Impacts of Surface Air Temperature variability on agricultural droughts of southern Africa: The case of the Free State Province, South Africa

By

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Thesis submitted in fulfilment of the requirements for Doctor of Philosophy in Environmental Geography

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July 2018

DECLARATION

I declare that this thesis, submitted in fulfilment of the Doctor of Philosophy degree in Environmental Geography at the University of the Free State, is my independent work, which hasnot been submitted in any form to another university or faculty. I furthermore cede copyright of the thesis in favour of the University of the Free State.All the work of others have been acknowledged by means of references.

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DECLARATION 2: PUBLICATIONS

My role in each of the papers and presentations is indicated. The * indicates the corresponding author. The co-authors of the manuscript publications directed and supervised the research that forms the basis for the thesis.

Chapter 2

1. Mbiriri, M.*, Mukwada, G., & Manatsa, D. (2018). Spatiotemporal characteristics of severe dry and wet conditions in the Free State Province , South Africa. *Theoretical and Applied Climatology*.

Chapter 3

2. Mbiriri, M.*, Mukwada, G., & Manatsa, D. (2018). Influence of altitude on the spatiotemporal variations of meteorological droughts in mountain regions of the Free State Province, South Africa (1960–2013). *Advances in Meteorology*, *2018*(January), 1–11. https://doi.org/10.1155/2018/5206151

Chapter 4

3. Mbiriri, M.*, Mukwada, G., & Manatsa, D. (2018). About surface temperature and their shifts in the Free State Province, South Africa (1960-2013). Applied Geography

Chapter 5

4. Mbiriri, M.*, Mukwada, G., & Manatsa, D. (2018). Impacts of Surface Air Temperature variability on agricultural droughts in Southern Africa: A case of the Free State Province, South Africa (1960-2013).

Work still under review

My roles were data extraction, analysis and writing up the papers.

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DEDICATIONS

I dedicate this thesis to my father, Shame Mbiriri, my sisters Patience and Josephine Chelsy, my beloved brother, Brian and my late mother, Evangelista Mbiriri.

ABSTRACT

The Free State Province of South Africa is an agricultural region and a leading producer of food crops, including maize, the staple crop for the country. With the Drakensberg Mountains occupying much of its eastern part, the province does not only have a complex topography but also a highly varied climate. This makes the region, especially the highlands vulnerable to climate change. Increased temperatures are set to enhance the intensity of drought due to a reduction in the availability of water resources for crop farming due to excessive evapotranspiration. But the extent to which the rising temperatures have modified the agricultural droughts in relation to the variability of topography in this region has not yet been assessed. In this study, the impact of surface air temperature (SAT) variability on agricultural droughts in the province is assessed for the period between 1960 and 2013. This is achieved by using two drought indices, the Standardized Precipitation Index (SPI), and the Standardized Precipitation Evapotranspiration Index (SPEI) where the former is based solely on precipitation and the later incorporates the effect of evapotranspiration. Evapotranspiration is driven by a number of variables which include wind speed, radiation, humidity and temperature. The severity and frequency of droughts is expected to increase under climate change that is primarily driven by increased temperatures. The impact of altitude on agricultural drought characteristics is also considered. Gridded monthly precipitation, SAT and SPEI data were extracted from Climate Explorer`s database, while SPIs for individual grid points were calculated using the Drought Indices Calculator (DrinC). In order to characterise drought, the clustering method of Hot-Spot analysis was employed to divide the province into homogenous regions based on altitude. All maps were produced using spatial interpolation techniques in ArcMap V.10.2.

The results revealed that although the average total precipitation increases from west to east following increasing altitude, the high-altitude regions have shown higher occurrences of severe droughts (SPI $\leq$-1.282) in recent years, compared to the low-lying western regions. The differences between adjacent clusters are more pronounced during the early summer sub-season (October-December) than in the late summer sub-season (January-March). The observed spatiotemporal heterogeneity in SPI variability reveals that the factors governing drought interannual variability vary markedly within the region for the two subseasons. Among these factors is altitude. To ascertain the influence of altitude on agricultural drought, an Analysis of Variance test was performed. The results show a significant relationship between drought severity and altitude during the OND but could not be confirmed for JFM. The impact of altitude is also partly manifested in the strong relationship between meridional winds and SPI extremes. Wet seasons are observed when the winds are northerly and droughts when winds are southerly of the Free State Province. When the winds are largely northerly, Free State lies predominantly in the windward side of the Drakensburg Mountains but lies in the rain shadow when the winds are predominantly southerly. The relationship between El Nino Southern Oscillation and SPI indicates stronger correlations for the early summer sub-season than for the late summer sub-season while on the overall, presenting a diminishing intensity with height over the province.

The Sequential Regime Shift Detection (SRSD) was used to test for significant abrupt shifts in the variability of precipitation in the province and results were confirmed by the Cumulative Summation (CUSUM) method. A significant positive shift in average SPI, during the OND subseason was detected for the far western low-lying and central regions of the province around the 1990s. Temperature, on the other hand shows a significant abrupt shift around 2003 for maximum temperature (Tmax) during the early sub-season and around 1983 for minimum temperature (Tmin) during the late sub-season. The OND Tmax shift coincides with that in cloud cover, with a strong correlation between the two variables. It is intriguing to note that the significance of temperature change is stronger towards the highland regions, to the north and northwest of the province. This shift in temperature is further investigated to explore the impact it has on the intensification of agricultural droughts in the province. It is concluded that despite the observed significant increase in temperature, SPEI does not reflect any significant effect of temperature on drought intensification. In conclusion therefore, precipitation could be the major determinant of droughts in the Free State Province since there is no significant difference between SPI and SPEI variability. There is need to investigate the role of other factors, that may also contribute to drought intensification in the province; such as humidity, solar radiation and wind speed which may have neutralised the well-known impact of temperature on agricultural drought characteristics of the province.

ACKNOWLEDGEMENTS

I would like to acknowledge the following individuals and organizations for their assistance in making this research a success. My sincere gratitude and respect go to my promoter Prof. G. Mukwada and co-promoter, Prof. D. Manatsa, for their unwavering support and undivided attention they gave to my research. There is no doubt that without their assistance, the completion of the thesis would not have been possible.

I am indebted to the University of the Free State and the Afromontane Research Unit for their illustrious efforts in making this research a success by providing complete financial support.

I am particularly thankful to my family, Shame Mbiriri, my father, my sisters, Patience and Josephine Chelsy, my brother, Brian, all colleagues and friends, particularly Dr. Iorkyaa Ahemen, Mrs Lea Koenig and Mr Calvin Mudzingiri for their love, sacrifice, moral support and encouragement. May the good Lord bless you. Above all, To God Be the Glory for His everlasting grace, love, kindness and courage to remain strong till the completion of all the necessary requirements for the PhD program.

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CHAPTER 1: INTRODUCTION

1.1 Background

Southern Africa is a region characterized by high interannual rainfall variability (Nicolson, 1986) and its vulnerability to climate change has been confirmed (Turpie & Visser 2015). The sensitivity of the various components comprising the climate system makes any disruption in one component to trigger changes in the whole system (Baede et al. 2007). The two main climate elements, precipitation, and temperature are expected to deviate from their long-term average and the effect could manifest as increased frequency and severity of extreme climate events such as droughts and floods (FAO 2004; Wilhite 2000). Droughts are a natural phenomenon, which can be regarded as the world`s most damaging and costliest natural hazard (Buckland et al. 2000; Yu et al. 2014). The term, 'the global-change-type drought' was first used by Breshears et al., (2005) to describe droughts related to precipitation shortages and warmer conditions. It is, however, important to acknowledge that not all droughts are associated with higher than normal SAT (Hanson 1991).With nearly 70 percent of the world`s poor dependant on agriculture, increased frequency and severity of drought will be devastating (Filipe & Tamara 2012; IPCC 2014). This has driven the need to understand the phenomenon, leading to considerable research attention in many parts of the world. Population growth and economic growth are projected to place more demand on the already vulnerable agricultural sector (Zhu et al. 2008). South Africa, like most southern African countries, has an economy that is highly dependent on agriculture. Dependency on agriculture and high levels of poverty in South Africa increase the vulnerability of the country to droughts (Ncube et al. 2015).

South Africa`s climate is largely diverse but dominated by semi-aridity(El Chami & El Moujabbe 2016). The greater part of the country receives its rainfall during the summer season, while the south-western region, receives its rainfall in winter (Ncube et al. 2015). With an average annual rainfall of about 497 mm, an average well below the world average of 860 mm (Schur 2002), South Africa is extremely vulnerable to impacts of climate change, especially in terms of agricultural production. Within the context of global climate change, warming processes may aggravate drought impacts, increasing the severity of drought as a consequence of water loss by evapotranspiration (Dai 2011). The term, evapotranspiration refers to a combination of two processes, namely evaporation from open bodies of water, wetlands, and snow, including bare soil, and transpiration from vegetation (Wossenu & Assefa 2013). Evapotranspiration has the ability to consume up to 80% of precipitation (Abramopoulos et al.

1988). Two principal factors, solar radiation and wind speed influence the process of evapotranspiration the most (Zotarelli et al. 2010). This does not however, mean that the other factors are not important. These two factors show a significant relationship with other factors, for example, the time taken by maize plants to intercept radiation and grow is significantly associated with temperature (Muchow et al. 1990). The influence of solar energy varies with latitude, time of the day, season and cloud cover, while wind speed determines the nature of heat and moisture transfer processes (Hanson 1991). Increased evapotranspiration due to increased warming further reduces the availability of water resources, an already finite and “vulnerable” resource (Schur 2002). Studies on Europe project the expansion of the area susceptible to drought by 40% (±24%), affecting up to 42% (±22%) more of the population if temperature increases (Samaniego et al. 2018). Higher temperatures are also known to encourage the proliferation of weeds, pests and diseases which further reduces the yield (Nelson et al. 2009).Since most weeds that grow during the warm season have their origins in tropical climate regions, any small increase in temperature triggers their growth and proliferation (Patterson et al. 1999).The same applies with pests. In the United Kingdom, an increase in winter temperatures has been associated with an increased variability in the aphid population (Malloch et al. 2006). The ultimate yield is reduced markedly, exposing livelihood systems that are dependent highly on agriculture to poverty, hunger, and starvation (Buckland et al. 2000).Consequently, the whole socio-economic structure of the agriculture-based economy is affected (El Chami & El Moujabber 2016:104). The lack of alternative structures that are strong enough to cushion economies from the impacts of drought further increases the vulnerability of most Less Economically Developed Countries (LEDCs) (Newton et al. 2011).Therefore, drought presents itself as a challenge toward meeting the Sustainable Development Goals of the United Nations.

Agricultural drought links various characteristics of meteorological (or hydrological) drought to agricultural impacts, leading to water shortages, differences between actual and potential evapotranspiration, soil water deficits and reduced groundwater. Yet, drought is expected to intensify with the projected temperature increase. In this thesis, the impact of temperature was assessed through a comparative analysis of an index that utilises precipitation only, the Standardised Precipitation Index (SPI) with the Standardised Precipitation Evapotranspiration Index (SPEI), which is based on water balance (Precipitation and Evapotranspiration) making it suitable for studying the effects of global warming on drought severity (Wang et al., 2018).

The main factors controlling the climate of southern Africa include orography, the subtropical high-pressurecenters in the Atlantic and Indian Oceans, the Inter-tropical Convergence Zone (ITCZ) and the Angola low (Fauchereau et al. 2003; Usman & Reason 2004).Summer rainfall, which is important for agriculture in most parts of southern Africa is associated with the migration of the ITCZ (Manatsa & Reason 2016) and the El Niño Southern Oscillation (ENSO). About 30 percent of rainfall variability in southern Africa is influenced by ENSO (Tyson & Preston-Whyte 2000; Rouault & Richard 2005). The ENSO episodes, which are El Niño and La Niña, manifest as Sea Surface Temperature (SST) fluctuations in the western Indian Ocean. Warm (cool) SSTs to the east and cool (warm) SSTs to the west of South Africa are expected during the wet (dry) spells (Cook et al. 2004). Although a strong relationship exists between ENSO and drought, not all droughts are associated with ENSO (Edossa et al. 2014). For example the 1997/98 southern African drought showed weaker correlation with ENSO (Mason & Tyson 2000). The ITCZ determines the seasonality of the precipitation across tropical Africa (Mavhura et al. 2013) while the Angola low, also known as the Namibian low, is a strong contributor of January-March rainfall through its tropical-temperate troughs (Cook et al. 2004). In the face of climate change due to increased greenhouse gas emissions, the frequency and magnitude of ENSO is likely to be altered (Sun et al. 2016). This will have a cascading effect on the whole climate system, resulting in increased frequency of extreme events such as droughts.

1.1.1 The Free State Province, South Africa

The Free State Province, located in the interior of South Africa, is one region that exhibits complex terrain, hence it offers a good case for comparison of drought characteristics between flat plains to the southwest and highland areas to the northeast. Part of the Drakensberg Mountains makes the highland regions in the province, which borders Lesotho. Popularly known as the Maluti-Drakensberg Mountains, they are the highest mountains in southern Africa and play an important role in influencing the type and amount of precipitation received at some locations (Nel & Sumner 2006). The Maluti-Drakensberg Mountains are South Africa`s main watershed from which the Orange River originates. The Orange River is one of the major sources of water supply for commercial farming in the country. Research confirms that climate change impacts will be severe on mountain regions of the world (Hastenrath 2001; Halada 2010). In Kenya, significant warming has been observed in the highland regions compared with low-lying regions (Ongoma et al. 2017). Therefore, understanding how climate is evolving in the mountain regions of the Free State provides a starting point in the analysis of current and future water resources and agricultural management strategies.

The Free State Province experiences a continental climate characterized by warm-wet summers and cold-dry winters. Most agricultural activities occur during the summer season when crops grow largely under rain-fed conditions (Moeletsi & Walker 2012). Alongside Mpumalanga and North-West Provinces, the three provinces are the leading provinces in crop production, with the Free State Province regarded as the breadbasket of South Africa (Turpie & Visser 2015). Under global warming conditions, coupled with high interannual rainfall variability, heat stress is likely to limit food production in the future. Agricultural drought has been explained in terms of a reduction in precipitation and an increase in temperatures, resulting in a decrease in agricultural output (Vicente-Serrano et al. 2010). However, understanding drought, in general, has been challenging due to its slow onset and difficulty in determining its cessation (Wilhite et al. 2000). In an effort to quantify and monitor drought, some indices have been developed(Vicente-Serrano, Beguería, Lorenzo-Lacruz, et al. 2012). Drought indices range from simple to complex ones, with most traditional methods based on water supply indices derived solely from precipitation time series. In this study, agricultural drought was assessed using two drought indices, the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) in the Free State Province of South Africa for the period between 1960 and 2013.

In southern Africa, a degree of global warming is projected to increase temperature variability by ~15% (Bathiany et al. 2018). Increase in temperature and high evapotranspiration have the potential to aggravate drought effects (Paulo et al. 2012). However, studies on agricultural droughts have mainly concentrated on modeling and have been based on isolated individual stations due to lack of observed climate data and this presents challenges on monitoring and management of droughts in the region (World Meteorological Organization (WMO) 2005). In this thesis, gridded climate data at a resolution 0.5^{o}X 0.5^{o} were used, covering the Free State Province of South Africa. Assessing the impact of surface air temperature (SAT) variability on the spatial and temporal distribution of agricultural droughts formed the anchor of this thesis. This is the first study in the province to assess the impact of SAT on agricultural drought using two drought indices. The Free State Province, with its heterogeneous topography also allows for an assessment of the influence of altitude on agricultural variability of drought.

1.2 Drought definitions and types

Drought is one phenomenon that lacks a universal definition (Gao et al. 2016). Coupled with difficulties in quantifying it, defining its onset and cessation due to its slow evolution, understanding drought has become complicated (Wilhite 2000). Such confusion contributes to lack of action or failure to choose the appropriate course of action and ad hoc responses to the societal and environmental implications (Conway 2008). In an effort to understand drought, Quiring (2009) classified the definitions into either conceptual or operational categories. Conceptual definitions are formulated in general terms to explain what a drought is, while operational definitions are more specific because they help to identify drought characteristics such as the start of a drought, its cessation and degree of severity. Conceptual definitions have limited application in real-time drought assessments (Wilhite & Glantz 1985). Conceptual definitions describe drought as, "...a long period of dry conditions during a usually wet season with potential to cause harm to the crop." (Random House Dictionary 1969). Wilhite and Glantz (1985) classified drought types into four (operational-based definition):

- Meteorological drought: defined solely on the basis of the degree of dryness and the duration of the dry period. It is described by a reduction in rainfall supply compared with a specified average condition over some specified period. Meteorological drought is often referred to as climatological drought because it is expressed in terms of a thirty-year precipitation period, which has been agreed to, by international convention. Various studies have analyzed meteorological droughts, for example, in Bangladesh (Rahman & Lateh 2016; MacDonald & Tingstad 2007).
- Hydrological drought: This exists when the amount of water on natural, artificial and subsurface reservoirs has decreased to levels inadequate to meet the demand within a water management system. Demands may include water for irrigation, hydroelectrical power generation, and other household and industrial uses. Examples of studies that have analyzed hydrological droughts include those undertaken in Austria (Van Loon & Laaha 2015) and Bangladesh (Shahid & Hazarika 2010).
- Socio-economic drought: This describes the direct and indirect impacts of a usually meteorological, agricultural or hydrological anomaly on the social and economic wellbeing of a population. Examples of studies on economic drought include a study on the economic impact of drought in Kenya (Kabubo-Mariara & Karanja 2007) and South Africa`s rural areas (Turpie & Visser 2015).

- Agricultural drought: Also known as soil moisture drought (Gao et al. 2016), agricultural drought refers to a state of imbalance between soil moisture and crop water demand at different growth stages enough to cause physiological damage to the plant or reduce yield. For most crops such as soybean (*Glycine max* L.) and maize (*Zea maize*), drought at the flowering stage is devastating, resulting in a significant reduction in yield (Moloi et al. 2016; El Chami & El Moujabbe 2016). Excessive evapotranspiration alters the metabolic functions within a plant, such as reduced photosynthesis (Jaleel et al. 2009).Agricultural drought links various characteristics of meteorological drought to agricultural impacts in terms of deviation from the norm and evapotranspiration. Studies that have analyzed agricultural droughts include (Alam et al. 2011; Potop et al. 2012).

From the descriptions of the types of drought, one common feature of drought is moisture deficit. However, the timescale over which precipitation deficits accumulate functionally separates different types of drought (Lorenzo-Lacruz et al. 2010). This explains the connectedness of the different drought types, although the relationship is not always a causative one. A study by Mahmoodi & Zeinivand (2014) revealed that there is a significant relationship between meteorological and hydrological droughts. The discharge of rivers in the Kashkan River Basin in the Lorestan Province of Iran showed a significant reduction in response to meteorological droughts (Mahmoodi & Zeinivand 2014). Thus, drought analysis involves quantifying and monitoring variables that define a drought condition within a system. Due to the absence of a solely physical variable that can be used to quantify droughts, drought indicators/ indices have been developed and continue to be modified, a process that seems never-ending. This situation explains the complex nature of the drought phenomenon.

1.3 Drought Indices

The use of drought indices as proxies for understanding the drought phenomenon where objective data are unavailable has become common across the world (Spinoni et al. 2014; Yu et al. 2014; Vicente-Serrano, Chura, et al. 2014). Examples of indices include the Palmer Drought Severity Index (PDSI) (Palmer 1965), the Standardized Precipitation Index (SPI) (Mckee et al. 1993), the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010) and the Standardized Wetness Index (SWI) (Liu et al. 2017). While there is no one superior index (Vicente-Serrano et al. 2010), some indices have become popular for their outstanding characteristics and these include the SPI and the SPEI which were used in this study. The response of different systems to drought conditions varies with a time scale (Lorenzo-Lacruz et al. 2010). At a short time scale, SPI can be used to identify soil moisture drought, which impacts on crop development, that is agricultural drought (Vicente-Serrano et al. 2010).

The simplicity in its calculation and minimum data requirement gives SPI wider acceptance over the other indices(Svoboda et al. 2012). At different time scales, the SPI has the ability to identify different types of droughts (Vicente-Serrano, Chura, et al. 2014). However, the SPI has been criticized for using only precipitation data in its calculation, neglecting other variables such as temperature, wind speed and humidity which have marked effects on drought severity (Zhao & Running 2010; Nguyen et al. 2015). In recognition of this limitation, Vicente-Serrano et al., (2010) developed the SPEI, which is a modification of SPI. The SPEI combines the sensitivity of the PDSI to changes in evaporation demand caused by temperature with the multi-scalar dimension characteristic feature of the SPI. The multi-scalar characteristic of the SPI and SPEI allows the two indices to be used in monitoring drought impacts on both natural and socio-economic systems (Lorenzo-Lacruz et al. 2010).

Results from a global-scale analysis showed that the SPEI correlates better with anomalies in different hydrological, agricultural and environmental variables than the SPI (Vicente-Serrano, Beguería, Lorenzo-Lacruz, et al. 2012). The SPI and SPEI are obtained using the same log-logistic probability, enabling comparison between series of the two indicators. The difference between SPI and SPEI, therefore, relates to the impact of temperature on drought conditions.

1.4 Statement of the problem

Drought is a naturally occurring feature (Potopova & Mozny 2011), which has a history of occurrence in all climate zones, although its severity and frequency varies spatially. In southern Africa, drought is the most important natural hazard socially, economically and environmentally (Buckland et al. 2000). The need to adapt to a more variable climate and meet the needs of the growing population through food security presents the need to understand the extent to which each of the meteorological variables influences agricultural drought. Any change in any one of the climate variables has a potential to disturb the whole climate system. The influence of each of the variables controlling the evapotranspiration process varies with location(Shan et al. 2015). Jiri & Mafongoya (2018) acknowledge the uncertainty arising from the impact of climate change, making the issue one of those that requires urgent attention. Response to climate change has not been the same across space, with mountain regions being the most easily affected, yet they play an important role in provision of water and other ecosystem services (Hastenrath 2001). With a global mean temperature increase of between 0.5 ^{o}C and 2 ^{o}C recorded during the last 150 years, it can be expected that such increases have had consequences for drought conditions (Vicente-Serrano, Beguería, Gimeno, et al. 2012). It is important, therefore, to understand the dynamics at small scale, especially where such climate variability has the potential to threaten sensitive systems such as agriculture. In South Africa, the Free State Province is one of the three most important provinces including Mpumalanga and North West, in agriculture production. Partly located within the Drakensberg Mountains in the east, the Free State Province provides a good case to understand the variability of temperature with altitude.

However, until recently, research based on climate data in the southern hemisphere has lagged behind due to the unavailability of meteorological data (Baede et al. 2007). Generally, in Africa, there is a lack of quality controlled historical data prior to 1960, mainly as a result of technological and scientific underdevelopment due to war, poverty and political instability (Desanker & Magadza 2001).To overcome this challenge, the use of reanalysis data has become popular in climate studies (Spinoni et al. 2014; Wang et al. 2018). Hulme et al. (2001) observed that between 1901 and 1995 inland southern Africa warmed at 2 ^{o}C per century. Projections indicate a further increase by 1.5^{o}C to 6 ^{o}C by 2100, with inland areas of central southern Africa experiencing the greatest increase (Desanker 2018). Such warming has the ability to increase evapotranspiration and produce a water vapour deficit (Wossenu & Assefa 2013). While precipitation is the main driver of drought conditions, the role of warming-induced drought stress has been made evident in recent studies, for example, the 2003 drought in the United States of America (Rebetez et al. 2006). Most farmers use rainfall as the determinant factor for decision-making (Badini & Dioni 2004). This reflects the little attention given to temperature, yet its impacts can be equally devastating. However, there is still need to understand the impact of the observed global average temperature increase on agricultural production (Lobell et al. 2011). This thesis provides the basis for understanding how observed global average temperatures may have impacted agriculture at a smaller scale, hence its focus on the Free State Province, considering the importance of agriculture in the Free State Province to the economy of South Africa (Moeletsi et al. 2013).Apart from job creation, agriculture is important for food security, rural development and foreign trade (National Treasury 2003). It is therefore imperative that drought, a climate anomaly is better understood in terms of space and time statistics (Hanson 1991). However, defining drought using a single variable index may not be sufficient for decision making and policy development (Nguyen et al. 2015). As such, two indices, the SPI and SPEI were used in this study. While SPI detects droughts resulting from precipitation deficiency, SPEI has the capacity to detect an intensification of drought severity due to increasing temperature (Du et al. 2013). Most of the previous studies in the Free State Province analyzed one climate variable at a time, such as rainfall (Moeletsi & Walker 2012) or used indices that are derived from an individual variable, for example the Heat Index (Moeletsi 2017).This study offers a platform to determine the extent to which the interaction of different variables influences agricultural drought. With topography as one of the factors influencing evapotranspiration, in this study, the influence of altitude on agricultural drought was assessed. The eastern region of the Free State Province provides an appropriate case to understand how topography influences drought evolution and assists in advancing knowledge on climate variability and climate change in southern Africa as a whole. Such knowledge is important for drought impact mitigation through identification of best working adaptive strategies. Research findings from this study will set a step towards the fulfilment of the one of the 2030 Millennium Development Goals of improved agricultural sustainability(El Chami & El Moujabbe 2016).

1.5 Aim and objectives

1.5.1 Aim

To assess the impact of surface air temperature (SAT) variability on agricultural droughts in southern Africa, using the case study of the Free State Province of South Africa.

1.5.2 Objectives of the study

1. To characterise agricultural drought using the Standardized Precipitation Index in the Free State Province of South Africa between 1960 and 2013.

2. To assess the influence of altitude on agricultural droughts in the Free State Province of South Africa between 1960 and 2013.

3. To characterise drought using Standardized Precipitation Evaporation Index in the Free State Province of South Africa between 1960 and 2013.

4. To account for the differences between SPEI and SPI based drought characteristics over the Free State Province, South Africa

1.6 Structure of the thesis

This thesis consists of six chapters:

Chapter 1 introduces the research key concepts on which this thesis is based. These include drought, climate, climate variability and climate variability. The problem addressed by the research study is described in this chapter, together with the aim and objectives of this work. Each of the succeeding chapters is based on one of the objectives noted above. Detailed literature is reviewed in the introduction, results and discussion sections of each of the chapters in accordance with the objective of the chapter.

Chapter 2 discusses the characteristics of agricultural droughts using the Standardized Precipitation Index (SPI) in the Free State Province between 1960 and 2013, while Chapter 3 discusses the influence of altitude on the spatiotemporal variations of meteorological droughts in the province, over the same period.

Chapter 4 analyzes temperature characteristics and variations in the Free State Province, focussing on the temperature shifts that have occurred in the province between 1960 and 2013. This lays the basis for the succeeding chapter, Chapter 5, which focuses on the impact of SAT variability on agricultural droughts. Chapter 5 also provides a comparative analysis of SPI and SPEI defined agricultural droughts in the province.

The thesis is concluded with Chapter 6, which summarizes the results and makes recommendations for researchers in the area, as well as for water resources managers and policymakers. The work presented in chapters 2, 3 and 4 is based on three published papers while the Chapter 5 based paper is still under review. As a result, self-citations are found in this thesis.

CHAPTER 2: SPATIO-TEMPORAL CHARACTERISTICS OF DROUGHT AND WET CONDITIONS USING THE STANDARDIZED PRECIPITATION INDEX (SPI) IN THE FREE STATE PROVINCE, SOUTH AFRICA

2.1 Brief chapter synopsis

This chapter is based on the paper which was published as:

Mbiriri, M., Mukwada, G., & Manatsa, D. (2018). Spatiotemporal characteristics of severe dry and wet conditions in the Free State Province, South Africa. *Theoretical and Applied Climatology*. https://doi.org/10.1007/s00704-018-2381-0

2.2 Abstract

This paper assesses the spatiotemporal characteristics of agricultural droughts and wet conditions in the Free State Province of South Africa for the period between 1960 and 2013. Since agriculturally the Free State Province is considered the breadbasket of the country, understanding the variability of drought and wet conditions becomes necessary. The Standardized Precipitation Index (SPI) computed from gridded monthly precipitation data was used to assess the extreme rainfall conditions. Hot-spot analysis was used to divide the province into five homogenous clusters where the spatiotemporal characteristics for each cluster were analysed. The results show a west to east increase in seasonal average total precipitation. However, the eastern part of the province demonstrates higher occurrences of droughts, with SPI≤-1.282. This is despite the observation that the region shows a recent increase in droughts, unlike the western region. It is also noted that significant differences in drought/wet intensities between clusters are more pronounced during the early compared to the late summer period.

Keywords agricultural drought, spatiotemporal, precipitation, Free State Province

2.3 Introduction

Drought occurrence is among the most devastating phenomena in the world, costing billions of dollars to governments. While climate models show that eventually, no area is going to be spared by the effects of future climate change, Africa is amongst the continents that have been identified as the most vulnerable. Southern Africa`s droughts, in particular, are projected to intensify not only in frequency but also in their spatial extent (Buckland et al. 2000). Because the impact of natural disasters is much greater for developing countries than developed countries (Spencer & Urquhart 2016), most countries in southern Africa will be exceedingly vulnerable because of their economies which are not strong enough to cushion them from the impacts. South Africa has suffered multiple effects of drought, varying from dwindling water supplies, effects on staple crops and increased government expenditure on food importation. Population migration, company closures, and reduced living conditions are among other impacts. For example, the 1992/1993 drought forced the government to import food, which weighed heavily on the trade deficit of the country (South African Weather Services 2017). The knock-on effect of crop failure was seen in the population drift from rural areas into the cities, farm labourlay-offs and farm closures. There was also an increase in indebtedness in the agricultural sector (South African Weather Services 2017). South Africa is one of the top ten maize producers in the world (12,365,000 tons as of 2013). Most of this maize is produced by the Free State Province under rain-fed conditions (Moeletsi and Walker 2012; DAFF 2010) and hence making the province the country's granary. Although the contribution of agriculture to the country`s Gross Domestic Product is small and declining, it still plays an important role in the creation of wealth and safety nets, especially in the rural areas (Filtane 2016).

Many aspects and implications of drought have been researched on in southern Africa (Ujeneza and Abiodun 2015; Manatsa et al. 2010 and Africa at large (Glantz 1987; Vicente-Serrano, Beguería, Gimeno, et al. 2012). However, little research has been done to analyze droughts at a smaller scale like the provincial level. Shortage of data due to the sparsity of meteorological stations in southern Africa has made this type of research difficult. As recommended by the World Meteorological Organization (Hayes et al. 2011), South Africa Weather Services has embraced the Standardized Precipitation Index (SPI) as an index to determine the severity of dry and wet conditions in the country. The SPI, developed by McKee et al. (1993), is a multi-scalar index based on a precipitation frequency approach. It is widely accepted for its solid theoretical development, robustness, and versatility in drought analyses (Redmond 2002). While it is simple in its calculation as it requires precipitation data only, its ability to attain unprecedented values if the same magnitude of 'climatic shocks' occurs in future gives it a unique 'open-ended' characteristic feature absent in other indices. The SPI has been extensively used in many research works around the world, for example in Kuwait (Almedeij 2014; Ntale & Gan 2003); Argentina (Seiler et al. 2002); Spain (Lana et al. 2001); Korea (Min et al. 2003); Hungary (Domonkos 2003); China (Wu et al. 2001); East Africa (Ntale & Gan 2003); and Europe (Lloyd-Hughes & Saunders 2002) for real-time monitoring or retrospective analysis of droughts. The index, however, does not capture the influence of other factors, other than precipitation, that may determine drought conditions such as temperature, wind speed and water holding capacity of the soil (Vicente-Serrano and López-Moreno 2011). For example, given that global temperature has increased by between 0.5 °C and 2 °C during the last 150 years, it can be expected that such increases have had consequences for drought conditions (Vicente-Serrano, Beguería, Gimeno, et al. 2012).

