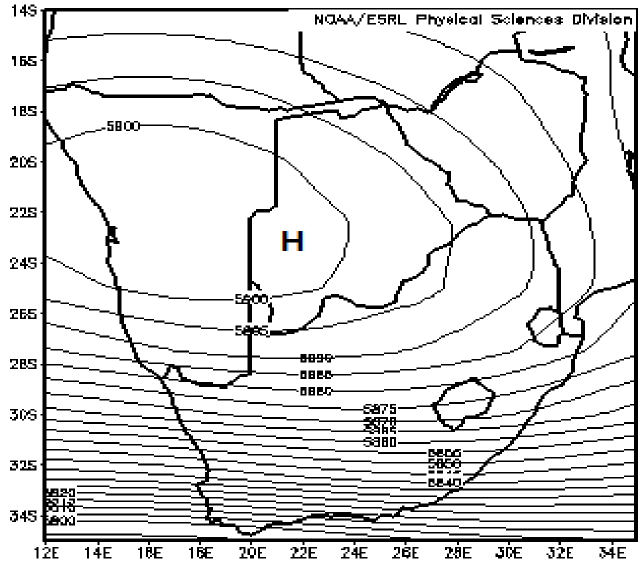


Figure 4.25: Mean summer (DJF) 500 hPa geopotential height (m) over southern Africa

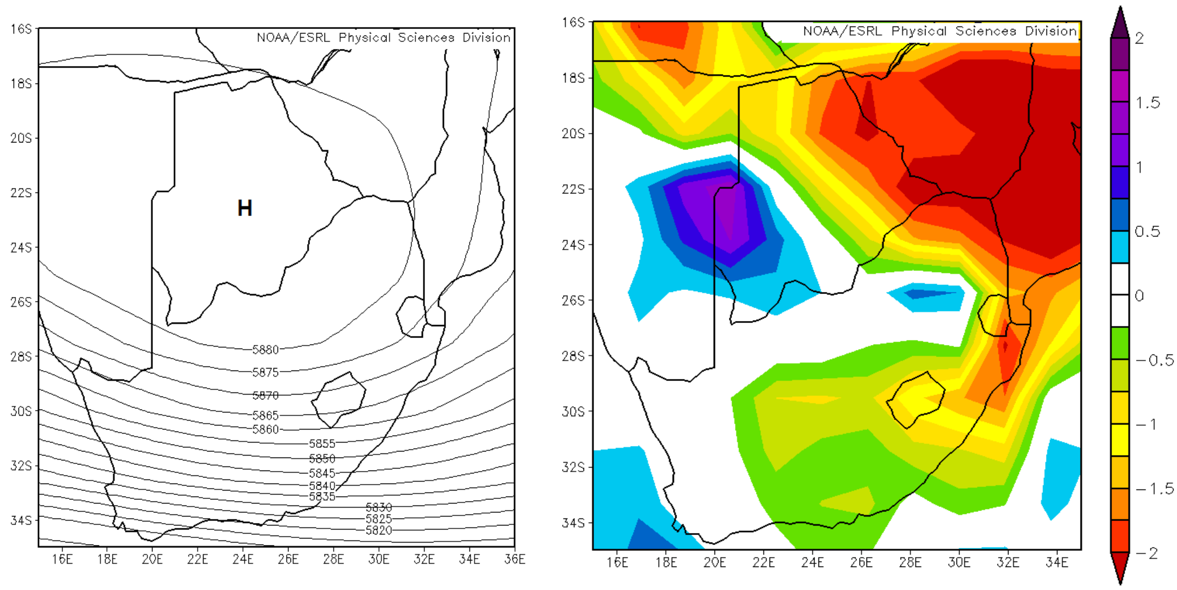


Figure 4.26: Geopotential height (m) at 500 hPa during JFM 2002 over southern Africa and rainfall anomaly for JFM 2002

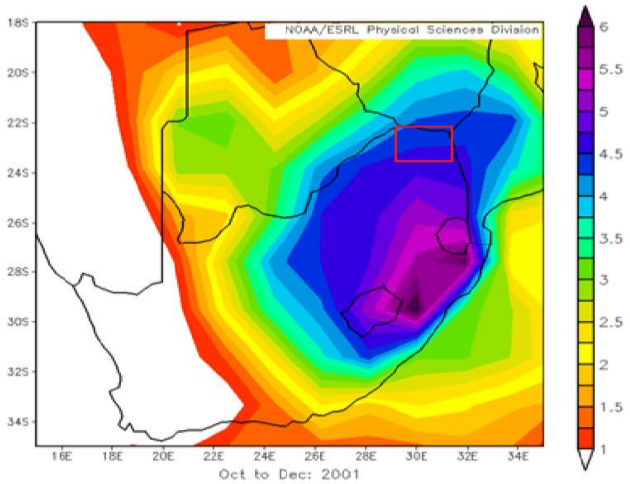
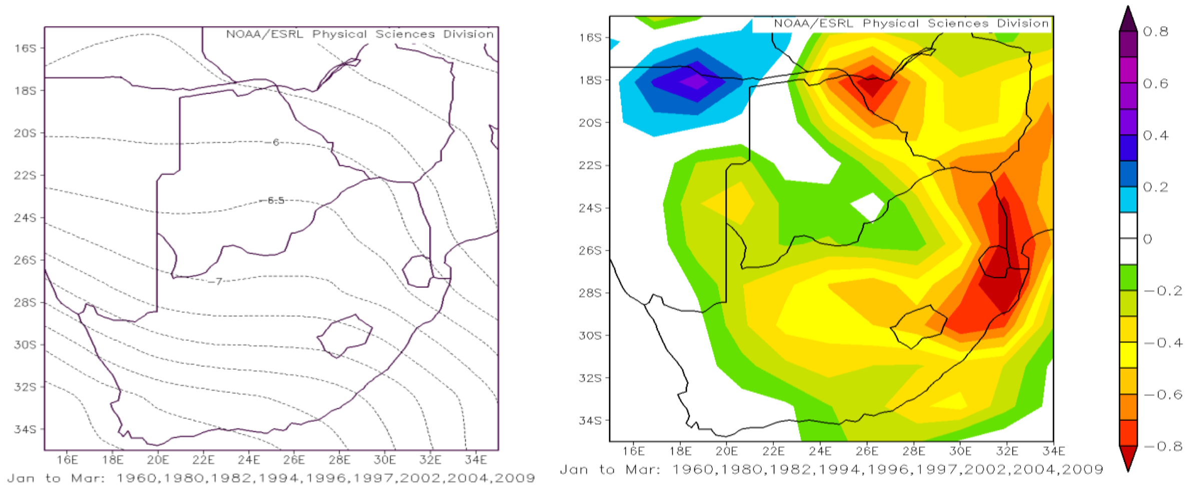


Figure 4.27: Mean monthly rainfalls (mm) OND 2001 over South Africa (Limpopo)



a) b)

Figure 4.28: a) Geopotential height (m) at 500 hPa and b) Composite rainfall anomaly (mm) differences for the January-February-March (JFM) season during El Nino years between 1960 and 2014.

