Historical and future changes in climate records and extremes in South Africa

by

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A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy (Geography)

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15 February 2024

Declaration

I declare that this thesis, which I submit for the degree PhD in Geography at the University of Pretoria, is my original work unless explicitly acknowledged by citation of published sources. Furthermore, I would like to recognise that Chapters 2 to 4 have been co-authored with my promotor and supervisor, with Ms Johnston having assisted with Chapter 4 by writing the software to do the bias correction of the model data but the analysis, write-up of the articles as well as all graphics were completed by myself. It has never been submitted for any degree or examination purposes at any other institution.

Charlotte May McBride (20311062)

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DATE:……15/02/2024……………………………

Acknowledgements

I want to thank:

- The Lord for His sustaining strength.
- My Mom and Dad for all their sacrifices to enable me to be where I am today.
- My husband, for his constant support, advice, and love.
- My family and friends for their continued prayers, love and support.
- Dr. Andries Kruger for all the numerous meetings, sound advice and proofreading.
- Prof. Liesl Dyson for our coffee meetings, guidance, and proofreading.
- University of Pretoria for the study bursary.
- The South African Weather Service for supporting my studies.

"They will be like a tree planted by the water that sends out its roots by the stream. It does not fear when heat comes; its leaves are always green. It has no worries in a year of drought and never fails to bear fruit." Jeremiah 17:8

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List of acronyms

AR5	Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
AR6	Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
CMIP	Coupled Model Intercomparison Project
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CORDEX	Coordinated Regional Climate Downscaling Experiment
DEA	Department of Environmental Affairs
IPCC	United Nations Intergovernmental Panel on Climate Change
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
mm	Millimetres
NGOs	Non-Government Organizations
POT	Peak-Over-Threshold
RCP	Representative Concentration Pathways
RCP4.5	Scenario that stabilises radiation forcing at $4.5Wm^{-2}$ in the year 2100 without exceeding that value
RCP8.5	Scenario that has radiation forcing at 8.5Wm-2 by 2100, with emissions continuing to rise throughout the twenty-first century
RPs	Return Periods
RPVs	Return Period Values
SAWS	South African Weather Service
WCRP	World Climate Research Program
WMO	World Meteorological Organization

Contents

Abstract

Extreme climate events, by definition, are rare. However, due to climate change, the frequency and intensity of these events are changing, with many regions across the globe experiencing an increase in the occurrence of these. It is unequivocal that these types of events are expected to continue to increase into the future. Their impacts are expected to affect societies differently depending on various social-economic, political, and environmental factors. However, no matter where a particular society finds itself, there will be a need to respond to these changes to lessen the negative impacts of these types of events. With scientific knowledge about how our climate is changing, formulating mitigation and adaptive interventions becomes more accessible, especially if that knowledge is at a national or local level. *Accordingly, the main objective of this research is to determine the historical and projected changes in the likelihood of occurrence of climate records and extremes over South Africa and the possible consequences of these changes on relevant socio-economic sectors.* The research focused on using statistical methods to understand the changing landscape of probabilities of weather and climate extremes. Therefore, the magnitude of the values to be investigated was on the scale of record-breaking observations and extreme values associated with multiple-year return periods. The warming trend at individual stations, specifically the positive (right) tails of the distributions, was considered in the study. Consequently, extreme value theory was applied to study temperature and precipitation extremes changes. Various statistical approaches were pursued depending on the nature of the variable under consideration. For example, the Peak-Over-Threshold (POT) method was applied in the precipitation study because extreme can occur multiple times in wet years and not in dry years, and thus, using threshold values rather than the highest annual value becomes applicable. Threshold and critical values were also considered in the projections of temperature extremes and daily rainfall extremes to analyse changes in the distribution of these values. Considering that the research focuses on both changes from a historical and future perspective, both observational data and model projections were analysed, focusing on daily temperature and precipitation extremes. Key findings of the study were an increase in the expected number of record-breaking daily maxima of maximum and minimum temperatures compared to a stationary climate. For example: On average, the highest maximum to lowest minimum records ratio was 1:1 in 1951, increasing to 9:1 in 2019. In addition, different spatial patterns in terms of breaking daily high temperature records were observed, with stations

in the interior of South Africa presently experiencing the highest probability of breaking daily maximum temperature records. For daily highest minimum temperature records, the present probabilities are less defined on a regional basis. In contrast, the number of daily lowest maximum and minimum temperature records decreased below the expected in a stationary climate, so much so that in some locations, no records were broken in the last decade. The average warming trend was able to predict the occurrence of records to an extent. When considering the projected occurrence of high-temperature extremes into the far future (2036-2095), it was found that most stations showed a decrease in return periods and, therefore, a consequent increase in return period values (RPVs). The most significant changes were expected to occur under the RCP8.5 scenario compared to RCP4.5, with these changes most evident at the end of the century. Even after bias correction, the models underestimated the extent of the warming in the right tails of the temperature distributions, and thus, the projected changes found in the study are seen as a conservative estimation of potential changes in extreme temperatures in the future. In terms of daily rainfall extremes across South Africa, this study found that most stations experienced an increase in the probability of receiving more than 50mm per day, considered to be significant, over the last century. The same applies to values greater than 75mm, i.e. heavy rainfall, and 115mm, defined as very heavy rainfall. Maximum values expected for relevant return periods have also increased. In summary, the research quantitatively confirms the widely held expectation that under an anthropogenically caused non-stationary climate, the probabilities of climate extremes are changing towards a situation of higher-than-expected probabilities of records and extremes, specifically with regards to daily values of temperature and rainfall. *Therefore, the research contributes to the quantification of the changing probabilities in records and extremes and, if used, may contribute to the development of climate change-relevant adaptation measures in climate-sensitive sectors, e.g. agriculture, health, disaster management and the insurance and building industries*. In addition, the estimations of changes in extreme events can assist in the spatial allocation of resources to mitigate specific weather and climate hazards.

Chapter 1: General Introduction

1.1. Background

Global warming and associated climate change have had significant local effects in many regions of the world (Goodess, 2013). It is unequivocal that human influences have led to increased atmospheric greenhouse gas concentrations, which in turn has warmed the atmosphere, ocean and land (IPCC, 2021). The warming atmosphere has brought about observable changes in the mean state of climate parameters, such as temperature and precipitation (Al-Ghussain, 2019), and therefore, it can be accepted that the current climate is in a non-stationary state.

According to the Intergovernmental Panel on Climate Change (IPPC) Assessment Report Six (AR6) Working Group 1 (WG1), the world was 1.1°C warmer in the period 2011-2020 compared to pre-industrial temperatures. For Southern Africa, the rate of warming in recent decades is about twice that of the global average (Engelbrecht *et al.*, 2015) and is projected in the AR6 report to warm by 2.0°C to 2.5°C by 2041-2060, relative to 1850-1900, under the intermediate emissions scenario. The AR6 also states that Southern Africa is a region of the world that shows significant increases in mean air temperature, extreme hot events, and agricultural and ecological droughts. The report also states that in the future, the sub-Saharan region will likely experience a general decrease in precipitation but an increase in floods and heavy precipitation events.

In a warming world, it follows that warm or hot surface temperature extremes should become more frequent, while cool or cold extremes should become less so. There is already evidence of this across South Africa (New *et al.*, 2006; Kruger and Sekele, 2013). Due to their high impact, extreme events have been a feature in the assessment of any changes in the climate (Trewin and Vermont, 2010). As an important example, global warming is the main driving force for daily maximum temperatures to keep breaking previous records above the expected frequencies at which records have been broken historically. These hot temperature records have increased worldwide since the 1960s, with interdecadal climate variabilities and El Niño events also contributing to enhancing the occurrences thereof during favourable conditions for high temperatures (Su *et al.*, 2017). Coumou *et al.* (2013) showed that new warm monthly temperature records have increased due to climate change over the 1880-2010 period, five-fold worldwide relative to the expected number of records in a stationary climate.

Changes in the intensity and/or frequency of extreme rainfall events can also be the result of a warming world largely due to changes in the water-holding capacity of the atmosphere (Allan et al., 2014). However, other factors also have a role to play, such as changes in atmospheric circulation patterns, atmospheric stability, latent heat, moisture convergence, cloud size, and the degree of mesoscale organization (Guerreiro *et al.*, 2018). Negative trends in rainfall enhance the probability of increased frequencies of dry periods and prolonged droughts, while increases in rainfall or rainfall intensity can have the opposite effect, enhancing the probability of floods to occur. Since changes in extreme rainfall patterns can be highly regionalized (Westra *et al.*, 2013; Contractor *et al.*, 2021), local studies into changing rainfall patterns are important if effective adaptation measures are to be undertaken.

Thus, weather and climate extremes are predicted to be changing globally under the effects of global warming (Slater *et al.*, 2021), with Donat *et al.* (2013) stating that significant widespread changes in temperature extremes are likely along with increases in the severity and frequency of wet and dry extreme events. It should be noted that this warming in both the observed and projected data is occurring at a faster rate over land compared to the ocean (Manabe, 2019).

1.1.1. What are extreme events?

Stephenson *et al.* (2008) recognized that extreme events were “generally easy to recognize but difficult to define.” This could be why there are various definitions of extreme events in the scientific literature and why there is considerable confusion around the term extreme event (Zwiers *et al.*, 2013). This confusion may be because the word extreme can be used to point to an impact or a characteristic of a climate variable. In terms of impacts, extremes can be understood in terms of financial impacts or number of lives lost. However, some extremes, while falling in the upper tail of the distribution, may occur each season and thus would not be considered as extreme in the statistical sense (Zwiers *et al.*, 2013). Other events may fall in the tail of a probability distribution but, for some reason, may not be realized as an extreme due to its low impact (Seneviratne, 2012). Thus, extremes can be seen differently in space and time and often depend on context (Stephenson *et al.*, 2008). A place in India affected by monsoon rainfall events would not classify 80mm of rainfall per 24 hours as extreme; however, if this fell over Calitzdorp in the Little Karoo in South Africa, this would be classed as both the highest daily rainfall record and an extreme. Even the language (severe, rare, high-impact, extraordinary, unprecedented) scientists and the media use to describe events is often used interchangeably, leading to further confusion (Stephenson *et al.*, 2008).

The other consideration when defining extreme events is when they occur simultaneously with other events, and so in and of themselves, they would not be extreme in a statistical sense; however, due to the combined impact with other extreme conditions, their impact crosses social, ecological or physical systems critical thresholds (Seneviratne, 2012).

Not all extreme weather events result in severe impacts. An example is a Tropical Cyclone that does not come close to land. If there is no infrastructure at risk, low or no population in the affected area or if adequate emergency response measures are in place, impacts may be low (Zwiers *et al.*, 2013). However, if buildings have been built in a substandard manner, even a moderate event can result in damages and thus be considered extreme.

To define extreme events statistically, various mathematical methods have been employed. For example, one could consider exceedances above a very high or below a very low threshold value. The number of exceedances can then be counted. This is described in statistics as a non-homogenous Poisson process (Coles *et al.*, 2001). The choice of a threshold becomes important in this case as a low threshold with respect to, say, maximum temperatures may lead to the inclusion of too many “non-extreme” values, but if the threshold is too high, there may not be enough values to analyse for meaningful results (Tramblay *et al.*, 2013). One could choose a threshold based on its relation to an impact, for example, the threshold used to define a heat wave where the maximum temperature is at least 5°C warmer than the recorded mean of the hottest month for a period of at least 3 days at a given location (Mbokodo *et al.*, 2020). Another method would be to select a weather or climate variable which falls in the 10th or 90th percentile of the observed probability density function (e.g., using tail distributions such as the generalized Pareto distribution) (Turasie, 2021). For rare events, and thus those that one has a limited number of observations for, the pooling of events across some regions could be considered.

In this study, records were defined as the highest or lowest daily minimum or maximum temperatures to occur at a station over its observational history. For extreme temperatures, critical values based on the Universal Thermal Climate Index (Bröde *et al.*, 2012) and temperatures considered stressful to agriculture (Morrison, 1983; Zhu and Troy, 2018; Blackshaw and Blackshaw, 1994; Bohmanova *et al.*, 2007) were considered. Further analysis of current and projected changes in 1:10-, 1:50- and 1:100-year RPVs were also analysed, with 1:50- and 1:100-year RPVs being considered as extreme (Xu *et al.*, 2018). In the analysis of extreme precipitation events, threshold values identified in a study by Dyson (2009) were considered as being significant (>50mm), heavy (>75mm) and very heavy (>115mm) rainfall events and thus used in this study. The Generalised Extreme Value (GEV) distribution, specifically Type I (Gumbel), was used to determine the probability of receiving 50mm or more on a rainy day (≥1mm), with the Peak-Over-Threshold (POT) method then used to determine RPVs for 1:10-, 1:50-, and 1:100-year for each station; once again, the 1:50- and 1:100-year RPVs being considered extreme rainfall values.

1.1.2. South Africa and extremes

South Africa's climate is highly variable (Tyson and Preston-Whyte, 2000) and often prone to extreme weather and climate events, e.g. floods (Sen Roy and Rouault, 2013; Ndlovu and Demlie, 2020) and droughts (Rouault and Richard, 2004; Vogel and Olivier, 2019; Chikoore and Jury, 2021). We have seen evidence of this in recent times (2015-2017), with Cape Town facing day zero, meaning the first city to run out of water due to prolonged drought conditions (Wolski *et al.*, 2021; Sousa *et al.*, 2018), and the Durban floods of April 2022 where some 448 people lost their lives and numerous were displaced (Hattingh, 2022). A national disaster was declared as the government sought speedy ways to fix damages. At least five farm workers died from heat stroke in the Northern Cape in January 2023 (Roffe *et al.*, 2023). During events of this nature, the public and governments often become more aware of climate change and extreme events. Against this backdrop, it is little wonder that extreme weather events have emerged as an indicator that our climate is changing (Sen Roy and Rouault, 2013), with extraordinary extreme events expected with every degree of warming (Fischer and Knutti, 2015).

Several studies (Kruger and Sekele, 2013; MacKellar *et al.*, 2014; Kruger and Nxumalo, 2016; Van Der Walt and Fitchett, 2021) have found a decline in the frequency of low minimum temperatures and an increase in high maximum temperatures for South Africa. New *et al.* (2006) found that during the period 1961 to 2000, the occurrence of extreme hot (above the 95th percentile) days and nights had increased by 8.2 and 8.6 days/decade, respectively, while extreme cold (below the 5th percentile) days and nights had decreased by 3.7 and 6.0 days/decade respectively for Southern and West Africa. Archer *et al.* (2018) found that the Southern African region's annual maximum temperature was projected for the period 2080-2099 to change by about 3°C for Representative Concentration Pathways (RCP) 4.5 to 5°C for RCP8.5 over the interior, with coastal areas showing less of an increase by 1.5 to 2°C relative to 1971-2000. RCPs describe a range of possible future greenhouse gas and aerosol emission scenarios (Van Vuuren *et al.*, 2011). The frequency and duration of heat waves were also projected to increase over South Africa (Engelbrecht *et al.*, 2015; Mbokodo *et al.*, 2020).

Mason *et al.* (1999) found that 70% of South Africa had seen a significant increase in extreme rainfall intensity over the period 1931-1990. Several studies (New *et al.*, 2006; Kruger and Nxumalo, 2017; Kruger, 2006) have found that daily rainfall has increased in intensity, while some have shown an increase in dry spell duration (New *et al.*, 2006; Kruger and Nxumalo, 2017). Extreme hourly precipitation events have increased across South Africa for the summer season (Sen Roy and Rouault, 2013).

In terms of model projections, Shongwe *et al.* (2009) found over the western parts of Southern Africa a statistically significant decrease in mean precipitation during the austral summer months in the future. The study also found a significant shortening of the rainy season due to a notable delay in the onset of the season. In contrast, a study by Lim Kam Sian *et al.* (2022) for Southern Africa showed a projected increase in heavy downpours during the wet season, while the dry season was shown to be getting dryer and more pronounced under the RCP8.5 than the RCP4.5 scenario. This agrees with research by Engelbrecht *et al.* (2013) and Pinto *et al.* (2016), who also found a projected increase in extreme rainfall events over Southern Africa. These results support the latest IPCC's Assessment Report Six (AR6), which stated that Southern Africa is likely to experience an increase in the frequency and length of droughts. Yet, extreme rainfall events are likely to be more frequent and intense, with an increased likelihood of flooding (Lawrence *et al.*, 2022).

1.1.3. Society and environment

The frequency and intensity of extreme climate events causing loss of life, severe damage, and significant economic and societal losses, have been projected to increase in a warmer climate (Ziervogel *et al.*, 2014; Myhre *et al.*, 2019; Zhao *et al.*, 2020). Developing countries will likely feel these effects more due to their limited capacity for climate change adaptation (Turasie, 2021). Grasham *et al.* (2019) point out that climate extremes such as floods and droughts sustain and aggravate poverty. This could be because climate change poses a risk to food security and water resources, disrupting developmental goals of reducing poverty and limiting sustainable development (Nhemachena *et al.*, 2020).

Agriculture contributes significantly to South Africa's economy (Poonyth *et al.*, 2001), with both irrigated and rainfed agriculture impacted by extremes in rainfall and temperature. Irrigation agriculture depends on the availability of water stored in dams or rivers, while rainfed agriculture depends on rain falling over a specific area (Meza *et al.*, 2021). Thus, both types of farming need to look at different water conservation strategies to cope with drought and look to retain soil moisture and using drought and heat-tolerant crops (Ruwanza *et al.*, 2022). However, any coping, adaption and recovery strategies will need to be actioned at household, community and state levels (Williams *et al.*, 2018). *For this to happen, adequate knowledge of the changes in frequency and spatial distribution of extremes in daily temperature and precipitation will be needed.*

Weather and climate extremes also have significant implications for human health. These risks depend to a large extent on socio-demographic changes such as population growth, urbanization patterns and social vulnerabilities (Asefi-Najafabady *et al.*, 2018). Chen and Sun (2021) noted that exposure to precipitation extremes negatively affects human health due to exposure to infectious diseases in the contaminated ground and surface water during and after their occurrence. High temperature extremes are linked to heat stress, heat exhaustion and even death (Gosling *et al.*, 2009; Garland *et al.*, 2015; Fotso-Nguemo *et al.*, 2023). Heat waves are expected to increase in frequency and duration in the future across South Africa (Mbokodo *et al.*, 2020), adding to prevailing heat stress challenges. Thus, the urgent call made by Huang *et al.* (2011) for an evidence-based assessment of the health impacts of climate change is pertinent. *Once again, this will require spatial information regarding the frequency and intensity of the projected changes in climate at the regional and local levels.*

Many aspects of society are thus now facing the realization that their plans for the future need to include the consequences of a changing climate (Warnatzsch and Reay, 2019). With extremes tending not to show a linear occurrence pattern (Cooley, 2013), society may find it difficult to adapt to nonlinear trends rather than an altered mean condition (Rahmstorf and Coumou, 2011). *South Africa is no exception, and it's against this backdrop that this research into the trends and probabilities of climate records and extremes in both the historical and projected climate of South Africa has been investigated in a quantitative approach.*

1.2. Research problem

With a changing climate, it will be important to understand what those changes are and plausibly will be as humanity seeks to mitigate and adapt to them. No longer can humanity deny the reality of their hand as the number one driver of climate change. As we continue to pollute the atmosphere with increasing amounts of greenhouse gases, we must find solutions to the ever-increasing global warming crisis. *With Southern Africa being particularly vulnerable to climate change, there is a need to analyse the trends and probabilities of climate extremes and records in both the historical and projected climate of South Africa.*

It has already been established through previous research (see section 1.1.2) that there are indeed significant changes in the frequencies and intensity of extreme weather and climate events across South Africa. *This research intends to take these findings further by considering the spatial pattern of record-breaking daily temperature records across South Africa, exploring extremes with return periods of multiple years, as well as the changes in the likelihood of exceedance of critical thresholds.*

A lot of decision-making around extremes has primarily been made assuming a stable climate (Nuri Balov and Altunkaynak, 2019). However, due to climate change, this assumption could lead to significant underestimations of risk. Thus, by studying extremes within a non-stationary climate context, those affected will be in a much better position to manage the risks and to assist in evidence-based preparation and planning to minimize damage caused by such events. It is widely acknowledged that adaptation measures to climate change should consider the increase in climate extremes that could, in turn, increasingly test the abilities of socio-economic sectors to absorb the impacts of climate and weather extremes. *The research aims to assist in quantifying the increase in the probabilities of extremes and weather records to occur, which will, therefore, help, if used, in planning adaptation measures to climate change.* This understanding of changes or variability in extreme events at the local level is essential for policymakers, urban planners, NGOs, disaster managers, farmers, and developers of infrastructure, to name a few, to be in a better position to allocate resources to adapt and mitigate against the effect of these extremes.

1.3. Aims and objectives of the study

The research idea was first triggered by the increasing number of questions from the public and media regarding the perceived increase in the number of daily temperatures and rainfall records as measured by the South African Weather Service (SAWS) climate observation network. An in-depth study of the perceived increase in climate records has yet to be conducted in South Africa, and thus, there was a need to provide a scientifically validated answer to this question. However, although records are considered at times to be extremes, due to the rarity of breaking records, there was a need to consider extremes that did not necessarily break previous climate records, but due to their potential to cause severe societal impacts, the quantification in the trends of their probabilities becoming a widening of the focus of the study.

The main objective of the research is thus to determine whether there are historical and project changes in the occurrence of climate records and extremes and the probable effects of these changes on relevant socio-economic sectors. This objective can be subdivided into the following aims or research questions:

1) Are there any trends in the rate of occurrence of daily climate temperature records, and can these be linked to the observed acceleration in the general historical warming?
2) Are there observed changes in the occurrence of the number of days above health-related critical temperature thresholds over South Africa?
3) Are there any future changes in the occurrence of the number of days above health-related critical temperature thresholds over South Africa?
4) Has the probability of receiving significant amounts of rainfall on a rainy day changed over the last century over South Africa.
5) Are there spatial differences in terms of the trends in frequency and intensity of extreme events considering South Africa's complex climatology, and can these differences be regionalised?
6) Are there possible effects of current and future changes in the prevalence of climate extremes on selected socio-economic sectors?

The thesis comprises a series of connected but stand-alone chapters which address the above objectives.

1.4. Approach

1.4.1. Data

The data sets analysed will consist of two categories of data, i.e. observed data and climate model projections. The primary focus of the research will be the analysis of the most relevant daily surface temperature (maximum and minimum) and daily rainfall data.

1.4.2. Observed data

SAWS has developed a set of homogenised daily near-surface maximum and minimum daily temperature data recorded at 25 stations, with at least 90% data availability from 1931 to the present. This data set, developed by Kruger and Nxumalo (2016), is the primary data set to be analysed for historical trends of temperature records and extremes. Daily near-complete precipitation data, recorded at 70 stations in South Africa from 1921 to the present, used by Kruger and Nxumalo (2017), will be the primary data set used to analyse for historical trends of extreme daily precipitation events. This data set was selected based on the length and completeness of records, as well as the representability of the South African rainfall climate.

1.4.3. Climate model projections

Dynamical downscaling modelling performed under the auspices of the Coordinated Regional-climate Downscaling Experiment (CORDEX) (Jones *et al.*, 2011) was used in the study. The primary data sets most relevant to this study are the future projections of the near-surface temperature for the projection period of 2036–2095. Two RCPs, i.e. RCP4.5 and RCP8.5, were considered.

1.4.4. Methods

The first part of the research (Chapter 2) investigated record daily temperature events. These were counted and compared to the expected number of records as these decayed with time. The warming trend was also considered in this study.

Thereafter, the research focuses on events considered not only anomalous but also extreme (Chapter 3), with return periods typically more than a year and in most cases, multiple years. The study considered the projected changes in maximum daily temperature extremes by fitting the generalized extreme value (GEV) distributions (Gumbel) to the data. The 1:10-, 1:50- and 1:100-year Return Periods Values (RPVs) and Return Periods (RPs) were estimated.

The number of daily maximum temperatures breaking critical temperature thresholds were also counted to give an indication if there was a change in the number of these events in the future.

In Chapter 4, changes in extreme daily precipitation events were considered by dividing observation data for each station into two periods to facilitate comparisons. The gamma distribution was applied to estimate the probability of receiving more than 50mm, 75mm and 115mm on a rainy day in the two periods. Further analysis of projected changes in 1:10-, 1:50- and 1:100-year return period values (RPVs) using the Peak-Over-Threshold (POT) method was done. The study then analysed precipitation events above threshold values considered as being significant (>50mm), heavy (>75mm) and very heavy (>115mm) rainfall events.

1.5. Thesis outline

Chapter 1 introduces the topic and an outline of the aims and objectives of the study. Chapter 2 provides, in the form of a published peer-reviewed journal paper, a look into the trends in the probabilities of breaking daily temperature records in the non-stationary climate of South Africa. The temporal and spatial distribution of the frequency of breaking highest and lowest daily maximum and minimum temperature records over South Africa from 1951 to 2019 was explored. Chapter 3, in the form of a journal paper under review, looks at projected changes in daily temperature extremes for selected stations over South Africa. Chapter 4, in the form of a peer-reviewed paper, explores the changes in the characteristics of historical (1921-2020) extreme daily rainfall. Chapter 5 summarises the main findings, concluding remarks and recommendations for future research.

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Chapter 2: Trends in probabilities of temperature records in the non-stationary climate of South Africa

Preface

This chapter consists of one published peer-reviewed paper as follows:

McBride, C. M., Kruger, A. C. and Dyson, L. 2021. Trends in probabilities of temperature records in the non-stationary climate of South Africa. *International Journal of Climatology* **42**(3): 1692-1705. doi.org/10.1002/joc.7329

In this chapter, the study's first objective was to determine if any trends in the rate of occurrence of daily temperature records could be detected and whether this could be linked to the observed acceleration in the general historical warming in South Africa. This is the first analysis to investigate the rate at which temperature records are broken in the context of global warming over South Africa. The findings are important in terms of adaptation to the future of extreme temperature impacts in Southern Africa. If used, the results will benefit those tasked with developing climate change response strategies so that the consequences and risks of the increased frequency of record-breaking temperature events can be included.

The study used specific year-day temperatures and compared these to all previous days for a particular location to determine if a temperature would break a previous record. The highest and lowest maximum and minimum temperatures were considered. Because each event was considered to be independently and identically distributed, i.e. having a gap of 364 days between each value, prolonged weather events could not influence the occurrence of such records and could, therefore, be deemed statistically independent. The number of records per station was then compared to a theoretical probability of breaking records in a non-stationary climate. Since climate records are rare, there was a need to use the Monte Carlo method to generate a range of likely values. These were then used to determine confidence intervals to allow the study to assess the degree of certainty that the number of records breaking events was outside expected limits. The warming trend was then considered at each station because this has changed over time and can play a role in breaking records over the observational period. Because the individual stations' warming trend was considered, spatial differences were explored, thus addressing Objective 5 of the study. The consequences of the findings were also briefly discussed, considering societal and environmental impacts, thus addressing Objective 6.

According to reviewers' comments, changes to the article have been added in italics and are not reflected in the published paper. This also applies to other relevant chapters.