In this study, we analysed drought at 3 and 6 months scale as SPI at a short time scale can be used to identify agricultural drought. Agricultural drought or soil moisture drought (Gao et al. 2016) occurs when there is insufficient moisture in the soil to sustain crops and forage leading to a decrease in agricultural productivity. These short-term scales were also used in previous work and are recommended as adequate for the part and overall monitoring of the growing season's performance (Manatsa et al. 2010; Rouault and Richard 2005; Edwards and Mckee 1997). The Free State Province is important for its contribution to food security in the country. As such, an assessment of the evolution of agricultural droughts and mapping of drought-prone areas within the province was undertaken, and this knowledge will assist in planning for drought mitigation strategies.

2.4 Data and Methods

2.4.1 Study area

Figure 2. 1 shows the location of the Free State Province in South Africa. The province is situated between latitudes 26.6 °S and 30.7 °S and between longitudes 24.3 °E and 29.8 °E sprawling over high plains and stretching along the Maluti-Drakensberg Mountains bordering Lesotho. The province covers an area of 129,825 km². Cultivated land covers approximately 32,000 km² with natural veld and grazing land covering a further 87,000 km² of the province (Department of Agriculture, Forestry,and Fisheries, DAFF 2010). Field crops yield almost two-thirds of the gross agricultural income of the province although mining on the rich goldfields reef is its largest employer. The Free State Province is also the country`s leader in the production of biofuels, that is fuel from crops, with some ethanol plants under construction in the grain-producing western region. Animal products contribute a further 30%, with the balance generated by horticulture (DAFF 2010).

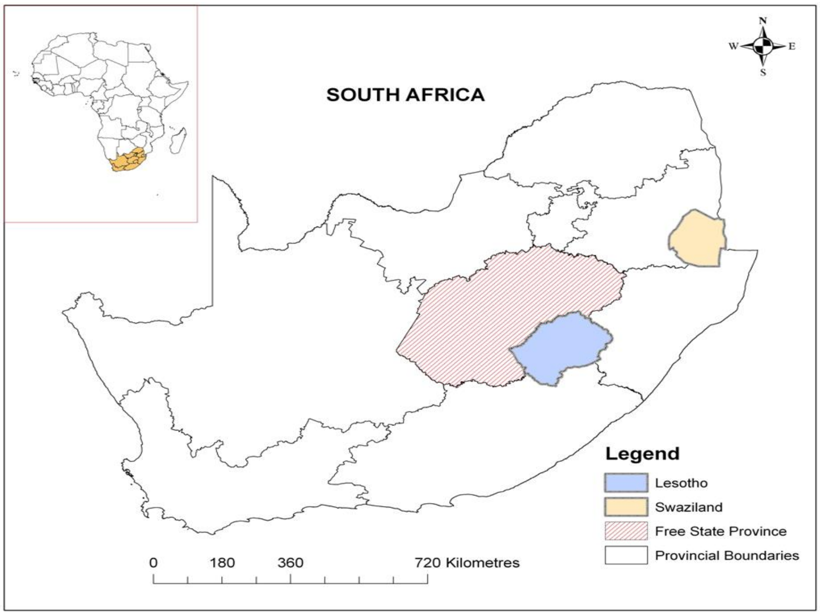


Figure 2.1: Location of the Free State Province, South Africa

2.4.2 Seasonal Climatic Characteristics

The Free State Province experiences a continental climate that is characterised by warm to hot summers and cool to cold winters. The rainfall season spans from October to March. Thus water availability for crop production is determined by the amount received during this period. Seasonal rainfall varies considerably over the province. Several factors determine the amount of precipitation an area receives, including altitude, distance from the sea and aspect, among other factors. The dominant factor influencing the variability of precipitation in the province is yet to be established.

The forces that control the summer season rainfall in southern Africa vary within this season. Between October and December, usually regarded as early summer, the atmosphere has a distinct extra-tropical nature with frequent cut-off lows while during late summer period (January-March) tropical circulation systems are much more prevalent over southern Africa (Dyson and Van Heerden 2002; Manatsa and Reason 2016; D'Abreton and Lindesay 1993). Thus, the season was analysed in three parts, October to December (OND), January to March (JFM), and a complete season which merges OND to JFM of the succeeding year (ONDJFM). Hence in this work 1991/92 represents the OND of 1991 and the JFM of 1992. In cases where the OND period only was made reference to, the complete season identity was used but taking into consideration that the OND sub-season would be for the year 1991. The 3-month and 6 month scales were selected because they have an appropriate estimation of seasonal precipitation which has a significant progressive effect on crop yield.

Monthly mean precipitation (mm) covering the 1960-2013 period was extracted from Climate Explorer`s Climate Research Unit (CRU) gridded data file from Climate Explorer at 0.5^{o} X 0.5^{o} spatial resolution (available from https://climexp.knmi.nl). The selected period of 54 years is well beyond the minimum climatic analysis duration of 30 years recommended in the WMO guidelines (Sivakumar et al. 2011). Using these data, the province was divided into 5 homogenous sub-regions or clusters (Figure 2. 2) based on the average total precipitation for the October to March rainfall season. This was done using Hot Spot Analysis in ArcGIS (version 10.3). Hot spot analysis is a local spatial pattern analysis tool which works by considering each feature within the context of neighbouring features and determining if the local pattern (a target feature and its neighbours) is statistically different from the global pattern (all features in the dataset). The z-score and *p*-value results associated with each feature determine if the difference is statistically significant or not. This enabled the comparison of droughts and wet characteristics between and among the different areas within the province. Data from the grid points that are located in the immediate surroundings of the province were also included in the analysis for purposes of interpolation during spatial analysis.

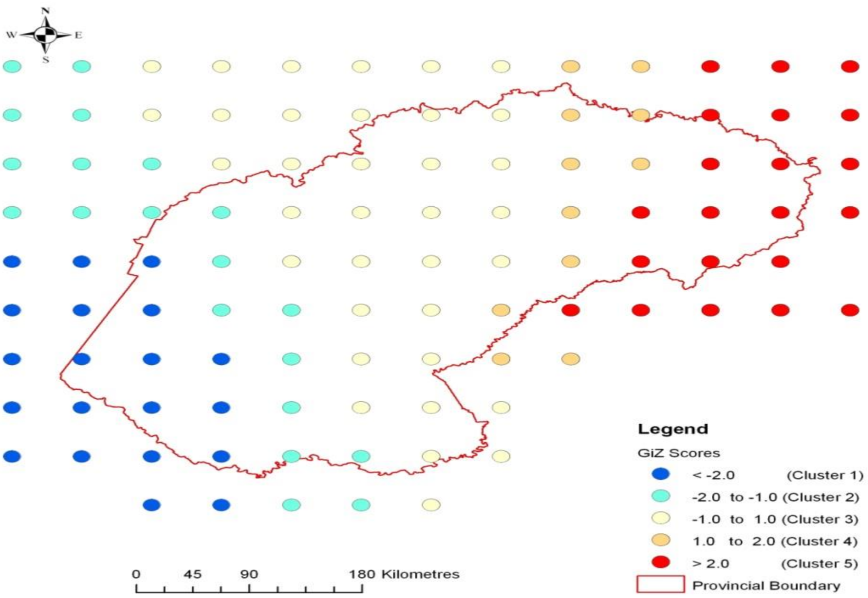


Figure 2.2: Locations of sub-regions/clusters in the Free State Province [cluster 1 (blue), Cluster 2 (Turquoise), Cluster 3 (cream), Cluster 4 (brown) and Cluster (red)] from Hot Spot Analysis performed using average total precipitation between October and March.

The Drought Indices Calculator, DrinC, was used to calculate the SPI for each of the grid points included in the study. Details on SPI calculation using DrinC can be found in (Tigkas et al.

2015). The SPI calculation for any location is based on the long-term precipitation record for a desired period, which is then fitted to a probability distribution and converted into a normal distribution. According to this distribution, the mean SPI for the location and desired period is zero (Edwards and Mckee 1997). Positive SPI values indicate greater than median precipitation while negative values indicate less than median precipitation (Dlamini 2013). Several research work have used the DrinC, for example those undertaken in Italy (Capodici et al. 2008); Malta (Borg 2009) and Iran (Darani et al. 2011). Yevjevich et al. (1978) suggest that for a drought index to be effective, it should be derived locally, be adapted to the climate of the territory, and conceptually and comprehensively used to describe droughts in the region. Therefore, the SPI classification that was developed by Agnew (1999) and modified by (Manatsa et al. 2010) was adopted, to meet the southern Africa Regional Climate Outlook Forum (SARCOF) guidelines (Table 2. 1). Three essential elements which distinguish droughts from one another were analysed: intensity, duration, and spatial extent (White 2011). The scope of this study was limited to severe and extreme droughts and wet conditions within the Free State Province as these have a greater impact on agricultural yield. A study on the impact of drought on grape yield in the Western Cape Province of South Africa revealed that years of poor yield coincide with moderate or severe drought periods with ($r \approx -0.9$) (Araujo et al. 2016).

Table 2.1Categorization of dryness/wetness

SPI Value occurrence	% Occurrence	Nominal SPI class
>1.645	≤5	Extremely wet
1.644 to 1.282	6-10	Severely wet
0.842 to 1.281	11-20	Moderately wet
0.524 to 0.841	*21-33*	*Slightly wet*
-0.523 to 0.523	34-50	Normal
-0.841 to 0.524	*21-33*	*Slight drought*
-1.281 to -0.842	11-20	Moderate drought
-1.644 to -1.282	6-10	Severe drought
<-1.645	≤5	Extreme Drought

(Adapted from by Agnew, 1999 and modified by Manatsa et al. 2010:291)

2.4.3 Computing SPI

The SPI is equivalent to Z-score used in statistics (Almedeij 2014). It is based on the conversion of the precipitation data to probabilities, based on long-term precipitation records that are computed at different time scales. Compared to other drought indices, for example the Palmer Drought Severity Index, the SPI gives a better representation of abnormal wetness and dryness (Guttman 1999). The multi-scalar characteristic of the SPI enables the identification of different types of droughts (Edwards and Mckee 1997). Details about the theoretical background of SPI can be found in (Lloyd-Hughes and Saunders 2002). SPI trends were investigated using the linear regression model. We plotted the Kernel densities on the data according to each cluster to check whether the data is normally distributed. As shown in Figure 2. 3, the data show a fair approximation to normal distribution. As such, parametric test (ANOVA) was performed to check for any significant differences in the drought and wet characteristics between clusters.

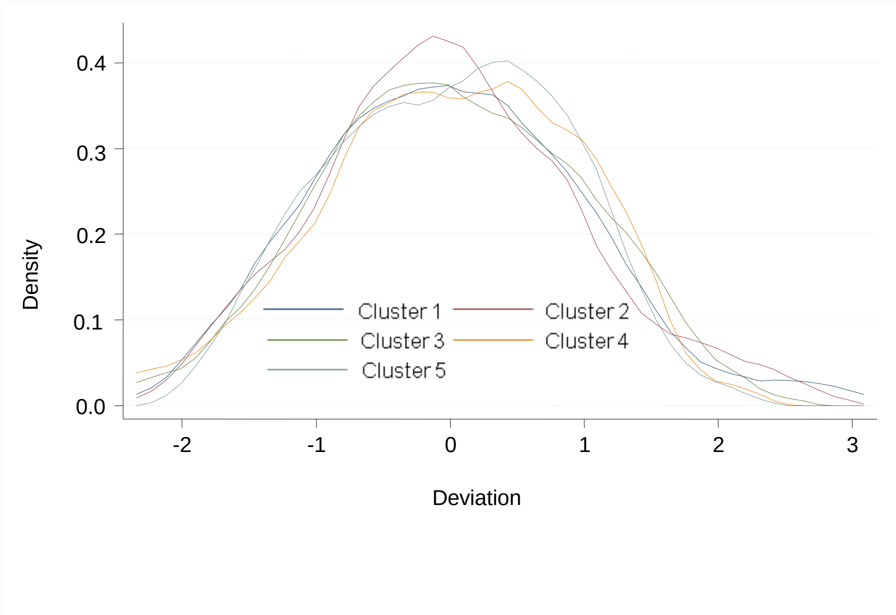


Figure 2.3Distribution of the provincial averaged 6 months SPIs expressed in Kernel densities versus standard deviation for clusters 1-5.

Since the SPI is normalised, it represents wetter and drier climates in the same way. The trend analysis was performed for the province as a whole, and then separately for each of the clusters. Annual drought/wet percentage of area for each cluster was calculated based on the ratio of the number of grid points with SPI $\leq$-1.282 to the number of grid points in that particular subregion/ cluster. For any area, a drought year is defined as a year in which at least 40% of the area (in this case expressed as the number of grid points) is affected by the drought (Yu et al. 2014).

2.5 Results and Discussion

2.5.1 Distribution of seasonal average rainfall in Free State

Figure 2. 4 illustrates the distribution of seasonal average precipitation (October-March) over the Free State Province. There is a clear west-east gradient in average total precipitation received in the Free State Province.

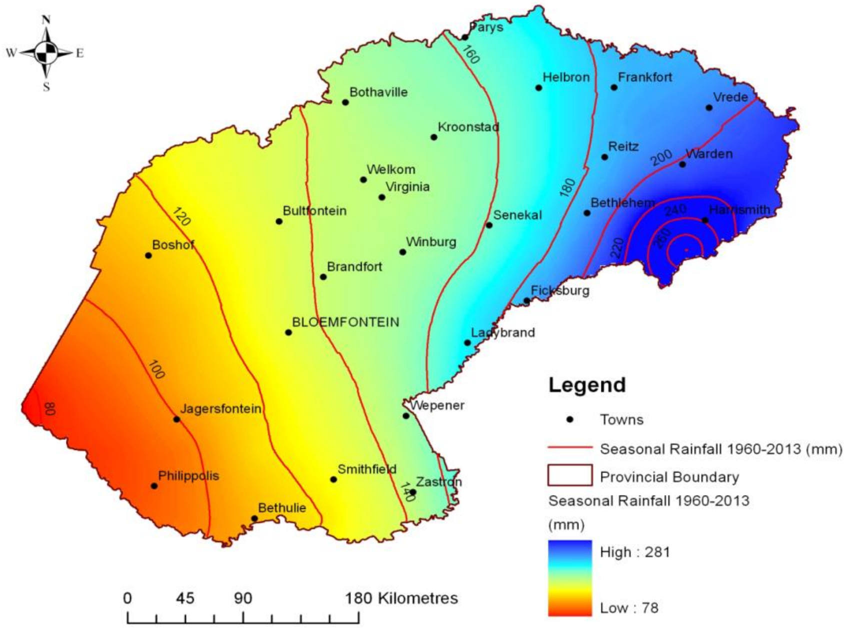


Figure 2.4Seasonal average rainfall distribution over the Free State Province (season covers October-March). The data is averaged for the period 1960-2013.

2.5.2 Drought intensity variations

The seasonal averaged SPIs for the Free State region were plotted for the three seasons; OND, JFM and ONDJFM for the 1960-2013 period from a regional perspective down to cluster level. Figure 2. 5 shows the SPI variations over time for all the seasons analysed. The most intense drought was experienced during the OND subseason in the 1994/95 season with SPI value of -1.98. The second most intense drought occured during the JFM period of the 1991/92 rainfall season with SPI value of -1.755. The other two JFM seasons that experienced severe droughts were recorded in 2006/07 and 1982/83. In total, SPI_3 OND identified five seasons whose droughts were in severe category, including 1994/95, 1990/91, 1972/73, 1965/66 and 1997/98, all of which were either severe or extreme. There were no droughts (SPI ≤ -1.282) identified by the SPI_6 ONDJFM. This was despite the fact that 1994/95 OND subseason was the driest for the entire study period. The 1994/95 JFM SPI of -0.127 contributed to the reduction of the seasonal SPI. This suggests that while the season started off as dry, the later summer subseason was generally wet. South African Waether Services (SAWS) records show that there were droughts that affected South Africa during the whole season, for example 1991/92, 1969/70, and 1982/83 but these were not identified in the Free State at the 6-month scale. This deviation can be explained as the effect of using averages. Extremely low SPI values and extremely high values when averaged results in near zero values. This problem can be overcome by first performing a Hot Spot Analysis in order to delineate homogeneous regions, whose SPI characteristics were analyzed separately.

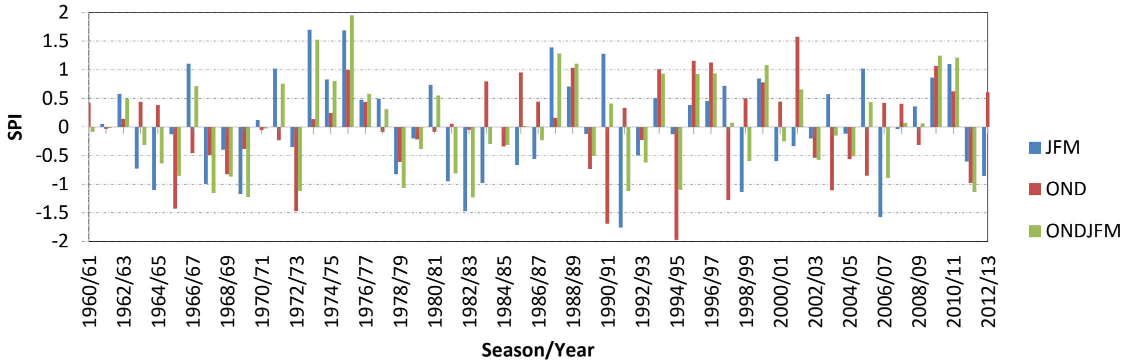


Figure 2.5Annual variation of averaged SPIs for the Free State Province for OND (SPI_3), JFM (SPI_3) and ONDJFM (SPI_6). Data are from 1960-2013

On the other end, the wet years that recorded SPIs ≥ 1.282, at the 6-monthscale were 1987/88, 1973/74 and 1975/76. SPI_3 OND identifies only 2001/02 and SPI_3 JFM identifies 1987/88, 1975/76 and 1973/74. What is interesting about the wet years is that the seasons identified by SPI_3 JFM are identical in intensity to those identified by SPI_6 ONDJFM.Overall, the dominant rainfall systems for the region are of tropical origin that moves in sympathy with the Intertropical Convergence Zone during the late part of the rainfall season. The rest of the results are displayed in Tables 2. 2, 2. 3 and 2. 4 while figures 2. 6 a-c, show temporal variations of drought/wet intensity per cluster over the 53 years for each of the seasons. At national level, there has been a decline in the area planted (Goldblatt and von Bormann 2010) which may be due to the increase in intensity and spatial extent of dry conditions during the growing season. Establishing if there is a link between SPI and crop production in the province is beyond the scope of this work.

Table 2.2Distribution of severe and extreme dry/wet seasons at 6-month scale across clusters of the Free State Province between 1960 and 2013

Dry Seasons					Wet Seasons			
Cluster	**Total Number of Drought seasons (SPI ≤-1.282)**	**Year**	**SPI Value**	**Drought description**	**Total Number of Wet seasons SPI ≥1.282**	**Years**	**SPI Value**	**Wetness description**
1	2	1998/99	-1.894	Extremely dry	5	1993/94	1.411	Severely wet
		1969/70	-1.329	Severely dry		1987/88	1.433	Severely wet
						2010/11	1.584	Severely wet
						1975/76	2.422	Extremely wet
						1973/74	2.675	Extremely wet
2	2	1969/70	-1.519	Severely dry	4	2010/11	1.500	Severely wet
		1967/68	-1.402	Severely dry		1987/88	1.627	Severely wet
						1975/76	2.345	Extremely wet
						1973/74	2.384	Extremely wet
3	3	1991/92	-1.558	Severely dry	4	1973/74	1.401	Severely wet
		1969/70	-1.354	Severely dry		1988/89	1.429	Severely wet
		1967/68	-1.326	Severely dry		2009/10	2.555	Extremely wet
4	3	1982/83	-1.881	Extremely dry	2	2009/10	1.511	Severely wet
		1991/92	-1.669	Extremely dry		1995/96	1.800	Extremely wet
		2011/12	-1.552	Severely dry				
5	4	1981/82	-1.695	Extremely dry	2	1999/00	1.351	Severely wet
		1982/83	-1.579	Severely dry		1995/96	2.282	Extremely wet
		2011/12	-1.418	Severely dry				
		1965/66	-1.377	Severely dry				

Table 2.3Distribution of severe and extreme dry/wet seasons across clusters of the Free State Province between 1960 and 2013 during the OND subseason

Dry Seasons					**Wet Seasons**			
Cluster	**Total Number of Drought seasons (SPI ≤-1.282)**	**Years**	**SPI Value**	**Drought description**	**Total Number of Wet seasons SPI ≥1.282**	**Years**	**SPI Value**	**Wetness description**
1	4	1997/98	-2.163	Extremely dry	5	1988/89	1.296	Severely wet
		1994/95	-1.999	Extremely dry		1993/94	1.373	Severely wet
		1972/73	-1.717	Extremely dry		1991/92	1.401	Severely wet
		1990/91	-1.414	Severely dry		2001/02	1.432	Severely wet
						1985/86	1.778	Extremely wet
2	5	1994/95	-2.665	Extremely dry	4	1988/89	1.296	Severely wet
		1972/73	-1.605	Severely dry		1975/76	1.297	Severely wet
		1997/98	-1.593	Severely dry		1996/97	1.470	Severely wet
		1990/91	-1.579	Severely dry		2001/02	1.505	Severely wet
		1965/66	-1.378	Severely dry				
3	5	1990/91	-1.946	Extremely dry	3	1995/96	1.284	Severely wet
		1994/95	-1.869	Extremely dry		2009/10	1.447	Severely wet
		1965/66	-1.599	Severely dry		2001/02	1.754	Extremely wet
		1972/73	-1.505	Severely dry				
		1997/98	-1.461	Severely dry				
4	4	1990/91	-2.156	Extremely dry	3	2009/10	1.334	Severely wet
		1965/66	-2.079	Extremely dry		2001/02	1.529	Severely wet
		2003/04	-1.697	Extremely dry		1995/96	1.672	Extremely wet
		1994/95	-1.597	Severely dry				
5	4	2003/04	-1.777	Extremely dry	3	1983/84	1.298	Severely wet
		1994/95	-1.664	Extremely dry		2001/02	1.519	Severely wet
		1990/91	-1.376	Severely dry		1995/96	1.626	Severely wet
		1972/73	-1.324	Severely dry				

Table 2.4Distribution of severe and extreme dry/wet seasons across clusters of the Free State Province between 1960 and 2013 during the JFM subseason

Dry Seasons					Wet Seasons			
Cluster	**Total Number of Drought seasons (SPI ≤-1.282)**	**Years**	**SPI Value**	**Drought description**	**Total Number of Wet seasons SPI ≥1.282**	**Years**	**SPI Value**	**Wetness description**
1	4	1998/99	-1.951	Extremely dry	4	2010/11	1.410	Severely wet
		1963/64	-1.473	Severely dry		1987/88	1.428	Severely wet
		1982/83	-1.391	Severely dry		1975/76	2.201	Extremely wet
		1983/84	-1.390	Severely dry		1973/74	2.695	Extremely wet
2	6	1991/92	-1.807	Extremely dry	5	2010/11	1.421	Severely wet
		1982/83	-1.573	Severely dry		1990/91	1.440	Severely wet
		1969/70	-1.455	Severely dry		1987/88	1.835	Extremely wet
		1963/64	-1.420	Severely dry		1975/76	2.097	Extremely wet
		1967/68	-1.295	Severely dry		1973/74	2.380	Extremely wet
		2006/07	-1.287	Severely dry				
3	3	1991/92	-2.259	Extremely dry	4	1971/72	1.452	Severely wet
		2006/07	-1.813	Extremely dry		1987/88	1.496	Severely wet
		1982/83	-1.488	Severely dry		1973/74	1.601	Severely wet
						1975/76	1.945	Extremely wet
4	4	1991/92	-2.357	Extremely dry	2	1990/91	1.594	Severely wet
		2006/07	-1.900	Extremely dry		1966/67	1.737	Extremely wet
		1982/83	-1.762	Extremely dry				
		2012/13	-1.304	Severely dry				
5	3	2006/07	-1.557	Severely dry	2	1966/67	1.510	Severely wet
		1981/82	-1.439	Severely dry		1995/96	1.728	Extremely wet
		1978/79	-1.378	Severely dry				

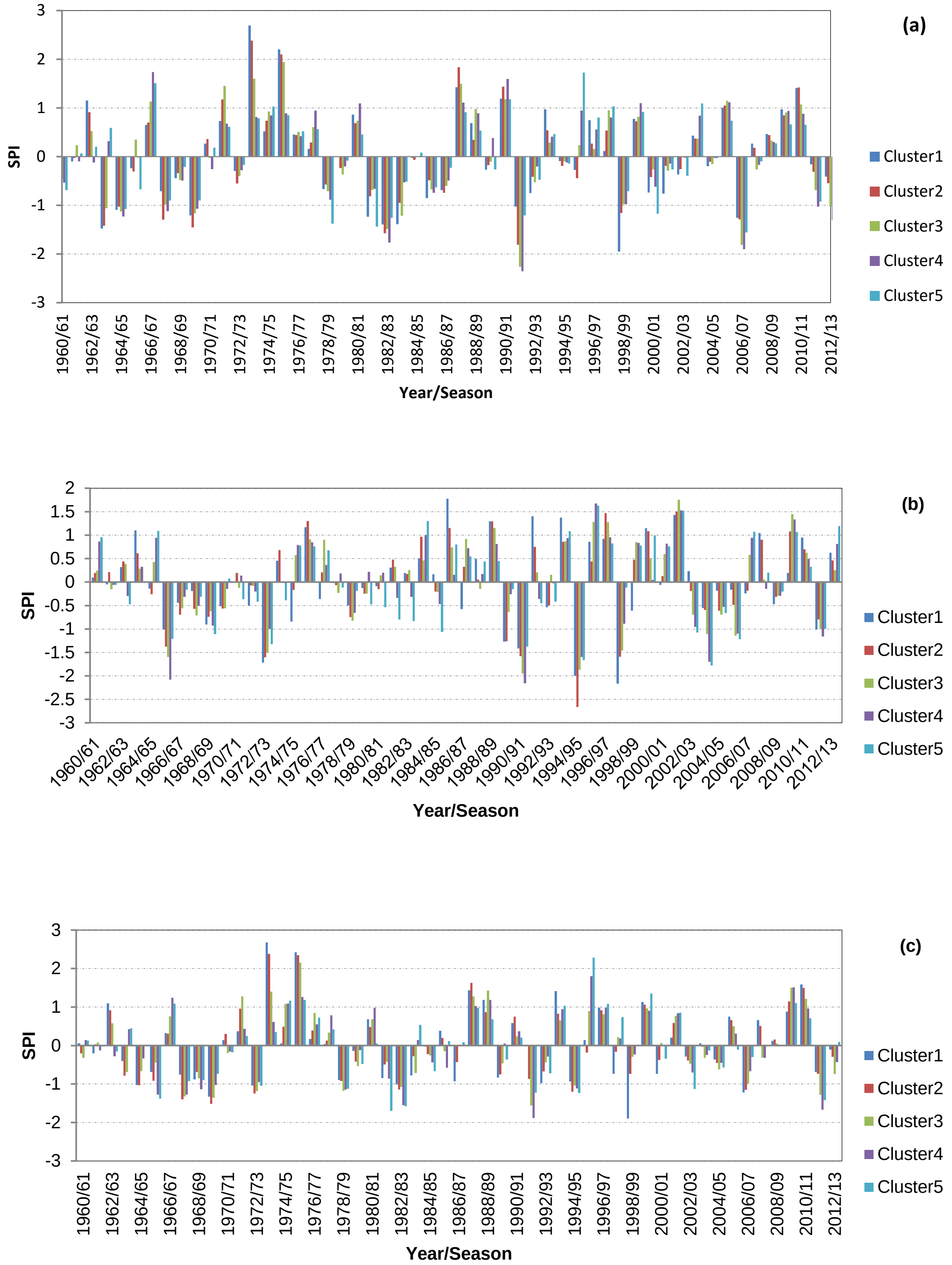


Figure 2.6Temporal annual variation of SPI at 3 and 6 months scale in the five clusters of the Free State for (a) JFM ((SPI_3), (b) OND (SPI_3) and (c) ONDJFM (SPI_6). Data are for 1960-2013.

Tables 2. 2, 2. 3 and 2. 4 show that there are variations in the years identified as dry (SPI ≤ -1.282) or wet (SPI ≥ 1.282) in each cluster. The SPI_6 ONDJFM identifies eight seasons with at least ≤ -1.282 (severe drought) from different clusters while the SPI_3 JFM identifies eleven years. SPI_3 OND identifies six seasons of at least a severe drought magnitude. There are more seasons in common identified at SPI_3 JFM with those identified at SPI_6 ONDJFM. SPI_3 OND identifies only 1965/66 season as a common drought season with SPI_6 ONDJFM. The spatial coverage of these drought and wet years is best expressed as percentage area coverage. Yu et al. (2014) recommended at least 40% area coverage for a year to be considered as dry or wet. In this study, severe/ extreme dry (wet) years with at least 40% area coverage by drought SPI ≤ -1.282 or wet conditions SPI ≥ 1.282 were considered. Figure 2. 7 shows the temporal variations of percentage area coverage by at least severe drought/ severe wet conditions severe dry/wet conditions in the province for the ONDJFM season.

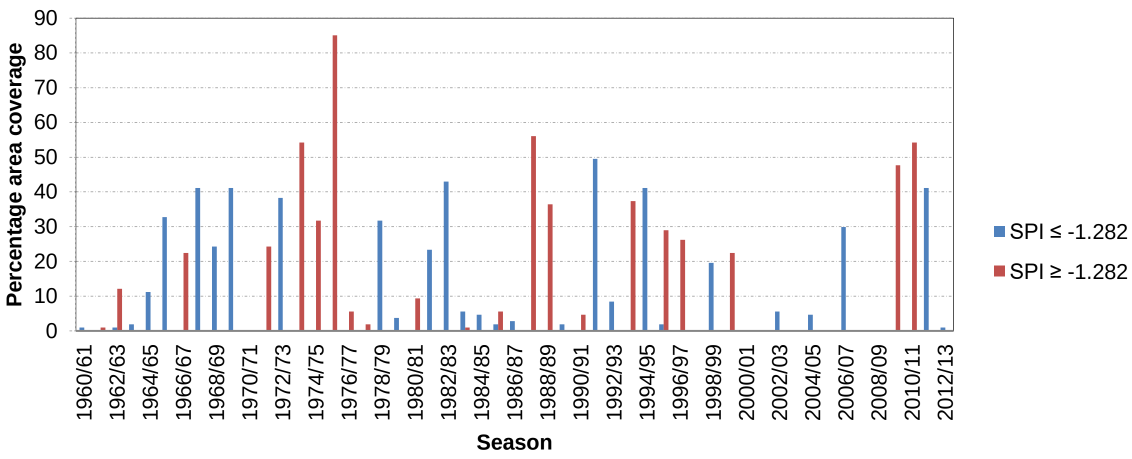


Figure 2.7Temporal variations of total percentage area covered by drought/ wet conditions in the Free State Province (SPI ≤-1.282 and SPI ≥1.282) for ONDJFM season.

