An analysis of extreme temperature events in South Africa: 1960-2015

Adriaan Johannes van der Walt

1818767

A Thesis submitted in fulfilment of the academic requirements for the degree of Doctor of Philosophy

School of Geography, Archaeology and Environmental Studies

University of the Witwatersrand, Johannesburg

October 2020

Declaration

I declare that this thesis is my own, unaided work, except where otherwise acknowledged. It is being submitted for the Degree of Doctor of Philosophy in Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for examination for any degree at this or any other university.

____

Adriaan Johannes van der Walt

27_day of_October_2020_at_Bloemfontein_

Abstract

Extreme Temperature Events (ETEs), which include heatwaves, warm spells, cold waves and cold spells, have disastrous impacts on human health and ecosystems. The frequency, intensity, and duration of ETEs is projected to increase due to climate change. Successful adaptation to ETEs requires an understanding of the contemporary frequency of these events, and their likely occurrence under climate change. However, very little research has been conducted on ETEs in South Africa, and only a few attempts have been made to identify and examine trends.

This study addresses this gap in the literature through four key contributions. The first is a review of the published studies on ETEs and their effects in South Africa, providing key methodological and theoretical directions for future research. The second is the first statistical classification of seasonal boundaries in South Africa based on temperature data. This is imperative in facilitating the analysis of seasonal ETEs, and seasonal-resolution trend calculation. The third and fourth contributions involve the calculation of cold and warm ETEs respectively, using the ET-SCI for the first time in South Africa, and comparing the results to those for the ETCCDI.

The review of the literature demonstrates the paucity of research in South Africa, and some of the key methodological challenges pertaining to the temporal and spatial resolution of data points; the indices used; and the interpretation of the results. The statistical classification of seasons demonstrates that the majority of the stations can be classified into four distinct seasons, while the statistically classified seasonal brackets include summer (October/November/December/January/February/March), early autumn (April) and late autumn (May), winter (June/July/August), and spring (September). The analyses of ETEs demonstrate that both hot and cold ETEs pose threats to South Africa and reveal a considerable spatial heterogeneity in the trends for each ETE index, providing input towards more effective adaptation planning for the regions under greatest risk.

Keywords: Extreme temperature events (ETEs), Heatwaves, Cold Waves, Seasonal classification, ET-SCI, ETCCDI

List of works

This study is organised in chapters as stand-alone research papers submitted to peer-reviewed journals for publication. One of the four papers has been published; one has been accepted and is under preparation for publication and two papers are under review. Four papers, one of them previously published, is the minimum requirement for PhD by publication in the School of Geography, Archaeology and Environmental Sciences at the University of the Witwatersrand. A fifth paper is in a draft format and attached as Supplementary Material (Draft Article); it will not form part of the evaluation process for this thesis. However, references will be made to this manuscript due to the framework of the thesis and its contribution to the body of knowledge on extreme temperature events and the vulnerability of Africa, as well as in a global context. Below are the details of published, accepted, and submitted papers to national and international peer-reviewed journals; these include the citation, impact factor, and contribution of each author.

1. Van der Walt, A.J. and Fitchett, J.M. (2020) Statistical classification of South African seasonal divisions on the basis of daily temperature data. *South African Journal of Science*. Accepted. Impact factor for 2019: 1.866.

Project leader (30% contribution) conceptualised the scope of this paper. Van der Walt A.J (70% contribution) collected, analysed and produced the map in text. Van der Walt A.J collated and led the writing of the manuscript, with input from the project leader.

2. Van der Walt, A.J. and Fitchett, J.M. (2020) Trend analysis of cold extremes in South Africa: 1960-2016. *International Journal of Climatology*. Accepted. Impact factor for 2019: 3.928. Project leader (30% contribution) conceptualised the scope of this paper. Van der Walt A.J (70% contribution) collected, analysed and produced the maps in text. Van der Walt A.J collated and led the writing of the manuscript, with input from the project leader.

3. Van der Walt, A.J. and Fitchett, J.M. (2020) Exploring extreme warm trends in South Africa: 1960-2016. *Theoretical and Applied Climatology*. Accepted. Impact factor for 2019: 2.882 Project leader (30% contribution) conceptualised the scope of this paper. Van der Walt A.J (70% contribution) collected, analysed and produced the maps in text. Van der Walt A.J collated and led the writing of the manuscript, with input from project leader.

4. Van der Walt, A.J. and Fitchett, J.M. (2020) Extreme temperature events in South Africa: A Review. *South African Geographical Journal*. Under Review. Impact factor for 2019: 1.154 Project leader (30% contribution) conceptualised the scope of this paper. Van der Walt A.J (70% contribution) collected, analysed and produced the maps in text. Van der Walt A.J collated and led the writing of the manuscript, with input from the project leader.

5. Van der Walt, A.J. and Fitchett, J.M. Extreme temperature events: African vulnerability in the global context. Draft manuscript. Project leader (30% contribution) conceptualised the scope of this paper. Van der Walt A.J (70% contribution) collected, analysed and produced the maps in text. Van der Walt A.J collated and led the writing of the manuscript, with input from the project leader.

Work not related to this study will be presented in the following three sections:

Conference presentations:

1. Society of South African Geography Conference 1-5 October 2018 – Letimela, O. and Van der Walt, A.J., An investigation of temperature patterns in the Free State: 1950-1980.

2. Society of South African Geography Conference 1-5 October 2018 – Van der Walt, A.J., Fitchett, J.M. and Curtis, C., Statistical classification of South African Seasonal Divisions on the Basis of Daily Temperature Data.

3. The South African Wildlife Management Association Conference 1-5 September 2019 – Mukwevho, R., Van der Walt, A.J. and Deacon, F. Exploring how extreme temperature events influence movement patterns of giraffes (*Giraffa Camelopardalis*) in the Rooipoort Nature Reserve, Northern Cape Province, South Africa.

Conference Proceedings:

1. Van der Walt, A. and Barker, C.H., 2017, "'n Ruimtelike analitiese ondersoek na seisoenale reënval- en temperatuurpatrone oor Suider-Afrika', *Suid-Afrikaanse Tydskrif vir Natuurwetenskap en tegnologie* 36(1), a1469. https://doi.org/10.4102/satnt.v36i1.1469

Acknowledgements

I would like to thank my supervisor Prof. Jennifer Fitchett for all the support, wisdom and guidance throughout my PhD journey. You assisted me in producing a thesis and five articles that I am truly proud of. You encouraged me and challenged me to be a more innovative researcher. You also helped me to develop my critical thinking and improve my writing skills which helped me to be a better academic. I valued your time, countless messages of motivation and support, proofreading and editing, during the past four years. You are a fantastic supervisor, and I don't think I could ever say thank you enough for giving me the chance to pursue a PhD.

I also would like to thank Prof. Christopher Curtis, who assisted me at the initial start of my PhD journey and provided valuable comments and input.

I gratefully acknowledge the support, as well as financial support, from the Faculty of Natural and Agricultural Sciences, the Department of Geography, Post Graduate School of the University of the Free State and the Carnergie Bursary.

To my colleagues in the Department of Geography, I would like to thank you for the support, kindness and continuous encouragement throughout my PhD journey.

I would also like to thank the anonymous reviewers for their valuable comments and inputs during the review process.

My friends, future in-laws, family (my dad, mom, two brothers and their wives) need to be thanked. Without your continuous support and encouragement, I would not be here today. In particular, thank you to my Dad for constantly reminding me to stay positive.

Finally, I would like to thank my partner Chris. Thank you for your continuous support and constantly reminding me that I need to focus and finish. Thank you for giving me the opportunity, time and space to pursue my PhD and further my academic career.

Table of Contents

List of Figures

List of Tables

List of General Acronyms

AO: Artic Oscillation

ARC: South African Agricultural Research Council

CCAM: Conformal Cubic Atmospheric Model

CCI: Commission for Climatology and Indices

CH: Continental-High

CRED: Centre for Research on the Epidemiology of Disasters

El Niño: El Niño Southern Oscillation

EM-DAT: Emergency Events Database

ENSO: El Niño-Southern Oscillation

ET: Extreme temperature

ETCCDI: Expert Team on Climate Change Detection

ETE: Extreme Temperature Event

ETE: Extreme Temperature Events

ETEs: Extreme Temperature Events

ET-SCI: Expert Team on Sector-Specific Climate Indices

IOD: Indian Ocean Dipole

IPCC AR5: Fifth Assessment Report of the Intergovernmental Panel on Climate Change

IPCC: Intergovernmental Panel on Climate Change

ITCZ: Intertropical Convergence Zone

JCOMM: Joint Commission for Oceanography and Marine Meteorology

La Niña: La Niña Southern Oscillation

LTAS: Long-Term Adaption Scenarios Flagship Research Programme

MJO: Madden-Julian Oscillation

NOA: North Atlantic Oscillation

PDO: Pacific Decadal Oscillation

RCA: Rossby Centre Regional Mode Version 4

RCM: Regional Climate Model

RCP: Representative Concentration Pathway

RCP4.5: Representative Concentration Pathway medium-to-low concentration greenhouse gasses

RCP8.5: Representative Concentration Pathway high-to-low concentration greenhouse gasses

SAA: South Atlantic Anticyclone

SAM: Southern Annular Mode

SAWS: South African Weather Service

SIA: South Indian Anticyclone

SIOD: Subtropical Indian Ocean Dipole

SST: Sea Surface Temperatures

WHO: World Meteorological Organisation

WRCP: World Climate Research Programme

List of Statistical Acronyms

$.yr^{-1}$ or $.y^{-1}$: Per year

.decade: Per decade

ASW: Average Silhouette Width

Approximate: Terminology used due to the two-decimal rounding of the values

CDSI: Cold spell duration indicator

CHF: Excess Cold Factor

CPCC: Cophenetic Correlation Coefficient

$CSDI_d$: User-defined Cold Spell Duration Indicator

CWD: Duration of cold wave days

CWN: Number of cold waves

DTR: Diurnal temperature range

ECI: Extreme climate index

EHF: Excess Heat Factor

FD: Frost days

GUI: Graphical user interface

HWD: Heatwave duration days

HWN: Number of heatwaves

IDW: Inverse Distance Weighted

LOWLESS: Locally weighted polynomial regression

MK: Mann-Kendall trend test

QM: Quantile-Matching

SHI: Standardised Heat-wave Index

SR/ρ: Spearman's Rank correlation coefficient

SS: Theil-Sen's slope estimator

SU: Summer days

SU35: Very hot days were TX>35°C

T_{max}: Daily maximum temperatures

T_{min}: Daily minimum temperatures

TN: Daily minimum temperatures

TN10p: Cool nights

TN90p: Warm nights

$TNlt_2$: Frost days below were TN <-2°C

TNMean: Mean minimum temperatures

TNn: Minimum TN

TNx: Maximum TN

TX: Daily maximum temperatures

TX10p: Cool days

TX90p: Warm days

TXb_dTN_d: User-defined consecutive number of cold days and nights

TX_dTN_d: User-defined consecutive number of hot days and nights

TXMean: Mean maximum temperatures

TXn: Minimum TN

TXx: Maximum TX

WSDI: Warm spell duration indicator

$WSDI_d$: User-defined Warm Spell Duration Indicator

Chapter 1: Introduction

1.1. Background

Extreme climatic events have had significant impacts on civilisation throughout history (Jahn, 2015). Projections of an increased severity and frequency of extreme climatic events are now widely accepted by scientists globally and locally (Nicholls *et al*., 2012; Boero *et al*., 2015; Jahn, 2015; Ebi & Bowen; 2016). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that climate change over recent decades has already started to heighten extreme climatic events (Smith, 2011; Hartmann *et al*., 2013). These extreme climatic events can be defined as rare, infrequent, unpredictable phenomena; they are characterised by wide variations in weather conditions over relatively short time periods, including severe storms, droughts, floods, heatwaves, cold waves and frost (Thibault & Brown 2008; Heim Jr, 2015; Easterling *et al*., 2016). These events often had a dramatic impact on the economies and societies of the affected countries throughout the Quaternary, including the earliest foundation of civilisation, and the demise of civilisations as far apart as East Asia, New Mexico and the Mayan lowlands (Conner, 2016). The IPCC argues that the increased frequency and severity of climatic extremes witnessed over recent decades will increase exponentially throughout the 21st century (Mueller & Seneviratne, 2012; Nicholls *et al*., 2012; Kharin *et al*., 2013b). Simultaneous with this increase in severe climatic events has been a continued increase in both population and infrastructure in some climatically vulnerable regions (Adger *et al*., 2003; Mirza, 2011). Landscape use and social infrastructure changes often further increase this vulnerability (Easterling *et al*., 2000a). There is little doubt that both the human society and the natural environment have become more vulnerable to extreme weather and climatic events (Easterling *et al*., 2000b, 2016). The risks of severe climatic events are especially concerning to societies that are dependent on resources which are sensitive to changes in climate, including farming, fishing and forestry, and to those that have more pressing immediate needs relative to long term development of adaptive infrastructure (Mirza, 2003; Herold *et al*., 2017). These risks in low-income countries and developing countries, such as South Africa, are exacerbated where agriculture and food security relates to the livelihood of populations (Adger *et al*., 2003; Herold *et al*., 2017).

Global mean temperature has increased by approximately 0.74°C since the late 19th century (Yu & Li, 2015; Mueller *et al*., 2016), and the broad consensus is that extreme temperature events (ETE; i.e. heat events; heatwaves; warm spells, cold events, cold waves, cold spells) may become more frequent and intense as the global mean rises (Alexander & Perkins, 2013; Perkins-Kirkpatrick & Gibson, 2017; De Perez *et al*., 2018; Baldwin *et al*., 2019). Over the past two decades, several high-impacts ETE events occurred in the Global North. For instance, Europe experienced a pronounced summer warming accompanied by severe heatwaves in 2003, 2010 and 2015 (Luterbacher *et al*., 2016). The exceptional heatwave of 2003 caused ~70,000 heat-related deaths and had significant impacts on agriculture, ecosystems, economies, and infrastructure (Barriopedro *et al*., 2011; Yu & Li, 2015; Orth *et al*., 2016; Simmonds, 2018). Other examples include a cold spell in 2008 that caused 140 000 deaths in subtropical China, with an approximate economic loss of more than US$ 22.3 billion (Ponjoan *et al*., 2017; Han *et al*., 2017), and the heat wave in Russia that caused 55 000 deaths in 2010 (Otto *et al*., 2012; Ragone *et al*., 2018). A more recent, though somewhat less dramatic example, is the heatwave in June 2019 that resulted in 1,500 fatalities in France (Osborne, 2019). A disproportionate number of studies focus on warm extreme temperature events (Barnett *et al*. 2012; Scott 2015; Martinez *et al*. 2018). Relative less work has been done on extreme cold events (i.e. cold waves and cold snaps), many of which are linked to cold air outbreaks that affect regions of the mid-latitudes (Johnson, 2018; Smith & Sheridan 2020) and could have devastating environmental impacts (Chen *et al*., 2019) and societal consequences (Scott, 2015; Díaz *et al*. 2019).

Exposure to heat and cold extreme temperature events over prolonged periods results in adverse health outcomes and could lead to hyperthermia or hypothermia, respectively (Scott, 2015; Allen & Scott, 2018; Founda *et al*., 2019). Thermal stress (i.e. heat stress and cold stress) can result in respiratory and cardiovascular diseases, heat stroke and exhaustion, decreased metabolic activity, damage to the brain, heart, lungs and kidneys, and can ultimately result in mortality (Lee, 2014; Barnett *et al*., 2012; Scott, 2015; Allen & Scott, 2018; Ngwenya *et al*., 2018, Founda *et al*., 2019). The consideration of the societal (i.e. human fatalities, illness and economic loss) and environmental (e.g Easterling *et al*., 2000a; Kenyon & Hegerl, 2008; Smith, 2011; Coumou *et al*., 2013; Morak *et al*., 2013; McCann & Swaby, 2016; Chen *et al*., 2019) consequences of ETEs has prompted considerable interest, and research of ETEs in the global North is growing. Researchers are keenly aware that these events could increase and change in frequency, intensity, severity, and seasonal timing (Alexander *et al*. 2006; Ding *et al*., 2010; Perkins *et al*. 2012; Song *et al*., 2014; Sheridan & Allen, 2015; Easterling *et al*., 2016; Perkins-Kirkpatrick *et al*. 2017; Allen & Sheridan, 2018). However, it is a growing field, although gaps remain on climate extremes, and particularly ETEs, in developing countries and specifically in South Africa (New *et al*., 2006; Collins, 2011; Sheridan & Allen, 2015; Otto *et al*., 2015; Abatan *et al*., 2018; Scovronick *et al*., 2018). Despite the obvious importance of ETEs, the majority of climatological research has focused on rainfall and extreme rainfall events; disagreement on the starting dates and definitions of different seasons in South Africa persists (Klopper *et al*., 1998; Klopper, 1999; Durham, 2011; Weather SA, 2017; Roffe *et al*., 2020). This is a particularly critical shortcoming in South Africa and an emerging field of study, due to the significant heterogeneity of the climate (Kruger & Nxumalo, 2017).

1.2. Rationale and Contribution to Existing Knowledge

South Africa, a developing country, has recorded several ETEs over recent decades. The majority involved warm extreme events; less focus is placed on extreme cold events in the news media and scientific literature. The most recent ETEs involve the record-high mean winter temperatures in the Eastern Cape in 2019 for the winter months (June, July, August), followed by unseasonably high maximum temperatures exceeding 35°C, recorded on 7 September 2019 in Cape Town (Head, 2019). Between 1-3 March 2016 the southern regions of the Western Cape experienced unseasonably extreme cold conditions, with temperatures <-6°C (Brophy, 2016). Again in 2019, several cold fronts hit Gauteng during June and July, leading to at least one casualty due to hypothermia (Matlhare, 2019). The most recent intense cold front, on 6 July 2020, led to very cold temperatures across the country, together with snowfall on the southern region and infrastructural damages to informal settlements due to flooding in the Western Cape (Pace 2020).

This increased attention raises the question of whether ETEs are becoming more frequent and more severe in South Africa. Surprisingly, less focus has been placed on ETEs, in particular the frequency, intensity and incidence of these events in a developing country like South Africa (New *et al*., 2006; Collins, 2011; Ziervogel *et al*., 2014; Sheridan & Allen, 2015; Otto *et al*., 2015; Abatan *et al*., 2018; Scovronick *et al*., 2018). In addition, there is little consensus as to distinct seasonal boundaries in a South African context: even the South African Weather Service (SAWS) points out that there are no official designation and definitions of seasons (SAWS, 2019). Many South Africans depend on the seasonal characteristics of length and timing of growing seasons and harvest (Battisti *et al*., 2009; Moeletsi *et al*., 2011; Tshiala *et al*., 2011; Botai *et al*., 2017). Climatic seasons also influence resource management, energy demand, tourism, social and economic planning, hydrology and health amongst others (De

Cian *et al*.,2013; Lazenby *et al*., 2014; Ziervogel *et al*., 2014; Fitchett *et al*., 2016). It is important to understand and quantify the seasonal divisions of South Africa, in reference to ETEs, for future research. As already mentioned very little research has been done on ETEs in South Africa, and research is slowly emergning to identify and examine trends. These are discussed and examined in one of the first review papers on ETEs in South Africa presented in this thesis (Chapter 5). This chapter reviews the methodological approaches to define ETEs; it outlines the extreme temperature indices adopted; explores selection methods of meteorological stations and proposes an approximate number of stations to adequately portray temperature variability on a national and regional level. It also analyses the study periods, examines the data quality and homogeneity, analyses statistical trends and, finally, presents the results. To address this issue of seasonal divisions of South Africa, Chapter 6 presents the very first statistical classification of South African seasons on the basis of daily temperatures, which – given that it is the only study of its kind - contributes substantially to the existing body of knowledge.

To contribute to the body of knowledge on ETEs in South Africa, Chapter 7 and 8 examine trends of extreme cold temperatures and extreme warm temperature, respectively. The trend analysis solely on extreme cold temperature events will be the first study in a South African context. It uses the World Meteorological Organisation (WMO) Commission for Climatology and Indices (CCI) Expert Team on Sector-Specific Climate Indices (ET-SCI; Alexander & Herold 2016; Yosef *et al*. 2019) for the first time in a South African context, for both cold and warm extremes. The ET-SCI are sector-specific indices derived from the Expert Team on Climate Change Detection (ETCCDI; Alexander & Herold 2016; Yosef *et al.* 2019); the indices consider health, water and agriculture and can identify short ETEs (3 days) and are more relevant in a South African context. The trend analysis includes a seasonal analysis, comparing and extending the research period (>30 years) on previous studies which used the WMO ETCCDI (Zhang *et al*. 2018) to identify and examine ETEs.

The general discussion (Chapter 9) presents three cross cutting themes across the four research papers, that integrates and exand on the findings of each research paper with the existing literature. Finally, there is potentially much research which may follow on from this research project, as discussed in Chapter 10 (Conclusion). This is discussed here because the ET-SCI could be used on new locations and for comparison between 30-year period time frames. In addition, the shortage of research on ETEs over South Africa as well as the high inter-annual climate variability and pronounced seasonal cycle makes this a relevant and necessary research topic, for both academic and societal purposes.

1.3. Study Aim and Objectives

The primary objective of this research is to investigate the frequency, incidence, and climatology of annual and seasonally anomalous temperature events over South Africa over the period 1960-2015. This study will not only produce a comprehensive record of annual and seasonally anomalous ETEs, but will also seek to more clearly distinguish South African seasons based on mean temperature.

To examine these hypotheses and to address the primary aim of this research the specific objectives of this research are:

1. To determine the statistical boundaries for the timing of seasons in South Africa based on temperature.
2. To determine the frequency of occurrence of annually and aseasonally cold temperature events over the period 1960-2015.

3. To determine the frequency of occurrence of annually and aseasonally warm temperature events over the period 1960-2015.
4. To identify any consistent synoptic features that may be related to these anomalous ETEs.
5. To explore the temporal patterns in these events, including progressive increases under climate changes, and any cyclical association with sunspots, volcanic events, El Niño-Southern Oscillation (ENSO) and the Subtropical Indian Ocean Dipole (SIOD/IOD).

1.4. Structure of Thesis

This thesis has been divided into 10 chapters. They are structured as follows:

This introductory chapter provides the background, including the rationale for this PhD, followed by the aims and objectives of the study. The introductory chapter is followed by the study region chapter (Chapter 2), which is aimed at providing readers with a background on South Africa, the study region. In this chapter focus is placed on providing a description of the climate and weather, with specific emphasis on the temperature characteristics, as well as a description of the topography, surrounding oceans and synoptics.

The data and methodology chapter (Chapter 3) is presented next. First, the process of selecting meteorological stations is covered, as well as the process of data cleaning. This is followed by an outline of methodological procedures undertaken for each of the individual papers (Chapters 5-8), which includes determining statistical approaches, selection of temperature indices, spatial interpolation, and data presentation and thought process throughout.

The overview of chapters (Chapter 4) follows this. This chapter is aimed at providing the reader with the logic of each paper, the thought process, as well as links between each paper. Next, the core objectives are addressed through separate chapters written up as research papers (Chapter 5-8) for journal publication. Chapter 5 presents a review of extreme temperature events in South Africa. The statistical classification of South African seasonal divisions on the basis of daily temperature data is presented in chapter 6 and has been accepted for publication in the *South African Journal of Science*. Chapter 7 presents trend analysis of cold extremes in South Africa: 1960-2016. Chapter eight explores extreme warm temperature trends in South Africa: 1960-2016. Each of these research paper chapters has a cover page with a summary of where it has been submitted to, when it was submitted, status and the role of each author. The discussion chapter (Chapter 9) explores each paper with a thematic discussion that cross cuts chapters 5 to 8 and provides an overarching conclusion for the PhD research. This chapter also presents an overview of the main limitations of the research, the contribution of the findings to knowledge of ETEs in South Africa, and possible avenues for future work.

Chapter 10 is the final chapter. It reflects on the extent to which the research aims and objectives have been achieved. Also, this chapter reflects on the key findings of this study as well as their significance.

It should be noted that a comprehensive reference list follows the concluding chapter. In the case of chapters 5 to 8, a reference list is included according to the reference style of the respective journal the manuscript was submitted to.

Chapter 2: Study Region

2.1. Introduction

This study is focused on analysing extreme temperature events and the trends thereof using SAWS meteorological stations, located across South Africa. A discussion on the data used, selection, collection and location of the meteorological stations can be found under Chapter 3 (Data and Methodology). What follows in this chapter is a description of the geographic location, topographical characteristics, present-day climate, socioeconomic landscape and human-health of the study region. The climate section in this chapter will mainly focus on synoptic features which contribute to temperature variability. Also, it is important to note that a reasonable degree of duplication of information may occur due the inclusion of study region sections in three of the submitted papers (chapters 6 to 8).

2.2. Geography: Location and Topography

South Africa occupies the most southern tip of Africa, spanning the subtropics and mid-latitudes between 22-35°S, and 17-33°E, and covers a surface area of 1,219,602km^2 (Figure 1; Mokoena, 2019). South Africa shares common boundaries with Namibia, Botswana, Zimbabwe, Mozambique and Eswatini (Swaziland), while Lesotho is landlocked by South African boundaries. To the west and southwest South Africa is bordered by the Atlantic Ocean, which hosts the cold Benguela Current that flows northwards along the west coast. To the south and east the country is bordered by the Indian Ocean, which hosts the warm Mozambique and Agulhas Current that skirts the east and south coast as far as Cape Agulhas (Davis-Reddy & Vincent, 2017; Mokoena, 2019). The topography of South Africa is complex and predominantly characterised by the escarpment (i.e. Great Escarpment) which separates the high-lying interior plateau and the low-lying coastal plain (Figure 1; Grab & Knight, 2018;

Roffe, 2019; Mokoena, 2019). The Great Escarpment extends through Limpopo, western Eswatini and southeastern Mpumalanga before reaching its highest elevation along the border of Lesotho and KwaZulu-Natal province, with elevations reaching 3,482m in the KwaZulu-Natal Drakensberg (Grab & Knight, 2018; Mokoena, 2019). The inland plateau is characterised by wide plains with an approximate average height of 1,200m.asl (Mokoena, 2019) while the high plateau - the western, eastern and southern escarpments - have an approximate average height of 1,250m.asl (Landman *et al*., 2017). In addition, the Cape Fold Belt mountain range is located in the southwestern Cape and along the southern coast, with the highest approximate point of 2249m.asl (Grab & Knight, 2018).

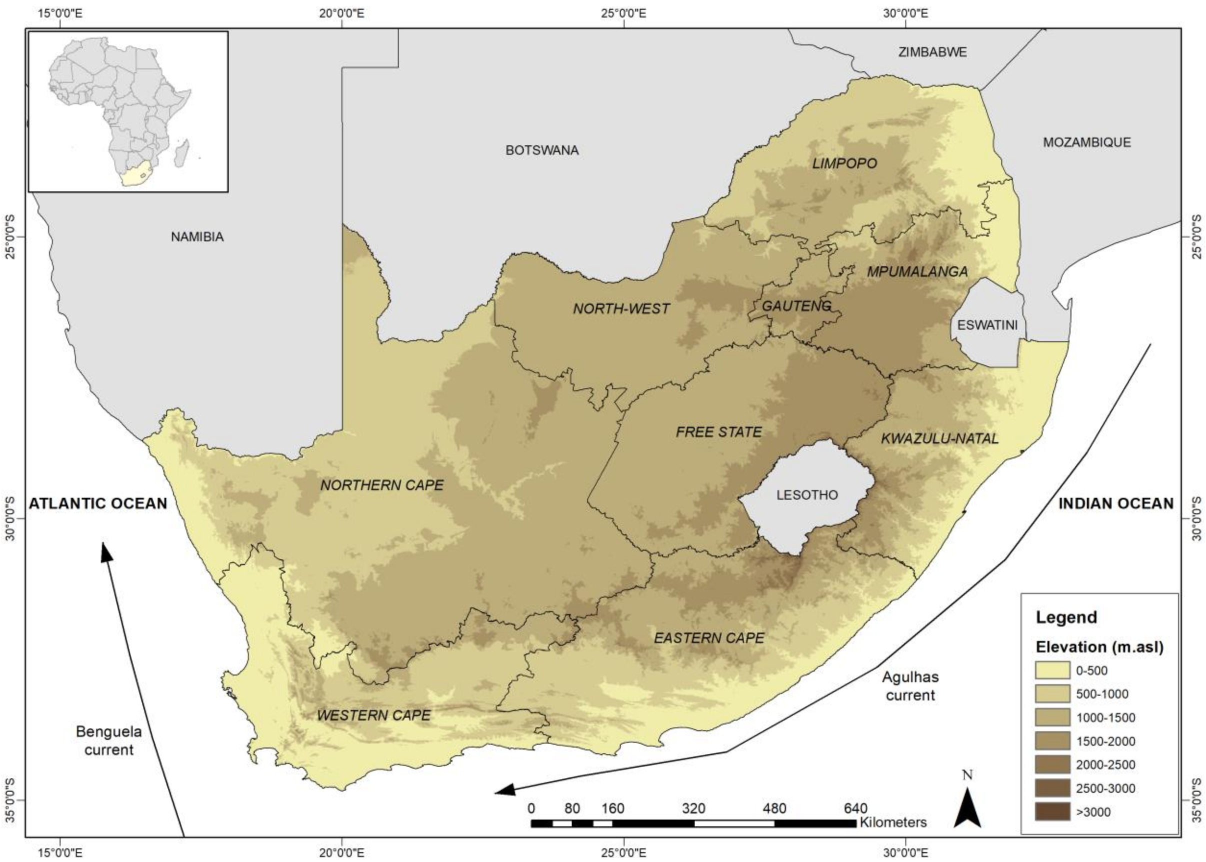


Figure 2.1: Map of study region of South Africa, topography and the surrounding oceans and their respective ocean currents.

2.3. Climate and Weather

The generalised climate of South Africa varies from warm, arid conditions in the west, to humid subtropical conditions in the north and east, with the interior parts classified as semi-arid (Doran, 2014; Landman *et al*., 2017; Lennard, 2019; Roffe, 2019). South Africa's latitudinal position within the tropical, subtropical and mid-latitude pressure regimes, in turn, produces pronounced seasonal difference in rainfall and temperature patterns (Doran, 2014). The intra-annual migration of the Inter-Tropical Convergence Zone (ITCZ) and Southern Hemisphere Westerlies (Tyson & Preston-Whyte, 2000; Jury, 2013; Doran, 2014) play a role in these seasonal differences, too. For example, summer temperatures are warmer compared to winter temperatures across the country (Landman *et al*., 2017). South Africa's climate and weather, and in particular its temperature, is governed by complex interactions between the subtropical location, the altitude of the interior plateau, the position of the subcontinent with respect to the atmospheric circulation features and proximity to as well as temperature of the surrounding oceans (Tyson & Preston-Whyte, 2000; Doran, 2014; Davis-Reddy & Vincent, 2017; Jury, 2018; Landman *et al*., 2018; Lennard, 2019; Roffe *et al*., 2019). The abovementioned physical controls will be discussed separately, although these controls do not exist in isolation but interact with one another. It is also worth mentioning that South Africa's climate is impacted by numerous large-scale teleconnections which modulate temperatures and may contribute to ETEs. These are mentioned in the discussion below, as well as expanded on in Supplementary Material (Draft Article).

The complex topography influences the temperature of the country in numerous ways. The orography of South Africa influences the temperature distribution over the country where the escarpment forms a climatic division between the high plateau and the low-lying coastal regions in the east and southeast (Klopper *et al*., 1998). In general, the southern and eastern escarpments experience the lowest mean temperatures, due to the decrease in temperature with altitude; frost is also common in these areas (Engelbrecht & Landman, 2010; Davis, 2011; Landman *et al*., 2017; Mokoena, 2019). As, such warmer temperatures are experienced along the coastal and northern parts of KwaZulu-Natal, the lowveld of Mpumalanga, the Limpopo valley, the North-West and the interior of the Northern Cape Province (Landman *et al*., 2017). Temperatures in interior South Africa tend to be lower than other countries at similar latitudes due to greater elevation above sea level (Mokoena, 2019). For instance, temperatures on the interior plateau (1694m.asl) may reach 30°C in summer and drop below freezing point or lower in the same area during winter (Mokoena, 2019). However, it should be noted that the coastal plain's temperatures are more moderate due the influence of the surrounding oceans.

The surrounding oceans influence the climate and temperature across South Africa in various ways: being in close proximity; through the influence of the ocean currents; or through interaction between the ocean and the atmosphere (i.e. teleconnections; Kruger, 2008; Landman *et al*., 2017; Lennard, 2019). The warm southward flowing Agulhas Current causes the east coast to be significantly warmer than the west coast, whereas the northwards flowing cold Benguela Current induces lower temperatures along the west coast (Doran, 2014; Engelbrecht & Landman, 2010; Landman *et al*., 2017).

Although not fully understood, natural modes of variability have been related to rainfall and temperatures variations, and to temperature extremes globally and for southern Africa (Nicolson, 2001; Nicholls *et al*., 2012; You *et al*., 2013; He *et al*., 2017; Loikith *et al*., 2017). The most prominent natural phenomenon is the El Niño Southern Oscillation (ENSO), which involves prolonged warming (El Niño) or cooling (La Niña) periods of the east-central Pacific Ocean sea surface temperatures (SSTs) (Landman *et al*., 2017). Other mechanisms include the

North Atlantic Oscillation (NOA), the Southern Annular Mode (SAM), the Madden-Julian Oscillation (MJO), the Artic Oscillation (AO), the Indian Ocean Dipole (IOD), and the Pacific Decadal Oscillation (PDO) (Mason & Jury, 1997; Nicholls *et al*., 2012; You *et al*., 2013; Ning & Bradley, 2015 He *et al*., 2017; Loikith *et al*., 2017; Liu *et al*., 2018).

As previously noted, the latitudinal position in the tropical, sub-tropical, mid-latitude temperature and pressure regimes may influence the day-to-day weather and seasonal rainfall and temperatures (Tyson & Preston-Whyte, 2000). The subtropical pressure regime or control on South African weather and climate is through a discontinuous high-pressure belt, circling the southern hemisphere at about 30°S, of semi-permanent high-pressure systems (i.e. subtropical anticyclones) known as the South Indian Anticyclone (SIA), the Continental-High (CH) and the South Atlantic Anticyclone (SAA; Tyson & Preston-Whyte, 2000; Cherchi *et al*., 2018; Roffe, 2019). The latitudinal and longitudinal position of the SAA and SIA vary significantly throughout the year and move northwards about 6° in winter (Tyson & Preston-Whyte, 2000). During summer, meanwhile, the SAA, SIA and CH migrate south due to the seasonal migration of the ITCZ (Tyson & Preston-Whyte, 2000; Lennard, 2019). These anticyclones produce warm, sunny, clear skies; they are a function of the descending poleward limb of the tropical Hadley cell and the Ferrel cell, and are associated with strong subsidence (Tyson & Preston-Whyte, 2000; Lennard, 2019; Roffe, 2019). Subsidence is prevalent in subtropical climates (Tyson & Preston-Whyte, 2000). Prevailing anticyclones for extended periods in summer produce severe heat waves and drought (Tyson & Preston-Whyte, 2000). Over the interior, heat waves associated with strong anticyclones can last up to between 4 and 7 days, with increases of >5°C in temperatures (Tyson & Preston-Whyte, 2000). Abrupt increases of >5°C from one day to the next, in particular in coastal areas, are associated with the occurrence of a strong continental anticyclone as a result of subsidence and warming associated with berg winds (Tyson & Preston-Whyte, 2000). Berg winds are associated with large-scale pre-frontal divergence and warming of subsiding air moving offshore (Tyson & Preston-Whyte, 2000). Berg winds and coastal lows usually occur together and influence the climate and weather of the coastal and adjacent inland areas. Coastal lows are generated from cyclonic vorticity with eastward movement of air off the high interior plateau, which are initiated on the west coast and disseminate southward to Cape Town. Coastal lows seldom extend inland of the Cape Fold mountains and Kwazulu-Natal province (Tyson & Preston-Whyte, 2000; Kruger *et al*., 2010). These systems produce warm offshore airflow ahead and cool onshore airflow behind; this resembles and can be mistaken for a cold front (Tyson & Preston-Whyte, 2000). Both these systems are most common in late winter and early spring (Davis *et al*., 2016), and result in high maximum temperature anomalies during winter in coastal meteorological stations (Tyson & Preston-Whyte, 2000).

The tropical control on South Africa is only evident in summer and is usually associated with the large-scale atmospheric feature, the ITCZ, and warm easterly winds between the ITCZ and the subtropical anticyclone belt (Tyson & Preston-Whyte, 2000; Doran, 2014). The ITCZ represents an area of intense convective activity associated with low pressure, which moves south during the Southern Hemisphere summer, approximately ˜17°S over the eastern parts of southern Africa (Tyson & Preston-Whyte, 2000; Doran, 2014; Nicholson, 2018). Also associated with the southward movement of the ITCZ are the easterly waves and lows, situated around the northern sector of the subtropical anticyclones (Tyson & Preston-Whyte, 2000; Lennard, 2019; Roffe, 2019). The easterly waves are semi-stationary over southern Africa and are characterised as a barotropic wave associated with warm, humid easterly wind

(Tyson & Preston-Whyte, 2000; Lennard, 2019). Flowing from east to west, ahead of and to the west of the trough, subsidence ensures no rainfall and hot conditions across the interior and eastern parts of the country (Tyson & Preston-Whyte, 2000; Lennard, 2019). Also, the easterly waves are characterised as a well-defined boundary separating moist air and drier air, to the north-east from the south-west (Tyson & Preston-Whyte, 2000). The associated easterly wave are a thermal low which contributes to convection rainfall across the interior and eastern parts of the country (Tyson & Preston-Whyte, 2000; Lennard, 2019).

The temperate control on South Africa is characterised with the northward migration of the ITCZ, subtropical high-pressure belt and the mid-latitude Westerlies during the winter months. The climate of South Africa in winter is influenced by the northward movement of the circumpolar Westerlies and is exerted through traveling perturbations from the Westerlies, with six unique classes of baroclinic disturbances which are i.e. cold fronts, coastal lows and berg winds, cut-off lows, ridging anticyclones and westerly waves (Tyson & Preston-Whyte, 2000; Singleton & Reason, 2007; Mahlalela *et al*., 2018; Sousa *et al*., 2019; Lennard, 2019; Roffe, 2019). Westerly waves are baroclinic, Rossby waves which have a frequency of occurrence between 2 and 8 days (Tyson & Preston-Whyte, 2000). During winter, ahead of the trough, which is typically located over the interior and eastern parts of the country, there is subsidence and associated clear skies (Tyson & Preston-Whyte, 2000; Lennard, 2019). At the rear of the trough located over the Western Cape there is surface convergence and uplift-associated clouds and rainfall (Tyson & Preston-Whyte, 2000; Lennard 2019). Associated with westerly perturbations are the more intense form and low-pressure system cut-off lows and cold fronts (i.e. mid-latitude cyclones; Tyson & Preston-Whyte, 2000; Lennard & Hegerl, 2015; Landman *et al*., 2017; Lennard, 2019). The cut-off lows are associated with sunny days, clear skies, cold nights and sometimes frost in the interior parts of the country (Landman *et al*., 2019). Mid-latitude cyclones occur throughout the year, although it is only during winter that their cold front arms reach the southern and interior regions of the country (Tyson & Preston-Whyte, 2000; Landman *et al*., 2017; Roffe, 2019). Cold fronts are associated with atmospheric circulation systems which occur in the mid- and upper-levels of the atmosphere, thus causing snowfall over the mountainous regions in the Western and Eastern Cape provinces, and occasionally over the interior parts of the country. Cold fronts tend to intrude northwards over the interior plateau during the transition months (i.e. April and September); depending on the strength of the pressure gradient forcing the cold fronts across South Africa, the front could reach Gauteng, but can occasionally penetrate Limpopo (Stander, 2013; Stander *et al*., 2016; Landman *et al*., 2017). The associated cold snaps, following the passage of the cold front, can last up to four days over South Africa, and are attributed to the frontal perturbations in the westerlies (Tyson and Preston-Whyte, 2000; Stander *et al*., 2016). These cold snaps may result in snowfall and cold temperatures over the Free State, Gauteng, KwaZulu-Natal, and Mpumalanga provinces (Stander *et al*., 2016; Landman *et al*., 2017). Summer cold fronts and their passage and existence across South Africa are debatable, and may be associated with severe weather conditions over the interior and meso-scale wind shears and low-convergence (Tyson & Preston-Whyte, 2000).

The subtropical location of the country means it is possible that interactions between synoptic scale mid-latitude waves and tropical weather systems can combine to form composite synoptics, typically orientated from northwest to southeast, known as Tropical Temperature Troughs (TTT; Mason & Jury, 1997; Tyson & Preston-Whyte, 2000; Crétat *et al.*, 2012; Hart *et al*., 2012; Vigaud *et al*., 2012; Roffe, 2019). Many different combinations are possible and when these systems act in conjunction, heavy and widespread rainfall may occur which substantially contributes to the summer rainfall across large parts of the country (Tyson & Preston 2000, Crétat *et al.*, 2012; Hart *et al*., 2012; Roffe, 2019). These combinations can also influence the temperatures across South Africa. For instance, the combination of a deep cut-off low and a ridging anticyclone to the south of the continent contributes to snow and rainfall over the South African Highveld (Tyson and Preston-Whyte, 2000).

2.4. Socioeconomic landscape and Human Health

In 2019 it was estimated by Statistics South Africa that the population of South Africa is 58.78 million (Mokoena, 2019). Approximately 28% of the population is younger than 15 years while 9% (5.3 million) is 60 years and older. The highest percentage (23.9% or 1.27 million) of elderly people reside in Gauteng. Cities, towns and informal settlements currently host 78% of the country's population (Le Roux *et al*., 2017), while the remaining percentage of the population lives in rural areas - some of these rural residents rely on emerging agriculture sector and natural resources for their livelihood (Chersich *et al*., 2018). Although cities and towns are becoming locations of choice for the urban poor and youth, they are challenged with poverty, unemployment, pollution, crime, service delivery issues and income equality (Le Roux *et al*., 2017). About a quarter of the whole population is unemployed and over half live below the poverty line (Chersich & Wright, 2019). Also, it is estimated that 14% of the country's 14.45 million households are informal (i.e. informal settlements and backyard shacks) (Le Roux *et al*., 2017). Access to social and economic resources and networks, health, and income influence the adaptive capacity of households, communities and neighborhoods in towns and cities. Social vulnerability can be identified, for example where there are high illiteracy rates, informality, ethnic minorities, violent crimes, and backlogs of basic services (Le Roux *et al*., 2017). Applying the social vulnerability index using available public data, it was found that the most vulnerable communities correlate with former homeland areas in the Eastern Cape, Kwazulu-Natal, Limpopo and North-West provinces (Le Roux *et al*., 2017). Similar to the social vulnerability index, the economic pressure index makes use of different economic proxies (i.e. diversity of the economy). This index has found that densely settled former homelands along the eastern coast and the northern parts of the country are areas under the most significant economic pressure, as well as surrounding areas of metropolitans and major towns (Van Huyssteen *et al*., 2013; Le Roux *et al*., 2017). The southern and eastern coastal towns are characterised by a high in-migration and unemployment rate (Van Huyssteen *et al*., 2013), with an estimated 3.5 million people reside along the coastline within the first 5-7km from within coastline. Of these an approximate 40% are considered to live below the poverty line (Le Roux *et al*., 2017).

Public health in South Africa is in a very unique situation; the system is burdened with illnesses found in both developing countries (i.e. communicable diseases) and developed countries (i.e. non-communicable diseases known as lifestyle diseases) which puts additional pressure on an already struggling health care sector (Garland, 2017). Life expectancy at birth is estimated for males at 61.5 years and 67.7 years for females (Mokoena, 2019). The infant mortality rate is estimated at 22,1 per 1000 live births (Mokoena, 2019), and the Human Immunodeficiency Virus (HIV) prevalence rate is approximately 13%. An estimated 19.07% of the population between 15-49 years is HIV positive, with a total of 7,97 million people living with HIV in South Africa (Mokoena, 2019). The high incidence of HIV and tuberculosis, and the incidence of chronic illnesses and non-communicable diseases (i.e. cardiovascular diseases, respiratory diseases and cancers) in South Africa, exacerbates the need for basic services and sanitation (Ziervogel *et al*., 2014; Wright *et al*., 2015; Chersich *et al*., 2018).

2.5. Conclusion

Due to South Africa's latitudinal location, its climate – and in particular the temperature - is governed by the tropical, subtropical and temperate synoptic features. The complex topography and surrounding oceans additionally play an important role. In addition, the socioeconomic landscape and human health concerns highlight the importance of exploring ETEs and how these could exacerbate and impact an already vulnerable population. This highlights that it is key to explore ETEs and how they may have changed under current climate change conditions.

Chapter 3: Data and Methodology

3.1. Introduction

This chapter outlines the data and methodology procedures followed. It starts with a description of the data required, the criteria and selection process of the meteorological stations and identification of the temporal study period. Next, the data quality and cleaning of the datasets used will be discussed; then there is a discussion on the importance of data homogenisation and the procedures used in each research paper. This is followed by a summary, in the form of a flow diagram, of each methodological approach used in each research paper (Chapters 5-8). Next, the chosen statistical approaches and interpolation techniques used in each research paper will be discussed. Finally, a discussion on the process of selection of the temperature indices will be presented, as well as a description of each index used to identify the ETEs.

3.2. Temperature data required

Climate data, including daily maximum (TX; T_{max}) and minimum (TN; T_{min}) temperature in degrees Celsius (°C), has been obtained from the SAWS. The temperature readings are the highest and lowest readings recorded over a 24-hour period.

3.3. Meteorological station selection

The SAWS's countrywide observational network consists mostly of rainfall stations, automatic rainfall stations, climate stations and a total of 231 automatic weather stations (SAWS, 2020). All of these meteorological/weather stations were assessed for use in this study, and only a few were selected based on different sets of criteria and due to the missing data of the meteorological stations, as highlighted in the data limitation section (see Section 9.6.1 of Chapter 9). Weather stations were selected for inclusion using different sets of criteria relevant to each research paper (Chapters 6-8). Firstly, a general set of selection criteria will be discussed, given that the processes and data sets used in each research paper were similar. Thereafter the discussion will be focused on each research paper (Chapters 6-8). It is important to note that the selected weather stations are similar, to some extent, to those used in previous temperature-related studies across the country (e.g. New *et al*., 2006; Kruger & Sekele, 2012; Mackellar *et al*., 2014; Davis *et al*., 2016; Van Wilgen *et al*. 2016; Kruger & Nxumalo, 2017; Kruger *et al*., 2019; Mbokodo *et al*., 2020).

3.3.1. General selection process and criteria

Firstly, a weather station required at least 30 years of daily maximum and minimum temperature data to be included in the study. According to WMO standards, a minimum of 30 years of data is required (WMO, 2000) to obtain a reliable estimate of the mean and averages on climate. Secondly, while many of the SAWS weather stations started earlier than the 1960s and 1970s, data was not available or there were gaps in the data prior to the 1960s (Boitai *et al*., 2015; Kruger and Nxumalo, 2017). Thirdly, weather stations were selected which are relatively evenly spatially distributed over South Africa. Research indicates that data from only 20 stations which are relatively evenly distributed across South Africa is enough to define temperature variability and to get a perspective on the historical climate (Jones & Trewin, 2002; Vose & Menne, 2004; Trewin, 2010; Kruger & Nxumalo, 2017). However, it is recommended that >20 stations be used due to the heterogeneity of South Africa's climate (Kruger & Nxumalo, 2017). Lastly, a weather station was selected only if at least 90% of the TX and TN data was available for the chosen period after the data cleaning process (Mackellar *et al*., 2014; Kruger & Nxumalo, 2017; Kruger *et al*., 2019), described under Section 3.4. According to the so-called WMO 5/3 rule, a valid year is one with at least nine valid months, with no more than five missing days in a month and three consecutive missing days (WMO, 2017; Fioravanti *et al*., 2019). In addition, a valid year must contain at least one valid month per season, and at least 90% of the years must be valid in the time series with no more than four consecutive missing years (WMO, 2017; Fioravanti *et al*., 2019).

3.3.2. Criteria for statistical classification of seasonal divisions (Chapter 6)

There were only 35 stations which met the general criteria, as well as spanning the country ranging from 22-35 °S and 15-33 °E with an intended 1 ° interval to obtain a spatial distribution of stations (Table 2; Figure 1 of Chapter 6; Table 3.1). The year 1980 was selected as the start of the temporal period for each of the stations, to obtain the same time frame. The year 2015 was selected as the final year for this particular research paper. This allowed for stations to have at least a minimum of 30 years of data available for the statistical analyses.

3.3.3. Criteria for extreme cold and warm temperature events (Chapters 7 and 8)

Only 20 stations were selected from a subset of the 35 stations used in Chapter 6, for both research papers, relatively evenly distributed across South Africa (Table 3.1; Table 7.2; Figure 7.2); this was due to the extension of the research period to >50 years for each of the chosen stations. Each of the selected stations had a continuous dataset of daily TX and TN for at least 50 years. As the number of years recorded increases, the influence of incorrect or inaccurate readings and trends decreases (Arguez & Vose, 2011). A uniform start date of 1960 was used up to the most recent available data (2016) at the time of the study, to obtain a record of >50 years.

Table 3.1: Meteorological stations used (stations with an asterix next to it are the subset stations used in Chapter 7 and 8).

Province	Station Name	SAWS Code	Latitude	Longitude	Altitude
Eastern Cape	East London*	00595729	-33.03	27.83	124m
	Dohne*	00798116	-32.52	27.47	899m
	Mthatha	0127272A4	-31.55	28.67	745m
	Port Elizabeth*	00351795	-33.98	25.60	60m
Free State	Bloemfontein*	02615161	-29.10	26.30	1354m
	Bethlehem	03315859	-28.24	28.33	1689m
	Welkom	03643001	-27.99	26.66	1344m
Gauteng	Johannesburg Int*	*04763990*	-26.14	28.23	1706m
	Zuurbekom*	04755288	-26.30	27.81	1580m
KwaZulu-Natal	Cedara*	02394820	-29.54	30.27	1071m
	Durban*	0240808A2	-29.97	30.95	96m
	Escourt	03006901	-29.01	29.86	1144m
	Shaleburn	02376184	-29.80	29.35	1614m
Limpopo	Mara*	072200991	-23.14	29.56	894m
	Warmbad Towoomba*	05895941	-24.90	28.32	1143m
	Polokwane	0677802BX	-23.84	29.45	1226m
Mpumalanga	Skukuza*	05961793	-24.99	31.59	276m
	Carolina	04801547	-26.07	30.11	1667m
Northern Cape	Calvinia	0134479A3	-31.48	19.76	975m
	De Aar	01698801	-30.66	23.99	1286m
	Fraserburg	01130258	-31.91	21.51	1264m
	Kimberley*	02904684	-28.80	24.77	1198m
	Pofadder	0247668A4	-29.12	19.38	984m
	Springbok	0214700B2	-29.66	17.87	1006m
	Sutherland	00882931	-32.38	20.67	1459m
	Upington*	03174765	-28.43	21.27	836m
	Vanwyksvlei*	01935613	-30.35	21.82	965m
North-West	Vryburg*	04322383	-26.95	24.65	1245m
	Mahikeng	05080470	-25.80	25.54	1280m
Western Cape	Cape Agulhas*	00030204	-34.83	20.01	11m
	Cape Columbine*	00606209	-32.83	17.86	62m
	Mossel Bay*	0012215	-34.19	22.13	135m
	Cape Town*	0021178A3	-33.96	18.60	42m
	Vredendal*	0106880A2	-31.67	18.50	42m
	George	00126617	-34.00	22.38	197m

3.4. Data quality and cleaning

The WMO recommends that thorough quality controls of climate data sets be enacted before statistical analysis is performed (Klein Tank *et al*., 2009; WMO, 2011; Fioravanti *et al*., 2019). The selected stations' data sets were subjected to quality control due to missing data and possible outliers that may occur due to human-induced error or faulty measuring equipment (Klein Tank *et al*. 2009; Salameh *et al*. 2018). Erroneous data can also compromise the performance of the homogenisation process (Domokos & Coll, 2017; Fioravanti *et al*., 2019). For this studye visible outliers were checked, and two decimal point rounding was used to maintain consistency throughout (Van der Walt & Fitchett, 2020). In the case of the statistical classification seasonal divisions research paper (Chapter 6), missing weather station data, up to 5 days was replaced with adjacent station data, within a 10km radius; if this was not possible, it was replaced with the five-day running average (Van der Walt & Fitchett, 2020). For both extreme cold and warm temperature events (Chapters 7 and 8), missing TX or TN data were cross validated with adjacent stations within a 50km radius, for any given day up to a maximum of 5 days; this was due to the sparsity of weather stations with a 50-year data set. Where cross-validation was not possible, data was replaced with the five-day running average. In addition, leap days were removed from the analysis. If the data was not available for more than five consecutive days in a month, the year was excluded. Many researchers fail to mention that the ETCCDI calculates only monthly indices if no more than 3 days are missing in the month, while annual values are not calculated if >15 days in a year are missing (Zhang *et al*., 2018). Threshold indices are calculated if at least 75% of the data is present (Zhang *et al*., 2018).

To ensure consistency, additional quality control was performed in both the extreme cold and warm temperature events research papers (Chapters 7 and 8). The additional quality control was performed on each weather station's data series using the R-based ClimPACT v2 software packages, which were used to calculate the ET-SCI (Alexander & Herold, 2016); the RClimDex v1.9 software package was used to calculate the ETCCDI (Zhang *et al*., 2018). Both these software packages flag outliers in the format of either boxplots or tables, to alert the user to pay more attention and make corrections only if needed (Klein Tank *et al*., 2009; Alexander & Herold, 2016; Zhang *et al*., 2018). Furthermore, both software packages allow the user to set the outlier threshold in terms of the standard deviations for the particular calendar day above the threshold; the default threshold of three standard deviations was used (Zhang & Yang, 2004; Alexander & Herold, 2006; Zhang *et al*., 2018; Kruger & Nxumalo, 2017).

3.5. Data homogenisation

The quality-controlled data time series was checked for non-climatic shifts that may exist in the data sets because of unavoidable changes in aspects including observation site, station relocation, instrument observing practices, and automation of the weather stations during the observation period amongst others (Klein Tank *et al*., 2009; WMO, 2009; Wang *et al*., 2010; Aguilar *et al*., 2013; Kruger & Nxumalo, 2017). Data homogenisation is done to identify and adjust any artificial non-climatic variations in climate data, ensuring that time fluctuations in data are only caused by variations in climate (Vincent *et al*., 2002; Klein Tank *et al*., 2009; Kruger & Nxumalo, 2017; Yosef *et al*., 2019). Several homogenisation methods have been developed and used (e.g. Alexanderson, 1986; Vincent *et al*., 2002; Wang, 2003, 2008a, 2008b; Della-Marta & Wanner, 2006; Reeves *et al*., 2007; Vincent *et al*., 2012; Nemec *et al*., 2013; Salameh *et al*., 2018; Yosef *et al*., 2019), each with their own advantages and disadvantages. These methods often depend on the types and inhomogeneity to be detected and adjusted (e.g. Vincent *et al*., 2002, 2012; Wang 2008a; Nemec *et al*., 2013; Kruger &

Nxumalo, 2017; Salameh, *et al*., 2018), which makes it difficult to select an appropriate method beforehand. The WMO ETCCDI developed a software program, through experts and a series of workshops in different parts of the world, referred to as the RHtestV4 (Tank *et al*., 2009). This software program is an R-based software package, which detects and adjusts multiple change points in time series (Wang 2008a, 2008b; Whang & Feng, 2013). The RHtestV4 includes the provision of Quantile-Matching (QM) adjustments, which are estimated with the use of a reference series (Wang & Feng, 2013). In addition, this software package allows for mean-adjustments, offers the choice of using the whole or part of the segment before or after a shift, gives users choice of segment to which the base series is to be adjusted, and offers choices regarding the nominal level of confidence at which to conduct the test. All these functions are available in the graphical user interface (GUI) mode (Wang & Feng, 2013). The statistical procedures are based on the penalised maximal t-test (Wang 2008a) and the penalised maximal F-test (Wang 2008b), which are embedded in the recursive testing algorithm (Wang 2008a), with the lag-1 autocorrelation of the time series being empirically accounted for (Wang *et al*., 2007; Wang 2008a, 2008b; Wang & Feng, 2003). Given that the software package was developed under the auspices of the WMO ETCCDI, it was the preferred package to use in this research. It is important to note that the RHtestV4 software was only applied to the extreme cold and warm temperature events research papers (Chapters 7 and 8), due to the extent of the research period. The RHtestV4 was carried out without a reference series due to the difficulty in identifying and constructing an appropriate reference period in developing countries such as South Africa with a sparse distribution of long-term stations (Kruger & Nxumalo, 2017). The necessary adjustments were applied to the daily data time series (see Supplement Material Chapter 7, Supporting Table 1) and loaded into the RClimDex v1.9 and ClimPACT v2 software packages to calculate the ETCCDI and ET-

SCI temperature indices, respectively described in section 3.8. To ensure homogeneity in the statistical classification of the seasonal divisions research paper (Chapter 6), the data quality and cleaning and using the SAWS database as a primary source (Roffe, 2019) was deemed sufficient (Chapter 6 Data and Methodology).

3.6. Methodological approaches (Chapter 5-8)

A flow diagram of each research paper will be presented under each subsection below.

3.6.1. Review of ETEs in South Africa (Chapter 5)

The literature was consulted, together with a wide-ranging search using different keywords and phrases to locate the known publications on ETEs in South Africa.

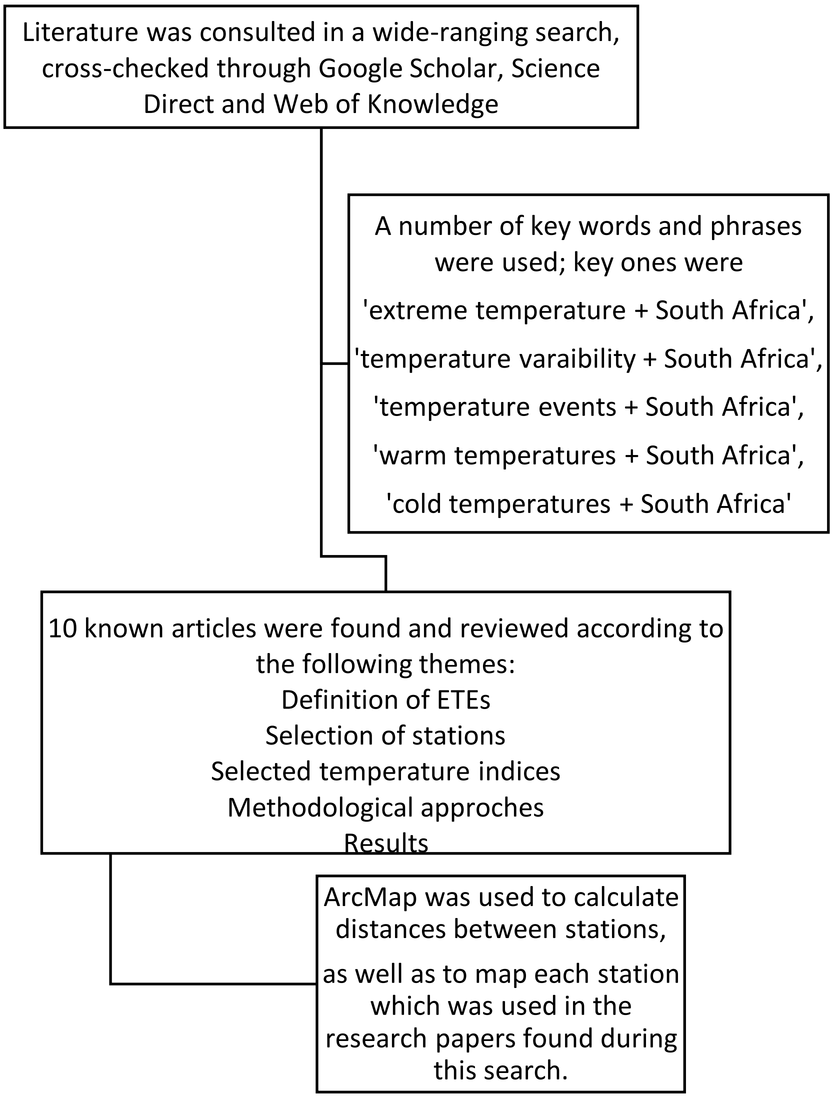


Figure 3.1: Methods used in Review paper of ETEs in South Africa

3.6.2. Statistical classification seasonal divisions (Chapter 6)

Temperature data was collected from the SAWS and aggregated into mean monthly temperature per weather station for each year. Thereafter a hierarchical clustering analysis using Ward's D minimum variance method was applied to get the results.

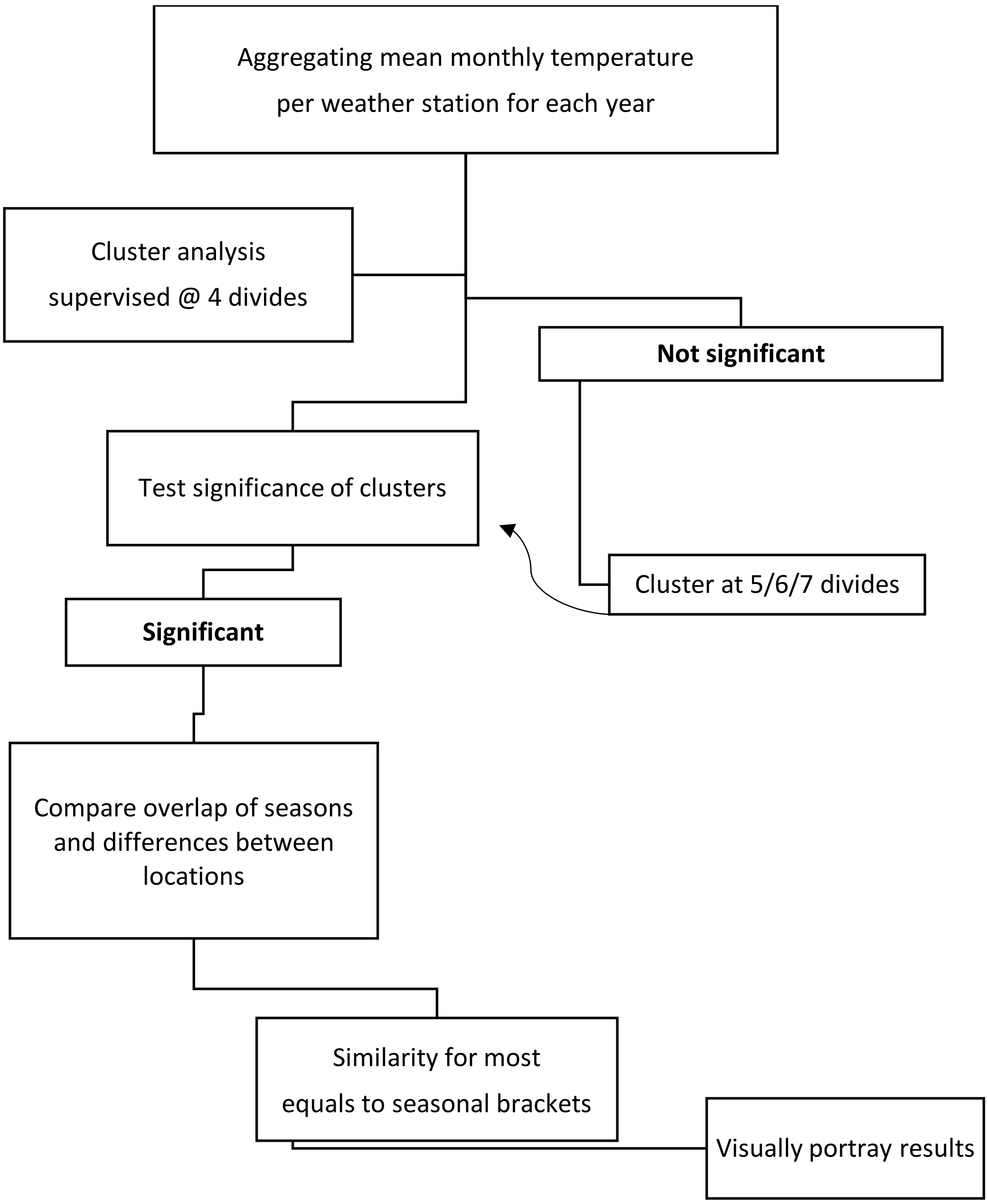


Figure 3.2: Method to determine seasonal distribution and brackets

3.6.3. Extreme cold and warm temperature events (Chapters 7 and 8).

Temperature data was collected from the SAWS climate database (see Chapters 7, and 8); thereafter data cleaning and quality checks were done per weather station. Then each index was calculated per weather station, followed by the trend analyses for each index.

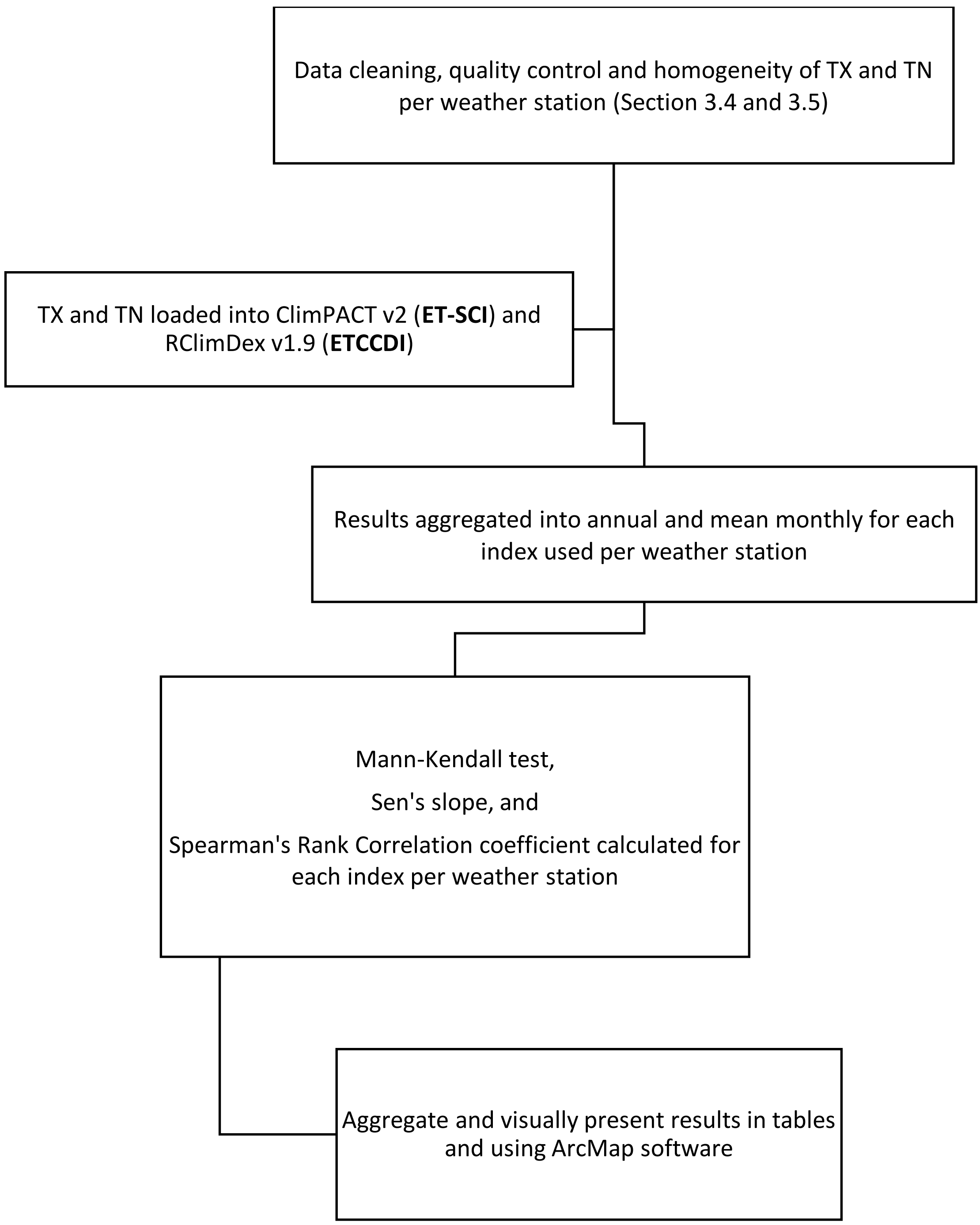


Figure 3.3: Method to determine extreme cold and warm temperature events

3.7. Statistical approaches

There are a number of statistical approaches which were developed to group a set of entities according to similarity, as well as statistical trend analyses of time series data. The statistical approaches used in the research papers (Chapters 6-8) will be described and discussed in detail see Section 3.7.1 below, together with the motivation for why the statistical approach was chosen. This discussions starts with the cluster analysis of the statistical classification of seasonal divisions on the basis of daily temperature in South Africa (Chapter 6) and is followed by the statistical approaches used in determining the trends of extreme warm and cold temperature events in South Africa (Chapters 7 and 8).