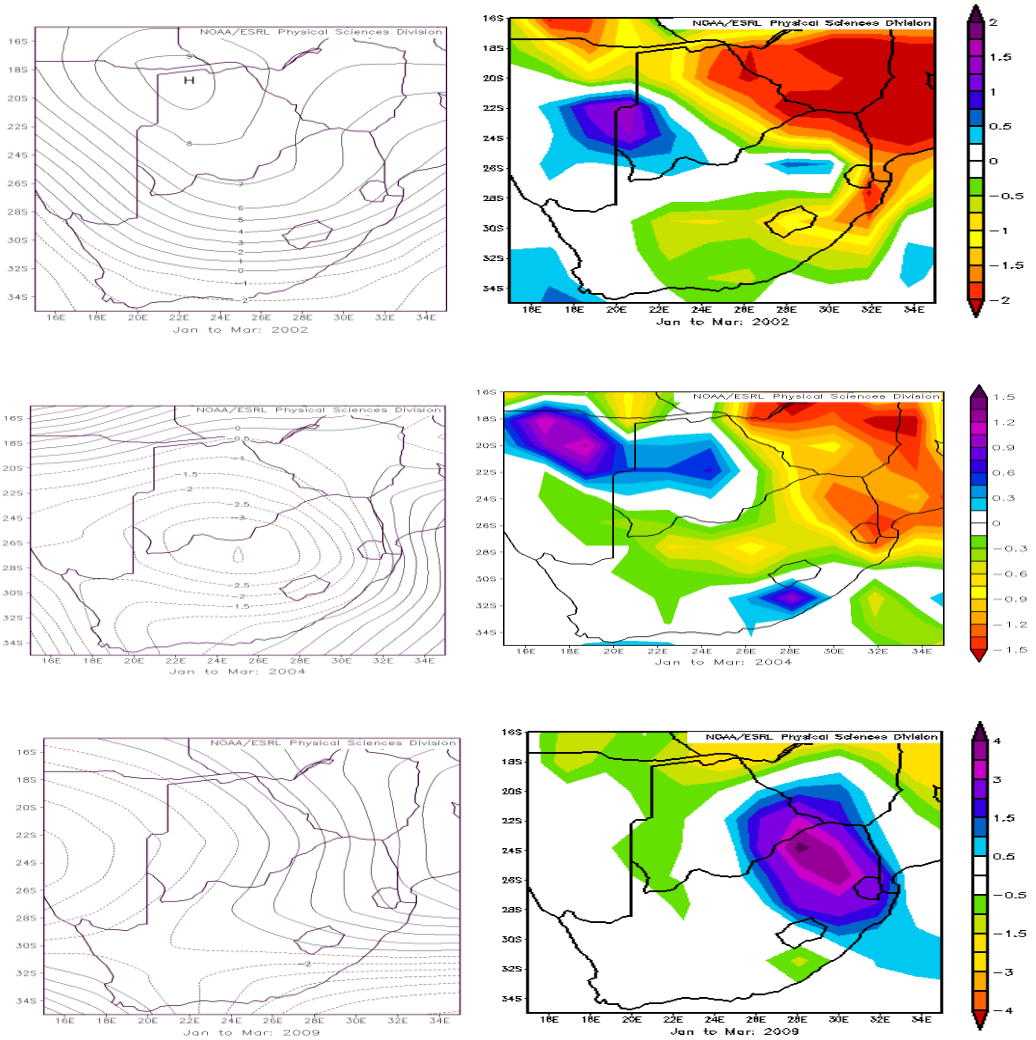
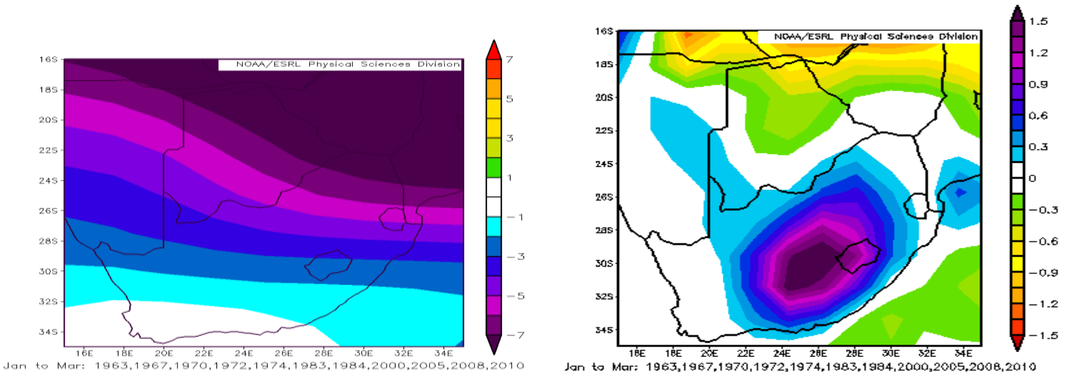
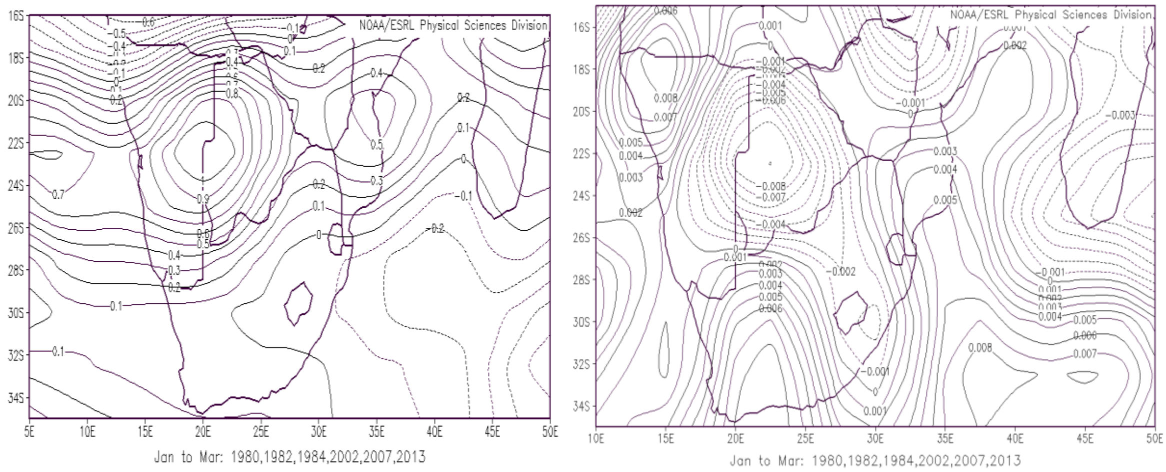


Figure 4.29: Geopotential height (m) at 500 hPa and Composite rainfall anomaly (mm) differences for the January-February-March (JFM) season during 2002, 2004 and 2009



a) b)

Figure 4.30a) Geopotential height (m) at 500 hPa and b) Composite rainfall anomaly (mm) difference for JFM season during La Nina years between 1960 and 2014



a) b)

Figure 4.31a) Composite anomaly zonally wind (m/s) at 850hPa, and b) Omega (Pa/s) at 850hPa for neutral summers between 1960 and 2014

4.10 The oceans and extreme events

Tropical and subtropical oceans have an impact on surface air temperatures, air pressure, circulation and rainfall patterns which may affect remote locations via teleconnections. This may lead to extreme events at seasonal timescales over adjacent land areas (Jury *et al*., 1992). The main factor controlling the rainfall over certain environment is the unique oceanographic setting (Pinto, 2015; Tyson & Preston-White, 2000; Nicholson, 2003). Southern Africa rainfall is generally influenced by sea-surface temperature variability in the tropical Pacific Ocean. The tropical, Pacific, SWIO, equatorial and South Atlantic Ocean basins are regions responsible for the variation in extreme rainfall.

4.10.1 Tropical Pacific Ocean

A correlation of the SOI and GPCP rainfall over the study area shows positive values (Figure 4.32). In the study, when there is positive SOI there is precipitation. ENSO peaks during DJF, coinciding with the summer rainfall season over southern Africa. Several studies suggest that the equatorial Pacific Ocean seems to have more effect on climate and weather of South Africa, especially precipitation which is the most crucial meteorological parameter over Limpopo. Over the eastern part of South Africa (including Limpopo) rainfall decreases during El Niño seasons (Nicholson & Kim, 1997; Philips *et al.,* 1998).

In South Africa, extreme drought events are usually linked with El Niño (Lindesay & Vogel, 1990). The occurrence of El Niño and La Niña events may be determined using various indices, but the Southern Oscillation Index (SOI) and a Nino3.4 index are used in this study (Figure 4.33). In southern Africa, extreme drought events occur mostly during ENSO warm phase and the occurrence of extreme floods usually coincides with La Nina years (Rouault & Richard, 2005). In addition to warm ENSO phase, extreme drought events over the area may also be triggered by various global and local factors such as SSTs, negative Indian Ocean Dipole (IOD) and frequent cyclogenesis over the South West Indian Ocean (SWIO) (Masih *et al.,* 2014). According to Richard *et al.,* (2001), extreme droughts that occurred between 1970 and 1988 were more intense than the 1950-1969 droughts over southern Africa.

Using the SOI (Table 4.1), considering that the index of >1 is identified as a La Niña event and the index of < -1 in this study is identified as an El Niño event, we then identified 13 La Niña events and 17 El Niño events from 1960 to 2014. Most of the identified El Niño events during the study period (1960–2014) peak in the austral summer over the study area. In this study, El Niño events prove to be frequent than La Niña events. El Niño and La Niña events were further analysed in order to investigate the influence of SSTs to rainfall variability over Limpopo during these events. Anomalies of 850 hPa wind vector, 500 hPa relative humidity, SSTs, and GPCP precipitation were the climatological parameters used for this analysis, and also show the characteristics of the atmosphere during ENSO events.