The distribution of SPI_6 ONDJFM droughts shows that cluster 5, in the extreme eastern part of the province has the highest occurrence of droughts (five) in the severe and extreme categories and the lowest count of wet years in the severe wet and extreme wet categories. A unique aspect of cluster 5 is that while all the other clusters experienced breaks in extreme drought conditions, this cluster had two consecutive seasons of at least severe drought, 1981/82-1982/83.

The eastern parts of the province experienced severe-extremely dry seasons in the later decades compared to the western areas. Both clusters 4 and 5 experienced the 2011/12 severe drought, while cluster 2 last experienced a drought of the same magnitude during the 1969/70 season (Figure 2. 8). SPI_3 OND results show that the extreme west and central parts of the province, making up clusters 1, 2 and 3 had their last recorded severe drought in the 1997/98 season. The eastern parts experienced extreme drought during the 2003/04 season. This observation suggests that the eastern parts of the province are getting drier. This shift towards more severe drought conditions in areas that have a low historical record of severe droughts can be linked to an observed increase in the frequency of the negative southern Oscillation phase (Wolter & Hastenrath 1989).

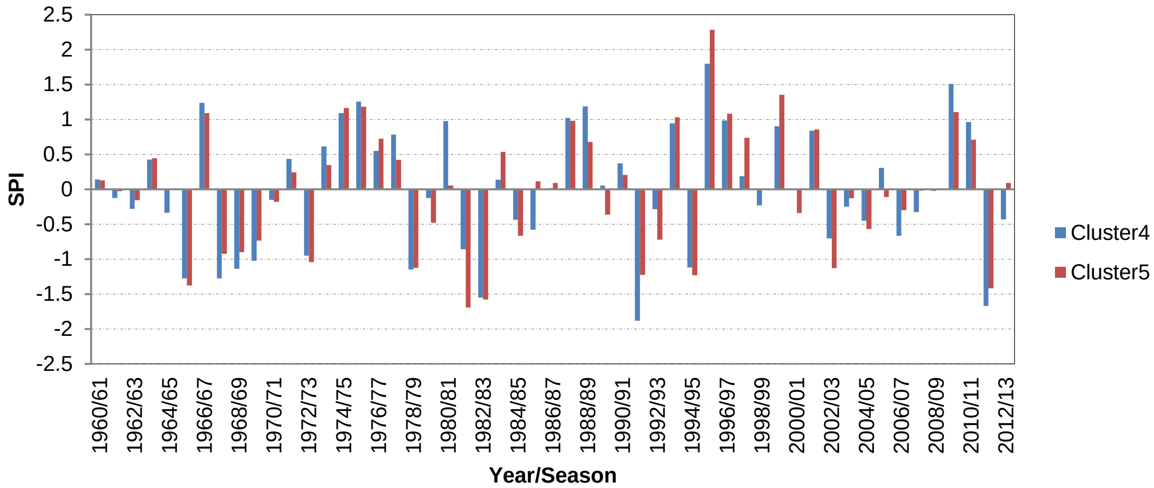


Figure 2.8Temporal annual variations of SPI_6 in the eastern parts of the Free State Province (Clusters 4 and 5) over the study period 1960-2013.

Regarding wet conditions (characterized by SPI≥ 1.282 for the ONDJFM season), cluster 5 experienced its wettest season during the 1999/2000 season, while the rest of the clusters had at least a wet season after 2009. It is interesting to note that for the OND sub-season, before the 2001/02 widespread wet season, the last wet season had been experienced in the 1990s. Before 1983, save for cluster 2 during the 1975/76 season, the rest of the province did not have any wet season with SPI≥ 1.282 during the OND period (Figure 2. 6b). Thissuggests that the OND sub-season has become wet recently compared to the past.

With respect to the JFM sub-season, cluster 2 recorded the highest incidences of both dry (SPI≤ -1.282) and wet (SPI≥ 1.282) seasons. However, a downward trend can be observed in the number of wet and dry seasons, from the western to the eastern parts of the province. Thisillustrates that during the JFM sub-season, the western parts of the region are usually drier than the eastern parts. The same pattern was observed for the wet conditions during the same period in the region. The western extreme and central parts of the province have more wet occurrences in the JFM sub-season than the eastern areas. This is despite the fact that on average, the east receives far more seasonal precipitation than the extreme west (Moeletsi & Walker 2012). This means that the JFM precipitation varies more, regarding deviation from the mean in the west than in the east.

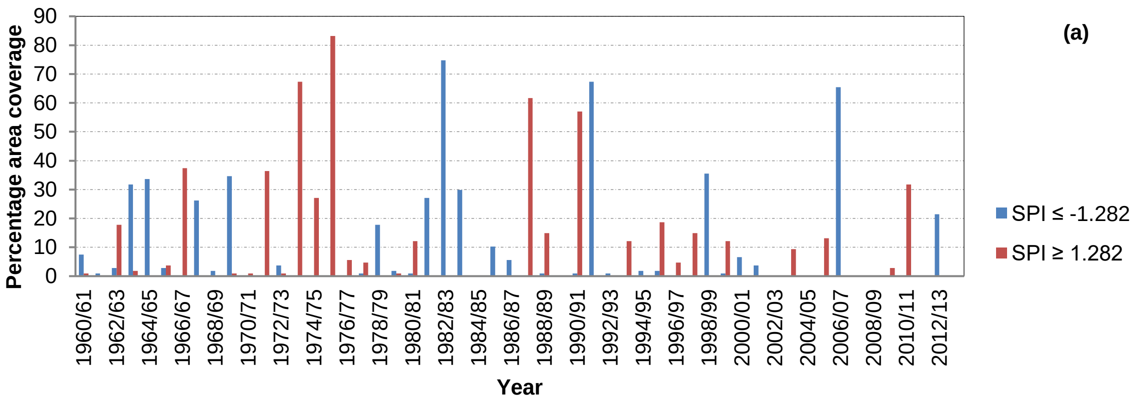
To test for any significant differences in drought intensity between clusters, One-way Analysis of Variance was performed using SPSS for the period 1960 to 2013 for each of the sub-seasons. This included a multiple comparison procedure to identify the exact clusters with significant differences. Table 2. 5 shows the results for SPI_6 multi-cluster comparison. The results show that for the SPI_6 there is a clear division between the east and the west. Clusters 1, 2 and 3 are not significantly different from each other which is the same for clusters 4 and 5. Thus, there are three main groups which are significantly different, the east, the central and the west. However, during the OND period, average SPIs show that cluster 1 is significantly different from clusters 2 and 3,but there is no significant difference between clusters 2 and 3. This implies that cluster 1 is unique within the western region during the OND sub-season. To the eastern part of the province, the significant differences also exist between neighbouring clusters 4 and 5. Thus, there are more significant differences in the OND period than there are for the whole season. It is intriguing to note that the JFM period has an almost homogenous pattern in as far as drought intensity is concerned. Significant differences are only noted between cluster 2 and cluster 3 and between clusters 2 and 5. During the JFM period, the neighbouring clusters, 2 and 3, show significant difference while clusters 1 and 2; 4 and 5 show significant differences during the OND sub-season. This suggests that there is a unique climatic forcing that makes cluster 2 significantly different from others and this deserves further investigation. These results agree with variations of drought/wet occurrences (Tables 2. 2, 2. 3 and 2. 4) observed over the province.

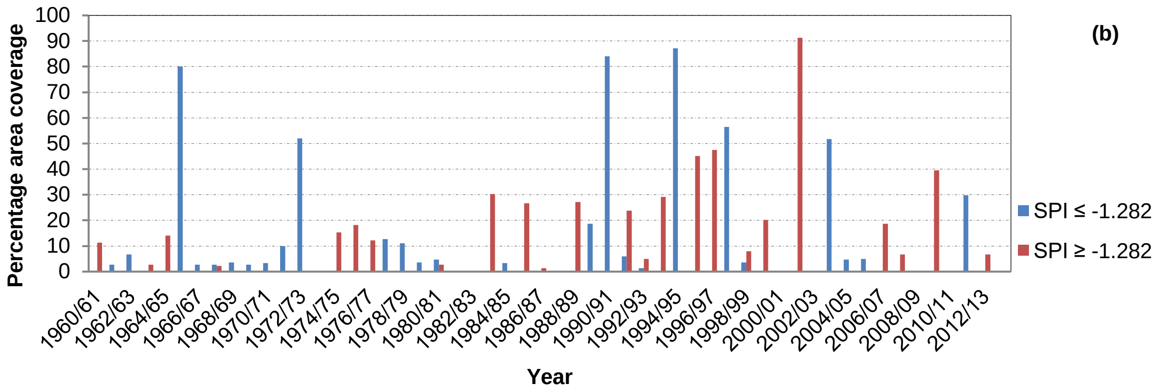
Table 2.5SPI_6 multiple cluster comparison ANOVA results

Cluster (I)	Cluster (J)	Mean Difference (I-J)	Std. Error	Sig.
1	2	-0.00082	0.00217	0.707
	3	-0.00139	0.00196	0.481
	4	0.00611*	0.00253	0.017
	5	0.01086*	0.00217	0.000
2	3	-0.00057	0.00190	0.765
	4	0.00692*	0.00248	0.006
	5	0.01168*	0.00211	0.000
3	4	0.00749*	0.00230	0.002
	5	0.01225*	0.00190	0.000
4	5	0.00476	0.00248	0.058

2.5.3 Drought/wet percentage area coverage

The spatiotemporal characteristics of droughts (SPI≤ -1.282) and wet years (SPI≥ 1.282) in the Free State Province were analysed. The 40% area coverage threshold for a drought or wet year was adopted (Yu et al. 2014). Using this threshold, three seasons experienced at least severe drought conditions in the Free State Province during the JFM sub-season (Figure 2. 9a); 1982/1983 (75%), 1991/1992 (67%) and the 2006/2007 (65%). These correspond with the provincial averaged JFM droughts in terms of intensity, although 1991/1992 was the worst in terms of severity. Thus, 1991/1992 JFM sub-season was extremely dry and was the second leading in terms of area coverage after the 1982/1983 drought. These results concur with observations by (Unganai & Kogan 1998) although 2006/2007 falls outside their study period.





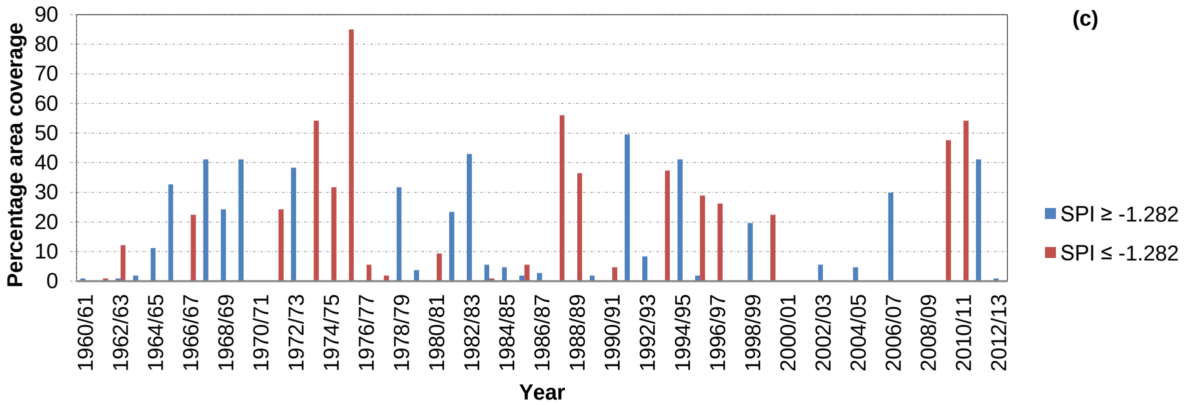


Figure 2.9Annual variability of total percentage area covered by severe drought and severe wet conditions as denoted by SPI values over Free State Province at SPI_3 (a) JFM, (b) OND and SPI_6 (c) ONDJFM time scale between the period 1960-2013.

For the OND sub-season (Figure 2. 9b), there were six drought years covering at least 40% of the province. These seasons match the years on the severity scale, with the 1994/1995 OND sub-season as extremely dry. Consequently, the 1994 drought was both the worst intense in terms of severity and covered the largest area in the history of droughts during this sub-season. In the wet category, 2001/2002 OND sub-season had the highest percentage coverage of 83%. For the 6-month scale (Figure 2. 9c), there were no years with severe or extreme drought conditions covering at least 40% of the province. The driest years in the province were only moderately dry. Of these moderately dry years, the highest percentage coverage was 50% during the 1991/92 season and 1982/83 (43%). However, the spatial distribution of SPIs for the whole season (Figure 2. 10a) shows that the extreme south-western areas had severe drought, which is an indication that using large area average may be misleading. The moderately dry years fall within the dry periods of 1964 to 1970; 1991 to 1995 and again from 2002 to 2005as identified by (South African Weather Services 2017). By 1987, the 1983/1984 drought wasthe worst in central and southern Africa (Downing 1987). However, this was only a continuation of the drought that had started in 1982 (Unganai & Kogan 1998), which had 43% area coverage in the Free State province. It would be misleading to conclude that the whole of southern Africa had a drought of the same severity. Rather, some areas were more affected by drought conditions than others. Thus, using the average index for the large area may be misleading in describing the dryness/wetness of the area because it eliminates extreme cases. These variations are illustrated on the maps showing the distribution of drought and wet conditions inthe Free State Province for selected years with outstanding provincial area average SPI values (Figures 2. 10a-f).

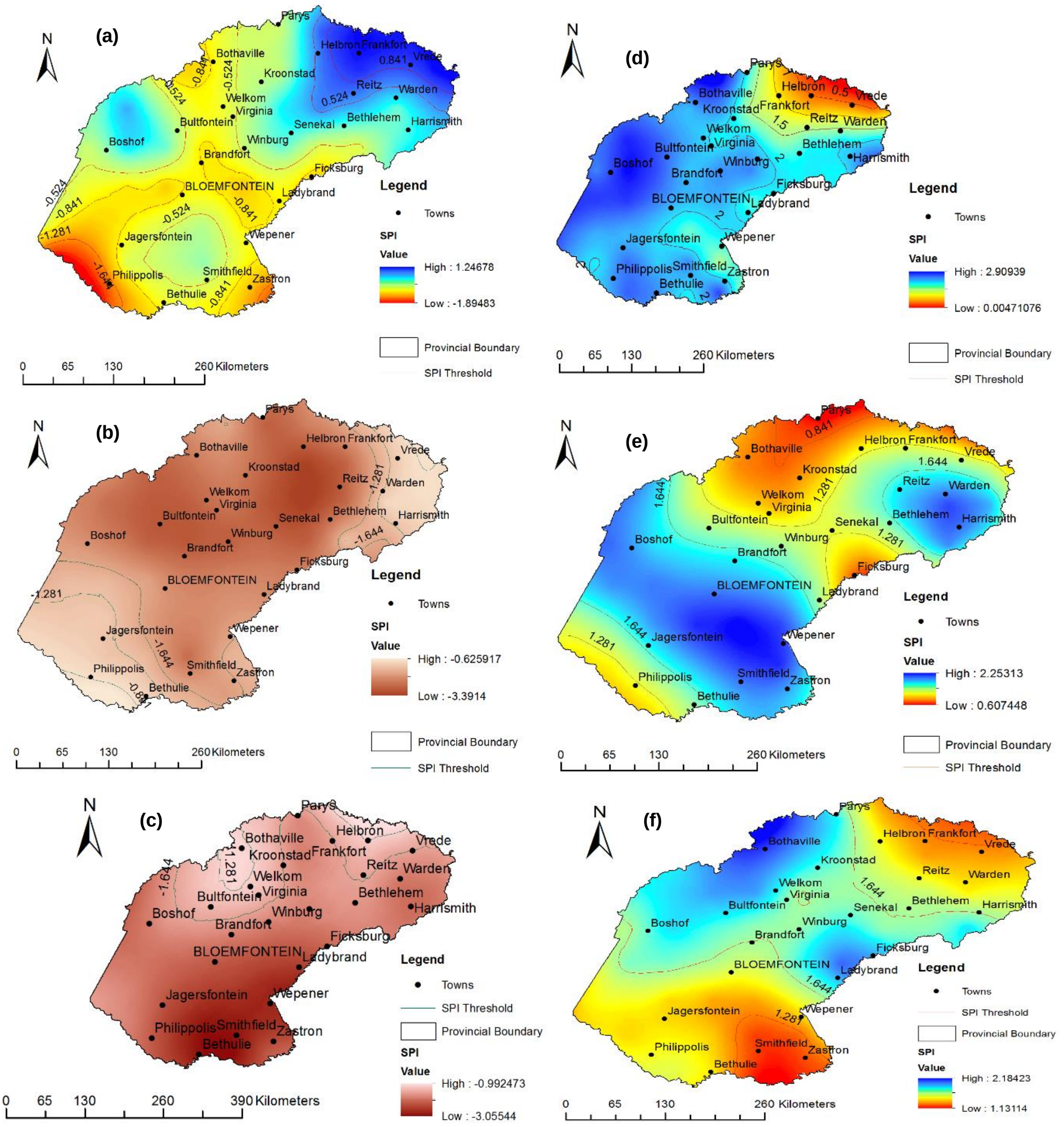


Figure 2.10Spatial distribution of drought (a) 1983/84 SPI_6 (b) 1992 SPI_3(JFM) (c) 1994 SPI_3 (OND) and wet (d) 1975/76 SPI_6 (e) 1988 (JFM) (f) 2001 (OND) conditions over Free State Province. Only the driest and wettest years are shown for each timescale.

2.5.4 Variations in drought duration

Since the Free State Province has heterogeneous seasonal climate characteristics, drought duration was analysed per cluster within each sub-season. Drought duration was also analysed at provincial scale. Results show that duration of drought varies across clusters and with seasonality. We developed a program within Microsoft Excel Developer to analyse drought duration. Drought duration was calculated from the time the SPI value dropped to -1, as the start to the time when the SPI value returned to +1 (Yu et al. 2014). For the OND sub-season for the whole province, a wet sub-season came after 23 years, after a drought that had started in 1965. By cluster analysis, the drought that started in 1965 lasted the longest in Cluster 3 (23 years) while in clusters 1 and 2, the drought ended in the 10th year. A comparison of drought duration between the two sub-seasons shows that JFM droughts have a much shorter duration than OND droughts. For the JFM sub-season, a wet season came after 14 years, drought having started during the 1991/1992 season; thus, it ended in 2006. The year 2006 coincides with the SAWS` end-of-drought year for the 2000-2005 drought period. Areas to the west of the province experienced this long drought spell but reduced in duration in the eastern parts of the province (Clusters 4 and 5 with each lasting 8 and 4 years, respectively). JFM droughts increased in duration in the 1980s, while OND droughts show a decrease between the 1960s and 1995. For the entire growing season (SPI_6), the longest drought lasted for 9 years, 1964/1965- 1973/1974 in cluster1 and 2; 1978/1979- 1987/1988 in clusters 3 and 4. The 1991/1992 drought lasted the longest in cluster 3, which is the central part of the province, for 8 years. The ONDJFM season droughts lasted between 6 and 9 years making the season with the smallest range, followed by JFM with 12 and OND with the highest, 22 years. It is important to note however, that for OND sub-season, the 23 years between 1965 and 1988 influenced the range, at the provincial level. At the provincial level, the longest drought lag for JFM sub-season was 14 years (1991/1992- 2005/2006), 23 years for OND (1965/1966- 1988/1989) and 9 years (1978/1979- 1987/1988) for the SPI_6. This points to the idea that the OND sub-season has more consecutive droughts than the JFM sub-season. This calls for government and stakeholder intervention to improve awareness among farmers and to educate them on drought management strategies to reduce their vulnerability to drought. Strategies may include the adoption of policy instruments such as, but not limited to, extension agrometeorology through which farmers` preparedness and decision-making skills can be improved(Stigter et al. 2013).

2.6 Conclusions

The results of this study show that droughts within the province are unevenly distributed, with different areas experiencing either drought or wet conditions during the same seasons annually. The eastern parts of the Free State Province experience the shortest drought duration periods, regardless of the sub-season and yet these areas experience drought in different years from the rest of the province. This suggests that there is a need to assess the performance of the season at a much smaller spatial scale since a season may be ‘good’ nationally but ‘very bad’ in some local areas. While the eastern part of the Free State Province generally receives more precipitation than the rest of the region, it has the highest frequency of drought years, followed by the central region of the province. However, there could be other factors other than altitude influencing precipitation variability differences between the western and the eastern parts of the province. Regardless of the situation of the cluster within the province, the JFM sub-season`s performance largely controls the general outlook and behaviour of the total growing season. This means that what happens in the early summer season has little influence on whether the season can be regarded as dry or wet although this does not make this sub-season less important. While previous studies have focused on the southern African region as a whole, what happens on a small scale has remained unexplored, leaving the societies vulnerable to climate variability impacts. Notably, in the Free State Province, there are more significant differences between clusters during the early summer period than the late summer period. There is thus, a need to pay attention in monitoring the climatic variations and changes taking place in the Free State Province to ensure that its status as the country’s breadbasket is not compromised.

CHAPTER 3: INFLUENCE OF ALTITUDE ON THE SPATIOTEMPORAL VARIATIONS OF METEOROLOGICAL DROUGHTS IN MOUNTAIN REGIONS OF THE FREE STATE PROVINCE, SOUTH AFRICA (1960–2013)

3.1 Brief chapter synopsis

This chapter is based on the paper which was published as:

Mbiriri, M., Mukwada, G. & Manatsa, D. 2018. Influence of Altitude on the spatiotemporal variations of meteorological droughts in mountain regions of the Free State Province, South Africa (1960-2013). Advances in Meteorology 2018, 1-11. https://doi.org/10.1155/2018/5206151

3.2 Abstract

The Standardized Precipitation Index (SPI) was computed for October to December (OND) and January to March (JFM) summer sub-seasons for the Free State Province, South Africa, toassess the influence of altitude on drought severity and frequency. The observed spatiotemporal heterogeneity in the SPI variability revealed that the factors governing drought interannual variability varied markedly within the region for the two subseasons. Strong correlations between r = 0.76 and 0.93 across the clusters in both subseasonswere observed. Significant shift in average SPI, towards the high during the OND sub-seasonwas detected for the far western low-lying and central regions of the province around the 1990s. An ANOVA test revealed a significant relationship between drought severity and altitude during the OND sub-season only. The impact of altitude is partly manifested in the strong relationship between meridional winds and SPI extremes. When the winds are largely northerly, Free State lies predominantly in the windward side of the DrakensbergMountains but lies in the rain shadow when the winds are mostly southerly. The relationship between ENSO and SPI indicates stronger correlations for the early summer sub-season than for the late summer sub-season while overall presenting a diminishing intensity with height over the Province.

Keywords meteorological drought, spatiotemporal, precipitation, Free State Province; South Africa

3.3 Introduction

Climate change impacts have been well recognized by researchers, environmentalists and politicians (Zolina et al. 2010; Singh & Masuku 2014; Batisani & Yarnal 2010). The recurrence of extreme climate events has been identified as evidence of climatic change (IPCC 2014).Studies in America (Costa & Santos 2011), Europe (Moberg & Jones 2005) and Asia (Zhang et al. 2013), have been done to examine the prevalence of extreme climate variables. In Africa, similar studies have been done in the north and central parts of the continent (Esper et al. 2007; Vicente-Serrano, Beguería, Gimeno, et al. 2012) but with little attention given to the south. Southern Africa is regarded as semi-arid with high annual rainfall variability that has drought as a common feature (Palmer & Ainslie 2006). The impact of drought is ranked top compared to other natural disasters (Bryant 2005). While several studies have been done on climate variability in terms of rainfall, contrasting results have been observed especially for semi-arid regions (Batisani & Yarnal 2010). Research studies that have been done on high elevation areas since the 1990s have concluded that climate change will severely affect the mountain regions of the world (Hastenrath 2001; Zuo & Oerlemans 1997). For example, the frequency of extreme droughts has increased in the mountainous regions of Northeast and North China (Zhang et al. 2013). In recognition of this reality, the United Nations Secretary-General declared the year 2002, “The International Year of Mountains.” In the face of climate change, mountain biota will suffer the most, as it is adapted to relatively narrow ranges of precipitation and temperatures (Halada 2010). Studies on mountain regions are slowly gaining attention in other parts of the world such as America (MacDonald & Tingstad 2007), Asia (Shahid & Hazarika 2010) and slowly in Africa (Viste et al. 2013; Hastenrath 2001).

A number of drought indices have been developed to understand drought. A drought index is a quantitative measure that characterizes drought levels by assimilating data from one or several indicators, for example, precipitation (Zargar et al. 2011). Among the most widely used indices is the Palmer Drought Severity Index (PDSI), Crop Moisture Index and the Standardized Precipitation Index (SPI) (Sivakumar et al. 2011). SPI has become popular due to simplicity in its calculation, as it only requires rainfall data. It also allows for the detection of various types of drought that affect different systems and regions while enabling calculation of estimates of the duration, magnitude, and intensity of drought (Vicente-Serrano, Chura, et al. 2014). Agricultural drought, also known as soil moisture drought exists when the available soil moisture is insufficient to sustain the crops and forage resulting in a decrease in agricultural productivity (Angelidis et al. 2012). While SPI was designed for meteorological droughts, it can also be used to detect agricultural drought when calculated on a short time scale since soil moisture conditions respond to precipitation anomalies on a relatively short scale (Angelidis et al. 2012). On a longertimescale (say 12 or 24 months), the SPI is more suitable for water resources management purposes. The SPI is based on the probability of precipitation occurrence over a given period. Since precipitation is not normally distributed, a mathematical transformation is applied so that the transformed precipitation values follow a normal distribution. It is after this transformation to normal distribution that the classification of frequencies of the extreme and severe droughts experienced at any location and timescale becomes consistent (Vicente-Serrano, Chura, et al. 2014). The SPI, however, like any other index, has its limitations; it does not take into account the contribution of other variables to drought severity,e.g. the atmospheric evaporative demand (Beguería et al. 2014). Also, SPI does not provide reliable estimations in arid climates (Wu et al. 2007). Despite these shortcomings, the SPI remains one of the most widely and acceptable indices in climate research, with its tried and tested effectiveness in decision making (Hayes et al. 2011).

Understanding the climatic conditions in mountain regions is not only important for agriculture but biodiversity studies also since life in the mountains is not driven by elevation *per se* but by the climatic conditions associated with elevation (Körner et al. 2011). In this study, the only part of the mountain range that lies within the political borders of the Free State Province was consideredto provide a comparative analysis between mountainous (to the east) and low-lying areas located to the west of the province. An in-depth analysis of mountain related intensity, frequency and spatial extent of extreme droughts at a higher resolution is necessary for a more comprehensive assessment of drought impacts. This work focused on short-term meteorological droughts (3-month SPIs for December and March) because they can serve as proxies for agricultural droughts which are important in the Free State Province. Understanding these droughts is critical for assessing the resilience of the region in the future. Hence, the objective of this study is to analyze severe to extreme drought as well as severe and extreme wet conditions in mountain regions of southern Africa, with particular emphasis on the Drakensberg Mountains within the borders of the Free State Province of South Africa for the period between 1960 and 2013.

3.4 Materials and methods

3.4.1 Study Area

The study area is confined to the political borders of the Free State Province of South Africa (Figure 3. 1). The province is situated between latitudes 26.6° S and 30.7° S and longitudes 24.3° E and 29.8° E and sprawls over high plains which stretch over the Maluti-Drakensberg Mountains along the border with Lesotho. The Drakensberg Mountains cover approximately 1,125 km^2 and reach heights of over 3,475 metres above sea level. It is South Africa`s main watershed and is the source of the Orange River, one of the major sources of water supply for commercial agriculture in the country. The province covers an area of 129,825 km^2. The climate of the Free State Province is highly influenced by the geographic location, which is continental and is characterised by warm to hot wet summers and cool to cold, dry winters. The rainfall season spans from October to March. Greatest amounts are received in January and February, giving the JFM subseason more average total precipitation than the OND subseason, with 56 percent contribution towards the seasonal total precipitation.A west to east seasonal monthly average precipitation increase has been observed over the province with the extreme west receiving a monthly average of not more than 50 mm while the extreme east receives an approximate of over 100 mm during the October to March period (Figure 3. 2).

