Agroclimatic Variability in the Free State Province: A Case Study in the Setsoto Municipality.

School of Animal, Plant and Environmental Science

Student: Abubakar Hadisu Bello (1364152)

Supervisors: Dr. Solomon Newete, Prof Mary Scholes

A research report submitted to the Faculty of Science, University of the Witwatersrand in partial fulfillment of Master of Science.

Feb 2019

ABSTRACT

This study investigated the impacts of agroclimatic variability; minimum and maximum temperatures and rainfall on maize yield in the Setsoto municipality in the central eastern part of the Free State province of South Africa from 1985 to 2016. This study focused on the Setsoto municipality, because it has been shown that the variability and uncertainty in temperature and rainfall across weather stations, even those close to each other is high. This variability may be impacting maize yield. The daily minimum and maximum temperatures and the rainfall were obtained from the Agricultural Research Council (ARC) and the South African Weather Service (SAWS) for a period from 1985 – 2016. The annual maize yield data was obtained from the Department of Agriculture Forestry and Fisheries (DAFF).

In this study the monthly as well as the growing period (Apr -Oct) minimum and maximum temperatures for the period between 1985 and 2016 varied across the four target stations (Clocolan, Senekal, Marquard and Ficksburg) of the Setsoto municipality. In Clocolan, the monthly minimum temperature and the entire growing period significantly declined by 0.2 to 0.12 °C year^{-1}. A similar trend was also observed in Marquard for some of the months. The maximum temperature trend increased significantly across all the stations by 0.04 - 0.05 °C year^{-1} during the growing period, while on a monthly basis it increased between 0.018 - 0.12 °C year^{-1} mostly in October, November and March ($P < 0.005$). The temperature effects were most influential in the months of November and February when leaf initiation and kernel filling occur, respectively. The results showed there was no significant change in rainfall during the growing period across the municipality. Neither the onset nor the cessation of the rains changed significantly over the study period. The duration of the rainfall in all the four stations of the municipality used in this study was sufficient for maize production. Nevertheless, the maize yields of these stations were low, ranging from 1.96 – 2.89 tons ha^{-1}. Although, rainfall does show a strong positive correlation with yield, it is also affected by number of environmental factors among which are the rainfall distribution through the season, minimum and maximum temperatures, soil nutrients as well as other edaphic factors. One unit of rainfall (mm) can increase the maize yield by 0.005 and 0.015 t ha-^{1}year^{-1}

The overall variation in maize production in Setsoto municipality was due to the variable agroclimatic anomalies, the minimum and maximum temperatures as well as the rainfall ranged from 13.5-15.2%, 21.4-43.2% and 17-47.3% respectively over the period of this study. The increasing minimum and maximum temperatures at all of the stations showed that: where the minimum temperature is currently too low for optimal growth, an increase in these temperatures will increase yield; and the overall increase in both the minimum and maximum temperatures over time will have a negative impact on crop yield, but the magnitude of the effect is dependent on when exactly the increases during the growing season occurs. There are some concerns that as temperatures and rainfall variability increase the area will become marginal for maize production. Yield is not controlled only by agroclimatic variables, but together with a combination of a number of farming practices including area of land planted, fertilizer and pesticide usage etc.

Keywords: Agroclimatic variability; Minimum and Maximum temperatures; Maize yield; Rainfall patterns; Setsoto Municipality; Free state province; El Nino

Declaration

I, Abubakar Hadisu Bello, humbly declare that this work is my own. It is being submitted for the research report component of the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signed on this day 7th…. **of** ……February. **2019 at** the university of the Witwatersrand …

Signature ……… ………………… **Date 7**th February 2019

Acknowledgement

My profound and sincere appreciations are offered to my supervisor’s Dr Solomon Newete and Prof Mary Scholes for their patience and understanding during the period of this research. Your contributions have been immensely helpful from conceptualization to implementation of this study. Thank you for offering me the opportunity to work under your tutelage and guidance. I will forever remain grateful. I have learnt a lot from your supervision during the course of the study and you have exposed me to scientific writing skills and research commitment.

I am very grateful to the Agricultural Research Council (ARC) for the provision of the maize yield and weather data and to the South African Weather Service (SAWS) for allowing me to use their rainfall data. I would also like to thank the National Research Foundation (NRF) for their financial assistance through the bursary awarded to me.

Last, but not least, I would like to thank my family for their support and understanding during my long stay in South Africa. Most especially I am indebted to my daughters (Fadal and Farha) and my wife Fatimah Muhammad. I would also like to thank my brother, Ashir Muhmmed, for his support during my academic sojourn. May God bless you all.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Acronym	Description
ARC	Agricultural Research Council
CCAM	Conformal-cubic atmospheric model
CSIR	Council for Scientific and Industrial Research
CV	Coefficient of variance
DAFF	Department of Agriculture, Fisheries and Forestry
DTR	Diurnal temperature range
ENSO	El Niño-Southern Oscillation
GHG	Greenhouse gas
GP	Growing Period
ha	Hectare
IDW	Inverse Distance Weighting
IDWm	Modified Inverse Distance Weighting
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
MAKESENS	Finnish Meteorological Institute
Max	Maximum
MDG	Millennium Development Goals
Min	Minimum
MK	Mann Kendall Test
Q	Sen's slope estimator
SD	Standard Deviation
SSA	Sub-Saharan Africa
SAWS	South African Weather Service
Tmax	Maximum Temperature
Tmin	Minimum Temperature
VS-MPR	Vovk-Sellke Maximum p –Ratio
WMO	World Meteorological Organization
Z	MK trend Test

CHAPTER 1: GENERAL INTRODUCTION

The number of climate change impacts, often experienced as extreme and unpredictable weather conditions, are increasing threatening the future of agricultural production (Black and Thompson, 1978; Chloupek *et al.*, 2004; Alexander *et al.*, 2006). The combination of climate and weather variability are important factors defining crop production and yield which are integral parts of farming planning and decision making (Ewert *et al.*, 2015; Phalkey *et al.*, 2015). There is worldwide consensus that climate change is real, rapidly advancing and a widespread threat (Mishra *et al.*, 2014). The challenge of climate change is a global phenomenon that threatens millions of livelihoods by affecting agricultural activities, food security, water resources, health, social systems and the functioning of ecosystems (Barros *et al.*, 2014). Over 60% of the population in the Sub-Saharan Africa (SSA) lives in rural areas where food access is dependent on subsistence farming (Connolly-Boutin and Smit, 2016). The looming climate change effects will have far more pronounced negative impacts on the livelihoods in this region than the rest of the continent (Kahsay *et al.*, 2017). Temperature and rainfall are the two most important climatic factors affecting agricultural production (Cooper *et al.*, 2008; Lobell and Field, 2007; Riha *et al.*, 1996). Temperature mainly affects the length of the growing season while rainfall affects plant production (leaf area and photosynthetic efficiency) (Olesen and Bindi, 2002). There is extensive literature on the effects of temperature and rainfall on crop yield. Cooper *et al.* (2008) found that rainfall variability within the rainy season is equally important for crop production as the total amount of rainfall. Daily and monthly rainfall and temperature data are essential for crop yield studies (Lesk *et al.*, 2016).

Studies on climatic variability for Southern Africa are varied and diverse in their conclusions. Kruger (2006) concluded that there is no evidence in the change of South African rainfall in the last century, but there are some specific areas which showed significant changes in their rainfall attributes between 1910 and 2004. South Africa's rainfall scenario shows high inter-annual variability ranging between 50–200% over the last 20 years with a linear trend (Kane 2009). The south west of South African region have been experiencing severe drought and improved rainfall pattern in north of Malawi, Mozambique and Zambia (Shongwe *et al.*, 2009). In their studies of Malawi rainfall Ngongondo *et al.* (2011) reported non-statistical significant at 5% changes in monthly, seasonal and annual trend.

Maize is the most important crop grown in Southern Africa. Furthermore, South Africa is amongst the ten highest maize producing countries in the world (Landman *et al.*, 2017). The country has an average production of 12 million tons per year; contributing approximately 2% of the world's maize production (FAOSTAT, 2012). The Free State province alone produces over 35% of the maize in South Africa (Blignaut *et al.*, 2009). Overall, the environmental conditions and natural resources of the Free State are conducive for maize production, although incidences of agroclimatological hazards causes detrimental effect on production (De Jager *et al.*, 1998). This is corroborated by Smale and Jayne (2014) who found that because of climate variability, the output of maize production varies annually in Southern Africa. Since only 1% of the cultivated area uses irrigation for maize production (Mukhala and Groenewald, 1998), there is a particularly high reliance on rainfall and thus vulnerability to drought. Other hazards impacting on production include late cessation of frost that damages early planted crops, early onset of frost affecting crops at later stages of their growth, and low temperatures during the 'growing period'. Such effects are resulting in reduced maize crop production in the province (Allemann, 1997; Moeletsi, 2010; Van den Berg *et al.*, 2013). Given the importance of the Free State as a hub of maize production for South Africa and beyond, this study characterizes the agroclimatic variability of a selected area in the province. It further investigates the impact that this variability has on maize production.

1.2. Rationale of the study

Climatic variability is a common feature of the Free State province as has been shown in previous studies (Moeletsi *et al.*, 2013; Moeletsi and Walker, 2012). Studies for the whole province have shown patterns in rainfall and temperature from east to west, however, these studies do indicate that a more in-depth understanding of regions is needed as the variability is extremely high. The Free State is the third-largest province of South Africa comprising 10.6% of the country's land mass (approximately 129,825 km^2) (Davis *et al.*, 2006). The agricultural maize production in the Setsoto municipality is declining due to increasing agroclimatic variability and other environmental hazards such as erosion and overgrazing (Buso, 2003). This study has focussed on the Setsoto municipality because it has been shown that the variability and uncertainty of rainfall and temperature across weather stations, even those close to each other is high. This research report explores the variability in the Setsoto Municipality which is under the administrative district of Thabo Mofutsanyana in the Free State province. Four areas were studied, Senekal and Marquard have been studied extensively, but Ficksburg and Clocolan has received very limited attention. Maize production from this Municipality contributes significantly to the food security at the local level. Possible future decreases in rainfall and increases in temperatures will negatively impact the maize production.

1.3. Aim and Objectives of the Study

The aim of this study is to evaluate the impacts of agroclimatic variability on maize production in the Setsoto municipality of Thabo Mofutsanyana District area in the Free State province, South Africa.

The main objectives are to:

- Examine the effects of climatic trends; specifically changes in the minimum and maximum temperatures in the growing period (October to April) between 1985 and 2016.
- Evaluate the maize yield trends of the Setsoto municipality between 1985 and 2016.
- Determine the relationship between climate variability and maize yield in the Setsoto municipality for the 30-year period.
- Investigate trends in the rainfall and temperature across the growing period including the onset, cessation and duration of the rainfall.

CHAPTER 2: LITERATURE REVIEW

2.1 Global climate change and agriculture

Some studies forecast that an increase of 70% to 210% in food production is required by 2050 and 2100, respectively to ensure global food security (Clay, 2011; Gornall *et al.*, 2010) . A study by Padgham (2009) on 12 food-insecure regions of the world, reported that climate change will have a significant impact on agricultural production and food security of Sub-Saharan Africa (Fantaye *et al.*) and the Asian regions by 2030, as a result of climate variability.

The current food production in SSA and South Asia will not meet the needs of the increasing population (Foley *et al.*, 2011; Haub *et al.*, 2012). Furthermore, food security, economic growth and poverty eradication are extremely difficult to achieve in SSA (Bazilian *et al.*, 2012). According to Lim *et al.* (2016) malnutrition exceeds household disease burden in certain instances in SSA. Therefore, crop yield intensification is important for improving food security for the region's growing population (Van Ittersum *et al.*, 2016). There are stagnating or declining yield trends in some regions where orthodox intensification in food production is being used (FAO, 2014). Despite the gains in global agricultural production, there are approximately 800 million people undernourished globally (Garibaldi *et al.*, 2017). The increase in population in SSA will put pressure on food availability for the people living within the region. SSA did not meet the Millennium Development Goals (MDG) by 2015, for multiple reasons. The fights against hunger and ensuring environmental sustainability have been hindered by shifting climatic conditions such as increasing temperatures and by rising CO_2 emission levels (Mupedziswa and Kubanga, 2017).

Climate change impacts differ depending on local and regional environmental conditions and on differences in vulnerability to climate change (IPCC, 2014). Understanding these concepts will help people to cope and develop adaptation strategies. If the main cause of climate change is anthropogenic, then it is our responsibility to act and change our lifestyle to reduce our environmental footprint and slow down the climate change impacts. Coping and adapting to impacts of climate change without curbing our climatic footprints will exacerbate the inevitable consequences (Altieri and Nicholls, 2017).

2.2 Climate Change in Southern Africa

A third of the African population lives in areas with an arid climate and is vulnerable to climate change impacts (Altieri *et al.*, 2015). Thus, understanding the underlying factors that influence the climatic change of the region could improve forecasting and reduce the devastation in the region (Richard *et al.*, 2001). The African climate is influenced at the macro level, namely by the El Niño-Southern Oscillation (ENSO), the West African Monsoon and the Inter-Tropical Convergence Zone (ITCZ) (Collier *et al.*, 2008). The intra-decadal oscillations are recognized to be influenced by the Pacific ENSO and by interactions with the Atlantic and Indian Ocean climates (Fauchereau *et al.*, 2003a).

The climate variability in Africa can be the combination of macro-level effects and anthropogenic influences such as land cover changes. These bring about annual variation in rainfall and temperature (Mason, 2001). Reseachers have for years attempted to model and predict the impacts of ENSO, but it remains complicated and poorly understood as the drivers keep changing (Hulme *et al.*, 2001). What is known is that global warming may be linked to climate change and increases the occurrence of extreme weather events including flooding and droughts (Collier *et al.,* 2008). Observed surface air temperatures have shown an accelerating warming trend since 1960, increasing by 0.03 °C annually in some areas of Africa (Conway *et al.*, 2004). The South African average air temperature has increased by 1.2 °C since 1960 and the warming rate has increased at a pace double the average global rate (Scholes *et al.*, 2015; Moeletsi *et al.*, 2011).

Lack of rainfall or high evaporation and insufficient soil moisture may induce plant stress (Berdanier and Klein, 2011), limit crop growth and development. If such conditions do not improve, this can lead to reduced crop yield (Hamza and Anderson, 2005). The temporal and spatial precipitation patterns over Africa are less predictable than the temperature patterns, with large spatial and temporal variability (Hulme *et al.*, 2001). Gauteng and the Free State provinces are home to most of the country's urban population and the food basket of the nation, respectively (Scholes *et al.*, 2015). Agricultural production is susceptible to climate variability in the region. Higher temperatures can decrease crop yields and animal production (Dube *et al.*, 2013). According to Scholes *et al.* (2015), for each one-degree Celsius rise in temperature, crop yield decreases by 5%. Temperatures above optimal levels create biochemical challenges for plant cells especially the enzymes associated with the photosynthetic pathway (von Caemmerer and Furbank, 2016).

Climate change in Africa impacts across the continent's sub-regions. For instance, multi-decadal variability, prevails in the Sahel (Agnew and Woodhouse, 2010). The Eastern African climate data, where precipitation level is suggested to increase by 10%, is an example of anticipated positive climate changes in the continent (King'Uyu *et al.*, 2000). Contrary to this, central Africa has seen a decline in the amount of rainfall received (Phillips *et al.*, 2002). The southern and northern parts of Africa are expected to be about 4 to 6 °C hotter by 2080 and the precipitation will decrease by 10-20% (Collier *et al.*, 2008). Southern Africa experiences large swings in rainfall over the annual cycle arising from changes in solar radiation and north–south displacement of the Hadley cells (Xie, 2004). Zonal circulations also plays a key role; in summer, easterly winds draw moisture from the south west Indian Ocean and the warm Agulhas Current, whereas in winter, westerly winds bring dry air from the South Atlantic Ocean and the cool Benguela Current (Jury, 2013).

Christensen *et al.* (2007) showed that the El Niño occurrence in the Pacific Ocean is associated with droughts that may be prolonged such as those often experienced in southern Africa. They also showed that the variability in the climate was due to a combination of ocean and terrestrial factors. In fact it has proven very difficult to accurately predict the South African rainfall pattern over the last century (Scholes *et al.*, 2015). Scholes *et al.* (2015) found that the periodic droughts and floods associated with ENSO over southern Africa are unable to correctly predict the timing and relative severity of future extreme climatic events in the region. Nevertheless, projections of climate and weather data are constantly improving; so examining historical records and current trends, helps to determine the magnitude and the extent of climate change (Solomon, 2007; IPCC, 2014). Studies have shown the importance of land cover in better understanding the climate. Christensen *et al.* found that land cover positively mitigates climate change. An increase in vegetation cover leads to a reduction in the temperature by 1 °C in tropical Africa (Bounoua *et al.*, 2000). Linked to decreasing land cover, atmospheric dust and deforestation are equally important contributors to climate change in Africa (Wang and Eltahir, 2002). Human actions, including removal of land cover and deforestation are drivers of local and global environmental changes that also affect the biogeochemical cycles negatively (Matson *et al.*, 1999; Steffen *et al.*, 2005). These influences contribute to increasing greenhouse gas levels, which are further exacerbated by large scale intensive agricultural activities (Giorgi *et al.*, 2009; Xue, 1997).

2.3. Climate variability and Agriculture

Rainfall changes could be attributed to inter-decadal climate variability rather than warming of sea-surface temperatures (Field *et al.*, 2001). However, it is also known that land cover changes and related fluctuations in atmospheric composition can translate into changes in rainfall. The increased volume of Greenhouse Gases (GHG) concentrations in the atmosphere can also transform the rainfall pattern and subsequently the hydrological cycle (Hulme, 1992; Bandyopadhyay *et al.*, 2016). The periods with higher temperatures, therefore, have lower rainfall across the world and vice versa with the exception of the tropics (Tyson *et al.*, 1975; Dezfuli *et al.*, 2015). Despite this clear relationship, it is often difficult to detect linear trends and shifts in rainfall patterns because of lack of normality in the time series of climate data (Fauchereau *et al.*, 2003b).

A study by Dasgupta *et al.* (2014) indicated that the mean global temperature increases by 0.5 °C per annum. This rising temperature trend suggests that there is an increase in warm indices (hot days, hottest days) and a decrease in extreme cold indices (cold days, cold nights) (Aguilar *et al.*, 2009). Studies across the world show that minimum temperatures are increasing at a faster rate than the maximum temperatures (Hulme *et al.*, 2000; New *et al.*, 2006; Nicholson *et al.*, 2013). This disturbing difference in the trends of minimum and maximum temperature changes is attributed to global warming (Cleaveland ,2016), resulting from rising greenhouse gases, just like other climate change drivers (like carbon dioxide), and raise both the minimum and maximum temperatures at the same rate (Gustafson *et al.*, 2017).

