OBSERVED AND PROJECTED CLIMATE CHANGE EFFECTS ON LOCALIZED DROUGHT EVENTS: A CASE STUDY FOR SUGARBELT WITHIN KWAZULU-NATAL MIDLANDS, SOUTH AFRICA

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Agrometeorology School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science (CAES), University of KwaZulu-Natal (UKZN), Pietermaritzburg Campus, South Africa. The research was financially supported by University Capacity Development Programme and UKZN CAES through Trioka Funds.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

[redacted]

Signed: Professor MJ Savage

Date: 11 April 2021

DECLARATION 1: PLAGIARISM

I, Zoleka Ncoyini, declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

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Date: 11/04/2021

DECLARATION 2: PUBLICATIONS IN PREPARATION

This thesis is presented in a manuscript format. Specific manuscripts are either in preparation or have been submitted to a journal.

Chapter 2

Z. Ncoyini*, M.J. Savage, S. Strydom, 2020. Historic and future climate parameters trends and its impact on drought and local farming: a review. I reviewed the literature and prepared the manuscript. In preparation.

Chapter 3

Z. Ncoyini*, M.J. Savage, S. Strydom, 2020. Observed extreme precipitation and air temperature trends for 1966-2017 within the sugarbelt area, Kwazulu-Natal midlands, South Africa. Manuscript submitted for publication in Weather and Climate Extremes Journal.

Chapter 4

Z. Ncoyini*, M.J. Savage, S. Strydom, 2020. Reference evaporation and drought prevalence under climate change conditions in the Wartburg area of the midlands of Kwazulu-Natal, South Africa. In preparation.

Chapter 5

Z. Ncoyini*, M.J. Savage, S. Strydom, 2020. The impact of climate change on drought in the rural agricultural community of Wartburg, Kwazulu-Natal, South Africa. In preparation.

Chapter 6

Z. Ncoyini*, M.J. Savage, S. Strydom, 2020. Limited access to climate information hampers the use of climate information by small-scale sugarcane farmers in South Africa: a case study. Manuscript submitted for publication in the Journal Climate Services.

ABSTRACT

The projected increase of air temperature across the globe has been associated the increased vulnerability of resource-poor farming communities to climate variability. Past and possible changes in climate trends for the study area within the KwaZulu-Natal (KZN) midlands sugarcane belt are presented in this study. An analysis of the climatic trend for two time-periods (1966-1994 and 1997-2017) is undertaken. Various analytical tools which include Expert Team on Climate Change Detection and Indices (ETCCDI), the Penman-Monteith model, linear regression and Man-Kendall (MK) test, the de-trended method, surface humidity index (SHI), Run's theory, statistical downscaling method (SDSM), drought indices and a survey through questionnaires were applied.

The ETCCDI analysis showed that air temperatures during day-time have become warmer resulting in a decrease in the number of cool days. with night-time air temperatures showing an opposite trend. The Penman-Monteith model results showed a statistically insignificant decreasing short-grass reference evapotranspiration (ETo) trend for the study site for the 1966 to 2017. The statistical downscaling results indicated an increasing trend for both minimum and maximum air temperature for the period of 2011-2099.

Except for the results of extreme minimum air temperature, the results of the study are consistent with other climate studies conducted worldwide. Nevertheless, the findings of this study provide evidence that despite the general global warming observation across the world, there are areas that experience a paradoxical minimum air temperature trend that is often overlooked in global and national studies. The study also emphasizes the possible influence of microclimate on climate trends. Most importantly, the study results highlight the critical role that individual local weather stations play in informing local farming communities and relevant stakeholders that are less knowledgeable about local climate change.

Descriptive analysis based on the survey data for the study area found that the majority of the small-scale sugarcane farmers (69%) in the study area are poorly informed about the accessibility, availability and possible use of climate information. A large number of the participants (> 50%) have never used either seasonal climate information or climate warnings in their decision making. The few individuals (31%) who have received the information from different sources highlighted the delayed delivery of the information. Despite significant progress on climate modelling and possible information dissemination channels, access to

climate information by small-scale farmers still has not improved and many have not captured the substance of climate change. This finding needs a further investigation.

The study is useful in informing land-use planning decisions based on the observed and projected climate trends. Through identification of possible impacts of increased extreme rainfall and decrease in short grass reference evapotranspiration as well as projected changes in air temperature and precipitation, the sugarcane farming community can determine whether sugarcane farming will be commercially viable under climate change conditions or determine sugarcane varieties that align with the detected and projected climate changes of the study area.

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CHAPTER 1: INTRODUCTION

1.1 Rationale for the research

There is growing evidence that local climate could respond differently to climate change in physiographically diverse regions. This is substantiated by increasing inconsistency and incoherency in precipitation extreme trends among neighbouring stations (New, 2006; Mekasha et al., 2013). The literature also highlights that the degree of agricultural susceptibility to climate change hinges on diverse local environmental and management factors. KwaZulu-Natal (KZN) is one of the provinces with fewer weather stations compared to the rest of the provinces in the country. Thus, the majority of studies conducted in South Africa at a national level are limited to the use of data from only about five stations across the whole province (Kruger, 2006; Kruger & Sekele, 2013). The province has a varied climate altogether, with the north inland climate different from that of the south coast. Thus, the inclusion of an acceptable number of stations for different climate zone is always advisable to ensure that the findings are the true representation of the area.

This study, therefore, uses data from weather stations that have not been included in the previous studies to investigates the effects of climate change on localized extreme weather events, particularly drought in the KZN midlands, South Africa. This study specifically focuses on a sugarcane area in the midlands, which most past studies have not included in their analysis.

1.1.1 Background and justification for the study

Globally, evidence shows that the mean surface temperature has been increasing since the 19th century (Allen et al., 2018). Over the past two decades, southern Africa's surface temperature has been rising twice the rate of global temperature increase (Engelbrecht et al., 2015). This increase has been associated with changes in rainfall patterns and increased frequency of extreme weather events such as floods, drought, and wildfires. There is high confidence that the characteristics of extreme weather events and climate events over Africa will continue to change due to climate change (IPCC, 2014).

A general shift from a wet condition to a drier condition has been observed in southern Africa (Meque, 2015). South Africa recently experienced the most severe and prolonged drought in the country since the 1940s, particularly for regions such as north-eastern Mpumalanga, part of eastern Free State and northern KwaZulu-Natal (Swemmer et al., 2018). Although the event was not induced by climate change, its severity and intensity are likely to have been influenced by increased heat due to global warming (Trenberth et al., 2014; Vicente-Serrano et al., 2014). The effects of such changes in climate conditions are anticipated to have different effects across various regions. Different areas within South Africa can have different experiences from the same climate extremes. This is because the effects of specific extreme weather events are not only determined by the intensity and severity of the event, but also by the pre-existing conditions. For example, at a national scale, the 2014/15 drought was less severe compared to the previous drought events in the 1960s, 1980s, and 1990s (Swemmer et al., 2018). However, for provinces such as KZN, Mpumalanga, and Free State the 2014/15 drought events were more severe (Swemmer et al., 2018). Such differences are also influenced by the spatial and temporal variation of precipitation within the provinces.

KwaZulu-Natal is characterized by a varied climate due to its diverse and complex topographic nature. Kruger (2006) confirmed the heterogeneity of rainfall trends across districts in South Africa. This heterogeneity suggests that in order to understand the increased vulnerability of farming communities to climate change effects owing to fewer resources (Alig & Mercer, 2011), local studies are necessary to assist in the development of local adaptation based on local experiences.

1.1.2 Possible changes in microclimate as global warming continues

Different approaches have been employed to understand the changes in microclimate as global warming intensifies. The changes in microclimate range from variation in historical extreme weather trends, historical grass reference evaporation (ETo) trends and projections of future drought events. In addition, the strategies adopted by farmers in order to deal with such changes has been a serious concern.

1.1.2.1 Historical drought and extreme precipitation trends

Climate Change Detection, Monitoring, and Indices as recommended by Expert Team (ET) on Climate Change Detection, and Indices (ETCCDI) is one of the widely used approaches to study climate change throughout the world (Zhang, 2013). The indices focus primarily on climate extremes derived from daily weather station data. Computations of extreme indices enable investigation of changes in air temperature and precipitation related extreme trends at a station resolution. However, until recently studies that address climate change implications have always been at a relatively large scale. Yet previous studies have shown that effects of global warming on a national level or above can conceal the effects at a field or local scale (Pielke et al., 2002; Shongwe et al., 2009). Mackellar et al. (2014) . In other words, the effects of global warming at a nation scale can hide the effects at field or local level. Kruger & Nxumalo (2017) provided updated analysis on the trends on rainfall and air temperature in South Africa.

However, these studies did not include weather stations in the sugar belt areas of the KZN province in South Africa. Despite the close proximity (over 50 km apart) of the weather station used in these studies to the sugar belt area in KZN midlands, precipitation can vary significantly within a short distance. While changes in the average of climate variables may be relatively small, changes in the frequency and intensity of climate extremes may be larger (Jobert & Hewitson, 1997). Also, different weather stations in the study area indicated differences in long-term local changes in the microclimate of the study area (Strydom & Savage, 2018).

1.1.2.2 Historical ETo trends

The differences in the long-term trends of various microclimate factors in the study site can have a significant effect on evaporation trends. The potential changes in evaporation demands as a result of global warming can have a significant implication for water resources. However, very few effective measurement techniques exist for monitoring actual evapotranspiration at an appropriate scale. Water movement to the atmosphere is quite complex as it is affected by temporal and spatial changes of effective parameters which include plant cover, crop-specific water-use efficiency, and climatic conditions (Jerszurki et al., 2017). As such empirical methods have become popular for estimating evaporation from crops.

The ETo is widely used as the basis for estimating crop evapotranspiration and computing specific crop water requirements (Kosa, 2009; Gu et al., 2017). It is defined as the evaporation rate of the reference crop that is free from water stress and diseases. Allen et al. (1998: pg 5) specifically defined reference evaporation as “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sm^{-1} and an albedo of 0.23".

The use of ETo enables a realistic characterization of microclimate effects of a field evaporative transfer of water from soil-plant surfaces to the atmosphere (Tabari et al., 2016). Although there are several empirical methods to estimate ETo, the Penman-Monteith (PM) method has been recommended as the universal standard by the Food and Agriculture Organization of the United Nations (FAO) to determine ETo (Allen et al., 1998) at either hourly or daily times scales and for short-grass and tall-crop surfaces. The PM technique considers various climatic parameters that influence the evaporation process which includes, solar irradiance (Rs), air temperature (Tair), wind speed (WND) and water vapour pressure deficit based on relative humidity (RH). Global warming affects microclimates through subsequent changes in solar radiation, absolute humidity, net terrestrial radiation and precipitation which in turn influence ETo (Collins et al., 2013). The response of evaporation to changes in Rs, WND, Tair and RH is well comprehended (Liu & Zeng, 2004; Kousari et al., 2012; Xu et al., 2014; Sun et al., 2017; Ma et al., 2017). However, the correlation of ETo with changes in rainfall is relatively unclear. Atmospheric humidity mainly depends on the surface moisture content that is linked to rainfall trends directly influences the evaporative demand of the atmosphere. The surface humidity index (SHI) (Hulme et al., 1992) is a useful tool for evaluating the correlation between rainfall and ETo.

1.1.2.3 Climate change and projected future adverse weather events

According to the Clausius-Clapeyron law described by Trenberth (2006), as the atmospheric heat increases the ability of air to hold water vapour will increase stimulating a rise in potential evapotranspiration. According to Penman (1956), potential evapotranspiration is defined as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height, and with adequate water status in the soil profile" (Allen et al., 1998: pg 5). The effects of an increase in potential evapotranspiration will manifest through changing the hydrological cycle leading to more precipitation extremes (Trenberth, 2006; Abiodun et al., 2017).

Global and regional future predictions are conducted consistently to understand the impacts of climate change on the hydrological system. However, the results from either global or regional studies are obtained from Global Climate Models (GCMs) or an average of meteorological observations (Mason et al., 1999; New et al., 2006). On the other hand, studies conducted at a national scale often include only a few weather stations that meet their data requirements of a continuous record (Kruger, 2006; Kruger & Nxumalo, 2017). This shows a gap in understanding the possible future climate variation in local areas, especially areas that either has poor climate data or lack the weather stations to provide the necessary data. As a result, there is still uncertainty about possible scenarios for future agriculture production under a shifting climate, particularly for the rural communities that depend on agriculture (Schreiner et al., 2018).

In order to understand the impact of climate change on a local scale, downscaling GCM data to the finer resolution is recommended. Downscaling is the process that is used to derive fine-resolution spatial or temporal climate information from coarse-resolution GCM data. Downscaling of GCM data enables identification and analysis of extreme events at a specific location (Wilby et al., 2002).

Future predictions of air temperature and rainfall changes using different plausible scenarios are the basis for future drought assessment. Generally, statistical and dynamical downscaling techniques are used for climate change projections. However, the statistical downscaling method has been widely preferred (Manhood & Babel, 2012; Mtongori, 2016; Saymohammadi et al., 2017). Statistical downscaling is preferred because of its major advantages which include easy applicability of statistical downscaling (SD) to any GCM output; being computationally inexpensive; ability to provide site-specific information from GCM scale output; ability to derive variables that are not available from RCMs; and can directly incorporate observations into a method (Chen et al., 2011). Because of the complex climate systems which are generally associated with uncertainties, the use of multiple GCMs for future climate projections is recommended. As such scenarios from both the models provided by the Coupled Model Intercomparison Project (CMIP5) phase 5 (CanESM2) (Gillet et al., 2012; Stott et al., 2013) and Hadley Centre (HadCM3) (Johns et al., 2003; Chou et al., 2012) have been used in this study. The projected climate based on Representative Concentration Pathway (RCP) 8.5 and 4.5, as well as Special Report of Emission Scenarios (SRES) scenarios A2 and B2, enables estimation of drought events through drought indices. Using data derived from the GCM projections of future precipitation and air temperature trends, drought indices can be computed.

Drought indices basically convert precipitation and/or air temperature data into probabilities on medium-terms precipitation or climatic water balance (i.e the difference between precipitation and reference evapotranspiration (P – ETo) records into a normal distribution with an average and a standard deviation of 0 and 1, respectively (Botai et al., 2019). According to the drought classification, a drought exists when the drought index reaches a value of -1 and below and should last for at least one month (Lee at al., 2017).

Drought indices have been widely used for computing, monitoring and analysing drought patterns across the world. Both historical and projected changes in climate are believed to have an influence on drought occurrences as well as severity and intensity. Thus, drought indices, specifically the Standardised Precipitation Index (SPI) (Mckee et al., 1993) and Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), are found useful for assessing the effects of global warming on drought patterns whereas statistical Run’s theory enables the assessment of variation of future drought characteristics. Hence with increasing probability of climate extremes, such as drought and floods under climate change, timely and effective drought projection as well as the evaluation of changes in drought characteristics has become an important subject. A better understanding of how different locations will be affected by global warming enables 1) vulnerability assessment in order to improve the ability of the vulnerable people to cope with climate change (Xu et al., 2020) 2) accurately modelling of responses of the ecosystem so as to understand the subsequent shift in the distribution of species due to climate change as well as to describe the resilience of species and ecosystem to changes in climate (Nitschke &Innes, 2008) 3) potential threats identification and 4) effective adaptation strategy development to increase small-scale farmers resilience and minimise possible losses (Adzawla et al., 2020).

1.1.2.4 Access to climate information as an adaptation tool

Climate extremes can directly and indirectly impact agricultural productivity, which raises concerns for the sustainability of small-scale farmers' livelihoods. It is likely that under climate change conditions, indigenous knowledge may not be applicable as rainfall patterns have become irregular. Thus, other possible ways to help farmers cope with climate change are needed. While most researchers believe that the use of seasonal climate information can assist farmers to cope and adapt to changing climate conditions, insufficient uptake and use of seasonal forecasts by small-scale farmers have been reported (Vogel, 2000; Ziervogel and Calder, 2003; Chisadza et al., 2020). Despite the progress in assessing the impact of forecast use amongst small-scale and smallholder farmers, these studies have focused on ex-post evaluation through monitoring actual access to forecast by farmers and how farmers benefit from using the forecast. The limitations of these studies are that results are geographically restricted and cannot be scaled up.

1.2 Aims and objectives

The main aims of the research projects are discussed in this section. The objectives of the study, in order to achieve the main aim, are explored.

1.2.1 Aims

The main aim of the study is to assess historical and future extreme weather changes, particularly drought, within the sugarcane areas in the midlands of KwaZulu-Natal.

The study intends to achieve the following aims:

1. analyse the historical trends of air temperature and precipitation extremes;
2. investigate the effects of dry conditions on the ETo trends;
3. model the possible future changes in the KZN midlands drought characteristics;
4. quantify the benefits of accessing climate information by small-scale sugarcane farmers to mitigate the prospective impacts of adverse weather.

1.2.2 Specific objectives

The specific objectives are:

1. an analysis of historical air temperature and precipitation trends in the KZN midlands using the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang, 2013);
2. computation of ETo using the PM method and analysis of ETo trends as well as studying the effects of drought on ETo using drought indices (SPI) and SHI;
3. employ HadCM3 and CanESM2 models to simulate future changes in KZN drought using a statistical downscaling model and drought characteristics using Statistical Run's theory

4. the evaluation of the access to and use of climate information to small-scale sugarcane farmers through the use of questionnaires to gather information on whether farmers do access the information or not.

1.3 Outline of the thesis structure

Each chapter of the thesis is independent, with the experimental chapters containing an introduction, materials and methods, results, discussion and conclusions sections.

Chapter 2 focuses on previous research on climate change and associated impacts on adverse weather occurrence. The emphasis is on describing the importance of considering the geographically, socio-economic and vulnerability differences within the region in climate change impact studies. The modelling of future climate changes is also discussed.

Chapter 3 is the first experimental chapter that focuses on the historical trends of air temperature and precipitation in the sugarcane area in the KZN midlands. Using ETCCDI (Zhang, 2013), air temperature and precipitation extremes from four different weather stations in the study site were analysed.

Chapter 4 is devoted to the understanding of the annual and seasonal long-term ETo trends. Computation of daily ETo is presented. The correlation between dry conditions and ETo derived through the use of SPI and SHI is also discussed.

In Chapter 5, a statistical downscaling model is utilized to model the future air temperature and precipitation trend for the study site. In this chapter, the simulated possible future microclimate data were used to detect potential drought events using drought indices (SPI and SPEI). Drought duration, intensity and severity based on Run's Theory are also presented.

Chapter 6 focuses on the accessibility and use of climate information by small-scale sugarcane farmers as one of the tools to mitigate and adapt to climate change and adverse weather conditions. Through face to face interviews and questionnaires data on access to, the use and the benefits of using climate information was collected and analysed.

Chapter 7 documents the overall conclusion of the study, revisits the aims and objectives, the main contribution of the research, the limitations encountered and possible future research.

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Lead to Chapter 2

In the previous chapter, the effects of global warming on climate change and the variation of climate across the province due to differences in terms of proximity to the ocean and elevation were pointed out. Thus, the importance of including local weather stations in climate change assessment studies is highlighted. Chapter 2, therefore, presents reviews of the climate change implication for South Africa, projected changes in climate, the subsequent effects of climate change on different climate parameters and crop yields as well as adaptation to climate change.

CHAPTER 2: HISTORICAL AND FUTURE CLIMATE PARAMETERS TRENDS AND IMPACT ON DROUGHT AND LOCAL FARMING: A REVIEW.

2.1 Abstract

Climate extremes, such as drought, floods and heatwaves can cause crop yield losses and threaten the livelihoods and food security of farming communities throughout the world. Although such extremes are experienced by both large-and small-scale farmers worldwide, there is consensus that small-scale farmers are particularly vulnerable due to their direct dependence on agricultural production and a wide range of challenges already facing small-scale farmers.

Various reports, papers, and article documents related to the observed and projected changes on extreme air temperature and rainfall in South Africa and other parts of the world are reviewed. The projected changes in drought event occurrences as well as the use of climate information as a coping mechanism to minimize the adverse impacts of climate extremes on agricultural production were also reviewed. According to the reviewed literature, there has been a consistent upward air temperature trend in most parts of South Africa whereas the rainfall trend was found to be inconsistent.

It is widely acknowledged that ETo sensitivity to different meteorological variables differs from one region to another. As such, global and regional ETo trends do not follow a similar pattern, with global ETo showing an increase while regional ETo was found to be decreasing in many parts of the world. The contrasting ETo trends indicate the diverse response of ETo to heterogeneous climate conditions experienced worldwide.

The downscaling of climate data to obtain high resolution for impact assessment studies using Global Circulation Models (GCMs) stimulated different ideas within the research community. Downscaling, using either the statistical or dynamical method, is still preferable for assessing local and regional climate compared to the use of raw GCM output.

Throughout the world almost all farmers, both large-and small-scale have, experienced climate change and are faced with the impacts. However, due to the different coping mechanisms and adaptation abilities, the severity of climate change impacts substantially differs between the two groups of farmers.

Keywords: *Drought; Downscaling Method; Climate Change and Climate Projections*

2.2 Introduction

The definitions of climate change, climate extremes, and drought as well as the causes of droughts in general are presented and the effects of climate change on the observed and projected drought trends in southern Africa are reviewed. The influence of increasing air temperature and decreasing precipitation on reference evapotranspiration are also discussed, given that evapotranspiration contributes towards drought occurrences. An overview of the observed and projected effects of climate change and drought on the different spatial scales is presented. National adaptation and mitigation strategies to climate change are reviewed to ascertain their effectiveness at a local level.

2.3 Definitions and concepts

2.3.1 Climate change and climate or weather extreme

Climate change is generally described as changes in weather conditions and the distribution of weather compared to the long-term average conditions. These changes are not restricted to a specific meteorological variable but include all forms of climate deviations despite their physical causes (Intergovernmental Panel on Climate Change (IPCC), 2007; IPCC, 2018). Although climate change is often associated with anthropogenic forcing, it can also result from natural forcing (Cubasch, et al., 2013; IPCC, 2018). According to the fifth assessment report of IPCC (2014:pg 5: IPCC, 2018:pg 6), climate change is referred to "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer". No universal definition exists for an extreme climate event. However, Otto et al. (2015) described an extreme weather event as a rare phenomenon driven by changes in external climatic drivers. Such changes include daily air temperature, daily rainfall, remarkably warm monthly air temperatures and hurricanes. These events can also be defined by the impact an event has on society (Easterling et al., 2000). The IPCC (2018) defined an extreme event as the occurrence of weather parameter above (or below) a threshold value near the upper (or lower) end of its observed range in a specific region. In simple terms, extreme weather events may be defined as exceptional and rare events at a specific location and period. These conditions can range from the small spatial scale (cyclones, floods) to large scale (droughts and heat).

Weather and climate extreme events are a result of natural climate variability and form part of climate variability. Cubasch et al. (2013) indicates that climate change either as a result of anthropogenic or natural forcing can lead to changes in the likelihood of occurrence and severity of extreme and climate events. This implies that even in the absence of anthropogenic forcing of climate, different forms of natural weather and climate extremes would still take place. The implication is that anthropogenic climate change does not cause weather and climate extremes, rather it causes changes in the likelihood and timing of their occurrence, their magnitude, the spatial extent, the duration of the extremes which may lead to unprecedented extremes (Field et al., 2012). Also, it is difficult to know where and when an extreme event will occur as well as how it will occur. Some extreme events are the consequence of accumulated weather or climate events that are individually not considered extreme for example a continuous rainfall or lack of over an extended period may result in a flood and drought (Seneviratne et al., 2012) while others develop strictly as extreme events (e.g a hailstorm and cyclone). Hence, it is quite challenging to accurately predict the occurrence of weather and climate extremes.

2.3.2 Drought

Drought is part of natural climate variability that takes place virtually throughout the world, even in high rainfall areas (Wilhite & Glantz, 1985). Drought characteristics differ both in space and time for different regions. Unlike other extreme events, drought usually develops slowly over a large area and can develop over both short periods and extended periods of various seasons. Because drought develops gradually, it is difficult to identify and often gets recognition once water-shortages are established (Wilhite & Glantz, 1985). Until there are obvious effects of inadequate water supply on human activity, below-normal precipitation is not perceived as drought (Maybank et al., 1995). Several definitions of drought have been proposed based on case-specific conditions. For example, Redmond (2002) defined drought as an inadequate supply of water to meet demands. Spinoni et al. (2014) defined drought as a temporary climate aberration associated with low rainfall and differs from permanent aridity. Aladaileh et al. (2019) defined drought as longer periods of inadequate precipitation relative to the long-term average for a particular area. According to Hassan Gana (2018), drought is the shortage of rainfall or water that affects people’s livelihood and the environment, both directly and indirectly.

Drought is among the least understood and least manageable climate phenomena affecting the world in recent times (Eslamian et al., 2017). Wilhite & Glantz (1985) emphasized the use of different definitions of drought as drought affects many sectors differently within society. As a result, drought is categorized into two definitions, that is, conceptual and operational. Conceptual drought definitions are general definitions that lack relevance to the current situation while operational definitions include definitions that describe the beginning, the duration and the end of the drought event (Hisdal et al., 2000). Operational drought definitions are typically classified into four categories, that is, meteorological, hydrological, agricultural and socioeconomic drought. These definitions provide a clear understanding of the process of drought occurrence and its subsequent environmental and socioeconomic impacts. Yu et al. (2015) emphasized that in general, drought occurrence is induced by below-normal precipitation (meteorological) which results in reduced soil moisture affecting crop growth (agricultural) and reduced streamflow and reservoir levels (hydrological) thus affecting social and economic activities (socioeconomic). Maybank et al. (1995) pointed out that a simple shortfall in precipitation does not constitute a drought event, but it must be an insufficiency that falls short the normal or anticipated amount.

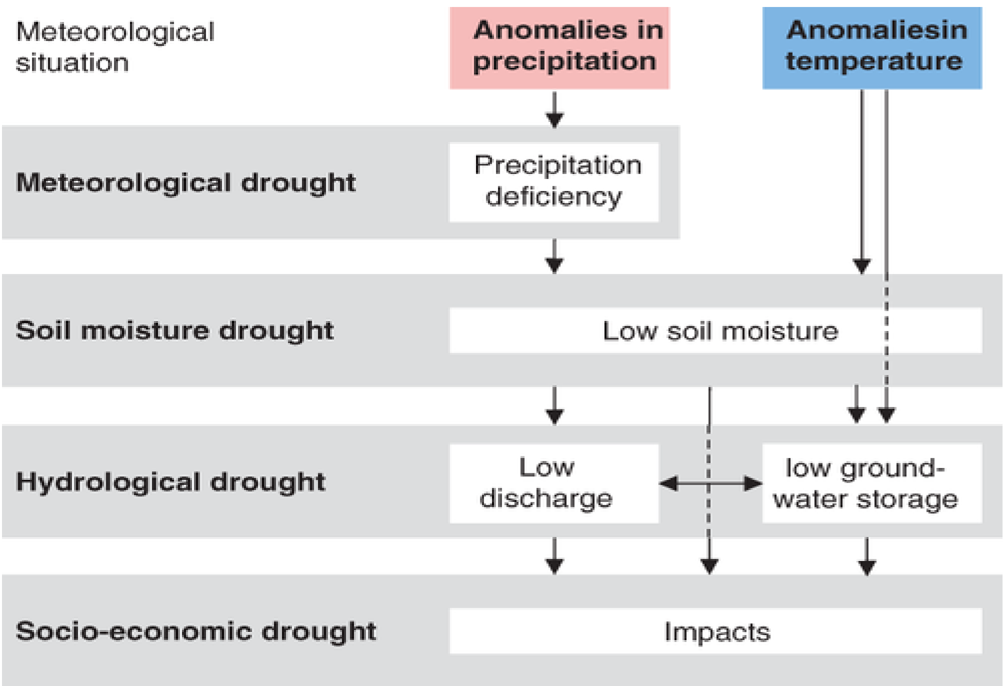

Figure 2.1:Scheme representing different categories of drought and their development (adapted from Van Loon, 2015)

2.4 Climate change over southern Africa and South Africa

There has been ongoing research on climate-observed trends and projected trends for southern Africa as well as South Africa. This section reviews the previous work regarding climate change effects on climatic variables, particularly air temperature and rainfall at regional and national levels.

2.4.1 Observed climate trends and signals of climate change

For southern Africa, New et al. (2006) used air temperature indices calculated through RClimDex software (Zhang & Yang, 2004) to assess near-surface air temperature trends for southern Africa. An increase in hot days and warm nights were reported throughout the region, with hot days increasing faster (5 days decade^{-1}) than the warm nights increase (3 days decade^{-1}) over 1961-2000. The study also showed that the number of extremely hot (95th percentile) days and nights have increased by more than 8 days decade^{-1}). Also, Davis-Reddy & Vincent, 2017) in their study found that warming has been noticeable in southern Africa since the 1970s and attributes the warming partly to air temperature increases during the summer and autumn months (Fig. 2.2). Jury (2013) used data from the Global Historical Climate Network (GHCN) for the surface air temperatures to present air temperature trends. Despite different values given by different models, the study indicated an upward trend of up to more than 0.4 °C year^{-1}.

Rainfall indicators across different countries have shown different results for rainfall trends in southern Africa. Fauchereau et al. (2003) reported that, based on the review studies on modelled rainfall changes under a doubled-CO_2 concentration and findings of the observed changes in daily and seasonal rainfall, rainfall variability has changed substantially. This change showed an increase in interannual variability since the late 1960s. Contrary to these findings, New et al. (2006) reported that the overall results suggest that daily rainfall intensity has increased while the total rainfall and days with heavy rainfall showed a decrease. Another study also detected insignificant statistical evidence of substantial general wetting or drying across the region as it is mainly marked by a strong variation between months and years (Fig. 2.3) (Davis-Reddy & Vincent, 2017). Drought events are reported to have become more intense and widespread (Masih et al., 2014).

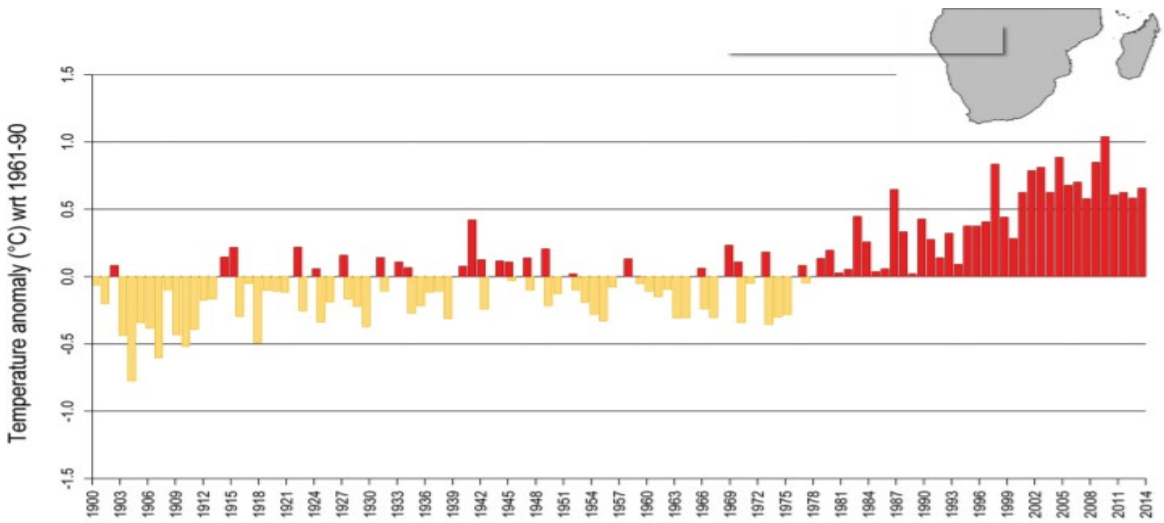

Figure 2.2: Mean annual air temperature anomaly (°C) over southern Africa from 1900 to 2014 with respect to the long-term average climatology 1961-1990; based on the gridded CRUTEMv4 data set. Red represents a positive anomaly and yellow a negative temperature anomaly (Davis-Reddy & Vincent, 2017).

At a national level, several studies on air temperature response to the rising GHG concentration in the atmosphere have been conducted. For example, Hughes & Balling (1996), Kruger & Sekele (2013), Mackellar et al. (2014) and Kruger & Nxumalo (2017a) have investigated changes in past air temperature trends across South Africa. Hughes and Balling (1996) examined air temperature trends for urban and non-urban areas for 1885 to 1993 and reported that an air temperature increase in the last three decades of the study period was as a result of urbanization and an overall increase in regional air temperature.

For 1960-1990, maximum air temperature (Tmax) increased consistently throughout South Africa, irrespective of the spatial scale or the location of the station (Hughes & Balling, 1996). Maximum air temperature showed a statistically insignificant increasing rate of 0.11 ^{o}C decade^{-1} for small towns while an increase of 0.12 ^{o}C decade^{-1} was observed for cities. Minimum air temperature (Tmin) was found to increase at a slower rate of 0.07 ºC decade^{-1} at non-urban stations and this increase was non-significant. Significant increasing Tmin trends were recorded for large cities (0.34 ^{o}C decade^{-1}) (Hughes & Balling, 1996).

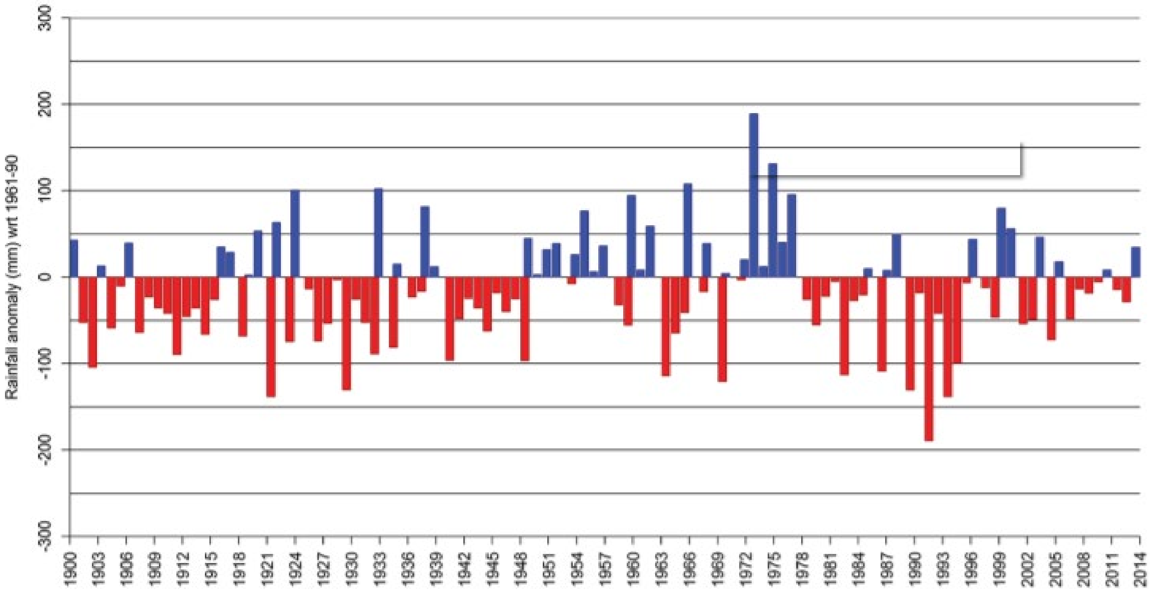

Figure 2.3: Mean annual rainfall anomaly (mm) over southern Africa from 1901 to 2014 with respect to the long-term average climatology 1961-1990; based on the gridded CRU TS 3.23 data set. Red represents positive anomaly and blue a negative anomaly (Davis-Reddy & Vincent, 2017.

Also, Kruger & Sekele (2013) investigated extreme air temperature trends for 28 stations from 1960 to 2009. The study employed RClimDex software to compute ten core sets of temperature indices as described by the Expert Team on Climate Change Detection and Indices (ETCCDI). These indices enable a description of specific characteristics of extremes, such as frequency, intensity and persistence. The analysis confirms an increase in warm extremes and a decrease in cold extremes. These changes were more pronounced in the western half of the country, parts of the northeast and east relative to other parts of the country (Kruger & Sekele, 2013). A recent study (Jury, 2018) also indicated that South Africa has experienced significant warming of more than 0.02 °C yr^{-1} from 1980 to 2014. On the contrary, in their more recent study, Kruger & Nxumalo (2017a) concluded that despite a marked increase in air temperature trends after the 1960s at some stations, the countrywide air temperature trends show no acceleration for the period 1951-2015.

Specifically, in South Africa, statistically significant increases in extreme rainfall have generally been recorded between 1931 and 1990, with major increases in the intensity of extreme rainfall taking place over 1961 to 1990. Mason et al. (1999) concluded that the observed increase in high rainfall events cannot be attributed to global warming. For a similar period (1910-2004), Kruger (2006) also reported that an increase in longer dry periods due to increased sporadic heavy precipitation accompanied by dry periods in-between have been observed in some parts of the country (particularly Free State and Eastern Cape). Significant increases in heavy precipitation were recorded for southern Free State, Eastern Cape and some parts of KwaZulu-Natal. However, despite some significant changes in extreme rainfall events over specified areas, the largest part of the country showed no significant precipitation variation over the study period. Another study, which covered a relatively short period (1960-2010) reported mixed rainfall signals between seasons and across meteorological stations (Mackellar et al., 2014). The study indicated weak regional precipitation trends and emphasized that individual stations exhibit clear trends showing a general decrease of precipitation in autumn (Mackellar et al., 2014). However, due to a lack of spatial coherence in extreme precipitation trends, the study could not conclude whether precipitation extremes trends are increasing or decreasing. In order to provide updates on changes in precipitation trends, Kruger & Nxumalo (2017b) extended the length of the study period (1921-2015) and included more meteorological stations to examine general trends in annual, seasonal and extreme rainfall events in South Africa. The study noted that despite the evident uniformity between the individual station and district rainfall trends, some inconsistency exists. For 1921 to 2015, the study reported an increased annual rainfall in the southern interior while the eastern part showed a decrease. The majority of stations indicated insignificant increases in extreme rainfall while daily rainfall intensity continued to show a significant increasing rate.

2.4.2 Climate change projections

The rapid increase in air temperature and other evidence of climate change worldwide, including the associated impacts of such changes on various sectors, encourages further analyses of future climate (Aguilar et al., 2005; Alexander et al., 2006; Sheikh et al., 2015; Kruger & Nxumalo, 2017). These studies are primarily for ensuring preparedness for climate adaptation and mitigation by different stakeholders. The climate projections for southern Africa and Africa are generated from different scenarios, resolution, methods, and periods (Niang et al., 2014). As a result, there have been speculations that the differences in precipitation trends contribute to the precipitation projections given by various Global Circulation Models (GCMs) (Kwon & Sung, 2019).

Nevertheless, previous studies revealed that anthropogenically induced climate change is likely to manifest through an increase in precipitation extremes instead of changes in long-term average rainfall (Joubert et al., 1996). Also, climate models are found to be more consistent in projecting extreme rainfall events and the number of rainfall days compared to projecting seasonal totals (Pohl et al., 2017).

However, the majority of the studies on climate projection tend to focus on the analysis of precipitation changes (Engelbrecht et al., 2012). For example, Engelbrecht et al. (2009) projected yearly rainfall variation over southern Africa and found that annual rainfall total changes are likely to be less than 10% and insignificant. However, for regions such as south-western Cape of South Africa, north-eastern South Africa, and Zimbabwe, the study projects significant decreases in rainfall. The changes in rainfall were different from the seasonal scale, which showed larger and statistically significant changes over larger areas. However, some studies projected a pronounced decrease in the number of rainfall days, and a substantial increase in rainfall amounts during wet days by the end of the 21st century (Pohl et al., 2017). The prevalence of extreme rainfall was projected for southern Africa (Engelbrecht et al., 2012), with some regions expected to become generally drier, particularly Zimbabwe, Zambia and Angola (Engelbrecht et al., 2011). Shongwe et al. (2009) also predicted the increased probability of extreme wet events accompanied by delays in the start of rainfall season and early termination of the rainfall season in southern Africa. However, they predicted that dry extremes are expected over the western parts of the region.

Downscaling techniques were also utilized to simulate future changes in precipitation at a finer spatial resolution across the region. Kalognomou et al. (2013) used ten Regional Climate Models (RCMs) as specified in coordinated Regional Climate Downscaling Experiment (CORDEX) framework to simulate precipitation (Nikulin et al., 2012) over southern Africa. Their study found biases between observed and the simulated seasonal variability of rainfall. However, after bias correction, RCMs simulated precipitations indicated drier conditions for the southern African region compared to GCMs (Haensler et al., 2011).

Air temperature for Africa, in general, is projected to increase throughout the seasons and at a faster rate relative to the global average during the 21st century (Collins et al., 2013). In southern Africa, the majority of the studies projected air temperature increases of about 3 ºC by 2050 and beyond. For example, a study for the Zambezi Basin indicates that by 2050 a maximum increase of 2.9 ºC in air temperature is projected (Beck & Bernauer, 2011; Graham et al. (2011) predicted a 3 ºC increase for the Thukela Catchment in South Africa for the period of 1961 to 2100, an increase of up to 3 ºC by 2050 was also projected in Zimbabwe (Mujere & Mazvimavi, 2012) and as well as for South Africa, Swaziland and Lesotho (Hewitson & Tadross, 2011). The projected increase in southern Africa is expected to range between 3.5 to 4 ºC by 2050 depending on the season (Daron, 2014). However, earlier studies projected air temperature changes between 2 and 5 ºC by 2080 and 2070s respectively (Arnell et al., 2003; Tadross et al., 2005). Also, studies on air temperature extremes, particularly in South Africa, projected a warming trend. For example, Kruger et al. (2019) using dynamically downscaled data at a resolution of 0.44º x 0.44º analyzed the projected temperature extreme trends based on the ETCCDI across 22 stations in South Africa. The results indicated that South Africa is likely to experience a rising warm night trend (up to 2.5% of warm nights) and declining cold night trends (-2.5 %). This indicates that the southern African region will continue to warm until the end of the 21st century.

2.5 Climate projections for high-resolution areas

Climate projections are mainly performed using GCMs. Global Circulation Models simulate the behaviour of the climate system, its components and their interactions, based on the physical laws. Because of the large size of the climate system and the long-term period that is considered for climate studies, GCM results are often characterized by the spatial and temporal coarseness (Rummukainen, 1997). Consequently, the usefulness of GCMs results at finer resolutions is restricted since the course resolution prevents GCMs from simulating numerous smaller-scale processes and impacts of the terrain which have an influence in shaping regional to local scale climates. The coarse resolution also hinders their application in simulating the changing weather conditions and climate variability over a short-term period, both of which are very useful in predicting the occurrence of impactful climate extremes at regional to local scale (Conlon et al., 2016).

Even though some GCMs have proven to simulate the current atmospheric general circulation at the continental scales, they still show significant errors at smaller scales required for national and regional assessments. These errors are attributable to the inability of the models to explicitly represent small-scale processes (Mtongori, 2016). One way to capture the influences of weather systems and smaller features on the climate is to downscale GCM output. Evidence shows that results from high-resolution limited area models improved their accuracy and they tended to outperform global models in simulating extreme rainfall events (Pohl et al., 2017).

In order to obtain high-resolution projections, two techniques are commonly utilized: the dynamical and statistical downscaling methods. Comparison studies between dynamical and statistical downscaling methods suggest neither of the methods is superior as they perform fairly well in different regions (Hellström et al., 2001; Boe et al., 2007; Tiwari et al., 2019). This indicates that both approaches have comparable skills to produce regional climate data.

2.5.1 Dynamical downscaling

The dynamical downscaling technique is based on Regional Climate Models (RCMs). It utilizes nested modelling in which RCMs are driven by boundary conditions from GCMs (Giorgi et al., 1990). The RCMs are basically the same as GCMs in terms of the formulation of the grid-scale dynamics and sub-scale physics and differ mainly in horizontal resolution and time-step (Mtongori, 2016). For RCMs to simulate regional climate, the large-scale circulation needs to be realized through the lateral boundary conditions (Mtongori, 2016). The RCMs are very useful for supplementing spatial information in the absence of long-term or evenly distributed observations. The drawbacks of RCMs are that they are relatively computationally intensive and subject to errors from the driving model. In addition, RCMs require bias correction before their application. Large amounts of boundary data collected previously from applicable GCM experiments are also a requirement for a successful application of RCMs.