3.7.1. Cluster analysis

Cluster analysis has been widely documented in climate science globally (Kalkstein *et al*., 1987; Unal *et al*., 2003; Aliaga *et al*., 2017; De la Barreda *et al*., 2020; Costa *et al*., 2020), particularly in temperature related studies (Unal *et al*., 2003; Rebetez & Reinhard, 2008; Gibson *et al*., 2017; Fioravanti *et al*., 2019; Costa *et al*., 2020). Cluster analysis has also been widely applied in climate science across South Africa, in particular rainfall studies (e.g. Favre *et al*., 2016; Phakula *et al*., 2018; Burl *et al*., 2019), as well as temperature related studies (Kruger & Sekele, 2013; Diriba *et al*., 2015; Rangata *et al*., 2020). Cluster analysis is a statistical method used to group entities and find homogeneous and inhomogeneous climate zones between entities based upon meteorological parameters (Unal *et al*., 2003; Roffe, 2019). Both hierarchical and non-hierarchical techniques have been used in atmospheric research studies (Adabi *et al*., 2020). Hierarchical cluster analysis techniques include agglomerative hierarchical clustering (AHC) (Roffe, 2019; Adabi *et al*., 2020), whereas non-hierarchical techniques incorporate *k*-means cluster analysis, among others (Roffe, 2019; Adabi *et al*., 2020; Govender & Sivakumar, 2020).

To statistically classify the seasons of South Africa (Chapter 6), the agglomerative hierarchical clustering using Ward's D minimum variance method is applied (see Cluster analysis Chapter 6). This has been widely documented in climate science (Fioravanti *et al*., 2019), defined by the Euclidean distance as a similarity measure between variables (Mimmack *et al*., 2001; Unal *et al*., 2003; Bocard *et al*., 2011; Wilks, 2011; Casto *et al*., 2020). Ward's minimum variance method (Ward, 1963) identifies the smallest variations in the within-cluster sum of squares due to the merging of two clusters (Govender & Sivakumar, 2020). It groups elements *W*, whose sum of squares or sum of errors are minimum (Casto *et al*., 2020), according to the following equation:

$$W = \sum_{i=1}^{n} x_i^2 - \frac{1}{n} (\sum_{i=1}^{n} x_i)^2 \tag{1}$$

where *n* is the number of elements and x_i is the *i*th element of the group (Ward, 1963). This method was utilised because it minimises the within-cluster variance at each stage of merging (Govender & Sivakumar, 2020), and it enhances an objective statistic (Tennant & Hewiston, 2000; Roffe, 2019). In addition, the number of clusters is defined by the user, the clusters' characteristics are analysed at every step and a decision can be made when the number of clusters has an interpretable solution and a homogenous cluster (De la Barreda *et al*., 2020). A silhouette width method can be used (De la Barreda *et al*., 2020) to assess the validation of the cluster quality significance test. In addition, the silhouette width value measures the degree of confidence of between-group distances and strong within-group homogeneity (Studer, 2013; Van der Walt and Fitchett, 2020).

Following this, cluster analysis was performed utilising the cluster, vegan and rioja packages in R (Bocard *et al*., 2011; Wilks, 2011). The cluster analysis was initially supervised at four seasonal divides and validated by using the dendogram package average silhouette width (ASW) calculation (Kodinariya *et al*., 2013; de la Barreda *et al*., 2020; Van der Walt and Fitchett, 2020). If not significant, two, three, five and six seasonal divides were used respectively (Figure 3.2), until the cluster was significant, using order of magnitude put forward by Kaufman and Rousseew (2009). A silhouette width value closest to one suggests an optimal number of groups, whereas negative values indicate that the samples in the grouping are in the wrong group. Values close to zero propose that the samples may fall between groups (Kaufman & Rousseew, 2009). Additionally, the structure of the cluster dendogram and the cophenetic correlation coefficient (CPCC) were used to interpret, evaluate, and validate consistencies within the cluster and groups (Kaufman & Rousseew, 2009; Bocard *et al*., 2011; Van der Walt & Fitchett, 2020). The CPCC measures the correlation between the original pairwise distance matrix and the cophenetic distance metric of the dendogram, which allows for verification of the quality of the grouping (Li *et al*., 2015; Crow *et al*., 2018; Carvalho *et al*., 2019; Van der Walt & Fitchett, 2020). CPCC values closest to one suggest a high-grouping quality (Carvalho *et al*., 2019; Van der Walt & Fitchett, 2020). The cluster analysis results for maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) temperatures respectively were tabled (Table 3 of Chapter 6).

3.8. Temperature indices (ET-SCI and ETCCDI)

There are a number of temperature indices to identify and explore temperature extremes and variability. In the following subsections (Section 3.8.1 and 3.8.2) a summary will be provided of the ETCCDI and ET-SCI, followed by a definition and discussion on each of the temperature indices used in chapters 7 and 8. It is important to note that both research papers on the trend analysis of extreme warm and cold temperature events (Chapters 7 and 8) are the first to make use of the ET-SCI indices in South Africa.

3.8.1. Background to ETCCDI, software and indices

Internationally agreed indices derived from daily temperature and precipitation that represent more extreme aspects of the climate are overseen by the Commission for Climatology (CCI)/World Climate Research Programme (WRCP)/Joint Commission for Oceanography and Marine Meteorology (JCOMM) Expert Team on Climate Change Detection and Indices (ETCCDI), which was established in 1999 (Alexander & Herold, 2016). The core set includes 27 descriptive extreme indices for temperature and precipitation, which were developed to detect climate changes. These indices were developed to be statistically robust, to cover a wide range of climates and to have a high signal-to-noise ratio (Klein Tank *et al*., 2009; Alexander & Herold, 2016). An added advantage is that the indices can overcome most of the restrictions on the distribution of daily data; daily temperature and precipitation results can also be compared consistently across different countries (Klein Tank *et al*., 2009; Alexander & Herold, 2016). The ETCCDI indices can be grouped into four categories: (1) absolute indices; (2) threshold indices; (3) percentile indices; (4) duration indices (Alexander & Herold, 2016; Zhang *et al*., 2018). These indices are used for both observation and models on a regional or global level and can be coupled with trend detection techniques (Alexander

& Herold, 2016). As previously discussed, the R-based software, RClimDex software was developed to assist in the calculation of these indices.

Only six extreme temperature indices were selected from the core set indices for each research paper, depending on whether it was a warm or cold extreme temperature index. The selected indices are similar to those used in previous studies which examined extreme temperature trends in South Africa (e.g. New *et al*., 2006; Kruger & Sekele, 2013; Mackellar *et al*., 2014; Davis *et al*., 2016; Kruger & Nxumalo, 2017; Kruger *et al*., 2019). For the purpose of comparison to the ET-SCI, we also present an extension on previous analyses of the ETCCDI indices at an annual and seasonal time scale for the period 1960-2016 (Chapter 7,8). All the selected ETCCDI will be discussed and defined below (Zhang *et al*., 2018):

3.8.1.1. FD (Frost days)

Frost days are referred to as meteorological frost (TN<0°C). Let TN_{ij} be the daily minimum temperature on day i in the period j. Count the number of days where:

$$TN_{ij} < 0℃ \tag{2}$$

3.8.1.2. SU (Summer days)

Summer days are referred to as TX>25°C. Let TX_{ij} be the daily maximum temperature on day i in the period j. Count the number of days where:

$$TX_{ij} > 25℃ \tag{3}$$

3.8.1.3. TXx (Maximum TX)

The maximum daily TX each month. Let TX_{ij} be the daily maximum temperature in month i, period j. The maximum daily maximum temperature each month is then:

$$TX_{ij} = \max(TX_{ij}) \tag{4}$$

3.8.1.4. TNx (Maximum TN)

The maximum daily TN each month. Let TN_{ij} be the daily minimum temperatures in month i, period j. The maximum daily minimum temperature each month is then:

$$TN_{ij} = \max(TN_{ij}) \tag{5}$$

3.8.1.5. TXn (Minimum TX)

The minimum daily TX each month. Let TX_{ij} be the daily maximum temperature in month i, period j. The minimum daily maximum temperature each month is then:

$$TX_{ij} = \min(TX_{ij}) \tag{6}$$

3.8.1.6. TNn (Minimum TN)

The minimum daily TN each month. Let TN_{ij} be the daily minimum temperature in month i, period j. The minimum daily minimum temperature each month is then:

$$TN_{ij} = \min(TN_{ij}) \tag{7}$$

3.8.1.7. TN10p (Cool nights)

The count of days where TN are below the 10th percentile. Let TN_{ij} be the daily minimum temperature on day i, in the period j and let $TN_{in}10$ be the calendar day 10th percentile centered on a 5-day window (calculated using a bootstrap procedure described in Zhang *et al*., 2015, 2018). The percentage of time is determined where:

$$TN_{ij} < \ TN_{in}10$$

(8)

3.8.1.8. TX10p (Cool days)

The count of days where TX are below the 10th percentile. Let TX_{ij} be the daily maximum temperature on day i, in the period j and let $TX_{in}10$ be the calendar day 10th percentile centered on a 5-day window (calculated using a bootstrap procedure described in Zhang *et al*., 2015, 2018). The percentage of time is determined where:

$$TX_{ij} < \ TX_{in}10$$

(9)

3.8.1.9. TN90p (Warm nights)

The frequency of warm nights where TN is above the 90th percentile. Let TN_{ij} be the daily minimum temperature on day i, in the period j and let $TN_{in}90$ be the calendar day 90th percentile centered on a 5-day window (calculated using a bootstrap procedure described in Zhang *et al*., 2015, 2018). The percentage of time is determined where:

$$TN_{ij} > \ TN_{in}90$$

(10)

3.8.1.10. TX90p (Warm days)

The frequency of warm days where TX is above the 90th percentile. Let TX_{ij} be the daily maximum temperature on day i, in the period j and let $TX_{in}90$ be the calendar day 90th percentile centered on a 5-day window (calculated using a bootstrap procedure described in Zhang *et al*., 2015, 2018). The percentage of time is determined where:

$$TX_{ij} > \ TX_{in}90 \tag{11}$$

3.8.1.11. WSDI (Warm spell duration indicator)

Let TX_{ij} be the daily maximum temperature on day i in the period j and let $TX_{in}90$ be the calendar day 90th percentile centered on a 5-day window (calculated using a bootstrap procedure described in Zhang *et al*., 2015, 2018). Then the number of days per period is summed up where, in the interval, of at least six consecutive days:

$$TX_{ij} > \ TX_{in}90 \tag{12}$$

A spell can continue into the next year and is accounted against the year in which the spell ends.

3.8.1.12. CDSI (Cold spell duration indicator)

Let TN_{ij} be the daily minimum temperature on day i in the period j and let $TN_{in}90$ be the calendar day 10th percentile centered on a 5-day window (calculated using a bootstrap procedure described in Zhang *et al*., 2015, 2018). Then the number of days per period is summed up where, in the interval, of at least six consecutive days

$$TN_{ij} > \ TN_{in}10$$

(13)

A spell can continue into the next year and is accounted against the year in which the spell ends.

3.8.2. Background to ET-SCI, software, and indices

The World Meteorological Organisation (WMO) Commission for Climatology (CCI) Expert Team on Sector-specific Climate Indices (ET-SCI) agreed upon 34 core set indices in July 2011. These were in part developed from the indices developed and maintained by the ETCCDI (Alexander & Herold, 2016). The ET-SCI has developed a number of climate indices for use in sector applications, based on experts from health, agriculture and water sectors (Alexander & Herold, 2016). In addition, the ET-SCI developed user defined indices and new heatwave and cold wave indices over a shorter period (i.e. 3 days) compared to the ETCCDI indices WSDI and CDSI. It is important to note that the ET-SCI hasn't been used before in South Africa. All the selected ET-SCI indices used in chapters 7 and 8 will be discussed and defined below (Alexander & Herold, 2016):

3.8.2.1. $TNlt_2$ (Hard freeze days)

The annual number of hard freeze days when TN are below -2°C:

$$TN < -2℃ \tag{14}$$

3.8.2.2. SU35 (Very hot days)

The annual number of very hot days where TX are above 35°C:

$$TX >= 35℃ \tag{15}$$

3.8.2.3. TXb_dTN_d (User-defined consecutive number of cold days and nights)

Annual count of *d* consecutive days where both TX and TN are below the 5th percentile:

$$TX < 5\text{th percentile and TN} < 5\text{th percentile, where } 10 \geq d \geq 2$$

(16)

3.8.2.4. $CSDI_d$ (User-defined Cold Spell Duration Indicator)

Annual number of days contributing to events where *d* or more consecutive days where TN are below the 10th percentile:

$$TN < 10th \text{ percentile}$$

(17)

3.8.2.5. CWN (Cold wave number)

The number of cold waves that occur each year defined by the Excess Cold Indices and Factor (ECI; ECF). The ECI and ECF are defined as follows (Nairn & Fawcett, 2013):

$$ECI_{sig} = \frac{T_i + T_{i+1} + T_{i+2}}{3} - T_{05},$$

(18)

where T_{05} is the 5th percentile of (T_i) for the climate reference period, and

$$ECI_{accl} = \frac{T_i + T_{i+1} + T_{i+2}}{3} - (T_{i-1} + \cdots + T_{i-30})/30,$$

(19)

leading to the excess cold factor,

$$ECF = -ECI_{sig} \times \min(-1, ECI_{accl}).$$

(20)

The ECI_{sig} measures the degree of excess cold, whereas the ECI_{accl} measures cold stress. When the ECF is negative a cold wave is in progress (Nairn & Fawcett, 2013).

3.8.2.6. CWD (Cold wave duration)

The length of the longest cold wave identified by the CWN, defined by the EHF. See discussion and equation above.

3.8.2.7. TX_dTN_d (User-defined consecutive number of hot days and nights)

Annual count of *d* consecutive days where both:

$$TX > 95\text{th percentile and TN} < 95\text{th percentile, where } 10 \geq d \geq 2 \tag{21}$$

3.8.2.8. $WSDI_d$ (User-defined Warm Spell Duration Indicator)

Annual number of days contributing to events where *d* or more consecutive days experience:

$$TX > 90\text{th percentile} \tag{22}$$

3.8.2.9. HWN (Heatwave number)

The number of individual heatwaves that occur each summer (November to March in the southern hemisphere). A heatwave is defined as 3 or more days where the Excess Heat Factor (EHF) is positive. The EHF is a combination of two excess heat indices (EHI; Perkins & Alexander 2013, Perkins personal comms 2015):

$$EHI\ (accl.) = \left[\frac{TM_i + TM_{i-1} + TM_{i-2}}{3}\right] - [TM_{i-3} + \cdots + TM_{i-32})/30] \tag{23}$$

$$EHI\ (sig.) = \left[\frac{TM_i + TM_{i-1} + TM_{i-2}}{3}\right] - TM_{90} \tag{24}$$

Where TM_i represents the average daily temperature for day *i* and TM_{90} is the 90th percentile of *TM*, which is calculated within the user-defined base period, over the calendar year and using a 15-day running window. TM is calculated via $TM = (TX + TN)/2$.

3.8.2.10. HWD (Heatwave duration days)

The length of the longest heatwave identified by the HWN, defined by the number of days. See discussion above the previous equation.

3.9. Statistical trend analysis

Statistical trend calculation has been widely applied in climate science, particularly in extreme temperature trend studies globally (i.e. Toreti & Desiato, 2008; Almazroui *et al*., 2014; Abatan *et al*., 2016; Shrestha *et al*., 2017; Abatan *et al*., 2018; Rahimi & Hejabi, 2018; Salameh *et al*., 2019; Yosef *et al*., 2019; Poudal *et al*., 2020) and in South Africa (i.e. Kruger & Shongwe, 2004; New *et al*., 2006; Kruger & Sekele, 2013; Mackellar *et al*., 2014; Davis *et al*., 2016; Kruger & Nxumalo, 2017; Kruger *et al*., 2019). Several trend estimation methods have been developed for climate time series data and include not only linear curves, but also accelerated increases, other non-linear behavior, and nonparametric descriptions (Mudelsee, 2019). The most commonly used is the simple linear regression, to estimate the linear trend (slope) and statistical significance via a Student-*t* test (i.e. Croitoru *et al*., 2016; Kruger & Nxumalo, 2017; Shrestha *et al*., 2017; Abatan *et al*., 2018; Kruger *et al*., 2019). It must be noted that linear regression methods are prone to overestimate or underestimate slopes if a time series contains very low or very high values at the beginning or ending of the period (Abatan *et al*., 2016; Caloiero *et al*., 2017). The robust non-parametric Mann-Kendall trend test (MK; Mann, 1945; Kendall, 1955) is considered the most appropriate method to analyse trends in a climatological time series (Onoz & Bayazit, 2003; Machiwal & Jha, 2008; Some'e *et al*., 2013), particularly for extreme temperature time series (New *et al*., 2006; Mackellar *et al*., 2014; Abatan *et al*., 2016; Davis *et al*., 2016; Caloiero *et al*., 2017; Rahimi & Hejabi, 2018; Abatan *et al*., 2018; Salameh *et al*., 2019; Yosef *et al*., 2019; Casto *et al*., 2020; Poudal *et al*., 2020). The MK trend test compares the relative magnitudes of sample data and identifies monotonic trends with an added advantage of its low sensitivity to change points due to inhomogeneous time series (Tabari & Talaee, 2011; Abbas *et al*., 2018; Yosef *et al*., 2019; Casto *et al*., 2020; Poudel *et al*., 2020). The Theil-Sen slope estimator (Sen, 1986) is used in conjunction with the MK test, to quantify the magnitude of the trend slopes between every pair-wise combination and to examine the median slope value (Sen, 1986; Davis *et al*., 2016; Yosef *et al*., 2019; Poudel *et al*., 2020).

To calculate the trends of extreme warm and cold temperature events (Chapter 7, 8), the Mann-Kendall trend test was used together with the Sen slope estimator to calculate the trends of each index per weather station. In addition, the Spearman's Rank correlation coefficient was also calculated and used to cross-validate the MK trend test results and, if no MK trend was found. Research indicates that both these methods are equally strong for long-term data analysis (Daniel, 1978; Yue *et al*., 2002; Rahman *et al*., 2017); however, the MK test is more interpretable and provides an unbiased estimate of the population parameters (Daniel, 1978; Yue *et al*., 2002).

The MK trend analysis tests whether to reject the null hypothesis (H_0) or to accept the alternative hypothesis (H_a), where no significant trend is present; H_a means a monotonically increasing (or decreasing) trend is evident (Mann, 1945; Kendall, 1975). The test static *S*, which has mean zero, is calculated accordingly:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\ (x_j - x_i)$$

(25)

where

$$\text{sgn}\left(x_j - x_i\right) = \begin{cases} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases}$$

(26)

where variance of the test statistic is:

$$\text{Var}(S) = \frac{n\ (n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}$$

(27)

Where n is the number of data points, m is the number of tied groups, and t_i is the number of observations in the *i*th tied group. Where the sample size n>10 the standard normal variable *Z* is computed:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\text{Var}(S)}}, \text{if } S > 0 \\ 0, \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\text{Var}(S)}}, \text{if } S < 0 \end{cases}$$

(28)

A positive value of *Z* indicates an increasing trend, and vice versa. With the two-tailed test, at a given significance level α, the null hypothesis H_0 is rejected for an absolute value $|Z| \geq Z_{1-\alpha/2}$. Tests for significance are conducted at the 5% level (α = 0.05) (i.e. Phanda *et al*., 2014; Caloiero *et al*., 2017; Karki *et al*., 2019; Yosef *et al*., 2019; Poudel *et al*., 2020).

The magnitude of the slope, β, was obtained from Sen's non-parametric estimator of the slope, which is calculated as follows (Sen, 1968):

$$\beta = \text{Median}\left[\frac{x_i - x_j}{i - j}\right], j < i$$

(29)

where β is Sen's slope estimate. β > 0 indicates an upward trend in the time series.

The Spearman's Rank correlation coefficient (SR) is another non-parametric test (Spearman, 1904) which can be used to detect monotonic trends with a time series and to measure the degree of association between two variables (Daniel, 1978; Yue *et al*., 2002; Rauf *et al*., 2016). The Spearman's Rank correlation coefficient was calculated accordingly (Spearman, 1904; Sneyers, 1990;):

$$\rho = 1 - \frac{6\sum_{i=1}^{n}[R(X_i - i]^2}{n(n^2 - 1)}$$

(30)

were $R(X_i)$ is the rank of the ith observation X_i in the sample of size n.

The Mann-Kendal test, Sen's Slope estimator and Spearman's Rank correction coefficient were calculated using the add-in software XLSTAT 2020.2.1 (Addinsoft, 2020). The results were tabled, for each index and per station (see Supplement Material Chapter 7; Supporting Table 2-9 and Chapter 8; Table 8.3-8.8).

3.10. Spatial interpolation

The presentation of point data alone provides locations specific results and there is a need to interpolate to understand the spatial patterns across the whole country. Thus, to get a country wide perspective, spatial interpolation was used to visually present mainly the results of the seasonal classification in South Africa (Chapter 6), as well as the mean TX and TN in chapters 7 and 8.

Several spatial interpolation techniques have been used for mapping climate related variables, which can be grouped into non-geostatistical (deterministic) and geostatistical interpolation methods (Chai *et al*., 2011; Tiengrod & Wongseree, 2013; Li & Heap, 2014). Non-geostatistal interpolation methods include inverse distance weighting (IDW), and non-linear interpolation as spline (Chai *et al*., 2011; Di Piazza *et al*., 2016). Geostatistical interpolation methods include different varieties of kriging (i.e. ordinary, simple, and universal) (Di Piazza *et al*., 2016). The appropriate interpolation method depends on the spatial data properties, the aim of the study, complexity of topography and density of meteorological stations (Chai *et al*., 2011; Kayikçi & Kazanci, 2016). For the purpose of this study, deterministic interpolation method IDW was used, given that in comparative studies of spatial interpolation methods to estimate temperature variability over complex terrains, IDW performed well (e.g. Cao *et al*., 2009; Chai *et al*., 2011; Kayikçi *et al*., 2016; Yang *et al*., 2016). In addition, it has been found that IDW interpolates station data accurately (Zhou & Zhang, 2014). IDW is an interpolation method which estimates the values of an attribute at predicted points, weighted by an inverse function of the distance between the predicted point and sample points (Coa *et al*. 2009; Tiengrod & Wongseree, 2013). A general form of IDW is (Coa *et al*., 2009; Tiengrod & Wongseree, 2013):

$$Z_{(s_0)} = \sum_{i=1}^{n} \lambda_i Z_{(S_i)} \tag{31}$$

where $Z_{(s_0)}$ represents the estimated value at location s_0, *n* denotes the number of points around the estimated point, and λ_i is:

$$\lambda_i = \frac{d_{i0}^{-p}}{\sum_{i=1}^{n} d_{i0}^{-p}} \tag{32}$$

where d_{i0}^{-p} is the distance between location s_0 and the location s.

The IDW tool in ArcMap software was used to visually display the spatial patterns, the cluster analysis outputs and start and end dates of summer and winter in chapter 6, along with the mean TX and TN in chapters 7 and 8.

3.11. Conclusion

The data for all the research papers was collected from the SAWS climate database, whereby 35 and a smaller subset of 20 weather stations were selected and determined to have sufficient data available to address the objectives set out under Section 1.3 of Chapter 1 (Introduction). The data was quality controlled, cleaned and checked for non-climatic shifts using data homogenisation techniques and the timeseries was adjusted accordingly. Statistical methods were compared to literature and applied to each relevant research paper to address the objectives and aims of the specific research paper at hand.

Chapter 4: Overview of Papers

4.1. Introduction

This chapter provides an overview of each research paper produced, outlining the logic, significance and importance of each (Chapters 5 to 8) and their collective contribution to knowledge. This includes a brief description of the fifth research paper (Supplement Material: Draft Article). This will be followed by the distinct linkages between the different research papers and how these papers as a unit present new knowledge, as well as contributing to understanding the importance of exploring and examining ETEs in South Africa.

4.2. Extreme temperature events in South Africa: A Review (Chapter 5)

The societal and environmental consequences of ETEs have prompted considerable interest, and research of ETEs in the Global North is growing (Perkins-Kirkpatrick *et al*., 2017; Allen & Scott, 2018; Chen *et al*., 2019). However, there remains a paucity of research on climatic extremes, particular ETEs in Africa (see Section 4.2 and Supplementary Material Draft Article) and specifically South Africa (New *et al*., 2006; Collins, 2011; Otto *et al*., 2015; Abatan *et al*., 2018; Scovronick *et al*., 2018). As in most countries in Africa, South Africa faces many pressing socio-economic needs and environmental stressors (Pasquini *et al*., 2013; Mambo & Murambadora, 2017). The country's location, topography, surrounding oceans, and atmospheric dynamics heighten its vulnerability to extreme climatic events (Smith & Sheridan 2020). Several weather-related disasters have been recorded in the Centre for Research on the Epidemiology of Disasters' (CRED) Emergency Events Database (EM-DAT). From these disasters, only three severe ETEs were recorded. Two of these were cold events on 6 July 1996 and 21 May 2007, which resulted in 30 casualties in KwaZulu-Natal province and 22 casualties in Gauteng and the Eastern Cape provinces, respectively. Only one heatwave was recorded in the CRED database, on 1 January 2016; it lasted for 10 days and caused 11 fatalities and 20 injuries (EM-DAT CRED, 2020). Due to poor health surveillance and poor reporting of their impacts, ETEs are considered under-reported in many developing countries, South Africa among them (Ngwenya *et al*., 2018; Scovronick *et al*., 2018; Harrington & Otto, 2020). In fact, many ETEs have been informally recorded in South Africa and have received attention due to their frequency, incidence, and severity.

South Africa arguably has the most advanced research observation and climate modelling on the continent (Ziervogel *et al*., 2014). However, only a limited number of studies have made use of statistically and dynamically downscaled data and focused on extreme temperature (ET) and ETEs (Ziervogel *et al*., 2014).

In this review paper literature was consulted, employing a wide-ranging search using key words and phrases e.g. 'extreme temperature + South Africa', 'temperature events + South Africa', and 'temperature trends + South Africa', and cross-checked through Google Scholar, Science Direct and Web of Knowledge. Although research on ETEs in South Africa is limited, 10 emerging observational studies were examined that used meteorological station data as their primary data source. This review paper explores several aspects. First it considers the methodological approaches to define ETEs; second, it examines the extreme temperature indices adopted; and third, it outlines the methods used to select meteorological stations and proposes the approximate number of stations to adequately portray temperature variability on a national and regional level. Fourth, this review paper analyses the study periods. It then examines the data quality and homogeneity, as well as unpacking the statistical trend analysis used and results found by each study. Finally, projections of ETEs under current climate change conditions are reflected upon, along with the implications of cold and warm ETEs in a

South African context. Ultimately, this review paper argues for a greater research focus to improve the understanding of ETEs.

4.3. Statistical classification of South African seasonal divisions on the basis of daily temperature data (Chapter 6).

A wide range of activities is influenced by differences in seasonality. This is particularly the case in the agricultural sector, which must consider the length of growing seasons, the timing of sowing and harvest, and the necessity of irrigation (Van der Walt & Fitchett, 2020). In addition, climatic seasons influence tourism activities, resource management and energy demand, economic planning, hydrology and health (Van der Walt & Fitchett, 2020). The ability to accurately determine the beginning and end of seasons is crucial and of great importance (Van der Walt & Fitchett, 2020). However, in a South African context, there is almost no consensus on distinct seasonal boundaries. The most common seasonal boundaries are the astronomical, meteorological and phenological divisions, which most studies use. Some climatologists and research studies, meanwhile, classify seasons on an ad-hoc basis specific to the study region, with classifications such as hot-season or post-rainy season for convenience and to suit the data output, rather than having a direct relationship to calendar months (Van der Walt & Fitchett, 2020).

This paper presents one of the very first uniform statistical classifications of South African seasonal divisions on the basis of daily temperature data. For this study, daily maximum and minimum temperature data was obtained from 35 selected SAWS meteorological stations (Figure 1; Table 2 of Chapter 6) that had at least 30 years of data, spanning the period 1980-2015. The daily average temperature (T_{avg}), was also calculated for the study period. Seasonal divisions were classified using cluster analysis and visually presented using ArcMap software, as described in Section 3.7.1 and 3.8. This research provides an insight into the complexity of seasonality across South Africa (Van der Walt & Fitchett, 2020), as well as a direction for temperature-related studies. It also outlines newly proposed seasonal brackets using temperature metrics. This knowledge is crucial for many different sectors in South Africa, especially for the development of adaptation strategies in monitoring seasonal temperature variability (Van der Walt & Fitchett, 2020), and seasonal ETEs.

4.4. Trend analysis of cold extremes in South Africa: 1960-2016 (Chapter 7)

A disproportionate number of studies focus on extreme warm temperatures, compared to extreme cold temperatures. Although less research has been done on extreme cold events ('cold waves' or 'cold snaps'), many of these events have adverse effects on regions in the midlatitudes (Johnson *et al*., 2018) and may have profound environmental (Chen *et al*., 2019) and societal consequences (Scott, 2015; Díaz *et al*. 2019). Exposure to extreme cold temperatures can result in adverse outcomes. The human body can lose heat faster than it produces it, which could lead to cold stress (hypothermia), resultant cardiovascular and respiratory diseases and, ultimately, premature mortality (Barnett *et al*., 2012; Scott, 2015). The little research that has been done on cold events has largely focused on the Northern Hemisphere, partly due to the greater continental landmass as well as its proximity to the north pole (Johnson *et al*., 2018). This results in a focus on extreme cold events in developed countries rather than in developing countries where people are more vulnerable to these events (Chen *et al*. 2019). Furthermore, the lag between cold weather and the impacts on health is usually longer compared to warm weather and shows greater variability by cause (Smith and Sheridan, 2018).

Extreme cold temperatures pose significant threats to South Africa due to the country's limited preparedness relative to high income countries and its low adaptive capacity, along with its urgent development needs and relatively inadequate infrastructure. This study focusses specifically on extreme cold temperature events for the period 1960-2016 and explores these events on an annual and seasonal scale. This study is the first to make use of the ET-SCI in South Africa. These sector-specific climate indices consider health, water and agriculture; they are derived from the ETCCDI, as discussed in Section 3.9.2. For comparative purposes, an extension on previous analyses of the ETCCDI at annual and seasonal timescales was presented for the full time period. This study will be the first to use both the ET-SCI and ETCCDI to identify extreme cold trends in a South African context. The results not only contribute to the awareness and recognition of the frequency and duration of extreme cold temperature in South Africa but suggest that anomalously extreme cold events may persist in a 'warming world'.

4.5. Exploring extreme warm temperature trends in South Africa: 1960-2016 (Chapter 8)

Exposure to high temperatures over a prolonged period, i.e. heatwaves and warm spells, will result in heat stress (hyperthermia; Lee 2014; Founda *et al*. 2019) which may lead to heat-related illnesses such as cardiovascular diseases, heatstroke, heat exhaustion, and premature mortality (Ngwenya *et al*. 2018). Several high-impact extreme warm temperature events have been recorded in the Global North, among them the 2003 European and 2010 Russian heatwaves which resulted in more than 70,000 and 10,000 human fatalities, respectively (Simmonds 2018; Ragone *et al*. 2018). These events received significant public and scientific attention due to the severity and societal impacts (Perkins *et al*. 2012; Simmonds 2018). This sparked a global interest in these extreme heat events, particularly under current climate change projections that indicate the likely increase in incidence, duration and severity of heatwaves and warm spells across both the Northern and Southern hemispheres (Alexander *et al*. 2006; Perkins *et al*. 2012; Perkins-Kirkpatrick *et al*. 2017). Despite the increase in attention, these events are still inadequately understood and sometimes ignored (Lee 2014; Pelling *et al*. 2017), especially in developing countries such as South Africa.

The region's exposure, without reduction in vulnerability to extreme weather such as heatwave events, is likely to increase significantly throughout the 21st century (Davis-Reddy & Vincent 2017). These expected increases in vulnerability to extreme heat events pose a significant threat to a developing country (Abatan *et al*. 2016) like South Africa. South Africa faces pressing socio-economic development needs, compounded by environmental stressors; this, combined with a growing and urbanising population, implies greater exposure to these events (Pasquini *et al*. 2013; Davis-Reddy & Vincent 2017). This study aims to provide updated trends of extreme warm temperature on an annual and seasonal timescale for the period 1960-2016, for all ETCCDI temperature indices previously used. This study is the first to use ET-SCI, which are sector-specific climate indices that consider health, water and agriculture and are derived from the ETCCDI. This study attempts to understand the nature of heat events, as well as to examine the frequency, incidence, and severity of these events at different spatial and temporal scales, which is vital for adaption purposes.

4.6. Extreme temperature events: African vulnerability in the Global context (Supplementary Material: Draft Article)

Extreme climatic events have always had and will continue to have dramatic impacts on societies and ecosystems. The Fifth Assessment Report (Nicholls *et al*., 2012; Hartman *et al*., 2013) and the 2018 Special Report of the IPCC affirm that climate change has increased the intensity, incidence and severity of climatic extremes, in particular ETEs, and may continue into the future (Smith, 2011; Mueller & Seneviratne, 2012; Nicholls *et al*., 2012; Hartmann *et al*., 2013; Kharin *et al*., 2013; IPCC 2018, Akinyemi & Abiodun, 2019). Observational and modelled projections identified regional hotspots, over lower latitude countries including those in sub-Saharan Africa, with severe changes in both anomalous temperatures and heat stress (Harrington & Otto, 2020). Also, widespread persistent changes to extreme temperatures have occurred earlier than predicted, over large parts of the world (Li *et al*., 2018). Research into the frequency of ETEs and casualties caused over recent decades is mainly focused on the Global North and neglects most of the world's less developed regions (Sheridan & Allen, 2015; Perkins-Kirkpatrick *et al*., 2017; Allen & Scott, 2018; Chen *et al*., 2019; CRED, 2019; Harrington & Otto, 2020), for which such events are likely to have significant impacts (Mirza, 2003; Thornton *et al*., 2014; Abatan *et al*., 2018; Nangombe *et al*., 2019).

The associated risks of these events are expected to increase in low-income, developing countries where adaptive capacity is limited (Herold *et al*., 2017; Filho *et al*., 2018). These risks in developing countries are exacerbated where agriculture and food security constitute the livelihood of populations, as is the case in most African countries (Herold *et al*., 2017; Akinyemi & Abiodun, 2019). Further, developing countries face multiple barriers to implementing detection frameworks, such as poor governance, sparsely distributed meteorological station networks, expertise, and poor reporting structures on ETEs (Harrington & Otto, 2020).

Only a limited number of review papers exist that focus primarily on ETEs, in the context of a developing country. Most review papers provide an overview of extreme climatic events (Easterling *et al*., 2000; Coumou & Rahmstorf, 2012), in reference to vulnerability to climate change (Thornton *et al*., 2014); attribution of extreme events (Stott *et al*., 2016); and modelling of extreme events (Bellprat, 2019) in relation to ETEs. Furthermore, many of these review papers concentrate on the Global North with very little focus on the Southern Hemisphere. Researchers reviewing scientific advances i.e. in extreme heat events and cold events highlight the disproportionate number of studies examining the developed world (Sheridan & Allen, 2015; Chen *et al*., 2019; Harrington & Otto, 2020) and recommend that more research is needed in developing countries (Horton *et al*., 2016; Harrington & Otto, 2020), such as those in Africa.

This paper will be one of the very first review papers in an African context, which will explore international literature on ETEs and contribute to the limited ETEs research that has already been done in the Southern Hemisphere. It will also examine existing research on ETEs in Africa, and highlight the continent's vulnerability to these events in a global context, as well as emphasising the importance of research on these events in a developing country with limited adaptive capacity to climatic changes. This review starts off by defining ETEs. Thereafter, the international literature on ETEs is examined, together with the climatological drivers of these events. Finally, a critical analysis of research already conducted on the African continent is presented, in the context of its vulnerability to ETEs.

4.7. Connections and links among papers, and contribution to new knowledge

In these papers, a critical analysis of ETEs is presented. In short and as a unit these papers (Supplementary Material: Draft Article, Chapters 5 to 8) achieve three aims. Firstly, they review and examine the vulnerability of the African continent to ETEs; secondly, they provide the very first critical analysis on ETE studies in South Africa and propose the approximate number of stations to adequately portray temperature variability on a national and regional level. Thirdly, they present newly defined seasonal divisions, as well as start and end dates of seasons based on temperature metrics. Fourthly, they present updated trends on previously used ETCCDI on an annual and seasonal scale for both extreme cold and warm temperature events on an annual and seasonal scale. Ultimately, collectively, they present the very first trend analysis of ET-SCI in a South African context for both extreme cold and warm temperature events on an annual and seasonal scale.

The regional review of ETEs in South Africa highlights the paucity of research that has been done not only on climate extremes, but in particular ETEs. In addition, an approximate number of stations is proposed to adequately portray temperature variability on a national and regional level. The extreme cold and warm temperature trend analyses were conducted to contribute to existing knowledge of ETEs; this extends on previous trends of the ETCCDI and presents the very first trends of the sector-specific ET-SCI, on an annual and seasonal scale. Additionally, the extreme cold temperature research paper is one of the very first papers which solely focuses on trends of extreme cold events. This prevents biased results and provides the opportunity for better understanding of extreme cold events, seeing that these anomalously extreme cold events may persist in a 'warming world'. The statistical classification of the newly proposed seasonal divisions grants new insight into temperature variability and seasonality across South Africa, as well as presenting the opportunity to examine and explore the seasonality of ETEs in South Africa, based on temperature metric seasonal boundaries.

4.8. Conclusion

These papers, as a unit, critically analyse ETEs in South Africa and contribute to existing knowledge as well as presenting new knowledge on ETEs in a South African context. This is crucial for the development or update of adaptive policies and preventative measures.

Chapter 5: Extreme temperature events in South Africa: A Review

5.1. Brief synopsis

This review paper presents the first review of ETEs in South African context, which explores the existing literature on ETEs in South Africa and argues for greater research focus to improve the understanding of ETEs.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Jennifer M Fitchett
Methodology	Adriaan J van der Walt & Jennifer M Fitchett
Validation	Adriaan J van der Walt
Formal analysis	Adriaan J van der Walt
Investigation	Adriaan J van der Walt
Resources	Adriaan J van der Walt
Data curation	Adriaan J van der Walt
Writing – the original draft preparation	Adriaan J van der Walt
Writing – review and editing	Adriaan J van der Walt & Jennifer M Fitchett
Visualisation	Adriaan J van der Walt
Supervision	Jennifer M Fitchett
Project leader	Jennifer M Fitchett

According to the above-mentioned CRediT system the author contribution was calculated as follows:

Van der Walt, A.J – 70%

Fitchett, J.M – 30%

Submitted to: South African Geographical Journal

Impact Factor: 1.154

Reason for selection: The flagship journal of the South African Geographical Society

Submission data: 04 August 2020

Current status: Under review

The version to follow is exactly as submitted to the journal on 4 August, with the addition of contiguous page numbers for this thesis

5.2. Abstract

Extreme Temperature Events (ETEs), including heatwaves, warm spells, cold waves and cold spells, have disastrous impacts on human health and ecosystems. The frequency, intensity, and duration of ETEs is projected to increase due to climate change. However, very little research has been published on ETEs in South Africa, and only a few attempts have been made to identify and examine trends. Currently, 10 known publications examined ETE across South Africa, with the majority of studies using the South African Weather Service (SAWS) climate database as primary source. The general findings indicate that the incidence and duration of extreme warm temperatures are increasing, while cold extremes are decreasing. However, inconsistencies exist in the indices used to identify ETEs, selection of meteorological stations, study period, and statistical methods used to examine trends. We review the methodological approaches to define ETEs, the extreme temperature indices adopted, explore selection methods of meteorological stations and propose approximate number of stations to adequately portray temperature variability on a national and regional level, analyse the study periods, examine the data quality and homogeneity, statistical trend analysis, and results. Finally, we reflect on projections of ETEs under current climate change conditions, and the implications of cold and warm ETEs in a South African context.

Key words: Extreme temperature events (ETEs), Extreme temperature indices, Meteorological stations, Data quality, South Africa

5.3. 1. Introduction

Africa is considered to be the most vulnerable continent to climate change, due to the high exposure and low adaptive capacity (Otto *et al*., 2015; Russo *et al*., 2016; Ceccherini *et al*., 2017; Nkemelang *et al*., 2018). Based on the Centre for Research on the Epidemiology of

Disasters' (CRED) Emergency Events Database (EM-DAT) between 2000-2019, Africa experienced 1,143 weather-related catastrophes, which affected a total of 337 million people and resulted in 46,078 fatalities (EM-DAT CRED, 2019). It is estimated that extreme temperature events (ETEs) affected 27 million people across Africa, which resulted in 270 fatalities, and 260 injuries (EM-DAT CRED, 2020).

Heat and cold events over prolonged periods can lead to hyperthermia or hypothermia, respectively. Thermal stress can result in heat- and cold-related illnesses including cardiovascular diseases, respiratory diseases, heat stroke, damage to the brain, heart, lungs and kidneys, decreased metabolic activity and can result in mortality (Scott 2015; Allen & Scott, 2018). The societal and environmental consequences of ETEs prompted considerable interest, and research of ETEs in the global north is growing (Perkins-Kirkpatrick *et al*., 2017; Allen & Scott, 2018; Chen *et al*., 2019). However, there remains a paucity of research on climatic extremes, in particularly ETEs, in Africa, and specifically South Africa (New *et al*., 2006; Collins, 2011; Otto *et al*., 2015; Abatan *et al*., 2018; Scovronick *et al*., 2018).

South Africa faces many pressing socio-economic challenges and environmental stressors (Pasquini *et al*., 2013; Mambo & Murambadora, 2017). The location, orography, oceanic surroundings, and atmospheric dynamics of the country heightens the vulnerability to extreme climatic events (Smith & Sheridan 2020). In the past three decades, the EM-DAT recorded 91 weather related-disasters in South Africa which resulted in 1,792 casualties, 2,409 injuries, left 58,000 people homeless, and affected an estimated 2 million people across the country (EM-DAT CRED, 2020). Of these weather-related disasters, three severe ETEs were recorded. On 6 July 1996, a cold wave in KwaZulu-Natal Province resulted in 30 casualties. Gauteng and the Eastern Cape Province experienced a cold snap on 21 May 2007, which lasted for two days and led to 22 casualties. The only heatwave recorded in this database occurred in North-West Province on 1 January 2016 which lasted for 10 days and resulted in 11 fatalities and 20 injuries (EM-DAT CRED, 2020). However, due to poor health surveillance, the impacts of ETEs are considered under-reported in many developing countries, including South Africa (Ngwenya *et al*., 2018; Scovronick *et al*., 2018).

Indeed, over the past five years many ETEs were informally recorded in South Africa and received media attention due to their frequency, duration, and severity. In 2019, several cold fronts have been documented in Gauteng during the end of June and beginning of July, which led to cold days and nights, which led to at least one casualty due to hypothermia in Dobsonville, Soweto (Matlhare, 2019). The most recent intense cold front in South Africa occurred on 6 July 2020, which was followed by another cold front on 11 July (Pace 2020). This led to very cold temperatures across the country, together with snowfall on the southern high ground and infrastructural damages to informal settlements due to flooding in the Western Cape (Pace, 2020). At the end of September 2019, parts of the Eastern Cape and Western Cape experienced unseasonable record high mean maximum temperatures for September (Head, 2019).

South Africa arguably has the most advanced research observation and climate modelling on the continent (Ziervogel *et al*., 2014). However, only a limited number of studies have made use of statistically and dynamically downscaled data and focused on extreme temperature (ET) and ETEs (Ziervogel *et al*., 2014). This review paper critically explores the existing literature on ETEs in a South African context and argues for a greater research focus to improve the understanding of these events. We explore discrepancies between papers in defining ETEs and the indices used, the statistical approaches in trend analysis, and the selection of meteorological stations for inclusion. We also consider the published projections for ETEs under climate change, and the reported impacts on the implications of these events.

5.4. 2. *Defining ETEs and indices thereof*

Extreme climatic events can be defined as rare, infrequent, unpredictable climate phenomena, characterized either by the meteorological characteristics or the consequent impacts (Stott *et al*., 2016; Vogel *et al*., 2019). However, there is little consensus in the published literature regarding the classification process for ETEs (Allen & Scott, 2015; Radovic & Ilglesias, 2019), and no universal definition exists for ETEs (Perkins-Kirkpatrick & Gibson 2017; Sheridan & Lee, 2018). The lack of a consistent definition or classification process poses considerable challenges in the characterization of these events (Seneviratne & Zwiers, 2015). The most common terms used to classify ETEs in the literature include warm (cold) events, heatwaves (cold waves), warm (cold) spells. Each of these have a specific definition and criteria, yet the details on each remain disputed. At the most simplistic, the South African Weather Service (SAWS) classify a heat wave as "the maximum temperature (TX) should meet or exceed the average maximum temperature of the hottest month for that particular place by 5°C, as well as persist for at least three days or more" (SAWS 2020; Malherbe *et al*., 2020, p.2). Heatwaves can similarly be simplistically defined as a period where at least three consecutive days exceed their respective calendar-day 90th percentile for maximum temperatures (Perkins-Krikpatrick & Gibson, 2017). Following this approach, cold waves can be defined as a temperature drop that persist at least two consecutive days below a certain threshold (WMO, 2016). However, some specify that the minimum temperature (TN) must be at least three consecutive days below the 10th percentile (Zhang *et al*., 2018b). Warm and cold spells can likewise be defined in terms of a set threshold, but the time span is extended to at least six days. However, this definition is problematic due to the rarity of six-day events (Phanda *et al*., 2014).

These simplistic definitions of ETEs are determined by the extent of the deviation from the statistical mean daily, monthly, or annual temperatures for a given location or region (Easterling *et al*., 2000; Lewis & King, 2017). The threshold for which a deviation is indicative of an 'extreme event', however, is largely debated (Lewis & King, 2017). Another distinction concerns definitions based on absolute temperatures versus percentiles (Horton *et al*., 2016). Absolute temperatures are of importance to societal and environmental impacts such as resilience of infrastructure, whereas percentiles facilitate comparisons between locations, relative to the local climatology (Horton *et al*., 2016). Alternative approaches classify events on the basis of the societal impact such as mortalities resulting from ETEs (Easterling *et al*., 2000; Lewis & King, 2017). In these instances, the human thermal threshold plays a role in classifying an ETE (Vardoulakis *et al*., 2014; Napoli *et al*., 2018). Recent approaches such as the Universal Thermal Climate Index (UTCI) attempt to explore thermal comfort as a measure of ETE, coupling the temperature with a wider range of meteorological parameters such as humidity and windspeed (Błażejcyk *et al*., 2013; Napoli *et al*., 2018). These allow for ETEs to be classified on the basis of the biometeorological impact without deaths necessarily occurring, which standardizes for the impact of varied levels of healthcare (Napoli *et al*., 2018). The most widely used approaches to calculate ETEs are the indices developed and recommended by the World Meteorological Organization (WMO) CCI/CLIVAR Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI/ETCCDI; Zhang *et al*., 2018b; Ren *et al*., 2018), which describe characteristics of extremes that include the frequency, amplitude and duration (Tank *et al*., 2009). These indices can be grouped into four categories (1) absolute indices (e.g. TXx, TNx, TXn, TNx) (2) threshold indices (e.g. SU25, FD); (3) percentile indices (e.g. TX90p, TN90p, TX10p, TN10p) (4) durations indices (e.g. WSDI, CDSI) (Supplement material 1; Alexander & Herold, 2016). The key approach of indices is the calculation of the number of days in a year that exceed a specific threshold (Tank *et al*., 2009; Yu & Li, 2015). Many of the indices are percentiles threshold-based, to assess moderate extremes that typically occur a few times every year rather than high impact, one in a decade weather event (Yu & Li, 2015).

Discrepancies were found in the approaches to classify and identify the ETEs across the 10 publications (Table 1; Table 2). These methods range from indices which were developed by Collins (2000), used together with temperature forecasting categories from SAWS (Supplement material 2; Kruger & Shongwe, 2004), threshold and percentile-based indices (Supplement material 3; Mackellar *et al*., 2014), threshold based indices and temperatures above the norm (Van Wilgen *et al*., 2016), the Standardized Heat-wave Index (SHI; Malherbe *et al*., 2020), and the most extensively used ETCCDI temperature indices (Supplement material 1; New *et al*., 2006; Kruger & Sekele, 2012; Davis *et al*., 2016; Kruger & Nxumalo, 2017; Kruger *et al*., 2019; Mbokodo *et al*., 2020). The indices used by Kruger and Shongwe (2004), Mackellar *et al*. (2014) and Van Wilgen *et al*. (2016) are similar to the ETCCDI indices. However, different sets of threshold values were used in identifying the ETEs. For instance, Kruger and Shongwe (2004) combined indices developed by Collins (2000) and temperature categories employed by the forecasting division of SAWS, defining a hot-day event as 3-5 consecutive days with maximum temperatures (TX) ≥30°C , and a cold-day event as 3-5 consecutive days with minimum temperatures (TN) ≤19°C. Van Wilgen *et al*. (2016) used two methods: first identifying months in the top and bottom 2.5% of normalized monthly TX and TN, and then the occurrence of temperatures > 35°C and <0°C. Malherbe *et al*. (2020, p.2) used the SHI, "a comparison of a three-day cumulative TX relative to the historical distribution of such cumulative values during the relevant month", to investigate droughts in the Kruger National Park using the extreme climate index (ECI), derived by combining a temperature-based (e.g SHI) and rainfall-based index.

The remaining studies made use of the percentile-, absolute- and duration-based indices (Figure 1: Table 1). Percentile-based indices are more evenly distributed in space than fixed thresholds and are arguably meaningful in every climatic region (Tank *et al*., 2009; Yin & Sun, 2018). In addition, percentile-based indices assess relative extreme events e.g. heatwaves (cold waves) which can occur during colder (warmer) seasons that may not reach a specific ET threshold, but could affect the growing season, and the agricultural and economic sectors (Mboko *et al*., 2020). The absolute indices were used five times, similar to the duration indices (Figure 1). On further investigation, it is evident that New *et al*. (2006), Mackellar *et al*. (2014), and Davis *et al*. (2016) used the threshold indices and only New *et al*. (2006) incorporated the cold days (ID index) in their analysis. Whereas only three authors used the annual diurnal temperature range (DTR; Figure 1; e.g. New *et al*., 2006, Davis *et al*., 2016, Mboko *et al*., 2020).

Table 5.1: (Table 1) Indices used by publications grouped into absolute, threshold, percentile, and duration indices.

Studies	Absolute indices	Threshold indices	Percentile indices	Duration indices
Kruger and Shongwe, 2004		x		
New et al., 2006	x	x	x	x
Kruger and Sekele, 2012	x		x	x
Mackellar et al., 2014		x	x	
Davis et al., 2016	x	x	x	x
Van Wilgen et al., 2016		x		
Kruger and Nxumalo, 2017	x		x	x
Kruger et al., 2019	x		x	x
Malherbe et al., 2020				x
Mbokodo et al., 2020	x		x	
Total	*6*	*5*	*7*	*6*

Table 5.2: (Table 2) Published ETE studies in South Africa

Authors	Research topic	Study Period	Study Region	Stations used	Data	Indices used	Statistical analysis
Kruger and Shongwe, 2004	Temperature trends in SA	1960–2003	South Africa	26	SAWS	Percentile and threshold-based & temperature categories (SAWS)	Linear trend
New et al., 2006	Trend in daily climate extremes	1961–2000	southern Africa	8	SAWS	ETCCDMI	Kendall's tau and least square linear trend
Kruger and Sekele, 2012	Trends in extreme temperature indices	1962–2009	South Africa	28	SAWS	ETCCDI	Linear trends and *t*-test
Mackellar et al., 2014	Observed and modelled trends	1960–2010	South Africa	30	CCWR & SAWS	Percentile & threshold-based indices	Man-Kendall and Sen's slope
Davis et al., 2016	Recent trends in the climate of Namaqualand	1982–2009	Namaqualand	5	SAWS	ETCCDI	Mann-Kendall and Theil–Sen's slope
Van Wilgen et al., 2016	Rising temperatures and changing rainfall patterns in SA's national parks	1960–2010	South Africa	19	SAWS	Threshold-based and above the norm	Linear regression and LOWLESS
Kruger and Nxumalo, 2017	Surface temperature trends	1931–2015	South Africa	27	SAWS	ETCCDI	Linear trends and *t*-test
Kruger et al., 2019	Historical and projected trends in near-surface temperature indices	1951–2005	South Africa	22	SAWS	ETCCDI	Linear trends and *t*-test
Malherbe et al., 2020	Drought in the Kruger National Park	1961–2017	Kruger National Park	3	SAWS	SHI	-
Mbokodo et al., 2020	Heatwave in the future warmer climate	1983–2012	South Africa	24	SAWS	ETCCDMI	Kendall's tau-based slope estimator

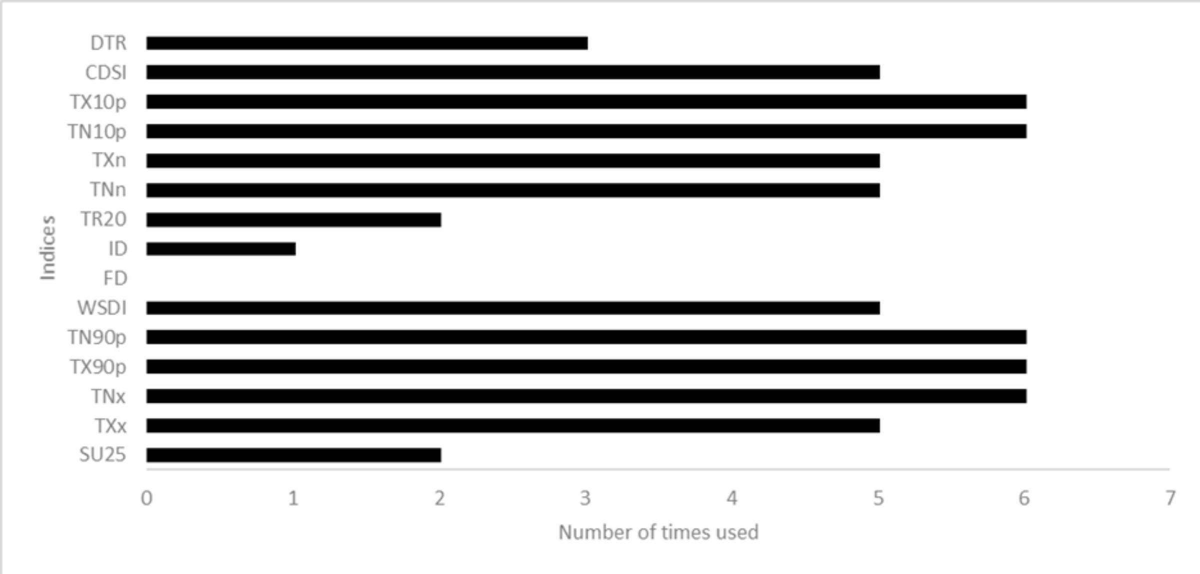


Figure 5.1: (Figure 1) Number of times ETCCDI temperature indices were used.

5.5. 3. Review of results and methodologies used to calculate ETEs from meteorological station data in South Africa

Although research on ETEs in South Africa is limited, emerging observational studies examine ETEs using meteorological station data (Table 2). Some of these studies combined station data with modelled data to project future ET trends over the same period to identify possible strengths or weaknesses in the modelled approaches (e.g. Mackellar *et al*., 2014; Kruger *et al*., 2019; Mboko *et al*., 2020). For this review, only observational studies' methodologies and results will be examined.

5.6. 4. *Meteorological Stations Data*

All but one (Mackeller *et al*., 2014) of the studies used the SAWS climate database as primary source. Mackellar *et al*. (2014) combined the SAWS databased with data collected by the Computing Centre for Water Resources (CCWR; Table 2). It is important to note that this study is the only study which does not provide a list of stations, and thus is excluded from most of the analyses.

A total of 64 meteorological stations were used across the remaining studies, spatially distributed across South Africa (Figure 2; Supplement material 4). Only Kruger and Sekele (2012) and Mackellar *et al*. (2014) broadly grouped the meteorological stations to present their results. Kruger and Sekele (2012) used general characteristics of the mean temperatures in South Africa while Mackellar *et al*., (2014) used the Long-Term Adaption Scenarios Flagship Research Programme (LTAS), for assessment of climate change on water resources and divided South Africa into six water management zones.

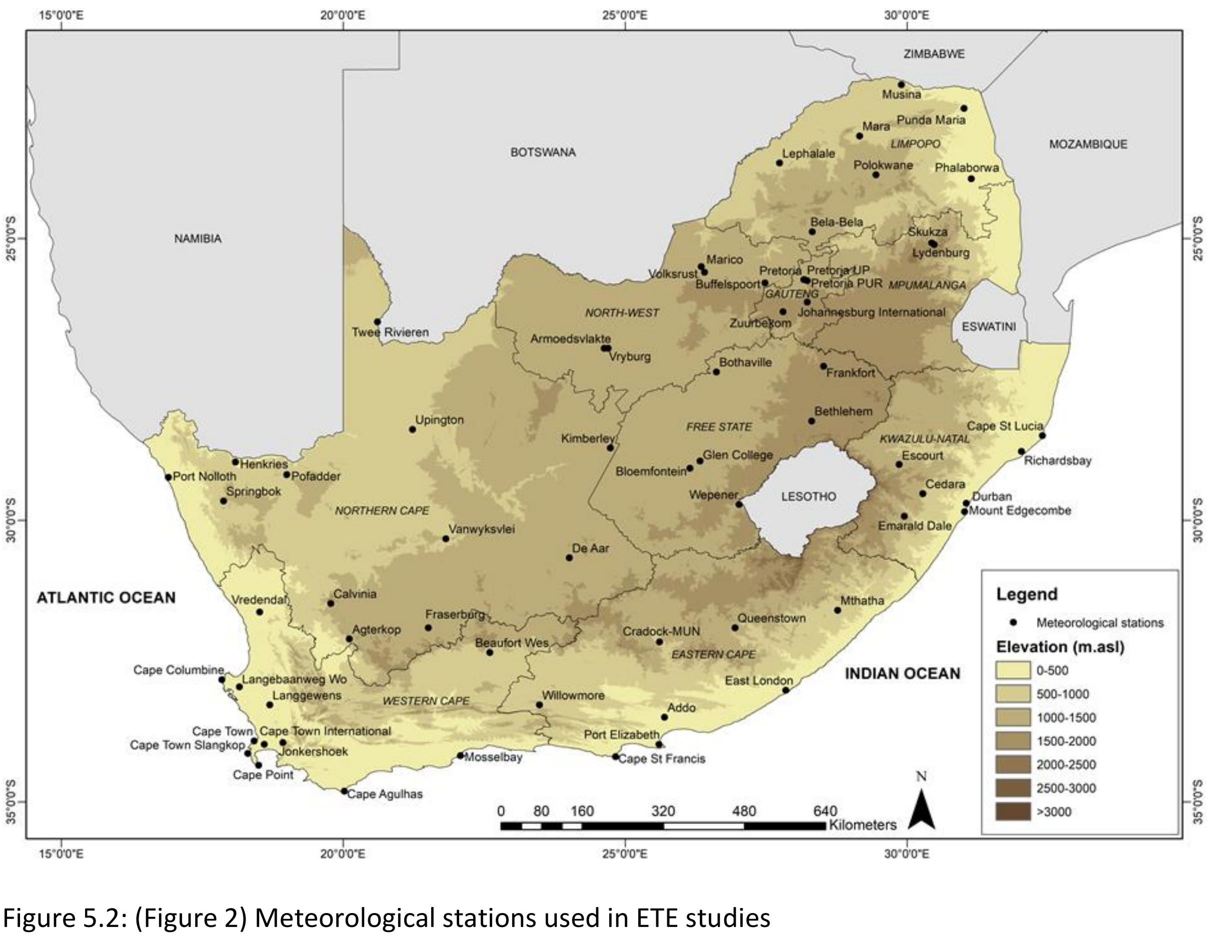


Figure 5.2: (Figure 2) Meteorological stations used in ETE studies

Some stations are used more frequently than others (Figure 3). Stations that have been used ≥4 times include Musina and Polokwane located in Limpopo, Skukuza in Mpumalanga, Vryburg in North-West, Emerald Dale in KwaZulu-Natal; Upington, Vanwyksvlei and Pofadder in the Northern Cape; Mosselbay, Cape Agulhas, Langegewens, Cape Point, Cape Columbine in the Western Cape; Port Elizabeth in the Eastern Cape and Glen College in the Free State Province (Figure 3). The data availability and quality of the stations played a significant role in station selection.

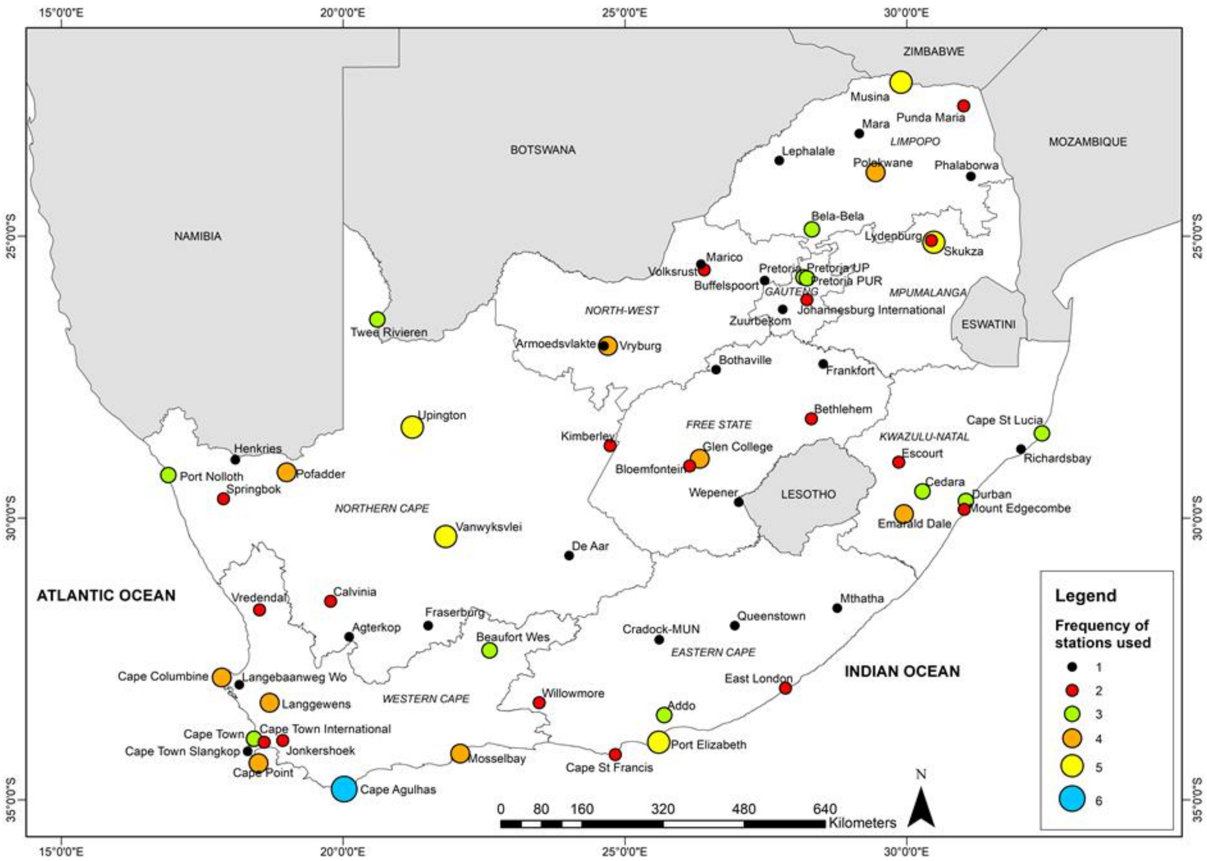


Figure 5.3: (Figure 3) Number of times each meteorological station was used.

Davis *et al*. 2016 investigated regional climate trends, using only five stations located in the Namaqualand region. Malherbe *et al*. (2020) and Van Wilgen *et al*. (2016) each used a selection of stations located near or in the Kruger National Park, and South Africa's national parks, respectively. New *et al*. (2006) examined southern African daily climate extremes, thus including stations from neighboring countries and only eight stations in South Africa. The rest of the studies examined ET and ETE trends across South Africa (Table 2).

The optimal spatial resolution to monitor temperature variability over areas of interest remains contentious (Trewin, 2010). For example, Jones and Trewin (2002) and Vose and Menne (2004) recommend that a station density of 100-200 stations is sufficient to define temperature variability to a recent degree of accuracy over the size of United States (9,826,675km^2) or Australia (7,692,024 km^2). Applying these recommendations to South Africa on national and provincial levels by using surface areas as captured in the South African Yearbook (SAYB) 2018/2019 (Mokoena, 2019), a network of approximately 21 stations would provide a recent degree of accuracy of the countrywide temperature variability (Table 3). This aligns with the argued spatial density used by Kruger and Nxumalo (2017). The approximate minimum number of stations on a provincial level, to provide an adequate idea of the temperature variability would thus be three stations for the Eastern Cape Province, two stations for the Free State, Kwazulu-Natal, Limpopo, North-West and Western Cape Province, one stations for Gauteng Province and six stations for the Northern Cape Province (Table 3). However, due to the heterogeneity of South Africa's climate in comparison to the surface area (Kruger & Nxumalo, 2017), it can be argued that more stations are required.

Table 5.3: (Table 3) Approximate minimum number of stations equated from Jones and Trewin (2002) and Vose and Menne (2004), together with stations used by authors on a provincial and national level.

Provinces	Size (km^2)	Approx. min number of stations	Kruger and Shongwe, 2004	New et al., 2006	Davis et al., 2016	Van Wilgen et al., 2016	Kruger and Nxumalo, 2017	Kruger et al., 2019	Malherbe et al, 2019	Mboko et al., 2020
Eastern Cape	168966	3	4	2	-	2	1	1	-	3
Free State	129825	2	2	1	-	1	1	1	-	3
Gauteng	18178	1	2	1	-	-	5	2	-	1
KwaZulu-Natal	94361	2	4	1	-	-	2	4	-	3
Limpopo	125754	2	3	-	-	1	3	3	3	3
Mpumalanga	76495	1	1	-	-	1	1	-	-	2
Northern Cape	372889	6	2	1	5	6	2	3	-	5
North-West	140882	2	1	-	-	-	2	1	-	2
Western Cape	129462	2	7	2	-	5	8	7	-	2
South Africa	**1219602**	**21**	*26*	*8*	*5*	*19*	*27*	*22*	*3*	*24*

Using ArcMap 10.7.1 software to map the stations included in the studies, the minimum, maximum and average distance between the nearest neigbours (Table 4), were calculated using the ‘calculate distance band from neighbour’ count tool, which employs the Euclidean distance method (Bajjali, 2018). The minimum and maximum distance between stations used were 43km and 298km, respectively, while the average distance was 155km (Table 4). The shortest distance of 1km was evident for the stations in Kruger and Nxumalo (2017) due to Pretoria PUR and Pretoria which are in close proximity. Whereas the longest and average distance of 502km and 237km respectively were found in New *et al*. (2006), which used eight stations evenly distributed across South Africa. These results, together with the results from the surface areas, can be used as a set of parameters in selecting meteorological stations to examine temperature variability across South Africa and other climatological features which use station data.

Table 5.4: (Table 4) Maximum, minimum, and average distance between stations used in publications.

Studies	Number of stations	Maximum (km)	Minimum (km)	Average (km)
Kruger and Shongwe, 2004	26	278	6	109
New et al., 2006	8	502	54	237
Kruger and Sekele, 2012	28	290	5	154
Davis et al., 2016	5	121	106	115
Van Wilgen et al., 2016	19	354	29	188
Kruger and Nxumalo, 2017	27	325	1	124
Kruger et al., 2019	22	326	42	148
Malherbe et al., 2020	3	146	140	141
Mbokodo et al., 2020	24	340	5	180
Averages	***18***	***298***	***43***	***155***

5.7. 5. *Study period*

Most of the studies use records commencing in the 1960s and extending into the 2000s and 2010s (Table 2; Figure 4), due to the reports of data gaps prior to 1960 (New *et al*., 2006; Kruger & Sekele, 2012; Mackellar *et al*., 2014; Kruger & Nxumalo, 2017). According to the WMO, a general rule is to use at least a 30-year period to get a reliable estimate of the mean and average (WMO, 2000). The majority of studies adhered to this rule, except Van Wilgen *et al*. (2016) which included study periods with <30 years. Only two studies examined ETEs, Kruger and Nxumalo (2017) and Kruger *et al*. (2019) using data sets starting in the 1950s and 1930s, respectively (Figure 3). However, it is important to note that Kruger and Nxumalo (2017) only examined warm and cold spells (WSDI and CDSI) over the period of 1981 to 2010, and not the extended period (Table 2). Furthermore, almost all the studies examine ETEs at an annual resolution, and only a few attempts investigate ETEs on an annual and seasonal resolution (e.g. Mackellar *et al*., 2014; Davis *et al*., 2016; Malherbe *et al*., 2020). The period of overlap between all of the studies, and thus the period for accurate comparison of the impact of methodological choices on result, is 1980-2010 (Figure 4).