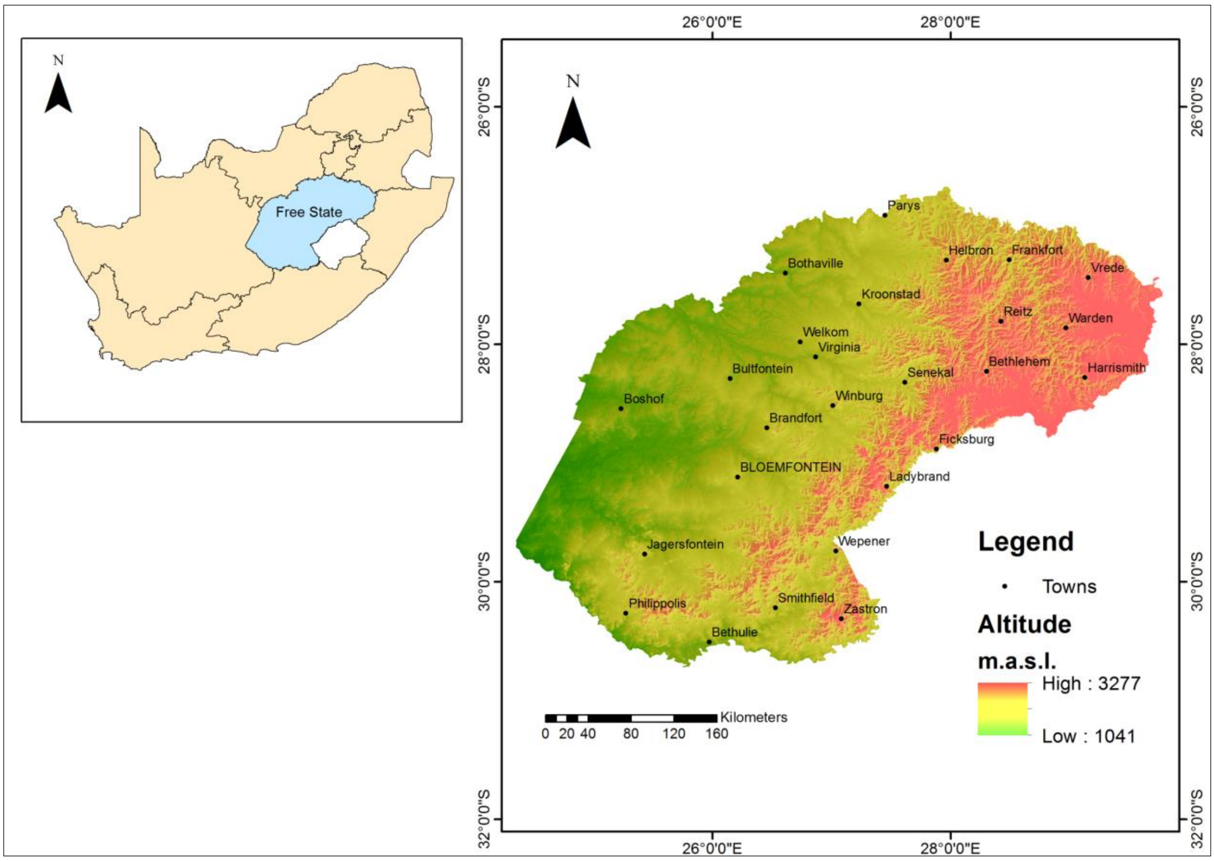


Figure 3.1Location of the Free State Province in South Africa

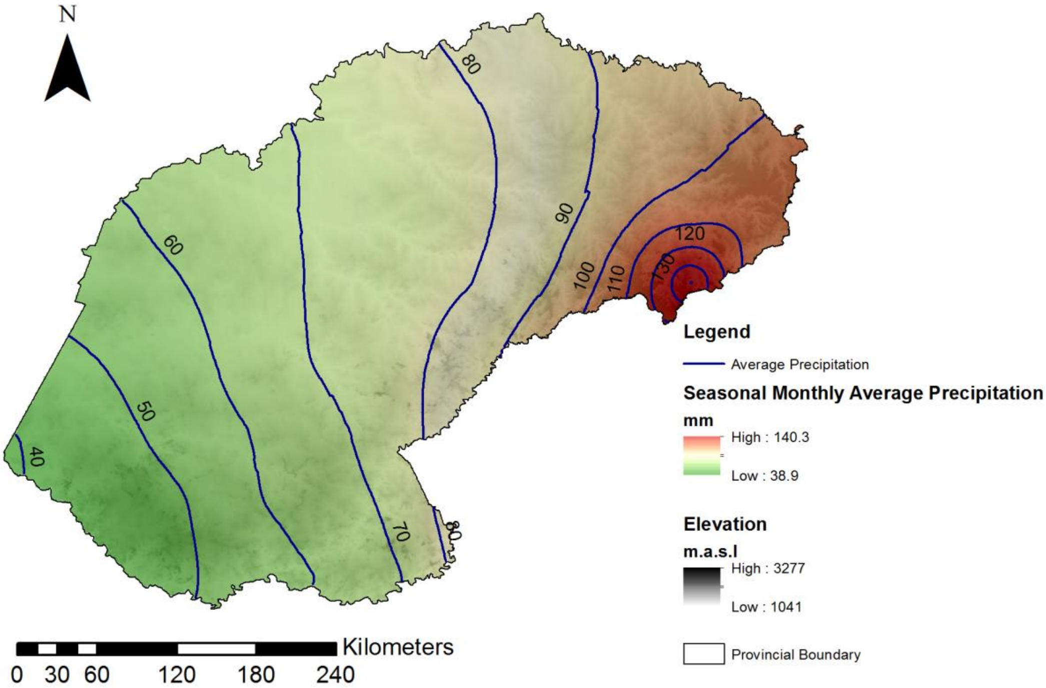


Figure 3.2Distribution of seasonal monthly average precipitation (October-March) for Free State Province in South Africa. The data are from 1960 to 2013.

3.4.2 Data

Monthly mean precipitation (mm) covering the 1960-2013 period was extracted from Climate Explorer`s Climate Research Unit (CRU TS4.01) gridded data file at 0.5° X 0.5°spatial resolution (available from https://climexp.knmi.nl). The wind data were downloaded from ERA-interim (Resolution T255) which is currently the largest global atmospheric reanalysis dataset and is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The analysis was done online using Climate Explorer. These data products are principally derived from observations in line with the World Meteorological Organisation guidelines and are freely available online. In many developing countries observational data with required data lengths and quality are unavailable (Cook et al. 2004). It is because of this limitation that the use of reanalysis data has gained popularity within the climate science field. Several studies have shown that while the use of these datasets may not be as accurate as station data, the difference is insignificant in many of the cases (Cannon et al. 2015). The period of 53 years meets the minimum climatic analysis duration requirement outlined in the World Meteorological Organization guidelines (Sivakumar et al. 2011).

A total of 107 grid points was used in the analysis covering the Free State Province. The grid points in the immediate borders of the province were included as the influence of these points contributes to the overall climate characteristics of areas within the province (Figure 3. 3). The province was divided into three homogenous sub-regions or clusters based on altitude. This was done using Hot Spot Analysis (HSA) in an ArcGIS (version 10.3) environment. The use of special analyses such as HSA helps in identifying groups of locations with high spatial homogeneity, and it has been shown that such segregation may significantly increase the quality of interpolation results(Saghafian & Bondarabadi 2008). Cluster analysis does not require *a priori* knowledge on data structure such as normality condition as required in other statistical tests (Everitt et al. 2011).

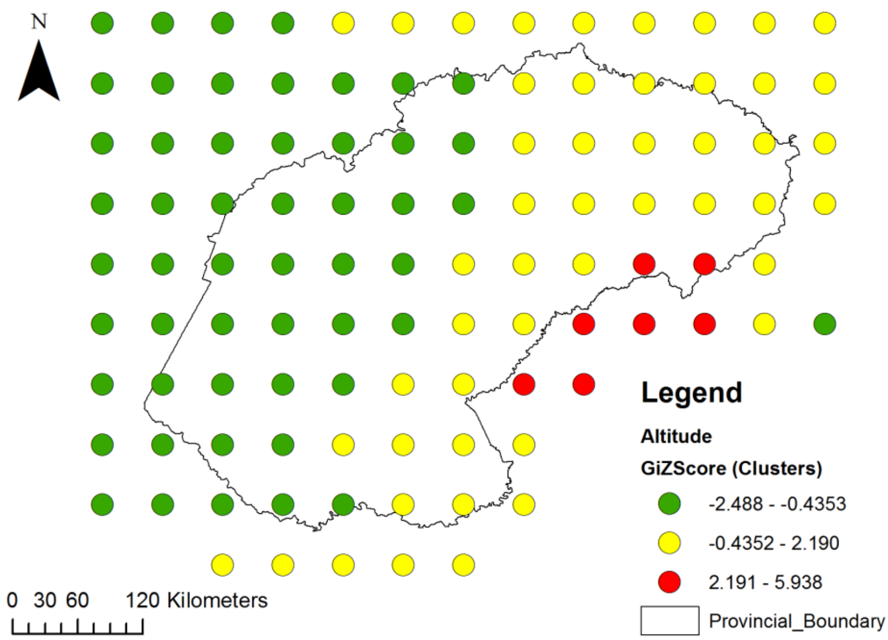


Figure 3.3Locations of clusters in the Free State Province [cluster 1(green), Cluster 2 (yellow) and cluster 3 (red)].

HSA is a local spatial pattern analysis tool which works by considering each feature within the context of neighbouring features and determines if the local pattern (a target feature and its neighbours) is statistically different from the global pattern (all features in the dataset). The *Z*-score and *p*-value results associated with each feature determine if the difference is statistically significant or not. Hence, this variable could potentially improve the results of other interpolation techniques when used instead of elevation as an auxiliary variable. The clustering by HSA enables the comparison of drought and wet characteristics of the different areas within the province. Further, the Inverse Distance Weighting (IDW) method of interpolation was used in preparing the frequency maps. The IDW technique assumes that each measured point has a local influence that diminishes with distance. Thus it gives an output surface that is sensitive to clustering and the presence of outliers.

Monthly precipitation values were used to compute SPIs at 3-month scale, for periods January-March and October-December using Drought Indices Calculator (DrinC). The distinct climate controls of the sub-seasonal rainfall in southern Africa warranted that the analysis be done by splitting October- December from January-March. During October to December, usually regarded as early summer, the atmosphere has a predominant extra-tropical nature with frequent cut-off lows (Singleton & Reason 2007). In January and February, tropical circulation systems are much more prevalent over South Africa with local convection dominating (Dyson & Van Heerden 2002). The two sub-seasons were arranged for analysis in such a way that OND_SPI for 1960 matched JFM_SPI for 1961. This is because the rainfall season overlaps two calendar years thus, the continuous season of October to March is split into October-December of the previous year (1960) and January-March of the following year (1961). To avoid splitting the precipitation season, the meteorological year in southern Africa starts in July and ends in June of the following calendar year and hence is usually referred to as a season 1960/61. In this study, the sub-seasons were analyzed separately. Trends in the two subseasons were studied using parametric tests for these are regarded as more powerful especially for data that is independent and normally distributed (Akinsanola & Ogunjobi 2017).

3.4.3 Computing SPI

The SPI was calculated using monthly precipitation data for 53 years (1960 - 2013) following the detailed procedure described by (Mckee et al. 1993) and expressed using the formula:

$$SPI = \frac{x_i - \bar{x}}{s} \quad , \qquad (1)$$

Where x_i is the monthly rainfall amount, $\bar{x}$ is the mean, *s* is the standard deviation of rainfall calculated from the whole time series of monthly values.

Using the SPI classification by (Manatsa et al. 2010) (Table 3. 1), only severe to extreme droughts (SPI ≤-1.282) were analyzed to amplify the drought signal.

Table 3.1Categorization of dryness/wetness

SPI Value occurrence	% Occurrence	Nominal SPI class
≥1.645	≤5	Extremely wet
1.282 to 1.644	6-10	Severely wet

0.842 to 1.281	11-20	Moderately wet
0.524 to 0.841	21-33	Slightly wet
-0.523 to 0.523	34-50	Normal
-0.841 to -0.524	21-33	Slight drought
-1.281to -0.842	11-20	Moderate drought
-1.644 to -1.282	6-10	Severe drought
≤-1.645	≤5	Extreme drought

[Adapted from (Agnew 2000) and modified by (Manatsa et al. 2010) to enhance suitability for application in southern Africa. The original classification was developed by (Mckee et al. 1993).

Frequencies of drought years and the proportion of at least severe drought years in the two subseasons in the three individual clusters were calculated. (N) represents the total count of drought years from slight drought to extreme drought. The percentage frequencies were calculated as follows:

$$Frequency(\%) = \frac{Number\ of\ severe(extreme)\ drought\ years}{Total\ number\ of\ drought\ years\ in\ 53\ years} \times 100, \quad (2)$$

where drought is the total count of SPIs ≤ -0.524

To determine how drought severity is linked to altitudinal variability we applied the composite analysis technique. We extracted the five worst drought years of at least SPI ≤ -1.282 at the provincial scale. The years comprised of 1965, 1972, 1990, 1994, and 1997. Averages for each of the clusters were plotted for the five severe drought years.

3.5 Results and Discussion

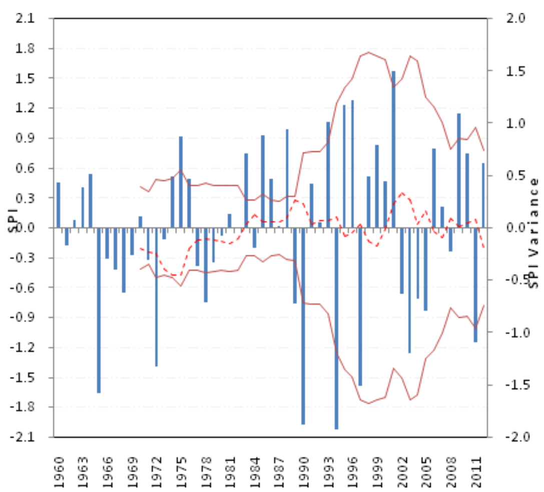
3.5.1 Temporal variations of drought intensity in the Free State Province

Using grid point data, average SPIs were calculated for the whole province to give the provincial average SPI and for individual clusters. The inclusion of provincial scale was done to enable comparison of drought (wet) years at provincial scale with those at cluster scale. Such comparison would assist in determining the ideal spatial scale to use for drought preparedness and response for the region. Figures3. 4 (a) and 3.4 (b) illustrate the temporal evolution of the SPI at the provincial level for OND and JFM, respectively. For the OND sub-season, severe drought years (SPI ≤-1.282) were 1994 (-2.023), 1990 (-1.974), 1965 (-1.653), 1997 (-1.580) and 1972 (-1.393) while the wettest year (SPI ≥1.282) was 2001 (1.575). A shift to higher variance in the ten years running variance (red line) is confirmed as a statistically significant shift in variance by the Sequential Regime Shift Detector (SRSD), which has a p-value of 0.002

in the early summer sub-season (OND). This systematic pattern in variance could represent a coherent influence from an external large-scale process. The 10-year running mean (dashed line in Figure 3. 4) indicates that on average the pre-1980s were characterized by rainfall deficits whilst the post-1980s period had predominantly surplus rainfall. However, it is during the latter period when the worst two droughts occurred in 1990 and 1994.

During the JFM sub-season, severe droughts (SPI≤-1.282) were experienced in 1992 (-1.990), 2007 (-1.601) and 1983 (-1.459). The severe wet years (SPI ≥1.282) experienced during the same subseason were 1974 (1.706), 1976 (1.699), 1988 (1.600), and 1991 (1.366). There appears to have been a shift to a wetter epoch after 1987 although the period is punctuated with more extreme droughts. From the 10-year running variance (solid line), it can be noted that the interannual variability of SPI for JFM in Fig 3. 3(b) is less variable and the SRSD indicates that the period is devoid of any significant shift. Thus, between 1960 and 2013, more severe drought (count) conditions were experienced during the OND sub-season than during the JFM subseason; five (5) years against three (3) years while more severe wet years were experienced during the JFM sub-season than during the OND subseason. A two-tailed paired samples t-test revealed that there is a significant difference between OND and JFM drought/wet magnitude for the 53 years period. The JFM sub-season has more intense droughts/wet conditions than OND sub-season t (49) = 6.727 and p≤ 0.05. It can be noted that the manifestation of the SPIs in the two sub-seasons differs markedly which indicates contrasting processes responsible for the drought`s development within the subseasons.

(a)



(b)

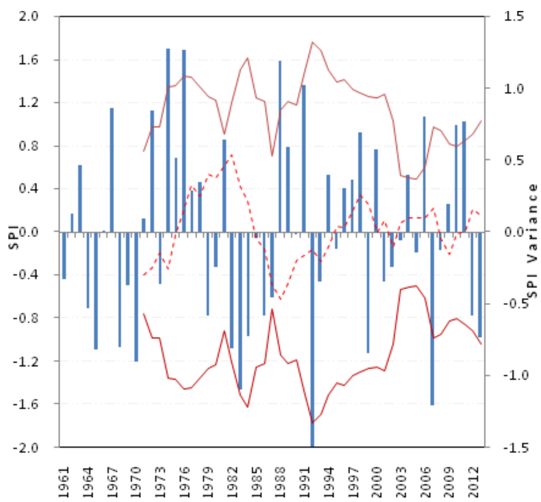


Figure 3.4Temporal manifestations of the SPI (bars) for (a) OND and (b) JFM at provincial level. In the insert are the 10-years running variance envelope (solid lines) and mean (dashed line). The SPIs are from 1960 to 2013.

The 10-year running mean demonstrates that the decades before the early 1990s had epochs of successive drought and wet years before oscillating around the mean thereafter. Overall, it is noted that the region is marked by droughts whose magnitudes have intensified in the last three decades. Since the JFM SPI patterns appear to be more random, we are more inclined to investigate further the OND period in search of less complex systematic drivers of the regional extreme events. It appears there is no clear-cut reason for the occurrence of wet or dry extremes in the region during JFM and hence it is likely that more local factors, which are not simple to identify in the absence of modeling, play a major role.

The local relationships to the SPI interannual and spatial variability of the Free State are still largely unknown. However, SPI values are dependent on a combination of several unrelated factors, such as the number of rainfall events, their intensity, the onset and cessation of the season. An outstanding characteristic of the Free State region is its extreme spatial heterogeneity in SPI. It could be assumed that the heterogeneity is a result of the complex topography of the region that is largely shaped by the western parts of the Drakensberg Mountains. It is therefore interesting to investigate how this topography influences the drought signal throughout the region.

The three clusters obtained from HSA were maintained for the rest of the analysis and were used to assess the differences in drought evolution between low-lying areas and mountain regions in the southern part of Africa. Severe drought years at provincial scale between 1960 and 2013 were selected only for the OND sub-season to show the variation in drought intensity for each of the clusters. This is because the JFM subseason is devoid of any significant shift in SPI as well as a well-defined pattern of variability. From Figure 3. 5(a), Cluster 3 has the highest drought frequency and the highest percentage of severe droughts while clusters 1 and 2 both have equal frequencies and proportion of severe droughts but lower than those experienced in Cluster 3. Thus, although Cluster 3 recorded the highest frequency of droughts, more extreme droughts occurred in Cluster 1. The severe droughts proportion is increasing with cluster while the extreme droughts are decreasing. The *t*-test results for significant difference between droughts of adjacent clusters revealed that although there are no significant differences between the adjacent clusters` composites, Clusters 1 and 3 show a significant difference with p = 0.1054 (90% confidence level). Figure 3. 5b shows the distribution of drought severity in the three clusters in the composite years summarized in Figure 3. 5a. The composite years for the three clusters are 1965, 1972, 1990, 1994 and 1997. Drought severity decreases with increasing altitude, a transition from Cluster 1 to Cluster 3 during the OND subseason only. None was observed during the JFM sub-season. However, Cluster 2 experienced the most intense droughts in 3/5 years of the worst drought years at the provincial level. The variation of drought intensity with cluster indicates that the droughts are not evenly distributed in a season and could have their evolution strongly influenced by relief.

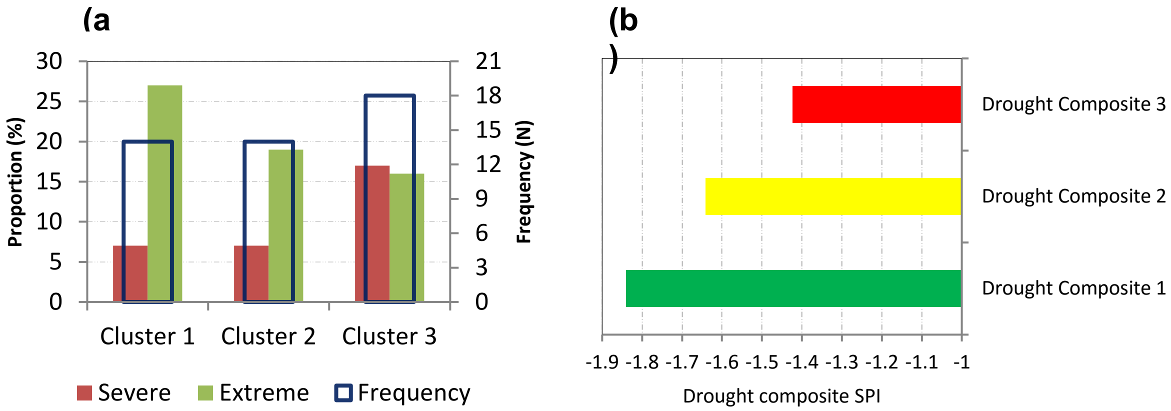


Figure 3.5(a) Proportion of severe (extreme) droughts to total drought Frequencies (SPI≤ 0.524) and (b) composite SPIs for Clusters 1, 2 and 3 during the OND subseason. The composite years are 1965, 1972, 1990, 1994 and 1997.

To measure the association of the SPI records in the three clusters during the OND sub-season, linear correlation coefficient *r*, was calculated. Pearson correlations of the SPI among the three clusters for the OND sub-season show that there is a significant positive relationship between Cluster 1 and Cluster 2 (*r*=.895**), Cluster 1 and Cluster 3 (*r*=.763**) and between Cluster 2 and Cluster 3 (*r*=.894**). This result implies that dry/wetness variations in all the clusters are highly correlated. It clearly shows that the relationship between clusters is weaker and more varied for OND, an indication of weaker spatiotemporal homogeneity. SRSD found a statistically significant shift in SPI variance in Clusters 1 and 2 around 1990 (*p*= 0.000 and *p*= 0.003 resp.) during the OND sub-season (Figure 3. 6). While there is a strong positive correlation between the clusters, the result of the distribution of the differences between the paired clusters (paired differences) shows that there is no statistically significant difference between the pairs during the JFM sub-season.

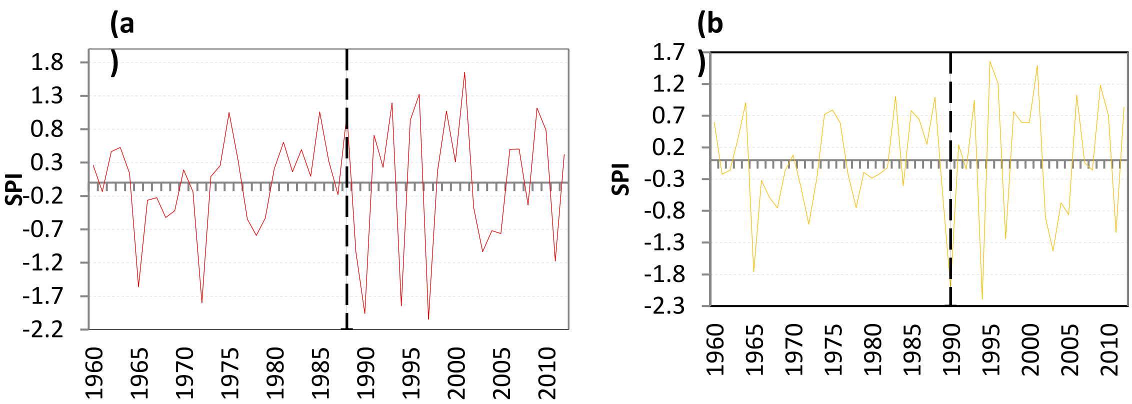


Figure 3.6Temporal manifestations of SPI with results of the SRSD superimposed to show the shift in the variance (dashed line)for (a) Cluster 1 and (b) Cluster 2 during the OND sub-season. The data is from 1960 to 2013.

The spatial distribution of drought frequencies in the two sub-seasons is shown in Figure 3. 6. The figure shows hot spots for drought (SPI ≤-1.282) years during the two sub-seasons. The highest frequency of droughts is concentrated within the central belt of the province, giving a more horizontal belt of areas most prone to droughts of great intensity during the early summer sub-season (Figure 3. 6a). This suggests further investigation into the identification and analysis of the factors that may be contributing to the increased vulnerability of these areas to severe droughts during the OND sub-season. Common conditions known to bring aridity are associated with anticyclonic conditions, but usually, their spatial scales of influence are too large to account for the differing drought conditions within Free State Province. During the JFM subseason, however, the areas prone to severe droughts are to the extreme north-eastern tip, the central west and the extreme south-eastern areas of the province (Figure 3. 6b).

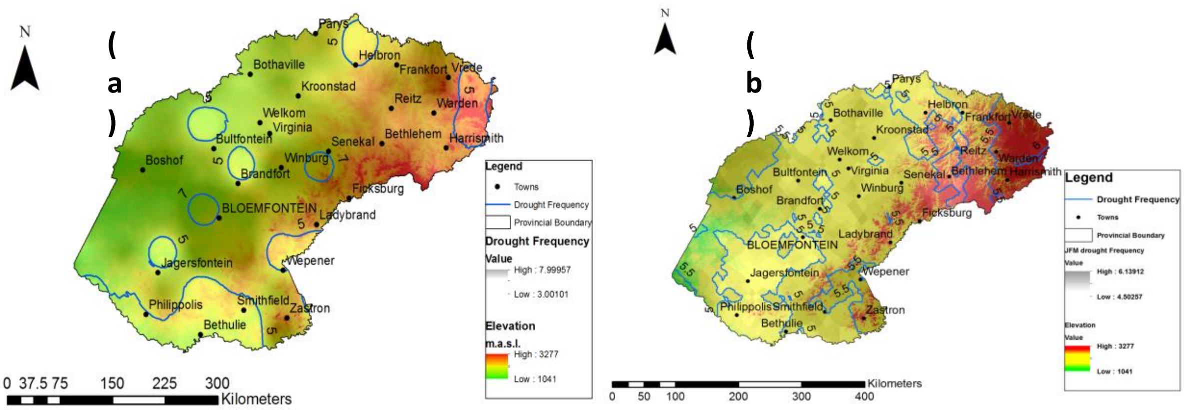


Figure 3.7Frequency of drought years (SPI ≤-1.282) for (a) OND and (b) JFM for period 1960-2013.

The influence of altitude on drought severity was tested using ANOVA. Results are shown in Table 3. 2. The results show that altitude has a significant influence on drought severity in the Free State province in the OND subseason but not during the JFM subseason (in brackets). This influence is shown to be significant ($F_{\{8, 2637\}}$= 2.54; p>0.01). This means that the OND droughts vary significantly with altitude while the JFM drought variations are not associated with variations in altitude, confirming that the systems that bring precipitation to the region are different. Those for the OND are altitude related while those for the JFM are not. This implies that relief rainfall, which is wind-related, is a possible candidate to explain the relationship between droughts and altitude during the OND period.

Table3.2Influence of altitude on drought severity for OND and JFM sub-seasons (in brackets).

Altitude	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	669848.947 (235716.673)	8	83731.118 (29464.584)	2.536 (.888)	.009 (.526)
Within Groups	8706611.38 (87500743.65)	2637	33017.297 (33181.928)	-	-
Total	87736460.33 (87736460.33)	2645	-	-	-

Analysis of variance results on the altitudinal influence on drought/wet frequency reveal significance during the JFM sub-season only for both severe drought and severe wet conditions (in brackets) (Table 3. 3). This means that frequencies of JFM severe drought and wet episodes vary with altitude.

Table 3.3Influence of altitude on severe drought (wet) frequencies for JFM subseason

Altitude	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	964097.644 (1072072.773)	10 (12)	96409.764 (89339.398)	5.591 (5.856)	.000 (.000)
Within Groups	672483.237 (564508.107)	39 (37)	17243.160 (15256.976)	-	-
Total	1636580.880 (1636580.880)	49 (49)	-	-	-

3.5.2 Wind Patterns associated with drought/wet events over Free State

Convection is less prominent during the OND period, and hence relief rainfall should dominate the mountainous region of Free State. Moreover, since relief has been found to significantly impact on the subseasonal drought magnitude, then a more likely factor to affect the rainfall received at a particular place is its wind speed and direction. This is because these two parameters determine the amount of moisture carried by an air mass and the rate of relief forced adiabatic cooling which is subsequently translated to rainfall. This implies that a particular place can be in the rain shadow/windward side of the mountain depending on the prevailing wind average characteristics of that season. Therefore, in this section, we analysed the wind characteristics for the drought and wet events to determine the extent of the wind impacts in defining the drought/wet spatial properties for selected seasons for the Free State Province.

The strong linkage between drought and altitude is an interesting observation (Table 3. 2). Rain producing systems in the vicinity of the Drakensberg Region consist of two types (Nel et al. 2010). The predominant sources of rainfall are large-scale line thunderstorms and orographically induced storms. The former is more prevalent during the solar enhanced convection of the JFM sub-season. As such, the latter are related to the surface wind characteristics like humidity, wind speed and direction, which should account for most of the rainfall during OND as this has a large bearing on the windward and rain shadow aspect of a particular place. In this regard, Figure 3. 8 presents the drought/wet composites in relation to the zonal and meridional anomalous winds at the near surface (850 hPa). It is noted that the surface winds appear to be the most robust link to the drought and wet events during this sub-season. During drought, near-surface winds are westerly (a), northerly (b) with an anomalous high pressure having built up to the west of the region (c). Thisis further illustrated in Figure3. 8(c) where the vector winds are southeasterly over the Free State region that are driven by a low-pressure anomaly situated to the southeast of the subcontinent as indicated by the geopotential heights. This is bound to advect relatively cold and relatively drier maritime winds into the region. The wet year composites indicate the opposite where the winds are strongly northerly (e) with almost no zonal wind anomaly (d). Figure 3. 8(f) reiterates the corresponding vector winds, which are northerly over the region that are driven by a high-pressure anomaly area to the southwest of the region as reflected by the geopotential heights. These winds advect relatively warmer and humid tropical air into Free State that is forced to rise as they approach the Drakensberg uplands to the south. We hypothesize that the low-level northerlies would enhance the orographic effects of the Drakensberg highlands over the Free State Province, where the rainfall has been noted to generally increase with altitude. Therefore, northerly wind anomalies are linked to wet events while southwesterly wind anomalies are linked to droughts over the Free State Region.

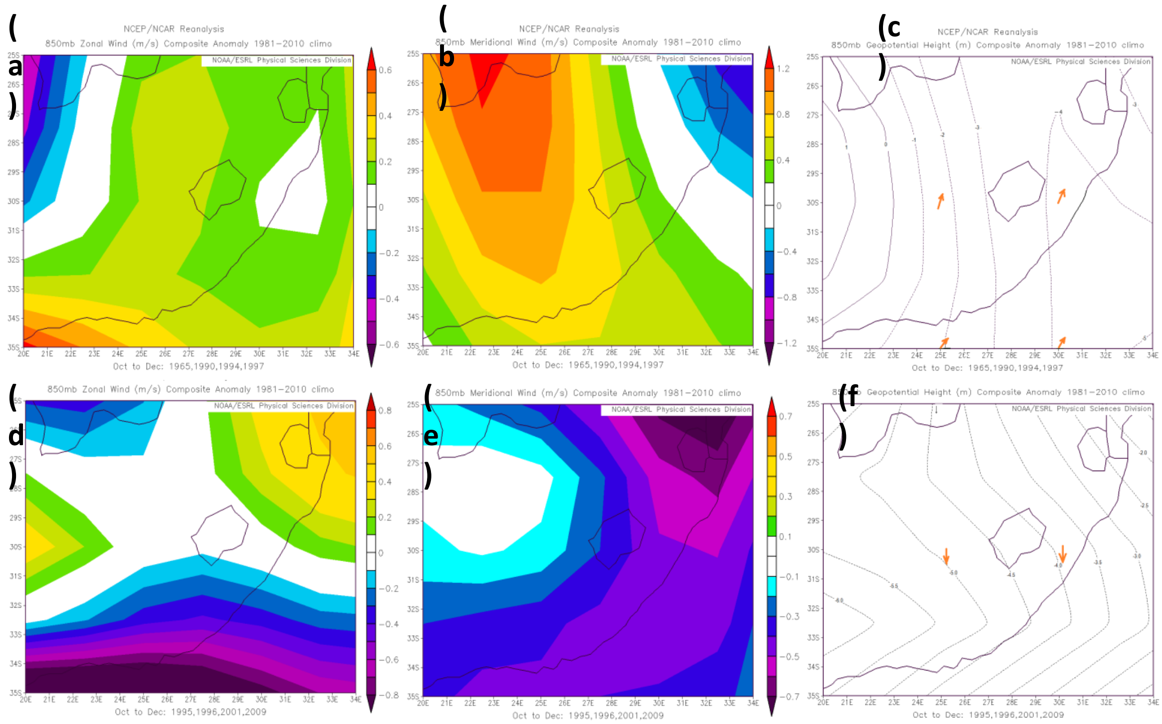


Figure 3.8Zonal, meridional and geopotential height anomalies for droughts (a), (b) and (c) and wet events (d), (e) and (f) respectively. Scalar winds are indicated in (c) and (f) with the years constituting the composites shown in the inserts.