As observed by Zhou *et al.* (2010) the diurnal temperature range (DTR) cycle involves solar heating during the day and radiative cooling at night. In line with these findings, Wild *et al.* (2007) found a direct relationship between changes in DTR and surface solar radiation. Easterling *et al.* (2007) reported that a decrease in the DTR is influencing the global mean temperature. The DTR has decreased because the minimum temperatures have been rising at a much faster rate than the maximum temperatures (Walther *et al.*, 2002; Easterling, 1997). The decrease in the DTR influences the growth of crops. Maize grows optimally in areas with average daily temperatures of 19–28 ºC (Butterfield *et al.*, 2017); at 20 ºC, maize can germinate rapidly, within five to six days. The critical temperature for maize is around 32 ºC (Du Plessis, 2003). Hawkins *et al.* (2013) found that, yield decreased as the days with maximum temperature above 32 °C increased in the last five decades. While in Sub-Saharan

Africa as temperature rise above 30 °C maize yield loss of between 1 to 1.7% was detected depending on water availability (Lobell *et al.*, 2011). All these findings have implications to crops and livestock farming which invariably have impacts on food security and socio-economic development at local and national scales.

2.3.1. Greenhouse Gases and Agricultural Production

While agricultural production is essential for the survival of humankind, it is one of the major contributors to the increases in GHGs (Tilman and Clark 2014). Vermeulen *et al.* (2012) estimated the contribution of food systems to global anthropogenic GHG to be between 19–29%. Thornton and Lipper (2013) gave this a higher estimate at 30-40% of the globe's anthropogenic GHG emissions. The United Nation's Food and Agricultural Organization (FAO) reported that there was a significant increase in GHG emissions from 2001 to 2011 (FAO, 2014). They further found that developing countries accounted for 14% of this increase attributed to the expansion of total agricultural outputs (FAO, 2014). This trend can be expected to continue. Smith *et al.* (2007) estimated that three-quarters of agricultural GHG emissions occur in developing countries, and they predicted that this share may rise to above 80% by 2050 largely due to agricultural expansion expected with the growth of the population (Smith *et al.*, 2007). This finding is substantiated by Marius (2009) who observed that with the increases in global population the food demand increases, and this is expected to subsequently increase the total GHG emissions from the agricultural sector.
Sources of indirect emissions include the runoff and leaching of fertilizers, emissions from land-use changes, as well as the use of fossil fuels for mechanization, transport, agro-chemical and fertilizer production (David and Lal, 2013). Deforestation also contributes to the indirect emissions of GHGs and it exacerbates global warming due to an immediate reduction in photosynthetic drawdown. The most significant indirect emissions are changes in natural vegetation and land use, which include deforestation and soil degradation (Yibekal *et al.*, 2013).

2.3.2. Fertilizer use and GHG emissions

Increases in fertilizer use will also translate into increases in greenhouse gas (GHG) emissions (Smith *et al.*, 2007). Fertilizers, agrochemicals and livestock by-products used for agricultural production are examples of direct emissions contributors. Despite the adaptive mitigation drives, it is difficult to curtail emerging trends of climate change (Waldman *et al.*, 2017). Other agricultural practices such as tillage, irrigation, continuous cropping and production of livestock feed also contribute to GHG emissions (Snyder *et al.*, 2009). South African agriculture accounts for utilization of 0.5% of fertilizers produced globally and 42% of fertilizer application goes to maize production (DAFF, 2015). Maize production accounts for 62% of the nitrogen based fertilizer produced in South Africa (FertASA, 2013). There is no provincial or municipality data available for fertilizer consumption based on a crop by crop basis (Cole *et al.*, 2017). There is no household field survey data for maize crop management for the Free State province (Beletse *et al.*, 2015). Fertilizer applications depend on the soil type, nitrogen use in the Free State ranges between 0.08 to 0.12 tons ha^{-1} and Phosphorus between 0.04 to 0.05 tons ha^{-1} (Beletse *et al.*, 2015).

Agricultural practice accounts for 50% of non-carbon dioxide emissions on global scales (World Bank report, 2008). Manure is rich in nitrogen and contributes to the buildup of GHG through the release of nitrous oxides emitted into the atmosphere (Faubert *et al.*, 2017). The release of nitrogen oxide from the decomposition of fertilizers used in crop production is a major source of GHGs, because of its longer persistence in the atmosphere than carbon dioxide; it can further undergo reduction processes (e.g. acid rain formation), which influence the biogeochemical cycles. Globally, agriculture contributes 58% of the total N_2O emission (Busari *et al.,* 2015), and it creates 4.5 million tons of nitrous oxide annually (IPCC, 2007).

2.3.3. Climate modelling

There is irrefutable evidence of global climate change, and its impacts are widely manifested across the world (IPCC, 2014). Climate modelling and statistical downscaling with recalibration methods are being used to produce high-resolution outcomes of regional projections of climate change (Maraun *et al.*, 2010; Rummukainen, 2010; Kim *et al.*, 2014). Engelbrecht and Engelbrecht (2016) demonstrated the use of dynamical downscaling projections of climate for South Africa, and Hewitson *et al.* (2014) used statistical methods for the regional climatic modeling. Other models, include the work on the conformal-cubic atmospheric model (CCAM) for climate modelling developed by the researchers at the Council for Scientific and Industrial Research (CSIR) of South Africa (McGregor, 2005; McGregor and Dix, 2008). Over the years CCAM has been used to study daily weather variability up to multi-decadal variations (Engelbrecht *et al.*, 2011). The CCAM projected the increased temperature as witnessed over southern Africa over five decades and the model predicted significant warming will occur during the 21st century (Engelbrecht *et al.*, 2015).

Most climate model projections of GHG, rainfall and temperature are not certain (Challinor *et al.*, 2007; Lobell and Burke, 2008). According to IPCC report (2014), temperature as well as rainfall variability are likely to increase. The use of rainfall as a crop yield estimator will be challenged in future (Landman *et al.*, 2017), because predicted increases in temperature will negatively affect soil moisture levels by the end of the century (Engelbrecht and Engelbrecht, 2016; Engelbrecht *et al.*, 2009a). According to Thornton *et al.* (2011), the future temperature conditions will be an important determinant of crop yield estimation for Africa.

Climate change increases the incidence of drought (Seneviratne *et al.*, 2012), thus aggravating the risk associated with agricultural systems. It is important to review and evaluate potential adaptation mechanisms by linking drought and climate change (Easterling *et al.*, 2007; Smit and Wandel, 2006). The agriculture sector is the economic sector worst hit by frequent drought occurrences. Drought reduces crop yield, and increases risk and production costs (Leu, 2015). This exerts financial stress on farmers; it also worsens poverty and hunger in rural areas (Al-Amin *et al.*, 2009). Therefore, finding ways to adapt to drought and other climate variability is important for food and nutrition security.

2.4. Climatic change and agriculture in Sub-Saharan Africa and South Africa

Human actions, including removal of land cover and deforestation are drivers of local and global environmental changes that also affects the biogeochemical cycles negatively (Matson *et al.*, 1999, Steffen *et al.*, 2005). These influences contribute to increasing greenhouse gas levels, which are further exacerbated by large scale intensive agricultural activities (Giorgi *et al.*, 2009; Xue, 1997). The study conducted by Diro *et al.* (2011) linked East African rainfall with the increasing temperature of the Pacific Ocean and cooling of the Western Indian Ocean. Aguilar *et al.* (2009), studied climate extremes in Southern and West part of Africa and they found that warm days have increased, and cold days have decreased from 1952-2003. They also found that the rainy season in southern Africa is shortening. Ahmed *et al.* (2013) reported an increase in temperature in Africa over the period of the 19^{th} to 20^{th} century, this increase was higher than the global temperature rises for the same period. Climate studies in southern Africa have long predicted that the region will get warmer and drier (Hulme *et al.*, 2001) and some recent studies have shown that this is already occurring. One such study is that of Russo *et al.* (2016); (IPCC, 2014) who reported that already the

African continent is experiencing longer duration of heatwave for the past 50 years. According to IPCC (2014) mean temperature of subtropical Africa has been rising twice as fast as the global rate of increase. Hence, both mean, maximum and minimum temperatures were expected to increase above the global average for African continent in 21st century (James and Washington, 2013; IPCC, 2014; Seneviratne *et al.*, 2016).

A decrease in the annual total rainfall has been reported in some parts of Southern Africa like Zimbabwe and eastern parts of South Africa. For instance, Hulme (1992) reported a rainfall decrease of about 5% in southern Africa, while Hulme *et al.* (2001) showed a rainfall decrease of between 5% and 15% for the region. These results suggest a significant change in the mean annual rainfall (Fauchereau *et al.,* 2003a). However, this change is associated with an increase in the frequency of intense rainfall events and a decrease in the number of rain days (Fauchereau *et al.,* 2003b). Since rainfall patterns affect the distribution and functioning of plants and animals (Russo *et al.*, 2016) such changing rainfall patterns and distribution need to be well understood. The Southern Oscillation and the Southern Hemisphere are predominantly found in the north-eastern half of South Africa (Kruger, 1999). The Southern Oscillation cycle occurs in every 10-12-years (Tyson *et al.*, 1975). Understanding such rainfall cycles helps to strengthen the resuls of the predictive modelling for the frequency of floods and tropical cyclones (Malherbe *et al.*, 2014), and is important, especially in predicting the occurrence of multi-year droughts. Giugni *et al.* (2015) proposed that increased atmospheric CO_2 concentrations are the cause of the rise of mean winter surface temperatures. This in turn is resulting in decreased rainfall in the south-Western Cape, while total rainfall on the eastern coast of South Africa is increasing (Engelbrecht *et al.*, 2009b).

2.5. Maize production in South Africa

Maize (*Zea mays* L**.**) is the most common staple crop used in Sub-Saharan Africa (Fantaye *et al.*) (Hansen *et al.*, 2011). It is a dominant component in the diets of most households in the region, and it is a carbohydrate used as a good source of energy. On average a decreasing trend of 10-20% in maize production has been projected by 2050 for the tropics as a result of climate change (Jones and Thornton, 2009). Southern Africa is prone to extreme climatic conditions affecting crop yields (Collier *et al.*, 2008). Maize is an important staple food crop and the environments in which it is found growing are prone to high temperature anomalies (Lobell and Burke, 2010). Maize grows optimally between (13–28°C) (Muchow *et al.*, 1990).

Lobell and Asner (2003) found that maize and soya bean yields decreased by 17% in the USA with every unit (°C) of temperature increase.

CHAPTER 3: STUDY AREA AND METHODOLOGY

This chapter is divided into several sections and subsections: The first section describes the study area for this study, while the second section describes the data acquisition and the selection of the weather stations used for this study. The third section details the management of missing data, using one approach, for temperature (the UK traditional method, used in semi-arid areas for giving a better estimate of missing temperature data) and another approach for the rainfall (the modified inverse distance weighting method IDWm). Section four explains the different methods used for the analysis of climatic trends in detail under the subsections of 'the Mann Kendal, non-parametric statistical test and the 'Sen's slope estimator'. The combined use of these two approaches has been shown to produce the most robust climatic trends. Prior to the use of the MK, a pre-Whitening test was conducted in order to investigate the serial correlation that may exist in the time series. The final sections (3.5 and 3.6) are on the climate and yield variables using the Pearson correlation analysis.

3.1 Study Area

The Setsoto Municipality falls under the administrative district of Thabo Mofutsanyane in the Free State province (Figure 3.1). This study is conducted in the Setsoto municipality which has a total area of about 5948.35 km^2 (Figure 3.1). The seasonal rainfall usually starts from October and ends in April but more than 80% of the rainfall occurs from October to March (Moeletsi *et al.*, 2013; Moeletsi and Walker, 2012). The soil type is shallow, loamy soil with moderate water holding capacity (Hensley *et al.*, 2006). Soil degradation and overgrazing are prominent environmental problems which have not received adequate research attention (Buso, 2003). Agriculture contributes about 18% of the economy in the Setsoto Municipality, but this amount is declining due to a high variability of rainfall and degrading environmental conditions Specific information on land and environmental issues is scarce at the municipal level but available at the district (Thabo Mofutsanyana) and provincial (Free State province) levels. The average rainfall of Thabo Mofutsanyana is 600 mm per annum (Beletse *et al.*, 2015). The province has the highest number of farming units in South Africa (Landbou, 2010; DAFF, 2013) with the vast, fertile and arable lands of the province producing significant proportions of the nation's agricultural produce which includes over 35% of the maize, 35% of the wheat, 53% of the sorghum, 45% of the sunflowers, 33% of the potatoes, 32% of the groundnuts, 26% of the dry beans, 24% of the wool and almost 90% of the country's cherries (DAFF, 2013).

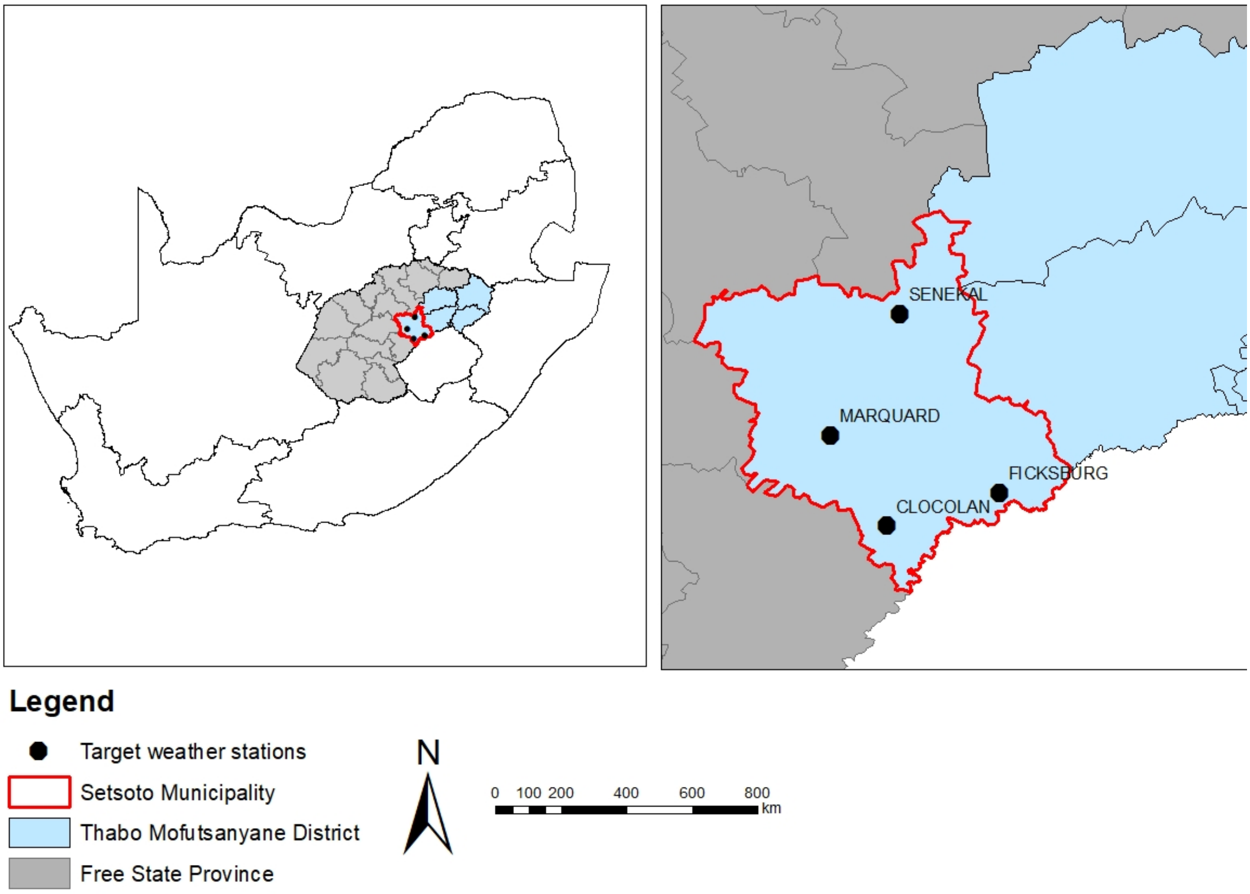

Figure 3.1: Map of the Free State province of South Africa showing the locations of the study area, the Setsoto Municipality and the target weather stations.

3.2 Data acquisition

The daily maximum and minimum temperature data for the study area were obtained from the Agricultural Research Council (ARC) meteorological database and the South African Weather Service (SAWS). The daily rainfall data for the period 1985-2016 were obtained from SAWS and ARC. In this study, an agricultural year is defined from July to June of the preceding year. This allows the presentation of the growing period from October to April of the following year as a continuous record. The missing rainfall, Tmin and Tmax data are less than 10% which satisfies the world meteorological organization (WMO) criteria for a robust climatic data analysis.

Maize yield data (tons ha^{-1}) for the Setsoto municipality) for the period between 1985 to 2016 were obtained from the South African Department of Agriculture, Forestry and Fisheries

(DAFF). There was however, no complete set of available data for the area under cultivation for the study period. Yield data for Ficksburg is from 1985-2005 only. However, this study period is between1985-2016. Most of the statistical analysis was computed using quantum XL 2016 and JASP 0.9.0.1 statistical software.

3.2.1. Selection of Target Stations

The study area included the weather stations in Clocolan, Marquard, Senekal and Ficksburg, which were selected as the target stations based on their spatial location. Ficksburg and Clocolan are found the South East and South Western part of Setsoto municipality whereas Senekal is located in North Eastern part of Setsoto while Marquard is in the central part of the municipality. However, availability of weather stations and completeness of data play important roles in the selection of the target stations. If the target stations had missing data, it was necessary to select neighbouring stations. These neighboring stations were selected based on their availability of data and proximity to the target stations. Table 3.1 shows the target weather stations and neighbouring stations used for the estimation of missing data and their characteristics.

Table 3.1: List of weather stations used for this study with their longitudes, latitudes, elevation, duration of data availability and their data type (R for rainfall and T denotes both the minimum and maximum temperature).