A.C. Kruger and L. Dyson co-authored the paper. The conceptualisation of the paper, collection, and analysis of data, together with the graphical outputs in the paper, was conducted by myself.

Trends in Probabilities of Temperature Records in the Non-Stationary Climate of South Africa

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Abstract

The temporal and spatial distribution of the frequency of breaking highest and lowest daily maximum and minimum temperature records over the period of 1951 to 2019 has been investigated for South Africa. Temperature records are station specific and defined as either larger or smaller than any previous values in a time series of specific year-days. Daily maximum and minimum temperatures from a homogenised time series of 25 weather stations in South Africa were analysed. Aspects considered to influence the frequency of record-breaking events were the warming trend and variance. The study found that the record-breaking frequencies of the highest daily maximum (high Tmax) and some high daily minimum temperature (high Tmin) records were higher than the theoretically expected number in a stationary climate. This was particularly apparent near the end of the analysis period. The ratio of highest maximum to lowest minimum temperature records was almost an equal 1:1 ratio near the start of the analysis period and increased to about 4:1 in the last decade of the period. Focusing on the last decade, i.e. 2010 – 2019, the study found that there is a different spatial pattern between the occurrence of high Tmax and high Tmin records. For high Tmax records, the highest number were mostly recorded by stations over the central parts of the country (e.g. Kimberley, Glen College and Bloemfontein). In contrast, the highest number of high Tmin records were less confined spatially. Even when considering the general warming due to climate change, many more high temperature records are broken than expected in certain regions and on average. We deduce that the higher than expected numbers of high Tmax and high Tmin records in the latter part of the analysis period were mainly due to the variability in the warming trend with acceleration in the last decade.

Keywords: *South Africa, record-breaking temperature records, temperature extremes, warming, climate change.*

2.1. Introduction

There is general consensus among climatologists that there is sufficient evidence of climate change, especially increases in surface temperature (Donat *et al.*, 2013), confirmed in the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) (Stocker *et al.*, 2014). This change, which shows a positive warming trend over most regions of the world since at least the 1950s, cannot be explained by natural variability alone (Brown *et al.*, 2008; Collins, 2011) and the altering of the atmospheric composition by humans is changing this variability (Karl and Trenberth, 2003).

One of the consequences of human-induced changes in the general climate is that specific extreme weather and climate events are likely to increase (Stott, 2016). These extreme values would fall into the tails of the variable's distribution (Zwiers *et al.*, 2013). Any change in the distribution's mean or variance or both will affect the occurrence of extreme events (Meehl *et al.*, 2000). Thus, in a warming climate, the mean temperature and variability are likely to change and, thus, the occurrence of hot extreme events (Tamarin-Brodsky *et al.*, 2020). These changes in mean temperature and in extreme events are, however, not linear, and small changes in the mean state can result in large changes in the occurrence of extreme events (Mearns *et al.*, 1984; Meehl *et al.*, 2000). Record-breaking temperatures fall into the realm of these types of events (Rowe and Derry, 2012) and, by their very nature, are rare events (Stephenson *et al.*, 2008; Field *et al.*, 2012; Otto, 2019). This makes their analysis difficult as one considers changes in the trend of a diminishing number of events (Rowe and Derry, 2012).

According to the IPCC (2019), global surface temperatures are currently increasing at around 0.2°C per decade. This increase in the warming trend has also been documented in a number of studies for South Africa, where the acceleration in the general warming has occurred over the last number of decades (Kruger and Nxumalo, 2017; Van Der Walt and Fitchett, 2021). This warming trend shows variability across the country, with stations located in the central parts showing less of a positive trend than those located in the western and eastern parts of the country (Kruger and Nxumalo, 2017). With this warming comes the concern that in the future highest daily maximum temperature records will be broken more often than lowest daily minimum temperature records (Benestad, 2004; Finkel and Katz, 2018). This increase in temperature trend, along with other climate change-related threats, poses challenges for how South Africa is able to respond in terms of water, food security, human and ecosystem health and development (Ziervogel *et al.*, 2014).

Policymakers are showing an interest in the risks associated with extreme weather and climate events, especially if these are likely to increase (Brulle *et al.*, 2012; Omondi *et al.*, 2014). In addition to policymakers, the general public, who experience climate change mainly through the occurrence of extreme events, want information on these events and how their frequencies are expected to change (Parey *et al.*, 2007; Easterling *et al.*, 2016). Thus, the occurrence of climate change related extreme weather events has become an increasingly important climate research topic (Poudel *et al.*, 2020), with researchers beginning to pay more attention to climate record-breaking statistics to shed light on whether and how the occurrence of daily temperature records is affected by a changing climate (Wergen *et al.*, 2014). Understanding record-breaking events will prove to be important as any change in the frequency of extreme weather events may influence how especially developing countries are able to adapt (Mirza, 2003). With Africa being especially vulnerable to climate change (Lennard *et al.*, 2018), there is a need for more research into such events (Stephenson *et al.*, 2008), particularly in light of vulnerable communities having to respond to these events (Van Wesenbeeck *et al.*, 2016).

There is a general lack of research focused on the breaking of specific station's individual highest or lowest observed daily or monthly temperature records. Zwiers *et al.* (2013) point out that the use of in-situ data is extremely important in our understanding of changes in extremes. Studies around short-lived high-temperature extremes also provides a different look at how changes are occurring compared to studies that focus on annual or seasonal time frames (Papalexiou *et al.*, 2018). Research on breaking temperature records has largely been concentrated in the Northern Hemisphere: USA (Abatzoglou and Barbero, 2014; Rowe and Derry, 2012); Europe (Elguindi *et al.*, 2013; Beniston, 2015); China (Zhong-Hua *et al.*, 2012; Deng *et al.*, 2018); Korea (Cho *et al.*, 2011); Lebanon (Hayek *et al.*, 2020) with Australia (Trewin and Vermont, 2010) the exception. Only one global study could be found (Anderson and Kostinski, 2010) and this contained very few stations in the Southern Hemisphere. The presented research endeavours to contribute by investigating breaking temperature records at several continental and maritime locations in South Africa*. Studies of 'record-breaking' may be measuring different things – e.g. Trewin and Vermont (2010) looks at a time series as a whole and the timing of the record value within that time series, rather than records being broken successively over time. This study follows the first approach.* We investigate whether the changing climate, i.e. general warming, can be linked to the occurrences of extreme record surface temperatures in in-situ measurements over South Africa. Several authors (Li *et al.*, 2005; Seneviratne *et al.*, 2014; Fischer and Knutti, 2015) indicate that there has been an increase in temperature extremes in recent decades. The warmest years in South Africa's temperature record have occurred in the last decade (Blunden and Arndt, 2020), and this period will, therefore, be a particular focus of the analysis and discussion.

The analysis of the temperature data in this paper attempts to determine whether the breaking of temperature records in South Africa conforms to the probabilities of records in a stationary climate and, if not, whether the general warming trend sufficiently explains the observed temperature records in South Africa, especially over the last decade.

2.2. Data

Near-surface daily observational temperature data for the period 1951 to 2019 from 25 stations across South Africa were selected for analysis. The start year of 1951 was chosen as this was the earliest year for which all of the stations in the study had sufficient data, i.e. more than 90% of data for every year in the time series. Missing data was not replaced, as any attempt to do this would be unlikely to result in a record value (Rowe and Derry, 2012). Data sets did not include data for the 29th of February as these temperatures would need to be compared every 4 years making any identified records difficult to add to a yearly time series. Consolidating the start of the period between all stations ensures that the number of records broken in a set year is not affected by the different number of previous years in the time series (Meehl *et al.*, 2009). The 25 stations included 16 interior and 9 coastal stations. The locations of the stations are presented in Figure 2.1.

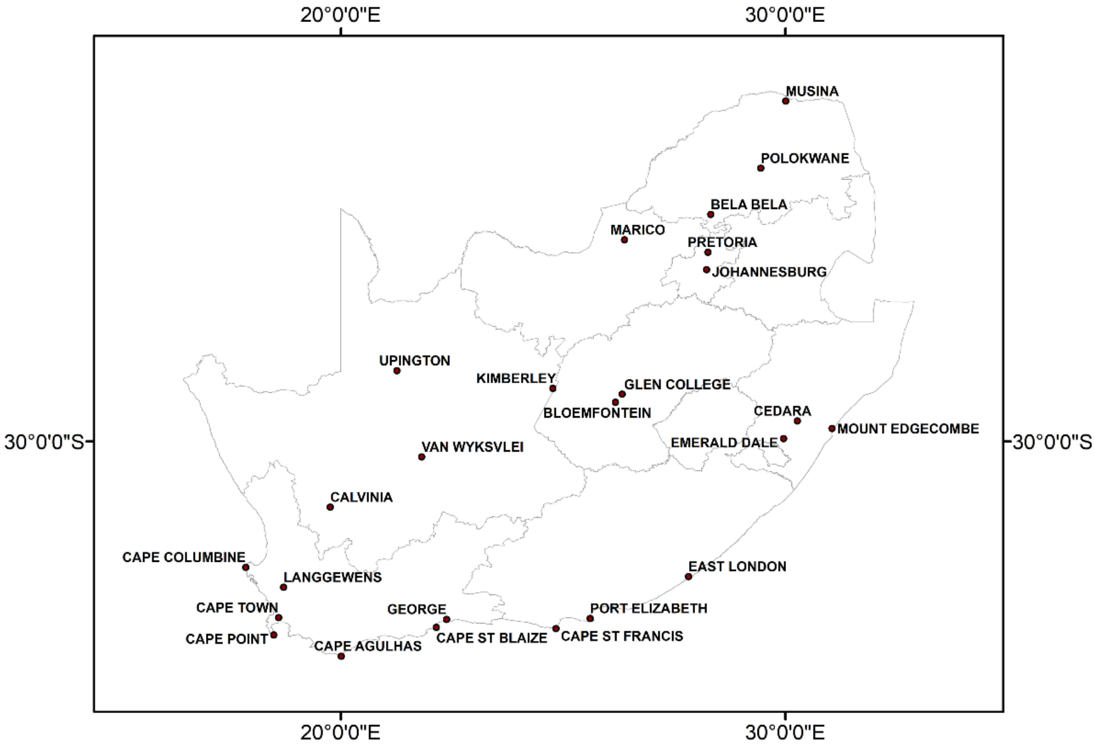

Figure 2.1: *Locations of the 25 stations used to study the occurrences of temperature records over the period 1951 – 2019. The station list with coordinates and elevations is in Appendix A.*

The station data was quality controlled, and any suspicious records were checked either with the original climate hard copy return or using a graphical interface to check for non-meteorological spikes or sensor problems. The data was homogenised using the RHtestsV4 software package (http://etccdi.pacificclimate.org/software.shtml). Details of the homogenisation methods and procedures are found in the RHtestsV4 user manual (Zhang and Yang, 2004). *The homogenisation was conducted without reference series since stations were situated far apart, and not one station could be deemed properly homogenous to serve as a reference.*

2.3. Methodologies

The range of analyses attempts to provide insight into whether and how the warming in South Africa influenced the observed frequency of temperature records. This includes comparisons of the observed number of records against the expected in a stationary climate and whether the observed warming can sufficiently explain the deviation from the frequencies of the expected in a stationary climate. In addition, possible regional differences in the frequency of record-breaking occurrences were investigated. Established approaches (Franke *et al.*, 2010; Wergen and Krug, 2010; Pan *et al.*, 2013) to accommodate a warming trend in the estimation of the expected number of records were considered. Because it has been established that global warming is accelerating (Li *et al.*, 2021), deviation from expected frequencies of records during the last decade will be of particular focus. The Mann-Kendall test was used to test for trend significance at the 5% level. Possible temporal changes in long-term warming trends were established with the Student's *t*-test, and the results were applied to explain the increased frequencies of daily highest Tmax and Tmin records. Following are the methodologies discussed in detail:

2.3.1. Expected frequencies of records in a stationary climate

To determine whether a temperature record was broken, a specific year-day was compared to all previous days in the same position within the year sequence (e.g. 9 July with all previous 9 Julys) (Pan *et al.*, 2013). The compared values can be considered to be independently and identically distributed (i.i.d) (Krug, 2007). This means that days around a record do not influence the next value in the series, as each value is separated by 365 days (Wergen and Krug, 2010). *For tie values, the first value in the time series was taken as the year in which this value broke the record.*

Following the above methodology and comparison of values, the first year all stations broke the particular record being checked every day (365 records per station), the following year, fewer record-breaking events are probable and so on for each subsequent year.

The expected frequency of breaking records should occur at a predictable probability of

$$P_n = \frac{1}{n} \qquad (1)$$

where *n* is the length of the time series in years (Wergen and Krug, 2010). *Although, practically, n varies according to the number of available years, this cannot be considered in the methodology as it will result in a misalignment of years between stations*. In a stationary climate, the annual ratio of Tmax and Tmin records would remain near-constant (Meehl *et al.*, 2009). With every year added to the data series, the more unlikely it becomes to break a record if the climate is stationary, following the probability of 1/*n* (Meehl *et al.*, 2016; Arnold *et al.*, 2011). The observed deviations from the expected rate of new records and the changes in the ratios were therefore examined to determine whether the climate records followed a non-stationary rate of probability.

Bootstrapping simulations (1000), which is a form of Monte-Carlo simulations with replacement, were used to estimate the 95% confidence intervals of the expected number of records per year.

2.3.2. Interior and coastal stations

Stations were divided into interior and coastal to possibly reveal additional insights into the occurrence of record-breaking statistics. A study looking into monthly mean maximum and minimum temperature trends in South Africa from 1940 to 1989 found that most coastal stations showed significant temperature increases compared to interior stations (Muhlenbruch-Tegen, 1992). *However, a more recent study by Kruger and Shongwe (2004), looking at data from 1960 to 2003, showed a positive higher trend in annual mean maximum temperatures over the central interior compared to coastal stations. It was also noted that stations situated over the central parts of the country showed no significant positive trends in annual mean minimum temperature. A later study (1960-2010) found annual mean maximum temperatures had increased significantly across the country, with the central interior showing the strongest increase (MacKellar et al., 2014). This study also found that the central interior* *showed a cooling of annual mean minimum temperatures, leading to an increased diurnal temperature range (MacKellar et al., 2014).*

2.3.3. Records in a warming climate

To accommodate for a warming trend in the climate, Krug (2007), Wergen and Krug (2010), Pan *et al.* (2013), and Wergen *et al.* (2014) developed and applied a trend term in the probability estimation of record-breaking events:

$$P_n \approx \frac{1}{n} + \frac{v}{\sigma}\,\frac{2\sqrt{\pi}}{e^2}\sqrt{\mathrm{In}\left(\frac{n^2}{8\pi}\right)} \qquad (2)$$

where n is the number of years, v = mean temperature trend and σ = standard deviation, π = pi and e = Euler–Mascheroni constant. The first term, 1/n, is the theoretical expected number of records in a stationary climate (Equation (1)), and the next expression after the addition sign is defined as the trend term (Wergen and Krug, 2010). When there is no trend (stationary climate) v = 0. Following the approach of (Wergen and Krug, 2010), the expected number of high Tmax and high Tmin records was estimated, taking into account the mean warming trend at each individual station. By way of example, Bloemfontein, after 68 years (last year of the record) should record approximately 5 highest Tmax records in a stationary climate, but when taking the warming trend of 0.29°C/decade into account, the expected number of records is 9.

The results are mapped using inverse distance weighting as the interpolation method. This method uses neighbouring stations; we used six stations to estimate cell values. The closer a station is to a point being estimated, the more influence that point has in the averaging process (Johnston et al., 2001). This interpolation method performs well when the sample density is low (Bhowmik, 2012).

2.3.4. Temporal change in trend

The Mann-Kendall test was used to test trend significance at the 5% level. To test where the warming trend is changing over time, the Student’s t-test was used to evaluate the statistical significance of the differences, at the 5% confidence level, between the linear trend of the time series for the years prior to and the years after every year. The change in trend was then used in Equation (2) to compare the probable number of records between when the trend is considered to be constant or changing over time.

2.4. Results

2.4.1. Ratios

The breaking of Tmax and Tmin records in South Africa has not always occurred at the same frequency throughout the period under investigation. The ratio of high Tmax to low Tmin records per year (Figure 2.2) at the start of the study period was approximately 1:1. This ratio, however, steadily increased in favour of Tmax over the years and since the 1980s, showed a marked increase in interannual variability. Even though a general increasing trend is discernible, the ratio is anomalously high in specific years. These are 1999 (5:1), 2005 (5:1), and 2016 (8:1), with a maximum of 9:1 in 2019. The trend in the ratio of Tmax to Tmin is statistically significant at the 5% confidence level. *An additional observation is that spikes in annual record counts mostly occurred in El Niño years, contributing to the occurrence of anomalously high numbers of maximum temperature records over South Africa. Quite often, during El Niño years, a relatively higher number of maximum temperature records are broken. These record-breaking temperatures seem to clearly contribute to the general higher-than-expected frequencies of records since the mid-1980s.*

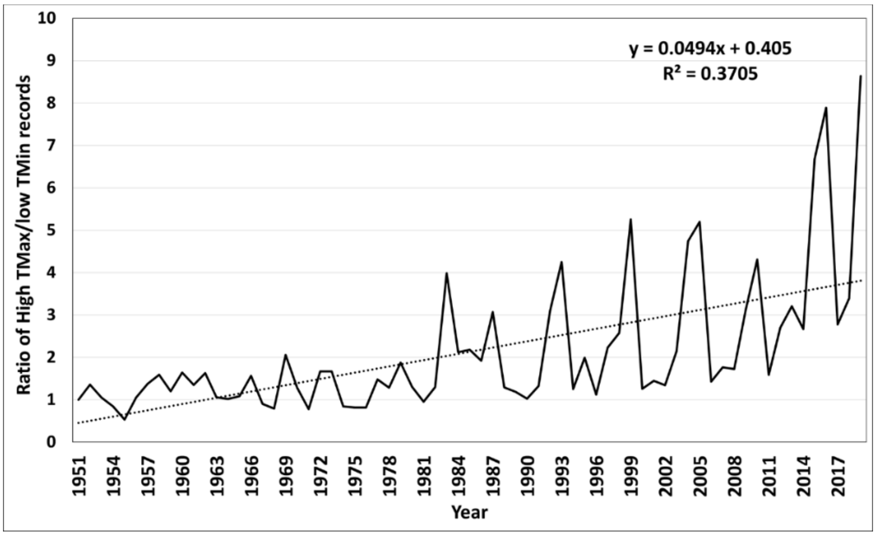

Figure 2.2: *Annual average ratio of high Tmax to low Tmin records for all stations for the period 1951 to 2019 for the 25 stations analysed.*

2.4.2. Frequencies of records

It is evident that there is a gradual decrease in the number of records per year (Figure 2.3) due to the fact that it becomes less probable to break previous records as one moves forward in the time series (following Equation 1). However, in the latter part of the analysis period, the number of high Tmax (low Tmin) records does not strictly follow the expected occurrence of records but shows an increase (decrease), especially in the last decade. High Tmax records (dots) often exceeded the upper 95% confidence intervals since 1983, whereas the low Tmin records (triangles) stays within the 95% confidence interval, albeit close to the lower end. Interior stations' high Tmax records showed a greater deviation from the expected number of records (Figure 2.3b) when compared to those of coastal stations (Figure 2.3c). The interior stations exceeded the upper confidence interval for the first time in 1970, but this happened much later (1998) for coastal stations. Records at interior stations also exceeded the upper 95% confidence interval fourteen times, while at coastal stations only three times. The spread of low Tmin records shows a similar pattern for both interior and coastal stations, and these rarely fall outside the confidence limits. The number of times low minimum records exceeded those of high maximum records in a given year for interior (coastal stations) was 14 (7). The last time this happened for interior (coastal) stations was 2000 (1981).

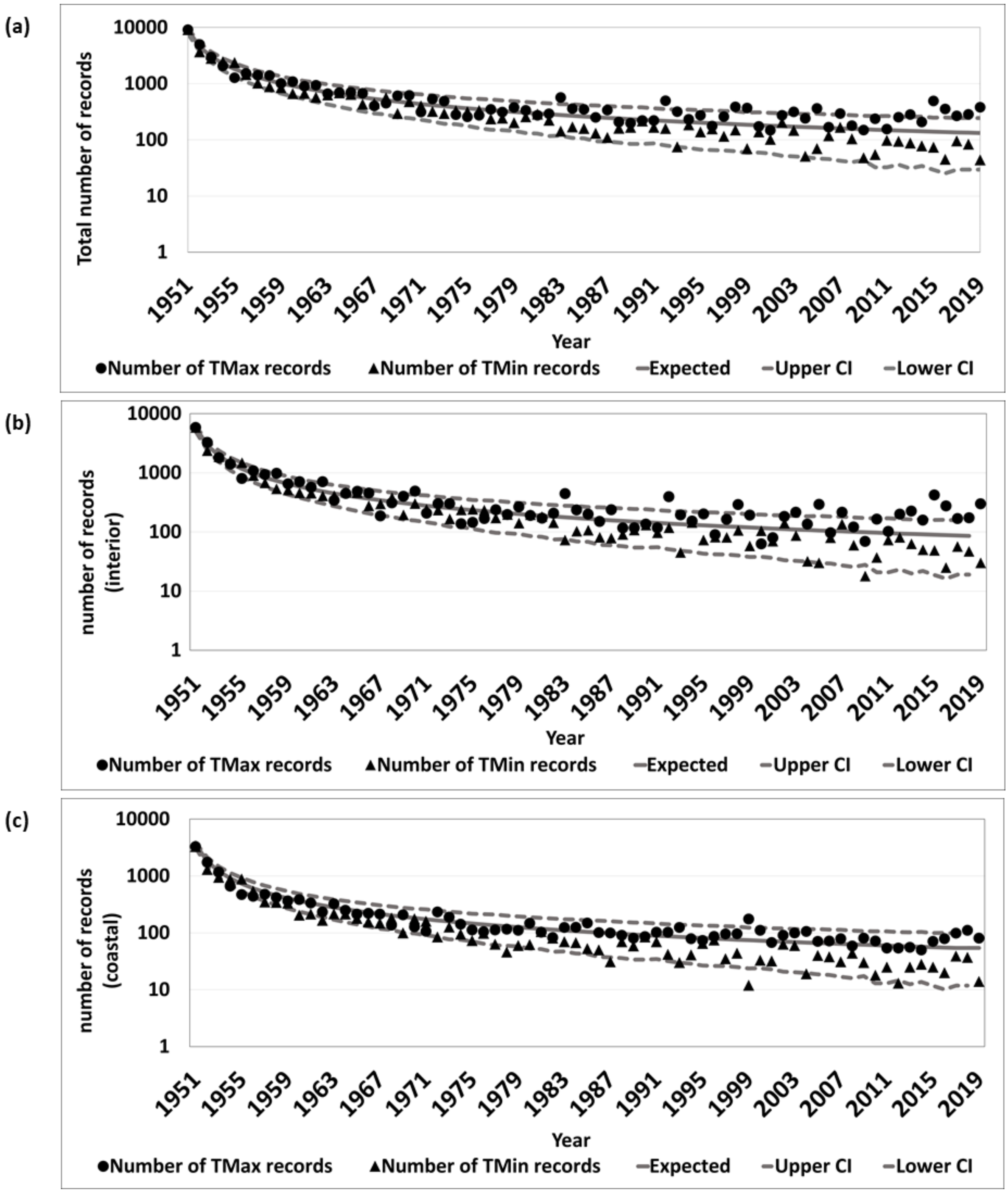

Figure 2.3: *Yearly total number of high Tmax (dots) and record low Tmin (triangles) records for all stations (a), interior stations (b) and coastal stations (c). Grey dashed lines are upper and lower 95% confidence intervals. A solid grey line is the expected number.*

The frequency of the occurrence of high Tmax and high Tmin and low Tmax and low Tmin records was investigated from 1951 to 2019. The annual sum of records of high Tmax and high Tmin exceeded the expected number of records from the 1980s to the present for most years (Figure 2.4). This exceedance of the expected number of records was similar for high Tmax and high Tmin for most of the period except for the last 4 years from 2015 (Table 2.1). For the period 2010-2019, the year with the highest number of records for high Tmax and high Tmin was 2015, one of the hottest years on record for South Africa (Blunden and Arndt, 2016). For the year 2015, the number of high Tmax records is more than three times what is expected in a stationary climate (Table 2.1). Low Tmax and low Tmin records occurred at a lower frequency than the expected number of records in a stationary climate and, toward the end of the period, showed a similar deviation from the expected as with the Tmax but in the opposite direction (Figure 2.4). In the last decade, in some years, some stations failed to break even a single low Tmax or Tmin record.

Diurnal temperature ranges were investigated to see if this could shed light on the spatial pattern of breaking records across the country. This study found almost the same number of positive and negative trends, which agrees with research by Kruger and Shongwe (2004) and New et al. (2006) and thus shows no clear pattern of change. This makes it difficult to link these trends with record breaking events.

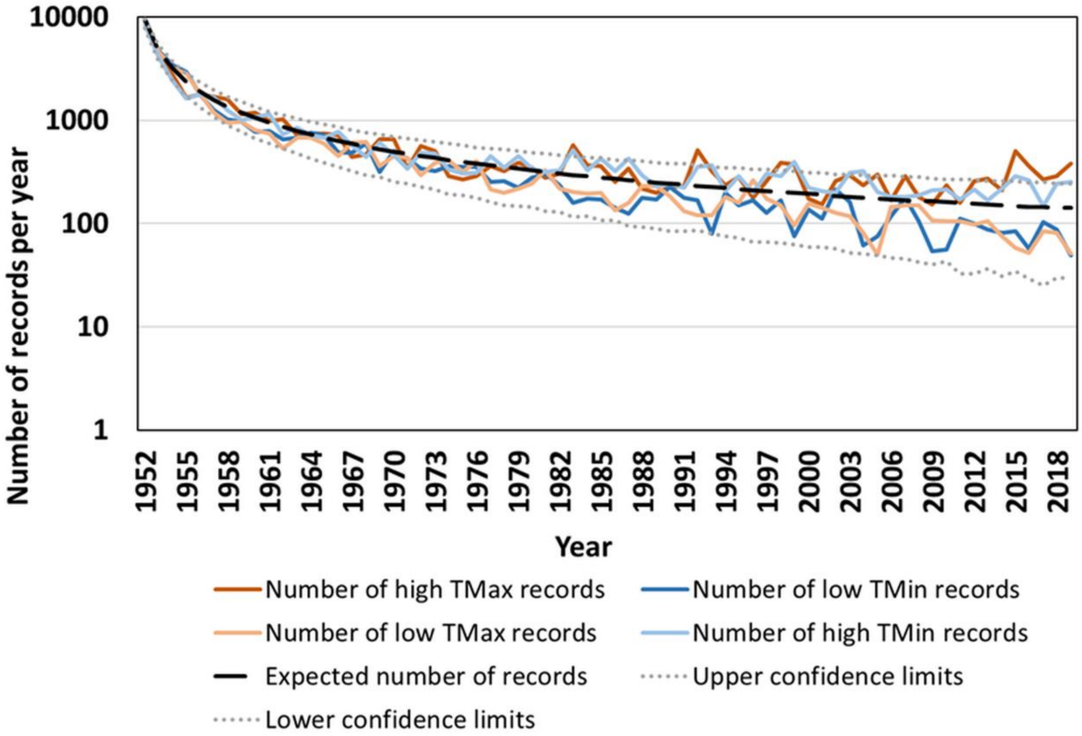

Figure 2.4: *Annual total temperature records for 25 stations over South Africa from 1951 to 2019. The black dashed line is the expected number of records 1/n in a stationary climate, high Tmax: dark orange, low Tmax: light orange, low Tmin: dark blue and high Tmin: light blue. The grey dotted line shows the 95% confidence limits.*

Table 2.1: The annual total number of temperature records for all stations in the study over the last decade (2010 – 2019). The last column is the expected number of records in a stationary climate 1/n.