2.5.2 Statistical downscaling

The statistical downscaling technique can be categorized into three: transfer function, weather typing and weather generator. The transfer function is premised on the concept that regional climate is conditioned by two factors: the large-scale forcing and regional/local physiographic features. The transfer function establishes a statistical relationship between large-scale atmospheric variables and local climate (Wilby et al., 2002). The weather typing approach is based on the notion that specific local meteorological variables are linked to certain atmospheric circulation. It thus involves grouping local meteorological variables according to the classes of atmospheric circulation (von Stoch et al., 1993). The weather generator method is based on the modification of its parameters in relation to changes as per GCM projections (Zhang, 2005).

The utility of statistical downscaling is based on four assumptions. The first assumption is that there is a stationarity relationship between large-scale and local variables, meaning the relationship that is derived from the recent climate will be the same in a future climate. In order to explain satisfactorily the local climate variability, there should be a strong link between the local variables (predictand) and the large-scale forcing (predictor). It is also assumed that long-term high quality large-scale and local data are available to sufficiently establish robust relationships in the current climate and that the GCM should be able to accurately simulate the predictor variable (Hellström et al., 2001; Diaz-Nieto & Wilby, 2005).

The major advantages of statistical downscaling are mentioned in **chapter 1**. However, there are drawbacks associated with the application of the SDM which include the failure to verify the stationarity assumption and the unavailability of long-term data to institute a robust relationship. The inconsistency of the strong predictor variables for the current climate change signals as well neglecting land surface forcing and generating regional climates based only on the atmospheric variables despite the contribution of land-use practices to the atmospheric conditions (Mtongori, 2016).

2.5.3 Confidence in using downscaled data for impact studies

The credibility of GCMs future climate projections at global and continental scales has been confirmed (Randall et al., 2007). However, GCM projections at a finer scale have been questioned due to the uncertainty associated with downscaling techniques. Generally, GCM projections are associated with uncertainties that are attributed to different sources such as internal and model uncertainty (Hawkins & Sutton, 2009). Downscaling uncertainty that arises from downscaling methods adds to the existing uncertainties and quantifying it is challenging (Daniels et al., 2012). Alliance (2009) suggested that the quality of downscaled scenarios can be jeopardised due to a failure of the downscaling method to correct GCM errors. Errors from large scale projections are carried through to the regional scale irrespective of the downscaling process. Also, through the downscaling model - models have different characteristics that are not consistent with the GCMs, thus it incorporates local information. As a result, the plausibility, accuracy, and precision of the downscaled data are different from what the GCMs would provide if the spatial resolution was permitting.

The confidence in the reliability of the downscaled outputs partly relies on the ability of the downscaling technique to simulate the baseline climate (Dibike et al., 2008). Many studies have been conducted to analyze the uncertainty in downscaling output due to downscaling methods. For example, Khan et al. (2006) assessed the uncertainty associated with different statistical downscaling techniques such as Statistical Downscaling Model (SDSM), Long Ashton Research Station Weather (LARS-WG) and Artificial Neural Network (ANN) through determining uncertainties in their downscaled results. The uncertainty was evaluated by comparing the observed monthly means and variances of daily maximum and minimum air temperature with the downscaled monthly mean and variances for each month of the year at a 95% confidence interval. Their findings indicate that GCMs have different abilities in reproducing the uncertainty. Based on confidence interval comparison, the SDSM and the LARS-WG reproduced the uncertainty for the downscaled temperature quite well than ANN.

The study by Dibike et al. (2008) also assessed the uncertainty associated with SDSM using different predictors. The study found that levels of uncertainty were not consistent across the predictors, indicating that uncertainty can stem from the GCM (predictor) used for simulation but not the downscaling method. The conclusion of the study was that the ability of the downscaling technique to accurately reproduce the baseline climate depends on the season and the location of the climate stations under consideration.

A comparison of different downscaled datasets indicates that the projected future (2071-2099) climates were marked by dissimilarity but the degree of the projected climate change relative to the baseline climate was highly similar (Jiang et al., 2018). However, Wilby et al. (2004) proposed that downscaled scenarios based on a single GCM or emission scenario do not equate to increased confidence in projections. Therefore, researchers should ensure that downscaled results intended to be incorporated into impact studies must have been generated from various downscaling methods and derived from several predictors (GCMs) (Wilby et al., 2004); Najafi

& Kermani, 2017; Jiang et al., 2018). This will enable identification of uncertainties associated with different model structures, emission scenarios, parameterization schemes and the sensitivity of climate (Mtongori, 2016).

Cooney, (2012) suggested that despite the efforts made to control uncertainty, uncertainty remains a part of climate change and it is important to be cognizant of such uncertainties and to make informed decisions based on them. Cooney (2012) further pointed out that uncertainty does not make the information useless but understanding the degree of uncertainty assists in making sound decisions. Daniel et al. (2012:pp 10) also pointed out that "uncertainty is not the same as incorrect information, nor does it mean we know too little to act". Thus, despite the uncertainty associated with downscaling, downscaling techniques have additional benefits for climate projections because, unlike GCMs, downscaling takes local and regional climate drivers into account (Daniels et al., 2012). As a result, downscaling is still preferable to the use of raw-GCM outputs in the impact studies (Vigaud et al., 2013) under certain circumstances.

2.6 Effects of climate change and droughts

2.6.1 Effects of climate change on grass reference evapotranspiration trends

The increasing surface temperature is expected to change the dynamic interaction between evapotranspiration and soil water. Evapotranspiration is mostly affected by three climate factors independently, that is, demand-supply and energy (Zhang et al., 2015). Air temperature and wind speed represent the demand while solar radiation and precipitation represent the energy and supply, respectively. Investigations into the sensitivity of grass reference evaporation to variations in meteorological variables has been conducted across different regions of the world. The findings indicated ETo sensitivity to these factors differs from one area to another. For example, ETo in various climatic regions of USA proved to be sensitive to water vapour pressure (Irmak et al., 2006) while solar radiation and air temperature were found to have a great influence on ETo variation in semi-arid regions of southern Spain (Estévez et al., 2009). In the semi-arid regions of China, Liang et al. (2008) found that ETo was more sensitive to relative humidity variations and less sensitive to air temperature changes.

Reference evapotranspiration plays a critical role in estimating actual crop water use. This is achieved through multiplying ETo by a stage-specific crop coefficient (Djaman & Irmak, 2012). Thus, in addition to climate variables, biological factors such as plant growth, canopy structure, and stomatal processes regulate the actual evapotranspiration process (Li et al., 2012; Khanmohammadi et al., 2017). Xu et al. (2016) suggested that high CO_2 concentrations in the atmosphere triggers plant stomatal closure, which in turn increases the resistance of the water vapour flow to the atmosphere and thus reduces evapotranspiration. Higher air temperatures stimulate growth rates and shorten the growing season of annual crops (Moratiel et al., 2010). Such changes can interfere with seasonal evapotranspiration rates. A decrease in evapotranspiration due to a shorter growing season was observed in Bangladesh (Mahmood, 1997).

However, as the air temperature continues to increase, the capacity of the atmosphere to hold moisture is expected to increase as governed by the Clausius–Clapeyron equation (Trenberth, 2006). This will potentially increase evaporation and/or precipitation due to high concentration of carbon dioxide and other gases in the atmosphere (Trenberth, 1998). Global studies indicated that from 1982 to 2013 nearly 29% of the global land area showed a significant increasing evapotranspiration trend. This increase was attributed to global warming and a dry atmosphere (increasing water vapour pressure deficit) (Zhang et al., 2015). Over 1982 to 1997 global annual evapotranspiration increased by about 6.1 to 8.1 mm $year^{-1}$ per decade. The increasing trend stopped after the 1998 El Niño event due to dry conditions, particularly in Africa and Australia (Jung et al., 2010).

Regional studies indicate contrasting trends, and this inconsistency in the ETo trends may be assigned to the non-uniformity effects of increasing air temperature across different regions. A decreasing ETo trend has been reported in China (Xu et al., 2006); and India (Bandyopadhyay et al., 2009), and Nebraska (Irmak et al., 2012) while an increasing trend was observed in South Florida (Abtew et al., 2011) and Iran (Tabari et al., 2011). The observed increase was mainly driven by an increase in air temperature, declining relative humidity, and increasing water vapour pressure deficit while the decrease was attributed to a reduction in net radiation, an increase in relative humidity, and a decrease in wind speed and an increase in precipitation which in turn reduces solar and net radiation, respectively. The contrasting ETo trend is indicative of a divergent response to ETo changes to climate change.

The possible reason for the differences in observed ETo despite the consistent increase in surface air temperatures can be partly explained by the complementary relationship hypothesis

(Bouchet, 1963) as cited in Yu & Zhang (2009). The hypothesis suggests that a complementary feedback mechanism exists between ETa and ETo., particularly for large homogenous surfaces that have low advection of heat and moisture. It considers ETo as a function of the feedback mechanism between a surface with limited water availability and evaporative demand of the overlying atmosphere. It shows that ET_a = ETo = ET_w, where ETw is the wet environmental evaporation, for a particular environment when the surface moisture is sufficient and radiation energy is the only limiting factor for evapotranspiration. Under limited soil moisture, ETa < ET_w whereas ETo increases due to an increase in sensible heat flux which heats and dries the atmosphere. This simply means that decreases in actual evapotranspiration which reduces water vapour pressure deficit and cools the atmosphere will cause an increase in the drying power of the air, thus ETo, (and vice versa). However, this hypothesis was proved inaccurate for regions at elevations beyond 1000 m asl (Yu & Zhang, 2009). In addition, Vadeboncoeur et al. (2018) suggested that the effects of warmer nights can counteract the increase in water vapour pressure deficit through an increase in daytime humidity to balance the water vapour pressure deficit.

2.6.2 Effects of climate change on drought frequency, severity, and intensity

Climate change impacts are diverse and can either be beneficial or detrimental depending on the economic sector, region and the period under consideration. The impact of climate change is projected to manifest through increased frequency and duration of hot and precipitation events (Dogondaji, 2013). Research on past and future spatial-temporal drought characteristics have been conducted on a global, national and regional scale (Dai et al., 2004; Dai, 2013; Masih et al., 2014; Trenberth et al., 2014; Vincente-Serrano et al., 2014). Assessments of the observed drought changes imply that drying may have already been progressing across the globe. Using the Palmer Drought Severity Index (PDSI) (Palmer, 1965), Dai et al. (2004) investigated the effects of surface warming on drought events. Their study discovered that dry areas have increased from 12 to 30% since the 1970s. However, Sheffield et al. (2012) discovered that previous studies have overestimated potential global drought trends as a result of climate change. They attributed the overestimation to the technique used to calculate ETo which only considers the effects of air temperature variability. Their study indicated that there have been minimal changes in global drought over the past six decades.

The recent study suggested that during a drought event, the observed widespread drying is primarily driven by surface warming since PDSI is smaller in the absence of heat. There is growing evidence that global aridity trends have been increasing and might even become worse under a continuous warming climate (Dai, 2013). The expansion of aridity is attributed to the widespread increase in evaporative demand, thus increasing ETo. Increasing ETo does not only cause drying in areas with below-normal precipitation but also causes droughts in areas that would have experienced little drying under normal circumstances (Cook et al., 2014). The implication is that increased heat from global warming does not necessarily result in drying but rather is likely to aggravate droughts when they occur (Trenberth et al., 2014). This has resulted in contradicting views as to whether the incidence of drought and drought severity is increasing under global warming or not.

Despite the importance and usefulness of global studies on raising awareness of climate change and its possible impacts, the associated uncertainty cannot be ignored. Most global studies use low-resolution climate data which is highly susceptible to uncertainty owing to the unavailability of high-quality long-term data from ground weather stations (Vincente-Serrano et al., 2014). The lack of high-quality data implies that the findings of these studies are not a representation of the entire world but only the areas with adequate data. Regional studies provide evidence of increased drought severity due to increased atmospheric evaporative demand (Vincente-Serrano et al., 2014). Masih et al. (2014) reviewed over 100 studies to analyze the geospatial and temporal variation of African droughts from 1900 to 2013. Their study concluded that there have been widespread, more intense and frequent drought in most African countries over the past five decades. Also, Adisa et al. (2020) scientifically analyzed 332 scientific publications to understand how the research on drought monitoring has evolved. Their findings showed that the majority of studies (75%) focus on agricultural and hydrological drought studies while the remaining 25% was shared among socioeconomic and meteorological studies. Their study also indicated that the African continent has experienced drought during 1984, 1989, 1992, and 1997.

Notwithstanding contrasting views about the past global drought trends, projection studies still show that drought events will become more frequent under climate change. For example, Dai (2013) analyzed coupled climate model simulations under intermediate future greenhouse gas (GHG) emissions scenarios from the Coupled Model Intercomparison Project phase 3 (CMIP3)

(IPCC, 2007) and the new phase 5 (CMIP5) (IPCC, 2013) to detect how drought might change under increased GHG concentration in the atmosphere. The study results show that warming has contributed towards increasing global drought areas which have risen by nearly 8% from 2000 to 2010. Further drying over various land areas is projected due to either increased evaporation or reduced precipitation (Dai, 2013).

Projections indicate that high ETo may consequently increase the land areas experiencing drying from 12 to 30% by the end of the 21st century (Cook et al., 2014). Sheffield & Wood (2008) employed eight models and three Special Report of Emission Scenarios (SRES) (A2, A1B, and B1) to investigate prospective changes of drought trends through analyzing global soil moisture and drought characteristics over land areas. Their study found a significant increase in short-term drought frequency both globally and in most regions. The frequency of long-term drought indicated both increases and decreases but decreases were only detected in small areas of high latitude.

2.6.3 Effects of climate change on agricultural yield

Climate plays a critical role in ensuring the attainment of the maximum potential yield of crops. Maximum potential yield requires that each crop and cultivar be exposed to a specified optimal climate variable otherwise it will be compromised. The effects of high air temperatures and water stress vary depending on the crops, cultivar, and environment (Fahad et al., 2017). High air temperatures and water stress can compromise yields through physical damages, physiological disruption, and biochemical changes (Wahid et al., 2007). While an increase of carbon dioxide concentration in the atmosphere is associated with increased assimilation and hence yields, a decrease in available soil water has detrimental effects on plant growth and ultimate crop yield (Zhao & Li, 2015).

The effects of climate change on agricultural yield will be both direct and indirect. Agricultural yields will be directly affected through changes in climate variables while indirect impacts will be through changes in land suitability, changes in weeds, diseases as well as pest and insect infestation (Lobell & Gourdji, 2012; Zhao & Li, 2015; Lesk et al., 2016). For more insight on this, numerous studies have been conducted investigating how agricultural yield responds to changes in climate conditions. Focusing on climate extremes, Lesk et al. (2016) assessed the influence of extreme weather disasters on global crop production. Their study revealed that over

1964-2007, the average national cereal production for countries in Africa, Asia, Australia, the Caribbean, Europe, Latin America and North America declined by nearly 10% due to drought and extreme heat. Losses due to drought were mainly as a result of reduced harvested area and yield, whereas extreme heat only caused yield reduction. The effects of the recent past droughts were found to be more severe (~7%).

Future projections indicate that in Africa, crop losses amounting to 30% are expected by 2080 (Parry et al., 2004). Lobell & Gourdji (2012) pointed out that as the atmospheric temperature continues to increase, land suitability for crop production will increase and allow the expansion of agricultural production. However, the highly suitable land will decrease while moderate and marginally suitable land will increase (Lobell & Gourdji, 2012). Also, Bals (2008) as cited in Chijioke et al. (2011), suggested that agricultural land located in tropical areas of sub-Saharan Africa is likely to become unsuitable for crop production. Grassland areas will become less suitable for pastures, leading to reduced agricultural yield. The increase in global average air temperature will also affect agricultural yield through changes in the growing season. The majority of global land areas indicate a significant rise in the duration of the growing season which may contribute positively towards crop yields under sufficient soil moisture availability (Muller et al., 2015).

Ray et al. (2019) found that climate change already has an impact on agricultural yields. The study showed that the impacts ranged from a yield decrease of 13.4% to an increase of 3.5% across different crops. On average, yield reduction ranged from -2551 to 982 kilograms per hectare per year with sugarcane showing the largest increase of 982 kilograms per hectare per year. Southern Africa was among the region with substantial negative impacts on agricultural yields from climate change (Ray et al., 2019). The increasing global yields are stimulated by increased carbon dioxide concentration in the atmosphere and decreases are partly attributed to warming trends (Lobell & Gourdji, 2012). Climate change can also indirectly influence crop yields through changes in fertilizer supply, diseases, and pests (Wang et al., 2018). In the absence of effective adaptation, an average decrease ranging between 3.1 to 6.0% is projected for a 1^{o}C increase in global average air temperature by the end of the 21st century (Zhao et al., 2017).

The effects of climate change are also experienced at the household level. Livestock production as the main asset in most households in rural communities is highly vulnerable to climate change and extremes. Owing to the expected decrease in grassland areas, livestock numbers will therefore decrease. Also, high air temperatures increase the exposure of animals to parasites and diseases (Furstenburg & Scholtz, 2009). In addition, extreme weather events are catastrophic to livestock production causing enormous losses. For example, during the recent past drought in South Africa livestock losses of up to 43% were recorded and total economic losses from the livestock exceeded R10 billion (Swemmer et al., 2018).

2.6.4 Effects of climate change and drought on sugarcane productivity

The climate change impact on sugarcane productivity is vast and diverse. However, the majority of previous studies tend to focus on fewer effects such as increased atmospheric CO_2 levels and high air temperatures (De Souza et al., 2008; Vu & Allen, 2009; Allen et al., 2011; Marin et al., 2013). The major drawback of these studies is that they do not fully consider the long-term effects of climate change. The impacts of climate change on the possible decrease in soil moisture due to increasing evapotranspiration as well as adverse effects on crop nutrients are still unclear for the sugarcane crop. Also, there are concerns over possibilities that existing studies might be overestimating the potential benefits of climate change due to the negligence of some climate change threats to agricultural production, such as erratic weather extremes, water availability limitations, and risks of diseases (Zhao & Li, 2015).

The general effects of heat and water stress have been well documented in the literature (Wahid & Close, 2007; Inman-Bamber et al., 2012; Ferreira et al., 2017). Heat stress and drought are the major growth restraining and detrimental climatic factors for sugarcane. Heat stress is defined as an air temperature exceeding the threshold level over a long period such that it substantially damages the plant (Irmak, 2016). The optimum air temperature for sugarcane is 32-33 ^{o}C, exposure to an air temperature above this adversely affects crop growth and subsequently reduces yield (Ebrahim et al., 1998).

Sugarcane exposure to higher air temperatures triggers morphological changes such as reduction of total biomass, early drying of leaves, smaller internodes and increased tillering (Rasheed, 2009; Vu & Allen, 2009). Heat stress causes changes in the physiological and biochemical processes which subsequently reduces crop growth and yield (Wahid & Close, 2007). Heat stress affects leaf water potential despite non-limiting water supply and the optimum relative humidity of the air. Elevated air temperatures also affect the ripening and quality of sugarcane. High temperatures adversely affect the germination of the sugarcane crop, reduce the activity of sucrose phosphate synthase, and reduce the number of photosynthesis pigments (Hussain, 2018).

Previous studies have employed both experimental data and crop simulation models to assess the observed and projected effects of the changing climate. Both experimental work and crop models simulation suggests a general increase in sugarcane yields under elevated CO_2 concentration and high air temperatures (De Souza et al., 2008; Vu & Allen, 2009; Marin et al., 2013). An experimental study by Allen et al. (2011) conducted in a greenhouse at CO_2 levels of 360 and 710 µmol $^{-1}$ with four plausible air temperatures (baseline, 1.5, 3, 4.5 °C) indicated that the benefits of increasing CO_2 concentration in sugarcane productivity exceed the expected 10% increased for C_4 plants. The study found that increases in sugarcane dry weight, fresh weight, juice volume as with the stem juice and sucrose are more sensitive to CO_2 concentration increases compared to plant biomass. A study in Mexico also showed a positive impact of climate change on sugarcane yields (Baez-Gonzalez et al., 2018). Future predictions also suggest a general increase in sugarcane as the global atmospheric CO_2 concentration continues to increase. In their studies, Marin et al. (2013) and Singels et al. (2018) using the DSSAT-Canegro model, found that yield under dryland and irrigated areas will increase but the dryland yields are likely to experience larger gains due to improved water use efficiency and quickened canopy development. However, these studies have been criticized for their limited ability to completely reveal the interactions of CO_2 concentration and other factors under field environments (Zhao & Li, 2015).

The expected accelerated growth and biomass accumulation in sugarcane crop as suggested by crop modelling projection (Singels et al., 2018) and on pots (Vu & Allen Jr, 2009) may be negatively impacted by the increased frequency and intensity of extreme weather events under climate change conditions (Vu & Allen, 2009; Knox et al., 2010). Hussain (2018) found sugarcane production and yields proved to be highly sensitive to extreme weather and/or climate events, particularly drought. A reduction in sugarcane production ranging from 16 to 46% was recorded in Fiji due to extreme weather events (Zhao & Li, 2015).

The vulnerability of sugarcane to water deficit depends on the crop growth stage (Zhao & Li, 2015). The tillering and stem elongation stages tend to be highly susceptible to water stress relative to other stages (Ferreira et al., 2017). Moderate stress has positive effects on sugarcane crops during the maturation stage through increasing sucrose content. However, sugarcane cannot tolerate severe stress and drought, see Fig. 2.4, reported in Ferreira et al., (2017). As a result, severe stress significantly affects both cane and sucrose yield. Generally, under water-deficit conditions, sugarcane crop responses include stomatal closure, leaf senescence, and reduced leaf area, inhibition of stalk and leaf growth (Inman-Bamber et al., 2012). Also, the increased vulnerability of sugarcane production and yield to increased diseases, insects and weeds due to high air temperature (Chandiposha, 2013) is not well documented in the literature. Yet, it has been reported that high air temperatures will increase the incidence of pests and diseases and are likely to introduce new pests and diseases (Park et al., 2008). In addition, the prevalence of extreme weather events particularly high air temperatures promotes overwinter pests (pests that fear and hide from cold weather) and disease pathogens (Zhao & Li, 2015).

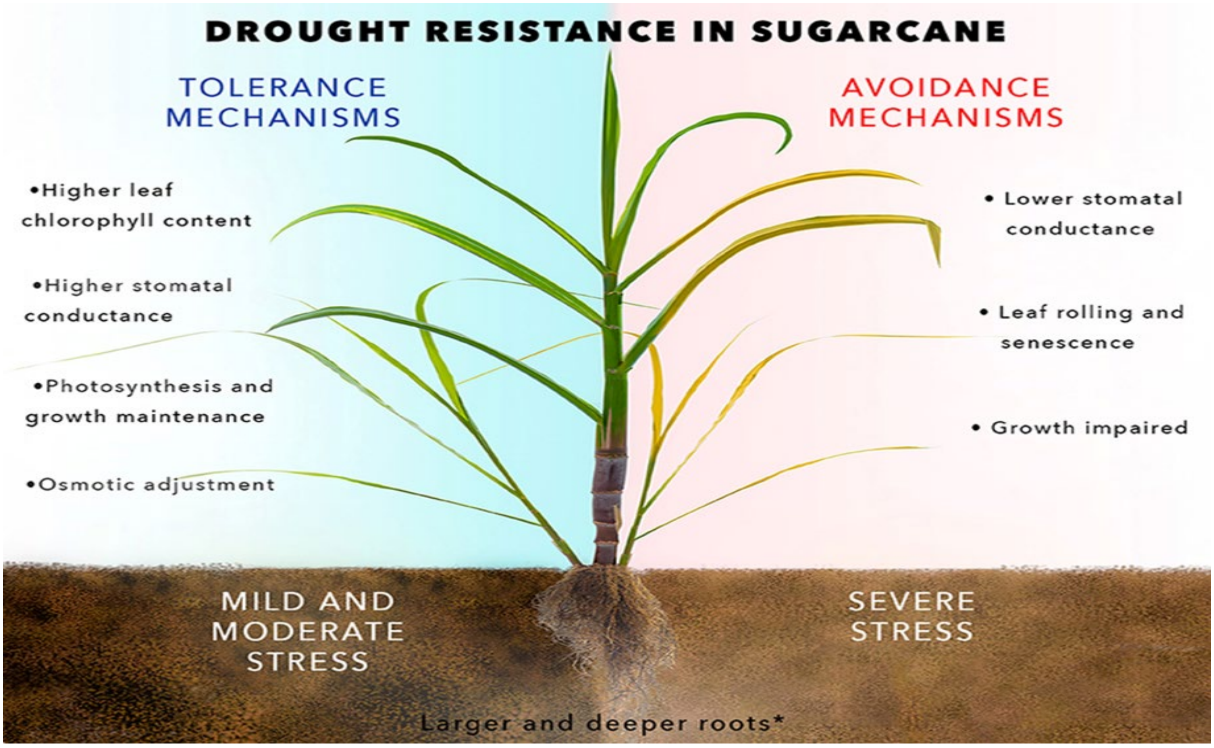

Figure 2.4: Sugarcane drought response mechanisms (adapted from Ferreira et al. 2017)."

2.7 Adaptation by farming communities

A study in South Africa revealed that climate condition presents a significant factor that affects rural livelihoods (Thomas et al., 2007). The subtle changes in climate such as hotter days, intermittent rainfall patterns and delays in the start of the rainfall season have forced farming communities to either adapt or collapse. The reliance of the majority of rural communities on farming forces them to adapt to climate change to continue with farming (Dasgupta et al., 2014). However, the low adaptation capacity due to insufficient information on how climate change is affecting their production and the possible responses to climate change increases their susceptibility to climate variability (Dasgupta et al., 2014). Small-scale and smallholder farmers across the globe have experienced the impacts of climate change through rising air temperatures, irregular and unpredictable rainfall and extreme weather events which adversely affect the crop yields, increases the incidence of pests and diseases, resulting in a loss of income (Belay et al., 2017; Harvey et al., 2018; Phuong et al., 2018).

In Central America, a study found that virtually all the farmers participating agreed that they had experienced climate change and had faced the impacts of it (Harvey et al., 2018). The study discovered that the severity of climate change impacts experienced by farmers, their coping strategies as well as their adaptation needs substantially differed from one farmer to the other (Harvey et al., 2018). Also, Drolet & Sampson (2017) found that each of the six different communities included in their study experienced the impacts of climate change in a different manner. This may originate from the complications associated with on-farm decision-making including the climate change issues that need to be managed at a farm level. Evidence indicates that endogenous factors that substantially vary from region to region largely determine the community response to climate change (Duerden, 2004). In South Africa, the different adaptation capacities between different farming groups were also observed (Wilk et al., 2013). Hence, given various cultures, social history, and land-use practices within the region, responses to climate change are likely to be different within and between regions.

This, therefore, calls for the development of different approaches that are community-based and be grounded in a local community experience (Drolet & Sampson, 2017). Community-based adaptation operates at the local level in areas that are susceptible to climate change impacts. It assists in identifying and developing community-based activities that improve the adaptation capacity of the local people (Jessica & Tim, 2009). Despite the successes of community-based adaptation, concluding that they have improved the long-term resilience of communities is a challenge as its implementation across the region is still in its infant stages (Jessica & Tim, 2009).

A southern African study revealed that small-scale farmers usually adapt to climate change through using various crop and/or crop varieties, soil conservation, planting trees and irrigation (Bryan et al., 2009). But, despite their perceived climate change in the region, the vast majority of farmers failed to adjust their farming practices accordingly. Their failure to adapt was attributed to limited access to credit, fertile land, and information. The study also suggests that wealth, access to credit, extension services as well as climate information have a major influence on the farmers' adaptation decision (Bryan et al., 2009). Lack of access to climate information increases the vulnerability of the farmers to climate vagaries (Ezra, 2016). Vermeulen et al. (2012) suggested that through improved climate information services, farmers can improve the manner in which they deal with agricultural risks related to climate variability and extreme events.

2.7.1 Access to climate information for adaptation to climate change

"Climate services have a role to help improving farmers' livelihoods in the context of climate change" (Lugen, 2016: pg 21). Climate information can substantially assist in understanding the prospects of climate as it has a major influence on society. It allows for the analysis of the extent and nature of impacts due to past and present climate experiences as well as the likely impacts in the future due to climate change (Niang et al., 2014). Climate information is mainly categorized into three groups, such as past, present, and future. Climate information that is often available for decision-making is mainly climate forecasts which cover various timescales such as, daily weather forecasts (short-range), weekly forecasts (medium-range), seasonal forecasts (long-range) and El Niño events (long-term) (Lötter et al., 2017). Climate information in South Africa is mainly issued by the South African Weather Service through different channels (Ziervogel & Calder, 2003). Daily weather forecasts are often disseminated through media sources such as television, radio, cell phones and newspaper while the seasonal climate forecast is issued through online sources such as e-mails and internet bulletins. Seasonal climate forecasts are normally supplied for a period ranging from one to six months, indicating the expected amount of rainfall over a particular period (Ziervogel & Calder, 2003).

Although this information can assist in understanding whether the season will be good for planting or not, the distribution of rainfall as an important aspect of seasonal rainfall is excluded (Ziervogel & Calder, 2003). This makes it difficult for some farmers to make use of such information given that they are mainly interested in knowing when they can start planting and the probability of crop survival throughout the season (Moeletsi & Walker, 2012). The implication of this mismatch between the type of information required by the prospective end-users and the available information indicates that seasonal climate information does not address the needs of a particular group of end-users. Consequently, irrespective of the free access to seasonal climate information in South Africa over the past ten years, the uptake by small-scale farmers has been low (Ziervogel, 2004). In addition to the unsuitability of the information provided, other factors hampering the uptake and use of seasonal climate information by small-scale farmers were identified in Lesotho (Ziervogel & Downing, 2004). These included the inability to understand the forecast due to the language and the technical terms used; the ill-timed product delivery and the coarse spatial resolution of the forecast as well as the failure for the information to reach prospective users due to poor dissemination.

A recent study in Kenya by Muema et al. (2018) analyzed factors that influence the access and uptake of climate information by smallholder farmers. Their results indicate that the age of the household head and frequent exposure to climate extremes negatively influence the likelihood of accessing climate information. The study also revealed that farmers who owned a radio and television, had access to improved seeds and household income was likely to access climate information (Muema et al., 2018).

Attempts to improve seasonal climate forecasts have been made so as to enhance the potential usefulness of the local climate information to the specific end-user (Archer, 2003). The improvements were possible through increasing the number of meteorological stations and observers, ensuring that the forecast reaches the potential end-user timeously and increasing communication between the information providers and the public either directly or via stakeholders. Also, through including the feedback mechanism which allows the end-users to provide feedback to the forecasts providers to enable effective information dissemination (Ziervogel & Downing, 2004). User's participation in producing and dissemination of climate information was found to be useful in ensuring that the information content is relevant and appropriate for their needs (Roncoli et al., 2009).

Regardless of the effort to improve seasonal climate forecast accessibility and usefulness, the weather station coverage is still very sparse (MacKellar et al., 2014). The issue of limited network of weather stations has been observed across the African continent. The uneven distribution of weather stations tends to be worse in rural areas as most stations are positioned in cities and towns. The existing weather stations in rural areas often lack maintenance and thus present poor-quality data with huge gaps of missing observations (Dinku, 2019). Dinku (2019) associated the sparse weather station density to a declining investment towards installing new and maintaining the old weather stations, social or political conflict, and challenging and remote geography of rural areas in Africa.

Despite the perceived inutility and low uptake of climate information in southern Africa, climate information is still viewed as one of the key elements in addressing the adaptation needs to improve adaptive capacities under climate change conditions (Lugen 2016). Previous studies suggested that one way to mitigate the risks caused by climate change is through improving access to climate information and improve spatial coverage. However, for end-users to realize the benefits of accessing the information they have to understand and apply the information into their decision making (Tarhule & Lamb, 2003).

2.8 Conclusions

To ensure the sustainability of farming communities' livelihood and food security under climate change conditions, it is important to understand climate-related factors that threaten both agricultural yield and its stability. In this study, both historic and projected climate extremes and relevant aspects have been reviewed. Many researchers evaluated changes in extreme air temperature using ETCCDI, drought patterns through drought indices and future changes in air temperature and precipitation through the use of GCMs and downscaling methods. The majority of studies attested to the increasing air temperature and inconsistent precipitation trends worldwide. The existing literature indicates that climate is becoming more extreme in some areas suggesting that the impacts of climate change will not be uniform.

Although downscaling techniques enables analysis of climate change trend at a local scale, the shortage of available data present limitations and thus, currently, there is no strong evidence on the microclimatic basis that extreme weather/climate events are increasing in severity and frequency.

Despite the farming communities’ perception of climate change and their experiences of extreme weather and climate, adaptation to climate change continues to be a challenge. This may emanate from the fact that adaptation strategies cannot uniformly apply to all farming communities in different regions. Differences in cultures, social history and land-use practices across the region enforce different responses to climate change from region to region. Thus, the development of a community-based adaptation together with improved access to climate information would be the best possible way to increase farming communities' resilience to climate change as well as to reduce other potential losses.

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Lead to Chapter 3

Chapter 2 presented a review of climate change and its consequences. Several techniques that have been used for assessing historical climate extremes patterns were also reviewed in the previous chapter. In Chapter 3, the ETCCDI is utilized in order to evaluate historical extreme air temperature and precipitation for the study site. Chapter 3 mainly argues that extreme climate trends should not be generalized based on the findings from nearby stations.

CHAPTER 3: OBSERVED EXTREME PRECIPITATION AND AIR TEMPERATURE TREND FOR 1966-2017 WITHIN THE SUGARBELT AREA, KWAZULU-NATAL MIDLANDS, SOUTH AFRICA

3.1 Abstract

As the climate continues to warm, air temperature and precipitation patterns are expected to change throughout the world. Due to sparse automatic weather station network density across South Africa, studies previously conducted have included few stations for the KwaZulu-Natal (KZN) province and only one station for the study site. Extreme events, particularly precipitation can substantially vary from one station to the next within the same hydroclimatic zone.

This study aims to provide insight into how extreme air temperature and precipitation have changed over the past 48 years, separated into two time periods (1966-1994 and 1997-2017), in the sugarbelt area of KZN midlands. Datasets used were from four weather stations located in the sugarcane belt in KZN midlands. To ensure the quality of the datasets, the data were quality controlled using RClimDex 1.1 software. Using adjusted homogeneous datasets, the extreme precipitation and air temperature indices defined by the World Meteorological Organisation Expert Team on Climate Change Detection (ETCCDI) and Indices were computed using RClimDex 1.1.

The results generally show that daytime air temperature is increasing while the night-time air temperature is decreasing throughout the study period. As such, warm days and cool days are shown to be increasing and decreasing respectively. From the precipitation indices analysis, the study sites are shown to have been experiencing more extreme events leading to increases in annual precipitation totals. However, consecutive wet days and the intensity of continuous rainfall over 5-day periods appear to be decreasing suggesting that precipitation has become more extreme over the study site. The observed trend is partly consistent with results from similar studies conducted in South Africa. The observed precipitation changes confirm the projected increase in extreme precipitation as the air temperature increases throughout the globe.

Keywords: *ETCCDI, Extreme indices, RClimDex, Microclimate*

3.2 Introduction

Climate change, which often manifests as increased volatility of extreme weather events across the world, is a serious threat to society and the environment. The intense impacts of extreme weather events that have been observed and experienced by people in many parts of the world have stimulated increased interest in understanding and predicting changes in air temperature and rainfall extremes (dos Santos, 2013; Sheikh et al., 2015; Halimatou et al., 2017; Larbi et al., 2018; Rahimi & Hejabi, 2018; Sein et al., 2018; Popov et al., 2019). These studies concur with the positive trends of maximum and minimum air temperature with a significant increase in warm nights and substantial decreases in cold nights. The previous studies on precipitation indices indicate high levels of variability. These changes imply risks for human lives, ecosystems, and economies. Over the past 19 years (1998-2017) more than 11 thousand extreme events that occurred worldwide resulted in deaths of more than a half-million and losses of about 3.47 trillion dollars (Eckstein et al., 2018).

3.2.1 Historical air temperature trends

A range of studies on air temperature and precipitation variability have been conducted in South Africa. Muhlenbruch-Tegen (1992) cautions about relying on average air temperature when analysing the temperature variability indicating that in many cases trends in minimum and maximum air temperature counteract each other resulting in little evidence of trends in air temperature. The findings of Muhlenbruch-Tegen (1992) suggest that throughout 1940-1989, the average air temperature trend showed no significant changes, whereas minimum and maximum air temperatures showed an increase and a decrease, respectively in South Africa. South African air temperature trends were also investigated by Kruger & Shongwe (2004) from 1900 to 2003. Contrary to the Muhlenbruch-Tegen (1992) findings, Kruger & Shongwe (2004) indicated that the majority of stations investigated showed a significant increase in annual average air temperature (0.13 ºC decade^{-1}). Kruger & Shongwe (2004) attests to air temperatures increasing at a decreasing rate given that over 1991-2003 annual average temperature was found to be increasing at 0.09 ºC decade^{-1} whereas over 1960-2003 it was increasing at 0.11 ºC decade$^{-1.}$ In South Africa, the study suggests a general decrease in cold days and nights and an increase in warm days and nights. Moreover, a study by New et al. (2006) indicated an increasing trend of the monthly maximum value of daily air maximum temperature and a minimum value of daily minimum air temperature, suggesting a decrease in cold extremes.

Using RClimDex software, Kruger & Sekele (2013) investigated trends in extreme daily maximum and minimum air temperature indices for 28 weather stations in South Africa. They also found that warm extremes have generally increased while cold extremes have decreased across South African weather stations. However, their study revealed that the annual absolute maximum and minimum air temperatures did not show similar behaviour to the other indices and thus suggested that individual extreme events are not always linked to long-term climate trends.

An update on the South African trends of daily maximum and minimum air temperature extremes by Kruger & Seleke (2013) corroborated an upward trend in air temperature extremes except for a number of cool days and cool nights which showed a decrease for some stations. Recent studies (MacKellar et al., 2014; Kruger & Nxumalo, 2017; Kruger et al., 2019) confirm the findings of the previous studies suggesting an increase in warm temperature indices and decrease in cooler temperature indices. However, Kruger & Nxumalo (2017) report incoherencies between regional seasonal trend magnitudes with the majority of stations showing autumn as the warmest season. The average seasonal trend for the country, however, confirmed that summer is the season with the strongest warming. In their study, Kruger & Nxumalo (2017) also discovered that various stations within proximity showed different results and concluded that the results cannot be entirely attributed to climate variability and change but also to other factors that might have an influence on local air temperature.

3.2.2 Historical precipitation trends

Focusing only on data from South African weather stations that have not been relocated, Mason et al. (1999) assessed changes in the intensity of extreme precipitation events over the period of 1931 to 1990. The study results suggest that the large parts of the country have experienced rainfall with high intensity over 1931-1990. The increased rainfall intensity was, however, not attributed to global warming but was associated with palaeo-floods during the Little Ice Age that was the largest ever recorded during hydrographic records. Also, Groisman et al. (2005)

confirmed that intense precipitation events have become more frequent during 1906 to 1997 in the eastern parts of South Africa.

Extending the period of study, Kruger (2006) examined the spatial variation of extreme precipitation trends across South Africa for the period of 1910 to 2004. The study found an inconsistency in annual precipitation trends over 38 meteorological stations. However, the results generally showed an upward trend of days with extreme precipitation and the daily precipitation amount. The study showed that in spite of the increase of events with extreme precipitation, the annual precipitation amount showed an insignificant increase.

3.3.3 Evaluation of observed air temperature and precipitation extremes in South Africa

There have been studies evaluating observed surface temperature and precipitation extremes for South Africa. However, most of the studies were conducted on a national scale with a lack of detailed information about local patterns of climate change. Meteorological stations used in these studies are not uniformly distributed across the country and province. Stations are clustered around some areas, particularly the major metropolitan areas and often sparse in mountainous areas. Also, some stations do not possess long-term high-quality weather data and are therefore not well represented in regional studies.

For example, the authors of previous studies have included few stations for the province of KZN in their analysis. Kruger & Seleke (2013) included only two stations that were not part of the KZN midlands while only one station for the KZN midlands was included in the study of Kruger & Shongwe (2004). Kruger (2006) highlighted the low density of weather stations in KZN and MacKellar et al. (2014) argued that stations within the same hydroclimatic area may fail to represent the heterogeneity of the area. Kruger & Nxumalo (2017) emphasizes that rainfall amounts across districts lack homogeneity, particularly in areas with complex topography. Sein et al. (2018) discourage the use of climate data from a limited number of stations for extreme analysis and suggest that the results can potentially indicate misleading climate extremes.

This chapter assesses the historical trends of air temperature and precipitation in the study area. Unlike other studies that rely on the use of one or two commonly used indices, this chapter derives strength in the sense that this study will apply a total of 17 unique indices to obtain in depth analysis and conclusions on the nature of extremes in the area of study. This study aims to provide new insights on trends of extreme weather indices, on a local scale, using observed daily air temperature and precipitation of the KZN midlands. The KZN midlands area was selected as the case study given that it is the heart of the high-quality agricultural production in the province and specifically, Wartburg was chosen as the study site because it's among the largest sugarcane producing areas within the midlands area. In addition, the study sites have been excluded in similar studies previously conducted in the KZN province and South Africa.

3.3 Materials and methods

3.3.1 Study area

The KwaZulu-Natal province is located on the eastern seaboard of South Africa characterized by a subtropical climate with generally warm summers and mild winters. Compared to other provinces in South Africa, much of the land is cultivated, with an area of 6.5 million hectares suitable for farming purposes (Grant, 2016). Sugarcane production covers about 400 000 hectares (South African Cane Growers Association, n.d.). Sugarcane is the most important cash crop of the province producing nearly 78% of the industry's total production. About 91% of the total sugarcane production in KZN is dryland (Joubert, 2015). Hence, climate change, particularly dry conditions as a consequence of global warming, could adversely affect crop production and impact the South African economy. Dryland sugarcane has been subjected to adverse weather conditions over the past recent years which led to a decrease of roughly 14% in sugarcane production. For the 2009/10 season, a loss of about 2.64 million tonnes was recorded in the sugarcane industry (Singels et al., 2011) and in the 2010/11 season, the loss amounted to over 3 million tonnes leading to a shortfall of 51% in exports (South African Cane Growers Association (SACGA), 2011). This indicates the negative impact of extreme weather on the South African economy due to significant losses in agricultural production.

3.3.2 Data and quality control

Records of daily precipitation, maximum and minimum air temperature were obtained from four meteorological stations (see Table 3.1) located in the sugarbelt areas in the midlands of KwaZulu-Natal.

Table 3.1: Climate data used in this study

Station name	Latitude (S)	Longitude (E)	Altitude (m)	Data period	No. of data records	No. of missing data
Bruny's Hill	29°25' 0"	30°41'0"	990	1998-2017	7305	139
Eston	29°52' 0"	30°31'0"	785	1997-2017	8035	219
Powerscourt	29°59' 0"	30°38'0"	630	1997-2017	8035	78
Windy Hill	29º29'25"	30°34'17"	988	1966-1994	10592	322

To be confident in the analysis of the extreme air temperature and precipitation trends, it was necessary to homogenize data in order to remove potential non-climatic effects. This is a key step because artificial change points in a data series could considerably bias the results of climate trends, variability and extreme (Alexander, 2016). A homogeneous climate time series assures that the detected variations are only as a result of climatic variation and not by changes in station location, observation processes, practice and instrumentation (Acquaotta & Fratianni, 2014). Prior to homogenizing climate data, the data underwent a quality control data process which was carried out using the R-based software tool RClimDex 1.1 (Zhang & Yang, 2004) The software identifies duplicate dates, outliers, coherence between the maximum and minimum air temperature, and consecutive days with the same values. During the quality control process, incorrect air temperature data, such as minimum air temperature greater than maximum air temperature was detected and removed. Also, through quality control, air temperature outliers were identified using a standard deviation (σ) threshold of 3.5. The outliers which were greater than 3.5σ were validated manually by comparing their values with days before and after the event and with the same date at the nearest station (Aguilar et al., 2005), and were replaced or removed.