	Weather station	Latitude	Longitude	Elevation (m)	Data Type	Data period (years)
1	Senekal-AGR	-28.32200	27.6200	1433	R	40
2	Ficksburg	-28.82700	27.9040	1628	R&T	32
3	Marquard	-28.66500	27.4250	1497	T&R	40
4	Clocolan	-28.92108	27.5840	1602	R&T	26
5	Senekal-Driepan	-28.38900	27.5865	1587	R&T	21
6	Paul Roux	-28.29900	27.9480	1569	R	39
7	Rosendal	-28.5000	27.9167	1676	R&T	20
8	Lambertianin	-28.8200	27.5820	1646	R	32
9	Uintjieshoek	-28.5830	27.5200	1600	R	21

3.3. Management of missing data for temperature and rainfall

The UK method was selected for the infilling of daily Tmax and Tmin because of the technique's ability to accommodate the differences in altitude and its local effects (Xia *et al.*, 1999; Moeletsi, 2013). For example, missing temperature data (Tmax or Tmin) for any day in October (in any year) at the Senekal-AGR weather station was calculated by first calculating the divergence factors, for the month of October, for each of the neighboring stations (Senekal-Driepan and Marquard), these two divergence factors were then added to the observed values of that particular day in October for the stations of Senekal-Driepan and Marquard. These two values were then averaged and were used as the value in Senekal for that day in October. The divergence factor is calculated by taking the difference of the mean October temperature of the time series of the two neighboring stations with the target station, which is the station with missing data (Firat *et al.*, 2012). This procedure was repeated for each day for which there were missing data.

Rainfall missing data were estimated using the modified Inverse Distance Weighting method (IDWm), this was to accommodate the influence of elevation on rainfall (Golkhatmi *et al.*, 2012; Viale and Garreaud, 2015). The differences in the elevation between the neighboring and the target stations are used in the estimation of the missing rainfall values (Barrios *et al.*, 2018). The difference in the elevation modifies the conventional IDW method by highlighting the importance of nearby stations with similar elevations. This method is simple to apply, and it has been used by many other researchers (Golkhatmi *et al.*, 2012; Kanda *et al.*, 2018; Wang and Zou, 2018).

3.4. Methods used for climate trend analysis

In this study, the non-parametric Mann Kendall test (Sneyers, 1991) was used for the detection of significance in the climate trends, because the climatic data were not independent and normally distributed. The free and open software package developed by the Finnish Meteorological Institute (MAKESENS) was used for the Mann Kendall test and Sen's slope estimator. The Sen's slope estimator allows for the significance of the trend to be analyzed. The MK test is robust, simple and frequently used in climate, environmental and hydrological studies (Bandyopadhyay *et al.*, 2016; Ewert *et al.*, 2015; Hulme, 1992; Mahony and Hulme, 2016; Pablos *et al.*, 2017).

The seasonal trends for Tmin, Tmax and Rainfall during the growing period with yield data are determined using a linear regression model. It has been suggested that before applying Mann Kendall trend analysis and Sen's slope estimator, a pre-whitened test, to test for serial correlation, should be conducted (Latif *et al.*, 2018).

3.4.1. Serial Correlation

Von Storch (1999) suggested the use of the pre-whitening procedures to eliminate the effects of serial correlation before applying the Mann Kendall test to a time series. These procedures were implemented as described below for the computation of the lag-1 for serial correlation assigned by r1. The coefficient r1 of data x can be determined:

$E_{(xi)} = 1/n\sum_{i=1}^{n} xi$.. As suggested by Kendall and Stuart (1968) and Salas *et al.* (1980)

1. If the trend in r1 is not significant at 5% then the MK and Sen's slope estimator must be applied. If the calculated r1 is significant, then the critical r1 value must be obtained by applying the pre-whitening time series computed as ($x2-r_1x_1$, $x_3-r_1x_2$, …, $xn-r_1 x_{n-1}$) before using the MK and Sen's slope estimator.

2. If the critical value of r1 is greater than zero, then a one-tailed probability is calculated in order to find the significance and if r1 is less than zero then a two-tailed probability is conducted.

3. The probabilities are computed based on the work of (Anderson, 1942; Salas, 1980). In the case of positive autocorrelations a one tailed or two-tailed test was used (Gocic and Trajkovic, 2013).

3.5. Evaluation of Maize Yield Anomalies and correlation with Climate Variables

The Pearson correlation coefficient which has proven to be an appropriate method for gaining insights into this type of study (Milošević *et al.*, 2015) was used to determine the relationship between maize yield and climatic variables for the months of the growing period, October to April. To investigate the correlations between monthly climate and crop yield, Tmin and Tmax anomalies and rainfall anomalies were correlated with detrended yield values to investigate the impacts of agroclimatic variables on maize production for the period of the study. Detrended yield values were used in order to prevent autocorrelation and to minimize the potential of finding an effect which may not be valid and only the growing months (October-April) were used. The Vovk-Sellke Maximum p –Ratio (VS-MPR) was then applied to the Pearson correlation output to obtain the statistical significance of the values.

3.6.1 Rainfall Onset, Cessation and Duration

Rainy days are used to determine the rainfall onset and cessation (Herrero *et al.*, 2010), and the length of the rainy season is the difference between the onset and cessation. Rainfall onset and cessation are important variables that influence crop yields (Kabanda and Nenwiini, 2016; Shaw, 1988), as are the dates of onset of the growing periods. There are several different ways to calculate the onset of the rains (Kabanda, 2016; Stern, 1981; Taye, 2012). In this study, the onset of a growing season is taken as the period after September 1 when the sum of the rainfall within at least two consecutive days is more than 25mm, and with no dry days exceeding 10 days in the following 30 days. This conforms to the widely used benchmark for the determination of onset for rain-dependent maize production in most of southern Africa's semi-arid region (FEWSNET, 2009; SADC–RRSU, 2004). Conversely, the end of a growing season is determined by the availability of soil water stored when the rain stops.

CHAPTER 4: RESULTS

In this chapter, the results are split into nine sections. The first five sections dwell on monthly variation of minimum temperature, maximum temperature, and the variation of the Tmin and Tmax during the growing period with their descriptive statistics. Section four and five are on rainfall distribution in Setsoto during the growth period and maize yield across the municipality. Section six is about the climate trends data quality checks for autocorrelation prior the Mann Kendall test and the Sen's slope estimator for both Tmin, Tmax and rainfall trends detections. Section seven is on the implementation of Mann Kendall test, and Sen's slope estimates for the variable's analysis. Section eight is on the correlation between the detrended yield and Tmin, Tmax and rainfall anomalies across the Setsoto municipality. The last section deals with the rainfall characteristic of Setsoto, among which are the rainfall onsets, cessations and duration.

4.1. Monthly variation of minimum temperature (Tmin) during the growing period

The mean monthly minimum temperature was analyzed for the entire data set, 32 years and four target stations. The mean monthly minimum temperature in October was between 7.9 °C and 12.2 °C. Senekal and Ficksburg recorded the lowest Tmin of 1.7 °C for the month of October, while the highest Tmin of 15.4 °C was recorded in Clocolan. November mean monthly minimum temperatures were between 10.0 °C and 12. 5 °C with the lowest Tmin (2.3 °C) being recorded in Ficksburg and the highest (17.2 °C) in Clocolan (Table 4.1). The December mean monthly minimum temperature increased by 2 °C across the stations ranging between 12.3 and 15.5 °C. The lowest Tmin recorded was 2.0 °C in Ficksburg and the highest was 18.5 °C in Clocolan (Table 4.1). The lowest minimum temperature recorded for Ficksburg was 2.6°C in January in and the highest for the same month was 19.0 °C at Clocolan. The mean monthly minimum temperature ranged from 13.1 °C in Ficksburg to 16.5 °C in Clocolan. The values were similar for all the stations except for Ficksburg and Clocolan, where the lowest record Tmin of 1.4 °C and the highest Tmin of 19.9 °C were recorded in the month of February, respectively, the mean monthly minimum temperature across the different stations ranged from 12.2 °C to 15.9 °C. The lowest Tmin of 2.1°C was recorded in March in Ficksburg and the highest Tmin of 18.6 °C for the same month was recorded in Clocolan. The mean monthly minimum temperature ranged from 10.3 °C to 14.3 °C. There was a decrease of 2°C in the minimum temperature from February to March (Table

4.1). The mean monthly minimum temperature in April ranged from 5.9 °C to 10.7 °C. The lowest Tmin recorded was 0.0 °C in Marquard and the highest was 18.6 °C in Clocolan.

Table 4.1: Monthly minimum temperature (Tmin in °C) for Marquard, Clocolan, Ficksburg and Senekal weather stations (Descriptive Statistics in Setsoto Municipality for the period between 1985 and2016).

Results	Marquard				Clocolan				Senekal				Ficksburg			
	Mean	SD	Lowest	highest	Mean	SD	Lowest	highest	Mean	SD	Lowest	highest	Mean	SD	Lowest	highest
Oct	10.1	1.7	7.3	13.4	12.2	3.2	6.3	15.4	9.5	1.8	1.7	12	7.9	2.6	1.7	13.4
Nov	12.5	1.7	8.8	15.3	13.9	2.8	8.7	17.2	11.4	1.6	4.2	14.2	10	2.1	2.3	13.5
Dec	14.3	1.1	12	16.7	15.5	1.8	12.4	18.5	13.6	1.1	8.4	15.7	12.3	2.6	2	16.6
Jan	14.8	0.8	12.9	16.3	16.5	1.6	13.5	19	15	0.6	13.8	16.3	13.1	2.6	2.6	15.5
Feb	13.4	1.5	10.2	16.9	15.9	1.9	10.6	19.9	14.5	1	11.5	16.2	12.5	2.8	1.4	16.7
Mar	10.3	2.8	4.9	14.8	14.3	2.5	9.9	18.6	12.5	1.1	10.1	15.2	10.7	2.3	2.1	13.8
Apr	5.9	3.1	0.0	10.1	10.7	2.7	4.5	15	7.9	1.3	5.3	10.1	6.5	1.8	2.4	11.5

4.2 Monthly variation of maximum temperature (Tmax) during the growing period

The mean monthly maximum temperature in October ranged from 24.7 °C to 28.3 °C. The lowest recorded was in Ficksburg at 20.8 °C and the highest was in Marquard at 30.3 °C. The monthly mean temperature for November ranged from 25.5 °C to 29.6 °C whilst the mean monthly temperature in December was between 26.9 °C and 29.9 °C, the Tmax has an increase of 1 °C since November. The lowest recorded Tmax in Ficksburg for the two months (November and December were 20.8 °C but the highest of Tmax of 35.5 °C was in Clocolan. The mean monthly maximum temperature for January ranged from 27.5 °C recorded in Ficksburg to 30.6 °C in Clocolan. Marquard and Senekal recorded monthly maximum temperatures of 29.1°C and 29.5 °C, respectively. The Clocolan area is on the western side of the municipality. The maximum temperature in January did not exceed 36.0 °C (Table 4.2). The spatial distribution of mean monthly maximum temperatures for February was similar to the January temperatures across the stations. The difference between them was only less than 0.6 °C the highest recorded Tmax was 37.7 °C for Clocolan while the mean Tmax ranged from 26.7 °C to 29.6 °C. The mean maximum temperatures in the month of March ranged from 25.3-27.8°C. There was a decrease 1.7 °C from the previous month of February across the Setsoto municipality (Table 4.2). However, the mean maximum temperature in the month of April ranges between 22.4 °C to 24.2 °C. The highest recorded monthly Tmax in the month of April is 29.5 °C at the Clocolan station and the lowest is 17.6 °C also in Clocolan (Table 4.2).

Table 4.2: Monthly maximum temperature °C for Marquard, Clocolan, Ficksburg and Senekal Descriptive Statistic in Setsoto Municipality for the period between 1985 and 2016.

Results	Marquard				Clocolan				Senekal				Ficksburg			
	Mean	SD	Lowest	highest	Mean	SD	Lowest	highest	Mean	SD	Lowest	highest	Mean	SD	Lowest	highest
Oct	26.1	1.8	22.5	30.3	28.3	3.2	22.4	33	26	1.8	22.3	29.9	24.7	1.8	20.8	28.3
Nov	27.3	2	23.5	31.2	29.2	3.4	23.4	35	27	1.8	23.5	31	25.5	2	20.8	29.6
Dec	28.7	1.9	24.7	33.8	29.9	3.1	24.8	35.5	28.7	1.8	24.7	33.8	26.9	2	23.2	32.4
Jan	29.1	1.9	25.1	33.9	30.6	2.8	25.1	36	29.5	2.3	26.2	35.2	27.5	1.8	23.6	33
Feb	28.2	2	23.9	33	29.6	3.2	22.4	35	28.5	2.6	23.9	37.7	26.7	2.1	20.5	30.5
Mar	26.5	1.4	23.8	29.7	27.8	3.3	21.6	34.2	26.3	1.5	23.8	29.7	25.3	1.8	22.3	33
Apr	23.4	1.7	20.5	26.3	24.2	3.1	17.6	29.5	23.2	1.7	20.5	26.2	22.4	1.5	19.9	26.4

4.3. Variation in the minimum and maximum temperatures during the growing period (October-April)

The range of the average mean Tmin was from 10.4 ℃to 14.2 ℃and for Tmax 25.6 ℃to 28.6 ℃(Table 4.3). The lowest observed Tmin of 5.6 ℃and the Tmax of 22.1 ℃were found in Ficksburg. The highest Tmin and Tmax recorded during the growing period in Clocolan were 16.4 ℃and 31.2 ℃, respectively. The CV of the Tmin and Tmax was between 5.8% to 16.0% and 3.8% to 8.3% respectively (Table 4.3).

Table 4.3: Mean, minimum, maximum, SD and CV (%), Growing period for the minimum and maximum temperatures.

	Tmin				Tmax			
	Marquard	**Clocolan**	**Senekal**	**Ficksburg**	**Marquard**	**Clocolan**	**Senekal**	**Marquard**
Mean	11.6	14.2	12.1	10.4	27.1	28.6	27.7	11.6
lowest	10.0	9.9	9.4	5.6	24.7	24.1	25.1	10.0
Highest	13.4	16.4	13.4	13.9	29.5	31.2	30.4	13.4
SD	0.7	2.1	0.7	1.7	1.1	2.4	1.1	0.7
CV	6.2	14.9	5.8	16.0	4.0	8.3	3.8	6.2

4.4. The growing period and annual rainfall from 1985 to 2016

The average rainfall for the growing period in Setsoto ranged from 540.71 mm to 632.38 mm with the CV ranging between 29% and 21% (Table 4.4). Ficksburg had the highest rainfall during the growing period (1154.10 mm) and Marquard had the lowest rainfall (204.10 mm). The patterns of rainfall variations of the growing period were similar between Senekal and Marquard and Clocolan and Ficksburg with only observed differences of about 3% between them. The rainfall of the growing period accounts for approximately 88% of the annual rainfall (Table 4.4).

Mean annual rainfall over Setsoto municipality ranged from 613 mm to 718 mm (Table 4.4). The summer months from October to April account for most of the annual rainfall in the municipality. The highest annual rainfall values observed were in Ficksburg with 1224 mm (Table 4.4). The lowest value ranged from 259 mm to 397 mm. Low annual rainfall below (613 mm) can be found in all part of the municipality. Clocolan and Ficksburg have annual rainfalls of above 670 mm while Senekal and Marquard mean annual rainfall above were 600 mm. The CV of annual rainfall was very high ranging from 34to 45(Table 4.4).

Table 4.4: Rainfall (mm) during the growing period October-April (mean, minimum, maximum, standard deviation and coefficient of variation) in Setsoto Municipality (1985-2016).

Stations	Average rainfall in growing period (mm)					Annual rainfall (mm)				
	Mean	**Min**	**Max**	**SD**	**CV**	**Mean**	**Min**	**Max**	**SD**	**CV**
Marquard	540.7	204.1	969.5	158.5	29	613.4	259.1	1029.7	178.2	34
Clocolan	593.2	329.6	888.7	122.9	21	677.1	386.5	1074.9	149.4	45
Senekal	569.9	310	952	149.9	26	645	386.8	1019.2	167.4	39
Ficksburg	632.4	359.2	1154.1	151.4	24	718.1	397.6	1224.1	168.8	43

4.5. Descriptive statistics for maize yield

The average maize yield for Setsoto from 1985 to 2016 ranged from 1.96 tons ha^{-1} to 2.89 tons ha^{-1}. The highest maize yield achieved during the study period from 1985 to 2016 was in 2016 with 6.18 tons ha^{-1} in Clocolan, while the lowest was 0.10 tons ha^{-1} in 1991 in Senekal (Figure 4.1). The maize yield CV for Setsoto over this period was between 37.8%- and 46.2-tons ha^{-1} per annum, with a standard deviation of between 0.91 to 1.31 tons ha^{-1} across the municipality (Table 4.5).

Table 4.5: The average maize yield (tons ha^{-1}) for the four stations in Setsoto Municipality from 1985- 2016 used for this study.

Statistics	Marquard	Clocolan	Senekal	Ficksburg
Average	2.33	2.72	1.96	2.89
Min	0.47	0.64	0.10	0.85
Max	5.00	6.18	4.34	5.96
SD	0.98	1.03	0.91	1.33
CV (%)	41.93	37.75	46.19	46.21

The data set available for Ficksburg in this study was only for 20 years (1985-2005), as opposed to a data set of 32 years in the other three weather stations. Each station showed high inter-annual variation in yield. But all seem to overlap at least in the first few years (1985 to 1995). The yield in Ficksburg seems to show the highest inter-annual variation between 1995 and 2005 (Figure 4.1).

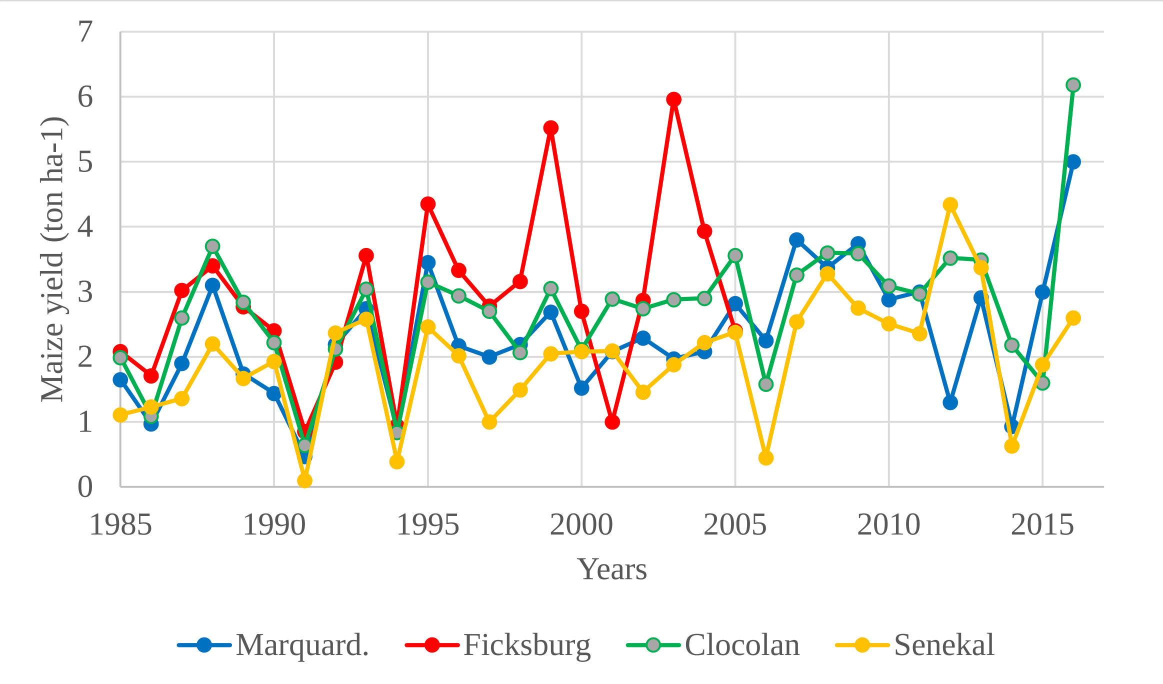

Figure 4.1: The annual maize yield (tons ha^{-1}) for the four stations in the Setsoto municipality from 1985 to 2016 used for this study.