Year	High Tmax	Low Tmax	Low Tmin	High Tmin	Expected
2010	237	106	55	215	152
2011	156	106	98	188	150
2012	254	98	94	248	147
2013	282	105	88	192	145
2014	208	76	78	238	143
2015	494	58	74	331	140
2016	355	52	45	302	138
2017	267	85	96	164	136
2018	285	81	84	260	134
2019	380	51	44	288	132

2.4.3. Records in a warming climate

Focusing on the last 10 years of the study period, the annual average expected number of records in a stationary climate for a station with data from 1951 is six per year. With the addition of the warming term presented in Equation (2), the frequency in the number of expected records is expected to be higher. The normalized warming trend v /σ for both high Tmax and high Tmin interpolated with the inverse distance weighting method shows where approximately the greater number of records should occur (Figure 2.5a and b). Regions with relatively higher v /σ should correspond with those regions where relatively more record-breaking events occur (Wergen and Krug, 2010). Figure 2.5(c and d) shows the expected number of high Tmax and Tmin records by application of Equation (2). Figure 2.5(e and f) presents the observed frequencies of records. The observed number of high Tmax records (Figure 2.5e) far exceeds the expected estimation (Figure 2.5c). Stations over the central parts of the country showed the highest number of high Tmax records (Figure 2.5e), with more than double the observed high Tmax records compared to what was expected (Figure 2.5c). Only Musina in the north of the country, by observing an average of four high Tmax records per year for the period, had less than the expected number of records.

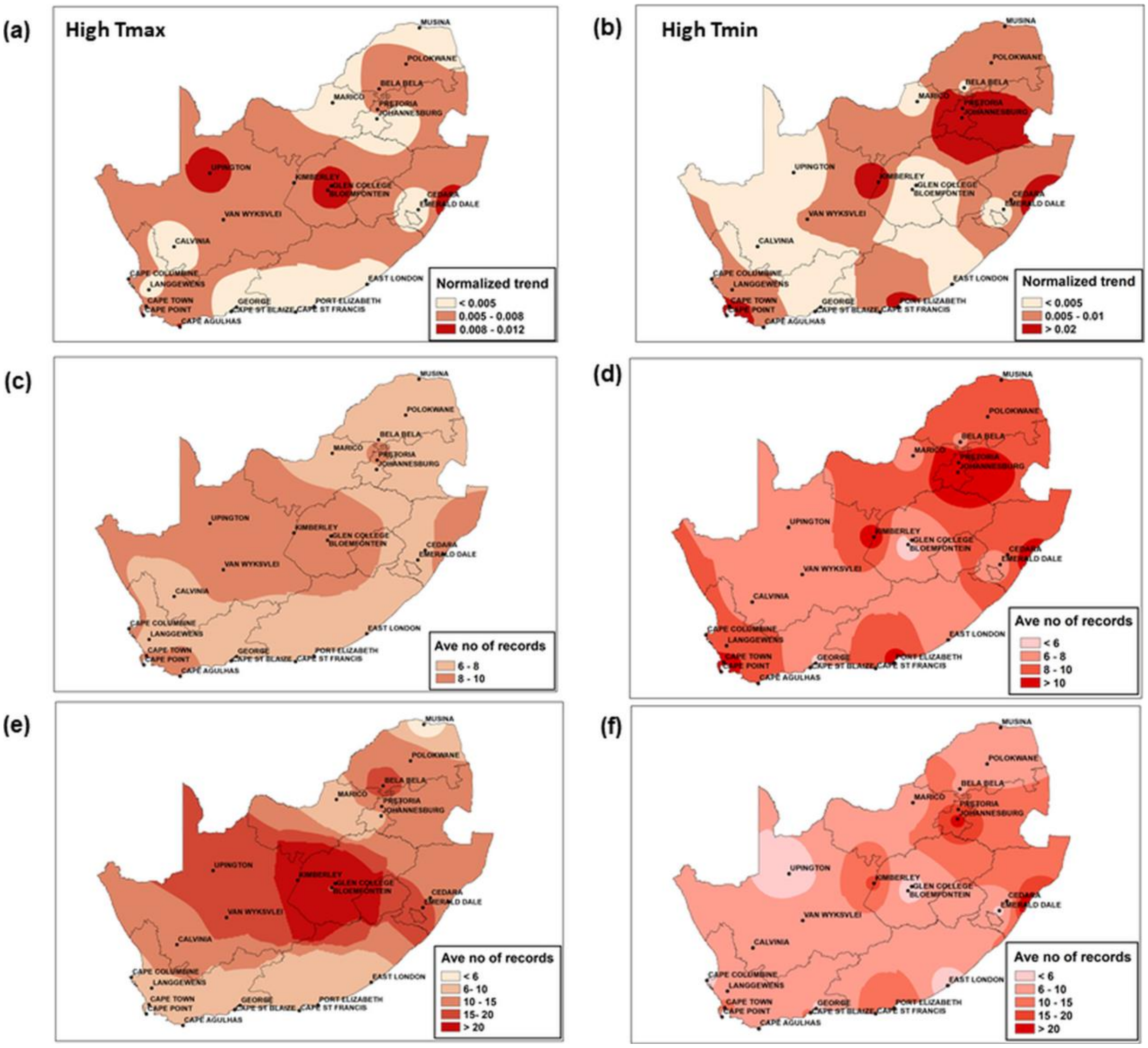

Figure 2.5: *The normalized warming trend v/σ for high Tmax (a) and high Tmin (b). Spatial distribution of the annual average number of expected high Tmax (c) and high Tmin (d) records with warming considered for the period 2010 to 2019. The annual average number of observed high Tmax (e) and high Tmin (f) records for the period 2010 to 2019. Inverse distance weighting was used as the interpolation method.*

The expected number of high Tmin records (Figure 2.5d) showed a different spatial pattern than high Tmax. George and Bloemfontein, on the south coast and central interior respectively, were expected to record less than an average of six Tmin records per year for the period 2010 to 2019 due to their negative warming trend for Tmin of -0.06°C/decade and -0.12°C/decade respectively. All other stations had positive warming trends for their Tmin and were expected to have more than six records per year. Eight stations recorded less than six high Tmin records per year for the period (Figure 2.5f). The rest of the stations all reported more than the average 6 high Tmin records per year. The stations recording the highest Tmin records were not confined to one region but were reported by stations distributed across the country, e.g. Kimberley, Johannesburg, Pretoria and Mount Edgecombe (Figure 2.5f). These stations showed observed high Tmin records more than double the expected.

2.4.4. Acceleration of warming trend

The breaking of more high Tmax and high Tmin records is to be expected in a warming climate. However, in this study, the frequency in occurrence of these records did not show a steady increase above the expected but rather showed periods where relatively high numbers were recorded, followed by periods with less than expected records. Towards the end of the analysis period (2012 to 2019), Tmax records showed an upward trend in the number of records being recorded, compared to the expected number of records considering the mean warming trend, as can be observed in Figure 2.4. The Student's *t*-test for the difference in means before and after every year in the period from 1951 to 2019 was done to investigate if there were abrupt changes in the mean. Abrupt changes from a decrease to an increase in the absolute value of the Student's *t*-test indicate abrupt changes in the trend before and after the specific year. The highest absolute value of the test indicates the year at which the mean before and after a specific year is the most significant. For the annual average Tmax, this occurred around 1997, and for Tmin, it occurred around 1982. Kruger and Shongwe (2004) also found an abrupt change in trend in the early 1980s, when an acceleration in the mean warming trend in South Africa was observed. Other years of abrupt changes for Tmax in this study are 1981, 1991, 2001, 2012 and 2014, as shown in Figure 2.6(a) (open circles), and for Tmin, the years 1956, 1990, 1997, 2008 and 2013 (Figure 2.6b).

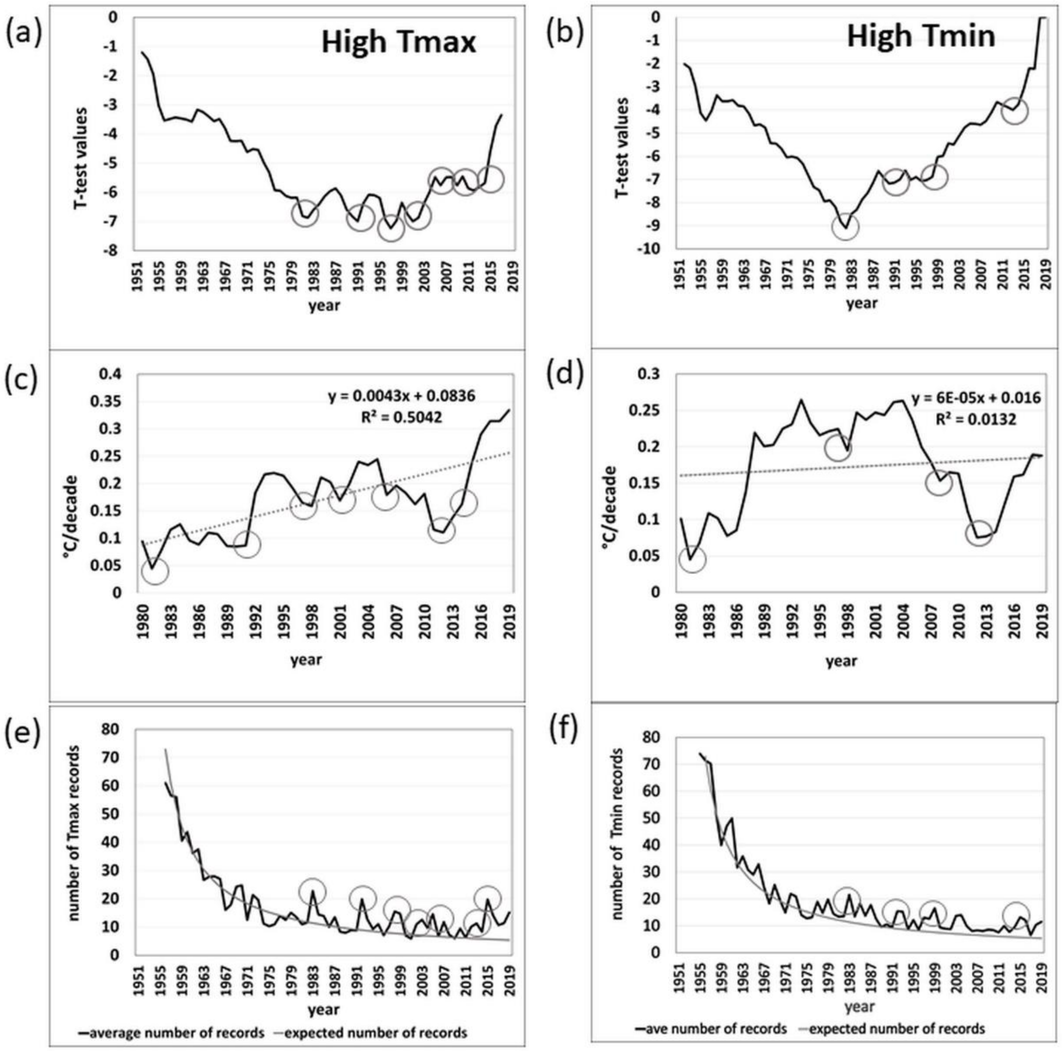

Figure 2.6: *T-test result of the difference in average mean temperature before and after the specific year in the time series for Tmax (a) and Tmin (b). Tmax (c) and Tmin (d) show the linear trend over a 30-year window centred on the specific year. The average number of high Tmax (e) and high Tmin (f) records for all stations per year for the analysis period – black line, the grey dotted line is the expected number of records in a non-stationary climate (warming considered). The open circles show abrupt changes in the mean temperature (a and b) and changes in mean trend (c and d) and these changes occur a year before peaks in records (e and f).*

The 30-year annual mean Tmax and Tmin temperature trends for all stations were calculated (Figure 2.6c and d). The Mann-Kendall test found the trend for mean temperatures to be significant at the 5% level. The trends are not constant for the whole period. For Tmax (Tmin), the average trend for the period 1951 – 1980 is 0.09°C/decade (0.10°C/decade), while for the period 1990 – present is 0.33°C/decade (0.19°C/decade). Abrupt changes in the mean (Figure 2.6a and b) corresponds to years where abrupt changes in the temperature trend occurred. In the following year, after the abrupt change, the number of records is higher than the general trend in the frequency of the occurrence of these records, as presented in Figure 2.6(e and f) for Tmax and Tmin, respectively. These abrupt changes i.e. increases in the mean and temperature trend, are the cause for the number of records of both high Tmax and high Tmin to occur beyond the expected frequency, taking into account the average warming trend.

To investigate whether the acceleration in trend can explain the anomalously large numbers of Tmax records over the last decade, the trend v in Equation 2 was adjusted for each decade according to the average trend over the previous 30 years. Figure 2.7 presents the expected annual average number of records over the previous decade in the case of no trend, the constant warming trend of 0.20°C/decade and the variable warming trend with the trend over the latest decade of 0.34°C/decade. The observed annual average number of records over the previous is also shown. It can be seen that the observed records over the last decade (2010 – 2019) coincide most closely with the variable warming trend line. Therefore, the increased warming rate explains the recent relatively high number of high Tmax records better than if constant warming is assumed.

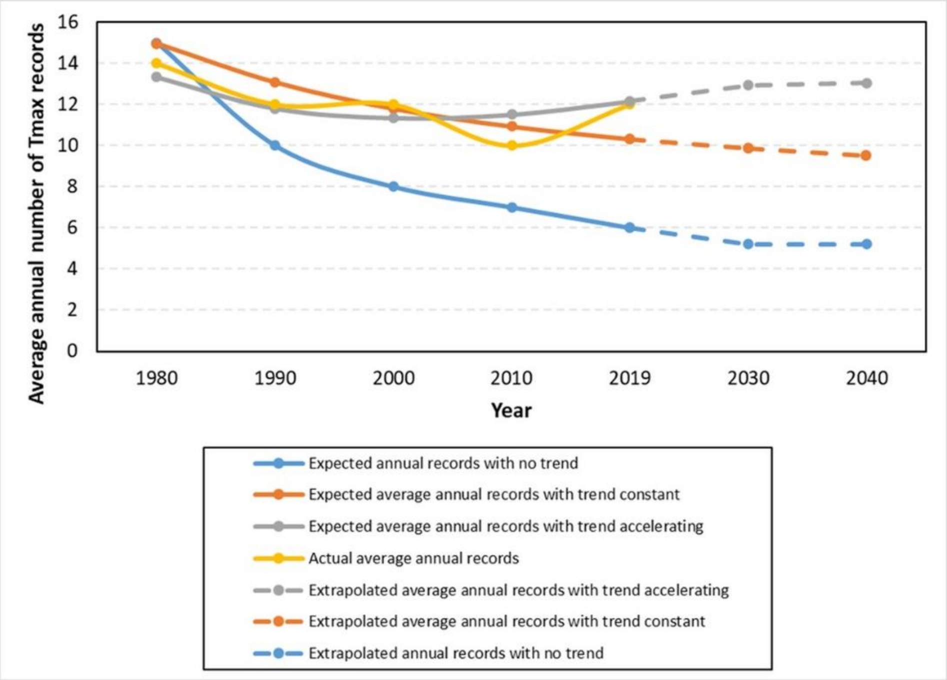

Figure 2.7: *The expected annual average number of records over the previous decade in the case of no trend (blue line), the constant warming trend of 0.20°C/decade (orange line) and the variable warming trend with the trend over the latest decade 0.34°C/decade (grey line). The dotted lines show the extrapolated values for each line up to the year 2040.*

2.5. Summary and discussion of results

The occurrence of high Tmax, low Tmin, high Tmin and low Tmax records for a selected number of stations for the period of 1951–2019 across South Africa were analysed. This study is the first in South Africa that focus on record-breaking events rather than trends in the mean temperature or extreme temperature indices. This analysis was based on in situ climatic data rather than model data, as model data cannot always simulate extreme events effectively (Choi *et al.*, 2009).

2.5.1. Ratios

The ratio of high Tmax versus low Tmin records was the expected 1:1 in 1951 but increased to a record 9:1 in 2019, the last year of the analysis period. This shows that recently record-high temperatures occurred much more frequently than record lows. Researchers such as Meehl *et al.* (2009) and Trewin and Vermont (2010) found in their studies of record-breaking events in the USA and Australia that record highs were declining less slowly than record lows. The ratios in the USA and Australia were below 1:1 around 1960, increasing to around 2:1 from late 1990 to early 2000. Similar findings were found in this study as during the first decade (1951-1960), South Africa's ratio was 2:1 and during the period 1997 to 2009, it averaged 4:1. The ratio values found in this study show that high Tmax records were increasing at a higher rate towards the end of the study period than what USA and Australia studies found, which only considered the years up to 2006 and 2009 respectively. Studies in Europe for the period 1951 to 2013 showed similar high ratios in favour of high Tmax from the 1990s (Beniston, 2015), comparable to the South African results. A study considering the period 1880-2010 (Coumou *et al.*, 2013) found a fivefold increase in the number of high records globally while studying monthly mean values. This seems to suggest that high ratios in favour of maximum temperatures are rapidly increasing due to the increase in the number of high Tmax records rather than just a reduction in low Tmin records.

2.5.2. Occurrence of records

This study found that there was a different spatial pattern in the occurrence of the number of Tmax and Tmin records. Stations that recorded the highest occurrence of Tmax records don't necessarily record the highest number of Tmin records. For high Tmax records, the largest exceedances of observed vs. expected number of records were recorded by stations over the central parts of the country (Kimberley, Glen College and Bloemfontein). For high Tmin records, the spatial distribution of stations where the largest exceedances of observed vs. expected records was not confined to one region but was more widely distributed (Kimberley, Johannesburg, Pretoria and Mount Edgecombe). Research by Driver and Reason (2017) shows how the stronger than average Botswana High can be associated with increased subsidence and reduced cloud cover, leading to dry summers and above-average daytime temperatures over most of southern Africa. While Mahlobo *et al.* (2019) has also noted a decreasing cloud cover and increasing sunshine or solar radiation due to the strengthening of the Hadley cell. These findings can be associated with the expected number of Tmax records observed in the regions.

2.5.3. Interior and coastal stations

When comparing the interior and coastal stations, coastal stations are not showing as high ratios in favour of high Tmax records as interior stations. This could be due to the ocean's role in regulating temperature (Newell, 1979; Lambert and Chiang, 2007). In the last ten years of this study period, Cape Town and Cape Agulhas observed fewer average number of Tmax records per year than expected when considering their warming trend. For Tmin records, the coastal stations recording less than expected records were East London, George and Cape Columbine. These differences in the occurrence of records between interior and coastal stations will require further investigation if South Africa wants to formulate its climate change response strategy into local planning regimes, as stated in its National Climate Change Response Green Paper (DEA, 2011).

2.5.4. Acceleration of warming trend

This study shows that the number of high Tmax and some high Tmin records have increased above what is expected, even when the mean warming trend per station is considered. The increase in the number of records in recent years is due to the increase in the long term climatic warming trend. This increase in trend is nonlinear and concurs with studies by Trewin and Vermont (2010) in Australia and Pan *et al.* (2013) for China.

The change in the warming trend was, to some extent, able to predict the occurrence of temperature records. This agrees with studies by Wergen and Krug (2010) in their analysis of temperature records in central Europe. The increase in warming implies that a stabilization of the expected number of records will occur later in the future than is the case where near-constant warming (the same as over the analysis period) is assumed. Figure 2.7 presents an extrapolation of the increase in warming and an assumed constant warming trend. It is shown that by 2040, the difference between the expected records with accelerated warming is, on average, about four more per year (13 vs. 9), while currently, it is about two per year (12 vs. 10). The expected increase in Tmax records into the future also agrees with studies that show that temperature trends over South Africa are likely to increase (Engelbrecht *et al.*, 2015; Kruger *et al.*, 2019). Extended periods of high temperature by way of heat waves have also been projected to increase over South Africa (Russo *et al.*, 2014; Engelbrecht *et al.*, 2015; Russo *et al.*, 2016; Perkins-Kirkpatrick and Gibson, 2017; Mbokodo *et al.*, 2020), which will likely increase the occurrence of record-breaking temperatures. The mechanisms for driving the occurrence of record-breaking heat extremes and heat waves have been cited in the literature as El Niño, blocking high-pressure systems and soil-moisture feedbacks (Coumou *et al.*, 2013; Perkins, 2015). Particularly, over Southern Africa, the strengthening of the subtropical high-pressure belt is likely to play a role (Engelbrecht *et al.*, 2015) in that the subsiding branch of the circulation system is associated with clear skies and adiabatic warming.

The occurrence of record-breaking temperature extremes has different ramifications due to their spatial location. For high Tmax records, the exceedances occurred over regions which are important to South Africa agriculturally (Mbiriri, 2018). This is of concern as extreme temperature events can have disastrous effects on agriculture (Mearns *et al.*, 1984). Shew *et al.* (2020) showed that wheat yield losses were linked to heat extremes in South Africa. Maize, a stable crop for many South Africans, was also likely to decrease in yields as a result of the number of days where temperatures were greater than 30°C (Mangani *et al.*, 2019). There is a further concern in terms of the spread of pests and pathogens in a warming climate, which will add to crop losses (Mafongoya *et al.*, 2019). South Africa also has a rich biodiversity, and changes in temperature can change the vegetation structure of biomes where woody vegetation encroachers grasslands due to increases in temperature and CO^2 (Ziervogel *et al.*, 2014; Engelbrecht and Engelbrecht, 2016). The increase in above expected number of high Tmin temperatures occurred over highly populated areas such as Johannesburg and Pretoria. These high temperatures can cause heat-related illnesses, putting certain sectors of the population, such as the elderly, very young and people with certain pre-existing medical conditions, especially those without access to air conditioning, at risk (Luber and McGeehin, 2008). This is further exacerbated by the fact that many in South Africa live in informally constructed homes, resulting in highly fluctuating temperatures with indoor temperatures between 4 to 5 °C warmer than outdoor temperatures (Maller and Strengers, 2011). This is a concern as research in South African major cities found that a 1°C increase in daily ambient apparent temperature resulted in a 0.9% increase in the mortality rate (Wichmann, 2017). These are just some consequences of an increase in temperature for South Africa, but many more related to a wide range of social, economic and developmental aspects are possible (Ziervogel *et al.*, 2014).

With Africa's projected annual average temperature to increase by 1.5 times the global rate (Engelbrecht et al., 2015), adaptation could prove to be increasingly difficult, especially if the warming trend is nonlinear rather than just a monotone altered mean condition (Rahmstorf and Coumou, 2011). There will be even more stress on the more vulnerable sectors of society, who are more susceptible to change, suffer greater costs, and have less capacity to take mitigating action compared to those with access to resources (Mirza, 2003). With this in mind, policymakers, governmental departments, non-profit organisations (NGOs), disaster managers, farmers and infrastructure developers, to name a few, will need to understand the consequences and risks of the increased frequency of record-breaking temperature events in order that their response strategies are more meaningful. This also means that any international investment and/or donor funding needs to focus more on creating adaptive capacity rather than just responding to certain disasters (Mirza, 2003). With the impacts of climate change with respect to increases in extremes being substantiated by observations, adaptation measures to expect climate extremes should become more focused.

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Synopsis

By investigating trends in the occurrences of climate temperature records the study addressed Objective 1. The findings established that high Tmax records occurred more often than low Tmin records and that the ratio of occurrence has changed from 1:1 in 1951 to 9:1 in 2019. The study also found that the strongest trends in the probabilities of high Tmax and Tmin records did not coincide spatially. The high Tmax records with the largest exceedances occurred over the central parts of the country in places like Kimberley, Glen College and Bloemfontein. While high occurrences of high Tmin records were not confined to a specific region of the country, with places such as Kimberley, Johannesburg, Pretoria and Mount Edgecombe on the East coast having the highest number of these records. What was notable was that coastal stations did not show as high ratios in favour of high Tmax records as interior stations, which may point to the role of the ocean as a moderator of atmospheric temperatures. These findings assist in addressing Objective 5 of the research.

When considering the stations' individual warming trends, it was found that temperature records (Tmax and Tmin) had increased above what was expected. *The study thus concluded that the variable warming trend accelerating to about 0.34°C/decade recently was primarily accountable for the more than expected number of high-temperature records towards the end of the study period.*

With an increase in the trend of record-breaking daily high-temperature records above what is expected comes the concern that these temperatures could have severe social and environmental impacts. Humans and animals are designed to live within specific temperature ranges, and exposure to extreme unprecedented temperatures can negatively affect their health and in severe cases, lead to heat-related mortality. Similarly, plants are susceptible to high temperatures, which can negatively affect them depending on their stage of development. Thus, any exposure to record temperatures should be met with concern. These trends in record-breaking events should be considered when adaptation strategies are being developed by government, policy and decision-makers.

There was then an imperative to investigate to what extent the frequency and intensity of extreme temperatures were projected to change in the future, and which are discussed in the following chapter.

Chapter 3: Projected changes in temperature extremes for selected locations over South Africa

Preface

This chapter consists of one research paper that has been submitted for peer-review as follows:

McBride, C. M., Kruger, A. C., Johnston, C. and Dyson, L. 2023. Projected changes in temperature extremes for selected locations over South Africa. Submitted to Weather and Climate Extremes.

Having considered the trend in breaking temperature records, the study extended the scope to consider projected changes in hot temperature extremes. Most of the same climate stations as in the previous chapter were considered to facilitate comparisons. Observational temperature data at 22 locations and model data projections from the Coordinated Regional Climate Downscaling Experiment (CORDEX) were considered in this study. The projection data was corrected using a trend-preserving bias correction method developed by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). Two study periods of mid- (2036-2065) and far-future (2066-2095) were analysed for two Representative Concentration Pathways of RCP4.5 and RCP8.5. The bias correction method did enhance the representativity of actual observations, although an underestimation of the RPVs was still evident to some degree. Thus, the resultant values are considered to be conservative estimations. The study showed projected decreases in return periods of specific hot temperature extremes, implying more frequent recurrences and, therefore less time between extreme events. Not all locations were affected in the same manner, with interior stations showing a shorter interval between return periods as compared to coastal stations. The paper is expected to advance our understanding of projected changes in temperature extremes across South Africa, which addresses Objectives 2, 3, 5 and 6.