After quality control, data homogeneity was assessed using the RHtestV4 and RHtest_dlyPrcp (Wang et al., 2010) which are available online at http://etccdi.pacificclimate.org. The programs can be used to detect multiple steps changes in minimum and maximum air temperature as well as precipitation which were either documented or undocumented in a time series without reference series (Wang & Feng, 2013). Given the high noise associated with daily series, which makes homogeneity test complicated (Wang et al., 2010; Wang & Feng, 2013), monthly series were used to identify undocumented step changes. Wang & Feng (2013) suggest that a daily homogeneity test be performed focusing on the detected monthly series step changes to test their significance. In this study, a similar approach was adopted to check if monthly and daily series change points were in agreement. In addition, to gain confidence in the detected changes, additional homogeneity tests such as the Pettit test (Pettitt, 1979), standard normal homogeneity test (Alexandersson, 1986; Alexandersson & Moberg, 1997) and Buishand range test (Buishand, 1982) (see Appendix 1) were used to check if they detected the same step changes and the significance of the detected step changes. The XLSTAT- Time Series Analysis module (XLSTAT V. 4.5, 2019) which contains the abovementioned homogeneity test was used. Time series were deemed inhomogeneous if all tests detected the same step change or if all three additional tests detect a similar statistically significant step change. Wang (2003) notes that if one intends to obtain a homogenous climate data series through the removal of bias, an adjustment to a trend type change in a climate series should be applied only if there is adequate evidence to support the change. But access to metadata can be a serious challenge given that significant quantities of metadata are only available in paper form and still need to be digitised (Venema et al., 2018). Adjustments to data were applied when it was considered necessary, for example, step changes that were detected during El Niño years were not adjusted as they are likely to have been influenced by climate while data step changes that were supported by the majority of the test performed were adjusted. The data that were detected to be inhomogeneous were adjusted through a penalized maximum F test (Wang, 2008). Specifically, a quantile-matching technique in RHtestV4 (Wang et al., (2010) was used to adjust daily records. This test allows the time series to be tested without a reference series. This method was chosen due to the complexity of data adjustment and the unavailability of metadata from the data supplier. Some shifts that were detected both in the air temperature and precipitation series were common at the stations. Shifts that were common across the stations were not corrected since metadata was not available to affirm the changes and the shifts were likely to be as a result of climate change.

3.3.3 Extreme indices and trend analysis

Seventeen indices were used to assess climate change in the KZN midlands area. The selected indices are part of the core set of 27 indices that have been developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang, 2013) to standardize the definition and analysis of extreme. The selected indices can be classified into four categories:

1. Absolute indices that show maximum and minimum values within a year (TNx, TNn, TXx, TXn)
2. Air temperature indices that are percentile-based representing the coldest and warmest deciles for both minimum and maximum air temperature (TN10p, TX10p, TN90p, and TX90p).
3. Threshold-based indices are defined as the number of days on which precipitation falls above or below a specific threshold (RX1day, Rx5day, R10mm, R20mm, R95p, R99p, PRECPTOT).
4. Duration-based indices defined as periods of excessive dryness and wetness (CDD, CWD)

Table 3.2: Definition of the indices used in the study (Zhang, 2013)

Index	Descriptive name	Definition	Units
Indices of warm temperature extreme			
TXx	Maximum value of daily maximum air temperature	Monthly maximum value of daily maximum air temperature	^{o}C
TXn	Minimum value of daily maximum air temperature	Monthly minimum value of daily maximum air temperature	^{o}C
Tx90p	Warm days	Number of days when TX > 90th percentile	day
TN90p	Warm nights	Number of days when TN > 90th percentile	day
Indices of cold temperature extreme			
TNn	Minimum value of daily maximum air temperature	Monthly minimum value of daily maximum air temperature	^{o}C
TNx	Maximum value of daily maximum air temperature	Monthly maximum value of daily maximum air temperature	^{o}C
TX10p	cold days	Percentage of days when TX < 10th percentile	day
TN10p	Cold nights	Percentage of days when TN < 10th percentile	Day
Indices of precipitation extreme			
RX1day	Maximum of 1-day precipitation amount	Monthly maximum 1-day precipitation	Mm
Rx5day	Maximum of 5-day precipitation amount	Monthly maximum of consecutive 5-day precipitation	Mm
R10mm	Number of heavy precipitation	Annual count of days when PRCRP > 10 mm	Day
R20mm	Number of very heavy precipitation	Annual count of days when PRCRP > 20 mm	day
CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	day

CWD	Consecutive wet days	Maximum number of consecutive days with RR > 1 mm	day
R95p	Very wet days	Annual total PRCP when RR > 95^{th} percentile	Mm
R99p	Extremely wet days	Annual total PRCP when RR > 99^{th} percentile	Mm

The extreme indices were computed using RClimDex (1.1) (Zhang & Yang, 2004). The trend of extreme precipitation, minimum and maximum air temperature was analysed using simple temporal regression analysis. Trends for air temperature indices were analysed on both seasonal and annual bases while precipitation extreme indices were analysed at an annual scale only. These trends were computed for each weather station, however, simple regression was fit for both time series to detect the trends for both 1960 to 1994 and 1997 to 2017 (arithmetic average of the three stations).

3.4 Results

3.4.1 Trends in seasonal and annual extreme air temperature

The analysis of seasonal and annual air temperature reveals a variety of changes from 1966 to 1994 and 1997 to 2017 in the study area. The seasonal time series of minimum and maximum air temperature extreme over 1966-2017 showed both warming and cooling trends. Regional series of various extreme indices for different seasons are shown in Figures 3.2 to 3.5. For the autumn season (Figure 3.2), TXx, TX90p and TN10P showed an agreement of the trends between these two study periods indicating a statistically significant ($p < 0.05$) increasing TXx and TX90p trend and statistically insignificant ($p > 0.05$) increasing TN10p trend. The magnitude of the changes is greater for the former period compared to the recent past period. Over 1966-2017 TNn indicates a significant decreasing trend for the study area. Inconsistency in TXn, TX10p, TNx, and TN90p was observed.

The regression analysis indicated a statistically significant increase in TXn and TX10p during 1966-1994 and a statistically insignificant decrease in the same indices during 1997-2017. For TNx and TN90p neither periods experienced a statistically significant trend ($p > 0.05$).

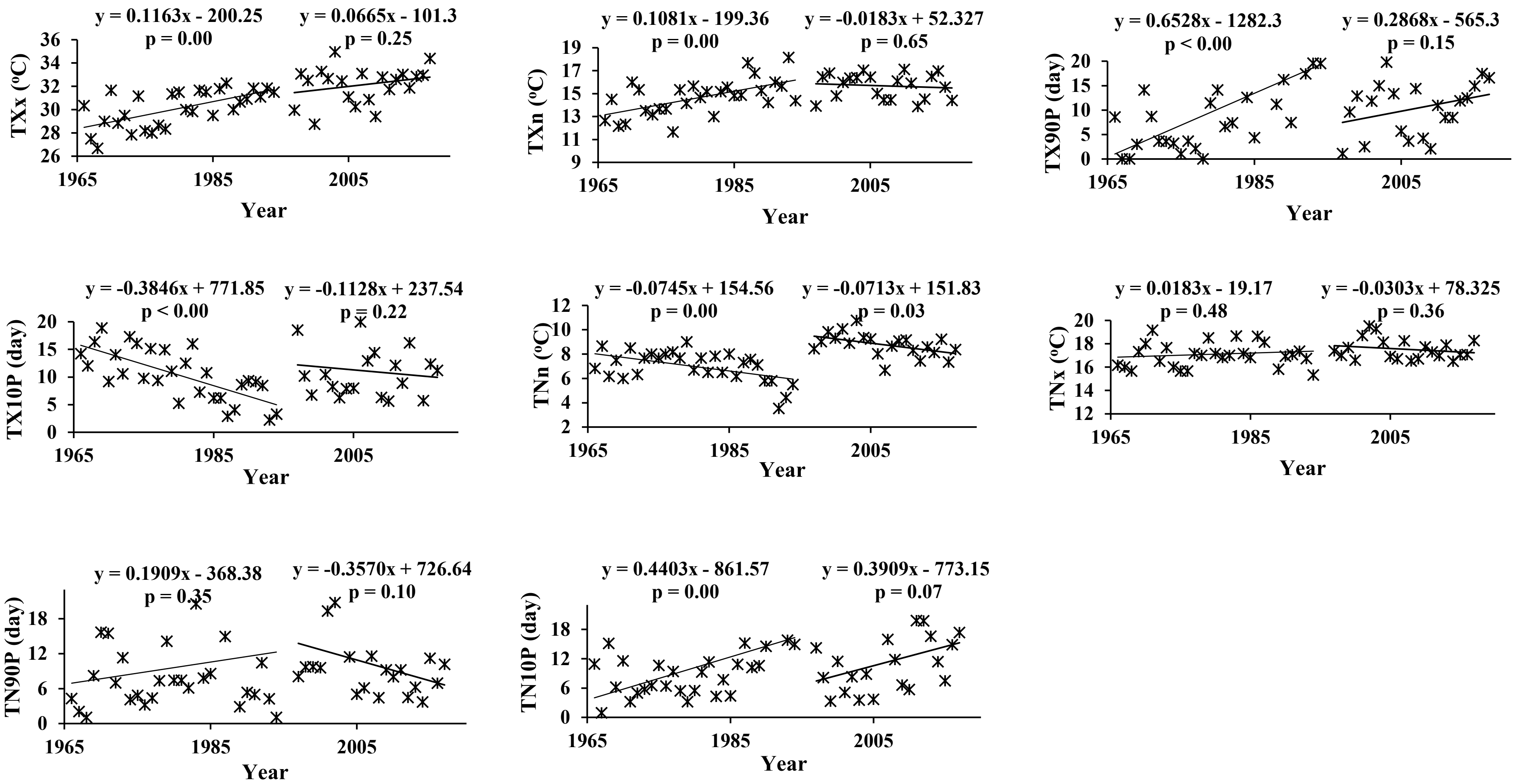

Figure 3.1: Temporal trends of seasonal (autumn) extreme maximum and minimum air temperature for the study area from 1966 to 2017

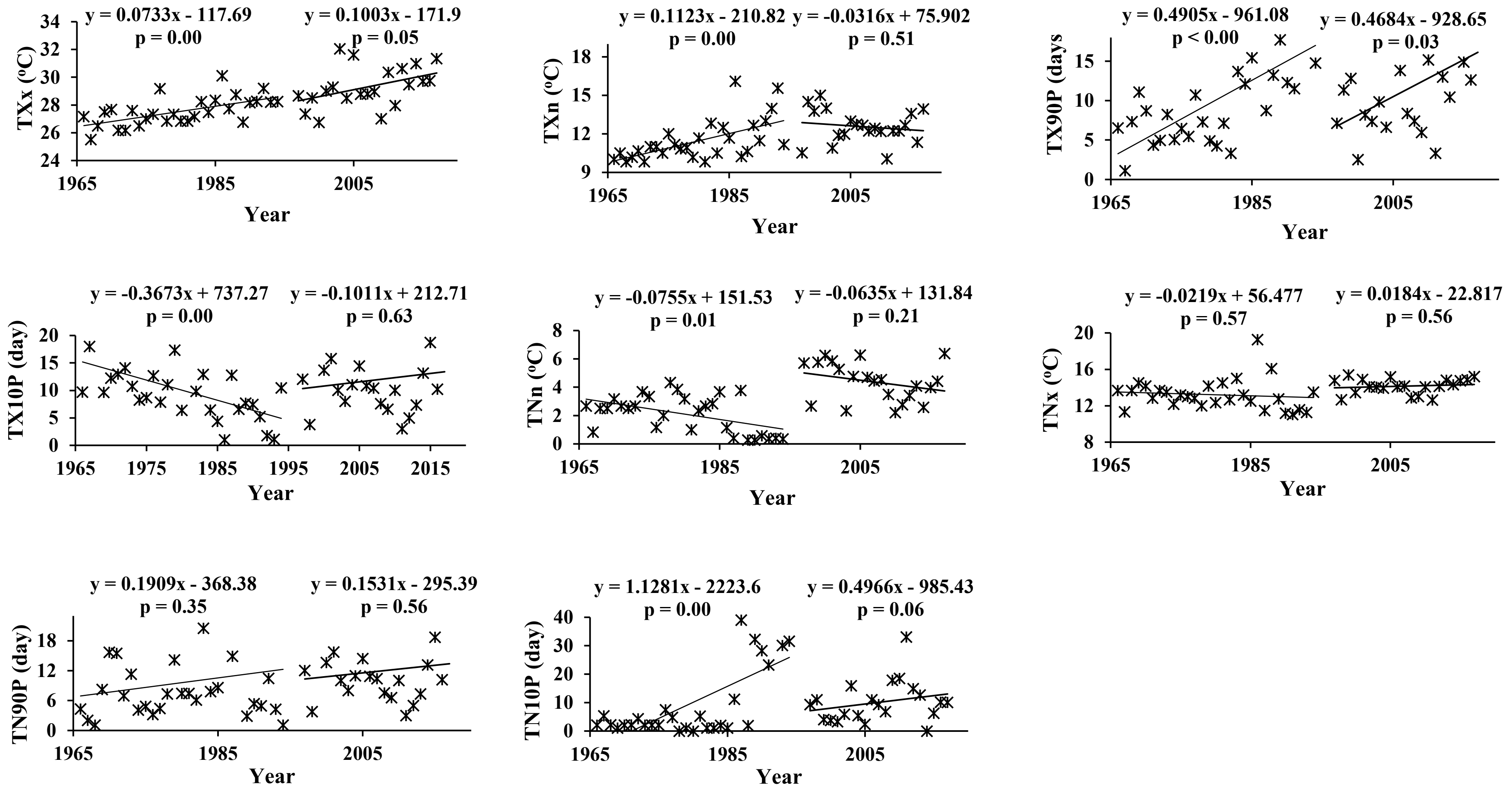

Figure 3.2: Temporal trends of seasonal (winter) extreme maximum and minimum air temperature for the study area from 1966 to 2017

Throughout the seasons, TNx lack coherence between the two periods with 1966-1994 indicating either a statistically insignificant ($p > 0.05$) increase or decrease whereas 1997-2017 consistently shows a statistically insignificant ($p > 0.05$) decreasing trend. For the winter season (Figure 3.3), trends of TXx, TXn, TX90p, TNn and TN10P were not different from the one observed during autumn. However, TX10p showed a decreasing trend for both time periods.

Similar trends for the spring season for all extreme air temperature indices (Figure 3.4) were observed with an exception of TXx which showed a statistically insignificant trend for the 1997-2017 period and TXn which followed a warming trend for both time periods although statistically insignificant for the latter period. For TN10p, both time periods indicated a statistically insignificant positive trend during the spring season. The results for the summer season (Figure 3.5) suggest that the study area experienced an increase in maximum air temperature indices except for TX10 (cool days) which portrays a decreasing trend for both time periods. The TNn showed a statistically insignificant decrease over 1966-2017 while the other 3 indices (TNx, TN90 and TN10p) appeared to be decreasing and increasing respectively over 1997-2017. Despite lack of consistency in the seasonal trends of extreme air temperature results, these results suggest that the maximum value of Tmax (TXx), number of warm days (TX90), and cool nights are increasing whereas number of cool days (TX10p) and minimum value of Tmin (TNn) are decreasing in the study area. The regression results for annual maximum Tmax value (TXx) (Figure 3.6) shows that TXx is increasing at a rate 0.069 and 0.003 ºC annum^{-1} for 1966-1994 and 1997-2017 respectively but the minimum Tmax value (TXn) increase (0.094 ºC annum^{-1}) is only observed during 1966-1994 (Figure 3.6). For 1997-2017, the study area experienced a statistically insignificant decrease (-0.012 ºC annum^{-1}) in TXn. The annual trends of both cool days (TX10p) and warm days (TX90p) were decreasing during the study periods 1966-2017. The rate of decrease during 1997-2017 (-0.119 and -0.113 and ºC annum^{-1}) is lower than the decreasing rate during 1966-1994 (-0.280 and -0.225 ºC annum^{-1}). In addition, these trends were found to be statistically insignificant for the latter period. The minimum air temperature indices results suggest a statistically insignificant ($p > 0.05$) decrease in annual maximum (TNn) and minimum Tmin (TNx) value for both time periods. Specifically, from 1966 to1994 (1997-2017) TNn and TNx indicated a decreasing trend of -0.038 (-0.029) and -0.022 (-0.049) ºC annum^{-1} respectively. Positive trends for cool nights (TN10p) and warm nights (TN90p) were observed for the study area over 1966-1994.

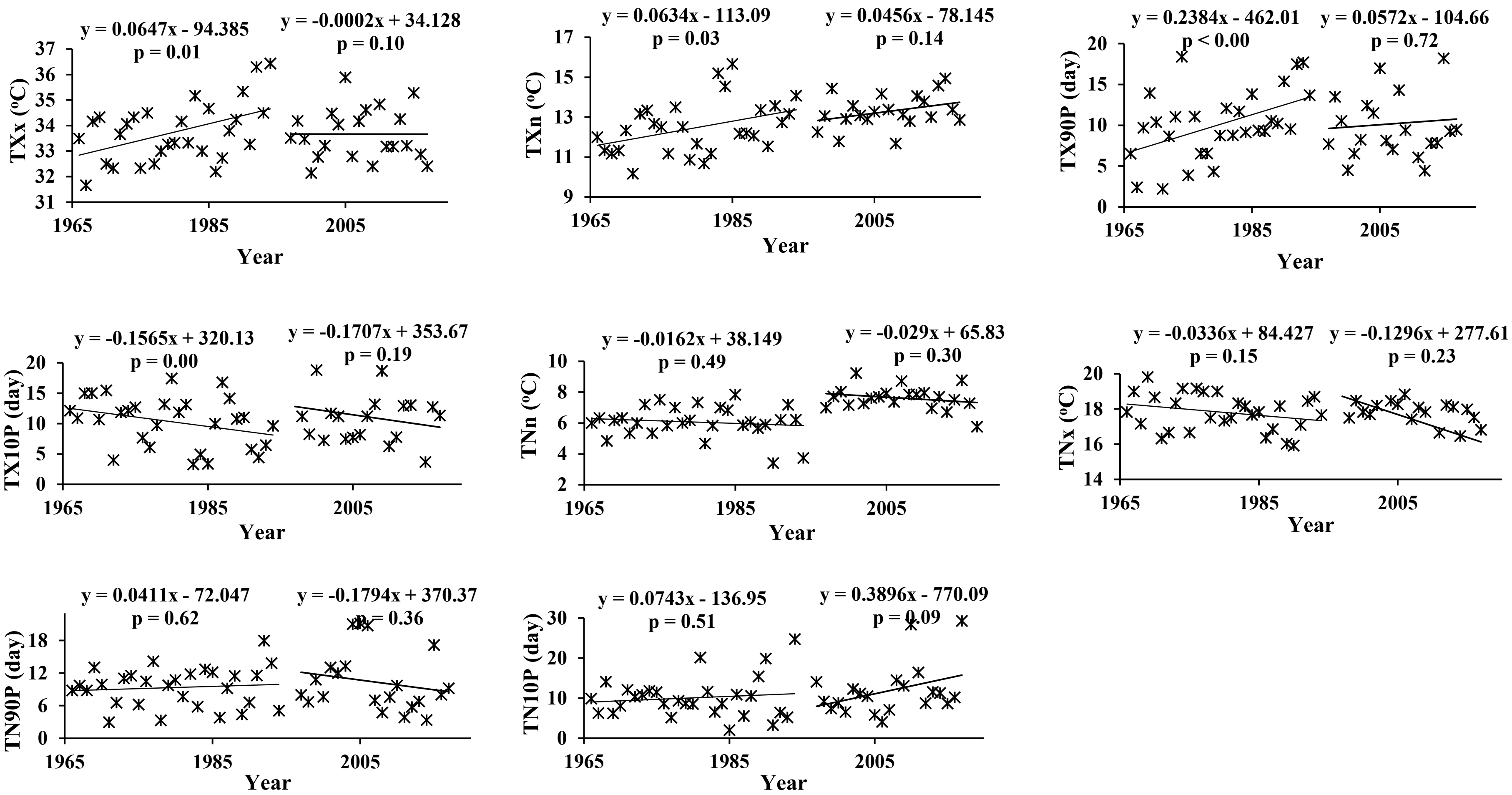

Figure 3.3: Temporal trends of seasonal (spring) extreme maximum and minimum air temperature for the study area from 1966 to 2017

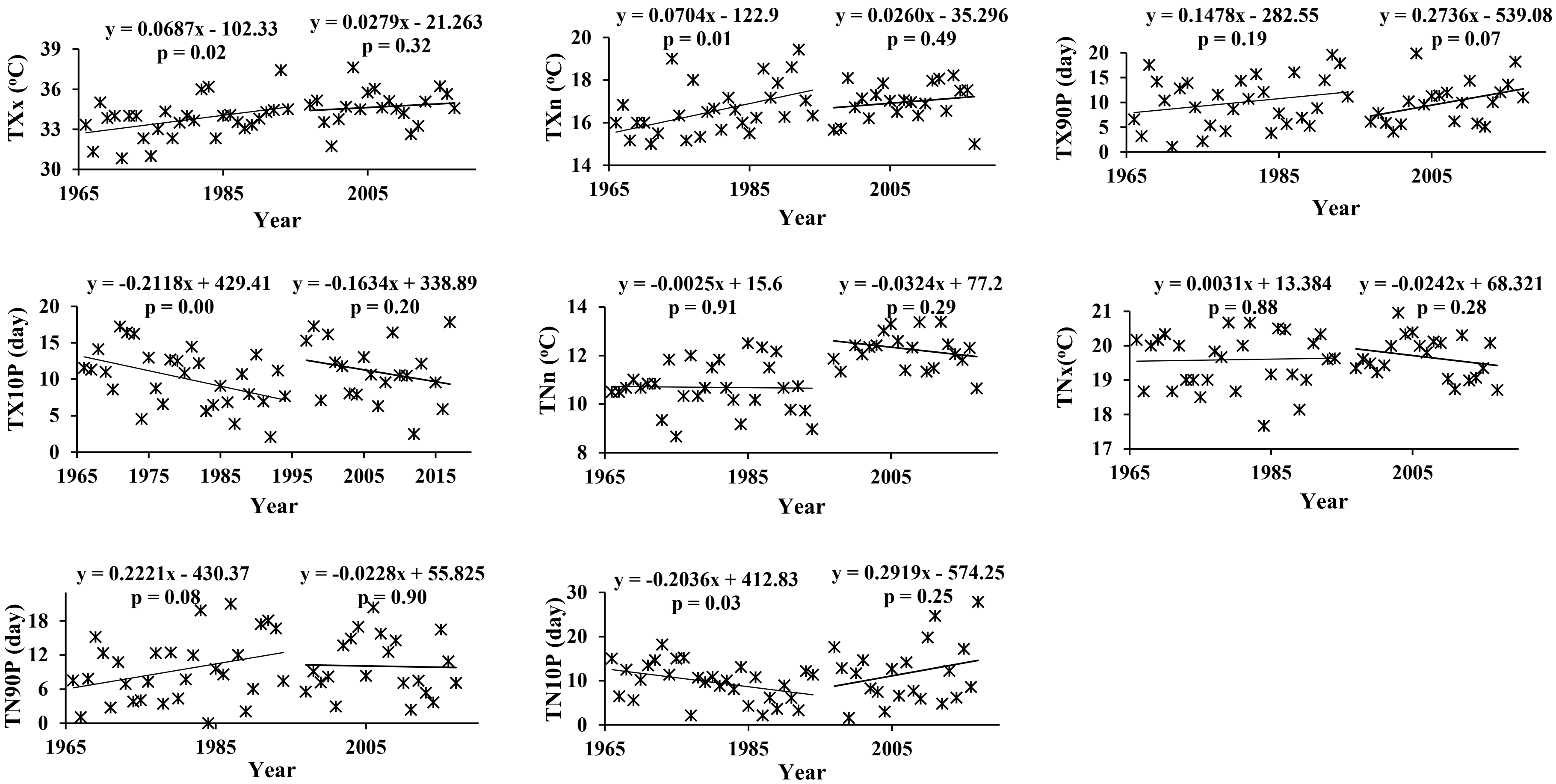

Figure 3.4: Temporal trends of seasonal (summer) extreme maximum and minimum air temperature for the study area from 1966 to 2017

Cool nights (TN10p) were found to be statistically increasing at 0.365 and 0.405 ºC $annum^{-1}$ for 1966-1994 and 1997-2017 periods respectively while cool days (TN90p) were increasing at 0.092 ºC $annum^{-1}$ for the former period. For 1997-2017, TN90p was found to be decreasing at -0.010 ºC $annum^{-1}$, however, this trend for TN90p was found to be statistically insignificant ($p > 0$).

3.4.2 Trends in annual extreme precipitation indices

Figure 3.7a-i shows the regional average of precipitation indices from 1966 to 2017 for the study area. During 1966-1994, the maximum number of CDDs showed a positive significant trend of 0.797 days $annum^{-1}$, while the maximum number of CWDs was found to be decreasing insignificantly at -0.036 days $annum^{-1}$. From 1997 to 2017, a statistically insignificant ($p > 0.05$) decreasing trend of -0.479 and -0.025 days $annum^{-1}$ was observed for both CDD and CWD respectively.

The regression analysis of regionally averaged CDD and CWD during both time periods indicates that the highest number of CDD (93.3 days) was observed in 1998 followed by 88 days in 1993. The years with the highest number of CDDs coincide with the previous El Niño years (1992-1993 and 1997-1998) in South Africa. The study results indicate that the highest number of CWD (10 days) was observed over the 1966-1994 period suggesting a reduced temporal rainfall distribution. The number of days with precipitation greater than 10 and 20 mm (R10mm and R20mm) showed a statistically significant decrease in both indices over the former period and an increase over the 1997-2017 period. A statistically significant ($p < 0.05$) increase of 0.341 days $annum^{-1}$ between 1997-2017 was observed for R10mm whereas a statistically insignificant increase of 0.126 mm $annum^{-1}$ was observed for R20mm over the same period.

Despite the increasing R10mm and R20mm over 1997-2017, the maximum number of days with heavy precipitation (R10mm and R20mm) was found in 1978 (49 days) and 1973 (20 days) respectively. The results suggest that although the study area appears to be experiencing heavy precipitation in the recent past years, their magnitude has not exceeded that previously experienced.

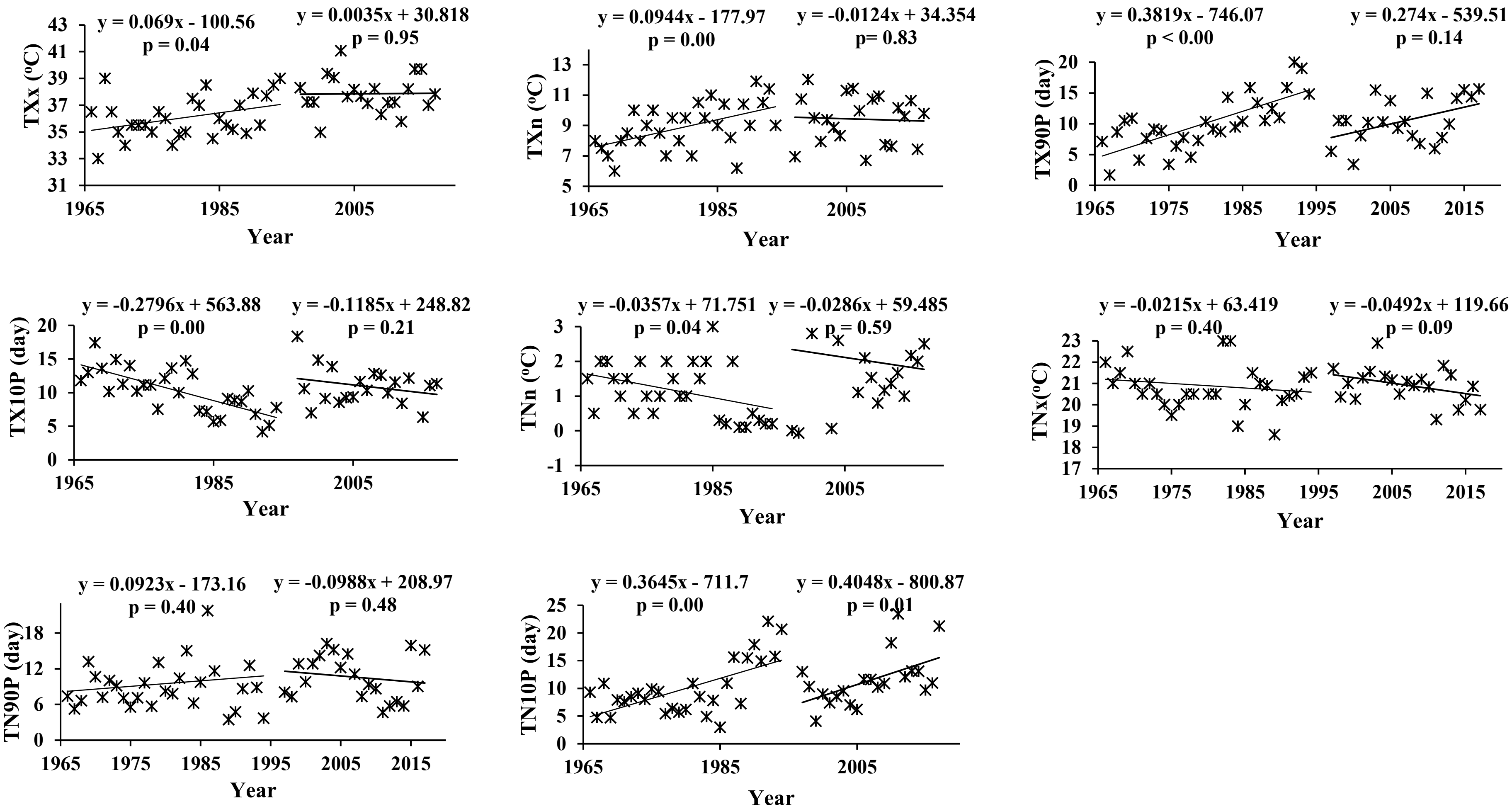

Figure 3.5: Temporal trends of annual extreme maximum and minimum air temperature for the stud area from 1966 to 2017

As was the case with the increase in R10mm and R20mm during 1997-2017, the maximum amount of rainfall over 1 day (Rx1day) and the maximum amount of rainfall over 5 days indicated a statistically insignificant increasing trend over the same period. Rx1day and Rx5day showed a positive trend of 0.1738 and a negative trend of -0.337 mm annum^{-1} respectively during 1997-2017.

The regression analysis results showed that Rx1day and RX5day are in accord with the 1987 floods that were experienced in Pietermaritzburg. The study results indicate that for the study site Rx1day and Rx5day reached an amount of 248 and 455 mm respectively during 1987. Over the recent past (1997-2017) the highest amount of rainfall over a day and 5 days only amounted to 104 mm (1999) and 131 mm (2011) respectively. Very and extremely wet days (R95p and R99p) also showed a statistically insignificant decreasing trend during 1966-1994 and an increasing trend during the latter period. The trend of very wet and extremely wet days was increasing at 8.421 and 7.404 mm annum^{-1}. However, the extremely wet days (R99p) positive trend was statistically insignificant. Annual precipitation total showed 1966-1994 a statistically significant ($p < 0.05$) decreasing trend whereas during 1997-2017 a statistically significant

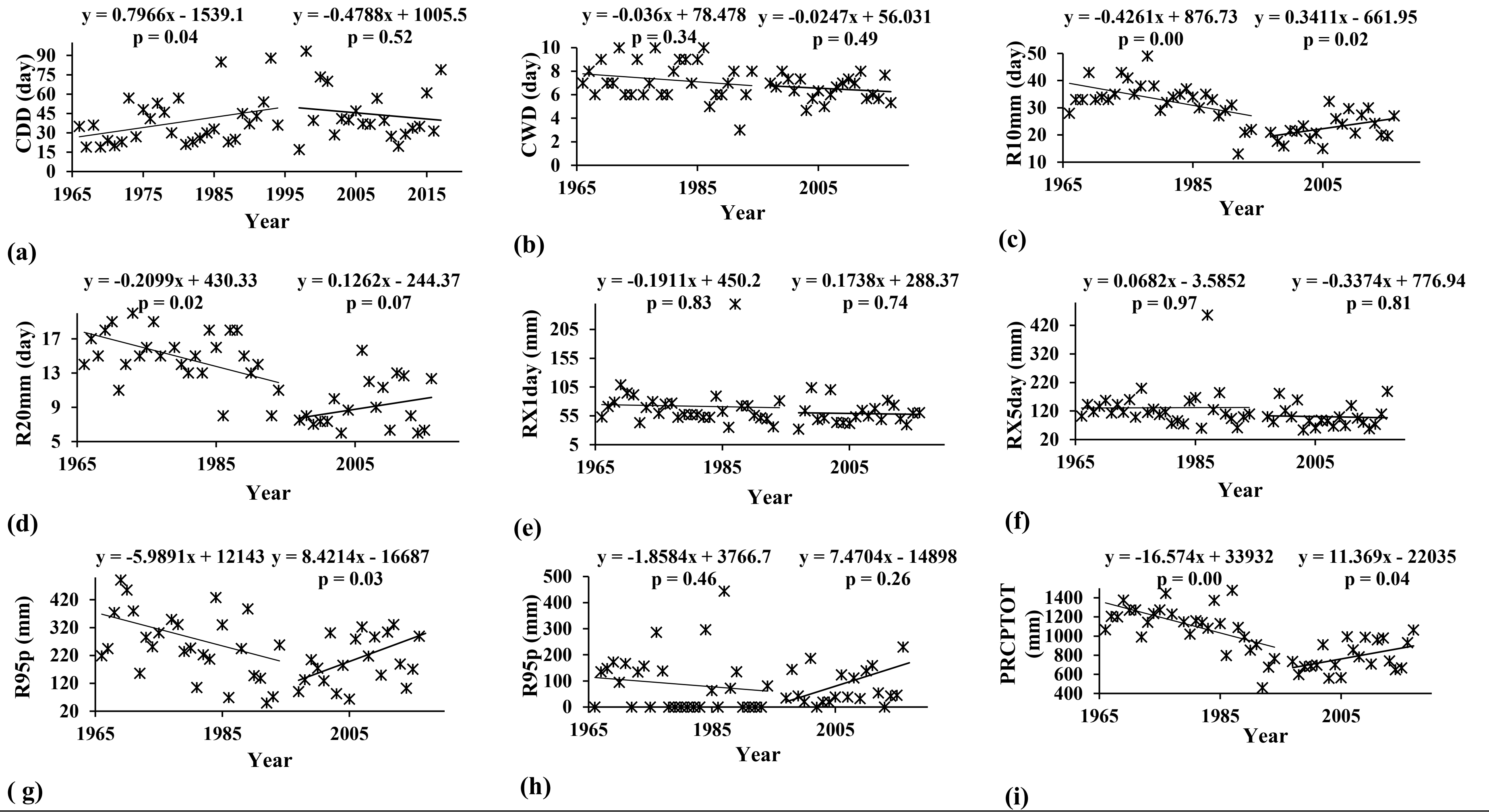

Figure 3.6: Trend for regionally averaged precipitation indices over the study area for 1966 to 2017. (a) CDD; (b) CWD; (c) R10mm; (d) R20mm; (e) Rx1day; (f) Rx5days; (g) R95p; (h) R99p; (i) PRCP

($p < 0.05$) increasing trend of 11.693 mm annum-1 for the study was observed. The results suggest that the latter period is confronted with an increased frequency of extreme precipitation.

3.5 Discussion

3.5.1 Seasonal and annual variation of absolute temperature extremes trends

The study investigated the variability of extreme weather for the study area within the sugarcane belt of the KZN midlands. The study findings showed that extreme temperature trends over the study period are not consistent between seasons. However, some similar seasonal tendencies from season to season were found to exist. The differences in the length of the dataset for the former period might have contributed to the inconsistences between the two study periods. This is particularly because during the 1966-1992 period dry events were more prevalent, hence a strong increase in temperature extreme trends relative to the latter period. Also, the decreases during the 1997-2017 period might be as a result of the prevalence in rare low temperature events that were projected to increase in areas of high latitudes (Collins, et a., 2013).

The findings presented by this study partly agree with similar studies previously conducted in South Africa. While a general increase in extreme air temperature indices (TXx, TXn, TNn, and TNx) has been previously reported for South Africa, the study results confirm that monthly maximum value of daily maximum air temperature (Txx) is increasing throughout the seasons except for spring where a decrease is observed for the period of 1997-2017. The annual time series for TXx also display an increasing trend for both time series confirming that maximum air temperature values are increasing in the study area. The increasing maximum air temperature values have been reported across the globe (Halimatou et al., 2017; Aguilar et al., 2005; Larbi et al., 2018). Minimum air temperatures are reported to show significant increases in many parts of the world; the study results suggest the decreasing trend of the coldest day trends throughout 1966-2017 indicating that the coldest day of the year (TNn) is becoming colder. Also, cool nights have been increasing at 0.365 and 0.405 ºC annum $^{-1}$ for 1966-1994 and 1997- 2017 respectively. However, this paradox has also been observed at a nearby station (Kruger et al., 2019). Given the reported general warming throughout the world, it becomes difficult to explain the possible reason behind this paradox. However, it is fair to suggest that the prevalence of frost in high altitude (> 800 m) areas is likely due to frequent colder nights.

Furthermore, the most severe frost that occurred in 2014 might have contributed to relatively low TNn values (Ramburan et al., 2015). In addition, the decreasing trend of TNn can be explained by the fact that extreme events are represented by specific events on an annual basis. Thus the magnitude of particular events may not reflect the general warming in the time series, specifically for short-term series (Kruger & Sekele, 2013). Also, the TNn results might confirm the possibility of the contribution of other factors than climate variability and change to the decreasing TNn (Kruger & Nxumalo, 2017). For example, recent prevalent drought occurrences in the study site might have contributed to the decreasing TNn considering that the absence of clouds and sufficient water vapour to enhance downward longwave radiation. In the absence of clouds which act as an insulator for night-time temperatures, the surface tends to lose heat more efficiently. This, therefore, suggests that dry conditions increase maximum temperatures but decrease minimum temperatures, and hence increase the DTR. Variability of TXn and TNx displayed temporal incoherency in almost all the seasons. Over 1966-1994 a clear upward TXn trend was observed across all seasons whereas a negative trend is shown for autumn and winter during 1997-2017. Subsequently, annual variations for TXn show that the monthly minimum value of maximum air temperature has been increasing (decreasing) over the first period (1997-2017). Similarly, the maximum value of minimum air temperature (TNx) showed a negative slope for the second period. This implies that there is a substantial decrease in both higher and lower values for minimum air temperature for 1997-2017.

Decreasing minimum air temperature results were reported in Mexico (Lopez-Diaz et al., 2013) and the decreasing Tmin trend was attributed to less effective infrared incident radiation since less infrared radiation is trapped by the surface owing to inadequate atmospheric water vapour, resulting in radiation frost (Lopez-Diaz et al., 2013). A clear upward TXn trend can be explained by the findings of Kruger & Shongwe (2004) who reported that a pronounced increase in air temperature during the early ’80s was likely to contribute towards the general increase in average air temperature in South Africa. The rise of cold nights and warm days detected in the recent past indicates the misleading results from mean air temperature analysis.

3.5.2 Seasonal and annual variation of percentile temperature extremes trends

A similar pattern of increasing TXx and decreasing TNn is apparent in the variation of warm days (TX90) and cool days (TX10p) and well as warm (TN90p) nights and cool nights (TN10p). TX90p and TX10p showed an increasing and decreasing trend throughout the seasons for the entire study period. The positive trend of warm days was also found (Kruger &

Sekele, 2013) in a nearby station and South Africa in general from 1962 to 2009. However, similar studies conducted recently in South Africa (Kruger & Nxumalo, 2017; Kruger et al., 2019) showed that a station nearby the study site displayed no trend over 1931-2015 and 1951 to 2005 respectively. Nevertheless, the study results suggest that warm day increase is more profound during the winter season at a rate of 0.49 days annum^{-1} followed by summer season at 0.27 days annum^{-1} over 1997-2016. An increase in warm days during the winter season means a possible reduction of frost occurrence and hence improves the production of sugarcane in the study area. Warm days due to high air temperatures coupled with a dry atmosphere (Strydom & Savage, 2018) promote evapotranspiration rates which could be detrimental to dryland farming relying on limited water sources. Several studies across the globe have confirmed that night-time air temperatures are increasing at a higher rate causing a substantial decrease in cool nights (Alexander et al., 2006; Donat et al., 2013). The TX90p results are consistent with TXn results indicating that warm nights are increasing over 1966-1994 and decreasing over 1997-2017. These results partly confirm the findings (Kruger & Shongwe, 2004) which reported a slow increase in average air temperature (0.01 ºC) over 1991-2003 relative to an increase of 0.04 ºC over 1960-1990. Despite the temporal coherency between two time periods under study, the TN10p results do not, however, correspond to the findings of similar studies in South Africa. A clear upward trend of TN10p, although statistically insignificant was observed over the entire study period. These findings suggest that the study area has been experiencing cooler night-time air temperatures. Previous studies associate the increase in TN10p with the reduction in night cloud cover (Revadekar et al., 2013). From this study, it can be concluded that for the study area, major decreases in TNn, TN90 and TNx occur in autumn and summer respectively whereas major increases in TXx, TX90, and TN10 take place in winter.

Increasing maximum and decreasing minimum air temperatures widen the range of diurnal temperatures. There have been reports that crop yields are negatively correlated to a large range of diurnal temperature due to water and heat stress induced by hot days (Lobell, 2007).
Decreased air temperature either during daytime or night-time causes deterioration in the carbon budget (Uehara et al., 2009). Given that sugar yield is determined by the high sucrose concentration and stem fresh weight, a poor carbon budget tends to restrict stem growth and sucrose concentration in sugarcane (Uehara et al., 2009). Thus, low temperatures either occurring during the day or the night are associated with poor stem elongation and decreased fresh stem weight.

3.5.3 Annual variation of extreme precipitation trends

It has been confirmed that the consequences of climate change would be felt primarily through changes in precipitation patterns. As air temperature increases due to increased concentration of greenhouse gases in the atmosphere, the water-holding capacity of air also increases resulting in greater moisture content in the atmosphere (Trenberth, 2011). High atmospheric content in conjunction with warmer near-surface temperature is likely to increase global precipitation (Fowler & Hennessy, 1995). This study confirms a significant increase in total precipitation over 1997-2017 for the study site. The increase in precipitation was projected to be achieved through significant increases in the frequency of extreme rainfall events (Mason & Joubert, 1997), meaning increases in rainfall per day, instead of increases in the number of rain days. Mason et al. (1999) attested that over half of the country has experienced a significant increase of intense rainfall events since the 1930s. Recent similar studies showed that the indices of total extreme rainfall (R99 and R95) for the KZN province displays an insignificant upward trend (MacKellar et al., 2014; Kruger & Nxumalo, 2017). Also, this present study confirms that the study area experienced a statistically insignificant decreasing trend for the 1966-1994 time period and a significant upward trend for the latter time period. Similar results were observed for Rx1day although not significant. The results of R10mm and R20mm also displayed similar significant trends, indicating an increased frequency of days with rainfall greater than 10 and 20 mm. However, the highest amount of rainfall received over a consecutive 5-day period (Rx5day) appears to be decreasing during 1997-2017 suggesting that the magnitude of continuous rainfall is decreasing in the study area. The statistically insignificant decreasing trend of the amount of 5-days rainfall for the study site over 1997-2017 demonstrates the increase in extreme precipitation events. The results of this study, however, are not in agreement with some previous studies (Kruger & Nxumalo, 2001; Kruger et al., 2019) who reported an insignificant decrease in R10mm, R20mm and total annual rainfall.