To illustrate the strong regional connection of the wind factor to the SPI, we present in Figures3. 9(a) and (b) the spatial correlation of the averaged Free State SPI with the surface zonal and meridional winds. The significant association with the two wind fields is quite conspicuous where the droughts are related to westerly and southerly wind anomalies while wet episodes are linked to the reverse wind anomalies. The impacts appear to weaken drastically towards the summit of the Drakensberg Mountains. This weakening demonstrates the visible impacts of the increasing altitude from the west and north of the mountains. Thus, despite the amount of moisture that is carried by the winds to determine the drought/wet episodes, the direction of the wind relative to the uplands also determines which place become the rain-shadow and which does not.

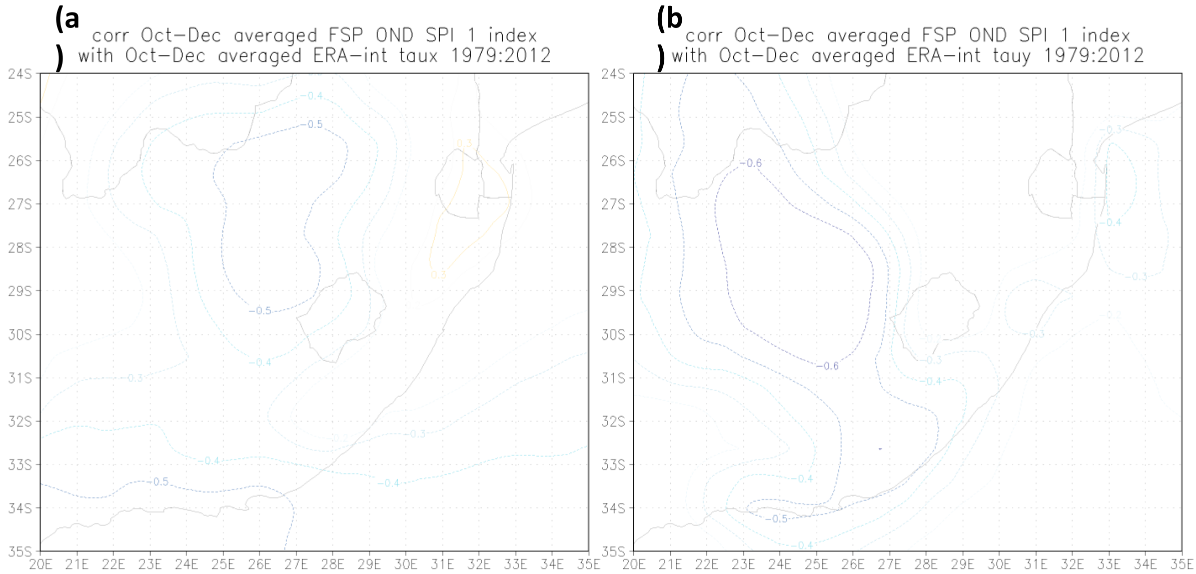


Figure 3.9Spatial correlation of Free State OND SPI with (a) zonal surface winds and (b) meridional surface winds during OND for the period from 1960 to 2013. Tau-x and tau-y mean surface winds in the zonal and meridional direction respectively.

3.5.3 Altitude modified SPI relationship with ENSO

The ENSO relationship with the JFM SPI for Free State is weak with an inverse correlation value of -0.29 and a *p*-value of 0.032 while that for OND SPI is relatively stronger with a value of -0.385 and a *p*-value of 0.004. In Figure 3. 10(a) we present the relationship between ENSO and the three clusters during OND and JFM. It is interesting to note that the relationship is strongly determined by the clusters in both cases hence signifying the impact of relief on the ENSO's influence on the extreme rainfall events. It is evident that ENSO's impacts are strongest in the lowlands but weakest over the highlands. Relief modifies the rainfall received at a place and the higher the altitude, the more modification to rainfall occurs. Hence, this observation reiterates the important role played by relief in weakening ENSO's impacts on the rainfall events. It is, however, noted that the correlations are stronger for the OND than for the JFM period for all clusters. Figure 3. 10(b) supports the observation that El Nino not only does impact more strongly on the OND than the JFM period but also shows a greater influence on Cluster 1. As such, the altitude for the Free State Province strongly demonstrates a robust relationship with ENSO.

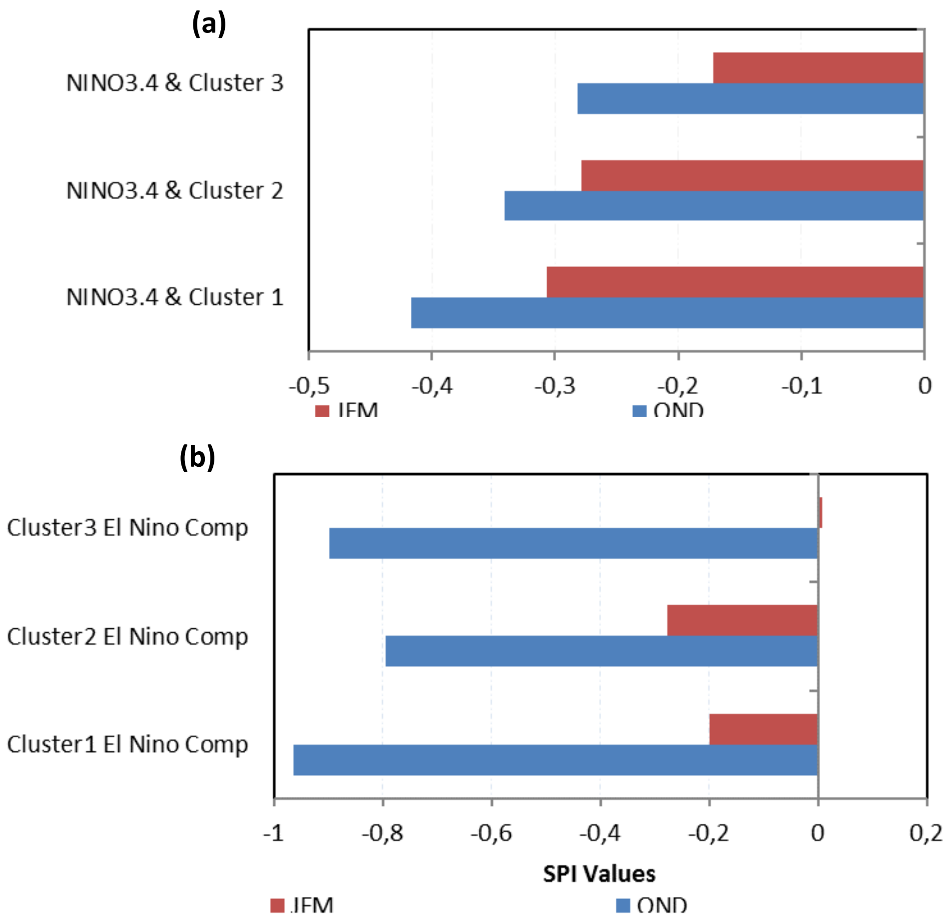


Figure 3.10(a) Relationship between ENSO and the three clusters, and (b) the El Nino composite SPI values for the three clusters during OND and JFM. The data are from 1960 to 2013,and the El Nino composites are comprised of the lowest Nino 3.4 values of 1965/66, 1972/73, 1982/83, 1987/1988, 1991/92, 1997/98 and 2002/03.

3.6 Conclusions

The objective of the study was to assess the influence of altitude on drought severity and frequency in the Free State Province of South Africa. The study revealed the spatial heterogeneity in the SPI over Free State and showed that the factors governing interannual drought variability varied markedly within the region and from the early part of the rainfall season to late sub season. Highland areas (Cluster 3) have the highest frequency of droughts although more extreme droughts occurred in the extreme western low-lying regions (Cluster 1). Significant differences among clusters during the early summer season, OND, were observed. These results are evidence that altitudinal variations have a significant impact on drought severity during the early summer season but not in the late summer season. The study targeted droughts of SPI $\leq$ -1.282. The relationship between ENSO and SPI indicates stronger correlations for the early summer sub-season than for the late summer sub-season. The local impacts of ENSO are strongly impacted on by altitude where the lower regions are stronger but weaker at higher altitudes. Mountains are an important ecosystem resource that warrants effective conservation strategies for what transpires in the region govern numerous economic activities often well beyond the boundaries of the mountain areas themselves. It is from this perspective that Disaster Management agencies need to consider the vulnerability of the province to drought conditions.

CHAPTER 4: ABOUT SURFACE TEMPERATURE AND THEIR SHIFTS IN THE FREE STATE PROVINCE, SOUTH AFRICA (1960-2013)

4.1 Brief chapter synopsis

This chapter is based on the paper which was published as:

Mbiriri, M., Mukwada, G., & Manatsa, D. (2018). About surface temperature and their shifts in the Free State Province, South Africa (1960-2013). *Applied Geography. Elsevier*

4.2 Abstract

The study analysed the temperature variability in the Free State Province, South Africa between 1960 and 2013. The three parameters considered were minimum temperature (Tmin), maximum temperature (Tmax) and diurnal temperature range (DTR) during the summer agricultural season spanning from October to March. Spatial interpolation of temperature characteristics was done using ArcMap V.10.2. Results show that the late summer sub-season (January-March) generally experiences warmer temperatures than the early summer sub-season (October-December). A significant shift towards warmer temperatures was detected for Tmax during the October-December sub-season around 2003 and 1983 for the January-March sub-season for Tmin. The OND Tmax shift coincides with that in cloud cover, suggesting that the reduced cloud cover could have contributed to the Tmax shift. It is found that the significance of temperature change is stronger towards the north and northwestern regions of the province.

Keywords agricultural drought, temperature variability, temperature shift, diurnal temperature range, Free State Province

4.3 Introduction

There is overwhelming evidence of climate change in different places across the globe (Mahato 2014; Manatsa and Reason 2016; Seager and Vecchi 2010).The impacts are most felt in Less Economically Developed Countries (LEDCs) compared to their Most Economically Developed Countries (MEDCs) counterparts given that they have weaker coping capabilities (Buckland et al. 2000; IPCC 2014).A noticeable increase in the frequency of extreme events ranging from drought to floods has been recorded. These extremes have been explained in terms of precipitation and temperature variability, both temporally and spatially, although it has not been spatially and temporally uniform (Ji et al. 2014; Rigor et al. 2000). In southern

Africa, complications emanating from increased surface air temperatures (SAT) are emerging as serious threats, with impacts that are comparable to those resulting from deficits in rainfall (Manatsa, Matarira, et al. 2015). Temperature plays a crucial role in the processes of climate change and climate variability because its variations can impact on the global hydrologic cycle and energy balance through thermal forcing (Caloiero 2017). Southern Africa largely falls in a moisture constrained region (Kapangaziwiri et al. 2012) and increasing temperatures are likely to worsen the problems associated with water scarcity already experienced in the region. This makes studying temperature variability imperative (Collins 2011).

A study on the sensitivity of agricultural production to changes in South Africa`s climate between 1970 and 2006 shows that the country is highly susceptible to climate change (Blignaut et al. 2009b). Free State Province is one of the main maize producing provinces in South Africa amongst North West and Mpumalanga Provinces. In total, they account for approximately 83% of total production (DAFF 2014). The eastern part of the Free State Province, bordering Lesotho is punctuated by the Maluti-Drakensberg Mountains which form part of the main escarpment in southern Africa (Nel & Sumner 2006). The impacts of climate change on mountain ecosystems extend to the hydrological, ecological, and societal systems (Beniston 2005; Ji et al. 2014).

Some studies have been done on the Free State Province using data from a few stations primarily due to the limited availability of observation data (Kruger & Shongwe 2004). As such the results may not provide a good representation of the whole province, given the associated complexity of the terrain. This study, therefore, provides an in-depth analysis of the spatial and temporal variability of temperature at a much finer scale. The variables used in this analysis include minimum temperature (Tmin), maximum temperature (Tmax) and diurnal temperature range (DTR). We included DTR because it is independent of internal climate variation, making it a better signature of climate change than the mean temperature (Manatsa, Morioka, et al. 2015). The objective was to identify the abrupt shifts in surface air temperatures, analyze the spatial variations of temperature and the trends in temperature time series in the Free State Province between 1960 and 2013.

4.4 Data and Methods

4.4.1 Study Area

This study focuses on the Free State Province of South Africa whose location is shown in Figure 4. 1. The province covers a total area of about 129,825 km^2 and lies between latitudes 26.6 $^{\circ}$S and 30.7 $^{\circ}$S and between longitudes 24.3° E and 29.8 $^{\circ}$E (Davis et al. 2006). The eastern Free State region is characterised by rugged terrain and is associated with livestock farming rather than crop production. Approximately 32,000 km^2 is under cultivation, while 87,000 km^2 is covered with natural veld and under grazing (DAFF 2010). Agriculture in the province is mostly rain-fed with less than 10% of the arable land under irrigation (Moeletsi & Walker 2012). This makes the agricultural output highly sensitive to temperature variability since increased evapotranspiration is capable of depleting soil moisture.

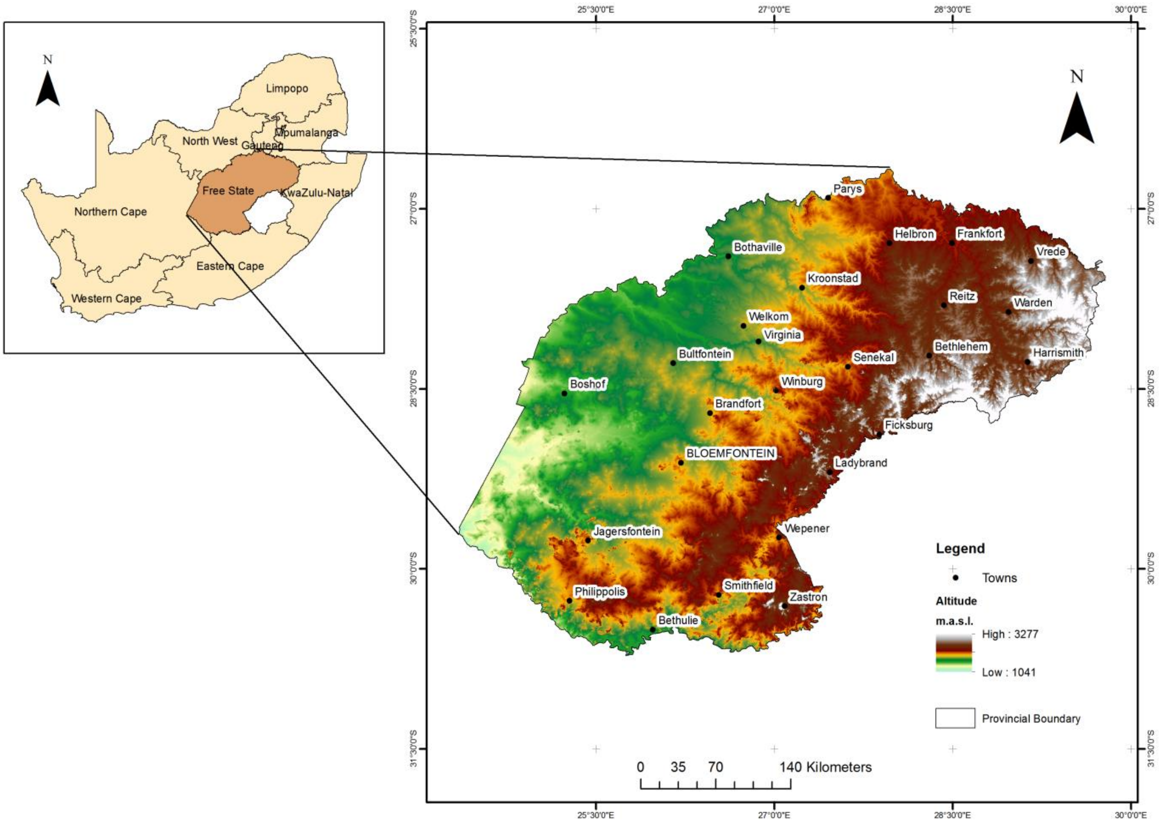


Figure 4.1Location of the Free State Province, South Africa and its elevation (metres above sea level).

The Free State Province experiences a continental climate characterised by warm to hot summers and cool to cold winters. The rainfall season (summer) spans from October to March, with the highest mean monthly rainfall received in January and February while winter spans from April to September (Rutherford & Westfall 1986).

4.4.2 Data

We analysed the temperature variability within the agricultural summer season (October - March) between 1960 and 2013. Before 1960, data availability in southern Africa was limited (Jury 2014). The 54 year period dataset is good enough for temporal and spatial analysis (Manatsa, Morioka, et al. 2015). Monthly land surface air temperature data were downloaded from Climate Explorer`s Climate Research Unit (CRU) gridded data file at 0.5° X 0.5°spatial resolution. The data products are principally derived from observations in line with the World Meteorological Organisation guidelines and are freely available. CRU datasets have been validated and are widely used in climate research (El Kenawy & Mccabe, 2016; Ongoma, Chen, Gao, & Sagero, 2017). The temperature variables analysed include maximum temperature (Tmax), minimum temperature (Tmin) and diurnal temperature range (DTR). DTR is defined as the difference between the mean daily maximum temperature (Tmax) and minimum temperature (Tmin), at each grid point for each season (Braganza et al. 2004). We analysed the agricultural season in two parts, October to December (OND) and January to March (JFM) as the processes that control the summer season rainfall in the southern African subregion are different. Between October and December, the subregion has a distinct extra-tropical nature with frequent cut-off lows while between January and March tropical circulation systems are more prevalent (Manatsa & Reason 2016; D'Abreton & Lindesay 1993). The general temperature characteristics of the two sub-seasonsare presented in Table 4.1. The late season generally has higher average Tmax and Tmin than the early sub-season, while the mean DTR is higher during the OND sub-season than the JFM sub-season. Tmax and DTR variance are greater for JFM than for OND (more than double) while Tmin variance is greater for OND than JFM. Higher variance means that the variable becomes less predictable, for example, Tmax and DTR during the JFM sub-season and Tmin during the OND sub-season.

Table 4.1Temperature characteristics for OND and JFM sub-seasons (1960 - 2013).

		Tmax		Tmin		DTR	
Sub-season	N	Mean	Variance	Mean	Variance	Mean	Variance
OND	54	27.6	0.7	12.1	0.4	15.5	0.6
JFM	54	28.5	1.8	14.4	0.2	14.1	1.5

4.4.3 Methods

Identification of the shift point helps identify the potential driver of the observed change (Manatsa, Matarira, et al. 2015). The Sequential Regime Shift Detection (SRSD) V.6.1 developed by Rodionov (2005) was used to detect the abrupt changes in the long-term time series for the mean and variance while the cumulative sum (CUSUM) was used to ascertain the obtained shift alternatively. The variables used for this analysis are Tmax, Tmin, DTR and cloud cover. Recently, changes in variance have become popular in shift detection techniques. This is because changes in the variance may have a greater impact on temperature extremes than changes in the mean (Rodionov 2016). The procedure for detecting regime shifts in the mean and variance is similar, except that for variance, it is based on the F-test while the Student t-test is used for the mean (Rodionov 2005). The Student's t-test is used for exploratory, rather than confirmatory data analysis, while the F-test compares the ratio of the sample variances for two regimes with the critical value *Fcrit.* Details on calculations are explained in (Rodionov 2005). In this study, we used the parameters; probability p = 0.05, cut-off length l = 20, tuning constant = 2, subsample size = 12 and prewhitening was done for shift detection in variance, while the other parameters remained as in the mean. Generally, the magnitude of the shiftis determined by the cut-off length. When the cut-off length increases, the degree of freedom also increases, implying that the statistically significant difference between the mean values of two successive regimes becomes smaller. The "prewhitening" procedure removes the red noise component that is caused by autocorrelation from the time series (Rodionov 2006; Rodionov 2004). However, there are also limitations of using the prewhitening procedure. It increases the chances of missing the true regime shift but once detected, the significance level of that regime shift can be accurately estimated. The CUSUM technique involves plotting the cumulative sum of standardized values over time whereby each value is subtracted from the mean of the time series giving a new time series of residuals, which are used for the calculation of the cumulative sum. When plotted, the change points in the slope can visually be determined (Ibanez et al. 1993). While the SRSD is upheld for its robustness, the CUSUM method was considered for its simplicity to validate the results.

Trends in the temperature variables at sub-season scale were investigated using the linear regression model. Using Stata V.13, we ran a linear regression model with all the data converted into logarithms to ensure data linearity. The regression was specified as follows:

$$lnAltitude = constant + b_1 lVar\_OND + lb_2 Var\_JFM \quad (1)$$

$$lnAltitude = constant + b_1 lMean\_OND + b_2 lMean\_JFM \quad (2)$$

Where lnAltitude is the log of altitude, lVar and lMean are the log of temperature variance and mean respectively in the specified sub-season and $b_{1,}$and b_2 are coefficients.

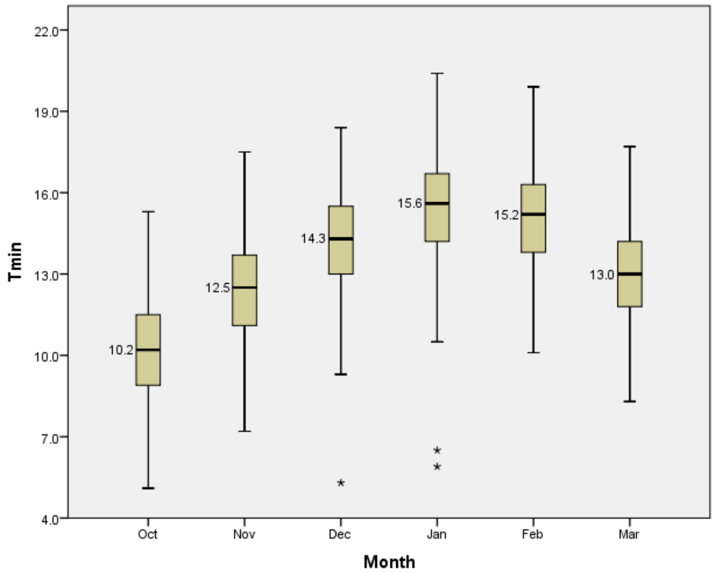
All the trend results were evaluated at the 5 % level of significance to ensure an effective exploration of the trend characteristics of the province`s temperature patterns. Pearson`s correlation, *r,* was calculated to establish the significance of the relationships between variables. Thisis supported by the idea that knowledge about one of the variables carries information about the other (Cohen & Cohen 1984). Mapping of the spatial distribution of temperature in the Free State province was performed in ArcGIS (version 10.2) using the ordinary kriging method. The ordinary kriging method has higher accuracy compared to other methods such as inverse distance weighting and splines (Liu et al. 2016).

4.5 Results and Discussion

4.5.1 Monthly Temperature characterization

Monthly Tmax for Free State indicates that on average October has the lowest mean value (26.2 ˚C) and January has the highest mean (30.1 ˚C). Tmax deviates from the annual mean the most in February probably due to increased afternoon cloud cover while Tmin deviates the most in October when night cloud cover is at its minimum. January, which is the period of maximum solar angle, has the highest monthly average for both Tmax and Tmin, 29.8 ˚C and 15.3 ˚C respectively. Figures 4. 2(a) and 4. 2(b) show monthly box plots of the mean and quartiles for the averaged Free State Province for Tmin and Tmax, respectively. In the 54-year period, January 1983 recorded the highest Tmax (32.8 ˚C) while the lowest monthly Tmax was recorded in October 1976 (22.9 ˚C). The 1982/83 drought was one of the most devastating droughts widely documented in the history of southern Africa (Manatsa et al. 2010; Geyser & Cutts 2014). High monthly average temperature value helps to explain the possible contributing factors to drought. High temperatures in January could have helped intensify the drought, or the drought itself could have increased temperatures (Unganai 1997). Thus, a two-way relationship exists between temperature and drought.

(a)



(b)

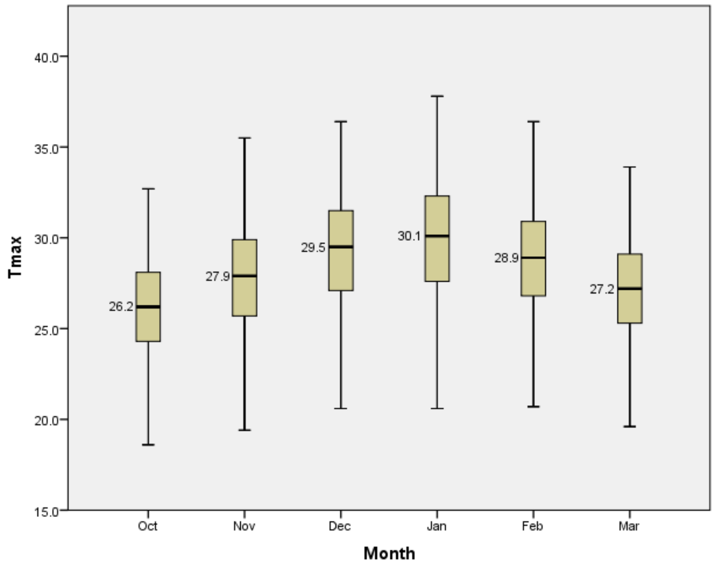


Figure 4.2Monthly temperature characteristics (in Degrees Celsius) of (a) Tmin and (b) Tmax for October to March using box and whisker plots. Extreme data points that deviate from the interquartile range are shown as an asterisk (*). The temperature data are from 1960 to 2013.

A robust regression analysis that utilises natural logarithms for maximum and minimum temperature against altitude was performed for the sub-season means and variance for each of the grid points for the study period. The results presented in Table 4. 2 show that average minimum temperature does not significantly vary with altitude in both sub-seasons. As for variance, minimum temperature significantly varies with altitude during the OND sub-season where a 1 % increase in variance is associated with a 0.52 % decrease in altitude. However, maximum temperature shows a significant variation in both variance and mean although the direction of association varies with season. A 1 % increase in average maximum temperature in OND is associated with a 4.75 % decrease in altitude at 1% level of significance while during the JFM sub-season a 1 % increase in average Tmax is associated with a 3.53 % increase in altitude at 5 % level of significance. Thus, altitude has a more significant influence on average maximum temperature in the early summer sub-season than it has in the late summer sub-season. The OND sub-season result agrees with the universal law that the higher you go, the cooler it becomes primarily due to the influence of the adiabatic lapse rates. However, what is observed in the late summer sub-season is against the odds. Tmax variance significantly varies with altitude during the JFM sub-season where a 1 % increase in variance is associated with a 0.37 % increase in altitude at 5 % level of significance. This means that high altitude areas experience higher variations in maximum temperature in late summer sub-season, suggesting an ‘oscillation’ type of pattern if compared to what transpires in the early summer sub-season. Altitude is one of the four factors that control the climate of mountain regions; amongst latitude, continentality and topography (Barry 2008). The role of the other factors though considered insignificant at the regional scale cannot be underestimated in controlling what happens in the province at a local scale. The influence of these factors can be investigated in a separate study.

Table 4.2OLS regression analysis results for temperature (mean and variance) with altitude.

Sub-season/variable	Tmax	Tmin
OND_mean	-4.75***	
	(1.734)	
OND_variance	-0.23	
	(0.146)	
JFM_mean	3.53**	
	(1.436)	
JFM_variance	0.37**	
	(0.175)	
JFM_mean		0.00044
		(0.714)
JFM_variance		0.22*
		(0.122)
OND_mean		0.12
		(0.546)
OND_variance		-0.52***
		(0.095)
_cons	12.3***	6.86***
	(1.574)	(0.618)
N	107	107
R^2	0.227	0.430

Standard errors in parentheses

$^{*}p< 0.10$, $^{**}p< 0.05$, $^{***}p< 0.01$

4.5.2 Temperature Temporal Trends

Spatial trends in Tmin and Tmax at sub-season scale are presented in Figure 4. 3. It can be noted that in general Tmax is increasing at a faster rate than Tmin an observation that is consistent with the findings of MacKellar et al., (2014). However, in Fig. 4. 3a the trends over Free State are largely insignificant at 90% confidence level for the OND period while though significant, the trends are more suppressed over the southern parts of the province compared to the rest of the region for JFM. During this period, areas to the north and northeast of the province show warming rates of about 0.015 ˚C per year translating to 0.145 per decade. Even though, this rate of change is below the Tmin global average of 0.0186 per year (Easterling et al. 1997). Figure 3c shows that Tmax is increasing in a south-north pattern during the OND sub-season by between 0.025 ˚C per year and 0.029 ˚C per year, implying that the greatest change occurred in the northern areas. This increase in Tmax is greater than the global average of 0.17 $^{\circ}$C per decade since 1970 (Blunden & Arndt 2017). For JFM, the greatest increase is over the north west of the province. This observation shows that the higher altitudes of the Free State Province have temperature increases that are lower than the low-lying areas to the southwest.