4.6 Climate Trend Analysis

Serial Correlation of Minimum, Maximum Temperature and Rainfall (October-April)

The autocorrelation of Tmin and Tmax across the four stations in Setsoto were positively correlated except for the minimum temperature in Senekal with a value of -0.00332 which was not significant (Figure 4.2). The strongest autocorrelation for both Tmin (0.8772) and Tmax (0.877) was in Clocolan and the weakest autocorrelation for Tmin was in Senekal.

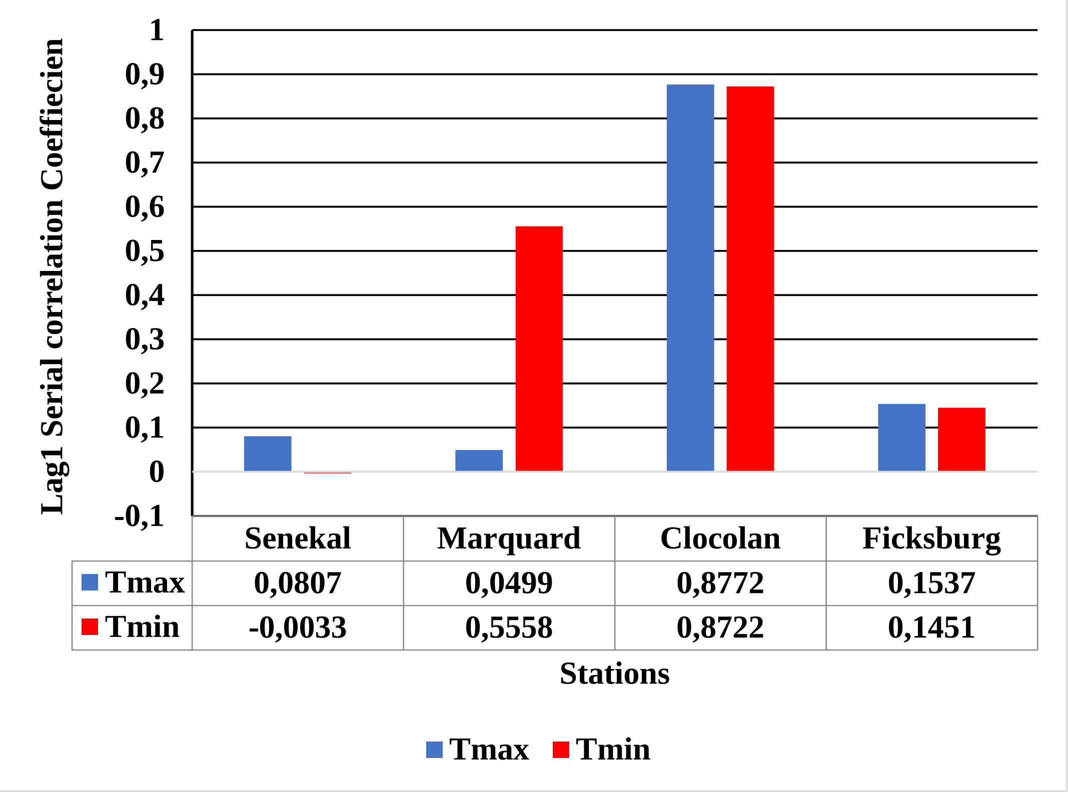

Figure 4.2: The Setsoto Lag-1 Autocorrelation for minimum and maximum temperatures.

The rainfall autocorrelation for Setsoto were negative for the period of the study except in Marquard station which was positively autocorrelated (Figure 4.3).

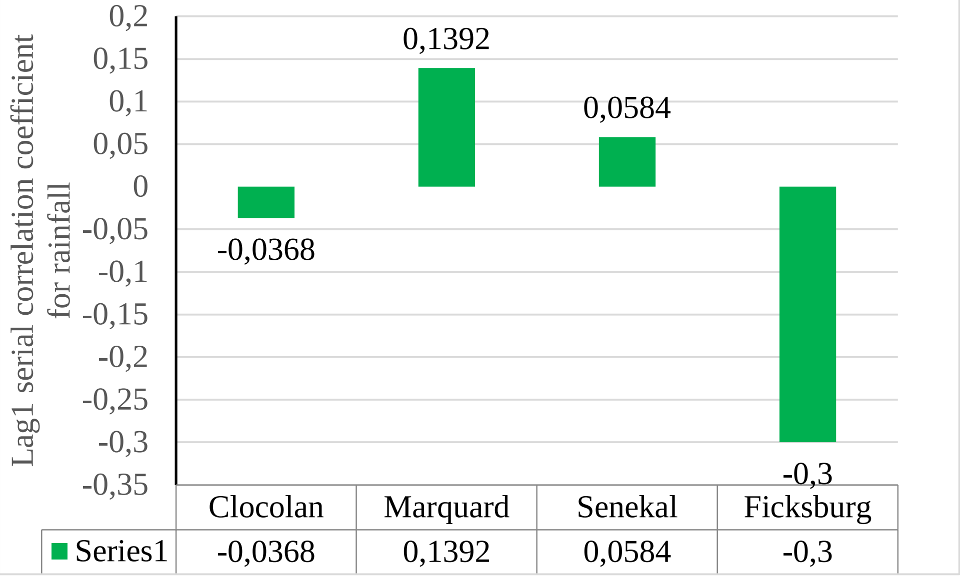

Figure 4.3: The Setsoto Lag-1 Autocorrelation for Rainfall.

4.7. The Trend in Climatic Variables analysis

4.7.1. Minimum and maximum Temperature Trends

The Mann Kendal non-parametric test for the detection of trend and the Sen's slope estimator on minimum and maximum temperature variables for the period of study from 1985 to 2016 are presented in Table 4.6 and 4.7. The Clocolan monthly and the growing period minimum temperatures showed a negative trend at the 0.001 significance except in the months of November and April which have a negative trend at the 0.05 significance level. The values of the Sen's slope are all less than zero (Table 4.6). In Senekal station the Tmin did not show any trend for the period of the study except for the month of January, where an increase of 0.02°C year^{-1} was reported, compared to the increasing trend of 0.05℃ per annum shown in Ficksburg at the 0.05 significance level. In Marquard station the Tmin trend showed a positive trend across the months in October, November and December at the rates of (an 0.09, 0.09 and 0.06) °C increase year^{-1} at respectively and the growing period at 0.01 significance level. The February, March, April and the growing period trends are negative with decrease of minimum temperatures of 0.1, 0.2, 0.25 and 0.05 °C year^{-1} (Table 4.6)

Table 4.5: Setsoto monthly growing period minimum temperature annual trends during the growing period from 1985-2016. MK trend (Test Z) and Sen's slope estimate (Q). NB: + denote significance when alpha =0.1, *** denote significance when alpha =0.001, ** denote significance when alpha =0.01 and * denote significance when alpha = 0.05

Months	**Marquard**			**Clocolan**			**Senekal**			**Ficksburg**		
	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2
OCT	**2.72***	0.09	0.25	**-3.5*****	-0.18	0.55	0.62	0.01	0	-0.05	0	0
NOV	**2.64***	0.09	0.25	**-2.47***	-0.15	0.35	-0.1	-0.01	0	-0.15	-0.01	0
DEC	**3***	0.06	0.36	**-3.61*****	-0.12	0.42	0.73	0.01	0.02	0.58	0.02	0
JAN	0.36	0.01	0	**-3.51*****	-0.12	0.43	**1.64***	0.02	0.1	**2.3***	0.05	0.1
FEB	**-3.71***	-0.1	0.34	**-3.34*****	-0.12	0.46	0.89	0.02	0.05	1.61	0.07	0.06
MAR	**-3.91***	-0.23	0.6	-3.57	-0.2	0.5	0.97	0.02	0.04	1.49	0.05	0.03
APR	**-4.25***	-0.25	0.61	-2.39	-0.15	0.35	-1.43	-0.04	0.06	0.84	0.03	0
GP	**-3.52***	-0.05	0.42	**-3.7*****	-0.14	0.42	1.39	0.01	0.01	1.51	0.03	0.03

In Clocolan in the March and April maximum temperature trend was decreasing by 0.16 and 0.14 ℃year^{-1} (at 0.05 significance level). In Senekal maximum temperature is increasing by 0.12 ℃in October at 0.001 significance. In November, maximum temperature increased by 0 .08 ℃year^{-1} (at 0.05 significance level) while during the growing period 0.05 ℃year^{-1} (at 0.05 confidence level). The trend of maximum temperature in Ficksburg maximum temperature increased in the months of November, February and March (0.10, 0.09 and 0.06) ℃year^{-1} (at 0.05 significance level). While in during the growing period maximum temperature increase by 0.04 ℃at 0.05 significance level. In October at 0.01 significance level the maximum temperature increased by 0.11 ℃year^{-1} (respectively). In Marquard, maximum temperature in October increase by (0.12, 0.80) ℃year^{-1} (at 0.01 and 0.1 significance levels while during the growing period maximum temperature increased by 0.04 ℃year^{-1} at 0.05 significance level (Table 4.7)

Table 4.6: Monthly Maximum Temperature (℃) and its annual trends during the growing period for the period 1985-2016. MK Test Z denote Mann Kendall trend analysis test, and Q denote 'the Sen's slope estimate' for the Setsoto municipality.

Months	**Marquard**			**Clocolan**			**Senekal**			**Ficksburg**		
	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2
OCT	**3.71****	0.12	0.4	-0.68	-0.05	0.02	**3.91*****	0.12	0.38	**3.02****	0.11	0.26
NOV	**1.9+**	0.08	0.11	-0.31	-0.03	0	**2.38***	0.08	0.15	**2.09***	0.1	0.14
DEC	0.76	0.04	0.04	0.13	0	0	0.44	0.02	0.03	1.52	0.06	0.12
JAN	0.26	0.01	0.01	-1.01	-0.04	0.02	-0.05	0	0.01	1.28	0.04	0.02
FEB	0.83	0.03	0.01	-1.1	-0.1	0.01	0.66	0.03	0.05	**1.96***	0.09	0.19
MAR	1.61	0.06	0.1	**-2.01***	-0.16	0.14	1.12	0.04	0.07	**2.5***	0.06	0.02
APR	1.1	0.05	0.03	**-2.11***	-0.14	0.06	0.7	0.04	0.01	-0.29	-0.01	0
GP	**2.38***	0.04	0.23	-1.23	-0.06	0.24	**2.29***	0.05	0.22	**2.12***	0.04	0.21

NB: + denote significance when alpha =0.1, *** denote significance when alpha =0.001, ** denote significance when alpha =0.01 and * denote significance when alpha = 0.05.

4.7.2 Rainfall Trends Analysis

The Mann Kendal non-parametric test for the detection of trend and the Sen's slope estimator on rainfall variables for the period from 1985 to 2016 are shown in Table 4.8. In all the stations used for this study only the month of January showed positive trend of increasing in rainfall for the Ficksburg station 2.34 mm $year^{-1}$ at a 0.05 significance level (Table 4.8).

Table 4.7: Monthly rainfall (mm) and its annual trends during the growing period from 1985-2016 for the Setsoto municipality. MK Test Z denotes Mann Kendall trend analysis test, and Q denotes 'the Sen's slope estimate'.

Months	**Marquard**			**Clocolan**			**Senekal**			**Ficksburg**		
	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2	Test z	Q	R^2
OCT	-1.44	-1.09	-1.38	-1.38	-1.38	0.049	-1.36	-1.00	-1.31	-1.31	-0.88	0.014
NOV	0.63	0.69	-0.68	-0.68	-0.41	0.002	-0.05	-0.08	-0.26	-0.26	-0.39	0.039
DEC	0.00	0.00	0.97	0.97	1.12	0.031	0.19	0.33	0.65	0.65	0.52	0.039
JAN	-0.02	-0.02	1.12	1.12	1.62	0.042	1.62	2.11	2.06	**2.06***	2.34	0.179
FEB	0.73	0.60	0.44	0.44	0.43	0.011	-0.78	-0.59	-1.04	-1.04	-0.69	0.011
MAR	-0.94	-1.05	-0.99	-0.99	-0.64	0.037	-0.58	-0.56	-0.41	-0.41	-0.46	0.033
APR	-1.09	-0.74	-1.09	-1.09	-0.46	0.005	-0.10	-0.05	-0.44	-0.44	-0.45	0.134
GP	-1.36	-3.22	0.05	0.05	0.11	0.002	0.19	1.05	0.21	0.21	0.55	0.027

NB: + denote significance when alpha =0.1, *** denote significance when alpha =0.001, ** denote significance when alpha =0.01 and * denote significance when alpha = 0.05.

4.7.3 Maize Yield Trends

There were positive annual increasing trends for maize yield in Marquard and Clocolan stations by 0.05- and 0.039-tons ha^{-1}. In Senekal, maize yield showed an increasing trend of 0.043 tons ha^{-1} which was significant at 0.05 confidence level (Table 4.9).

Table 4.8: Annual maize yield trends during the study period from 1985-2016. MK Test Z denotes Mann Kendall trend analysis test, and Q denotes 'the Sen's slope estimate'.

	Test Z	Q	R^2
Marquard	**2.76****	0.050	0.218
Clocolan	**2.45****	0.039	0.196
Senekal	**2.92***	0.043	0.183
Ficksburg	1.27	0.054	0.119

+ denote significance when alpha =0.1, *** denote significance when alpha =0.001, ** denote significance when alpha =0.01 and * denote significance when alpha = 0.05.

4.8. Maize Yield Correlation with Climatic Variables

The minimum and maximum temperature anomalies and rainfall anomalies are calculated to allow a valid interpretation of those factors which may be correlated with maize yields, which may not only be climatic variables.

4.8.1 Minimum and maximum Temperature anomalies

The data in figure 4.4 show the number of occasions in which the minimum temperature is either above or below the mean across the years. Fluctuations in Tmin are more pronounced in Ficksburg with the greatest negative anomalies in 1987 and 2001 (Fig 4.4).

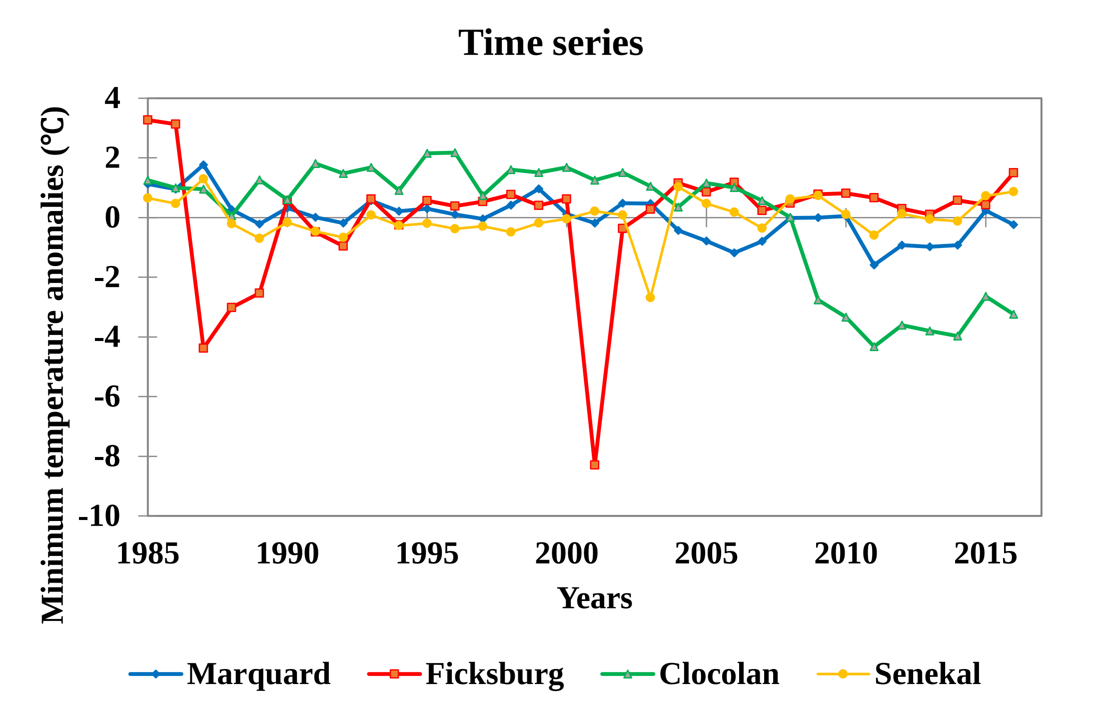

Figure 4.4: Minimum temperature anomalies for the four stations in the Setsoto Municipality of Free State Province from 1985 to 2016 used for this study.

The Tmax anomalies for Clocolan were above the baseline throughout the period of the study. It steadily increased between 1987 and 2004 and was then unstable till 2016. The declining trend was -0.0742 per annum, but still above the baseline. The Tmax at the other target stations-maintained a rising degree profile above the baseline with many variations (Figure 4.5).

.