Theoretically, a decrease in consecutive dry days (CDD) would imply that consecutive wet days (CWD) are increasing. However, temporal changes in the CDD and CWD trends are not coherent, particularly for the 1997-2017 period as both indices show a statistically insignificant decreasing trend despite that the CDD decrease was more pronounced than the CWD decrease. The results are consistent with the previous study conducted at the national level using the nearby station (Kruger & Nxumalo, 2017) which indicated an insignificant decrease in both indices over 1921-2015. The decrease of CWD can be explained by the increase in extreme daily rainfall which is believed to be occurring at the expense of continuous moderate and light precipitation (Trenberth, 2011).

Despite the significant increase in total annual precipitation trend, the temporal distribution of this rainfall is concerning given the increase in RX1day and R95 which are indicative of high rainfall amounts being received over a relatively short time period. The amount of rainfall received through heavy rains over a short period of time is often less beneficial to dryland farming because the timing, amount and distribution of rainfall during the farming season play a crucial role in the productivity of dryland farming. There are several long-term and short-term negative effects that are associated with high rainfall intensities. High intense precipitation can increase the rate of soil erosion (Mohamadi & Kavian, 2015) and loss of soil nutrients which in turn decreases soil fertility and productivity (Fraser et al., 1999). Sugarcane crops are particularly sensitive to precipitation patterns given that each phase of the crop growth has specific climate requirements. High rainfall during the ripening period has been proved to be unfavourable for sugarcane crop (Malik & Tomar, 2003).

3.6 Conclusions

The study found a statistically insignificant increase in the extreme maximum air temperature trend for the study site for 1966-2017 and the results partially correspond to similar studies conducted at a national scale using a few weather stations. More warm days (TX90p) and fewer cool days (TX10p) have been experienced for the study period. Unlike previous studies that indicated a pronounced air temperature increase in autumn, this study showed that major increases in maximum air temperature occurred during winter indicating that the cooler season is becoming warmer. However, extreme minimum air temperature trends exhibited a different trend compared to previous studies. Minimum air temperature showed a decreasing trend causing an increase of cool nights (TN10p) and a decrease of warm nights (TN90p). Although previous studies found a decrease in TN10p and an increase in TN90p, a decreasing trend of TNn which is consistent with an increase in cool nights was observed for the study sites. The observed decreasing minimum air temperature trend can be attributed to microclimate influences. Also, considering that the study used a dataset of 26 and 20 years, it is possible that the results are indicative of a natural decadal variability rather than anthropogenically forced climate change. However, contrary to the study findings the general global warming observation may be indicative of the areas that experience a paradoxical minimum air temperature trend across the globe which are often overlooked in global and national studies. The findings of this study, therefore, conclude that the study sites are amongst those few regions that experience paradoxical trend despite the observed general increase in air temperature across the country. This suggests that local climate conditions might be experiencing a different air temperature trend and thus need further investigation.

Despite the inconsistent findings of minimum air temperature, precipitation variation displays an apparent increasing trend of extreme precipitation events during 1997-2017. The precipitation findings are consistent with the previous similar studies in South Africa. However, substantial differences have been observed between the results observed from a weather station located in Wartburg and the nearby station often used to represent KZN midlands for climate change studies. This study concludes that due to inconsistency of the results between the study site weather stations and the nearby station, the vulnerability of farming communities to climate change can be underestimated or overestimated through using the nearby station.

3.7 Acknowledgements

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Appendix 1

Table 3.3: Detected change points using different homogeneity tests for various stations.

Test	**Bruny's Hill Detected Change Point**					
	Tmin	**p-value**	**Tmax**	**p-value**	**Precipitation**	**p-value**
RHtestV4	1998 & 2015	< 0.05	None	< 0.05	2007	< 0.05
Pettit	2007	0.05	2006	0.80	2005	0.00
STD normal Homogeneity test	2007	0.06	1999	0.45	2005	0.10
Buishand range	2007	0.02	2006	0.24	2005	0.05
		Eston Detected Change Point				
RHtestV4	None	< 0.05	1998	< 0.05	2003	< 0.05
Pettit	2010	0.89	2002	0.52	2013	0.62
STD normal Homogeneity test	2010	0.66	1997	0.03	2017	0.82
Buishand range	2010	0.32	2002	0.20	2013	0.86
		Powerscourt Detected Change Point				
RHtestV4	**1998**	< 0.05	None	< 0.05	2003 & 2010	< 0.05
Pettit	2007	0.49	2000	0.57	2005	0.28
STD normal Homogeneity test	2017	0.25	1997	0.03	2005	0.38
Buishand range	2007	0.74	2001	0.27	2005	0.14
		Windy Hill Detected Change Point				
RHtestV4	**1985**	**< 0.05**	**1992**	**< 0.05**		**< 0.05**
Pettit	1986	0.92	1984	0.00	1989	0.27
STD normal Homogeneity test	1986	0.09	1984	0.00	1991	0.11
Buishand range	1886	0.04	1984	0.00	1981	0.18

Lead to Chapter 4

Historical air temperature and precipitation trends were probed in Chapter 3. In Chapter 4, ETo changes due to historical climate change conditions are analysed. The PM technique is used to quantify ETo for the study period. The influence of specific climate parameters on the ETo trend is examined using the de-trended method.

CHAPTER 4: REFERENCE EVAPORATION AND DROUGHT PREVALENCE UNDER CLIMATE CHANGE CONDITIONS IN THE WARTBURG AREA OF THE MIDLANDS OF KWAZULU-NATAL, SOUTH AFRICA

4.1 Abstract

Climate change reality is widely recognised and its effects are becoming apparent in many parts of the world. Changes observed include rainfall variations, increased air temperatures and prevalence of climate extremes (droughts and floods). Evaporation is expected to reflect these changes. Due to the susceptibility of the African continent to dry conditions under climate change, understanding the response of reference evaporation to drought is essential.

This study, therefore, aimed to 1) analyze the seasonal and annual ETo trends in the KwaZulu-Natal midlands area of South Africa for the period 1966-2017 using a linear regression model, 2) quantify the contribution of each meteorological variable towards the ETo variability, 3) identify wet and dry years using the Standardized Precipitation Index (SPI) and analyze the magnitude of change during dry years relative to wet years, and 4) evaluate the correlation between drought and ETo using the Surface Humid Index (SHI) and the Pearson correlation coefficient.

The results indicate a generally statistically insignificant decreasing ETo over the period studied. The climate variables analyzed indicates an average decreasing trend in wind speed, solar irradiance, and relative humidity while average air temperature exhibited no significant change. Relative humidity and solar irradiance were found to have a significant influence on ETo variation. The results indicated that ETo increases during dry years and decreases during wet years. The magnitude of change analysis indicated that during drought, ETo increases at a faster rate relative to wet years. However, this only occurred at the beginning of a drought event with ETo decreases as the rainfall deficits intensify. The correlation analysis exhibits a negative relationship between rainfall and ETo, suggesting that ETo decreases as the SHI increases. The correlation analysis using the Pearson correlation coefficient indicates that SHI has a significantly negative correlation with ETo ($r = -0.6\ 4$, $p < 0.05$) and has a significantly positive correlation with precipitation ($r = 0.95$, $p < 0.05$). A negative significant correlation was also observed between ETo and precipitation ($r = -0.40$, $p = 0.05$). The study results conclude that although high evaporative demand during dry years resulted in increased ETo, low water vapour

pressure deficit as a result of adequate precipitation also resulted in an increase in ETo to a certain extent.

Keywords: *Drought events, Penman-Monteith, SHI, SPI*

4.2 Introduction

Temporal changes in climate factors such as precipitation and air temperature have been observed throughout the world. As such, evapotranspiration is expected to respond to these changes. Different approaches have been adopted to understand the response of reference evaporation (ETo) to climate change as well as relative changes of each climate variable on ETo. Sensitivity analysis has been extensively used to study the sensitivity of ETo to the changes of key climatic variables (Hou et al., 2013; Du et al., 2015; Patle & Singh, 2015). Other studies have been conducted to assess the response of ETo to climate change and global warming (Liu et al., 2010; Wang et al., 2012; Gao et al., 2017). Although it was generally expected that global warming would increase evaporation (Trenberth, 2011), previous studies have reported a significant decrease in pan evaporation and reference evaporation in many parts of the world. For example, decreases in reference evaporation were reported in Australia (Roderick & Farquhar, 2004), China (Xu et al., 2006), South Africa (Hoffman et al., 2005), India (Bandyopadhyay et al., 2009) and sub-Saharan Africa (Marshall et al., 2012). These decreases can be attributed to the fact that the evaporative process is governed by both radiative and aerodynamic components.

4.2.1 ***Background of ETo***

Evapotranspiration is an essential parameter which not only determines crop water requirements and evaporative demand of the atmosphere but also plays a key role in irrigation scheduling, regional water allocation (Sun et al., 2017), as well as the energy balance of the earth-atmospheric system (He et al., 2017). Evapotranspiration (ET) is used to describe two different processes, that is, evaporation (E) and transpiration (T). Evaporation refers to a process in which water evaporates from the soil or surfaces of the plant while transpiration involves the change of liquid water contained in plant tissues into water vapour in the atmosphere (Allen et al., 1998). Evapotranspiration is described in three different concepts: actual evapotranspiration (ETa), potential evapotranspiration (ETp) and reference evaporation (ETo). In the literature, ETp and ETo are used interchangeably, which causes confusion. For example, Chen et al. (2005:pg 123) defined ETo as "the potential ET of grass". Hence it is important to emphasize the difference between these concepts. Potential evapotranspiration was first introduced in 1948 and Penman (1956) defined it as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height, and with adequate water status in the soil profile" (Wang et al., 2012; pg 2) and adequate nutrients. In the 1990s, a standard and formal concept of ETo was introduced with detailed land-surface conditions as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23" (Allen et al., 1998: pg 5). Although ETp and ETo may appear to possess similarities, Allen et al. (1998) discouraged the use of ETp when referring to ETo due to the lack of clarity in its definition.

4.2.2 Different techniques for ETo estimation

ETo expresses the atmospheric evaporating demand at various locations and times of year without taking into consideration crop characteristics and soil factors. Only climatic factors such as solar irradiance, air temperature, relative humidity and wind speed have an effect on ETo (Allen et al., 1998) in addition to the assumed fixed surface resistance. Various methods ranging from physical to empirical are used to estimate reference evaporation (Chen et al., 2005; El & Abdrabbo, 2015; Lang et al., 2017). Popular methods that are generally used include class-A pan, FAO P-M, Priestley–Taylor, Hargreaves, Blaney-Criddle, and Thornthwaite methods. The widely used method for the estimation of ETo is the Penman-Monteith method (Hou et al., 2010; Łabędzki et al., 2011; Gu et al., 2018) as the sole technique recommended by the Food and Agriculture Organization of the United Nations (FAO) to determine ETo (Allen et al., 1998) at either hourly or daily times scales and for short-grass and tall-crop surfaces.

4.2.3 Climate change influences on ETo

Global circulation model predictions indicate the high probability of dry periods in many parts of Africa under climate change conditions (IPCC, 2012; Jury, 2013; Kusangaya et al., 2014; Naumann et al., 2018). Of particular concern is the likely increase of ETo due to increased heat which can conceivably accelerate drying and heating of the soil surface resulting in the depletion of soil moisture. As the soil surface warms, the atmospheric demand for water vapour is likely to increase. If the atmospheric moisture is not sufficient to support the increase, the aridity would intensify. However, given that ETo is independent of the soil surface and precipitation, there is a lack of an in-depth consideration of the correlation between precipitation and ETo, particularly in South Africa.

4.2.4 Observed ETo trend and causal factors

Numerous studies have been conducted across the world to understand the effects of meteorological factors variation on ETo changes (Xu et al., 2006; Bandyopadhyay et al., 2009; Marshall et al., 2012; Ma et al., 2017). In South Africa, Hoffman et al. (2011) studied the changes in pan evaporation, rainfall, wind run, air temperature and water vapour pressure deficit in Cape Floristic region over 1974 to 2005. Their study found a significant decrease in pan evaporation and partly associated the decrease with the observed significant wind run. Also, Tongwane, et al. (2017) investigated seasonal variation of reference evaporation in the eastern Free State of South Africa. They found that water vapour pressure deficit greatly influences ETo in the eastern Free State.

Despite the fact that these studies provide useful information on the response of ETo to the abovementioned changes, the inconsistencies in terms of the effect of major meteorological factors' condition on ETo trends across different parts of South Africa in particular, highlights that variation in ETo is mainly regulated by micro-climate conditions. This, therefore, necessitates an analysis of ETo trends at a local scale in order to consider local land use, land cover, topography aspects and other related factors. However, due to a sparse network density for microclimate measurements, understanding changes in microclimate parameters and its influence on other related elements becomes a challenge and hence a dearth of recent studies investigating the changes in ETo, specifically in South Africa, as climate conditions change.

This study, therefore, investigates and addresses the gap in knowledge by 1) analyzing the seasonal and annual ETo trends in the KwaZulu-Natal (KZN) midlands for the period of 1966-2017 using linear regression analysis; 2) quantifying the contribution of each meteorological variable towards the ETo variability using a detrending method; 3) identifying historical wet and dry years using the Standardized Precipitation Index (SPI) (McKee et al., 1993) and analyzing the magnitude of change during dry years relative to wet years using regression analysis; 4) evaluating the correlation between drought and ETo using the Surface Humid Index (SHI) (Hulme et al., 1992) and the Pearson correlation coefficient.

4.3 Materials and method

4.3.1 Study area

The province of KwaZulu-Natal is situated on the eastern seaboard of South Africa and has a geographic area of about 92180 km^2 which represents 7.6% of the country's total geographic area. It is the province with the second largest population, approximately 11.3 million people, 19.2% of the country's total population. It is characterized by a diverse landscape that is classified into highland and lowland regions with an altitude that ranges between 1000 and 3300 m, and 400 to 1000 m above sea level respectively. This diverse topography exerts a major influence on the climate and local weather, resulting in higher areas in the north and west being cooler and receiving more rainfall. The average air temperature varies from 16 ^{o}C in the west to 18 ^{o}C in the east. The rainfall season occurs during summer while the dry period occurs in winter. An east-west rainfall gradient exists, ranging from 560 to 1000 mm with a long-term average rainfall of 927 mm. The study was conducted within the sugarbelt area in KwaZulu-Natal midlands, South Africa. Figure 4.1 shows the geographical areas of KwaZulu-Natal and the area in which the study was conducted.

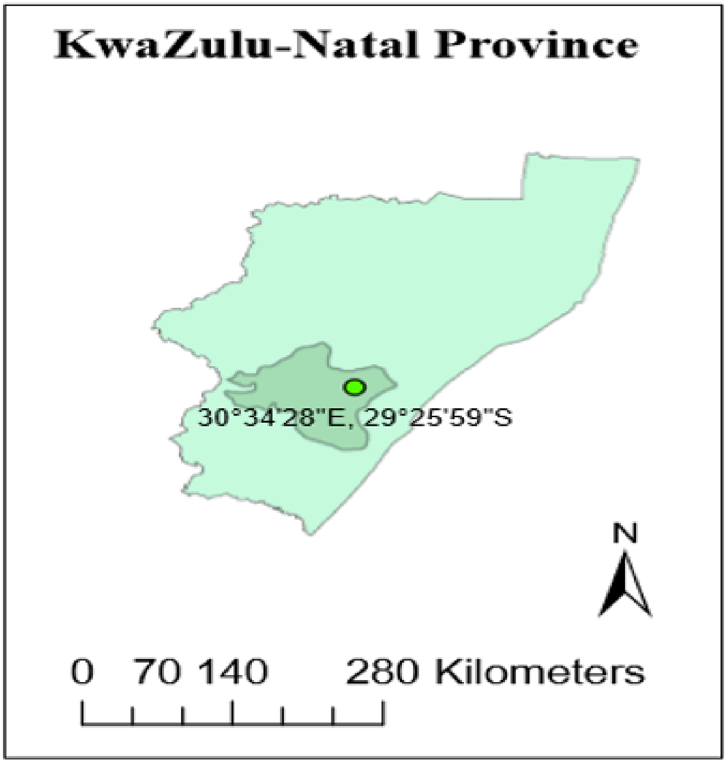


Figure 4.1: Map showing the study area within KwaZulu-Natal Province

4.3.2 Data and methodology

Both monthly and daily meteorological data from four stations (see Table 4.1) in the sugarbelt area in KZN midlands used in this study are available from the South African Sugarcane Research Institute (SASRI). For this study, the daily data were accessed from the SASRI website:
https://sasri.sasa.org.za/weatherweb/weatherweb.ww_menus.menu_frame?menuid=1.The data for all stations were of acceptable quality with only two missing years. The datasets included daily observations of maximum and minimum air temperature, solar irradiance, wind speed, rainfall and maximum and minimum relative humidity for at least 20 years.

Table 4.1: Geographical characteristics of the studied stations

Station name	Latitude (S)	Longitude (E)	Altitude (m)	Data period
Bruny's Hill	29°25' 0"	30°41'0"	990	1997-2017
Eston	29°52' 0"	30°31'0"	785	1997-2017

Powerscourt	29°59' 0"	30°38'0"	630	1997-2017
Windy Hill	29°29'25"	30°34'17"	988	1966-1994

Daily meteorological data were used as an input for the estimation of reference evaporation using the Penman-Monteith method (Allen et al., 1998):

$$\boldsymbol{ET_0} = \frac{\mathbf{0.408}\,(\boldsymbol{I_{net}}-\boldsymbol{F_s})+\boldsymbol{\gamma}\frac{\boldsymbol{C_n}}{\boldsymbol{T+273}}\boldsymbol{U_2 vpd}}{\boldsymbol{\Delta}+\boldsymbol{\gamma}\,(\mathbf{1}+\boldsymbol{C_d}\,\boldsymbol{U_2})} \tag{4.1}$$

$$\boldsymbol{ET_0} = \frac{\mathbf{0.408}\,(\boldsymbol{I_{net}}-\boldsymbol{F_s})+\boldsymbol{\gamma}\frac{\mathbf{900}}{\boldsymbol{T+273}}\boldsymbol{U_2 vpd}}{\boldsymbol{\Delta}+\boldsymbol{\gamma}\,(\mathbf{1+0.34}\,\boldsymbol{U_2})} \tag{4.2}$$

where ET_o is the daily reference evaporation (mm day^{-1}), I_{net} the net radiation (MJ m^{-2} day), F_s is a soil heat flux density (MJ m^{-2} day^{-1}), T (ºC) the mean air temperature at 2 m height, U_2 the wind speed at 2 m height (m s^{-1}), C_n (K mm s^3 Mg^{-1} d^{-1}) the numerator constant that changes with a reference type, viz. short-grass or tall-crop and calculation time step, C_d (s m^{-1}) the denominator which changes with reference to type and calculation time step, vpd (kPa) the water vapour pressure deficit, Δ (kPa ºC^{-1}) the slope of the saturation water vapour pressure vs temperature curve, and γ the psychrometric constant (kPa ºC^{-1}).

4.3.2.1 Trend analysis for annual ETo data

To obtain the slopes of linear regression, the least square method was used to assess trends in the time series:

$$y_i = b + mx_i \tag{4.3}$$

where y_i is the fitted trend over a given period, b and m the estimated regression slope and the regression constant respectively, and x_i the period of the dataset in years. The trends were also calculated using the non-parametric Mann-Kendall (MK) statistical test, a widely used technique to assess time-series trends to detect the significance levels of the trends. The MK test is commonly employed to detect monotonic trends in a series of environmental data, climate data and environmental data (Du et al., 2015; Khanmohammadi et al., 2017). The MK analysis is preferred since it does not require the dataset to conform to a specific statistical distribution. Also, it is not affected by outliers (Gao et al., 2017). The MK application requires an application of a pre-whitening method to eliminate the possible effects of a series correlation on the trend value.

In this study, an initial series correlation test was performed, and no significant correlation was found in the Windy Hill time series whereas other stations showed significant serial correlation for a few months. The pre-whitening procedure was therefore applied to monthly data for the months that showed significant serial correlation to remove 1-lag correlation. The MK analysis was then applied to a new time series to detect the annual and seasonal trends of ETo. The daily ETo values, which were used for the computation of the long-term monthly and annual trends, were calculated using a spreadsheet for daily Penman-Monteith grass reference evaporation from meteorological data (Savage, 2018). The MK test and Sen's slope estimator for ETo and climate variable trends were calculated using the Excel-based template MAKESENS 2.0 beta, developed by the Finnish Meteorological Institute (Salmi et al., 2002). The MK test statistic S was calculated using:

$$S = \Sigma_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn\left(X_j - X_k\right) \qquad (4.4)$$

where X_j and X_k are the data values at the time j and k respectively, n the period length of the dataset and sgn the function which is calculated as:

$$sgn(X_j - X_k) = \begin{cases} 1 \text{ if } X_j - X_k > 0 \\ 0 \text{ if } X_j - X_k = 0 \\ -1 \text{ if } X_j - X_k < 0 \end{cases} \qquad (4.5)$$

If n > 10, the test statistic Z nearly conforms to a standard normal distribution:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \qquad (4.6)$$

where *Var (S)* represents the variance of statistic *S*. A positive value of Z depicts an upward trend while a negative value indicates a decreasing trend. The decision of either to accept or reject the null hypothesis, Ho, i.e., there is no significant trend in the time series depends on whether the computed *Z* statistics are less or more than the critical value of *Z* statistics obtained from the normal distribution table at the 5% significance level (Koudahe et al., 2017). The magnitude of the trend was measured using Sen's estimator (β) (Koudahe et al., 2017; Qin et al., 2017).

$$\beta = Median\left(\frac{X_j - X_k}{j-k}\right), 1 < k < j \quad (4.7)$$

where β is the estimated slope of the ETo trends. A value of β greater than zero indicates a significant increasing trend and a value of β that is less than zero represents a significant decreasing trend.

4.3.2.2 Influence of each climate variable on the changes in ETo

In order to assess the contribution of each climate variable on reference evaporation, a detrending method was used. This is a simple and effective method for quantifying the impacts of changing climate parameters on ETo and it has been widely used (Xu et al., 2006; Lieu et al., 2013; Qin et al., 2017) in climate change studies. The first step of this method is to remove the variation trend in different meteorological variables so as to establish a stationary dataset for each meteorological station. This was achieved using a multiplicative model which assumes that:

$$Y = f(t) \quad (4.8)$$

Where f is the function of time. Then Y can be disintegrated to:

$$Y = TSI \quad (4.9)$$

Where T is the long-term trend of a particular variable for an original time series, S represents the seasonal component and I is the the irregular component of the time series. The T values can be derived from a simple linear regression model using the original time series:

$$T = mx + c \quad (4.10)$$

Where x is the year. Applying the multiplicative model, both sides of the equation are devided by the T values, hence:

$$\frac{Y}{T} = SI \quad (4.11)$$

Where SI is the detrended series consisting of only the seasonal and irregular variation. Secondly, the calculation of ETo using one detrended variable while keeping other variables unchanged was performed. Following this step, the contribution of changes in meteorological parameters on ETo variation using an evaluating indicator R was quantified as indicated in Qin et al. (2017) as follows:

$$R = \sum_{k=1}^{n} \frac{(\mathrm{ET}_o^o - \mathrm{ET}_o^R)}{\mathrm{ET}_o^o\ k} \tag{4.12}$$

where ET_o^o and ET_o^R (mm) represents the original and the revised daily ETo values respectively using the detrended dataset and n is the period length of the dataset. A positive R indicates that the change of climatic factor has positive effects on the changes in ETo whereas a negative R denotes a negative effect of changes of this climatic parameter to the ETo changes. An R-value of zero shows that the change of this climate factor results in insignificant impacts on changes of ETo. Large values of absolute R are indicative of a greater impact of the changes of this climate factor on the ETo changes (Qin et al., 2017).

4.3.2.3 Analysis of magnitude of change during dry years versus wet years

To identify dry and wet periods, the Standardized Precipitation Index (SPI) (McKee et al., 1993) was used. The SPI is a normalized index representing the likelihood of drought occurrence. This is achieved by comparing the observed rainfall amount and rainfall climatology at a certain geographical location over a long-term reference period. It enables rainfall to be quantified over different time scales (e.g 3-, 6-, 12- or 24-month rainfall) (Chi, 2013). The SPI is widely preferred due to the fact that it requires less data, is relatively easy to compute, enables drought characterization at various timescales as well as possesses the ability to adequately represent both wet and dry periods. The SPI has been accepted by the World Meteorological Organization as the reference index to characterize drought. To calculate SPI, a record of at least 30 years is required although 50 years has been recommended (Zargar, 2011). This study used 20-29 years of data depending on the availability of data at each weather station. However, to validate the results, data from three weather stations that are close to each other were combined. The combined dataset was for 1966-2017 excluding two years of missing data (48 years). The SPI was calculated using the combined dataset and the results are within a reasonable deviation from the SPI values calculated using 20-29 years of data. From the results, for each station one dry and one wet year was selected. Using the Penman-Monteith equation, daily ETo was calculated for both dry and wet years for all stations. To assess the magnitude of change in the long-term trends, linear regression analysis was employed between time series and ETo annual series. In addition, SHI, as suggested by Hulme et al. (1992), was used to analyze the correlation between ETo and drought. This index is convenient for computing moisture availability. The index SHI is calculated as the ratio of temporal precipitation (P) to ETo at an annual timescale. A SHI of 1 indicates a balance between precipitation and ETo while values greater than 1 indicate that ETo is less than precipitation. A SHI value 1 less than 1 is indicative of a condition where ETo is greater than precipitation. In addition, an increasing trend of the SHI index exhibits a decreasing trend of dryness and vice-versa. Furthermore, Pearson correlation analysis was conducted between SHI, ETo and P.

4.4 Results

4.4.1 Trends in ETo

Figure 4.2a-d shows that the corresponding slope of change of annual ETo for four meteorological stations over the period of 1966 to 2017 is -5.13, -1.09, 5.10 and -0.18 mm a^{-1} respectively, which are statistically insignificantly decreasing. Table 4.2 indicates that for ETo, the annual Sen's slope estimator for Bruny's Hill, Eston, Powerscourt and Windy Hill is -11.14, -0.29, 0.21, -1.38 mm a^{-1} respectively, which indicates agreement with the slopes shown in Figure 4.2a-d. There is no consistency in terms of seasonal ETo variation across these stations in the sugarcane belt of the study area. There were decreases in ETo for different seasons in Windy Hill and Bruny's Hill stations. For the Eston, ETo appears to be decreasing in all seasons except autumn. The Powerscourt shows a decline in ETo only in spring and summer. The differences amongst the stations can be attributed to climatic and geographical differences. Based on three weather stations (Bruny's Hill, Eston and Windy Hill), the slope shows a general decreasing trend in annual ETo for the study area. On the other hand, a statistically insignificant increasing annual ETo trend was observed for Powerscourt. The seasonal and annual ETo results based on the MK test for each climate station are shown in Table 4.2. The average decreasing trend in autumn, winter, spring, and summer for all stations is 0.256, 0.723, 1.335 and 3.209 mm a^{-1} respectively for the study area. Based on these observations, the rate at which ETo is decreasing is faster in summer and spring seasons than in winter and autumn. The decreasing trend was statistically significant ($p < 0.05$) for two stations at a seasonal time scale. Bruny's Hill and Powerscourt showed a significant decrease in summer at a significance level of 95%. The Eston station indicated a decreasing trend in ETo in winter at a significance level of 90%.

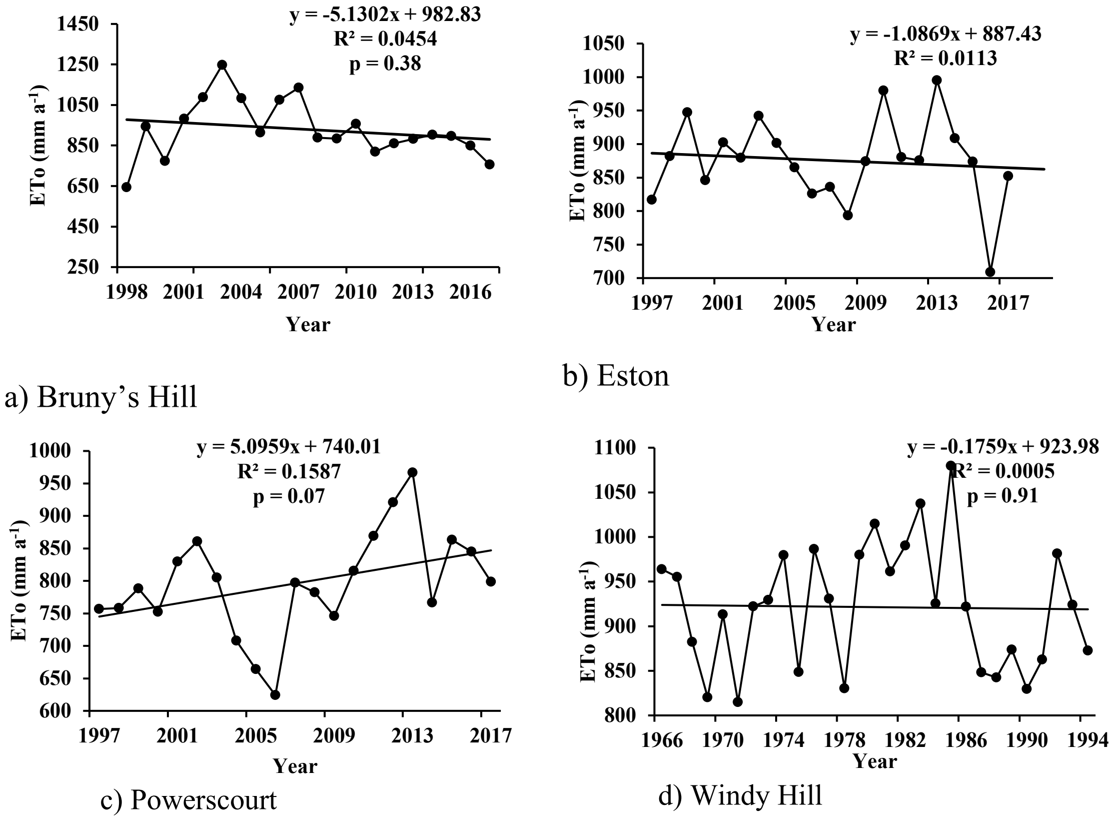


Figure 4.2: Annual ETo for various stations in the Wartburg area

At the annual time scale, the slopes of the regression relationships indicate the average negative ETo trend of -0.324 mm a^{-1} while the MK test shows a negative trend of -3.209 mm a^{-1} for the study area. According to the MK test, only one station with a decreasing trend (Bruny's Hill) is statistically significant ($p < 0.05$). Other meteorological stations indicate a statistically insignificant decreasing trend. In terms of the magnitude of trends for each station, the highest ETo decrease was observed for the Bruny Hill's.Furthermore, the monthly changes of ETo based on the MK statistical test are shown (Fig 4.3). The index Z values based on MK statistical test are illustrative of how ETo changes as meteorological variables vary due to seasonal variation. Notably, the increases in ETo for the Powerscourt and Eston stations during the autumn and winter months reached a maximum of 2.21 and 0.88 mm respectively.

The monthly ETo trends result of Fig 4.3 shows that monthly ETo trends do not follow a similar pattern with some stations indicating high ETo during winter months while ETo reaches a maximum during summer months for other stations. The results suggest that maximum ETo occurred in February, March, July, and November for Bruny's Hill, Eston, Powerscourt, and Windy Hill stations respectively. Minimum values for ETo were observed in July and September for Bruny's Hill and Windy Hill respectively, while they were observed in July and October for Eston and Powerscourt respectively. However, it is worth noting that during the summer months, almost all stations displayed statistically insignificant negative trends, except the Windy Hill station which showed a statistically significant ($\beta < 0.05$) (data not shown) positive trend in November. These differences are likely to be caused by the spatial variations in terms of topography, land cover and the location of each weather station.

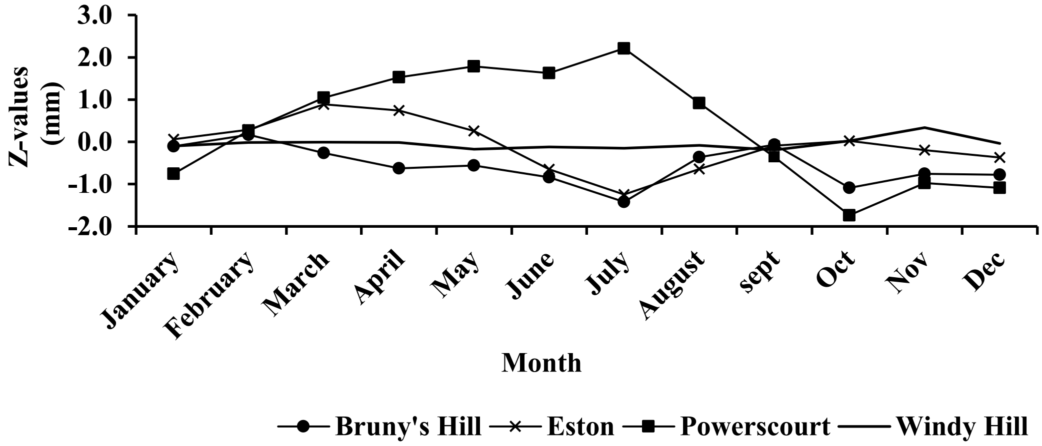


Figure 4.3: Monthly ETo trends based on MK analysis in the Wartburg area for 1966 to 2017

4.4.2 Trend analysis of annual and seasonal weather variables

ETo depends on wind speed (WND) and solar irradiance (Rs), water vapour pressure deficit (vpd) calculated from the relative humidity (RH) and air temperature (Tave) (Allen et al., 1998). A positive correlation between ETo and Tave, WND, as well as Rs exists while a negative relationship between RH which corresponds to a decrease in vpd and ETo has been observed (Fig. 4.3). This means that high Tave, WND, and Rs increases ETo while an increase in RH causes a decrease in ETo. Table 4.3 shows the results of the MK test for annual and seasonal weather variables at 1, 5, and 10% significance levels. There was a general decrease in annual WND, RH and Rs across all stations. An inconsistent trend was found in the Tave, however, the results, for all the stations, showing a mean decreasing annual trend of Tave at a negligible rate of 0.014 $^{o}C\ a^{-1}$ were observed (data not shown). The statistically significant annual decreasing trend for Tave was observed for Bruny's Hill while other stations show either a statistically insignificant decrease or statistically insignificant increase. Annual WND indicated a statistically significant decreasing trend for Bruny's Hill and Windy Hill. There was a general decrease in annual Rs for all stations, however, only two stations (Bruny's Hill and Powerscourt) were statistically significant. Powerscourt showed a statistically significant annual decreasing trend for RH while the remaining stations showed either a statistically insignificant decrease or statistically insignificant increases.

Table 4.2: MK test results for seasonal and ETo trends for the various stations for 1966 to 2017

Station	Season	*Z*	*β*
Bruny's Hill	Autumn	-1.07	-1.743
	Winter	-1.46	-2.531
	Spring	-1.27	-2.523
	Summer	-2.04	-3.448*
	Annual	-2.37	-11.142*
Eston	Autumn	0.51	0.178
	Winter	-1.66	-1.209+
	Spring	-0.76	-0.708
	Summer	-1.18	-1.038
	Annual	-0.39	-0.529
Powerscourt	Autumn	0.69	0.466
	Winter	1.18	1.487
	Spring	-1.18	-1.876
	Summer	-2.57	-2.033*
	Annual	0.09	0.212
Windy Hill	Autumn	-0.76	-0.468
	Winter	-1.06	-0.742
	Spring	-0.28	-0.234
	Summer	-0.02	-0.026
	Annual	-0.54	-1.380

*** $p = 0.001$ level of significance, ** $p = 0.01$ level of significance, * $p = 0.05$ level of significance, + $p = 0.1$ level of significance

The seasonal trend of the climate variables demonstrated in Table 4.3 indicates a decrease in Rs for all seasons, with Bruny's Hill showing a statistically significant decrease throughout the year. Powerscourt indicated a statistically significant decrease in Rs for all seasons except autumn. Decreasing trends in WND and RH are frequent in the sugarcane belt in the study area and the statistically significant negative trends for wind speed are found in different seasons for different stations. A statistically significant decreasing trend for WND occurs mainly in summer and occasionally during other seasons. There was an inconsistent seasonal trend in Tave for all stations under study. Statistically significant seasonal Tave increasing trends were observed in Windy Hill and Eston while a decreasing trend was observed for autumn and summer for Bruny's Hill and Eston. Powerscourt showed statistically insignificant changes in Tave. Due to the increasing and decreasing trend for RH in different stations, an inconsistent seasonal trend for relative RH is noted for the sugarcane belt in the study area. However, Powerscourt shows a statistically significant decrease in RH for all seasons while other stations indicate both statistically significant decreases and statistically significant increases in different seasons.

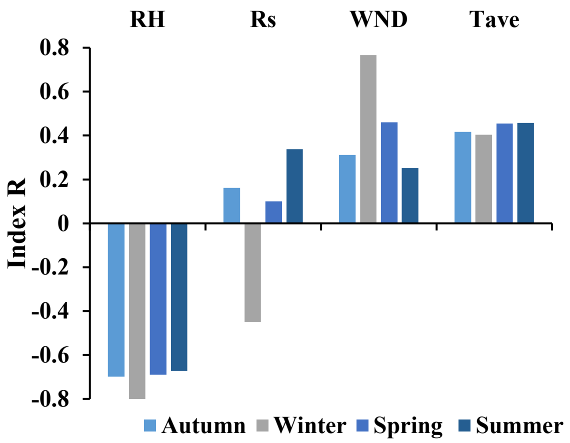
Table 4.3: Trend analysis for seasonal and annual rainfall, average air temperature, wind speed, solar irradiance and relative humidity

Station	Season	Precipitation (mm)	Tave (°C)	Wind (m s^{-1})	Rs (MJ m^{-2})	RH (%)
Bruny's Hill	Autumn	7.085**	-0.047+	-0.046+	-2.89*	-
	Winter	2.615+	-	-0.068*	-3.27***	-
	Spring	-	-	-0.081**	-2.17**	-0.554+
	Summer	-	-	-0.029+	-	-
	Annual	18.24*	-0.047*	-0.041*	-2.81***	-0.633**
Eston	Autumn	-	-	-	-	-
	Winter	3.489+	0.065*	-	-	-
	Spring	-	-	-	-	0.373+
	Summer	-	-0.078*	-0.032*	-5.330*	-
	Annual	-	-	-	-	-
Powerscourt	Autumn	-	-	-	-	-0.458**
	Winter	-	-	-	-3.048**	-0.332+
	Spring	-	-	-	-2.856+	-0.394+
	Summer	-	-	-	-2.867+	-0.471**
	Annual	-	-	-	-2.544	-0.398**
Windy Hill	Autumn	-	-	-0.022**	-	-
	Winter	-	0.048**	-0.01*	-1.215+	-
	Spring	-	-	-	-	-
	Summer	-3.926*	-	-	-	-0.145+
	Annual	-7.303+	0.029*	-0.019*	-	-

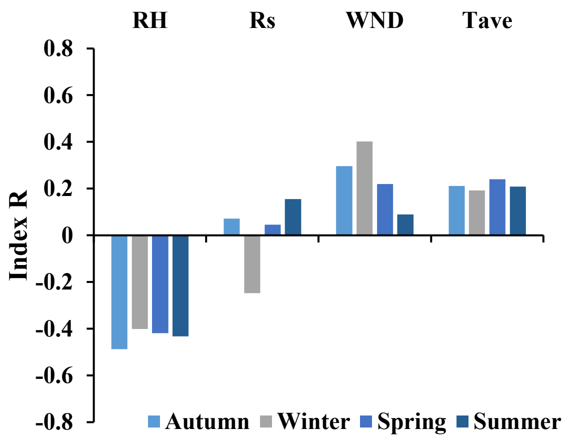
*** p = 0.001 level of significance, ** p = 0.01 level of significance, * p = 0.05 level of significance, + at p = 0.1 level of significance

4.4.3 Influence of climate variables on changes in ETo

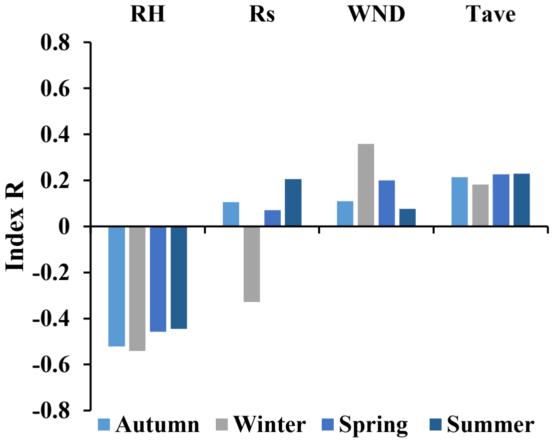
Using the Penman-Monteith method and the detrended method, the influence of each climate variable on the annual and seasonal ETo changes for four weather stations was calculated (Fig. 4.4). The results show a consistent variation from one station to another in terms of the contributing driving factor. There is clear evidence that RH exerts a negative contribution on ETo throughout the year for all weather stations except for Windy Hill while Rs contributes negatively during the winter season. In this case, Rs and RH appear to make substantial negative contributions to the stations in the study area compared to other parameters. The influence of Tave and WND to ETo variability exhibits a consistently positive effect on all stations. A major positive contribution to ETo changes in winter was noted for WND. The seasonal ETo trends indicate that the decreasing trends in spring and summer were noted mainly due to a decrease in Rs and an increase in RH. For example, for Bruny's Hill and Eston, the decreasing trend was likely due to a decrease in Rs and an increase in RH. Although the influence of a decreasing RH appears to have been offset by changes for other variables for the seasonal ETo parameter contribution for other weather stations, the RH decreasing trend for Powerscourt seem to contribute towards the increase in ETo. The overall contribution of each variable towards ETo variation indicates that changes in ETo during autumn and winter can be attributed to RH and Rs. It appears that in winter, the negative contribution of Rs and RH offset the positive contribution of other climate variables to ETo variation.



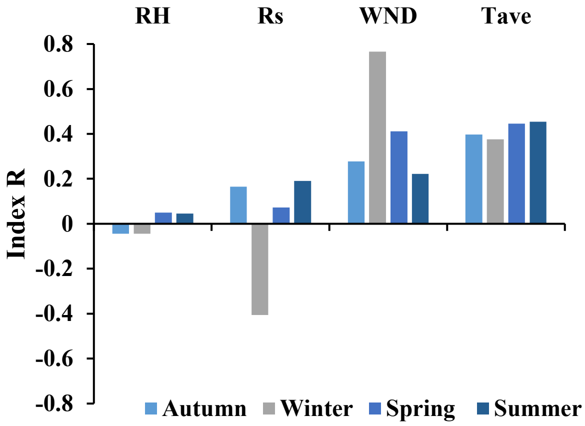
a) Bruny's Hill



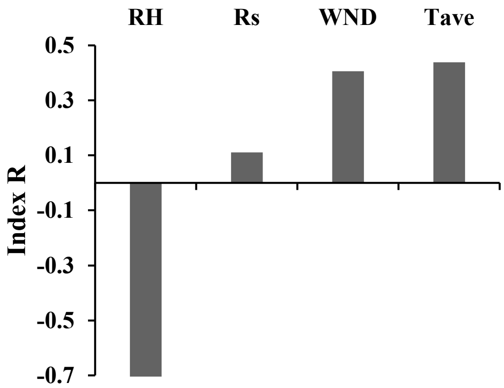
b) Eston



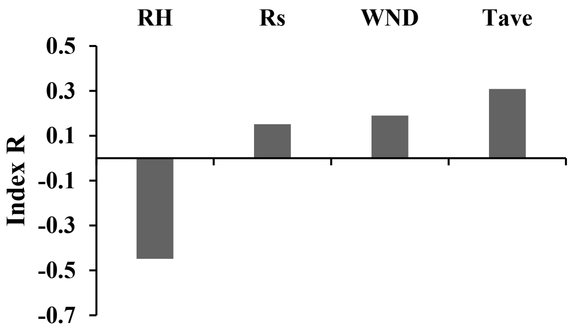
c) Powerscourt



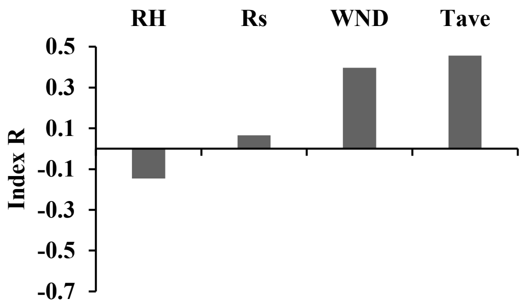
d) Windy Hill



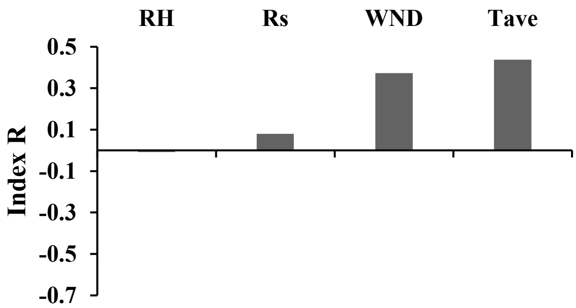
e) Bruny's Hill



f) Eston



g) Powerscourt



h) Windy Hill

Figure 4.4: Index R showing the contribution of each climate variable to ETo seasonal (a to d) and annual (e to h) variability in the Wartburg area.