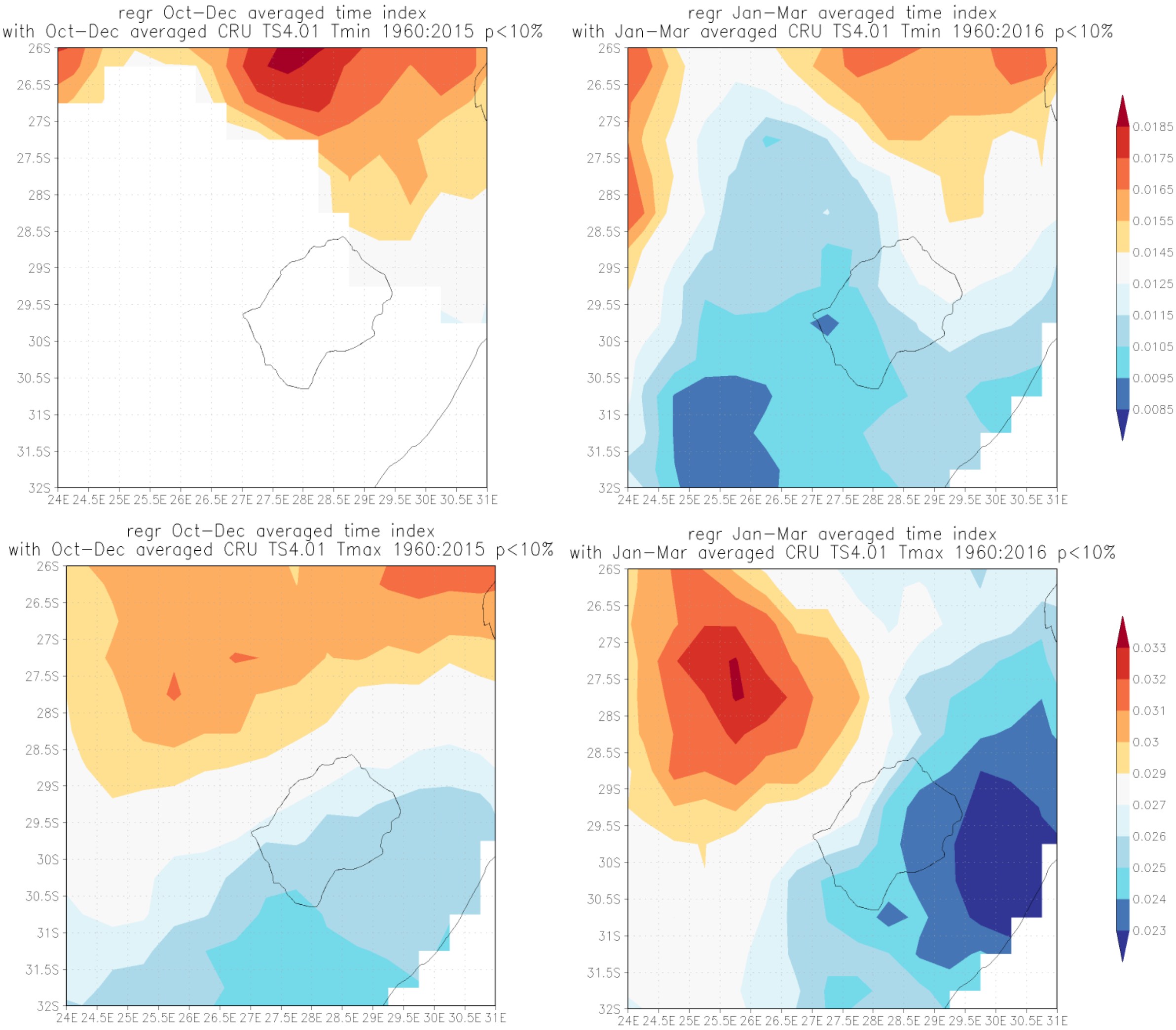


Table 4.3Spatial distribution of temperature trend for Tmin and Tmax for OND and JFM sub-seasons.

The maps were plotted using Climate Explorer knmi CRU4 Reanalysis Temperature data. All values are significant at p < 10. The insert is a map showing the boundaries of Lesotho.

DTR trends for the two sub-seasons are displayed in Figure 4. 4. DTR is generally higher for OND than JFM. While both sub-seasons show an increasing trend in DTR, OND shows a significantly increasing trend at 5 % level of significance (p=0.049), implying that the difference between Tmin and Tmax is widening. The gap widened due to an increasing trend in the Tmax during the early summer sub-season. The recent study on South Africa which combined Northern Cape, southern Free State and parts of Eastern Cape, also showed that Tmax had increased more significantly than Tmin (MacKellar et al. 2014). Variations in DTR have been linked to cloud cover, soil moisture and water vapour although with different effects in different locations (Balcerak 2013; Manatsa, Morioka, et al. 2015). Clouds modulate the solar radiation reaching the surface, hence pose the greatest damping effect on Tmax and DTR. A negative relationship exists between temperature and cloud cover as reported in (Jones & Trewin 2000). Soil moisture reduces DTR because it increases surface latent heat release, slowing down the daytime rise of surface temperatures while atmospheric water vapour increases both Tmax and Tmin and has a small effect on DTR, mainly because its greenhouse warming effect has little diurnal variation (Braganza et al. 2004). The increasing trend in DTR that is predominantly due to accelerated warming in Tmax observed in this study concurs with findings from research carried in the Canadian Prairies (Betts et al. 2013). However, in West Africa and China, a declining DTR was observed and was associated with a reduction in precipitation and cloud cover (Zhou et al. 2009).The reduction in DTR has been attributed to either a reduction in vegetation cover or a reduction in soil emissivity whose effect can lead to increased night-time temperature through increased soil heating and reduced outgoing longwave radiation (Zhou et al. 2007). The increasing DTR over the Free State Province will assist in further understanding the evolution of climate change including the extent of possible impacts in the sub-region.

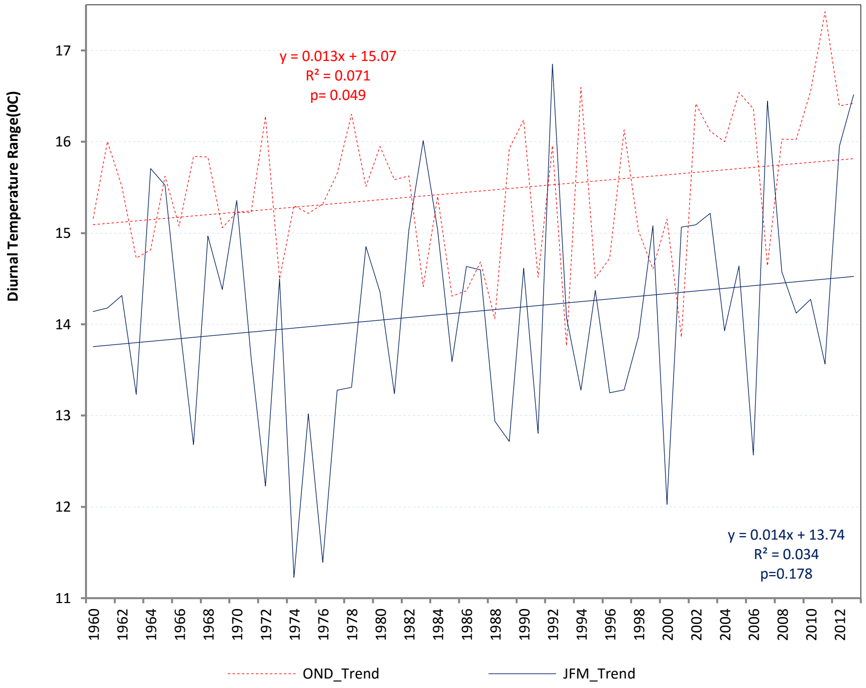


Table 4.4Average temperature trends for the Free State Province for DTR for OND (broken line) and JFM (solid line). The data spans from 1960 to 2013. In the insert are the corresponding regression lines.

4.5.2.1 Maximum Temperature variability

The SRSD technique was used to check for any change points in the mean and variance of Tmax. The results are shown in Figure 4. 5. A shift was detected in the Tmax mean during the early summer season around 2003 with a significance at $p=0.001$. From the results, Tmax increased by 1.1 °C, that is from 27.3 °C to 28.4 °C. The magnitude of temperature change is great considering that the average global surface temperature increase of 0.85 (0.65 to 1.06) °C was observed between 1880 and 2012(IPCC 2014).

Further analysis was done to determine which months had contributed to the early summer sub-season warming the most. The results revealed that October and November contributed to a significant increase in the mean Tmax ($p < 0.000$ and 0.001 respectively) while a shift in variance was detected around 1993 in October only. The variance more than doubled after 1993 (1.447 against 0.330), with a p-value of 0.001. This observation is in agreement with results from a study by Blignaught, Ueckermann and Aronson (2009) which covered the nine provinces of South Africa for the period 1970-2006. Findings showed that both temperature variance and the average temperature had increased in almost all provinces except Mpumalanga. Simulation model results show that temperature increases have a potential of crop yield reduction in the maize-growing regions of sub-Saharan Africa of 3–20% except for mountainous regions in South and East Africa (Waha et al. 2013). The warming climate puts additional stresses on water resources, whether or not future rainfall is significantly altered (Hulme et al. 2001). Due to the prominence of the Tmax shifts for OND, the temperature for the Free State Province was analysed in two epochs, the pre-2003 and post 2002 epochs.

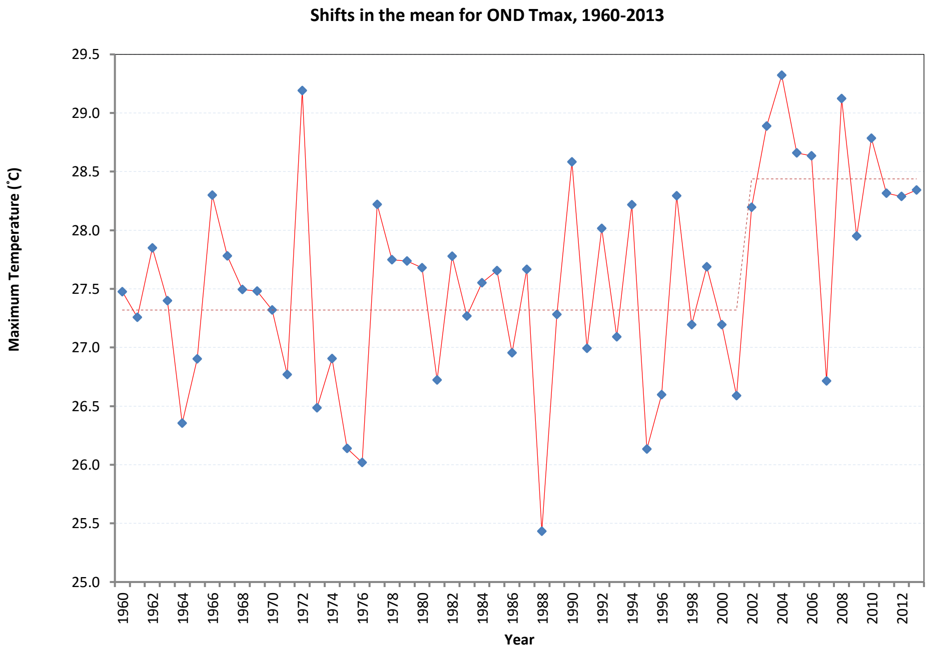
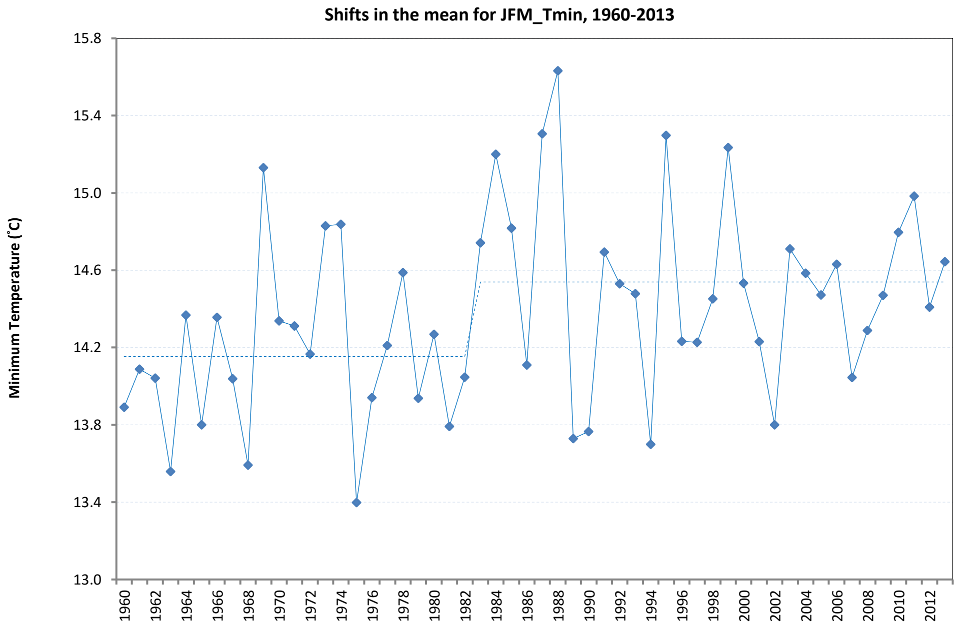


Table 4.5Temporal manifestation of Tmax with results of the SRSD superimposed to show the shift in the mean (broken line) for OND means.

4.5.2.2 Minimum Temperature variability

Figure 4. 6 shows Tmin trends for the Free State Province. JFM sub-season shows a significant shift in the average Tmin around 1983 (Figure 4. 6a) while a significant shift in variance was detected around 2003 with a p-value of 0.026 (Figure 4. 6b). The average minimum temperature during the JFM sub-season increased from 14.2 ˚C to 14.5 ˚C. It is interesting to note that the early sub-season coincides with the seasonally stratified period of the transition of the strength of the Mascarene High (MH), which marks the seasonal shift of the climatologically south-easterly winds (Roxy et al. 2011; Manatsa, Morioka, et al. 2015).

(a)



(b)

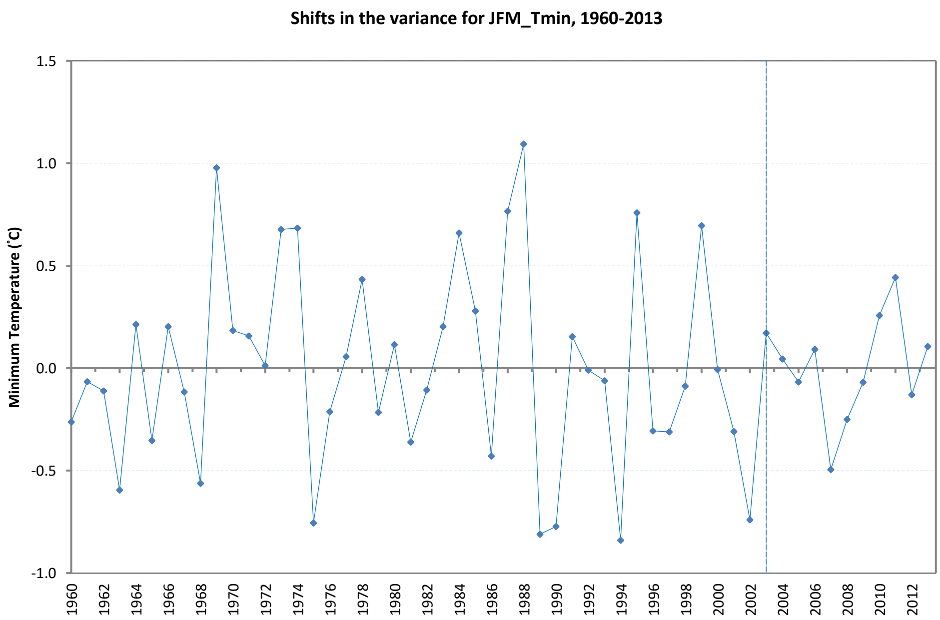


Figure 4.6Temporal manifestation of Tmin with results of the SRSD superimposed to show the shift (broken line) for JFM (a) mean and (b) variance. The step-like feature shows the shift point in the mean and the magnitude of change in the mean (a). The data are from 1960 to 2013.

4.5.2.3 Diurnal Temperature Range

Results from the SRSD test for DTR during the OND sub-season show a significant shift (increase) in the mean DTR around 2003 from 15.2 °C to 16.2 °C with a $p < 0.001$. This coincides with the shift point for the early season maximum temperature. It can therefore, be confirmed with confidence that the climate shifted around 2003, as shown in Figure 4. 7. No significant shift in DTR during the JFM sub-season was detected. Variance did not show any significant shift during the period under study.

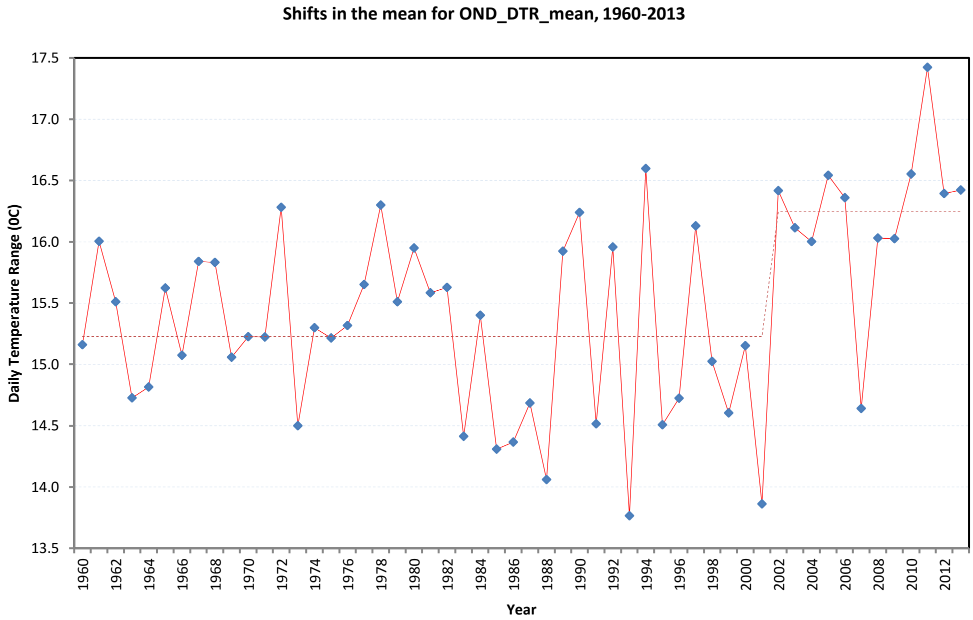


Figure 4.7Temporal manifestation of DTR with results of the SRSD superimposed to show the shift in the mean (broken line) for the OND sub-season.

4.5.3 Spatial temperature variations

The average Tmax differences between the pre-2003 and the post-2002 epochs in the Free State Province are spatially expressed for the OND sub-season (Figure 4. 8). It is interesting to note that, Tmax shows an increase in the whole of Free State Province (Figure 4. 8a). In terms of temperature change, the lowest difference has happened to the southeast and the highest to the north. A t-test was done to check for any significant difference between the pre-shift and post-shift period for individual grid points. P-values were then mapped in Figure 4. 8b. The magnitude of the difference in Tmax means between the pre-shiftandpost-shift epochs vary across the province. The most significant change in Tmax during the OND sub-season has occurred to the north and north-eastern parts of the province. JFM did not show any significant shift in Tmax hence was not analysed further. However, the significant shift for JFM was in

Tmin around 1983. Figure 4. 8 (c) and (d) show the spatial distribution of Tmin change during the JFM sub-season between the epochs (1960-1982) and (1983-2013) and the significance level of the change expressed by p-value, respectively.

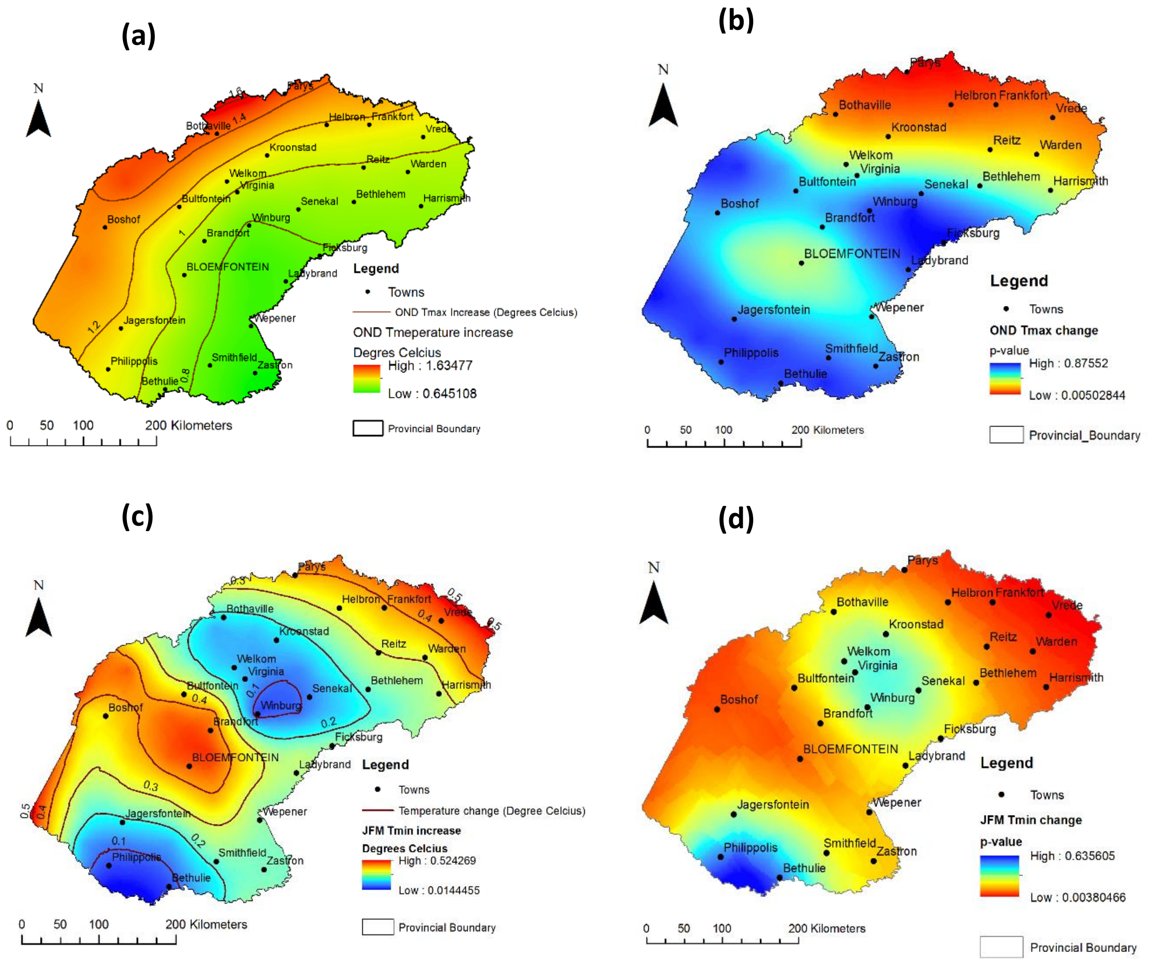


Figure 4.8(a) Spatial distribution of Tmax OND mean change between 1960-2002 and 2003-2013 epochs with (b) showing the significance level of OND Tmax change as given in p values, and (c) JFM average Tmin change between 1960-1982 and 1983-2013 epochs with (d) depicting the significance level of JFM Tmax change as given by p values. The maps are for the Free State Province.

We further investigated the relationship between temperature change (*p*-value) and altitude in the two sub-seasons; OND for Tmax and JFM for Tmin. We only selected these two variables for which significant shifts were detected. Results show that there is a statistically significant negative correlation between changes in JFM Tmin and altitude (corr =-0.352 with a p-value0.0084). A strong negative correlation between Tmin and altitude explains that high altitude areas have significantly warmed more than low-lying areas. This result concurs with what has been observed over Kenya, where highland areas have warmed more significantly than their low lying counterparts (Ongoma et al. 2017). However, for OND, Tmax change has no significant relationship with altitude.

Possible drivers of the temperature changes that have been observed in the Free State Province were investigated. The investigation included exploration of the relationship between temperature and cloud cover as one of the factors that have been documented as contributing to the DTR variability (Balcerak 2013; Betts et al. 2013). Trends for Tmax and cloud cover (%) are shown in Figure 4. 9. While Tmax shows a significantly increasing trend (*p*=0.008), cloud cover shows a declining trend although it is not significant. Although the trend may not be significant for cloud cover, SRSD detected a significant shift in cloud cover around 2003 coinciding with the shift point for Tmax during the OND sub-season. The correlation between Tmax and cloud cover during the OND sub-season is high (-0.658) with a *p*-value< 0.001. Thus, as cloud cover decreases, Tmax increases. As such, the shift in Tmax during the early summer season further strengthens the observed relationship between Tmax and cloud cover. This concurs with earlier observations that the relationship between DTR and cloud cover is strongest (20.6) over western Europe, North America, eastern Asia, southern South America, and southern Africa (Braganza et al. 2004). At a much smaller scale, this result confirms the suggestion that the simulated temperature increase observed over South Africa may be related to a decrease in cloud cover (MacKellar et al. 2014).

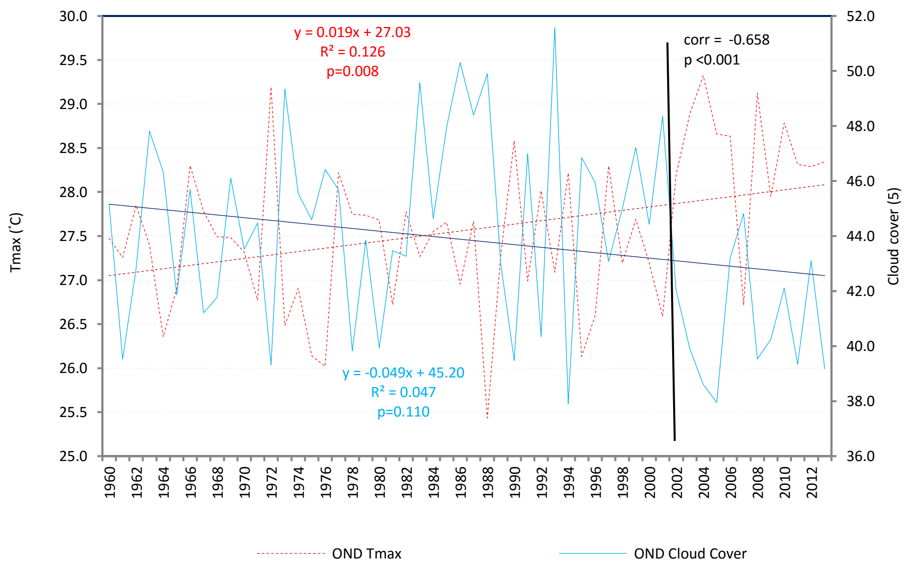


Figure 4.9Temporal trends for Tmax (brokenline) and cloud cover during the OND sub-season for the Free State Province. The black vertical line indicates the coinciding shift point. The data are from 1960 to 2013.

4.6 Conclusions

In this study, the temperature characteristics (Tmax, Tmin, and DTR) and trends in the Free State Province between 1960 and 2013 during the summer agricultural season that spans from October to March were explored. The results showed that JFM average temperature is generally higher than that of OND for both Tmax and Tmin. Tmax and Tmin showed significant abrupt shifts towards warmer temperatures. Tmax significantly shifted during the early sub-season (OND) around 2003 while Tmin significantly shifted during the late sub-season (JFM) around 1983. The difference in the means for the two sub-seasons is significantly wider in Tmin than in Tmax. Correlation results for Tmax and cloud cover revealed a strong negative relationship and had a coinciding shift suggesting that the OND Tmax shift could be largely due to cloud cover changes. Temperature change significance displays a southwest to north/northeast direction towards stronger values. Since Tmin has been observed to be controlled more by land use, especially urbanisation than any other factors, an analysis into land use changes in the province may help explore possible sources of the observed temperature increase. Findings call for more proactive strategies in the management of water resources in the province and beyond as the observed temperature increases are likely to increase evapotranspiration, depleting water resources. Cultivation of crops tolerant to higher temperatures is recommended.

CHAPTER 5: IMPACTS OF SURFACE AIR TEMPERATURE VARIABILITY ON AGRICULTURAL DROUGHTS IN SOUTHERN AFRICA: A CASE OF THE FREE STATE PROVINCE, SOUTH AFRICA

5.1 Abstract

In this study, we analysed the role of temperature in the intensification of agricultural droughts in the Free State Province of South Africa between 1960 and 2013 using two drought indices, the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). Pearson product-moment correlation analysis was performed to investigate the relationships between temperature and precipitation. The results indicate that maximum temperature (Tmax) and minimum temperature (Tmin) have significantly increased across the whole province. Sequential Regime Shift Detection analysis technique revealed that areas to the southwest have experienced the greatest increase in the average Tmax around 2003 of 1.2 °C and the magnitude of change decreases towards the highland areas in the north-eastern regions of the province. Tmin showed a significant shift in the mean (0.3 °C increase; p= 0.003) and a decrease in variance (0.179; p= 0.004) around 1983 and 2003, respectively. However, despite the observed significant increase in temperatures, SPEI does not reflect any significant effect of temperature on drought intensification. This calls for further exploration on the role of other factors that influence drought to enhance understanding of drought evolution and improve monitoring as well as the development of adaptation strategies in the province.

5.2 Introduction

Climatic change processes have predominantly two impacts on drought intensification. It either causes a reduction in precipitation and/or increase in temperature, leading to an increase in drought severity (Vicente-Serrano et al. 2010). The decrease in precipitation increases the likelihood of crop failure which has a negative effect on production, while higher temperatures encourage weed and pest proliferation as well as reduces available moisture in the soil through evapotranspiration which subsequently may reduce crop yield, a condition referred to as agricultural drought (Nelson et al. 2009). Thus, agricultural drought, in general, describes the temporary imbalance of water availability due to a breakdown of the rainfall regime which subsequently affects the hydrological and agricultural activities (Pereira et al. 2002). Although it is usually a temporary condition, agricultural drought impacts can lead to disasters with far-reaching effects on other sectors, socially and economically within a country and beyond its political boundary. The vulnerability of rain fed agricultural activities to drought has increased in both developed and developing countries. However, agricultural production is the leading means of livelihood for 70 percent of the world's poor and is the primary means of their food security (Filipe & Tamara 2012). This calls for a detailed understanding of the factors influencing agriculture starting with an understanding of the interplay between climate factors such as precipitation and temperature. To appreciate this interplay, various drought indices have been developed, the Palmer Drought Severity Index (PDSI), Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI) being the most widely used. Indices are good proxies to determine drought conditions in a variety of environmental, hydrological and agricultural systems (Vicente-Serrano et al. 2012).On short term scale, (3-6 months) SPI and SPEI describe drought affecting vegetation and agricultural practices (agricultural drought) while on a long-term scale (12-24 months)they are used in Water Resources Management (Edwards & Mckee 1997).

In the face of climate change, agriculture is expected to be affected by temperature increase and declining rainfall patterns (IPCC 2012). Southern Africa is among the most vulnerable regions to climate change (Turpie & Visser 2015). South Africa is classified as a water-stressed country, with an average annual rainfall of 500 mm (the world average annual rainfall is 860 mm) (Dennis & Dennis 2012) while according to the World Bank (2010) the country`s temperatures have significantly increased. The temperature increase will affect the water balance due to increased evapotranspiration affecting water resources and agriculture. Evapotranspiration affects, among other systems, the consumptive use of water by crops and natural vegetation as it is controlled by soil moisture content and the capacity of the plants to transpire, which is conditioned by the climatic demand of the atmosphere (Pereira et al. 2002). Although the Free State Province is regarded as the bread-basket of South Africa, its importance in agricultural production extends to the regional level of southern Africa (Turpie & Visser 2015).

In this study, we analysed the role of temperature in the intensification of agricultural droughts in the Free State Province of South Africa between 1960 and 2013 using two drought indices, the SPI and SPEI. The two indices are similar in calculation except that SPI uses only precipitation while SPEI combines precipitation and evapotranspiration. These indices have precipitation as a common input variable, hence the comparison of the two indices assists in accounting for the role of temperature in the intensification of drought. The effect of temperature on the intensification of droughts has been associated with the northern mid-high latitudes while in Africa, southeast Asia and Australia droughts are a product of reduced precipitation (Dai 2013). It is against this background that we investigated the role of temperature in the intensification of droughts since recent studies show that temperatures have generally increased in southern Africa (Manatsa et al. 2017) yet the impact of temperature increase on droughts in this region has not been conclusively analysed.