The paper was co-authored by A.C. Kruger, C. Johnston and L. Dyson. Ms. Johnston facilitated the program coding for bias correction. The conceptualization of the paper, collection and analysis of data together with the graphical outputs in the paper, was conducted by myself.

Projected changes in daily temperature extremes for selected locations over South Africa

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Abstract

Extreme events, especially very high temperatures, are expected to increase as a consequence of climate change. It is thus essential that localised studies be done to quantify the magnitude of potential changes so that proper planning, especially effective adaptation measures, can be affected. This study analysed annual extreme daily maximum temperatures for future climate change scenarios at 22 locations in South Africa, through analysis of the Coordinated Regional Downscaling Experiment (CORDEX) model ensemble datasets. The multi-model simulations were validated against observational data obtained from the South African Weather Service for the period 1976-2005. Two study periods of mid- (2036-2065) and far-future (2066-2095) were analysed for two Representative Concentration Pathways, i.e., RCP4.5 and RCP8.5. Bias correction was done on the model data for enhanced representativity of actual observations. However, systematic underestimations of extremes were still evident. The Generalized Extreme Value (GEV) distributions were fitted to the bias-corrected projections, and 1:10-, 1:50- to 1:100-year Return Periods Values (RPVs) were estimated. RPVs are likely to increase under both RCPs in the mid-and far-future periods, with the largest increase in RPVs set to occur towards the end of the century under the highest emission scenario. All stations showed an increase in the frequency of days with maximum temperatures above specific critical thresholds, with some stations under the RCP8.5 scenario *expected to experience temperatures of greater than 32°C (35°C) for more than 200 (100) days per year by the end of the century, an increase from a baseline of approximately 70 to 150 (14 to 83). Return Periods for 38°C for most stations are projected to be shorter than a year. Considering the likely underestimation of most of the results, the general implication is a strong likelihood that most places in South Africa will experience a strong increase in the intensity, duration, and frequency of very hot extremes in future, with potentially dire consequences to relevant socio-economic sectors.*

Keywords: *climate projections, scenarios, extreme temperatures, CORDEX, return periods, South Africa*

3.1 Introduction

As the global climate is warming, it is expected that the intensity and frequency of climatic extremes are likely to be affected (Fischer and Knutti, 2014; Saddique *et al.*, 2020). These changes in extreme events are likely to have a larger impact on human health and natural systems compared to the expected changes in the mean climate (Katz and Brown, 1992). According to the IPCC's Working Group I contribution to the Sixth Assessment Report (Arias *et al.*, 2021), the mean global temperatures have increased by 1.09°C (0.95°C to 1.2°C) during the period 2011-2020 from the preindustrial period of 1850 to 1900. RCPs are considered, which describe different climate futures and are dependent on the volume of greenhouse gases emitted in the future. The pathway numbers refer to the radiative forcing values in the year 2100. (Meinshausen et al., 2011). The IPCC's Working Group I contribution to the Fifth Assessment Report, which was the last IPCC report to use RCPs, highlights that the global mean surface temperatures averaged in the period 2081-2100 are "likely" to show a projected increase of 1.5°C relative to the preindustrial period if the world continues to follow a Representative Concentration Pathway (RCP) of 4.5 and 8.5 (high confidence). There is also high confidence that global average temperatures will likely be 2 °C above the pre-industrial period, under RCP8.5, by the end of the century (IPCC, 2013). The IPCC's Working Group I contribution to the Sixth Assessment Report goes on to state that there is now high confidence that the frequency of hot extremes has increased globally (Arias *et al.*, 2021).

With Africa projected to warm at a higher rate than the global average (Engelbrecht et al., 2015; Nangombe et al., 2019), the increase in the breaking of high Tmax and Tmin records is a reality across the country (see Chapter 2), low resilience and limited capacity (Fotso-Nguemo *et al.*, 2023) and large reliance on rain-fed agriculture (Serdeczny *et al.*, 2017) it is essential that changes in climate extremes are researched at a local level. Many studies have shown that hot extreme events have serious consequences for human, animal and crop health in the African context (Maluleke and Mokwena, 2017; Wichmann, 2017; Chersich *et al.*, 2018; Hlahla and Hill, 2018; Mafongoya *et al.*, 2019; Olabanji *et al.*, 2020), compared to more-developed parts of the world. In terms of human health, there have been studies done on increases in child mortality rates (Chapman *et al.*, 2022), heat stress (Garland *et al.*, 2015; Fotso-Nguemo *et al.*, 2023), increase in cardiovascular disease (Bühler *et al.*, 2022), and increases in hospital admissions (Makunyane *et al.*, 2023), all due to hot extremes. These temperature-related mortality impacts are very dependent on a wide range of socioeconomic and physiological factors (Asefi-Najafabady *et al.*, 2018), and thus the local context needs to be considered. Research into agricultural production has also noted the adverse effects of temperature extremes, which include, for example, cattle reducing their feed intake when temperatures reach above 35°C (Blackshaw and Blackshaw, 1994), implying less milk production and a general deterioration in animal health (Morrison, 1983; Bohmanova *et al.*, 2007). High temperatures during specific developmental stages of plant growth for crops such as wheat, maize and rice can significantly reduce yields (Rosenzweig *et al.*, 2001; Sarr *et al.*, 2019). In the developing world, this was equated to a 2.66 % lower growth in agricultural output for every 1°C increase in temperature (Dell *et al.*, 2012). Other impacts include more frequent, longer and more intense heat waves (Mbokodo *et al.*, 2020; Mbokodo *et al.*, 2023), changes in vector-borne disease outbreak patterns (Anyamba *et al.*, 2014), increase in armed conflict (Burke *et al.*, 2009) and increase in fire-danger days (Engelbrecht *et al.*, 2015), amongst others. As all these impacts are related to hot extremes, the expected increases thereof, rather than in the mean temperature, are more likely to affect society (Hegerl *et al.*, 2004).

Studies have shown that the trend in mean annual temperature for South Africa has increased in recent decades (Collins, 2011; Kruger and Sekele, 2013; MacKellar *et al.*, 2014; Kruger and

Nxumalo, 2016; Kruger *et al.*, 2020), with trends in hot extremes also having increased across the country (New *et al.*, 2006; Kruger and Sekele, 2013; Kruger *et al.*, 2019; Kruger *et al.*, 2020; McBride *et al.*, 2021; Van Der Walt and Fitchett, 2021). In terms of future projections, Almazroui *et al.* (2020) found that according to temperature projections over different African regions using the CMIP6 ensemble of models, temperatures are projected to increase over the eastern parts of South Africa from the present climate (1981-2010) under the RCP4.5 and RCP8.5 scenarios during the period 2030-2059 (2070-2099) by 1.4 (2.3)°C and 1.7 (4.1)°C respectively. Over the western parts of the country for the same periods and RCPs, projected increases of 1.6 (2.7)°C and 1.9 (4.7)°C are expected. The median projection of change in annual maximum temperatures from the CORDEX data for a similar period of 2080-2099 but compared to a present climate of 1971 to 2000 conducted by Archer *et al.* (2018) showed an increase of about 3°C for RCP4.5 to 5°C for RCP8.5 for the interior of the country, while coastal stations showed 1.5 to 2°C less of an increase.

A study by Hegerl *et al.* (2004) showed that it is now possible to detect anthropogenic influences by examining trends in extreme temperatures. Analysis of projections from model data sets such as those from the Coordinated Regional Climate Downscaling Experiment (https://cordex.org/domains/region-5-africa/) are suitable tools for looking at climate variability and change (Endris *et al.*, 2013; Iturbide *et al.*, 2022). These models are the primary tools for studying possible future climate changes (Kharin *et al.*, 2005) and can provide estimates for future extreme temperature changes.

This paper will thus focus on likely changes in the probabilities of future hot temperature extremes for 22 locations with homogeneous temperature time series over the CORDEX simulation period across South Africa. This type of research can assist in the mitigation and management of these types of events (Zwiers *et al.*, 2011; Frías *et al.*, 2012; Kuang *et al.*, 2021; Lee *et al.*, 2020), as well as evidence-based planning and preparedness (Turasie, 2021).

We use probable future changes in the occurrence of daily maximum temperatures above pre-defined thresholds, return period values (RPVs) for specified return periods, and likely future changes in return periods (RPs) of extreme temperatures from that expected in the present-day climate. Probability estimations are done by application of the Generalized Extreme Value (GEV) distribution, which has also been used by Kharin and Zwiers (2005), Kharin *et al.* (2007), Kharin *et al.* (2013), Kuang *et al.* (2021) and Turasie (2021) in related studies. By estimating RPs of specific magnitudes, one can estimate probabilities of occurrences of these events and be in a better position to plan for adaptation interventions (Almazroui *et al.*, 2021; Turasie, 2021). Therefore, understanding these changes will enable better local preparedness and assist in developing the necessary policy interventions (Ziervogel and Zermoglio, 2009).

The paper is set out with an introduction in Section 1, followed by a discussion of the data and methods, including bias correction, in Section 2. Results are presented in Section 3, while Section 4 discusses the results and summarises the implications.

3.2 Data and methods

3.2.1 Representative concentration pathways

When considering climate change, it makes sense to use a standard set of scenarios or “Representative Concentration Pathways” (RCPs), which contain air pollution emission, greenhouse gas concentration and land use trajectories (Van Vuuren *et al.*, 2011). This study considers two of these pathways: the intermediate scenario of RCP4.5 with radiation forcing levels of 4.5W/m2, where emissions peak around 2040 and then decline. The second is the RCP8.5, with radiation forcing levels of 8.5W/m^2, where emissions are not expected to decrease throughout the 21st century (Meinshausen *et al.*, 2011).

3.2.2 Data and methods

Model data was obtained from the CORDEX (https://cordex.org/domains/region-5-africa/) and in the form of dynamic downscaling to a 0.44° horizontal resolution by the Rossby Centre Regional Model (RCA4) forced across its lateral boundaries by nine Atmosphere-Ocean General Circulation Models (Table 3.1), run under CMIP5 (https://wcrp-cmip.org/cmip-phase-5-cmip5/. CMIP is a project of the World Climate Research Program (WCRP). Although CMIP6 model runs are already available (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=overview), the CORDEX downscaling is still being planned (https://wcrp-cordex.github.io/simulation-status/CORDEX_CMIP6_status.html). Historical simulations were created for the period 1976 – 2005 (current climate), while the projected data sets cover two future periods, i.e., mid- (2036-2065) and far-future (2066-2095). The historical simulations were compared to near-surface daily South African Weather Service temperature data at 22 locations (Figure 3.1.). The data were quality controlled and homogenized (Kruger *et al.*, 2019) and is the dataset used for ongoing research into mean and extreme temperature trends and records over South Africa (Kruger and Nxumalo, 2017; McBride *et al.*, 2021). The trigonometrical estimation method was used to estimate the model surface temperature at each station's location (Kruger *et al.*, 2019).

The historical simulations and future projections of the nine Atmosphere-Ocean General Circulation Models downscaled by RCA4 were considered for calculating the probabilities in hot extreme temperatures. The approach for the study was to take the annual highest daily maximum temperatures for the observed and the model data for each location and compare these for a common historical period of 1976-2005 to check for systematic errors in the models. Bias correction was then done to align the model data with the observations for each station. These corrections were then applied to the two projection periods of 2036-2065 (mid-) and 2066-2095 (far-futures). In the validation process, it is expected that the gridded CORDEX data values will reflect more rain days and fewer extremes than the point data against which it is validated. Alignment between annual maxima of the observations and model simulations were tested with the Kolmogorov–Smirnov (K-S) test at the 5% significance level. The rate of occurrence and probability of occurrence were investigated for a range of pre-defined extreme temperature thresholds. The study then looked at the potential risk of an extreme temperature by investigating the average number of days above critical temperatures for all models for the RCP4.5 and RCP8.5 for the mid- and far-futures. The average interval period between events, referred to as return periods (RPs), was estimated. The future RPs of the present RPVs, given the projected extreme value distribution parameters from the RCP4.5 and RCP8.5 for the mid-and far-future scenarios, were also determined.

Table 3.1: Projections from nine Atmospheric-Ocean General Circulation Models used in this study, after downscaled by RCA4.

Model	Institute (country)	Reference
A. CanESM2m	CCCMa (Canada)	(Arora *et al.*, 2011)
B. CNRM-CM5	CNRM-CERFACS (France)	(Voldoire *et al.*, 2013)
C. CSIRO-Mk3	CSIRO-QCCCE (Australia)	(Rotstayn *et al.*, 2013)
D. IPSL-CM5A-MR	IPSL (France)	(Hourdin *et al.*, 2013)
E. MICRO5	AORI-NIES-JAMSTEC (Japan)	(Watanabe *et al.*, 2011)
F. HadGEM2-ES	Hadley Centre (UK)	(Hirabayashi *et al.*, 2013)
G. MPI-ESM-LR	MPI-M (Germany)	(Ilyina *et al.*, 2013)
H. NorESMI-M	NCC (Norway)	(Tjiputra *et al.*, 2013)
I. GFDL-ESM2M	GFDL (USA)	(Dunne *et al.*, 2012)

Figure 3.1: *Locations of the 22 climate stations with temperature time series across South Africa, which were used in the analysis. The station list with coordinates and elevations is in Appendix B.*

3.2.3 Bias correction

A trend-preserving bias correction method developed by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel *et al.*, 2013) was applied to the CORDEX dataset. The data is divided into months, and the monthly mean and variance are corrected by constant offsets and multiplicative correction factors. Thus, the whole data sets were corrected, not just the extreme values, and by correcting the mean and variance biases, the extreme values may then be improved (Xu *et al.*, 2021). The correction factors are derived from the observational data and the simulated data for all nine models for the period 1976 to 2005:

Mean offset for each month:

$$C = (\sum_{i=1}^{n=30} T_{iObs} - \sum_{i=1}^{n=30} T_{iModel})/30 \quad (1a)$$

The correction for each month's daily temperature is then:

$$\tilde{T}_{ij}^{model} = C + T_{ij}^{model} \quad (1b)$$

i = for the specific year

j = for the particular day

Variance correction:

$$f(\Delta T_{Model}) = B \,.\, \Delta T_{Model} \quad (1c)$$

B is the slope of the linear regression on the rank ordered *Obs* ($\Delta \mathrm{T}_{Obs}$) and *Model* data ($\Delta \mathrm{T}_{Model}$) for a given month over the common 30-year period. The constant offsets and multiplicative correction factors are then applied to the simulated projection data.

The K-S goodness-of-fit test was used to validate the bias correction method. Similar studies have used such approaches (Ahmadalipour *et al.*, 2017; Xu *et al.*, 2017; Lim Kam Sian *et al.*, 2022). This nonparametric test quantifies the maximum distance between the empirical distribution functions derived from two different data samples, in this case, the observed and the model data (Lanzante, 2021). The 5% significance level was chosen; thus, if the *p-value* is larger than 0.05, the null hypothesis is accepted, that the samples are drawn from the same distribution. The statistic is defined as follows (Lim Kam Sian *et al.*, 2022):

$$D_{n,m} = \max\ |Obs_n(TXx) - \ Model_m(TXx)| \tag{2}$$

D = maximum distance between the empirical distribution functions

Obs = observational data

Model = simulated data

n and *m* = the number of elements for observational and model data respectively

TXx = highest annual maximum temperature

The effect of correcting the variance was not fully explored in terms of the distribution shapes of the tail of the distribution before and after the bias correction. However, the addition of the correction for variance is expected to be positive and thus provide more conservative estimates of return periods.

3.2.4 Critical values

Based on the literature, certain daily maximum temperatures were viewed as critical thresholds:

- +35°C - causes severe loss to crop yields for maize and wheat (Zhu and Troy, 2018) and cattle reducing their feed intake and dairy cows reduce their milk production (Morrison, 1983; Blackshaw and Blackshaw, 1994; Bohmanova *et al.*, 2007),
- +32 to +38°C - strong heat stress, +38 to +46°C - very strong heat stress and > 46°C - extreme heat stress in humans (Bröde *et al.*, 2012)

A count of daily maximum temperatures from all models for each station above 32°C, 35°C, 38°C and 46°C was made and averaged on an annual basis to quantify the probable annual frequency of temperatures above these thresholds in the mid-and far-futures under RCP4.5 and RCP8.5, compared to the present-day climate.

3.2.5 Extreme value analysis

The GEV model was applied to estimate the probabilities of extreme events (Kim Yeon-Hee *et al.*, 2020). This is considered the best-fit distribution for analyzing extreme maximum temperature (Ng *et al.*, 2022). Annual maximum temperatures for each station for both observed and model outputs were used as the series of independent observations to which the GEV distribution was fitted by the method of *L* moments (Hosking, 1990).

The GEV is defined as:

$$F(x) = e^{-(1-ky)^{1/k}} \quad k \neq 0 \tag{3.1a}$$

$$F(x) = e^{-e^{(-y)}} \qquad k = 0 \tag{3.1b}$$

k = shape parameter (determines the type of extreme value distribution)
y = standardised or reduced variate

When *k* = 0, the GEV is considered an Extreme Value Distribution Type I (Gumbel).

The standardized or reduced variate *y* is given by:

$$y = (x - \beta)/\alpha \tag{3.2}$$

α = scale or dispersion parameter
β = mode of the extreme value distribution
x = the extreme value

To estimate *α* and *β* we used the method of moments (Wilks, 2011):

$$\alpha = s\sqrt{6}/\pi \tag{3.3}$$

$$\beta = \bar{x} - \gamma\alpha \tag{3.4}$$

s = standard deviation of sample
$\bar{x}$ = sample mean
γ = 0.57721… Euler's constant

The focus was on 1:10-year return periods as a measure of more immediate outcomes, whereas the 1:50- and 1:100-year values provided a metric of more exceptional extremes of temperature (Xu *et al.*, 2018). This study averaged the RPVs from the participating models that passed the K-S test to give each station a "mean model" value (Alexander and Arblaster, 2009; 2017). This “mean model” value can thus be considered the consensus of the models. CORDEX model evaluations have shown that using mean model values is preferable as they outperform individual models (Soares *et al.*, 2019). Box-and-whisker plots were used to illustrate the interquartile model ranges for the 1:10- and 1:50-year RPVs. This provided an indication of the spread of values obtained from the various models.

In addition, the annual maximum temperature return period values for 1:10-, 1:50- and 1:100-years, based on the *recent period* (1976 – 2005), were then used together with the location and scale parameters of the future scenarios to calculate the future RPs for these particular present-day RPVs:

$$x = \frac{1}{e^{\left(\frac{\beta - TX_m}{\alpha}\right)}} \tag{4}$$

α = location parameter
β = scale parameter
TX_m = mean model return period value

3.3 Results

3.3.1 Validation of bias-corrected hot annual extreme simulations

In Figure 3.2, box-and-whisker plots illustrate how well the bias-corrected model temperatures were at representing the 1:10- and 1:50-year RPVs per station compared to the same return periods calculated from the observed temperatures for the period of 1976-2005. The respective observed 1:10- and 1:50-year RPVs per station are shown as yellow dots on the graph, with the desired outcome to be inside the associated box-and-whisker plot. The bias-corrected temperatures have more stations where the observed RPVs have their values within their box-and-whisker plots (Figure 3.2b and d) compared to the non-bias-corrected data (Figure 3.2a and c). Most stations show that the bias-corrected data are closer to the observed data values (Figure 3.2b and d) than before bias correction. However, some notable exceptions exist, namely at Cape Agulhas, Port Elizabeth and Cape Columbine, where the non-bias-corrected model temperatures were closer to the observations than the bias-corrected temperatures. This could be due to the 30-year reference period not being adequate in enabling the variability at these individual stations to be adequately sampled (Hempel *et al.*, 2013), but more so that the models are not effective in simulating the very high extremes that occur from time to time due to off-shore flow (Jury, 1985; Schumann and Martin, 1991). Nevertheless, considering all stations, the bias correction is effective in making the simulated data more representative of the observed data.

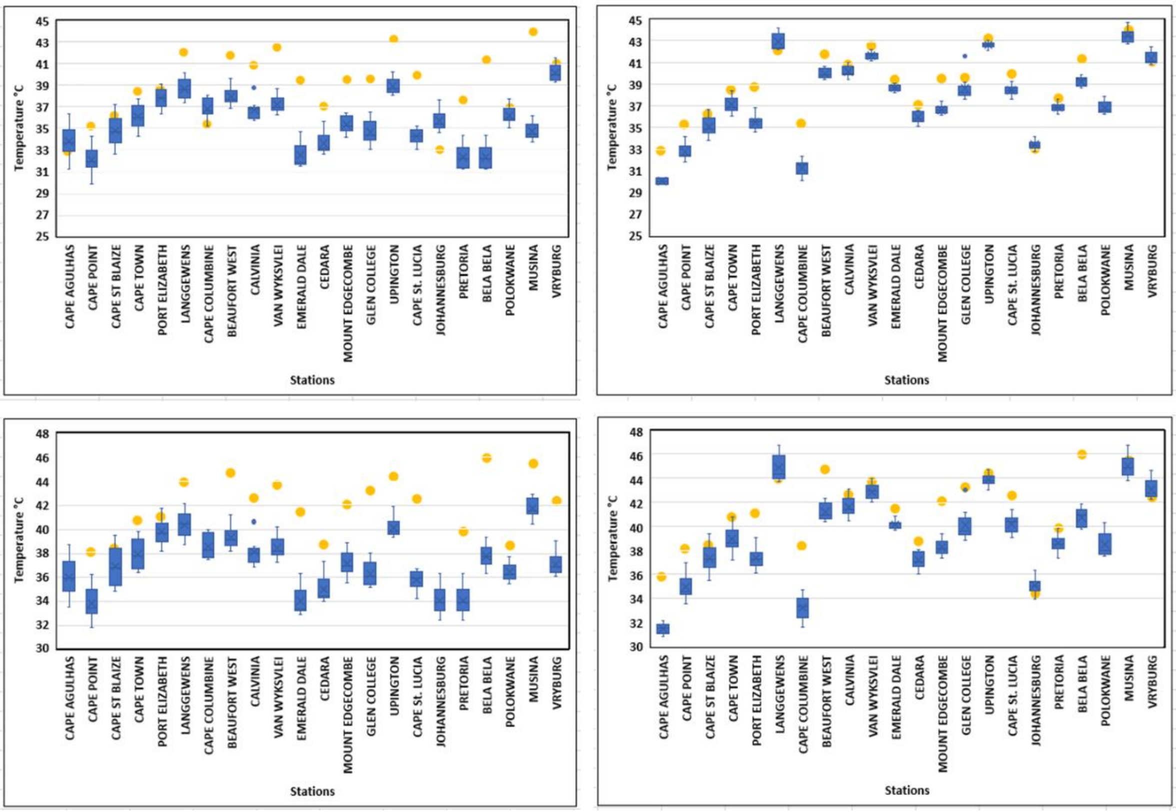

Figure 3.2: *Box-and-whisker plots from all models for 1:10 year and 1:50 year RPVs. Graphs a and c are obtained from the non-bias corrected data for 1:10 year and 1:50 year, respectively, while b and c are from the bias-corrected data for 1:10 year and 1:50 year, respectively. The bottom and top of the blue boxes in the graphs show Q_1 and Q_3. The minimum models' value is the bottom whisker, and the top whisker is the maximum models' value. The models' median is displayed with the line in the middle of each box. The floating blue points show outliers. The observed RPVs are shown with yellow dots.*

This underestimation of the observed 1:10 year RPVs meant that stations such as Port Elizabeth and Cape Columbine (Cape Agulhas and Mount Edgecombe) estimated the 1:10 year RPV to be 3.2°C and 4.1°C (2.8°C) lower than the observed RPVs. The interior stations showed less of a discrepancy between model mean and observed RPVs, with stations like Vryburg, Johannesburg and Langgewens even having slightly higher RPVs of 0.5°C, 0.4°C and 1.0°C, respectively, compared to the observed RPVs. This underestimation of RPVs was also seen in the 1:50-year values, with coastal stations such as Cape Columbine, Cape Agulhas, Mount Edgecombe and Port Elizabeth recording RPVs of 5.0°C, 4.3°C, 3.7°C and 3.6°C, respectively below the observed 1:50-year RPVs. Interior stations like Glen College, Beaufort West and Bela Bela also recorded below the observed 1:50-year RPVs by 2.9°C, 3.3°C and 5.1°C. The reason the models are not always able to represent observational RPVs well is probably due to the coarse resolution of the models compared to point measurements from observations (Iturbide *et al.*, 2022). Complex topography and boundaries between land and sea can also lead to large uncertainties and biases in simulating extreme events (Giorgi, 2019). Despite the above discrepancies between the observations and the model simulations, there was general agreement among the simulations from the models regarding increases in RPVs. Detailed K-S test results are presented in Table 3.2, indicating, in general, an improved fit for individual models after bias correction in terms of hot annual extreme values. 9% of the models passed the K-S test before bias correction compared to 66% after bias correction.

Only the models that passed the K-S test were used and averaged for each station to calculate RPVs and RPs. For example, Cape Point had only one model (CSIRO-Mk3) deemed acceptable by the K-S test for results from GEV analysis after bias correction, and thus, this was the only model considered for the calculation of RPVs and RPs for this station. Three stations (Port Elizabeth, Cape Columbine and Mount Edgecombe) did not have any of their models pass the K-S test at the 5% level, and thus their RPs and RPVs were not estimated. However, these stations did have models which passed the K-S test before bias correction, but further investigation showed that the relatively higher variance of these datasets affected the bias correction procedure in such a way as to decrease the correlation between the observations and simulations. Therefore, these stations' data were not used to calculate the RPs and RPVs due to the risk of underestimation of projected extreme temperature statistics. Other stations had variable results, but it is evident that the bias correction was more successful with interior stations than those closer to the coast in terms of annual maximum temperatures.

Table 3.2: K-S results for validation of bias-corrected annual maximum temperature simulations for each model per station: Red: Reject, Black: Accept hypotheses at the 5% level.