The contribution of the climate parameters on the annual ETo is clear. All the stations indicate a major positive influence on ETo by Tave followed by WND. The only parameter which appears to have a substantial negative effect is RH. Thus, the general ETo decrease in the study area can largely be attributed to the increase in RH and partly to the decreased Rs given its minimal contribution. The positive effects of Tave on ETo are offset by the negative effects of RH leading to a decreasing trend. Therefore, RH and Rs are the major contributors to the ETo trends in Wartburg over the study period.

4.4.4 ETo variation during dry and wet years

Figure 4.5 shows the annual ETo for different meteorological stations in Wartburg from 1966 to 2017. The annual ETo for the study area ranges between 516 and 1248 mm. The highest ETo values for most of the stations were recorded during dry years whereas the lowest ETo values were observed during both dry and wet years. In particular, in Bruny's Hill, Powerscourt, and Windy Hill station the highest ETo values occurred at the beginning of a dry period while Eston ETo values were high during the dry season.

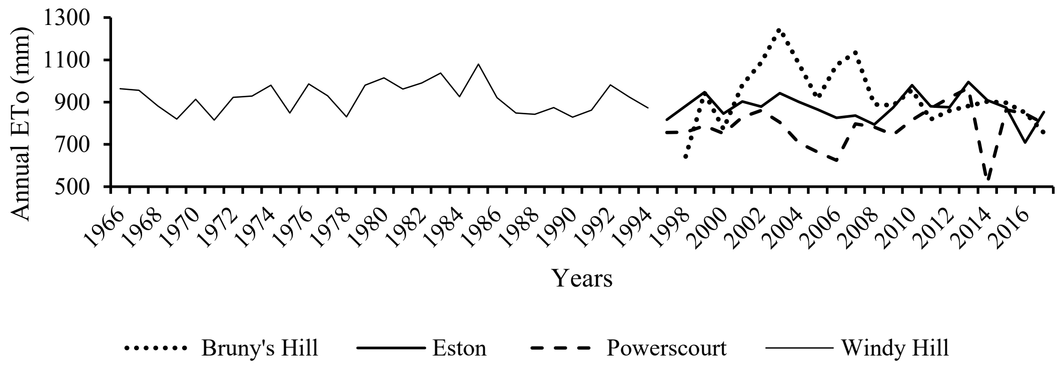
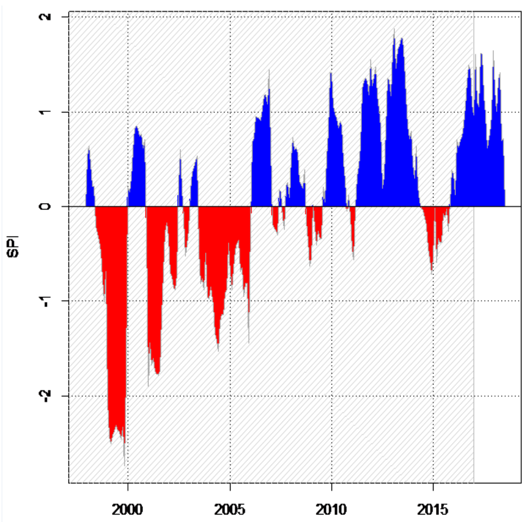
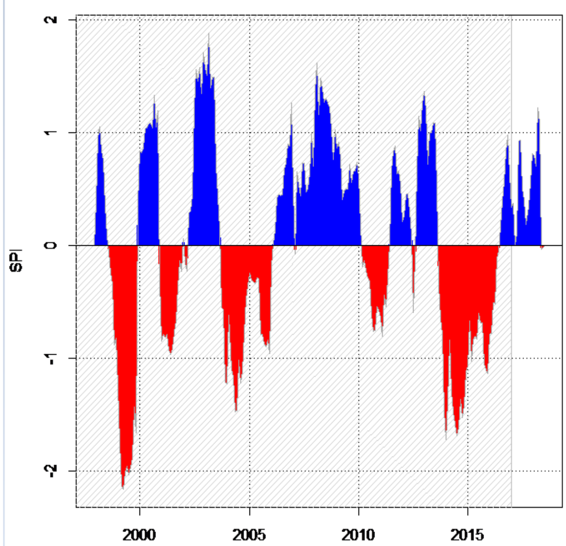


Figure 4.5: Monthly ETo trends based on MK analysis in the Wartburg area for the period of 1966 to 2017

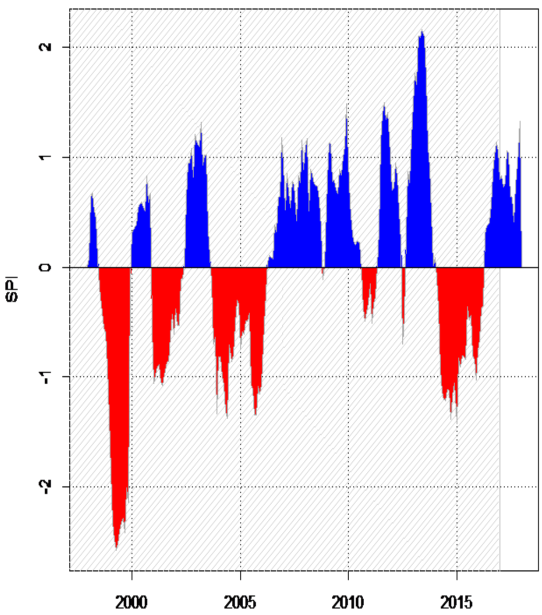
However, an increase in ETo values is not only regulated by the increased atmospheric demand but also by the availability of water of the surface. The results indicate that for the Bruny's Hill station, the highest ETo value of 1248 mm was recorded in 2003 and a minimum value of 755 mm in 2016. The Eston station experienced the highest ETo in 2013 and the lowest in 2016. The Powerscourt station recorded its maximum ETo value (938 mm) in 2013 and a minimum of 516 mm in 2014. For each station, SPI was employed to characterize meteorological drought for the study area. The SPI was computed using a 12-month timescale. Figure 4.6 illustrates the results of the SPI for each station. To illustrate dry and wet periods for each meteorological station, the selection of wet years and dry years is shown in Table 4.4.



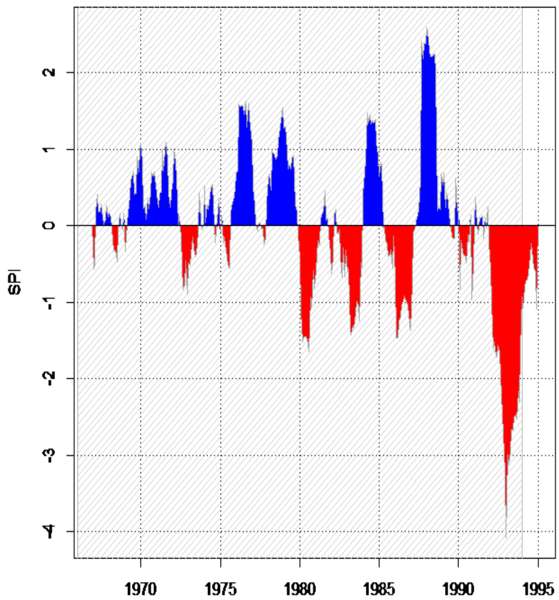
a) Bruny's hill



b) Eston



c) Powerscourt



d) Windy Hill

Figure 4.6: Drought characterization using SPI for 1966 to 2017 for the four stations

Table 4.4: Selected dry and wet periods for each station based on SPI values

Station	Dry years	Wet years
Bruny's Hill	1999	2006
	2001	2012
	2004	2013
	2014	2017
Eston	2004	2000
	2013	2002
	2014	2003
	2015	2008
Powerscourt	1999	2013
	2005	
	2014	
Windy Hill	1980	1976
	1982	1978

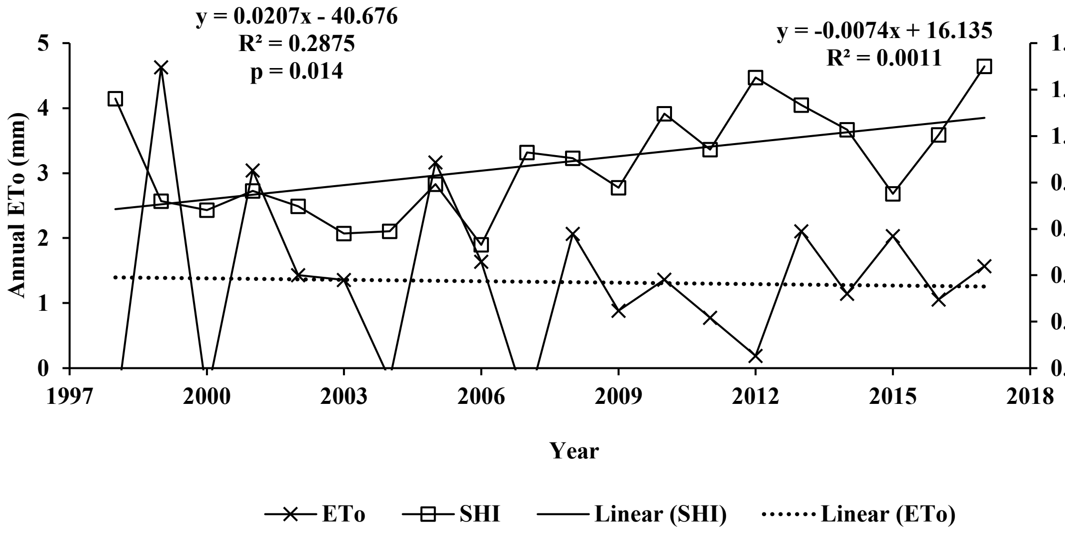
1986	1984
1992	1988
1993	

The results show that ETo during dry and wet years follows the same trend. However, ETo is slightly greater during dry compared to wet years for all stations. For almost all stations, ETo increases at a greater rate during dry years relative to wet years. For the selected dry years, ETo was increasing at 1.90 mm month^{-1} for Bruny's Hill, 0.34 mm month^{-1} for Eston, 1.92 mm month^{-1} for Powerscourt stations and 1.88 mm month^{-1} for Windy Hill. For wet years, the change was 1.075, -0.03, -0.34 and 2.35 mm month^{-1} for Bruny's Hill, Eston, Powerscourt and Windy Hill stations respectively.

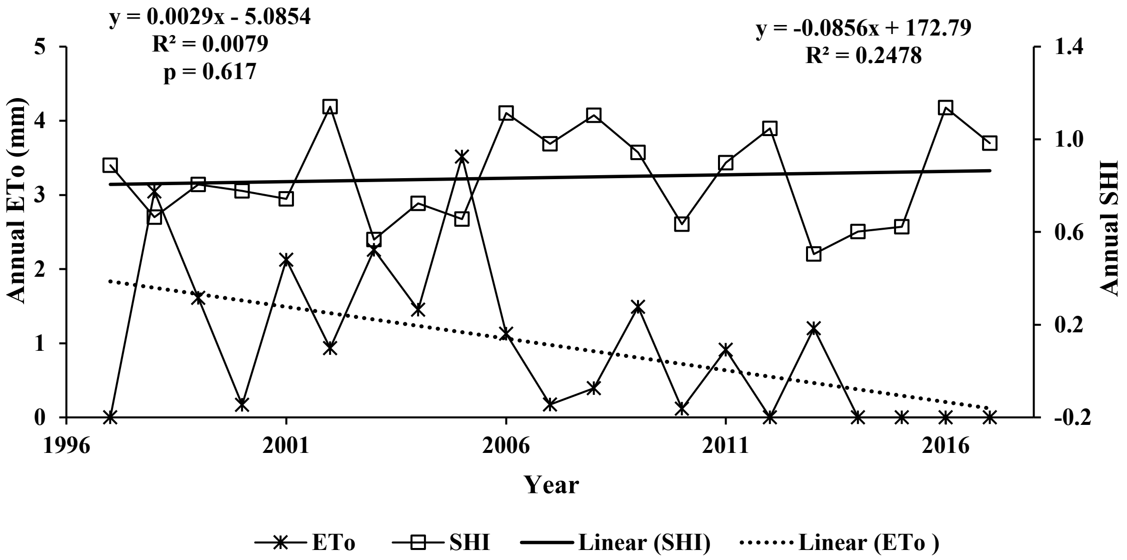
4.4.5 Correlation of ETo to drought

Although rainfall is not used for the determination of ETo, it is believed that there is a significant correlation between rainfall and ETo. Allen et al. (1998) emphasized that the surface of a green grass crop should be well watered for reliable grass reference evaporation estimation. This means that the lack of adequate soil/atmospheric moisture affects reference evaporation as well as actual evaporation. Given the threats posed by droughts to economic and environmental systems, understanding such correlation is important. To analyze the correlation in ETo and dryness/wetness, SHI was used. Annual ETo and SHI trends for all four stations are shown in Fig. 4.7. It is worth noting that the temporal variation of SHI and ETo indicate opposite changing patterns with few incidences where the change follows a similar pattern. As the SHI decreases, ETo increases, and vice versa. Three meteorological stations show an increasing sequential annual SHI trend and decreasing ETo trends. An increasing SHI trend for the recent years indicates that the intensity of dryness or drought for the study area is decreasing.

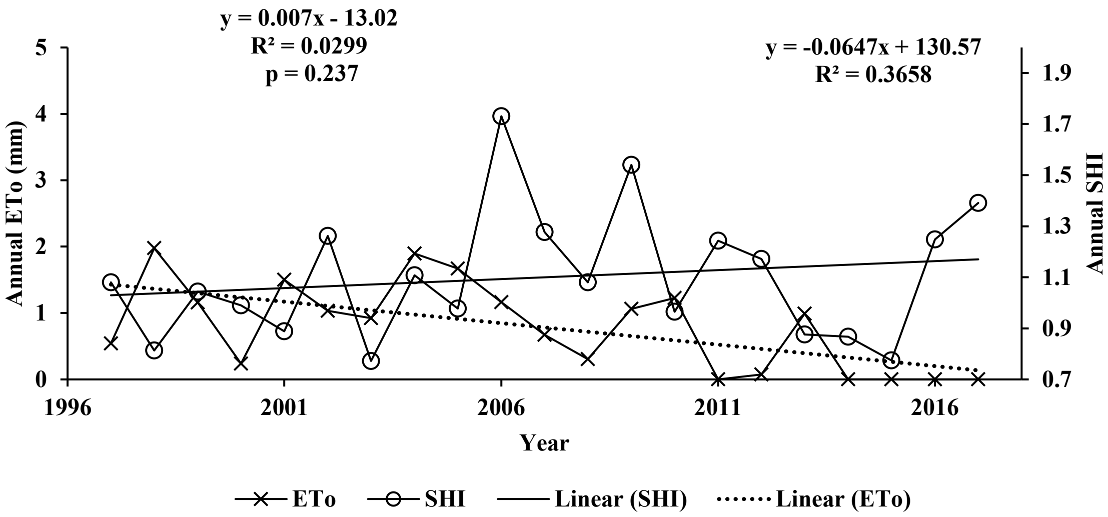
Figure 4.7 b and 4.7 d illustrate a decreasing ETo trend during 2014/15 which was considered one of the driest years in South Africa. The stations during this period recorded rainfall amounts ranging between 544.6 and 668.9 mm. It is important to note that during this period, SHI increases to over 1, suggesting an increase in ETo which results in soil water depletion.



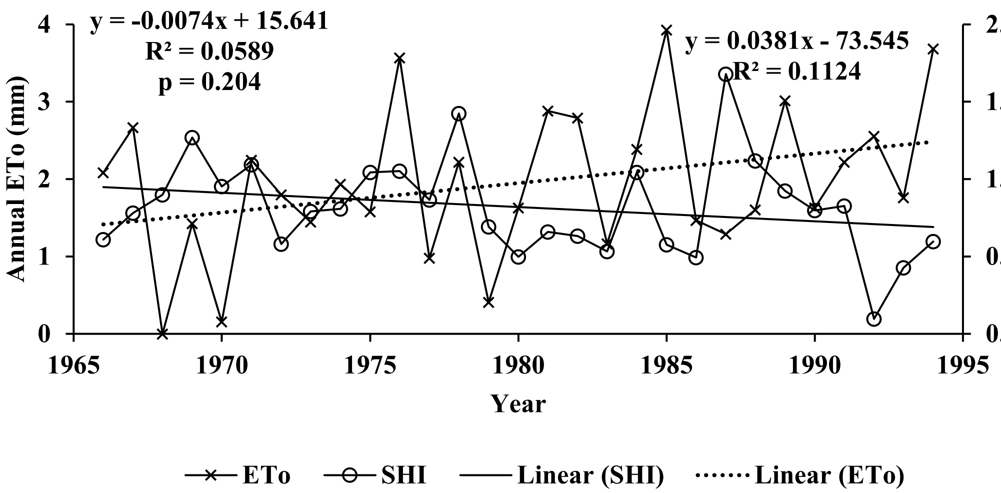
a) Bruny Hill



b) Eston



c) Powerscourt



d) Windy Hill

Figure 4.7: Temporal variation in the average annual ETo and annual SHI for the four stations

Therefore, in the absence of adequate water for ETo to occur, ETo starts to decrease. The correlation analysis indicates that SHI has a statistically significant negative correlation with ETo (r = -0.64, $p < 0.05$) and has a statistically significant positive correlation with rainfall (r = 0.95, $p < 0.05$). A negatively statistically significant correlation was also noted between ETo and rainfall (r = -0.40, p = 0.05).

4.5 Discussion

4.5.1 Observed grass reference evaporation trends for the study area

This study analyzed the ETo variation and its effects on drought. The results indicate a statistically insignificant decline in ETo on an annual scale (Fig. 4.2). The magnitude of the decrease was more for Bruny's Hill station compared to the other stations. Statistically significant seasonal trends were observed in Bruny's Hill and Eston for summer and winter respectively. These findings correspond to the widely acknowledged general decrease in ETo during the winter months which are characterized by low Tave and Rs which results from reduced sunshine duration. A decreasing trend during summer months can be explained by the decrease in solar irradiance which is believed to be the main driver of ETo (de Bruin et al., 2019). These observations are in agreement with earlier findings by Hoffman (2005) who found a decline in pan evaporation over South Africa due to a decline in wind speed over 1974-2005. These results are aligned with studies across the globe which suggest that under climate change conditions, ETo has been decreasing. A statistically significant decreasing trend in ETo was found in India (Bandyopadhyay et al., 2009). Xu et al. (2006) and Ma et al. (2017) reported a decreasing trend in ETo in different parts of China. Marshall et al. (2012) also found a decreasing trend in ETa for sub-Saharan Africa.

4.5.2 Influence of climate variables on changes in ETo

The MK test indicated that Tave, WND and Rs significantly influence the ETo changes for the Bruny's Hill station, but ETo trends in other stations proved to be substantially determined by either one or two climate variables. The decrease in Rs appears to have an impact on ETo change resulting in decreasing ETo trends. It has been confirmed that ETo variations can be attributed to precipitation/ soil moisture content, Tave, WND, Rs and RH (Xu et al., 2014). However, there is a lack of scientific consensus about meteorological variables which have a major influence on ETo across the globe (de la Casa & Ovando, 2016). Hence, the relative importance of each climate variable, as well as its influence on ETo variation, varies both spatially and temporally. This can be partly attributed to the different geographical positions of the study areas as well as the research period (Ma et al., 2017). Geographical locations differ in terms of proximity to the ocean and elevation. Atmospheric evaporative demand in coastal areas tends to be lower than in inland areas, thus water vapour pressure deficit substantially influences

ETo variation (Aydin et al., 2015). Also, it has been proved that coastal areas have limited energy (Castellucci et al., 2016; Gu et al., 2018) which in turn reduces the effects of solar radiance and air temperature on ETo variation. The effects of climate variables on ETo changes depends also on the topography. For example, a study by Gu et al. (2018) found that ETo increased by 5.4-fold in plain areas compared to areas atop a hill. They did not associate the increase with any specific climate variable but partly with the impacts of open water close to the plain area. The WND proved to be the most influential climate factor in the study conducted in Iran (Dinpashoh et al., 2011; Kousari et al., 2012) and China (Xie et al., 2013) while Tave was found to make large contributions on ETo changes in the Arabian Peninsula (El-Nesr et al., 2010). Sun et al. (2017) found that Rs was the main contributor to the ETo trends in the south-west of China. Water vapour pressure deficit and wind speed had major impacts on ETo variability in Canada (Burn & Hesch, 2007). Ma et al. (2017) found a decreasing ETo trend in the north-east of China and attributed this to decreased WND and sunshine hours.

In the present study, the contribution of each variable was analyzed for each station and the results indicate that in general, Rs and RH contributed significantly towards ETo changes over the period of study. This can be explained by the significant decrease of Rs for Bruny's Hill as well as the significant decrease of the RH for Powerscourt. Although Tave appears to have declined in winter for most of the stations, the ETo response does not reflect these changes which indicate the minor impact of Tave on ETo. Plattle & Sigh (2015) attest to the reduced sensitivity of ETo to Tave decline compared to Tave increase. These results agree with the observation of the general decrease in pan evaporation across the globe due to 1) increased precipitation (Irmark et al., 2012); 2) changes in diurnal air temperature range and water vapour pressure deficit linked to decreasing Rs (Roderick & Farquhar, 2002); and 3) Rs reduction attributed to increased cloud cover as a result of aerosols (Roderick & Farquhar, 2002; Liu & Zeng, 2004). Despite the general decrease in ETo and pan evaporation, a recent study by Stephen et al. (2018) indicates that in Australia the general decrease of pan evaporation lasted until the late 1990s and started to increase in 1994. The study attributed the increase to Tave increases.

4.5.3 Magnitude of change of ETo during dry and wet years

Although only four major meteorological variables play a direct influence on ETo variability, precipitation is also found to play an important role. Ukkola & Prentice (2013) suggest that precipitation in a water-limited area explains up to 90% of ET changes. Changes in ETo and how it responds to dry and wet periods are important for agricultural production, particularly under climate change conditions. The present study analyzed how ETo responds during dry years using a linear regression model. The results indicate that ETo increases during dry years and decreases during wet years. The magnitude of change indicates that during drought ETo increases at an increased rate relative to wet years. However, this only occurs at the beginning of a drought event and atmospheric "event" starts to decrease as the rainfall decreases. Sonia et al. (2010) suggests that the reduction of soil moisture due to limited rainfall increases soil water absorption and reduces atmospheric and soil moisture events. De la Casa & Ovando (2016) found a negative relationship between pan evaporation and rainfall, indicating that a decline in pan evaporation due to increased rainfall may lead to an increase in terrestrial evaporation. Teuling et al. (2013) confirm that high grass reference evaporation normally corresponds to decreased rainfall. Teuling et al. (2010) further described the ET-drought relationship through three stages: 1. when ET does not depend on soil moisture; 2. ET is becoming self-limiting; 3. ET becomes minimal due to inadequate soil moisture. In opposition to the widely acknowledged decrease of ETo as a result of low rainfall, the increased ETo as a result of reduced precipitation is likely to have adverse effects on growing crops.

4.5.4 Correlation of ETo to drought

Long-term SHI and ETo variations were analyzed for the period of the study. The results indicate that ETo decreased as the SHI increased (Fig. 4.7). Negative ETo anomalies were detected for Eston and Powerscourt stations during the 2014/15 period. Low ETo as a result of dry conditions often accompanied by extreme air temperatures which in turn decreases evaporative losses. The SHI, however, failed to capture the negative ETo anomalies and treated the decrease in ETo as a normal decrease which resulted in increased SHI. These results correspond to the findings by He et al. (2017) that the relationship between evapotranspiration and drought index indicates that ET increases at the onset of the rainfall deficit period and decreases as dryness becomes severe. The results of this study are in contrast to a study by Gao et al. (2017) which suggests that less rainfall induces higher ETo, and ETo decreases with increases in precipitation.

4.6 Conclusions

Grass reference evaporation (ETo) response is linked to the changes of different meteorological variables, however, its response with respect to rainfall differs. This study for the KwaZulu-Natal midlands of South Africa explored the temporal trends of seasonal and annual ETo and causative variables were calculated using a detrended method for each of four weather stations within the sugarcane belt of the KZN midlands. In addition, the correlation between drought events and ETo was analyzed to clarify the manner in which ETo responds during dry periods, which can assist in determining suitable measures for mitigation and adaptation for adverse weather. There is no consistent significantly decreasing ETo trend for the whole area for both seasonal and annual trends, but the results indicate inconsistent annual and seasonal changes for all stations. None of the stations indicated a statistically significant annual and seasonal increase. According to the MK trend analysis, only Bruny's Hill exhibited a statistically significant decreasing annual trend. Thus, a general insignificant decreasing ETo was observed in the study area. The causative variable analysis indicates that relative humidity and solar irradiance were dominant factors in causing changes in ETo for all stations. Solar irradiance showed a minimal contribution on ETo changes relative to other variables and this can be attributed to its high decreasing rate. Finally, the SPI and annual ETo observations indicate that some dry years exhibit high ETo values, whereas for other dry years ETo values are similar to these for wet/normal years. The linear regression model results, therefore, indicate that during drought ETo increases at a greater rate compared to wet years until atmospheric humidity becomes inadequate for further increase in ETo which then starts to decrease. This suggests that adequate atmospheric moisture (rainfall) causes increase in ETo to a certain extent, however, a negative correlation exists between rainfall and ETo. The results from this study will assist to better understand the possible ETo variation as a result of climate change and its potential impacts on agriculture and hydrological systems. This should help support the development of measures to sustain agriculture and water resources.

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4.8 References

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Lead to Chapter 5

In Chapter 5, projected air temperature, rainfall and drought frequency for the study site are presented. The chapter presents SDSM which is used to simulate air temperature and rainfall for the analysis of future drought occurrences. The previous Chapters (3 and 4) mainly focused on historical climate trends while Chapter 5 provides insight on the projected drought events due to changes in air temperature and rainfall. The relatively short-term climate data from other stations restricted the stations to be included in the projection of climate change, thus only Windy Hill was included in this Chapter. The projected air temperature and rainfall data are then used to compute drought indices to determine the projected drought trend for the study site.

CHAPTER 5: THE IMPACT OF CLIMATE CHANGE ON DROUGHT IN THE RURAL AGRICULTURAL COMMUNITY OF WARTBURG, KWAZULU-NATAL, SOUTH AFRICA

5.1 Abstract

Water and water-related issues are becoming a critical threat to the African region due to climate change. The vulnerability of different areas within the sub-continent varies owing to the heterogeneity of topography, climate, access to resources, farmer resilience as well as adaptation capacity. As a result, site-specific studies are encouraged to increase the awareness, resilience and adaptation capacity at the local level.

In this study, conducted in the KwaZulu-Natal midlands of South Africa, the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) were used to analyse changes in future drought characteristics for a specific meteorological site from the Representative Climate Pathways (RCP8.5 and RCP4.5) as well as Special Report of Emission Scenarios (SRES) A2 and B2 climate projection of CanESM2 and HadCM3 models respectively for the period of 2011-2040 (P1), 2041-2070 (P2) and 2071-2099 (P3) periods. Changes in the future drought characteristics (duration, intensity, and severity) were also assessed using statistical Run's theory.

The results indicate that under all the forcing scenarios both minimum and maximum air temperatures will continue to increase until the end of the century reaching a maximum increase range of 1.72 to 3.14 °C and 1.54 to 3.48 °C respectively based on the worst-case scenario RCP8.5. In the case of rainfall, a positive trend is predicted, but with a declining trend for the near future period (2011-2040) for all scenarios. The projected drought characteristics indicate that droughts are more likely to occur in the near future due to climate change. Although the Global Circulation Models (GCMs) showed inconsistencies in predicting future drought occurrences, 2029, 2038, 2043 and 2047 were projected as dry years by both GCMs at different time-scales. The Run's theory results indicate a projected increase in drought severity but a decrease in intensity relative to historical drought events for the study site.

The implication is that under climate change conditions, the duration of drought will increase but the average rainfall anomaly below the rainfall threshold level will be close to normal. However, with increasing air temperatures even moderate drought events can have a substantial adverse impact on agricultural production due to crop losses resulting from either increased evapotranspiration or heat stress induced by limited soil moisture. These results

indicate that in the absence of adaptation the risk of small-scale farmers, particularly for sugarcane, which is largely planted in the area, to production losses will heighten and hence increase the likelihood of increased poverty, food insecurity, and unemployment.

Keywords: *Climate variability; Future drought characterization; SDSM; SPEI; SPI*

5.2 Introduction

Meteorological variables such as rainfall and air temperature are the most influential factors that affect the global climate. Climate projections based on Global Circulation Models (GCMs) suggest that the rate at which global air temperature is increasing will induce substantial changes to other climate parameters, thus causing the occurrence of extreme weather events. The IPCC (2014) noted that given the continuous increase of anthropogenic greenhouse gas concentration, surface air temperature increases are expected throughout the world leading to frequent heat extremes and heat waves. The anticipation of the changes in precipitation as a result of climate change is, however, different from one region to another as predictions indicate more rainfall at higher latitudes and less rainfall in most subtropical land areas (Giorgi et al., 2019). Projections of future rainfall have been found to be more complex as projections show some uncertainties and biases between the observed and projected rainfall values. However, based on the likelihood of the possible changes, adaptation decisions can still be devised (Engelbrecht et al., 2015).

These changes will undoubtedly have adverse effects on climate-sensitive sectors. This is due to climate change affecting hydrological aspects of the region through changes in the magnitude and timing of rainfall, evaporation and transpiration rates due to increased air temperatures, and soil moisture (Stagl et al., 2014). Water supply and agricultural sectors are the most threatened sectors under climate change. Climate-related disasters pose a serious threat for developing countries where livelihoods depend primarily on agriculture. There is a consensus that droughts have become more intense and widespread in southern Africa (New et al., 2006; Ujeneza & Abioudun, 2015; Abiodun et al., 2019). Although not consistent throughout the country, significant changes in rainfall have been observed in South Africa for 1910-2004 (Kruger, 2006). The air temperature trends for 1960-2003 also showed a positive undulating pattern across the country (Kruger & Shongwe, 2004). An increasing trend of extreme, severe and moderate drought events over the central parts of South Africa have been observed for 1952-1999 (Eddosa et al., 2014). The vulnerability of regions to such changes is not homogeneous. The KwaZulu-Natal province is amongst the most vulnerable areas in South Africa to climate change with increased frequency of extreme events over the past century. The heterogeneity within the province should be accounted for given that exposure, ability to cope, access to resources and poverty levels differ considerably (Gbetibouo et al., 2005).

Further changes in climate can cause more extreme events, resulting in large negative impacts. Thus, predicting climate extreme is critical at all levels to evaluate the impact of potential climate change on the human and natural environment. The widely adopted approach for predicting changes in climate variables on a global level is through global circulation models (GCMs). These models such as HadCM3 (Johns et al., 2003; Chou et al., 2012) and CanESM2 (Gillet et al., 2012; Stott et al., 2013) make use of quantitative methods to simulate interactions of the atmosphere, ocean, land surface and ice. Over the last 20 years, GCMs have undergone major advances to ensure that they produce a more accurate and reliable guide to the future of climate change (Musgrave, 2016). Although GCMs are the principal tools for projecting future changes in the climate system, their findings cannot be used at a finer spatial resolution to assess the local impacts due to their coarse resolution. As such, different downscaling methods have been developed to bridge the gap between the coarse resolution results from GCMs and the resolution needed for impact assessment. Downscaling can be applied to both spatial and temporal aspects of climate projection. Spatial downscaling refers to the techniques of obtaining fine spatial climate information from coarse resolution output, for example, 200-km-gridcell-GCM output to a specific location or weather station. Temporal downscaling refers to deriving finer temporal GCM from coarse resolution GCM output.

The downscaling technique is divided into two categories, statistical and dynamical downscaling. Statistical downscaling is based on instituting an empirical relationship between large-scale climate state (atmospheric predictors) and local climate characteristics such as land-use, topography, land-sea contrast (Wilby et al., 2004) that are not adequately described by the GCMs. Statistical downscaling employs linear regression and a stochastic weather generator. The advantages of the statistical method are that it is computationally less demanding and can be quickly used for impact assessment to provide onsite local information (Dorji et al., 2017; Li et al., 2018). One disadvantage of the statistical downscaling method is the assumption of stationarity of statistical relationships in the future (Trzaska et al., 2014). The dynamical downscaling method often referred to as the regional climate model, involves nesting of the higher resolution regional climate model within a coarse resolution GCM. The major limitation of dynamic downscaling is that it is computationally demanding. Boe et al. (2007) and Li et al. (2018) provide a detailed comparison of the two downscaling techniques.

Numerous studies have been conducted worldwide to understand past and possible future changes in climate extremes as a result of global warming. Lee et al. (2016) investigated the observed changes in drought and the association between drought and climate change using GCM outputs. In Korea, Jang (2018) used the Representative Concentration Pathways (RCP) to analyze the possible future climate extremes. In Greece, Vasiliades et al. (2007) assessed the effectiveness of drought indices to monitor droughts under climate change conditions. Saymohammadi et al. (2017) used HadCM3 (SRES A2 emission scenario) statistically downscaled output to predict temperature and rainfall changes as a result of climate change. Other similar studies were conducted in China (Leng et al., 2015), Ethiopia (Feyissa et al., 2018), Iran (Emami & Koch, 2018), and Pakistan (Manhood & Babel, 2012). Similar studies were also conducted in southern Africa: Abiodun (2019) projected future droughts at specific global warming levels; Ujeneza et al. (2015) examined the drought characteristics related to temporal and spatial changes using GCMs and the Standardised Precipitation Evapotranspiration Index (SPEI). Pinto et al. (2016) projected extreme precipitation using the Coordinated Regional Climate Downscaling Experimental (CORDEX) protocol models. The limitation of these studies is that they were conducted at a regional level. This resolution is not suitable for local impact assessment studies as regional observation might mask local level trends. It has been observed that results indicated significant trends at the finer scale but not at the regional scale (Dookie et al., 2018). In addition, it is less certain how changes in meteorological processes at individual sites will be affected, and yet these potential changes are the major concerns of policymakers (Dennis & Dennis, 2012).

The aim of the study is to examine changes in the characteristics of future drought patterns for a localised agricultural community within the sugarbelt region of KwaZulu-Natal, South Africa. The main focus is to show how rural areas more involved in the agricultural sector are likely to be affected by climate change. The study identifies the projected prevalence of intense and severe drought patterns in the region and investigates the likely changes in future droughts under Representative Concentration Pathway (RCP) 8.5 and 4.5 as well as Special Report of Emission Scenarios (SRES) scenarios A2 and B2 for a specific meteorological site.

5.3 Materials and methods

5.3.1 Study site

The Wartburg area is situated at a latitude of 29.4332°S and a longitude of 30.5812°E and an altitude of 1000 m above sea level. It is inland in the province of KwaZulu-Natal (KZN) which is located in the southeast of South Africa. The climate of the KZN midlands area is described as a subtropical climate due to warm, wet summers and cool, dry winters. The province is one of the areas which engages in many agricultural activities in South Africa and the midlands area is amongst the areas with high-quality farming. The province has about 6.5 million ha of farming land. Sugarcane is the most important cash crop planted in the fields of the province. The KZN midlands is one of the areas where sugarcane production is mainly practiced under dryland conditions. The province experienced one of the most severe droughts in history during 2014/2015 which resulted in water shortages. Consequently, the inevitable lack of sufficient water led to significant agricultural production losses with irrigated areas subjected to restricted irrigation.

5.3.2 Climate data

The daily observed maximum (Tmax) and minimum air temperature (Tmin) and rainfall data for the study area were collected from the South African Sugarcane Research Institute, particularly for the Windy Hill meteorological station (29.49028°S, 30.57139°E). The data were for the period of 1966-1994. To ensure that the dataset conforms to a standardized long-term dataset (30 years), a two-year period of data was generated using ClimGen (Stöckle et al., 1999). Daily predictors data required for this study were obtained from the government of Canada through the website: http://climate-scenarios.canada.ca/?page=pred-hadcm3#archived. These included predictors of the National Center of Environmental Prediction (NCEP), National Center for Atmospheric Research (NCAR), HadCM3 for A2 and B2 scenarios, CaneESM2 for 4.5 and 8.5 scenarios (Government of Canada, 2019). The HadCM3 GCM model was selected due to its successful application across different regions. In addition, HadCM3 is considered the best GCM for the prediction of climate variability and change. This judgment is based on the statistical performance analysis conducted by Babel et al. (2014) of five GCMs, in which HadCM3 has proven to be more accurate in estimating climate variable changes compared to its counterparts (CCSR/NIES, CGCM3, CSIRO, ECHAM4) (Shrestha et al., 2014). Its ability to capture the characteristics of historical climate change as a result of natural and anthropogenic forcing has increased its use in studies (Saymohammadi et al., 2017). HadCM3 is an Atmospheric Ocean Generation model (AOGM) developed at the Hadley Centre for climate prediction and research in the United Kingdom. It has a spatial resolution of 2.5° latitude and 3.75° longitude. The HadCM3 comprises two SRES scenarios, A2 which describes a very heterogeneous world with the absence of concerted measures to mitigate climate change impacts, resulting in average warming of 2 to 5.4 °C and scenario B2 which portrays a heterogeneous world with local adaptation measures in place, leading to a rise in surface warming of 1.4 to 3.8 °C.

The climate change research community discourages the reliance on a single model when predicting future climate conditions. This argument is based on high uncertainty associated with a single GCM. Thus, CanESM2 was also employed for the simulation. CanESM is a second generation of the Canadian Earth System model, which is the 4th generation coupled global climate model of the coupled model intercomparison, phase 5. It is the only GCM from the Coupled Model Intercomparison Project (CMIP) phase 5 of which large-scale predictors can be applied directly in the statistical downscaling model. The CanESM2 consists of four independent pathways: RCP 8.5 which is considered as the high gas emissions, RCP 6.0 the intermediate emissions, RCP 4.5, intermediate emissions and RCP 2.6 which represents the lowest emissions.

5.3.3 SDSM

The Statistical Downscaling Model (SDSM) (version 4.2.6) used in this study was accessed from the Department of Geography in King's College, London through the website: https://sdsm.org.uk/software.html. The SDSM enables the generation of climate change time series data at specific sites that have adequate data for model calibration. The SDSM which was developed by Wilby et al. (2002), is described as a decision support tool for assessing the effects of local climate change and is fundamentally based on the statistical downscaling method of Wilby & Dawson (2012). It is a combination of multiple linear regression and a stochastic weather generator. The SDSM uses a series of equations to generate a statistical relationship between global and local level predictants. The downscaling process by the SDSM software involves a series of tasks such as data quality control and transformation: for identification of data errors and specification of outliers and for the applicable transformation of data; screening variables for the selection of appropriate downscaling predictor variables; model calibration, weather generator, scenario generator and frequency and statistical analysis. Two different sub-models are nested in the SDSM, the conditional and unconditional, and are used to determine the occurrence of rainfall, the amount of evaporation and the variation in air temperature. In conditional models, there is a direct linear dependency on predictor variables while for unconditional models a direct linear relationship between the predictant and the chosen predictor is found (Manhood et al., 2015). SDSM has been employed in various countries across the world to test its capabilities (Chu et al., 2009; Nury & Alarm, 2014; Saymohammadi et al., 2017; Mirgol & Nazari, 2018; Tahir et al., 2018). The observation from previous studies indicates that the SDSM can produce reliable predictions of intense rainfall as well as rainfall at seasonal time-scales. The SDSM has also proven its ability in providing station level climate parameters for different GCMs and future climate scenarios (Liu et al., 2017).

5.3.4 Methodology

In order to identify grid cells for the models corresponding to the specific weather station, the grid cells were first imposed on the South African region and the cells were selected accordingly. The data used in this study corresponds to the grid cell number Box_ 08X_45Y and 012X_22Y for HadCM3 and CanESM2 respectively. Historical data are available for both air temperature and rainfall for the period of 1961-2001 for HadCM3 and 1961-2005 for CanESM2 as well as the NCEP data for both models respectively. For each model, there are about 28 predictor variables which are derived from the NCEP/NCAR reanalysis data. Due to a large number of predictor variables, large-scale predictors were screened using Pearson’s product-moment correlation in the SDSM. The predictors were therefore selected based on the correlation matrix, partial correlation, and p-value. This process was undertaken to verify the statistically significant correlation between large-scale predictors and predictions for calibration. The predictors which showed statistically significant agreement with the predictant were then selected for model calibration purposes. This permitted the synthesis of simulated data and 20 ensembles (default) were created.

The calibration of the station data against the grid-cell data was carried out through the downscaling of the SDSM linear regression. Daily data for the period of 1960-1984 were used for the calibration of Tmax, Tmin, and rainfall for HadCM3 and CanESM2. With the calibrated model, 20 ensembles were simulated for 1960-1984, feeding NCEP/NCAR, A2, B2 (HadCM3) and historical (CanESM2) data. The mean values of these ensembles were used in this study. The validation of the model was carried out using the observed weather station dataset for the period of 1985-1996 using monthly time series. This study also used root mean square error (RMSE) and coefficient of determination (R^2) as well as monthly mean and standard deviation to evaluate the performance of the model.

5.3.5 Bias correction

Sometimes, differences between GCM predictors and local level characteristics can cause bias in the downscaled data. These biases can be attributed to the increased radiative forces from greenhouse gases, particularly in rainfall trends (MacKellar et al., 2014). Biases often occur when the mean of the GCM data differs substantially from the observed mean for a particular variable. These biases are removed through a bias correction process. A bias correction process is necessary when there is a possibility of biases between the downscaled and observed data in order to obtain reliable results for climate analyses at a local level. In the present study, a simple bias correction method by Salzman et al. (2007) was adopted. The biases of daily average air temperature were corrected using:

$$T_d = T_s - \bar{T}_g - \bar{T}_o \tag{5.1}$$

where T_d is the bias-corrected daily air temperature for the period under study, T_s the biased daily air temperature generated by the model, $\bar{T}_g$ the long-term mean monthly values of simulated temperature for the study period (1980-1996) and $\bar{T}_o$ the long-term mean monthly observed air temperature for the study period. Daily rainfall biases were corrected using:

$$P_d = P_s \times \frac{\overline{P_o}}{\overline{P_g}} \tag{5.2}$$

where P_d is the bias-corrected daily rainfall for the period under study, P_s the biased daily rainfall generated by the model, $\overline{P_o}$ the long-term mean monthly values of the observed air temperature for the study period, and $\overline{P_g}$ the long-term mean monthly values of simulated air temperature for the study period. Manhood & Babel (2012) suggested the use of recent datasets to ensure improved results, hence in this study bias correction was used using the 1980-1996 dataset. After the adjustments were made to the daily maximum and minimum air temperature and rainfall data, monthly mean values were calculated for the computation of drought indices for future periods in the 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2099) for the four scenarios SRES A2, SRES B2, RCP 4.5 and RCP 8.5 at different timescales.