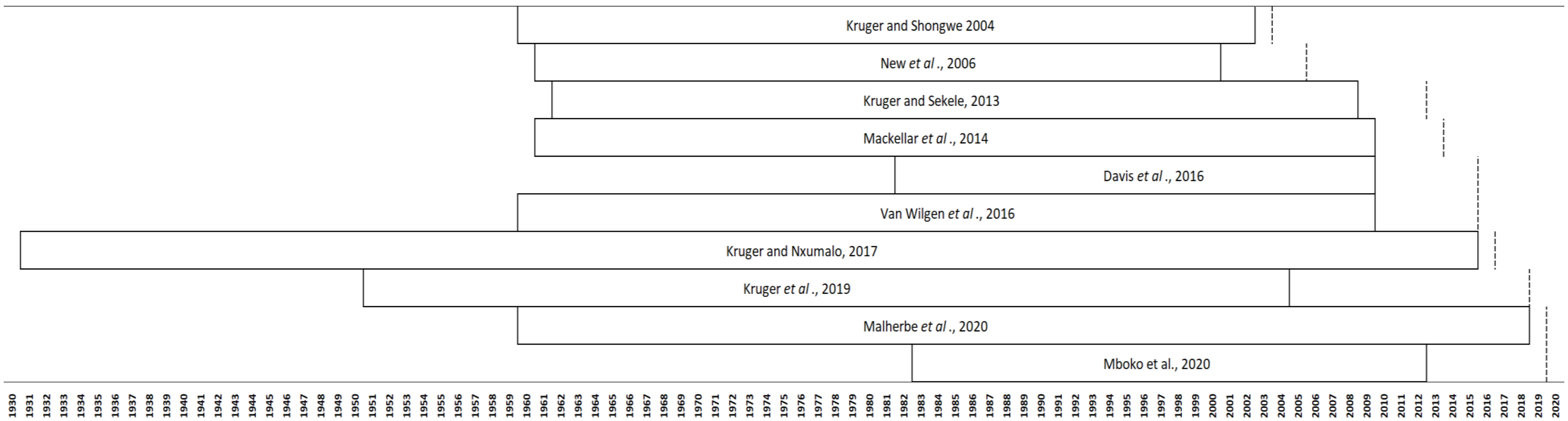


Figure 5.4: (Figure 4) Study periods used by authors (the dotted line indicates the year of publication).

5.8. 6. *Data quality and Homogeneity*

Meteorological data are prone to errors due to system malfunction, and resultant data gaps, incorrect values and possible outliers, and usually contain artificial shifts due to inevitable changes, such as human-induced error or faulty measuring equipment (Klein Tank *et al*., 2009; Salameh *et al*., 2018). These can lead to bias in the results of climate trends and extreme analysis (Kruger & Nxumalo, 2017). Data quality checks and homogenization techniques are used, which is key for time series data analysis in order to identify and adjust for non-climatic variations (Klein Tank *et al*., 2009; Kruger and Nxumalo, 2017). Some of the methods used include the use of metadata from the stations to check for inconsistencies over the study period (Kruger & Shongwe, 2004; Kruger & Sekele, 2012; Makcellar *et al*., 2014), RClimDex software for quality control checks (New *et al*., 2006; Davis *et al*., 2016; Mboko *et al*., 2020), including only stations with ≤10% missing data or >20 years (Van Wilgen *et al*., 2016), and combining the RClimDex software with RHtestsV4 software (Kruger & Nxumalo, 2017; Kruger *et al*., 2020), developed and recommended by the WMO ETCCDI, which detects, and adjusts multiple change points that could exist, using the penalized maximal *t*-test and *F*-test (Kruger and Nxumalo, 2017; Zhang *et al*., 2018b).

5.9. 7. *Statistical trend analysis*

In additional to the identification of the ETEs, statistical trend analysis was used in some cases over the respective study periods (Table 2). These statistical analyses range from linear trend analysis (Kruger & Shongwe, 2004), non-parametric Mann-Kendall test together with the Sen's slope estimator (Mackellar *et al*., 2014; Davis *et al*., 2016; Mbokodo *et al*., 2020), non-parametric Kendall's tau test, similar to the Mann-Kendall test, together with the least square linear trend (New *et al*., 2006), linear trend analysis, together with the *t*-test (Kruger & Sekele, 2012; Kruger & Nxumalo, 2017; Kruger *et al*., 2019) and linear regression, with locally weighted polynomial regression (LOWLESS) (Van Wilgen *et al*., 2016). In total, four studies used the Mann-Kendal test together with the Sen's Slope, while four studies use Linear trends and *t*-test. It is evident in all these studies and in the literature that there are multiple methods to analyze time series data trends. Many studies make use of the non-parametric Mann-Kendall test because it makes no assumptions about the distribution of the data or the linearity of any trends (New *et al*., 2006; Davis *et al*., 2016). However, the specific reasons for the selection of statistical approaches are not clearly stated.

5.10. 8. *Results*

Kruger and Shongwe (2004) found that there was a general increase in days with warmer temperatures while days with cooler temperatures have decreased. In general, most of the stations (23 of 26) showed an increase in hot-day events, with a decrease in cool-day events (Kruger & Shongwe, 2004). Significant increases in warm-night events occurred in the interior and coastal stations across South Africa, with some spatial coherence on the West coast, Eastern Cape, Kwazulu-Natal, Gauteng, and Mpumalanga Province. Similar significant decreases in cold-night events occurred in the same areas (Kruger & Shongwe, 2004). New *et al*. (2006) made similar observation and found a significant decrease in the number of cold days and nights over South Africa, with significant average increases in warm days and nights (0.160 and 0.194°C/decade). Furthermore, a general decrease in average cold spell events were evident (-0.54 days/decade), except for significant increases experienced in Emerald Dale in KwaZulu-Natal and Port Elizabeth in the Eastern Cape Province. However, significant increases were experienced in average warm spells (2.4 days/decade) across the country (New *et al*., 2006).

The majority of the stations used by Kruger and Sekele (2012), are calculated to have experienced increases in warm extremes, with the strongest trends along the southern coastline. The western half and the northern interior of South Africa experienced the strongest increasing trends (Kruger & Sekele, 2012). Also, signs of significant increases in heatwaves in the extreme northern parts of the western and northeastern interior (6.74 days/decade), especially during the warm summer months were found, while significant decreases in cold spells were detected in the northeastern interior (-4.08 days/decade) and northern part of the western interior (Kruger & Sekele, 2012). In general, Mackellar *et al*. (2014), found that high ETs have increased significantly in frequency, while a decrease was found in low ETs annually and seasonally, but particularly in the western and northern interior of the country.

Davis *et al*. (2016) reported that the occurrence of warm extremes has increased, and cold extremes decreased over the Namaqualand region, together with increases in warm spell days in all the stations used, with two stations (Pofadder and Springbok) being statistically significant. Similarly, a marked increase in number of days >35°C has been found in most of the national parks (Van Wilgen *et al*., 2016), with significant increases in five parks(Addo Elephant, Kalahari Gemsbok, Mapungubwe, Richtersveld and West Coast), two of which are located in the Namaqualand region . The highest rates of temperature increase were found in SANParks, Mapungubwe. Temperatures <0°C were occurring progressively less frequently in Kalahari Gemsbok and Mokala, with temperatures annually dropping below this threshold in Mountain Zebra, Tankwa Karoo and Golden Gate Highlands.

Kruger and Nxumalo (2017) report that all stations (25 of 27), except Calvinia in the Northern Cape Province, experienced negative trends in cold nights. The opposite trend was found for warm nights, with statistically significant positive trends for most stations (22 of 27). In contrast to the findings of Kruger and Sekele (2012) and Mackellar *et al*. (2014), non-significant trends were found in the central parts of the country (Kruger & Nxumalo, 2017). In addition, an overwhelming majority of stations reflected a general warming trend in annual ET, in contrast to Kruger and Sekele (2012). Negative trends in duration of cold spells were found (-1 day/decade) in all the stations used by Kruger and Nxumalo (2017), with the strongest negative trends of -1.5 days/decade in the Northern Province and Cape Point, and decline of 8 days/decade for Pretoria University Experimental Farm. The majority of stations (20 of 27) showed positive trends in warm spell events over the study period, in agreement with Mackellar *et al.* (2014), (Kruger *et al*., 2019), and Davis *et al*., 2016, particularly for the Northern Cape Province. Similar to Davis *et al*. (2016) and Kruger and Nxumalo (2017), Kruger *et al*. (2019) found a general decrease in cold spells, with isolated significant decreases evident in the northern parts of South Africa. Also, they found general increases in warm spell events, with most of the stations in the western half of the country being statistically significant.

It is clear from Malherbe *et al*. (2020) that the number of heat-wave days and heatwaves increased over the study period 1961-2017, in particularly in 2015 and 2016 in all three stations (Phalaborwa, Skukuza and Punda Maria) used. Mboko *et al*. (2020) indicate that South Africa experience a substantial spatial variability of heatwave occurrences seasonally, with a higher frequency in the northern parts, with Punda Maria calculated to have experienced 45 heatwave events from 1983 to 2012. Most of these events occur in the austral summer, except for the western to south-west coastal regions experiencing heatwaves mainly between May and August. It is evident heatwaves occur more frequently during winter in the west coast region. In general, Mboko *et al*. (2020) found that the southern parts of the country experience shorter lived heatwaves, whereas the extreme northern parts of Limpopo experiences heatwaves that last for six days or more.

In summary, the majority of the studies agree that extreme warm events are increasing, while extreme cold events are decreasing. However, most of the studies indicate that the significant increases or decreases vary among stations. These discrepancies could be attributed to the station's locations (i.e. heat island) or due to non-climatic influences on the data sets (Kruger and Nxumalo, 2017).

5.11. 9. Climate change projections

Given the significant impact of ETEs it is important to understand how these may change in the future. Research show that the mean annual temperature has increased by at least 1.5 times the global average of 0.65°C over the past five decades (Nkemelang *et al*., 2018).The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) for Representative Concentration Pathway (RCP) 8.5 suggests the interior parts of the country will be 3-6°C warmer by 2081-2100 (Ziervogel *et al*., 2014). Several modelling studies have been conducted to project future temperature changes over South Africa (e.g. Russo *et al*., 2016; Engebrecht *et al*., 2015; Landman *et al*., 2018). The most recent work includes Kruger *et al.* (2019) and Mboko *et al*. (2020), with a focus mainly on ETEs. Kruger *et al*. (2019) used the Rossby Centre Regional Mode Version 4 (RCA4) regional climate model (RCM) in light of observed greenhouse gases defined by the Representative Concentration Pathways (RCP), for the period 2006-2095 across South Africa, reporting a decreasing trend in cold nights, with notably stronger increasing trends in warm nights (Kruger *et al*., 2019). Although differences were found between the medium-to-low concentration RCP4.5 and high-to-low concentrations RCP8.5, warm spells are expected to increase, but less so in the southeast part of the country (Kruger *et al*., 2019). The majority of the stations in the rest of the country show trends of >+0.6 warm spell days/decade under RCP4.5 (Kruger *et al*., 2019). Future trends in cold spells under RCP 4.5 are spatially variable, while a more pronounced decrease in cold spells is evident in the central and northern parts under RCP8.5 with decreases <-6 days/decade (Kruger *et al*., 2019). RCMs obtained from the Conformal Cubic Atmospheric Model (CCAM) for periods 2010-2039, 2040-2069 and 2070-2099 using the RCP4.5 and RCP8.5, indicate that over a 30-period the average TX may rise >6°C for most of the interior parts of South Africa by 2070-2099 (Mboko *et al*., 2020). Furthermore, the north-western parts are expected to have the most dramatic increase in frequency of heatwaves, with the interior expecting to have no pronounced increase (Mboko *et al*., 2020). Overall it is expected that the heatwaves across the region will last longer under future climate change (Mboko *et al*., 2020).

5.12. 10. Implications of cold and warm ETEs.

The socioeconomic impacts of ETEs have been a subject of public concern and are well documented in literature and in previous IPCC reports (Abatan *et al*., 2018). Warm and cold ETEs can have severe consequences for human health, ecosystems, and socioeconomic development (Abatan *et al*., 2018), in particularly in a developing country, such as South Africa which faces pressing socioeconomic needs (Pasquini *et al*., 2013; Mambo and Murambadora, 2017).

In general, ETs (i.e. hot and cold) are among the leading causes of mortality resulting in >26 million deaths annually, with >75% of cases occurring in low- or middle-income countries (Zhou *et al*., 2018). Abnormally high temperatures over a prolonged period (i.e. heatwaves and warm spells) will results in heat stress (hyperthermia; Founda *et al*., 2019) which could lead to heat-related illness including cardiovascular disease, heatstroke and mortality (Nqwenya *et al*., 2018). Abnormally low temperatures over a prolonged period (i.e. cold waves and cold spells) increase the risk of cold stress (hypothermia; Zhang *et al*., 2018a) which could lead to cardiovascular diseases and mortality. These stresses on a population level depend on the underlying disease problems in that population (Scott, 2015), and socio-economic vulnerability (Zhang *et al*., 2018a). This increases the risk for the majority of South Africa's population which are burdened with comorbidities (Garland, 2017); 14.45 million households are informal settlements of which 57% are classified as socioeconomically vulnerable households (Le Roux *et al*., 2017). Furthermore, any effects could be exacerbated by South Africa's limited adaptive capacity, infrastructure, health resources and threatened ecosystems (Pasquini *et al*., 2013; Zievogel *et al*., 2014; Davis *et al*., 2017; Mambo & Murambadora, 2017).

Increases in cold and warm ETEs potentially would impact ecosystems (Leriorato & Nakamura, 2019). Extreme heat exacerbates wildfires which pose significant threats to plantations and national parks across South Africa (Van Wilgen *et al*., 2016; Davis-Reddy & Vincent, 2017). Both cold and warm ETEs could change plant and animal distributions and delay phenological events (Wang *et al*., 2016; Van Wilgen *et al*., 2016). Furthermore, ETEs could disrupt agricultural practices, decrease crop yields, and cause livestock loss (Stander *et al*., 2016; Lötter, 2017; Mangani *et al*. 2018; Leriorato & Nakamura, 2019). These could lead to significant negative impacts to regions which support extensive livestock farming (e.g. Northern Cape and Eastern Cape), grain production (e.g. Free State) and wine production (e.g. Western Cape) and will have dire effects on communities which depend solely on the emerging agriculture sector for their livelihoods. Furthermore, ETEs may put strain on an already burdened energy systems due to the higher demand for electricity during warm and cold periods i.e. the use of fans and air-conditioners or heaters (Stander *et al*., 2016; Lubega *et al*., 2018). In addition, the tourist industry could also be affected. It has been found that temperature plays a significant role in tourism, in particularly outdoor tourism activities (Noome & Fitchett, 2019).

5.13. 11. Conclusion

The examination and identification of ETEs across South Africa using different networks of meteorological stations and indices is a growing field. This study is the first of its kind to review the methods used to classify ETEs and to quantify possible selection methods of climatological stations across South Africa. Selection, classification, and identification efforts in examining ETEs were demonstrated to be inconsistent. The inconsistencies are most apparent in selection of stations and methods used to identify ETEs, as well as ET trends. The main problem with using meteorological station data is that the data is plagued with large gaps and inhomogeneities (WMO, 2000; Collins, 2011). Additionally, the number of weather stations has decreased drastically since the 1980s (Davis-Reddy & Vincent, 2017). Furthermore, most of the studies analyse warm and cold extremes, which can lead to bias in the interpretation of the results (Scott, 2015). Thus, it is important to re-evaluate the approaches to the selection of stations, as well as indices used in a South African context.

5.14. 12. References

Abatan, A.A., Abiodun, B.J., Lawal, K.A. & Gutowski Jr W.J. (2018). Trends in extreme temperatures over Nigeria from percentile-based threshold indices, *International Journal of Climatology*, 36, 2527-2540.

Alexander, L. & Herold, N. (2016). Climpact2 Indices and Software, The University of South Wales, Sidney, Australia. https://github.com/ARCCSSextremes/climpact2.

Allen, M.J. & Sheridan, S.C. (2015). Mortality risks during extreme temperature events (ETEs) using a distributed lag non-linear model. *International Journal of Biometerology*, 62:57—67,

Bajjali, W. (2018). *Geostatistical Analysis. In: ArcGIS for environmental and water issues*. Springer Textbooks in Earth Sciences, Geography and Environment. Springer, Cham.

Blażejcyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., Psikuta, A., & Kampmann, B. (2013). An introduction to the universal thermal climate index (UTCI). *Geographia Polonica*, 86(1), 5–10.

Ceccherini, G., Russo. S., Ameztoy, I., Marchese, A.F. & Moreno,-C. (2017). Heatwaves in Africa 1984-2015, observations and reanalysis. *Natural Hazards and Earth System Sciences*, 171, 115—125.

Chen, J., Yang, J., Zhou, M., Yin, P., Wang, B., Liu, J., Chen, Z., Song, X., Ou, C-Q. & Liu, Q. (2019). Cold spell and mortality in 31 Chinese capital cities: Definitions, vulnerability and implications. *Environmental International*, 128, 271-278.

Collins, D.A., Della-Marta, P.M., Plummer, N. & Trewin, B. (2000). Trends in annual frequencies of extreme temperature events in Australia. *Australian Meteorological Magazine*, 49(4), 277–292.

Collins, J.M. (2011). Temperature variability over Africa. *Journal of Climate*, 24, 3649—3666,

CRED (2019). *Disasters in Africa: 20-year review (2000-2019)*, Centre for Research on the Epidemiology of Disasters, CRED, Brussels

CRED (2020). The International Disaster Database, EM-DAT query tool, Centre for Research on the Epidemiology of Disasters, CRED, Brussels, https://www.emdat.be/

Davis, C.L., Hoffman, M.T. & Roberts, W. (2015). Recent trends in climate of Namaqualand, a megadiverse arid region of South Africa. *South African Journal of Science*, 112(3/4).

Davis, C.L., Waagsaether, K. & Methner, N. (2017). *Development of risk assessment methodology and vulnerability index. In Climate change over South Africa: From trends and projected changes to vulnerability assessment and the status quo of national adaption strategies*. Chapter 3 in DEA. South Africa's 3rd National Communication to UNFCCC. Pretoria: Department of Environmental Affairs.

Davis-Reddy, C.L. & Vincent, K. (2017). *Climate risk and vulnerability: A handbook for southern Africa* (2nd ed). CSIR. Pretoria. South Africa

Easterling D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. & Mearns, L.O. (2000). Climate Extremes: Observations, modeling and impacts. *Science*, 289, 2068—2074.

Engelbrecht, F., Adegoke, J., Bopape, M.J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. & Gatebe, C., (2015). Projections of rapidly rising temperatures over Africa under low mitigation. *Environmental Research Letters*, 10.

Founda, D., Pierros, F., Katavoutas, G. & Keramitsoglou, I. (2019). Observed trends in thermal stress at European cities with different background climates. *Atmosphere*, 10, 436,

Garland, R. (2017). Human health. In Mambo J, Faccer K, (eds). *Understanding the Social and Environmental Implication of Global Change*. African Sun Media: Stellenbosch.

Head, T. (2019). Seven South African weather records that were broken in 2019. *The South African*. https://www.thesouthafrican.com/news/weather/hottest-day-in-south-africa-ever-weather-records/ [Accessed: 9 July 2020].

Horton, R.M., Mankin, J.S., Lesk, C., Coffel, E. & Raymond, C. (2016). A review of recent advances in research on extreme heat events. *Current Climate Change Report*, 2, 242-259.

Jones, D.A. and Trewin, B. (2002). On the adequacy of digitised historical Australian daily temperature data for climate monitoring. *Australian Meteorological Magazine*, 51: 237-250.

Kabanda, T.H. & Palamuleni, L.G. (2011). Seasonal weather events and their impact on buildings around Mafikeng, North West Province, South Africa. *Life Science Journal*. 8(S1).

Kruger, A.C. & Shongwe, S. (2004). Temperature trends in South Africa: 1960-2003. *International Journal of Climatology*, 24, 1929-1945.

Kruger, A.C. & Sekele, S. (2013). Trends in extreme temperature indices in South Africa: 1962-2009. *International Journal of Climatology*, 33:661—676.

Kruger, A.C. & Nxumalo, M. (2017). Surface temperature trends from homogenized time series in South Africa: 1931-2015. *International Journal of Climatology*, 37 (5), 2364—2377.

Kruger, A.C., Rautenbach, H., Mbatha, S., Ngwenya, S. & Makgole, T.E. (2019). Historical and projected trends in near surface temperature indices for 22 locations in South Africa. *South African Journal of Science*, 115(5/6).

Landman, W.A., Engelbrecht, F.A., Hewiston, B., Malhebe, J. & Van der Merwe, J. (2018). Towards bridging the gap between climate change projections and maize producers in South Africa. *Theory and Applied Climatology*, 10.

Le Roux, A., Mans, G., Van Hyssteen, E. & Van Niekerk, W. (2017). *South Africa's present-day climate*. In Mambo J, Faccer K, (eds). Understanding the Social and Environmental Implication of Global Change, African Sun Media: Stellenbosch.

Leriorato, J.C. & Nakamura, Y. (2019). Unpredictable extreme cold events: a threat to range-shifting tropical reef fishes in temperate waters. *Marine Biology*. 166(220).

Lewis, S.C. & King, A.D., (2017). Evolution of mean, variance and extremes in the 21st century temperatures. *Weather and Climate Extremes*, 15, 1—10.

Lötter, D. (2017). *South Africa's present-day climate*. In Mambo J, Faccer K, (eds). Understanding the Social and Environmental Implication of Global Change, African Sun Media: Stellenbosch

Lubega, W.N. & Stillwell, A.S. (2018). Maintaining electric grid reliability under hydrologic drought and heatwave conditions. *Applied Engineering*, 210, 538-549.

Mackellar, N., New, M. & Jack C. (2014). Observed and modelled trends in rainfall and temperature for South Africa: 1960—2010. *South African Journal of Science*, 110(7/8).

Malherbe, J., Smit, I.P.J., Wessels, K.J. & Beukes, P.J. (2020). Recent droughts in the Kruger National Park as reflected in the extreme climate index. *Journal of Range and Forage Science*, 37(1).

Mamabo, J. & Murambadora M. (2017). *Municipal vulnerability to climate change*. In Mambo, J. and Faccer, K., 2017 2nd ed. Understanding the social and environmental implications of global change. African Sun Media. ISBN 978-0-992236-06-9.

Mangani, R., Tesfamariam, E., Bellocchi, G. & Hassen, A. (2018). Modelled impacts of extreme heat and drought on maize yield in South Africa. *Crop and Pastor Science* 69, 703-716.

Matlhare, A. (2019). One more freezing night, Gauteng cold front to end Wednesday. *The Star*. https://www.iol.co.za/the-star/news/one-more-freezing-night-gauteng-cold-front-to-end-wednesday-28418895 [Accessed: 8 July 2020].

Mbokodo, I., Bopape, M-J., Chikoore, H., Engelbrecht, F. & Nthaduleni, N. (2020). Heatwaves in the future warmer climate of South Africa. *Atmosphere*, 11,712.

Mokoena, M., (2019). *South African Official Yearbook: South Africa Yearbook 2018/19, 26th edition*. Government Communications (GCIS). Pretoria.

Napoli C.D., Pappenberger, F. & Cloke, H.L. (2018). Assessing heat-related health risk in Europe via the Universal Climate Index (UTCI). *International Journal of Biometeorology*, 62, 1155—1165.

New, M., Hewitson B., Stephenson D.B., Tsiga A., Kruger, A., Manhique A., Gomez, B., Coelho C.A.S., Masisi, N., Kuluanga, E., Mbambalala, E., Adesina, F., Saleh, H., Kanyanga, J., Adosi, J., Bulane, L., Fortunata L., Mdoka, ML. & Lajoie, R. (2006). Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research*, 111.

Ngwenya, B., Oosthuizen, J., Cross, M., Frimpong, K. & Chaibva, C.N. (2018). A review of heat stress policies in the context of climate change and its impacts on outdoor workers: evidence from Zimbabwe. *International Journal of Society and Ecological Sustainable Development*, 9(1), 1—11.

Nkemelang, T., New, M. & Zaroug, M. (2018). Temperate and precipitation extremes under current, 1.5°C and 2.0°C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability. *Environmental Research Letters*, 13.

Noome, K. & Fitchett, J. (2019). An assessment of the climate suitability of Afriski Mountain Resort for outdoor tourism using the Tourism Climate Index (TCI). *Journal of Mountain Science*, 16(11), 2453-2469.

Otto, F.E.L., Boyd, E., Jones, R.G., Cornforth, R.J., James R., Parker, H.R., & Allen, M.R., (2015). Attribution of extreme weather events in Africa: a preliminary exploration of the science and policy implications. *Climate Change*, 132, 531—543.

Pace, A., (2020). Storms leaves damage in its wake, intense cold front arrives. Eyewitness news, https://ewn.co.za/2020/07/11/another-cold-front-expected-on-monday, Accessed on 23 July 2020

Panda, K., Mishra, A., Kumar, A., Mandal, K.G., Thakur, A.K. & Srivastava, R.C. (2014). Spatiotemporal patterns in the mean and extreme temperature indices of India, 1971-2005. *International Journal of Climatology*, 34, 3585-3603.

Pasquini, L., Cowling, R.M. & Ziervogel G. (2013). Facing the heat: Barriers to mainstreaming climate change adaption in local government in the Western Cape Province, South Africa. *Habitat International*, 40, 225-232.

Perkins-Kirkpatrick, S.E. & Gibson, P.B. (2017). Changes in regional heatwave characteristics as a function of increasing global temperature. *Scientific Reports*, 7.

Radovic, V. & Iglesias, I. (2019). *Extreme weather events: Definition, classification and guidelines towards vulnerability reduction and adaption management*. In Climate Action. Encyclopaedia of the UN Sustainable Development Goals. Springer Nature Switzerland,

Ren, F.M., Trewin, B., Brunet, M., Dushmanta, P., Walter, A., Baddour, O. & Korber, M. (2018). A research progress review on regional extreme events. *Advances in Climate Change Research*, 9, 161—169.

Russo, S., Marchese, A., Silmann, J. & Immé, G. (2016). When will unusual heat waves become normal in a warming Africa? *Environmental Research Letters*, 11.

Salameh, A.A.M., Gamiz-Fortis, S.R., Castro-Diez, Y., Hammad, A.A. & Esteban-Parra, M.J. (2019). Spatio-temporal analysis for extreme temperature indices over the Levant region. *International Journal of Climatology*, 39, 5556–5582.

Scott, R. (2015). Between extremes: health effects of heat and cold. *Environmental Health Perspective*. 123(11).

Scovronick, N., Sera, F., Acquaotta, F., Garzena, D., Fratianni, S., Wright, C.Y. & Gasparrini, A. (2018). The association between ambient temperature and mortality in South Africa: a time-series analysis. *Environmental Research*, 161, 229—235.

Seneviratne S.I. & Zwiers, F.W. (2015). Attribution and prediction of extreme events: Editorial on special issue. *Weather and Climate Extremes*, 9, 2—5.

Smith, E.T. & Sheridan, S.C. (2020). Where do cold air breaks occur and how have they changes over time? *American Geophysical Union*.

SAWS (2020) Weather Questions. https://www.weathersa.co.za/home/weatherques. Accessed on 23 July 2020.

Stander, J.H., Dyson, L. & Engelbrecht, C.J. (2016). A snow forecasting decision tree for significant snowfall over the interior of South Africa. *South African Journal of Science*.

Tank, A.M.G.K., Zwiers, F.W. & Zhang, X. (2009). Guidelines on Analysis of extremes in a changing climate in support of informed decision adaptation. *World Meteorological Organization*, WMO-TD No. 1500.

Trewin, B. (2010). Exposure, instrumentation, and observing practice effects on land temperature measurements. *Wiley Interdisciplinary Reviews: Climate Change*, 1: 490-506.

Tshiala, M.F., Olwoch, J.M & Engelbrecht F.A. (2011). Analysis of temperature trends over Limpopo Province, South Africa. *Journal of Geography and Geology*, 3(1), 13—21.

Van Wilgen, N.J., Goodall, V., Holness, S., Chown, S.L. & McGeoch, M.A. (2016). Rising temperatures and changing rainfall patterns in South Africa's national parks. *International Journal of Climatology*, 36, 706—721.

Vardoulakis, S., Dear, K., Hajat, S., Heaviside, C., Eggen, B. & Mchael, A.J. (2014). Comparative assessment of the effects of climate change on heat- and cold-related mortality in the

United Kingdom and Australia. *Environmental Health Perspectives*, 122(12), 1285—1292.

Vose, R.S. and Menne, M.J. (2004). A method to determine station density requirements for climate observing networks. *Journal of Climate*, 17:2961-2971.

Vogel, E., Donat, M.G., Alexander, L.V., Meinshausen, M., Deepak, K.R., Karoly, D., Meinshausen, N., & Frieler K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, 14.

WMO (2000) Detecting trends and other changes in hydrological data. Available at: https://water.usgs.gov/osw/wcp-water/detecting-trends.pdf. Accessed on 3 August 2020.

WMO (2016) Guidelines on the definition and monitoring of extreme weather and climate events. https://www.wmo.int/pages/prog/wcp/ccl/opace/opace2/documents/DraftversionoftheGuidelinesontheDefinitionandMonitoringofExtremeWeatherandClimateEvents.pdf Accessed on 23 July 2020

Yin, H. & Sun, Y. (2018). Detection of Anthropogenic influence on fixed threshold indices of extreme temperature. *American Meteorological Society*, 31, 6341—6352.

Yu, Z. & Li, X. (2015). Recent trends in daily temperature extremes over northeastern China (1960-2011). *Quaternary International*, 380-381, 35—35.

Zhang, P., Bassil, K., Gower, S., Katic, M., Kiss, A., Gogosis, E. & Hwang, S.W. (2018a). Cold-related injuries in a cohort of homeless adults. *Journal of Social Distress and the Homeless*.

Zhang, X., Feng, Y. & Chan, R. (2018b) *Introduction to RClimDex v1.9*. Climate Research Division, Environment Canada. Downsview. Ontario. Available from https://github.com/ECCC-CDAS/.

Zhou, M.G., Wang, L.J., Lui, T., Zhang, Y.H., Lin, H.L., Luo, Y., Xiao, J.P., Zeng, W.L., Zhang, Y.W., Wang, X.F., Gu, X., Rutherford, S., Chu, C. & Ma, W.J. (2014). Health impact of the 2008 cold spell on mortality in the subtropical China: the climate and health impact national assessment study (CHINAs). *Environmental Health*, 13, 60.

Ziervogel, G., New, M., van Garderen E.A., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J. & Warburton M. (2014). Climate change impacts and adaption in South Africa. *Wiley Interdisciplinary Reviews of Climatic Change*, 5, 605—620.

Chapter 6: Statistical classification of South African seasonal divisions on the basis of daily temperature data

6.1. Brief synopsis

In South Africa, there is no to very little consensus on distinct seasonal boundaries. This paper presents one of the very first uniform statistical classifications of South African seasonal divisions on the basis of daily temperature data.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Jennifer M Fitchett
Methodology	Adriaan J van der Walt & Jennifer M Fitchett
Validation	Adriaan J van der Walt
Formal analysis	Adriaan J van der Walt
Investigation	Adriaan J van der Walt
Resources	Adriaan J van der Walt
Data curation	Adriaan J van der Walt
Writing – the original draft preparation	Adriaan J van der Walt
Writing – review and editing	Adriaan J van der Walt & Jennifer M Fitchett
Visualisation	Adriaan J van der Walt
Supervision	Jennifer M Fitchett
Project leader	Jennifer M Fitchett

According to the above-mentioned CRediT system the author contribution was calculated as follows:

Van der Walt, A.J – 70%

Fitchett, J.M – 30%

Submitted to: South African Journal of Science

Impact Factor: 1.866

Reason for selection: The nature of the paper and the mission of the journal which focus on high-quality original research from Africa or on African-relevant issues that will be of interest to readers in any discipline and are beneficial for Scholars, educators, the general public and policymakers.

Submission data: 13 November 2019

Revised: 10 June 2020

Accepted: 11 June 2020

Published: 29 September 2020

The version to follow is exactly as published in the journal on 29 September 2020, with the addition of contiguous page numbers for this thesis.

Statistical classification of South African seasonal divisions on the basis of daily temperature data

AUTHORS:
Adriaan J. van der Walt[1,2]
Jennifer M. Fitchett[1]

AFFILIATIONS:
[1]School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Johannesburg, South Africa
[2]Department of Geography, University of the Free State, Bloemfontein, South Africa

CORRESPONDENCE TO:
Jennifer Fitchett

EMAIL:
Jennifer.fitchett@wits.ac.za

DATES:
Received: 13 Nov. 2019
Revised: 10 June 2020
Accepted: 11 June 2020
Published: 29 Sep. 2020

HOW TO CITE:
Van der Walt AJ, Fitchett JM. Statistical classification of South African seasonal divisions on the basis of daily temperature data. S Afr J Sci. 2020;116(9/10), Art. #7614, 15 pages. https://doi.org/10.17159/sajs.2020/7614

ARTICLE INCLUDES:
☒ Peer review
☐ Supplementary material

DATA AVAILABILITY:
☐ Open data set
☐ All data included
☒ On request*
☐ Not available
☐ Not applicable
*from South African Weather Service

EDITOR:
Yali Woyessa

KEYWORDS:
seasonality, classification, climatology, biometeorology, Euclidean cluster analysis

FUNDING:
University of the Free State; DSI-NRF Centre of Excellence for Palaeoscience

Across South Africa, a wide range of activities is influenced by differences in seasonality. In a South African context, there is little consensus on the timing of seasonal boundaries. Inconsistency exists through the use of ad-hoc approaches to define seasonal boundaries across South Africa. In this paper, we present one of the very first uniform statistical classifications of South African seasonal divisions on the basis of daily temperature data. Daily maximum and minimum temperature data were obtained from 35 selected South African Weather Service meteorological stations that had sufficiently complete data sets and homogeneous time series, spanning the period 1980–2015. An Euclidean cluster analysis was performed using Ward's D method. We found that the majority of the stations can be classified into four distinct seasons, with the remaining 12 stations' data best classified into three seasons, using T_{avg} as the classifier. The statistically classified seasonal brackets include summer (October/November/December/January/February/March), early autumn (April) and late autumn (May), winter (June/July/August), and spring (September). Exploring the boundaries of seasons, the start of summer and end of winter months follow a southwest to northeastwards spatial pattern across the country. Summers start later and winters end later in the southwestern parts of the country, whereas in the northeast, summers start earlier and winters end earlier.

Significance:

- The findings contribute to the common knowledge of seasonality in South Africa.
- New seasonal divisions in South Africa are proposed.

Introduction

Seasonal differences in climate, day length, and plant activity form the primary environmental control on a wide range of activities. These activities include economic and agricultural practices[1], which are affected by the length and timing of growing seasons[2,3], the related timing of sowing and harvest, and the necessity for irrigation and fertilisation. Climatic seasons also influence resource management and energy demand[4], tourism[5], social and economic planning[6], hydrology[1] and health[7]. The capacity to accurately determine the start and end of seasons is thus of critical importance. However, in the South African context, there is little consensus as to distinct seasonal boundaries. This lack of consensus is unusual. For most parts of the northern hemisphere[8,9] – including Italy[10], USA[11], China[12], Poland[13] and Finland[14] – seasonal boundaries are well established and clearly communicated.

South Africa is classified as a semi-arid country[15] which is situated in the mid-latitudes and subtropics[16,17]. The South African climate is influenced by major synoptic systems, including the semi-permanent subtropical high-pressure systems[16] and the variability of the Inter-Tropical Convergence Zone (ITCZ)[18-20]. The resultant continental anticyclones, ridging anticyclones, westerly waves, tropical easterly waves, and cut-off lows[16,21,22], produce a pronounced climatic seasonality across the country[20]. However, there is little consensus on the timing of seasons in South Africa, and approaches in defining seasonal boundaries often vary on the basis of the application (Table 1).[18] The South African Weather Service (SAWS) even highlights that there is no official designation and definitions of seasons.[23]

The most basic classifications commonly used are astronomical, meteorological and phenological divisions.[23] Astronomical summer is defined as the period from the summer solstice to the vernal equinox. By this classification, autumn is defined to conclude at the winter solstice, and winter spans the winter solstice to the spring equinox.[23,24] It is well known that the earth–sun geometry affects the seasons; however, there is no direct link between astronomical seasons and mean weather variations.[24,25] Meteorological classification refers to the subdivision of four equal-length periods of 3 months each, mostly and commonly used in the temperate latitudes.[23] In South Africa, the meteorological classification of temperature seasonality is the most widely used (Table 1).[2,26-29] Most agroclimatological studies use the conventional break of 3 months but may extend it to the farming season of the specific regions that are under investigation and use two distinct seasons, summer and winter (Table 1).[30] Climate modelling projections and analyses of influences of climatic factors studies often use six run-on seasons that coincide with synoptic circulations, with the latter coinciding with epidemiological seasons of heightened disease-risk.[31] Some climatologists classify seasons on an ad-hoc basis that is appropriate to specific regions, with classifications such as hot season, cold season, post-rainy season and growing season, with no direct relationship with calendar months. These seasons are defined for convenience and to suit the data output rather than to drive sensible analytical processes.[25-27] Phenological studies can also be used to define annual seasonality, and to reveal shifts in the timing of these events[32], as phenological shifts are often directly related to changes in local air temperatures[33].

Classification of South African seasons based on rainfall patterns is similarly complicated due to the variety of rainfall regimes, and thus likewise no standard definition has been adopted[18], and discrepancies exist between the seasonal brackets of rainfall and temperature-related classifications[34]. The differences are further complicated by the influence of distance from large water bodies, and the variation in heat from the Indian and Atlantic Oceans.[24]

Here we present one of the first statistical classifications of South African seasonal divisions on the basis of daily temperature data for 35 weather stations spanning the country. We argue that this method represents a more standardised and objective approach to the classification of seasons, particularly in a region that spans the subtropics and mid-latitudes.

Study region

South Africa is located within the latitudes 22–35°S and longitudes 17–33°E, and is bordered by the Atlantic Ocean in the west and southwest and the Indian Ocean to the south and southeast. It shares political boundaries with Mozambique, Zimbabwe, Botswana, Namibia and Eswatini (Swaziland), and encloses Lesotho (Figure 1).[35] The climate of South Africa, in particular temperature, is governed by the complex interaction between the subtropical location, the altitude of the interior plateau, the position of the subcontinent with respect to the major atmospheric circulation features, and the oceans on all sides except the north.[19,20,36] The subcontinent lies within the subtropics, with rainfall dominated by convective storms in the north and mid-latitude cyclones to the south.[16,37] The influence of the tropical and temperate pressure regimes, and the intra-annual migration of the inter-tropical convergence zone (ITCZ) results in pronounced seasonal differences in rainfall and temperature patterns over South Africa.[19] The ITCZ shifts with the monthly and seasonal changes of the sun's maximum insolation and the location of dominant atmospheric high- and low-pressure systems.[19,37] The high-pressure systems sit over the southern tip of the subcontinent in summer, and over the interior during winter. These high-pressure systems are interrupted by mid-latitude cyclones.[38] The influences of the subtropical high-pressure belt, and the mid-latitude westerlies with associated fronts vary significantly inter- and intra-annually over the subcontinent.[38] These interactions between tropical and temperate disturbance have significant consequences for the weather of the subcontinent.[16] The orography of South Africa influences the temperature distribution over the country such that the escarpment forms a climatic division between the high plateau and the low-lying coastal regions in the east and southeast (Figure 1).[19] The southern and eastern escarpments are the regions with the lowest temperatures, due to the decrease in temperature with altitude.[39,40] The oceans surrounding South Africa influence the temperatures experienced along the coastal areas.[39,40] The Indian Ocean, on the east, is warmed by the western boundary Agulhas Current, while the Atlantic, on the west coast, is cooled by the eastern boundary Benguela Current (Figure 1).[19,39] All these factors result in a broad east–west temperature gradient, with the Northern Cape experienceing the lowest rainfall and highest temperatures in the country.[39,40]

Table 1: Published temperature seasonality classifications for South Africa

Publication	Research topic	Seasonal temperature brackets	Seasonal temperature brackets approach
Karl et al., 1993[26]	Daily maximum and minimum temperatures	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Three-month mean
Klopper et al., 1998[27]	Seasonal maximum temperature predictability in South Africa	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Climatological austral seasons
Craig et al., 2004[31]	Malaria case data in KwaZulu-Natal	Nov/Dec/Jan/Feb/Mar (summer) Mar/Apr/May/Jun (autumn) Jun/Jul/Aug (winter) Aug/Sep/Oct/Nov (spring)	Defined approach
Kruger and Shongwe, 2004[28]	Temperature trend in South Africa	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Subdivided into four seasons
Benhin, 2006[30]	Climate change and South African agriculture	Dec/Jan/Feb/Mar/Apr/May (summer) Jun/Jul/Aug/Sep/Oct/Nov (winter)	Mean monthly temperatures; farming seasons
Tshiala et al., 2011[2]	Analysis of temperature trends in Limpopo	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Defined following the usual conventions
Lazenby et al., 2014[7]	Seasonal temperature prediction over southern Africa and human health	Sep/Oct/Nov; Oct/Nov/Dec; Nov/Dec/Jan Dec/Jan/Feb; Feb/Mar/Apr (summer to late summer)	Southern Africa is mainly controlled by influences from the tropics
Kruger and Nxumalo, 2017[29]	Temperature trends in South Africa	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Mean monthly temperatures
Tshiala and Olwoch, 2010[56]	Tomato production in Limpopo	Dec/Jan/Feb (summer) Mar/Apr/May (autumn) Jun/Jul/Aug (winter) Sep/Oct/Nov (spring)	Mean monthly temperatures

Data and methodology

For this study, daily maximum and minimum temperature data were obtained from 35 selected SAWS meteorological stations (Figure 1; Table 2) that had a minimum of 30 years of data, sufficiently complete data sets and homogeneous time series, spanning the period 1980–2015. These stations were selected as they span the country, ranging from 22°S to 35°S and 15°E to 33°E with an intended 1° interval (Figure 1). Before performing any statistical techniques, exploratory data analysis was applied to investigate the data homogeneity due to inevitable changes in aspects including observation sites, station relocation, observation practices/procedures and time.[29] However, in the context of the study, sudden increases or decreases in values over a prolonged period would not have significantly influenced the results. Visible outliers in the data series were checked by comparison with data from surrounding stations spanning the period of interest as well as reports of anomalous weather in the media.

Table 2: Information on selected meteorological stations

Province	Station name	Climate number	Latitude	Longitude	Altitude (m.asl)
Eastern Cape	East London	00595729	-33.03	27.83	124
	Dohne	00798116	-32.52	27.47	899
	Mthatha	0127272A4	-31.55	28.67	745
	Port Elizabeth	00351795	-33.98	25.60	60
Free State	Bloemfontein	02615161	-29.10	26.30	1354
	Bethlehem	03315859	-28.24	28.33	1689
	Welkom	03643001	-27.99	26.66	1344
Gauteng	Johannesburg Int	*04763990*	-26.14	28.23	1706
	Zuurbekom	04755288	-26.30	27.81	1580
KwaZulu-Natal	Cedara	02394820	-29.54	30.27	1071
	Durban	0240808A2	-29.97	30.95	96
	Escourt	03006901	-29.01	29.86	1144
	Shaleburn	02376184	-29.80	29.35	1614
Limpopo	Mara	072200991	-23.14	29.56	894
	Warmbad Towoomba	05895941	-24.90	28.32	1143
	Polokwane	0677802BX	-23.84	29.45	1226
Mpumalanga	Skukuza	05961793	-24.99	31.59	276
	Carolina	04801547	-26.07	30.11	1667
Northern Cape	Calvinia	0134479A3	-31.48	19.76	975
	De Aar	01698801	-30.66	23.99	1286
	Fraserburg	01130258	-31.91	21.51	1264
	Kimberley	02904684	-28.80	24.77	1198
	Pofadder	0247668A4	-29.12	19.38	984
	Springbok	0214700B2	-29.66	17.87	1006
	Sutherland	00882931	-32.38	20.67	1459
	Upington	03174765	-28.43	21.27	836
	Vanwyksvlei	01935613	-30.35	21.82	965
North-West	Vryburg	04322383	-26.95	24.65	1245
	Mahikeng	05080470	-25.80	25.54	1280
Western Cape	Cape Agulhas	00030204	-34.83	20.01	11
	Cape Columbine	00606209	-32.83	17.86	62
	Cape St Blaze/Mossel bay	00122517/0012215	-34.18/-34.19	22.15/22.13	135
	Cape Town	0021178A3	-33.96	18.60	42
	Vredendal	0106880A2	-31.67	18.50	42
	George	00126617	-34.00	22.38	197

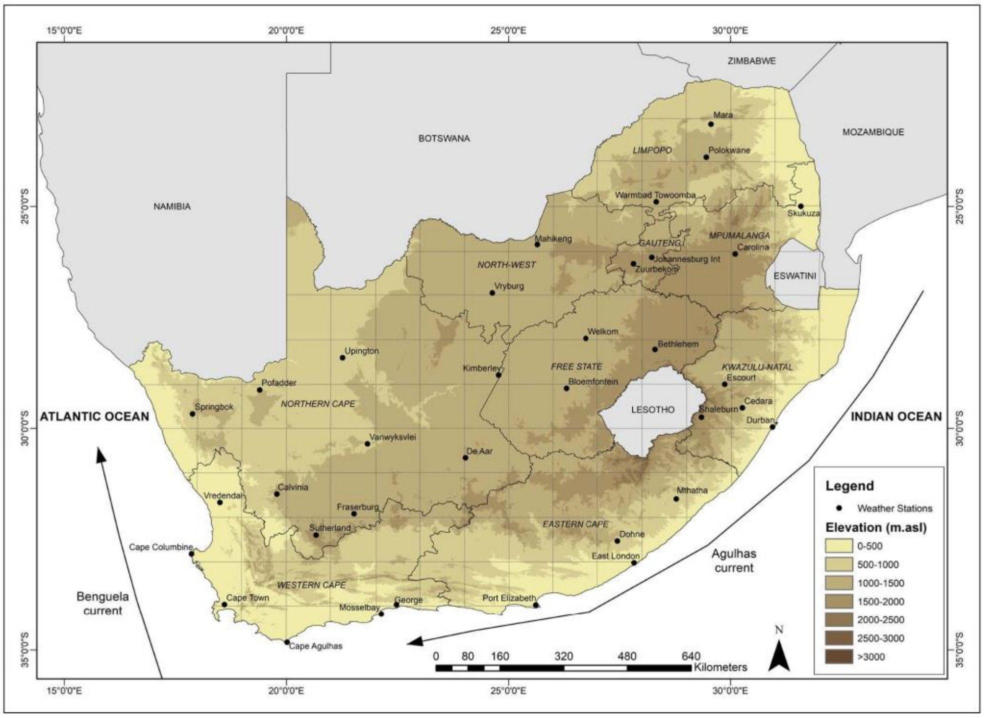


Figure 1: Map of the study region of South Africa, indicating 1° intervals used to select the meteorological stations across South Africa, the topography, the surrounding oceans and their respective ocean currents.

The data sets of the selected stations were subjected to quality control. As a first step, all dates and times were checked, and two decimal point rounding was used to maintain consistency throughout. Missing weather station data were replaced with data from a station adjacent to the site within a 10-km radius, or, if not possible, replaced with the 5-day running average. If data were not available for more than five consecutive days, that period was excluded from the analysis.

Cluster analysis

Cluster analysis was performed using Ward's D method, defined by the Euclidean distance between variables, utilising the cluster, vegan and rioja packages in R.[41-43] Euclidean cluster analysis was initially supervised at four seasonal divides and validated by using the dendogram package average silhouette width (ASW) calculation.[44] The ASW value measures the degree of confidence in between-group distances and strength of within-group homogeneity.[45] If not significant, two, three, five and six seasonal divides were used serially until the cluster was significant, using orders of magnitude put forward by Kaufman and Rousseeuw[46] as reference for measures. The ASW was calculated, together with the cophenetic correlation coefficient (CPCC) for interpretation, evaluation and validation of consistencies within the cluster and groupings.[42,47] The CPCC measures the correlation between the original pairwise distance matrix and the cophenetic distance matric of the dendrogram. This allows for the verification of the quality of the grouping.[47-49] The closer the cophenetic correlation coefficient is to a value of one, the better the grouping quality.[49] The cluster analysis results for maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) temperatures are given in Table 3. To investigate the spatial patterns, the cluster analysis outputs, and start and end dates of summer and winter, were spatially interpolated using the Inverse Distance Weighted (IDW) method using ArcGIS software.[50] It has been found that IDW interpolates station data accurately.[51] Additionally, annual mean graphs were produced for each of the temperature metrics.

Results

Cluster analysis

Results will mainly focus on T_{avg}, with reference to T_{max} and T_{min} only where statistically relevant. The cluster analysis reveals that the majority of the stations, 23 out of the 35, are most appropriately classified into four seasons (Table 3). The remaining 12 stations are best classified into three seasons. All the stations in the Limpopo, KwaZulu-Natal and North-West Provinces are clustered into four seasons, and those in the Eastern Cape are clustered into three seasons. All these stations have a statistically strong grouping (CPCC>0.7) and distinct cluster structures (ASW>0.5), except for Cedara (ASW=0.47) in KwaZulu-Natal, with a weaker cluster structure. The weaker cluster structures are also prominent in the Eastern Cape stations (ASW<0.5). The cluster analysis results revealed that Dohne (CPCC=0.7009) in the Eastern Cape has the lowest quality of grouping among the 35 stations analysed.

The three stations in the Free State, two of which (Bethlehem and Welkom) are classified into four seasons and one (Bloemfontein) into three seasons, have a good quality grouping (CPCC>0.7) and distinct cluster structure (ASW>0.5). A similar degree of confidence in cluster structures is found in both the Mpumalanga stations, Skukuza and Carolina, which are divided into three and four seasons, respectively. These two stations have a higher quality grouping (CPCC>0.8) than those in the Free State. A higher quality grouping is also prevalent in both the Gauteng stations, with Johannesburg Int (International) classified into four seasons, and Zuurbekom into three. However, a weaker cluster structure is calculated for Zuurbekom (ASW=0.45).

The Northern Cape and Western Cape are noticeably different from the rest of the provinces, with a more significant variation in the degree of confidence for the cluster structures. Six of the nine stations in the Northern Cape are clustered into four seasons with good cluster groupings (CPCC>0.7). However, most of these stations have a weak cluster structure (ASW<0.5), except for Fraserburg (ASW=0.5). The remaining three stations – De Aar, Kimberley and Springbok – are divided into three seasons with a good quality grouping; however, weaker structures are visible in Kimberley (ASW=0.46) and Springbok (ASW=0.42). In the Western Cape, four out of the six stations are classified into four seasons and the other two (Mosselbay and Cape Columbine) into three seasons. Similar to the Northern Cape, all stations clustered into four seasons display a good quality of grouping, but a weak cluster structure (ASW<0.5), with the weakest cluster structure calculated for Cape Agulhas (ASW=0.46). Mosselbay (ASW=0.51; CPCC=0.8011) is the only station in the WC with a distinct cluster structure and a good quality grouping. By contrast, the cluster analysis identified Cape Columbine (ASW=0.4) with the weakest cluster structure among all the stations that were analysed.

While similarities are found in the number of seasonal groupings returned for the different temperature metrics, the highest number (15 stations) have consistent classifications for T_{min} and T_{avg}. Only six stations have consistent seasonal classifications when considering T_{max} and T_{min}, and three stations when considering T_{max} and T_{avg}. Only seven stations – Dohne, Port Elizabeth, De Aar, Bloemfontein, Cape Columbine, Welkom and Escourt – have the same number of seasonal groupings for all three temperature metrics.

For the majority of stations (23), classification using T_{max} returns three seasons, with 9 stations classified into two seasons, and only 3 classified into four seasons (Table 3). The majority of these stations have a strong grouping (CPCC>0.7), except for Dohne (CPCC=0.6714), located in the Eastern Cape. However, the degree of confidence in the cluster structures is low due to the weak cluster structures (ASW<0.5) for most of the stations except for Johannesburg Int, Zuurbekom, Mara, Mahikeng, Springbok and Cape Town with an ASW>0.5. The cluster analysis for T_{min} classifies the majority of the stations (21) into four seasons, with 13 stations classified into three seasons, and only 1 station (Springbok) classified into two seasons. Similar to T_{max}, the grouping quality for the stations is good. However, the cluster structures for most of the stations are distinct with only 19 stations returning an ASW<0.5.

Spatial analysis of the cluster analysis results (Figure 2) indicates that most parts of the country experience three seasons, with the greatest spatial variability visible in T_{max}. Similarities in the classification of seasons are visible for T_{max}, T_{min} and T_{avg}, but more so for T_{min} and T_{avg}. The western and central regions of the country, and parts of the Eastern Cape, have three distinct seasons, when classified using T_{max}, T_{min} and T_{avg}. Areas surrounding Springbok are similarly classified as having only two distinct seasons.

Table 3: Output of the cluster analysis including cluster groups (CG), average silhouette widths (ASW) and cophenetic correlation coefficient (CPCC) scores

Stations					T_{max}				T_{min}				T_{avg}
		CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups
EASTERN CAPE	East London	2	0.47	0.7293	May/Jun/Jul/Aug/Sept/Oct/Nov Dec/Jan/Feb/Mar/Apr	3	0.5	0.7487	May/Jun/Jul/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.45	0.7475	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sep/Oct/Nov
	Dohne	3	0.37	0.6714	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sep/Oct/Nov	3	0.42	0.7091	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sept/Oct/Nov	3	0.44	0.7009	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sept/Oct/Nov
	Port Elizabeth	3	0.38	0.7833	Dec/Jan/Feb/Mar/Apr Jun/Jul/Aug/Sep May/Oct/Nov	3	0.49	0.7627	May/Jun/Jul/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.47	0.7385	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/May/Sep/Oct/Nov
	Mthatha	2	0.39	0.6644	Dec/Jan/Feb/Mar/Apr/Nov May/Jun/Jul/Aug/Sep/Oct	4	0.48	0.7663	Jun/Jul May/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.42	0.7125	May/Jun/Jul/Aug Dec/Jan/Feb/Mar Apr/Sep/Oct/Nov
FREE STATE	Bethlehem	3	0.34	0.8042	May/Jun/Jul/Aug Dec/Jan/Feb Mar/Apr/Sep/Oct/Nov	4	0.48	0.8057	Jun/Jul May/ Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	4	0.53	0.8149	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Bloemfontein	3	0.34	0.7867	May/Jun/Jul/Aug Dec/Jan/Feb Mar/Apr/Sep/Oct/Nov	3	0.48	0.7565	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	3	0.5	0.7545	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug
	Welkom	4	0.44	0.7066	Dec/Jan/Feb/Mar/Oct/Nov Jun/Jul May/Aug Apr/Sep	4	0.48	0.7415	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep Jun/Jul May/Aug	4	0.54	0.8245	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov

Table 3 continues on the next page

Table 3 continued

		Stations			T$_{max}$				T$_{min}$				T$_{avg}$
		CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups
GAUTENG	Johannesburg Int	3	0.5	0.8364	Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov Jun/Jul May/Aug	3	0.45	0.8170	May/Jun/Jul/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	4	0.51	0.8458	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Zuurbekom	2	0.53	0.8299	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.47	0.8307	May/Jun/Jul/Aug Apr/Sep Dec/Jan/Feb Mar/Oct/Nov	3	0.45	0.8357	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep
KWAZULU-NATAL	Cedara	2	0.37	0.6561	Dec/Jan/Feb/Mar Apr/May/Jun/Jul/Aug/Sep/Oct/Nov	4	0.52	0.8056	Jun/Jul May/Aug Apr/Sept/Oct Dec/Jan/Feb/Mar/Nov	4	0.47	0.7686	Jun/Jul May/ Aug Dec/Jan/Feb/Mar Apr/Sep/Oct/Nov
	Durban	3	0.47	0.7316	Jun/Jul/Aug/Sep/Oct Dec/Jan/Feb/Mar Apr/May/Nov	4	0.52	0.7680	Jun/Jul May/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	4	0.52	0.7125	Dec/Jan/Feb/Mar Jun/Jul/Aug Apr/Nov May/Oct/Sep
	Escourt	4	0.37	0.8278	Jun/Jul May/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	4	0.54	0.8278	May/Jun/Jul/Aug Apr/Sep Dec/Jan/Feb Mar/Oct/Nov	4	0.54	0.8212	Jun/Jul May/Aug Apr/Sept/Oct Dec/Jan/Feb/Mar/Nov
	Shaleburn	2	0.46	0.7406	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.42	0.8214	May/Jun/Jul/Aug Apr/Sept Dec/Jan/Feb Mar/Oct/Nov	4	0.52	0.8103	Jun/Jul May/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov
LIMPOPO	Mara	2	0.52	0.8130	Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov May/Jun/Jul/Aug	4	0.50	0.8444	Jun/Jul May/ Aug Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct	4	0.5	0.8460	Jun/Jul May/ Aug Dec/Jan/Feb/Mar/Nov Apr/Oct/Sep
	Polokwane	3	0.45	0.8186	Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov Jun/Jul May/Aug	3	0.55	0.8248	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug	4	0.5	0.8332	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Warmbad Towoomba	3	0.48	0.7906	Dec/Jan/Feb/Mar/Sep/Oct/Nov Jun/Jul Apr/May/Aug	4	0.56	0.8526	May/Aug Jun/Jul Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	4	0.57	0.8729	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
MPUMALANGA	Skukuza	2	0.48	0.7837	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.51	0.8365	Jun/Jul May/Aug Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct	3	0.51	0.8307	May/Jun/Jul/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov
	Carolina	3	0.46	0.7622	Dec/Jan/Feb/Mar/Sep/Oct/Nov Jun/Jul Apr/May/Aug	4	0.52	0.8357	May/Aug Jun/Jul Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	4	0.5	0.8440	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
NORTH-WEST	Mahikeng	2	0.57	0.8271	May/Jun/Jul/Aug Dec/Jan/Feb/Mar/Apr/Sep/Oct/Nov	4	0.56	0.8424	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	4	0.58	0.8514	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov
	Vryburg	4	0.46	0.8226	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov	3	0.5	0.7625	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	4	0.58	0.8348	Jun/Jul May/Aug Apr/Sep Dec/Jan/Feb/Mar/Oct/Nov

Table 3 continues on the next page

Table 3 continued

Stations					T_{max}				T_{min}				T_{avg}
		CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups	CG	ASW	CPCC	Seasonal Groups
NORTHEN CAPE	Calvinia	3	0.47	0.7246	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/May/Oct/Sep	3	0.47	0.7567	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/May/Oct/Nov	4	0.48	0.7864	Jun/Jul/Aug May/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar
	De Aar	3	0.44	0.7561	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	3	0.49	0.7198	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/May/Oct/Sep	3	0.5	0.7209	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug
	Fraserburg	3	0.48	0.7297	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug	4	0.53	0.8077	Jun/Jul/Aug May/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	4	0.5	0.7349	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/Oct May/Sept
	Kimberley	3	0.41	0.7382	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	4	0.46	0.7703	Jun/Jul May/Aug Apr/Sep/Oct Dec/Jan/Feb/Mar/Nov	3	0.46	0.7536	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug
	Pofadder	3	0.43	0.7750	Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar/Nov Apr/Oct	4	0.48	0.7947	Jun/Jul/Aug May/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	4	0.48	0.7967	May/Sep Jun/Jul/Aug Dec/Jan/Feb/Mar Apr/Oct/Nov
	Springbok	2	0.55	0.7802	May/Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar/Apr/Oct/Nov	2	0.49	0.7412	Dec/Jan/Feb/Mar/Apr May/Jun/Jul/Aug/Sep/ Oct/Nov	3	0.42	0.7426	Dec/Jan/Feb/Mar/Apr/Nov Jun/Jul/Aug May/Sep/Oct
	Sutherland	3	0.46	0.7292	Dec/Jan/Feb/Mar/Nov Apr/May/Sep/Oct Jun/Jul/Aug	3	0.51	0.7618	May/Jun/Jul/Aug/Sep Apr/Nov/Oct Dec/Jan/Feb/Mar	4	0.49	0.7774	Jun/Jul/Aug May/Sep Apr/Oct Dec/Jan/Feb/Mar/Nov
	Upington	3	0.42	0.7494	Dec/Jan/Feb/Mar/Oct/Nov Apr/Sep May/Jun/Jul/Aug	4	0.51	0.8192	May/Sep Jun/Jul/Aug Dec/Jan/Feb/Mar Apr/Oct/Nov	4	0.46	0.7155	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug May/Sep Apr/Oct
	Vanwyksvlei	3	0.48	0.7221	Dec/Jan/Feb/Mar/Nov Apr/Sep/Oct May/Jun/Jul/Aug	4	0.51	0.7300	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/Oct May/Sep	4	0.47	0.7276	Dec/Jan/Feb/Mar/Nov Jun/Jul/Aug Apr/Oct May/Sep
WESTERN CAPE	Cape Agulhas	3	0.43	0.7670	May/Jun/Jul/Aug/Sep/Oct Dec/Jan/Feb/Mar Apr/ Nov	4	0.48	0.7685	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct	4	0.46	0.7741	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct
	Cape Columbine	3	0.41	0.7861	Dec/Jan/Feb/Mar/Apr/Nov Jun/Jul/Aug May/ Sep/Oct	3	0.37	0.7612	Dec/Jan/Feb/Mar/Apr/Nov May/Oct Jun/Jul/Aug/Sep	3	0.4	0.7666	Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar Apr/May/Oct/Nov
	Cape Town	3	0.53	0.7893	May/Jun/Jul/Aug/Sep Apr/Oct/Nov Dec/Jan/Feb/Mar	3	0.5	0.7516	May/Jun/Jul/Aug/Sep Dec/Jan/Feb/Mar Apr/Oct/Nov	4	0.49	0.7757	Jun/Jul/Aug May/ Sep Apr/Oct/Nov Dec/Jan/Feb/Mar
	George	3	0.42	0.7453	Dec/Jan/Feb/Mar Apr/May/Nov Jun/Jul/Aug/Sep/Oct	4	0.48	0.7606	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct	4	0.49	0.7635	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/Nov May/Oct
	Mosselbay	3	0.42	0.8017	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep/Oct Apr/May/Nov	4	0.47	0.7862	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep May/Oct Apr/ Nov	3	0.51	0.8002	Dec/Jan/Feb/Mar Jun/Jul/Aug/Sep Apr/May/Oct/Nov
	Vredendal	3	0.44	0.7630	Dec/Jan/Feb/Mar/Apr/Nov Jun/Jul/Aug May/Sep/Oct	3	0.47	0.7862	Dec/Jan/Feb/Mar May/ Jun/Jul/Aug/Sep Apr/Oct/Nov	4	0.47	0.8011	Dec/Jan/Feb/Mar Jun/Jul/Aug May/Sep Apr/Oct/Nov

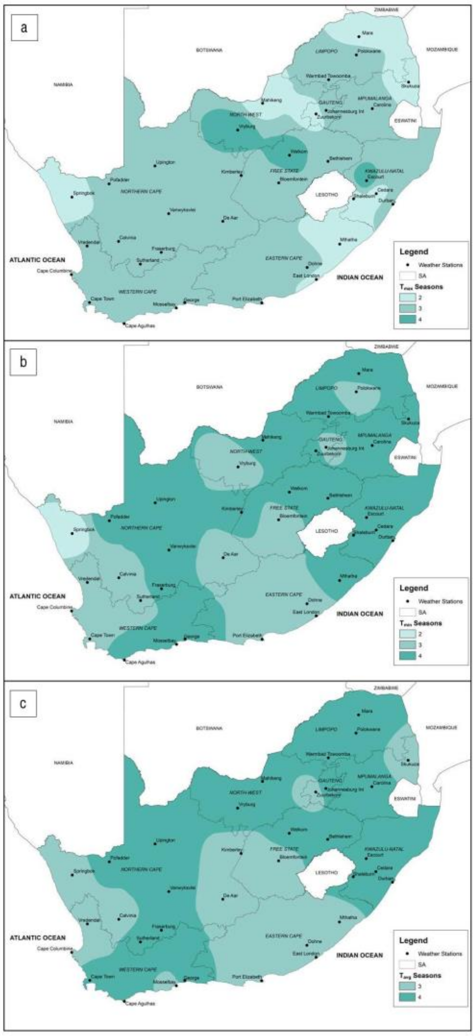


Figure 2: (a) Maximum (T_{max}), (b) minimum (T_{min}) and (c) average (T_{avg}) temperature seasonal groupings.

Seasonal timetable

Several variations of monthly classifications have been calculated (Tables 3 and 4), which will be referred to as 'seasonal brackets'.

Summer: There is unanimous agreement across seasons and temperature metrics that December, January, February and March can be grouped into the summer seasonal bracket. October and November can tentatively be included in the summer season, with a 31% agreement among stations for October and an overall 59% agreement for November. A total of 30% of stations classify October as falling within spring, 26% in late spring, 5% in early spring, and 8% in the winter seasonal bracket. In comparison, 21% of the remaining stations classify November as falling in spring, 17% in late spring, and 3% in winter. The latest start of summer is December. The longest summer season is calculated for Mthatha (Eastern Cape) using T_{avg} as the classifier, spanning the earliest start month of September and persisting until April.

Autumn: For 43% of the stations, April falls within the early autumn bracket, whereas for 39% of stations, April is grouped in the main autumn seasonal bracket. The remainder of the stations group April into summer (15%), winter (2%) and late autumn (1%). A total of 41% of the stations classify May into the late autumn bracket, 35% into the winter bracket, and 24% into the main autumn bracket. Autumn starts as early as March for Bethlehem, Bloemfontein and Zuurbekom using T_{max} and T_{min} as the classifier. Using T_{avg} as the classifier, the majority of stations indicate the start of autumn in April. Springbok (Northern Cape) has the latest classified start of autumn, in the month May. Stations with only 1 month of autumn, using T_{avg} as classifier, include Bloemfontein, Zuurbekom, Skukuza, De Aar, Kimberley and Springbok

Winter: There is unanimous agreement across stations and temperature metrics that June and July are grouped into the winter bracket. There is 71% agreement among stations that August additionally forms part of the winter bracket with only 25% of stations classifying August in early spring and 4% in the main spring seasonal bracket. Cedara and Vanwyksvlei experience the longest winter, commencing in April and ending in November for Cedara and October for Vanwyksvlei, both using T_{max} as the classifier. Winter in East London and Springbok starts a month later in May and ends in November. Stations with the shortest winter (June to July) classified by T_{avg} include Shaleburn, Mara, Polokwane, Warmbad Towoomba, Carolina, Bethlehem, Welkom, Johannesburg Int, Cedara, Escourt, Mahikeng, Vryburg, Cape Agulhas, Cape Columbine and George.

Spring: Interestingly, the most disputed month across all stations is September. However, 29% of the stations agree that September can tentatively be included in the spring bracket. The remainder comprise a 25% agreement that September can be included in the winter, 23% in early spring, 16% in late spring and 9% in the summer bracket. Some stations are classified as experiencing early spring in August, using T_{min} as the classifier. These stations are Mthatha, Bethlehem, Welkom, Cedara, Durban, Escourt, Mara, Warmbad Towoomba, Skukuza, Carolina, Mahikeng and Kimberley. Stations with the shortest spring (only the month of August), calculated using T_{max}, are Johannesburg Int, Polokwane, Warmbad Towoomba, and Carolina. Interestingly, all these stations are situated in the northern parts of the country. Classified by T_{min}, the longest spring is observed in Mthatha (Eastern Cape) and Durban (KwaZulu-Natal), starting in August and ending in November. The latest start for spring – November – classified by T_{max}, is visible in Durban, Cape Agulhas and Mosselbay. Stations at East London, Mthatha, Zuurbekom, Cedara, Shaleburn, Mara, Skukuza, Mahikeng and Springbok each have two classified seasons, and therefore no autumn or spring.

Start and end dates of summer and winter

A distinct, southwest to northeast spatial pattern is apparent for the start and end dates of summer and winter across all the temperature metrics (Figures 3a–f and 4a–f). Summer broadly commences earlier in the northeastern and interior parts of the country and later along the southwestern parts and the south coast. The earliest start of summer is visible in T_{max} for the northern parts of the country, and in parts of KwaZulu-Natal for T_{avg}. The earliest end of summer is calculated using T_{min}, with parts in KwaZulu-Natal and Gauteng ending in February (Figure 3e). The greatest variability in the spatial patterns is recorded T_{max}, for which the northern and southern region summer ends in April, similar to T_{avg} for the southern region. However, there is a consensus amongst the temperature metrics that, for most parts of the country, summer ends in March, whereas for the western parts of the country, the season ends a month later in April.

For the majority of the country, winter starts in June, with the season starting earlier for a few interior regions. The greatest spatial variability in the timing of the start of winter is observed in T_{max} (Figure 4a). For areas in the Western Cape and Northern Cape, winter is classified as starting in May, similar to the start of winter using T_{min}. For parts of KwaZulu-Natal, winter is calculated to start as early as April. Regarding the end of winter, the greatest spatial variability is similarly observed for calculations using T_{max}, for which winter ends latest in the southwest of the country and along the east coast. For the western parts of the Northern Cape, winter ends later using T_{max} and T_{min}. Similar to the end of summer maps (Figure 4d–f), a distinct southwest to northeast spatial movement of end dates is visible for all the temperature metrics used. For the southwestern parts of the country, winter ends later, whereas moving northeastwards to the interior, the winter months end earlier, except for some parts in Gauteng, Limpopo and the North-West.