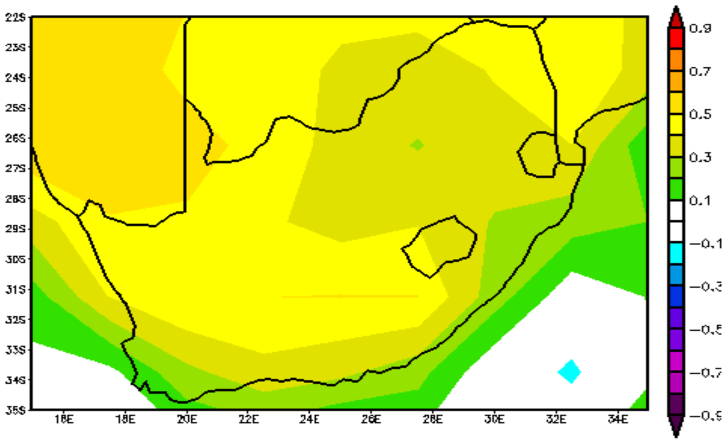


Figure 4.32: Correlation of DJF GPCP precipitation (mm) with SOI over South Africa from 1960-2014

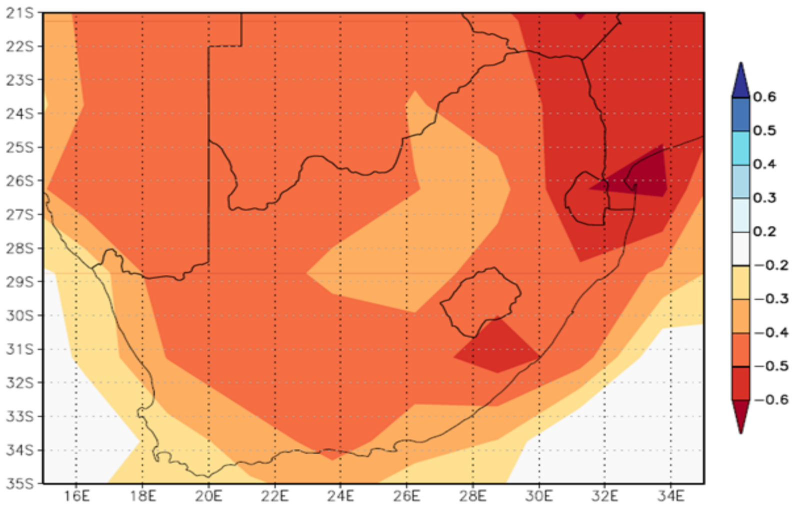


Figure 4.33: Correlation of DJF GPCP precipitation with Nino 3.4 over South Africa

Table 4.1: El Niño and La Niña years from 1960 to 2014, NOAA (2016)

El Niño years	La Niña years
1963/64	1967/68
1965/66	1970/71
1968/69	1971/72
1972/73	1973/74
1976/77	1975/76
1977/78	1984/85
1982/83	1988/89
1986/87	1998/99
1987/88	1999/00
1991/92	2000/01
1994/95	2007/08
1997/98	2008/09
2002/03	2010/11
2004/05	
2006/07	
2009/10	
2014/15	

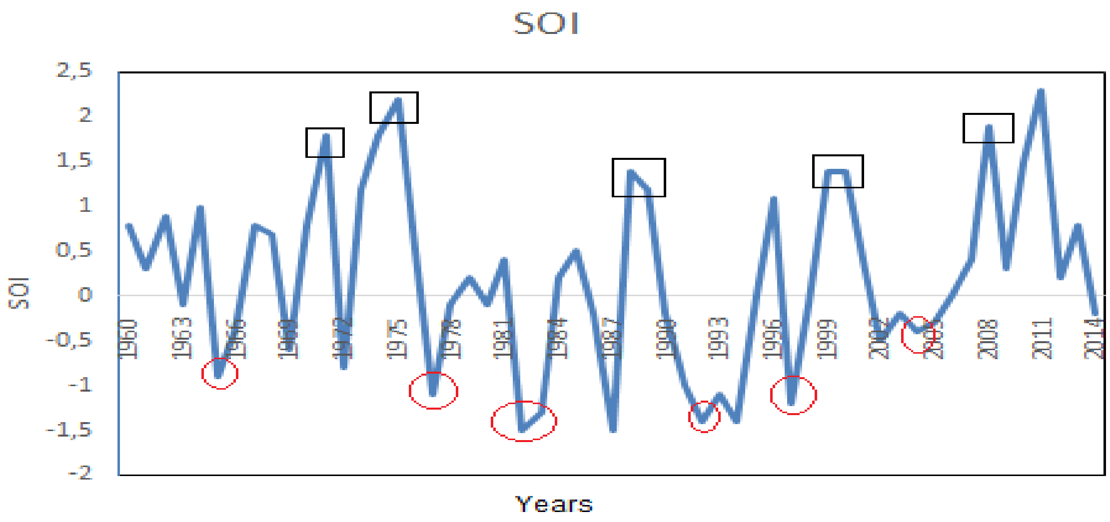


Figure 4.34: SOI from 1960-2014, showing El Nino (Red circles) and La Nina (Black Box) mature years

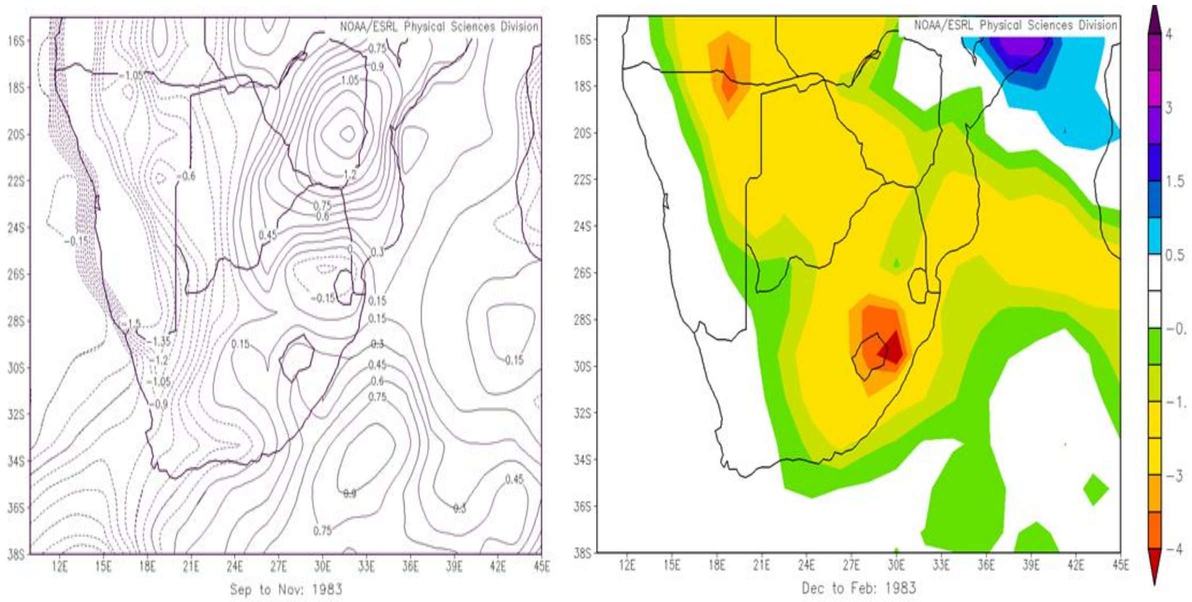
4.10.2 Indian Ocean

In this section, the extreme 1983 and 1992 drought events were analysed. The extreme 1992 drought event occurred under strong El Niño conditions whereas the 1983/84 drought occurred during the presence of a weak La Niña in the eastern equatorial Pacific (Figure 4.35). The 1992 event is much more widespread, as with SST anomalies extending to the Mozambique Channel (Figure 4.36). During the extreme drought event of 1992/93, anomalous rainfall was recorded for DJF only (≤ -2mm) (Figure 4.36b). During El Nino years 1983 and 1992 illustrated in Figures 4.35a and 4.36a, warmer than normal SSTs are found over the Southwest Indian Ocean (SWIO) and Southeast Atlantic Ocean. SST anomalies are plotted for SON for both extreme drought events 1983/84 and 1992/93 (Figure 4.35 and 4.36). Anomalies rainfall events for DJF for both extreme droughts are plotted and depict below rainfall over the region. Limpopo receives below rainfall (Figure 4.35) as the extreme drought was widespread over the southern Africa.