5.3.6 Drought indices used in the study

The study employed two drought indices: the Standardized Precipitation Index (SPI) (Mckee et al., 1993) and the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) to predict the potential impacts of climate change on the future drought occurrences as well as to characterize possible future drought events based on duration, intensity, and severity. Both indices have been frequently used in many parts of the world (Khan et al., 2017; Lee et al., 2017; Jang, 2018) and over southern Africa (Edossa et al., 2014; Botai et al., 2016; Botai et al., 2019) for defining and monitoring droughts. The wide application of the SPI was driven by its robustness, and versatility for drought analysis, easy computation, and reduced data demand. While SPI has been criticized for its main limitation which is the consideration of only precipitation in its calculation and its failure to include other variables that can influence droughts, such as air temperature, evapotranspiration, wind speed, and soil moisture (Vicente-Serrano et al., 2010), it has the ability to be calculated over multiple timescales. This feature, that other complex drought indices lack, is very important as it enables analysis of precipitation from the shortest timescale until it accumulates to years (Lee et al., 2017). This also permits the use of SPI in monitoring both short-term and medium-term water deficits.

Although SPI is highly recommended for drought characterization, its major limitation of considering only precipitation has been criticized, thus SPEI was developed to overcome it. The SPEI calculation is based on SPI algorithms (Vicente-Serrano et al., 2010). The major difference is that it also takes into account the effects of air temperature on drought occurrences, and it is calculated as the difference between precipitation (P) and potential evapotranspiration (PET). Thus the classification of drought is similar for both indices. In the present study, drought indices were calculated using SPEI and SPI script embedded in R software (R Core Team, 2013). For the calculation of potential evapotranspiration, which is required for SPEI computation, the SPEI script on the software offers four options for calculating PET based on data demand ranging from the least data demanding method (Thornthwaite) to the most data demanding method (Penman-Monteith). The Penman-Monteith method is normally considered the best option, however, it requires a comprehensive dataset which is not always accessible (Abiodun, 2019). Therefore, for this study due to limited data availability, the Hargreaves air temperature based method (Hargreaves & Samani, 1985) was used to compute PET. It is calculated based on daily maximum and minimum air temperature range and the latitude of the study site. The Hargreaves air temperature based method is believed to produce sensible results given that it is linked to solar radiation through the daily air temperature range and the mean extraterrestrial radiation (Yates & Strzepe, 1994). A detailed description of SPI and SPEI calculation can be found in Beguería et al. (2014).

5.3.7 Analysis of drought characteristics

The impacts of drought on different sectors depend on the characteristics of a particular drought event. Drought events differ in intensity, severity, and duration. These characteristics are often analyzed using a probabilistic methodology proposed by Yevjevich (1967). This method has shown the capability of estimating the return periods of extreme events (Lee et al., 2017). In the present study, Run's theory was applied to characterize drought based on SPEI and SPI for future periods. According to the theory, drought severity expresses a cumulative lack of rainfall below the normal level. Drought duration is the total period during which rainfall is continuously below normal and can be expressed in weeks, months, or years. Drought intensity is derived by dividing drought severity by drought duration and indicates the mean of the rainfall below the threshold level. Simply put, the severity indicates the accumulation of monthly drought index (negative values equal or less than -1) while duration and intensity show the duration of drought in months and the ratio of severity to the duration of drought respectively.

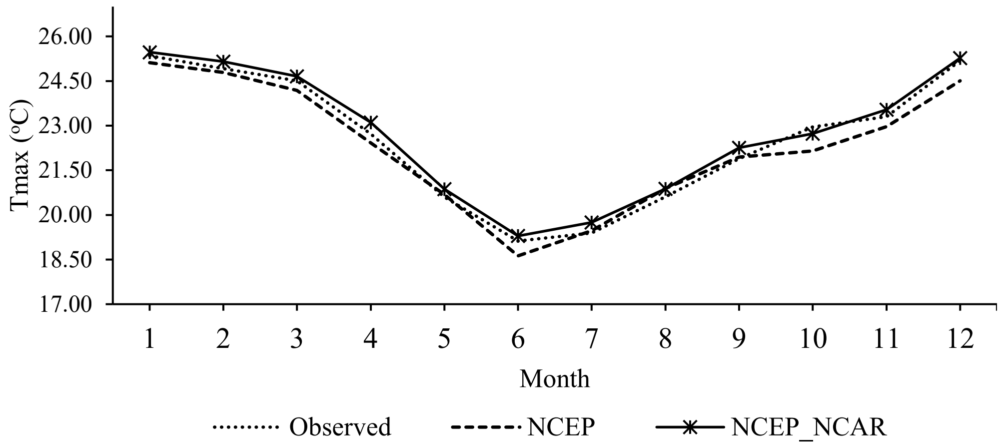
5.4 Results

This section mainly presents the outcomes of the study. First, the SDSM calibration and validation results are explained, highlighting the application of bias correction. The performance of the models based on the deterministic metric such as RSME and R^2 is also shown. Second, the simulated long-term climate data is analysed using SPI and SPEI drought indices for determining future drought trend in the study site.

5.4.1 Calibration of the SDSM

Results from the calibration of the model demonstrate a good correlation between the simulated and observed monthly rainfall totals as well as the average minimum and maximum air temperature. Figures 5.1 and 5.2 show the observed versus the simulated values of monthly average maximum (Tmax) and minimum (Tmin) air temperatures as well as monthly rainfall for the calibration of the model. The results of different predictors for both the Tmax and Tmin calibration indicate a similar pattern with small biases between the simulated and observed data. The air temperature values downscaled from the NCEP slightly underestimate the maximum air temperature whereas NCEP_NCAR predictors slightly overestimate the maximum air temperature almost throughout the year. The NCEP predictors appear to perfectly simulate the observed Tmax for May and July while the NCEP_NCAR predicators correctly simulate the observed Tmax for October, November and December.

The agreement between simulated Tmin by both predictors and the local meteorological station data is not as good in the winter months compared to the rest of the year. The rainfall calibration results also show an overestimation using the NCEP_NCAR predictor and underestimation for the NCEP predictor for the whole year (Figure 5.2).



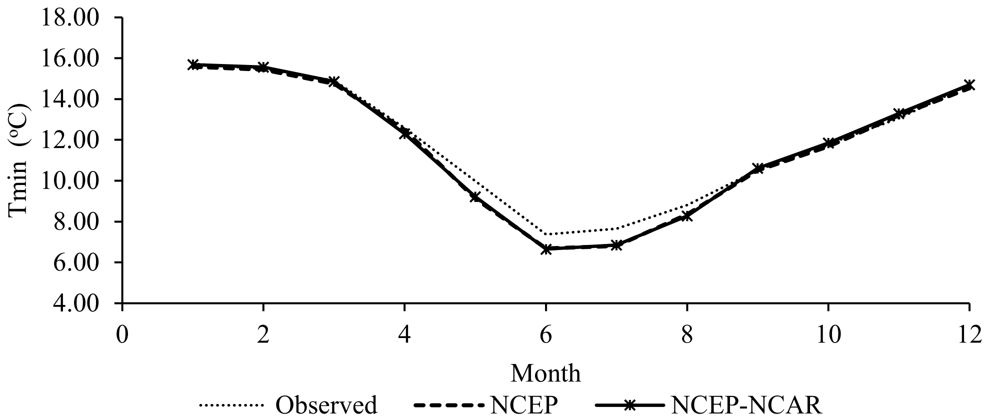


Figure 5.1: Comparison of monthly observed and simulated of monthly Tmax and Tmin using SDSM for the calibration period 1966 to 1984

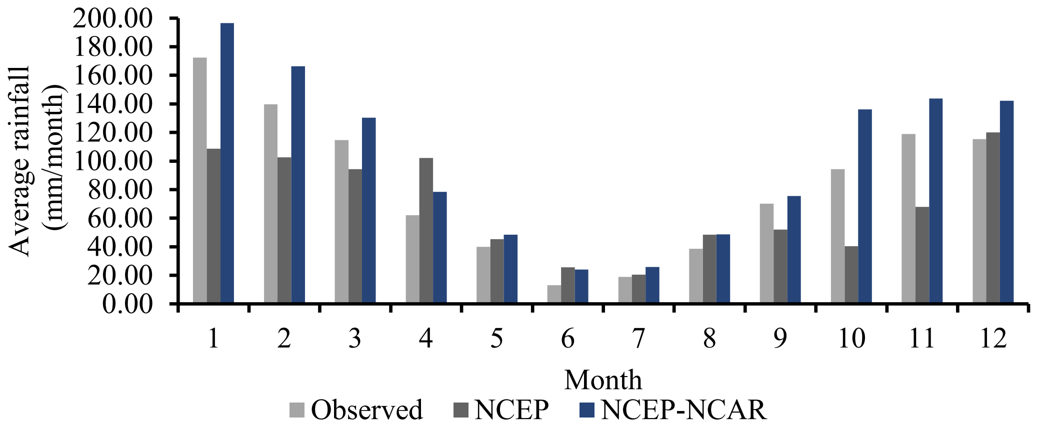


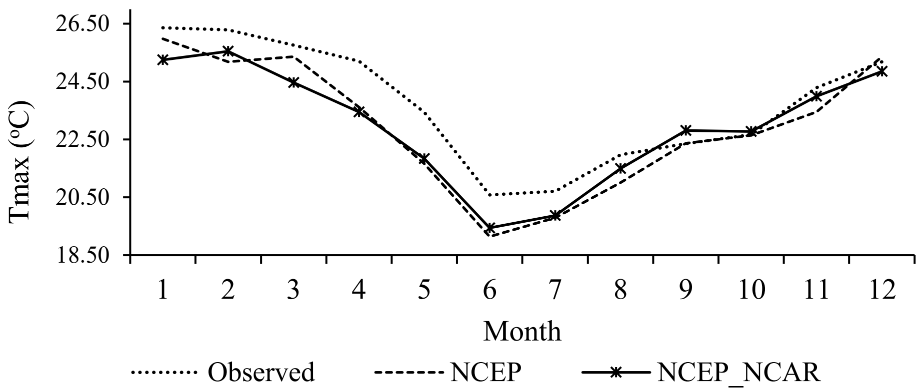
Figure 5.2: Comparison of monthly observed and simulated rainfall using SDSM for the calibration period 1966 to 1984

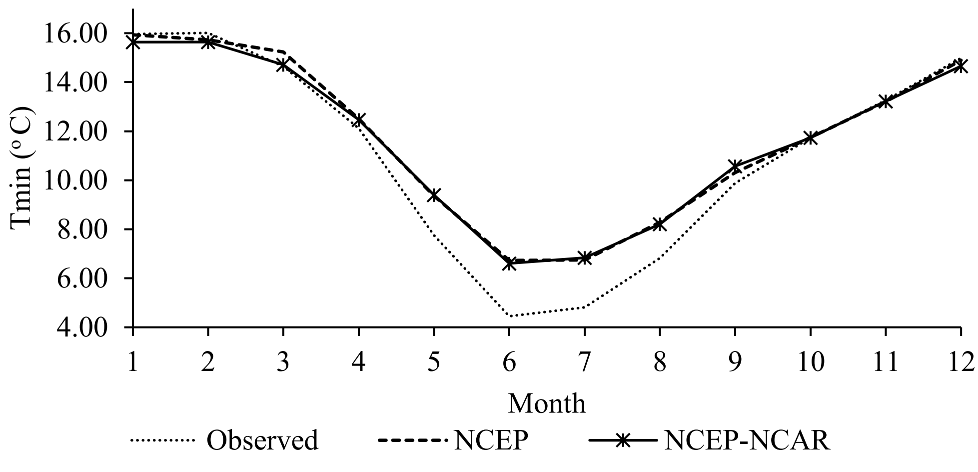
5.4.2 Validation of the SDSM results

The SDSM-downscaling model is validated using an observed 11-year period (1985-1996) data set. For validation, four sets of data were generated for the period of 1985 to 1996, extracting NCEP, NCEP-NCAR, HadCM3 and CanESM2 variables. The observed monthly mean of Tmax, Tmin, and rainfall are illustrated in Figure 5.3. Table 5.1 shows the statistical results of simulated data. Despite air temperature simulation from different scenarios showing a similar pattern, the precipitation results are not satisfactory.

As shown in Table 5.1, the models appear to simulate Tmin and Tmax better than rainfall. For example, in the case of Tmin, the R^2 and RMSE of NCEP are 0.99 and 0.98 ºC, for NCEP_NCAR and HadCM3 are 0.99 and 0.97 ºC and 0.66 and 2.33 ºC respectively. The R^2 and RMSE for Tmax are 0.87 and 0.93 for NCEP whereas for HadCM3 R2 and RMSE ranges between 0.50 to 0.51 and 2.32 to 2.36 ºC respectively. For rainfall, results show R^2 and RSME ranging between 0.56 to 0.76 and 24.53 to 40.05 mm. Similar behaviour is also observed for CanESM2 data in Table 5.1. However, results obtained using the NCEP_NCAR and NCEP are superior to HadCM3 and CanESM2 models for all the predictants. This shows that SDSM is good in simulating air temperature compared to rainfall.

Although bias is observed biases between the simulated and the observed results, a similar pattern that is indicated by Tmax and Tmin shows the capability of the abovementioned models to simulate air temperature for the study site. Thus these models were employed for this simulation study.





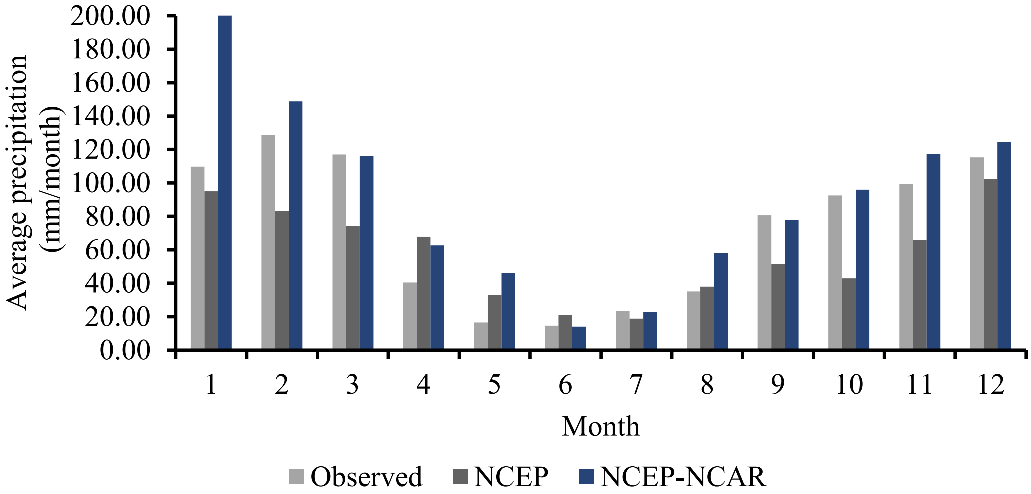


Figure 5.3: Validated Tmax, Tmin and rainfall before bias correction using SDSM for the validation period of 1985 to 1996

Table 5.1: Before bias correction statistical results for the comparison of the observed and simulated rainfall and the maximum and the minimum air temperatures for the validation period 1985-1996.

	Tmax				**Tmin**				**Rainfall**			
	Mean	Std dev	RMSE	R^2	Mean	Std dev	RMSE	R^2	Mean	Std dev	RMSE	R^2
	(°C)	(°C)	(°C)		(°C)	(°C)	(°C)		(mm)	(mm)	(mm)	
Observed	23.59	2.06			11.09	4.11			72.76	43.56		
A2	22.43	2.90	2.36	0.50	11.44	3.09	2.33	0.66	60.59	15.07	34.53	0.56
B2	22.44	2.87	2.32	0.51	11.42	3.10	2.33	0.67	60.82	14.95	34.98	0.52
CanEMS2	22.55	1.63	1.35	0.79	11.62	2.82	1.43	0.97	81.60	49.95	32.76	0.57
NCEP	22.99	2.28	0.87	0.93	11.73	3.42	0.98	0.99	57.84	27.92	28.53	0.69
NCEP_NCAR	23.02	1.99	0.82	0.92	11.65	3.31	0.97	0.99	91.04	55.77	40.05	0.76

5.4.3 Validation results after bias correction

Although the model was acceptable for the estimation of future climate parameters, the results showed biases. To remove biases between simulated and observed data, a bias correction method was applied using eqs. 5.1 and 5.2 to improve validation results and to obtain reliable future predictions. The statistical results for Tmin, Tmax, and rainfall after bias correction are displayed in Table 5.2 and the mean monthly observed data are compared with the bias-corrected generated mean monthly data in Figures 5.4 and 5.5. Validation results after bias correction indicate improved R^2 and reduced RMSE for both maximum and the minimum air temperatures as well as rainfall.

The graphical results in Figure 5.4 and the statistical results in Table 5.2 indicate that SDSM simulates maximum, minimum air temperature and rainfall acceptably well after the removal of biases. The application of bias correction enhanced the results by minimizing the difference between the generated and observed data and hence improved the correlation (Table 5.2). After bias correction, the monthly mean and standard deviation of the generated monthly data are much closer to the observed data. The corrected results of HadCM3 and CanESM2 were satisfactory to demonstrate the applicability of the SDSM model. Based on the statistical performance metrics of RMSE values for monthly rainfall and air temperature, CanESM2 improved more than HadCM3 in both air temperature and rainfall projections with RMSE values for air temperature ranging from 0.08 to 0.20 ºC while RSME value for rainfall projections was 1.15 mm. The statistical analysis also revealed that the SDSM is superior in simulating air temperature compared to rainfall. In general, the bias-corrected results and the graphical representation of simulated and observed scenarios revealed that the CanESM2 and HadCM3 models perform fairly well in simulating climate variables for the study area. Based on the plausible validation results and the acceptable behaviour of the model, the model was employed in the present study for the prediction of future Tmax, Tmin and rainfall for the study area.

Table 5.2: Statistical maximum and minimum air temperature and rainfall monthly results for the observed and simulated after bias correction for the validation period 1985-1996.

	Tmax				**Tmin**				**Rainfall**			
	Mean (ºC)	Std dev (ºC)	RMSE (ºC)	R^2	Mean (ºC)	Std dev (ºC)	RMSE (ºC)	R^2	Mean (mm)	Std dev (mm)	RMSE (mm)	R^2
Observed	23.59	2.06			11.04	4.22			72.76	43.56		
A2	23.77	1.74	0.37	0.99	11.00	4.21	0.08	0.99	72.81	43.19	1.17	0.99
B2	23.67	1.80	0.51	0.94	11.06	4.22	0.05	0.99	72.82	43.57	2.94	0.99
CanEMS2	23.77	2.09	0.20	0.99	11.03	4.23	0.08	0.99	72.83	43.69	1.15	0.99
NCEP	23.76	2.11	0.19	0.99	10.99	4.20	0.10	0.99	72.79	43.28	1.16	0.99
NCEP_NCAR	23.78	2.10	0.22	0.99	10.97	4.18	0.13	1.00	72.68	43.34	1.38	0.99

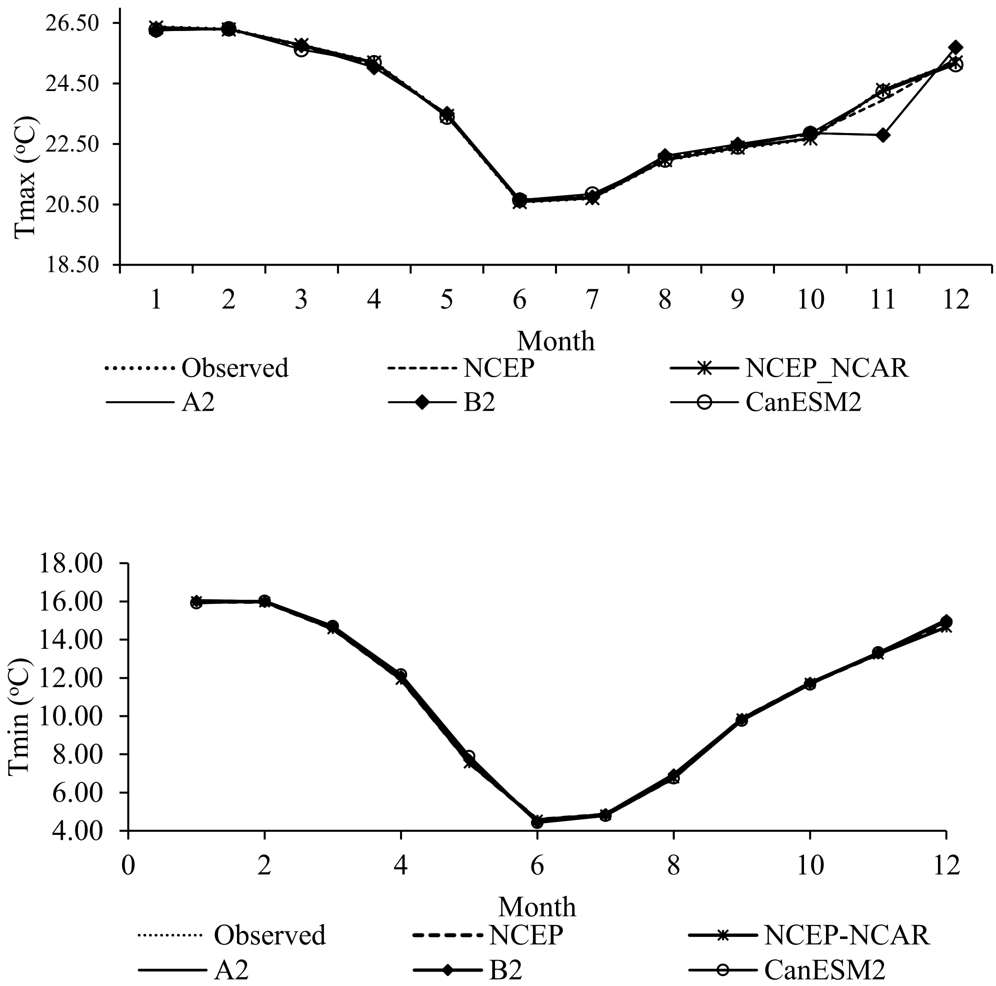


Figure 5.4: Validation of monthly observed and simulated Tmax and Tmin after bias correction using SDSM for the validation period 1985 to 1996

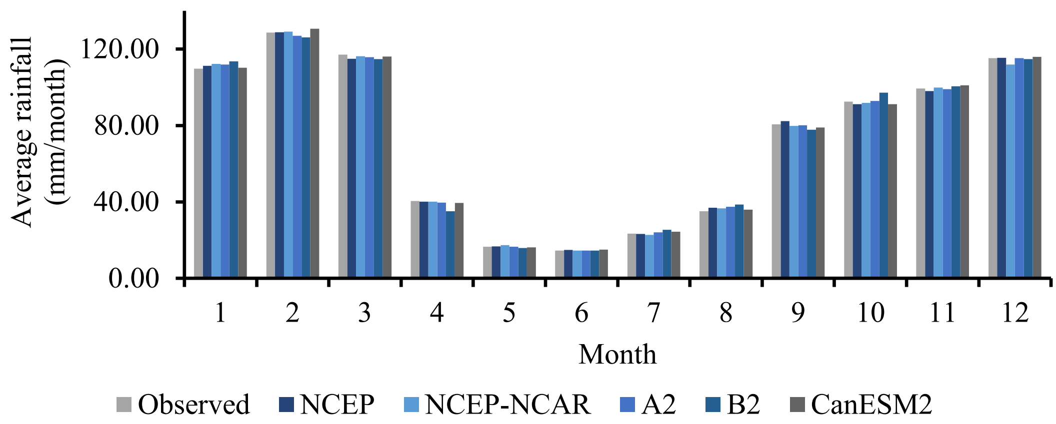


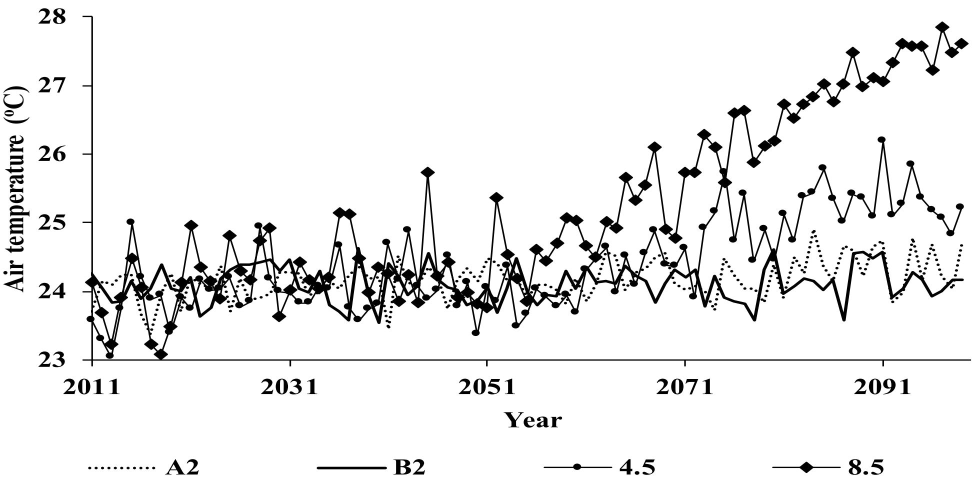
Figure 5.5: Validation of monthly observed and simulated rainfall after bias correction using SDSM for 1985 to 1996

5.4.4 Projected trend of average maximum and minimum air temperature and annual rainfall

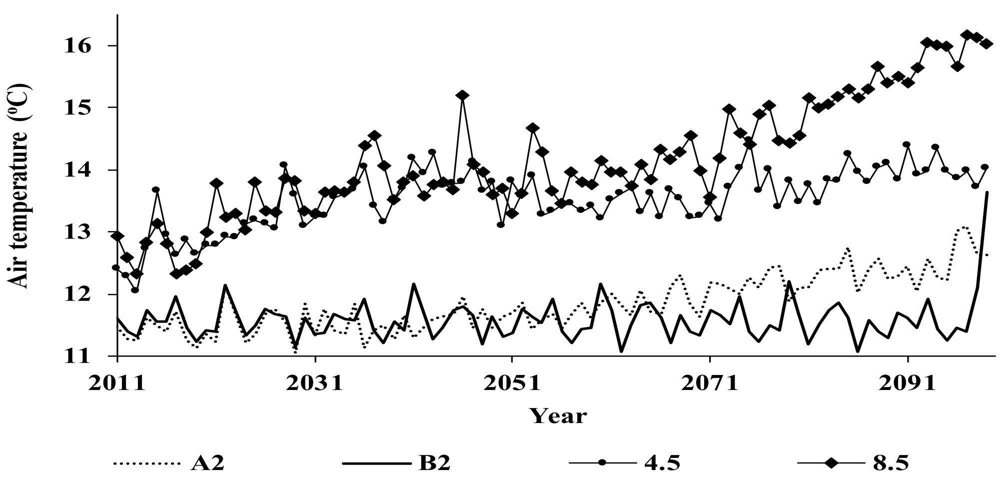
Figure 5.6 shows the general trends of Tmax, Tmin and rainfall for the study period. Scenarios indicate a statistically significantly positive trend for both Tmin and Tmax throughout the study period. The results agree with the consensus that under climate change conditions, the air temperature will increase. However, the CanESM2 scenarios displayed a pronounced increase in air temperature compared to the HadCM3 scenarios for 2011 to 2099. Based on CanESM2 RCP 8.5 and RCP 4.5, Tmax is projected to increase from 24.1 to 27.6 ºC and 23.6 to 25.2 ºC respectively for 2011 to 2099. The HadCM3 A2 and B2 scenarios project an increase of Tmax from 23.7 to 24.9 ºC and 24.2 to 24.5 ºC respectively. The results suggest an increase of up to 3.5 ºC relative to the 2011 projected maximum air temperature data. For Tmin, the CanESM2 RCP 8.5 and RCP 4.5 scenarios predicted an increase from 12.9 to 16.6 ºC and 12.4 to 14.0 ºC respectively. The A2 and B2 scenarios showed a smaller increase from 11.6 to 13.8 ºC and 11.6 to 13.7 ºC respectively. The HadCM3 SRES scenarios appear to have projected the air temperature for the whole period relative to the observed.

According to the results, Tmax is projected to increase at a greater rate than Tmin reaching the highest increase of 3.5 ºC. In the case of rainfall, a generally positive trend is predicted.
Rainfall trends show inconsistent results, with CanESM2 scenarios indicating a declining trend for the near future period (2011-2040) and begin to increase in the 2040s whereas HadCM3 scenarios predict a general decreasing trend. A wetting trend is observed after 2040 until 2088 where rainfall begins to decrease again. The annual rainfall shows a relative increase to 946.5 and 906.0 mm based on RCP 8.5 and RCP 4.5 scenarios whereas A2 and B2 scenarios project a decreasing rainfall trend to 1035.4 and 1186.2 mm respectively. The rainfall changes are based on the 2020s average annual rainfall.

a) Tmax



b) Tmin



c) Rainfall

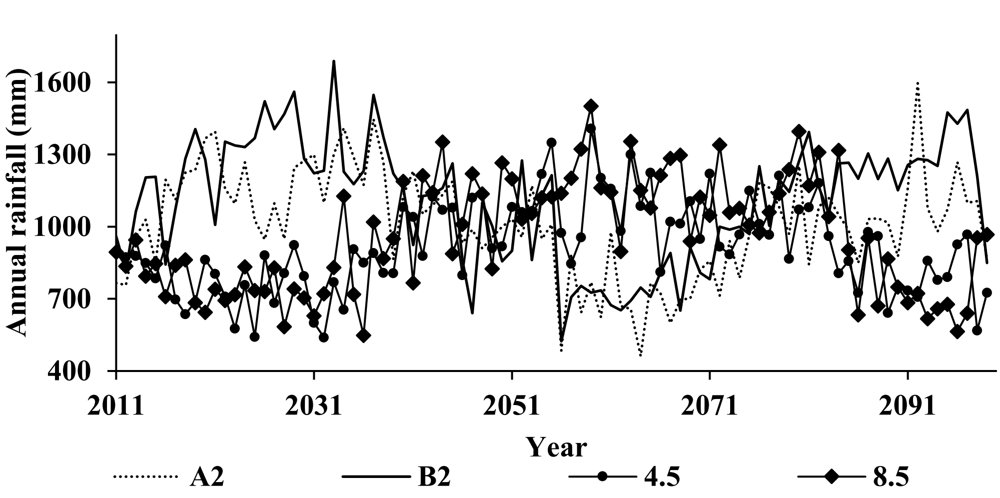


Figure 5.6: Projected future annual Tmax, Tmin and rainfall using SDSM from CanESM2 and HadCM3 for 2011-2099

The overall analysis of the results indicates a general increase in air temperature for all periods (the 2020s (P1), 2050s (P2), and 2080s (P3)) for the selected GCM scenarios (Tables 5.3 and 5.4), However, the magnitude of these increases differed for the different scenarios. The scenario RCP 8.5 projected that the average monthly Tmax for the three periods (P1, P2 and P3) would be 24.2, 24.6 and 26.8 ºC respectively. These values were found to be 1.2, 1.7 and 3.8 ºC greater than the observed monthly average Tmax. The RCP 4.5 scenario also projected an increasing trend for all periods, indicating that average monthly Tmax would be 23.9, 24.2 and 25.1 ºC, which are 0.98, 1.19 and 2.17 ºC greater when compared with the observed monthly Tmax.

Temporal regression analysis was conducted to analyse the rate and the significance of changes in average yearly Tmax, Tmin and total rainfall. The results indicate an increasing rate of 0.007 to 0.164 and 0.022 to 0.052 ºC $annum^{-1}$ in Tmax based on RCP 4.5 and RPC 8.5 scenarios. The increase projected by RCP 8.5 was found to be statistically significant ($p < 0.05$) for all three prospective periods while the RCP 4.5 scenario projected a statistically significant increase in Tmax for P1 and P2 only. Both HadCM3 scenarios (A2 and B2) predicted a general increase in Tmax for the three future periods relative to the observed. The A2 scenario projected a rise of Tmax to 24.1, 24.1 and 24.1 ºC for P1, P2 and P3 respectively, each being 1.12, 1.22 and 1.33 ºC greater when compared to the observed period. The Tmax is projected by B2 to increase to be 24.1 for all three periods, P1, P2 and P3 respectively, an increase of 1.10, 1.15 and 1.17 ºC relative to the observed period. For the HadCM3 scenarios, the increase was found to be statistically insignificant ($p > 0.05$). A similar trend for the average monthly Tmin was projected for all the scenarios (Table 5.4). The results suggest that the air temperature will continue to increase until the end of the 21st century.

Table 5.3: Overall change of Tmax for future climate generated using HadCM3 and CanESM2 model scenarios (changes based on the 1966-1996 Tmin mean)

GCM scenarios	Periods	Overall Tmax change	Slope (annum^{-1})	Significance < 0.05
Observed	1966-1996	22.96		
HadCM3 A1	2020s (P1)	24.08		
	2040s (P2)	24.18		
	2080s (P3)	24.29		
	ºC change P1 vs obs	1.12	0.008	$p > 0.05$
	ºC change P2 vs obs	1.22	0.009	$p > 0.05$
	ºC change P3 vs obs	1.33	0.012	$p > 0.05$
HadCm3 B2	2020s (P1)	24.06		
	2040s (P2)	24.11		
	2080s (P3)	24.13		
	ºC change P1 vs obs	1.10	0.003	$p > 0.05$
	ºC change P2 vs obs	1.15	0.002	$p > 0.05$
	ºC change P3 vs obs	1.17	0.006	$p > 0.05$
RCP 4.5	2020s (P1)	23.94		
	2040s (P2)	24.15		
	2080s (P3)	25.13		
	ºC change P1 vs obs	0.98	0.066	$p < 0.05$
	ºC change P2 vs obs	1.19	0.167	$p < 0.05$
	ºC change P3 vs obs	2.17	0.012	$p > 0.05$
RCP 8.5	2020s (P1)	24.17		
	2040s (P2)	24.63		
	2080s (P3)	26.80		
	º C change P1 vs obs	1.21	0.022	$p > 0.05$
	º C change P2 vs obs	1.67	0.074	$p < 0.05$
	º C change P3 vs obs	3.84	0.057	$p < 0.05$

Table 5.4: Overall change of Tmin for future climate generated using HadCM3 and CanESM2 model scenarios (changes based on the 1966-1996 Tmin mean)

GCM scenarios	Periods	Overall Tmin change	Slope (annum^{-1})	Significance < 0.05
Observed	1966-1996	11.53		
HadCM3 A2	2020s (P1)	11.87		
	2040s (P2)	12.37		
	2080s (P3)	13.00		
	ºC change P1 vs obs	0.34	0.023	$p < 0.05$
	ºC change P2 vs obs	0.84	0.033	$p < 0.05$
	ºC change P3 vs obs	0.82	0.029	$p < 0.05$
HadCM3 B2	2020s (P1)	11.54		
	2040s (P2)	11.57		
	2080s (P3)	11.64		
	ºC change P1 vs obs	0.01	0.002	$p > 0.05$
	ºC change P2 vs obs	0.04	-0.005	$p > 0.05$
	ºC change P3 vs obs	0.11	0.013	$p > 0.05$
RCP 4.5	2020s (P1)	13.13		
	2040s (P2)	13.59		
	2080s (P3)	13.87		
	º C change P1 vs obs	1.60	0.049	$p < 0.05$
	º C change P2 vs obs	2.06	0.025	$p < 0.05$

	ºC change P3 vs obs	2.34	0.065	$p < 0.05$
RCP 8.5	2020s (P1)	13.33		
	2040s (P2)	13.95		
	2080s (P3)	15.19		
	º C change P1 vs obs	1.80	0.055	$p < 0.05$
	º C change P2 vs obs	2.42	0.012	$p < 0.05$
	º C change P3 vs obs	3.66	0.070	$p < 0.05$

However, the models display different behaviour for rainfall. Overall, the models showed inconsistency in determining the period with the highest rainfall; the CanESM2 model scenarios predict high rainfall during the 2050s while according to the HadCM3 model scenarios, high rainfall is expected during the 2020s and 2080s (Table 5.5). The results suggest that the two models disagree on the direction of future rainfall predicted, with HadCM3 scenarios predicting a decreasing rate ranging between -13.025 to -18.124 mm annum^{-1} according to B2 and A2 scenarios respectively while CanESM2 RCP 4.5 and RCP8 8.5 projects an increasing rate of 1.989 to 4.373 mm annum^{-1} respectively during P2. However, the increase projected by CanESM2 were statistically insignificant whereas the decreases were found to be statistically significant. The discrepancies can emanate from the differences in the GCMs and scenarios used for downscaling, the selection of representative predictors, the spatial and temporal resolution of observed and predictor datasets and the downscaling techniques applied (SDSM). The summary of the projected rainfall trend for the respective periods are presented in Table 5.5.

Table 5.5: Overall change of rainfall for future climate generated from HadCM3 and CanESM2 model scenarios (changes based on the 1966-1996 rainfall mean)

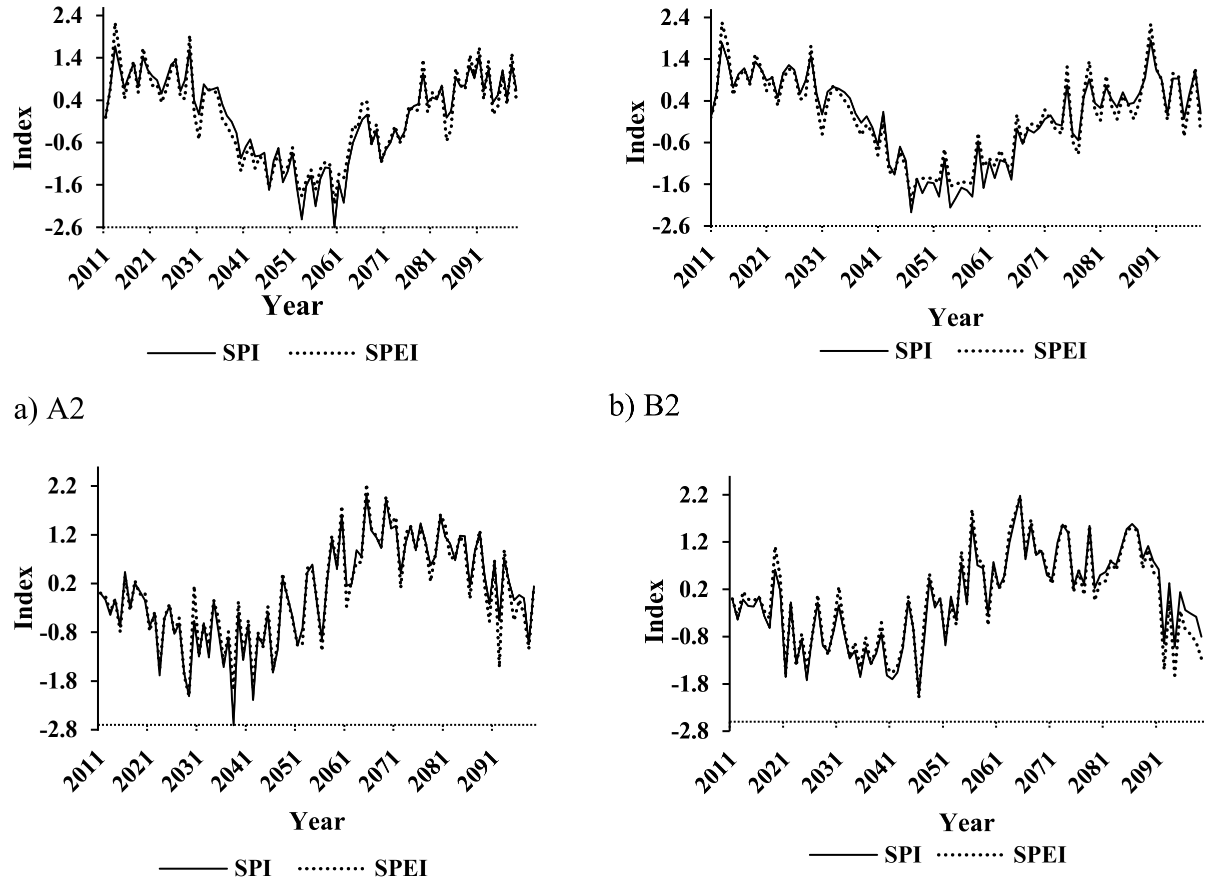
GCM scenarios	Periods	Overall rainfall change	Slope (annum^{-1})	Significance < 0.05
Observed	1966-1996	960.37		
HadCM3 A2	2020s (P1)	1141.00		
	2040s (P2)	869.25		
	2080s (P3)	1028.30		
	% change P1 vs obs	18.83	9.178	$p < 0.05$
	% change P2 vs obs	-9.51	-18.10	$p < 0.05$
	% change P3 vs obs	7.81	6.894	$p > 0.05$
HadCM3 B2	2020s (P1)	1261.76		
	2040s (P2)	881.41		
	2080s (P3)	1173.52		
	% change P1 vs obs	31.38	11.092	$p < 0.05$
	% change P2 vs obs	-8.22	-13.025	$p < 0.05$
	% change P3 vs obs	23.51	11.008	$P < 0.05$
RCP 4.5	2020s (P1)	782.61		

	2040s (P2)	1063.49		
	2080s (P3)	907.44		
	% change P1 vs obs	-18.51	0.687	$p > 0.05$
	% change P2 vs obs	10.74	1.979	$p > 0.05$
	% change P3 vs obs	-5.66	-12.730	$p < 0.05$
RCP 8.5	2020s (P1)	799.27		
	2040s (P2)	1138.85		
	2080s (P3)	951.48		
	% change P1 vs obs	-16.77	2.842	$p > 0.05$
	% change P2 vs obs	18.58	4.373	$p > 0.05$
	% change P3 vs obs	-1.44	-19.678	$p < 0.05$

5.4.5 Predicted drought events using SPI and SPEI for 2011-2099

SPEI and SPI were used at 6-, 12- and 24- months period during the period of 2011 to 2099 to compute the likelihood of drought occurrence based on generated future data. The intention was to capture the effects of changes in air temperature on drought characteristics. The 6-month time-scale was considered in order to understand possible changes during the rainy period whereas a 12-month scale was inclusive of the dry season to capture the effects of changes in air temperature on the drying trend during that period. The 24-month time scale was for detecting longer drought events. For the 6-month analysis, only August to January months inclusive were considered so as to understand the possible future changes during the rainfall season. The study period was divided into three periods, namely the 2020s (P1), 2050s (P2) and 2080s (P3). Figures 5.7, 5.8 and 5.9 indicate the 6-, 12- and 24-month drought occurrence results respectively. The drought trend follows the same pattern for all three periods despite the inclusion of winter months in the 12-and 24-month drought analysis. However, SPI6 progression appears to be slow. The drought anomaly initially decreased during the 2020s for all scenarios. However, the RCP 4.5 and RCP 8.5 scenarios suggest the prevalence of mild to moderate drought events from 2011 until the mid-2050s while A2 and B2 scenarios indicate possible drought events in the late 2020s until the late 2050s. Both SPEI and SPI show a wetter trend in the early 2020s which starts to decrease in the late 2020s for A2 and B2 scenarios. The SPEI and SPI values based on the RCP 4.5 and RCP 8.5 indices suggest an increased drought severity and intensity during 2011-2055 with SPEI showing a drought intensity of -2.12 and -2.09 for 2029 and 2046 respectively while the SPI indicates an intensity of -2.70 and -2.02 for the same years.

According to A2 and B2 SPI-6 results, drought events with the highest severity are anticipated from 2040 to 2073 reaching an intensity of -2.27 in 2047 and -2.60 in 2060. For A2 and B2 scenarios, SPEI6 revealed only moderate and mild drought events during 2040-2073. These results suggest that both SPI and SPEI detect drought events that are within the same category with slight differences, this happens despite the inclusion of air temperature in SPEI computation.