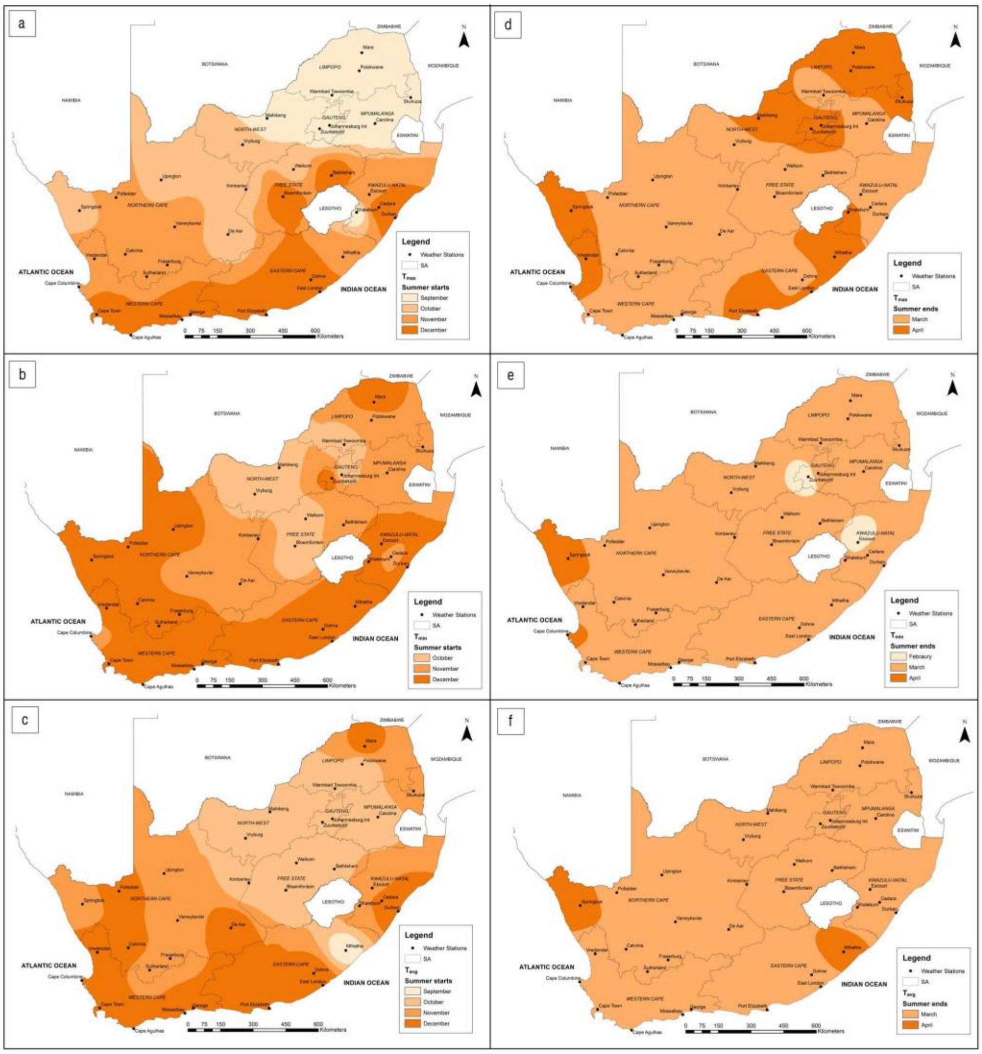
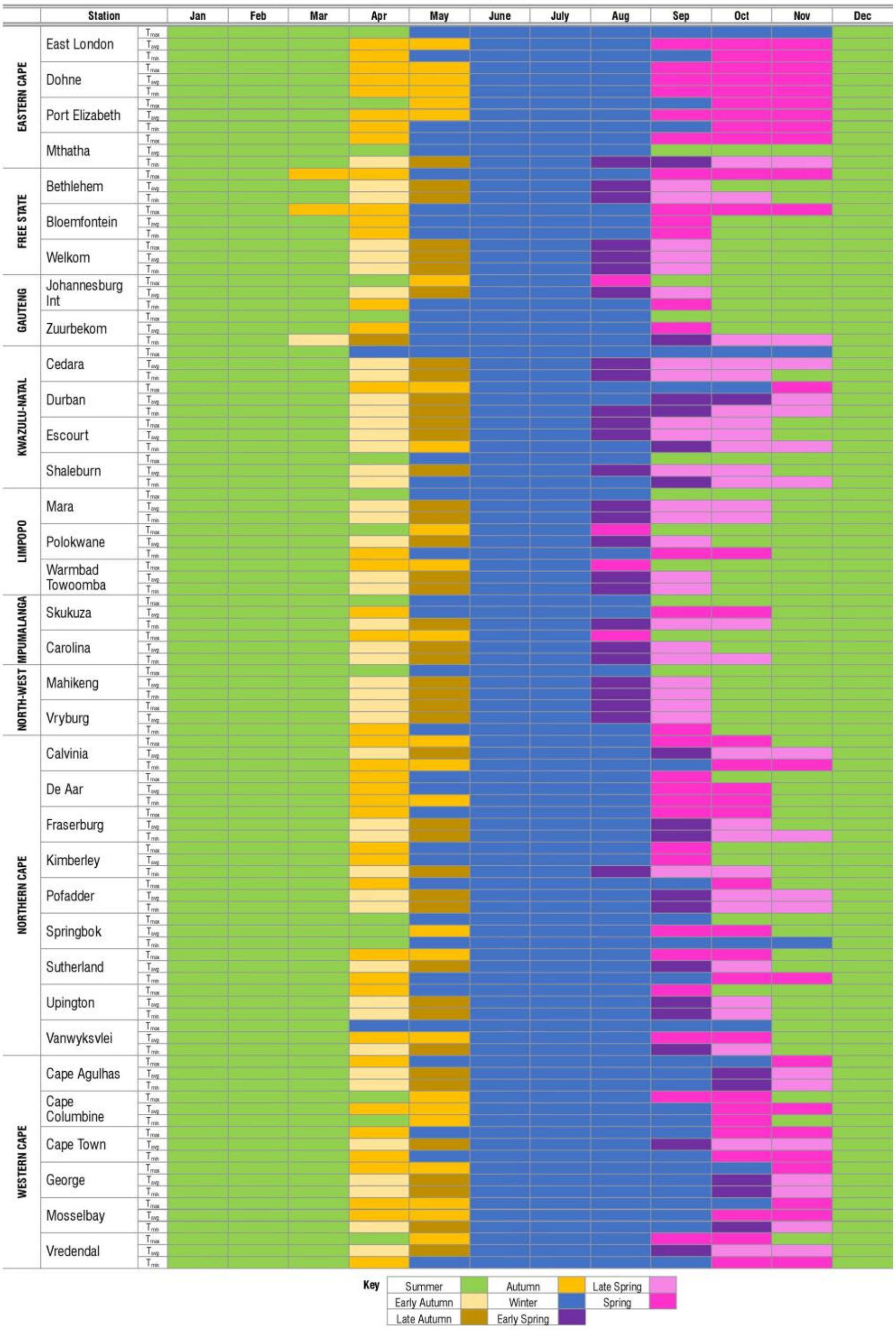


Figure 3: (a–c) Start of summer and (d–f) end of summer.

Table 4: Seasonal timetable of maximum (T_{max}), minimum (T_{min}) and average (T_{avg}) temperatures



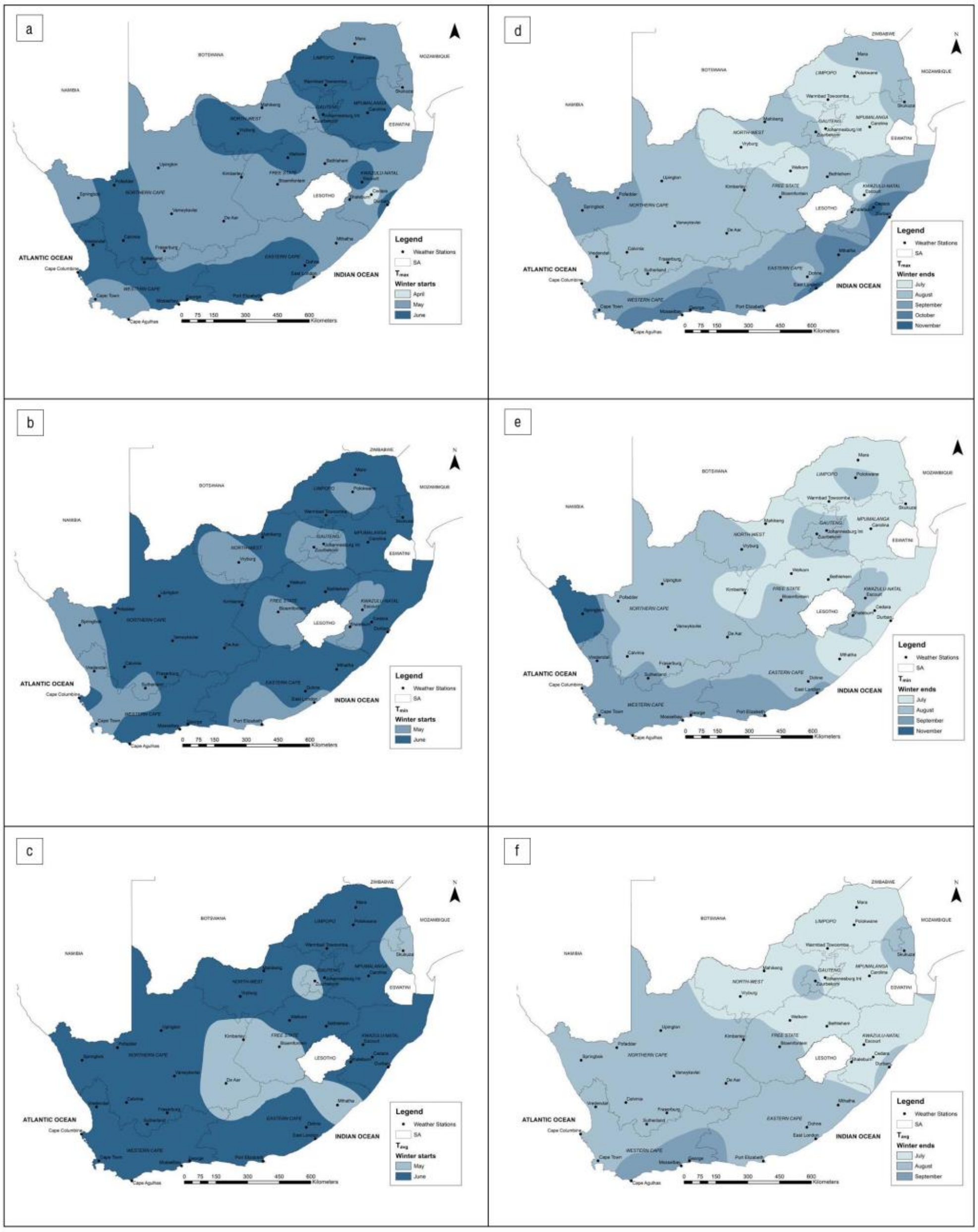


Figure 4: (a–c) Start of winter and (d–f) end of winter.

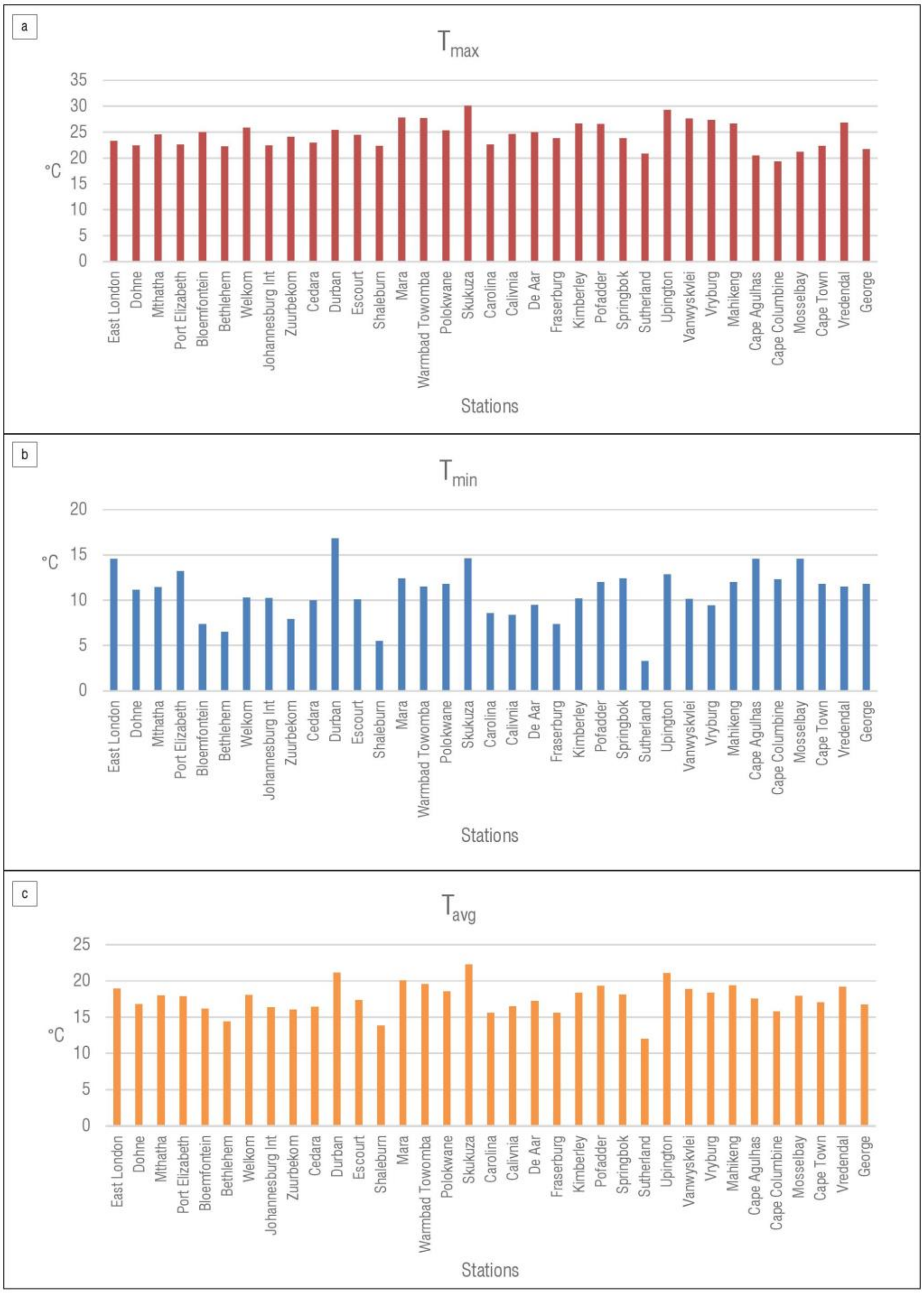


Figure 5: Annual mean of (a) maximum (T_{max}), (b) minimum (T_{min}) and (c) average (T_{avg}) temperatures for the selected stations, 1980–2015.

Discussion and conclusion

We present one of the first statistical classifications of seasons across South Africa using daily temperatures. Daily temperature data across the country were used as a distinctive marker to classify the seasons due to the detectability of temperature changes compared to rainfall across South Africa. Through statistical analysis and results captured in the seasonal timetable (Table 4), new seasonal brackets are put forward in accordance with the agreement of seasons and temperatures among stations used in this research.

Aggregated for the whole country, based on T_{max}, T_{min} and T_{avg}, our results show that the weather stations agree that the following seasonal brackets can be used:

- Summer (October/November/December/January/February/March)
- Early autumn (April)
- Late autumn (May)
- Winter (June/July/August)
- Spring (September)

These proposed seasonal brackets challenge our 'common knowledge' of four equal length seasons of 3 months each[2,26-29], and the ad-hoc approaches some researchers use in South Africa[25-27]. Noticeable similarities occur between the two seasonal divisions of months used to define farming seasons[30] as well as monthly summer divisions related to the positions of South Africa related to disease-risk seasons.[7] However, the proposed longer duration of summer and shorter spring seasons may conflict with the agricultural practices used currently, in particular, the current observed length and timing of the growing season across the country.[1-3] Additionally, these proposed seasonal brackets may assist in the explanation of current delays and advances in seasonal phenological events[33], and challenges in the tourism sector where most outdoor attractions are dependent on the seasonal climate[5].

However, the high spatio-temporal variability in temperatures (e.g. annual mean temperatures Figure 5) presents a complex picture of seasonality. This presents challenges in defining seasonal brackets for a given location or region, particularly where regional climate regimes change within a small geographic area[24], and due to the complexity of South Africa's climate[29]. Discrepancies have been found among the different temperature metrics. However, the majority of the stations (23 out of the 35), are divided into four seasons, using T_{avg} as the classifier, with the remaining 12 stations clustered into three seasons. Interestingly, some stations within the same province (e.g. Johannesburg Int and Zuurbekom in Gauteng) have different seasonal groupings. With closer inspection, these differences may occur due to the location and elevation of the stations (Table 2). For example, it has been found that built-up areas such as Johannesburg may be warmer in late winter than rural areas due to the urban heat island[52] and higher elevations tend to be cooler than lower elevations[53]. Taking the above-mentioned into consideration, the importance of selecting the relevant temperature metric, e.g. T_{max}, T_{min} and T_{avg}, is highlighted for analysis purposes, as this selection can return different results as portrayed in the results.

In general, the findings of the start and end dates of summer and winter (Figures 3 and 4) coincide with the pressure regimes, as well as the interannual migration of the ITCZ.[19,37] The results indicate that summer starts later (ending earlier) and winter starts earlier (ending later) in the southwestern and southern regions of the country. These results coincide with the movement of the cold front of the mid-latitude cyclones during the winter months.[38] While, during summer, the southward movement of the ITCZ and the position of the subtropical high-pressure system are associated with warmer conditions, which may result in the patterns found. Summers start earlier, and winters start and end later in the northeastern parts of the county. These patterns are found independently from the notable link between temperatures and weather systems. The patterns also show the annual progression of temperatures which follow a southwest to a northeastwards spatial pattern across the country.

The key limitations of this study are the nature of the temperature data sets. The data sets are not perfect and inherent errors may be present for a number of reasons.[29] Furthermore, inhomogeneity is not likely to play a significant role in this study as the consistency was ensured by using only SAWS data sets.[54] Mean daily temperature data were quantified using T_{max} and T_{min}; this is a limitation as hourly temperature readings may provide accurate values of mean daily temperatures.[54] Furthermore, we acknowledge that station measurements are unable to display complete areal coverage as these are location-specific[54,55], which is particularly an issue for the interpolated maps presented throughout. A limited number of stations that have long-term temperature records was selected using a broad grid approach, as discussed, to get a relatively good spatial representation of the country. To overcome this limitation, future research may benefit from the inclusion of temperature data from additional weather stations from other organisations, such as the South African Agricultural Research Council. Such addition would, however, require greater efforts at data homogenisation and quality checking, which introduce a further set of limitations.

Finally, this research provides an insight into the complexity of seasonality across South Africa, as well as direction for climate-relevant research with temperature data as the primary input. Possibly the most significant contribution of this research is the newly proposed seasonal brackets using temperature metrics. The knowledge presented here is crucial for agriculture practices, resource management, tourism and other temperature-dependent activities, especially to develop adaptive strategies in monitoring seasonal changes in temperatures under climate change.

Acknowledgements

We acknowledge the financial and collegial support offered to A.v.d.W. from the Faculty of Natural and Agricultural Sciences and the Geography Department at the University of the Free State. J.M.F. received funding from the DSI-NRF Centre of Excellence for Palaeoscience. We thank Professor Christopher Curtis for advice on earlier stages of the project.

Competing interests

We declare that there are no competing interests.

Authors' contributions

A.v.d.W.: Data collection, data analysis, data curation, validation, writing – the initial draft, writing – revisions. J.M.F.: Conceptualisation, methodology, validation, writing – revisions, student supervision, project leadership.

Data availability

Data are owned by the South African Weather Service and can be obtained from them on request.

References

1. Battisti DS, Naylor RL. Historical warmings of future food insecurity with unprecedented seasonal heat. Science. 2009;323(5911):240–244. https://doi.org/10.1126/science.1164363
2. Tshiala MF, Olwoch JM, Engelbrecht FA. Analysis of temperature trends over Limpopo Province, South Africa. J Geogra Geol. 2011;3(1):13–21. https://doi.org/10.5539/jgg.v3n1p13
3. Attribution of extreme weather events in the context of climate change. Washington DC: National Academic Press; 2016. https://doi.org/10.17226/21852
4. De Cian E, Lanzi E, Roson R. Seasonal temperature variations and energy demand. Clim Change. 2013;116(3–4):805–825. https://doi.org/10.1007/s10584-012-0514-5
5. Fitchett J, Robinson D, Hoogendoorn G. Climate suitability for tourism in South Africa. J Sustain Tour. 2016;25:851–867. https://doi.org/10.1080/09669582.2016.1251933
6. Ziervogel G, New M, Van Garderen EA, Midgley G, Taylor A, Hamann R, et al. WIREs. Clim Change. 2014;5:605–620. https://doi.org/10.1002/wcc.295
7. Lazenby MJ, Landman WA, Garland RM, DeWitt DG. Seasonal temperature prediction skill over southern Africa and human health. Meteorol Appl. 2014;21:963–974. https://doi.org/10.1002/met.1449

8. Cohen JL, Furtado JC, Barlow M, Alexeev VA, Cherry JE. Asymmetric seasonal temperature studies. Geophys Res Lett. 2012;39(4):1–7. https://doi.org/10.1029/2011GL050582

9. Kutta E, Hubbart JA. Reconsidering meteorological seasons in a changing climate. Clim Change. 2016;137(3–4):511–524. https://doi.org/10.1007/s10584-016-1704-3

10. Brunetti M, Maugeri M, Monti F, Nanni T. Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. Int J Climatol. 2006;26(3):345–381. https://doi.org/10.1002/joc.1251

11. Allen MJ, Sheridan SC. Evaluating changes in season length, onset and end dates across the United States (1948-2012). Int J Climatol. 2016;36:1268–1277. https://doi.org/10.1002/joc.4422

12. Dong W, Jiang Y, Yang S. Response of the starting dates and lengths of seasons in Mainland China to global warming. Clim Change. 2010;99:81–91. https://doi.org/10.1007/s10584-009-9669-0

13. Czernecki B, Miętus M. The thermal seasons variability in Poland, 1951-2010. Theor Appl Climatol. 2017;127:481–493. https://doi.org/10.1007/s00704-015-1647-z

14. Hiltunen L, Haukka J, Ruuhela R, Suominen K, Parton T. Local daily temperatures, thermal seasons, and suicide rates in Finland from 1974 to 2010. Environ Health Prev Med. 2014;19:286–294. https://doi.org/10.1007/s12199-014-0391-9

15. Vigaud N, Pohl B, Crétat J. Tropical-temperate interactions over southern Africa simulated by a regional climate model. Clim Dyn. 2012;39:2895–2916. https://doi.org/10.1007/s00382-012-1314-3

16. Tyson PD, Preston-Whyte RA. The atmosphere and weather of southern Africa. 2nd ed. Cape Town: Oxford University Press Southern Africa; 2000. https://doi.org/10.1002/joc.725

17. Engelbrecht C, Landman W, Engelbrecht F, Malherbe J. A synoptic decomposition of rainfall over the Cape south coast of South Africa. Clim Dyn. 2015;44(9–10):2589–2607. https://doi.org/10.1007/s00382-014-2230-1

18. Roffe SJ, Fitchett JM, Curtis, CJ. Classifying and mapping rainfall seasonality in South Africa: A review. S Afr Geogr J. 2019;101(2):158–174. https://doi.org/10.1080/03736245.2019.1573151

19. Doran JD. Regional climate messages: Southern Africa. Scientific report from CARIAA Adaption at Scale in Semi-Arid Regions (ASSAR) Project. Unpublished report; 2014.

20. Davis-Reddy CL, Vincent K. Climate risks and vulnerability: A handbook for southern Africa. 2nd ed. Pretoria: CSIR; 2017.

21. Dyson LL, Van Heerden J. A model for the identification of tropical weather systems (MITS) over South Africa. Water SA. 2002;289(3):249–258.

22. Lennard C, Hegerl G. Relating changes in synoptic circulation to surface rainfall response using self-organising maps. Clim Dyn. 2014;44(3–4):861–879. https://doi.org/10.1007/s00382-014-2169-6

23. Weather SA. Weather questions [webpage on the Internet]. No date [cited 2019 Aug 20]. Available from: http://www.weathersa.co.za/home/weatherques

24. Alpert P, Osentinsky I, Ziv B, Shafir H. A new seasons definition based on classified daily synoptic systems: An example for the Eastern Mediterranean. Int J Climatol. 2004;24(8):1013–1021. https://doi.org/10.1002/joc.1037

25. Trenbreth KE. What are seasons? Bull Am Meteorol Soc. 1983;64(11):1276–1282. https://doi.org/10.1175/1520-0477(1986)064<1276:WATS>2.0.CO;2

26. Karl TR, Jones PD, Knight R, Kukla G, Plummer N, Razuvzyev V, et al. Asymmetric trends of daily maximum and minimum temperature. Bull Am Meteorol Soc. 1993;74(6):1007–1023. https://doi.org/10.1175/1520-0477(1933)074<1007:anporg>2.0.co;2

27. Klopper E, Landman WA, Van Heerden J. The predictability of seasonal maximum temperature in South Africa. Int J Climatol. 1998;18(7):741–758. https://doi.org/10.10029(sici)1097-0088(19980615)18:7<747::aid-joc279>3.0.co;2-b

28. Kruger AC, Shongwe S. Temperature trends in South Africa: 1960–2003. Int J Climatol. 2004;24(15):1929–1945. https://doi.org/10.1002/joc.1096

29. Kruger AC, Nxumalo M. Surface temperature trends from homogenized time series in South Africa: 1931–2015. Int J Climatol. 2017;27(5):1–52. https://doi.org/10.1002/joc.4851

30. Benhin JK. Climate change and South African agriculture: Impacts and adaption options [document on the Internet]. c2006 [cited year month day]. Available from: https://www.weadapt.org/sites/weadapt.org/files/legacy-new/knowledge-base/files/5370f181a5657504721bd5c21csouth-african-agriculture.pdf

31. Craig MH, Kleinschmidt I, Nawn JB, Le Sueur D, Sharp BL. Exploring 30 years of malaria case data in KwaZulu-Natal South Africa: Part 1. The impact of climatic factors. Trop Med Int Health. 2004;9(12):1247–1257. https://doi.org/10.111/j.1365-3156.2004.01340.x

32. Whitecross MA, Witkowski ETF, Archibald S. Savanna tree-grass interactions: A phenological investigation of green-up in relation to water availability. S Afr J Bot. 2017;108:29–40. https://doi.org/10.1016/j.sajb.2016.09.003

33. Fitchett JM, Grab SW, Portwig H. Progressive delays in the timing of sardine migration in the southwest Indian Ocean. S Afr J Sci. 2019;115(7/8), Art. #5887, 6 pages. https://doi.org/10.17159/sajs.2019/5887

34. Mackellar N, New M, Jack C. Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010. S Afr J Sci. 2014;110(7/8), Art. #2013-0353, 13 pages. https://doi.org/10.1590/sajs.2014/20130353

35. Government Communications (GCIS). South Africa yearbook 2015/2016. 23rd ed. Pretoria: Government Communications; 2016.

36. Dube LT. Climate of southern Africa. S Afr Geogr J. 2002;84(1):125–138. https://doi.org/10.1080/03736245.2002.9713763

37. Nicholson SE. The ITCZ and the seasonal cycle over the equatorial Africa. Bull Am Meteorol Soc. 2018;99(2):337–348. https://doi.org/10.1175/BAMS-D-16-0287.1

38. Kruger AC, Goliger AM, Retief JV, Sekele S. Strong wind climatic zones in South Africa. Wind Struct An Int J. 2010;13(1):37–55.

39. Engelbrecht F, Landman W. South Africa's present-day climate. In: Southern Africa risk and vulnerability atlas. Pretoria: CPD Print; 2010. p. 2–5.

40. Davis CL. Climate risk and vulnerability: A handbook for southern Africa. Pretoria: CSIR; 2011.

41. Unal Y, Kindap T, Karaca M. Redefining the climate zones of Turkey using cluster analysis. Int J Climatol. 2003;23:1045–1055.

42. Bocard D, Gillet F, Legendre P. Numerical ecology with R. New York: Springer; 2011. https://doi.org/10.1007/978-1-4419-7976-6

43. Wilks DS. Cluster analysis. Int Geophys. 2011;100:603–616. https://doi.org/10.1002/joc.1376

44. Kodinariya TM, Mwakwana PR. Review on determining number of clusters in K-means clustering. Int J Adv Res Comput Sci Manag Stud. 2013;1(6):90–95.

45. Studer M. WeightedCluster Library Manual: A practical guide to creating typologies of trajectories in the social sciences with R. LIVES Working Papers. 2013;24:1–32. https://doi.org/10.12682/lives.2296-1658.2013.24

46. Kaufman L. Rousseeuw PJ. Finding groups in data. An introduction to cluster analysis. New York: John Wiley and Sons; 1990. https://doi.org/10.1002/9780470316801

47. Li R, Nathan JBK, Yang J, Wang Y. A phylogenetically informed delineation of floristic regions within a biodiversity hotspot in Yunnan, China. Sci Rep. 2015;5:1–7. https://doi.org/10.10.1038/sreps09396

48. Crow TM, Albeke SE, Buerkle CA, Hufford KM. Provisional methods to guide species specific see transfer in ecological restoration. Ecosphere. 2018;9(1):1–14. https://doi.org/10.1002/ecs2.2059

49. Carvalho PR, Munita CS, Lapolli AL. Validity studies among hierarchical methods of cluster analysis using cophenetic correlation coefficient. Braz J Radiat Sci. 2019;7(2A), Art. #668. https://doi.org/10.15392/bjrs.v7i2a.668

50. Zhou Y, Zhang J. Application of GIS in downscaling regional climate model results over the province of Ontario. Environ Syst Res. 2014;3(1):8. https://doi.org/10.1189/2193-2697-3-8

51. Contractor S, Alexander LV, Donat MG, Herold N. How well do gridded datasets of observerd daily precipitation compare over Australia? Adv Meteorol. 2015, Art. #325718, 15 pages. https://doi.org/10.1155/2015/325718

52. Scott AA, Waugh DW, Zaitchik BF. Reducing urban heat island intensity under warmer conditions. Environ Res Lett. 2018;13(6), 064003. https://doi.org/10.1088/1748-9326/aabd6c

53. National Oceanic and Atmospheric Administration (NOAA). Anomalies vs temperature [webpage on the Internet]. c2020 [cited 2019 Sep 17]. Available from: https://www.ncdc.noaa.gov/monitoring-references/dyk/anomalies-vs-temperature

54. Roffe SJ. A statistical analysis of rainfall seasonality across South Africa [thesis]. Johannesburg: University of the Witwatersrand; 2019.

55. Rana S, McGregor J, Renwick J. Precipitation seasonality over the Indian subcontinent: An evaluation of gauge, reanalyses, and satellite retrievals. J Hydromet. 2015;16:631–651.

56. Tshiala MF, Olwoch JM. Impact of climate variability on tomato production in Limpopo Province, South Africa. Afr J Agric Res. 2010;5(21):2945–2951.

Chapter 7: Trend analysis of cold extremes in South Africa: 1960-2016

7.1. Brief synopsis

This study focusses specifically on extreme cold temperature events for the period 1960-2016 and explores these events on an annual and seasonal scale. This study is the first to make use of the ET-SCI in South Africa. The results not only contribute to awareness and recognition of the frequency and incidence of extreme cold temperatures in South Africa but suggest that these events may persist in a 'warming world'.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Jennifer M Fitchett
Methodology	Adriaan J van der Walt & Jennifer M Fitchett
Validation	Adriaan J van der Walt
Formal analysis	Adriaan J van der Walt
Investigation	Adriaan J van der Walt
Resources	Adriaan J van der Walt
Data curation	Adriaan J van der Walt
Writing – the original draft preparation	Adriaan J van der Walt
Writing – review and editing	Adriaan J van der Walt & Jennifer M Fitchett
Visualisation	Adriaan J van der Walt
Supervision	Jennifer M Fitchett
Project leader	Jennifer M Fitchett

According to the above-mentioned CRediT system the author contribution was calculated as follows:

Van der Walt, A.J – 70%

Fitchett, J.M – 30%

Submitted to: International Journal of Climatology

Impact Factor: 3.928

Reason for selection: The nature of the paper and the aim and scope of the journal which focus and aims to span the well-established but rapid growing field of climatology.

Submission data: 13 June 2020

Revised: 14 August 2020

Conditionally Accepted: 23 September 2020

Resubmitted: 05 October

Accepted: 23 November 2020

The version is the accepted version, with the addition of contiguous page numbers for this thesis.

7.2. Abstract

Extreme cold events ('cold waves’) have disastrous impacts on ecosystem and human health. Evidence shows that these events will still occur under current increasing mean temperatures. Little research has been done on extreme cold events, especially in developing countries such as South Africa. These events pose a significant threat due to the low adaptive capacity, urgent development needs and relatively inadequate infrastructure in South Africa. This study presents annual and seasonal, spatial and temporal trend analyses of extreme cold temperature events for the period 1960-2016. We apply the World Meteorological Organisation Commission for Climatology and Indices Expert Team on Sector-Specific Climate Indices (ET-SCI) to South Africa for the first time, with comparison to the World Meteorological Organisation Expert Team on Climate Change Detection (ETCCDI) indices previously used in South Africa . The extreme cold indices are calculated using the RClimDex and ClimPACT, respectively. Trends were calculated using the non-parametric Mann-Kendall test, Spearman Rank Correlation Coefficient and Sen's slope estimates. A decreasing trend is found for annual cold spell duration and cold wave frequency, at rates of 0.10 days.y^{-1} and 0.02 events.y^{-1}, respectively. Seasonally, coldest day temperatures increased in autumn, with increases of 0.02°C.y^{-1} for the period 1960-2016. Regionally, increasing trends in annual cold spell duration days were evident in stations located in the Western Cape, Eastern Cape, North-West Province, at a rate of 0.03 days.y^{-1}. Increasing trends in cold waves were observed for stations in Northern Cape, Gauteng, KwaZulu-Natal and the Eastern Cape Province, at a rate of 0.01 events.y^{-1}. These results contribute to the awareness and recognition of the incidence and duration of cold extreme events in South Africa, seeing that studies suggest that anomalously cold events may persist in a warming world.

Key words: Extreme cold events, cold waves, ET-SCI, ETCCDI indices, Mann-Kendall test, Sen's slope

7.3. 1. Introduction

There is a broad consensus that extreme temperature events will become more frequent and intense as the global mean temperature rises (e.g. Alexander and Perkins 2013; Perkins-Kirkpatrick and Gibson 2017; De Perez et al. 2018; Baldwin et al. 2019). However, a disproportionate number of studies focus on warm extremes (Barnett et al. 2012; Scott 2015; Martinez et al. 2018). Less work has been conducted on extreme cold events ('cold waves' or 'cold snaps'), many of which are linked to extreme cold air outbreaks that affect large regions of the midlatitudes (Johnson et al., 2018), and may have profound environmental (Chen et al. 2019) and societal consequences (Scott, 2015; Díaz et al. 2019). The little research that has been conducted on cold stress events has largely focused on the Northern Hemisphere, partly due to the greater continental landmass, and the proximity to the north pole (Johnson et al. 2018). This results in a focus on cold extremes in developed countries rather than developing countries where people are more vulnerable to these events (Chen et al. 2019).

Exposure to extreme cold temperatures results in adverse health outcomes. The human body can lose heat faster than it produces it, which could lead to cold stress (hypothermia), resultant cardiovascular and respiratory diseases) and mortality (Barnett et al. 2012; Scott 2015). It has been estimated that 148,279 deaths were attributed to the 2008 cold spell in subtropical China, with an approximate economic loss of more the US$ 22.3 billion (Zhou et al. 2014; Han et al. 2017). Furthermore, the cold-related mortality between 1993 and 2006 exceeded heat-related mortality in Australia and the United Kingdom (Scott, 2015). The reason is that cold weather is more pronounced in these regions, which make these regions more vulnerable to cold extremes (Zhou et al. 2014; Scott 2015; Han et al. 2017). Furthermore, the lag between cold weather and its impacts on health is usually longer compared to hot weather and shows a greater variability by cause (Smith and Sheridan 2018). South Africa, a developing country, has recorded several extreme cold events over recent decades (Davis-Reddy and Vincent 2017). However, in contrast to heatwaves, much less focus has been placed on extreme cold events in the news media and scientific literature. In 1996, heavy snowfall events caused 17 deaths and damages across the country (Stander et al. 2016), of which communication and power cuts occurred in the Free State and KwaZulu-Natal Provinces, with road closures between Gauteng and the latter. On 22 July 2002, a cold event associated with snowstorms resulted in the loss of lives, livestock, and infrastructure in KwaZulu-Natal, of which the Eastern Cape had to be declared a disaster area (Muirhead 2002). On 27 June 2007, very cold conditions caused numerous power failures and road closures due to the strain on the power grid (e.g. Añel et al. 2017) and the heavy snowfall in KwaZulu-Natal, and flight delays from OR Tambo International Airport in Johannesburg because of the snow on the wings of aircraft (Stander et al. 2016). The most recent extreme cold event involved unseasonably extremely cold conditions, with temperatures <-6°C in the southern regions of the Western Cape spanning 1-3 March 2016 (Brophy 2016).

Extreme cold temperatures pose a significant threat to South Africa due to the lack of preparedness of the country. South Africa's urgent socio-economic development needs and threatened ecosystem services reduce the adaptive capacity, particularly in the rural areas of the country (Pasquini et al., 2013; Ziervogel et al., 2014). Extremely cold temperatures have significant impacts on the agriculture (Wenal et al. 2019), ecosystems (Leriorato and Nakamura 2019) recreation activities and tourism (Kodra et al., 2011; Giddy et al., 2017), energy demand and infrastructure (de' Doate et al. 2013), phenological shifts (Wang et al.

2016) and human-health in particular in poor rural areas (Scott 2015; Zhao et al. 2017; Pascal et al. 2018). Therefore, understanding the frequency and intensity of extreme cold events in a warming climate is a key societal issue, since their fate directly impact different sectors (Cattiaux et al. 2010).

Several indices have been developed to identify and quantify extreme cold temperature events, of which most were developed by the World Meteorological Organization (WHO) Expert Team on Climate Change Detection and Indices (ETCCDI; Zhang et al. 2018). These indices can be grouped into four categories: (1) absolute indices (e.g. coldest day TNn, coldest night TXn); (2) threshold indices (e.g. frost days FD, hard freeze $tnLtm_n$); (3) percentile indices (e.g. cold days TX10p, cold nights TN10p) (4) durations indices (e.g. cold spell duration, CDSI) (Alexander and Herold 2016). Numerous studies have used these indices for analysing changes at regional and global scales (e.g. Alexander et al. 2006; Perkins-Kirkpatrick and Gibson 2017). Most recent studies in South Africa examined both warm and cold extremes using the ETCCDI indices and found a general decrease in extreme cold events based upon temperature data from the South African Weather Service (SAWS) between the periods; 1961-2000 (New et al. 2006); 1962-2009 (Kruger and Sekele 2013), 1960-2010 (Mackellar et al. 2014), 1931-2015 (Kruger and Nxumalo 2017) and 1951-2005 (Kruger et al. 2019). New et al. (2006) only used eight meteorological stations located in South African, and included neighboring countries stations in their analysis, which could lead to bias in results of South Africa. Kruger and Sekele (2013) used a base period of 1971-2000 for their analysis. While Kruger and Nxumalo (2017) used a base line period of 1981-2010 to examine percentiles and warm and cold spells, and not the extentended period. Kruger et al. (2019) focussed predominantly on projected extreme temperature trends. In addition, these studies failed to examine threshold and percentile-based indices on a seasonal timescale with a specific focus on extreme cold temperature events, which are important to many sectors in particularly agricultural.

This study is the first to make use of the Expert Team on Sector-Specific Climate Indices (ET-SCI) in South Africa. The ET-SCI were developed by the WMO Commission for Climatology and Indices (CCI) (Alexander and Herold 2016; Yosef et al. 2019). The ET-SCI indices are sector-specific climate indices that consider health, water and agriculture derived from the ETCCDI (Alexander and Herold 2016; Yosef et al. 2019). The study presented here is also the first to focus specifically on extreme cold temperature events for the period 1960-2016, and to explore these events at a seasonal scale . For the purpose of comparison, we also present an extension on previous analyses of the ETCCDI indices at annual and seasonal time scales for the full time period. This will be the first study using the ET-SCI indices, together with the ETCCDI, to identify extreme cold trends in a South African context, which is important in view of health, water, and agricultural adaption strategies and policies on a regional and national basis.

7.4. 2. Study Site

South Africa, located between 22-35 °S and 17-33 °E (Figure 1; Roffe 2019), is prone to cold conditions due to the latitudinal location (Lennard, 2019). The topography of South Africa further affects the probability for cold events, with a high altitude central plateau (Figure 1; Grab and Knight 2018). While the low-lying coastal regions generally have a more mild climate, the west coast is affected by the cold Benguela current, which contribute to the advection of cold air over the coast (Tyson and Preston-Whyte 2000; Landman et al. 2017).

The influences of the subtropical high-pressure belt and the mid-latitude westerlies with associated fronts vary significantly interannually over the subcontinent (Lennard 2019). The occurrence of cold cut-off lows and mid-latitude cyclones (cold front) during winter bring cold weather and occasional snow to the mountainous regions of the Western and Eastern Cape, over the Drakensberg Mountains to the east (~3500m.asl), and occasionally, over the interior parts of the country (Landman et al. 2017; Grab and Knight 2018). These cold fronts can linger over the southern region, typically for two to three days (Doubell et al. 2018; Cowling et al. 2019). Cold snaps produced by cold fronts, can intrude northwards into the country and can produce extreme cold weather and snowfall over the Free State, Gauteng and Mpumalanga (Landman et al. 2017), which can last about two days with exceptional cases up to four days (Tyson and Preston-Whyte 2000).

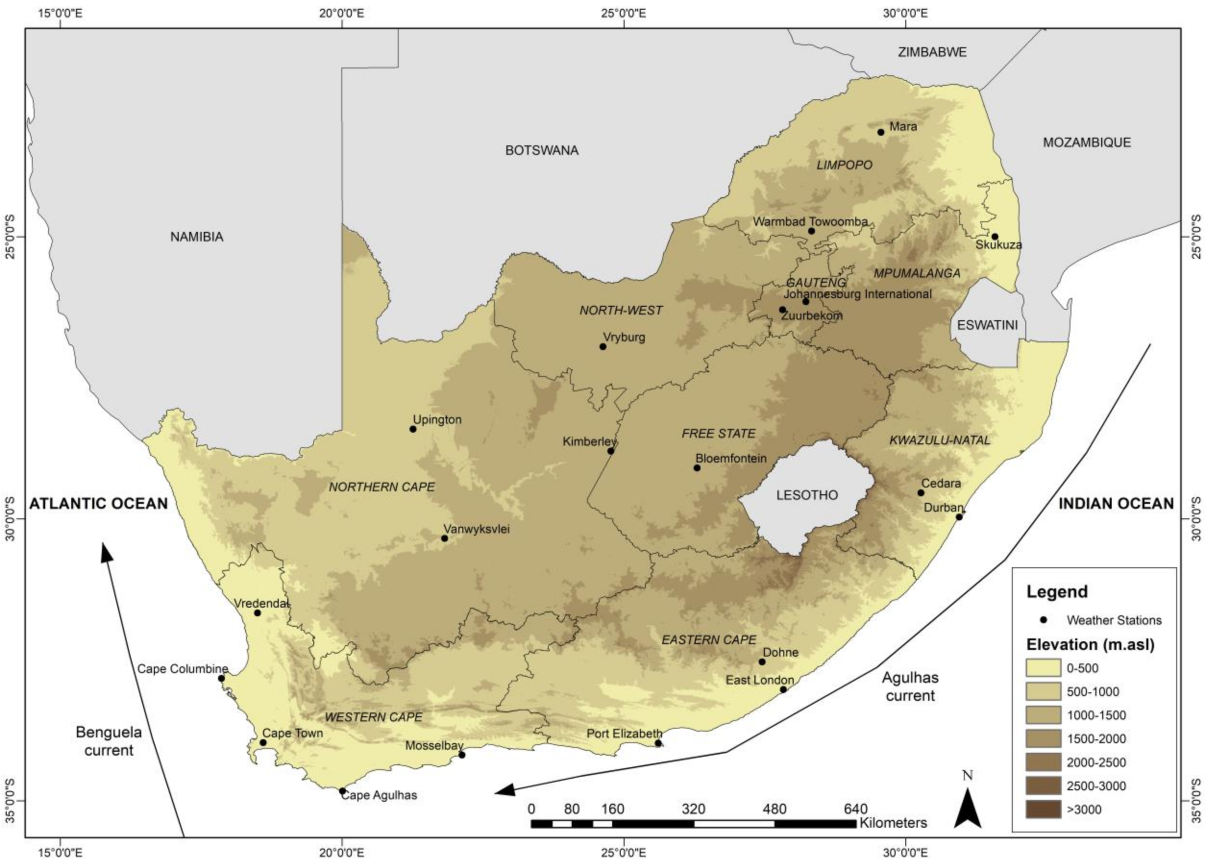


Figure 7.1 (Figure 1): Geographic location of selected meteorological stations.

7.5. 3. Data and Methodology

7.5.1. 3.1 Data Source

Daily maximum (TX) and minimum (TN) temperature data for the period 1960-2016 were obtained from 20 selected South African Weather Service (SAWS) meteorological stations (Figure 1, see also Table 1). Following the same practices as in a previous study (Van der Walt and Fitchett in press), only 20 stations relatively evenly distributed over South Africa were used as it deemed enough to define temperature variability and get a perspective on the historical climate over South Africa (see Kruger and Nxomalo, 2017). Each of the selected weather stations has a continuous dataset of daily maximum and minimum temperature for at least 50 years.

Table 7.1 (Table 1): Selected meteorological stations information.

Province	Station Name	Climate Num	Abbrev	Lat	Long	Year Period	Altitude
Eastern Cape	Dohne	00798116	DH	-32.52	27.47	1960-2016	899m
	East London	00595729	EL	-33.03	27.83	1960-2016	124m
	Port Elizabeth	00351795	PE	-33.98	25.60	1960-2016	60m
Free State	Bloemfontein JBM Hertzog	02615161	BFN	-29.10	26.30	1962-2016	1354m
Gauteng	Johannesburg Int	04763990	JHB	-26.14	28.23	1959-2016	1706m
	Zuurbekom	04755288	ZB	-26.30	27.81	1959-2016	1580m
KwaZulu-Natal	Cedara	02394820	CD	-29.54	30.27	1959-2016	1071m
	Durban	0240808A2	DBN	-29.97	30.95	1960-2016	96m
Limpopo	Mara	072200991	MR	-23.14	29.56	1959-2016	894m
	Warmbad Towoomba	05895941	WBT	-24.90	28.32	1959-2016	1143m
Mpumalanga	Skukuza	05961793	SK	-24.99	31.59	1960-2016	276m
Northern Cape	Kimberley	02904684	KB	-28.80	24.77	1959-2016	1198m
	Upington	03174765	UP	-28.43	21.27	1960-2016	836m
	Vanwyksvlei	01935613	VW	-30.35	21.82	1961-2016	965m
North-West	Vryburg	04322383	VB	-26.95	24.65	1960-2016	1245m
Western Cape	Cape Agulhas	00030204	CA	-34.83	20.01	1959-2016	11m
	Cape Columbine	00606209	CC	-32.83	17.86	1959-2016	62m
	Mosselbay	0012215	MB	-34.19	22.13	1959-2016	135m
	Cape Town	0021178A3	CPT	-33.96	18.60	1959-2016	42m
	Vredendal	0106880A2	VL	-31.67	18.50	1959-2016	42m

7.5.2. 3.2 Data Quality and Homogeneity

The data were quality controlled to check for inhomogeneity, days with missing data and possible outliers (Klein Tank et al. 2009; Salameh et al. 2018), that may occur due to human-induced error, or faulty measuring equipment. Two decimal point rounding was used to maintain consistency throughout. Missing TN and TX daily data were cross validated with adjacent stations within a 50km radius and if not possible, replaced with the five-day running average. If the data were not available for more than five consecutive days, the year was excluded. Furthermore, years with <90% completeness were discarded from the data set. In order to ensure consistency, the additional quality control was performed on each station's data series using the R-based RClimDex v1.9 and ClimPACT v2 software package followed by the application of the RHtests version 4 software packages (RHtestsV4; Wang 2008a, 2008b; Vincent et al. 2012; Wang and Feng 2013) for homogenization. The outlier threshold, which the software uses to check and identify outliers in the data series, was set to three standard deviations (Zhang et al. 2018). However, not all outliers are truly erroneous, and their inclusion, exclusion or adjustment can significantly affect extreme analysis (Klein Tank et al. 2009). After testing for outliers, the datasets were tested for spatial and temporal homogeneity using the RHtestsV4 software. The RHtestsV4 can detect and adjust for multiple change points in a time series, based on various statistical measures (Wang 2008a, 2008b; Wang and Feng 2013).

7.5.3. 3.3 Extreme temperature indices

This study examines and compares trends in extreme cold temperature indices on an annual and seasonal timescale. The seasons are defined according to the astronomical divisions: summer encompassing December through January, autumn spanning March through May, winter from June to August and spring from September to November (Van der Walt and Fitchett 2020).

A core set of 34 indices are defined by the ET-SCI, coordinated by the WMO Technical Commission for Climatology (CCI) (Alexander and Herold 2016). These indices monitor the frequency and intensity of moderate cold events, with the advantage of sector specific application (Alexander and Herald 2016). A final set of five ET-SCI and six ETCCDI indices were selected for this study (Table 2) due to the applicability in the South African context, and this study represents the first analysis of these indices for this region. These 11 extreme cold temperature indices were computed using the R software packages; RClimdex v1.9 for ETCCDI indices (Zhang et al. 2018) and ClimPACT v2 for the ET-SCI indices (Alexander and Herold 2016).

The ET-SCI user-defined Cold Spell Duration Index ($CDSI_n$) was set to three consecutive days where TN<10th percentile, because the six-day consecutive cold spell events (CDSI) are rarely identified, and shorter cold spells can cause irreparable damages (Panda et al. 2014), and can significantly influence the mortality rate (Nairn and Fawcett 2015). Furthermore, the $CDSI_n$ indices were calculated based on an alternative version of the Excess Heat Factor (EHF) namely the Excess Cold Factor (CHF; see Nairn Fawcett 2015). Moreover, the user defined TXb_nTbN_n was set to two consecutive days. Descriptions and definitions of the different indices used are shown in Table 2. Note that all the above-mentioned indices used were calculated for the base period of 1960-2016.

Table 7.2 (Table 2): ETCCDI and ET-SCI cold temperature indices used in this study (adapted from Alexander and Herold, 2016; Zhang *et al*., 2008).

	Indices	**Long name**	**Definitions**	**Units**
ETCCDI indices	FD	Frost days	Annual number of days when TN<0°C	days
	TXn	Max TX (Coldest day)	Monthly maximum value of daily minimum temperature (TXn = max)	°C
	TNn	Min TN (Coldest night)	Monthly minimum value of daily minimum temperature (TNn = min)	°C
	TN10p	Cool nights	Count of days where TN<10th percentile	%
	TX10p	Cool days	Count of days where TN<10th percentile	%
	CDSI	Cold spell duration indicator	Count of days of at least six days where TN<10th percentile	days
ET-SCI Indices	$tnLtm_2$	Hard freeze	Annual number of days when TN<-2°C	days
	$CDSI_n$	User-defined CDSI	Annual number of days with at least n consecutive days when TN < 10th percentile	days
	TXb_nTNb_n	User-defined consecutive number of cold days and nights	Annual number of consecutive days where both TX<5th percentile and TN<5th percentile where 10 >= n >= 2	Number of events
	CWN	Cold wave number as defined by the Excess Cold Factor (ECF)	The number of individual cold waves that occur each year in each extended winter (May-September) . (See Nairn and Fawcett (2013) for more information)	events
	CWD	Cold wave duration as defined by the CWN	The number of longest cold wave identified by CWN.	days

7.5.4. 3.4 Trend analysis and significance

The robust non-parametric Mann-Kendall test (e.g. Caloiero et al., 2017; Abatan et al. 2018; Yosef et al. 2019) and was used to analyse the trend of each of the extreme cold temperature indices over the period 1960-2016 in each station. The Mann-Kendall test identifies monotonic trends in time series data and represents probability (Mann 1945; Kendall 1955). This test does not require the data to be distributed normally, with the advantage of having a low sensitivity to change points due to inhomogeneous time series (Abbas et al. 2018). In addition, the non-parametric Spearman's Rank correlation coefficient (ρ) (Spearman, 1904), was used to cross-validate the Mann-Kendall test's trend results if no trend were found.

Furthermore, the Kendall's slope estimator, namley the Sen's Slope (SS) was used to quantify the magnitude/rate of the trend for specific indices (Sen 1968; Panda et al. 2014; Caloiero et al. 2017). We consider a trend to be significant if it is statistically significant at 5% level (e.g. Phanda et al. 2014; Caloiero et al. 2017; Abatan et al. 2018; Karki et al. 2019; Yosef et al. 2019). The ClimPACT software calculates the linear trends which were used to assist in the analysis of the CDSI, $CDSI_3$, CWN and CWD. ArcMap software was used to display the trends visually, using the Mann-Kendall test values as an identifier. The Inverse Distance Weighting (IDW) tool within the software was used to spacially interpolate the annual TNMean.

Greater emphasis was given to the Mann-Kendall test and the Sen's Slope to identify and quantify the magnitude/rate and the trends, respectively.

7.6. 4.1 Cold extremes

7.6.1. 4.1.1 Introduction

This study presents the first analysis of the ET-SCI computed extreme cold events for South Africa. These are presented first, followed by the ETCCDI indices for the purpose of comparison. For all statistical details on results presented in the following sections please see supplementary Tables S2-S9. Using the ET-SCI indices, a greater number of cold events are calculated using CWN (average = 1.9 p.a) than TXb_2TNb_2 (average = 0.06 p.a), for the period 1960-2016 (Table 3). The greatest mean annual number CWN are recorded for Mara (2.23), and Vanwyksvlei (2.18), followed by Warmbad Towoomba and Johannesburg International (2.17) (Table 3). Using the TXb_2TNb_2, the greatest mean annual number of events are recorded for Cape Columbine (0.17) and Johannesburg International (0.14), followed by Vanwyksvlei (0.08). The results of the annual mean number of TXb_2TNb_2 and CWN among stations agree to some extent (e.g. Johannesburg International and Warmbad Towoomba) (Table 3).

The greatest number of annual cold wave days are calculated for $CDSI_3$ (average = 10.96) compared to CWD (average = 5.83) and $tnLtm_2$ (average = 9.92) (Table 3). The mean annual number of $tnLtm_2$ are 9.92 days. Zuurbekom experience the greatest mean annual number of $CDSI_3$ (13.63), followed by Mara and Vanwyksvlei (13.63). The greatest mean annual CWD values are calculated for Zurbekom (9.63) and Warmbad Towoomba (8.14), followed by Mara (7.56). The greatest mean annual $tnLtm_2$ values are recorded in Bloemfontein (45.89) and Zuurbekom (39.57), followed by Vryburg (20.8) (Table 3). Concurrence is found between $tnLtm_2$ $CDSI_3$ (e.g. Zuurbekom and Vryburg), CWD and $CDSI_3$ (e.g. Zuurbekom and Mara), and to some extent bewteen CWD and $tnLtm_2$ (e.g. Zuurbekom).

Using the ETCCDI indices, the averaged number of cold wave days calculated using CDSI is 1.22 days, whereas for FD it is quantified at 14 days (Table 3). The greatest mean annual number of CDSI-calculated days are recorded in Zuurbekom (4.4) and Warmbad Towoomba (2.2), followed by Vryburg (2) and Bloemfontein (1.9) While, the greatest mean annual number of FD-calculated days are found for Bloemfontein (72) and Zuurbekom (61). The ET-SCI indices broadly agrees with the results of the ETCCDI indices. For instance, in Bloemfontein, a greater number of cold days are calculated for the ET-SCI indices (i.e. CWD, $CDSI_3$, $tnLtm_2$), and for the ETCCDI indices (i.e. FD, CDSI). The average number cold wave days and cold spell days are greater for the ET-SCI $CDSI_3$ (average = 10.96) and CWD (average = 5.83), than the ETCCDI index CDSI (average = 1.22).

Table 7.3 (Table 3): Average annual cold events and days per stations for the period 1960-2016. Note: Symbol *, and colours red (increase) and blue (decrease) indicate statistical significance and trend direction of the Mann-Kendall test results, as collated in Table S2 and Table S8.

Station	ET-SCI					ETCCDI	
	TXb_2TNb_2 (events)	CWN (events)	CWD (days)	$CDSI_3$ (days)	$tnLtm_2$ (days)	FD (days)	CDSI (days)
Dohne	0.06	1.4	4	9.70	0.02	0.2	0.3
East London	-	1.6	4.5	8.35	0.02	-	-
Port Elizabeth	0.02	1.6	4.49	5.02	-	0.05	0.1
Bloemfontein	0.02	2	6.90	13.14	45.89	72	1.9
Johannesburg Int	0.14	2.17	6.52	12.64	2.84	8.7	1.4
Zuurbekom	0.02	1.75	9.63	15.13*	39.57*	61*	4.4
Cedara	-	1.62	4.86	13.11*	2.04	9.9	1.1
Durban	0.02	1.98*	6.68*	12.61*	-	-	1.3*
Mara	-	2.23	7.56*	13.63	0.67	4.2	0.8
Warmbad Towoomba	0.16	2.17*	8.14	12.76	2.57	11	2.2
Skukuza	-	2.05*	7.20	12.96	0.22	2.2	1.7
Vryburg	0.04	2.08	6.67	13.63	20.8	45	2
Kimberley	0.05	1.89	5.04	11.09*	12.72*	28*	1.4*
Upington	0.05	2.07	4.86	13.22	2.95	12	1.8
Vanwyksvlei	0.08*	2.18	5.49	12.42	8.65	31	1
Cape Agulhas	0.04	2.07	4.89	8.75	-	-	0.8
Cape Columbine	0.17	1.98	4.77	6.63*	-	-	0.4
Mosselbay	0.08	1.45	4.83	11.13	-	-	1.1
Cape Town	-	1.67*	4.77	5.57*	-	0.3*	0.3
Vredendal	0.04	2.05	4.79	7.80*	0.02	0.1	0.5
Average	*0.06*	*1.9*	*5.83*	*10.96*	*9.92*	*14*	*1.22*

7.7. 4.2 ET-SCI indices

7.7.1. 4.2.1 Frost days ($tnLtm_2$)

In general, the overall number of days below -2°C decreased by 0.02 days.y^{-1}. The remaining five stations experience increasing trends in annual $tnLtm_2$ (Figure 2a). These stations are located in Eastern Cape, Gauteng, KwaZulu-Natal, Mpumalanga, North-West and Northern Cape Provinces, with rate increases of 0.08 days.y^{-1} and 0.32 days.y^{-1} experienced in Vryburg and Kimberley, respectively (Figure 2a).

In summer, an observered average of 0.17 frost days were evident while the ρ results found a decreasing trend in $tnLtm_2$ for East London of 0.16 days.y^{-1}. Nine stations exhibit trends in autumn. Only three stations: Johannesburg Int, Warmbad Towoomba and Kimberley experience increasing trends in $tnLtm_2$ with trend increases of >0.08 days.y^{-1} for the period 1960-2016. The remaining six stations: Bloemfontein, Cedara, Vryburg, Upington, Vanwyksvlei and Zuurbekom experience decreasing trends in $tnLtm_2$, with only the latter station experiencing a rate decrease of 0.06 days.y^{-1} in $tnLtm_2$. In winter, only 12 stations exhibit trends, of which six stations experience increasing trends and Kimberley being statistically significant (Table 4). These stations are located in the Eastern Cape, KwaZulu-Natal, Limpopo, Mpumalanga, North-West at Vryburg, and Northern Cape at Kimberley, with only the latter two stations experiencing rates of increase of >0.03 days/y^{-1}. Decreasing trends are experienced in the remaining stations, of which Zuurbekom in Gauteng is statistically significant. Decreases in $tnLtm_2$ are only evident in Zuurbekom and Vanwyksvlei, at rates of >0.07°C.y^{-1}. In spring, only six stations exhibit trends, four of which are decreasing trends with Zuurbekom displaying a statistically significant trend, at 0.26 days.y^{-1}. Increasing trends are evident in Vryburg and Kimberly, at >0.02 days.y^{-1}.

7.7.2. 4.2.2 Two consecutive days of Cold days and nights (TXb_2TNb_2)

Only 13 out of the 20 stations exhibit trends in TXb2TNb2, with only Vanwyksvlei in the Northern Cape province experiencing a significant trend, at a decrease of 0.31 events.y^{-1} (Figure 2b). Ten stations experience decreasing trends, which are located in the Eastern Cape, Gauteng at Zuurbekom, Northern Cape and Western Cape, at >0.02 events.y^{-1} (Figure 2b). The remaining three stations: Johannesburg Int in Gauteng, Durban in KwaZulu-Natal and North-West at Vryburg, experience increasing trends of >0.03 events.y^{-1} (Figure 2b).

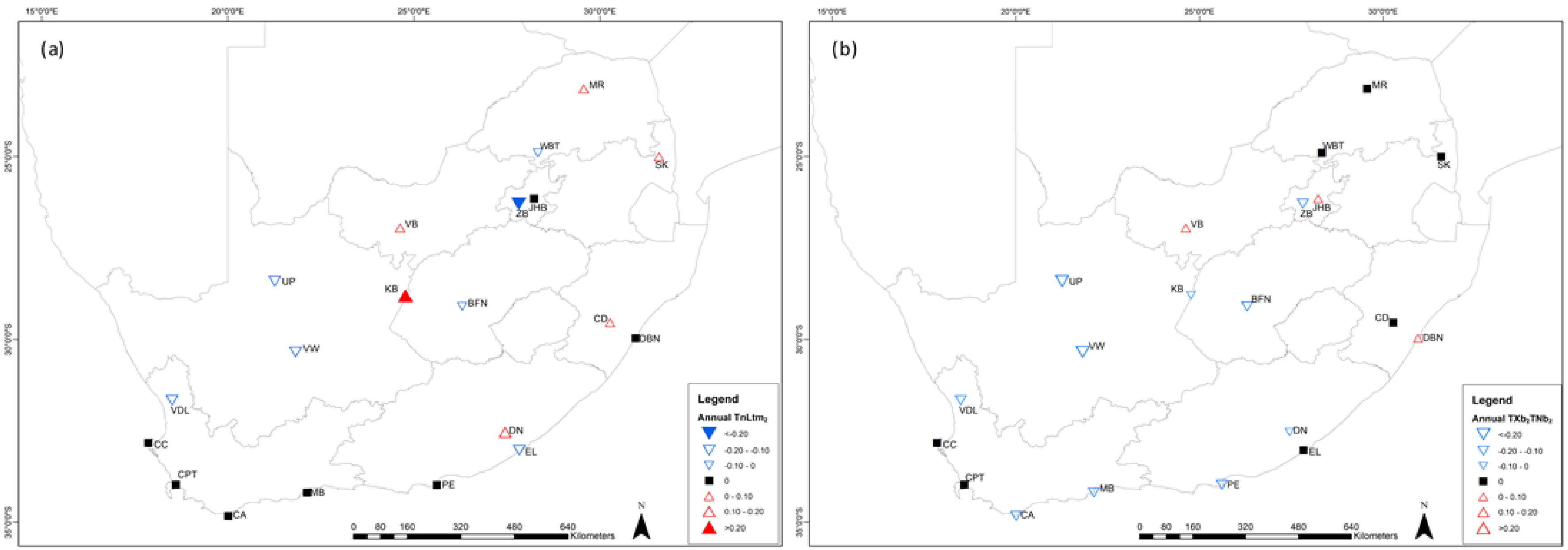


Figure 7.2 (Figure 2): Annual trends of (a) $TnLtm_2$ and (b) TXb_2TNb_2. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trends. Solid triangles indicate trends that are statistically significant at the 5% level. For all statistical variables please see supporting Table S2.

Table 7.4 (Table 4): Number of positive and negative statistically significant stations, as well as non-significant and no trends calculated by the Mann-Kendall test at a 5% confidence level (as collated in Table S2-S9) for the ETTCDI and ET-SCI indices on an annual and seasonal scale.

Indices	**Annual**			**Summer**			**Autumn**			**Winter**			**Spring**		
	Positive and significant	Non-significant/ no trend	Negative and significant	Positive and significant	Non-significant/ no trend	Negative and significant	Positive and significant	Non-significant/ no trend	Negative and significant	Positive and significant	Non-significant/ no trend	Negative and significant	Positive and significant	Non-significant/ no trend	Negative and significant
ET-SCI															
tnLtm$_2$	1	18	1	-	20	-	1	18	1	1	18	1	-	19	1
TXb$_2$TNb$_2$	-	19	1	-	-	-	-	-	-	-	-	-	-	-	-
CDSI$_3$	1	13	6	-	-	-	-	-	-		-	-	-	-	-
CWN	-	15	5	-	-	-	-	-	-	-	-	-	-	-	-
CWD	-	18	2	-	-	-	-	-	-	-	-	-	-	-	-
ETCCDI															
TNMean	10	9	1	12	7	1	9	10	1	7	13	-	5	1	14
TXn	4	16	-	3	17	-	-	19	1	2	18	-	1	19	-
TNn	4	15	1	10	10	-	5	14	1	4	15	1	5	15	-
TX10p	-	-	20	-	9	11	-	3	17	-	10	10	-	8	12
TN10p	1	9	10	1	6	13	1	12	6	1	14	5	1	14	5
FD	1	17	2	-	-	-	-	-	-	-	-	-	-	-	-
CDSI	1	18	1	-	-	-	-	-	-	-	-	-	-	-	-

7.7.3. 4.2.3 Cold Spells ($CDSI_3$), Cold waves (CWN) and Cold wave duration days (CWD)

Of the 20 stations, 16, experience decreasing trends in annual $CDSI_3$ (Figure 3a), six of which are statistically significant (Table 4). These stations are located in Gauteng, KwaZulu-Natal, and Western Cape, at >0.09 days.y^{-1} (Figure 3a). The strongest rate decreases are evident in stations located in Gauteng at Zuurbekom and KwaZulu-Natal, at rates of >0.19 days.y^{-1} (Figure 3a). The remaining four stations experience increasing trends, of which only Kimberley is displaying a statistically significant trend (Figure 3a). These stations are located in the Western Cape, Eastern Cape at East London and Port Elizabeth, North-West and Northern Cape, with rates of increase >0.03 days.y^{-1} evident for the latter three stations (Figure 3a). Overall, a decreasing trend in $CDSI_3$ of 0.10 days.y^{-1} has been calculated.

A general decreasing trend in annual cold wave events (CWN) were found. Only 15 of the 20 stations, experienced a decreasing trend (Figure 3b), five of which are statistically significant. These stations are located in Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, and Western Cape, with rates of decrease >0.02 events.y^{-1} (Figure 3b). The remaining five stations experience increasing trends; these are located in the Eastern Cape, Gauteng, KwaZulu-Natal and Northern Cape Provinces, with a rate of 0.02 events/y^{-1} evident in only Kimberley (Figure 3b). Overall, a decrease in CWN at a rate of 0.02 events/y^{-1} has been found.

The CWD index identifies the duration (days) of the cold waves identified by the CWN index. The majority of stations (14 of 20), experience decreasing trends in annual CWD, two of which are statistically significant (Figure 3c). These significant stations are located in KwaZulu-Natal at Durban and Limpopo at Mara, with rates of decreases of 0.07 days.y^{-1} and 0.08 days.y^{-1}, respectively (Figure 3c). While not displaying a statistically significant decreasing trend, rates of decrease >0.03 days.y^{-1} have been calculated for Zuurbekom, Warmbad Towoomba and Skukuza (Figure 3c). Four of the remaining stations experience increasing trends, with only

Port Elizabeth and Kimberley experiencing an increase, at a rate of >0.01 days.y^{-1} (Figure 3c). Whereas Bloemfontein and Vryburg experience decreases at a rate of >0.01 days.y^{-1} in annual CWD (Figure 3c). Overall, a decreasing linear rate of 0.03 events/y^{-1} in CWD has been found.