Model name **Station name**	**CanES M2m**	**CNRM-CM5**	**CSIRO-Mk3**	**IPSL-CM5A-MR**	**MICRO 5**	**HadGE M2-ES**	**MPI-ESM-LR**	**NorES MI-M**	**GFDL-ESM 2M**
Cape Agulhas	0.07	0.01	0.13	0.07	0.04	0.04	0.04	0.07	0.02
Cape Point	0.01	0.00	0.13	0.02	0.00	0.00	0.00	0.00	0.00
Cape St. Blaize	0.39	0.00	0.80	0.24	0.24	0.00	0.00	0.01	0.00
Cape Town	0.59	0.04	0.59	0.59	0.13	0.01	0.39	0.07	0.07
Port Elizabeth	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
Langgewens	0.00	0.39	0.02	0.07	0.39	0.13	0.04	0.13	0.13
Cape Columbine	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Beaufort West	0.07	0.04	0.59	0.80	0.39	0.39	0.04	0.00	0.24
Calvinia	0.80	0.39	0.95	0.80	0.95	0.59	0.07	0.59	0.80
Vanwyksvlei	0.01	0.00	0.04	0.13	0.13	0.01	0.04	0.07	0.04
Emerald Dale	0.23	0.80	0.24	0.39	0.80	0.39	0.80	0.59	0.80
Cedara	0.01	0.13	0.00	0.59	0.07	0.07	0.80	0.07	0.39
Mount Edgecombe	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Glen College	0.24	0.24	0.04	0.24	0.24	0.24	0.24	0.00	0.07
Upington	0.04	0.07	0.04	0.39	0.13	0.01	0.13	0.04	0.13
Cape St. Lucia	0.04	0.13	0.80	0.24	0.24	0.59	0.59	0.07	0.59
Vryburg	0.07	0.13	0.95	0.80	0.04	0.95	0.80	0.07	0.80
Johannesburg	0.13	0.39	0.80	0.80	0.39	0.80	0.59	0.59	0.80
Pretoria	0.24	0.80	0.80	0.80	0.95	0.39	0.80	0.95	0.39
Bela Bela	0.39	0.39	0.39	0.13	0.59	0.07	0.59	0.59	0.59
Polokwane	0.13	0.95	0.24	0.39	0.95	0.24	0.39	0.80	0.59
Musina	0.39	0.80	0.07	0.07	0.39	0.39	0.80	0.59	0.59

3.3.2 Critical temperature analysis

For the critical temperature analysis, we looked at all stations in the study, regardless of whether the station passed the K-S test. This was because counts of these critical temperatures were compared for each station's observed and projected model runs, and thus, it was not fundamentally relevant whether the specific stations passed the K-S test or not. When considering critical temperatures (Table 3.3) as defined in Section 3.2.4, under the two RCPs, the number of days above these critical temperature thresholds will become more frequent during the 2036-2095 period for all stations except for Cape Agulhas. For daily maximum temperature of 32°C and above, only four stations (Vanwyksvlei, Vryburg, Upington and Musina) recorded more than 100 days a year in the present climate (Table 3.3: grey column). The number of stations predicted to receive 100 days or more daily maximum temperature of 32°C and above will increase to six stations for the mid-future, further increasing to eight stations in the far future under RCP4.5. If the RCP8.5 pathway is followed, 13 stations will be predicted to receive 100 days or more of above 32°C in the far future. Under RCP8.5, by the end of the century, all stations except Cape Agulhas are set to measure temperatures above 32°C at least once a year, with six stations (Glen College, Bela Bela, Vanwyksvlei, Vryburg, Upington and Musina) projected to experience more than 200 days per year with daily maximum temperatures above 32°C.

Three stations (Vanwyksvlei, Musina and Upington) are set to experience 100 days or more annually of daily maximum temperatures above 35˚C in the mid-future under the RCP4.5, which is up from their present annual average frequencies of 59, 78 and 83 days respectively. By the end of the century, Vryburg (44 days annually in the present climate) will join these stations in measuring more than 100 days above 35˚C. Under the RCP8.5 scenario, by the end of the century, a further two stations (Glen College, Bela Bela) are forecast to experience these temperatures for more than 100 days on average, which is far above their current rate occurrence of 13 and 17 days, respectively.

What is more concerning is that some stations (Vanwyksvlei, Upington and Musina) under the RCP8.5 scenario are set to experience temperatures of greater than 38°C for more than 100 days per year for the far future, up from a current average of 23 days. Upington currently has no recorded temperatures above 46°C for the period of 1976 to 2005; however, by the end of the century under the RCP8.5 scenario, this is projected to increase to an average of 5 days a year.

Table 3.3: Present and projected average number of days per year with temperature above certain critical thresholds. Grey blocks the observation (1976-2005), green blocks indicate the RCP4.5 and yellow RCP 8.5. Days greater than 100 in blue and above 200 in red.

Station Name	Obs (1976 – 2005)				RCP4.5 (2036-2065)				RCP4.5 (2066-2095)				RCP8.5 (2036-2065)				RCP8.5 (2066-2095)			
	32°C	35°C	38°C	46°C	32°C	35°C	38°C	46°C	32°C	35°C	38°C	46°C	32°C	35°C	38°C	46°C	32°C	35°C	38°C	46°C
Cape Agulhas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cape Columbine	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	2	0	0	0
Cape Point	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	3	1	0	0
Cape St. Blaize	1	0	0	0	3	1	0	0	4	1	0	0	4	1	0	0	7	2	1	0
Port Elizabeth	2	0	0	0	6	1	0	0	8	1	0	0	8	1	0	0	16	4	1	0
Johannesburg	1	0	0	0	13	1	0	0	21	2	0	0	19	2	0	0	64	18	3	0
Cape Town	7	1	0	0	16	3	0	0	20	4	1	0	20	4	1	0	38	11	2	0
Mount Edgecombe	10	1	0	0	24	3	0	0	30	4	0	0	30	3	0	0	51	10	1	0
Cedara	11	1	0	0	30	5	0	0	36	8	1	0	35	7	0	0	65	22	4	0
Cape St. Lucia	26	4	0	0	54	13	1	0	64	16	2	0	65	16	2	0	110	36	7	0
Polokwane	19	2	0	0	57	11	1	0	72	18	2	0	71	17	2	0	128	53	12	0
Emerald Dale	33	7	0	0	69	25	5	0	82	33	8	0	80	32	7	0	127	67	25	0
Pretoria	22	2	0	0	70	16	2	0	91	26	3	0	86	24	3	0	153	72	21	0
Langgewens	49	20	5	0	75	36	13	0	85	44	17	0	87	44	17	0	118	69	32	1
Beaufort West	60	20	2	0	93	42	10	0	104	50	14	0	104	51	15	0	142	83	33	0
Calvinia	58	18	2	0	97	45	11	0	110	55	16	0	100	51	15	0	151	94	41	0
Vanwyksvlei	114	60	15	0	154	102	46	0	166	116	59	0	165	114	59	0	201	156	102	2
Glen College	72	14	1	0	142	54	8	0	168	76	16	0	162	69	13	0	235	149	62	1
Bela Bela	82	17	1	0	153	58	11	0	178	78	19	0	174	75	18	0	246	147	59	0
Vryburg	110	44	9	0	163	93	34	0	180	113	49	0	178	109	46	0	228	165	98	3
Upington	141	83	28	0	178	125	67	0	192	141	83	0	192	140	82	0	229	182	130	5
Musina	152	78	25	0	204	127	58	0	195	127	63	0	216	140	70	0	234	171	105	3

3.3.3 Projected future temperature extremes changes

When looking at the RPs in terms of reaching critical temperatures, under the current climate, four stations (Cape Agulhas, Cape Point, Cape St. Blaize and Cape Columbine) have RPs of greater than a year for 32°C however, by the mid-future under RCP4.5 this drops to just two stations (Cape Agulhas, and Cape Columbine) (Table 3.4). When considering temperatures of 35°C and above under the RCP8.5, most stations will have RPs of less than 1 year by the end of the century. Considering daily temperatures of 38°C under RCP4.5 for the near-(far-) future, 10 (11) stations will experience return periods of less than a year, while under RCP8.5, this will increase to 11 (15). Daily maximum temperatures above 46°C are exceptional for South Africa, with 45.3°C the current high Tmax record for Upington and 42.5°C for Musina. What is of concern is that there is a possibility of exceeding this value (46°C) every 9 and 6 years for these two stations, respectively, in the far future under RCP4.5. If we consider the RCP8.5, then another four stations (Musina, Vanwyksvlei, Vryburg and Langgewens) are expected to experience return periods of less than three years for daily maximum temperatures of above 46°C by the end of the century. Thus, while temperatures above 46°C are presently not experienced at the stations in this study, under RCP8.5, these will occur at least once a year in places such as Vanwyksvlei, Glen College, Bela Bela, Vryburg, Upington and Musina by the end of the century.

Table 3.4: The RPs in years for critical temperatures to be reached under RCP4.5 and RCP8.5 for the period 2036-2065 and 2066-2095. Orange blocks represent RPs of less than a year while blue block RPs of over 1000 years.

Station Name	**RCP4.5 (2036-2065)**					**RCP4.5 (2066-2095)**					**RCP8.5 (2036-2065)**					**RCP8.5 (2066-2095)**				
	32°C	**35°C**	**38°C**	**46°C**	**48°C**	**32°C**	**35°C**	**38°C**	**46°C**	**48°C**	**32°C**	**35°C**	**38°C**	**46°C**	**48°C**	**32°C**	**35°C**	**38°C**	**46°C**	**48°C**
Cape Agulhas	34	706	🟦	🟦	🟦	11	144	🟦	🟦	🟦	10	136	🟦	🟦	🟦	4	31	270	🟦	🟦
Cape Columbine	4	41	427	🟦	🟦	2	13	97	🟦	🟦	2	15	103	🟦	🟦	🟧	5	35	🟦	🟦
Cape Point	🟧	7	58	🟦	🟦	🟧	3	20	🟦	🟦	🟧	4	20	🟦	🟦	🟧	1	11	🟦	🟦
Johannesburg	🟧	3	53	🟦	🟦	🟧	2	24	🟦	🟦	🟧	2	20	🟦	🟦	🟧	🟧	2	754	🟦
Port Elizabeth	🟧	2	13	🟦	🟦	🟧	1	8	🟦	🟦	🟧	1	8	🟦	🟦	🟧	🟧	2	294	987
Cape St. Blaize	🟧	1	8	965	🟦	🟧	1	5	380	🟦	🟧	1	8	606	🟦	🟧	1	2	83	206
Mount Edgecombe	🟧	🟧	7	🟦	🟦	🟧	🟧	4	🟦	🟦	🟧	🟧	6	🟦	🟦	🟧	🟧	1	🟦	🟦
Cedara	🟧	🟧	7	🟦	🟦	🟧	🟧	3	🟦	🟦	🟧	🟧	4	🟦	🟦	🟧	🟧	1	343	🟦
Polokwane	🟧	🟧	3	🟦	🟦	🟧	🟧	1	🟦	🟦	🟧	🟧	1	🟦	🟦	🟧	🟧	🟧	226	🟦
Cape Town	🟧	🟧	5	🟦	🟦	🟧	🟧	3	🟦	🟦	🟧	🟧	2	🟦	🟦	🟧	🟧	1	270	🟦
Pretoria	🟧	🟧	2	🟦	🟦	🟧	🟧	1	🟦	🟦	🟧	🟧	1	750	🟦	🟧	🟧	🟧	48	211
Cape St. Lucia	🟧	🟧	1	🟦	🟦	🟧	🟧	🟧	513	🟦	🟧	🟧	🟧	581	🟦	🟧	🟧	🟧	161	857
Glen College	🟧	🟧	1	287	🟦	🟧	🟧	🟧	74	307	🟧	🟧	🟧	95	399	🟧	🟧	🟧	4	12
Emerald Dale	🟧	🟧	🟧	522	🟦	🟧	🟧	🟧	250	🟦	🟧	🟧	🟧	134	714	🟧	🟧	🟧	10	40
Bela Bela	🟧	🟧	🟧	🟦	🟦	🟧	🟧	🟧	550	🟦	🟧	🟧	🟧	246	🟦	🟧	🟧	🟧	16	100
Beaufort West	🟧	🟧	🟧	🟦	🟦	🟧	🟧	🟧	520	🟦	🟧	🟧	🟧	378	🟦	🟧	🟧	🟧	38	383
Calvinia	🟧	🟧	🟧	298	🟦	🟧	🟧	🟧	213	🟦	🟧	🟧	🟧	139	🟦	🟧	🟧	🟧	14	91
Vanwyksvlei	🟧	🟧	🟧	100	🟦	🟧	🟧	🟧	30	292	🟧	🟧	🟧	22	154	🟧	🟧	🟧	2	13
Vryburg	🟧	🟧	🟧	44	248	🟧	🟧	🟧	19	111	🟧	🟧	🟧	20	97	🟧	🟧	🟧	2	10
Langgewens	🟧	🟧	🟧	32	187	🟧	🟧	🟧	11	52	🟧	🟧	🟧	10	43	🟧	🟧	🟧	3	11

Upington				**22**	**177**				**9**	**71**				**8**	**57**				**1**	**7**
Musina				**9**	**60**				**6**	**40**				**5**	**33**					**5**

The spatial distribution of change over South Africa for RCP4.5 and RCP8.5 for the mid-and far-futures shows a general increase in 1:10-year extremes, as shown in Figure 3.3. For RCP4.5 for the mid-future, most stations increase by 2°C to 3°C compared with the current climate. This warming will increase by a further 1°C in the future for this RCP. It is predicted that Glen College (central Free State) will have the highest increase of 4.2°C by the end of the century. Under the RCP8.5 scenario, the RPVs for the mid-future showed most stations are set to experience an increase in 1:10 year extremes of 2°C to 3.8°C. Thus, warming for the mid-future for RCP8.5 is similar to the warming expected for the far-future under the RCP4.5 scenario, indicating that the warming is expected to occur at an increased rate under RCP8.5 compared to RCP4.5. By the end of the 21st century, under the RCP8.5 scenario, most stations are anticipated to experience RPV changes of greater than 4°C with places such as Emerald Dale and Glen College by as much as 7.2°C and 8.9°C respectively. The averages of RPVs for the mid-future (far-future) under the RCP4.5 are 40.6°C (41.5°C); however, if RCP8.5 materializes, the average will increase to 43.8°C by the end of the century. The models generally underestimate the change compared to the observational period, meaning that the projected RPVs could be even higher.

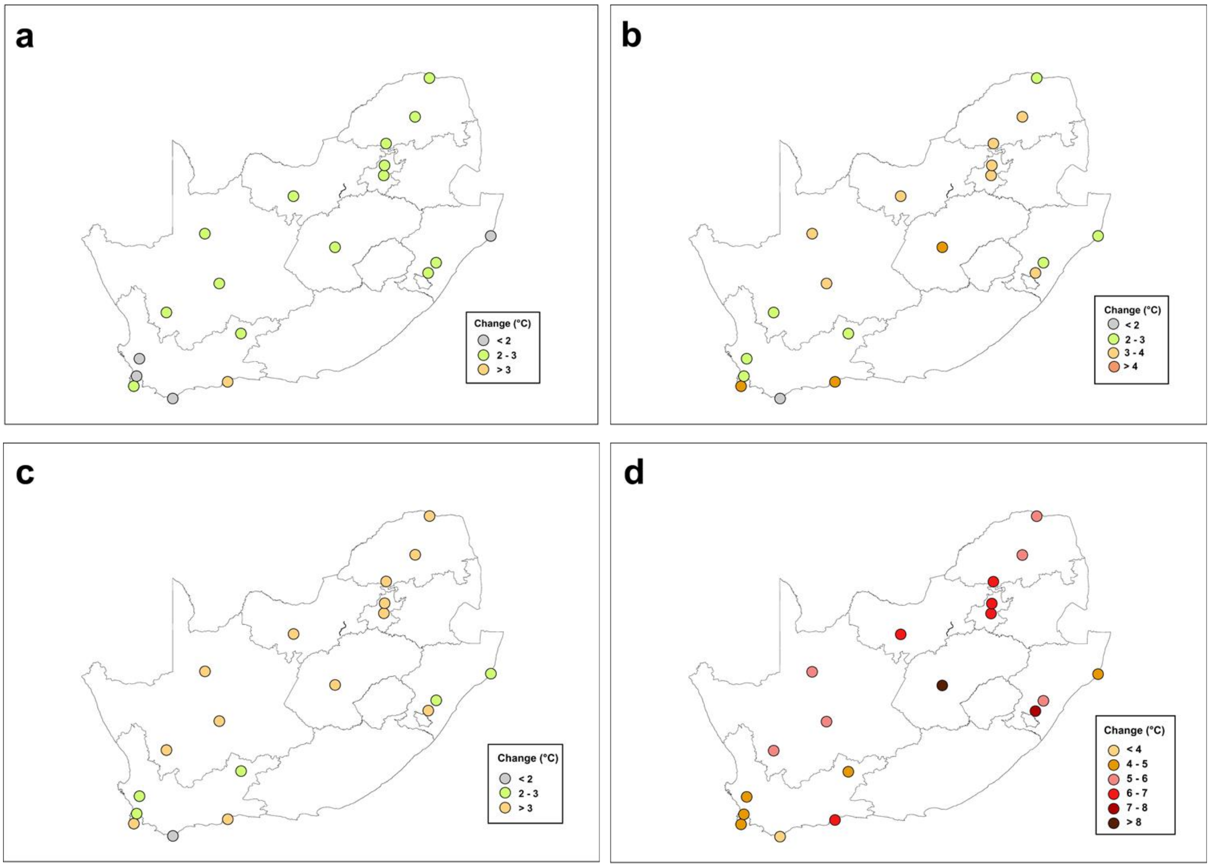

Figure 3.3: *The change in estimated 10-year RP for RCP4.5 for 2036-2065 (a) and for 2066-2095 (b), and RCP8.5 scenarios 2036-2065 (c) and 2066-2095 (d).*

Figure 3.4 presents the average increase in the 1:50-year RPVs, reflecting a similar spatial pattern to the results in Figure 3.3. In the mid-future for RCP4.5, the increase is predicted to be, on average, around 2.4°C, increasing by another degree in the far-future period. The RPVs are, on average, projected to be 42.4°C (43.3°C) for the mid-future (far-future) under RCP4.5. For the RCP8.5, mid-future change is forecast between 1.8°C and 3.8°C, increasing in the far future to above 4.0°C for all stations. Emerald Dale and Glen College are set to experience the greatest change, of 8.0°C and 10.8°C, respectively, by the end of the century. Under RCP8.5, these RPVs for mid-future (far-future) are projected to increase to an average of 43.5°C (46°C), respectively. Once again, the models generally underestimate the change compared to the observational period, which means that the projected RPVs could be even higher. This is especially true for stations like Cape Agulhas, Beaufort West, Cape Point and Bela Bela, which show more than 3°C underestimation in terms of the models representing the 1:50 year RPVs compared to the observed RPVs.

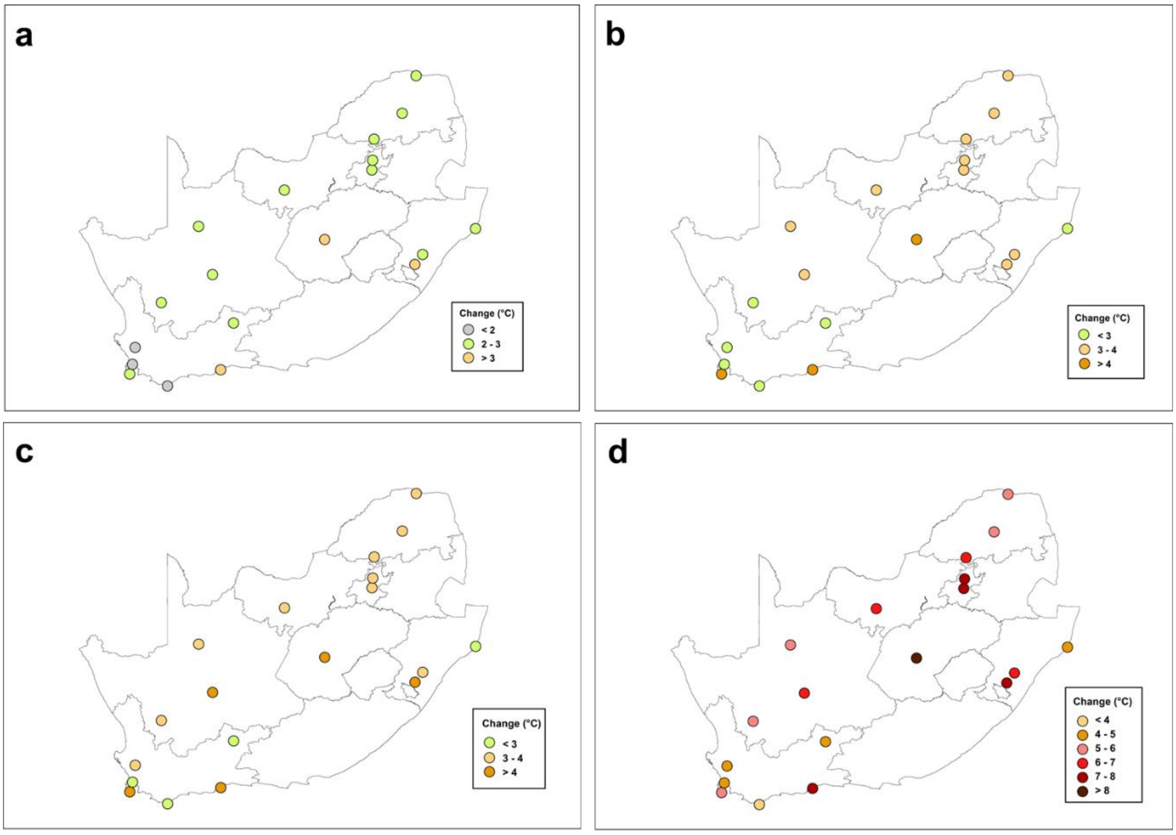

Figure 3.4: *The change in estimated 1:50 year RP for RCP4.5 for 2036-2065 (a), 2066-2095 (b), and RCP8.5 scenarios 2036-2065 (c) and 2066-2095 (d).*

3.3.4 Number of years to reach current RPVs

The study then investigated the number of years it would take to reach the current 1:10-, 1:50- and 1:100-year RPVs given the projected alpha and beta values taken from the RCP4.5 and RCP8.5 for the mid-and far-futures (equation 4) (Table 3.5). The current 1:10-year RPVs will be expected to occur annually at most places in the interior in the RCP4.5 scenario for the mid-future, while coastal stations are expected to have RPs of between 1.5 and 3.5 years.

Table 3.5: List of stations with their present RPVs (C°) for 1:10-, 1:50-and 1:100-year (green columns). This is followed by the number of years it will take to reach these values under the RCP4.5 and RCP8.5 for the two study periods of mid- (2036-2065) (blue columns) and far-future (2066-2095) (orange columns).

Station name	**RPVs (C°)**			**RCP4.5 (2036-2065)**			**RCP4.5 (2066-2095)**			**RCP8.5 (2036-2065)**			**RCP8.5 (2066-2095)**		
RPVs	*1:10 yr*	*1:50 yr*	*1:100yr*	*1:10 yr*	*1:50 yr*	*1:100yr*	*1:10 yr*	*1:50 yr*	*1:100yr*	*1:10 yr*	*1:50 yr*	*1:100yr*	*1:10 yr*	*1:50 yr*	*1:100yr*
Cape Agulhas	30.1	31.5	32.1	3.5	14.7	27.3	2.1	7.0	11.8	2.0	6.7	11.4	0.9	2.5	3.9
Cape Point	32.8	35.0	35.9	1.5	6.9	13.3	0.7	2.9	5.2	1.2	3.8	5.2	0.2	0.6	0.8
Cape St. Blaize	35.2	37.4	38.4	1.6	5.9	10.4	1.1	3.7	6.2	1.6	5.4	9.2	0.6	1.7	2.5
Cape Town	37.2	39.0	39.8	2.5	15.2	32.8	1.4	5.8	10.6	1.2	4.7	8.7	0.4	1.6	2.8
Cape St. Lucia	38.6	40.3	41.0	1.8	8.0	15.3	1.3	5.1	9.4	1.4	5.7	10.5	0.3	1.4	2.5
Langgewens	43.1	45.0	45.9	2.3	13.2	27.9	1.1	4.8	8.9	1.1	4.9	9.9	0.3	1.2	2.3
Beaufort West	40.1	41.3	41.8	0.6	2.8	5.4	0.3	1.5	2.8	0.3	1.5	2.8	0.0	0.2	0.3
Calvinia	40.3	41.7	42.3	0.9	3.7	6.9	0.4	1.8	3.6	0.5	1.9	3.5	0.1	0.3	0.5
Vanwyksvlei	41.8	43.0	43.5	0.7	2.9	5.4	0.2	0.9	1.7	0.3	1.1	1.9	0.0	0.1	0.2
Emerald Dale	38.8	40.2	40.9	0.7	2.7	4.8	0.3	1.3	2.3	0.3	1.1	1.9	0.1	0.2	0.3
Cedara	36.0	37.3	37.8	0.8	3.1	5.5	0.4	1.6	2.8	0.5	1.8	3.3	0.1	0.3	0.5
Glen College	38.7	40.2	40.8	0.9	2.9	4.8	0.4	1.2	1.9	0.5	1.5	2.4	0.1	0.3	0.4
Upington	42.8	44.0	44.5	0.7	2.7	4.8	0.3	1.1	2.0	0.4	1.2	2.0	0.0	0.1	0.2
Vryburg	41.5	43.2	43.9	0.9	3.8	7.1	0.4	1.6	3.1	0.6	2.2	3.8	0.1	0.2	0.4
Johannesburg	33.5	35.1	35.8	0.8	3.7	7.1	0.4	1.7	3.2	0.5	1.9	3.4	0.1	0.2	0.3
Pretoria	37.0	38.7	39.4	0.9	4.0	7.7	0.4	1.9	3.6	0.6	2.2	3.9	0.1	0.2	0.4
Bela Bela	39.4	40.8	41.5	0.6	3.3	6.9	0.3	1.4	3.0	0.4	1.6	3.0	0.0	0.1	0.2
Polokwane	37.0	38.6	39.3	0.9	4.4	8.6	0.5	2.3	4.4	0.6	2.4	4.5	0.1	0.3	0.5
Musina	43.6	45.2	45.8	1.0	4.2	7.8	0.5	2.4	4.6	0.6	2.5	4.5	0.1	0.3	0.6

In terms of the current 1:50-year RPVs for the RCP4.5, interior stations (coastal stations) are projected to reach these temperatures in 3 to 4 (6 to 15) years for the mid-future, while for the far future, this is expected to drop to 1 to 2 (3 to 7) years. For the RCP8.5, as expected, the current 1:50-year RPVs are reached earlier (mid-future), with most internal stations expected to reach these RPVs within a year by the end of the century. The coastal stations will reach this value in 3 or less years.

When considering RPVs of 1:100 years, these temperatures would be reached by most interior stations for mid-future (far-future) for the RCP4.5 in 5 to 9 years (2 to 5 years), while coastal stations are set for RPVs of 13 to 33 years (5 to 12 years). When considering the RCP8.5 scenario, most internal stations will reach the current RPVs in 1 year or less by the end of the century, with coastal stations having slightly longer RP of up to 4 years.

3.4 Discussion and conclusions

This study analysed the return periods of high daily temperature extremes over South Africa, focusing on projections of these conditions under two RCPs of 4.5 and 8.5 scenarios for two future periods (2036-2065 and 2066-2095). CORDEX model data was used, and the period of 1976-2005 was selected for comparison between observed and the model temperatures at 22 locations over South Africa. Bias corrections, which preserved the long-term trend with respect to the monthly mean values, were conducted to enhance confidence in the projected absolute values of the temperatures. This method is advocated for by Casanueva *et al.* (2020) because it maintains the original raw climate change signal while alleviating biases. To our knowledge, this is the first time this particular bias correction method was used to correct projection model data (CORDEX) over South Africa with observational point data. After the bias correction, the models showed an underestimation of the RPVs compared to the observational RPVs. This underestimation of maximum temperature when using CORDEX data has also been found over southwest Ethiopia (Demissie and Sime, 2021), Malawi (Warnatzsch and Reay, 2019), Africa (Soares *et al.*, 2019), Australasia (Evans *et al.*, 2021) and Australia (Di Virgilio *et al.*, 2019). Thus, it is suggested that the projected RPVs in this study could be higher, and therefore, the results should be used with caution. It should also be noted that uncertainty in RPVs will normally increase for longer time periods.