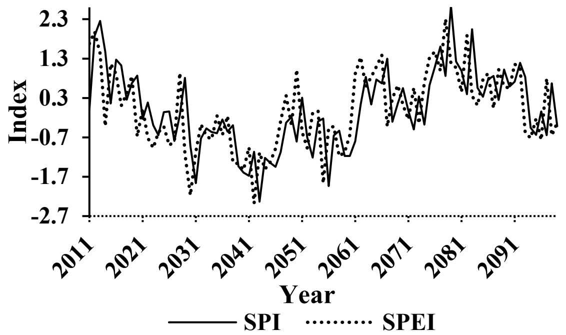


a) A2 b) B2 c) RCP 4.5 d) RCP 8.5

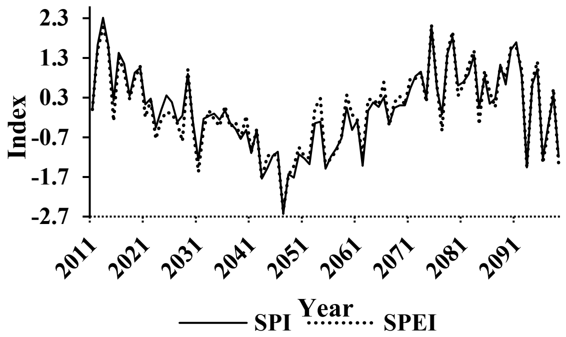
Figure 5.7: Projected drought occurrences using SPI and SPEI based on a) A2, b) B2, c) RCP 4.5, and d) RCP 8.5, scenarios at the 6-month time-scale.

A slight difference between the SPI and SPEI was observed with SPI consistently showing more intense results relative to SPEI for 2040-2073. The overall results indicate a possible drying trend under climate change conditions.

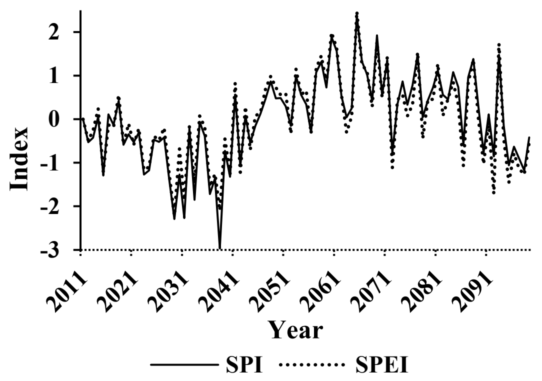
The evaluation of the drying trend for the 12-month analysis showed a reduced drought severity when compared to the 6-month analysis. The outcome of the 12-month analysis displayed a drying trend for 2028 to 2047, however, the SPI and SPEI analysis for the 12-month time-scale show the general high frequency of mild and moderately dry conditions with few extreme drought events. The implication is that although rainfall totals will be below normal, the magnitude of this shortage will be small. The SPI-12 results indicate that the severe and extreme drought events are predicted to occur in 2043 (-2.33), 2047 (-2.63) and 2031 (-2.27) as well as 2038 (-2.96) based on A2, B2 and RCP 8.5 respectively whereas SPEI-12 project an occurrence of severe and extreme drought in 2043 (-2.37), 2047 (-2.55) and 2029 (-2.29) as well as 2038 (-2.09). For the 24-month analysis, few drought events were projected over the study period. Only RCP 4.5 and B2 projected extreme drought events during the 2020s and 2050s. The RCP 4.5 scenario predicts extreme drought in 2029 (-2.05), 2061 (-2.08) and 2066 (2.20) based on SPEI while according to SPI, extreme droughts are expected in 2029 (-2.09), 2030 (-2.02), 2031 (-2.01), 2039 (-2.00) and 2066 (-2.09). The B2 scenario projected the occurrence of extreme drought events in 2047 and 2048 at an index of -2.13 (-2.01) and -2.34 (-2.36) for SPEI (SPI).



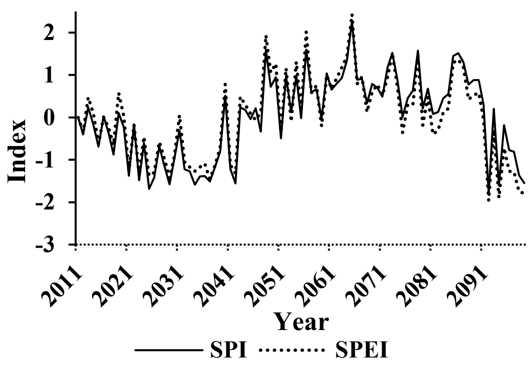
a) A2



b) B2



c) RCP 4.5



d) RCP 8.5

Figure 5.8: Projected drought occurrences using SPI and SPEI based on a) A2, b) B2, c) RCP 4.5, and d) RCP 8.5, scenarios at the 12-month time-scale

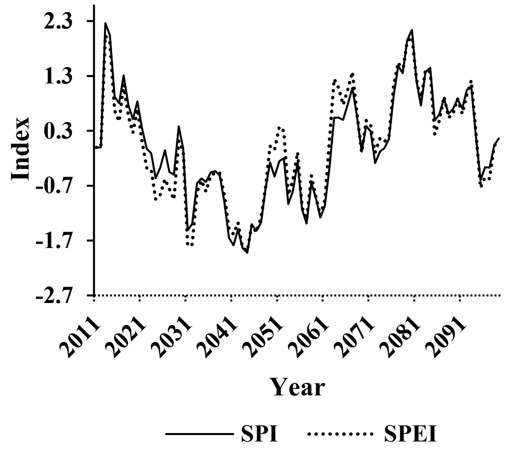
The consistency in terms of projected drought years for all scenarios is worth noting although at different time-scales. The scenarios commonly project extreme drought events in 2029, 2038, 2043, and 2047 but at different time-scales. This implies that extreme droughts should be anticipated in the near future in the area under study.

5.4.6 Analysis of future drought characteristics

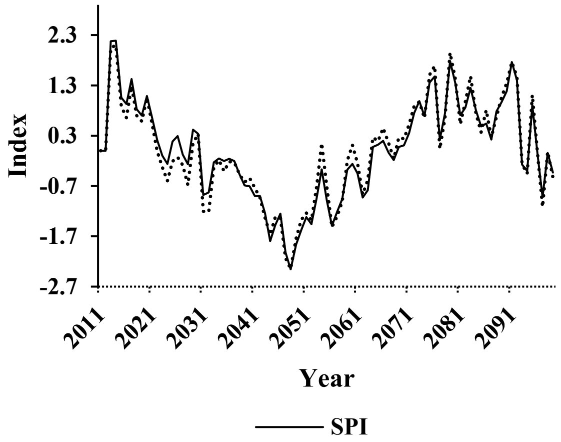
Possible changes in drought characteristics based on future drought events were investigated using the SPI and SPEI. The results indicate the inconsistency of scenarios in predicting such changes. Both increases and decreases in duration, severity and intensity relative to historical droughts are projected. Despite that, all scenarios predicted a higher severity of future droughts compared to historical drought characteristics, the is an equal probability of increasing or decreasing drought severity in the future with the 2080s expected to experience more decreases relative to the other periods. The projected drought characteristics at different time-scales also lack consistency. At a 6-month timescale, the historical drought duration, severity and intensity were 44 months, -70 and 1.63 respectively (see Table 5.6). All scenarios project an increased drought duration and severity at the 6-month time-scale but the intensity is projected to generally decrease for all three periods except for the A2 scenario which projects an increased intensity in the 2080s. This indicates high probability of longer droughts under climate change.

Based on the SPEI results in Table 5.7, the historical (1966-1996) drought duration, severity and intensity at the 12-month time-scale were 55 months, -84 and 1.53 respectively . The future projections at the 12-month scale indicate a general increase of these characteristics. The future drought events are predicted to be more severe (-225,-218) for the 2020s (RCP4.5, RCP8.5), (-144 and -247)2050s based on A2 and B2) and (-148) 2080s as predicted by RCP8.5. The scenarios also project a potential increase in drought duration over the same period, however, the projected drought events are generally less intense than the historical drought event's intensity. The lengthy drought events with mild to moderate intensity appear to become prevalent under climate change for the period under study. According to the SPEI at the 24-month time scale (see Table 5.8), drought is projected to become more severe from -81 to -214 and -139 based on RCP8.5 scenario for the 2020s and 2080s respectively. For the period of

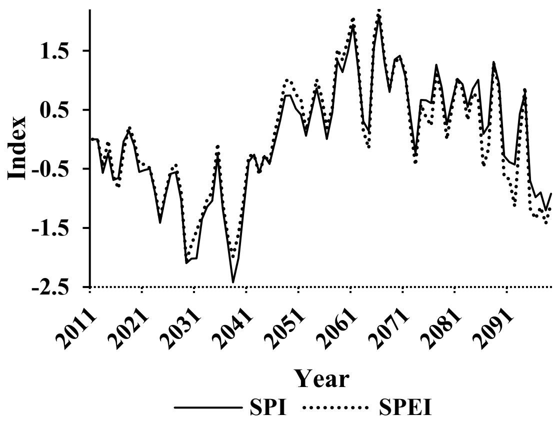
2050, the projection shows an accumulative negative rainfall anomaly of up to -241 for the B2 scenario. This indicates the high probability of future drought events with severity.



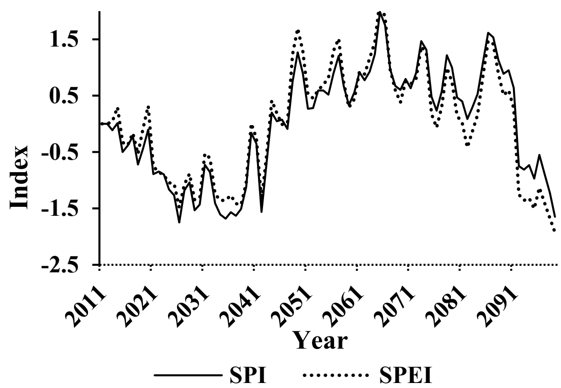
a) A2



b) B2



c) RCP 4.5



d) RCP 8.5

Figure 5.9: Projected drought occurrences using SPI and SPEI based on a) A2, b) B2, c) RCP 4.5, d) RCP 8.5 scenarios at the 24-month time-scale

Table 5.6: Possible future changes in drought characteristics at the 6-month timescale based on climate generated from HadCM3 and CanEM2 models

Scenarios		2020s			2050s			2080s		
		D	S	I	D	S	I	D	S	I
SPI-6	OBS	44	-70	1.63						
	RCP 4.5	75	-99	1.32	58	-81	1.39	39	-59	1.51
	RCP 8.5	81	-127	1.56	54	-71	1.31	43	-57	1.32
	A2	72	-95	1.32	108	-165	1.52	35	-59	1.68
	B2	61	-80	1.31	112	-176	1.57	35	-54	1.54

SPEI-6	OBS(1966-1996)	52	-71	1.37						
	RCP 4.5	73	-107	1.46	49	-71	1.45	48	-83	
	RCP 8.5	71	-85	1.20	42	-52	1.24	79	-148	1.73
	A2	78	-97	1.24	105	-184	1.75	30	-51	1.87
	B2	69	89	1.29	113	-158	1.40	36	-74	2.05

D-Duration (period of drought in months), S- Severity (accumulative of negative drought index), I-Intensity (ratio of severity to duration)

Table 5.7: Possible future changes in drought characteristics at the 12-month timescale based on climate generated from HadCM3 and CanESM2 models

Scenarios		2020s			2050s			2080s		
		D	S	I	D	S	I	D	S	I
SPI-12	OBS	47	-84	1.79						
	RCP 4.5	130	-225	1.73	5	-5	1.00	17	-25	1.47
	RCP 8.5	151	-218	1.44	22	-33	1.50	47	-63	1.34
	A2	48	-74	1.54	116	-144	1.24	1	-1	1.00
	B2	10	-12	1.20	167	-247	1.48	35	-54	1.54
SPEI-12	OBS(1966-1996)	55	-84	1.53						
	RCP 4.5	112	-187	1.67	8	-7	0.88	51	-75	1.47
	RCP 8.5	126	-167	1.32	21	-27	1.29	78	-119	1.52
	A2	71	-74	1.04	99	-144	1.45	1	-1	1.00
	B2	22	-27	1.23	157	-225	1.43	29	-40	1.38

D-Duration (period of drought in months), S- Severity (accumulative of negative drought index), I-Intensity (ratio of severity to duration)

Table 5.8: Possible future changes in characteristics at the 24-month timescale based on climate generated from HadCM3 and CanESM2 models

Scenarios		2020s			2050s			2080s		
		D	S	I	D	S	I	D	S	I
SPI-24	OBS	40	-81	2.02						
	RCP 4.5	150	-249	1.66	-	-	-	13	-13	1.00
	RCP 8.5	152	-221	1.45	13	-20	1.53	39	-50	1.28
	A2	49	-37	0.76	129	-224	1.73	5	-5	1.00
SPEI-24	OBS(1966-1996)	47	-74	1.67						
	RCP 4.5	128	-214	1.67	-	-	-	51	-120	2.35
	RCP 8.5	132	-173	1.31	13	-17	1.31	95	-139	1.46
	A2	64	-65	1.02	115	-197	1.71	10	-11	1.10
	B2	22	-28	1.27	175	-241	1.38	11	-12	1.09

D-Duration (period of drought in months), S- Severity (accumulative of negative drought index), I-Intensity (ratio of severity to duration
Indicates the absence of drought events. S- Severity, D-Duration, I-Intensity

5.5 Discussion

5.5.1 Projected air temperature

The results indicate that air temperature is expected to continue to increase in the area reaching a high in the 2080s for all scenarios. However, the pattern and the magnitude of future air temperature changes show differences across the GCMs. This may be attributed to the findings of Giorgi (2008) that indicated the dependence of regional temperature change sensitivity on the GCM sensitivity instead compared to local processes. Nevertheless, Giorgi & Coppola

(2010) confirm that the model regional sensitivity/ bias has a negligible effect on the projected regional change.

The CanESM2 scenario results also reveal that the incremental increases of minimum air temperatures are greater than that of maximum air temperature increases, suggesting warmer nights. However, a statistically significant decreasing Tmin trend projected by RCP4.5 for P2 is indicative that the rate of increase relative to the observed period will be low. The study findings correspond with other downscaling studies conducted worldwide and in southern Africa showing an increasing air temperature trend under global warming conditions (James & Washington, 2012; Engelbrecht et al., 2015; Dosio, 2017). Increasing air temperatures are associated with the prevalence of extreme heat events which is considered to be a major constraining factor in crop growth and yields. For example, warmer nights are detrimental to sugarcane production as they stimulate flowering which inhibits crop growth (Field, 2014).

It is imperative to consider the effects of increasing air temperature both to the environment and human life. High air temperatures induce increased evapotranspiration leading to the subsequent reduction of available soil moisture. Furthermore, increased air temperatures imply the prevalence of heat extremes such as heat waves, wildfires and intense storms. Under future scenario forcing, heatwave periods are projected to range between 20 and 80 days on an annual basis compared to just over three days under present-day conditions (Engelbrecht et al., 2015). The implication is that increased air temperatures as a result of climate change are not only a threat to agricultural productivity but also to biological life. Also, the effects of high surface temperatures accompanied by inadequate water supply to plants will result in high crop failures. This would mean a major loss for the community given that even those that are not directly involved in agricultural production often rent their gardens out for income (Swayimana small-scale farmers 2019, personal communication, 19 January).

5.5.2 Projected rainfall and drought occurrence

Although the results suggest a clear direction of future air temperature, the GCMs give no clear direction of rainfall changes for the area. The scenarios indicate the occurrence of drought at different periods. However, there were years that both CanESM2 and HadCM3 GCMs showed possible drought occurrences with different severity and intensity. These years include 2029, 2038, 2043 and 2047 indicating that in the study area, droughts are likely to be prevalent in the near future compared to a distant future. Previous studies have indicated that over 1960 to 2007, southern African region has experienced an increase in the frequency and intensity of drought (Nhamo et al., 2019). Also, Botai et al. (2020) projected frequent dry and wet conditions in the Limpopo river basin. However, dry conditions are expected to be common than wet conditions.

The prevalence of drought has implications on regional food availability and water security (Calow et al., 2010). The projected recurrent drought threatens the sustainability of small-scale farming given its reliance on dryland agriculture. During years of less rainfall, the majority of households face challenges of crop failures, yield and livestock losses leading to increased poverty. Despite that small-scale farmers in South Africa have managed to maintain livelihood under unfavourable conditions, their ability to cope with the projected climate extremes is improbable. They have always found it challenging to recover from such losses, particularly crop farmers, due to their inability to quantify losses which is a requirement for drought relief funds from the government.

It should be noted that in this study, in contrast to various previous studies, the results from drought indices showed that SPEI was consistently rendering results that are almost similar to SPI despite being slightly less negative than SPI. Possible uncertainty lies in the computation of ETo due to a possible underestimation of air temperature by the models. This is due to the water balance calculations being based on ETo instead of actual evapotranspiration. Also, the choice of GCM proved to have an effect on the downscaling procedure and therefore the differences in station level outcome (Laflamme et al., 2016). It was also noted that the choice of the reference dataset period, as well as bias-correction method used, can influence the uncertainty of downscaled GCM results (Leng et al., 2015).

Despite the inconsistencies between SPI and SPEI, the results from the study clearly suggest both wetting and drying trends with more wet years in the future. The study results are in agreement with the findings of Botai et al. (2020). This “non-linearity” and “non-directional” reaction of meteorological drought to the increasing air temperature was also observed by Leng et al. (2015) in China. It is difficult to understand the reason behind this “non-linearity”. However, it is worth noting that previously, the statistical downscaling technique has been found to perform relatively poorly is simulating daily rainfall (Pervez & Henebry, 2014). The poor performance appeared to be driven by: 1) the parent GCM; 2) climate change emission scenario chosen; 3) conditions of the observed data; 4) the method applied for downscaling (Hashmi et al., 2009). Additionally, Kwon & Sung (2019) suggest that the use of a historical baseline to assess future rainfall might be the underlying reason for weaker and fewer drought occurrences under climate change. This is because their study revealed that drought occurrence predictions that are based on future climate indicated an increase compared to drought predictions based on a historical baseline. This, therefore, indicates that more dry periods can be expected in future. Also, GCMs are found to be more skillful in predicting droughts at a short-timescale (3-month) compared to a longer time-scale (12-month) (Ujeneza & Abiodun, 2015). The inconsistency of the model in determining the timing of potential droughts is an indication of uncertainty in the model-projected rainfall. Thus, the use of an ensemble of different newly developed models might be useful for improving rainfall projections in the context of climate change.

5.5.3 Projected changes in drought characteristics

Based on SPI and SPEI, drought characteristics were analysed using Run's theory. The results indicate an increased drought duration and severity due to climate change when compared to the historical drought severity. One study in South Africa also showed an increased drought duration over a couple of recent past decades (Botai et al., 2016). Severe droughts are associated with reduced streamflow, which in turn disrupts agricultural and economical operations. The intensity of the projected droughts appeared to be relatively less than the historical drought intensity. However, it should be noted that most drought events identified for the historical period were associated with El Niño which has a large influence on the drought characteristics in South Africa (Shiferaw et al., 2014). This study did not take into account the effects of El Niño given the uncertainty of future changes of El Niño Southern Oscillation (ENSO) (Field, 2012) as cited by Davis et al. (2017).

The major implication of the projected changes for characteristics of drought is the high susceptibility of the agricultural sector and water resources in the study area to drought. The main concern is that South Africa is generally deemed a water-scarce country, which makes irrigation as a mitigation strategy less viable. This, therefore, implies that the increased severity of the projected drought events is highly likely to have adverse impacts on agricultural production if there are no alternative adaptation measures in place.

5.6 Conclusions

This study investigated the future occurrences of drought due to climate change. The results from both HadCM3 and CanESM2 indicate an upward air temperature trend until 2099. Increasing air temperature for agricultural communities that largely depend on rainfed agricultural production is a serious concern. High air temperatures could mean a collapse of small-scale sugarcane farming in the absence of adaptation, due to the likelihood of increased evapotranspiration. Despite two indices (SPI and SPEI) indicating possible drought occurrence at different periods, the overall results show that the study site is likely to experience drought events in the near future. The findings of this study highlight the importance of devising climate change impact adaptation policies that address agricultural rural communities in order to manage and mitigate the adverse impacts. In the interim, despite the financial challenges faced by small-scale farmers, it is of paramount importance to consider investing in drought and heat resistant varieties as coping mechanisms.

It should be noted that by the nature of the study the results are site-specific and have used projections of CanESM2 (RCP4.5 and RCP8.5) and HadCM3 (A2 and B2). This affords an opportunity for future research on a comprehensive similar study that can employ more meteorological stations across the province and make use of an ensemble from many climate models so as to allow a complete description of the potential impacts of climate change on drought characteristics. It will prove the usefulness of GCMs in the assessment of uncertainties associated with the projections and provide improved results for decision-makers. This research provides insight into climate model data used to understand the potential risk associated with climate change at the local level.

5.7 Acknowledgements

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Lead to Chapter 6

Previous chapters presented historical and possible future changes in air temperature and rainfall patterns. This chapter assesses the potential adaptation strategy to climate change. Through the use of questionnaires and face-to-face interviews, the study analyses access to and use of climate information as a tool to deal with climate change and climate extremes. The study focuses solely on small-scale sugarcane farmers in the area.

CHAPTER 6: LIMITED ACCESS TO CLIMATE INFORMATION HAMPER THE USE OF CLIMATE INFORMATION BY SMALL-SCALE SUGARCANE FARMERS IN SOUTH AFRICA: A CASE STUDY

6.1 Abstract

South Africa is continuously experiencing significant climate aberrations attributable to both climate change and the El Niño Southern Oscillation (ENSO). Air temperature increases, changes in precipitation patterns as well as increases in the frequency of extreme events are expected across the region. Agricultural production, either under dryland or irrigated will be affected by such climate vagaries. Small-scale farmers are disproportionately vulnerable to such changes owing to a series of factors constraining them from adaptation. Hence, a shift of the attention towards identifying adaptation strategies for small-scale farmers is necessary.

This study assessed the use of climate information by small-scale sugarcane farmers as a coping strategy under climate change conditions. Through the use of questionnaires and face-to-face interviews, data were collected from sixty-six farmers in the Swayimana community, KwaZulu-Natal Province, South Africa. Descriptive analysis indicates that the majority of small-scale farmers do not access climate information. Among other reasons, minimal access to and use of climate information can be attributed to the lack of knowledge in terms of the sources of information as well as lack of capacity to respond to the information provided. The study revealed that sugarcane small-scale farmers in South Africa still do not understand the climate change phenomenon and the associated effects of it. Thus, training of sugarcane small-scale farmers on climate change and its possible effects on sugarcane production is recommended.

Keywords: *accessing climate information; using seasonal climate forecast small-scale farmers; KwaZulu-Natal Midlands*

6.2 Introduction

Over 80% of the food utilized by underdeveloped and developing countries is produced by small-scale farmers (Donnati et al., 2018). Yet these small-scale farmers are perceived to be amongst the most vulnerable groups to climate change and climate variability (Harvey et al., 2018; Jamshidi et al., 2019). Amongst other reasons, the direct negative impacts of climate change on crops that serve as the major livelihood with limited ability to adapt exacerbate their vulnerability (Harvey et al., 2014). Small-scale farmers find it difficult to sustain agricultural practices considering the existing various challenges facing small-scale farming and an additional significant threat posed by climate change. Climate change and adverse weather associated with the El Niño Southern Oscillation have impacted past agricultural yield in South Africa. However, the sugarcane industry appears to constantly suffer the negative effects of adverse weather (BFAP, 2014; AGRI SA, 2016). In 2010/11 the South African sugarcane industry recorded its first lowest sugar yield since 2000 amounting to a 29.7% decrease (BFAP, 2014). Agriculture South Africa (AGRI SA) (2016) reported an estimated loss of about R2 billion in the sugarcane industry as a result of the 2015/16 drought event. Of concern is the vulnerability of the South African small-scale farming sector to climate variations given that farming, in general, is to a great extent rainfed. Nearly 73% of sugarcane production in the country is under rainfed conditions (AGRI SA, 2016).

Future predictions indicate a potential decrease in agricultural yields across the globe as a result of climate change. A possible varying yield trend is predicted for sugarcane under climate change. Unlike other field crops, sugarcane is a versatile plant that is grown under a wide range of climate conditions. Sugarcane grows throughout the year and hence is exposed to both warm-summer and cold-winter climate conditions. As a result, the yield of the crop depends on the exposure to suitable climate conditions during the entire growing period. Different stages of sugarcane crop growth require different optimal levels of different climate variables. The implication is, if a considerable difference exists between, for example, the optimum air temperature required and the air temperature experienced by the crop, crop growth will be affected, and in turn, affect the overall yield. Thus, the effects of climate change on sugarcane yield give different results for production. Field (2014) indicated that an increase in air temperature to 35 ºC in winter would lead to a yield increase due to the increased CO_2 assimilation which promotes sugarcane growth. However, an increase in night-time temperatures would lead to a decrease in yield given that high night-time temperatures induce flowering which in turn causes internodes to stop growing, and ultimately leaves, thus reducing sucrose and cane yield.

Prevalence of excessive rainfall has a negative effect on sucrose yields while frequent dry spells have a negative effect on cane yield as it requires more water for sustained growth. A reduction in precipitation during the last growth phase enhances efficiency in harvesting. The effects of inadequate water supply on sugarcane depends on plant growth stage and duration of stress. Drought at the early stages of growth leads to a reduction of sucrose yield while moderate drought at a later growth stage increases sucrose content in stalks (Hussain et al., 2018). The implication is that long-term microclimate variability can be advantageous and lead to good sugarcane yields or reduce the expected yields. South African commercial sugarcane farmers are well equipped and have adaptation measures in place. However, the adaptation of small-scale farmers who contribute about 10% to the sugarcane industry (Mbowa, 2015) is unclear.

Due to the increased frequency of weather extremes and the expected intense adverse effects of climate change, understanding the exposure and identifying adaptation measures have received attention from scientists. Several studies have indicated the usefulness of weather forecasts for reducing the vulnerability of rainfed agriculture to climate aberrations (Hansen, 2002; Meza et al., 2008; Dell, 2012; Manatsa et al., 2012; Mudombi & Nhamo, 2014). Although most studies indicate low level climate information usage by small-scale farmers, these studies were either conducted nearly a decade ago or excluded sugarcane farmers. Johnston (2008) indicates that climate information has generally been used in the sugarcane industry for estimating crop yields. The operational crop estimates are then distributed to farmers in order to avoid the possible loss or to take advantage of possible good climate conditions. Ziervogel & Calder (2003) affirmed that the sugarcane industry has been using climate forecasts for a long time and have benefited from using them. However, there is a lack of clear evidence of whether small-scale farmers also have had access to the information or not. Vogel (2000) suggested that research on the assessment of the usage and uptake of climate forecasts generally tends to focus on commercial farmers who have many alternative sources of climate information (Johnston, 2008). In addition, there is little information on what adaptation measures are needed to reduce farmers' vulnerability to climate change.

In this study, the access to and use of climate information by sugarcane small-scale farmers in the KwaZulu-Natal midlands, South Africa are assessed as a tool to deal with climate change and extreme weather events. In this study, climate information includes, daily forecast, seasonal climate forecast as well as future climate projections for the study site. Specifically, the study investigated climate changes experienced by small-scale sugarcane farmers and how it has impacted on sugarcane production. The study also evaluated the economic benefits of accessing and using the information by measuring the maximized outcomes (achieved yield) and minimized risks (reduced possible cost/damage) in the sugarcane sector through the use of climate information. The study explores the efficacy of using climate information to cope with extreme weather events and thus identifies the risk, coping and adaptation strategies used by farmers as well as highlights the key adaptation needs.

6.3 Materials and methods

6.3.1 Study area and population frame

The research was undertaken in Swayimana, a local community of Wartburg in KwaZulu-Natal midlands. The Swayimana community is located at a latitude of 29.4778 ºS, longitude of 30.6603 ºE and altitude of 919 m above sea level. The area accounts for 32 km^2 land area. The climate of the area is characterized by wet summers and dry winters with a long-term annual average precipitation of 881 mm and an average air temperature of 18 ºC (South African National Biodiversity Institute (SANBI), 2014). The study area was specifically selected because it is the largest of the four rural communities within the Wartburg area and has many sugarcane farming households. The study focused on small-scale sugarcane farmers, who have been participating in the sector for at least 5 years, to assess their access to and use of climate information. The small-scale farmers were surveyed for responses on whether they: had access to climate information, used the information, and benefited from using the information over the past years.

6.3.2 Sampling procedure and data collection techniques

A purposive sampling procedure was employed to select the sugarcane producing area within the midlands of KwaZulu-Natal. The study area was selected based on the availability of long-term climate information for the area, high probability of climate information, use of information provided by the Department of Agriculture and Cane Growers' representative and a number of small-scale sugarcane farmers who have been participating in the industry. From a large group of small-scale farmers, the prospective respondents were randomly selected. The study employed an explanatory research design in which face-to-face interviews with respondents were conducted for data collection. Ethical clearance for this study was obtained from the Humanities and Social Science Research Committee, University of KwaZulu-Natal (clearance number HSS/1173/017D). The questionnaires used consisted of both open- and closed-ended questions. The use of open-ended questions allowed respondents to provide insights about their personal experiences. To be eligible for the study, households had to have at least one adult who was responsible for planting sugarcane for at least 5 years.

The questionnaire interviews were conducted between 13 December 2018 and 05 February 2019. The interviews were carried out on an individual basis and in IsiZulu to ensure that questions were easy to understand by all the prospective respondents irrespective of educational background. The interviews conducted spanned a maximum of 30 minutes. A total of 66 questionnaires were completed through the interviews. The questions covered in the questionnaire included: i) general respondent traits such as gender, age group, level of education, size of the farm, years of sugarcane farming; ii) sugarcane farming and climate effects, which focused on the effects of climate change on sugarcane production; iii) climate information which included questions on the access, use, and benefits of using climate information. The collected data were then coded in Microsoft Excel and descriptive statistics were generated and interpreted for analysis purposes.

6.4 Results

6.4.1 Demographic information of the respondents

The demographic distribution of the respondents is shown in Table 6.1. The results indicate a virtually equal proportion of males and females. The majority (31%) of the respondents were elderly and over 60 years. Over 50% of the respondents had primary education, followed by 46% who had secondary education. Only 2% indicated they had a bachelor's degree. The majority (46%) of the respondents were producing sugarcane using 0.5-2 ha of land. However, most of the respondents with a farm size of more than a hectare indicated they either leased land from the neighbours who did not farm or were farming as a group within a family to efficiently use the land. The period for which the respondent had been producing sugarcane was an important factor in determining how long farmers have been exposed to climate aberrations and how they have used climate information or would have used climate information to alleviate the possible effects of climate change in the sugarcane production. Most respondents (80%) have been growing sugarcane for over five years while the rest indicated they had been farming for a period of 1 to 5 years. The latter group was included in this study because they have been farming sugarcane and stopped due to challenges and re-joined the industry in the past few years.

6.4.2 Reported climate effects on sugarcane production

The sugarcane industry has faced the challenge of declining sugarcane yields since the 1980s. This study assesses the changes in land area under sugarcane production and the changes that have occurred in the size of cultivated land over the past few years so as to assess whether climate change has had an impact on the changes of the cultivated land. The results in Table 6.2 show that the majority (66 %) of the respondents use all available land for sugarcane production while 34 % have allocated some land for the cultivation of other produce for home consumption. Only 18% of the respondents reported a decrease in the land area for sugarcane production while 42% reported no change. The lack of necessary resources (26%) such as finance and land area was reported as the main limiting factor for not increasing the land area under cultivation while poor climate conditions (20%) was presented as a significant cause for the declining land area under sugarcane cultivation. Some (17%) stated that yield increase and profit were the reason for increasing the sugarcane production area.

The findings show that based on the experience of the small-scale farmers in the study area, climate conditions have significantly affected sugarcane production. Nearly 80% (Table 6.2) of the respondents believe that climate has a major effect on sugarcane production. Respondents were asked to list climate risks that limit sugarcane production in the area. There were inconsistencies in determining the top climate-related risk that inhibits sugarcane production. However, the study analyzed climate variables that were commonly mentioned although ranked differently. Drought and high air temperatures were commonly identified as climate-related risks that adversely affected the sugarcane production in the area followed by high rainfall, and frost, respectively. The respondents noted a strange pattern of dry spells and high rainfall. During the winter periods, the respondents indicated that the prevalence of frost particularly in low lying areas adversely affected production. All these extreme climate conditions adversely impact small-scale sugarcane production.

Table 6.1: Demographic information of the respondents (n = 66)

Demographic variables	Indicator	Responses (%)
Gender of the sugarcane farmer	Male	51
	Female	49
Age (years)	<40	24
	41-50	20
	51-60	25
	>60	31
Level of education	Primary	52
	Secondary	46
	Bachelor degree	2
Farm size (ha)	<1	29
	1-2	46
	>2	25
Years in sugarcane farming	<1	3
	1-5	17
	5-10	40
	>10	40

Table 6.2: Climate effects on sugarcane production (n = 66)

Farming and climate effects	Indicators	Responses %
Land under sugarcane production	>1	32
	1-2	46
	<2	20
Changes in the cultivated land over the past 5 years	Increased	22
	Decreased	18
	Remained the same	42
	Don't know	17
Reason for a specified change	Poor climate conditions	20
	Easy maintenance and resistant to extreme weather conditions	8
	Lack of necessary resources	26
	To increase yield and profit	17
	Because of good rains	2
	No reason	14
	Don't know	14
Climate affect production	Yes	78
	No	22
Climate risk that negatively affects sugarcane production	Too much rainfall	35
	Drought	40
	High temperatures	40
	Hail/strong wind	14

	Frost	34
	Unusual rainfall pattern-late or early start of the rainfall season	3
	Diseases due to adverse weather	5

+ More than one choice

6.4.3 Access to and benefits of using climate information

The results (Table 6.3) show that 75% of the respondents have access to climate information. However, when it was categorized into daily weather, seasonal climate forecast and early warning, the results indicate that 100% of those who had access to climate information accessed daily weather forecasts. Seasonal climate forecast access was low as only 31% of respondents reported accessing and using it while 43% indicated accessing early warning information. A large number of respondents who accessed early warning information received it only once during the 2014/15 drought event. Those who only had access to daily weather forecasts indicated their lack of knowledge with regard to other forms of climate information. Television was the principal source of the daily weather forecasts followed by radio while the sugarcane farmers associations (Canegrowers and South African Farmers Development Association) and extension officers were sources for seasonal climate forecasts and early warning information respectively.

The respondents were asked if the meteorological information met the requirements in terms of assisting with taking informed farming decisions. Almost 60% expressed their satisfaction reasoning that it is the only available information and cannot fault it as it assists with day-to-day farming activity planning. The remaining 39% were not satisfied indicating that climate forecasts do not provide much help as it cannot be incorporated into seasonal farming decision planning. To understand whether the climate information the respondents accessed was useful or not, the respondents were asked if the climate information was sufficient for them to adapt and minimize potential adverse impacts on sugarcane production. The majority of the respondents (59%) stated that the information was insufficient. The insufficiency emerged from the inconsistent provision of seasonal climate forecasts and early warning as well as the rare sources of the necessary information in addition to the daily weather forecast.

The respondents (59%) indicated that despite their limited capacity to cope with adverse climate events, understanding the possible upcoming extreme climate events or unusual climatic patterns would assist. Some (41%) indicated that its usefulness would only be realized if accompanied by information on how to deal with the situation while others (59%) believed that it would enable them to prepare in advance with necessary measures in place. Those who believed that it would not be useful assigned the unhelpfulness of the information to the lack of adaptive or responsive capacity (48%), failure to understand the information provided (23%), the late arrival of the information (43%) and the unreliability of weather forecasts in general.

Furthermore, respondents who had no access to climate information were asked if they were willing to receive climate information. Those who already had access to the information were asked if they would like to receive additional information. Firstly, it is necessary to indicate that most of the farmers had no knowledge of climate information, particularly seasonal climate information and its importance to farming. Given their low levels of education and reliance on indigenous knowledge such information was new to them. Irrespective of the length of time in farming and having observed the changes in climate over the recent past years, most of them had never had or thought they could have seasonal climate information. As a result, only 57% (Table 6.3) provided answers to the question, indicating that access to any information that would assist in production (8%) would be useful. Others responded that they would like to receive both seasonal climate forecasts and early warnings (23%), early warnings (5%), seasonal climate information (6%), information on rainfall season (12%) as well as possible impacts on production information (3%). The remaining 43% did not need additional information or did not want to access the information. Besides the fact that the respondents generally did not know of the existence of climate information, understanding the underlying reason behind the lack of access to climate information was important. As expected, lack of knowledge on where to obtain the information was the main reason (47%), followed by those who gave no reason (24%). Amongst other reasons, failure to understand the forecast (14%), lack of knowledge on the usefulness of it (12%) and its existence (4%) were mentioned as reasons for not accessing the information. Respondents who had access to climate information (seasonal climate information and early warning) were asked if it was beneficial to access such information.

Table 6.3: Access to, use, and benefits of using climate information by small-scale sugarcane growers (n = 38)

Climate information	Indicators	Responses (%)
Access to climate information?	Yes	75
	No	25
Type of information accessed?	Daily weather forecast	100
	Seasonal weather forecast	31
	Early warning	43
Sources of information?	Television	82
	Radio	59
	Sugarcane organization	27
	Extension officer/organization leader	29
	Cell phone	8
	Local media	8
Does information meet the requirements?	Yes	59
	No	41
Is the information sufficient for minimizing potential negative climate effects?	Yes	41
	No	59
Information required?	Seasonal weather forecast	6
	Early warning	5
	Production impact information	3
	Information on rainfall season	12
	Any information that would assist in the production	8
	Combination of either seasonal or Early Warning with production information	23
What aspects of decision-making are influenced by climate information?	Type and amount of fertilizer and herbicides	2
	Type of cultivar to consider and when to plant	35
	Weeding	5
	Soil preparation	3
	Plan day-to-day farming activities	5

	To plan all the farming operations	8
	Combination of different aspects	9
	None	29
Is it beneficial to access climate information?	Yes	53
	No	39
Reasons for not accessing climate information?		
	No reason	24
	Do not know where to access it	47
	Cannot understand the forecast	14
	Never thought it is useful	12
	Never knew it exists	4
Would you like to receive (additional) climate information?	Yes	57
	No	43
Would you pay for such information?	Yes	57
	No	43
Thoughts about receiving an early warning on time? +	Would be helpful	57
	Only if it is accompanied by suggestions on how to prepare for the event	43
	Allows us to prepare in advance and put necessary measures in place	57
	Would not be helpful	48
	Do not have the capacity to mitigate possible adverse effects	48
	Lack of information because we rely on indigenous knowledge	23
	It is not reliable because the weather always changes	6
	It arrives late for us	23

+ More than one choice

Although quantifying the benefits of accessing climate information through sugarcane yields over the past years was one of the objectives of the study, virtually none of the small-scale sugarcane farmers kept records of either cost of production, yield achieved, or profit. However, they indicated that it is beneficial (53%) as it assists in decision making, for example, type and amount of fertilizer and herbicides to be applied, types of cultivars and time of planting, weeding (manual or otherwise), and the overall planning of farming activities. Those who were interested in receiving either climate information or additional climate information were asked if they could pay for it. Over half of them showed their willingness to pay while 43% of them indicated a lack of funds and an inability to pay.

6.4.4 Benefits of accessing and using climate information to cope with extreme climate events

This study was conducted to determine how the sugarcane industry, small-scale sugarcane farmers, in particular, have used climate information to mitigate the adverse impacts of the 2014/15 drought event. The respondents were asked about the climate changes that they have observed over the past decade so as to assess their perception of climate change. Although they believe that the Swayimana area has favourable climate conditions, particularly for sugarcane production, some noticeable changes in climate were observed. Table 6.4 shows the results of how the respondents have benefited from the use of climate information during the 2014/15 drought event. The majority of them (32%) observed the prevalence of storms and hail which tend to significantly affect sugarcane fields. High air temperatures (26%), dry spells (21%), high rainfall (24%) and frost (14%) were also observed in the area over the past 10 years. The results show that most of the farmers (62%) did not receive a warning in cases when extreme climate conditions occurred. Few individuals who received the warning about the 2014/15 drought event indicated that it was helpful because they planned accordingly. Over 83% indicate that they did not continue with planting as they were about to replant while 17% reported that they used advice from the extension officer. Advice included changes in weeding, type of fertilizer, timing and amount of fertilizer application and early harvesting.

The usefulness of the early warning did not apply to all the end-users. It was found unhelpful by some due to the late arrival of the warning (67%), lack of capacity to respond (11%) and lack of knowledge on how to cope with the situation (22%). The changes that were adopted after receiving the information cited by the respondents included changing type and amount of fertilizer applied, mulching, ceasing planting, manual irrigation, and early harvesting.

Table 6.4: Usefulness of climate information to cope with extreme weather events (n = 66)

Usefulness of climate information	Indicator	Responses (%)
Climate changes observed over the past decade +	No change	5
	High air temperatures	26
	Drought	21
	Intense and frequent adverse Weather	11
	Storms and hails	32
	Rainfall delays	9
	High rainfall	24
	Good rains	3
	Frost	14
Access to early warnings for the above-mentioned events?	Yes	32
	No	62
	No response	6
Was it helpful?	Yes	57
	No	43
How did it assist?	I planned accordingly (e.g., stopped planting)	83
	Extension officer advised on how to cope	17
Reason for unhelpfulness of the information?	It arrived late	67
	Had no knowledge on how to deal with the situation	22
	Lack of capacity to respond	11
Changes adopted/would be adopted after receiving the warning? +	The appropriate type and amount of fertilizer	42
	Stopped planting	58
	Minimized area	17
	Mulching	33
	Manual irrigation	25
	Early harvesting	17
	None	17
Impact on sugarcane yield	Decrease	42
	Increase	33
	No change	25

These changes have assisted in decreasing the negative impacts on sugarcane yield. However, others have indicated that no change was observed. The results regarding impacts are difficult to quantify given the lack of a long-term record of the sugarcane yield of the farmers. The method that they use for quantifying their yield is inappropriate as they mainly base it either on the number of sugarcane truckloads or income realised from the yield. As a result, the study findings on the impact of drought events on sugarcane yield indicate the perceived impact by the farmer, not the actual impact based on measurements.

6.4.5 Possible future adverse weather and impact on sugarcane production

Understanding how sugarcane farmers, in general, comprehend the impacts of climate change in climate extreme patterns and how these will affect the sugarcane production in the study area was important. It provides an insight into the vulnerability and exposure, given that under circumstances where farmers lack understanding of the negative impact on the production, they are likely to suffer most should climate extremes occur. In addition, their livelihood generally depends on sugarcane production, hence an unforeseen loss would not only result in profit losses but also increase poverty and food insecurity. The results in Table 6.5 show that 99% of the respondents have no knowledge about the possible future adverse weather due to climate change and 92% are not aware of the potential impacts that the predicted climate extremes could have on sugarcane production. The respondents were asked about the tools that are in place to deal with climate variation and variability. Over half of the respondents indicated that there are no tools in place while 38% of them reported relying on mulching to maintain soil moisture under dry and hot conditions. Recommendations regarding the usefulness of climate information by sugarcane small-scale farmers indicate that punctuality, the use of the end-users' language as well as accuracy are important to ensure the use of climate information by the sugarcane small-scale farmers.

Table 6.5: Knowledge of possible adverse weather trends in the near future (n = 66)

Possible future adverse weather	Indicator	Responses (%)
Awareness of possible adverse weather in the near future?	Yes	1.5
	No	98.5
Knowledge on the potential impacts on sugarcane production?	Yes	3
	No	92
	No response	5
Other tools in place to mitigate the possible impacts of adverse weather?	None	55

	Mulching	38
	No response	7
Recommendation on the usefulness of climate information?	Must be sent through pamphlets	3
	Must be on time	23
	Must be accurate	11
	Must be disseminated through radios	2
	Must be sent with recommendations	6
	Must be free	5
	Must be applicable to the needs of farmers	6
	Must be released frequently and explained verbally	5
	Must be in a language understood by the audience	14

6.5 Discussion

The study investigated the use and the benefits of climate information by small-scale sugarcane farmers in the Swayimana community of KwaZulu-Natal in South Africa. Sugarcane production in the study area is important due to the fact that it is often the sole source of income. Cockburn et al. (2014) reported that sugarcane production in the study area plays a significant role given its substantial contribution towards food security and as a stable source of income. The study results suggest that, unlike commercial sugarcane farmers who have access to and benefit from using climate information (Ziervogel & Calder, 2003), small-scale farmers have limited access to climate information (Table 6.1 and Table 6.4). This can be partly attributed to their low literacy levels. This reasoning is based on the fact that the sugarcane industry is widely known for using climate information for a long time at different levels of the sugarcane value chain from farmers to millers (Johnston, 2008).