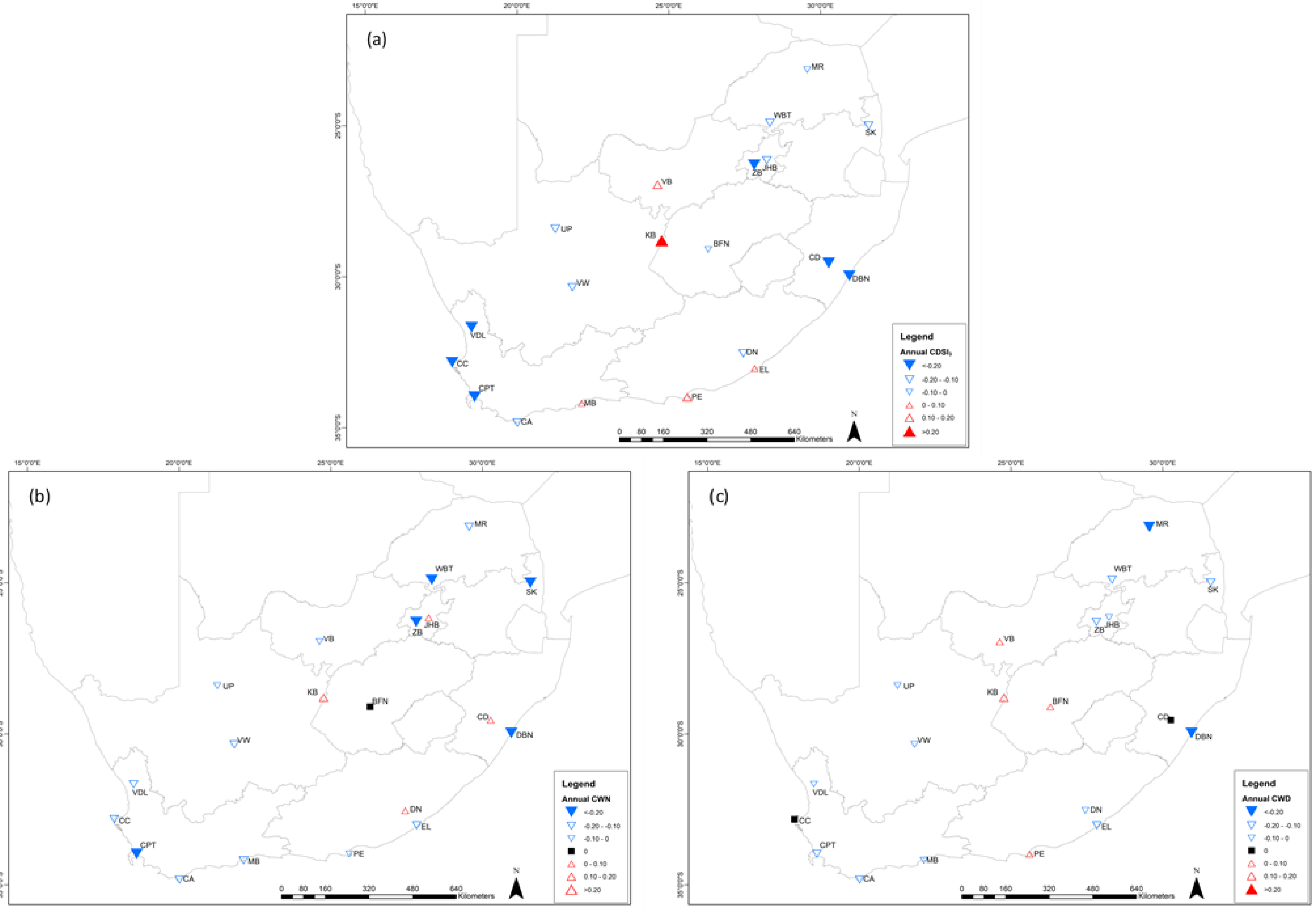


Figure 7.3 (Figure 3): Annual trends of (a) $CDSI_3$,(b) CWN and CWD. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trends. Solid triangles indicate trends that are statistically significant at the 5% level. For all statistical variables please see supporting Table S3.

7.8. 4.3 ETTCDI indices

7.8.1. 4.3.1 Mean minimum temperatures (TNMean)

There is a notable increase of >8°C in TNMean from the central parts of the country, towards the lower-lying areas of the escarpment and coastal regions (Figure 4a). A total of 15 out of 20 stations experience an increasing trend, ten of which are statistically significant (Figure 4a; Table 4). The majority of these stations are located along the west coast, Gauteng, KwaZulu-Natal, and Mpumalanga Provinces, with rates of increase of >0.01°C.y^{-1} (Figure 4a). The remaining five stations experience decreasing trends, one of which are statistically significant (Figure 4a; Table 4). These stations (except for Mara and Mosselbay) experience rates of decrease of >0.01°C.y^{-1}. Overall, the annual TNMean increased at a rate of 0.01°C.y^{-1}. The interior and coastal stations experience the same calculated increase.

At a seasonal timescale, the strongest trend increases in TNMean are calculated for summer, with an overall increase of 0.23°C for the period 1960-2016, followed by autumn, spring, and winter. The overall calculated rate of the increasing trend in TNMean for each season is 0.01°C.y^{-1}, except for spring which exhibits no substantial rate increase. The majority of the stations (18 of 20), experience increasing trends in TNMean in summer, 12 of which are statistically significant (Table 4). These stations are located along the west coast and in Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, and Eastern Cape province at Dohne, with rate increases of >0.01°C.y^{-1}. Only two stations experience decreasing trends: Port Elizabeth and Kimberley, of which the latter station is statistically significant at a rate decrease of 0.02°C.y^{-1}.

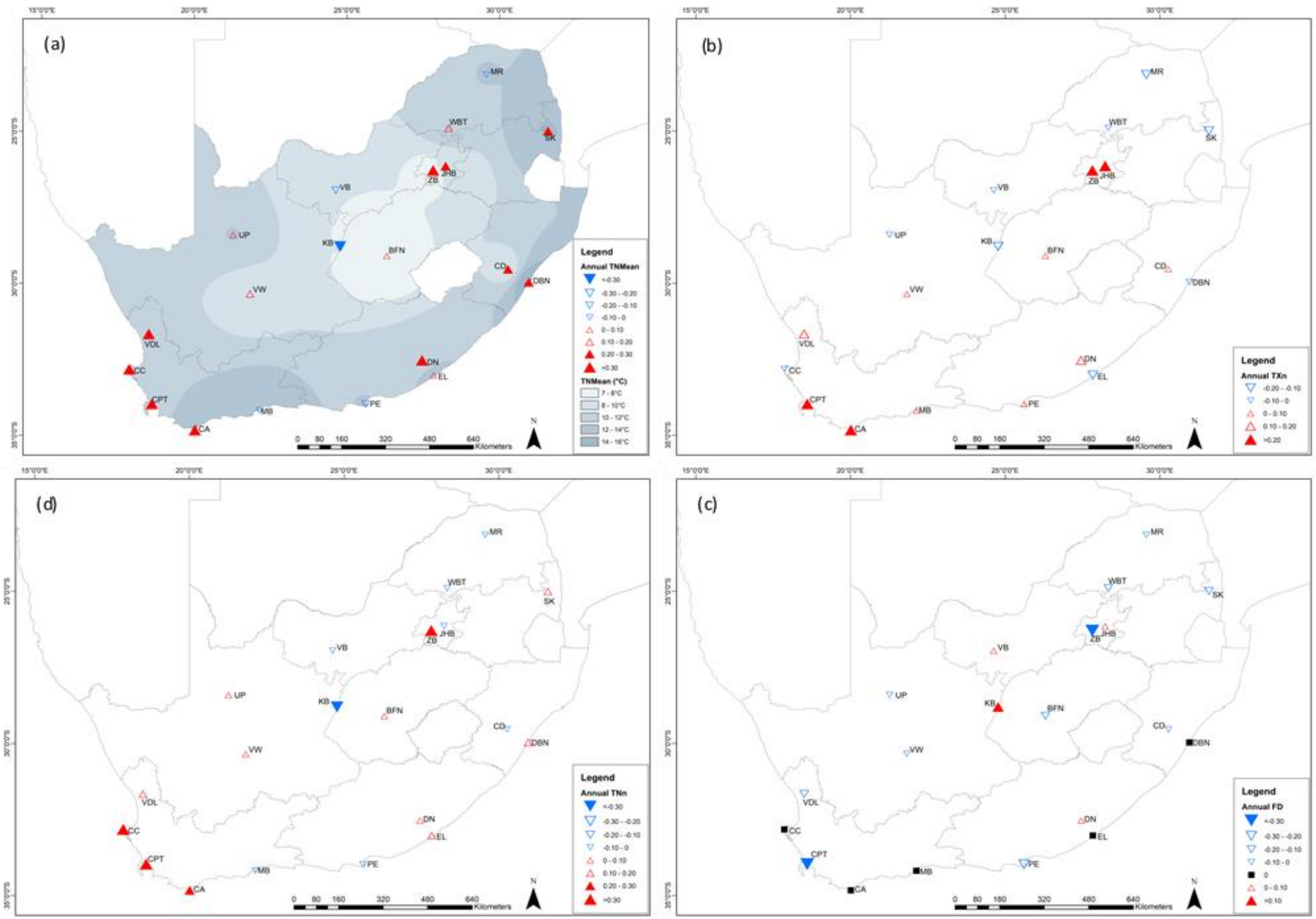


Figure 7.4 (Figure 4): Annual trends of (a) TNMean, (b) TXn, (c) TNn and (d) FD. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level. For statistical variables please see supplementary Table S2.

Similar trends are evident in the stations during autumn, with the strongest rate of increases, at a rate of >0.02°C.y^{-1}, experienced in Gauteng. While six stations experience decreasing trends in TNMean in autumn: Port Elizabeth, Bloemfontein, Mara, Vryburg, Kimberley and Mosselbay, with most of the stations experiencing rates of decrease of >0.01°C.y^{-1}.

Of the 20 stations, 13, experience an increasing trend in TNMean in winter, seven of which are statistically significant (Table 4). These stations are located along the west coast, and in the Eastern Cape at Dohne, Gauteng at Zuurbekom, KwaZulu-Natal province at Durban, with rates of increase of >0.01°C.y^{-1}. The remaining five stations experience decreasing trends: Mara, Upington, Port Elizabeth, Mosselbay, and Kimberley. The latter three stations experience rate decreases of >0.01°C.y^{-1} (Table 4). The majority of the stations (16 of 20), experience increasing trends in TNMean in spring, five of which are statistically significant (Table 4). These stations are located along the west coast and in Gauteng province, with rate increases of >0.01°C.y^{-1}. The remaining four stations experience decreasing trends in TNmean: East London, Port Elizabeth, Vryburg, and Kimberley. Only the latter three stations experience rate decreases of >0.01°C.y^{-1}.

7.8.2. 4.3.2 Coldest day (TXn) and coldest night (TNn)

Most of the stations (11 of 20), experience an increasing trend in coldest daytime temperatures (TXn; Figure 4b), four of which are statistically significant (Table 4). These stations are located in Gauteng and the Western Cape at Cape Agulhas and Cape Town, with rates of increase >0.02°C.y^{-1} (Figure 4b). The remaining nine stations located in Limpopo, North-West, Mpumalanga, Northern Cape, Western Cape, and Eastern Cape Provinces experienced decreasing trends, at rates >0.01°C.y^{-1} (Figure 4ba). No substantial overall rates of increase were calculated.

Similar to the annual TXn, the strongest and statistically significant calculated increase in TXn in summer is experienced in Gauteng, at a rate >0.02°C.y^{-1}. Most of the stations (12 of 20), experience decreasing trends in TXn in autumn, with Port Elizabeth in the Eastern Cape province being statistically significant, with rates of decrease of 0.02°C.y^{-1}. The remaining stations, located in the Northern Cape, Eastern Cape, Free State, Gauteng at Zuurbekom, KwaZulu-Natal, North-West, and Western Cape province, are experiencing rates of decrease >0.01°C.y^{-1}. Overall, TXn in autumn decreased by 0.02°C for the period 1960-2015. A total of 14 out of 20 stations experience an increasing trend in TXn in winter, two of which are statistically significant (Table 4). These stations are located in the Eastern Cape at Dohne and Northern Cape Province at Upington, with rates of increase >0.03°C.y^{-1}. Five stations experience decreasing trends in TXn; these are located in the Eastern Cape, Limpopo and Western Cape Provinces, with rates of decreases >0.01°C.y^{-1} experienced in East London, Mara, Mosselbay and Vredendal. Increasing trends in TXn in spring are experienced in 50% of the stations (10 of 20), with Cape Agulhas exhibiting a statistically significant increase at a rate >0.02°C.y^{-1}. The remaining stations experience decreases in TXn in spring. These stations are located in the Free State, KwaZulu-Natal, North-West, Northern Cape, and Eastern Cape Provinces, with rates of decrease >0.01°C.y^{-1}. The strongest decrease is evident in Vredendal, at a rate of 0.04°C.y^{-1}. In short, the strongest increasing trends are experienced in summer and winter, with mean rates of 0.01°C.y^{-1}.

The results for TNn (Figure 4c) indicate an increasing trend for most of the stations (12 of 20), four of which are statistically significant (Table 4). These stations are located along the west coast and in Gauteng Province at Zuurbekom, with rates of increases >0.02°C.y^{-1} (Figure 4c). The remaining eight stations experience decreasing trends, with only stations located in

Limpopo, North-West and Northern Cape at Kimberley experiencing rates of decrease >0.01°C (Figure 4c). Overall, an increase of 0.01°C.y^{-1} in annual TNn has been calculated.

The majority of stations (18 of 20), experience increasing trends in TNn in summer (Table 4), ten of which are statistically significant. These stations are located along the west coast and in Gauteng, Limpopo, KwaZulu-Natal at Cedara, and Northern Cape at Vanwyksvlei, with rates of increase >0.02°C.y^{-1}. Port Elizabeth experienced a decreasing trend in TNn in summer, at a rate of 0.01°C.yr^{-1}. Of the 20 stations, 15, experience an increasing trend in TNn in autumn , five of which are statistically significant (Table 4). These stations are located along the west coast and in Gauteng at Zuurbekom, and KwaZulu-Natal at Cedara, with rates of increase >0.02°C.y^{-1}. Decreasing trends are calculated for TNn for only three stations in autumn: Bloemfontein, Vryburg and Kimberley, with the latter being statistically significant, with rates of decrease of 0.05°C.y^{-1}. Increasing trends are experienced in 12 of the 20 stations for TNn in winter, four of which are statistically significant (Table 4). As for autumn, these stations are located along the west coast and in Gauteng province at Zuurbekom, with rates of increase of >0.02°C.y^{-1}. The remaining eight stations experience decreasing trends, with rates >0.01°C.y^{-1} only evident in Mara, Vryburg and Kimberley. Most of the stations (13 of 20), experience increasing trends in TNn in spring, five of which are statistically significant (Table 4). These stations are located along the west coast and in Gauteng province, with rates >0.02°C.y^{-1}. Six of the remaining seven stations experience decreasing trends, of which only stations located in the North-West and the Northern Cape province at Kimberley and Upington exhibit rates >0.01°C.y^{-1}.

In short, the strongest calculated trend and rates of increase of TNn, are calculated for summer, at a rate of 0.03°C.y^{-1}, followed by spring with a rate of increases of 0.02°C.y^{-1}. Autumn and winter experience increasing trends, at a rate of 0.01°C.y^{-1}.

7.8.3. 4.3.3 Frost days (FD)

In general, the frequency of days below 0°C is decreasing across the country. The majority of stations (12 of 15) are experiencing a decreasing trend, two of which are statistically significant (Figure 4d; Table 4). These stations are located in Gauteng and Western Cape province with decreasing trends >0.32 days.y^{-1} (Figure 4d). Overall, the calculated trend in the number of FD decreased with 0.05 days/y^{-1}. Increasing trends are calculated for stations located in the Eastern Cape at Dohne, Gauteng at Johannesburg Int, and Northern Cape at Vryburg and Kimberley, with an overall calculated increasing trend in FD of >0.05 days.y^{-1} (Figure 4d). The majority of stations (7 of 13), are calculated to experience decreasing trends (Figure 4d), with only Zuurbekom exhibiting a statistically significant trend, at a rate of decrease of 0.84 days.y^{-1} (Table 4).

7.8.4. 4.3.4 Cold days (TX10p) and cold nights (TN10p)

In general, the frequency of annual TX10p is decreasing across the country. All stations included in this study experience statistically significant decreasing trends (Figure 5a; Table 4), with an overall calculated rate of 0.10% days.y^{-1}. Stations with rates of decrease >0.10% days.y^{-1} are located in Limpopo and the Western Cape Provinces (Figure 5a).

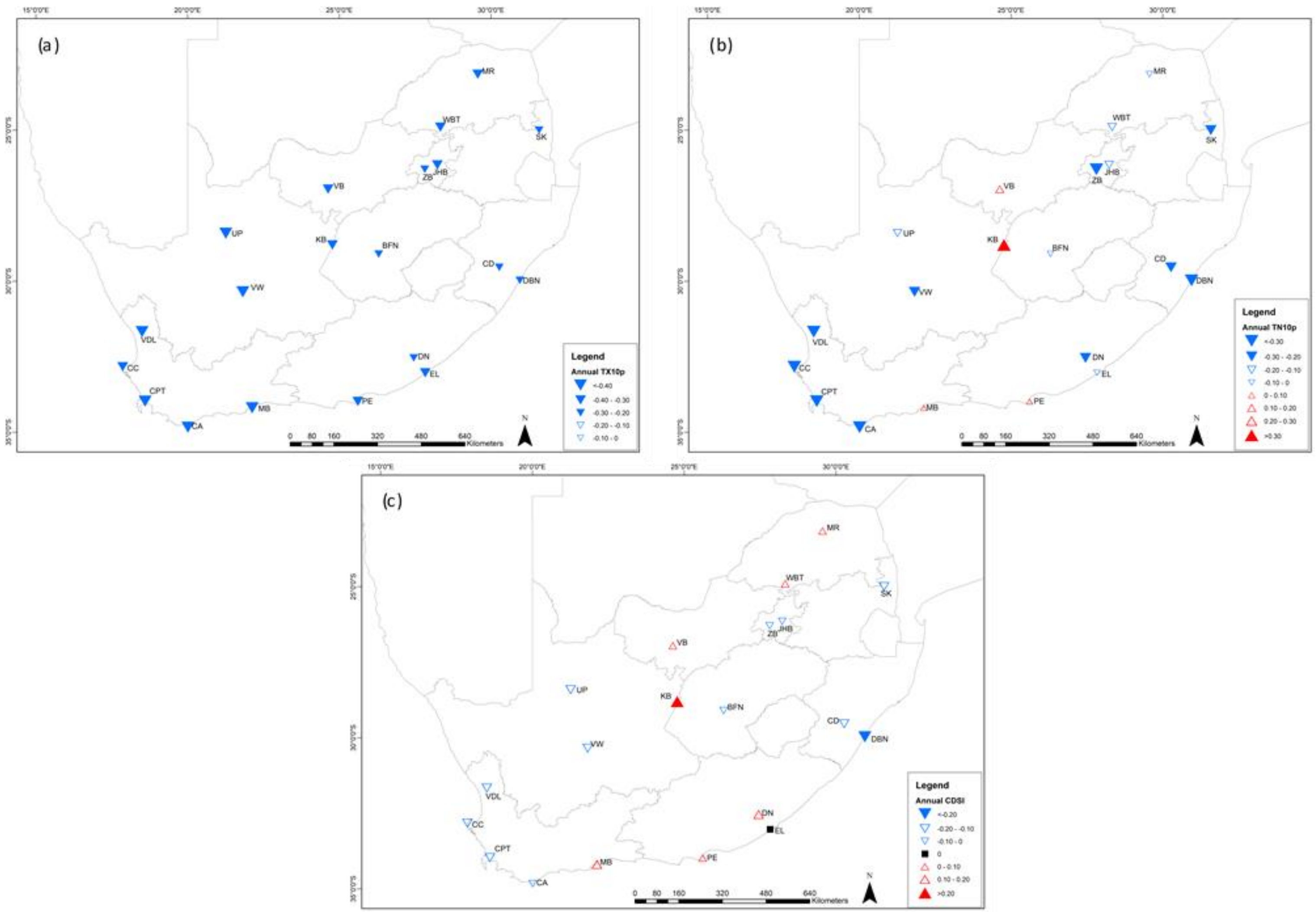


Figure 7.5 (Figure 5): Annual trends of (a) TX10p, (b) TN10p and (c) CDSI. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level. For statistical variables please see supplementary Table S1 and Table S2.

In summer, 18 out of 20 stations, experience decreasing trends in TX10p (Figure 6a), 11 of which are statistically significant (Table 4). These stations are located in the Eastern Cape, KwaZulu-Natal, Limpopo, Northern Cape and Western Cape Provinces, at rates of >0.08% days.y^{-1} (Figure 6a). The strongest rates of decrease are experienced in Northern Cape and Western Cape, with increases >0.15% days.y^{-}. The remaining two stations experience increasing trends (Figure 6a), with a rate of 0.01% days.y^{-1} evident only in Bloemfontein. Overall, a decreasing rate of 0.10% days.y^{-1} has been calculated for summer. All the stations experience decreasing trends in autumn (Figure 6b), 17 of which are statistically significant (Table 4). The strongest rates of decrease are experienced in stations located in the Western Cape, Northern Cape, North-West, Limpopo, Free State, Gauteng at Zuurbekom and Eastern Cape at East London, at rates of >0.11% days.y^{-1} (Figure 6b). Overall, a decreasing rate of 0.13% days.y^{-1} has been calculated for autumn.

All the stations experience decreasing trends in winter (Figure 6c), ten of which are statistically significant (Table 4). These stations are located in the Eastern Cape, Gauteng, Limpopo, KwaZulu-Natal, North-West, Northern Cape and Western Cape Provinces, at rates >0.07% days.y^{-1} (Figure 6c). The strongest rates of decrease are calculated for stations in Limpopo and Western Cape, at >0.13% days.y^{-1} (Figure 6c). Overall, a decreasing rate of 0.09% days.y^{-1} has been calculated in winter. In spring, all the stations experience a decreasing trend (Figure 6d), 12 of which are statistically significant. These stations are located in the Eastern Cape, Free State, Gauteng, Limpopo, North-West, Northern Cape, and Western Cape Provinces, at rates >0.08% days.y^{-1} (Figure 6d). The strongest decreasing rates for TX10p are evident in the Western Cape, at >0.11% days.y^{-1} (Figure 6d). Overall, a decreasing rate of 0.10% days.y^{-1} has been calculated in spring. In short, the strongest rate decrease in TX10p is evident in autumn, followed by summer, spring and winter.

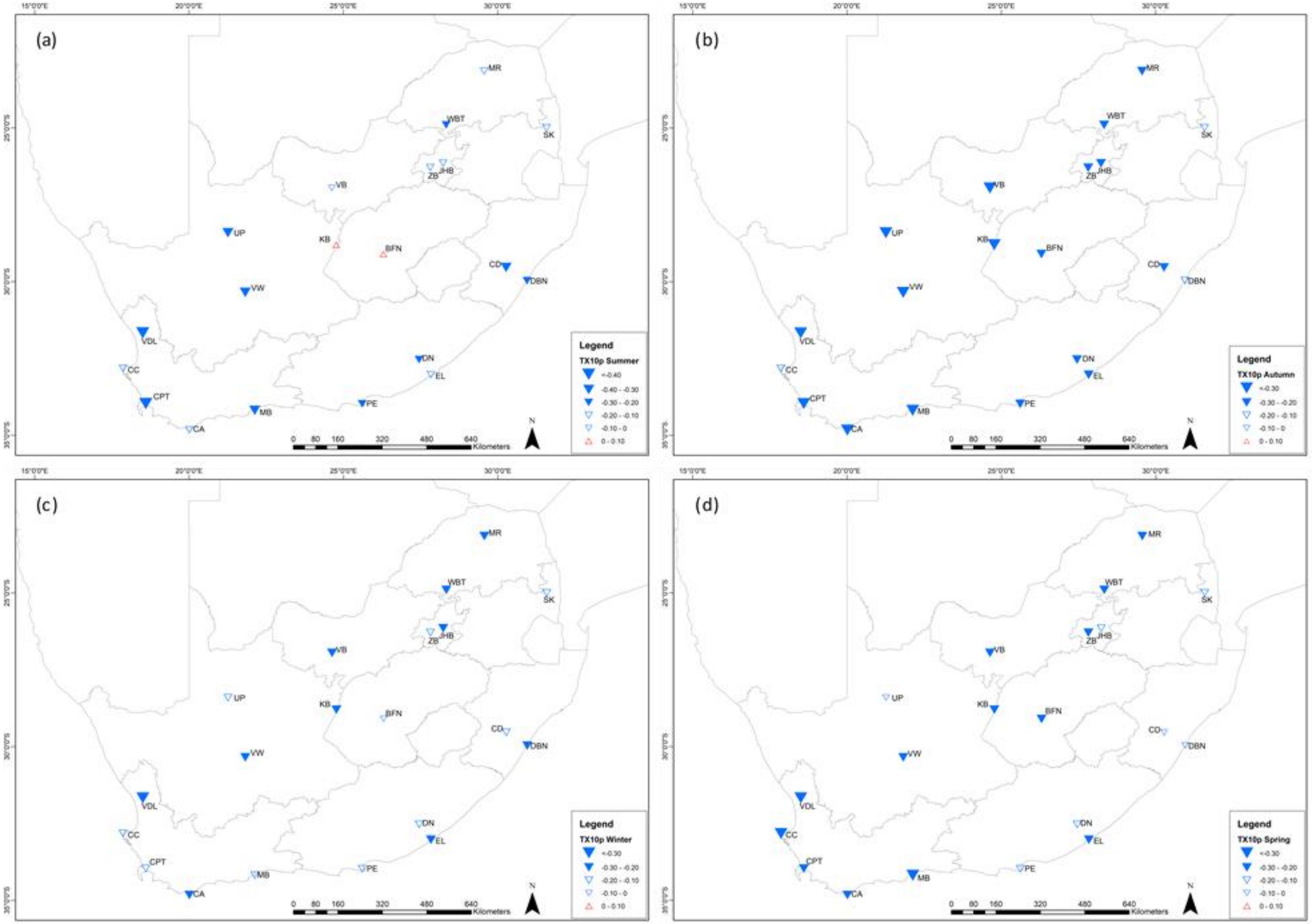


Figure 7.6 (Figure 6): Seasonal trends of TX10p (a) Summer, (b) Autumn, (c) Winter, and (d) Spring. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level. For statistical variables please see supplementary Table S8.

For annual TN10p, most of the stations (16 of 20), have experienced decreasing trends (Figure 5b), ten of which are statistically significant (Table 4). These stations are located in the Western Cape, Northern Cape, Mpumalanga, KwaZulu-Natal, Gauteng, and the Eastern Cape Province, at >0.07% days.y^{-1} (Figure 5b). The strongest decreasing rates are experienced in the Western Cape, KwaZulu-Natal at Durban, and Gauteng at Zuurbekom, at >0.11% days.y^{-1} (Figure 5b). Increasing trends are calculated for the remaining four stations: Port Elizabeth, Vryburg, Mosselbay and Kimberley at rates of >0.01% days.y^{-1}, with the latter station being statistically significant (Figure 5b). Overall, a rate of decrease of 0.07% days.y^{-1} has been calculated for TN10p country-wide.

In summer, decreasing trends are calculated for a total of 17 of 20 stations (Figure 7a) in TN10p, 13 of which are statistically significant (Table 4). These stations are in the Eastern Cape, Gauteng, Limpopo, Mpumalanga, Northern Cape and Western Cape, at >0.11% days.y^{-1} (Figure 7a). The strongest rates of decrease are experienced in the Western Cape, KwaZulu-Natal at Durban, and Gauteng at Johannesburg Int, at >0.15% days.y^{-1} (Figure 7a). Of the remaining three stations, Mosselbay experiences no detectable trend, while Port Elizabeth and Kimberley experience increasing trends, at rates of >0.03% days.y^{-1}, with the latter being statistically significant (Figure 7a). Overall, a decrease in TN10p at >0.11% days.y^{-1} has been calculated for summer. Most of the stations (15 of 20; Figure 7b) are experiencing decreasing trends in autumn, six of which are statistically significant (Table 4). These stations are located in the Western Cape, KwaZulu-Natal and Gauteng, at >0.12% days.y^{-1} (Figure 7b). Increasing trends are found for stations located in the Eastern Cape, North-West and Northern Cape province at Kimberley, at >0.05% days.y^{-1}, of which the latter is statistically significant (Figure 7b). Overall, a decreasing trend at a rate of 0.07% days.y^{-1} in TN10p has been calculated in autumn.

For winter, 15 of the 20 stations, experience decreasing trends in TN10p (Figure 7c), five of which are statistically significant (Table 4). These stations are located in Gauteng, KwaZulu-Natal, and the Western Cape, at >0.13% days.y^{-1} (Figure 7c). The strongest rate decreases are evident in Zuurbekom and Durban, at rates of >0.25% days.y^{-1}. The remaining five stations experience increasing trends at rates of >0.05% days/y^{-1} (Figuer 7c). These stations are located in the Eastern Cape, Gauteng, North-West, Western Cape and Northern Cape at Kimberley, with only the latter station being statistically significant (Figure 7c). Overall, a decreasing rate of 0.05% days.y^{-1} has been calculated for winter. In spring, 16 stations, experience decreasing trends (Figure 7d), five of which are statistically significant (Table 4). Similar to winter, these stations are located in Gauteng, KwaZulu-Natal and Western Cape, with rates of decreases >0.09% days.y^{-1} (Figure 7d). The remaining four stations experience increasing trends, of which only Kimberley is statistically significant (Figure 7d). These stations are located in the Eastern Cape at East London and Port Elizabeth, North-West and Northern Cape, with rates of >0.07% days.y^{-1} evident only in the latter three stations (Figure 7d). Overall, a decreasing rate in TN10p of 0.05% days.y^{-1} has been calculated in spring. In short, the strongest rate trend and rate increases are evident in summer, followed by autumn, winter and spring.

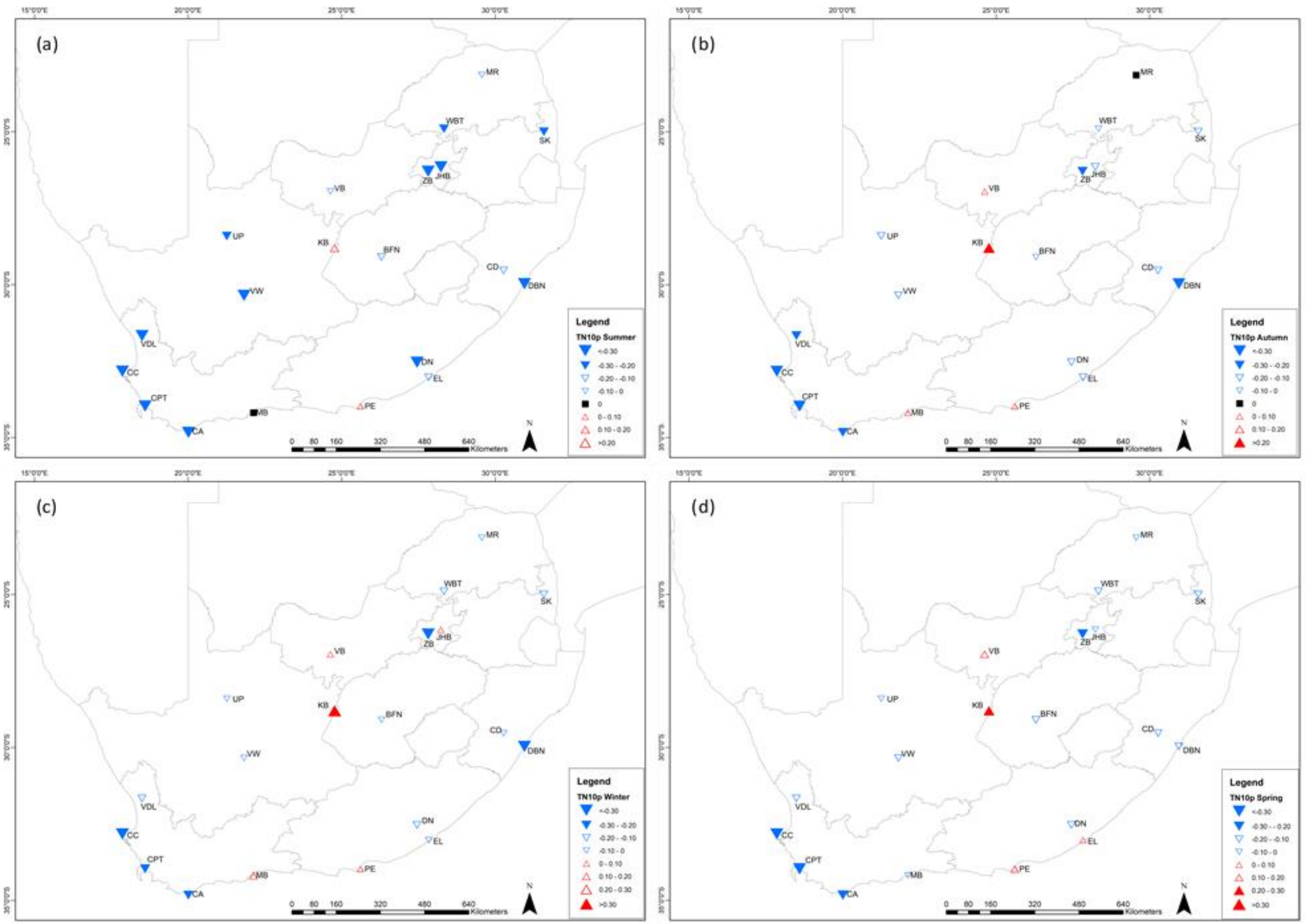


Figure 7.7 (Figure 7): Seasonal trends of TN10p (a) Summer, (b) Autumn, (c) Winter, and (d) Spring. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level. For statistical variables please see supplementary Table S9.

7.8.5. 4.3.5 Cold spells

Only 12 of the 20 stations, experience decreasing trends in annual CDSI (Figure 5c), of which only Durban in KwaZulu-Natal is displaying a statistically significant decreasing trend. The strongest decreasing trends are evident in Western Cape, Northern Cape and Mpumalanga, at >0.13 days.y^{-1} (Figure 5c). Increasing trends are evident in the Eastern Cape, Limpopo, and Western Cape at Mosselbay, with an increase of >0.01 days.y^{-1} for the period 1960-2016 (Figure 5c).

7.9. 5. Discussion

7.9.1. 5.1 Incidence of cold temperature extremes in South Africa

This study is one of the first to apply the ET-SCI indices in South Africa in exploring the incidence of only extreme cold temperature events and, for the period 1960-2016. These ET-SCI (e.g. TXb_2TNb_2, CWN, CWN), in particular the $CDSI_{3,}$ have been found to be more effective in measuring the frequency and intensity of cold waves, compared to the ETTCDI CDSI (Panda et al. 2014). Shorter cold events (i.e. two or three day events) can have significant impacts on many sectors, in particular agriculture (Panda et al. 2014). Using the ET-SCI, an average of 1.9 cold wave events/y^{-1} was calculated using CWN, for the period 1960-2016. However, an overall decreasing trend was found in the frequency of occurence of extreme cold events, with the duration and incidence of these events showing great variability over the country. This is evident in the trend analysis of the ET-SCI, TXb_2TNb_2, $CDSI_3$, CWN and CWD on an annual scale. For instance, duration of cold spell events ($CDSI_3$) decreased at a rate of 0.1 days.y^{-1}, or a mean one day per decade, countrywide, as would be expected under global scale warming in recent decades. However, more notable, some stations experienced increases in the duration of cold spell events, at comparable rates. These stations were widely distributed across the country, including Port Elizabeth and East London in the Eastern Cape, Vryburg in the North-West, and Kimberley in the Northern Cape Province. Similar results were found for the number of cold waves (CWN). Increasing trends in CWN have been observed in the Eastern Cape, Gauteng, KwaZulu-Natal and Northern Cape Provinces, with a rate increase of 0.02 events.y^{-1} evident in only at Kimberley in the Northern Cape Province. The heterogenous distribution of these increases in the incidence and duration of cold events across the country would suggest that there is no singular distinct causal mechanism. Changes in the dynamics of the Mascarene High over recent decades, and resultant atmospheric blocking, have been associated with anomalous temperatures, and in particular extreme cold events associated with the enhanced cut off lows (Xulu et al., 2020). While there is a considerable geographical distribution of cut off lows along the South African coastline (Singleton and Reason, 2007), these systems are unlikely to have induced an increase in cold events in regions of the Northern Cape and North West Province. Index outputs are insufficient to determine causal drivers, and efforts in climate modelling towards understanding this increase in extreme cold temperature events warrants further research.

Our findings are in partial agreement with previous studies indicating a general decreasing trend in extreme cold temperatures and cold waves (e.g. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017). In general, the number of days per year with low minimum temperatures have declinded. Similar to the findings of Kruger and Sekele (2013) and Kruger and Nxumalo (2017), cold days and nights have declined, particulary in the western parts of the country. Extending from previous studies, this study presents the first comprehensive seasonal analysis of the absolute (i.e. TNMean, TNx, TNn) and percentile-based (i.e. TN10p and TX10p) indices. In general, the seasonal results for the absolute-based indices indicate an increase in TNMean, TNx and TNn. Greater variability across the seasons is recorded for the coastal (e.g. Port Elizabeth and Mosselbay) and interior stations (e.g. Kimberley and Vryburg). The greatest spatial variability between stations is evident in spring (September/October/November) for both day- and night-time temperatures. This could be due to the transition between winter and spring. Similarly, decreasing trends are evident for the seasonal frequency of cold days and nights. However, it is evident that the frequency of cold nights is increasing in some of the interior stations (e.g. Vryburg and Kimberley), while the rest of the stations show a decrease in cold nights. This could be due to the location and elevation of these stations. However, seasonal observations are very important, particularly for the agricultural sector as these climatic changes may result in shifts in the onset and length of growing seasons (Thorton et al. 2014). Extending from the work of Kruger and Nxumalo (2017), our 50-year trend analysis for CDSI has found a smaller decreasing trend of 0.03 days.y^{-1}, for the period 1960-2016.

Future trends indicate that cold spells are projected to be quite spatially variable across South Africa, which is heightened with the use of some indices (Kruger et al. 2019). However, decreases are more pronounced in the central and northern parts of the country (Kruger et al. 2019. Which to a certain extent agree with the findings of this study.

7.9.2. 5.2 Possible climate mechanisms of cold extreme events

Very few seasonal or longer-period synoptic-scale studies of the drivers of extreme cold events in South Africa have been documented (Lengoasa, 1991). Cold weather and cold events are mainly produced by the occurrence of cold cut-off lowsand the cold fronts of mid-latitudinal cyclones predominantly during winter (Engelbrecht et al. 2012; Abiodun et al. 2016; Lennard 2019). Cold fronts are normally followed by a high-pressure systems over the Atlantic Ocean (Stander 2016). Cold fronts over South Africa are more frequent and well defined during the winter months, with a frequency of one to two systems per week (Tyson and Preston-Whyte 2000; Stander, 2013). These events exhibits a strong seasonality in their occurrence (Jury and Parker, 1998). A general eastward movement is exhibited by these events due to their location within the westerly belts (Stander, 2013). The cold air mass associated with cold fronts tends to exhibit a northeasterly movement across the interior plateau, depending on the characteristics of the strength of the pressure gradient force driving it across South Africa, which can extend as far north as the Gauteng Province (Jury and Parker, 1998; Stander 2013; Stander 2016). The magnitude is determined by the strength of the ridging anticyclone and the depth of the low pressure associated with the cold front east of the county (Stander 2016). Cold snaps, following the passage of the cold front, can last up to four days over South Africa which are attributed to frontal perturbations in the westerlies (Tyson and Preston-Whyte 2000; Landman et al. 2017). Moreover, there is the potential for cold air outbreaks in the polar masses to increase in regions such as South Africa, due to internal variability and external forcings (Smith and Sheridan, 2020). Where the Mascarene High induces atmospheric blocking, slow-propagrating cut off lows can develop from the westerly wave, resulting in enhanced rainfall and even colder temperatures (Xulu et al., 2020). Localized temperature differences may occur due to the location of the station within close proximity to the ocean, as well as elevation of the stations (Table 1). The colder sea surface temperatures along the west coast due to the cold Benguela, together with westerly flow contributes to the advection of cold air over the coast (Tyson and Preston-Whyte 2000; Landman et al. 2017). Furthermore, it has been found that higher elevations such as Johannesburg International and Kimberley tend to be colder than lower elevations (NOAA, 2020). For example, large areas of the high plateau of South Africa experience colder day and night temperatures, with more than five days experiencing temperature reductions of >10°C during winter relative to the lower parts of the plateau. In addition, built-up areas may be warmer than the rural areas (e.g. Johannesburg International and Zuurbekom) due to the urban heat island (Scott et al. 2018). This is important in the context of continually expanding urban centers, as the warming effects of the urban heat island may inhibit or ameliorate extreme cold events, and will do so over larger spatial areas as the urban footprint expands. This would be heightened under conditions of localised greenhouse gas emissions that are trapped under dominant high pressure conditions over the interior, which arise from transportation, heating and industry, either continually or under air pollution episodes (Jury, 2017).

An important avenue of future research will involve exploring the forcing mechanisms responsible for these extreme temperature events, and in particular cold events, in South Africa both currently and for future climate projections under potential retraction of the southern hemisphere jet stream due to the enhanced meridional gradient under global warming. It will also be of value to explore the role that larger scale climate variability plays in the incidence and severity of extreme climatic events, including the El Niño Southern Oscillation, Indian Ocean Dipole and the Southern Annular Mode.

7.9.3. 5.3 Regions of risk-related hazards

Although much of South Africa is situated within the subtropics, human comfort levels are affected by cold weather and cold events across South Africa (Jury and Parker 1998; Kodra and Ganguly 2014; Stander 2016). In our analysis of extreme cold temperature events over South Africa, we observe that the variations in the trends are not spatially uniform. Each province and station exhibits unique trends; for instance, increasing trends in of cold days, two-day consecutive cold days and nights, cold waves seem to occur more in stations located along south and east coast and in the Northern Cape, North-West, Gauteng province. These cold weather and cold events could lead to an increased risk of cold-related injuries (e.g. hypothermia) in the low-income and the homeless populations (Zhang et al. 2018), particularly in the vulnerable socio-economic communities found in Gauteng, KwaZulu-Natal, North-West and Eastern Cape province (Le Roux et al. 2017). Cold spells also result in a higher demand for electricity in populated areas (de' Doate et al. 2014; Stander et al. 2016), such as Gauteng and KwaZulu-Natal, which places strain on the already struggling infrastructure in place. Day to day weather can have significant impacts on outdoor tourism activities, particular in tourist activities along the coast and in Gauteng province (Giddy et al. 2017). It is estimated that 3.5 million people reside along the coastline, of which 40% live below the minimum living wage (Le Roux et al. 2017). These communities are especially vulnerable to potential increases in the frequency of extreme cold events, due to low adaptive capacity, and appropriate housing (Le Roux et al. 2017). Potential increases in cold events can impact the ecosystem (Leriorato and Nakamura 2019), changing plant and animal distributions, and delaying seasonal phenological events (Wang et al. 2016), and result in loss of livestock (Muirhead 2002), which may lead to irreparable damages to regions such as the Northern Cape and Eastern Cape which support extensive livestock farming (Lötter 2017), and house communities which depend solely on subsistence farming for their livelihoods.

In accordance with our results, it is important to highlight that decreasing tendencies of cold extremes across South Africa, may have positive effects. In particularly, for low income communities with low adaptive capacity, as well as vulnerable housing infrastructure. Furthermore, it could lead to reduction of energy consumptions and cost in the long-term.

7.9.4. 5.4 Looking forward: Climate change influence and adaptation

Our results show a decrease in annual extreme cold events, as would be expected in a warming country. However, studies suggest that cold events may continue to persist into the late 21st century across many regions of the world and even increase in frequency in certain countries (Kodra et al. 2011; Kodra and Ganguly 2014). It is therefore important to understand the incidence of cold events in South Africa, their current frequency, and the synoptic drivers, and to include projections of cold events in climate modelling outputs.

A broad hypothesis is that natural processes that drive anomalously cool weather will continue to do so despite a significant mean warming trend (Kodra et al. 2011; Kodra and Ganguly 2014). It is suggested that extreme cold events may be less severe or shorter than they have been in the recent past on average, but that this may increase a population's vulnerability to the rare cold events which do occur. People may become less acclimatized to these events, which would lead to more susceptibility to cold-related mortality when these events occur (Kodra et al. 2011; Kodra and Ganguly 2014; Smith and Sheridan 2020). This is especially important for the population of a developing country such as South Africa, with a low adaptive capacity and limited indoor thermal control. We therefore argue that it is important for = decision-makers to consider both extreme warm and extreme cold events in their infrastructural adaptation and their warning systems

7.10. 6. Conclusion

This study provides the first application of the ET-SCI indices in exploring extreme temperature events in South Africa. This is the first paper to explore cold extreme events, and their implications, in South Africa, and the first to explore extreme temperature at a seasonal scale. The ET-SCI indices used are more relevant in a South African setting, seeing that these indices can identify shorter cold extreme events, which may have a greater influence, particularly on the agricultural sector. Furthermore, by extending the analysis period results should be more robust than studies done over a shorter time period (Kruger and Nxumalo 2017). The importance of the incidence of ETEs are more apparent when exploring the long-term trends (e.g. higher frequency of hot days), than isolated reports of individual short-lived events which are often difficult to detect (Davis-Reddy and Vincent 2017).These findings contribute to the knowledge on the nature of cold events in a South African perspective, seeing that these events will still occur under current increasing mean temperatures. Furthermore, these results are crucial in order to frame mitigation and adaption strategies against anomalously cold events in a 'warming world'.

Overall our results show that the frequency and duration of cold events has decreased in South Africa; however, the duration and incidence of these events show great variability over the country for the period 1960-2016.

7.11. 7. Acknowledgements

We acknowledge the financial and collegial support offered to Adriaan J van der Walt from the Faculty of the Natural and Agricultural Sciences and the Geography Department at the University of the Free State. Jennifer M Fitchett received funding from the DST-NRF Centre of Excellence for Palaeoscience. The authors thanks Professor Christopher Curtis for suggestions and advice on earlier stages of the project. The authors would also like to thank Yang Feng for assistance with the download and usage of RClimDex and RHtestV4 software.

7.12. 8. References

Abatan AA, Abiodun BJ, Gutowski WJ and Rasaq-Balogun SA (2018) Trends and variability in absolute indices of temperature extremes over Nigeria: linkage with NAO. International Journal of Climatology 38:593-612. DOI: 10.1002/joc.5196.

Abiodun BJ, Omar SA and Jack C (2016) Using regional climate models to simulate extreme rainfall events in the Western Cape, South Africa. International Journal of Climatology 36:689-705. https://doi.org?10.10228/joc.43676.

Abbas F, Rehman I, Adrees M, Ibrahim M, Saleem F, Ali S, Rizwan M, Salik MR (2018) Prevailing trends of climate extremes across Indus-Delta of Sindh-Pakistan. Theor Appl Climatol 131:1101-1117. https://doi.org/10.1007/s0070-016-2028-y

Alexander LV, *et al* (2006) Global observed changes in daily climate extremes of temperatures and precipitation. Journal of Geophysical Research 111. https://doi.org/10.1029/2005JD006290.

Alexander L and Perkins S (2013) Debate heating up over changes in climate variability. Environmental Research Letters. 8. http://dx.doi.org/10.1088/1748-9326/8/4/041001.

Alexander L and Herold N (2016) Climpact2 Indices and Software, The University of South Wales, Sidney, Australia. https://github.com/ARCCSSextremes/climpact2.

Allen SMJ, Gough WA and Mohsin T (2015) Changes in the frequency of extreme temperature records for Toronto, Ontario, Canada. Theoretical and Applied Climatology 119:481-491. https://doi.org/10.1007/s00704-014-1131-1

Añel JA, Fernández-González, Labandeira X, López-Otero X and De la Torre L (2017) Impact of cold waves and heat waves on the energy production sector. Atmosphere 8: 209. https://doi.org/10.3390/atmos8110209.

Baldwin JW, Dessy JB, Vecchi GA and Oppenheimer M (2019). Temporally compound heat wave and global warming: An emerging hazard. Earth's Future. 7:411-427. https://doi.org/10.1029/2018EF000989.

Barnett AG, Hajat S, Gasparrini A and Rocklöv J (2012). Cold and heatwaves in the United States. Environmental Research. 112: 218-224. https://doi.org/10.1016/j.envres.2011.12.010.

Brophy S (2016) Weird weather: SA's most extreme weather events of 2016. Traveller24. Accessed on 21 April 2020. https://www.traveller24.com/News/WeatherUpdate/weird-weather-sas-most-extreme-weather-events-of-2016-20161223

Caloiero T, Coscarelli R, Ferrari E and Sirangelo B (2017) Trend analysis of monthly mean values and extreme indices of daily temperature in a region of southern Italy. International Journal of Climatology 37:284-297. DOI: 10.1002/joc.5003.

Cattaiux J, Vautard R, Cassou C, Yiou P, Masson-Delmotte V and Codron F (2010). Winter 2010 in Europe: A cold extreme in a warming climate. Geophysical Research Letters. 37. https://dx.doi.org/10.129/2010GL044613.

Chen J, Yang J, Zhou M, Yin P, Wang B, Liu J, Chen Z, Song X, Ou C-Q and Liu Q (2019) Cold spell and mortality in 31 Chinese capital cities: Definitions, vulnerability and implications. Environmental International. 128:271-278. https://doi.org/10.1016/j.envint.2019.04.049.

Cowling RM, Procheş Ş and Partridge TC (2009) Explaining the uniqueness of the Cape flora: incorporating geomorphic evolution as a factor for explaining its diversification. Molecular Phylogenetics and evolution 51:64-74.

Davis-Reddy CL and Vincent K (2017) Climate risk and vulnerability: A handbook for southern Africa (2nd ed). CSIR. Pretoria. South Africa

De Perez EC, van Aalst M, Bischiniotis K, Mason S, Nissan H, Pappenberger F, Stephens E, Zsoter E and Van den Hurk B (2018) Global predictability of temperature extremes. Environmental Research Letters. 13. https://doi.org/10.1088/1748-9326/aab94a.

De'Donato FK, Leone M, Noce D, Davoli M and Michelozzi P (2013) The impact of the February 2012 cold spell on health in Italy using surveillance data. Plos ONE. 8(4):1-9. https://doi.org/10.1371/journal.pone.0061720.

Díaz J, Carmona R, Mirón IJ, Luna MY and Linares C (2019) Tiem trends in the impact attributable to cold days in Spain: Incidence of local factors. Science of the Total Environment. 655:305-312. https://doi.org/10.1016/j.scitotenv.2018.11.254.

Doran JD (2014) "Regional Climate Messages: Southern Africa". Scientific report from CARIAA Adaption at Scale in Semi-Arid Regions (ASSAR) Project.

Doubell, H, Denga M, Rautenbach H, Rae K, Joubert W and Mengistu M (2018) Weathersmart news: Scientific meteorological and climatological news from the South African Weather Service. South African Weather Service. Accessed on 22 April 2020. https://www.weathersa.co.za/Documents/Corporate/165468%20SA%20Weather%20Service=WeatherSmart%20Newsletter_mailer2(1).pdf

Dube LT, (2002) Climate of southern Africa. South African Geography Journal 84(1):125-138 DOI:10.1080/03736245.2002.9713763.

Engelbrecht CJ, Engelbrecht FA and Dyson LL (2012) High-resolution model-projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. International Journal of Climatology 33(1):173-187.

Founda D, Pierros F, Katavoutas G, and Keramitsoglou I (2019) Observed trends in thermal stress at European cities with different background climates. Atmosphere, 10, 436, https://doi.org/10.3390/atmos10080436.

Giddy JK, Fitchett JM and Hoogendoorn G (2017) Insight into American tourist' experienced with weather in South Africa. Bulletin of Geography. Socio-economic Series. 35:57-71.

Grab SW and Knight J (2018) Southern African Montane Environments. In Holmes, P.J. and Boardman, J. (eds.). *Southern African Landscape and Environmental Change*. Routledge: Oxon.

Han J, Liu S, Zhang J, Zhou L, Fang Q, Zhang J and Zhang Y (2017). The impact of temperature extremes on mortality: a time series study in Jinan, China. BMJ Open. 7:e014741. https://doi.org/10.1136/bmjopen-2016-014741.

Johnson NC, Xie S-P, Kosaka Y and Li X (2018) Increasing occurrence of cold and warm extremes during the recent global warming slowdown. Nature Communications 9:1724. https://doi.org/10.1038/s41467-018-0404-y.

Jury, MR and Parker B (1998) Cold winters over the South African highveld: pattern recognition and preliminary models. South African Journal of Science 94: 473-481.

Karki R, Hasson SU, Gerlitz L, Talchabhadel R, Schickhoff U, Scholten T and Böhner J (2019). Rising mean and extreme near-surface air temperature across Nepal. International Journal of Climatology, 1-19. DOI: 10.1002/joc.6344.

Kendall MG (1955) *Rank Correlation Methods*. London: Charles Griffen, p. 196.

Klein Tank AMG, Zwiers FW and Zhang X (2009) Guidelines on analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation (WCDMP no. 72, WMO-TD no. 1500). Switzerland: World Meteorological Organization, 54 pp.

Kodra E, Steinhaeuser K and Ganguly AR (2011) Persisting cold extremes under 21st century warming scenarios. Geophysical Research Letters 38. https://doi.org/10.1029/2011GL047103.

Kodra E and Ganguly AR (2014) Asymmetry of projected increases in extreme temperature distributions. Scientific Reports 4:5884. https://doi.org/10.1038/srep05884.

Kruger AC and Sekele SS (2013) Trend in extreme temperature indices in South Africa: 1962-2009. International Journal of Climatology 33:661-676. DOI: 10.1002/joc.3455.

Kruger AC and Nxumalo M (2017) Surface temperature trends from homogenized time series in South Africa: 1931-2015. International Journal of Climatology 37:2364-2377. DOI: 10.1002/joc.4851.

Kruger AC, Rautenbach H, Mbatha S, Ngwenya S and Makgoale TE (2019) Historical and projected trends in near-surface temperature indices for 22 location in South Africa. South Africa Science Journal 115(5/6).

Landman WA, Malherbe J and Engelbrecht F (2017) South Africa's present-day climate. In Mambo J, Faccer K, (eds). Understanding the Social and Environmental Implication of Global Change, African Sun Media: Stellenbosch.

Le Roux A, Mans G, Van Hyssteen E and Van Niekerk W (2017) South Africa's present-day climate. In Mambo J, Faccer K, (eds). Understanding the Social and Environmental Implication of Global Change, African Sun Media: Stellenbosch.

Lengoasa JR (1991) Surface temperature field and circulation variations over southern Africa. South African Geographical Journal 73(2):41-47.

Lennard C (2019) Multi-Scale drivers of the South African weather and climate. In Knight J, Rogerson CM (eds). The Geography of South Africa. Springer: Switzerland.

Leriorato JC and Nakamura Y (2019) Unpredictable extreme cold events: a threat to range-shifting tropical reef fishes in temperate waters. Marine Biology. 166(220). https://doi.org/10.1007/s00227-019-3557-6.

Lötter D, (2017) South Africa's present-day climate. In Mambo J, Faccer K, (eds). Understanding the Social and Environmental Implication of Global Change, African Sun Media: Stellenbosch

Mackellar N, New M and Jack C (2014) Observed and modelled trends in rainfall and temperature for South Africa: 1960-2010. South African Journal of Science 110(7/8): 51-63. https://dx.doi.org/10.1590/sajs.2014/20130353.

Mann HB, (1945) Non-parametric tests against trend. *Econometrica*, 13, 245-259.

Martinez GS, Diaz J, Hooyberghs H, Lauwaet D, De ridder K, Linares C, Carmona R, Ortiz C, Kendrovski V and Adamonyte D (2018) Cold-related mortality vs heat-related mortality in a changing climate: A case study in Vilnius (Lithuania). Environmental Research. 166:384-393. https://doi.org/10.1016/j.envres.2018.06.001.

National Oceanic and Atmospheric Administration (NOAA) (2020) Anomalies vs Temperature: United States: National Centers for Environmental Information. Available from https://www.ncdc.noaa.gov/monitoring-references/dyk/anomalies-vs-temperature.

New M, Hewitson B, Stephenson DB, Tsiga A, Kruger A, *et al* (2006) Evidence of trends in daily extremes over southern and west Africa. Journal of Geophysical Research. 111. https//doi.org/10.1029/2005JD006289.

Muirhead R (2002) World weather disasters: July 2002. Journal of Meteorology. 273:359-360.

Nairn JR and Fawcett RJB, (2015) The Excess Heat Factor: A metric for heatwave intensity and its use in classifying heatwave severity. International Journal of Environmental Research and Public Health 12:227-253. DOI: 10.3390/ijerph120100227.

Panda K, Mishra A, Kumar A, Mandal KG, Thakur AK and Srivastava RC (2014) Spatialtemporal patterns in the mean and extreme temperature indices of India, 1971-2005. International Journal of Climatology 34:3585-3603. DOI: 10.1002/joc.3931.

Pascal M, Wagner V, Corsa M, Laaidi K, Ung A and Beaudeau P (2018) Heat and cold related-mortality in 18 French cities. Environmental International 121:189-198. https://doi.org/10.1016/j.envint.2018.08.049.

Pasquini L, Cowling RM and Ziervogel G (2013) Facing the heat: Barriers to mainstreaming climate change adaption in local government in the Western Cape Province, South Africa. Habitat Int 40:225-232. https://doi.org/10.1016/j.habitatint.2013.05.003

Perkins-Krikpartick SE and Gibson PB (2017) Changes in regional heatwave characteristics as a function of increasing global temperature. Scientific Reports. 7(1):1-12. http://dx.doi.org/10.1038/s41598-017-12520-2.

Perkins-Kirkpatrick SE, Fischer EM, Angélil O and Gibson PB (2017) The influence of internal climate variability on heatwave frequency trends. Environmental Research Letters 12. https://doi.org/10.1088/1748-9326/aa63fe.

Roffe SJ (2019) A statistical analysis of rainfall seasonality across South Africa. University of the Witwatersrand.

Salameh AAM, Gámiz-Fortis SR, Castro-Díez Y, Hammad AA and Esteban-Parra MJ (2018) Spatial-temporal analysis for extreme temperature indices over the Levant region. International Journal of Climatology 39:5556-5582. DOI: 10.1002/joc.6171.

Scott R (2015) Between extremes: health effects of heat and cold. Environmental Health Perspective. 123(11). https://dx.doi.org/10.1289/ehp.123-A275.

Scott AA, Waugh DW, Zaitchik BF (2018) Reducing urban heat island intensity under warmer conditions. Environmental Research Letters 13(6).

Sen PK (1986) Estimates the regression coefficient based on Kendall's tau. Journal of American Statistical Association 63:1379-1389.

Singleton AT, Reason CJC (2007). A numerical model study of an intense cut off low pressure system over South Africa. Monthly Weather Review 135:1128-1150

Smith ET and Sheridan SC (2018) The characteristics of extreme cold events and cold air outbreaks in the eastern United States. International Journal of Climatology 38. https://doi.org/10.1002/joc.5408.

Smith ET and Sheridan SC (2020) Where do cold air breaks occur and how have they changes over time? American Geophysical Union. https://doi.org/10.1029/2020GL086983.

Spearman C (1904) General intelligence objectively determined and measured. The American Journal of Psychology, 15:2, 201-292. DOI: 10.2307/1412107.

Stander JH (2013) Synoptic circulation patterns and atmospheric variables associated with significant snowfall over South Africa in winter. University of Pretoria.

Stander JH, Dyson L and Engelbrecht CJ (2016) A snow forecasting decision tree for significant snowfall over the interior of South Africa. South African Journal of Science. http://dx.doi.org/10.17159/sajs.2016/20160221.

Thorton PK, Ericksen PJ, Herror M and Challinor AJ (2014) Climate variability and vulnerability to climate change: A review. Global Change Biology 20:3313-3328. https://doi.org/10.111/gcb.12581.

Tyson PD and Preston-Whyte RA (2000) The atmosphere and weather of southern Africa. 2nd Ed. Cape Town: Oxford University Press Southern Africa. DOI: 10.1002/joc.725.

Van der Walt AJ and Fitchett JM (2020) Statistical classification of South African seasonal divisions on the basis of daily temperature data. South African Journal of Science (in press).

Van Huyssteen CW, Du Preez CC and Holmes PJ (2018) Agriculture and a changing biophysicial environment. In ed Holmes PJ, Boardman J (2018) Southern African landscapes and environmental change. Earthscan Studies in Natural Resource Management. Routledge. 228-248.

Vincent LA, Wang XL, Milewska EJ, Wan H, Feng Y and Swail V (2012) A second generation of homogenized Canadian monthly surface air temperature of climate trend analysis. Journal of Geophysical Research, 117. DOI: 10.1029/2012JD017859.

Wang X, Liu H, Gu M-B, Boucek R, Wu Z-M and Zhou G-Y (2016) Greater impacts from extreme cold spell on tropical than temperate butterflies in south China. Ecosphere 7(5). https://doi.org/10.1002/ecs2.1315.

Wang XL (2008a) Accounting for autocorrelation in detecting mean shifts in climate data series using penalized maximal *t* and *F* test. Journal of Applied Meteorology and Climatology 47: 2423-2444.

Wang XL (2008b) Penalized maximal F-test for detecting undocumented mean-shifts without trend-change. Journal of Atmospheric and Oceanic Technology 25(3): 368-384. DOI: 10.1175/2008/JTECHA982.1.

Wang XL and Feng Y (2013). RHtestsV4 User Manual. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada, 28pp. [Available online at https://github.com/ECCC-CDAS/RHtests/blob/master/V4_files/RHtestsV4_UserManual_10Dec2014.pdf]

Wenal G, Keqin D and Shuangshuang L (2019) Spatial-temporal variations in cold surge events in northern China during the period 1960-2016. Journal of Geographical Sciences 29(6):971-983. https://doi.org/10.1007/s11442-019-1668-0.

Xulu NG, Chikoore H, Bopape M-J and Nethengwe NS (2020) Climatology of the Mascarene High and its Influence on Weather and Climate over Southern Africa. Climate 8: 86, DOI: 10.3390/cli8070086

Yosef Y, Aguilar E and Alpert P (2019). Changes in extreme temperature and precipitation indices: Using an innovative daily homogenized database in Israel. International Journal of Climatology 39: 5022-5045.

Zhang X, Feng Y and Chan R (2018) Introduction to RClimDex v1.9, Climate Research Division, Environment Canada, Downsview, Ontario, Available from https://github.com/ECCC-CDAS/.

Zhao Q, Zhao Y, Li S, Zhang Y, Wang Q, Zhang H, Qiao H, Li W, Huxley R, Williams G, Zhang Y and Guo Y (2017) Impact of ambient temperature on clinical visits for cardio-respiratory diseases in rural villages in northwest China. Science of the Total Environment 612:379-385. https://doi.org/10.1016/j.scitotenv.2017.08.244.

Zhou, MG, Wang LJ, Lui T, Zhang YH, Lin HL, Luo Y, Xiao JP, Zeng WL, Zhang YW, Wang XF, Gu X, Rutherford S, Chu C, Ma WJ (2014) Health impact of the 2008 cold spell on mortality in the subtropical China: the climate and health impact national assessment study (CHINAs). Environmental Health 13:60. http://www.ehjournal.net/conent/13/1/60.

Ziervogel G, New M, Archer van Garderen E, *et al* (2014) Climate change impacts and adaption in South Africa. Wiley Interdisciplinary Reviews of Climatic Change 5:605-620. https://doi.org/10.1002/wcc.295

Chapter 8: Exploring extreme warm temperature trends in South Africa: 1960-2016

8.1. Brief Synopsis

This study attempts to understand the nature of heat events, as well as examine the frequency and duration of these events, and aims to provide updated trends of extreme warm temperature events on an annual and seasonal timescale for the period 1960-2016, for all the previously used ETCCDI temperature indices across South Africa. Also, this study will be the first to use and examine trends of the ET-SCI in a South African context.

Author contributions:

Contributor role	**Author contribution**
Conceptualisation	Jennifer M Fitchett
Methodology	Adriaan J van der Walt & Jennifer M Fitchett
Validation	Adriaan J van der Walt
Formal analysis	Adriaan J van der Walt
Investigation	Adriaan J van der Walt
Resources	Adriaan J van der Walt
Data curation	Adriaan J van der Walt
Writing – the original draft preparation	Adriaan J van der Walt
Writing – review and editing	Adriaan J van der Walt & Jennifer M Fitchett
Visualisation	Adriaan J van der Walt
Supervision	Jennifer M Fitchett
Project leader	Jennifer M Fitchett

According to the above-mentioned CRediT system the author contribution was calculated as follows:

Van der Walt, A.J – 70%

Fitchett, J.M – 30%

Submitted to: Theoretical and Applied Climatology

Impact Factor: 2.882

Reason for selection: The nature of the paper and the aim and scope of the journal which focus and offers the most significant developments from around the world in climate, atmosphere, and meteorology.

Submission date: 15 June 2020

Minor revisions: 13 October 2020

Resubmitted: 16 October 2020

Accepted: 19 November

The version to follow is the accepted version on 19 November 2020, with the addition of contiguous page numbers for this thesis. The PDF draft version is included as supplementary material (Supplement Material Chapter 8).

8.2. Abstract

Warm extreme temperature events or 'heatwaves' have disastrous impacts. Several high-impact heatwave events have recently occurred in the Global North, resulting in significant losses of human life and dire effects on economies. The expected increases in the frequency and intensity of extreme heat events under climate change poses a significant threat to South Africa. South Africa, a developing country, with an increasing population, faces many socioeconomic challenges. This study presents the first comprehensive annual and seasonal, spatial and temporal trend analyses of daily maximum and minimum extreme temperature events recorded from 20 meteorological stations across South Africa, spanning 1960-2016. Trend results based on the World Meteorological Organisation Expert Team on Climate Change Detection (ETCCDI) and the World Meteorological Organisation Commission for Climatology and Indices Expert Team on Sector-Specific Climate Indices (ET-SCI). Indices describing the characteristics of warm extremes are calculated using RClimDex and ClimPACT, respectively. The non-parametric Mann-Kendall test, Spearman Rank Correlation Coefficient and Sen's slope estimates were used to determine the statistical significance and magnitude of the calculated trend. Results show a general annual trend increase in maximum temperature at a rate of 0.02°C.y^{-1}. The majority of stations reveal statistically significant trends in warm days and nights; with the strongest, general annual trend increases experienced in warm days at a rate of 0.15%.yr^{-1}. Seasonally, the strongest increases of 0.11% days.yr^{-1} in warm days are evident for autumn, while increases of 0.07% days.y^{-1} are calculated for summer. A general increasing trend in heatwave events is recorded at 0.03 events.yr^{-1} countrywide.

Keywords: Extreme temperature events, ETCCDI indices, ET-SCI indices, Mann-Kendall test, Sen's slope

8.3. 1. Introduction

Over the past two decades, several high-impact extreme temperature events occurred in the Global North, most notably the 2003 European and 2010 Russian heatwaves which resulted in more than 70,000 and 10,000 human fatalities, respectively (Simmonds 2018; Ragone et al. 2018). These high-profile events garnered significant public attention due to the severe impacts on human health, ecosystems and socioeconomic development (Perkins et al. 2012; Simmonds 2018). More recently, less dramatic yet extraordinary extreme heat events have included the hottest heatwave in June 2019, resulting in 1,500 fatalities in France (Osborne 2019). The global interest in these extreme heat events is growing, particularly under current climate change projections indicating a likely increase in frequency and duration of heatwaves and warm spells across both the Northern and Southern Hemispheres (Alexander et al. 2006; Perkins et al. 2012; Perkins-Kirkpatrick et al. 2017).

In South Africa, the South African Weather Service (SAWS) defines heatwaves as climatological events where maximum temperatures are at least 5°C warmer than the recorded mean of the hottest month at a given location for a period of at least three days (Malherbe et al. 2020; SAWS 2020). By this definition, several heatwaves have been recorded over the past five years. The most recent involved record-high mean winter temperatures for the winter months (June, July and August) in the Eastern Cape in 2019, with mean daytime temperatures exceeding 20.9°C, followed by unseasonably, record-high maximum temperatures exceeding 35°C, recorded in Cape Town on 7 September 2019 (Head 2019). It is estimated that mean annual temperature in South Africa has increased by at least 1.5 times the global average, at an estimated 0.65°C over the past five decades (Ziervogel et al. 2014). Extreme climatic events are projected to increase in frequency and severity throughout the 21st century (Davis-Reddy and Vincent 2017). Without significant efforts to reduce the vulnerability of the region, exposure to extreme climate events, including temperature events, will increase (Davis-Reddy and Vincent 2017).

The expected increases in extreme heat events pose a significant threat to developing countries (Abatan et al. 2016), including South Africa. South Africa faces many pressing socio-economic development needs, compounded by environmental stressors and a growing and urbanizing population with greater exposure to these events (Pasquini et al. 2013; Davis-Reddy and Vincent 2017). Extreme temperatures have various impacts on ecosystems (Malherbe et al., 2020), agriculture (Mangani et al. 2018), water resources and energy (Lubega et al. 2018), infrastructure (Pasquini et al. 2013), tourism (Noome and Fitchett, 2019) and human health (Nana et al. 2019; Chersich and Wright, 2019). Regarding human health, exposure to abnormally high temperatures over a prolonged period (i.e. during warm spells and heatwaves) will result in heat stress (Lee 2014; Founda et al. 2019) which may lead to heat-related illnesses including cardiovascular disease, heatstroke, heat exhaustion, and mortality (Ngwenya et al. 2018). Despite these considerable threats, heat stress and heat events are inadequately understood and sometimes ignored (Lee 2014; Pelling et al. 2017), particularly in developing countries (Ngwenya et al. 2018). Therefore, given the increased attention due to the vulnerability of the society and ecosystems in South Africa (Pasquini et al. 2013), it is important to understand the nature of changes in temperature extremes in South Africa at different spatial and temporal timescales, which is vital for adaptation.

Several metrics have been developed to quantify extreme heat events; however, no universal definition exists (Perkins-Kirkpatrick and Gibson 2017). For instance, heatwaves can be defined as a period of consecutive days where conditions are hotter than usual, which includes seasonally extreme events such as summertime heatwaves, or seasonally anomalous warm spells occurring on an annual basis (Perkins et al. 2012). A set of metrics have been developed by the World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI; Zhang et al. 2018). These indices can be classified into duration indices, threshold indices, absolute indices and percentile indices (Klein Tank et al. 2009). Several studies have applied one or a combination of indices to examine trends in extreme temperature events globally (e.g. Alexander et al. 2006; Fischer and Shär 2010; Perkins et al. 2012; Perkins-Kirkpatrick and Gibson 2017), on the African continent (e.g. Abatan et al. 2016; Abatan et al. 2018), and specifically in South Africa (e.g. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017). Kruger and Sekele (2013) and Kruger and Nxumalo (2017) examined extreme temperature trends using a select few ETCCDI indices, for the periods 1962-2009 and 1931-2015, respectively. However, seasonal trends were not explored, and the time period of interest was limited. In the interests of global comparison, to explore the various facets of extreme temperature events, and to facilitate more precise attribution of the effects of these events, the WMO indices offer greater value than local definitions.