Several studies have considered the Indian Ocean as a major source of moisture for southern Africa and rainfall variation. It is also a basin conducive for tropical cyclogenesis (e.g Ash & Matyas 2012, Manatsa & Behera, 2014). Indian Ocean Dipole (IOD) is another phenomenon in addition to ENSO, which allows for the interaction between the atmosphere and the sea (Manatsa *et al.*, 2008). Indian Ocean Dipole is one of the factors that shape SST anomalies in the tropical Indian Ocean and its influence appears to be substantial in the zonal SST gradient and surface wind anomalies. The dipole is one of the most dominant modes of inter-annual variability in the Indian Ocean sea surface temperatures (Saji, 2005; Hong *et al.,* 2008; Mahala *et al.,* 2015). It is evident that IOD is relatively responsible for steering climate variability of surrounding landmasses (Marchant *et al.* 2007).

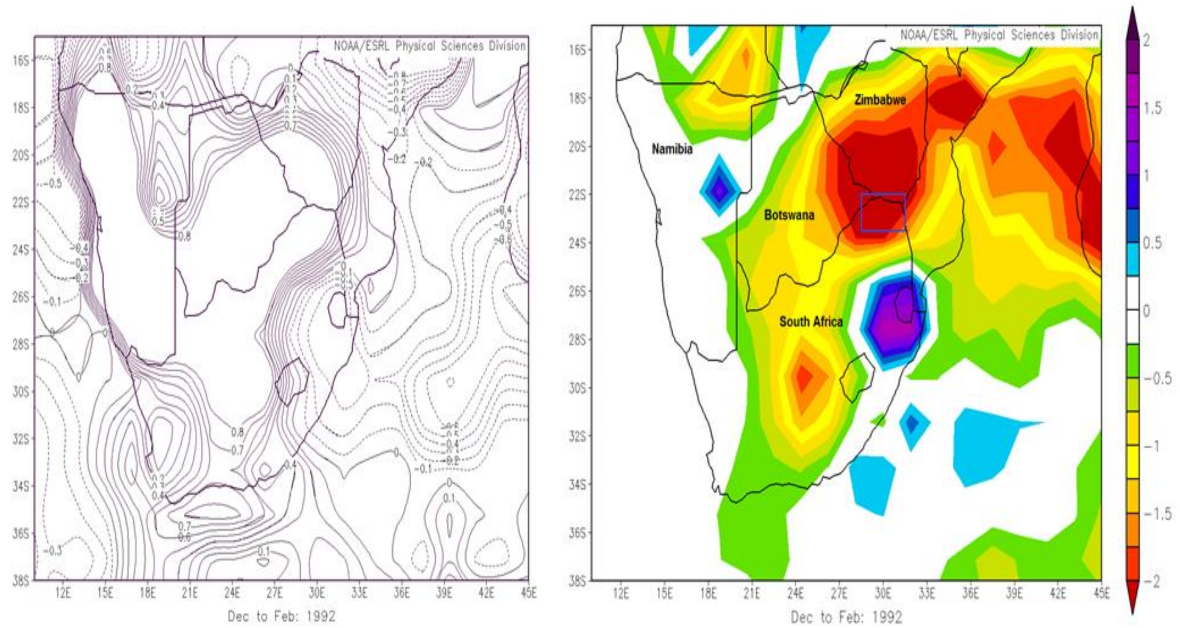
ENSO impacts rainfall over southern Africa via the positive IOD which changes the anomalous walker cell over the Indian Ocean. When the SSTs in the western Indian Ocean are warmer relative to the east, positive IOD dominates the enhancement of precipitation over eastern Africa (Mason & Jury, 1997). When the western Indian Ocean is cooler relative to the east, the negative IOD is normally associated with wet conditions over south-eastern part of southern Africa. IOD events that occurred independent of ENSO accounted for more control in the Indian Ocean variability than the events that occurred with ENSO (Saji & Yamagata, 2003). A study by Hong *et al.* (2008) indicate that about 40% of IOD events occur with ENSO and La Nina associated with the negative IOD while El Niño is associated with the positive IOD, for example, the 1997 strong El Niño, though Ashok *et al.* (2003) regarded it as being unpredictable. The severe and extreme droughts of 1983 and 1992 occurred in the presence of positive IOD, in addition to warm ENSO conditions.

Consequently, there are some years when the El Niño co-occurs with the negative IOD. Saji *et al.* (1999) discovered that the dipole mode accounts for about 12% of the sea surface temperature in the Indian Ocean during its active years. It was observed that a negative IOD event intensifies extreme TC activities as it does during La Nina (Mahala *et al.*, 2015; Currie *et al.,* 2013).



a) b)

Figure 4.35a) Sea Surface Temperature (k) at 850hPa SON and b) rainfall anomaly DJF 1992 over southern Africa



a) b)

Figure 4.36a) Sea Surface Temperature (k) at 850 hPa SON and b) rainfall anomaly DJF 1992 over southern Africa

4.10.3 Tropical Atlantic Ocean

During February to May 2001, southern Africa was influenced by tropical Atlantic when SST was anomalously warm in the South East Atlantic Ocean and various countries experienced above average precipitation and extreme floods which resulted to loss of life and destruction. Benguela Nino case of 2001 resulted to wide spread of extreme rainfall over southern Africa which also affected Limpopo due to extreme flooding (Figure 4.37). In late summer 2001, the Benguela Nino lasted from February to May which is a period of 4 months (Figure 4.37). In the tropical South Atlantic, a wide extent warming normally arises during a mature stage of El Nino, but Benguela Ninos does not constantly follow these tropical warmings (Binet *et al.,* 2001). A good example is a study by Shannon *et al.* (1986) which identified Benguela Nino in 1934, 1963, 1984 even though only the last one followed the mature stage of El Nino event (1983).

Benguela Niño events are irregular, normally peaking in late summer and may continue for a period of months (Florenchie *et al.,* 2003; Shannon *et al*., 1983). These anomalously warm events frequently cause significant rainfall anomalies, more especially in southern Africa (Hirst & Hastenrath 1983; Rouault *et al.*, 2003a) and can drastically modify fish distributions (Boyer *et al.,* 2001). The 1984 and 1995 Benguela Niño episodes were the most intense (Reason, *et al.,* 2006). Rouault (2012) indicated that this intrusion of warm tropical waters in the Benguela region occurs twice per year: in the late summer and late spring.

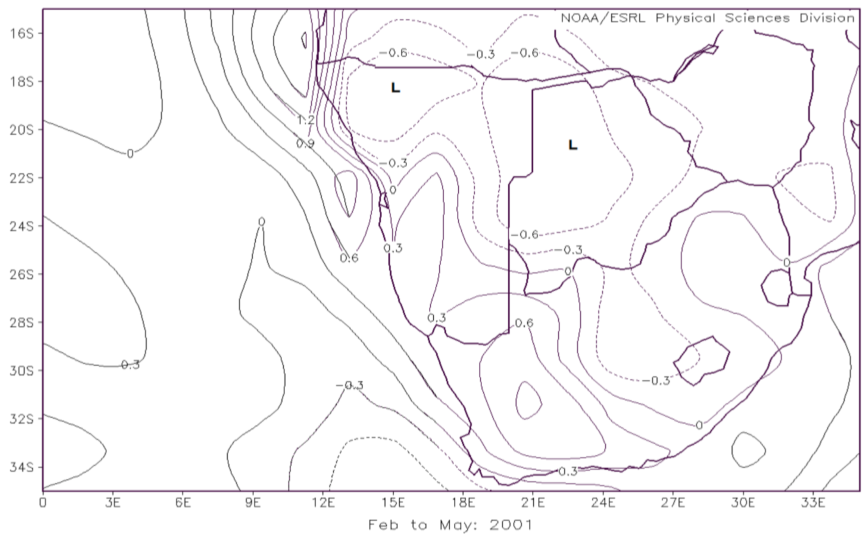


Figure 4.37 Anomalous Sea Surface Temperature (SST) (k), February to May 2001

4.11 Summary

This chapter provided the spatial variability of climate extremes over Limpopo province. Extreme climate events occurrences are associated with persistent Botswana high pressure systems which usually induce dry conditions over South Africa. In South Africa, extreme droughts are consistently associated with the formation and intensification of the mid-tropospheric Botswana High.