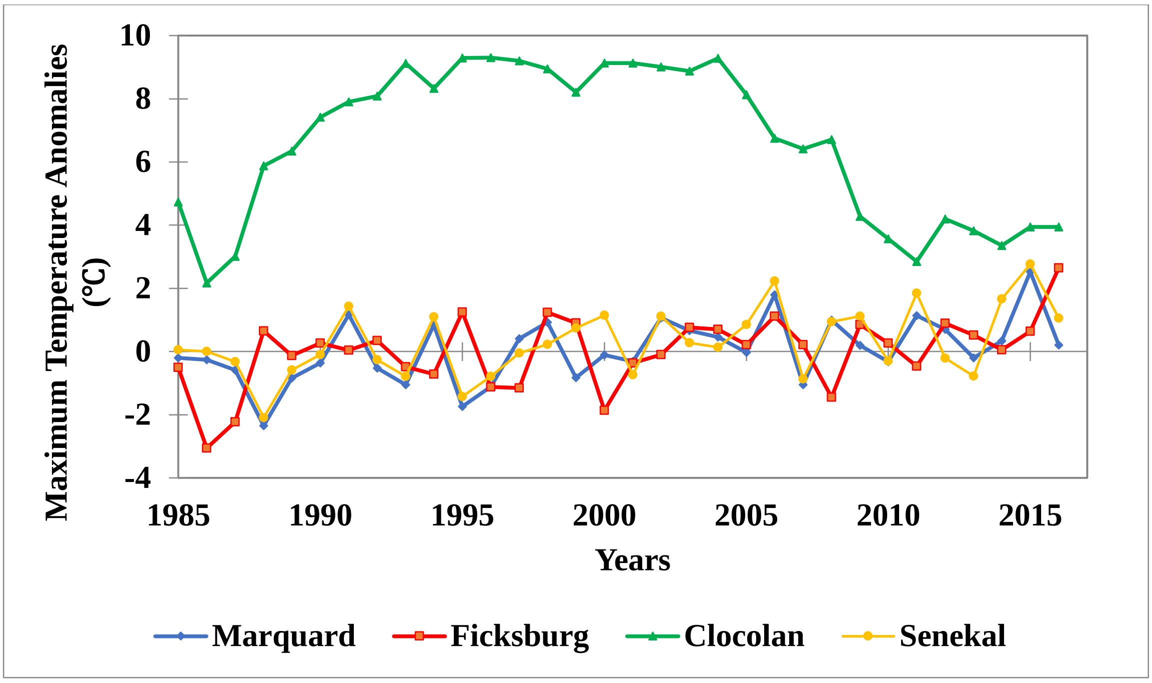

Figure 4.5: Maximum temperature anomalies for the four stations in the Setsoto Municipality of Free State Province from 1985 to 2016 used for this study.

The general trend of rainfall in Setsoto showed no significant difference between the different stations. The rainfall anomalies showed values below the baseline (zero value) accounting for more than 60% of the study period. In 1991, 1994, 2011 and 2015 lower rainfall anomalies were recorded (Figure 4.6), while the year 1996, 2006 and 2010 showed the highest positive rainfall anomalies (Figure 4.6).

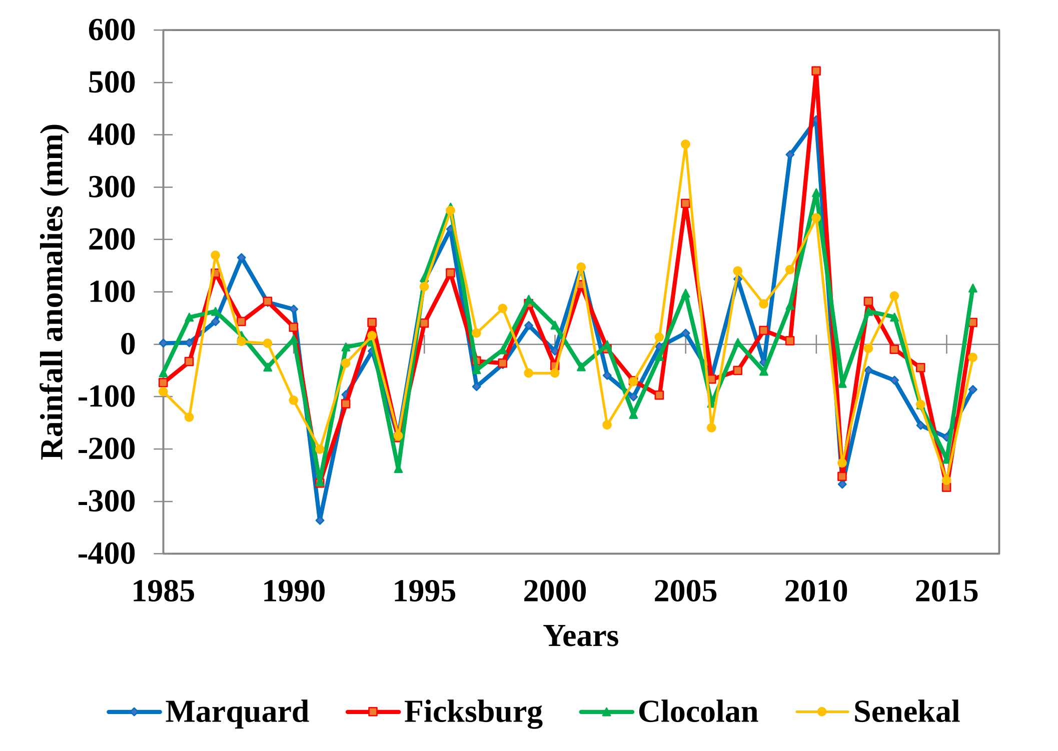

Figure 4.6: Rainfall anomalies for the four stations in the Setsoto Municipality of Free State Province from 1985 to 2016 used for this study.

4.8.2 De-trended Maize Yield correlation with rainfall, minimum and maximum Temperature anomalies

The Pearson correlation coefficient (r) and confidence interval levels of 0.05, 0.01 and 0.001 were used in this study to determine the relationship between yield and agroclimatic variables. Rainfall was positively correlated with yield during the growing period in Clocolan and with Tmax in Senekal (r = 0.46 and 0.48 respectively) (P = 0.008 and 0.0005 respectively) (Table 4.10). There was no correlation for the monthly or the growing period Tmin in any of the target stations. In November, only the Tmin in Marquard correlated with yield (r = 0.39, P < 0.027 and VS-MPR = 3.73). During the month of January, the yield in this station positively correlated with Tmin (r = 0.37 and P = 0.038 at 0.05 confidence level).

The Tmax in February was correlated with yield negatively in Marquard and positively in Senekal (r = -0.49 and 0.657; P = 0.005 and < 0.001' and VS- MPR = 14.709 and 835.835, respectively) at 0.01 and 0.001 confidence levels, respectively. Similarly, the rainfall in February was correlated with yield positively in Marquard (r = 0.42, P = 0.018, VS-MPR = 5.194) at 0.05 confidence level. There was also a strong correlation between them in

Clocolan ($r = 0.69$, $p < 0.001$ and VS-MPR = 2118.11), while in March, the Tmax in Senekal showed a positive correlation ($r = 0.4512$, $P = 0.003$, VS- MPR = 22.64) at 0.01 confidence level with yield (Table 4.10). There was no any correlation between yield, and Tmin or Tmax for the months of October, December and April during the period of this study.

Table 4.9: The correlation matrix for the monthly and growing period Tmin, Tmax and Rainfall variables with Maize yield in the three stations (the fourth station, Ficksburg, lacks sufficient data for analysis) of the Setsoto municipality from 1985-2016 (* P < 0.05, ** P < 0.01, *** P < 0.001). GP denotes growing period.

		Marquard			**Clocolan**			**Senekal**		
		Pearson's r	p-value	VS-MPR⁺	Pearson's r	p-value	VS-MPR⁺	Pearson's	p-value	VS-MPR⁺
GP	Tmin	0.03	0.87	1.00	0.12	0.52	1.00	0.02	0.90	1.00
	Tmax	-0.18	0.33	1.01	0.12	0.51	1.00	**-0.40***	0.02	4.43
	Rainfall	0.03	0.86	1.00	**0.46****	0.01	8.97	0.23	0.20	1.14
OCT	Tmin	0.07	0.69	1.00	-0.12	0.52	1.00	-0.03	0.89	1.00
	Tmax	0.06	0.74	1.00	0.02	0.93	1.00	-0.02	0.93	1.00
	Rainfall	0.01	0.95	1.00	0.22	0.24	1.08	0.15	0.40	1.00
NOV	Tmin	**0.42***	0.02	5.69	0.04	0.84	1.00	0.07	0.69	1.00
	Tmax	0.07	0.73	1.00	0.07	0.70	1.00	0.08	0.69	1.00
	Rainfall	-0.08	0.67	1.00	0.11	0.55	1.00	0.18	0.32	1.01
DEC	Tmin	**0.42***	0.02	5.69	0.05	0.80	1.00	-0.05	0.78	1.00
	Tmax	0.09	0.61	1.00	0.23	0.20	1.14	-0.09	0.62	1.00
	Rainfall	-0.04	0.83	1.00	-0.18	0.33	1.01	-0.05	0.80	1.00
JAN	Tmin	0.37	0.04	3.04	-0.22	0.23	1.10	0.25	0.16	1.24
	Tmax	-0.35	0.05	2.38	-0.02	0.90	1.00	**-0.37***	0.04	2.95
	Rainfall	0.05	0.77	1.00	0.22	0.23	1.09	0.25	0.17	1.22
FEB	Tmin	-0.07	0.71	1.00	0.15	0.42	1.00	0.20	0.28	1.03
	Tmax	**-0.51****	0.00	19.83	0.13	0.49	1.00	**-0.42***	0.02	5.43
	Rainfall	**0.45***	0.01	7.64	**0.68*****	< .001	2118.11	0.17	0.34	1.00
MAR	Tmin	-0.20	0.27	1.04	-0.28	0.13	1.40	0.02	0.93	1.00
	Tmax	-0.03	0.87	1.00	-0.09	0.63	1.00	**-0.47****	0.01	11.76
	Rainfall	-0.19	0.29	1.03	0.00	0.99	1.00	-0.12	0.51	1.00
APR	Tmin	-0.15	0.41	1.00	-0.08	0.67	1.00	-0.20	0.27	1.04
	Tmax	0.03	0.86	1.00	0.00	1.00	1.00	-0.17	0.36	1.00
	Rainfall	-0.16	0.38	1.00	-0.19	0.29	1.02	0.07	0.69	1.00

The maize yield in Setsoto showed a positive trend of increase in maize yield in Setsoto municipality. The years with yield that were below the average 1986, 1987, 1989-92, 1997-1999 1991 and 1993 in all the station used for this study. Yield in Senekal decreased to the lowest in 2006 and declining sharply in 2014 along with that of Marquard. The y continuously above means from 2006 to 2012 (Figure 4.7).

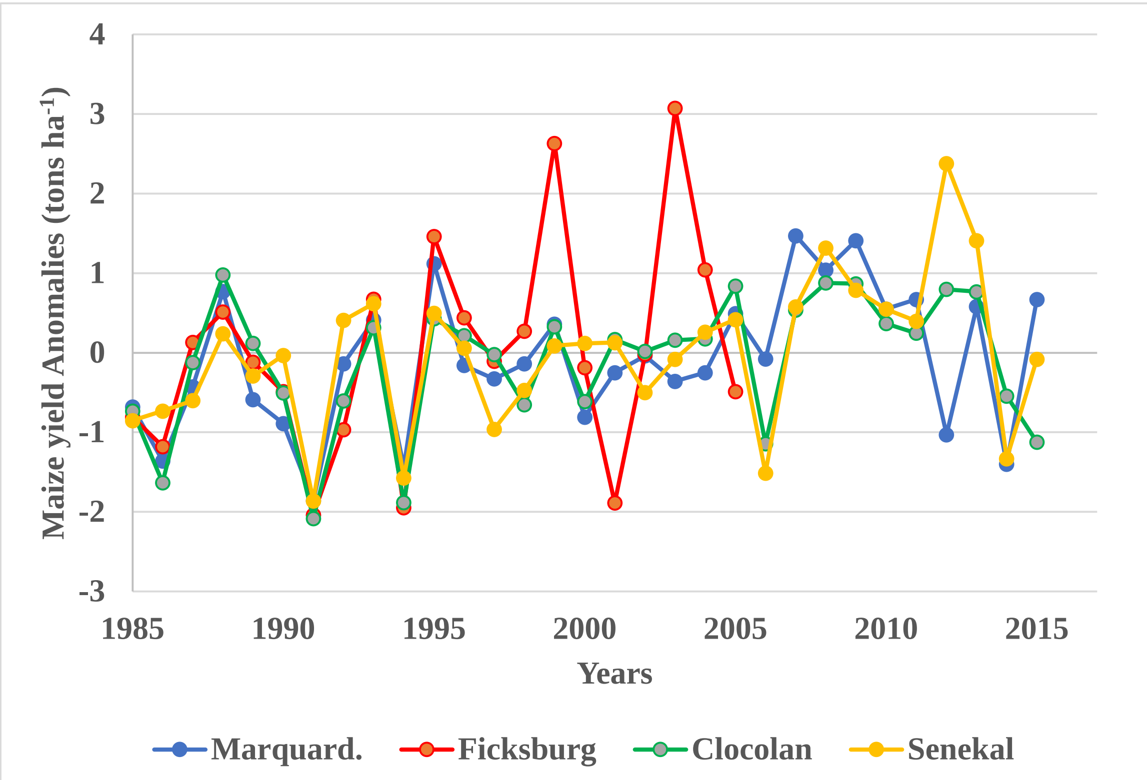

Figure 4.7: Maize yield anomalies for the four stations in the Setsoto Municipality of Free State Province from 1985 to 2016 used for this study.

4.8.3 Maize Yield Relationship with rainfall, minimum and maximum Temperature anomalies

The monthly minimum, and maximum temperatures as well as the rainfall that showed a significant correlation with maize yield (see table 4.10 above) were subjected to a regression analysis. | The yield was the dependent variable while monthly Tmin, Tmax and rainfall were the independent variables used across the different stations of the Setsoto municipality. The influence of the Tmin on maize yield during the months of the November and January in Marquard were significant ($P < 0.00027$ and $P < 0.038$, respectively) (Table 4.11). The Tmax during the month of February showed a significant negative impact on maize yield when a regression analysis was conducted ($P < 0.005$, $R^2 = 0.23$) while the same month for rainfall showed a positive impact on the maize yield in Marquard. An increase of one unit of rainfall in (mm) can increase the yield by 0.0921 tonsha^{-1} (Table 4.11)

In Senekal, maximum temperature in the months of February, March as well as the entire growing period (Oct-Apr) had significant positive impact on the maize yield ($P < 0.05$) (Table 4.11). In February, for every increase in degree Celsius of Tmax above the base temperature led to an increase of the yield by 0.3459 tons ha^{-1} year^{-1}, while an increase in Tmax in March and the whole season of the growing period (Oct-Apr) led to an increase of maize yield by 0.367 and 0.592 tons ha^{-1} respectively in Senekal (Table 4.11).

The effect of rainfall during the growing period and the month of February In Clocolan, showed a significant and positive relationship with the maize yield ($P < 0.05$) ($R^2 = 0.213$ and 0.47, respectively). An increase in rainfall by a unit (mm) led to 0.1028 to 01179 tons ha^{-1} .year^{-1} y (Table 4.11)

Table 4.11: A summary of regression results between detrended maize yield and the climatic (Tmin, Tmax and Rainfall) anomalies.

Months	**Marquard**			**Clocolan**			**Senekal**		
	Intercept	P	R^2	Intercept	p	R^2	Intercept	p	R^2
Nov Tmin	0.274	0.0027	0.152	Nil	Nil	Nil	Nil	Nil	Nil
Jan Tmin	0.572	0.038	0.135	Nil	Nil	Nil	Nil	Nil	Nil
Feb Tmax	-0.290	0.005	0.238	Nil	Nil	Nil	0.0290	0.000	0.432
Mar Tmax	Nil	Nil	Nil	Nil	Nil	Nil	0.408	0.003	0.262
GP Tmax	Nil	Nil	Nil	Nil	Nil	Nil	0.005	0.008	0.214
GP Rainfall	Nil	Nil	Nil	0.005	0.008	0.214	Nil	Nil	Nil
Feb Rainfall	0.0094	0.018	0.174	0.015	0.000	0.472	Nil	Nil	Nil
GP	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

4.9. Variation of Onset, cessation and duration of the rainfall

The earliest annual onset of rainfall was recorded on the 1st of October across all the stations used in this study, while the latest date for the onset was recorded on the 6th of December 1990 in Senekal (Table 4.12). The average onset is within the range of the 14th to the 21st October with SD of 14-17 days (Table 4.12).

Table 4.10: Rainfall Onset, Cessation and duration (Average, earliest, latest and standard deviation) in Setsoto Municipality (1985-2017).

Stations	**Onset**				**Cessation**				**Duration**			
	Average	**Earliest**	**latest**	**SD**	**Average**	**Earliest**	**latest**	**SD**	**Average**	**Minimum**	**Maximum**	**SD**
Senekal	21-Oct	01-Oct	06-Dec	17	09-Apr	10-Mar	27-Apr	15	172	98	206	25
Ficksburg	14-Oct	01-Oct	01-Dec	15	12-Apr	17-Mar	30-Mar	12	184	142	213	20
Clocolan	18-Oct	01-Oct	90-Nov	17	06-Apr	10-Apr	29-Apr	13	173	137	207	17
Marquard	18-Oct	01-Oct	02-Dec	14	11-Apr	17-Mar	30-Mar	11	175	95	200	21

During the period of the 32 years in this study, the date of onset varied across the four stations of the municipality (Figure 4.8). It shifted from the first 10 days of October to the second 10 days of October. The Senekal area showed high variation in the date of onset for 1990, 1992, 1994, 2004 and 2011 (Figure 4.8). The latest onset for Senekal was in early December, while that of Clocolan was within the first 10 days of November throughout the period of the study (Figure 4.8).

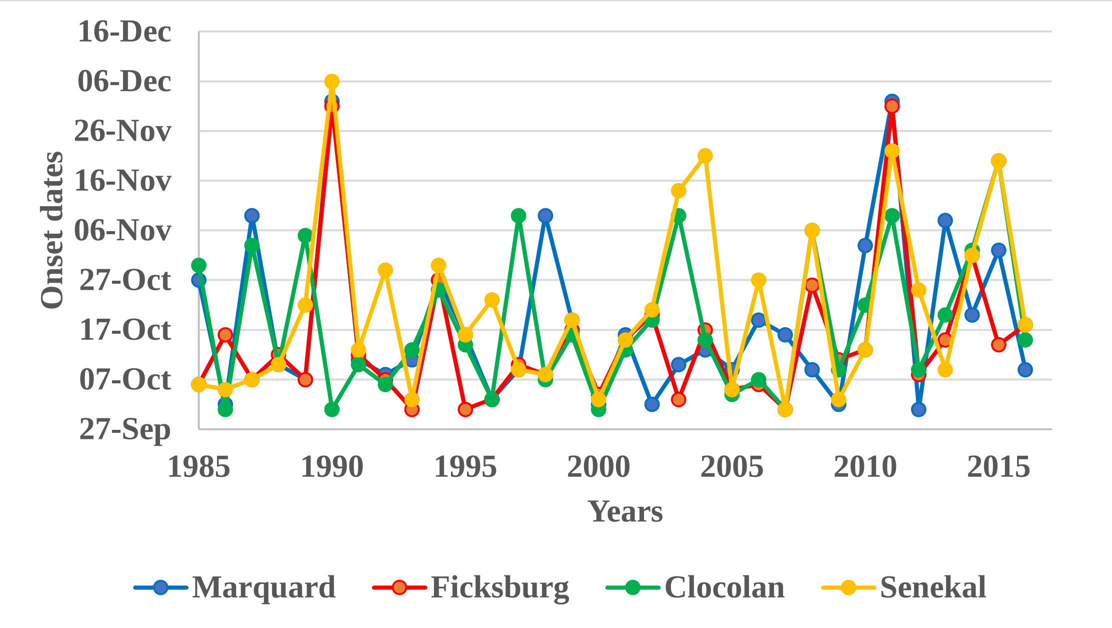

Figure 4.8: Rainfall onset dates for the four stations in the Setsoto Municipality of Free State Province from1985-2016.