This study aims to provide updated trends of daily maximum and minimum temperature extremes on an annual and seasonal timescale for the period 1960 to 2016, for all indices, previously examined. Additionally, this study will make use of the extreme temperature indices developed by the Expert Team on Sector-Specific Climate Indices (ET-SCI) which was established by the WMO Commission for Climatology and Indices (CCI) (Alexander and Herold 2016; Yosef et al. 2019). The ET-SCI developed several sector-specific climate indices that consider health, water and agriculture derived from the ETCCDI (Alexander and Herold 2016; Yosef et al. 2019). This will be the first study using the ET-SCI to identify trends in warm events in South Africa, which is important in view of health, water and agricultural adaption strategies on a regional and national basis.

8.4. 2. Study Site

South Africa is located in the southern tip of Africa, spanning the subtropics and mid-latitudes between 22-35 °S, and 17-33 °E, bordered by the Atlantic Ocean in the west and southwest, the Indian Ocean to the south and east (Figure 1). The climate of South Africa is governed by the complex interaction between the subtropical location, the altitude of the interior plateau, and proximity to, and temperatures of, the oceans. South Africa's latitudinal range results in pronounced seasonal difference in rainfall and temperature patterns over South Africa, together with the intra-annual migration of the inter-tropical convergence zone (ITCZ; Lennard 2019). The high-pressure belt is situated over the southern tip of the subcontinent in summer, and over the interior during winter (Tyson and Preston-Whyte 2000). These high-pressure systems are interrupted by troughs associated with cold fronts. The influences of the subtropical high-pressure belt and the mid-latitude westerlies with associated fronts vary significantly interannually over the subcontinent. These interactions between tropical and temperate disturbances have significant consequences for the weather of the subcontinent (Tyson and Preston-Whyte 2000). The topography of South Africa is complex and predominantly characterized by the escarpment which influences the temperature distribution over the country where the escarpment forms a climatic division between the high plateau and the low-lying coastal regions in the east and southeast and (Figure 1; Grab and Knight 2018). The eastern and southern escarpments are the regions with the lowest temperatures, due to the decrease in temperature with altitude (Engelbrecht and Landman 2010; Grab and Knight 2018). The altitude ranges between the highest point of ~3000m.asl in the Lesotho/KwaZulu-Natal border and ~2000m.asl in the southern escarpment (Grab and Knight 2018).

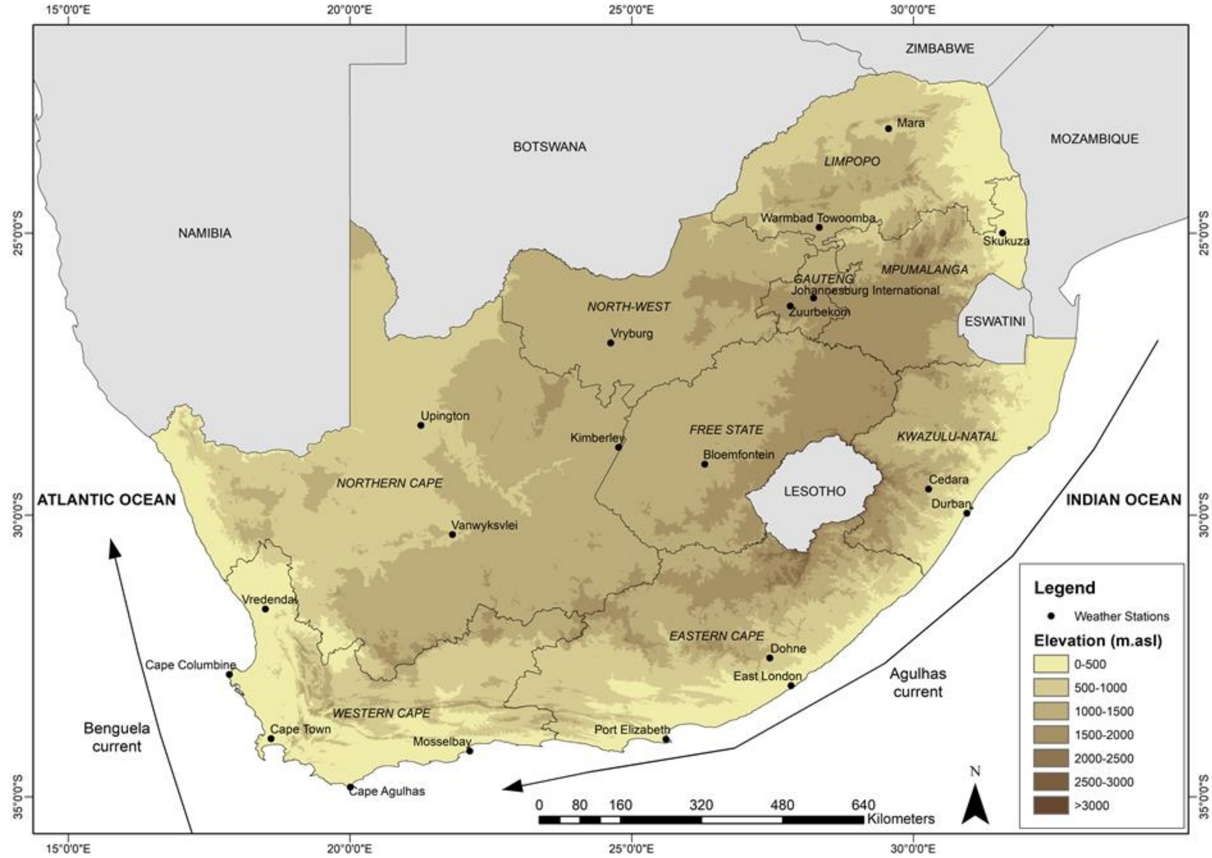


Figure 8.1 (Fig 1): Geographic location of selected meteorological stations.

8.5. 3. Data and Methodology

8.5.1. 3.1 Data

For this study, daily maximum temperature (TX) and minimum temperature (TN) data for the period 1960-2016 were obtained from 20 selected SAWS meteorological stations (Figure 1, Table 1), relatively evenly spatially distributed over South Africa. Only this discrete selection of weather stations were used to ensure consistency throughout the analysis period (cf. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017). Kruger and Nxumalo (2017) demonstrate that 20 stations are sufficient to define temperature variability to a reasonable degree across South Africa. The selection of the stations analysed in this study was based on the data quality length and, homogeneity of the time series, spanning at least 50 years.

Table 8.1 (Table 1): Selected meteorological stations information.

Province	Station Name	Climate Num	Abbreviation	Lat	Long	Year Period
Eastern Cape	Dohne	00798116	DH	-32.52	27.47	1960-2016
	East London	00595729	EL	-33.03	27.83	1960-2016
	Port Elizabeth	00351795	PE	-33.98	25.60	1960-2016
Free State	Bloemfontein	02615161	BFN	-29.10	26.30	1962-2016
Gauteng	Johannesburg International	*04763990*	JHB	-26.14	28.23	1959-2016
	Zuurbekom	04755288	ZB	-26.30	27.81	1959-2016
KwaZulu-Natal	Cedara	02394820	CD	-29.54	30.27	1959-2016
	Durban	0240808A2	DBN	-29.97	30.95	1960-2016
Limpopo	Mara	072200991	MR	-23.14	29.56	1959-2016
	Warmbad Towoomba	05895941	WBT	-24.90	28.32	1959-2016
Mpumalanga	Skukuza	05961793	SK	-24.99	31.59	1960-2016
Northern Cape	Kimberley	02904684	KB	-28.80	24.77	1959-2016
	Upington	03174765	UP	-28.43	21.27	1960-2016
	Vanwyksvlei	01935613	VW	-30.35	21.82	1961-2016
North-West	Vryburg	04322383	VB	-26.95	24.65	1960-2015
Western Cape	Cape Agulhas	00030204	CA	-34.83	20.01	1959-2016
	Cape Columbine	00606209	CC	-32.83	17.86	1959-2016
	Mosselbay	0012215	MB	-34.18	22.15	1959-2016
	Cape Town	0021178A3	CPT	-33.96	18.60	1959-2016
	Vredendal	0106880A2	VL	-31.67	18.50	1959-2016

All of the climate data were subjected to thorough data quality controls to identify errors, missing data and outliers (Klein Tank et al. 2009; Salameh et al. 2018). All dates and times were checked, and two decimal point rounding was used to maintain consistency throughout. Missing TN and TX daily data were replaced with stations adjacent to the site within a 10km radius, and if not possible, replaced with the five-day running average (Klein Tank et al. 2009). If data were not available for more than five consecutive days, the period was excluded. Years with <90% completeness were discarded from the data set (Mackellar et al. 2014; Abatan et al. 2016; Kruger and Nxumalo 2017; Kruger et al. 2019). Large data gaps in the timeseries were only found for three of the stations that were included in the study: Kimberley, Cedara and Dohne. However, 90% completeness could still be obtained through the aforementioned quality controls. The rest of the stations had only a few days of data missing for the full study period, which were replaced with the five-day running average (Klein Tank et al. 2009). The selected stations used are similar to those used in previous studies (Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017), due to the completeness of the records.

The statistical procedures in the R-based RClimDex v1.9 and ClimPACT v2 software package were used to flag missing values, identify outliers and aid with a visual inspection of the data series. It is important to note that the software does not calculate monthly indices if more than three days are missing in a month and if there are more than 15 missing days for the annual values (Zhang et al. 2018). The software allows the user to set the outlier threshold in terms of the standard deviation for the particular calendar day above the threshold, the default threshold of three standard deviations was used (Zhang and Yang 2004; Alexander and Herold 2006; Kruger and Nxumalo 2017; Zhang et al. 2018). Outliers in stations were compared to adjacent stations to determine whether an outlier was the result of systematic errors or natural factors. It is important to note that not all outliers are truly erroneous because their inclusion, exclusion or adjustment can significantly affect extreme analysis (Klein Tank et al. 2009).

The quality-controlled data time series were checked for non-climatic shifts that may exist in the data sets, which could result from changes in aspects such as observing site, instruments, station relocation, observing practices, time and automation of station during the period of data collection (Klein Tank et al. 2009; Aguilar et al. 2013; Kruger and Nxumalo 2017). Several methods have been used to examine and adjust non-climatic shifts in a data time series, and often depends on the types and magnitude of the inhomogeneity to be detected and adjusted (e.g. Vincent et al. 2002, 2012; Wang 2008a; Nemec et al. 2013; Salameh et al. 2018). For the homogeneity analysis, the R-based software package, RhtestsV4 adopted by the (ETCCDI) was used (Wang and Feng 2013). The RhtestsV4 detect and adjust for multiple change point in daily, monthly and annual time series. The statistical procedure is based on the penalized maximal *t*-test (Wang 2008a) and the penalized maximal *F*-test (Wang 2008b). Only the mean monthly time series was tested for inhomogeneities, due to the difficulty to test for non-climatic discontinuities in a daily time series (Wang and Feng 2013). The test was carried in this study without a reference series due to the difficulty in identifying and constructing an appropriate reference period, in particular for developing countries with a sparse distribution of long-term climate stations (Kruger and Nxumalo 2017). The necessary adjustments were applied to the daily data time series and loaded into the RClimDex and ClimPACT software to compute the extreme temperature indices.

8.5.2. 3.2 Extreme temperature indices

This study examines and compares trends in extreme warm temperature indices on an annual and seasonal time scale. The seasonal scale was based on the astronomical divisions of South Africa: summer spanning December through February, autumn encompassing March through May, winter from June to August, and spring from September to November (Van der Walt and Fitchett, 2020). While there is a degree of spatial heterogeneity in the seasonal brackets of South Africa when determined quantitatively (Van der Walt and Fitchett 2020), the astronomical divisions facilitate regional analysis and comparison.

A core set of 27 descriptive extreme indices for temperature and rainfall have been developed by the WMO (CCI)/World Climate Programme (WRCP)/Joint Commission for Oceanography and Marine Meteorology (JCOMM) ETCCDI (Klein Tank et al. 2009; Alexander and Herold 2016; Zhang et al. 2018). The ETCCDI can be grouped into four categories: (1) absolute indices (e.g. warmest day TXx, warmest night TXn); (2) threshold indices (e.g. summer days; SU25); percentile indices (e.g. warm days TX90p, warm nights TN90p); (4) duration indices (e.g. warm spell duration indicator; WSDI; Klein Tank et al. 2009; Zhang et al. 2018). These indices were designed to monitor the frequency and intensity of moderately extreme events, occurring several times per year rather than high-impact events (Klein Tank et al. 2009; Yosef et al.

2019). Only six extreme temperature ETCCDI were selected from the core set this study for purpose of comparison to previous studies (Table 2). In addition, five temperature indices were selected from the WMO CCI ECT-SCI, derived from the ETCCDI (Table 2). These indices have been developed for the use in sector applications, based on experts from agriculture, health and the water sector (Alexander and Herold 2016). These 11 extreme temperature indices were computed using the R software packages; RClimdex v1.9 for ETCCDI (Zhang et al. 2018) and ClimPACT v2 for the ET-SCI (Alexander and Herold 2016).

The ET-SCI user-defined Warm Spell duration index ($WSDI_n$) was set to three consecutive days where TX>90th percentile (e.g. $WSDI_3$), as research has indicated that three consecutive days of temperatures exceeding the 90th percentile (or broadly very hot weather) are required for the mortality rate to rise significantly above the antecedent rate (Nairn and Fawcett 2015). The HWN and HWD indices were calculated based on the Excess Heat Factor (EHF; cf. Perkens and Alexander 2013) with slight modifications to the EHF. Moreover, the user-defined TX_nTN_n indices were set to two consecutive days (e.g. TX_2TN_2). Shorter extreme warm events may affect many sectors, including health and infrastructure (Phanda et al. 2014). Detailed descriptions and definitions of the different indices used are recorded in Table 2. All the above-mentioned indices used were calculated for the base period of 1960-2016. ArcMap software was used to visually portray the trends, using the Mann-Kendall test as an identifier. The Inverse Distance Weighting (IDW) tool within the software was used to spatially interpolate the annual TXMean.

Table 8.2 (Table 2): ETCCDI and ET-SCI temperature indices used in this study for the period 1960-2016 (Adapted from Alexander and Herold; Zhang *et al*. 2018).

	Indices	**Long name**	**Definitions**	**Units**
ETCCDI indices	SU	Summer days	Count of days where TX (daily maximum temperature) >25°C	days
	TXx	Max TX (Warmest day)	The maximum monthly value of daily maximum temperature (TXx = max)	°C
	TNx	Min TX (Warmest night)	The monthly minimum value of daily maximum temperature (TNx = max)	°C
	TX90p	Warm days	Count of days where TX > 90th percentile	%
	TN90p	Warm night	Count of days where TX > 90th percentile	%
	WSDI	Warm spell duration indicator	Count of days in a span of at least six days where TX > 90th percentile	days
ET-SCI Indices	Txge35	User-defined TX	Count of days where TX (daily maximum temperature) >35°C	days
	$WSDI_n$	User-defined WSDI	Count of number of days with at least n consecutive days where TX>90th percentile	days
	TX_nTN_n	User-defined consecutive number of hot days and nights	The annual count of consecutive days where both TX>95th percentile and TN>95th percentile, where n >= 2 (and a max of 10)	Number of events
	HWN (EHF)	Heatwave number	The number of individual heatwaves that occur each summer (Nov – Mar in the southern hemisphere). A heatwave is defined as three or more days where either the Excess Heat Factor (EHF) is positive.	Events
	HWD (EHF	Heatwave duration	The length of the longest heatwave identified by the HWN	days

8.5.3. 3.3 Trend analysis and significance

Trend analyses for the various indices were performed for the period 1960-2016. To test whether the temperature series are non-stationary and to evaluate the magnitude of the trend, the non-parametric Spearman's Rank correlation coefficient (ρ) and Kendall's tau correlation coefficient (τ) was used. The Kendall's tau coefficient has the advantage of having a low sensitivity to change points due to inhomogeneous time series (Tabari and Talaee, 2011; Abbas et al. 2018). The Spearman's Rank correlation coefficient is calculated from ranks, while

Kendall's tau represents probability (Allen et al. 2015). Since time is the dependent variable in this study, Kendall's tau correlation coefficient takes on a special case called the Mann-Kendall test (MK) (cf. Allen et al. 2015). Sen's Slope (SS) was used to quantify the magnitude of the trend for specific indices (Sen 1968). Tests for statistical significance are conducted at the 5% level (cf. Phanda et al. 2014; Caloiero et al. 2017; Karki et al. 2019; Yosef et al. 2019). The ClimPACT software calculates the linear trends which were used to assist in the analysis of the HWN and HWD. ArcMap software was used to display the trends visually, using the Mann-Kendall test values as an identifier.

8.6. 4. Results

8.6.1. 4.1.1 Mean maximum temperatures (TXMean)

There is a notable increase of >8°C in TXMean from the southwestern to the northeastern parts of the country over the period 1960-2016, with lower TXMean along the west and south coast (Figure 2). The majority of the stations (19 of 20), have statistically significant increasing trends, with overall rate increases of 0.02°C.yr^{-1} (Figure 2; Table 3). The strongest statistically significant trend increase is evident in the Western Cape province at Vanwyksvlei, at a rate of increase of 0.05°C.yr^{-1}. The interior stations calculate a stronger increase of 0.03°C.yr^{-1}, compared to the coastal stations (0.02°C.yr^{-1}).

At a seasonal timescale (Table 4), the strongest trend and rates of increase are calculated for autumn, with a mean increase of 0.03°C.yr^{-1}. The strongest increases in autumn are calculated for stations located in Limpopo, Northern Cape, Eastern Cape at Dohne, Free State at Bloemfontein, Gauteng at Zuurbekom and the Western Cape province at Vredendal, at >0.04°C.yr^{-1} (Table 4). The overall calculated rate of increase in winter and spring TXMean is 0.02°C.yr^{-1}. The strongest increases in TXMean in winter are calculated for stations located in

Limpopo, Northern Cape, Free State, Gauteng at Zuurbekom, Mpumalanga at Skukuza, Western Cape province at Vredendal at >0.03°C.yr^{-1} (Table 4). In spring, the strongest increase is experienced in the Free State, Gauteng, Limpopo, Mpumalanga, Northern Cape, and the Western Cape province at Vredendal and Mosselbay with rate increases of >0.03°C.yr^{-1} (Table 4). In general, the calculated rate increase in TXMean is stronger in the interior stations for each season (>0.02°.yr^{-1}), compared to the coastal stations (Table 4).

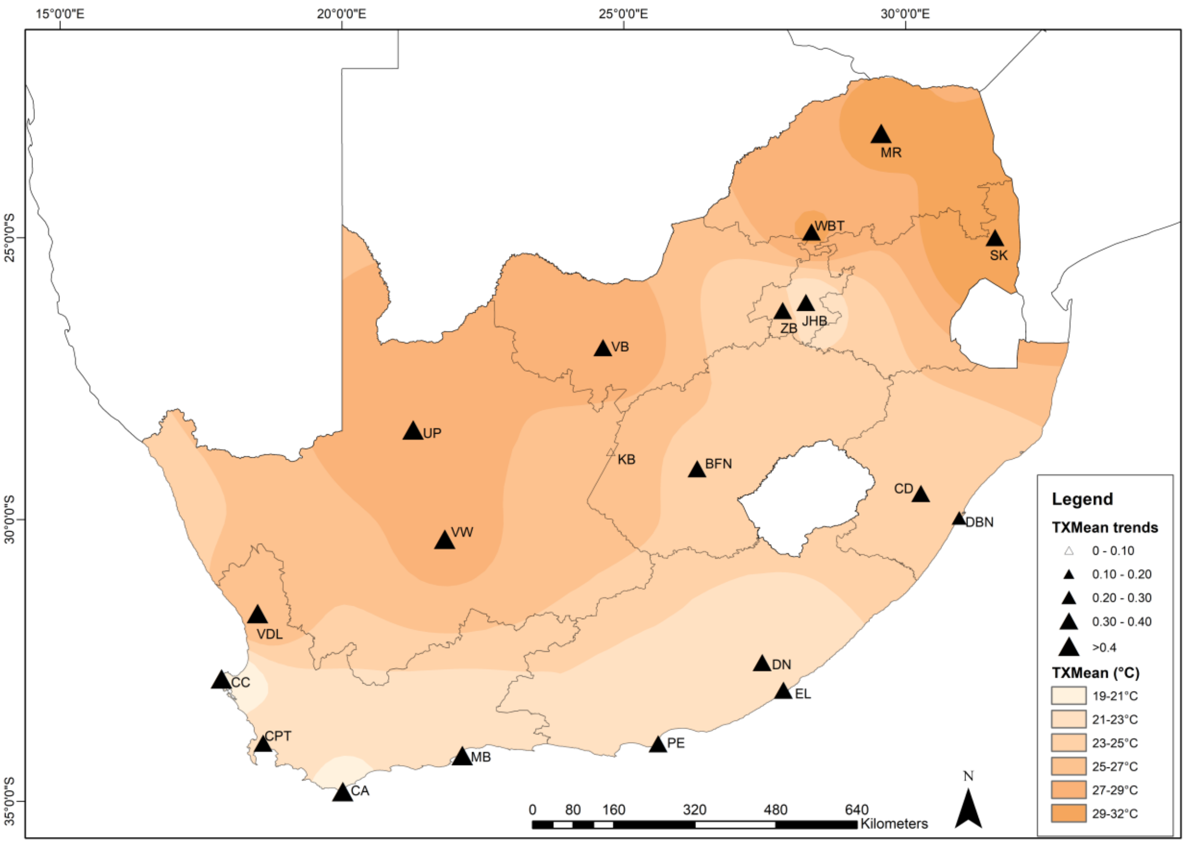


Figure 8.2 (Fig 2): Trends of TXMean over the period 1960-2016. Open downward, and upward triangles indicate negative and positive trends. Solid upward triangles indicate trends that are statistically significant at the 5% level.

Table 8.3 (Table 3): Increasing and decreasing trends in extreme warm temperature trends during 1960-2016.

Station	**TXMean**	**TXx**	**TNx**	**SU**	**TXge35**	**TX90p**	**TN90p**	**TX$_2$TN$_2$**
Dohne	**0.34** (**0.48**; 0.02)	0.03 (0.04; -)	-0.03 (-0.04; -)	**0.31** (**0.47**; 0.47)	0.06 (0.08; -)	**0.29** (**0.40**; 0.10)	**0.23** (0.24; 0.13)	0.13 (0.15; -)
East London	**0.33** (**0.51**; 0.01)	-0.03 (-0.04; -0.01)	- (0.01; -)	**0.20** (**0.34**; 0.27)	0.01 (0.01; -)	**0.26** (**0.40**; 0.05)	0.01 (0.03; -)	-
Port Elizabeth	**0.38** (**0.53**; 0.01)	**0.20** (**0.27**; 0.04)	0.06 (0.10; 0.01)	**0.29** (**0.41**; 0.35)	**0.22** (**0.30**; -; 0.02)	**0.23** (**0.35**; 0.05)	**-0.19** (**-0.30**; -0.06)	-
Bloemfontein	**0.37** (**0.52**; 0.03)	0.18 (0.25; 0.03)	0.12 (0.18; 0.03)	**0.33** (**0.48**; 0.57)	0.18 (0.25; 0.09)	**0.37** (**0.51**; 0.22)	-0.17 (-0.23; -0.06)	0.20 (0.24; -)
Johannesburg Int	**0.35** (**0.52**; 0.02)	0.14 (0.21; 0.01)	0.05 (0.08; 0.01)	**0.27** (**0.41**; 0.56)	0.07 (0.09; -)	**0.30** (**0.45**; 0.13)	**0.25** (**0.36**; 0.13)	**0.23** (**0.28**; -)
Zuurbekom	**0.35** (**0.49**; 0.03)	**0.29** (**0.41**; 0.05)	0.06 (0.09; 0.01)	**0.26** (**0.38**; 0.82)	**0.30** (**0.38**; -)	**0.38** (**0.51**; 0.22)	**0.32** (**0.45**; 0.12)	**0.30** (**0.37**; -)
Cedara	**0.33** (**0.47**; 0.02)	**0.19** (**0.28**; 0.03)	0.10 (0.11; 0.01)	**0.34** (**0.48**; 0.59)	0.16 (0.21; -)	**0.32** (**0.45**; 0.12)	0.15 (0.14; 0.07)	0.04 (0.05; -)
Durban	**0.29** (**0.43**; 0.01)	0.13 (0.18; 0.02)	0.04 (0.05; -)	**0.19** (**0.28**; 0.30)	0.17 (0.21; -)	**0.31** (**0.44**; 0.08)	0.17 (**0.29**; 0.06)	-
Mara	**0.49** (**0.68**; 0.04)	**0.34** (**0.50**; 0.04)	**0.25** (**0.35**; 0.04)	**0.49** (**0.67**; 0.84)	**0.34** (**0.49**; 0.42)	**0.52** (**0.70**; 0.21)	0.01 (0.01; -)	0.14 (0.17; -)
Warmbad Towoomba	**0.38** (**0.55**; 0.04)	**0.33** (**0.46**; 0.05)	0.08 (0.11; 0.02)	**0.41** (**0.57**; 0.51)	**0.40** (**0.52**; 0.40)	**0.37** (**0.50**; 0.20)	0.10 (0.14; 0.06)	0.23 (0.27; -)
Skukuza	**0.32** (**0.46**; 0.02)	0.11 (0.14; 0.01)	**0.28** (**0.42**; 0.05)	**0.40** (**0.40**: 0.56)	0.12 (0.16; 0.24)	**0.24** (**0.34**; 0.10)	**0.22** (**0.34**; 0.08)	-
Vryburg	**0.33** (**0.46**; 0.03)	**0.19** (0.28; 0.02)	**0.22** (**0.32**; 0.03)	**0.40** (**0.55**; 0.78)	0.08 (0.10; 0.08)	**0.31** (**0.45**; 0.17)	-0.10 (-0.15; -0.04)	0.04 (-; -)
Kimberley	0.15 (**0.56**; 0.02)	**0.24** (**0.34**; 0.02)	0.13 (0.18; 0.02)	**0.40** (**0.58**; 0.51)	**0.26** (**0.39**; 0.35)	**0.44** (**0.65**; 0.18)	**-0.25** (**-0.37**; -0.10)	**0.31** (**0.37**; -)
Upington	**0.58** (**0.58**; 0.03)	**0.32** (**0.46**; 0.03)	0.07 (0.11; 0.01)	**0.55** (**0.74**; 0.66)	**0.42** (**0.61**; 0.65)	**0.52** (**0.73**; 0.24)	0.04 (0.05; 0.02)	0.11 (0.13; -)
Vanwyksvlei	**0.59** (**0.78**; 0.04)	**0.38** (**0.55**; 0.03)	0.13 (0.19; 0.01)	**0.49** (**0.68**; 0.59)	**0.53** (**0.75**; 0.89)	**0.62** (**0.82**; 0.27)	0.04 (0.05; 0.01)	0.18 (0.22; -)
Cape Agulhas	**0.43** (**0.65**; 0.02)	0.15 (0.23; 0.03)	**0.28** (**0.40**; 0.02)	**0.45** (**0.65**; 0.40)	-0.10 (-0.12; -)	**0.47** (**0.72**; 0.14)	**0.39** (**0.57**; 0.14)	**0.32** (**0.38**; 0.01)
Cape Columbine	**0.42** (**0.58**; 0.02)	0.16 (0.23; 0.02)	0.30 (0.44; 0.02)	**0.27** (**0.40**; 0.16)	-0.01 (-0.01; -)	**0.31** (**0.47**; 0.08)	**0.26** (**0.37**; 0.11)	**0.23** (**0.28**; -)
Mosselbay	**0.49** (**0.70**; 0.02)	0.08 (0.15; 0.02)	0.15 (0.24; 0.02)	**0.47** (**0.68**; 0.52)	0.14 (0.18; -)	**0.49** (**0.71**; 0.14)	0.03 (0.02; 0.01)	0.21 (0.26; -)
Cape Town	**0.38** (**0.54**; 0.02)	0.04 (0.05; -)	0.11 (0.15; 0.01)	**0.40** (**0.57**; 0.58)	0.17 (0.24; -)	**0.28** (**0.43**; 0.06)	**0.38** (**0.56**; 0.12)	0.07 (0.09; -)
Vredendal	**0.63** (**0.81**; 0.05)	**0.47** (**0.67**; 0.08)	**0.26** (**0.39**; 0.02)	**0.57** (**0.75**; 0.75)	**0.53** (**0.74**; 0.57)	**0.57** (**0.77**; 0.15)	**0.30** (**0.41**; 0.07)	0.12 (0.14; -)
Averages	0.40 (0.57; 0.02)	0.20 (0.28; 0.03)	0.13 (0.19; 0.02)	0.37 (0.53; 0.54)	0.20 (0.28; 0.35)	0.38 (0.54; 0.15)	0.11 (0.15; 0.04)	0.19 (0.24; -)

** Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS).*

Table 8.4 (Table 4): Trend analysis of seasonal mean maximum temperatures (TXMean) for the period 1960-2016.

Stations	**TXMean**			
	Summer	*Autumn*	*Winter*	*Spring*
Dohne	0.10 (0.13; 0.01)	**0.37** (**0.53**; 0.04)	**0.20** (**0.30**; 0.02)	**0.30** (**0.38**; 0.03)
East London	0.16 (0.23; 0.01)	**0.33** (**0.48**; 0.02)	**0.20** (**0.29**; 0.01)	**0.28** (**0.40**; 0.01)
Port Elizabeth	**0.32** (**0.43**; 0.01)	**0.35** (**0.49**; 0.02)	0.14 (0.22; 0.01)	**0.23** (**0.32**; 0.01)
Bloemfontein	0.10 (0.16; 0.01)	**0.30** (**0.42**; 0.04)	**0.35** (**0.49**; 0.03)	**0.34** (**0.51**; 0.03)
Johannesburg Int	0.15 (0.21; 0.01)	**0.23** (**0.34**; 0.02)	**0.34** (**0.48**; 0.02)	**0.30** (**0.45**; 0.03)
Zuurbekom	0.19 (**0.28**; 0.02)	**0.32** (**0.45**; 0.04)	**0.32** (**0.45**; 0.03)	**0.27** (**0.41**; 0.03)
Cedara	**0.32** (**0.45**; 0.02)	**0.31** (**0.45**; 0.03)	**0.29** (**0.41**; 0.02)	**0.11** (0.15; 0.01)
Durban	**0.22** (**0.32**; 0.01)	**0.28** (**0.40**; 0.02)	**0.26** (**0.38**; 0.02)	**0.06** (0.07; -)
Mara	**0.23** (**0.35**; 0.02)	**0.28** (**0.41**; 0.04)	**0.51** (**0.69**; 0.04)	**0.43** (**0.59**; 0.04)
Warmbad Towoomba	**0.27** (**0.39**; 0.03)	**0.24** (**0.37**; 0.04)	**0.43** (**0.60**; 0.04)	**0.33** (**0.48**; 0.04)
Skukuza	0.06 (0.07; 0.01)	0.18 (0.26; 0.02)	**0.31** (**0.45**; 0.03)	**0.29** (**0.40**; 0.03)
Vryburg	0.07 (0.10; 0.01)	**0.27** (**0.38**; 0.04)	**0.37** (**0.53**; 0.03)	**0.26** (**0.37**; 0.03)
Kimberley	**0.32** (0.21; 0.02)	**0.28** (**0.48**; 0.04)	**0.30** (**0.40**; 0.02)	**0.29** (**0.42**; 0.02)
Upington	**0.44** (**0.44**; 0.03)	**0.47** (**0.47**; 0.05)	**0.33** (**0.33**; 0.03)	**0.31** (**0.31**; 0.03)
Vanwyksvlei	**0.51** (**0.72**; 0.04)	**0.49** (**0.67**; 0.06)	**0.34** (**0.52**; 0.03)	**0.40** (**0.58**; 0.04)
Cape Agulhas	**0.29** (**0.43**; 0.01)	**0.33** (**0.50**; 0.02)	**0.28** (**0.44**; 0.01)	**0.35** (**0.52**; 0.02)
Cape Columbine	**0.36** (**0.49**; 0.02)	**0.26** (**0.38**; 0.01)	**0.27** (**0.39**; 0.02)	**0.28** (**0.42**; 0.02)
Mosselbay	**0.41** (**0.59**; 0.02)	**0.47** (**0.63**; 0.03)	**0.21** (**0.29**; 0.01)	**0.37** (**0.53**; 0.03)
Cape Town	**0.42** (**0.59**; 0.03)	**0.29** (**0.42**; 0.02)	0.11 (0.17; 0.01)	0.16 (0.24; 0.01)
Vredendal	**0.55** (**0.75**; 0.06)	**0.58** (**0.77**; 0.05)	**0.29** (**0.43**; 0.03)	**0.40** (**0.56**; 0.04)
Averages	0.27 (0.37; 0.02)	0.33 (0.46; 0.03)	0.29 (0.41; 0.02)	0.29 (0.41; 0.02)

**Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS).*

8.6.2. 4.1.2 Warmest day (TXx) and warmest night (TNx)

At an annual scale, the warmest daytime (TXx; Figure 3a) and warmest night-time (TXn; Figure 3b) temperatures demonstrate a general warming trend in terms of frequency and occurrence over many parts of the country, with stronger trends observed in TXx (Table 3). The majority of stations (19 of 20) display an increasing trend (TXx; Figure 3a; Table 3), except East London which experiences a decreasing trend, with a rate decrease of 0.01°C.yr^{-1}. Overall, the TXx trends increased at a rate of 0.03°C.yr^{-1}. Similar results are evident from the

Spearman's Rank Correlation Coefficient. The strongest statistically significant increase of TXx is experienced predominantly in the northern interior parts of the country, with increases of >0.02°C.yr^{-1} (Table 3).

In general, increasing trends were calculated for each season (Table 5). The strongest overall calculated rate of the increasing trend is evident in autumn (0.04°C.y^{-1}) (Table 5), followed by winter (0.03°C.yr^{-1}). The lowest overall calculated increasing trend is evident in summer, with increases of 0.02°C.yr^{-1}. Most of the stations which experience statistically significant increasing trends in summer are located in Limpopo, Gauteng, KwaZulu-Natal, Northern Cape and the Western Cape province, with increases of >0.02°C.yr^{-1} (Table 5). Decreasing trends are evident in East London and Skukuza in summer, at 0.01°C.yr^{-1} (Table 5). In autumn, only five stations experience statistically significant increases, located in KwaZulu-Natal at Durban, Northern Cape and Western Cape province, with rate increases of >0.03°C.yr^{-1} (Table 5). Statistically significant increasing trends for winter are evident in 50% of the stations, at rates of >0.03°C.yr^{-1} (Table 5). For spring, statistically significant increasing trends are evident in stations located in Limpopo, Northern Cape at Vanwyksvlei and Upington, and the Western Cape province at Vredendal, with rate increases of >0.02°C.yr^{-1}, while decreasing trends are calculated for stations located in KwaZulu-Natal at Durban and the Western Cape province at Cape Town, at rates of 0.02°C.yr^{-1} and 0.01°C.yr^{-1} respectively (Table 5).

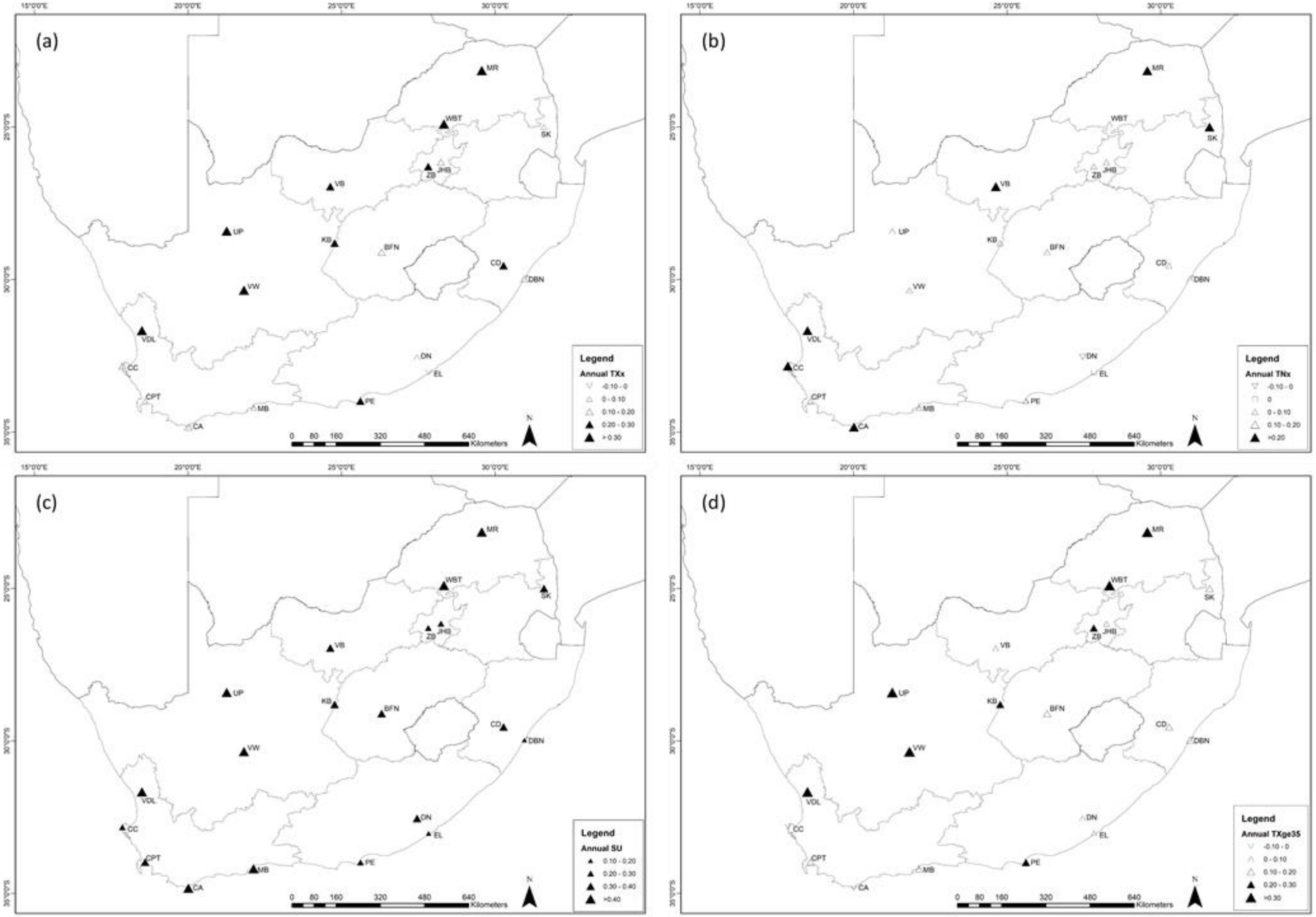


Figure 8.3 (Fig 3): Annual trends of (a) TXx, (b) TNx, (c) SU25, and (d) TXge35. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level.

Table 8.5 (Table 5): Trend analysis of seasonal warmest daytime (TXx) and night-time (TNx) temperatures for the period 1960-2016.

Stations	**TXx**				**TNx**			
	Summer	*Autumn*	*Winter*	*Spring*	*Summer*	*Autumn*	*Winter*	*Spring*
Dohne	0.03 (0.02; -)	0.18 (0.25; 0.04)	0.10 (0.14; 0.02)	0.23 (**0.31**; 0.04)	0.05 (0.06; 0.01)	**0.29** (**0.41**; 0.05)	0.10 (0.14; 0.01)	0.08 (0.14; 0.01)
East London	-0.03 (-0.08; -0.01)	0.15 (0.26; 0.03)	0.11 (0.16; 0.02)	0.06 (0.08; 0.03)	- (-0.02; -)	**0.19** (**0.30**; 0.03)	0.12 (0.18; 0.02)	0.08 (0.11; 0.01)
Port Elizabeth	- (-; -)	**0.27** (**0.35**; 0.06)	0.11 (0.16; 0.02)	0.02 (0.04; 0.01)	0.14 (0.20; 0.01)	**0.20** (**0.29**; 0.03)	0.07 (0.12; 0.01)	0.17 (0.25; 0.02)
Bloemfontein	0.16 (0.24; 0.03)	0.10 (0.14; 0.02)	**0.22** (**0.32**; 0.04)	0.11 (0.17; 0.01)	-0.02 (-0.01; -)	0.10 (0.16; 0.02)	0.11 (0.18; 0.03)	0.14 (0.21; 0.04)
Johannesburg Int	0.10 (0.14; 0.01)	0.11 (0.15; 0.02)	**0.22** (**0.30**; 0.03)	0.25 (**0.34**; 0.03)	0.12 (0.18; 0.02)	0.14 (0.19; 0.02)	0.04 (0.06; 0.01)	0.05 (0.07; 0.01)
Zuurbekom	**0.21** (**0.31**; 0.04)	0.19 (0.27; 0.04)	**0.35** (**0.49**; 0.05)	0.25 (**0.38**; 0.04)	0.09 (0.13; 0.02)	**0.21** (**0.30**; 0.05)	0.09 (0.13; 0.03)	0.05 (0.08; 0.01)
Cedara	**0.20** (**0.28**; 0.03**)**	0.17 (0.24; 0.03)	0.16 (0.23; 0.03)	0.12 (0.20; 0.02)	**0.21** (**0.31**; 0.02)	**0.26** (**0.38**; 0.04)	0.08 (0.10; 0.01)	0.11 (0.15; 0.02)
Durban	0.15 (0.22; 0.02)	**0.20** (**0.32**; 0.03)	0.07 (0.10; 0.01)	-0.10 (-0.13; -0.02)	0.09 (0.15; 0.01)	**0.24** (**0.35**; 0.03)	0.10 (0.15; 0.02)	0.05 (0.07; 0.01)
Mara	0.19 (**0.28**; 0.02)	0.22 (**0.32**; 0.04)	**0.36** (**0.50**; 0.04)	**0.34** (**0.49**; 0.04)	0.12 (0.17; 0.03)	0.15 (0.23; 0.03)	**0.29** (**0.40**; 0.06)	**0.20** (**0.29**; 0.04)
Warmbad Towoomba	**0.26** (**0.35**; 0.04)	0.10 (0.14; 0.02)	**0.21** (**0.32**; 0.03)	**0.35** (**0.50**; 0.04)	**0.19** (0.27; 0.04)	0.04 (0.05; 0.01)	0.14 (0.22; 0.03)	-0.02 (-; -0.01)
Skukuza	-0.08 (-0.12; -0.01)	0.04 (0.06; 0.01)	**0.21** (**0.29**; 0.04)	0.18 (0.26; 0.02)	0.06 (0.08; 0.01)	**0.22** (**0.32**; 0.05)	**0.24** (**0.35**; 0.05)	0.17 (0.25; 0.03)
Vryburg	0.10 (0.15; 0.01)	0.06 (0.11; 0.01)	0.17 (0.27; 0.03)	0.14 (0.19; 0.01)	0.08 (0.13; 0.02)	0.17 (0.26; 0.04)	**0.23** (**0.33**; 0.03)	0.05 (0.07; 0.01)
Kimberley	**0.20** (**0.29**; 0.02)	0.14 (0.22; 0.03)	0.14 (0.22; 0.02)	0.15 (0.22; 0.02)	0.11 (0.15; 0.03)	0.11 (0.16; 0.02)	0.13 (0.19; 0.02)	**0.24** (**0.35**; 0.05)
Upington	**0.32** (**0.46**; 0.03)	**0.25** (**0.36**; 0.04)	**0.30** (**0.41**; 0.05)	**0.26** (**0.36**; 0.02)	**0.32** (**0.46**; 0.08)	0.15 (0.21; 0.03)	0.10 (0.16; 0.01)	0.14 (0.19; 0.03)
Vanwyksvlei	**0.37** (0.54; 0.03)	**0.30** (**0.42**; 0.05)	**0.33** (**0.46**; 0.05)	**0.34** (**0.52**; 0.04)	**0.24** (**0.35**; 0.06)	0.16 (0.22; 0.03)	0.15 (0.20; 0.02)	0.17 (0.24; 0.04)
Cape Agulhas	**0.20** (0.27; 0.02)	**0.19** (**0.29**; 0.05)	0.09 (0.12; 0.02)	0.16 (0.24; 0.05)	**0.19** (**0.28**; 0.02)	**0.24** (**0.35**; 0.02)	**0.24** (**0.36**; 0.02)	**0.25** (**0.37**; 0.02)
Cape Columbine	0.21 (0.29; 0.05)	0.16 (0.23; 0.03)	0.14 (0.19; 0.02)	0.02 (0.03; 0.01)	0.16 (0.21; 0.01)	0.03 (0.04; -)	0.29 (0.43; 0.02)	0.23 (0.33; 0.02)
Mosselbay	0.16 (0.22; 0.03)	0.17 (0.25; 0.05)	0.15 (0.21; 0.02)	0.18 (0.26; 0.06)	0.09 (0.12; 0.01)	**0.25** (**0.34**; 0.02)	0.11 (0.16; 0.01)	**0.27** (**0.37**; 0.02)
Cape Town	0.10 (0.12; 0.02)	0.17 (0.24; 0.04)	0.01 (0.01; -)	-0.05 (-0.09; -0.01)	**0.24** (**0.34**; 0.03)	**0.18** (**0.29**; 0.02)	0.07 (0.10; 0.01)	0.09 (0.15; 0.01)
Vredendal	**0.43** (0.62; 0.08)	**0.32** (**0.44**; 0.06)	**0.21** (**0.30**; 0.03)	**0.36** (**0.50**; 0.07)	**0.35** (**0.47**; 0.05)	**0.22** (**0.33**; 0.03)	**0.24** (**0.37**; 0.02)	**0.29** (**0.40**; 0.04)
Averages	0.16 (0.23; 0.02)	0.17 (0.25; 0.04)	0.18 (0.26; 0.03)	0.17 (0.24; 0.03)	0.14 (0.20; 0.02)	0.18 (0.26; 0.03)	0.15 (0.22; 0.02)	0.14 (0.21; 0.02)

The TNx results (Figure 3b) similarly reveal an increasing trend for the majority of stations, five of which are statistically significant. These stations are located in Limpopo, Mpumalanga, North-West and Western Cape province with rate increases of >0.02°C.yr^{-1} (Figure 3b; Table 3). Bloemfontein also exhibits a strong rate increase of 0.03°C.yr^{-1}. In general, the overall calculated rate of the increasing trend over the country is 0.02°C.yr^{-1} (Table 3).

At a seasonal timescale (Table 5), the strongest overall increasing trend and rate of the increasing trend are calculated for autumn, with an overall increase of 0.03°C.yr^{-1}, followed by summer, spring and winter with rate increases of 0.02°C.yr^{-1}, respectively (Table 5). Most of the stations (18 of 20) experience increasing trends in summer, of which seven are statistically significant (Table 5). These stations are located in KwaZulu-Natal, Limpopo, Northern Cape and Western Cape province, with rate increases of >0.02°C.yr^{-1} in TNx, while Bloemfontein in the Free State province exhibits a decreasing trend of 0.02°C.yr^{-1}, for the period 1960-2016 (Table 5). Most of the stations (11 of 20) experience statistically significant increasing trends in autumn, which are located in the Eastern Cape, Gauteng at Zuurbekom, KwaZulu-Natal, Mpumalanga and Western Cape province, with rate increases of >0.02°C.yr^{-1} (Table 5). The strongest rate increases of 0.05°C.yr^{-1} in TNx are experienced in Zuurbekom, Dohne and Skukuza (Table 5).

All the stations experience increasing trends in winter, with the strongest rate increases of >0.03°C.yr^{-1} evident in stations located in the Free State, Gauteng at Zuurbekom, Limpopo and North-West province (Table 5). Most of the stations (19 of 20) experience increasing trends in spring, of which five being statistically significant (Table 5). The strongest rate increases of >0.04°C.yr^{-1} are evident in stations located in the Free State, Limpopo at Mara, Northern Cape at Kimberley and Vanwyksvlei, and Cape Town province at Vredendal (Table 5).

In short, an increasing trend is calculated for the TXx and TNx temperatures countrywide. Seasonal timescale findings indicate stronger increasing trends and rates of increases in warmest TXx in winter, and stronger TNx temperatures in autumn.

8.6.3. 4.1.3 Summer days (SU and TXge35)

All the stations experience a statistically significant increase in the number of summer days above 25°C (SU; Figure 3c), with an overall calculated rate of 0.54 days.yr^{-1} (Table 3). Stations with rate increases >0.54 days.yr^{-1} are located in the Free State, Gauteng, KwaZulu-Natal at Cedara, Limpopo at Mara, Mpumalanga, the North-West, Northern Cape at Upington, Vanwyksvlei and Western Cape province at Cape Town and Vredendal (Figure 3c; Table 3).

Most of the stations (18 of 20) experience increasing trends in days above 35°C (TXge35; Figure 3d), of which eight are statistically significant. These stations are located in Limpopo, Northern Cape, Eastern Cape at Port Elizabeth, and Western Cape province at Vredendal, with rate increases of >0.02 days.yr^{-1} (Table 3). The remaining two stations located in the Western Cape exhibit decreasing trends. Overall the calculated rate increase across the country is 0.35 days.yr^{-1}, for stations which exhibit rate increases (Table 3).

In summer, most of the stations (15 of 20) experience increasing trends in TXge35 (Table 6), of which four stations are statistically significant. These significant stations are located in the Northern Cape and Limpopo province at Warmbad Towoomba, at a rate increase of >0.17 days.yr^{-1} (Table 6). Four stations experience decreasing trends, which are located in the Eastern Cape at Dohne and East London, North-West at Vryburg, and Mpumalanga province at Skukuza, with rate decreases of >0.05 days/yr^{-1} in the latter two stations (Table 6). Most of the station (18 of 20) experience increasing trends in autumn (Table 6), of which six being statistically significant. Only four stations exhibit rate increases, which is located in

Mpumalanga, the Northern Cape at Upington and Vanwyskvlei, and the Western Cape province at Vredendal, with a rate increase of >0.04 days.yr^{-1} (Table 6). Only six stations: Port Elizabeth Durban, Mara, Warmbad Towoomba, Skukuza and Vredenal experience increasing trends in winter, with trend increases of >0.08 days.yr^{-1} for the period 1960-2016 (Table 6). Most of the stations (15 of 20) experience increasing trends in spring (Table 6), ten of which are statistically significant. Only seven of these statistically significant stations experience rate increases of >0.10 days.yr^{-1}, which are located in Limpopo, Mpumalanga, Northern Cape and Western Cape province at Vredendal (Table 6). Of the remaining stations, four experience decreasing trends which are located in the Eastern Cape at East London, KwaZulu-Natal at Durban and the Western Cape province at Cape Agulhas and Cape Town, with trend decreases of >0.02 days.yr^{-1} for the period 1960-2016 (Table 6).

Table 8.6 (Table 6): Seasonal trend analysis of days above 35ºC (TXge35), for the period 1960-2016.

Stations	**TXge35**			
	Summer	*Autumn*	*Winter*	*Spring*
Dohne	-0.01 (-0.01; -)	0.05 (0.06; -)	- (-; -)	**0.29** (**0.37**; -)
East London	-0.04 (-0.04; -)	0.06 (0.07; -)	- (-; -)	-0.02 (-0.03; -)
Port Elizabeth	0.02 (0.02; -)	**0.24** (**0.31**; -)	0.19 (0.23; -)	0.10 (0.12; -)
Bloemfontein	0.15 (0.21; 0.06)	**0.25** (0.30; -)	- (-; -)	0.20 (0.25; -)
Johannesburg Int	0.07 (0.09; -)	- (-; -)	- (-; -)	- (-; -)
Zuurbekom	0.19 (0.25; -)	0.06 (0.07; -)	- (-; -)	**0.44** (**0.54**; -)
Cedara	0.13 (0.17; -)	**0.29** (**0.35**; -)	- (-; -)	0.02 (0.03; -)
Durban	0.18 (0.22; -)	**0.23** (**0.28**; -)	0.08 (0.09; -)	-0.10 (-0.13; -)
Mara	0.19 (0.26; 0.13)	0.17 (0.24; -)	0.13 (0.16; -)	**0.44** (**0.58**; -)
Warmbad Towoomba	**0.31** (**0.43**; 0.17)	0.22 (**0.28**; -)	0.13 (0.16; -)	**0.36** (**0.47**; 0.19)
Skukuza	-0.06 (-0.07; -0.06)	0.07 (0.10; 0.04)	0.17 (0.22; -)	**0.29** (**0.39**; 0.21)
Vryburg	-0.06 (-0.08; -0.05)	0.04 (0.06; -)	- (-; -)	**0.23** (**0.32**; 0.13)
Kimberley	**0.21** (**0.29**; 0.24)	0.07 (0.10; -)	- (-; -)	**0.31** (**0.41**; 0.10)
Upington	**0.33** (**0.48**; 0.27)	**0.30** (**0.44**; 0.18)	- (-; -)	**0.34** (**0.48**; 0.20)
Vanwyksvlei	**0.50** (**0.70**; 0.55)	**0.33** (**0.49**; 0.13)	- (-; -)	**0.44** (**0.60**; 0.19)
Cape Agulhas	- (-; -)	0.05 (0.06; -)	- (-; -)	-0.18 (-0.22; -)
Cape Columbine	0.08 (0.09; -)	-0.01 (-0.01; -)	- (-; -)	0.02 (0.02; -)
Mosselbay	0.03 (0.04; -)	0.15 (0.18; -)	- (-; -)	0.08 (0.10; -)
Cape Town	0.08 (0.12; -)	0.19 (0.25; -)	- (-; -)	-0.13 (-0.15; -)
Vredendal	0.41 (**0.57**; 0.26)	**0.47** (**0.65**; 0.21)	0.18 (0.22; -)	**0.28** (**0.38**; 0.11)
Averages	0.14 (0.20; 0.16)	0.17 (0.23; 0.11)	0.13 (0.15; -)	0.18 (0.24; 0.14)

**Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS).*

8.6.4. 4.1.4 Warm days (TX90p) and warm nights (TN90p)

In general, the frequency of annual TX90p is increasing across the country. All the stations experience statistically significant increasing trends (Figure 4a), with an overall calculated rate increase of 0.15% days.yr^{-1}. Stations with rate increases >0.20 days.yr^{-1} are located in the Free State, Limpopo, Gauteng at Zuurbekom and the Northern Cape province at Upington and Vanwyskvlei (Table 3). Generally, the interior stations show a stronger calculated rate increase of 0.18% days.yr^{-1}, compared to the coastal stations (0.10% days.yr^{-1}).

In summer, the majority of the stations (18 of 20), experience an increasing trend in TX90p (Figure 4b), of which ten being statistically significant. These statistically significant stations are located in the Eastern Cape, KwaZulu-Natal, Limpopo, Gauteng, Northern Cape and Western Cape (Figure 4b), with rate increases of >0.09% days.yr^{-1} (Table 7). The two remaining stations experience decreasing trends (Figure 4b), at a rate decrease of 0.06% days.yr^{-1} evident only in Skukuza (Table 7). Overall, an increasing rate of 0.11% days.yr^{-1} in TX90p has been calculated in spring. All the stations experience increasing trends in autumn (Figure 4c), 15 of which are statistically significant. The strongest rate increases are experienced in stations located in the Northern Cape, with rate increases of >0.20% days.yr^{-1}. Overall, an increasing rate of 0.17% days.yr^{-1} in TX90p has been calculated (Table 7).

All the stations experience an increasing trend in winter (Figure 4d), 14 of which are statistically significant (Figure 4d). These stations are predominantly located in the northeastern interior parts of the country, with increases of >0.11% days.yr^{-1} in TX90p (Figure 4d; Table 7). The south and west coast stations experience smaller insignificant trend increases, at a rate of >0.02% days.yr^{-1} for TX90p (Figure 4d; Table 7). The overall, calculated rate increase in TX90p in winter is 0.15% days.yr^{-1}. Similar to winter, all the stations in spring experience an increasing trend, with 14 trends statistically significant (Figure 4e). These statistically significant stations are located in the Free State, Gauteng, Limpopo, Mpumalanga, North-West, Northern Cape, Eastern Cape at East London, and the Western Cape province at Cape Agulhas, Mosselbay and Vredendal, with rate increases of >0.08% days.yr^{-1} (Figure 4e; Table 7). Overall, a calculated rate increase is experienced in TX90p in spring of 0.14% days.yr^{-1}. In short, the strongest rate increase in TX90p is experienced in autumn, followed by winter (Table 7).

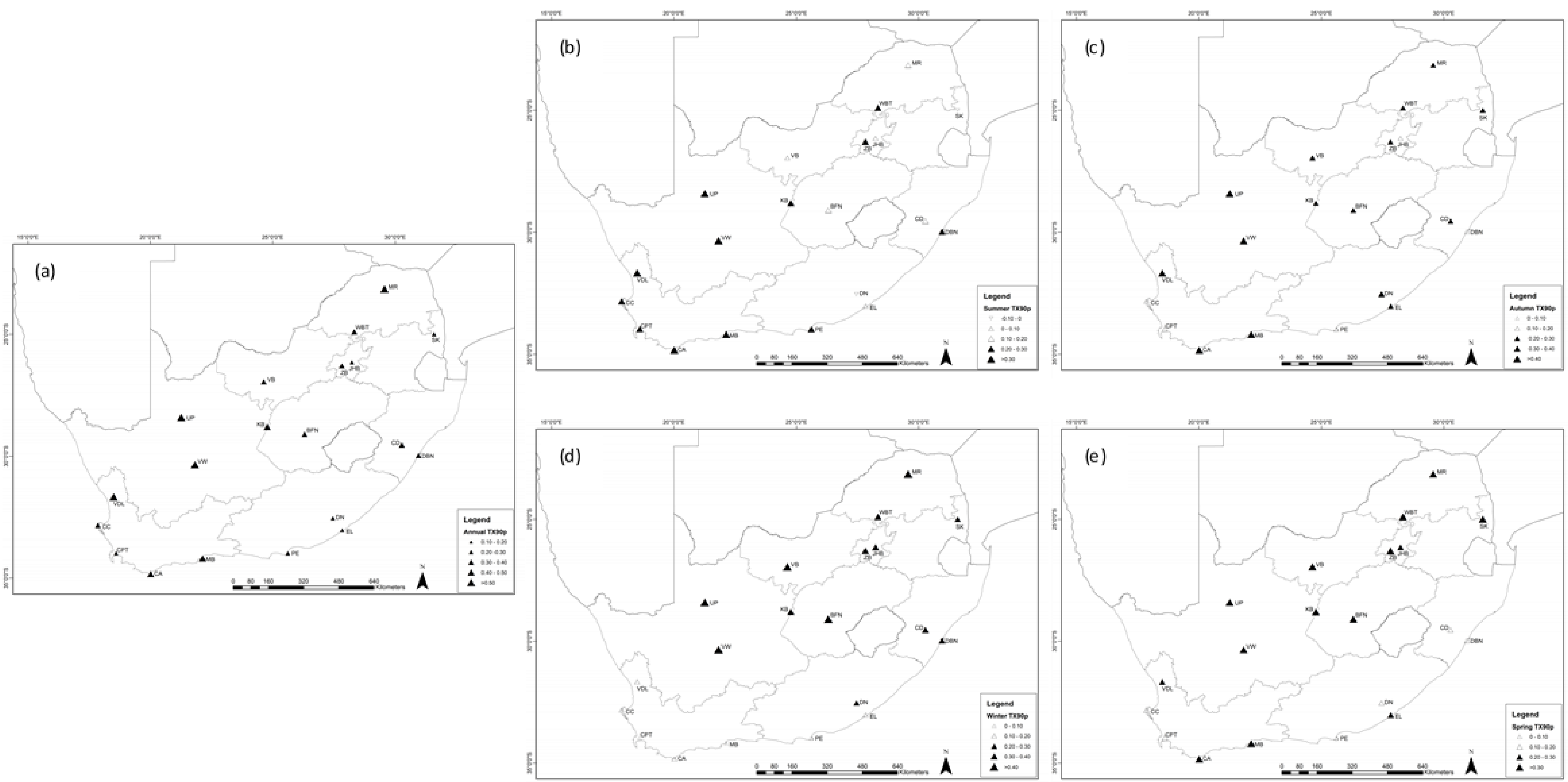


Figure 8.4 (Fig 4): Annual trends of (a) TX90p and mean seasonal temperature trends of (b) TX90p Summer, (c) TX90p Autumn, (d) TX90p Winter, and (c) TX90p Spring. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level.

Table 8.7 (Table 7): Trend analysis of seasonal frequency of warm days (TX90p) and warm nights (TN90p) for the period 1960-2016.

Stations	**TX90p**				**TN90p**			
	Summer	*Autumn*	*Winter*	*Spring*	*Summer*	*Autumn*	*Winter*	*Spring*
Dohne	-0.01 (-0.03; -)	**0.35** (**0.47**; 0.23)	**0.29** (**0.40**; 0.17)	0.16 (0.24; 0.06)	**0.25** (**0.31**; 0.13)	**0.21** (0.24; 0.14)	0.11 (0.15; 0.05)	0.08 (0.06; 0.07)
East London	0.05 (0.08; 0.01)	**0.21** (**0.31**; 0.08)	0.11 (0.15; 0.03)	**0.21** (0.35; 0.08)	0.07 (0.08; 0.03)	-0.03 (-0.06; -0.01)	0.01 (0.01; -)	-0.03 (-0.05; -0.01)
Port Elizabeth	**0.23** (0.32; 0.09)	0.13 (0.19; 0.05)	0.08 (0.11; 0.03)	0.06 (0.09; 0.02)	0.08 (0.12; 0.05)	**-0.28** (**-0.42**; -0.13)	**-0.20** (**-0.34**; -0.09)	-0.05 (-0.08; -0.02)
Bloemfontein	0.14 (0.19; 0.09)	**0.26** (**0.37**; 0.20)	**0.46** (**0.63**; 0.28)	**0.38** (**0.55**; 0.22)	-0.13 (-0.18; -0.08)	-0.15 (-0.23; -0.09)	0.08 (0.12; 0.03)	-0.12 (-0.15; -0.08)
Johannesburg Int	0.08 (0.12; 0.06)	0.18 (0.27; 0.12)	**0.33** (0.49; 0.19)	**0.30** (0.44; 0.18)	**0.24** (**0.35**; 0.12)	**0.19** (**0.27**; 0.12)	0.15 (0.23; 0.08)	0.17 (0.24; 0.08)
Zuurbekom	**0.20** (**0.28**; 0.12)	**0.29** (**0.42**; 0.25)	**0.36** (**0.51**; 0.21)	**0.36** (**0.48**; 0.22)	**0.23** (**0.33**; 0.13)	0.16 (0.23; 0.11)	**0.22** (**0.33**; 0.13)	-0.01 (0.01; -)
Cedara	0.17 (0.23; 0.08)	**0.28** (**0.39**; 0.18)	**0.32** (**0.45**; 0.16)	0.18 (0.27; 0.07)	0.11 (0.15; 0.05)	0.06 (0.07; 0.03)	0.14 (0.18; 0.08)	-0.07 (-0.11; -0.03)
Durban	**0.20** (**0.29**; 0.09)	0.17 (0.25; 0.11)	**0.32** (**0.42**; 0.13)	0.17 (0.24; 0.06)	0.16 (0.22; 0.08)	0.15 (0.25; 0.07)	**0.19** (**0.29**; 0.09)	-0.08 (-0.11; -0.03)
Mara	0.18 (0.24; 0.11)	**0.28** (**0.42**; 0.21)	**0.50** (**0.68**; 0.25)	**0.54** (**0.72**; 0.26)	0.07 (0.10; 0.04)	0.02 (0.02; 0.01)	-0.05 (-0.09; -0.02)	0.01 (-0.03; -)
Warmbad Towoomba	**0.25** (**0.37**; 0.17)	**0.21** (**0.32**; 0.15)	**0.40** (**0.56**; 0.21)	**0.38** (**0.52**; 0.23)	0.14 (0.18; 0.08)	0.05 (0.06; 0.02)	0.11 (0.14; 0.04)	0.13 (0.17; 0.05)
Skukuza	-0.09 (-0.15; -0.06)	**0.23** (**0.33**; 0.14)	**0.23** (**0.33**; 0.11)	**0.37** (**0.50**; 0.15)	0.17 (0.27; 0.07)	0.13 (0.18; 0.08)	0.11 (0.15; 0.04)	0.11 (0.16; 0.06)
Vryburg	0.01 (-; -)	**0.27** (**0.40**; 0.18)	**0.42** (**0.55**; 0.23)	**0.34** (**0.47**; 0.20)	-0.13 (-0.20; -0.08)	-0.07 (-0.10; -0.04)	0.08 (0.10; 0.04)	-0.14 (-0.20; -0.06)
Kimberley	**0.20** (**0.30**; 0.14)	**0.28** (**0.41**; 0.20)	**0.37** (**0.53**; 0.20)	**0.43** (**0.64**; 0.20)	**-0.19** (**-0.27**; -0.12)	-0.17 (-0.23; -0.10)	**-0.20** (**-0.30**; -0.10)	**-0.28** (**-0.39**; -0.12)
Upington	**0.37** (**0.54**; 0.20)	**0.43** (**0.61**; 0.29)	**0.54** (**0.74**; 0.28)	**0.33** (**0.51**; 0.16)	-0.03 (-0.05; -0.01)	0.14 (0.21; 0.08)	-0.01 (-0.03; -)	-0.06 (-0.08; -0.03)
Vanwyksvlei	**0.48** (**0.67**; 0.26)	**0.44** (**0.62**; 0.34)	**0.54** (**0.74**; 0.26)	**0.41** (**0.59**; 0.21)	0.12 (0.15; 0.05)	0.13 (0.19; 0.05)	0.02 (0.04; 0.01)	-0.09 (-0.11; -0.06)
Cape Agulhas	**0.38** (**0.56**; 0.22)	**0.43** (**0.60**; 0.20)	0.13 (0.19; 0.06)	**0.34** (**0.49**; 0.19)	**0.31** (**0.46**; 0.20)	0.03 (0.05; 0.01)	**0.23** (**0.34**; 0.12)	**0.38** (**0.52**; 0.23)
Cape Columbine	0.30 (0.44; 0.14)	0.15 (0.23; 0.06)	0.19 (0.28; 0.08)	0.16 (0.23; 0.06)	**0.23** (0.33; 0.13)	0.11 (0.17; 0.05)	**0.22** (**0.32**; 0.11)	0.16 (0.19; 0.08)
Mosselbay	**0.46** (**0.66**; 0.19)	**0.47** (**0.63**; 0.17)	0.08 (0.12; 0.03)	**0.39** (**0.54**; 0.16)	0.16 (0.24; 0.08)	-0.14 (-0.21; -0.07)	**-0.19** (**-0.29**; -0.09)	0.14 (0.17; 0.09)
Cape Town	0.23 (0.36; 0.09)	0.11 (0.16; 0.04)	0.06 (0.09; 0.02)	0.14 (0.20; 0.07)	**0.40** (**0.56**; 0.21)	**0.21** (**0.30**; 0.10)	0.07 (0.12; 0.03)	**0.20** (**0.31**; 0.10)
Vredendal	**0.42** (**0.57**; 0.16)	**0.54** (**0.73**; 0.22)	**0.20** (**0.32**; 0.10)	**0.21** (**0.32**; 0.10)	**0.33** (**0.48**; 0.16)	0.11 (0.15; 0.04)	-0.06 (-0.09; -0.02)	0.01 (0.03; -)
Averages	0.21 (0.30; 0.11)	0.29 (0.41; 0.17)	0.30 (0.41; 0.15)	0.29 (0.42; 0.14)	0.13 (0.18; 0.07)	0.04 (0.06; 0.02)	0.05 (0.07; 0.03)	0.02 (0.03; 0.02)

*Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS).

For annual TN90p, most of the stations (16 of 20), have experienced increasing trends (Figure 5a; Table 3), of which eight are statistically significant. These stations are located in the Western Cape, Mpumalanga, Gauteng and Eastern Cape province at Dohne, which experience rate increases of >0.08% days.yr^{-1} (Figure 5a; Table 3). Decreasing trends of >0.04% days.yr^{-1} are calculated for the remaining four stations: Bloemfontein, Vryburg, Port Elizabeth and Kimberley with the latter two being statistically significant. Overall, a calculated rate increase of 0.04% days.yr^{-1} has been found in TN90p countrywide.