The limited access to climate information may emanate from the fact that seasonal climate forecasts are mainly disseminated through an internet website, e-mails and third-party agents. Despite the wide use of smartphones by small-scale farmers, their access to e-mails or internet is still limited. In an attempt to facilitate access and utility of climate forecasts by intended end-users, hard copies have been produced for extension officers for dissemination. Unexpectedly, this study shows that extension officers who primarily disseminate information to small-scale farmers were not the major source of climate information (Table 6.3). The reliance on sources such as television, radio and sugarcane organizations indicate a lack of climate information provision by the extension officers despite the efforts made to improve the access to and use of climate information by a larger group of prospective end-users (Johnston, 2008).

Extension officers have been found to misinterpret the information (Roncoli, 2006). Maponya & Mpandeli (2012) suggest that farmers who receive information about climate change from extension officers are prone to high adverse effects compared to those who received it somewhere else. This emanates from the fact that some extension officers fail to comprehend what climate change entails and hence fail to provide relevant information to farmers. This can partly be attributed to a variety of factors such as: i) some extension officers' qualification is not applicable to render extension services; ii) inadequate relevant training courses to keep extension officers updated (Maponya & Mpandeli, 2012). Patt et al. (2005) found that in South Africa the majority of people tend to misinterpret most of the basic forecast terms. Safdar et al. (2014) also reported that in most cases, extension officers fail to guide farmers on how to cope with climate extremes in order to sustain production during extreme weather/climate situations.

Relatively modest access to early warning indicates that dissemination is primarily restricted to ENSO predictions as most of the early warning recipients received the warning for the first time in 2014/15 (Table 6.4). Although this is useful in ensuring that mitigation measures are in place, it does not promote access to and use of climate information by small-scale farmers. This has been the case since early 2000 as suggested by the Hudson and Vogel (2003) study cited in Johnston (2008). Small-scale farmers receive early warning information when climate hazards are experienced nationally. This, therefore, implies that in addition to low levels of education (lack of knowledge), inadequate sources and channels of information dissemination play a significant role in hampering access to climate information.

Given that extension officers were not the main and reliable sources of climate information, farmers have to personally source out the information. However, the language used on climate forecasts either disseminated through an internet website, e-mails, or third-party agents is also a limiting factor. This was also proved during the interviews as the majority of the participants lacked an understanding of some climate concepts. Participants did not understand what seasonal climate forecasts or early warnings were. Language has been characterized as a serious barrier to knowledge transfer that can cause gaps in the information available in the scientific community (Amano et al., 2016). The inaccessibility of climate information in terms of language has been identified previously. This inaccessibility emanates from the high use of scientific terminology and technical figures when transferring climate information (Jones et al., 2017). This, therefore, implies that prospective end-users' technical capacity should keep up in order to effectively use the available climate information. A similar study conducted in KwaNgwanase in KwaZulu-Natal (Jiyane & Fairer-Wessels, 2012) indicated that climate information is often disseminated through face to face setting or pamphlets. The study also showed that despite having pamphlets in either isiZulu or English or a combination of both English and isiZulu, the majority of community members often fail to effectively use the pamphlets.

The usefulness and benefits of the seasonal forecasts and early warning depends on a series of factors. Accessibility, comprehensibility, punctuality, the lead-time as well as accuracy determines the usefulness of the forecast by the end-user. Surprisingly, a large number of respondents accessing only daily weather forecasts indicated they were satisfied with the information irrespective of its inability to be integrated into seasonal farming-decisions (Table 6.3). This is an indication that farmers make decisions based on weather conditions, that is, a rainfall event at the beginning of the rainfall season is an indication of a good and normal season. They do not factor in the issues of rainfall distribution throughout the season. However, it should be noted that respondents replied based on their capacity; some of them had no knowledge about seasonal climate forecasts while others perceived that daily weather forecast is the sole climate information that can be accessed. Nevertheless, there was a clear indication from those who accessed information that the information was not sufficient to adapt to and minimize the potential adverse impacts of climate change (Table 6.3). The problems that were associated with the information that they received previously are 1) limited ability to cope with extreme weather events due to lack of resources and knowledge 2) failure to understand the information provided in some cases 3) late arrival of the information.

Studies have been conducted to understand the relation between access to climate information and adaptation to climate change. In Burkina Faso, Ingram et al. (2002) indicated that the best climate forecast information provides no assistance to farmers in the presence of physical constraints to take necessary actions. Mahlangu & Lewis (2008) study support this statement as it indicates that small-scale farmers do not prioritize sugarcane production when the financial returns are declining because they engage in sugarcane production as the main livelihood strategy for income generation purposes. So even in the presence of an accurate forecast, making an effort to improve practices is not an option if the returns are declining. A substantial decrease in the profitability of sugarcane farming has been recorded. Between the periods of 2000/01 to 2010/11, the net farm income of the Midlands farmers declined by 26% (BFAP, 2014). Decreasing financial returns as a result of reduced sugarcane quality during dry seasons and other relevant factors mean less money is generated to meet various household needs (Mahlangu & Lewis, 2008).

Climate, particularly rainfall variability (Singels & Bezuidenhout, 1999) has a major influence on sugarcane production. The study herein, therefore, intended to make use of the sugarcane yield data for the past years and climate data to assess the access to and benefits of using climate information on sugarcane production. This would show how accessing the information benefits end-users in cases of both adverse weather and good weather conditions. Frei (2010) indicated that the benefits of accessing climate forecasting are realized when the farmer achieves high profit as a result of improved decision-making based on meteorological and climatic information.

The present study acknowledged other factors involved to achieve greater yields in addition to good weather conditions. Farmers were to provide the yield data along with production costs so as to assess the reason underlying yield increases. However, none of the small-scale farmers had records of either yield or production costs. According to their record techniques, a decrease in yield was determined by reduced financial returns from the mill while others counted the number of truckloads per harvest (data not shown). The sizes of the trucks were also not known by the farmers. The farmers who received climate information, particularly from Canegrower's Association, mentioned that their yield did not decrease as a result of adverse weather conditions as they always ensure that necessary precautions are in place. Also, they had not noticed improved yields as a result of good weather conditions. This analysis, therefore, is restricted to the available information and might be biased as it is based on the observation of respondents (27%) (Table 6.3). This affords an opportunity for future studies exploring the benefits of using climate information from small-scale sugarcane farmers who have records of yields and production costs.

The limitations to quantify the benefits of using climate information, however, is not indicative of fewer benefits from accessing climate information. Similar studies conducted suggest that access to and use of climate forecasts by subsistence farmers has contributed positively. Using the relative harvest index, Patt et al. (2005) assessed the effects of seasonal climate forecasts amongst subsistence farmers in Zimbabwe. Their findings, although with some study limitations, indicated that farmers who use climate information are “better off” compared to not using them. Roncoli et al. (2009) also showed that seasonal climate forecasts played a prominent role in the farmers’ decision making. Through the evaluation of participants’ responses, the use of forecasts proved to be beneficial to the farmers, but farmers indicated they benefited only through cognitive skills rather not tangible benefits.

The results show a willingness to access climate information by small-scale farmers (Table 6.3), however, there is clearly confusion in terms of indicating the information they would like to receive. The chances that farmers mentioned seasonal climate forecasts and an early warning may have been increased by hearing about it during the interviews. In addition to the abovementioned, farmers were also interested in rainfall season forecasts, that is, the start and end of the rainfall season as well as the amount of rainfall during the season. They were more interested in receiving information that would assist in increasing production rather than climate information alone. These findings are aligned with the study by Johston (2008) which indicated that farmers often need information that applies to their specific needs. This would assist in crop selection decision making and advice on the resource that would be needed to enable an appropriate response to the forecast information.

Both seasonal climate forecasts and early warnings are believed to be useful as they assist in farmer’s decision-making. The usefulness of the early warning depends on timeously reaching the targeted end-users. The main focus was on the 2014/15 drought event to understand how small-scale farmers have incorporated the warning into their farming decision and the benefits of it. A relatively small number of respondents who accessed early warning information indicated that they have benefited from it (Table 6.3). Nevertheless, this benefit cannot be quantified given their inability to compare with previous years’ harvest or with the seasonal expected harvests. The benefit was mainly derived from delaying the planting time as it saved the money that would have been lost from sugarcane germination failure or poor sugarcane quality. Those who had crops in their various growth stages opted for changes in the type and amount of fertilizers they used. They indicated that a specific fertilizer is used during dry conditions and they tend to apply more. Others preferred early harvesting. The farmers, however, were not confident about their mitigation strategies implying that they only apply available options and not the best practice to counteract the possible impact. Based on sugarcane physiology some of the measures taken by farmers are not beneficial. For example, Scarpari and Beauclair (2004) reported that an accumulated water deficit greater than 130 mm in the months before harvest is positive for sucrose accumulation in stalks. The implication is that early harvesting due to dry conditions is less beneficial. Also, considering that sugarcane production is the major livelihood of the respondents, delaying planting means longer periods without having an income. Chand et al. (2010) suggested a soaking of setts in saturated lime water as a strategy to deal with dry soils during planting time. Their findings indicated that soaked setts trigger germination and result in an early tillering phase. This implies that short-term dry periods can be overcome using this technique instead of delaying planting. Generally, for the uptake of nutrients by plants, the availability of water is required. In the case of sugarcane, fertilizer can be used to counteract the drought effects on crop growth. The application of potassium has been found to promote sugarcane growth and increase yield during water stress periods. This method, though effective, was found to be more costly by farmers.

Given that the public awareness of climate change has increased, farmers should have a better understanding of what climate change means and the possible impacts of climate change in their production. Modelling studies across the world have reported on how climate is likely to change due to global warming and its potential impacts on sugarcane production (Chandiposha, 2013; Baez-Gonzalez et al., 2018). However, this information rarely reaches small-scale farmers who are generally illiterate (Table 6.1). As a consequence, this study indicates that the majority of the participants (Table 6.5) do not know how climate is likely to be and the potential effects of the projected changes on sugarcane production in the study area. Lack of such information increases the susceptibility of small-scale farmers' productivity to adverse effects of climate change. Continuous productivity under climate change conditions requires adaptation and mitigation strategies to be in place. Yet, small-scale sugarcane farmers have no adaptation measures in place and have no idea on how they can adapt to climate change (Table 6.5).

6.6 Conclusions

The study provided an analysis of access to and use of climate information by sugarcane small-scale farmers in KZN midlands in South Africa. Although previous studies showed a wide use and benefits of using climate information across the sugarcane production chain, the study results indicate that small-scale farmers are not part of climate information users within the industry in South Africa. The findings of the study are similar to that of others that were conducted almost two decades ago. There have been no changes with regards to access to climate information by small-scale farmers in spite of improved technology to model as well as to disseminate the information. In addition, despite the reasons mentioned by farmers for the lack of access and use, small-scale farmers have not captured the substance of climate change impacts both generally and in sugarcane production. This observation is supported by their lack of interest in receiving climate information. This may be attributed to the inadequate training of small-scale farmers in general on the aspects of climate change and its impacts. Hence, a further investigation is needed for more clarity.

As shown in the study, most of the farmers were pensioners who are illiterate. The language used in climate information dissemination is often not understood by the majority of farmers who are not native speakers. Thus, appropriate training on climate information analyses, climate change and variability as well as possible impacts is required. In addition, for sustainable livelihood under climate change conditions, training on record-keeping is also necessary. Farmers do not understand the cause of declining sugarcane profitability. Such training would enable farmers to keep track of sugarcane production in terms of both the cane yield and sucrose yield. Understanding changes in climate and the associated potential effects of sugarcane production can enable farmers to understand the need to utilize climate information. Access to seasonal climate forecasts enables the planning of management strategies and resource allocation to respond to anticipated climate forecasts. These strategies can act as a means of adaptation to climate variability at a seasonal time-scale.

The limitations of the study are acknowledged. The absence of yield and production cost halted the quantification of benefits from using climate information. Also, this study only focused on small-scale sugarcane farmers within KwaZulu-Natal midlands who farm under dryland. Hence, a comprehensive study that will include small-scale farmers who farm under irrigated and dryland, as well as farmers with long-term yield, production costs, and climate information use data is recommended so as to assess the usefulness of climate information by the sugarcane small-scale farming group. This research proves the vulnerability differences across the farming group within the same industry. It could serve as a basis for evidence for the need for the design of appropriate training required to address and prepare for possible future climate change impacts and thus adopt appropriate adaptation and mitigation measures for small-scale farmers within the sugarcane industry.

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6.8 References

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CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.1 Introduction

Small-scale sugarcane farmers are already facing a challenge of a significant decrease in sugarcane production in South Africa due to changes in the dynamics of global trade which resulted from the liberalization of the international trade market (mkhungo et al,.2018). Climate change poses an additional crisis of increased crop uncertainty and poor yields. This exacerbates an already dire situation. However, despite the overall changes of climate across the globe, the limited access to climate information results in the majority of small-scale farmers continuing using the basic agronomic practices with no plans in place to adapt to climate change. Consequently, the observed climate variability accompanied by a lack of adaptation strategies presents a substantial threat to the long-term sustainability of small-scale sugarcane production in South Africa.

In this study, several methods were used to analyze historical and future extreme weather changes, particularly drought in a specific study site in South Africa. Historical climate trends from the Expert Team on Climate Change Detection and Indices analysis give clear insight into how local climate is changing as global warming heightens and whether the regional climate is becoming more or less beneficial for rainfed farming, particularly sugarcane farming. Also, given the reliance of small-scale sugarcane farmers on rainfed farming, it is necessary to study other meteorological factors that may aggravate the impact of climate extreme on sugarcane production. For example, changes in short-grass reference evaporation (ETo) as a result of climate change can significantly alter crop water requirements and hence water resource management. Therefore, small-scale sugarcane farmers need to investigate ways of continuing profitable farming under climate change conditions.

The knowledge of historical weather extreme trends is useful in both managing water resources and enabling prediction of future extreme weather variation. Understanding both historical and future trends enables better preparation for mitigation and adaptation measures to cope with climate change. The use of climate information has been considered as one of the coping strategies when an extreme weather event is anticipated. The last part of the study was conducted to assess whether small-scale farmers have access to and use climate information to deal with weather/climate extremes.

7.2 Revisiting the aims and objectives

The main aim of the study was to assess historical and future extreme weather changes, particularly drought, in the Wartburg area of KwaZulu-Natal midlands. The study intended to use data from weather stations that have never been included in South African climate change and climate extreme study analyse. The specific objectives were to:

- analyze the historical trends of air temperature and precipitation extremes in the midlands of KwaZulu-Natal;
- investigate the effects of dry conditions on ETo trends. This was achieved through the use of drought indices (SPI and SPEI) to detect dry years and the Penman-Montieth method to compute ETo;
- model the possible future changes in the KZN midlands drought characteristics. This was conducted by employing HadCM3 and CanESM2 to simulate future changes in KZN drought using statistical downscaling model and drought characteristics using Run's theory. Possible changes in drought characteristics based on future drought events were investigated using the SPEI and SPI;
- characterize the benefits of accessing climate information by small-scale sugarcane farmers to mitigate the prospective impacts of adverse weather through the use of questionnaires to gather information on whether farmers do access the information or not.

7.3 Study findings

The study findings reveal that throughout 1966-1994 and 1997-2017, maximum air temperature (TXx) has been increasing. Surprisingly, minimum air temperature results indicated a downward trend suggesting that the number of cold days (TN90) and cold nights (TN10) have been increasing over the study period for the area under study. Extreme rainfall events have been increasing resulting in an upward trend of annual rainfall total. Days with high rainfall amounts (R10mm and R20mm) appear to have been increasing significantly causing a decrease in the amount of rainfall received over consecutive days as displayed by a decrease in consecutive wet days.

Both regression and the Mann-Kendall method consistently showed a decreasing ETo trend for the study site. Despite the increase in extreme air temperature, there has been a general decreasing ETo trend in the study area over 1966-1994 and 1997-2017. A decrease ranging between 0.18 to 5.13 mm a^{-1} was observed across the weather stations. The findings showed that, for the study site, a statistically significant decrease in solar irradiance and an insignificant increase in relative humidity (data not shown) have proved to greatly influence ETo patterns. The ETo results affirm a statistically significant negative correlation with precipitation as confirmed by the Pearson correlation coefficient.

The projected changes in air temperature and precipitation using the Statistical Downscaling Method showed that air temperature will continue to increase until the end of the 21^{st} century. Based on RCP8.5 an increase of up to 3.5 ºC and 3.7 ºC for maximum and minimum air temperature respectively, is projected for the study area. These increases are more pronounced from the 2050s. However, SPI and SPEI results detected common plausible future drought events in 2029, 2038, 2043 and 2047 but at different time scales. According to Run's theory, the drought events projected are expected to be less intense but severe. This implies that the accumulation of months with an index value less than -1 are likely to increase but the magnitude of the accumulated index is less likely to reach a point of extreme drought (an index of -2 and below). This, therefore, indicates that the study area may expect the prevalence of mild and moderate drought events over the next two decades.

Virtually all farmers who participated in the questionnaire study had no access to any kind of seasonal climate information. Most of the participants relied on the daily and weekly weather forecast to plan their daily activities and have never used seasonal climate information to make informed decisions. Although some participants indicated that they accessed and have used climate information, particularly early warning, they have not benefited from using it because of the ill-timed arrival of the information and lack of information on how to counteract the impact of adverse weather.

7.4 Contributions to new knowledge

The research undertaken highlights the fact that there is a dearth of studies focusing on local level small-scale farmers. The nature of the study was different from previous studies as it mainly focused on analysing climate variations of a local sugarcane production site to understand climate variation as a result of climate change and adaptation measures in place for sugarcane production. The study findings suggest that the study site might be experiencing different climate trends compared to the nearby station that has been widely used in most national studies. The results of this study raise the question of microclimate effects on local climate change trends. Thus, a better understanding of local climate variations is important as it would enable farmers, particularly small-scale, to adjust farming decisions to existing and expected changes, thus reducing production risks. Specifically, the study, therefore, contributes to the existing knowledge through:

i. emphasizing that even though climate trends indicate a relatively similar trend to the previously reported studies, the historical climate trends for the study area do not always correspond to the nearby stations. This study, therefore, concludes that based on the findings of changes in minimum air temperature for the study sites, studies at a low-resolution scale partly conceal actual trends at the local level;

ii. discovering that despite global warming, ETo trends indicate a declining trend and concluding that air temperature does not contribute much to the ETo trend in the study site. Also, the study confirmed that the downward ETo trend was a result of decreased solar radiation and increased relative humidity;

iii. evaluation of SDSM applicability to model future changes in air temperature and precipitation for a single site in KZN midlands. The study findings demonstrated that SDSM can be applied to simulate future changes in air temperature while simulating precipitation proved to be challenging as the two models employed disagreed on the future precipitation trend for the study site;

iv. discovering that the majority of sugarcane small-scale farmers in the study are less informed and still need to be trained about climate change and its possible impacts on both human nature and sugarcane production. The findings of the study echoed that despite increased innovation in weather and climate forecasting as well as dissemination of climate information, small-scale sugarcane farmers in the study area still have no access to it and have not used the information to reduce the impact of adverse climate.

7.5 Challenges, limitations, and recommendations

7.5.1 Challenges and limitations

A key limitation and greatest challenge, as this is the case in many studies, was the absence of long-term quality data for the study site given that most AWS systems were installed in the late 1990s to replace the manual weather stations (Chapters 3 and 4).

Due to the use of relatively short-term data climatologically, this may have a negative impact on the outcome of this research. The absence of the required long-term data restricted the use of different meteorological stations for the study area for projecting plausible future trends of air temperature and precipitation for the projection of the likelihood of drought occurrence (Chapter 5).

Data collection through questionnaires (Chapter 6) presented challenges because the majority of participants could not understand the content of the questionnaire, although it was translated to isiZulu. To circumvent the challenge, data had to be collected through one-on-one interviews which were time-consuming. Unfortunately, all the participants included in the study could not provide the necessary information regarding their yield and production costs during dry years. This led to a shift in emphasis of the study to an analysis of their benefit from using climate information. Also, this study has focused on small-scale sugarcane farmers in the KZN midlands and mostly those that relied on farming as the main livelihood due to the fact that literature on access to and use of climate information by small-scale sugarcane farmers has been scant. The timing of data collection which was mainly during weekdays automatically excluded those that are at work during the week.

7.5.2 Recommendations

Based on the study results, a significant increase in extreme climate events, particularly droughts and extreme rainfall poses a serious threat to small-scale sugarcane farmers. To reduce the vulnerability of the agricultural communities to extreme climate events, region-specific adaptation strategies should be developed based on the understanding of local climate change. The study recommends that key policymakers consider locally based studies as they assist in identifying areas that are subject to extreme and rapid shifts in climate as well as determine which areas are more vulnerable based on agricultural production aspects of the area.

The indisputable change in air temperature patterns necessitates the need for clear and relatively precise weather and seasonal climate forecasting skills and effective reporting to ensure that those that are deemed vulnerable to climate extremes receive the relevant information timeously. Therefore, the research recommends that extension officers should be trained in climate change, adaptation and mitigation and communication strategies. Public awareness of climate change, the possible consequences, and adaptation strategies are recommended for rural agricultural communities in South Africa.

Also, farming communities need more training on how to access and use seasonal climate information and early warnings. This would assist in minimizing their susceptibility to adverse impacts of extreme weather and/or climate not only in terms of minimizing production losses but also through reducing infrastructure damages and loss of lives.

7.6 Future possibilities

The research described in this thesis intentionally focused on small-scale sugarcane farmers from a specific study site that has been excluded in previous studies. Future research should be extended to other sugarcane growing areas in the southern Africa region. Such a study would givea clear insight into the vulnerability of small-scale sugarcane production to climate vagaries. Currently, small-scale farmers contribute about 10 % to the total annual sugarcane production with the potential to decrease in the future due to a significant decrease in the number of small-scale sugarcane farmers.

The study results suggest an increased rainfall extreme trend over the past decades. Further studies on how such changes have affected sugarcane production in the study area, and other areas, would be insightful. Despite the global warming trend, the study suggests an increase in the number of cold days and nights. It would be informative to undertake a study that would mainly focus on all the meteorological stations that showed similar trends across the country. This would provide insight into the possible causes of a decreasing air temperature trend.

This study analyzed historical and possible climate trends and not the relationship between climate trends and sugarcane production due to the absence of small-scale production data. While most studies conducted predict an increase in sugarcane production under climate change conditions due to increased carbon dioxide concentration in the atmosphere, changes in the frequency of extreme events such as drought, flood and heat stress which would possibly adversely impact on sugarcane production, have not been sufficiently explored across the province. Future research on the relationship between the changes in the frequency and intensity of climate extremes and sugarcane production across the sugarbelt areas in the province would be insightful.

The study also noted that extension services were not the main source of climate information for farmers. Investigating the efforts made by the government to ensure that extension officers are receiving the relevant training in climate change, acquiring and properly delivering and communicating climate information to prospective end-users would be useful. Also, it is important to consider that more education on how to access and properly interpret data is needed for prospective end-users in order to be able to incorporate climate information into their decision-making.

7.7 Final comments and summary conclusions

Generally, the findings of the study highlight the importance of local studies in determining climate variation as global warming progresses. The results of the study conclude that:

- based on the findings of the air temperature trend, particularly daily minimum air temperature, changes in local climate should not be generalized based on the results from the weather station in close proximity;
- despite the increasing daytime air temperatures, the ETo trend continues to decline due to reduced solar irradiance reaching the surface and increased relative humidity as suggested by the Clausius-Clapeyron relationship;
- Statistical Downscaling Model has proved its applicability for projecting air temperature and rainfall for the study area in the KwaZulu-Natal midlands of South Africa. However, it has shown relatively poor performance in precipitation projection. Based on the projected rainfall and air temperature, the study area is expected to experience droughts in the near future;
- virtually all of the small-scale sugarcane farmers who participated in the study have not accessed or used climate information to mitigate adverse weather impacts on sugarcane production. These farmers also do not know the possible effects of climate change on the frequency and intensity of extreme weather as well as the potential impacts of such

changes in sugarcane production. There are no adaptation measures in place and the small-scale farmers have no plans to adapt to climate change.

APPENDIX A: QUESTIONNAIRE FOR DATA COLLECTION

Uyacelwa ukuba uphendule imibuzo ngokuthi ufake uphawu [√] ebhokisini elifanele uphinde ubhale endaweni oyinikeziwe.

A. Imininingwane

[Khetha ibhokosi elifanele]

1. Ubulili ....
2. Iminyaka yakho ....
3. Izinga lemfundo:

   Ibanga aphansi ☐ Ibanga eliphezulu ☐ Iziqu ze-Bachelors ☐ Iziqu ze-Honours ☐ Iziqu ze-Masters ☐ Iziqu zobuDokotela ☐ Okuhlukile ☐ Sicela uchaze ngako

4. Usuneminyaka emingaki kwezolimo ?

   ....

5. Useniminyaka emingaki ulima umoba?

   ....

6. Uwulima into engakanani?

   Ulima into eningi ☐ Ulima into encane ☐

A. Imibuzo

7. Lingakanani ipulazi lakho ngokwama-*hecture*? .... ha
8. Ingakanani indawo otshala kuyo umoba ngokwama-*hecture?*..................................ha
9. Eminyakeni emihlanu esidlulile, lungakanani ushitsho oselwenzekile endaweni otshala kuyo umoba ?

   Lwehlile ☐ Lwenyukile ☐

10. Yiziphi izinto ezidala lolu shintsho?

   ....
   ....
   ……………………………………………………………………………………………

11. Uyawuchelela umoba wakho?

    Yebo ☐ Cha ☐ Uma uthe yebo,uchelela ngento ebalelwa kwangaki amaphesenti …..............................

12. Ngabe uyalugcina ulwazi lwamazinga emvula nokushisa? Uma uthe yebo, ulugcina isikhathi esingakanani?

    Yebo ☐ No ☐ Uma uthe yebo, Iminyaka emingaki ....

13. Ngabe ukushintshashintsha kwesimo sezulu sinawo umthelela kokwenzeka epulazini lakho?

    Yebo ☐ Cha ☐

14. Bala izinto eziyingozi mayelana nokushintsha kwesimo sezulu eziphazamisa imikhiqizo yakho noma ukutshala. Zibale ngokulandelana.

    1. ....
    2. ....
    3. ....

B. Ukuthola ulwazi ngesimo sezulu

15. Uyakwazi ukuthola ulwazi ngezexwayiso noma ukubikezela kwesimo sezulu kanye nangokushintshashintsha kwaso?

    Yebo ☐ Cha ☐

16. Unesikhathi esingakanani uthola lolu lwazi?

    Ulwazi ngokushintsha kwesimo sezulu .... years
    Ukubikezela kwezinkathi zonyaka zesimo sezulu .... years
    Izimpawu noma izexwayiso zesimo sezulu .... years

17. Hlobo luni lolwazi lwesimo sezulu okwazi ukulithola?

    a. ....
    b. ....
    c. ....
    d. ....
    e. ....

18. Useke wahlangabezana nezinkinga ngokuqondana kolwazi lwesimo sezulu olubale ngenhla? Uma uthi yebo,iziphi lezo zinkinga?

Yebo ☐ Cha ☐

Izinkinga ....

....

....

19. Useke wahlangabezana nenkinga ngokufika ngesikhathi esifanele kwalolu lwazi olubalile? Uma uthi yebo, chaza/cacisa.

Yebo ☐ Cha ☐

Chaza/Cacisa

………..

....

....

20. Ngabe lolu lwazi ulibona lusezingeni elifanele? Nika izizathu zempendulo yakho.

Yebo ☐ Cha ☐

Izizathu

....
....
....
....
....

21. Bala ukuthi ulwazi uluthola kuphi noma kanjani. Nikeza nezizathu ezikwenza ukhethe leyomithombo yolwazi.

Imithombo yolwazi	**Isizathu sokuwukhetha**
1.	
2.	
3.	

4.	
5.	

22. Iziphi izinto noma izinqumo ozithathayo ezidalwa ulwazi olutholayo mayelana nesimo sezulu?

....
....
....
....
....
....

23. Kuyo yonke le minyaka uhlola noma uthola ulwazi ngesimo sezulu, ngabe kukhona yini okukusize ngakho ukuba nalolu lwazi? Chaza.

Yebo ☐ Cha ☐

....
....
....
....
....
....

C. Iqhaza lolwazi ngesimo sezulu ekunciphiseni ezinye izinkinga ezingadalwa isimo sezulu esidala umonakalo (izimvula ezinamandla, ukushisa kakhulu, umoya onamandla kanye nesomiso).

24. Iluphi ushintsho lwesimo sezulu osuke walibona kule minyaka eyishumi eyedlulile?

....
....
....
....
....

25. Ngabe izimpawu noma izexwayiso ngesimo sezulu ziyaba khona ngaphambi kokuthi kwenzeke izehlakalo noma izimo ozibalile?

Yebo ☐ Cha ☐

Uma uthe yebo, ngabe zaba wusizo? Chaza.
....
....
....
....
....

Uma uthe cha, ucabanga ukuthi zingaba usizo? Chaza.

....
....
....
....

26. Ukushintshashintsha kwesimo sezulu okubalile ngasenhla kube nomthelela ongakanani noma kube nezinga elingakanani kwimikhiqizo yakho?

Linyukile ☐ Lehlile ☐ Liyafana/Alikho ☐

Cela ugcwalise loku okungezansi:

Iminyaka	**Imikhiqizo elindelekile ngokwamathani(tons)**	**Imikhiqizo evelile ngokwamathani (tons)**
2005/6		
2006/7		
2007/8		
2008/9		
2009/10		
2010/11		
2011/12		
2012/13		
2013/14		
2014/15		
2015/16		

27. Ucabanga ukuthi umthelela wokushintshashintsha kwesimo sezulu kube nomthelela ongakanani kuloku okuvelile noma okukhiqizile?

Mkhulu ☐ Mncane ☐ Awukho umthelela ☐

28. Lolu shintsho lunamuphi umthelela kwimikhiqizo yakho ngokwentengo yezezimali? Cela ugcwalise ngezansi:

Iminyaka	Imikhiqizo elindelekile inani lemali/ngokwama-hectare (ha)	Imikhiqizo evelile ngokwenani

		lemali/ngokwama-hectare (ha)
2005/6		
2006/7		
2007/8		
2008/9		
2009/10		
2010/11		
2011/12		
2012/13		
2013/14		
2014/15		
2015/16		

29. Uluphi ushintsho olwaba /olwalungaba khona uma wenza izinto noma uthatha izinqumo ezithile ngokutshala ukube izexwayiso zesimo sezulu zaba khona ngonyaka ka-2014/15 lapho kwakunesomiso khona?

....
....
....
....
....

30. Ngabe lolu shintsho lwaba/lwaluzoba nongakanani umthelela kwimikhiqizo yakho?

Omkhulu ☐ Omncane ☐ Akwenzekanga lutho ☐

31. Ngabe imikhiqizo yakho ibizoba namuphi umehluko ukube ubungenalo ulwazi mayelana nezimo zokushintshashintsha kwesimo sezulu samanje?

....
....
....
....

32. Iziphi izinto ezithikameza/ezivimba ukusebenzisa noma ukuthola ulwazi mayelana nesimo sezulu kanye nokushintsha kwesimo sezulu?

....

....

....

....

....

33. Iziphi izinto/amathuluzi owasebenzisayo ukunciphisa imithelela noma imiphumela engemihle ngenxa yesimo sezulu esidala umonakalo?

....

....

....

D. Ukushintsha kwesimo sezulu kanye nesimo sezulu esidala umonakalo

34. Ngabe uyazi ngesimo sezulu esidala umonakalo esingase sibe khona esikhathini esizayo?

    Yebo ☐ Cha ☐

35. Uyazi ngomthelela wokushintsha kwesimo sezulu ongase uphazamise/uthikameze imikhiqizo yakho?

    Yebo ☐ Cha ☐

    Uma uthe yebo, ngabe unawo amacebo okuthi ungahlanganisa kanjani izinto ezingaba nomthela esikhathini esizayo kwizindlela zakho zokulawula isimo sezulu esingekho sihle?

    Yebo ☐ Cha ☐

    Uma uthe yebo, chaza.
    ....
    ....
    ....
    ....
    ....

36. Ngabe ulwazi ngesimo sezulu onayo yanele yini ukunciphisa umthelela omubi kwimikhiqizo yakho?

    Yebo ☐ Cha ☐ Angilusebenzisanga lolo lwazi ☐

    Uma uthe cha, iluphi ulwazi olwengeziwe ongathanda ukulithola mayelana nesimo sezulu?

....
....
....
....

37. Ngabe lolu lwazi luzokusiza ngani?

....
....
....

38. Uma lolu lwazi kungathiwa luyadayisa, ungalukhokhela?

Yebo ☐ Cha ☐

39. Uma uthe yebo, ungalikhokhela malini ngokwakh? R.........................../ngenyanga

40. Iziphi izincomo onazo ngolwazi olunikeziwe mayelana nesimo sezulu kanye nokubikezela kwaso?

....
....
....
....

41. Izphawulo onazo ngokuthola ulwazi ngezexwayiso zesimo sezulu kanye nokunye okuthinta sona isimo sezulu.

....
....
....
....
....

Ngiyabonga kakhulu ngokuthi ube yingxenye yalolu cwanigo. Uma ungathanda ukwazi ngemiphumela yalolu cwaningo, ngicela ungithinte kuleli kheli ncoyiniz@ukzn.ac.za

APPENDIX B: COVER LETTER

Mrs. Zoleka Ncoyini
Agrometeorology Discipline
Room 107 Rabie Saunders Building
University of KwaZulu-Natal
P/Bag X01
Scottsville
3209

Mnu/Nks/Nkk

Igama lami nginguZoleka Ncoyini, ngifundela iziqu zobuDokotela (PhD) kwi-Agrometeorology eNyuvesi yaKwaZulu Natal. I-Agrometeorology izifundo ezimayelana nesimo sezulu, ukushitsha kwaso kanye nokusebenzisa ulwazi olumayelana naso isimo sezulu ukukhuthaza noma ukulekela imikhiqizo kwezolimo. Ngenza ucwaningo ngokushitshashitsha nokubikezela kwesimo sezulu kanye nomthelela waso kwezomnotho. Isihloko salolu cwaningo sithi *'Observed and projected climate change effects on localized drought events: A case study for sugarbelt within Kwazulu-Natal midlands, South Africa'*. Lolu cwaningo luzogxila kubalimi bomoba ngoba ngokwemibhalo kuvela ukuthi abalimi bomoba ibona aseke babakwazi ukuthola noma ukubona izexwayiso okanye ukubikezela kwesimo sezulu ngezinkathi zonyaka (seasonal climate forecast) eminyakeni eminingi.

Lolu cwaningo luhlose ukubheka ukuthi balimi bakwazi kanjani ukuthola ulwazi ngokushintshashintsha kwesimo sezulu okungaba ukushisa kakhulu noma isomiso esikhulu. Umcwaningi uzobheka ukuthi abalimi balahlekelwa inzuzo engakanani ngokwazi mayelana nesixwayiso, ukubikezela kwesimo sezulu.

Kunemibuzo umcwaningi azoyibuza abalimi ngenhloso yokuqoqa ulwazi. Izinhloso zalolu cwaningo:

- Ukubheka ukuthi abalimi bomoba iyiphi inzuzo esebeyizuzile ngokwazi ukubheka isimo kanye noshintsho lwesimo sezulu eminyakeni eyedlule ikakhulukazi inzuzo abayenza kule minyaka kade kunesimo sezulu esingesihle (ukushisa kakhulu, izimvula ezinamandla,umoya omkhulu kanye nesomiso).

- Ukubheka ukuthi abalimi bomoba bahlola noma baluthola kanjani ulwazi ngesimo sezulu kanye nokuthi ngabe lolo lwazi lunawo yini umthelela kwizinqumo abazithathayo.
- Ukubheka indima edlalwa ukukwazi ukubona ukubikezela kanye nezexwayiso zesimo sezulu ngokwezinkathi zonyaka ekunciphiseni izimo zezulu ezidala umonkalo embonini yezomoba.

Njengomlimi womoba KwaZulu Natali Midlands, ngiyakholwa ukuthi useke wahlangabezana nezimo zezulu ezidala umonakalo ekutshaleni nasekukhiqizeni umoba nokungenzeka ukuthi ubukwazi ukuyibona ingozi noma kube nezixwayiso ezithile ngesimo sezulu. Ngicela ukuthi ube yingxenye yalolu cwaningo ngokuthi ugcwalise noma uphendule imibuzo ebhaliwe ngemuva. Ukubamba iqhaza kulolu cwaningo kuzothatha imizuzu engamashumi amathathu esikhathi sakho.

Okunye okuyinhloso yalolu cwaningo ukuthola ulwazi ngezimo zesimo sezulu esidala umonakalo esingalindeleka ngomuso noma esikhathini esizayo uma kusetshenziswa izindlela zesimanje zokutshala embonini yezomoba. Ukuba kwakho yingxenye yalolu cwaningo kuzosiza nokunikeza ulwazi olufanele kuzosiza ekubambeni iqhaza kwizinqumo ezithathayo kwezokukhiqiza umoba. Kulabo abangenalo ulwazi ngokuhlola, ukubheka noma ukubona izexwayiso kanye nokubikezela kwesimo sezulu bangasizakala ngemiphumela yalolu cwaningo ukuze nabo babe nolwazi bakwazi futhi ukuhlola noma ukubheka isimo sezulu.

Ngicela ukukwazisa ukuthi ukuba kwakho yingxenye yalolu cwaningo kumahhala ayikho inkokhelo ozoyithola. Uvumelekile ukuhoxa ekubeni yingxenye yalolu cwaningo noma inini uma udinga ukuhoxa. Abukho ubungozi noma okungase kubeke impilo yakho engcupheni uma ubamba iqhaza kulolu cwaningo. Ngicela ungalibhali igama lakho kanye neminye imininingwane eveza ubuwena lapho ozobe uphendula khona imibuzo. Ngicela imibuzo uyiphendule ngesineke nangokwethembeka.

Ngiyabonga ngokuthatha isikhathi sakho ungisiza ukwenza noma ukuqhuba lolu cwaningo oluhlose ukufeza izifundo zami. Ngicela uma usuqedile ukuphendula imibuzo nokugcwalisa ezindaweni ezifanele ungibuyisele kuleli kheli elibhaliwe ngezansi. Ulwazi oluqoqiwe luzoba ulwazi oluzosiza kakhulu mayelana nesimo sezulu esidala umonakalo ophazamisa ukutshalwa nokukhiqizwa komoba. Lolu lwazi lungaphinde futhi lusetshenziswe emizamweni yokunciphisa isimo sezulu esidala umonakalo kwezolimo KwaZulu Natali.

Uma unemibuzo noma okukukhathazayo ngalolu cwaningo ungathinta uZoleka Nconyini kuleli kheli nconyiniz@ukzn.ac.za, inombolo ithi (033-260-6395). Ungathinta futhi umeluleki wami uSolwazi Savage savage@ukzn.ac.za noma kule nombolo (033-260-5514). Noma futhi ungathinta uDkt Clulowa clulolwa@ukzn.ac.za ,inombolo (033-260-5510).

Ngiyabonga kakhulu ukubamba kwakho iqhaza.

Ozithobayo

…………………… …..............

Zoleka Ncoyini
School of Agriculture, Earth, and Environmental Sciences
Discipline of Agrometeorology
Room 107 Rabie Saunders Building
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P/Bag X01
Scottsville
3209

APPENDIX C: DECLARATION OF CONSENT

PROJECT TITLE: OBSERVED AND PROJECTED CLIMATE CHANGE EFFECTS ON LOCALIZED DROUGHT EVENTS: THE CASE STUDY OF SUGARCANE BELTS IN KWAZULU-NATAL MIDLANDS, SOUTH AFRICA

RESEARCHER	**SUPERVISOR**
Full Name: Zoleka Ncoyini	Full Name: Michael John Savage
School: Agriculture, Earth and Environmental Sciences	School: Agriculture, Earth and Environmental Sciences
College: Agriculture, Engineering, and Science	College: Agriculture, Engineering and Science
Campus: Pietermaritzburg	Campus: Pietermaritzburg
(Agriculture campus)	(Agriculture campus)
Proposed Qualification: PhD	Contact details: 0332605514
Contact: 0727071261/0332606395	Email: savage@ukzn.ac.za

Email: ncoyiniz@ukzn.ac.za / zncoin@gmail.com

HSSREC RESEARCH OFFICE

Zoleka Ncoyini

Agrometeorology Discipline

Room 107 Rabie Saunders Building

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Scottsville

3209

I, Zoleka Ncoyini (student number, 216075527), a PhD candidate in Science in Agrometeorology, at the University of KwaZulu Natal invite you to participate in a research project entitled: "OBSERVED AND PROJECTED CLIMATE CHANGE EFFECTS ON LOCALIZED DROUGHT EVENTS: THE CASE STUDY OF SUGARCANE BELTS IN KWAZULU-NATAL MIDLANDS, SOUTH AFRICA". The main aim of the study is to assess the possible effects of the adverse weather on the South African economy due to the impacts in the agricultural and environmental sectors.

Your participation will greatly assist in providing useful information regarding impacts of adverse weather on sugarcane farming as well as adaptation to and mitigation of adverse weather effects by sugarcane farmers in the Midlands of KwaZulu-Natal. By signing, you indicate that you understand the contents of this letter and you are willing to participate in the study.

Declaration of Consent: Quantifying the benefits of accessing weather forecasts and early warnings

I………………………………………………………………………………………………….
……(full names of participant) hereby confirm that I understand the contents of this document and the nature of the research project, and I consent to participating in the research project.

I understand that I am at liberty to withdraw from the project at any time, should I so desire.

SIGNATURE OF PARTICIPANT____________________

DATE___________________

APPENDIX D: ETHICAL CLEARANCE

UNIVERSITY OF KWAZULU-NATAL™
INYUVESI YAKWAZULU-NATALI

6 March 2018

Mrs Zoleka Ncoyini 216075527
School of Agricultural, Earth and Enviromental Sciences
Pietermaritzburg Campus

Dear Mrs Ncoyini

Protocol reference number: HSS/1173/017D
Project title: Quantification of the economic benefits that access to weather forecasting and early warning information provides to sugarcane farmers: A case study in near Wartburg, KwaZulu-Natal

Full Approval – Expedited Application

In response to your application received 21 July 2017, the Humanities & Social Sciences Research Ethics Committee has considered the abovementioned application and the protocol has been granted **FULL APPROVAL**.

Any alteration/s to the approved research protocol i.e. Questionnaire/Interview Schedule, Informed Consent Form, Title of the Project, Location of the Study, Research Approach and Methods must be reviewed and approved through the amendment /modification prior to its implementation. In case you have further queries, please quote the above reference number.

PLEASE NOTE: Research data should be securely stored in the discipline/department for a period of 5 years.

The ethical clearance certificate is only valid for a period of 3 years from the date of issue. Thereafter Recertification must be applied for on an annual basis.

I take this opportunity of wishing you everything of the best with your study.

Yours faithfully

[redacted]

Professor Shenuka Singh (Chair)
Humanities & Social Sciences Research Ethics Committee

/pm

cc Supervisor: Prof MJ Savage & Dr AD Clulow
cc Academic Leader Research: Professor Onisimo Mutanga
cc. School Administrator: Ms Marsha Manjoo

Humanities & Social Sciences Research Ethics Committee
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Website: www.ukzn.ac.za

1910 - 2010
100 YEARS OF ACADEMIC EXCELLENCE

Founding Campuses: Edgewood Howard College Medical School Pietermaritzburg Westville