The rainfall cessation for Senekal and Clocolan was in the first 10 ten days of April, whereas that of Marquard and Ficksburg was within the second ten days of April (Figure 4.9). It is evident that rainfall cessation is occurring faster during the rainy season. Senekal witnessed more cessation of rain which occurred in the second ten days of March compared to all the others. Marquard cessation earliest date was on the 17 of March (Figure 4.9). Ficksburg had more frequent cessation on the third ten days of April compared to Senekal Clocolan and Marquard.

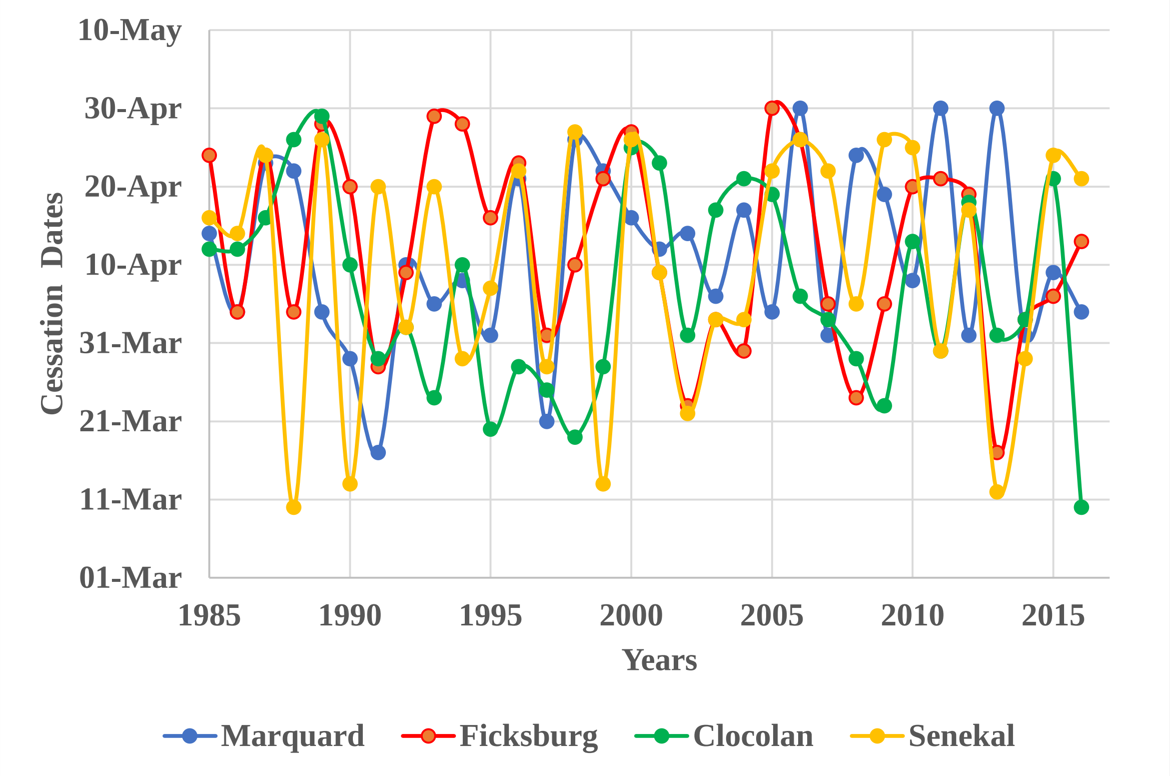

Figure 4.9: Rainfall cessation dates for the four stations in the Setsoto Municipality of Free State Province from 1985-2016.

The entire duration of the growing season for the rain-fed maize production for the period of the study (from 1985 to 2016) was above the average requirement of 120 days (Figure 4.10), except in 1990 (98 days) in Clocolan and 2011 (95 days) in Marquard. The average duration of the rainy season lasted from 172 to 184 days across the municipality. The shortest rainfall duration recorded was 95 days in Marquard in 2011, while the longest was 207 days in Caloocan in 2000 (Figure 4.10).

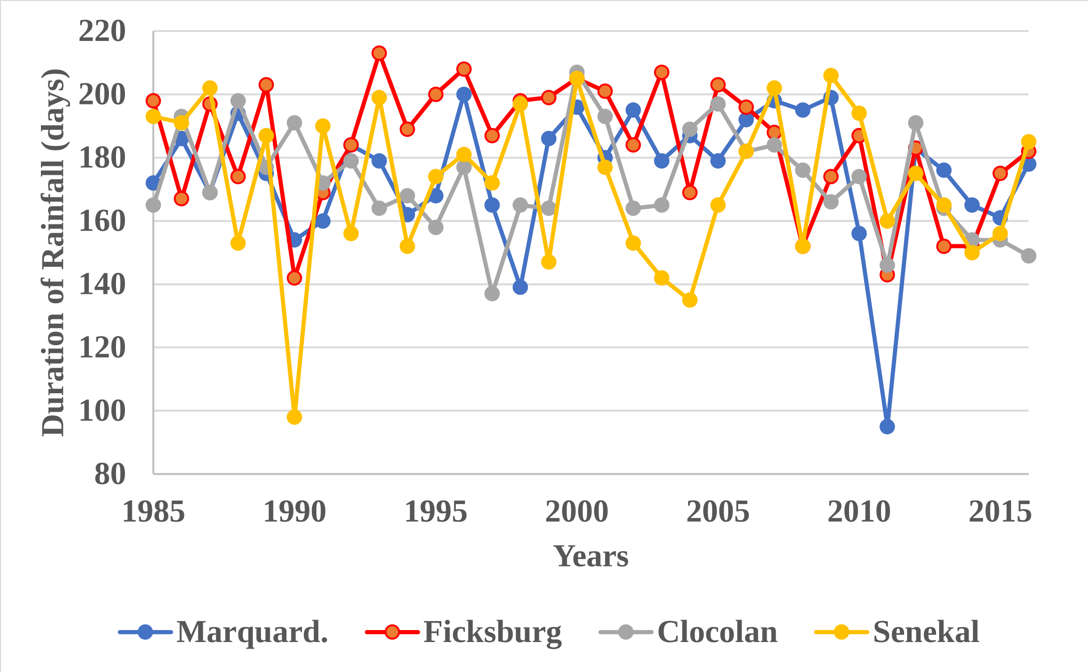

Figure 4.10: The Duration of the rainy annual season for the four stations in the Setsoto Municipality of Free State Province from 1985 to 2016.

CHAPTER 5: DISCUSSION

5.1. Climate trends during the growing period

The Tmin and Tmax trends showed variation across the weather stations used in this study. For instance, the Tmin in Clocolan, showed a declining trend throughout the growing period between October and April, while in Marquard the minimum temperature increased between October and December. The maximum temperature was consistently increasing in all the stations except for Clocolan, where a decline was only reported for the month of March. The November and February trends are important for maize production that involves planting (leaf initiations, leave and roots growth) and development (tussling and grain filling) of maize, respectively.

5.1.1 Minimum temperatures

A commonly occurring pattern in climate change studies shows minimum temperatures to be increasing globally and in Sub-Saharan Africa (SSA) (Russo *et al.* (2016); (IPCC, 2014). In this study, the minimum temperatures changed showing an overall significant increase during the maize growing period of the Setsoto municipality. There have been differences in each station with some months showing a significant decrease or increase and others remaining unchanged. Overall the minimum temperatures increased by 0.035 °C year^{-1}, resulting in an increase of 1.22 °C for the entire period of the study over 32 years. This is similar to the projected mid altitude minimum temperature increases for subtropical Africa of 2.6 °C century^{-1} (Haverkort *et al.*, 2013). Similar findings have been published by the IPCC (2014), with the proviso that anthropogenic and greenhouse emissions remain at 2014 levels. Most predictions of greenhouse gas-induced climate change suggest that this warming will continue, and in the scenarios with increased anthropogenic emissions, warming will accelerate Africa's-induced climate change in the next 125 years (Thornton *et al.*, 2009). These results also fall within the projected century temperature increases of 3 °C, but only for extreme events (Haverkort *et al.*, 2013.).

5.1.2. Maximum temperatures

The maximum temperature of most SSA are expected to increase above the global average (IPCC, 2014). The increasing trend of maximum temperature for Southern Africa is nonlinear and its intensity is expected to increase drought and crop failure (Collier *et al.*, 2008). In this study from 1985 to 2016, the maximum temperatures have also changed, showing an overall significant increase, during the maize growing period across the stations in the Setsoto municipality. The only months with a significant decrease was March and April in Clocolan, while the rest of the months either remained unchanged or showed a significant increase. The annually maximum temperatures increased by 0.08 °C year^{-1}, giving an increase of 2.56 °C for the entire study period of 32 years. These data are similar to the projected Southern African maximum temperature increases for subtropical Africa of 3.5 °C century^{-1} (Engelbrecht *et al.*, 2015). These results also agree with the findings published by the IPCC (2014) with the. The results also fall within the projected temperature increases of 6.5 °C for the century (Dezfuli *et al.*, 2015; Engelbrecht *et al.*, 2015; IPCC, 2014; Lana *et al.*, 2018)

5.1.3 Rainfall

The rainfall trends for the study period of 32 years (from 1985 to 2016) in the Setsoto municipality showed no significant changes. This statement applies to the seasonal distribution of the rainfall, the total amounts of rainfall and yearly distributions. The only significant data were found for the month of January in Ficksburg where rainfall significantly increased by 2.34 mm year^{-1} (Table 4.8). Rainfall in the Free State province has high variability. The pattern, distribution, intensity and duration of rainfall varies spatially and temporally across different scales (Eggert *et al.*, 2015; Gehne *et al.*, 2016).

There is high variability in rainfall in the Free State province (Meletse and Walker 2012). There is no pattern of change detected in this study in the variability of the rainfall. The rainfall distribution is more important than the total seasonal rainfall for planning farming practices with the onset, duration and cessation of the rains being very important. Currently, all stations studied were suitable for maize production, but the interaction of increasing temperatures with evapotranspiration into the future will make some areas in the Free State province less suitable for maize production.

5.2. Maize Yield Trends in the Setsoto Municipality

Planting of summer maize varieties in South Africa traditionally starts in October (Moeletsi *et al.*, 2011). Agroclimatic and maize yield variability in SSA depends on the interactions between the combination of temperature, rainfall, and adaptive strategies (Thorntons *et al.*, 2009). Many scientists have recently postulated that arid and semi-arid areas in particular will be negatively impacted by high variability due to climate change with significant impacts on crop yield (Bergamaschi *et al.*, 2004; Shaw, 1988; Thornton *et al.*, 2009). The results from this study agree with other studies in SSA particularly with respect to temperatures and yield (Shaw, 1988; Bergamaschi *et al.*, 2004; IITA, 2004; Parry *et al.*, 2004; Thornton *et al.*, 2009; WRI, 2007).

There were positive trends in all the stations for maize yield from 1985 to 2016 (Table 4.9). Marquard has the highest maize yield increasing trend of 0.05 tons ha^{-1} year^{-1}, followed by Senekal with 0.043 tons ha^{-1} year^{-1}and Clocolan with 0.039 tons ha^{-1} year^{-1}. This general positive trend agrees with those found by Adisa *et al.* (2018) on a comparative analysis of maize yields for South Africa. The average maize yield for Setsoto during the period of this study was between 1.96 tons ha^{-1} to 2.89 tons ha^{-1} per annum with an inter-annual variability between 38-46% (Table 4.5). The maize yield in the Setsoto municipality is below the Free State provincial average maize yield of 3.8 tons ha^{-1} (Walker and Schulze, 2008; Adisa *et al.*, 2018). Maize production is said to be economically viable if 3.6 tons ha^{-1} is produced (Walker and Schulze, 2008), the data from this study showed that maize yield is below this limit. The yield trends in this study were low and it is only marginally economically viable to produce maize in these areas. The contribution to GDP from farming in the Setsoto municipality is decreasing (Marais and Cloete, 2016; Morakile, 2018) and it has been suggested that some farms are no longer being planted with maize or alternate crops. It is unfortunate that data on the number of hectares planted to maize each year in this Municipality and for the entire district is not available for this study. Maize production thrives under good agronomic practices and management. The use of fertilizers, pesticides, type of seeds and other agronomic practices (included tillage) can also affect maize production (Walker and Schulze, 2008). Data on each of these agronomic practices are very limited and was not available at the spatial or temporal scales of the Setsoto municipality and therefore could not be included in this study. Yields vary across the stations with high variability. The yield in Senekal has among the highest variability of 46.1% per annum and also recorded the lowest yield among the stations in the Setsoto municipality used for this study. The soil in Senekal has the lowest potential for maize production because the soil is shallow due to plinthic horizons in the top soil, which also renders the soil poor with respect to water storage (Hensley *et al.*, 2006).

5.3 Maize Yield Relationships with Climatic Variables

5.3.1. Minimum temperature and maize yield

The results from this study showed that the minimum temperatures were correlated with maize yield only for the Marquard station in the months of November and February, this relationship was also found to be the case in studies conducted by (Adisa *et al.*, 2018). temperature drives the physiological and morphological development of the maize plant, with each process requiring a different temperature e.g. work by Sanchez *et al*. (2014) showed that leaf initiation needs a minimum of 7 ℃, while shoot growth takes place above 14 ℃and root growth above 13 ℃. These minimum temperature conditions were not met for all cases except for the leaf initiation process in November (Table 4.1). However, in January the minimum temperature requirements for leaf initiation and shoot and root growth were met even for the late planting cultivars. Minimum temperatures, especially in November, seem to be critical for early establishment and growth of the seedlings which ultimately influences the yield. The correlation and the regression analyses provided evidence for the significance of the minimum temperature on yield in Marquard, especially in the months of November and January. However, the November minimum temperature trend showed an increase of 0.09 °C per annum (Table 4.3), which showed an increase of 1% in Tmin in November increased the yield by 0.274 tons ha^{-1} in Marquard. Climate change predictions for semi-arid region of SSA have changed from earlier studies which gave values of 1.6 °C to recent projections of above 2.4 °C by 2050, depending on GHS emissions and other anthropogenic activities (Cairns *et al.*, 2013). Increasing trends in minimum temperatures are predicted for SSA, but extreme climate events, especially the frequency and severity could negatively impact yields IPCC (2007).

5.3.2. Maximum temperature and maize yield

The results from this study showed that the maximum temperatures for the entire growing season were significantly correlated with maize yield only for Senekal. This was as a result of the significant correlation in the months of February and March. The stations of Clocolan and Ficksburg showed no correlation between the Tmax and maize yield, while those in Marquard showed a significant negative correlation. This result in Marquard was also similar to other studies which showed that temperatures above 30 °C have a negative impact on maize production in southern Africa (Lobell *et al.*, 2011). Senekal had the lowest maximum temperatures and a 1% increase of Tmax in the months of February, March and the entire growing period (Oct-Apr) could increase the maize yield by 0.029, 0.408 and 0.536 tons ha^{-1} (Table 4.11). On the other hand, Marquard had the highest maximum temperatures and a 1% increase of Tmax could decrease maize yield by 0.290 tons ha^{-1}. Lobell *et al.* (2011) showed that a 1% increase of maximum temperature above the optimal temperature for growth under drought stress could result in a maize yield decline of 1.7%.Thus, Clocolan has the highest mean Tmax value and SD value of 28.6°C and 2.4°C respectively. There are several studies which show that high temperatures, together with soil and plant water stress leads to a decline in crop yield (Fantaye *et al.*, 2018; Steward *et al.*, 2018). Maize yield in Marquard will be most vulnerable to water stress if the maximum temperatures continue to increase, especially at the anthesis stage, where the optimal temperature is 32°C and the maximum tolerable Tmax is 36°C (Lana *et al.*, 2018). Muchow (1990) showed that temperatures outside the range of 13-32 °C decrease the yield by shortening the period of the kernel filling. These conditions also apply in Marquard with high February maximum temperatures which prevailed when kernel filling would have taken place if planting took place in November.

5.4. Rainfall and maize yield

Rainfall is a key driver of yield (Scholes and Scholes, 2015). In this study, as the rainfall increased the yield also increased. The amount of rainfall in the month of February is particularly highly correlated (with r = 0.69) with yield in Clocolan and Marquard, adding further support to earlier evidence that the rainfall and temperatures in February have a strong influence on yield. The rainfall received in Clocolan has the lowest variability (CV 21%) when compared with the other stations (CVs up to 49%). Clocolan receives an average rainfall of 593 mm, which was similar to the 500 mm rainfall reported by Moeletse and Walker (2012) for the eastern part of the Free State province. The CV associated with the total rainfall of 21 – 49% across the four stations was high and if either the total rainfall decreases, or variability increases then the risk of crop failure will increase. The results in this study support the research of Moeletse *et al*. (2013) who identified November as critical for the start of the growing season in Senekal. Maize planted later than November become susceptible to frost from May onwards before the crops reach maturity (Moeletsi and Walker, 2012; Moeletse and Walker, 2013; Walker and Schulze, 2008) and exposed the crop to increased rainfall variability. Maize planted in early November, will allow for maximum tasseling and grain-filling in February, which is the most sensitive period for water stress, even more, sensitive than the early establishment stages (Mjelde *et al*., 1997). This study showed that a 1% increase in the rainfall amount in February and the overall growing period can increase the yield by 0.015 and 0.005 tons ha^{-1} respectively (4.11). In most African countries agricultural production depends solely on rainfall pattern, distribution and duration (Buckle, 1996; Hunter and Meentemeyer, 2005). This study confirmed the research by Fauchereau *et al.* (2003) and Hachigonta *et al*. (2008) who indicated that high variability of rainfall threatens rain-fed agriculture in South Africa. These findings are also similar to other previous work showing declining rainfall patterns in southern Africa (Chabala *et al.*, 2013; Jury, 2013).