For summer, increasing trends are calculated for the majority of the stations (16 of 20; Figure 5b; Table 7), seven of which are statistically significant. These significant stations are located predominantly in the Western Cape, Gauteng and Eastern Cape at Dohne, with a rate increase of >0.12% days.yr^{-1} (Table 7). The remaining four stations, which are located in the Free State and Northern Cape province, exhibit decreasing trends with rate decreases of >0.01% days.yr^{-1}. Kimberley is the only station with a statistically significant decrease (Figure 5b; Table 7). Overall, an increase of 0.07% days.yr^{-1} is calculated for TN90p in summer. Most of the stations (14 of 20) experience increasing trends for autumn (Figure 5c), three of which are statistically significant. These stations, Dohne, Johannesburg Int and Cape Town experience increases of >0.10% days.yr^{-1} in TN90p (Table 7). Decreasing trends in TN90 are evident in the remaining six stations at >0.04% days.yr^{-1}; only Port Elizabeth has a calculated statistically significant decrease (Figure 5c). Overall, a rate increase of 0.02% days.yr^{-1} has been calculated for TN90p in autumn. Increasing trends are evident in most of the stations (14 of 20) in winter (Figure 5d; Table 7), of which four are statistically significant. These stations: Zuurbekom, Durban, Cape Agulhas and Cape Columbine experience rate increases of >0.09% days.yr^{-1} in TN90p (Figure 5d; Table 7). The remaining six stations experience decreasing trends with rate decreases of >0.02% days.yr^{-1}, of which Port Elizabeth, Kimberley and Mosselbay being statistically significant (Figure 5d; Table 7). An overall increase of 0.03% days.yr^{-1} in TN90p has been calculated for winter (Table 7). In general, an increase of 0.02% days.yr^{-1} in TN90p is calculated for spring, with 50% of the stations exhibiting increasing trends (Table 7). Most of the stations with increasing trends are located in the Limpopo, Mpumalanga and the Western Cape province, of which Cape Agulhas and Cape Town being statistically significant, with a rate increase of >0.10% days.yr^{-1} (Figure 5e; Table 7). Stations with decreasing trends, with rate decreases of >0.01% days.yr^{-1} are located in the Eastern Cape, Free State, KwaZulu-Natal, North-West and Northern Cape province, of which Kimberley being statistically significant (Figure 5e; Table 7). In short, the strongest rate of increase in TN90p is evident in summer, followed by winter.

In addition to TX90P and TN90p, TX_2TN_2 was calculated. Only 16 out of the 20 stations exhibit trends, of which four are statistically significant (Table 3). These stations are located in Gauteng and along the west coast, with increases of >0.23 events.yr^{-1} for the period 1960-2016. Cape Agulhas exhibit the only rate increase of 0.01 events.yr^{-}1 in TX_2TN_2 events.

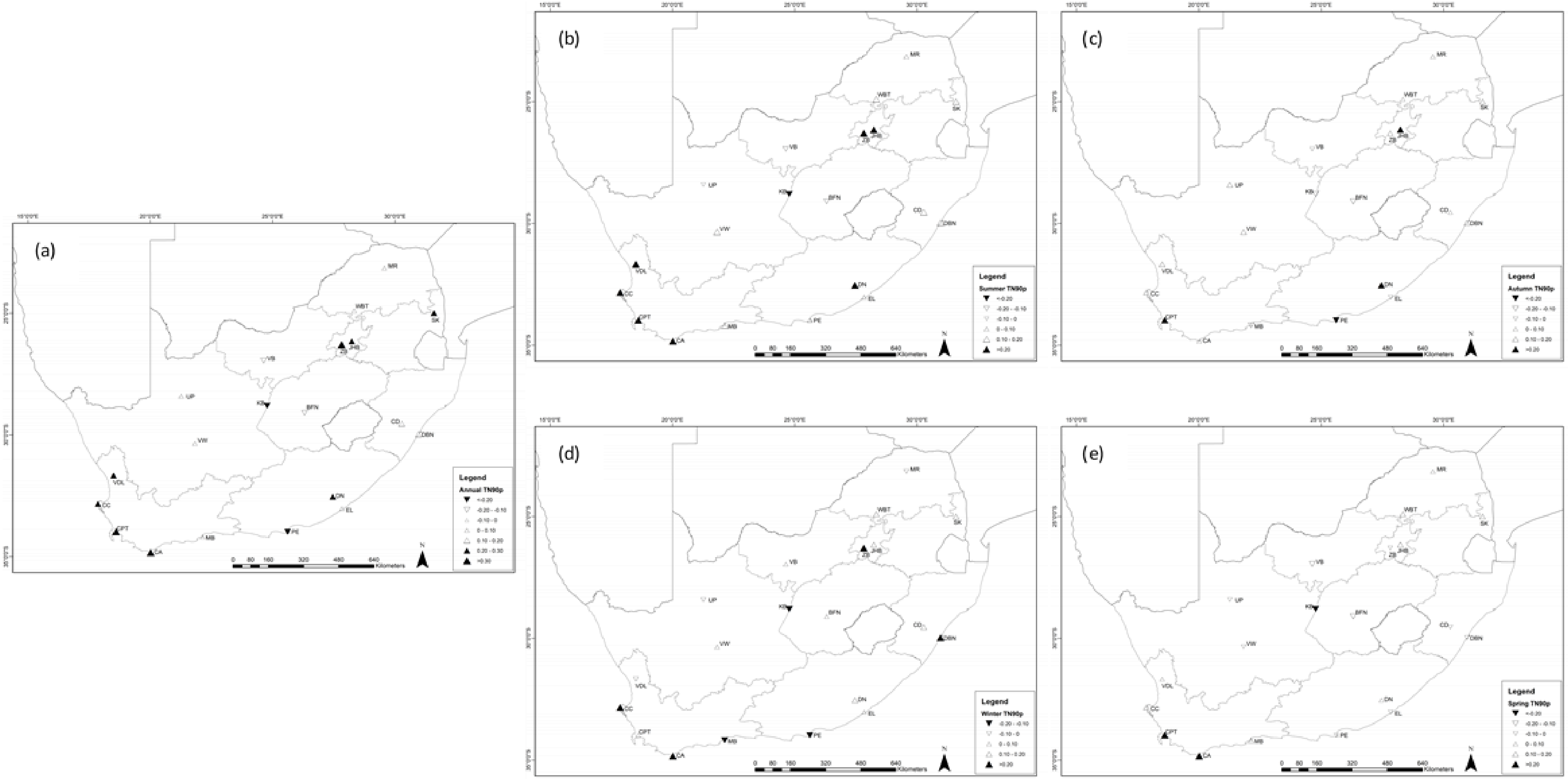


Figure 8.5 (Fig 5): Annual trends of (a) TN90p and mean seasonal temperature trend of (b) TN90p Summer, (c) TN90p Autumn, (d) TN90p Winter, and (c) TN90p Spring. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level.

8.6.5. 4.1.5 Warm spell duration indicator and Heatwaves

Most of the stations (18 of 20) experience increasing trends in WDSI, ten of which are statistically significant (Figure 6a). These stations are located in the Free State, Gauteng, KwaZulu-Natal, Limpopo, Northern Cape and the Western Cape province, with increases of >0.22 days.yr^{-1} for the period 1960-2016 (Table 8). The Spearman's Rank Correlation Coefficient display similar results. No substantial rate of the increasing trends was found in the stations (Table 8).

All sampled stations experience an increasing trend in $WSDI_3$ (Figure 6b; Table 8), 15 of which are statistically significant. These statistically significant stations are located in the Free State, Gauteng, Northern Cape, Limpopo, North-West, Eastern Cape at Dohne, KwaZulu-Natal at Cedara, and Western Cape province, which experience rate increases of >0.09 days.yr^{-1} in $WSDI_3$ (Figure 6b; Table 8). Smaller increasing trends are evident in the coastal stations, except for Cape Agulhas, Cape Columbine and Mosselbay with rate increases between 0.09 days.yr^{-1} and 0.25 days.yr^{-1} (Table 8). The overall calculated rate increase is 0.30 days.yr^{-1} for the $WSDI_3$ index over the country (Table 8).

Most of the stations (19 of 20) experience an increasing trend in heatwave events (HWN; Figure 6c), seven of which are statistically significant. These stations are located in the Free State, Gauteng, Limpopo, Northern Cape and Western Cape province, with linear rate increases of >0.02 events.yr^{-1} (Table 8). Kimberley is the only station experiencing a decreasing trend. The strongest linear rate increases are evident in Limpopo, Gauteng at Zuurbekom and the Western Cape province at Cape Agulhas, with rate increases of >0.05 events.yr^{-1} (Table 8). An overall, calculated linear rate increase of 0.03 events.yr^{-1} has been found for heatwave events across the country (Table 8).

The HWD index identifies the length (days) of the heatwaves identified by the HWN index. The results indicate that the number of days has increased, with an overall calculated linear rate increase of 0.04 days.yr^{-1} (Table 8). Most of the stations (18 of 20) experience increasing trends in HWD, three of which are statistically significant (Figure 6d). These significant stations are located in the Eastern Cape at Port Elizabeth, Gauteng at Zuurbekom, and Limpopo province at Warmbad Towoomba, which experience linear rate increases between 0.03 days.yr^{-1} and 0.16 days.yr^{-1} (Figure 6d; Table 8). However, linear rate increases of >0.05 days/yr^{-1} are also evident in non-significant stations: Johannesburg Int, Durban and Vryburg (Figure 6d; Table 8). Decreasing trends are calculated for the two remaining stations Cedara and Kimberley, with only the latter experiencing a linear rate decrease of 0.01 days.yr^{-1} (Table 8).

Table 8.8 (Table 8): Increasing and decreasing trends in warm spell duration days and heat waves during 1960-2016.

Station	WSDI	$WSDI_3$	HWN	HWD
Dohne	0.21 (0.26; -)	**0.24** (**0.31**; 0.09)	0.01 (-; -;0.02)	0.22 (0.32; -; 0.03)
East London	-	0.11 (0.13; -)	0.15 (0.19; -; -)	0.12 (0.15; -; 0.02)
Port Elizabeth	0.21 (0.25; -)	0.17 (0.23; -)	0.04 (0.06; -; 0.01)	**0.30** (**0.37**; -; 0.03)
Bloemfontein	**0.24** (**0.31**; -)	**0.39** (**0.54**; 0.44)	**0.36** (**0.45**; -; 0.03)	0.19 (0.26; 0.03; 0.03)
Johannesburg Int	0.16 (0.21; -)	**0.23** (**0.33**; 0.25)	0.20 (0.24; -; 0.03)	0.06 (0.08; -; 0.06)
Zuurbekom	**0.28** (**0.36**; -)	**0.27** (**0.37**; 0.36)	**0.46** (**0.59**; 0.06; 0.06)	**0.52** (**0.69**; 0.14; 0.16)
Cedara	**0.30** (**0.36**; -)	**0.23** (**0.31**; -)	0.24 (0.31; -; 0.02)	-0.03 (0.04; -; -)
Durban	-	0.17 (0.23; 0.08)	0.15 (0.21; -; 0.03)	0.24 (0.35; -; 0.05)
Mara	0.17 (0.21; -)	**0.51** (**0.68**; 0.41)	0.19 (0.24; -; 0.05)	0.05 (0.05; -; 0.01)
Warmbad Towoomba	**0.30** (**0.38**; -)	**0.35** (**0.50**; 0.39)	**0.34** (**0.45**; 0.03; 0.05)	**0.24** (0.32; 0.04; 0.10)
Skukuza	0.09 (0.12; -)	0.07 (0.11; -)	0.16 (0.20; -; 0.04)	0.08 (0.10; -; 0.02)
Vryburg	0.19 (0.24; -)	**0.27** (**0.39**; 0.44)	0.12 (0.18; -; 0.03)	0.24 (0.30; 0.05; 0.05)
Kimberley	**0.24** (**0.29**; -)	**0.36** (**0.52**; 0.32)	-0.14 (-0.18; -; -)	-0.23 (-0.31; -; -0.01)
Upington	**0.31** (-; -)	**0.45** (**0.64**; 0.44)	**0.31** (**0.39**; -; 0.03)	0.05 (0.07; -; -)
Vanwyksvlei	**0.31** (**0.39**; -)	**0.55** (**0.75**; 0.54)	**0.31** (**0.39**; -; 0.03)	0.19 (0.26; -; 0.04)
Cape Agulhas	**0.29** (**0.36**; -)	**0.45** (**0.62**; 0.25)	**0.27** (**0.37**; 0.03; 0.05)	0.14 (0.18; -; 0.02)
Cape Columbine	0.02 (0.02; -)	**0.22** (**0.32**; 0.09)	0.15 (0.20; -; 0.02)	0.10 (0.13; -; 0.02)
Mosselbay	**0.30** (**0.37**; -)	**0.44** (**0.57**; 0.14)	0.02 (0.03; -; -)	0.04 (0.03; -; 0.03)
Cape Town	**0.22** (**0.27**; -)	0.08 (0.41; -)	**0.28** (**0.37**; -; 0.02)	0.10 (0.14; -; 0.02)
Vredendal	0.18 (0.22; -)	**0.39** (**0.54**; 0.25)	0.15 (0.20; -; 0.02)	0.20 (0.27; -; 0.02)
Average trend	0.20 (0.23; -)	0.30 (0.42; 0.30)	0.19 (0.25; -; 0.03)	0.14 (0.18; -; 0.04)

** Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS; Linear trend).*

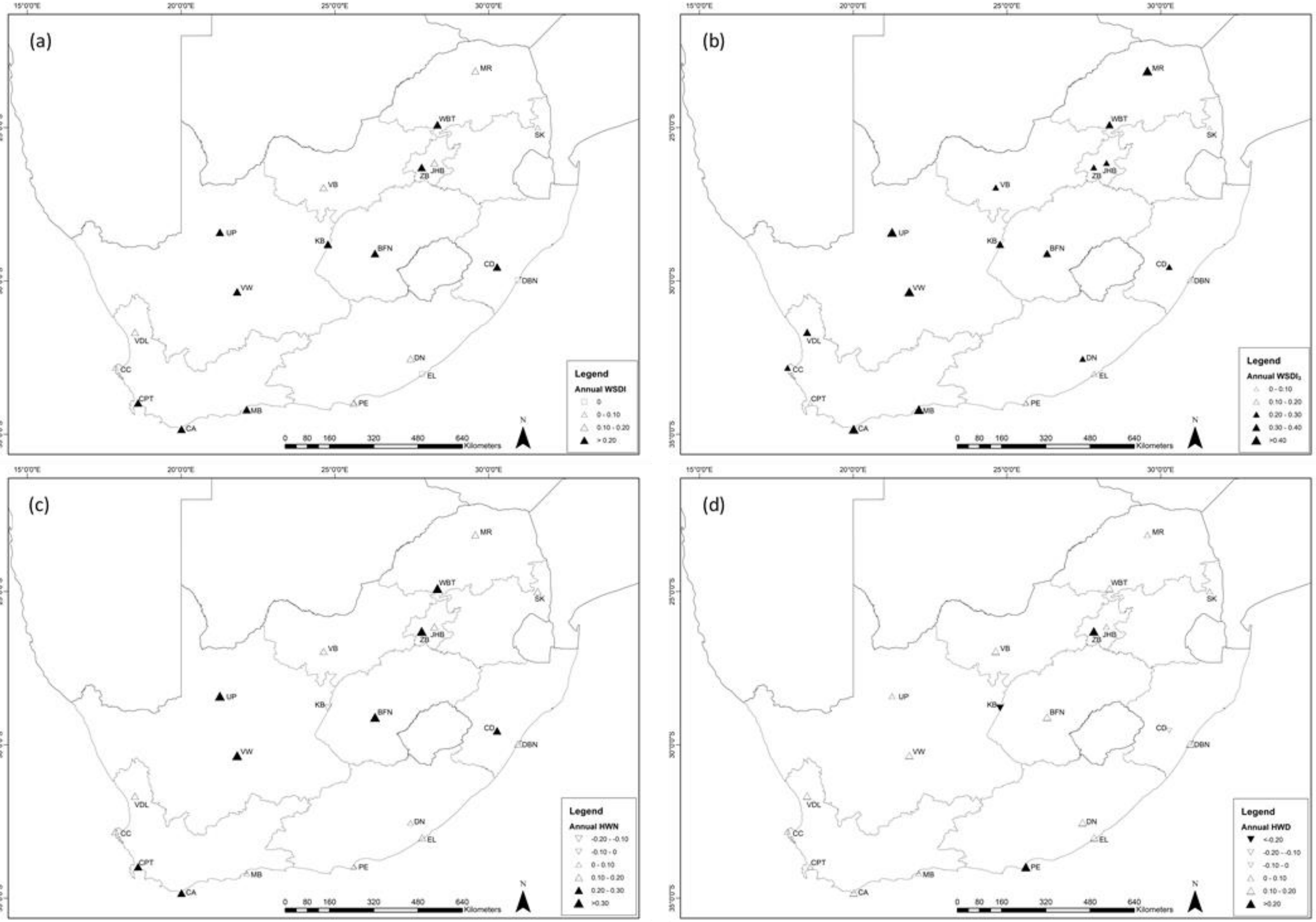


Figure 8.6 (Fig 6): Annual trends of (a) WSDI, (b) $WSDI_3$, (c) HWN and (d) HWD. Open downward, and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level.

8.7. 5. Discussion

This study is the first to apply the ET-SCI thermal stress indices to South Africa, exploring the incidence of warm extreme temperature events for the period 1960-2016. The general findings of the ETCCDI and ET-SCI indicate a warming trend and an increase in extreme warm temperature events on an annual and seasonal time scale over the study period. These findings are in agreement with the increasing global mean temperature trends (Yatim et al. 2019; NOAA 2020), increases in extreme warm temperature, and increases in the frequency of incidence of hot days (Hartmann et al. 2013; Mueller et al. 2016).

Consistent with previous studies on extreme warm events in South Africa (e.g. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017), most of our findings on an annual and seasonal time scale are in partial agreement. However, this study presents the first comprehensive seasonal trend analysis results of TXx, TNx, TX90p, TN90p. Observations on a seasonal timescale are very important. Unseasonably warmer temperatures may increase the risk of heat stress, due to an unprepared population (Lee 2014; Founda et al. 2019). Changes in seasonal temperatures may bring about shifts in the onset and length of growing seasons (Thorton et al. 2014), and contribute to a reduction in crop (Landman et al. 2017b) and grape yields (Araujo et al. 2016) in particular in the Western Cape. The warmer temperature may delay and advance seasonal phenological events (Fitchett et al. 2019).

This study presents the first trend analysis of the frequency of annual hot days where TX is above 25°C (SU25), and of seasonally hot days where TX is above 35°C. These events, in terms of a positive anomaly, may be an important classifier of the degree of heat stress. The core body temperature in humans increases significantly from exposure to these high temperatures (Ngwenya et al. 2018), which may lead to higher risks in the mortality rate due to heat stress, caused by inadequate housing and infrastructure to cope with the intense heat (Pasquini et al. 2013; Nana et al. 2019; Chersich and Wright 2019).

Our results demonstrate a general increase in warm spell days (WSDI) over a 50-year period, providing an extension to the work of Kruger and Nxumalo (2017). Studies have found that the WSDI index is less effective to measure the frequency and intensity of heatwaves (Perkins et al. 2012; Panda et al. 2014), for the reason that six-day consecutive warm spell events are rarely identified (see WSDI definition in Table 2). Therefore, $WSDI_3$, HWN and HWD indices were used to identify shorter warm spells (heatwaves). Together with the TX_2TN_2 index, which identify two consecutive warm days and night events. Research shows that it is not always daytime heat which is responsible for morbidity and mortality; humans need cooler night temperatures to recuperate to handle extreme heat the following day (Perkins 2015). A significant increase in $WSDI_3$ index was found, together with a general increase in heatwave events (HWN), and the number of heatwave days (HWD). Heatwaves can have significant impacts on many different sectors (Panda et al. 2014), in particular in a South African context. Extreme heat events disrupt agricultural practices and decrease crop yields (Mangani et al. 2018), which could have dire effects on the Free State's grain production and Western Cape's wine production. Heatwaves may devastate energy systems because with higher temperatures, the demand for electricity increases to supply air conditioners and fans (Lubega et al. 2018). Heatwaves also disrupt ecosystems; a study found that heatwaves induce fitness costs in birds which negatively impact their nesting growth and survival (Malherbe et al., 2016; Van Wilgen et al. 2016). Extreme heat can also contribute to and exacerbate wildfires – as has been seen in the 2019-2020 Australian fires (Ebbs, 2020). This poses significant threats to plantations and national parks, particularly in KwaZulu-Natal, Mpumalanga, and the Western Cape (Davis-Reddy and Vincent 2017). Heatwaves also have an impact on tourism; it has been found that temperatures play a significant role in outdoor tourism and tourist activities (Noome and Fitchett 2019). Tourist tends to stay indoors during heatwave events and are not always as accustomed to these warm events (Fitchett and Hoogendoorn 2018).

Extreme warm temperatures could have dire impacts and may result in human fatalities. An example of this are the health impacts and mortalities that resulted directly from the 2003 European and 2010 Russian heatwaves, and the secondary impacts on ecosystems and socioeconomic development that persisted long after (Perkins et al. 2012; Ragone et al. 2018). The increase in the frequency, duration and intensity of these events may amplify these impacts, particularly in a developing country such as South Africa, with a low adaptive capacity (Davis-Reddy and Vincent 2017).

Our findings are in agreement with previous studies indicating a general increasing trend in extreme warm temperature and heatwaves (e.g. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo, 2017). Similar to the findings of Kruger and Sekele (2013) and Kruger and Nxumalo (2017), the majority of interior stations experienced a statistically significant increasing trend in frequency of warm days and warm spells duration days, compared to the coastal stations. These spatial patterns coincide with recent projection studies indicating that there is a notable increase in frequency of warm spells, but less so in the south eastern part of the country (Kruger et al. 2019).

Large-scale climate drivers such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), affect the nature and timing of warm extreme temperatures events (Baudoin et al. 2017), together with local and regional synoptic circulation systems over the country. For instance, the decrease of warm days (TX90p) and nights (TN90p) in winter coincide broadly with the timing of movement of cold fronts over the subcontinent (Lennard, 2019). The increase in warm days in the interior stations can be linked to the sub-tropic high pressure situated in the interior parts of the country during summer (Kruger et al. 2010). Furthermore, studies suggest that anthropogenic forces (Angélil et al. 2017) may play a role. However, less research is focused on understanding these relationships between extreme heat events and large-scale modes of climate variability, and synoptic patterns in a South African context. This is an important avenue for future research.

As for any study, there are limitations. The ETCCDI and ET-SCI are far more robust approaches to assessing the occurrence of extreme temperature events, and preference should be given for these over ad-hoc local definitions. That said, when assessing the impact on human thermal comfort and stress, more complex indices such as the Universal Thermal Climate Index (UTCI) provide greater insight (Di Napoli et al 2018). This forms an important avenue for future research. This study is the first to explore extreme temperature events at a seasonal scale for South Africa. Assessing extreme temperature relative to a period of lower homogeneity allows for aseasonally warm winter days and aseasonally cold summer days to be classified as extreme events, which is important in terms of preparedness relating to clothing, outdoor activity and indoor temperature control. The seasonal brackets selected facilitate spatial analysis across the country, but over-estimate the length and timing of the shoulder seasons (Van der Walt and Fitchett 2020). Recent findings suggest, based on temperature metrics, that the South African summer is longer extending from October to March (Van der Walt and Fitchett 2020). Finally, while the selection of 20 stations represent the full database with sufficient period of coverage and competeness, and has been deemed sufficient for the spatial coverage of South Africa (Kruger and Nxumalo 2017), it does limit the accuracy of the IDW spatial interpolation. Future work should seek to test the interpolation accuracy between stations, if even from records of shorter duration, and ongoing efforts to improve the climate monitoring in South Africa are welcomed.

8.8. 6. Conclusion

This study provides one of the first comprehensive assessment on an annual and seasonal scale of extreme warm temperature events in South Africa, for the period 1960-2016. The findings of both the ETCCDI and ET-SCI indices produced significant results; however, the ET-SCI are more useful and can be applied in conjunction with many important sectors in a South African perspective. These findings have important implications on our natural system as well as society and set a precedent for likely future changes in extreme heat events resulting from further anthropogenic global warming. Furthermore, these results of extreme temperature events are crucial in order to frame mitigation and adaption strategies to counter the impacts of climate change, in an already vulnerable country.

8.9. 7. References

Abatan AA, Abiodun BJ, Lawal KA, Gutowski WJ (2016) Trends in extreme temperature over Nigeria from percentile-based threshold indices. Int J Climatol 36: 2527-2540. https://doi.org/10.1002/joc.4510.

Abbas F, Rehman I, Adrees M, Ibrahim M, Saleem F, Ali S, Rizwan M, Salik MR (2018) Prevailing trends of climate extremes across Indus-Delta of Sindh-Pakistan. Theor Appl Climatol 131:1101-1117. https://doi.org/10.1007/s0070-016-2028-y

Aguilar E, Vincent L, Zhang X (2013) Climate Data Homogenization Theory. Environmental Canada: Toronto, Canada.

Alexander LV, *et al* (2006) Global observed changes in daily climate extremes of temperatures and precipitation. J Geophys Res 111. https://doi.org/10.1029/2005JD006290.

Alexander L, Herold N (2016) Climpact2 Indices and Software, The University of South Wales, Sidney, Australia. https://github.com/ARCCSSextremes/climpact2.

Allen SMJ, Gough WA, Mohsin T (2015) Changes in the frequency of extreme temperature records for Toronto, Ontario, Canada. Theor Appl Climatol 119:481-491. https://doi.org/10.1007/s00704-014-1131-1

Angélil O, Stone D, Wehner M, Paciorek CJ, Krishnan H, Collins W (2017) An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. Am Meteorol Soc 30:5-16. http://doi.org/101175/JCLI-D-16-0077.1.

Araujo JA, Abiodun BJ, Crespo O (2016) Impacts of drought on grape yields in Western Cape, South Africa. Theor Appl Climatol 123:117-130. https://doi.org/10.1007/s00704-014-1336-3.

Baudoin MA, Vogel C, Nortje K, Naik M (2017) Living with drought in South Africa: lessons learnt from the recent El Niño drought period. Int J Disaster Risk Reduct 23:128-137. https://doi.org/10.1016/j.ijdrr.2017.05.005

Caloiero T, Coscarelli R, Ferrari E, Sirangelo B (2017) Trend analysis of monthly mean values and extreme indices of daily temperature in a region of southern Italy. International Journal of Climatology 37:284-297. https://doi.org/10.1002/joc.5003.

Cherisch MF, Wright CY (2019) Climate change adaption in South Africa: a case study on the role of the health sector. Glob Heal 15:22. https://doi.org/10.1186/s12992-019-0466-x

Davis-Reddy CL, Vincent K (2017) Climate risk and vulnerability: A handbook for southern Africa (2nd ed). CSIR. Pretoria. South Africa

Doran JD (2014) “Regional Climate Messages: Southern Africa”. Scientific report from CARIAA Adaption at Scale in Semi-Arid Regions (ASSAR) Project.

Dube LT, (2002) Climate of southern Africa. South African Geography Journal 84(1):125-138 https://doi.org/10.1080/03736245.2002.9713763.

Engelbrecht F, Landman W (2010) South Africa’s present-day climate. In: Southern Africa Risk and Vulnerability Atlas. Pretoria: CPD Print, 2-5.

Ebbs S (2020) Climate change can ‘supercharge’ wildfires in Australia through more extreme heat, drought. abcNews. https://abcnews.go.com/International/climate-change-supercharge-wildfires-australia-extreme-heat-drought/story?id=68096029. Accessed on 19 May 2020.

Fischer EM, Shär S (2010) Consistent geographical patterns in high-impact European heatwaves. Nat Geosci 3:398-403. https://doi.org/10.1038/ngeo866.

Fitchett JM, Hoogendoorn G (2019) Exploring the climate sensitivity of tourists to South Africa through TripAdvisor reviews. S Afr Geog J 101(1):91-109. https://10.1080/037362453.2018.1541022.

Fitchett JM, Grab SW, Portwig H (2019) Progressive delays in the timing of sardine migration in the southwest Indian Ocean. S Afr J Sci. 2019 115(7/8): 6 pages. https://doi.org/10.17159/sajs.2019/5887.

Founda D, Pierros F, Katavoutas G, Keramitsoglou I (2019) Observed trends in thermal stress at European cities with different background climates. Atmos 10(8): 436. http://doi.org/10.339/atmos10080436.

Grab SW, Knight J (2018) Southern African Montane Environments. In Holmes, P.J. and Boardman, J. (eds.). Southern African Landscape and Environmental Change. Routledge: Oxon.

Head T (2019) Seven South African weather records that were broken in 2019. The South African. https://www.thesouthafrican.com/news/weather/hottest-day-in-south-africa-ever-weather-records/. Accessed 26 February 2020

Karki R, Hasson SU, Gerlitz L, Talchabhadel R, Schickhoff U, Scholten T, Böhner J (2019). Rising mean and extreme near-surface air temperature across Nepal. Int J Climatol 1-19. https://doi.org 10.1002/joc.6344.

Kendall MG (1955) *Rank Correlation Methods*. London: Charles Griffen, p. 196.

Klein Tank AMG, Zwiers FW, Zhang X (2009) Guidelines on analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation (WCDMP no. 72, WMO-TD no. 1500). Switzerland: World Meteorological Organization, 54 pp.

Kruger AC, Sekele SS (2013) Trend in extreme temperature indices in South Africa: 1962-2009. Int J Climatol 33:661-676. https://doi.org/10.1002/joc.3455.

Kruger AC, Nxumalo M (2017) Surface temperature trends from homogenized time series in South Africa: 1931-2015. Int J Climatol 37:2364-2377. https://doi.org/10.1002/joc.4851.

Landman WA, Engelbrecht F, Hewitson B, Malherbe J, Van der Merwe J (2017a) Towards bridging the gap between climate change projections and maize producers in South Africa. Theor Appl Climatol. https://doi.org/10.1007/s00704-017-2168-8.

Landman WA, Malherbe J, Engelbrecht F, (2017b) South Africa's present-day climate. In Mambo J, Faccer K, (eds). Understanding the Social and Environmental Implication of Global Change, African Sun Media: Stellenbosh.

Lee WV (2014) Historical global analysis of occurrences and human casualty of extreme temperature events (ETEs). Nat Hazards 70:1453-1505. http://doi.org/10.1007/s11069-0.13-0884-7.

Lennard C (2019) Multi-Scale drivers of the South African weather and climate. In Knight J, Rogerson CM (eds). The Geography of South Africa. Springer: Switzerland.

Lubega WN, Stillwell AS (2018) Maintaining electric grid reliability under hydrologic drought and heatwave conditions. Appl En 210:538-549. http://dx.doi.org/10.1016/j.apenergy.2017.06.091.

MacKellar N, New M, Jack C (2014) Observed and modelled trends in rainfall and temperature for South Africa: 1960-2010. S Afr J Sci 110(7/8): 51-63. https://dx.doi.org/10.1590/sajs.2014/20130353.

Malherbe J, Smit IPJ, Wessels KJ, Beukes PJ (2020) Recent droughts in the Kruger National Park as reflected in the extreme climate index. Afr J Ran For Sci 37(1):1-17. https://doi.org/10.2989/10220119.2020.1718755.

Mangani R, Tesfamariam E, Bellocchi G, Hassen A (2018) Modelled impacts of extreme heat and drought on maize yield in South Africa. Crop Pas Sci 69: 703-716. https://doi.org/10.1071/CP18117.

Mann HB, (1945) Non-parametric tests against trend. Econometric, 13, 245-259.

Nairn JR, Fawcett RJB, (2015) The Excess Heat Factor: A metric for heatwave intensity and its use in classifying heatwave severity. Int J Environ Res Public Health 12:227-253. https://doi.org/10.3390/ijerph120100227.

Nana M, Coetzer K, Vogel C (2019) Facing the heat: initial probing of the city of Johannesburg's heat-health planning. S Afr Geogr J 101(2): 253-268. http://doi.org/1080/03736245.2019.1599412.

Nemec J, Bruder C, Chimani B, Auer I (2013) Trends in extreme temperature indices in Austria based on a new homogenized dataset. Int J Climatol 33:1538-1550. http://doi.org/10.1002/joc.3532.

Ngwenya B, Oosthuizen J, Cross M, Frimpong K, Chaibva CN (2018). A review of heat stress policies in the context of climate change and its impacts on outdoor workers: evidence from Zimbabwe. Int J Soc Ecol Sustain Dev 9(1):1-11. https://doi.org/10.4018/IJSESD.2018010101.

Nicholson SE (2018) The ITCZ and the seasonal cycle over the equatorial Africa. Bull American Metereol Soc 99(2):337-345. https://doi.org/10.1175/BAMS-D-16-0287.1.1.

Noome K, Fitchett J (2019) An assessment of the climate suitability of Afriski Mountain Resort for outdoor tourism using the Tourism Climate Index (TCI). J Mount Sci 16(11):2453-2469.

Osborne S (2019) France's summer heatwave killed 1,500 people, health minister announces. Independent. https://www.independent.co.uk/news/world/europe/france-heatwave-summer-dead-death-toll-europe-a9096806.html. Accessed 14 April 2020.

Panda K, Mishra A, Kumar A, Mandal KG, Thakur AK, Srivastava RC (2014) Spatiotemporal patterns in the mean and extreme temperature indices of India, 1971-2005. Int J Climatol 34:3585-3603. https:/doi.org/10.1002/joc.3931.

Pasquini L, Cowling RM, Ziervogel G (2013) Facing the heat: Barriers to mainstreaming climate change adaption in local government in the Western Cape Province, South Africa. Habitat Int 40:225-232. https://doi.org/10.1016/j.habitatint.2013.05.003

Pelling M, Leck H, Pasquini L, Ajibade I, Osuteye E, Parnell S, Lwasa S, Johnson C, Fraser A, Barcena A, Boubacar S (2018). Africa's urban adaption transition under a 1.5°C climate. Cur Op Environ Sustain 31:10-15. https://doi.org/10.1016/j.cosust.2017.11.005.

Perkins SE, Alexander LV, Nairn JR (2012) Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophys Res Lett 39. https://doi.org/10.1029/2012GL053361

Perkins SE, Alexander LV (2013) On the measurement of heatwaves. J Clim 26:4500-4517. https://doi.org/10.1175/JCLI-D-12-00383.1.

Perkins SE (2015) A review on the scientific understanding of heatwaves-their measurement, driving mechanisms, and changes at the global scale. Atmos Res 164-165:242-267. http://dx.doi.org/10.1016/j.atmosres.2015.05.014.

Perkins-Kirkpatrick SE, Gibson PB (2017) Changes in regional heatwave characteristics as a function of increasing global temperature. Sci Rep 7:12256. https://doi.org/10.1038/s41598-017-12520-2.

Perkins-Kirkpatrick SE, Fischer EM, Angélil O, Gibson PB (2017) The influence of internal climate variability on heatwave frequency trends. Environ Res Lett 12. https://doi.org/10.1088/1748-9326/aa63fe.

Ragone F, Wouters J, Bouchet F (2018) Computation of extreme heatwaves in climate models using a large deviation algorithm. Proceedings of the National Academy of Sciences of the United States of America 115:24-29.

Salameh AAM, Gámiz-Fortis SR, Castro-Díez Y, Hammad AA, Esteban-Parra MJ (2018) Spatial-temporal analysis for extreme temperature indices over the Levant region. Int J Climatol 39:5556-5582. https://doi.org/10.1002/joc.6171.

Sen PK (1986) Estimates the regression coefficient based on Kendall's tau. J American Stat Assoc 63:1379-1389.

Simmonds I, (2018) What causes extreme hot days in Europe. Environ Res Let 13. https://doi.org/10.1088/1748-9326/aacc78.

Spearman C, (1904) General intelligence objectively determined and measured. American J Psychol, 15:2, 201-292. https://doi.org/10.2307/1412107.

Tabari H, Talaee PH (2011) Temporal variability of precipitation over Iran: 1966-2005. J Hydrol 396(3):313-320

Thorton PK, Ericksen PJ, Herrero M, Challinor AJ (2014) climate variability and vulnerability to climate change: a review. Glob Chan Bio 20:3313-3328. https://doi.org/10.1111/gcb.12581.

Tyson PD, Preston-Whyte RA (2000) The atmosphere and weather of southern Africa. 2nd Ed. Cape Town: Oxford University Press Southern Africa. https://doi.org/10.1002/joc.725.

Van der Walt AJ, Fitchett JM (2020) Statistical classification of South African seasonal divisions on the basis of daily temperature data. S Afr J Sci (*in press*).

Van Wilgen NJ, Goodal V, Holness S, Chown SL, McGeoch MA (2016) Rising temperatures and changing rainfall patterns in South Africa's national parks. Int J Climatol 36:706-721. https://doi.org/10.1002/joc.4377.

Varghese BM, Barnett A, Hansen AL, Bi P, Hanson-Easey S, Heyworth JS, Sirn MR, Pisaniello DL (2019) The effects of ambient temperatures on the risk of work-related injuries and illnesses: Evidence from Adelaide, Australia 2003-2013. Environ Res 170:101-109. https://doi.org/10.1016/j.envres.2018.12.024.

Vincent LA, Zhang X, Bonsl BR, Hogg WD (2002) Homogenization of daily temperatures over Canada. J Clim 15:1322-1334.

Vincent LA, Wang XL, Milewska EJ, Wan H, Feng Y, Swail V (2012) A second generation of homogenized Canadian monthly surface air temperature of climate trend analysis. J Geophys Res 117. https://doi.org/10.1029/2012JD017859.

Wang XL (2008a) Accounting for autocorrelation in detecting mean shifts in climate data series using penalized maximal *t* and *F* test. J Appl Meteorol Climatol 47:2423-2444.

Wang XL (2008b) Penalized maximal F-test for detecting undocumented mean-shifts without trend-change. J Atmos Oceanic Tech 25(3):368-384. https://doi.org/10.1175/2008/JTECHA982.1.

Wang XL, Feng Y (2013) RHtestsV4 User Manual. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada, 28pp. [Available online at https://github.com/ECCC-CDAS/RHtests/blob/master/V4_files/RHtestsV4_UserManual_10Dec2014.pdf]

Yosef Y, Aguilar E, Alpert P (2019) Changes in extreme temperature and precipitation indices: Using an innovative daily homogenized database in Israel. Int J Climatol 39:5022-5045.

Zhang X, Feng Y, Chan R, (2018) Introduction to RClimDex v1.9, Climate Research Division, Environment Canada, Downsview, Ontario, Available from https://github.com/ECCC-CDAS/.

Ziervogel G, New M, Archer van Garderen E, Midgley G, Taylor A, Hamann R, Stuat-Hill S, Myers J, Warbuton M (2014) Climate change impacts and adaption in South Africa. Wiley Interdiscip Rev Clim Chang 5:605-620. https://doi.org/10.1002/wcc.295.

Chapter 9: General Discussion

9.1. Introduction

This chapter presents the general discussion, divided into three themes cross cutting all four research papers (Chapter 5-8). It also integrates and expands on the findings of each research paper with the existing literature. The following four themes will be discussed in the context of the findings: Firstly, the importance of statistically defined seasonal divisions; secondly, extreme events in "sunny South Africa"; thirdly, health hazards of ETEs in South Africa; and, finally, future threats of ETEs under current climate change projections. This is followed by a discussion on the limitations associated with this research.

9.2. Statistically defined seasons

The knowledge of delineation of seasons is of great importance to human activities, including economical and agricultural practices (see Introduction section of Chapter 6). Information about the start of warm and cold periods is of great importance especially to agriculture since it is closely related to the length and timing of growing seasons, timing of sowing and harvest, and the planning of both protection and support measures for various cultivations (see Introduction Section of Chapter 6; Argiriou *et al*., 2004; Battisti *et al*., 2009; Tshiala *et al*., 2011; Van der Walt & Fitchett, 2020). Seasonality of temperature changes can affect and influence resource management, national energy consumption, human health, tourism, social and economic planning, the environment and wildlife (Sparks and Braslavská, 2001; De Cian *et al*., 2013; Lazenby *et al*., 2014; Ziervogel *et al*., 2014; Fitchett *et al*., 2016; Garonna *et al*., 2016; Hekmatzadeh *et al*., 2020; Van der Walt & Fitchett, 2020). However, little consensus exists as to distinct seasonal boundaries in South Africa, and approaches in defining seasonal divisions often vary on the basis of the application (Van der Walt & Fitchett, 2020). Some researchers use ad-hoc approaches to classify seasonal divisions to suit the output rather than adopting a defined approach (Van der Walt & Fitchett, 2020). Thus, it is of critical importance to accurately determine the start and end of seasons (Van der Walt & Fitchett, 2020).

The findings of the statistical classification of South African seasonal divisions proposed the following seasonal brackets based on the temperature metrics used (T_{max}, T_{min} and T_{avg}; see Results and Conclusion Section of Chapter 6):

- Summer (October/November/December/January/February/March)
- Winter (June/July/August)
- Early autumn (April)
- Late autumn (May)
- Spring (September)

Previous research studies on ETEs in South Africa used seasonal divisions in their analyses (e.g. Kruger & Shongwe, 2004; Mackellar *et al*., 2013; Davis *et al*., 2016; Kruger & Nxumalo *et al*., 2017; Mbokodo *et al*., 2020). The studies which were examined used the meteorological classification. This classification method is the most commonly used in the temperate latitudes; this refers to the subdivision of four equal-length periods of three months each (Weather SA, 2019). In South Africa, this is the most widely used seasonal division classification (Table 1 of Chapter 6; Klopper *et al*., 1998; Tshiala *et al*., 2011; Kruger & Shongwe, 2004; Kruger & Nxumalo, 2017; Weather SA, 2019; Van der Walt & Fitchett, 2020). Many different studies on tourism, agriculture, human activities and human health, among others, use this conventional break of three months, or extend it to seasons of a specific region which are under investigation. Some even classify seasons based on an ad-hoc approach, with classifications such as hot-season, rainy-season, swimming season and growing-season, without direct relationship to calendar months (e.g. Klopper *et al*., 1998;

Craig *et al*., 2004; Benhin, 2006; Archer *et al*., 2008; Tshiala & Olwoch, 2010; Lazenby *et al*., 2014; Mastrorillo *et al*., 2016; Fitchett *et al*., 2017; Van der Walt & Fitchett, 2020). While these seasonal divisions may be suitable in the relevant research subdiscipline, interdisciplinary research might prove to be difficult to compare climate of different regions (Tuller, 1990; Van der Walt & Fitchett, 2020). The literature indicates that, for most parts of the Northern Hemisphere, including Italy, United States, China, Poland and Finland (Brunetti *et al*., 2006; Dong *et al*., 2010; Hiltunen *et al*., 2014; Allen & Sheridan, 2016; Czernecki & Miętus, 2017; Van der Walt & Fitchett, 2020) the seasonal boundaries (Cohen *et al*., 2012; Kutta & Hubbart, 2016) are well established and clearly communicated, even though some discrepancies exist among researchers on how to define the seasonal boundaries (e.g. Trenbreth, 1983; Tuller, 1990; Cheng & Kalkstein, 1997; Argiriou, 2004; Allen & Sheridan, 2016; Hekmatzadeh *et al*., 2020).

From the abovementioned discussion it is clear that statistical classification of seasons is important, and that the research and findings of the statistical classification using temperature metrics (i.e. T_{max}, T_{min} and T_{avg}) of South African seasons (see Results Section of Chapter 6) not only gives insight into temperature seasonality but also provides the opportunity for the scientific and public community to use these proposed seasonal brackets for interdisciplinary research purposes.

9.3. Extreme events in sunny South Africa?

The South African climate allows for a multitude of farming opportunities. South Africa has one of the world's most diverse agricultural sectors, ranging from commercial farming, including vegetables, fruits, nuts, as well as grain production (Goldblatt, 2010). "Sunny South Africa" is also marketed by various travel agencies (Fitchett & Hoogendoorn, 2018) as the ideal tourism destination. However, extreme events *do* occur in South Africa: the CRED EM-DAT has recorded a number of weather-related disasters over the past three decades in South Africa. These resulted in 1,792 casualties, 2,409 injuries, left 580,000 people homeless, and affected an estimated 2 million people across the country (EM-DAT CRED, 2020).

South Africa's urgent socioeconomic development needs and threatened ecosystem services, combined with a growing and urbanising population, reduces adaptive capacity and leads to greater exposure to extreme events, particularly in the poor rural areas of the country (Ziervogel *et al*., 2014; Pasquini *et al*., 2013; Davis-Reddy & Vincent 2017; Mambo & Murambadora, 2017). Only three severe ETEs were recorded and reported on by EM-DAT CRED (see Section 5.3), two of which were cold events and one a heat event. These events led to multiple injuries and casualties in various parts of the country (EM-DAT CRED, 2020; see Section 5.3). Exposure to heat or cold events over a prolonged period can lead to hyperthermia or hypothermia, respectively; these can have severe health implications, as discussed in detailed in the following section (Section 9.4). Yet, due to poor health surveillance and reporting infrastructure the impacts and number of events are under reported in many developing countries, including South Africa (Ngwenya *et al*., 2018; Scovronick *et al*., 2018). Additionally, studies suggested that even if heat/cold advisories are in place people remain unaware of the risks or deem it unnecessary to take precautions (Lee, 2014). Informal reporting by the news media (see Section 5.3, Section 7.3, Section 8.3), as well as the little work that has been done on ETEs studies across South Africa (Chapter 5), and the findings of both chapters 7 and 8 indicate that both warm and cold extreme events occur and are prevalent across South Africa.

For comparison purposes, the Fifth IPCC assessment reported that similar lower latitudinal regions and countries such as Australasia (viz., Australia and New Zealand) and South America experienced an observed mean temperature increase at a rate of 0.9°C since 1911, and increasing temperature trends of near by 0.7-1°C since the mid-1970s, respectively (Magrin *et al*., 2014; Reisinger *et al*., 2014). The near surface temperature increased at a rate of >0.5°C in most parts of Africa between 1901-2012 (Niang *et al*., 2014), whereas mean temperature increases at a rate of 0.65°C were evident for South Africa since the 1950s (DEA, 2013; DEA, 2016). It should be noted that these observed temperature increases, as well as ETEs, exhibit large spatial heterogeneity due to specific geographical and climatic features (Song *et al*., 2014).

Trend analysis studies suggest that in Australasia, there has been an increase in the frequency of hot extremes with decreases in cold extremes (Magrin *et al*., 2014; Caloiero, 2016), coupled with the statistically significantly increasing occurrence of hot days and hot nights compared to cool days and cold nights, respectively (Collins *et al*., 2000; Perkins and Alexander, 2013; Magrin *et al*., 2014; Perkin-Krikpatrick *et al*., 2016). Similar results were evident in South America, with an increasing occurrence of warm nights and hot extremes and negative trends in cold nights and cold extremes (Rusticucci, 2012; Reisinger *et al*., 2014; Lokith *et al*., 2017; Feron *et al*., 2019). Again, it was highlighted in these studies that these events exhibit large spatial heterogeneity (e.g. Collins *et al*., 2000; Rusticucci, 2012; Caloiero, 2016; Lokith *et al*., 2017). Compared to the findings of the trend analyses of this study (see Section 7.6 of Chapter 7 and Section 8.6 of Chapter 8), similar increasing trends in the frequency of warm extremes, warm days and nights were found, with decreasing trends in cold extremes and cold days and nights; however, some exceptions were highlighted in the results. However, it can be difficult to compare rates given that many researchers use different techniques and methods to calculate the extreme events. Broad comparison to lower latitudinal countries and regions (i.e. Australia and South America), the occurrence and frequency of ETEs on average in South Africa are similar to these regions.

9.4. Health Hazards of ETEs and vulnerability of South Africa

Multiple studies indicate that exposure to extreme heat and cold over prolonged periods can lead to hyperthermia or hypothermia, respectively. Thermal stress (e.g. hyperthermia or hypothermia) may results in severe heat- and cold-related illnesses and can lead to mortality anywhere in the world, as discussed in Section 5.3 and Section 5.11 of Chapter 5, Section 7.3 and Section 7.9.3 of Chapter 7, and Section 8.3 and Section 8.7 of Chapter 8.

To further emphasise these health impacts and the hazards of ETEs, Table 9.1 broadly summarises the direct impacts, indirect impacts, long-term impacts, as well as the more distal issues related to ETEs. Direct health impacts occur when the body temperature cannot be maintained, when the shelter or clothing is not appropriate, or the physiological responses are impaired (e.g. chronic diseases, ageing). Furthermore, these impacts can be exacerbated by drug/alcohol use (Table 9.1; Scott, 2015; McGregor, 2017). Indirect impacts refer to, for instance, impacts on health services or changes to an individual's behaviour (Table 9.1; Scott, 2015; McGregor, 2017). In addition, ETEs could cause long-term health impacts such as chronic respiratory diseases and cardiac dysrhythmias; they may even result in the disruption of thermoregulation and allow sepsis-related hypothermia during summer seasons (Scott, 2015). In some cases, researchers ascribe certain disorders to ETEs, which can be classified as distally related health issues and impacts. such as mental health disorders, memory loss, increased risk of still births, a rise in cases of Kawasaki disease, and even civil conflict during ETE events (Table 9.1; Scott, 2015; Rossati, 2017; Chan *et al*., 2019; Kanner *et al*., 2020).

Table 9.1: Direct, indirect, long-term and distal health issues and impacts (Adapted from McGregor, 2017)

	Extreme Heat	**Extreme Cold**
Direct Impacts	Classic heat-related illness: • Hyperthermia • Heat stroke • Heat exhaustion • Heat cramps • Dehydration • Damage to the internal organs (e.g. Brain, liver, kidneys; Scott, 2015) Increased risks of death from: • Respiratory disease • Cardiovascular disease • Underlying chronic disease (e.g. high blood pressure, renal diseases) Increased risk of hospitalisation from: • Respiratory disease • Diabetes • Heart disease • Underlying chronic disease (e.g. high blood pressure, renal diseases) • Use of alcohol or drugs (Scott, 2015)	Classic cold-related illness: • Hypothermia (Scott, 2015) • Frostbite • Cardiac dysrhythmias (Scott, 2015) • Decreased metabolic activity Increased risks of death from: • Respiratory disease • Cardiovascular diseases • Underlying chronic diseases (e.g. heart disease) • Epidemic spread of air-borne viral infections (Rossati, 2019) Increased risk of hospitalisation from: • Respiratory disease • Diabetes • Heart disease • Use of alcohol or drugs (Scott, 2015)
Indirect Impacts	Impact on health services: • Increased number of hospital admissions • Storage of medicine Increased risks of accidents: • Drowning • Work-related accidents • Injuries Potential disruptions to infrastructure: • Power • Water • Transport • Productivity	Impact on health services: • Increased number of hospital admissions • Storage of medicine Increased risks of accidents: • Traffic accidents • Injuries • Carbon monoxide poisonings Potential disruptions to infrastructure: • Power • Water • Transport • Productivity
Long-term impacts	Increased risks of death from: • Cardiac dysrhythmias (Scott, 2015) • Chronic respiratory diseases	Increased risks of death from: • Cardiac dysrhythmias (Scott, 2015) • Chronic respiratory diseases • Disruption of thermoregulation and allow sepsis-related hypothermia (Scott, 2015).
Distally Health impacts	Increased risks of death from: • Mental health (Rossati, 2017) • Increased risk of poor outcomes in pregnancy (e.g. still births; Kanner *et al.*, 2020) • Kawasaki disease (Chan *et al.*, 2019) • Civil conflict (Rossati, 2017)	Increased risks of death from: • Mental health (Rossati, 2017) • Memory loss (Scott, 2015) • Increased risk of poor outcomes in pregnancy (e.g. still births; Kanner *et al.*, 2020)

Together with the aforementioned possible health impacts, research indicates that a population's vulnerability to ETEs relates to its exposure and its capacity to adapt and respond to such ETEs over long or short timescales (McGregor, 2017; Le Roux et al., 2017). McGregor (2017) emphasises that determinants of vulnerability can be broadly categorised by demographic, health, physical, socioeconomic and institutional factors. The vulnerable communities can be potentially highlighted using these determinants. The physiology of the population plays a huge role in the demographic determinants, where the older population is more vulnerable to extreme temperature than younger people (McGregor, 2017; Le Roux et al., 2017). New immigrants and tourists may also be affected (McGregor, 2017; Le Roux et al., 2017). As discussed in Section 7.9.3 of Chapter 7, an increase in extreme cold events, over the period 1960-2016, was identified along the south and east coast and in the Northern Cape, North-West, and Gauteng provinces. Studies indicate that vulnerable socioeconomic communities are found in these provinces (see Section 2.4 of Chapter 2), particularly in Gauteng with the highest percentage of elderly people (21.5%) compared to other provinces (see Section 2.4 of Chapter 2) and the highest density of homeless people (Le Roux *et al*., 2017). Physical and socioeconomic determinants are especially important in a South African context: an estimated 14.45 million households are informal (Le Roux *et al*., 2017), with an estimated 3.5 million people residing along the coastline, of which 40% live below the minimum wage (Le Roux *et al*., 2017). These communities are especially vulnerable to increases in extreme cold events due to their low adaptive capacity and inappropriate housing (Le Roux *et al*., 2017).

Statistically significant increases in warm extremes were observed in almost all the provinces (see Section 8.6 and Section 8.7 of Chapter 8), which could have dire health consequences for communities living in informal settlements with improper housing and shelter (Le Roux *et al*., 2017). In addition, this may lead to higher risks in the mortality rate due to heat stress caused by inadequate infrastructure to cope with the intense heat (Chersich & Wright 2019). As discussed in Section 2.4 of Chapter 2, areas in the Eastern Cape, Kwa-Zulu Natal, Limpopo and North-West provinces are the most susceptible to ETEs; these former apartheid "homelands" house the most vulnerable communities, with low adaptive capacity and some livelihoods that depend on subsistence farming and natural resources (Van Hyssteen *et al*., 2013; Le Roux *et al*., 2017; Chersich *et al*., 2018). Additionally, the South African public health care system is burdened with both chronic illnesses and non-communicable diseases (Garland *et al*., 2017). Sadly, the health risks that may be impacted by climate change, in particular ETEs, are not new issues in South Africa. However, it is difficult to quantify the climate-health linkages in South Africa due to the lack of reporting systems and data (Garland *et al*., 2017).

9.5. Future threats of ETEs under climate change

Only a few known published attempts were made to model and project future near-surface scenarios (e.g. Mackellar *et al*., 2014; Engelbrecht *et al*., 2015; Russo *et al*., 2016; Landman *et al*., 2018), as well as attempt to project future climate zones (e.g. Engelbrecht & Engelbrecht, 2015) over Africa and southern Africa. Engelbrecht *et al*. (2015) used six Global Climate Models (GCMs), which were all downscaled to the African continent using the Conformal-Cubic Atmospheric Model (CCAM) regional model. Significant warming trends were found in all six model simulations. Great levels of warming were found in the subtropical versus tropical latitudes, with lower levels of coastal warming compared to the interior (Engelbrecht *et al*., 2015). However, differences remain in the finer details of the simulated patterns of warming

(Engelbrecht *et al*., 2015). Russo *et al*. (2016) used daily maximum temperatures to project future heatwaves over Africa, for the period 1979-2100, from 13 Regional Climate Model (RGM) simulations of the CORDEX-Africa multi-model scenario experiment. Four RGMs were driven by 13 different GCM with two different scenarios, in light of observed greenhouse gases defined by the Representative Concentration Pathways (RCP) medium-to-low concentration RCP4.5 and high-to-low concentrations RCP5.8, as adopted by the IPCC AR5 (Russo *et al*., 2016). In general, the results showed that in recent years Africa experienced an increase in hotter and longer heatwaves compared to the last two decades. Furthermore, it is projected that ETEs will occur on a regular basis by 2040 under scenario RCP8.5 (Russo *et al*., 2016). Landman *et al*. (2018) applied the regional Conformal-Cubic Atmospheric Model (CCAM), together with six GCM simulations of the Couples Model Intercomparison Project Phase 3 (CMIP3), all obtained for the A2 Special Report on Emission Scenarios (SRES), to project temperatures over southern Africa for the period 1961-2100. Findings indicate maximum temperature increases of >4°C over southern Africa under low mitigation towards the end the century (Landman *et al*., 2018). Engelbrecht & Engelbrecht (2015), projected changes in the Köppen-Geiger climate zones over southern Africa for the time in the future when the increase in global mean temperatures reaches thresholds of 1, 2 or 3°C, relative to present-day climatology. This was achieved by downscaling six different Coupled GCM (CGM) projections, together with the regional Conformal-Cubic Atmospheric Model under A2 SRES (Engelbrecht & Engelbrecht, 2015). When these thresholds are reached widespread shifts in the climate regimes are projected, with the most prominent changes in the southern and eastern expansion of the hot desert and hot steppe zone (Engelbrecht & Engelbrecht, 2015). The cold desert and steppe zones, meanwhile, are projected to decrease (Engelbrecht & Engelbrecht, 2015). Furthermore, the eastern temperate regions of South Africa as well as the Cape south coast are projected to contract, with a likely increase in warmer and drier climate over the Cape Fynbos regime (Engelbrecht & Engelbrecht, 2015). Elsewhere, Mackellar *et al*. (2014) used 11 different Global Climate Models (GCMs) obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) to statistically downscale temperatures to a South African perspective for the period 1960-2010. This study revealed that these models can reproduce patterns fairly well on an annual time scale, but patterns were region specific on a seasonal time scale (Mackellar *et al*., 2014).

Some of these studies, however, highlight that the simulation of the African climate can be very challenging due to the complexity and the diversity of processes to be represented (Laprise *et al*., 2013; Engelbrecht *et al*., 2015). In addition, spatial coverage of index datasets is still under-sampled in Africa and differences in the resolution of observational data may cause non-climatic spatial variation in trends (Zwiers *et al*., 2013; Engelbrecht *et al*., 2015).

For most parts of Africa, and particularly in South Africa, projections show that the near surface temperatures have and will increase in the near future (Niang *et al*., 2014; Russo *et al*., 2016). The possibility of a warmer future climate and further increases in the mean temperatures would not only increase the probability of more frequent hot ETEs, but the incidence and intensity are very likely to increase as well (Engelbrecht *et al*., 2015; Russo *et al*., 2016; Landman *et al*., 2018; Kruger *et al*., 2019; Mbokodo *et al*., 2020). Extreme cold temperature events could decrease in frequency and intensity (Russo *et al*., 2016; Kruger *et al*., 2019; Mbokodo *et al*., 2020). However, these events may still occur due to strong westerlies causing mid-latitude cyclones or cut-off lows, as discussed in Section 7.9.4 of Chapter 5. This could increase the South African population’s vulnerability to rare cold events, due to the possibility that the population may become less acclimatised to cold events, which could lead to more susceptibility to cold-related illnesses and mortality (Kodra *et al*. 2011;

Kodra & Ganguly 2014; Smith & Sheridan 2020). Given the significant impacts of ETEs, only a few known studies have attempted to model and project future ETE scenarios over South Africa (e.g. Mackellar *et al*., 2014; Kruger *et al*., 2019; Mboko *et al*., 2020), as discussed in Section 5.10 of Chapter 5. In general, all these studies projected that extreme warm events would increase across South Africa, with a decrease in extreme cold events.

Several approaches could be taken in terms of mitigation and adaption to these changes. One of these might be the introduction of green infrastructure to mitigate the heat, while providing shade to underlying surfaces (e.g. trees, vegetation; Pasquini & Enqvist, 2019). Another approach would be to explore and promote green technologies, both in the public and private sector (Fitchett *et al*., 2020), such as sustainable water heating, window size to protect against heat loss and ensure indoor thermal comfort. Other strategies might include the development of early heat/health warming systems, which may prevent multiple casualties (McGregor, 2016), is another strategy to consider Community education programmes on ETEs may also help people adapt to these events. Similarly, the climate change adaptation policies should be implemented at a municipal level. This can guide municipalities on what to do to adapt to ETEs or what to do during such events.

9.6. Limitations of the research

All research projects encounter some limitations. In this section, some of the limitations encountered during this project will be discussed. It is important to note these limitations since they may possibly influence the accuracy of the results and inform future research which is discussed in Section 10.4 of Chapter 10. This section will firstly focus on data limitations, then move on to analytical limitations. Ultimately, this section highlights the limitations encountered, measures to mitigate these limitations and possible measures to be considered for future research.

9.6.1. Data Limitations

Daily TX and TN datasets were only obtained for 35 meteorological stations for the analyses of Chapter 6 (Data and Methodology) and 20 meteorological stations for Chapters 7 and 8, respectively, from the SAWS climate database due to network limitations. South Africa's national temperature network, as discussed in Section 3.3 of Chapter 3, consists of several hundred stations. However, only between 30 and 40 have a record with <20% of missing data, with a similar number of stations having >80% missing data (DEA, 2016). Therefore, trend analysis can only be performed for tens rather than the whole network of stations (DEA, 2016). In addition, the initiative to interpolate the SAWS and other data to a fine spatial scale resolution of 1.7 x 1.7km ceased in 2004 (DEA, 2016).

The SAWS data has a relatively high level of accuracy due to numerous quality control processes undertaken on the datasets which form part of the climate database (Dyson, 2009; SAWS, 2019; Roffe, 2019). However, these obtained datasets were not perfect and numerous limitations (e.g. gaps and outliers) were encountered. These limitations were dealt with through data quality checks and data cleaning, as discussed in Section 3.4 of Chapter 3. For instance, the identification of outliers and gaps and rectifying these is discussed in Section 3.4 of Chapter 3. Furthermore, the mean monthly temperature was quantified using daily TX and TN. For future research purposes, hourly temperature data readings may improve the accuracy of the values of mean daily temperatures; however, the SAWS could not provide hourly data and thus to ensure consistency the TX and TN records were used.

Change points in the datasets were identified, as discussed in Section 3.5 of Chapter 3 to check for non-climatic shifts. As, discussed in Section 3.5 of Chapter 3, numerous methods have been developed to detect and adjust the inhomogeneity in datasets and the RHtestV4 was deemed appropriate for this study. In future research, this method can be compared to other methods, especially over smaller spatial scales, along with the further investigation of change points particularly for analysis of synoptic circulation and ETEs.

9.6.2. Analytical limitations

The study relied on different statistical analyses to generate the results, as discussed in Section 3.7 of Chapter 3. The cluster analysis was used, as discussed in Section 3.71 of Chapter 3, to statistically classify the seasonal divisions in South Africa (Chapter 6 Data and Methodology). The only limitation which emerged was which technique, hierarchical and non-hierarchical technique should be deemed appropriate to use to calculate the clusters. For future research purposes, the results could be compared and discussed in a South African context.

The chosen temperature indices from the ET-SCI and ETCCDI, as discussed in Section 3.8 of Chapter 8, had their own advantages and disadvantages. However, the chosen indices were decided to provide the best results, as well as to meet the aims and objectives of this study. Furthermore, the selection of the most appropriate trend analysis method was one of the greatest challenges or limitations in this study. As discussed in Section 3.9 of Chapter 3, multiple trend analysis methods exist to evaluate climate time series data; each method has its relative advantages and disadvantages. The MK trend analysis proved to be the most appropriate trend analysis, together with the Theil-Sen slope estimator to quantify the magnitude of the trend slopes, particularly for analyses of extreme temperature time series (see Section 3.9 of Chapter 3). The Spearman's Rank correlation coefficient was also calculated to evaluate and cross-validate the MK trend analysis. Studies indicate that both these methods are equally strong for long-term data analysis (Daniel, 1978; Yue *et al*., 2002; Rahman *et al*., 2017).

To spatially present the data the interpolation method, the IDW, was used in this study (see Section 3.10 of Chapter 3). The geostatistical interpolation method Kriging was initially used; however, this method was deemed not appropriate and it was found that IDW performed well in estimating temperature variability over complex terrains, as discussed in Section 3.10 of Chapter 3 (e.g. Cao *et al*., 2009; Chai *et al*., 2011; Kayikçi *et al*., 2016; Yang *et al*., 2016)

Chapter 10: Conclusions

10.1. Introduction

The significant societal and environmental impacts of ETEs has prompted considerable interest, and research of ETEs in the Global North is growing (Perkins-Kirkpatrick *et al*., 2017; Allen & Scott, 2018; Chen *et al*., 2019). However, research on ETEs in developing countries is a growing field, such as those in Africa, and specifically in South Africa (New *et al*., 2006; Collins, 2011; Otto *et al*., 2015; Abatan *et al*., 2018; Scovronick *et al*., 2018). To emphasise this issue, the review of ETEs in South Africa (Chapter 5) attempts to critically analyse the published works on ETEs to argue for greater research focus and to improve the understanding of ETEs. Very little research has been undertaken to understand ETEs in a South African context using observed meteorological records. In considering the seasonal characteristics of temperature across the country, little consensus exists on distinct seasonal boundaries, making it difficult to conduct temperature comparison studies or research on the seasonality of ETEs. As such, the statistical classification of South African seasonal divisions on the basis of daily temperature data (Chapter 6) provides a different approach to defining seasonal boundaries across the country based on temperature metrics. This knowledge is crucial for a developing country particularly where some livelihoods depend on knowledge of seasonal changes, as well as for the development of adaptation strategies and policies (Van der Walt & Fitchett, 2020). To address the knowledge gap and the dearth of research on ETEs in South Africa, the trend analysis of extreme cold temperature events (Chapter 7) and extreme warm temperature events (Chapter 8) was investigated on an annual and seasonal timescale for the period 1960-2016.

This conclusion chapter synthesises the work presented in the chapters, first by reflecting on the aims and objectives presented in Chapter 1 (Introduction) and how these were achieved. Following this, a synopsis of the key findings will be presented and the significance thereof, and finally the potential future research directions will be discussed.

10.2. Achievement of study aim and objectives

This PhD has not only advanced our understanding of seasonal boundaries based on temperature metrics in South Africa, but also our understanding of ETEs. The primary aim of this research was to investigate the frequency, incidences, and climatology of annually and seasonally anomalous temperature events over South Africa, over the period 1960-2015. The objectives were developed to address this primary aim through knowledge gaps highlighted throughout Chapter 1 (Introduction) and the research papers (Chapter 5-8). It should be noted that the limitations addressed in the discussion have not compromised the achievement of the study's objectives. The objectives are listed below, as presented in Section 1.3 Chapter 1 (Introduction), along with how these objectives were achieved.

1. *To determine the statistical boundaries for the timing of seasons in South Africa based on temperature*

This objective required a cluster analysis for each temperature metric used, for each selected meteorological station for the study period; the results of this are presented under Chapter 6 Results section. The details of the methodological approaches were captured under Chapter 6 Data and Methodology section. This objective was achieved through robust quality control, quantifying mean daily temperature (T_{avg}) derived from T_{max} and T_{min}, aggregating mean monthly temperatures per meteorological stations for each year, and finally performing hierarchical clustering using Ward's D minimum variance cluster analysis. Additionally, the average silhouette width and the cophenetic correlation coefficient were used to interpret, evaluate, and validate consistencies within the cluster and groups. To investigate the spatial patterns, the cluster outputs, along with the start and end dates of summer and winter, were mapped. The results of this objective are presented under the Chapter 6 Results section, and more specifically under Chapter 6 Discussion and Conclusion section. In summary, through statistical analysis and results captured in the seasonal timetable Table 4 in Chapter 6, new seasonal brackets are put forward in accordance with the agreement of seasons and temperatures among stations used in this research (Van der Walt & Fitchett, 2020).

2. *To determine the frequency of occurrence of annually and a-seasonally cold temperature over the period 1960-2015*

This objective required trend analysis of each selected ET-SCI and ETCCDI temperature index, for each selected station for the study period; the results of this are presented under Section 7.6, 7.7 and 7.8 of Chapter 7. The details of the data source, data quality and homogeneity, selection of temperature indices and trend analysis and significance (i.e. Mann-Kendall, Spearman's Rank correlation coefficient and Sen's slope) behind this objective were captured under Sections 7.5.1, 7.5.2, 7.5.3 and 7.5.4, of Chapter 7. The frequency and incidence of annual and seasonal cold temperature events were identified using the selected ET-SCI and ETCCDI temperature indices (Section 7.5.3), together with the trend analysis (i.e. Section 7.5.4; i.e. Mann-Kendall, Spearman's Rank correlation coefficient and Sen's slope). The results of this objective are presented under Section 7.6 and more specifically for the ET-SCI under Section 7.7 and 7.7.1, 7.7.2 and 7.7.3 of Chapter 7. The ETCCDI results are presented under Section 7.8, 7.8.1, 7.8.2, 7.8.3, 7.8.4 and 7.8.5 of Chapter 7. The discussions of these results are presented under Section 7.9 and more specifically under Sections 7.9.1, 7.9.2, 7.9.3 and 7.9.4 of Chapter 7. In summary, this research paper (Chapter 7) provides the first application of the ET-SCI indices in exploring ETEs in South Africa and concludes that extreme cold events may persist in a 'warming world'. The findings contribute to the nature of cold events in a South African context, important given that these events may still occur under current increasing mean temperatures.

3. *To determine the frequency of occurrence of annually and a-seasonally warm temperature events over the period 1960-2015*

This objective required trend analysis of each selected ET-SCI and ETCCDI temperature index, for each selected station for the study period; the results of this are presented under Section 8.5 of Chapter 7. The details of the data source, data quality and homogeneity (Section 8.5.1), selection of temperature indices (Section 8.5.2) and trend analysis and significance (Section 8.5.3; i.e. Mann-Kendall, Spearman's Rank correlation coefficient and Sen's slope) behind this objective were captured under Sections 8.5.1, 8.5.2 and 8.5.3, of Chapter 8. The frequency and incidence of annual and seasonal cold temperatures events were identified using the selected ETCCDI and ET-SCI temperature indices (Section 8.5.2), together with the trend analysis (Section 8.5.3; i.e. Mann-Kendall, Spearman's Rank correlation coefficient and Sen's slope). The results of this objective are presented under Section 8.6 and more specifically under Sections 8.6 and 8.6.1, 8.6.2, 8.6.3, 8.6.4 and 8.6.5 of Chapter 8. The discussions of these results are presented under Section 8.7 of Chapter 7. In summary, this research paper (Chapter 8) provides the first application of the ET-SCI indices in exploring extreme temperature events in South Africa. The general findings of both the ETCCDI and ET-SCI indicate a warming trend and increase in warm temperature events on an annual and seasonal time scale over the study period.