5.3 Data and Methods

5.3.1 Study area

Figure 5. 1 shows the location of the Free State Province in South Africa. The province is situated between latitudes 26.6° S and 30.7°S and, longitudes 24.3° E and 29.8°E covering an area of 129,825 km². The eastern parts of the province are bounded by the Maluti-Drakensberg mountain range that forms the border between South Africa and Lesotho. Climatologically, the Free State Province is classified as continental, characterised by warm to hot wet summers and cool to cold, dry winters. It is during the summer season when much of the effective rainfall is received for crop production, hence both subsistence and commercial farmers heavily rely on summer rains for crop production in a rain fed scenario.

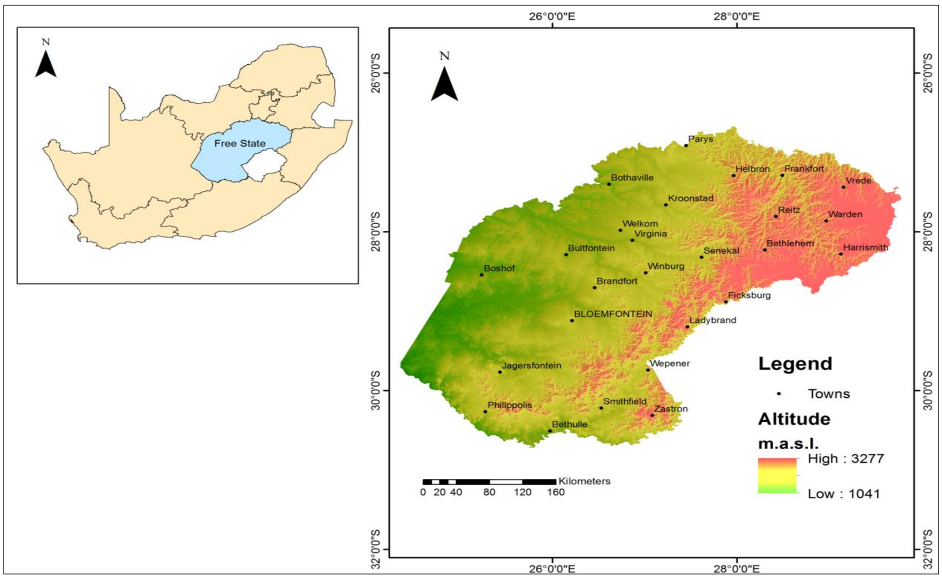


Figure 5.1The map of South Africa (left panel) with the Free State Province shown in blue and the geophysical map of the province (right panel) indicating the altitude and locations of the main towns (Mbiriri et al. 2018:3).

5.3.2 Data

Data series of monthly precipitation, maximum temperature, minimum temperature, diurnal temperature range and SPEI covering period 1960-2013 were downloaded from Climate Explorer`s Climate Research Unit (CRU) gridded data file from Climate Explorer at 0.5° X 0.5°spatial resolution (available from https://climexp.knmi.nl). Gridded datasets allow best estimates for climate variables at locations away from the observing stations (Haylock et al. 2008).Grid points within the boundaries of Free State and those in the immediate surroundings, which were considered for analysis, totaled 107. Figure 5. 2 shows the location of the grid points that were used in this study. Cluster analysis in ArcGIS was used to classify homogenous regions based on seasonal average precipitation following the procedure in (Mbiriri et al. 2018). Precipitation was used since it is the common variable in the calculation of SPI and SPEI. Mapping of drought characteristics was done using the ordinary kriging technique in ArcGIS. For each grid point, SPIs were calculated from precipitation data using the Drought index calculator (DrinC) following the procedure outlined by (Tigkas et al. 2015). We calculated SPIs at 3 and 6 months scales since short-term scales best capture the effect of water deficit responsible for causing a significant effect on vegetation and agricultural activities.

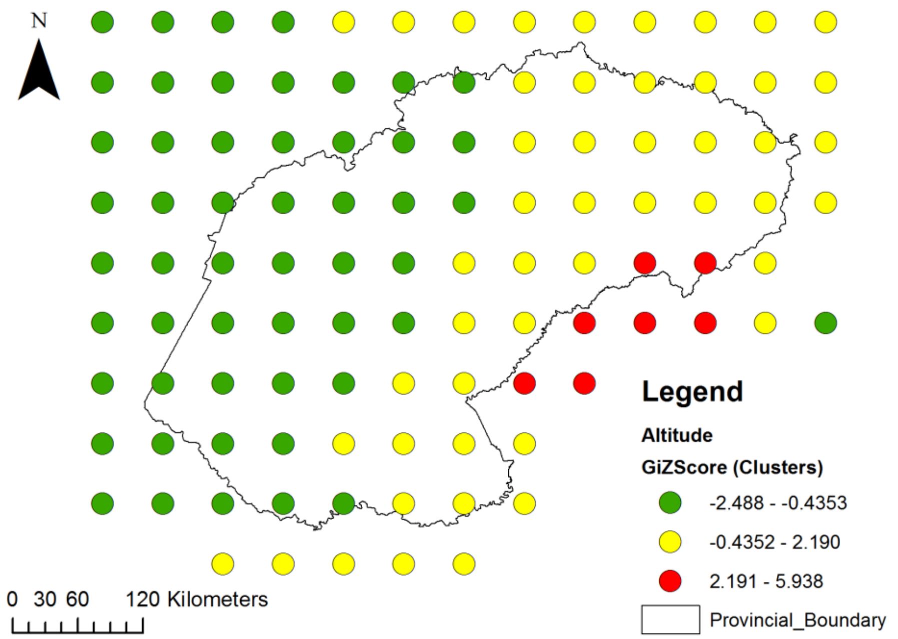


Figure 5.2Locations of clusters in the Free State Province [cluster 1(green), Cluster 2 (yellow) and cluster 3 (red)] (Mbiriri et al. 2018).

5.3.3 Drought indices

Phenomena such as drought are complex in nature, making them difficult to quantify hence the development and use of drought indices. Drought indices based on climate information have facilitated in the understanding of the drought phenomena, especially where objective data is unavailable (Vicente-Serrano, Chura, et al. 2014). While there are shortcomings associated with the use of drought indices, the advantages outweigh the disadvantages, hence making them the widely used in today`s research (Rouault & Richard 2005; Esper et al. 2007). The two indices utilized in the present study have precipitation as a common variable, while SPEI integrates temperature in its calculation.

5.3.3.1 The Standardized Precipitation Index

The SPI is a multi-scalar index that has been widely used due to its use of precipitation only yet it can identify different types of droughts (Edwards & Mckee 1997). We calculated SPIs at 3 months scale, October-December (OND), January-March (JFM) and 6 months scale covering the whole season, October-March (ONDJFM). Details about the calculation of SPI can be found in (Lloyd-Hughes and Saunders 2002).

5.3.3.2 The Standardized Precipitation Evapotranspiration Index

The SPEI, developed by (Vicente-Serrano et al. 2010)is a modification of the SPI. While the two indices share many common characteristics such as robustness, simplicity in calculation and being multi-scalar, the SPEI includes the temperature`s evapotranspiration role in identifying and characterizing drought (Vicente-Serrano et al. 2010). Thus, while SPEI has common characteristics with SPI, it carries the sensitivity of the Palmer Drought Severity Index to changes in evapotranspiration (Yu et al. 2014). Various studies have shown the importance of temperature in inducing drought stress (Vicente-Serrano, Lopez-Moreno, et al. 2014). Evapotranspiration expresses the evaporating power of the atmosphere at a specific location and time of the year, making it possible to compare ETo calculated at different locations or in different seasons. The reference evapotranspiration captured in the calculation of SPEI was calculated using the Penman-Monteith (PM) equation (Allen et al. 1998). The equation accounts for the effects of radiation, humidity and wind speed. The results obtained from the PM approach are comparable to those based on pan evaporation (Roderick et al. 2009) making this method to be considered as superior although the method used to calculate the evapotranspiration is not critical (Sivakumar et al. 2011). The same scale used for SPI calculation was adopted for SPEI, which is 3 and 6 months scales.

5.3.4 Drought characteristics measured

Drought characteristics that were measured and analysed include drought severity in terms of intensity and duration. Drought intensity is determined by the SPI/SPEI value using the classification in Table 5. 1. The focuswas on the drought conditions that impact negatively on yield, that is at least of severe category (SPEI ≤ -1.282). Drought duration was calculated as the difference between the year the SPI /SPEI value dropped to -1, and when the SPI/SPEI value returned to +1 (Yu et al. 2014). Figure 5. 3 shows an example of how drought duration was calculated. The spatial variability of droughts was analyzed using ArcGIS V.10.2, and Microsoft Excel was used for temporal variability.

Table 5.1Categorization of dryness/wetness

SPI Value occurrence	% Occurrence	Nominal SPI class
≥1.645	≤5	Extremely wet
1.282 to 1.644	6-10	Severely wet
0.842 to 1.281	11-20	Moderately wet
0.524 to 0.841	21-33	Slightly wet
-0.523 to 0.523	34-50	Normal
-0.841 to -0.524	21-33	Slight drought
-1.281to -0.842	11-20	Moderate drought
-1.644 to -1.282	6-10	Severe drought
≤-1.645	≤5	Extreme drought

[Adapted from (Agnew 2000) and modified by (Manatsa et al. 2010) to enhance suitability for application in southern Africa. The original classification was developed by (Mckee et al. 1993)].

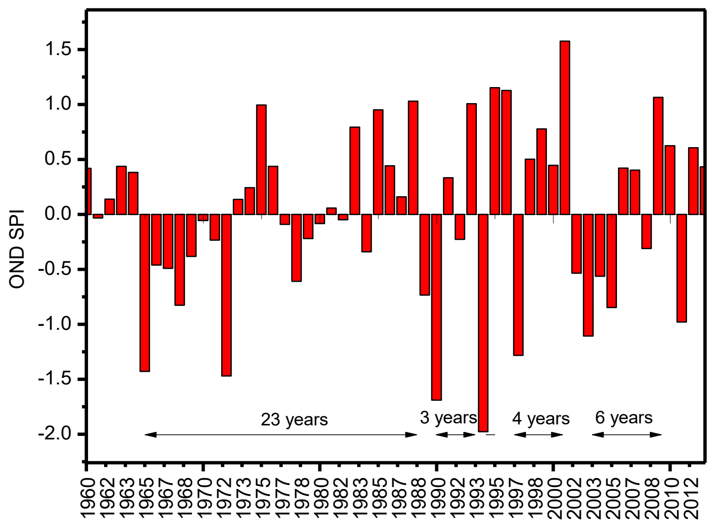


Figure 5.3Examples of drought duration identified by SPI during the OND sub-season between 1960 and 2013.

5.3.5 Statistical analysis and Shift detection methods

Trend analyses for SPI and SPEI were performed for the OND and JFM sub-seasons, as well as the ONDJFM season at both provincial and cluster levels. Both SPI and SPEI are normalised, therefore representing wetter and drier climates in a way that makes them comparable. Correlation analysis (Pearson product-moment correlation) was done to compare SPI to SPEI and other variables. The trends were computed using an ordinary least squares regression method and together with correlations were defined as significant p-values ≤ 0.05. Linear regression, however, assumes gradual change whereas in recent studies such as one by (Manatsa, Matarira, et al. 2015) revealed that there is a turning point in the linear trend behaviour in long-term southern African climate parameters. It is against this background that we utilized two methods, the Cumulative Summation (CUSUM) in Excel and the Sequential Regime Shift Detection (SRSD) method to identify any significant shifts in the climate variables under study. Until recently, studies concentrated on the shift in the mean. But in this study shifts in both the mean and variance were tested for. This is because recent research has shown that changes in the variance may have a greater impact than changes in the mean (Rodionov 2016).Since the data assume a normal distribution, a parametric test, Analysis of variance (ANOVA) was used to check for significant differences in the drought characteristics between clusters.

5.4 Results and Discussion

5.4.1 Climate characteristics of the Free State Province

The highest mean temperature in the province during the OND sub-season was recordedin 2004 (21.3 ˚C) followed by 2008 (21.1 ˚C). During the JFM sub-season, 1992 and 2013 (22.9 ˚C) were the warmest followed by 1999, 1984 and 1983 all of them recording 22.7 ˚C. Highest Tmax was recorded in 1992 (31.4 ˚C) during the JFM sub-season whose mean is 28.5 ˚C resulting in the highest mean temperature in the province. For Tmin, 1988 recorded the highest temperature (15.6 ˚C) against the average of 14.4 ˚C during the JFM sub-season. Figure 5. 4 presents the average precipitation and average temperature for the province during the two sub-seasons.

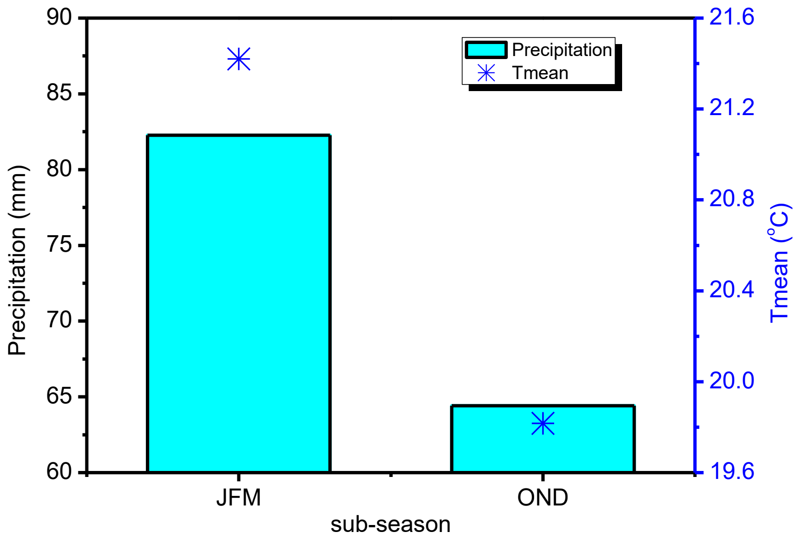


Figure 5.4The mean precipitation and SAT for OND and JFM. Data are calculated for the period 1960 to 2013.

5.4.2 Evolution of droughts

At the provincial scale, for both seasons SPI had much lower values than SPEI. SPI identified more (count) severely dry years than SPEI during the OND sub-season while SPEI identified more severe dry years than SPI during the JFM sub-season. A summary of the drought years at the provincial level is given in Table 5. 2. Relating to the province`s temperature evolution, it is clear that the JFM droughts of 2007, 1983, 1999 and 1970 were intensified by temperature. Tmean for the four years was above the 54 years average. Tmax seems to have contributed to the high averages recorded in the four years. Of these drought years, Tmin was above average during the JFM sub-season in 1983 and 1999. In terms of wetness, both SPEI and SPI identified the OND sub-season of 2001 as the wettest year (SPEI: 1.637; SPI: 1.576). For the JFM sub-season three wettest years (1974, 1976 and 1988) were common although SPEI had much higher indices in addition to 1991 and 2011 which had indices > 1.282. This suggests that SPEI is more sensitive to drought and wetness during JFM than during OND.

Table 5.2Drought years with SPI/SPEI ≤ -1.282 at 3 and 6 months scale for period 1960-2013.

OND				JFM				ONDJFM			
SPI		SPEI		SPI		SPEI		SPI		SPEI	
Year	**Value**	**Year**	**Value**	**Year**	**Value**	**Year**	**Value**	**Year**	**Value**	**Year**	**Value**
1994	-1.978	1994	-1.529	1992	-1.755	1992	-1.724	1982/83	-1.229	1982/83	-1.251
1990	-1.691	1990	-1.394	2007	-1.570	2007	-1.6	1982/83	-1.229	1982/83	-1.251
1972	-1.471					1983	-1.584				

1965	-1.429			1983	-1.473	1999	-1.379	1969/70	-1.224	1969/70	-1.230
1997	-1.284					1970	-1.325				

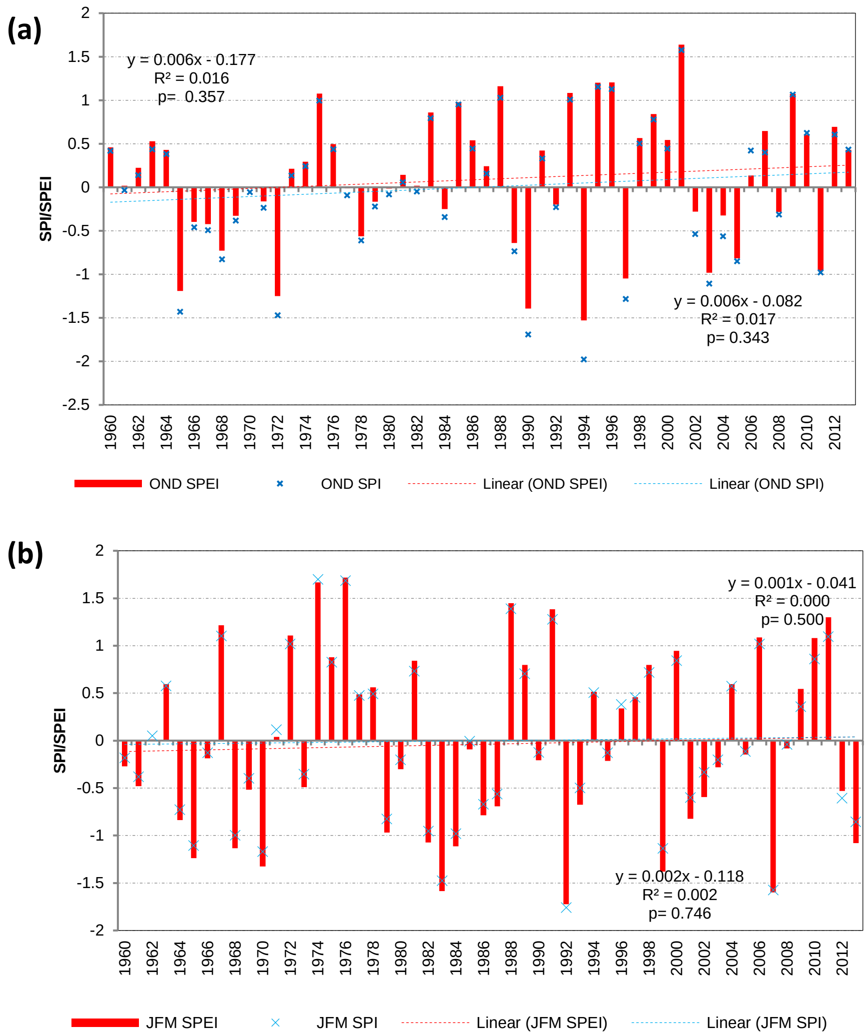


Figure5.5Temporal evolution of SPI and SPEI for (a) OND and (b) JFM sub-season for Free State Province between 1960 and 2013. Trends are shown by dashed lines.

Figure 5. 5 shows the general trends for SPI and SPEI between 1960 and 2013 at provincial scale. Both SPI and SPEI show an insignificant increasing trend towards wetter conditions for both OND and JFM sub-seasons, although it is much higher for OND than JFM. At 6 months scale (ONDJFM), there were no severely dry seasons (Figure 5. 6). The driest seasons were classified as moderately dry (SPEI_6: 1982/83 (-1.251); 1969/70 (-1.230) and SPI_6: 1982/83 (-1.229); 1969/70 (1.224). SPEI identified more severely wet seasons than SPI. The three common seasons; 1975/76, 1973/74 and 1987/88 had higher SPI values than SPEI suggesting that SPEI is more sensitive to drought than SPI. The drought and wet years identified at 6 months scale, however, coincide with SPEI_JFM severe drought and wet years. This finding

confirms the earlier observation that JFM plays a major role in determining the overall severity of drought/wetness during the growing season, regardless of the index used.

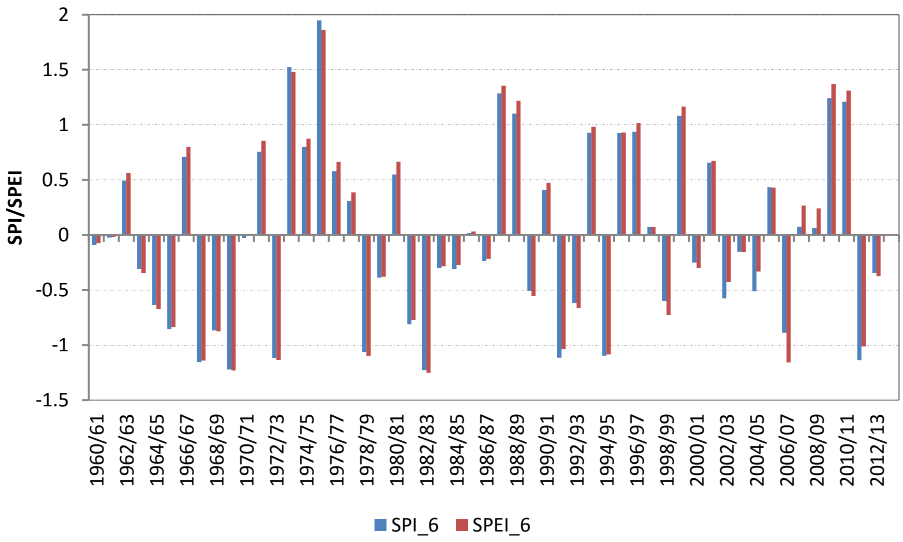


Figure 5.6Temporal evolution of SPI_6 and SPEI_6 for the Free State Province between 1960 and 2013.

Correlation analyses were between SPEI/SPI for the two sub-seasons and results showed that the two sub-seasons are significantly different. The correlation coefficients for OND SPI/JFM SPI (-0.019) and JFM SPEI/OND SPEI (-0.036) confirm the difference between the two sub-seasons. There is, however, a strong positive correlation between SPI and SPEI during both seasons, 0.994 and 0.995 for OND and JFM, respectively with p-values < 0.001. While this result may suggest that the use of SPI only is sufficient, monitoring drought using both indices is encouraged as a proactive approach to drought monitoring and preparedness. The rest of the results are presented in Table 5. 3. The small difference between SPI and SPEI in an individual sub-season accounts for evapotranspiration. For both SPI and SPEI, DTR and cloud cover appear to be strongly correlated than either Tmin or Tmax. This is because DTR and cloud cover can be used as a proxyfor the amount of moisture in the atmosphere hence rainfall which is the main determinant for both SPI and SPEI. During the OND sub-season, SPEI showed higher correlation coefficients with Tmax, cloud cover and DTR than SPI. Tmean does not only show a significant correlation with SPI during the OND sub-season but shows significant negative correlation to both SPEI and SPI during the JFM sub-season. Overall, JFM has higher correlation coefficients than OND suggesting a stronger connection of these variables to drought during the late summer sub-season than the early sub-season.

Table 5.3Correlation values among the time series analysed for the period 1960 to 2013.

OND Sub-season				JFM Sub-season	
Drought Index	Variable	Correlation Coefficient	p-value	Correlation Coefficient	p -value
SPEI	Tmax	-0.563	0.000	-0.812	0.000
	Cloud cover	0.669	< 0.001	0.914	< 0.001
	Tmin	0.097	0.484	-0.004	0.978
	DTR	-0.682	< 0.001	-0.894	< 0.001
	Tmean	-0.145	0.297	-0.678	< 0.001
SPI	Tmax	-0.535	< 0.001	-0.828	< 0.001
	Cloud cover	0.652	< 0.001	0.913	< 0.001
	Tmin	0.093	0.502	-0.006	0.992
	DTR	-0.649	0.095	-0.911	< 0.001
	Tmean	-0.308	0.023	-0.688	<0.001

At a much finer scale, results of the temporal evolution of SPEI and SPI between 1960 and 2013 for OND and JFM are presented in Figure 5. 7. Both SPEI and SPI show similar variability pattern in individual sub-seasons although the variability of SPEI values is higher than that of SPI values during the OND sub-season while for JFM, PET seems to intensify droughts in all clusters. In cluster 1, the effect of temperature was more pronounced before 2000 whereas in clusters 2 and 3 the effect shows a significant increase in recent years. Cluster 3 recorded the highest number of drought seasons regardless of the index with the most severe droughts recorded in1994 OND, 2007 JFM and 2006/07 (ONDJFM). Cluster 1 had the wettest season identified by SPEI during JFM (1976: 2.130) making the 1975/76 season the wettest at 6 months scale (2.270). A summary of the total number of at least severe drought/wet years in each cluster is presented in Table 5. 4. SPEI identified more drought years than SPI for the JFM sub-season while capturing the same years identified by SPI. The severity of droughts revealed by SPEI is higher than that revealed by SPI. The most severe droughts were recorded in the highland region that has the highest precipitation average, while the wettest season was experienced in the low-lying region that has the lowest average precipitation. For OND sub-season, after the 1994 drought, the second and third severe droughts occurred around 2003 in cluster 3 indicating that the highland areas have become drier in recent years. SPEI trends show an insignificant increasing pattern for OND and ONDJFM towards wet conditions and a decreasing pattern for JFM. However, Chi-square test results showed that drought severity has no significant relationship with the altitude-based clusters at both 3 and 6 months scale.

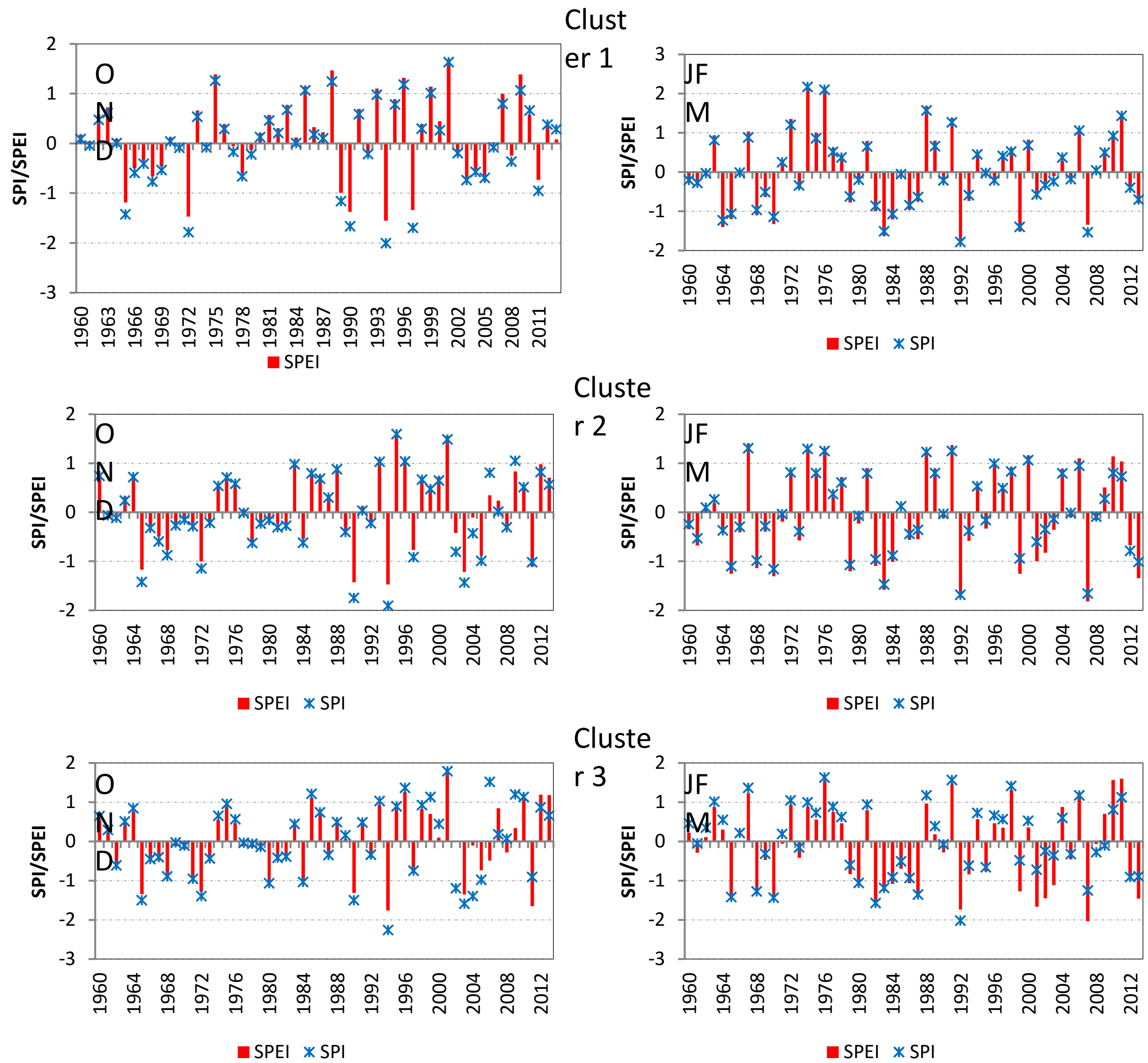


Figure 5.7Temporal evolution of SPI/SPEI in the three clusters of the Free State Province between 1960 and 2013.

Table 5.4Number of droughts/ wet years whose SPI/SPEI was at least ≤ -1.282/ ≥ 1.282.

Cluster	OND sub-season		JFM sub-season	
	Number of SPI droughts(wet) years (≤ -1.282/ ≥ 1.282)	Number of SPEI droughts(wet) years (≤ -1.282/ ≥ 1.282)	Number of SPI droughts(wet) years (≤ -1.282/ ≥ 1.282)	Number of SPEI droughts(wet) years (≤ -1.282/ ≥ 1.282)
Cluster 1	5 (1)	4(5)	4 (4)	6 (6)
Cluster 2	4(2)	2(2)	3 (2)	5 (4)
Cluster 3	6(3)	6 (1)	5 (4)	10(5)

5.4.3 Shift detection

Previous research has revealed that temperatures have increased over southern Africa (Manatsa & Reason 2016; Blignaut et al. 2009b). While SPEI results can confirm the role played by PET in drought intensification, we checked for significant shifts in mean and variance for SPEI series at provincial and cluster levels. Results at provincial scale are presented in Figure 5. 8 for Tmax, DTR and in Figure 5. 9 for Tmean. During the OND sub-season, the two indices show a significant shift in variance around 1988 suggesting that the common variable, precipitation, is the major determining factor in defining the season. Cloud cover variance significantly shifted around 1995 towards lesser variance during the OND sub-season. Shifts in the mean occurred around 2002 for Tmax, DTR, Tmean and cloud cover during the same sub-season. Average Tmax, DTR and Tmean increased by 1.1°C (p< 0.001), 1 °C (p< 0.001) and 0.6 °C (p= 0.002) respectively while mean cloud cover decreased by 3.9 % (p< 0.001). It is only cloud cover that showed a significant shift in both variance (1995) and mean (2002). While a significant shift in mean temperature is usually associated with a significant shift in mean SPEI, this has not been the case in the Free State Province. Rather, a shift in the SPEI variance was identified around 1988. A seemingly identical pattern in the variance of SPI and SPEI suggests that precipitation is the key variable responsible for the pattern during the OND sub-season. This means that the observed Tmax shift observed at provincial level during the OND sub-season has no significant association with drought severity during this sub-season. At the cluster level, a significant shift in mean Tmax was observed in all the three clusters during the OND sub-season around 2002. The spatial distribution of the difference in average Tmax between periods 1960-2002 and 2003-2013 revealed that significance decreases from southwest to northeast (not shown). The extreme southwest had an average Tmax increase of 1.2 °C; the central Free State recorded 1°C while the highland areas to the northeast had a 0.8

°C mean increase. However, this shift was not reflected in SPEI as would have been expected, suggesting that other factors, other than temperature could have played an important role in reducing the atmospheric moisture demand. These factors include, but are not limited to wind speed and relative humidity. However, exploring how each one of the factors is controlling drought in the Free State Province is beyond the scope of this study.