CHAPTER 6: CONCLUSIONS

Objective 1: To examine the effects of climatic trends; specifically changes in the minimum and maximum temperatures, as well as changes in the growing period (October to April) between 1985 and 2016.

In this study the monthly as well as the entire growing period (Oct-Apr) minimum and maximum temperatures for the period from 1985 to 2016, varied across the four different stations of the Setsoto municipality. In Clocolan, the minimum temperature declined significantly with the monthly minimum temperature and the entire growing period declined by 0.2 to 0.12 °C year^{-1}. A similar pattern was observed in Marquard in the months of February, March and April and for the growing period by 0.05 – 0.25 °C year^{-1}, while from October to December it showed an increasing trend of 0.09 °C year^{-1}. The minimum temperatures in Senekal and Ficksburg increased in January by 0.02 and 0.05 °C year^{-1}.

In Clocolan, the trend in the maximum temperature, for March and April, decreased significantly by 0.16 and 0.14°C year^{-1}, while in Senekal, it increased by 0.12 °C year^{-1} in October and November and by 0.05 °C year^{-1} during the growing period. The maximum temperature also increased at an average of 0.04 °C year^{-1} for the months of November, February and March and the growing period in Ficksburg. Whereas in Marquard, such increase was variable in October, November and in the growing period. The increasing minimum and maximum temperatures in all the stations of this study showed that: (1) where the minimum temperature is currently too low for optimal growth, an increase in these temperatures will increase yield and (2) the overall increase in both the minimum and maximum temperatures over time it can negatively impact yield, but the magnitude of the effect is dependent on when exactly the increases are taking place during the growing season. November and February have been highlighted as specific times at which the crop is most at risk.

There was no significant trend in the rainfall amounts or distribution patterns for all the stations of the municipality over the period of this study. The only significant trend observed was for January in Ficksburg, which showed a rainfall increase of 2.34 mm year $^{-1}$. Thus, this study indicates that the rainfall variability is increasing in the study areas, which could be attributed to a number of global and regional rainfall phenomena.

Objective 2: To evaluate the annual maize yield pattern of Setsoto between 1985 and 2016.

The maize yield in the Setsoto municipality increased in all the stations from 1985 to 2016. There were some periods where it did appear that the yield was below average, but the duration of this pattern did not allow for conclusive evidence about decreases in yield, since it was less than acceptable seven continuous years such kind of time series trend analysis. Similarly, there were periods from 2006-2012, where the yield was above the average maize yield per ha (2.42 tonsha^{-1}). There are some concerns, especially in the Senekal area, that it will no longer be economically viable for maize production. Yield is not just a product of climatic variables, but also a combination of other agronomic factors. The average rate of increase of yield in the Setsoto municipality is 0.044 tons ha^{-1} per annum across the stations. Yield is not controlled only by agroclimatic variables, but together with a combination of several farming practices including area of land planted, cultivar, fertilizer and pesticide usage etc. It was unfortunate that these aspects could not be studied as the data at the municipal level are very scarce. Perhaps, crop models could help to give a better correlation of the impact of climatic factors, as they integrate the individual effect of the climate variables on each of the crop growth and development stages.

Objective 3: Determine the relationship between climate variability and maize yield in the Setsoto municipality for the 30-year period.

Climatic variability was defined as changes in rainfall and temperatures. Overall there were correlations between rainfall, temperature and crop yield, which does provide evidence that agroclimatic factors do contribute to changes in maize yield. The strongest positive correlation (46-68%) with yield was for rainfall during the growing period in Clocolan. The changes in minimum temperature are having three different effects on the yield in area where:

- it is colder, the yield will be negatively impacted
- it is getting warmer, where the minimum temperature has previously limited yield, the yield will be positively impacted
- the minimum temperature has not been limiting (to date), an increase in temperature will lead to an increase of yield until the optimal temperature is exceeded. Increasing

maximum temperatures still show no negative impacts on maize yield except for a single month of February in Marquard.

Objective 4: To **i**nvestigate trends in the rainfall and temperature across the growing period including the onset, cessation and duration of the rainfall.

The duration of the rainfall, in all the four stations of the municipality was sufficient for maize production. Neither the onset nor the cessation of the rains showed any significant change over the study period. There are however, some concerns that as temperatures and the rainfall variability increase, this municipality of the Setsoto might become marginally viable for maize production.

REFERENCES

ADISA, O. M., BOTAI, C. M., BOTAI, J. O., HASSEN, A., DARKEY, D., TESFAMARIAM, E., ADISA, A. F., ADEOLA, A. M. & NCONGWANE, K. P. 2018. Analysis of agro-climatic parameters and their influence on maize production in South Africa. *Theoretical and Applied Climatology,* 134**,** 991-1004.

AGNEW, C. & WOODHOUSE, P. 2010. Climate change resilience and adaptation: Perspectives from a century of water resources development. Berghahn Journals.

AGUILAR, E., AZIZ BARRY, A., BRUNET, M., EKANG, L., FERNANDES, A., MASSOUKINA, M., MBAH, J., MHANDA, A., DO NASCIMENTO, D. & PETERSON, T. 2009. Changes in temperature and precipitation extremes in western central Africa, Guinea Conakry, and Zimbabwe, 1955–2006. *Journal of Geophysical Research: Atmospheres,* 114.

AHMED, M., ANCHUKAITIS, K. J., ASRAT, A., BORGAONKAR, H. P., BRAIDA, M., BUCKLEY, B. M., BÜNTGEN, U., CHASE, B. M., CHRISTIE, D. A. & COOK, E. R. 2013. Continental-scale temperature variability during the past two millennia. *Nature geoscience,* 6**,** 339.

AL-AMIN, A. Q., SIWAR, C. & JAAFAR, A. H. 2009. Energy use and environmental impact of new alternative fuel mix in electricity generation in Malaysia. *The Open Renewable Energy Journal,* 2**,** 25-32.

ALEXANDER, L., ZHANG, X., PETERSON, T., CAESAR, J., GLEASON, B., TANK, A. K., HAYLOCK, M., COLLINS, D., TREWIN, B. & RAHIMZADEH, F. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres,* 111.

ALLEMANN, J. 1997. Crop studies for the Frankfort, Reitz and Vrede Magisterial districts. Tech. Rep. GW/A/97/71, Agricultural Research Council, Vegetable and Ornamental Plant Institute, Pretoria, South Africa.

ALTIERI, M. A. & NICHOLLS, C. I. 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change,* 140**,** 33-45.

ALTIERI, M. A., NICHOLLS, C. I., HENAO, A. & LANA, M. A. 2015. Agroecology and the design of climate change-resilient farming systems. *Agronomy for sustainable development,* 35**,** 869-890.

ANDERSON, R. L. 1942. Distribution of the serial correlation coefficient. *The Annals of Mathematical Statistics,* 13**,** 1-13.

BANDYOPADHYAY, N., BHUIYAN, C. & SAHA, A. 2016. Heat waves, temperature extremes and their impacts on monsoon rainfall and meteorological drought in Gujarat, India. *Natural Hazards,* 82**,** 367-388.

BARRIOS, A., TRINCADO, G. & GARREAUD, R. 2018. Alternative approaches for estimating missing climate data: application to monthly precipitation records in South-Central Chile. *Forest Ecosystems,* 5**,** 28.

BARROS, V., FIELD, C., DOKKE, D., MASTRANDREA, M., MACH, K., BILIR, T. E., CHATTERJEE, M., EBI, K., ESTRADA, Y. & GENOVA, R. 2014. Climate change 2014: impacts, adaptation, and vulnerability-Part B: regional aspects-Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

BAZILIAN, M., NUSSBAUMER, P., ROGNER, H.-H., BREW-HAMMOND, A., FOSTER, V., PACHAURI, S., WILLIAMS, E., HOWELLS, M., NIYONGABO, P. &

MUSABA, L. 2012. Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. *Utilities Policy,* 20**,** 1-16.

BELETSE, Y. G., DURAND, W., NHEMACHENA, C., CRESPO, O., TESFUHUNEY, W. A., JONES, M. R., TEWELDEMEDHIN, M. Y., GAMEDZE, S. M., BONOLO, P. M. & JONAS, S. 2015. Projected Impacts of Climate Change Scenarios on the Production of Maize in Southern Africa: An Integrated Assessment Case Study of the Bethlehem District, Central Free State, South Africa. *HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 2.* World Scientific.

BERDANIER, A. B. & KLEIN, J. A. 2011. Growing season length and soil moisture interactively constrain high elevation aboveground net primary production. *Ecosystems,* 14**,** 963-974.

BERGAMASCHI, H., DALMAGO, G. A., BERGONCI, J. I., BIANCHI, C. A. M., MÜLLER, A. G., COMIRAN, F. & HECKLER, B. M. M. 2004. Water supply in the critical period of maize and the grain production. *Pesquisa Agropecuária Brasileira,* 39**,** 831-839.

BLACK, J. R. & THOMPSON, S. R. 1978. Some evidence on weather-crop-yield interaction. *American Journal of Agricultural Economics,* 60**,** 540-543.

BLIGNAUT, J., UECKERMANN, L. & ARONSON, J. 2009. Agriculture production's sensitivity to changes in climate in South Africa. *South African Journal of Science,* 105**,** 61-68.

BOUNOUA, L., COLLATZ, G., LOS, S., SELLERS, P., DAZLICH, D., TUCKER, C. & RANDALL, D. 2000. Sensitivity of climate to changes in NDVI. *Journal of Climate,* 13**,** 2277-2292.

BUSO, N. 2003. Municipal commonage administration in the Free State province: can municipalities in the current local government dispensation promote emerging farming? October.

CAIRNS, J. E., HELLIN, J., SONDER, K., ARAUS, J. L., MACROBERT, J. F., THIERFELDER, C. & PRASANNA, B. M. 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Security,* 5**,** 345-360.

CHALLINOR, A., WHEELER, T., GARFORTH, C., CRAUFURD, P. & KASSAM, A. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic change,* 83**,** 381-399.

CHLOUPEK, O., HRSTKOVA, P. & SCHWEIGERT, P. 2004. Yield and its stability, crop diversity, adaptability and response to climate change, weather and fertilisation over 75 years in the Czech Republic in comparison to some European countries. *Field Crops Research,* 85**,** 167-190.

CHRISTENSEN, J. H., HEWITSON, B., BUSUIOC, A., CHEN, A., GAO, X., HELD, R., JONES, R., KOLLI, R. K., KWON, W. & LAPRISE, R. 2007. Regional climate projections. *Climate Change, 2007: The Physical Science Basis. Contribution of Working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, University Press, Cambridge, Chapter 11.*

CLAY, J. 2011. Freeze the footprint of food. *Nature,* 475**,** 287.

CLEAVELAND, M. 2016. Plain Facts About Anthropogenic Global Climate Change and Warming: A Review. *Journal of the Arkansas Academy of Science,* 70**,** 64-76.

COLE, M. J., BAILEY, R. M. & NEW, M. G. 2017. Spatial variability in sustainable development trajectories in South Africa: provincial level safe and just operating spaces. *Sustainability Science,* 12**,** 829-848.

COLLIER, P., CONWAY, G. & VENABLES, T. 2008. Climate change and Africa. *Oxford Review of Economic Policy,* 24**,** 337-353.

CONNOLLY-BOUTIN, L. & SMIT, B. 2016. Climate change, food security, and livelihoods in sub-Saharan Africa. *Regional Environmental Change,* 16**,** 385-399.

CONWAY, D., MOULD, C. & BEWKET, W. 2004. Over one century of rainfall and temperature observations in Addis Ababa, Ethiopia. *International Journal of Climatology,* 24**,** 77-91.

COOPER, P., DIMES, J., RAO, K., SHAPIRO, B., SHIFERAW, B. & TWOMLOW, S. 2008. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems & Environment,* 126**,** 24-35.

DAFF 2015. South African Fertilizers Market Analysis Report 2015. *DAFF Report*.

DASGUPTA, P., MORTON, J. F., DODMAN, D., KARAPINAR, B., MEZA, F., RIVERA-FERRE, M. G., TOURE SARR, A., VINCENT, K. E., FIELD, C. & BARROS, V. 2014. Rural areas. *Climate change***,** 613-657.

DAVIS, J., TAVASCI, D. & MARAIS, L. 2006. Fostering rural and local economic development in the Free State of South Africa. *Natural Resources Institute, University of Greenwich, UK***,** 2-10.

DE JAGER, J., POTGIETER, A. & VAN DEN BERG, W. 1998. Framework for forecasting the extent and severity of drought in maize in the Free State Province of South Africa. *Agricultural Systems,* 57**,** 351-365.

DEZFULI, A. K., ZAITCHIK, B. F. & GNANADESIKAN, A. 2015. Regional atmospheric circulation and rainfall variability in south equatorial Africa. *Journal of Climate,* 28**,** 809-818.

DIRO, G., GRIMES, D. I. F. & BLACK, E. 2011. Teleconnections between Ethiopian summer rainfall and sea surface temperature: part I—observation and modelling. *Climate Dynamics,* 37**,** 103-119.

DUBE, S., SCHOLES, R. J., NELSON, G. C., MASON-D'CROZ, D. & PALAZZO, A. 2013. South African food security and climate change: Agriculture futures. *Economics: The Open-Access, Open-Assessment E-Journal*.

EASTERLING, W. E., AGGARWAL, P. K., BATIMA, P., BRANDER, K. M., ERDA, L., HOWDEN, S. M., KIRILENKO, A., MORTON, J., SOUSSANA, J.-F. & SCHMIDHUBER, J. 2007. Food, fibre and forest products. *Climate change***,** 273-313.

ENGELBRECHT, C. J. & ENGELBRECHT, F. A. 2016. Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and applied climatology,* 123**,** 247-261.

ENGELBRECHT, F., ADEGOKE, J., BOPAPE, M.-J., NAIDOO, M., GARLAND, R., THATCHER, M., MCGREGOR, J., KATZFEY, J., WERNER, M. & ICHOKU, C. 2015. Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters,* 10**,** 085004.

ENGELBRECHT, F., MCGREGOR, J. & ENGELBRECHT, C. 2009a. Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *International Journal of Climatology: A Journal of the Royal Meteorological Society,* 29**,** 1013-1033.

ENGELBRECHT, F., MCGREGOR, J. & ENGELBRECHT, C. 2009b. Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *International Journal of Climatology,* 29**,** 1013-1033.

ENGELBRECHT, F. A., LANDMAN, W. A., ENGELBRECHT, C., LANDMAN, S., BOPAPE, M., ROUX, B., MCGREGOR, J. & THATCHER, M. 2011. Multi-scale climate modelling over Southern Africa using a variable-resolution global model. *Water SA,* 37**,** 647-658.

EWERT, F., RÖTTER, R. P., BINDI, M., WEBBER, H., TRNKA, M., KERSEBAUM, K. C., OLESEN, J. E., VAN ITTERSUM, M. K., JANSSEN, S. & RIVINGTON, M. 2015. Crop modelling for integrated assessment of risk to food production from climate change. *Environmental Modelling & Software,* 72**,** 287-303.

FANTAYE, K. T., KRUSEMAN, G., CAIRNS, J. E., ZAMAN-ALLAH, M., GISSA, D. W., ZAIDI, P., BOOTE, K. & ERENSTEIN, O. 2018. Potential benefits of drought and heat tolerance for adapting maize to climate change in tropical environments.

FAO, U. 2014. FAOstat. *Retrieved Feb,* 2014.

FAOSTAT 2012. *FAOSTAT, Food Supply.*

FAUBERT, P., DUROCHER, S., BERTRAND, N., OUIMET, R., ROCHETTE, P., TREMBLAY, P., BOUCHER, J.-F. & VILLENEUVE, C. 2017. Greenhouse Gas Emissions after Application of Landfilled Paper Mill Sludge for Land Reclamation of a Nonacidic Mine Tailings Site. *Journal of environmental quality,* 46**,** 950-960.

FAUCHEREAU, N., TRZASKA, S., RICHARD, Y., ROUCOU, P. & CAMBERLIN, P. 2003a. Sea-surface temperature co-variability in the Southern Atlantic and Indian Oceans and its connections with the atmospheric circulation in the Southern Hemisphere. *International Journal of Climatology,* 23**,** 663-677.

FAUCHEREAU, N., TRZASKA, S., ROUAULT, M. & RICHARD, Y. 2003b. Rainfall variability and changes in southern Africa during the 20th century in the global warming context. *Natural Hazards,* 29**,** 139-154.

FERTASA 2013 Fertilizer consumption in South Africa 2012 (metric tonnes). . *Fertiliser Society of South Africa.* *http://www.fssa.org.za/Statistics/Estimated_fertilizer_use_by_crop_in_SA_for_2012.pdf.*

FIELD, J. C., BOESCH, D. F., SCAVIA, D., BUDDEMEIER, R., BURKETT, V. R., CAYAN, D., FOGARTY, M., HARWELL, M., HOWARTH, R. & MASON, C. 2001. Potential consequences of climate variability and change on coastal areas and marine resources. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change, Report for the US Global Change Research Program. Cambridge University Press, Cambridge, UK***,** 461-487.

FIRAT, M., DIKBAS, F., KOC, A. C. & GUNGOR, M. 2012. Analysis of temperature series: estimation of missing data and homogeneity test. *Meteorological Applications,* 19**,** 397-406.

FOLEY, J. A., RAMANKUTTY, N., BRAUMAN, K. A., CASSIDY, E. S., GERBER, J. S., JOHNSTON, M., MUELLER, N. D., O'CONNELL, C., RAY, D. K. & WEST, P. C. 2011. Solutions for a cultivated planet. *Nature,* 478**,** 337.

GARIBALDI, L. A., GEMMILL-HERREN, B., D'ANNOLFO, R., GRAEUB, B. E., CUNNINGHAM, S. A. & BREEZE, T. D. 2017. Farming approaches for greater biodiversity, livelihoods, and food security. *Trends in ecology & evolution,* 32**,** 68-80.

GIORGI, F., JONES, C. & ASRAR, G. R. 2009. Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorological Organization (WMO) Bulletin,* 58**,** 175.

GIUGNI, M., SIMONIS, I., BUCCHIGNANI, E., CAPUANO, P., DE PAOLA, F., ENGELBRECHT, F., MERCOGLIANO, P. & TOPA, M. E. 2015. The impacts of climate change on African cities. *Urban vulnerability and climate change in Africa.* Springer.

GOCIC, M. & TRAJKOVIC, S. 2013. Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Global and Planetary Change,* 100**,** 172-182.

GOLKHATMI, N., SANAEINEJAD, S., GHAHRAMAN, B. & PAZHAND, H. 2012. Extended modified inverse distance method for interpolation rainfall. *International Journal of Engineering Inventions,* 3**,** 57-65.