The statistical analysis of the daily temperature extremes in this study found that RPVs are likely to increase under both RCPs in the mid- (2036-2065) and far-future (2066-2095) periods. The highest increase in RPVs is set to occur towards the end of the century under a high emission scenario compared to the mid-future or under a RCP4.5 scenario. When considering extreme temperature changes, the 1:50-year RPVs under the RCP4.5 for mid- (far-) future for most stations are projected to increase by 2°C to 3°C (3°C to 4°C) compared with the period of 1976-2005. The 1:50-year RPVs for interior stations, under the RCP8.5 scenario, are projected to have temperature increases of greater than 5°C compared to the current climate by the end of the century. Interior stations showed higher RPVs for all scenarios and periods when compared to most coastal stations, indicating the possible moderating effect of the ocean on temperatures. These findings are very similar to those of Archer *et al.* (2018) and

Almazroui *et al.* (2020), who also found similar projected increases in temperatures with higher projected increases over the interior compared to coastal areas.

This study used one CORDEX regional climate model; thus, the results depend very much on this particular model. Future studies might like to consider other regional models to see if they provide similar findings and help better describe the uncertainties associated with the projections.

Despite the fact that this model possible underestimation high temperatures in this study, they still have the potential to exacerbate the projected increase in dry spells (Haensler *et al.*, 2011) and contribute to the frequency and intensity of heat wave events over South Africa (Engelbrecht *et al.*, 2015; Dosio, 2017; Mbokodo *et al.*, 2023) and increase the risk of high fire danger days (Singo *et al.*, 2023).

High temperatures are also of major concern for human, animal and crop health. More than half the stations in the study are set to record more than 100 days of temperature above 32°C annually by the end of the century under the RCP8.5. Six of these stations, all in the country's interior, are set to experience more than 200 days of temperatures above 32°C annually. These types of temperatures can cause adverse respiratory and cardiovascular effects and are of concern among the elderly, those in poor health and/or those with limited or no access to medical facilities (Garland *et al.*, 2015; Bühler *et al.*, 2022). In terms of agriculture, crop seedling diseases increase in temperatures above 32°C when the soil is saturated (Rosenzweig *et al.*, 2001), and dairy cows suffer severe heat stress in these temperatures (Bohmanova *et al.*, 2007). There is thus a need for awareness to be created to target vulnerable communities and industries regarding the dangers of the predicted changes in daily temperatures, as well as providing strategies to prevent loss of life and livelihoods.

In terms of higher temperatures above 35°C (38°C), six (three) of the stations in the study are expected to exceed these temperatures more than 100 days annually by the end of the century under the RCP8.5. These high temperatures are of major concern from a health perspective as they have the potential to cause heat cramps as well as possible heat exhaustion, which may lead to heat stroke, especially if one is engaged in physical activities such as manual labour or one does not have access to adequate air conditioning (Garland *et* *al.*, 2015; Fotso-Nguemo *et al.*, 2023). These temperatures may be exacerbated by the urban heat island effect, and thus, mitigation measures in terms of how we construct our houses and cities needs to be urgently reviewed (Luber and McGeehin, 2008). Rainfed agricultural systems are vulnerable to changes in climate (Serdeczny *et al.*, 2017), especially high temperatures (Zhu and Troy, 2018). These high temperatures can cause various degrees of damage depending on the duration of the temperatures and the developmental stage of the crop (Rosenzweig *et al.*, 2001). This, coupled with too much or too little rainfall, can make matters worse (Rosenzweig *et al.*, 2001). These high temperatures can also affect the behaviour of pollinators where, for example, honey bees spend more time collecting water to cool the hive than delivering crop pollination services (Rader *et al.*, 2013). There is thus a need to consider the vulnerability of the types of crops grown and those who grow crops and or keep livestock, especially where this is considered subsistence farming (Thornton *et al.*, 2021). Plans need to be implemented to assist these farmers with providing shade and necessary water for their crops and animals. In a study in KwaZulu-Natal by Hlahla and Hill (2018), it was found that local communities felt they lacked knowledge about climate change and believed they could do nothing to deal with the impacts, thus education on farming adaptions will become increasingly important as the climate changes.

It is suggested that consideration be given to changes in extremes rather than just looking at changes in the mean. This is because small changes in mean annual temperature can lead to significant changes in hot extremes. Therefore, industries affected by changes in climate will be advised not to base their assessments of future climate scenarios solely on changes in mean temperature. If they do this, they could be considering lower estimates of change rather than if they had considered changes related to extreme daily temperatures. By way of example, when looking at adaptation strategies to effectively reduce the impact of heat stress on domesticated livestock, if decisions are based solely on projected increases in mean temperature rather than changes in extreme temperatures, these interventions may not necessarily be adequate in providing the anticipated adequate protection for reducing the heat stress, and thus additional investment may be needed at a later stage.

The results of this study suggest that South Africa will experience a high increase in the intensity, duration, and frequency of hot extremes in the future. With extreme temperatures set to increase at a faster rate than the mean temperature increase, there is an urgent need for South Africa to heed the call made by Ziervogel *et al.* (2022) to become climate resilient and look for ways to develop "Climate Resilient Development Pathways". It also needs to do all it can to advocate for a global reduction of greenhouse gas emissions, as high concentrations of these gases in the atmosphere can lead to increases in localized hot extremes.

3.5 Acknowledgements

We thank the Coordinated Regional Climate Downscaling Experiment (CORDEX) for the availability of model data for this study.

3.6 References

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Synopsis

The spatial extent of extreme and record-breaking daily temperatures across South Africa has been demonstrated. The results indicate (and reconfirm the results in Chapter 2) the country's interior being not only the area prone to breaking more high Tmax and high Tmin records compared to the rest of the country, but also the area where projected increases in temperature are the strongest. Temperatures of 32°C and above can cause heat stress, with temperatures greater than 35°C resulting in severe crop yield losses and animal stress, while temperatures of 38°C and above can cause heat stroke. It is thus of concern that some stations analysed are projected to experience more than 200 days a year with temperatures greater than 32°C by the end of the century under RCP8.5 compared to an average of 112 days in the current climate. These same stations are also projected to record 100 days of temperatures greater than 35°C for the same period. Upington is set to experience, on average, 127 days per year of temperatures above 38°C under RCP8.5 by the end of the century. Upington currently (2010-2019) breaks 17 daily high Tmax records per year, indicating that it is in an area which experiences extreme events regularly, and this is likely to increase in the future. Another example is Glen College, which currently breaks around 26 high Tmax records a year and is projected to record 244 days of temperatures above 32°C and 152 days above 35°C by the end of the century under RCP8.5. Even under RCP4.5, by the end of the century, these stations will experience more than 100 days of temperatures greater than 32°C. This means that even if the world can limit its greenhouse gas emissions, these stations, amongst others across South Africa, will still experience an unusually high number of health-adverse hot extremes in future. This does not bode well for human and ecological systems, which are already struggling with very high temperatures.

With the objectives related to extreme temperatures addressed in the previous chapters, the remaining research focuses on extreme daily rainfall, which will address Objective 4.

Chapter 4: Changes in Extreme Daily Rainfall Characteristics in South Africa: 1921 – 2020

Preface

This chapter consists of one published peer-reviewed paper as follows:

McBride, C.M., Kruger, A.C. and Dyson, L., 2022. Changes in extreme daily rainfall characteristics in South Africa: 1921–2020. *Weather and Climate Extremes*, *38*, p.100517. https://doi.org/10.1016/j.wace.2022.100517.

South Africa, with its highly variable climate, is prone to localized flooding in many regions, and thus, the study investigated changes in extreme daily rainfall characteristics across the country. The research also considered the likelihood of breaking individual precipitation records, with some preliminary analysis done around this. These preliminary results found that most stations had broken the expected number or lower than the expected number of highest daily rainfall amounts annually. In itself, such a result suggests that no real changes occurred in the characteristics of extreme rainfall across the country. In light of this result, alternative approaches were considered to investigate possible changes in extreme rainfall in more detail due to its importance to many socio-economic sectors. Thus, it was decided to consider precipitation extremes in terms of exceeding predefined threshold values of 50mm, 75mm and 115mm based on previous research across South Africa to investigate the change in occurrence of extreme daily rainfall values. To quantify any historical changes over the last century, the study considered two 50-year periods of 1921-1970 (Period 1) and 1971-2020 (Period 2).

The results showed that although the number of rain days had not changed between the two periods, the probability of receiving extreme amounts of rainfall had. Continuous probability distribution (gamma distribution) was used to examine whether there were changes between Periods 1 and 2 for each of the 70 rainfall stations well distributed across South Africa. To investigate the changes in the probability of multi-year extremes, the fact that precipitation extremes may occur more than once a year was accounted for by applying the POT method.

Increases were evident in 1:10-, 1:50- and 1:100-year RPVs for most stations in the latter half of the analysis period. These stations also showed a decrease in RPs during this same period in terms of receiving significant rainfall (>50mm), heavy (>75mm) and very heavy (>115mm) rainfall.

After the research was published, it came to the author's attention that an error had been made in the calculations of the POT values. The journal was able to change the maps in the paper but not the text. It is to be noted that the corrections did not affect the main findings of the paper. However, the RPVs and RPs for some stations are incorrectly reported in the publication; the corrections are presented in the table below. This chapter contains the corrected text.

Table 1: Adjustments to RPVs as a result of corrections to POT distribution parameters. (Corrected values are hyperlinked to text in the paper)

RPV/RP	Station	Old value	Corrected value
1:10RPV	Hlobane, not Mount Edgecombe	80mm	50mm
1:10RPV	Kareedouw	138mm	87mm
1:10RPV	Dwars in die Weg	75mm	36mm
1:10RPV	Gingindhlovu	140mm	85mm
1:50RPV	Northern and eastern parts of the country	400mm	200mm
1:50RPV	Letaba District, Gingindhlovu and Mount Edgecombe	600mm	270mm
1:50RPV and 1:100RPV	The north-eastern and eastern parts of the country	400mm	150mm
Decrease in return periods	Stations over the western interior	5 years	10 years
1:50RPV	Dwars in die Weg not Calitzdorp	200mm	90mm
1:100RPV	Dwars in die Weg	250mm	103mm
An increase of	Dwars in die Weg	55% and 25%	67% and 72%

My co-authors are A.C. Kruger and L. Dyson. I conceptualised the paper and analysed and interpreted the results.

Changes in Extreme Daily Rainfall Characteristics in South Africa: 1921 – 2020

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Abstract

Many areas in South Africa are prone to localized flooding. With climate change already said to affect the intensity of rainfall, there is a need to investigate if there is a change in the probability of significant to extreme daily rainfall across South Africa. This was investigated through the analysis of the daily time series of 70 manual rainfall stations over the period 1921 to 2020. The analysis period was divided into two equal periods of 50 years for comparison. With the application of the gamma distribution, it is shown that most stations experienced an increase in the probability of receiving more than 50mm per day, defined as significant rainfall, in the latter half of the analysis period. Also, most stations showed an increase in their 1:50- and 1:100-year return period values, with some stations over the eastern parts showing increases of over 100mm. There was also an increase in the probability of "heavy rainfall" (>75mm) and "very heavy rainfall" events (>115mm) between the first and second half of the analysis period for most stations over the country when applying the Peak-Over-Threshold approach. In summary, the results indicate that, although the number of rain days has remained near-constant over the 1921 - 2020 period, the probability of experiencing significant and extreme daily rainfall events has generally increased for most South African regions. This is of concern as rainfall of this nature can have serious consequences in terms of flooding, erosion, and damage to agriculture and infrastructure.

Keywords: *daily rainfall, climate change, extremes, trends, variability, disaster risk reduction, return periods, flooding, South Africa*

4.1 Introduction

Changes, e.g. intensification, in the hydrological cycle have been cited as possible consequences of a changing climate (Lehmann *et al.*, 2018). These changes, especially in terms of frequency, intensity, and duration of precipitation events, can have many social and environmental impacts (Contractor *et al.*, 2021). With rainfall events expected to intensify (increased rainfall over shorter timeframes) globally in a warming world (Trenberth, 2011; Zhongming *et al.*, 2020; Contractor *et al.*, 2021; Du *et al.*, 2022) there is a real threat of increases in flooding events (Hirabayashi *et al.*, 2013) as well as possible damage to infrastructure which may have been designed according to a stationary climate (Smithers, 2012; Johnson *et al.*, 2021). If structures are thus not designed to take into account the potential extreme events in a changing climate, the loss of life and the economic impact could be significant (Johnson and Smithers, 2019). This was witnessed in the recent flooding event in South Africa, where over 40 000 people in the KwaZulu-Natal coastal areas suffered the effects of high rainfall, with some areas receiving record daily rainfall amounts (Pinto *et al.*, 2022).

Several global studies have found that the annual maximum daily rainfall extremes are increasing over land in intensity and/or frequency (Alexander *et al.*, 2006; Westra *et al.*, 2013; Donat *et al.*, 2013; Lehmann *et al.*, 2015; Dunn *et al.*, 2020; Seneviratne *et al.*, 2021; Lawrence *et al.*, 2022). These global studies show a lack of consistency in patterns of extreme rainfall over Southern Africa as well as low confidence in the trend over this region due to a lack of data and supportive regional analysis. Regional studies in the Northern Hemisphere (Zhang *et al.*, 2013); the UK (Christidis *et al.*, 2021); the USA (Mallakpour and Villarini, 2017) and Japan (Yamada *et al.*, 2020), however, found increases in intensity and frequency of extreme precipitation events. Lehmann *et al.* (2015) found for the period 1981 to 2010, a 12% higher occurrence of global record-breaking rainfall events compared to the frequency expected in a stationary climate.

Most of the above studies link the increases in intensity and/or frequency of extreme rainfall events to increases in temperature as a result of anthropogenic climate change. As surface temperatures increase due to climate change, the atmosphere's water content changes. These increases in the water-holding capacity of the atmosphere equate to ~7 % per degree of warming, assuming constant relative humidity (Clausius-Clapeyron rate) (Allan *et al.*, 2014). With more moisture available, the nature of rainfall events is thus likely to become more intense with increased rainfall rates (Trenberth *et al.*, 2003). Therefore, the intensity of extreme precipitation events is likely to increase, even in areas where average precipitation is projected to decrease (Westra *et al.*, 2013). Some studies have even suggested that the atmospheric response could exceed the Clausius-Clapeyron rate, especially for convective precipitation (Lehmann *et al.*, 2015). However, the relationship between extreme rainfall and atmospheric temperatures is complex, with other factors such as changes in the atmospheric circulation patterns, atmospheric stability, latent heat, moisture convergence, cloud size, and the degree of mesoscale organisation playing a role (Guerreiro *et al.*, 2018). Thus, changes in extreme rainfall patterns are thought to be highly regionalized (Westra *et al.*, 2013; Contractor *et al.*, 2021).

4.1.1 Rainfall patterns and extremes in South Africa

South Africa’s rainfall distribution is diverse and increases from below 200mm in the west to above 1200mm per annum in the east (Kruger, 2007). This is largely due to its geographic position being situated between 22˚ and 34°S, complex topography and the fact that the southern African subcontinent is surrounded by the warm Agulhas current on the eastern coast and cold Benguela current on the west (Tyson and Preston-Whyte, 2000). The position, together with the ocean influences, sets up a range of rain-producing mechanisms, ranging from mostly convective rainfall over the central, northern and eastern parts of the country in summer to mid-latitude cold fronts which move across the south-western Cape and southern coastal regions, mostly in the austral winter (Favre *et al.*, 2016). Therefore, South Africa can generally be divided into four seasonal rainfall zones, with their distinctive rain-producing mechanisms of summer, late summer, winter, and all-year maxima (Kruger, 2007).

Early research on rainfall patterns from 1880 to 1972 by Tyson *et al.* (1975) found no evidence of decreased annual rainfall over South Africa and showed no spatial clustering regarding trends. Later research by Sen Roy and Rouault (2013) found a positive trend in extreme hourly precipitation events during summer for most of South Africa, with the strongest trend over the southeast coastal region, extending inland in a north-eastward direction to include the country's western areas. An increase in trend for annual daily rainfall extremes was also found by Kruger and Nxumalo (2017) over the west of South Africa, including the southern interior, for the 1921 to 2015 period. When it came to the intensity of extreme rainfall, Mason *et al.* (1999) found that 70% of the country experienced significant increases when comparing the period 1931-1960 with that of 1961-1990. This study has also noted a decrease in extreme rainfall events over the northeastern part of South Africa, with Kruger and Nxumalo (2017) also observing a decrease in rainfall in some places over the far north-eastern parts of the country. In summary, historical studies showed overwhelming evidence of mostly increases in rainfall extremes over South Africa, although certain regions showed an opposite trend.

In conjunction with the observed historical trends, research using model projections of a future climate found the intensity of extreme rainfall is likely to increase in a warming world (Westra *et al.*, 2013). Engelbrecht *et al.* (2013) and Abiodun *et al.* (2020) found an increase in projected extreme rainfall events over Southern Africa. Pohl *et al.* (2017) found a likely increase in rainfall amounts associated with the 1% wettest days by the end of the 21st century over Southern Africa, although the number of rain days is expected to decrease.

4.1.2 Motivation for the research

In a country where rainfall is highly variable, such as South Africa (Van Rooyen *et al.*, 2010), there is a real need to understand any changes in the hydrological cycle if effective water resource management is to be planned for (Molobela and Sinha, 2011). There is also a need to understand extreme rainfall events as these are likely to cause flooding. Although flooding in South Africa may not be as frequent or affect as large areas as drought, these events can cause sudden disasters that have consequences, for example, for human life and settlements, water management, the built environment in general, and agriculture. The 11th to 13th April 2022 severe flood event, caused by a cut-off low, that devastated KwaZulu-Natal is an example of how heavy rainfall can be the cause of severe impact, with 443 human casualties and more than 40 000 people displaced (ECHO, 26 April 2022). The loss and damage of infrastructure is set to run into billions of South African Rand. Other recent extreme events in the country include the flooding of the Cape Town area on the 28th to 29th of June 2021, where an estimated 6300 people were affected, and more than 3250 buildings were flooded. The 23rd and 24th of January 2021 saw Tropical Cyclone Eloise cause severe flooding over large areas of the Limpopo Province. Other such events include Tropical Cyclone Eline on the 23rd and 24th of February 2000 and Tropical Cyclone Domoina on the 28th of January 1984, which caused extensive damage to infrastructure and loss of life. One of the most disastrous flooding events in living memory occurred on the 25th of January 1981 when a cut-off low was responsible for intense rainfall over the Laingsburg area where 425 mm fell in 24 hours, causing widespread destruction, with 102 people losing their lives (SAWS, 1991). The very heavy rainfall which occurred during these events was associated with well-organized synoptic-scale weather systems. However, localised extreme convective rainfall also occurs over South Africa, such as on the 9th of November 2016, when 90 mm of rain fell in an hour near OR Tambo International Airport in Gauteng (Simpson and Dyson, 2018). Thus, understanding any changes in the likelihood of extreme rainfall is critical for strategic planning for future extreme events, town and city planning and possible adaptation of the built environment for the design-life of structures to accommodate any possible increases in extremes (Smithers, 2012).

Osborn *et al.* (2000) suggested that one should consider the change in the number of wet days or the change in the distribution of intensities, or a combination of both, to investigate changes in the distribution of rainfall at a specific location. This paper examines, with applicable statistical analysis, any changes in the probability and return periods of multi-year extremes (with relatively low probabilities) of daily rainfall events over South Africa. The paper is divided into three sections: First, a description of the climate data sets and statistical methodologies are discussed. The results are presented in the second section, followed by a discussion of these results with concluding remarks, including a comparison to relevant climate projections.

4.2 Data and Methodology

Daily rainfall values from a total of 70 long-term rainfall stations were selected for analysis across South Africa, with locations presented in the map in Figure 4.1. The stations are spatially fairly well distributed across the country and have not moved location. All stations used a manual standard rain gauge for the whole study period, with daily measurements taken at 08:00 local time. The stations have near-complete data for the complete analysis period, i.e. at least 90% data availability. High rainfall values were checked where possible with original rainfall returns to ensure that amounts had been correctly captured. A similar approach to Mason *et al.* (1999) was adopted, whereby the data period is divided into two successive periods. In this study, the data from each station was split into two successive periods of 50 years each, i.e. 1921– 1970 and 1971–2020 (referred to as Period 1 (first) and Period 2 (second) hereafter).

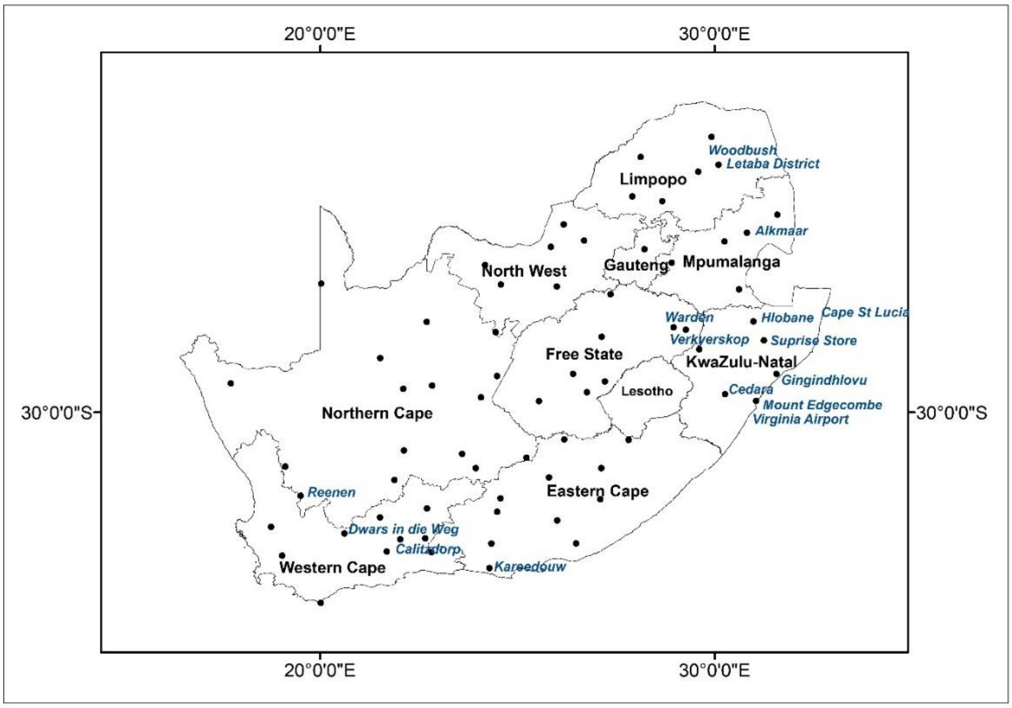

Figure 4.1: *Locations of the 70 rainfall stations which were used to analyse the changes in the occurrence of daily rainfall extremes over the period 1921 – 2020. Black text indicates provincial names plus Lesotho and blue text names of stations referred to in this study. The station list with coordinates and elevations is in Appendix B.*

4.2.1 Definition of significant and extreme rainfall events

When considering heavy daily rainfall events for the Gauteng Province (see Figure 4.1 for location), Dyson (2009) recommended that percentiles be used to identify and consequently define significant (90^{th} percentile), heavy (95^{th} percentile) and very heavy rainfall (99^{th} percentile). Utilizing all available rainfall data (>=1mm) over Gauteng, the 90^{th} percentile was determined to be approximately 59mm. This value was then adjusted to 50mm, the threshold value for *significant rainfall*, to correspond with what was used operationally by the South African Weather Service when issuing heavy rainfall warnings at the time. Due to the diverse rainfall climate of South Africa (Kruger, 2007), it follows that the categorisation of significant or extreme rainfall events based on percentiles alone can vary significantly on a regional basis, mainly due to the variability in the probabilities of specific rainfall amounts to occur. The 99^{th} percentile was calculated for all the stations in the database, and most of the stations had 99th percentile values of between 40mm and 60mm for both Periods 1 and 2 (Figure 4.2a and b). The threshold of 50mm was therefore also considered here as the threshold for *significant rainfall* for the country as a whole. There was an increase of 2% on average for the number of wet days from Period 1 to Period 2. This, and the distribution of the actual rainfall values, will affect the percentile values between the two periods. However, examining Figure 4.2, the majority of the country exhibits a 99th percentile value of between 40 and 60 mm, regardless of the analysis period.