The following were observed about variability and long-term trends of climate extremes in the perspective of Limpopo province:

a) The NCEP/NCAR model shows strongly negative OLR anomalies at the top of the atmosphere (i.e. 500 hPa), suggesting cloud covered conditions during the identified extreme floods. As a result, wet weather was experienced since OLR at 500 hPa is a proxy for precipitation and convective clouds. Upper level (i.e. 500 hPa) easterlies are predominant over Limpopo, especially during the 1999/2000 floods.
b) The climate of Limpopo province is also influenced by two anticyclones over southern Africa.
c) Extreme drought events are associated with the dominance of Botswana High and periods of high precipitation are characterized by persistence of the ITCZ.
d) During JFM 1983, the Botswana high was very strong and Limpopo province experienced one of the most widespread extreme droughts ever recorded.
e) In this study, the duration of COLs over South Africa and Limpopo province are categorised into 1-2 days, 3-4 days and >4 days.
f) Cut-off low system is a local driver of extreme rainfall events over the study area.
g) During the study period, (1960–2014) most of the identified El Niño events peak in the Austral summer over the study area.
h) In this study, El Niño events prove to be frequent than La Niña events.
i) This study shows that extreme rainfall events occurred over southern Africa during December, January and February.
j) The extreme droughts events are frequent and tend to cluster. The major droughts occurred in Limpopo during 1982/83 and 1991/92, but the latter was the most severe drought.

k) A correlation of the SOI and GPCP rainfall over the study area shows positive values, and when there is positive SOI, there is precipitation.

The tropical, Pacific, SWIO, equatorial and South Atlantic Ocean basins are regions responsible for the variation in extreme rainfall. Indian Ocean is a major source of moisture for southern Africa and rainfall variation. The next chapter provides Extreme Value Theory, Block Maxima approach, General extreme value distribution, estimation parameters and correlation analysis.

Chapter 5

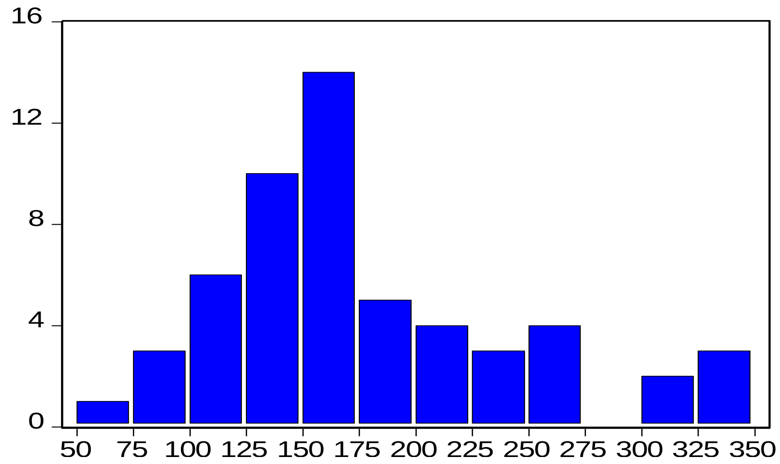
Modelling extreme events using extreme value theory

5.1 Introduction

The Generalised Extreme Value (GEV) distribution was fitted using the R packages 'ismev' and 'texmex' (Heffernan & Tawn, 2004; Heffernan & Stephenson, 2012). The package 'texmex' allows for maximum likelihood estimation (MLE), penalized MLE and Bayesian estimation, conditional extremes for multivariate analysis but also includes some univariate capabilities (Heffernan & Tawn, 2004). The aim of this chapter is to employ Extreme Value Theory to model climate extreme events in future.

5.2 Exploratory data analysis

In this study, the analysis was based on the historical maximum annual rainfall data from Thabazimbi station over Limpopo province from 1960 to 2014. Summary statistics of maximum yearly rainfall for the sampling period is given in Figure 5.1. The distribution of the sampling data is skewed to the right and leptokutic shown by the skewness value of 0.858 and a kurtosis value of 3.131 respectively. The Jarque-Bera test also confirms that the distribution of maximum rainfall is non normal.



Series: MAX	
Sample 1 55	
Observations 55	
Mean	178.4818
Median	165.5000
Maximum	326.8000
Minimum	72.10000
Std. Dev.	64.29908
Skewness	0.857780
Kurtosis	3.131046
Jarque-Bera	6.784059
Probability	0.033640

Figure 5.1 Summary statistics of the maximum rainfall data in the study area

Figure 5.2(a) shows the maximum rainfall (mm). The maximum rainfall data were obtained from South Africa Weather Service (SAWS). It is evident from Figure 5.2(a) and seems reasonable to assume that data is stationary.

Yearly blocks were used in fitting a 54 years' data set. The GEV distribution was then fitted to the block maxima data. Figure 5.2 (b), (c) and (d) show the density, normal quantile to quantile (QQ) and box plots respectively. The normal Q-Q plot of annual rainfall shows departure from a normal distribution at lower and upper tails of the data as shown on Figure 5.2(d). The distribution of the maximum rainfall is slightly skewed to the right as seen in Figures 5.2(b) and 5.2(d). It is very crucial to fit a distribution that is able to accurately predict the probability of extreme maximum annual rainfall. The tails of the distribution also contain rare events and those events can be catastrophic.

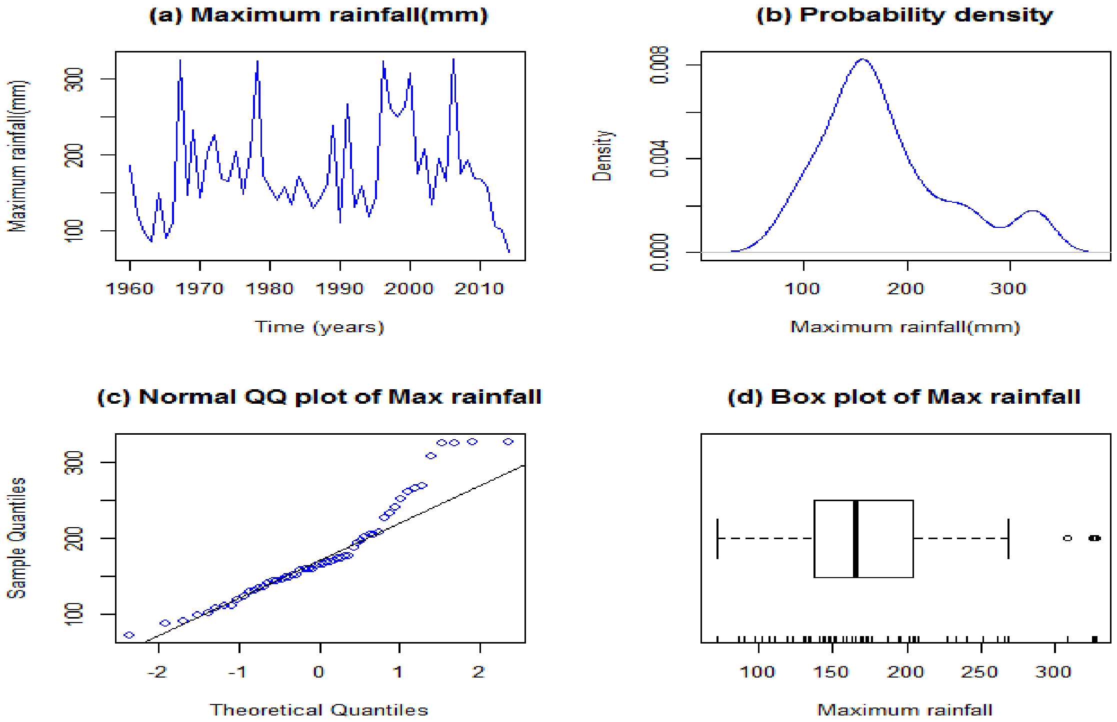


Figure 5.2: Maximum rainfall for Thabazimbi station for the period January 1960 to December 2014

5.2 Empirical results and discussions

Table 5.1 shows the maximum likelihood estimates of the stationary GEVD distribution (M_0) with the standard errors in parentheses. The results show that the data can be modelled using a Frechet class of distributions since ξ = 0.0139.

Table 5.1: Maximum likelihood estimates of the GEVD distribution parameters with standard errors in parentheses

$\hat{\xi}$	$\hat{\sigma}$	$\hat{\mu}$
0.0139(0.1072)	49.2921(0.1118)	149.1347(7.5378)

5.2.1 Diagnostic analysis

Figure 5.3 shows that the quantile to quantile (Q-Q) and the probability to probability (p-p) plots are almost linear showing a reasonable good fit of GEV distribution to the maximum rainfall data. As shown in Figure 5.3 bottom left panel, the observations are within the 95% confidence interval, meaning that the GEV distribution can be used for prediction of extreme high quantiles. Diagnostic plots for Thabazimbi station, probability plot, quantile plot, return level plot and density plot, provide solid evidence that GEV distribution is a good fit to the block maxima data. The probability plot in Figure 5.3 shows that the points are close to the reference line and the probability density plot shows that the GEV distribution follows the shape of the empirical distribution denoted by the histogram. The study results indicate that the data follow a GEV distribution and do not deviate from assumptions.