The shift in cloud cover variance preceded the shift in the means for Tmax, DTR and cloud cover during the OND sub-season. During the JFM sub-season, only Tmin showed a significant shift in both the mean and variance (Figure 5. 10). While average Tmin increased from 14.2 °C to 14.5 °C around 1983, its variance declined from 0.241 to 0.062 with p-value = 0.004 around 2003. The 1983 JFM was one of the seasons with the highest Tmeans (22.7 °C) among 1992, 1999, 1984 and 2013 and this can be related to the shift in Tmin observed around the same time. The shift in Tmin towards warmer conditions seems to have more impact on the intensification of droughts during the JFM sub-season at cluster level than Tmax increase during the OND sub-season. Thisis demonstrated by a conspicuous difference between SPI and SPEI. A comparative analysis between the epochs before the shift and after the shift falls beyond the scope of this study. However, it is important to note that while the the averages for minimum temperature and diurnal temperature range have increased, the average cloud cover has decreased.

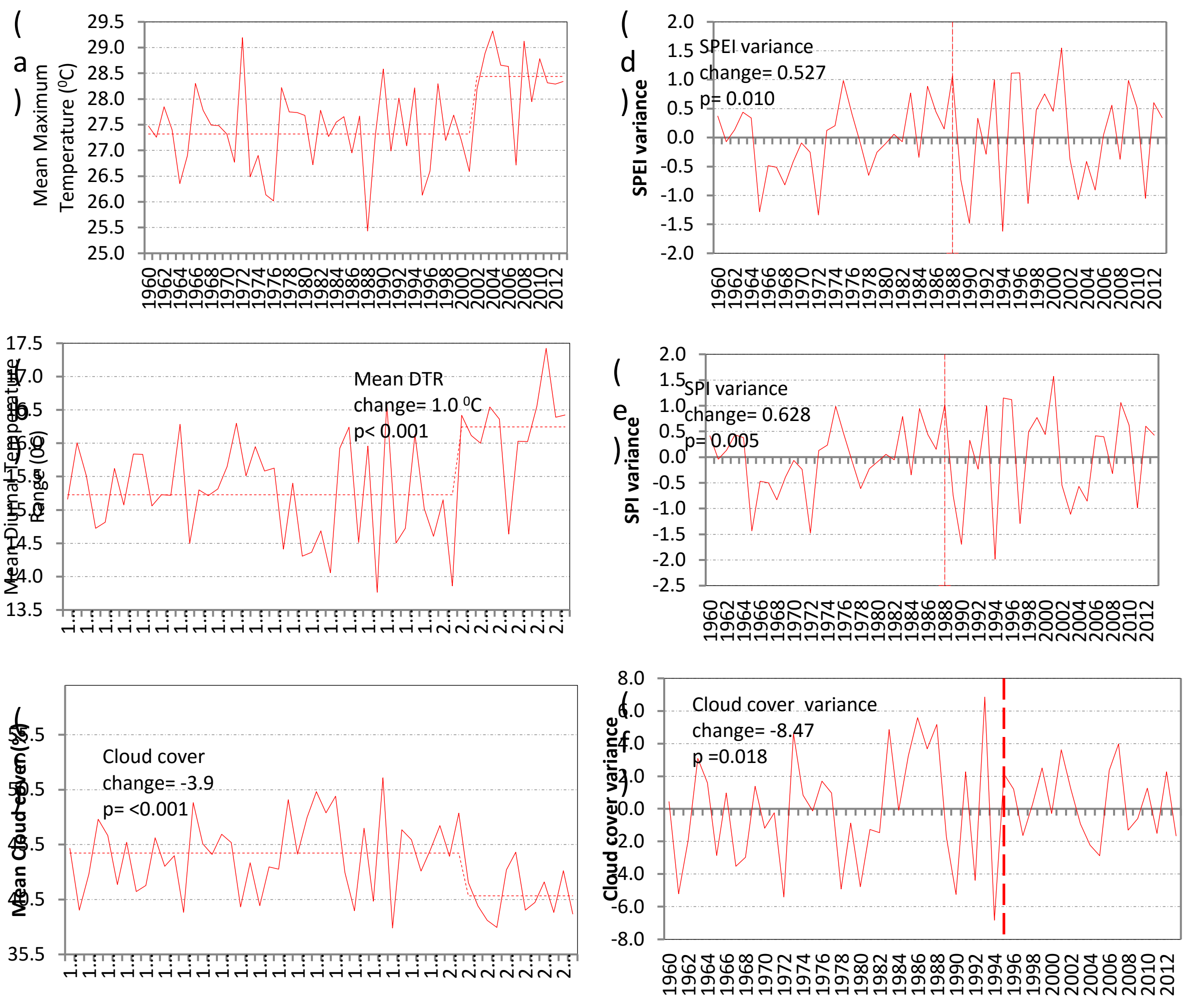


Figure 5.8Temporal manifestation of (a) Tmax, (b) DTR (c) Cloud cover with results of the SRSD superimposed to show the shift in the mean (dashed line) while (d) SPEI, (e) SPI and (f) Cloud cover show the shift in the variance (dashed line)for OND sub-season. The data are from 1960 to 2013.

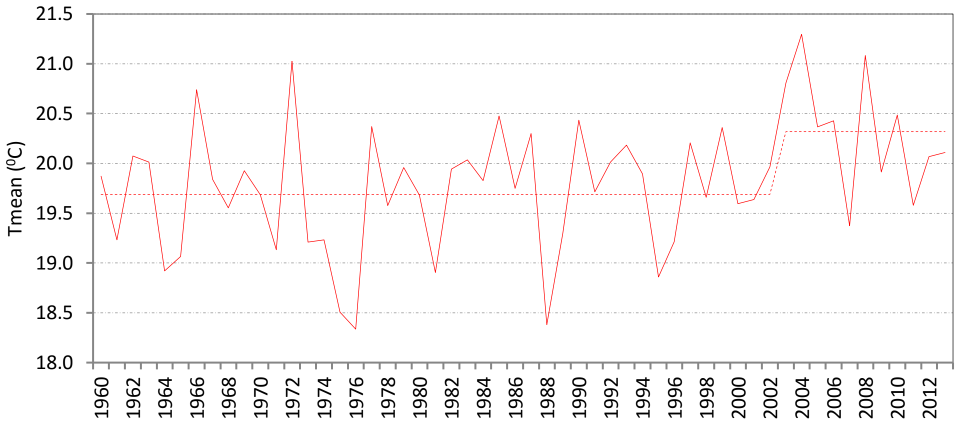


Figure 5.9Temporal manifestation of Tmean for period 1960-2013 with results of the SRSD superimposed to show the shift in the mean (dashed line)

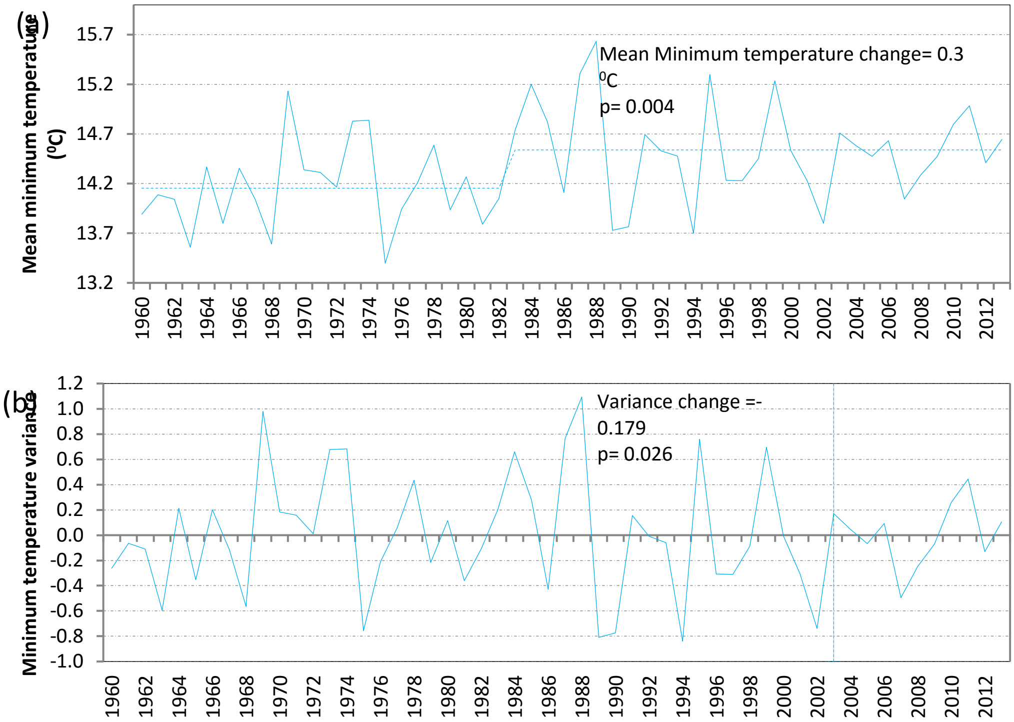


Figure 5.10Temporal manifestations of Tmin with results of the SRSD superimposed to show the shift in the (a) mean (dashed line) and (b)variance for JFM sub-season. The data are from 1960 to 2013.

5.4.4 Drought duration

SPEI and SPI identify almost the same droughts for both OND and JFMsub-seasons with little variations. Drought begins when the SPI/SPEI drops to -1 and ends when the value returns to +1 (Yu et al. 2014). The longest drought episode during OND started in 1965, lasting for 23 years (SPI) and 10 years (SPEI). The difference between SPI and SPEI duration is too much to ignore. Such a difference suggests that while the drought started in 1965, the atmospheric balance between precipitation and evapotranspiration returned to normal in 1975 although the average precipitation did not return to normal until 1988. This could be an indication that the SAT may have lowered around 1975. SPI cessation year (1988) coincides with the year around which variance of both SPI and SPEI shifted significantly towards the high. Another drought (SPI) started in 2003 coinciding with the Tmax shift towards the high and a shift in Tmin variance towards the low and ended in 2009. The relationship between temperature and SPI exists although the direction of the relationship cannot be confirmed at this stage. The results show SPI`s sensitivity to precipitation than SPEI during the early summer sub-season. For the JFM sub-season,the longest drought lasted for 14 years, starting in 1992 and ended in 2006 as identified by both SPI and SPEI. However, during the JFM sub-season SPEI droughts generally lasted longer than SPI droughts, for example, the drought that ended in 1972, SPEI identified 1968 as the start year while SPI identified 1970 as the start year. The drought that followed began in 1982 (SPEI) while for SPI it started in 1983 and ended in 1988. The only drought identified by SPI that lasted longer than SPEI was the 2007 drought, which ceased in 2010 (SPEI) but ceased in 2011 for SPI. The pattern for JFM indicates that SPEI identified a drought before SPI drought onset, for example, the 1968 and 1982 droughts. This suggests that an atmospheric moisture imbalance triggered by temperature increase precedes a below average precipitation season although it cannotbe ascertained how long the lag can be. It can be concluded, therefore, that during JFM, SPEI is more sensitive to drought and wetness than SPI. Drought duration shows an increasing pattern for both SPI and SPEI during the JFM sub-season,but no clear pattern can be noted for OND sub-season. The cumulative total number of drought seasons were calculated for each of the seasons. SPI had a higher total number of drought years during the OND sub-season (37) than SPEI (18) while SPEI had a higher total (32) than SPI (27) during the JFM sub-season. The observation of longer duration of droughts during the JFM sub-season concurs with the hypothesis that the inclusion of evapotranspiration in drought quantification affects not only the drought index values but also the assessment of drought events in terms of duration (Vicente-Serrano, Chura, et al. 2014). The late summer sub-season has a higher temperature average than the early summer sub-season making the effect of temperature on drought index more pronounced during this part of the growing season.

5.4.5 Spatial variation of droughts

To understand the spatial variation of drought in the Free State Province, the distribution of precipitation in the province during the two sub-seasonswas explored. Figure5. 11 shows the distribution of average precipitation for OND (a) and JFM (b)sub-seasons. While JFM average precipitation is higher than that of OND, the pattern is generally the same where the lowest total is observed to the southwest and the highest in the northeastern part of the province.This showsan increase in average precipitation with altitude.

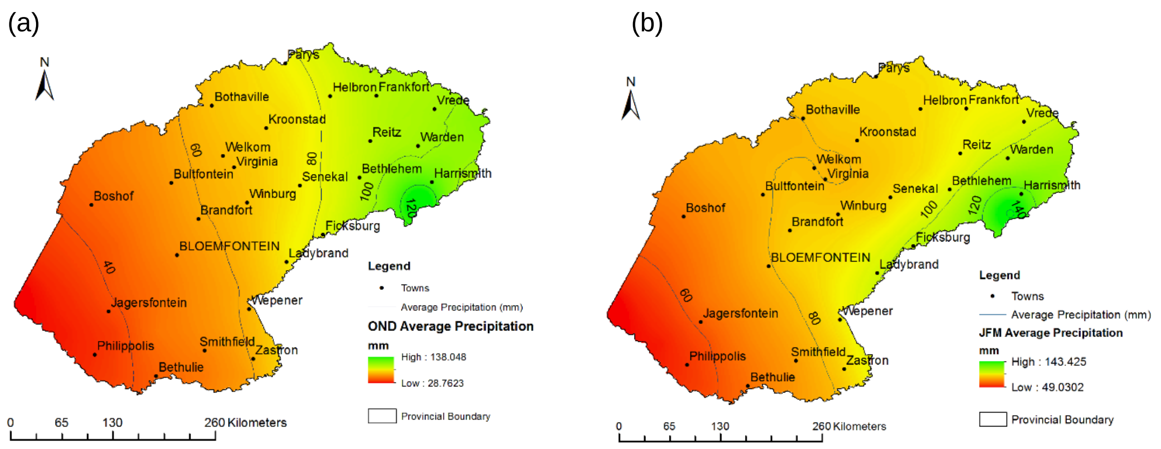


Figure 5.11Distribution of average precipitation for (a) OND and (b) JFM sub-seasons in the Free State Province between 1960 and 2013.

Temporal precipitation trends for the two sub-seasons do not show significant changes in average totals although an increasing trend can be noted for the OND sub-season at provincial scale. At the cluster scale, all the three clusters show an increasing trend in total average precipitation during the early summer sub-season. The sub-season with less precipitation is showing signals of increasing totals whereas the late summer sub-season shows a decline but insignificant trend in Cluster 3, where generally the highest precipitation averages are recorded. Coupled with increasing temperatures in the province, this is likely to intensify drought due to increase in atmospheric moisture demand. However, the effect of temperature on drought as defined by SPEI shows no significance. The temperature shift around 2003 was expected to have had an impact on SPEI but this has not been the case. This result concurs with the observation by Dai (2013) who concluded that the effect of temperature on the intensification of droughts is associated with the northern mid-high latitudes while in Africa, southeast Asia and Australia droughts are a product of reduced precipitation. While the effect of the method used in calculating evapotranspiration is insignificant (Beguería et al. 2014), it may be one of the contributing factors that overshadow the role of temperature increase on drought intensification.

A comparison of the distribution of drought conditions using SPI and SPEI over the Free State Province is presented in Figure 5. 12. Only those years with the lowest SPI/SPEI values at the provincial scale are presented. While the difference in spatial coverage is visually insignificant at six months scale (a and b), SPEI gives a wider coverage than SPI for the JFM than OND sub-season. The 1992 JFM drought had wider coverage as defined by SPEI than SPI explaining the role of temperature in drought intensification. Although precipitation was below average, the greatest proportion of the province suffered drought due to the impact of temperature. The highland areas in the northern and northeastern parts of the provincewere the hardest hit by the 1992/83 drought. The 1994 OND drought mostly affected the south-eastern parts while the 1992 JFM drought was widespread with minimum values recorded in the extreme southwest and northeastern areas. However, the minimum values of both SPI and SPEI to the southwest and northeast do not mean that these places were spared, and were the least affected.

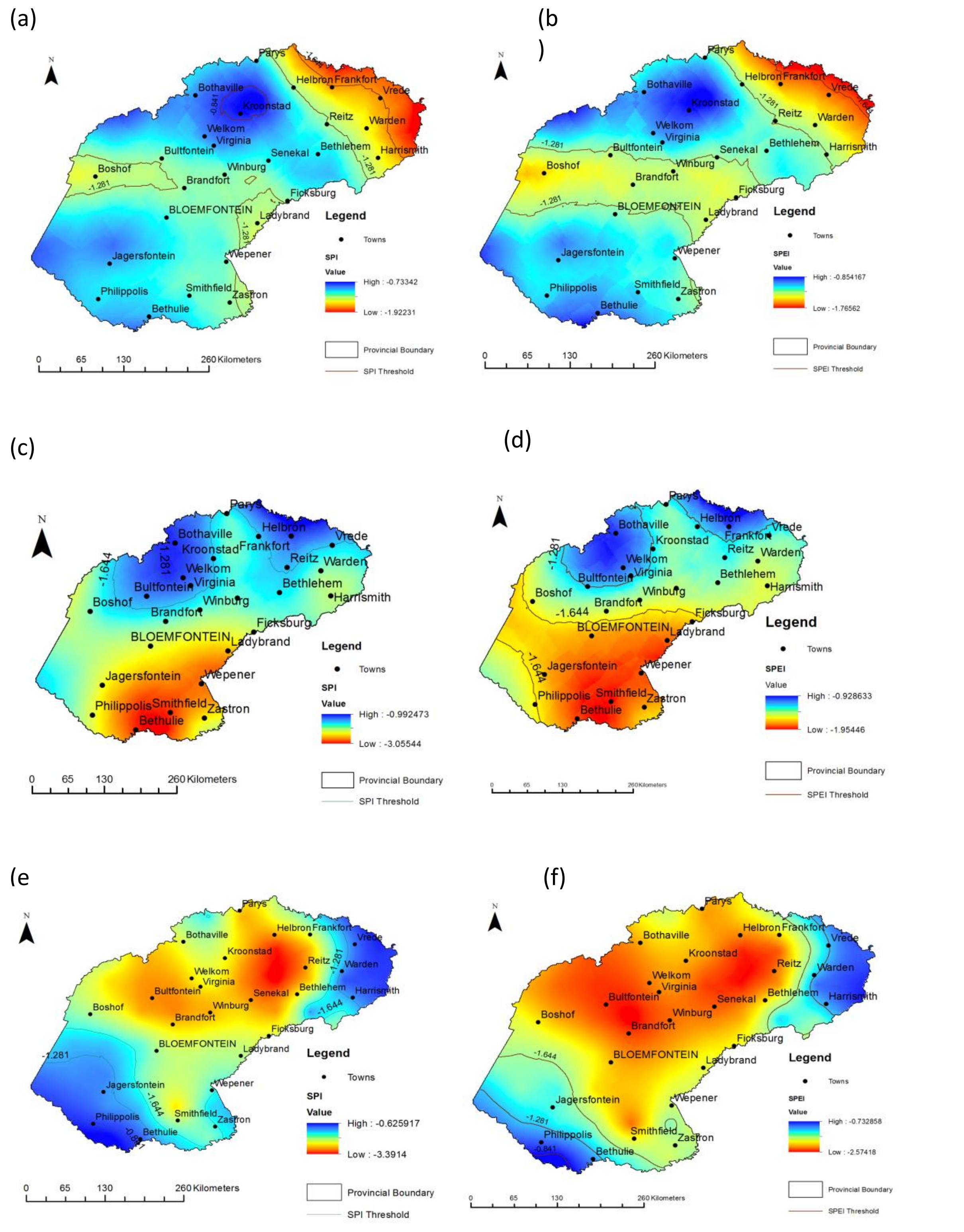


Figure 5.12Spatial variations of drought conditions (SPI and SPEI) during the worst drought years at six months (1982/83) and three months scale (OND 1994 and JFM 1992).

5.5 Conclusions

In this study, we analysed the role of temperature in the intensification of agricultural droughts in the Free State Province of South Africa between 1960 and 2013 using two drought indices, SPI and SPEI. The SPI uses only precipitation in its calculation while SPEIutilises both precipitation and evapotranspiration. Comparing the two indices, therefore, assists in accounting for the role of temperature in the intensification of drought. This is despite the fact other factors such as wind speed, topography and humidity are also important in influencing evapotranspiration. The results indicate that there has been a significant shift in Tmax towards warmer conditions across the whole province of the Free State during the early summer sub-season although the magnitude of change decreases with increasing altitude. The extreme south-western areas have experienced the greatest warming (1.2°C) with central regions showing a 1 °C increase and the least of 0.8 °C recorded in the north-eastern regions of the province. Tmin showed a significant shift in the mean (0.3 °C increase; p= 0.003) and a decrease in variance (0.179; p = 0.004) around 1983 and 2003 respectively. However, despite the significant increase in temperatures observed, SPEI does not reflectthe significant effect of temperature on drought intensification. Exploring the role played by other possible factors such as relative humidity and wind speed that are included in the calculation of evapotranspiration is recommended tounderstanding the evolution of droughts in the Free State Province.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Agricultural drought is a common phenomenon in most parts of the world. However, as revealed by this study, the frequency, magnitude and intensity of droughts have become so variable that food security is under threat. South Africa`s dependency on agriculture puts it in a vulnerable position, considering that the Free State Province, one of the major agriculturally productive provinces, is experiencing climate change. Coupled with a growing population and an increase in the number of people living in poverty, agricultural droughts may cause the shrinkage or collapse of the country`s economic system, since agriculture is the backbone of the economy, and is interconnected with the whole economic system of the country.

Efforts to understand the rainfall patterns in South Africa have given limited attention to temperature, yet a strong relationship exists between temperature and evapotranspiration, and agricultural yields. The focus of the thesis was the assessment of the impact of surface air temperature (SAT) variability on agricultural droughts during the summer agricultural season (October-March) in the Free State Province of South Africa between 1960 and 2013. Two drought indices were used to achieve the aim of this research study, namely the Standardised Precipitation Index (SPI) and the Standardised Precipitation Evapotranspiration Index (SPEI). The SPIs were calculated using the Drought Indices Calculator (DrinC) while monthly precipitation, temperature, and Standardised Precipitation Evapotranspiration Index data were obtained from the Climate Explorer`s Climate Research Unit (CRU) gridded data file at 0.5° X 0.5° spatial resolution (available from https://climexp.knmi.nl). The calculation of the SPI requires monthly precipitation average data only, while SPEI combines precipitation and evapotranspiration. The SPI is used in meteorological drought studies, but when calculated at a short-time scale, it adequately describes agricultural drought. The Penman-Monteith equation method was used in the calculation of the Evapotranspiration as recommended by the World Meteorological Organization. The spatiotemporal evolution of agricultural drought was analyzed at 3 months and 6 months scales.

The aim of the study was achieved by way of objectives and a number of methods that were employed to analyze the agricultural droughts in the province.

The objectives of the study were;

1. To characterise agricultural drought using the Standardized Precipitation Index in the Free State Province of South Africa between 1960 and 2013.

2. To assess the influence of altitude on agricultural droughts in the Free State Province of South Africa between 1960 and 2013.

3. To characterise drought using Standardized Precipitation Evaporation Index in the Free State Province of South Africa between 1960 and 2013.

4. To account for the differences between SPEI and SPI based drought characteristics over the Free State Province, South Africa.

Chapter 1 introduced the concept of agricultural droughts in the face of global climate change. The problem was defined and justification for the study was also given. The aim and objectives of the study are outlined, with the structure of the thesis presented in conclusion of the chapter. Chapter 2 presented an analysis of agricultural drought characteristics using SPI, drawing emphasis on severe and extreme drought and wet conditions based on Agnew`s (1999) classification in the Free State Province. Severe droughts are known to have a devastating impact compared with mild and moderate droughts. To give balance to the analysis, severe and extreme wet conditions were also analyzed. The province was divided into 5 homogenous sub-regions or clusters based on the 6-months seasonal average total precipitation. This process was performed using Hot Spot Analysis in ArcGIS Version 10.2. The purpose of clustering was to enable comparison of drought characteristics between sub-regions. In recognition of the sensitivity of mountains to global climate change, the influence of altitude on the spatiotemporal variation of droughts was assessed in Chapter 3. The characterization of droughts and the assessment of the influence of altitude were done using SPI while surface air temperature variability was assessed in Chapter 4. The occurrence of abrupt significant shifts was investigated using Rodionov`s Sequential Regime Shift Detection Technique and confirmed by the Cumulative Summation technique. Three temperature variables were used to achieve this objective; maximum temperature (Tmax), minimum temperature (Tmin) and Diurnal Temperature Range (DTR). Finally, a comparative analysis was performed between SPI and SPEI in relation to temperature to establish the role of temperature in the intensification of agricultural droughts in the province. Drought characteristics of the two indices were compared in terms of frequency, duration and intensity to establish the relationship between the two indices. In each of the chapters, relevant literature and methodologies were reviewed in line with the objective under investigation.

6.2 Conclusions

Based on the aim and objectives of the study, conclusions derived from the findings of this thesis are that:

1. The Free State Province has not been spared by the droughts that have been recorded in southern Africa as a whole. These include the 1972/73, 1982/83, 1991/92 and 1994/95 agricultural seasons. However, it is noted that the two subseasons (October-December and January-March) experience drought conditions during different years, for example while the early subseason recorded the most severe drought during the 1994/95 season, the late subseason had a most severe drought during the 1991/92 agricultural year. This implies that the agricultural season may start as bad, but can still have a fairly wet late subseason. However, while this may be the case, the impacts are usually devastating, as crops may fail during the vegetative stages, negatively affecting the ultimate yield.

2. Seasonal average total precipitation increases from west to east in response to increasing altitude. Unlike the western part of the province, the eastern part of the province demonstrates higher occurrences of severe droughts, though there is a general increase in drought frequency in the province as a whole. This reveals that high altitude regions to the north-east of the province with higher average total precipitation are more susceptible to damaging droughts compared with low altitude regions. It also implies that when a drought occurs in the province, the impact is likely to cause more damage in the regions that normally receive more precipitation revealing the sensitivity of mountain regions to the impacts of climate change and climate variability.

3. Significant differences in drought/wet intensities between clusters are more pronounced during the early than the late summer period.This suggests that altitude plays a more important role in determining drought severity during the October to March sub-seasonthan during the January-March subseason as confirmed by the ANOVA test. The relationship between ENSO and SPI also indicates stronger correlations for the early summer sub-season than for the late summer sub-season, while overall presenting a diminishing intensity with height over the province. The impact of altitude also manifests in the strong relationship between meridional winds and the SPI. When the winds are largely northerly, the Free State Province lies predominantly in the windward side of the Drakensberg Mountains, bringing above-average wet conditions, but the province lies in the rain shadow zone of southerly winds.

4. When compared with the early summer sub-season (October-December), the late summer sub-season (January-March) generally experiences higher temperatures, for both Tmax and Tmin. A significant shift towards warmer temperatures was detected for Tmax during the October-December sub-season around 2003 and 1983 for the January-March sub-season for Tmin. A strong negative correlation between OND Tmax shift and cloud cover exists suggesting an influential relationship between the two variables. While both showed a shift coincidence around 2003, establishing which one of them affects the other was beyond the scope of this study. It was found that the significance of temperature change is stronger towards the north and north-western regions of the province, pointing to the idea that the high altitude regions are more sensitive to global temperature changes than relatively low-lying regions. As such, the north-western regions could be more susceptible to intense droughts, and the proliferation of weeds, pests and diseases which may affect yields.

5. The relationship between Surface Air Temperature variability and agricultural drought shows no significance between the two variables. The observed significant increase in October-December Tmax (2003) and January-March Tmin (1983) in the Free State Province is not reflected in the SPEI. This suggests that temperature has an insignificant impact on the intensification of agricultural droughts in the Free State Province between 1960 and 2013. However, this does not imply that temperature is not important since it could have a significant influence in combination with other variables such as wind speed, radiation and relative humidity.

6. The observed significant shifts towards warm temperatures may not have any significant impact on the intensification of agricultural drought in the Free State Province but has the potential to reduce the water volume in water bodies. While the small-scale subsistence farmers who practice rain-fed agriculture are more vulnerable, commercial farmers who supplement rainfall with irrigation are likely to suffer the consequences of increased evaporation of water from their reservoirs as the levels of dam water may be reduced significantly. The impacts may cascade to farmers practising animal husbandry at both subsistence and commercial levels. This may mean a reduction in the herd in line with the available water resources. Eventually, food prices may rise due to increased reliance on supplementary feed for livestock or on irrigation. Increases of food prices present as a challenge for low-income groups, with likely consequences of malnutrition. Reduction in outputs, including those that subsistence farmers are currently producing, threatens food security due to shortages of basic foodstuffs. The subsequent result is shortage of raw materials for agribusiness and loss of jobs for both casual

and permanent employees contributing to an already rising unemployment in South Africa. The research findings provide a basis for analyzing possible impacts of the observed temperature changes on water resources, vegetation and land cover changes with the aim of finding sustainable adaptation strategies that can help to maintain and improve agricultural productivity in the Free State Province and beyond.

6.3 Recommendations

Following the findings of this study, the following recommendations are made:

1. Follow-up research is needed to investigate the possible explanations as to why the observed significant shift in the early summer sub-season towards warm temperatures does not have any significant effect on the intensification of agricultural drought in the region. This could involve an analysis of the role of other variables influencing evapotranspiration, as well as wind speed, humidity and radiation. Establishing the relationship between each of these variables or their combined effect on drought characteristics may assist in drought risk management, thus safeguarding agricultural productivity in the Free State Province. Climate modelling could also be done to identify how local factors influence the JFM sub-season.
2. The observed strong relationship between ENSO and SPI could contribute to the forecasting of events such as droughts in the province, although other indicators are also important. If used conjunctively with other indices, the accuracy of forecasts can be improved, hence contributing towards disaster preparedness and reduction. Recent occurrences of severe droughts in the highland regions of the Free State Province call for more research into adaptation options for farmers to adjust their practices, as well as to ensure that water resources managers and environmental policy planners take into account the possible impacts of these occurrences.
3. Since significant differences between clusters in drought or wet severity are more pronounced during the early summer sub-season than the late sub-season, farmers could reduce the impact of drought on their crops by practising irrigation farming during the early sub-season instead of waiting to irrigate in the late sub-season. More drought-tolerant crop varieties could be adopted in the generally drought-prone regions to the north and north-east of the province.
4. Although the impact of temperature increase during the early sub-season does not have a significant impact on the intensification of drought in the Free State Province, a proactive approach is recommended to reduce any other potential impacts the shift in temperature may have on other resources such as water and biodiversity. The association of higher temperatures with weeds and pests calls for close monitoring of these threats by the Department of Agriculture`s plant pathologists. Breeding for pest/disease tolerant animals and crop varieties,

as well as adoption of conservation agricultural strategies such as water harvesting is recommended.

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