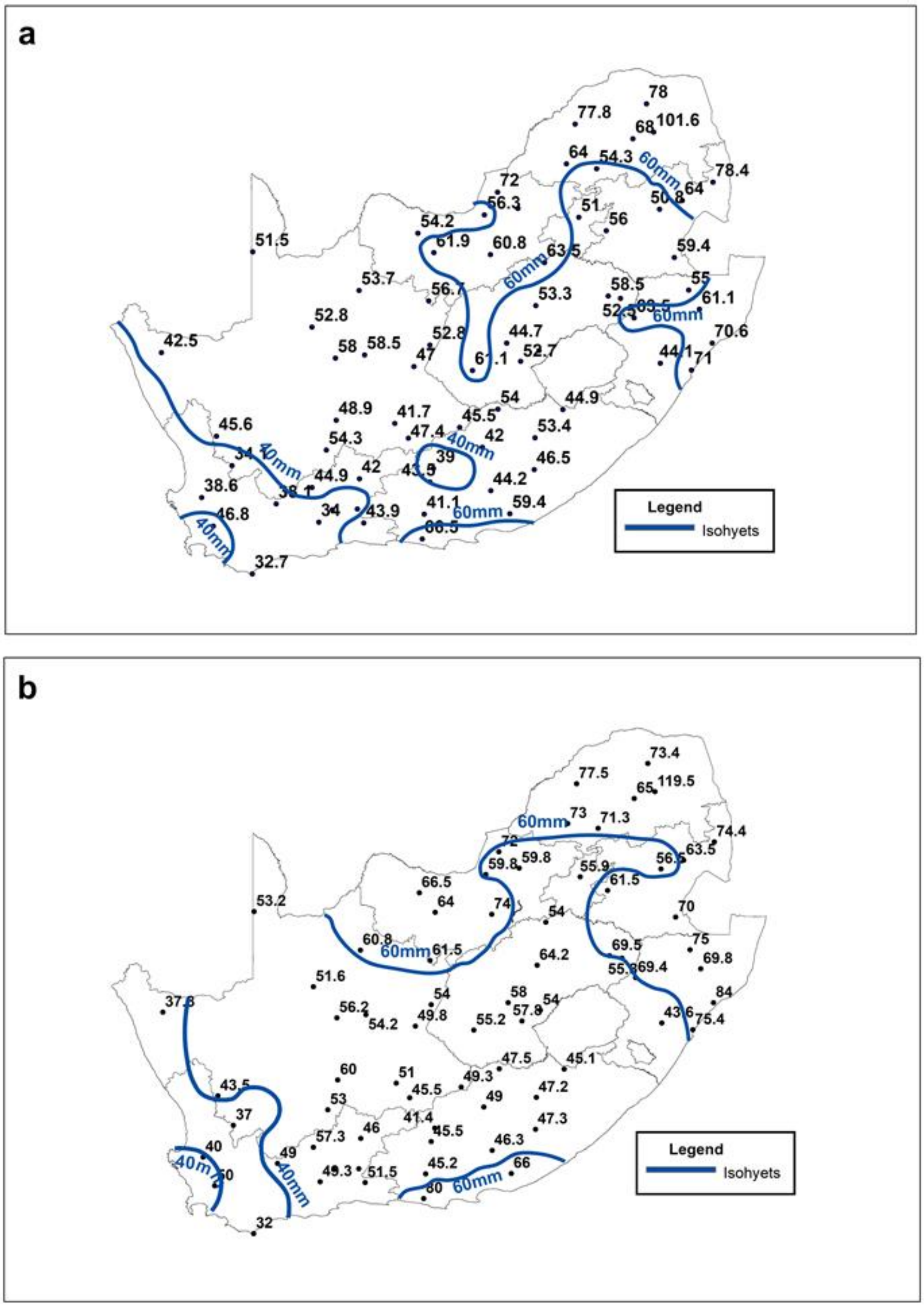

Figure 4.2: *99% percentile of all daily rainfall events (>=1mm) for Period 1 (a) and Period 2 (b). Isohyets were drawn for the 40mm and 60mm values.*

In terms of extreme rainfall events, daily amounts which are unlikely to occur every year, i.e. a return period of two years or longer, were considered. Extreme or very heavy daily rainfall was identified by Bradley and Smith (1994) when at least 125mm occurred at a station in 24 hrs, while Chen and Yu (1988) required a total of 130mm in a day. Dyson (2009) defined very heavy rainfall over Gauteng as a daily amount of 115mm. This value is somewhat less but in the same range as Bradley and Smith (1994) and Chen and Yu (1988); therefore, 115 mm was also adopted as the threshold for *very heavy rainfall* in this paper. The same logic was followed by classifying 75mm as a *heavy rainfall* event. Considering the 99th percentile values depicted in Figure 4.2, where values vary between 32mm and 120mm, daily rainfall threshold values of 75mm and 115mm were accepted to reasonably represent extreme event thresholds over South Africa in general. Using a percentile value alone to define an extreme rainfall event does not consider the impacts of such events. For example, if an extreme rainfall event is defined as 20mm according to a percentile-based value, the impact will probably be non-significant in terms of the likelihood of flooding or damaged infrastructure. Therefore, we reverted to absolute values of 50mm, 75mm and 115mm, as defined above. This definition informs the statistical approach to be followed in the estimation of the probability of specific heavy rainfall events to occur. In addition, the large spatial variability of the 99th percentile value motivated the further investigation of possible changes in the maximum rainfall amounts expected over specified return periods, which is not dependent on an absolute definition of a threshold for an extreme rainfall event.

4.2.2 Analysis methodology

Contingency tables have been used in various meteorological studies (Ihara *et al.*, 2007; Fowler *et al.*, 2010; Maldonado *et al.*, 2013; Mittermaier *et al.*, 2022). Therefore, as an initial approach, this method was used to examine individual stations' data with respect to changes in the general distribution of daily rainfall intensity. Rainfall events were counted which were pre-defined as below meaningful (i.e. 1 – 5mm) (meaningful being close to the typical daily evaporation rate), meaningful but not very heavy (5-50mm) and heavy or extreme (above 50mm), between Periods 1 and 2. Contingency tables of 3-row (below 5mm, 5-50mm and above 50mm) × 2-column (Periods 1 and 2) were constructed for each station with both row and column totals calculated (Conover, 1999). The χ^2-test for the difference in probabilities was applied to test whether there was any difference in the occurrence of daily rainfall in the predefined categories.

Following the results of the application of the data to contingency tables, the general distribution of daily rainfall was then examined to see if there were changes between Periods 1 and 2 for each rainfall station. The gamma distribution was used for this as it is a continuous probability distribution that is widely used in studies to model continuous variables such as rainfall that have a right-skewed distribution (Wilks, 2011; Martinez-Villalobos and Neelin, 2019). The probability density function (pdf) of the gamma distribution is defined as:

$$g(x) = \frac{1}{\beta^{\lambda}\Gamma(\gamma)} x^{\gamma-1} e^{-\frac{x}{\beta}} \tag{1}$$

β = scale parameter
γ = shape parameter
$\Gamma(\gamma)$ = ordinary gamma function.

However, this research mainly focuses on extreme daily rainfall values, and the gamma distribution can underestimate extreme behaviour, which is characterised by the right tail of the distribution (Papalexiou *et al.*, 2013; Cavanaugh *et al.*, 2015). Therefore, the analysis of extreme event probabilities was approached through the application of extreme value distributions. The most widely applied extreme value distribution is the Generalised Extreme Value (GEV) distribution, specifically Type I (Gumbel). It is a good fit for extreme rainfall, which has no negative values (Coles *et al.*, 2001).

GEV is defined as:

$$F(x) = e^{-(1-ky)^{1/k}} \quad k \neq 0 \tag{2.1a}$$

$$F(x) = e^{-e^{(-y)}} \qquad k = 0 \tag{2.1b}$$

k = shape parameter (determines the type of extreme value distribution)
y = standardised or reduced variate

When the shape parameter is equal to 0, the GEV is considered to be an Extreme Value Distribution Type I (Gumbel).

The standardized or reduced variate y is given by:

$$y = (x - \beta)/\alpha \tag{2.2}$$

α = scale or dispersion parameter
β = mode of the extreme value distribution
x = the extreme value

To estimate α and β we used the method of moments (Wilks, 2011):

$$\alpha = s\sqrt{6}/\pi \tag{2.3}$$

$$\beta = \bar{x} - \gamma\alpha \tag{2.4}$$

s = standard deviation of sample
$\bar{x}$ = sample mean
γ = 0.57721… Euler's constant

However, in the application of the GEV, significantly underestimation or overestimation of extremes can occur due to the fact that only a small sample of the total data set can be utilized (i.e. only one block (usually one year) maxima are used as input data). In some cases, some of these values might not even be considered extreme, e.g. the annual maximum during an exceptionally dry year. The Gumbel distribution was, therefore, only applied to investigate temporal changes in its distribution parameters (α = scale or dispersion parameter, β = mode of the extreme value distribution). Thus, an additional approach was followed to estimate more realistically the return periods for specific threshold values, as well as the expected maxima for specific return periods. Due to the fact that extreme values can occur more than once in a year, the sampling of these events can be improved by the application of e.g. the Peak-Over-Threshold (POT) method, which can then be used to estimate return periods for extreme events (Thiombiano *et al.*, 2017). The advantage of this method is that an extreme event or value is predefined and utilises all values above this threshold, providing that most of the values are independent, preferably more than 90% (Mailhot, 2013). The values above this threshold are known as exceedances and are assumed to have a generalised Pareto distribution with three parameters (Castillo and Hadi, 1997; Coles *et al.*, 2001), which could be simplified to the Exponential distribution with two parameters (e.g. if there is not sufficient motivation to use three distribution parameters). In the POT method, it is important to choose the threshold value in a manner that includes enough values which are considered to be extreme and not include too many non-extreme values, which will probably lead to an underestimation of very extreme low-probability values (Tramblay *et al.*, 2013). The 99th percentile of daily rainfall is widely considered to be the threshold of extreme rainfall (Thiombiano *et al.*, 2017), and therefore, the stations' 99th percentile rainfall values were considered to be the thresholds for each station for each period. The GPD was fitted to these values:

$$F(X) = 1 - [1 - \left(\frac{k}{\alpha}\right)(x - \xi)]^{1/k} \tag{3.1}$$

ξ = selected threshold. For k = 0 the GPD simplifies to the exponential (EXP) distribution

$$F(x) = 1 - e^{-[(x - \xi/\alpha]}$$

(3.2)

The crossing rate of the threshold is defined as

$$\lambda = n/M \tag{3.3}$$

n = total number of exceedances

M = total number of years in time series

Specific return periods (in years) can then be calculated from Abild *et al.* (1992):

$$X_T = \xi + \left(\frac{\alpha}{k}\right)[1 - \lambda T)^{-k]} \qquad if\ k \neq 0 \tag{3.4a}$$

$$X_T = \xi + \alpha \ln(\lambda T) \qquad if\ k = 0 \tag{3.4b}$$

The distribution parameters α and *k* can be estimated with

$$\hat{k} = \left[\frac{b_0}{2b_1 - b_0}\right] - 2 \tag{3.5a}$$

$$\hat{\alpha} = (1 + \hat{k})b_0 \tag{3.5b}$$

Using the above method, the return period values (RPVs) for 1:10-, 1:50-, and 1:100-year for each station for each period were estimated. These return periods were selected as these are generally used as input to design periods of infrastructures such as sewers, water-treatment plants and dams (Brière, 2014). The Student's *t*-test was used to test for significant differences between the average return period values of Periods 1 and 2 at the 95% confidence limit. Return periods were then estimated for the predefined 50mm, 75mm and 115mm thresholds.

The results were mapped using the inverse distance weighting method. This study used six stations to estimate cell values, with stations closer to the point being estimated having more influence on that point in the averaging process (Johnston et al., 2001). When stations are far apart, as in this study, this interpolation method performs well (Bhowmik, 2012).

4.3 Results

4.3.1 General distribution of rainfall amounts

When counting the number of wet days (>=1mm) for all the stations, we found, on average, a 2% increase between Periods 1 to 2. When dividing these rain days into three categories of below 1 - 5mm, 5 - 50mm and greater than 50mm, we found an average percentage increase of 15%, 0.3% and 4% in these events, respectively, between Period 1 and Period 2. A total of 66% of stations showed a significant difference at the 95% confidence interval when applying contingency tables between categories of 1 - 5mm, 5 - 50mm and greater than 50mm between Period 1 and Period 2.

4.3.2 Spatial change in probability of significant rainfall

To further investigate the findings from the contingency tables, the possible difference in probability of receiving 50mm or more on a rainy day from the gamma distribution (Equation 2.1) for the two periods was investigated. *81%* of stations were found to have a higher probability of receiving above 50mm in Period 2 compared to Period 1. These stations are depicted as blue dots in Figure **4.3**, and apart from a region along the western escarpment, are well distributed throughout South Africa. All the stations collectively showed a statistically significant increase in the probability of receiving greater than 50mm in Period 2 on a rainy day, compared to Period 1.

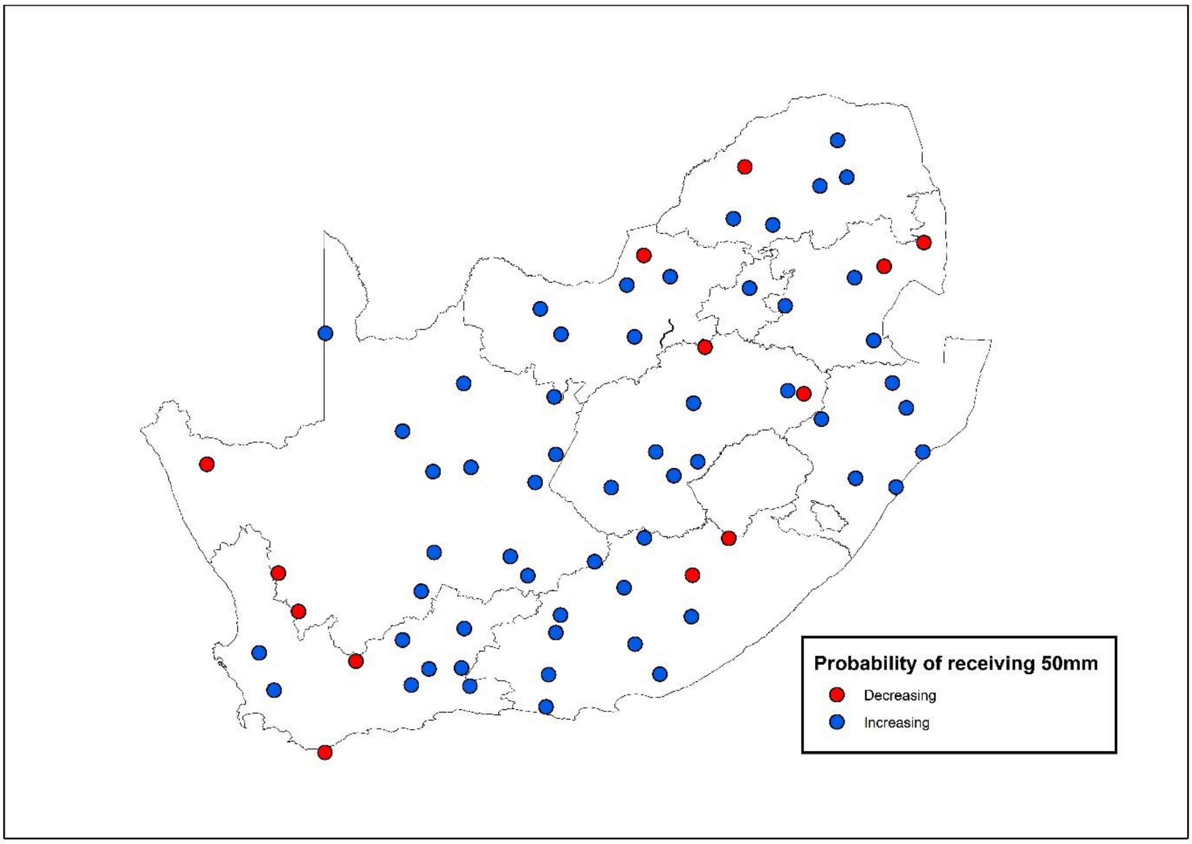

Figure 4.3: *Difference in the probability of receiving 50mm of rainfall on a rainy day, estimated from the Gamma distribution. Blue symbols indicate where the probability of receiving above 50mm is greater in Period 2 (1971-2020), while red symbols indicate the probability of receiving above 50mm is greater in Period 1 (1921-1970).*

Figure 4.4(a and b) illustrate the probability of receiving more than 50mm on a rainy day for Period 1 and Period 2, respectively, while Figure 4.4(c) presents the differences between these probabilities. Most stations showed an increase in Period 2 (Figure 4.4c), which corresponds to Figure 4.3 in terms of patterns of change but additionally shows where these differences are the largest. The largest difference in increased probability of receiving 50mm in Period 2 occurred over the northern parts of the country as well as isolated areas over the Free State and northern parts of KwaZulu-Natal (shaded light grey in Figure 4.4c), while areas showing less probability were situated over isolated areas in the western as well as north-western and eastern parts of the country (shaded black in Figure 4.4c). The averages of the shape and scale parameters of the gamma distribution for all stations were also found to be statistically different at the 95% confidence level. Some spatial irregularities are evident, e.g. between two stations in the eastern Free State (*Warden Skoolstraat, Verkykerskop*), which are situated very close to each other but show opposite direction of change. This could point to a data quality issue, although the data was checked, and no obvious errors could be detected. However, systematic observation errors cannot be excluded, e.g., underreporting of rainfall over an extended time period and/or if rainfall accumulations were reported to have occurred within a 24-hour period. The rainfall data for these two stations should be further investigated to try and explain these spatial anomalies.

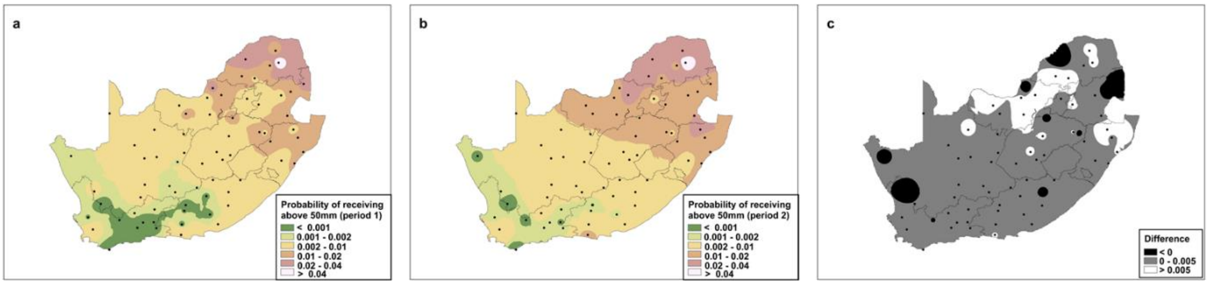

Figure 4.4: *The probability of receiving above 50mm of rainfall on a rainy day, estimated from the Gamma distribution – (a) Period 1 (1921-1970) and (b) Period 2 (1971-2020). Difference between Period 1 and Period 2 (c). Inverse distance weighting was used as the interpolation method. (Note: Categories are not of equal probability differences).*

4.3.3 Temporal change in extreme value distribution parameters

A 30-year moving window with the annual highest daily rainfall amounts was determined for each station for the period 1921-2020, for each year, i.e. 1921 represents a 30-year window of annual maximum values for 1921 to 1950, 1922 to 1951, etc., up to 1991 to 2020. The α and β – parameters were then calculated for these windows from the Gumbel distribution (Equation 2) and averaged for all stations to check for trend and/or any abrupt changes in the window mean over the 1921-2020 analysis period. The α and β – parameters showed positive trends, which were significant at the 95% confidence level (inserts in Figure 4.5a and b). To investigate any abrupt changes in the mean α and β – parameters, the differences in these means before and after every year were tested, starting in 1951. By observing changes from a decrease to an increase in the absolute value of the Student's *t*-test, one can identify abrupt changes in the means (McBride *et al.*, 2021). Years of abrupt change in the mean α– parameter were 1975 and 1995, while for the β – parameter, it was 1974-1975 (Figure 4.5a and b). The years of the most abrupt changes in the α– parameter were interspersed by years of less difference, which can be linked to the decade of above-normal rainfall in the 1970s followed by a very dry period in the 1980s (Kruger, 1999). The fact that the largest absolute value of the Student's *t*-test is close to the middle of the time series as a whole, i.e. 1921 to 2020, and visual inspection of the α and β – parameters, it can be assumed that the general change in the parameter is near-monotonous throughout the analysis period, providing confidence in dividing the analysis period into two equal sub-periods of equal length for comparative purposes. The α-parameter gives an indication of the variance, and the β-parameters take into account the mean and variance and thus, a steady increase in both these parameters points to an increase in variance over the study period, indicating that there is a greater likelihood of values falling into the tail of the distribution, i.e. more extreme events.

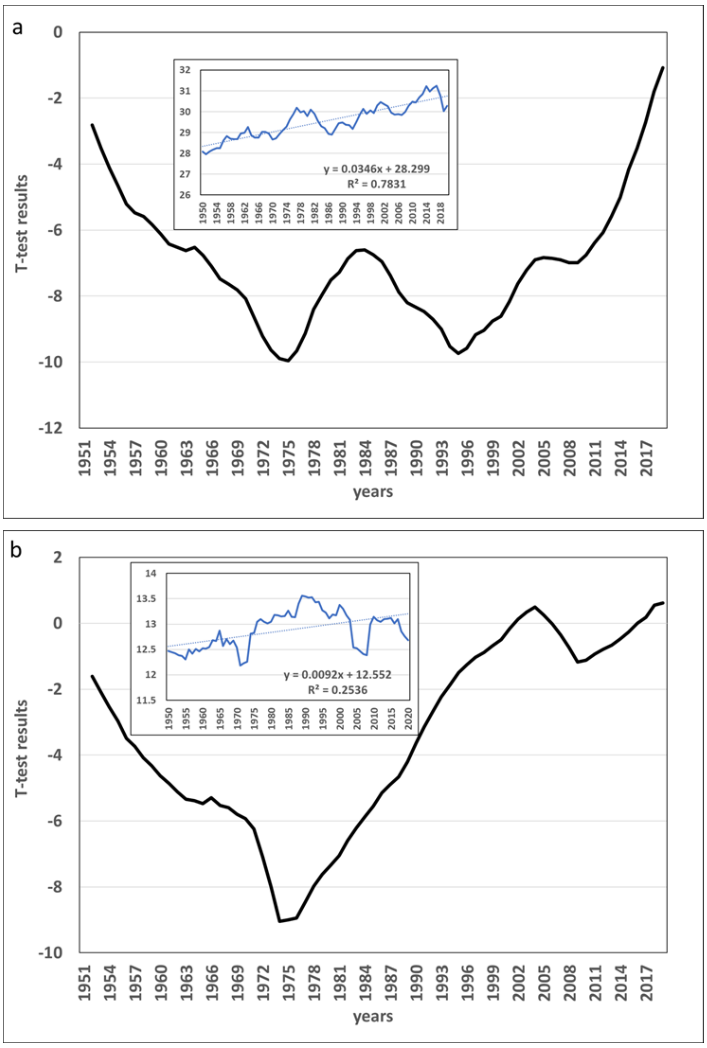

Figure 4.5: *Student's t-test results of the difference in average mean α (a) and β (b) values before and after the specific year for the time series 1921 to 2020. Insets are the trends.*

4.3.4 Probabilities of extreme daily rainfall events

The 1:10-, 1:50- and 1:100-year RPVs were calculated for both periods using the POT method (Equation 3). The results are depicted in Figure 4.6. RPVs were lower over the western parts of the country, while the eastern parts had higher values, which is expected in terms of the rainfall climate of South Africa, where rainfall decreases from east to west. However, there was an increase in RPVs for most stations across the country in Period 2, compared to Period 1, for all three return periods tested (Figure 4.6b,e and h). The difference between the 1:10-year return period between Periods 1 and 2 as a ratio (P2/P1) is largest over the eastern, central, southern and western interior (Figure 4.6c). Specifically, *Letaba District* in Mpumalanga and *Gingindhlovu* and *Hlobane* in the eastern parts of KwaZulu-Natal showed above 50mm increase from Period 1 to Period 2. For the 1:50-year return period, the biggest increase in values was also observed over the southern and western interior and eastern parts of the country for Period 2 (Figure 4.6f). The increase in RPVs from Period 1 to Period 2 for *Kareedouw,* situated over the southern part of the Eastern Cape (Figure 4.1) was 87mm, while *Dwars in die Weg,* situated in the Western Province, showed an increase of 36mm. The eastern parts of the country saw stations like *Letaba District* and *Gingindhlovu* experiencing an increase of more than 85mm in Period 2. A similar spatial pattern to the 1:50-year return period values could be seen for the 1:100-year return periods except for the southern parts of the Western Cape, where additional stations fell into the upper ratio category. There were isolated areas over the northwestern, central and northeastern parts of the country that showed increases in RPVs for Period 2 (Figure 4.6i). There was an increase in the number of stations over the northern and eastern parts of the country, which had RPVs of greater than 200mm, with stations like *Letaba District, Gingindhlovu* and *Mount Edgecombe* having maximum daily rainfall above 270mm per day as the 1:100-year event.

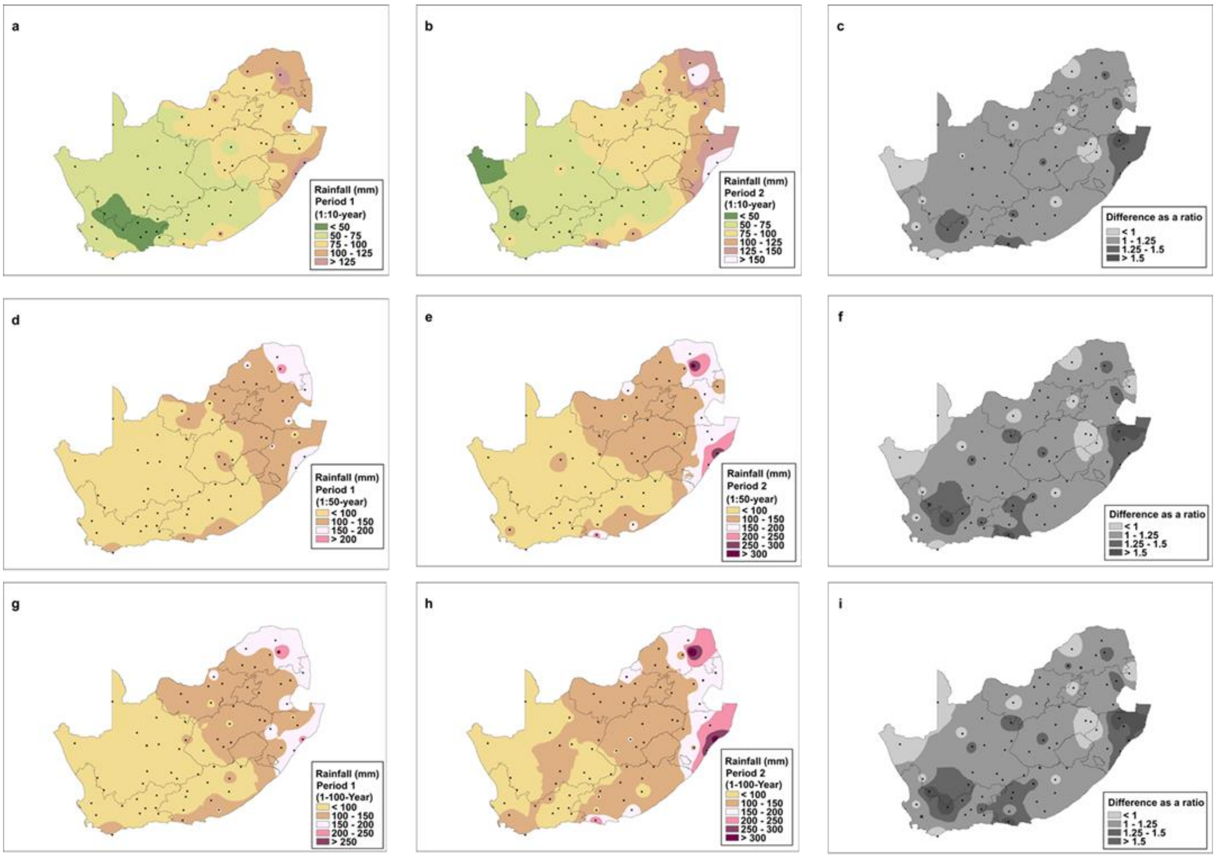

Figure 4.6: *Spatial distribution in 1:10- (a Period 1; b Period 2), 1:50- (d Period 1; e Period 2), and 1:100-year (g Period 1; h Period 2) return period values using the POT method. The second-period value was divided by the first to give the difference between the period as a ratio (1-10- c, 1-50- f and 1-100-year i). Inverse distance weighting was used as the interpolation method.*

Isolated areas over the extreme western parts of the Northern Cape, as well as over the eastern part of the Free State, Limpopo Province, Mpumalanga and the Eastern Cape, showed a reduction in RPVs for the second period for all three return periods (light grey areas depicted in Figure 4.6c, f and i). The average difference in RPVs of all stations was found to be significant at the 95% confidence interval (Student's t-test) for the 1:50- and 1:100-year return periods.