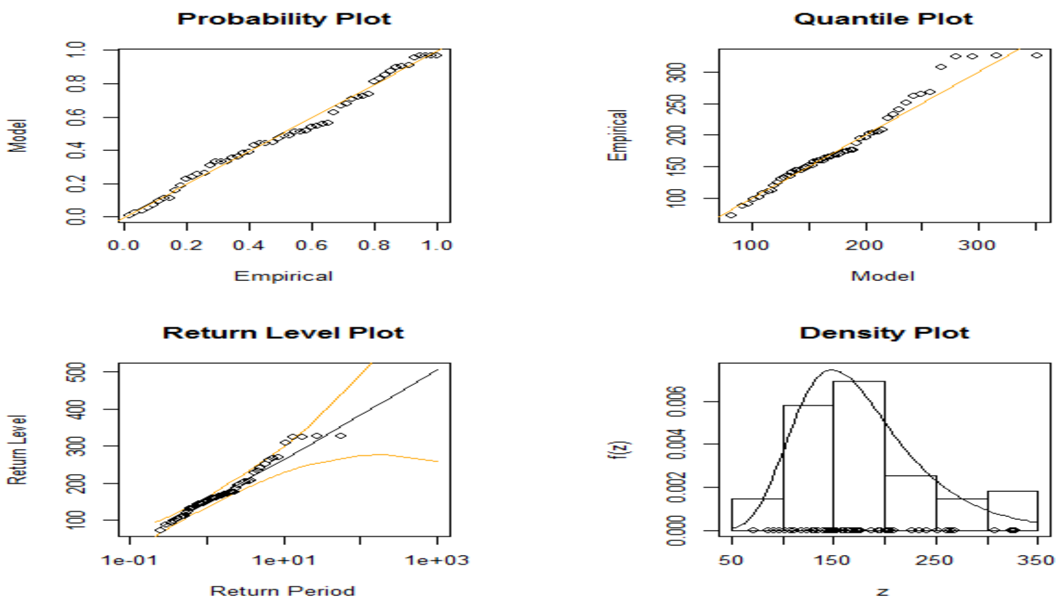


Figure 5.3: Diagnostic plots

5.2.2 Models

The models considered in this study are:

$X \sim \text{GEVD}(\mu(t), \sigma(t), \xi(t))$

$$M_0: \mu(t) = \mu \text{ , } \xi(t) = (\xi) \quad \sigma(t) = \sigma$$

The results of M_0 were discussed in Section 5.1. This is used as a base model. The other models considered are:

$$M_1: \mu(t) = \mu_0 + \mu_1 t$$

$$\mu(t) = \sigma$$

$$\xi(t) = \xi$$

$$\mu\,(t) = 146.1 + 0.1181t$$

$$\sigma\,(t) = \sigma = e^{-3.9} = 49.4024$$

$$\xi(t) = \xi = 0.007865$$

$$M_2: \mu(\text{t}) = \mu_2 + \mu_3 \text{SOI}$$

$$\sigma(t) = \sigma$$

$$\xi(t) = \xi$$

$$\mu(t) = 146.498 + 11.959 \text{ SOI}, \sigma = 49.4024, \xi = 0.007865$$

L = - 300.5607, AIC = 609.1214

where L denotes the log likelihood.

The parameter estimates of the models with standard errors in parentheses are given in Table 5.2.

Table 5.2: Parameter estimates

	M_0	M_1	M_2
$\hat{\mu}$: (intercept)	149.13(7.538)	146.10(12.02)	146.50(7.534)
$\hat{\sigma}$: (intercept)	49.29(5.512)	49.40(0.112)	47.56(0.113)
$\hat{\xi}$: (intercept)	0.0139(0.107)	0.007865(0.107)	0.0366(0.108)
$\hat{\mu}$: (t)		0.118(0.361)	
$\hat{\sigma}$: (SOI)			11.959(7.368)
Log. Likelihood	−301.8162	−301.761	−300.5607
AIC	609.6324	611.5235	609.1214

The full models after plugging the parameters estimates are:

M_0: $\mu(\mathrm{t}) = \mu = 149.1347$

$\sigma\ (\mathrm{t}) = \sigma = 49.292$
$\xi(\mathrm{t}) = \xi = 0.0139$

M_1: $\mu(\mathrm{t}) = 146.1 + 0.118\mathrm{t}$

$\sigma\ (\mathrm{t}) = \sigma = 49.40$
$\xi(\mathrm{t}) = \xi = 0.007865$

M_2: $\mu(t) = 146.498 + 11.959\ \mathrm{SOI}$

$\sigma\ (\mathrm{t}) = \sigma = 49.40$
$\xi(\mathrm{t}) = \xi = 0.007865$

5.2.3 Likelihood ratio tests

There are three models to select from. Choosing an appropriate model becomes an important matter with the possibility of modelling any sequence of the extreme value model parameters as functions of time or other covariates. As discussed earlier on this section, the maximum likelihood estimation of nested models leads to a simple test procedure of one model against the other. In all models, t denotes the time period which denotes a year in this study (1960 to 2014) and coded as $t = 1, \dots, 55$. A similar technique has been used by various researchers (e.g Katz *et al.,* 2002; Filici *et al.,* 2007; Feng *et al.,* 2007; Park *et al.,* 2010; Sugahara *et al.,* 2009; Maposa *et al*., 2014; among others). Since the models are nested, the best model is selected based on the deviance statistic which is given as $D = 2\{L(M_i) - (M_0)\}, i = 1,2, \ldots, p$ where p denotes the number of models and M_i is the model tested against the base model Mo. If $D > \chi_k^2$, we reject the null hypothesis of no improvement and conclude that model M_i provides a significant improvement over model M_0 at the 5% level of significance.

Now considering Mo and M_1, the deviance statistic is defined as

$$D = 2\,\{L\,(M_1) - L\,(Mo)\}$$

where $L(Mo)$ and $L\,(M_1)$ are the maximized log-likelihood under models Mo and M_1 respectively. A large value of D shows that model M_1 explains substantially more of variation in the data than Mo; small values of D suggest that the increase in the model size does not make any improvements in the model's capacity to explain the data. Therefore in this case $D_1 = 2\,\{L\,(M_1) - L\,(Mo)\}$

$$= 2\,\{-301.7617 - (-301.8162)\}$$

$$= 1.309$$

$x^2{}_1$ =3.84

Now $D_1 = 1.309 < \chi_1^2 = 3.841$, we fail to reject the null hypothesis and conclude that there is no significant improvement in the model fitting by adding the trend component t. For the model in which we add SOI as a covariate in the location parameter we get

$$D_2 = 2\,\{L\,(M_2) - L\,(Mo)\}$$

$$= 2\,\{-300.5607 - (-301.8162)\}$$

$$= 2.511$$

Since $D_2 = 2.511 < \chi_1^2 = 3.841$, we fail to reject Ho and conclude that there is no significant improvement in adding the SOI covariate at 5% level of significance. This implies that Mo can be used for predicting extreme quantiles of maximum rainfall in Thabazimbi area.

The profile likelihood of the shape parameter ξ for which the 95% confidence intervals for ξ is (-0.19568, 0.22349) is given in Figure 5.4. Major accuracy of the confidence interval is done by the use of the profile likelihood.

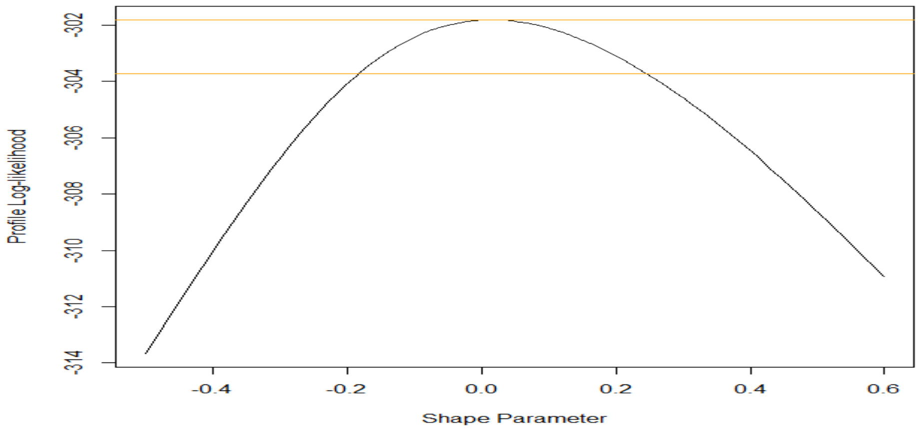


Figure 5.4: Profile likelihood plot of the shape parameter

5.2.4 Return levels

After the suitable model for data has been chosen, the interest is in deriving the return levels of extreme maximum rainfall. The return levels for 5 to 100 years are given in Table 5.3. The 100 year return level is 383.81mm. The predicted return levels together with the 95% prediction intervals are given in Figure 5.5.