GORNALL, J., BETTS, R., BURKE, E., CLARK, R., CAMP, J., WILLETT, K. & WILTSHIRE, A. 2010. Implications of climate change for agricultural productivity in the early twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 365**,** 2973-2989.

GUSTAFSON, E. J., MIRANDA, B. R., DE BRUIJN, A. M., STURTEVANT, B. R. & KUBISKE, M. E. 2017. Do rising temperatures always increase forest productivity? Interacting effects of temperature, precipitation, cloudiness and soil texture on tree species growth and competition. *Environmental Modelling & Software,* 97**,** 171-183.

HAMZA, M. & ANDERSON, W. 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil and tillage research,* 82**,** 121-145.

HANSEN, J. W., MASON, S. J., SUN, L. & TALL, A. 2011. Review of seasonal climate forecasting for agriculture in sub-Saharan Africa. *Experimental Agriculture,* 47**,** 205-240.

HATFIELD, J. L., BOOTE, K. J., KIMBALL, B., ZISKA, L., IZAURRALDE, R. C., ORT, D., THOMSON, A. M. & WOLFE, D. 2011. Climate impacts on agriculture: implications for crop production. *Agronomy journal,* 103**,** 351-370.

HAUB, C., GRIBBLE, J. & JACOBSEN, L. 2012. World population data sheet 2012. *Population Reference Bureau*.

HAVERKORT, A. J., FRANKE, A. C., ENGELBRECHT, F. A. & STEYN, J. M. 2013. Climate Change and Potato Production in Contrasting South African Agro-ecosystems 1. Effects on Land and Water Use Efficiencies. *Potato Research,* 56**,** 31-50.

HAWKINS, E., FRICKER, T. E., CHALLINOR, A. J., FERRO, C. A., HO, C. K. & OSBORNE, T. M. 2013. Increasing influence of heat stress on French maize yields from the 1960s to the 2030s. *Global change biology,* 19**,** 937-947.

HENSLEY, M., LE ROUX, P., DU PREEZ, C., VAN HUYSSTEEN, C., KOTZE, E. & VAN RENSBURG, L. 2006. Soils: the Free State's agricultural base. *South African Geographical Journal,* 88**,** 11-21.

HERRERO, M., THORNTON, P. K., NOTENBAERT, A. M., WOOD, S., MSANGI, S., FREEMAN, H., BOSSIO, D., DIXON, J., PETERS, M. & VAN DE STEEG, J. 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science,* 327**,** 822-825.

HEWITSON, B., DARON, J., CRANE, R., ZERMOGLIO, M. & JACK, C. 2014. Interrogating empirical-statistical downscaling. *Climatic change,* 122**,** 539-554.

HULME, M. 1992. Rainfall changes in Africa: 1931–1960 to 1961–1990. *International Journal of Climatology,* 12**,** 685-699.

HULME, M., DOHERTY, R., NGARA, T., NEW, M. & LISTER, D. 2001. African climate change: 1900–2100. *Climate research,* 17**,** 145-168.

IITA 2004. Annual report for 2004.

IPCC 2014. IPCC, 2014: climate change 2014: synthesis report. Contribution of Working Groups I. *II and III to the Fifth Assessment Report of the intergovernmental panel on Climate Change. IPCC, Geneva, Switzerland,* 151.

JAMES, R. & WASHINGTON, R. 2013. Changes in African temperature and precipitation associated with degrees of global warming. *Climatic change,* 117**,** 859-872.

JONES, P. G. & THORNTON, P. K. 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science & Policy,* 12**,** 427-437.

JURY, M. R. 2013. Climate trends in southern Africa. *South African Journal of Science,* 109**,** 1-11.

KABANDA, T. & NENWIINI, S. 2016. Impacts of climate variation on the length of the rainfall season: an analysis of spatial patterns in North-East South Africa. *Theoretical and Applied Climatology,* 125**,** 93-100.

KAHSAY, T. N., KUIK, O., BROUWER, R. & VAN DER ZAAG, P. 2017. The economy-wide impacts of climate change and irrigation development in the Nile basin: a Computable General Equilibrium approach. *Climate Change Economics,* 8**,** 1750004.

KANDA, N., NEGI, H., RISHI, M. S. & SHEKHAR, M. 2018. Performance of various techniques in estimating missing climatological data over snowbound mountainous areas of Karakoram Himalaya. *Meteorological Applications,* 25**,** 337-349.

KANE, R. 2009. Periodicities, ENSO effects and trends of some South African rainfall series: an update. *South African Journal of Science,* 105**,** 199-207.

KIM, J., WALISER, D. E., MATTMANN, C. A., GOODALE, C. E., HART, A. F., ZIMDARS, P. A., CRICHTON, D. J., JONES, C., NIKULIN, G. & HEWITSON, B. 2014. Evaluation of the CORDEX-Africa multi-RCM hindcast: systematic model errors. *Climate dynamics,* 42**,** 1189-1202.

KING'UYU, S., OGALLO, L. & ANYAMBA, E. 2000. Recent trends of minimum and maximum surface temperatures over Eastern Africa. *Journal of Climate,* 13**,** 2876-2886.

KRUGER, A. C. 1999. *The relationship between ENSO, seasonal rainfall, and circulation patterns in South Africa.* University of Cape Town.

KRUGER, A. C. 2006. Observed trends in daily precipitation indices in South Afica: 1910-2004. *International Journal of Climatology,* 26**,** 2275-2285.

LANA, M. A., VASCONCELOS, A. C. F., GORNOTT, C., SCHAFFERT, A., BONATTI, M., VOLK, J., GRAEF, F., KERSEBAUM, K. C. & SIEBER, S. 2018. Is dry soil planting an adaptation strategy for maize cultivation in semi-arid Tanzania? *Food Security,* 10**,** 897-910.

LANDMAN, W. A., ENGELBRECHT, F., HEWITSON, B., MALHERBE, J. & VAN DER MERWE, J. 2017. Towards bridging the gap between climate change projections and maize producers in South Africa. *Theoretical and Applied Climatology***,** 1-11.

LATIF, Y., YAOMING, M. & YASEEN, M. 2018. Spatial analysis of precipitation time series over the Upper Indus Basin. *Theoretical and Applied Climatology,* 131**,** 761-775.

LESK, C., ROWHANI, P. & RAMANKUTTY, N. 2016. Influence of extreme weather disasters on global crop production. *Nature,* 529**,** 84.

LEU, A. 2015. ecologicAl APProAcHeS for reducing externAl inPutS in fArMing. *AGROECOLOGY FOR FOOD SECURITY AND NUTRITION***,** 158.

LIM, S. S., ALLEN, K., BHUTTA, Z. A., DANDONA, L., FOROUZANFAR, M. H., FULLMAN, N., GETHING, P. W., GOLDBERG, E. M., HAY, S. I. & HOLMBERG, M. 2016. Measuring the health-related Sustainable Development Goals in 188 countries: a baseline analysis from the Global Burden of Disease Study 2015. *The Lancet,* 388**,** 1813-1850.

LOBELL, D. B. & ASNER, G. P. 2003. Climate and management contributions to recent trends in US agricultural yields. *Science,* 299**,** 1032-1032.

LOBELL, D. B., BÄNZIGER, M., MAGOROKOSHO, C. & VIVEK, B. 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature Climate Change,* 1**,** 42-45.

LOBELL, D. B. & BURKE, M. B. 2008. Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environmental Research Letters,* 3**,** 034007.

LOBELL, D. B. & BURKE, M. B. 2010. On the use of statistical models to predict crop yield responses to climate change. *Agricultural and Forest Meteorology,* 150**,** 1443-1452.

LOBELL, D. B. & FIELD, C. B. 2007. Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental research letters,* 2**,** 014002.

MAHONY, M. & HULME, M. 2016. Modelling and the nation: Institutionalising climate prediction in the UK, 1988–92. *Minerva,* 54**,** 445-470.

MALHERBE, J., ENGELBRECHT, F. A. & LANDMAN, W. A. 2014. Response of the Southern Annular Mode to tidal forcing and the bidecadal rainfall cycle over subtropical southern Africa. *Journal of Geophysical Research: Atmospheres,* 119**,** 2032-2049.

MARAIS, L. & CLOETE, J. 2016. Patterns of territorial development and inequality from South Africa's periphery: evidence from the Free State Province. Working Paper Series.

MARAUN, D., WETTERHALL, F., IRESON, A., CHANDLER, R., KENDON, E., WIDMANN, M., BRIENEN, S., RUST, H., SAUTER, T. & THEMEßL, M. 2010. Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. *Reviews of Geophysics,* 48.

MASON, S. J. 2001. El Niño, climate change, and Southern African climate. *Environmetrics,* 12**,** 327-345.

MATSON, P. A., MCDOWELL, W. H., TOWNSEND, A. R. & VITOUSEK, P. M. 1999. The globalization of N deposition: ecosystem consequences in tropical environments. *Biogeochemistry,* 46**,** 67-83.

MCGREGOR, J. L. 2005. *C-CAM: Geometric aspects and dynamical formulation,* CSIRO Atmospheric Research Dickson ACT.

MCGREGOR, J. L. & DIX, M. R. 2008. An updated description of the conformal-cubic atmospheric model. *High resolution numerical modelling of the atmosphere and ocean.* Springer.

MILOŠEVIĆ, D., SAVIĆ, S., STOJANOVIĆ, V. & POPOV-RALJIĆ, J. 2015. Effects of precipitation and temperatures on crop yield variability in Vojvodina (Serbia). *Italian Journal of Agrometeorology-Rivista Italiana di Agrometeorologia,* 20**,** 35-46.

MISHRA, B. K., AWAL, R., HERATH, S. & FUKUSHI, K. 2014. Trends and variability of climate and river flow in context of run-of-river hydropower schemes: a case study of Sunkoshi river basin, Nepal. *International Journal of Hydrology Science and Technology,* 4**,** 282-293.

MOELETSI, M. E. 2010. *Agroclimatological risk assessment of rainfed maize production for the Free State Province of South Africa.* University of the Free State.

MOELETSI, M. & WALKER, S. 2012. Rainy season characteristics of the Free State Province of South Africa with reference to rain-fed maize production. *Water SA,* 38**,** 775-782.

MOELETSI, M. E., MOOPISA, S. G., WALKER, S. & TSUBO, M. 2013. Development of an agroclimatological risk tool for dryland maize production in the Free State Province of South Africa. *Computers and electronics in agriculture,* 95**,** 108-121.

MOELETSI, M. E., WALKER, S. & LANDMAN, W. A. 2011. ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa. *Physics and Chemistry of the Earth, Parts A/B/C,* 36**,** 715-726.

MORAKILE, G. 2018. *Survey on Preferred Supplier Base Mechanism for Smallholder Farmers/Cooperatives to Derive Better Access to Government Market.*

MUKHALA, E. & GROENEWALD, D. 1998. Experiences and perceptions of black small-scale irrigation farmers in the Free State. *South African Journal of Agricultural Extension,* 27**,** 1-18.

MUPEDZISWA, R. & KUBANGA, K. P. 2017. Climate change, urban settlements and quality of life: The case of the Southern African Development Community region. *Development Southern Africa,* 34**,** 196-209.

NGONGONDO, C., XU, C.-Y., GOTTSCHALK, L. & ALEMAW, B. 2011. Evaluation of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region. *Theoretical and applied climatology,* 106**,** 79-93.

OLESEN, J. E. & BINDI, M. 2002. Consequences of climate change for European agricultural productivity, land use and policy. *European journal of agronomy,* 16**,** 239-262.

PABLOS, M., MARTÍNEZ-FERNÁNDEZ, J., SÁNCHEZ, N. & GONZÁLEZ-ZAMORA, Á. 2017. Temporal and Spatial Comparison of Agricultural Drought Indices from Moderate Resolution Satellite Soil Moisture Data over Northwest Spain. *Remote Sensing,* 9**,** 1168.

PADGHAM, J. 2009. Agricultural development under climate change: opportunities and challenges for adaptation. *World Bank, Washington DC*.

PARRY, M. L., ROSENZWEIG, C., IGLESIAS, A., LIVERMORE, M. & FISCHER, G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change,* 14**,** 53-67.

PHALKEY, R. K., ARANDA-JAN, C., MARX, S., HÖFLE, B. & SAUERBORN, R. 2015. Systematic review of current efforts to quantify the impacts of climate change on undernutrition. *Proceedings of the National Academy of Sciences,* 112**,** E4522-E4529.

PHILLIPS, O. L., MALHI, Y., VINCETI, B., BAKER, T., LEWIS, S. L., HIGUCHI, N., LAURANCE, W. F., VARGAS, P. N., MARTINEZ, R. V. & LAURANCE, S. 2002. Changes in growth of tropical forests: evaluating potential biases. *Ecological Applications,* 12**,** 576-587.

RICHARD, Y., FAUCHEREAU, N., POCCARD, I., ROUAULT, M. & TRZASKA, S. 2001. 20th century droughts in southern Africa: spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. *International Journal of Climatology,* 21**,** 873-885.

RIHA, S. J., WILKS, D. S. & SIMOENS, P. 1996. Impact of temperature and precipitation variability on crop model predictions. *Climatic Change,* 32**,** 293-311.

RUMMUKAINEN, M. 2010. State-of-the-art with Regional Climate Models. *Wiley Interdisciplinary Reviews: Climate Change,* 1**,** 82-96.

RUSSO, S., MARCHESE, A. F., SILLMANN, J. & IMMÉ, G. 2016. When will unusual heat waves become normal in a warming Africa? *Environmental Research Letters,* 11**,** 054016.

SALAS, J. D. 1980. *Applied modeling of hydrologic time series*, Water Resources Publication.

SCHOLES, R., SCHOLES, M. & LUCAS, M. 2015. *Climate Change: Briefings from Southern Africa*, Wits University Press.

SENEVIRATNE, S. I., DONAT, M., PITMAN, A., KNUTTI, R., WILBY, R., VOGEL, M. & ORTH, R. Allowable CO2 emissions based on regional and impact-related climate targets: The role of land processes. AGU Fall Meeting Abstracts, 2016.

SENEVIRATNE, S. I., NICHOLLS, N., EASTERLING, D., GOODESS, C. M., KANAE, S., KOSSIN, J., LUO, Y., MARENGO, J., MCINNES, K. & RAHIMI, M. 2012. Changes in climate extremes and their impacts on the natural physical environment.

SHAW, R. H. 1988. Climate requirement. *Corn and corn improvement***,** 609-638.

SHONGWE, M. E., VAN OLDENBORGH, G., VAN DEN HURK, B., DE BOER, B., COELHO, C. & VAN AALST, M. 2009. Projected changes in mean and extreme precipitation in Africa under global warming. Part I: Southern Africa. *Journal of climate,* 22**,** 3819-3837.

SMALE, M. & JAYNE, T. 2014. Maize in Eastern and Southern Africa:"Seeds: of success in retrospect. EPTD (Environment and Production Technology Division) discussion paper no. 97. International Food Policy Research Institute. Online.

SMIT, B. & WANDEL, J. 2006. Adaptation, adaptive capacity and vulnerability. *Global environmental change,* 16**,** 282-292.

SNYDER, C., BRUULSEMA, T., JENSEN, T. & FIXEN, P. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment,* 133**,** 247-266.

SOLOMON, S. 2007. *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC*, Cambridge University Press.

STEFFEN, W., SANDERSON, A., TYSON, P., JÄGER, J., MATSON, P., MOORE, B., OLDFIELD, F., RICHARDSON, K., SCHELLNHUBER, H. J. & TURNER, B. 2005. The Anthropocene era: How humans are changing the Earth system. *Global Change and the Earth System: A Planet Under Pressure***,** 81-141.

STEWARD, P. R., DOUGILL, A. J., THIERFELDER, C., PITTELKOW, C. M., STRINGER, L. C., KUDZALA, M. & SHACKELFORD, G. E. 2018. The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields. *Agriculture, Ecosystems & Environment,* 251**,** 194-202.

Thornton, P.K., Lipper, L., Baas, S., Cattaneo, A., Chesterman, S., Cochrane, K., Young, C.D., Ericksen, P.J., van Etten, J., Clerck, F.D. and Douthwaite, B., 2013. How does climate change alter agricultural strategies to support food security? Background paper for the conference" Food Security Futures: Research Priorities for the 21st Century" held in Dublin, Ireland, 11-12 April 2013.

THORNTON, P. K., JONES, P. G., ALAGARSWAMY, G. & ANDRESEN, J. 2009. Spatial variation of crop yield response to climate change in East Africa. *Global Environmental Change,* 19**,** 54-65.

THORNTON, P. K., JONES, P. G., ERICKSEN, P. J. & CHALLINOR, A. J. 2011. Agriculture and food systems in sub-Saharan Africa in a 4 C+ world. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* 369**,** 117-136.

TYSON, P. D., DYER, T. G. & MAMETSE, M. 1975. Secular changes in South African rainfall: 1880 to 1972. *Quarterly Journal of the Royal Meteorological Society,* 101**,** 817-833.

VAN DEN BERG, J., HILBECK, A. & BØHN, T. 2013. Pest resistance to Cry1Ab Bt maize: Field resistance, contributing factors and lessons from South Africa. *Crop Protection,* 54**,** 154-160.

VAN ITTERSUM, M. K., VAN BUSSEL, L. G., WOLF, J., GRASSINI, P., VAN WART, J., GUILPART, N., CLAESSENS, L., DE GROOT, H., WIEBE, K. & MASON-D'CROZ, D. 2016. Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences,* 113**,** 14964-14969.

VIALE, M. & GARREAUD, R. 2015. Orographic effects of the subtropical and extratropical Andes on upwind precipitating clouds. *Journal of Geophysical Research: Atmospheres,* 120**,** 4962-4974.

VON CAEMMERER, S. & FURBANK, R. T. 2016. Strategies for improving C 4 photosynthesis. *Current opinion in plant biology,* 31**,** 125-134.

VON STORCH, H. 1999. Misuses of statistical analysis in climate research. *Analysis of Climate Variability.* Springer.

Wang, G. and AB ELTAHIR, E.L.F.A.T.I.H., 2002. Impact of CO2 concentration changes on the biosphere-atmosphere system of West Africa. *Global Change Biology*, *8*(12), pp.1169-1182.

WANG, B. & ZOU, H. 2018. Another look at distance-weighted discrimination. *Journal of the Royal Statistical Society: Series B (Statistical Methodology),* 80**,** 177-198.

WRI 2007. Nature's benefits in Kenya, an atlas of ecosystems and human well-being. .

XIE, S.-P. 2004. The shape of continents, air-sea interaction, and the rising branch of the Hadley circulation. *The Hadley Circulation: Present, Past and Future.* Springer.

XUE, Y. 1997. Biosphere feedback on regional climate in tropical North Africa. *Quarterly Journal of the Royal Meteorological Society,* 123**,** 1483-1515.