4.3.5 Return periods for specific thresholds of daily rainfall

Following on from the fact that most stations were showing an increase in terms of receiving more extreme rainfall for specific return periods in Period 2 compared to Period 1, it is investigated here how this result translated into potential shortening of return periods for the predefined significant (>50mm), heavy (>75mm) and very heavy (>115mm) rainfall events (Dyson, 2009)). Figure 4.7 shows that there was a change in the spatial distribution between

Periods 1 and 2 in the stations that have estimated return periods of less than a year for 50mm (highlighted by the grey areas in Figure 4.7a and b). The number of stations with a return period of less than one year increased in Period 2 to include most stations over northern KwaZulu-Natal, Mpumalanga, and Limpopo provinces (Figure 4.7b). There was also a lowering in return periods over the western interior and southern parts as well as the eastern parts of the country (Figure 4.7c). The extreme western parts of the country and areas over the central interior showed an increase in return period for the 50mm return value (Figure 4.7c).

For a daily total of 75 mm, most of the eastern parts of the country had a return period of less than 10 years for both Periods 1 and 2. However, the number of stations with return periods of less than 5 years increased over this area in Period 2. The difference between Period 1 and 2 (Figure 4.7f) mimics that of 50mm (Figure 4.7c) to a large extent.

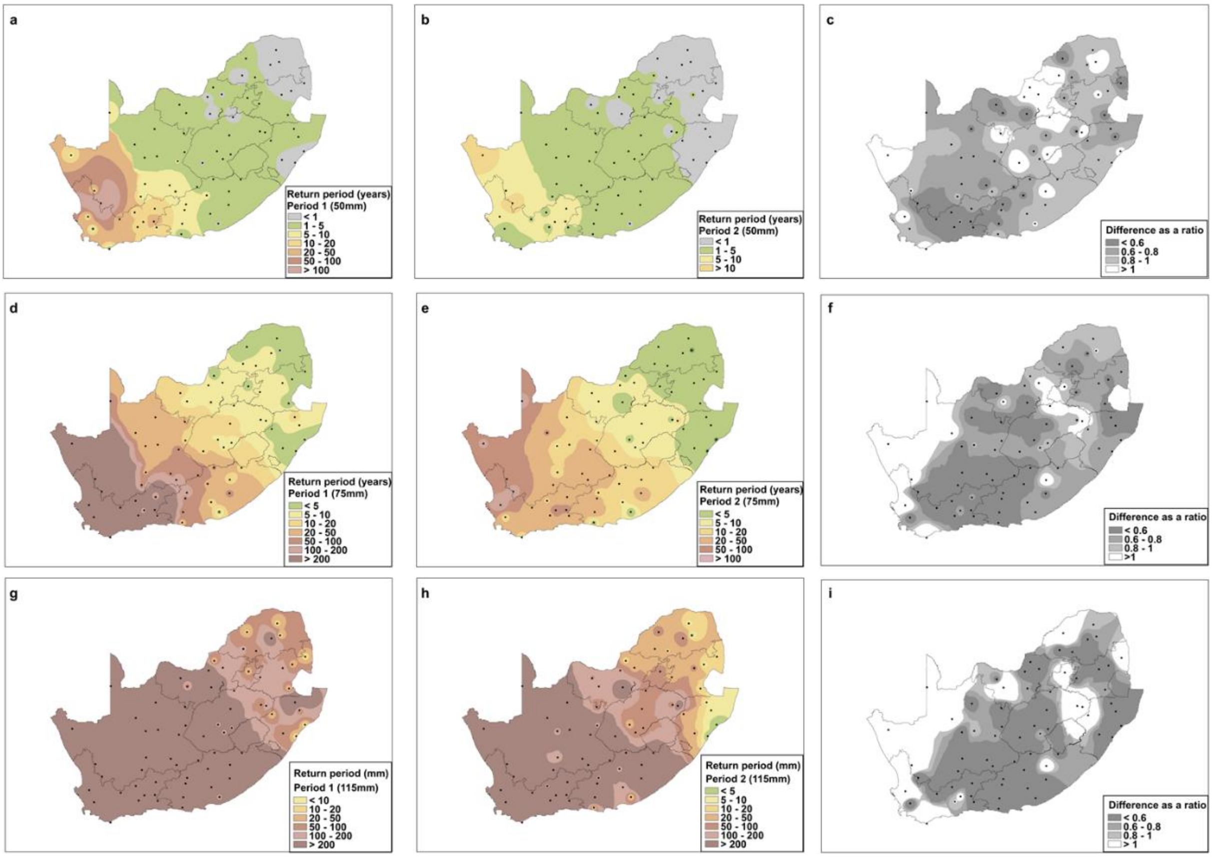

Figure 4.7: *Return periods for 50mm, 75mm and 115mm for both periods using the POT distribution. 50mm for period 1 (a), 50mm for period 2 (b); difference as a ratio Period 2/Period 1 (c); 75mm for period 1 (d), 75mm for period 2 (e); difference as a ratio (f) and 115mm for period 1 (g), 115mm for period 2 (h); difference as a ratio (i). Grey areas in figures (a and b) represent areas where return periods are less than a year. Inverse distance weighting was used as the interpolation method.*

In terms of receiving 115mm or more, the stations in the eastern parts of the country were shown to have return periods of less than 10 years, which is once again expected as this region generally receives more rain than the western parts of the country. What is noteworthy is that for most of the eastern parts of the country the return period is decreasing for 115mm. No stations had return periods of less than 5 years in Period 1 for 115mm (Figure 4.7g); however, this increase in Period 2 to include stations in KwaZulu-Natal (Figure 4.7h). Stations that showed the biggest decreases for this return period presented a similar spatial pattern to the 50mm and 75mm return periods (Figure 4.7c,f,i).

4.4 Discussion and Conclusion

In this study, we investigated if daily rainfall intensities across South Africa had changed during the past century by considering two 50-year periods, namely 1921-1970 (Period 1) and 1971-2020 (Period 2). To do this, we used observed daily rainfall from 70 stations well-distributed across South Africa. The number of rain days (>1mm) over the country was slightly higher (2%) in Period 2 compared to Period 1. As the study focused on significant to extreme rainfall events, the focus was on daily rainfall totals of 50mm or more, deemed by the SAWS weather forecast warning system to be potentially hazardous. Of the 70 stations considered, 64 experienced a statistically significant change in the general distribution of three rainfall categories (1-5mm, 5-50mm and >50mm). In order to understand if this change showed a difference in the probability of receiving above 50mm, the gamma distribution was fitted to all values above the 99th percentile. This showed a clear increase in the probability of receiving 50mm of rainfall or more on a rainy day over most parts of the country in the latter half of the analysis period.

The RPVs for 1:10-, 1:50- and 1:100-year were then calculated from the POT method, and most stations over the country showed an increase. The highest increase in rainfall values could be found over the north-eastern and eastern parts of the country, with some of these areas estimated to receive above 150mm for the 1:50 and 1:100 RPVs over the latter 50-year period. The central and western interiors also increased RPVs, although these were much lower in value (mm) than the eastern parts. These results support model projections which show increased rainfall in this region due to the expected enhancement of cloud-band formation (Engelbrecht *et al.*, 2009) and convective summer rainfall (Hewitson and Crane, 2006).

The decrease in RPVs in the Northern Cape for the second period also confirms the projections of reduced rainfall reported over this area by Tadross *et al.* (2005), Hewitson and Crane (2006) and Engelbrecht *et al.* (2009). This has been linked to the southward displacement of cold fronts in the winter months (Engelbrecht *et al.*, 2009), which could influence this increase in the time interval between extreme events over this region. Areas over the northern Free State into parts of KwaZulu-Natal and northern parts of the Eastern Cape also showed a decrease in RPVs for Period 2. It does not always follow that with a reduction in total mean rainfall amounts, there is accompanying reductions in extreme rainfall events; rather that, these extremes occur further apart. This analysis, therefore, provides improved confidence in the projections of the future rainfall climate of the region.

A similar spatial pattern emerged in the change in the estimated return periods for receiving significant rainfall (>50mm), heavy (>75mm) and very heavy (>115mm) rainfall. There was a decrease in return periods over the eastern and western interiors stretching southwards to the southern coastal areas. Areas over the eastern parts had return periods for 50mm of less than a year in Period 2, which had increased in extent from that of Period 1. Changes in the lowering of return periods could also be seen for 75mm and 115mm. The impact of receiving these large rainfall amounts more frequently poses challenges in terms of localized recovery from events that may have caused flooding damage to crops and infrastructure.

The decrease in return periods from above to below 10 years for stations over the western interior for receiving significant rainfall (>50mm) could have positive consequences for the Olifants and Gouritz catchments, as significant rainfall in the area could lead to more water in collection storage facilities such as dams. There was, however, also an increase in the probability of “heavy rainfall” events (>75mm) and “very heavy rainfall” events (>115mm) in Period 2 over this area, which is of concern with regards to the increased possibility of localized flooding. For example, the station Dwars in die Weg had in Period 2 return period values of over 90 mm for 1:50-year and around 103mm for 1-100-year, an increase of 67% and 72%, respectively.

With most stations having an increase in the likelihood of extreme rainfall towards the end of the analysis period, there is a need to relook how and where we build infrastructure in South Africa. If those in infrastructure planning and design base their work on stationary climate assumptions, they will underestimate the flood risk, which could lead to design failure, which will have negative social and economic effects. Old and poorly maintained infrastructure is particularly susceptible to heavy rain or flooding, and if one considers increased rainfall values for even return periods of 1:10 years, there is a real threat that these structures could fail in the short term. There is thus a need to review engineering design standards (climatological extreme value analysis) and give thought to how to budget for adapting existing infrastructure to climate-change risks. There is also the need to investigate land use planning and where human settlements are located, and into which areas cities and towns can expand, considering the change in the extreme rainfall climate. The loss of lives and infrastructure in the recent floods in KwaZulu-Natal was due to land and mudslides, which begs the question of whether houses and other infrastructure should have been built on this land in the first place (Hattingh, 2022). In summary, the results of this paper suggest, as did Pohl *et al.* (2017), that extreme rainfall events are likely to become more intense and are to become a "feature of climate change over South Africa".

4.5 References

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Synopsis

Considering trends in daily extreme rainfall in the historical climate, it was found that most regions in South Africa experienced an increase in the occurrence thereof. RPVs also increased for 1:10-, 1:50- and 1:100-year RPs over the last century. This finding was particularly evident over the eastern parts of the country, where the increases in significant (>50mm), heavy (>75mm) and very heavy (>115mm) daily rainfall was most conspicuous. RPs for 50mm are less than a year, while RPs for 75mm are less than five years for the second period of the study for a large number of stations in this area. Notably, two stations (Gingindhlovu and Mount Edgecombe) along the KwaZulu-Natal coast now have shorter than 5-year RPs for receiving at least 115mm daily.

Following the changes in current extreme daily rainfall events, the study moved to investigate changes in projections of extreme rainfall events. The model projection data from CORDEX was used, and the bias correction method developed by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) was employed (Hempel *et al.*, 2013). However, following exploratory work, it was found that model runs, even after bias correction, tended to underestimate the amount of rainfall for extreme events compared with observational data for the simulated period of 1979 to 2005. Gridded model simulations are prone to produce lower extreme precipitation values and more rain days due to the averaging of the area represented by the model grid point. It was thus felt that these model values could not be used to make meaningful contributions to understanding projected rainfall extremes over South Africa at specific point locations. As higher-resolution model data becomes available in the future, it is anticipated that the outputs of the models will become more relevant to specific locations and that the resultant analysis will provide results that are more robust to anticipated increases in the likelihood of localised flooding.

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Chapter 5: Summary and Conclusions

5.1 Summary:

The study commenced with the most poignant question: whether the breaking of daily temperature records across South Africa are consistent with the general warming observed. While several similar studies have been carried out for various parts of the world, it is the first time that this type of analysis has been done for South Africa. A notable finding of this study was that stations that broke the highest number of Tmax records were not necessarily those that broke the highest number of high Tmin records. Another thought-provoking finding was that some stations failed to break a single low Tmax or Tmin record from 2010 through 2019, consistent with the trends in multi-year extremes observed.

Consequently, the scope of the research widened by exploring projected changes in daily temperature extremes over South Africa. This is an integral part of the study in providing decision-makers with future RPVs and RPs of daily temperature extremes, which should be considered in planning climate change adaptation strategies and policy development. Consideration of the exceedance of critical temperatures in terms of the average number of days per year a place could expect under different RCPs, as presented in this research, is vital. Information of this nature is important in raising awareness about what the future may hold regarding changes in projected daily temperatures in a quantitative manner, with a view to mobilising the necessary resources for interventions. Planners and developers need this type of information to inform their strategies and plans and ensure climate-adaptive strategies can address the changing climate. Using a similar set of stations for historical and future-centred research makes comparisons of the results possible. Spatially, the results largely coincide: stations over the central interior of South Africa broke an annual average of more than 15 high Tmax records during the period 2010 to 2019. These same stations were also projected to have the greatest change in RPVs and return periods for both RCPs in future, regardless of the emission scenario. This is an important finding when looking at where climate change interventions to combat the potential impacts of high-temperature extremes need to be focused, especially in the light of probable limits to funding to roll out maximum interventions on a country-wide scale.

The second part of the research focused on changes in extreme daily rainfall characteristics in South Africa. South Africa is susceptible to flooding events that affect human and environmental health and well-being. Several studies have looked at precipitation extremes in South Africa before but tended to use the World Meteorological Extreme Climate Indices developed by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) as a basis. While this research is important (and acted as one catalyst for this research), this study took a more focused approach by applying extreme value theory to understand any changes in specific pre-defined precipitation extremes. Frequency analysis shows that most regions experienced an increase in the probability of receiving significant rainfall (> 50mm) per day, while a statistical probability analysis shows that trends in RPVs increased countrywide to such an extent that most regions exhibited a higher probability of receiving heavy rainfall (>75mm) and very heavy rainfall events (>115mm). This estimation of trends of return period values is significant, especially for engineering and hydrologic design considerations: The results are an indication that the hydrological design statistics are outdated as currently, many of the design statistics being applied in the industry have been calculated for South Africa with data that excludes at least the last two decades of observations, when a substantial number of extreme rainfall events occurred almost countrywide.

The significant results of the study are summarised below:

- **Regarding trends in probabilities of daily temperature records in the non-stationary climate of South Africa:**

  - The number of new highest daily maximum (high Tmax) and some high daily minimum daily temperatures (high Tmin) are occurring at a faster rate than expected in a stationary climate: In 1951, the ratio of high Tmax to low Tmin records per year was 1:1; however, by 2019, the ratio in that year was 9:1 in favour of High Tmax. This trend in the disproportionateness ratio of high to low records occurrence is accelerating.

- Interior stations recorded more high Tmax records than coastal stations and exceeded the 95% confidence intervals for a stationary climate earlier than coastal stations. Consequently, the spatial distribution of breaking high Tmax and Tmin records differed, with high TMax records tending to be concentrated over interior stations while high Tmin were more widely distributed.

- The occurrence of Tmax records, especially towards the end of the study period (2010 to 2019), could, to some extent, be linked to the observed acceleration in the general historical warming, which is not uniform across South Africa.

➢ **Regarding projected changes in daily temperature extremes for selected locations over South Africa:**

- The number of days above health-related critical temperature thresholds will become more frequent for most places in South Africa. This translates into shorter return periods for these values, increasing the frequency of needed interventions, e.g. relevant to human health and livestock management.

- Predictions of stations having 100 days or more for daily maximum temperatures of 32°C and above will increase from four (out of 22 across South Africa) in the current climate to six stations (eight) for the mid-future, further increasing to eight (thirteen) stations in the far-future under RCP4.5 (RCP8.5). Most stations will exceed 32°C at least once a year for all future periods and under both RCPs. In fact, by the end of the century under the RCP8.5, six of the analysed stations are expected to experience daily maximum temperatures of 32°C and above for over 200 days per year.

- For daily maximum temperature of 35°C and above under the RCP4.5 (RCP8.5) for the mid-future, three (four) stations are set to receive 100 days or more, and four (six) stations for the far-future. Sixteen stations will experience 35°C at least once per year for both periods under RCP4.5 and mid-future RCP8.5. This will increase to eighteen stations by the end of the century under RCP8.5, which will essentially include most of South Africa.

- When considering daily maximum temperature of 38°C and above, three stations (Vanwyksvlei, Upington and Musina, all located in relatively hot regions of the country) under the RCP8.5 by the end of the century will experience more than 100 days up from the current average of 23 days. Thirteen stations will have RPs of less than a year for daily maximum temperature of 38°C and above by the end of the century under RCP8.5, with a further six stations expected to have RPs of 2 or less years. Extrapolating this result to all of the identified regions prone to relatively high maximum temperatures points towards probable severe curtailment of socio-economic activities in those regions.

- Following on from the above, Musina will experience temperatures of 46°C and above at least once a year by the end of the century under RCP8.5. Therefore, it is expected that extreme heat stress will be experienced in the Limpopo River Valley in most years, which will require health-related restrictions and interventions.

- Current high temperatures, which can be categorised as rare, i.e. 1:50-year RPVs, will become more frequent. Under RCP4.5, most interior stations (coastal stations) are projected to reach these temperatures every 3 to 4 (6 to 15) years in the mid-future, while in the more distant future, this is expected to drop to 1 to 2 (3 to 7) years.

- Adding to the above, when considering RCP8.5, most interior stations are expected to experience the current 1:50 RPVs in most years by the end of the century. The coastal stations will experience these values approximately every three years or less.

- Most interior stations for mid-future (far-future) for the RCP4.5 will experience the current 1:100-year RPVs in 5 to 9 years (2 to 5 years) while coastal stations will experience these every 13 to 33 years (5 to 12 years). Under the RCP8.5 scenario, by the end of the century, these 1:100-year RPVs will be reached every year by interior stations, while most coastal stations will experience them every 4 years.

- **Changes in Extreme Daily Rainfall Characteristics in South Africa: 1921 – 2020:**

- The probability of receiving significant amounts of rainfall on a rainy day mainly increased over the last century over South Africa.

- The 1:10-, 1:50- and 1:100-year RPVs for most locations increased over the last century.
- For the predefined significant (>50mm), heavy (>75mm) and very heavy (>115mm) daily rainfall events, there was a shortening of RPs over most of the country.
- A large number of locations over the eastern parts of the country now experience return periods of less than a year (five) for 50mm (75mm) compared to over the course of the last century.
- Several locations along the eastern coast of South Africa presently have RPs of less than five years for 115mm per day, which points to regular flooding events.

The findings of this study have important implications for South Africa:

- An increase in high Tmax records and a projected increase in daily temperature point to *extended periods of hazardously high temperatures* and thus confirm studies which suggest heat waves will increase over South Africa.
- *Changes in the occurrence of extreme temperature and record-breaking daily temperature events can have serious negative consequences for agriculture*, such as yield losses, loss of milk production, and spread of pests and pathogens, to name a few. The decrease in low Tmin daily temperatures could have a negative effect on agriculture, where inadequate chilling in certain areas can affect certain species' survival or ability to reproduce and decrease the dormancy period of pests. Thus, consideration will need to be given to what crops and livestock can continue to thrive in which parts of the country. This means crop diversification and alternative livestock options may need to be considered.
- *Increases in critically high temperatures will increase cases of serious heat-related illnesses*, making people such as the elderly, very young and people with certain pre-existing medical conditions particularly vulnerable. Many South Africans have limited access to air conditioning and live in informally constructed homes with little or no protection from high temperatures. Many earn a living working outdoors, which can

compound matters. There is thus a need to address how we can make our living and working spaces more resistant to excessively high temperatures.

- The results suggest that the *nature of the rainfall cycle is changing*, with serious implications for a number of diverse sectors. One such sector is the agricultural industry, which supports many livelihoods in South Africa. Thus, the consequences of any change in rainfall, especially if it makes extremes more likely, will affect the ability of farmers to sustain their livelihoods.
- *With increased frequency and intensity of rainfall comes the need for more effective water management*. The need for flood prevention interventions has become imperative, especially for the eastern parts of South Africa, and thought should be given to how to mitigate against the increased expected frequency and risk of floods.
- *There is a need for South Africa to embrace the challenge by the World Meteorological Organization (WMO) for a renewed effort to develop climate services for all*. Vulnerable communities must have access to knowledge related to weather and climate extremes they are exposed to, plus strategies to cope. An integrated weather, climate and disaster management approach is vital to ensure the safety of life and property.

5.2 Conclusions:

The world is experiencing an increase in weather and climate extreme events due to global warming. Different regional climates of the world are responding differently to this warming. The human response to these changes is also different in many regions of the world, with social, environmental, political and economic differences coming into play. The response to these changing extremes is anything from none to developing and implementing policies, strategies and defence mechanisms to mitigate against the changes. However, without information and knowledge, developing the appropriate responses to reduce the risks associated with extreme events becomes difficult, if not impossible. There is a need to know what changes will take place, where and, if possible, when. This information and knowledge will need to be based on scientific methods that consider local weather observations. This study addresses the need for local information and knowledge regarding the changes in climate extremes and records in South Africa.

5.3 Recommendations for future studies:

- Investigate breaking climate records for different seasons, which may have ramifications for the agricultural sector.
- Exploring to understand, analyse and quantify compound weather and climate extremes. This would be important in understanding their potential risk to society, as occurring together often exacerbates the risks rather than if they occurred as isolated events, e.g., drought and high-temperature extremes. This information would be important for disaster management in managing multiple, simultaneous extreme events.
- The development of practical tools for managing future change needs to be explored. These can be by way of inputs to building standards or codes, crop models, for example. Translating the science in order to develop adaptation options (Slater *et al.*, 2021) needs to be researched.
- The climate projection analysis could be extended to the larger set of CORDEX regional climate model projections already available for analysis. However, for more updated research results, new CORDEX outputs derived from the CMIP6 outputs will be of even more value.
- As higher-resolution climate projection data becomes available, revaluation and expansion of the research presented can be undertaken.

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Appendix A

Temperature stations used in this thesis
(Elevation range due to station movement)

Station Name	Latitude	Longitude	Elevation (meters)
BELA BELA	-24.9	28.32	1143
BLOEMFONTEIN	-29.12	26.18	1354
CALVINIA	-31.48	19.76	975-980
CAPE AGULHAS	-34.83	20.01	11
CAPE COLUMBINE	-32.83	17.86	62
CAPE POINT	-34.35	18.49	208-227
CAPE ST BLAIZE	-34.18	22.15	60-76
CAPE ST FRANCIS	-34.21	24.84	9
CAPE TOWN	-33.96	18.6	42-46
CEDARA	-29.54	30.27	1071
EAST LONDON	-33.04	27.82	123
EMERALD DALE	-29.94	29.96	1154
GEORGE	-34	22.38	187
GLEN COLLEGE	-28.94	26.33	1297
JOHANNESBURG	-26.14	28.23	1676-1695
KIMBERLY	-28.81	24.77	1196
LANGGEWENS	-33.28	18.71	179
MARICO	-25.47	26.38	1082
MOUNT EDGECOMBE	-29.71	31.05	94
MUSINA	-22.35	30.01	525
POLOKWANE	-23.86	29.45	1226
PORT ELIZABETH	-33.98	25.61	59-60
PRETORIA	-25.75	28.26	1300-1380
UPINGTON	-28.41	21.26	793-841
VAN WYKSVLEI	-30.35	21.82	962

Appendix B

Rainfall stations used in this thesis

Station Name	Latitude	Longitude	Elevation (meters)
ALBERTVALE-FRM	-32.74	26.01	687
ALKMAAR	-25.45	30.82	776
BLAAUWKOP	26.5	30.27	1676
BLOUBOSKUIL	-32.44	22.71	877
BOETSAP	-27.97	24.45	1176
CALITZDORP - POL	-33.53	21.69	238
CAPE AGULHAS	-34.83	20.02	11
CARNARVON - POL	-30.97	22.13	1252
CEDARA	-29.54	30.27	1071
DORDRECHT CLARKS SIDING	-31.41	27.12	1684
DWARS IN DIE WEG	-33.07	20.62	607
EUREKA	-29.08	24.48	1122
EXWELL PARK	-32.21	27.1	914
FUNNYSTONE	-30.7	27.82	2286
GINGINDHLOVU	-29.03	31.57	100
GRAHAMSTOWN - TNK	-33.32	26.49	642
GRAPEVALE	-31.15	25.23	1468
HANGLIP	-23.02	29.92	8211
HLOBANE	-27.7	30.98	1262
HOFMEYR - MUN	-31.65	25.8	1261
HOPETOWN	-29.62	24.08	1104
HOPKINS	-27.71	22.7	1195
HUGHENDEN	-30.69	26.19	1388
IRENE	-25.87	28.22	1524
KALKFONTEIN	-23.9	29.58	1265
KAREEDOUW - POL	-33.95	24.29	335
KENDREW ESTATES	-32.52	24.48	612
LEKKERVLEI	-31.05	23.6	1305
LETABA DISTRICT	-23.73	30.1	891
MACHADODORP	-25.67	30.25	1559
MARYDALE - POL	-29.41	22.11	1059
MASELSPOORT DAM	-29.03	26.41	1310
MERWEVILLE - POL	-32.66	21.52	714
MOORSIDE	-28.4	29.61	1219
MOUNT EDGECOMBE	-29.71	31.05	94
NIEKERKSHOOP - POL	-29.33	22.84	1165
NIEUWOUDTVILLE SAPD	-31.37	19.12	727
NYLSVLEY	-24.65	28.67	1106
OTTOSDAL - POL	-26.81	26	1492

PIKETBERG-SAPD	-32.91	18.75	230
PRINCE ALBERT - TNK	-33.22	22.03	619
RANKINS PASS-POL	-24.53	27.91	1239
REENEN	-32.11	19.51	261
RICHMOND C/K - TNK	-31.42	23.94	1414
RIETFONTEIN SAPS	-26.74	20.03	825
RONDAWEL	-33.2	22.66	838
ROODEBLOEM	-32.18	24.57	814
ROOIRIVIER	-33.55	22.82	380
SAAIFONTEIN	-31.72	21.88	1250
SKUKUZA	-24.99	31.59	7581
SLANGFONTEIN	-29.72	25.55	1298
SLURRY	-25.81	25.85	1412
STEINKOPF	-29.27	17.74	821
STEYTLERVILLE - MAG	-33.33	24.34	419
SURPRISE STORE	-28.18	31.25	1040
SWARTRUGGENS - POL	-25.65	26.69	1257
TAFELKOPPIES	-26.88	30.62	1372
THE CLIFF	-29.49	26.76	1509
THORNLEA	-28.63	21.52	884
TUSCANY	-25.24	26.18	1085
VENTERSBURG - MAG	-28.09	27.14	1433
VERKYKERSKOP	-27.91	29.27	1830
VILLA NORA-POL	-23.53	28.13	847
VREDEFORT	-27.01	27.36	1434
VRUGBAAR	-33.63	19.04	175
VRYBURG PALMYRA	-26.27	24.18	1190
VRYBURG WELGELEVEN	-26.76	24.58	1257
WARDEN SKOOLSTRAAT	-27.85	28.96	1631
WATERLAND	-29.22	27.22	1574
WITBANK STREHLA	-26.21	28.91	1583