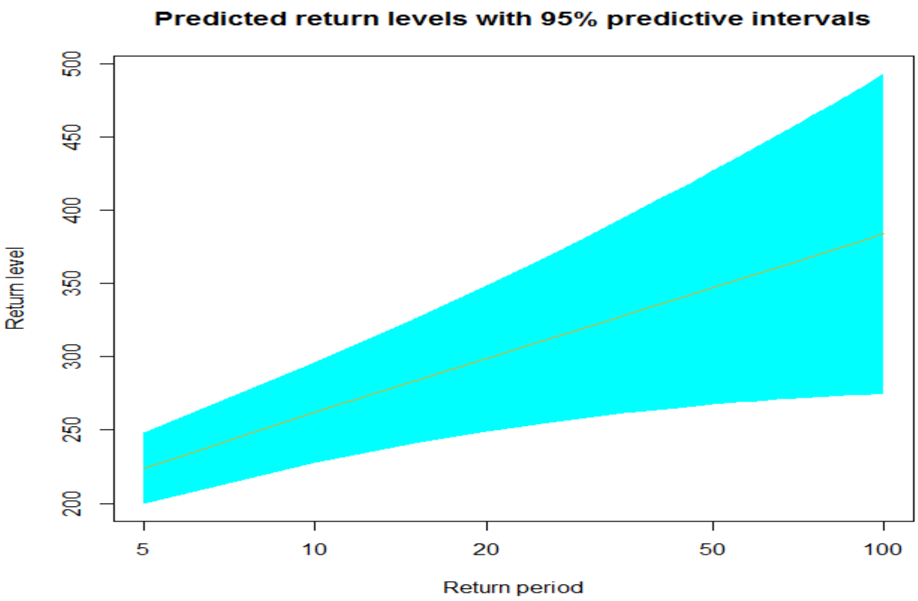


Figure 5.5: Predicted return level plot with 95% predictive intervals

The computed data for return levels predicted that the 5 year return period's return level is approximately 223.89 mm, which reveals that rainfall of 223.89 mm or more should occur at that station or location on the average once every five years. The 100 year return level was found to be 383.81mm, which means that 383.81mm should occur at Thabazimbi station once every 100 years (Table 5.3). This means that the probability that 383.81mm will be exceeded in 100 years is 0.01.

Table 5.3: Return level plot of maximum extreme rainfall (mm)

Years	LCL[1]	RL[2]	UCL[3]
5	199.77	223.89	248.01
10	227.74	261.93	296.12
15	240.90	283.58	326.26
20	248.87	298.82	348.7
25	254.87	310.60	366.88
30	258.30	320.22	395.35
35	261.34	328.34	395.35
40	263.73	341.59	407.03
45	265.67	341.59	417.52
50	267.26	347.15	427.04
55	268.58	352.18	435.78
60	269.70	356.78	443.85
65	270.64	361.01	451.37
70	271.45	364.92	458.39
75	272.14	368.57	465.00
80	272.14	368.57	465.00
85	272.74	371.99	471.23
90	273.71	378.22	482.74
95	274.10	381.09	488.08
100	274.44	383.81	493.19

[1]LCL=Lower Confident limit, [2]RL= Return level, [3]UCL= Upper confident limit

5.3 Correlation Analysis

There is a positive correlation between the Southern Oscillation Index (SOI) and maximum precipitation over the study area, (Figure 5.5). In the study, when there is positive SOI there is maximum precipitation. This shows that the study is highly vulnerable to extreme flood events and Limpopo province experiences extreme floods during La Niña event. Subsequently, weak La Nina events can also contribute to landfalls over southeast Africa. There are other phenomena such as the IOD which can work against the effort of La Niña (El Niño) to bring wet conditions or extreme floods events (dry conditions or droughts) over southern Africa (e.g. Richards *et al.*, 2000).

During summer OND, SOI is an indication of ENSO events which account for about 30% of rainfall variability over southern Africa (Tyson & Preston-Whyte, 2000). It is evident from Figure 5.4 that SOI plays a crucial role for extreme events over the study area.

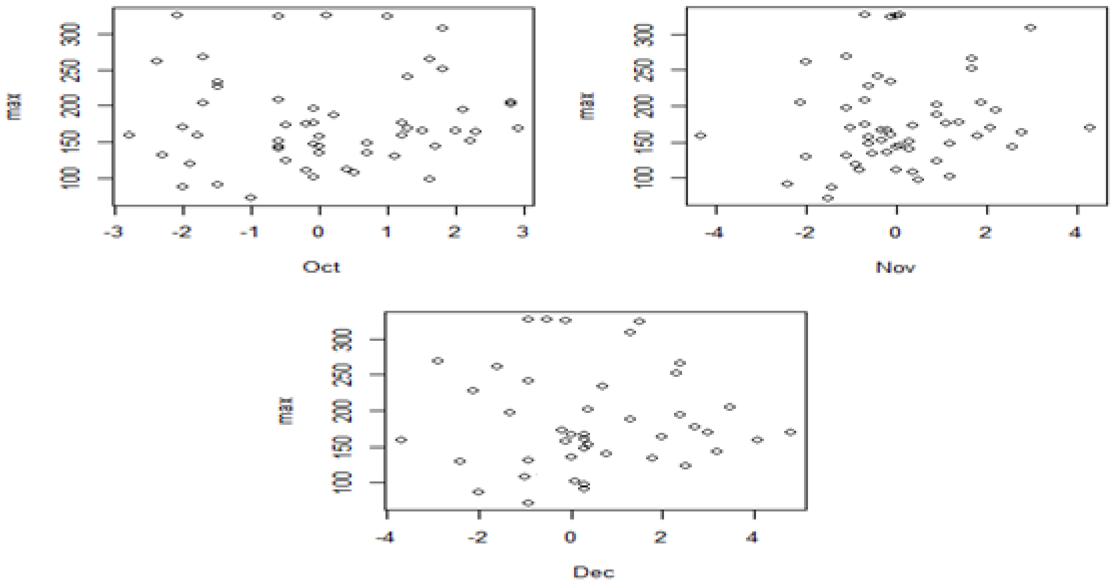


Figure 5.6 Correlation between maximum precipitation (OND) and SOI

Table 5.4 Correlation matrix table

	October	November	December	Max
October	1.000	0.693	0.648	0.048
November	0.693	1.000	0.779	0.129
December	0.648	0.779	1.000	0.048
Max	0.048	0.129	0.048	1.000

5.4 Summary

This chapter provided statistical modelling of extreme events over Limpopo province. Extreme maximum annual rainfall in Limpopo was modelled using GEV. The maximum annual rainfall data from 1960 to 2014 were fitted to the GEV. The distribution of the sampling data is skewed to the right and leptokutic shown by the skewness value of 0.858 and a kurtosis value of 3.131 respectively. After fitting the historical rainfall data to GEV using R package 'ismev' and 'texmex':-

a) The GEV distribution was fitted to the block maxima data, therefore the distribution of the maximum rainfall is slightly skewed to the right and the tails of the distribution also contain rare events and those events can be catastrophic.
b) The results show that the data can be modelled using a Frechet class of distributions since $\xi = 0.0139$.
c) Diagnostic plots for the selected station, probability plot, quantile plot, return level plot and density plot provide solid evidence that GEV distribution is a good fit to the block maxima data.
d) The study results indicate that the data follow a GEV distribution and do not deviate from assumptions.
e) After the suitable model for data has been chosen, the 100 year return level is 383.81mm, which means that 383.81mm should occur at Thabazimbi station once every 100 years.
f) There is a positive correlation between the Southern Oscillation Index (SOI) and maximum precipitation over the study area.

In this study, SOI plays a crucial role for maximum rainfall which results to extreme events over the study area. The study shows that when there is positive SOI, there is maximum precipitation. This shows that the study area is highly vulnerable to extreme events.

Chapter 6

Discussion, Conclusions and Recommendations

6.1 Introduction

The aim of this study was to analyse the variability and long-term trends of climate extremes over Limpopo province. Several studies have investigated extreme weather events over South Africa (e.g. Tebaldi *et al.,* 2006; Shongwe *et al*., 2009; Galarneau *et al.* 2012) with more attention on droughts and floods and less attention to long-term trends of climate despite the negative impacts of these events on the livelihoods in many regions across the country. Climate extremes such as droughts, floods and heat waves are occurring more frequently and becoming even more intense (Clark *et al.,* 2006; Fischer & Schär 2010). Weather related diseases such as cholera and malaria can also affect the health issues in the government/economic status.

This study addressed long-term trends of climate extremes in the context of South Africa as extreme events are increasing annually. The study also investigated the influence of El Niño Southern Oscillation (ENSO) on extreme frequency and duration. The aim of this chapter is to provide general conclusions of the study and recommendations for future studies to improve the understanding of climate extreme events. A discussion of the links between extreme events and other rising global issues is also presented. The following section summarises findings of this study.

6.2 Discussion of key findings

6.2.1 Weather system inducing extremes

Several studies suggest that there have been cases of extreme rainfall events related to cut-off lows over South Africa (e.g. Singleton & Reason, 2007). Cut-off lows tend to result in persistent heavy rainfall since the cold air aloft promotes deep convection. This study found that the most common month for COLs is April though other months such as MMJ also show high occurrence of COLs. In this study, a cut-off low event is called an extreme rainfall event if at least one station reports >50mm rainfall per day for more than 1 consecutive day. The study findings show that extreme rainfall events peak during austral summer (OND) and late summer (MMJ). The high event of extreme flooding is caused by tropical cyclones that are formed in the Mozambique Channel. Tropical cyclones generally develop only over seawater surface temperature which is greater than 26° C (Narita *et al.,* 2008). Several tropical cyclones which hit

South Africa, Mozambique and Madagascar such as tropical cyclone Dera, and Favio have affected various countries (Malherbe *et al.,* 2012).

6.2.2 Extreme climate events

Climate differs from one place to another, depending on a number of factors including latitude, distance from the sea, topography and prevailing winds. These extreme events are calculated in terms of monetary loss globally. Extreme events that take longer periods over a certain environment are referred to as climate extremes and their timescales vary with extreme weather events (IPCC, 2011). As this study used historical data set to focus on long-term trends of extreme events such as floods and droughts, it revealed that extreme events are becoming more frequent. In southern Africa, the occurrence of droughts usually coincides with El Nino years (Rouault & Richard, 2005).

This study also found that extreme floods events were rare in South Africa, but the rate of occurrence of floods has been increasing every year, which has resulted in loss of human lives, damage to properties and infrastructure as well as the destruction of the natural environment. Most of the floods events correspond with cold ENSO phase (La Nina) and there is a strong ENSO signal for most floods accompanied by an increase in upper easterlies. In addition to warm ENSO, severe floods are then observed during the negative IOD.

Positive correlation between SOI and DJF GPCP rainfall is observed over Limpopo, especially on the eastern parts of the province, suggesting that the province usually receives below (above) normal rainfall during negative (positive) SOI. Extreme floods events in Limpopo from 1960 to 2014 were regional, while few were widespread, such as the severe 1995/1996, 1999/2000 and 2010/2011 floods.

6.2.3 Extreme variability over Limpopo province

This study also found that extreme weather events are common during summertime over Limpopo province. The north eastern Lowveld is humid and hot in summer. The prevailing winds are north-easterly. Sometimes intrusions of cool south easterlies affect the Lowveld following the passage of a cold front. During the austral summer from October to March, the mean annual cycle of rainfall in the Limpopo shows a distinct peak. The annual cycle of rainfall in Limpopo differs from other areas such as the Western Cape province which receives much of its rainfall in the austral winter (JJA). Areas in the eastern coastline receive rainfall all year round.

More than half the extreme droughts identified in this study occurred during an El Niño event with a significant number occurring during non-ENSO years. The 1983/84 drought coincided with a weak La Niña event. It is also noted that since the droughts of the 1990s, the occurrence of extreme drought events over Limpopo, South Africa, has declined with near normal precipitation. Long-term trends show a partial recovery of rainfall and hydrology since about 1995.

6.2.4 Block Maxima

Block Maxima approach, which is the most classical model for extreme events, was applied in this study. This model is appropriate when the maximum observations of each period are assembled from a large number of identically and independently distributed variables. This study used generalized extreme value distribution and fitted historical weather data to the GEV distribution and found a trend in maximum precipitation. GEV model is suitable when the maximum observations of each period or block with a predefined and fixed length are assembled from a large number of identically and independently distributed variables (Coles, 2001).

In this study, the analysis was based on the historical maximum annual rainfall data from Thabazimbi station over Limpopo province, from 1960 to 2014. Yearly blocks were used in fitting a 54 years' data set to a GEVD, a block size had been chosen and individual block maxima had common distribution. The maximum likelihood method was used because $n > 50$. This study found that the normal distribution is good fit for this data; therefore, if the maximum annual rainfall of the distribution is skewed or heavy-tailed, the normal distribution is not misleading. The diagnostic plot also shows the maximum rainfall for Limpopo province for goodness of fit from 1960 to 2014.

In this study, the results show that the data can be modelled using a Frechet class of distribution since $\xi = 0.01390402$, the data best fitted the Frechet class of distributions. The estimates and standard errors the 95% confidence intervals for ξ are (-0.19568, 0.22349). The quantiles of maxima rainfall regressed against the quantiles of GEVD steers a straight line, this study proved that the data fairly fit the GEVD. The results in this study indicate that the data follow a GEVD and do not deviate from assumptions.

The maximum likelihood estimate for ξ is positive relating to a bounded distribution, in which the 95% confidence intervals for ξ is (-0.19568, 0.22349).

6.2.5 Return level of extremes

After the suitable model for data was chosen, the return levels of extreme maximum rainfall were derived. The return level of extreme maximum rainfall for 5 to 100 years was 383.81 mm. This revealed that rainfall value is the least maximum extreme value of rainfall which will occur after 100 years. The computed data for return level predicted that the 5 year return period’s return level is approximately 223.89 mm, which reveals that rainfall of 223.89 mm or more should occur at that location once every five years on average. The study also found the 100 year return level to be 383.81 mm, which means that 383.81 mm should occur in the study area once every 100 years. Extreme events in Limpopo province are expected to occur more frequently, last longer and become more intense.

6.3 Conclusions

The tropical, Pacific, SWIO, equatorial and South Atlantic Ocean basins are regions responsible for the variation in extreme rainfall. Extreme rainfall events in much of South Africa are mainly summer occurring events but dominate between December, January and February. This study modelled the future climate extreme events in Limpopo province. It was extensively indicated on other studies that during summer SOI is an indication of ENSO events which account for about 30% of rainfall variability over southern Africa (Tyson & Preston-Whyte, 2000). It is also clear that climate change may have evolving influences on climate extreme events. The modelled return levels of extreme maximum rainfall suggest that it may play a major role in driving rainfall changes over the study area. These return levels indicate how southern Africa communities may need to adapt and manage for future climate and weather extremes over this region.

6.4 Study limitations

Long term historical rainfall data was used in this study over the Limpopo province and selected station was used with accurate monthly rainfall data. Long term historical temperature data was not used due to lack of data and missing gaps from the selected station. In order to study extreme temperature events a complete temperature data is required to avoid bias for analysis. In addition, in this study the results showed that droughts last for different time scales and this study indicated that much of South Africa experiences dry conditions during warm temperature extremes. Therefore, in this study air temperature at 200hPa was used for analysis of Cut-off lows as displayed in Figure 4.24 chapter 4.

6.5 Recommendation for future work

This work focused on historical extreme events for the station data from 1960 to 2014. This study also contributes new scientific knowledge about the long-term climate extreme events with respect to South Africa for both the present and future climates. It was outlined earlier that long-term extreme events have not received accurate research attention over South Africa; as a result, the impacts of extreme events on health issues over the region are not well documented. It is also believed that this study will contribute in understanding the meteorological structure of climate extremes.

The parameters such as atmospheric temperature and vertical motion should also be considered in order to improve the understanding of the atmospheric state during extreme events. Numerous studies focus on ENSO induced extreme droughts, it is also recommended that future works should include other phenomena triggering regional, localized and widespread extreme events over South Africa. The majority of South Africans depend on rain-fed agriculture. This therefore takes the need to investigate the relationship between long-term extremes impacts on agricultural sector. Climate and weather information should be utilized in a manner that seeks to save lives and property in the society. Extreme events tend to be more frequent over the Limpopo as revealed in this study, therefore impacts of extremes events should not be investigated independently.

These are possible questions that can be addressed:

a) To what extent does a climate and weather extreme event affect agricultural production?
b) What role or contribution does this knowledge of modelled return levels play over Limpopo or South Africa at large?
c) To what extent does the ocean-atmosphere interaction influence the event and intensity of extremes in the Limpopo region?
d) Is there any relationship between long-term extreme events and human health status in Limpopo?

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