4. *To identify any consistent synoptic features that may be related to these anomalous ETEs*

As highlighted throughout this thesis, very few seasonal or longer-period synoptic-scale studies have been conducted in South Africa. Thus, this objective was addressed in three parts. The first was through the detailed discussion of the study region's (South Africa) climate and weather, in Section 2.3 of Chapter 2. Secondly, in each research paper (Chapter 7 and 8) reference was made to the location of the study site and climate factors, including synoptic features which may contribute to the extreme cold events in Section 7.4 of Chapter 7, and extreme warm events in Section 8.4 of Chapter 8. Lastly, the possible climate mechanisms were highlighted in each discussion section of each research paper (Chapter 7 and 8), specifically in Section 7.9.2, 7.9.3 of Chapter 7 and Section 8.7 of Chapter 8. Although this objective was achieved it can be further pursued, as discussed in Section 10.4 (Future research directions).

It is also important to highlight that the findings of the start and end dates of summer and winter (Figure 3 and 4 of Chapter 6) coincide with the pressure regimes, as well as the inter-annual migration of the ITCZ.

5. *To explore the temporal patterns in these events, including progressive increases under climate changes, and any cyclical association with; sunspots, volcanic events, El Niño-Southern Oscillation (ENSO) and the Subtropical Indian Ocean Dipole (SIOD/IOD)*

This objective was achieved through the discussion of climate mechanisms of extreme cold events in Section 7.9.2 of Chapter 7, and the influence of large-scale climate drivers which affect the nature of warm extreme temperature events, in Section 8.7 of Chapter 8. The candidate acknowledges that this objective can be further pursued, which is why an in-depth discussion is included on climate drivers in the fifth research paper in the Supplementary Material (Draft Article). This could be a future research direction, as discussed in Section 10.4 (Future research directions).

10.3. Significance of study and contribution to new knowledge

This study was undertaken to provide an analysis of ETEs in South Africa over the period 1960-2015. The results obtained and discussed in each research paper, as well as the general discussion (Chapter 9) of the research papers as a unit, highlights the PhD's significance and its contribution to new knowledge. The results presented by each research paper and as a unit have considerable academic and societal value. The PhD presents the very first review of ETEs in South Africa and argues for a greater research focus to improve the understanding of ETEs in South Africa. Additionally, an approximate number of meteorological stations are presented to adequately portray temperature variability on a national and regional level in South Africa, to be applied by climatological, meteorological, and temperature-related researchers in South Africa. Furthermore, this study presents the very first classifications of seasons which can be used extensively in agriculture, tourism, forestry, water resource management, health care, fishing and disaster risk management among others; this will be important for adaption strategies. Also, this study was first to use the ET-SCI in a South African context, to explore extreme cold and warm temperature events on an annual and seasonal scale. The extension of ETCCDI and the use of ET-SCI highlights the seasonal scale variations of both cold and warm ETEs in South Africa. In addition, the sole focus on extreme cold temperature trends highlights the importance and recognition of these events in South Africa, and emphasises that these anomalously cold events may persist in a 'warming world'.

This PhD has therefore laid the foundation for research focused on annual and seasonal extreme cold and warm events in South Africa. This research has not only shown the importance of the uniform classification of seasonal divisions, but also the importance of using sector specific indices in identifying extreme temperature trends in South Africa or elsewhere. The key findings are as follows, as highlighted in each research paper (Chapter 5-8):

Chapter 5:

- Currently, 10 known publications exist which examined ETE across South Africa, with the majority of studies using the SAWS climate database as primary source.
- A network of approximately 21 stations would provide a recent degree of accuracy of the countrywide temperature variability

- The majority of studies agree that extreme warm temperatures are increasing, while extreme cold events are decreasing. However, the statistically significant increases and decreases vary among stations

Chapter 6:

- New statistically classified seasonal divisions are put forward
    - Summer (October/November/December/January/February/March)
    - Early autumn (April)
    - Late autumn (May)
    - Winter (June/July/August)
    - Spring (September)
- The start of summer and end of winter months follow a southwest to northeastwards spatial pattern across the country.
- Summer start later and winters end later in the southwestern parts of the country, whereas in the northeast, summer start earlier and winters end earlier.

Chapter 7:

- A decreasing trend were found for annual cold spell duration and cold wave frequency, at rates of 1 days.decade and 0.2 events.decade for the period 1960-2016.
- Increasing trends in annual cold spell duration days were evident in stations located in the Western Cape, Eastern Cape, and North-West Province, at a rate of 0.3 days.decade for the period 1960-2016.
- The findings in general contribute to the awareness of the frequency and suration of extreme cold events in South Africa and that these events may persist in a ‘warming world’.

Chapter 8:

- A general increase in annual maximum tempertures were found at a rate of 0.2°C.decade.
- Statisitcally significant trends were found in warm days and warm nights for most of the stations; with the strongest, general annual trend increases experienced in warm days at a rate of 1.5%.decade.
- Seasonally, the strongest inceases of 1.1% days.decade in warm days were evident for autumn, while increases of 0.07% days.y^{-1} are calculated for summer.
- Lastly, a general increasing trend in heatwaves events were recorded at 0.3 events.decade across South Africa.

10.4. Future research directions

Through critical analysis of ETEs in South Africa key research gaps have been identified which could lead to future research directives on ETEs in the country. These future research directions, which will be discussed in the paragraphs below, are focused on building from the aims and objectives of this PhD research project. Based on the research findings and discussion (Chapter 9), the following future work has been identified.

This first and possibly the most important direction for future research surrounds the application of the seasonality classification approach across southern Africa and the African continent more broadly. It will also be key to communicate these findings effectively to different sectors such as agriculture, resource management, tourism and other temperature-dependent activities. This will help to develop adaptation strategies in monitoring season changes in temperatures under climate change (Van der Walt & Fitchett, 2020). Also related to the first research directive, it will be necessary to determine if these seasons are changing across South Africa, which may have impacts on crop yields. Recent findings suggest that rainfall seasonality is shifting over South Africa and that these trends present a concerning outlook for continued crop production and water resource management (Roffe *et al*., 2020), which emphasises the importance on further investigation of seasonal temperature boundaries across South Africa, as well as if the boundaries are shifting.

As a second direction, future research could assist with the widespread application of the ET-SCI across southern Africa, and Africa more broadly. It could also disseminate the use of the sector-specific climate indices and highlight the variability and trends of ETEs of particular interest to socioeconomic sectors. Additionally, it might assist in the characterisation and adaptation strategies of climate sensitivity of various sectors and regions in South Africa. As third direction, with direct linkages to the second, is the exploration and analysis of comfort indices together with the ET-SCI and ETCCDI. Examples include the UTCI, which attempts to explore thermal comfort measures of ETEs, coupling the temperature with a wider range of meteorological parameters such as humidity and windspeed (Błażejcyk *et al*., 2013; Napoli *et al*., 2018). These comfort indices allow for ETEs to be classified on the basis of the biometeorological impacts without deaths necessarily occurring, which provides a standardisation for the level of impact at varied levels of healthcare (Napoli *et al*., 2018).

It is imperative to use high quality data for any analysis, in particular climatological data. The fourth direction for future research includes a critical appraisal of the performance of gridded datasets against ground-based measured data (Meyer *et al.,* 2019). Both these datasets come with their advantages and disadvantages. For instance, regional inference based on an individual station is dependent on how well an individual meteorological station or group represents a particular region (Mackellar *et al*., 2014). A finer spatial resolution and grid/satellite-based estimates, meanwhile, may produce better results over a particular region.

Studies over smaller spatial scales may provide an improved understanding of the relationship between the geographic location, temperature variability and ETEs. This could be a fifth direction for future research. Such studies may assist researchers in understanding the locality in terms of position relative to the distribution of land and ocean proximity, land use, topography in terms of the terrain, and altitude. An additional, important future research direction is to explore high resolution microclimate analyses of heat stress. This involves the analysis of heat exposure and heat stress almost on a personal scale (Kuras *et al*., 2017; Kosaka *et al*., 2018). Examples include analyses of heat exposure and heat stress of athletes competing in outdoor sporting events, workers engaging in agriculture, construction, firefighting, manufacturing, military, or resource extraction who face prolonged heat exposure from outdoor conditions as well as extreme indoor environments such as heat generated by machinery or power equipment (Kuras *et al*., 2017; Kosaka *et al*., 2018). These activities and many more are essential for socioeconomic development, particularly in a South African context. This further emphasises the importance of this future research direction.

As a seventh direction, the investigation of synoptic features as drivers of ETEs across South Africa is important. For such research, focus can be placed on investigating changes and variability in the frequency and duration of synoptic features, and how this correlates with the frequency and incidence of both kinds of ETEs across the country. Furthermore, several studies report that teleconnection forcing mechanisms (e.g. ENSO, IOD, the Southern Annular Mode (SAM), the North Atlantic Oscillation (NOA), the Arctic Oscillation (AO), and the Pacific

Decadal Oscillation (PDO)) have been related to ETEs in various regions (e.g Nicholls *et al*., 2012; You *et al*., 2013; Ning and Bradley, 2015; Matsueda & Takaya *et al*., 2015; He *et al*., 2017; Loikith *et al*., 2017; Liu *et al*., 2018). Therefore, the fifth research paper attempts to highlight the importance of these mechanisms (Supplementary Material: Draft Article), by presenting a review of ETEs and Africa's vulnerability in the global context. In general, very few studies across Africa have explored the attribution of extreme climatic events, particularly the influence of large-scale drivers on ETEs (e.g. Otto *et al*., 2015; Abatan *et al*., 2018) as well as in a South African context.

Reference List

Abatan, A.A., Abiodun, B.J., Lawal, K.A. and Gutowski Jr, W.J. (2016). Trends in extreme temperature over Nigeria from percentile-based threshold indices. *International Journal of Climatology*, 36: 2527–2540.

Abatan, A.A., Abiodun, B.J., Gutowski, W.J. and Rasaq-Balogun, S.A. (2018). Trends and variability in absolute indices of temperature extremes over Nigeria: linkage with NAO. *International Journal of Climatology*, 38: 593–612. DOI: 10.1002/joc.5196.

Abbas, F., Rehman, I., Adrees, M., Ibrahim, M., Saleem, F., Ali, S., Rizwan, M. and Salik, M.R. (2018). Prevailing trends of climate extremes across Indus-Delta of Sindh-Pakistan. *Theoretical and Applied Climatology*, 131: 1101–1117. DOI:10.1007/s0070-016-2028-y.

Abiodun, B.J., Omar, S.A. and Jack, C. (2016). Using regional climate models to simulate extreme rainfall events in the Western Cape, South Africa. *International Journal of Climatology*, 36: 689–705. DOI:10.10228/joc.43676.

Adabi, A.M., Rowe, C.M. and Andrade, M. (2020). Climate regionalization in Bolivia: A combination of no-hierarchical and consensus clustering analyses based on precipitation and temperature. *International Journal of Climatology*, 40: 4408–4421.

Addinsoft. (2020). *XLSTAT statistical and data analysis solution*. New York, USA. [Software] Available from: https://www.xlstat.com.

Adger, W.N., Huq, S., Brown, K., Conway, D. and Hulme, M. (2003). Adaption to climate change in the developing world. *Progress in Development Studies*, 3(3): 179–195.

Aguilar, E., Vincent, L., and Zhang. X. (2013). *Climate Data Homogenization Theory*. Environmental Canada: Toronto, Canada.

Akinyemi, F.O. and Abiodun, B.J. (2019). Potential impacts of global warming levels 1.5°C and above on climate extremes in Botswana. *Climatic Change*, 154: 384–400. DOI:10.1007/s10584-019-02446-1.

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Kumar, K.R., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M. and Vazquez-Aguirre, J.L. (2006). Global observed changes in daily climate extremes of temperatures and precipitation. *Journal of Geophysical Research*, 111. DOI:10.1029/2005JD006290.

Alexander, L. and Perkins, S. (2013). Debate heating up over changes in climate variability. *Environmental Research Letters*, 8. DOI:10.1088/1748-9326/8/4/041001.

Alexander, L. and Herold, N. (2016). *Climpact2 Indices and Software*. The University of South Wales: Sidney, Australia. [Software] Available from: https://github.com/ARCCSSextremes/climpact2.

Alexanderson, H. (1986). A homogeneity test applied to precipitation data. *Journal of Climate*, 6: 661-675.

Aliaga, V.S., Ferrelli, F. and Piccolo, M.C. (2017). Regionalization of climate over the Argentine Pampas. *International Journal of Climatology*, 37: 1237–1247.

Allen, M.J. and Sheridan, S.C. (2015). Mortality risks during extreme temperature events (ETEs) using a distributed lag non-linear model. *International Journal of Biometerology*, 62: 57–67.

Allen, S.M.J., Gough, W.A. and Mohsin, T. (2015). Changes in the frequency of extreme temperature records for Toronto, Ontario, Canada. *Theoretical and Applied Climatology*, 119: 481–491. DOI:10.1007/s00704-014-1131-1.

Allen, M.J. and Sheridan, S.C. (2016). Evaluating changes in season length, onset, and end dates across the United States (148-2012). *International Journal of Climatology*, 36: 1268–1277.

Allen, M.J. and Sheridan, S.C. (2018). Mortality risks during extreme temperature events (ETEs) using a distributed lag non-linear model. *International Journal of Biometeorology*, 62(1): 57-67.

Alpert, P., Osentinsky, I., Ziv, B. and Shafir, H. (2004). A new seasons definition based on classified daily synoptic systems: An example for the Eastern Mediterranean. *International Journal of Climatology*, 24(8): 1013–1021.

Almazroui, M., Islam, M.N., Dambul, R. and Jones, P.D. (2014). Trends of temperature extremes in Saudi Arabia. *International Journal of Climatology*, 34: 808–826.

Añel, J.A., Fernández-González, M., Labandeira, X., López-Otero, X. and De la Torre, L. (2017). Impact of cold waves and heat waves on the energy production sector. *Atmosphere*, 8: 209. DOI:10.3390/atmos8110209.

Angélil, O., Stone, D., Wehner, M., Paciorek, C.J., Krishnan, H. and Collins, W. (2017). An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. *American Meteorological Society*, 30: 5–16. DOI:101175/JCLI-D-16-0077.1.

Araujo, J.A., Abiodun, B.J. and Crespo, O. (2016). Impacts of drought on grape yields in Western Cape, South Africa. *Theoretical and Applied Climatology*, 123: 117–130.

Archer, E.R.M., Oettlé, N.M., Louw, R. and Tadross, M.A. (2008). Farming on the edge in arid western South Africa: Climate change and agriculture in marginal environments. *Geography*, 93(2): 98–107.

Argiriou, A.A., Kassomenos, P.A. and Lykoudis, S.P. (2004). On the methods for the delimitation of seasons. *Water, Air and Soil Pollution: Focus*, 4: 65–74.

Arguez, A. and Vose, R.S. (2011). The definition of standard WMO climate normal: The key to deriving alternative climate normal. *Bulletin of the American Meteorological Society*, 92: 699-704.

Attribution of extreme weather events in the context of climate change (2016). Washington DC: National Academic Press. DOI:10.17226/21852.

Bajjali, W. (2018). Geostatistical Analysis. In: *ArcGIS for environmental and water issues*. Springer Textbooks in Earth Sciences, Geography and Environment. Cham: Springer.

Baldwin, J.W., Dessy, J.B., Vecchi, G.A. and Oppenheimer, M. (2019). Temporally compound heat wave and global warming: An emerging hazard. *Earth's Future*, 7: 411-427.

Barnett, A.G., Hajat, S., Gasparrini, A. and Rocklöv, J. (2012). Cold and heatwaves in the United States. *Environmental Research*, 112: 218-224.

Barriopedro, D.E.M., Fischer, J., Luterbacher, J., Trigo, R.M. and Garcia-Herrera, R. (2011). The hot summer of 2010: redrawing the temperature record map of Europe. *Science*, 332: 220-224.

Battisti, D.S. and Naylor, R.L. (2009). Historical warmings of future food insecurity with unprecedented seasonal heat. *Science*, 323(5911): 240–244. DOI: 10.1126/science.1164363.

Baudoin, M.A., Vogel, C., Nortje, K. and Naik, M. (2017). Living with drought in South Africa: lessons learnt from the recent El Niño drought period. *International Journal of Disaster Risk Reduction*, 23: 128–137.

Bellprat, O., Guemas, V., Doblas-Reyes, F. and Donat, M.G. (2019). Towards reliable extreme weather and climate event attribution. *Nature Communications*, 10. DOI: 10.1038/s41467-019-09729.

Benhin, J.K. (2006). Climate change and South African agriculture: Impacts and adaption options. [Online] Available from: https://www.weadapt.org/sites/weadapt.org/files/legacy-new/knowledge-base/files/5370f181a5657504721bd5c21csouth-african-agriculture.pdf.

Błażejcyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., Psikuta, A., and Kampmann, B. (2013). An introduction to the universal thermal climate index (UTCI). *Geographia Polonica*, 86(1): 5–10.

Bocard, D., Gillet, F. and Legendre, P. (2011). *Numerical ecology with R*. New York: Springer.

Boero, R., Bianchini, L. and Pasqualini, D. (2015). Vulnerability and adaption to severe weather events in the American southwest. *Weather and Climate Extremes*, 8: 12–25.

Botai, C., Botai, J., Muchuru, S. and Ngqana, I. (2015). Hydrometeorological research in South Africa: A review. *Water*, 7: 1580–1594.

Botai, C.M., Botai, J.O. and Adeola, A.M. (2018). Spatial distribution of temporal precipitation contrast in South Africa. *South African Journal of Science*, 114: 70–78.

Brophy, S. (2016). Weird weather: SA's most extreme weather events of 2016. *Traveller24*. [Online] Available from: https://www.traveller24.com/News/WeatherUpdate/weird-weather-sas-most-extreme-weather-events-of-2016-20161223 [Accessed: 21 April 2020].

Brown, S.J., Caeser, J. and Ferro, C.A.T. (2008). Global changes in extreme daily temperature since 1950. *Journal of Geophysical Research*, 113: 1–11.

Brunetti, M., Maugeri, M., Monty, F. and Nanni, T. (2006). Temperature and precipitation variability in Italy in the last two centuries from homogenized instrumental time series. *International Journal of Climatology,* 26(3): 345–381.

Burls, N.J., Blamey, R.C., Cash, B.A., Sweson, E.T., al Fahad, A., Bopape, M.M., Straus, D.M. and Reason, C.J.C. (2019). The Cape Town "Day Zero" drought and Hadley cell expansion. *Climate and Atmospheric Sciences*. DOI: 10.1038/s41612-019-0084-6.

Caloiero, T. (2017). Trend of monthly temperature and daily extreme temperature during 1951-2012 in New Zealand. *Theoretical and Applied Climatology*, 129: 111–127.

Caloiero, T., Coscarelli, R., Ferrari, E. and Sirangelo, B. (2017). Trend analysis of monthly mean values and extreme indices of daily temperature in a region of southern Italy. *International Journal of Climatology*, 37: 284–297.

Carvalho, P.R., Munita, C.S. and Lapolli, A.L. (2019) Validity studies among hierarchical methods of cluster analysis using cophenetic correlation coefficient. *Brazil Journal of Radiation Sciences*, 7(2A), Art. #668. DOI:10.15392/bjrs.v7i2a.668.

Cattaiux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V. and Codron, F. (2010). Winter 2010 in Europe: A cold extreme in a warming climate. *Geophysical Research Letters,* 37. DOI:10.129/2010GL044613.

Ceccherini, G., Russo. S., Ameztoy, I., Marchese, A.F. & Moreno, C. (2017). Heatwaves in Africa 1984-2015, observations and reanalysis. *Natural Hazards and Earth System Sciences*, 171: 115—125.

Chai, H., Cheng, W., Zhou, C., Chen, X., Ma, X. and Zhao, S. (2011). Analysis and comparison of spatial interpolation methods for temperature data in Xinjian Ugur Autonomous region, China. *Natural Science*, 3(12): 999–1010.

Chan, E.Y.Y., Ho, J.Y., Hung, H.H., Liu, S. and Lam, H.C.Y. (2019). Health impact of climate change in cities of middle-income countries: the case of China. *British Medical Bulletin*, 130: 5–24.

Chen, J., Yang, J., Zhou, M., Yin, P., Wang, B., Liu, J., Chen, Z., Song, X., Ou, C-Q. and Liu, Q. (2019). Cold spell and mortality in 31 Chinese capital cities: Definitions, vulnerability and implications. *Environmental International*, 128: 271-278. https://doi.org/10.1016/j.envint.2019.04.049.

Cheng, S. and Kalkstein, L.S. (2004). Determination of climatological seasons for the East Coast of the U.S. using air mass-based classification. *Climate Research*, 8: 107–116.

Cherchi, A., Ambrizzi, T., Behera, S., Freitas, A.C.V., Morioka, Y. and Zhou, T. (2018). The response of subtropical highs to climate change. *Current Climate Change Reports*, 4: 371–382.

Cherisch, M., Wright, C.Y., Venter, F., Rees, H., Scorgie, F. and Erasmus, B. (2018). Impacts of climate change on health and wellbeing in South Africa. *International Journal of Environmental Research and Public Health*, 15(9): 1–14. DOI: 10.3390/ijerph15091884.

Chersich, M.F. and Wright, C.Y. (2019). Climate change adaption in South Africa: a case study on the role of the health sector. *Globalization and Health*, 15: 22. DOI:10.1186/s12992-019-0466-x.

Coa, W., Hu, J. and Yu, X. (2009). A study on temperature interpolation methods based on GIS. *17th International Conference on Geoinformations*. IEEE: Fairfax, VA, USA.

Cohen, J.L., Furtado, J.C., Barlow, M., Alexeev, V.A. and Cherry, J.E. (2012). Asymmetric seasonal temperature indices. *Geophysical Research Letters*, 39(4): 1–7.

Collins, D.A., Della-Marta, P.M., Plummer, N. and Trewin, B.C. (2000). Trend in annual frequencies of extreme temperature events in Australia. *Australia Meteorological Magazine*, 49: 277–292.

Collins, J.M. (2011). Temperature variability over Africa. *Journal of Climate*, 24: 3649—3666.

Contractor, S., Alexander, L.V., Donat, M.G. and Herold, N. (2015). How well do gridded datasets of observed daily precipitation compare over Australia? *Advances in Meteorology*, Art. #325718: 15 pages. DOI: 10.1155/2015/325718.

Conner, L.H. (2016). *Climate change and Anthropos: planet, people and places*. Routledge: New York, 222.

Costa, R.L., de Mello Baptista, G.M., Gomes, H.B., dos Santos Silva, F.D., da Rocha Júnior, R.L., de Araújo Salvador, M. and Herdies, D.L. (2020). *Weather and Climate Extremes*, 28. DOI: 10.1016/j.wace.2020.100245.

Coumou, D. and Rahmstorf, S. (2012). A decade of extreme weather. *Nature Climate Change*. DOI: 10.1038/NCLIMATE1452.

Coumou, D., Robinson, A. and Rahmstorf, S. (2013). Global increase in record breaking monthly mean temperatures. *Climate Change*, 118: 771–782.

Cowling, R.M., Procheş, Ş. and Partridge, T.C. (2009). Explaining the uniqueness of the Cape flora: incorporating geomorphic evolution as a factor for explaining its diversification. *Molecular Phylogenetics and Evolution*, 51: 64–74.

CRED. (2019). *2018 Review of disaster events.* Brussels, 24 January 2019. [Online] Available from: https://www.emdat.be/2018-review-disaster-events.

Craig, M.H., Kleinschmidt, I., Nawn, J.B., Le Sueur, D. and Sharp, B.L. (2004). Exploring 30 years of malaria case data in KwaZulu-Natal South Africa: Part 1. The impact of climatic factors. *Tropical Medicine and International Health*, 9(12): 1247–1257.

Crétat, J., Richard, Y., Pohl, B., Roualt, M., Reason C. and Fauchereau, N. (2012). Recurrent daily rainfall patterns over South Africa and associated dynamics during the core of the austral summer. *International Journal of Climatology*, 32: 261–273.

Croituoru, A-E., Piticar, A., Cuipertea, A-F. and Roşca, C.F. (2016). Changes in heatwaves indices in Romania over the period 1961–2015. *Global and Planetary Change*, 146: 109–121.

Crow, T.M., Albeke, S.E., Buerkle, C.A. and Hufford, K.M. (2018). Provisional methods to guide species specific see transfer in ecological restoration. *Ecosphere*, 9(1): 1–14.

Czernecki, B. and Miętus, M. (2017). The thermal seasons variability in Poland, 1951-2010. *Theoretical and Applied Climatology*, 127: 481–493.

Daniel, W.W. (1978). *Applied nonparametric statistics*. Boston.

Davis, C.L. (2011). *Climate risk and vulnerability: A Handbook for southern Africa*. Council for Scientific and Industrial Research: South Africa, 92.

Davis, C.L., Hoffman, M.T. and Roberts, W. (2016). Recent trends in the climate of Namaqualand, a megadiverse arid region of South Africa. *South African Journal of Science*, 112(3/4): 1–9. DOI: 10.17159/sajs.2016/20150217.

Davis, C.L., Waagsaether, K. and Methner, N. (2017). *Development of risk assessment methodology and vulnerability index. In Climate change over South Africa: From trends and projected changes to vulnerability assessment and the status quo of national adaption strategies*. Chapter 3 in DEA. South Africa's 3rd National Communication to UNFCCC. Department of Environmental Affairs: Pretoria.

Davis-Reddy, C.L. and Vincent, K. (2017). *Climate risk and vulnerability: A handbook for southern Africa* (2nd ed). CSIR: Pretoria, South Africa.

De Cian, E., Lanzi, E., and Roson, R. (2013). Seasonal temperature variations and energy demand. *Climatic Change*, 116(3-4): 805–825. DOI: 10.1007/s10584-012-0514-5.

De la Barreda, B., Metcalfe, S.E. and Boyd, D.S. (2020). Precipitation regionalization and drought occurrence in the Yucatan Peninsula, Mexico. *International Journal of Climatology*, 40: 4541–4555.

De Perez, EC., van Aalst, M., Bischiniotis, K., Mason, S., Nissan, H., Pappenberger, F., Stephens, E., Zsoter, E. and van den Hurk, B. (2018). Global predictability of temperature extremes. *Environmental Research Letters*, 13. DOI:10.1088/1748-9326/aab94a.

De'Donato, F.K., Leone, M., Noce, D., Davoli, M. and Michelozzi, P. (2013). The impact of the February 2012 cold spell on health in Italy using surveillance data. *Plos ONE*, 8(4): 1–9. DOI: 10.1371/journal.pone.0061720.

DEA. (2013). *Long-term Adaption Flagship Research Programme (LTAS) for South Africa*. Climate Trends and Scenarios for South Africa: Pretoria, South Africa.

DEA. (2016). Climate change trends, risks impact and vulnerabilities. *South Africa's 1st Annual Climate Change Report*. Department of Environmental Affairs: Pretoria.

Della-Marta, P.M. and Wanner, H. (2006). A method of homogenizing the extremes and mean of daily temperature measurements. *Journal of Climate*, 19: 4179–4197.

Di Piazza, A., lo Conti, F., Viola, F., Eccel, E. and Noto, L.V. (2015). Comparative analysis of spatial interpolation methods in the Mediterranean area: application to temperature in Sicily. *Water*, 7: 1866–1888.

Díaz, J., Carmona, R., Mirón, I.J., Luna, M.Y. and Linares, C. (2019). Time trends in the impact attributable to cold days in Spain: Incidence of local factors. *Science of the Total Environment*, 655: 305–312. https://doi.org/10.1016/j.scitotenv.2018.11.254.

Ding, T., Qian, W. and Yan, Z. (2010). Changes in hot days and heat waves in China during 1961 – 2007. *International Journal of Climatology*, 30: 1452–1462.

Diriba, T.A., Debusho, L.K. and Botai, J. (2015). Modeling extreme daily temperature using generalized pareto distribution at Port Elizabeth, South Africa. *Proceeding of the 57th Annual Conference of SASA*, 41–48.

Dong, W., Jiang, Y. and Yang, S. (2010). Response of the starting dates and lengths of seasons in Mainland China to global warming. *Climatic Change*, 99: 81–91.

Domonkos, P. and Coll, J. (2017). Homogenisation of temperature and precipitation time series with ACMANT3: method description and efficiency test. *International Journal of Climatology*, 37: 1910–1921.

Doran, J.D, (2014). "Regional Climate Messages: Southern Africa". Scientific report from CARIAA Adaption at Scale in Semi-Arid Regions (ASSAR) Project, December 2014.

Doubell, H., Denga, M., Rautenbach, H., Rae, K., Joubert, W. and Mengistu, M. (2018). Weathersmart news: Scientific meteorological and climatological news from the South African Weather Service. *South African Weather Service*. [Online] Available from: https://www.weathersa.co.za/Documents/Corporate/165468%20SA%20Weather%20 Service=WeatherSmart%20Newsletter_mailer2(1).pdf. [Accessed: 22 April 2020].

Dube, L.T. (2002). Climate of southern Africa. *South African Geography Journal*, 84(1): 125–138. DOI:10.1080/03736245.2002.9713763.

Durham, J. (2011). 'A Temperature extreme index for the South African Region'. *Proceedings of the SASA 2011 Conference*. Council for Scientific and Industrial Research, 10.

Dyson, L.L. (2009). Heavy daily-rainfall characteristics over the Gauteng Province. *Water SA*, 35: 627–638.

Dyson, L.L. and Van Heerden, J. (2002). A model for the identification of tropical weather systems (MITS) over South Africa. *Water SA*, 289(3): 249–258.

Easterling, D.R., Evans, J.L., Groisman, P.Ya., Karl, T.R., Kunkel, K.E. and Ambenje, P. (2000a). Observed variability and trends in extreme climate events: a brief review. *Bulletin of the American Meteorological Society*, 81(3): 417–425.

Easterling D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. and Mearns, L.O. (2000b). Climate Extremes: Observations, modeling and impacts. *Science*, 289: 2068–2074.

Easterling, D.R., Kunkel, K.E., Wehner, M.F. and Sun, L., (2016). Detection and attribution of climate extremes in the observed record. *Weather and Climate Extremes*, 11: 17–27.

Ebbs, S. (2020). Climate change can 'supercharge' wildfires in Australia through more extreme heat, drought. *abcNews*. [Online] Available from: https://abcnews.go.com/International/climate-change-supercharge-wildfires-australia-extreme-heat-drought/story?id=68096029. [Accessed: 19 May 2020].

Ebi, K.L. and Bowen, K. (2016). Extreme events as sources of health vulnerability: Drought as an example. *Weather and Climate Extremes*, 11: 95–102.

Engelbrecht, C.J., Engelbrecht, F.A. and Dyson, L.L. (2012). High-resolution model-projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *International Journal of Climatology*, 33(1): 173–187.

Engelbrecht, F. and Landman, W. (2010). South Africa's present-day climate. In: *Southern Africa Risk and Vulnerability Atlas*. CPD Print: Pretoria, 2–5.

Engelbrecht, C.J. and Engelbrecht, F.A. (2015). Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theorical and Applied Climatology*, 123: 247–261.

Engelbrecht, C., Landman, W., Engelbrecht, F., Malherbe, J. (2015). A synoptic decomposition of rainfall over the Cape south coast of South Africa. *Climate Dynamics*, 44(9–10): 2589–2607.

Engelbrecht, F., Adegoke, J., Bopape, M-J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. and Gatebe, C. (2015). Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, 10. DOI: 10.1088/1748-9326/10/8/085004.

EM-DAT CRED (2019). *Disasters in Africa: 20-year review (2000-2019)*. Centre for Research on the Epidemiology of Disasters (CRED): Brussels.

EM-DAT CRED (2020). The International Disaster Database, EM-DAT query tool. Centre for Research on the Epidemiology of Disasters (CRED): Brussels. [Online] Available from: https://www.emdat.be/.

Favre, A., Philippon, N., Pohl, B., Kalognomou, E.A., Lennard, C., Hewitson, B., Nikulin, G., Dosio, A., Panitz, H.J. and Cerezo-Mota, R. (2016). Spatial distribution of precipitation annual cycles over South Africa in 10 CORDEX regional climate model present-day simulations. *Climate dynamics*, 46: 1799–1818.

Feron, S., Cordero, R.R., Damiani, A., Llanilo. P.J., Jorquera, J., Sepulveda, E., Asencio, V., Laroza, D., Labbe, F., Carrasco, J. and Torres, G. (2019). Observations and projections of heatwaves in South America. *Scientific Reports*, 9: 8173. DOI: 10.1038/s41595-019-44614-4.

Filho, W.L., Al-Amin, A.Q., Nagy, G.J., Azeiterio, U.M., Wiesböck, L., Ayal, D.Y., Morgan, E.A., Mugabe, P., Aparicio-Effen, M., Fudjumdjum, H. and Jabbour, C.J.C. (2018). A comparative analysis of climate-risk and extreme event-related impacts on well-being and health. *Policy Implications, International Journal of Environmental Research and Public Health*, 15: 331. DOI:10.3390/ijerph15020331.

Fioravanti, G., Pervitali, E. and Desiato, F. (2019). A new homogenized daily data set for temperature variability assessment in Italy. *International Journal of Climatology*, 39: 5635–5654.

Fischer, E.M. and Shär, S. (2010). Consistent geographical patterns in high-impact European heatwaves. *Natural Geoscience*, 3: 398–403. DOI:10.1038/ngeo866.

Fitchett, J.M., Robinson, D. and Hoogendoorn, G. (2017). Climate suitability for tourism in South Africa. *Journal of Sustainable Tourism*, 25(6): 851–867.

Fitchett, J.M. and Hoogendoorn, G. (2019). Exploring the climate sensitivity of tourists to South Africa through TripAdvisor reviews. *South African Geography Journal,* 101(1): 91–109. DOI:10.1080/037362453.2018.1541022.

Fitchett, J.M., Grab, S.W., Portwig, H. (2019). Progressive delays in the timing of sardine migration in the southwest Indian Ocean. *South African Journal of Science*, 115(7/8): 6 pages. DOI:10.17159/sajs.2019/5887.

Fitchett, A., Govender, P. and Vallabh, P. (2020). An exploration of green roofs for indoor and exterior temperature regulation in the South African interior. *Environment, Development and Sustainability*, 22: 5052–5044.

Founda, D., Pierros, F., Katavoutas, G. & Keramitsoglou, I. (2019). Observed trends in thermal stress at European cities with different background climates. *Atmosphere*, 10: 436.

Garland, R. (2017). Human health. In: Mambo J. and Faccer, K. (eds). *Understanding the Social and Environmental Implication of Global Change*. African Sun Media: Stellenbosch.

Garonna, I., de Jonge, R. and Schaepman, M.E. (2016). Variability and evolution of global land surface phenology over the past three decades (1982-2012). *Global Change Biology*, 22: 1456–1468.

Gibson, P.B., Perkins-Kirkpatrick, S.E., Alexander, L.V. and Fischer, E.M. (2017). Comparing Australian heat waves in the CMIP5 models through cluster analysis. *Journal of Geophysical Research: Atmospheres*, 122: 3266–3281.

Giddy, J.K., Fitchett, J.M. and Hoogendoorn, G. (2017). Insight into American tourists' experiences with weather in South Africa. *Bulletin of Geography. Socio-economic Series,* 35: 57–71.

Goldblatt, A. (2010). *Agriculture facts and trends South Africa*. WWF-SA: Cape Town.

Govender, P. and Sivakumar, V. (2020). Application of *k*-means and hierarchical clustering techniques for analysis of air pollution: A review (1980–2019). *Atmospheric Pollution Research*, 11: 40–56.

GCIS. (2016). *South Africa yearbook 2015/2016*. 23rd ed. Government Communications: Pretoria.

Grab, S.W. and Knight, J. (2018). Southern African Montane Environments. In: Holmes, P.J. and Boardman, J. (eds.). *Southern African Landscape and Environmental Change*. Routledge: Oxon.

Han, J., Liu, S., Zhang, J., Zhou, L., Fang, Q., Zhang, J. and Zhang, Y. (2017). The impact of temperature extremes on mortality: a time series study in Jinan, China. *BMJ Open*. 7:e014741. DOI:10.1136/bmjopen-2016-014741.

Harrington, L.J. and Otto, F.E.L. (2020). Reconciling theory with the reality of African heatwaves. *Nature Climate Change*, 10: 794–798.

Hart, N.C.G., Reason, C.J.C. and Fauchereau, N. (2012). Cloud bands over southern Africa: seasonality contribution to rainfall variability and modulation by the MJO. *Climate Dynamics*, 42: 119–121.

Hartmann, D.L., Klein Tank, A.M.G., Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M and Zhai, P.M. (2013). Observations: Atmosphere and Surface. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V and Midgley, P.M. (eds.). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.

He, S., Goa, Y., Li, F., Wang, H. and He, Y. (2017). Impact of Artic Oscillation on the East Asian climate: A review. *Earth-Science Reviews*, 164: 48–62.

Head, T. (2019). Seven South African weather records that were broken in 2019. *The South African.* [Online] Available from: https://www.thesouthafrican.com/news/weather/hottest-day-in-south-africa-ever-weather-records/. [Accessed: 26 February 2020].

Heim Jr., R.R. (2015). An overview of weather and climate extremes – Products and trends. *Weather and Climate Extremes*, 10: 1–9.

Hekmatzadeh, A.A., Kaboli, S. and Haghighi, A.T. (2020). New indices for assessing changes in seasons and in timing characteristics of air temperature. *Theoretical and Applied Climatology*, 140: 1247–1261.

Herold, N., Alexander, L., Green, D. and Donat, M. (2017). Greater increase in temperature extremes in low versus high income countries. *Environmental Research Letters*, 12: 1–3. DOI:10.1088/1748- 9326/aa5c43.

Hiltunen, L., Haukka, J., Ruuhela, R., Suominen, K. and Parton, T. (2014). Local daily temperatures, thermal seasons, and suicide rates in Finland from 1974 to 2010. *Environmental Health Preventive Medicine*, 19: 286–294.

Horton, R.M., Mankin, J.S., Lesk, C., Coffel, E. and Raymond, C. (2016). A review of recent advances in research on extreme heat events. *Current Climate Change Report*, 2: 242–259.

IPCC. (2018). Summary for Policymakers. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. [Online] Available from: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf.

Jahn, M. (2015). Economics of extreme weather events: Terminology and regional impact models. *Weather and Climate Extremes*, 10: 29–39.

Johnson, N.C., Xie, S-P., Kosaka, Y. and Li, X. (2018). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. *Nature Communications,* 9:1724. DOI:10.1038/s41467-018-0404-y.

Jones, D.A. and Trewin, B. (2002). On the adequacy of digitised historical Australian daily temperature data for climate monitoring. *Australian Meteorological Magazine*, 51: 237–250.

Jury, M.R. and Parker, B. (1998). Cold winters over the South African highveld: pattern recognition and preliminary models. *South African Journal of Science*, 94: 473–481.

Jury, M.R. (2013). Climate trends in southern Africa. *South African Journal of Science*, 109. DOI:10.1590/sajs.2013/980.

Jury, M.R. (2018). Climate trends across South Africa since 1980. *Water SA*, 44: 297–307.

Kabanda, T.H. & Palamuleni, L.G. (2011). Seasonal weather events and their impact on buildings around Mafikeng, North West Province, South Africa. *Life Science Journal*, 8(S1).

Kalkstein, L.S., Tan, G.R. and Skindlov, J.A. (1987). An evaluation of 3 clustering procedures for the use in synoptic climatological classification. *Journal of Climate and Applied Meteorology*, 26: 717–730.

Kanner, J., Williams, A.D., Nobles, C., Ha, S., Ouidir, M., Sherman, S. and Mendola, P. (2020). Ambient temperature and stillbirth: Risks associated with chronic extreme temperature and acute temperature change. *Environmental Research*, 189. DOI: 10.106/j.envres.2020.109958.

Karki, R., Hasson, S.U., Gerlitz, L., Talchabhadel, R., Schickhoff, U., Scholten, T. and Böhner, J. (2019). Rising mean and extreme near-surface air temperature across Nepal. *International Journal of Climatology*, 1–19. DOI: 10.1002/joc.6344.

Karl, T.R., Jones, P.D., Knight, R., Kukla, G., Plummer, N., Razuvzyev, V., Gallo, K.P., Linseay, J., Charlson, R.J. and Peterson, T.C. (1993). Asymmetric trends of daily maximum and minimum temperature. *Bulletin of the American Meteorology Society*, 74(6): 1007–1023.

Kaufman, L. and Rousseeuw, P.J. (1990). *Finding groups in data. An introduction to cluster analysis*. New York: John Wiley and Sons.

Kayikçi, E.T and Kazanci, S.Z. (2016). Comparison of regression-based and combined versions of Inverse Distance Weighted methods for spatial interpolation of daily mean temperature data. *Arabic Journal of Geosciences*, 9: 690. DOI: 10.1007/s12517-016-2723-0.

Kendall MG (1955) *Rank Correlation Methods*. London: Charles Griffen, p. 196.

Kenyon, J. and Hegerl, G.C. (2008). Influence of modes of climate variability on Global temperature extremes. *Journal of Climate*, 21: 3872–3888.

Kharin, V.V., Zwiers, F.W., Zhang, X. and Wehner, M. (2013). Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climate Change*, 119: 345–357.

Klein Tank, A.M.G., Zwiers, F.W. and Zhang, X. (2009). *Guidelines on analysis of Extremes in a Changing Climate in Support of Informed Decisions for Adaptation* (WCDMP no. 72, WMO-TD no. 1500). Switzerland: World Meteorological Organization, 54 pp.

Klopper E., Landman, W.A. and Van Heerden, J. (1998). The predictability of seasonal maximum temperature in South Africa. *International Journal of Climatology*, 18, 741–758.

Klopper, E. (1999). The use of seasonal forecast in South Africa during the 1997/98 rainfall season. *Water SA*, 25 (3): 311–316.

Kodinariya, T.M. and Mwakwana, P.R. (2013). Review on determining number of clusters in K-means clustering. *International Journal of Advances in Research of Computer Science Management Studies,* 1(6): 90–95.

Kodra, E., Steinhaeuser, K. and Ganguly, A.R. (2011). Persisting cold extremes under 21st century warming scenarios. *Geophysical Research Letters*, 38. DOI:10.1029/2011GL047103.

Kodra, E. and Ganguly, A.R. (2014). Asymmetry of projected increases in extreme temperature distributions. *Scientific Reports*, 4: 5884. DOI:10.1038/srep05884.

Kosaka, E., Lida, A., Vanos, J., Middel, A., Yokohari, M. and Brown, R. (2018). Microclimate variation and estimated heat stress of runners in the 2020 Tokyo Olympic Marathon. *Atmosphere*, 9(5): 192. DOI: 10.3390/atmos9050192.

Kruger, A.C. (2008). *Climate of South Africa. Surface Temperature. WS48*. Pretoria: South African Weather Services.

Kruger, A.C. and Sekele, S.S. (2013). Trend in extreme temperature indices in South Africa: 1962-2009*. International Journal of Climatology*, 33: 661–676. DOI: 10.1002/joc.3455.

Kruger, A.C., Goliger, A.M., Retief, J.V. and Sekele, S. (2010). Strong wind climatic zones in South Africa. *Wind and Structure, An International Journal*, 13(1): 37–55.

Kruger, A.C. and Shongwe, S. (2004). Temperature trends in South Africa: 1960-2003. *International Journal of Climatology*, 24: 1929–1945.

Kruger, A.C. and Nxumalo, M. (2017). Surface temperature trends from homogenized time series in South Africa: 1931-2015. *International Journal of Climatology*, 37: 2364–2377. DOI: 10.1002/joc.4851.

Kruger, A.C., Rautenbach, H., Mbatha, S., Ngwenya, S. & Makgole, T.E. (2019). Historical and projected trends in near surface temperature indices for 22 locations in South Africa. *South African Journal of Science*, 115(5/6).

Kuras, E.R., Richardson, M.B., Calkins, M.M., Ebi, K.L., Hess, J.J. Kintzinger, K.W., Jagger, M.A., Middel, A., Scott, A.A., Spector, J.T., Uejio, C.K., Vanos, J., Zaitchik, B.F., Gohlke, J.M. and Hondula, D.M. (2017). *Environmental Health Perspectives*. DOI: 10.1289/EHP556.

Kutta, E. and Hubbart, J.A. (2016). Reconsidering meteorological seasons in a changing climate. *Climatic Change*, 137(3-4): 511–524.

Landman, W.A., Malherbe, J. and Engelbrecht, F. (2017). *South Africa's present-day climate*. In: Mambo, J. and Faccer, K. (eds). *Understanding the Social and Environmental Implication of Global Change,* 2nd ed. Stellenbosch: African Sun Media. ISBN 978-0-992236-06-9.

Landman, W.A., Engelbrecht, F., Hewitson, B., Malherbe, J. and van der Merwe, J. (2018). Towards bridging the gap between climate change projections and maize producers. *Theoretical and Applied Climatology*, 132: 1153–1163.

Laprise, R., Hernández-Diáz, L., Tete, K., Sushama, L., Šeparović, L., Martynov, A., Winger, K. and Valin, M. (2013). *Climate Dynamics*, 41: 3219–3246.

Lazenby, M.J., Landman, W.A., Garland, R.M. and DeWitt, D.G. (2014). Seasonal temperature prediction skill over Southern Africa and human health. *Meteorological Application*, 21: 963–974. DOI:10.1002/met.1449.

Le Roux, A., Mans, G., van Hysteen, E. and van Niekerk, W. (2017). Profiling the vulnerabilities and risks of South African Settlements. In: Mambo, J. and Faccer, K. *Understanding the Social and Environmental Implications of Global Change*, 2nd ed. Stellenbosch: African Sun Media. ISBN 978-0-992236-06-9.

Lee, W.V. (2014). Historical global analysis of occurrences and human casualty of extreme temperature events (ETEs). *Natural Hazards,* 70: 1453–1505. DOI:10.1007/s11069-0.13-0884-7.

Lengoasa, J.R. (1991). Surface temperature field and circulation variations over southern Africa. *South African Geographical Journal,* 73(2): 41–47.

Lennard, C. and Hegerl, G. (2014). Relating changes in synoptic circulation to surface rainfall response using self-organising maps. *Climate Dynamics*, 44(3–4): 861–879.

Lennard, C. (2015). Relating changes in synoptic circulation to the surface rainfall response using self-organising maps. *Climate Dynamics*, 44: 861–876.

Lennard, C. (2019). Multi-Scale drivers of the South African weather and climate. In: Knight, J. and Rogerson, C.M. (eds). *The Geography of South Africa*. Cham: Springer.

Leriorato, J.C. and Nakamura, Y. (2019). Unpredictable extreme cold events: a threat to range-shifting tropical reef fishes in temperate waters. *Marine Biology,* 166(220).

Lewis, S.C. and King, A.D. (2017). Evolution of mean, variance and extremes in the 21st century temperatures. *Weather and Climate Extremes*, 15: 1—10.

Li, J. and Heap, A.D. (2014). Spatial interpolation methods applied in the environmental sciences: A review. *Environmental Modelling and Software*, 53: 173–189.

Li, R., Nathan, J.B.K., Yang, J. and Wang, Y. (2015). A phylogenetically informed delineation of floristic regions within a biodiversity hotspot in Yunnan, China. *Scientific Reports,* 5:1–7.

Li, C., Fang, Y., Caldeira, K., Zhang, X., Diffenbaugh, N.S. and Michalak, A.M. (2018). Widespread persistent changes to temperature extremes occurred earlier than predicted. *Scientific Reports*, 8: 1007.

Liu, X., Xu, Z., Peng, D. and Wu, G. (2018). Influences of the North Atlantic Oscillation on extreme temperature during the cold period in China. *International Journal of Climatology*, 39: 43–49.

Loikith, P.C., Detzer, J., Mechoso, C.R., Lee, H. and Barkhordarian, A. (2017). The influence of recurrent modes of climate variability on the occurrence of monthly temperature extremes over South America. *Journal of Geophysical Research: Atmosphere*, 122: 10,297–10,311.

Lötter, D. (2017). South Africa's present-day climate. In: Mambo, J. and Faccer, K. (eds). *Understanding the Social and Environmental Implication of Global Change*, 2nd ed. Stellenbosch: African Sun Media. ISBN 978-0-992236-06-9.

Lubega, W.N. and Stillwell, A.S. (2018). Maintaining electric grid reliability under hydrologic drought and heatwave conditions. *Applied Engineering*, 210: 538–549.

Luterbacher, J., Werner, J.P., Smerdon, J.E., Fernández-Donado, L., González-Rouco, F.J., Barriopedro, D., Ljungqvist, F.C., Büntgen, U., Zorita, E., Wagner, S., Esper, J., McCarroll, D., Toreti, A., Frank, D., Jungclaus, J.H., Barriendos, M., Bertolin, C., Bothe, O., Brázdil, R., Camuffo, D., Dobrovolny, P., Gagen, M., García-Bustamante, E., Ge, Q., Gómez-Navarro, J.J., Guiot, J., Hao, Z., Hegerl, G.C., Holmgren, K., Klimenko, V.V., Martín-Chivelet, J., Pfister, C., Roberts, N., Schindler, A., Schurer, A., Solomina, O., von Gunten, L., Wahl, E., Wanner, H., Wetter, O., Xoplaki, E., Yuan, N., Zanchettin, D., Zhang, H. and Zerefos, C. (2016). European summer temperatures since Roman times. *Environmental Research Letters*, 11: 024001. DOI:10.1088/1748-9326/11/2/024001.

Machiwal, D. and Jha, M.K. (2008). Comparative evaluation of statistical tests for time series analysis: application to hydrological time series. *Hydrological Sciences Journal*, 53(2): 353–366.

Mackellar, N., New, M. & Jack C. (2014). Observed and modelled trends in rainfall and temperature for South Africa: 1960—2010. *South African Journal of Science*, 110(7/8).

Magrin, G.O., Marengo, J.A., Boulanger, J-P., Buckeridge, M.S., Castellanos, E., Poveda, G., Scarano, F.R. and Vicuña, S. (2014). Central and South America. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White L.L. (eds.). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, pp. 1499-1566.

Mahlalela, P.T., Blamey, R.C. and Reason, C.J.C. (2018). Mechanisms behind early winter rainfall variability in the southwestern Cape, South Africa. *Climate Dynamics*, 53: 21–39.

Malherbe, J., Smit, I.P.J., Wessels, K.J. & Beukes, P.J. (2020). Recent droughts in the Kruger National Park as reflected in the extreme climate index. *Journal of Range and Forage Science*, 37(1).

Mamabo, J. and Murambadora M. (2017). *Municipal vulnerability to climate change*. In: Mambo, J. and Faccer, K. (eds.). *Understanding the social and environmental implications of global change*, 2nd ed. Stellenbosch: African Sun Media. ISBN 978-0-992236-06-9.

Mangani, R., Tesfamariam, E., Bellocchi, G. & Hassen, A. (2018). Modelled impacts of extreme heat and drought on maize yield in South Africa. *Crop and Pastor Science* 69: 703–716.

Mann, H.B. (1945). Non-parametric tests against trend. *Econometrica*, 13: 245-259.

Martinez, G.S., Diaz, J., Hooyberghs, H., Lauwaet, D., De ridder, K., Linares, C., Carmona, R., Ortiz, C., Kendrovski, V. and Adamonyte, D. (2018). Cold-related mortality vs heat-related mortality in a changing climate: A case study in Vilnius (Lithuania). *Environmental Research*. 166:384-393. DOI:10.1016/j.envres.2018.06.001.

Mason S.J. and Jury, M.R. (1997). Climatic variability and change over southern Africa: a reflection on underlying processes. *Progress in Physical Geography*, 21(1): 23–50.

Mastrorillo, M., Licker, R., Bohra-Mishra, P., Fagiolo, G., Estes, L.D. and Oppenheimer, M. (2016). The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change*, 39: 155–169.

Matlhare, A. (2019). One more freezing night, Gauteng cold front to end Wednesday. *The Star*. [Online] Available from: https://www.iol.co.za/the-star/news/one-more-freezing-night-gauteng-cold-front-to-end-wednesday-28418895. [Accessed: 21 April 2020].

Matsueda, S. and Takaya, Y. (2015). The global influence of the Madden-Julian Oscillation on extreme temperature events. *American Meteorological Society*, 28: 4141–4151.

Mbokodo, I., Bopape, M-J., Chikoore, H., Engelbrecht, F. and Nthaduleni, N. (2020). Heatwaves in the future warmer climate of South Africa. *Atmosphere*, 11,712.

McCann, L.P. and Swaby, A.N. (2016). Earth Hazards of the Southwestern US. In: Swaby, A.N., Lucas, D. and Ross, R.M. (eds.). *The Teacher-Friendly Guide to the Earth Science of Southwestern US*. Paleontological Research Institution (Special Publication 50). New York: Ithaca, pp. 329-372.

McGregor, G. (2017). Meteorological risk: extreme temperature. In: *Science for disaster risk management 2017: knowing better and losing less*. Luxembourg: Publications Office of the European Union, pp. 257–270.

Meyer, H., Schmidt, J., Detsch, F. and Naus, T. (2019). Hourly gridded air temperatures of South Africa derived from MSG SEVIRI. International Journal of Applied Earth Observation and Geoinformation, 78:261-267.

Mimmack, G.M., Mason, S.J. and Galpin, J.S. (2001). Choice of distance matrices in cluster analysis: defining regions. *Journal of Climate*, 14: 2790–2797.

Mirza, M.M.Q. (2003). Climate change and extreme weather events: can developing countries adapt? *Climate Policy*, 3 (3): 233–248.

Mirza, M.M.Q. (2011). Climate change, flooding in south Asia and implications. *Regional Environmental Change*, 11: S95–S107.

Moeletsi, M.E., Moopisa, S.G., Walker, S. and Tsubo, M. (2013) Development of an agroclimatology risk tool for dryland maize production in the Free State Province of South Africa. *Computers and Electronics in Agriculture*, 95: 108–121.

Mokoena, M. (2019). *South African Official Yearbook: South Africa Yearbook 2018/19, 26th edition*. Pretoria: Government Communications (GCIS).

Morak, S., Heger, G. and Kenyon, J. (2013). Detectable regional changes in the number of warm nights. *Geophysical Research Letters*, 38: L17703. DOI:101088/1748-9326/8/1/014055.

Mudelsee, M. (2019). Trend analysis of climate time series: A review of methods. *Earth-Science Reviews*, 190: 310–322.

Mueller, B. and Seneviratne, S.I. (2012). Hot days induced by precipitation deficits at the global scale. *National Academy of Science*, 109(31): 12,398–12,403.

Mueller, B., Zhang, X. and Zwiers, F.W. (2016). Historically hottest summers projected to be the norm for then half of the world's population within 20 years. *Environmental Research Letters*, 11. DOI: 10.1088/1748- 9324/11/4/044011.

Muirhead, R. (2002). World weather disasters: July 2002. *Journal of Meteorology*, 273: 359–360.

Nairn, J.R. and Fawcett, R.J.B. (2015). The Excess Heat Factor: A metric for heatwave intensity and its use in classifying heatwave severity. *International Journal of Environmental Research and Public Health*, 12: 227–253. DOI: 10.3390/ijerph120100227.

Nana, M., Coetzer, K. and Vogel, C. (2019). Facing the heat: initial probing of the city of Johannesburg's heat-health planning. *South African Geographical Journal*, 101(2): 253–268. DOI:1080/03736245.2019.1599412.

Nangombe, S., Zhou, T., Zhang, W., Zou., L. and Li, D., High-Temperature extreme events over Africa under 1.5 and 2°C of global warming. *Journal of Geophysical Research,* vol 124 (8). https://doi.org/10.1029/2018JD029747.

Napoli, C.D., Pappenberger, F. & Cloke, H.L. (2018). Assessing heat-related health risk in Europe via the Universal Climate Index (UTCI). *International Journal of Biometeorology*, 62: 1155—1165.

NOAA. (2020). *Anomalies vs Temperature*. [Online] Available from: https://www.ncdc.noaa.gov/monitoring-references/dyk/anomalies-vs-temperature.

Nemec, J., Bruder, C., Chimani, B., and Auer, I. (2013). Trends in extreme indices in Austria based on a new homogenized dataset. *International Journal of Climatology*, 33: 1538–1550.

New, M., Hewitson B., Stephenson D.B., Tsiga A., Kruger, A., Manhique A., Gomez, B., Coelho C.A.S., Masisi, N., Kuluanga, E., Mbambalala, E., Adesina, F., Saleh, H., Kanyanga, J., Adosi, J., Bulane, L., Fortunata L., Mdoka, ML. and Lajoie, R. (2006). Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research*, 111.

Ngwenya, B., Oosthuizen, J., Cross, M., Frimpong, K. and Chaibva, C.N. (2018). A review of heat stress policies in the context of climate change and its impacts on outdoor workers: evidence from Zimbabwe. *International Journal of Society and Ecological Sustainability Development*, 9(1): 1-11. https://doi.org/10.4018/IJSESD.2018010101.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham J. and Urquhart P. (2014). Africa. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White L.L. (eds.). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nicholls, S.I., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. and Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastranda, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M. and Midgley, P.M. (eds.). *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption. A special report on working groups I and II of the Intergovernmental Panel on Climate Change (IPCC).* Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, pp. 109-230.

Nicholson, S.E. (2001). Climatic and environmental change in Africa during the last two centuries. *Climate Research*, 17: 123–144.

Nicholson, S. (2018). The ITCZ and the seasonal cycle over equatorial Africa. *Bulletin of American Meteorological Society*, 99(2): 337–348.

Ning, L. and Bradley, R.S. (2015). Winter climate extremes over the northeastern United States and southeastern Canada and telecommunications with large-scale modes of climate variability. *American Meteorological Society*, 28: 2475–2493.

Nkemelang, T., New, M. and Zaroug, M. (2018). Temperate and precipitation extremes under current, 1.5°C and 2.0°C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability. *Environmental Research Letters*, 13.

Noome, K. and Fitchett, J. (2019). An assessment of the climate suitability of Afriski Mountain Resort for outdoor tourism using the Tourism Climate Index (TCI). *Journal of Mountain Science*, 16(11): 2453–2469.

Onoz, B. and Bayazit, M. (2003). The power of statistical trend detection. *Turkish Journal of Engineering and Environmental Sciences*, 27: 247–251.

Orth, R., Vogel, M.M., Luterbacher, J., Pfister, C. and Seneviratine, S.I. (2016). Did European temperatures in 1540 exceed present-day records? *Environmental Research Letters*, 11: 114021. DOI:10.1088/1748- 9326/11/11/114021.

Osborne, S. (2019). France's summer heatwave killed 1,500 people, health minister announces. *Independent*. [Online] Available from: https://www.independent.co.uk/news/world/europe/france-heatwave-summer-dead-death-toll-europe-a9096806.html. [Accessed: 14 April 2020].

Otto, F.E.L., Massey, N., Van Oldenborgh, G.J., Jones, R.G. and Allen, M.R. (2012). Reconciling two approaches to attribution of the 2010 Russian heat wave. *Geophysical Research Letters*, 39: Lo4702. DIO: 10.1029/2011GL050422.

Otto, F.E.L., Boyd, E., Jones, R.G., Cornforth, R.J., James R., Parker, H.R. and Allen, M.R. (2015). Attribution of extreme weather events in Africa: a preliminary exploration of the science and policy implications. *Climate Change*, 132: 531-543.

Pace, A. (2020). Storm leaves damage in its wake, intense cold front arrives. *Cape Town etc*. [Online] Available from: https://www.capetownetc.com/cape-town/weather/storm-leaves-damage-in-its-wake-intense-cold-front-arrives/. [Accessed: 21 July 2020].

Panda, K., Mishra, A., Kumar, A., Mandal, K.G., Thakur, A.K. and Srivastava, R.C. (2014). Spatialtemporal patterns in the mean and extreme temperature indices of India, 1971-2005. *International Journal of Climatology*, 34: 3585–3603. DOI: 10.1002/joc.3931.

Pasquini, L., Cowling, R.M. and Ziervogel G. (2013). Facing the heat: Barriers to mainstreaming climate change adaption in local government in the Western Cape Province, South Africa. *Habitat International*, 40: 225–232.

Pasquini, L. and Enqvist, J.P. (2019). *Green infrastructure in South African cities*. Technical Report. Report for cities support programme undertaken by African Centre for cities. The South African National Treasury's Cities Support Programme (CSP).

Pascal, M., Wagner, V., Corsa, M., Laaidi, K., Ung, A. and Beaudeau, P. (2018). Heat and cold related-mortality in 18 French cities. *Environmental International*, 121: 189–198. DOI:10.1016/j.envint.2018.08.049.

Pelling, M., Leck, H., Pasquini, L., Ajibade, I., Osuteye, E., Parnell, S., Lwasa, S., Johnson, C., Fraser, A., Barcena, A. and Boubacar, S. (2018). Africa's urban adaption transition under a 1.5°C climate. *Current Opinion in Environmental Sustainability*, 31: 10–15. DOI:10.1016/j.cosust.2017.11.005.

Perkins, S.E., Alexander, L.V. and Nairn, J.R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, 39. DOI:10.1029/2012GL053361.

Perkins, S. and Alexander, L. (2013). On the measurement of heatwaves. *International Journal of Climatology*, 26: 4500–4517.

Perkins, S.E. (2015). A review on the scientific understanding of heatwaves-their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research*, 164-165: 242–267. DOI:10.1016/j.atmosres.2015.05.014.

Perkins-Kirkpatrick, S.E., White, C.J., Alexander, L.V., Argüeso, D., Boschat, G., cowan, T., Evans, J.P., Ekström, M., Olivier, E.C.J., Phatak, A. and Purich, A. (2016). Natural hazards in Australia: heatwaves. *Climatic Change*, 139: 101–114.

Perkins-Krikpartick, S.E. and Gibson, P.B. (2017). Changes in regional heatwave characteristics as a function of increasing global temperature. *Scientific Reports*, 7(1): 1–12. DOI:10.1038/s41598-017-12520-2.

Perkins-Kirkpatrick, S.E., Fischer, E.M., Angélil, O. and Gibson, P.B. (2017). The influence of internal climate variability on heatwave frequency trends. *Environmental Research Letters*, 12. DOI:10.1088/1748-9326/aa63fe.

Phakula, S., Landman, W.A. and Berki, A.F. (2018). Forecasting seasonal rainfall characteristics and onset months over South Africa. *International Journal of Climatology*, 38: 889–900.

Ponjoan, A., Blanch, J., Alves-Cabratosa, L., Marti-Lluch, R., Comas-Cufi, M., Parramon, D., Del Mar Garcia-Gil, M., Ramos, R. and Petersen, I. (2017). Effects of extreme temperature on cardiovascular emergency hospitalizations in Mediterranean region: a self-controlled case series study. *Environmental Health*, 16: 32. DOI 10.1186/s12940-017-0238-0.

Poudal, A., Cuo, L., Ding, J. and Gyawali, A.R. (2020). Spatio-temporal variability of the annual and monthly extreme temperature indices in Nepal. *International Journal of Climatology*. DOI: 10.1002/joc.6499.

Radovic, V. and Iglesias, I. (2019). Extreme weather events: Definition, classification and guidelines towards vulnerability reduction and adaption management. In: *Climate Action*. *Encyclopaedia of the UN Sustainable Development Goals*. Cham: Springer.

Ragone, F., Wouters, J. and Bouchet, F. (2018). Computation of extreme heatwaves in climate models using a large deviation algorithm. *Proceedings of the National Academy of Sciences of the United States of America,* 115: 24–29.

Rahimi, M. and Hejabi, S. (2018). Spatial and temporal analysis of trends in extreme temperature indices in Iran over the period 1960–2014. *International Journal of Climatology*, 38: 272–282.

Rahman, M.A., Yunsheng, L. and Sultana, N. (2017). Analysis and prediction of rainfall trends over Bangladesh using Mann-Kendall, Spearman's rho test and ARIMA model. *Meteorology and Atmospheric Physics*, 129: 409–424.

Rana, S., McGregor, J. and Renwick, J. (2015). Precipitation seasonality over the Indian subcontinent: An evaluation of gauge, reanalyses, and satellite retrievals. *Journal of Hydrometeorology*, 16: 631–651.

Rantanga, M., Das, S. and Ali, M. (2020). Analysing maximum monthly temperature in South Africa for 45 years using functional data analysis. *Advances in Decision Sciences*, 24.

Rauf, A.U., Rafi, M.S., Ali, I. and Muhammad, U.W. (2016). Temperature trend detection un upper Indus basin by using Mann-Kendall test. *Advances in Science, Technology and Engineering Systems Journal*, 1(4): 5–13.

Rebetez, M. and Reinhard, M. (2008). Monthly air temperature trends in Switzerland 1901-2000 and 1975-2004. *Theory and Applied Climatology*, 91: 27–34.

Reeves, J., Chen, J., Wang, X.L., Lund, R. and Lu, Q.Q. (2007). A review and comparison of change point detection techniques for climate data. *Journal of Applied and Meteorological Climatology*, 46(6): 900–915.

Reisinger, A., Kitching, R.L., Chiew, F., Hughes, L., Newton, P.C.D., Schuster, S.S., Tait, A. and Whetton, P. (2014). Australasia. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.

Ren, F.M., Trewin, B., Brunet, M., Dushmanta, P., Walter, A., Baddour, O. & Korber, M. (2018). A research progress review on regional extreme events. *Advances in Climate Change Research*, 9: 161—169.

Roffe, S.J. (2019). A statistical analysis of rainfall seasonality across South Africa [Thesis]. University of the Witwatersrand, Johannesburg.

Roffe, S.J., Fitchett, J.M. and Curtis, C.J. (2019). Classifying and mapping rainfall seasonality in South Africa: a review. *South African Geographical Journal*, 101(2): 158–174. DOI: 10.1080/03736245.2019.1573151

Roffe, S.J., Fitchett, J.M. and Curtis, C.J. (2020). Determining the utility of a percentile-based wet-season start- and end-date metrics across South Africa. *Theoretical and Applied Climatology*, DOI:10.1007/s00704-020-03162-y.

Roffe, S.J., Fitchett, J.M. and Curtis, C.J. (2020). Investigating changes in rainfall seasonality across South Africa: 1987-2016. International Journal of Climatology, DOI: 10.1002/joc.6830.

Rossati, A. (2017). Global warming and its health impacts. *International Journal of Occupational and Environmental Medicine*, 8(1): 7–20.

Russo, S., Marchese, A.F., Silmann, J. and Immé, G. (2016). When will unusual heatwaves become normal in a warming Africa? *Environmental Research Letters*, 11. DOI: 10.1088/1748-9326/11/5/054016.

Rusticucci, M. (2012). Observed and simulated variability of extreme temperature events over South America. *Atmospheric Research*, 106: 1–7.

Salameh, A.A.M., Gamiz-Fortis, S.R., Castro-Diez, Y., Hammad, A.A. & Esteban-Parra, M.J. (2019). Spatio-temporal analysis for extreme temperature indices over the Levant region. *International Journal of Climatology*, 39: 5556–5582.

SAWS. (2017). *How are the dates of the four seasons worked out?* [Online] Available from: http://www.weathersa.co.za/learning/weather-questions/82-how-are-the-dates-of-the-four-seasons-worked-out. [Accessed: 31 May 2017].

SAWS. (2019). Weather Questions. *WeatherSA*. [Online] Available from: http://www.weathersa.co.za/home/weatherques. [Accessed: 20 August 2019].

SAWS. (2020). Weather Questions. *WeatherSA*. [Online] Available from: http://www.weathersa.co.za/home/weatherques. [Accessed: 23 July 2020].

Scott, A.A., Waugh, D.W. and Zaitchik, B.F. (2018). Reducing urban heat island intensity under warmer conditions. *Environmental Research Letters*, 13(6): 064003. DOI:10.1088/1748-9326/aabd6c.

Scott, R. (2015). Between extremes: health effects of heat and cold. *Environmental Health Perspective,* 123(11). DOI:10.1289/ehp.123-A275.

Scovronick, N., Sera, F., Acquaotta, F., Garzena, D., Fratianni, S., Wright, C.Y. & Gasparrini, A. (2018). The association between ambient temperature and mortality in South Africa: a time-series analysis. *Environmental Research*, 161: 229–235.

Sen, P.K. (1986). Estimates the regression coefficient based on Kendall's tau. *Journal of American Statistical Association*, 63: 1379–1389.

Seneviratne S.I. & Zwiers, F.W. (2015). Attribution and prediction of extreme events: Editorial on special issue. *Weather and Climate Extremes*, 9: 2—5.

Sheridan, S.C. and Allen, M.J. (2015). Changes in the frequency and intensity of extreme temperature events and human health concerns. *Current Climate Change Reports*, 1(3): 155–162.

Shrestha, A.B., Bajracharya, S.R., Sharma, A.R., Duo, C. and Kulkarni, A. (2017). Observed trend and changes in daily temperature and precipitation extremes over the Koshi river basin 1975–2010. *International Journal of Climatology*, 37: 1066–1083.

Simmonds, I. (2018). What causes extreme hot days in Europe. *Environmental Research Letters*, 13. DOI:10.1088/1748-9326/aacc78.

Singleton, A.T. and Reason, C.J.C. (2017). Variability in the characteristics of cut-off low pressure systems over subtropical southern Africa. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 27: 295–310.

Smith, E.T. and Sheridan, S.C. (2018). The characteristics of extreme cold events and cold air outbreaks in the eastern United States. *International Journal of Climatology*, 38. DOI:10.1002/joc.5408.

Smith, E.T. and Sheridan, S.C. (2020). Where do cold air breaks occur and how have they changes over time? *American Geophysical Union*. DOI:10.1029/2020GL086983.

Smith, M.D. (2011). An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *Journal of Ecology*, 99: 656–663.

Sneyers, R. (1990). *On the statistical analysis of series of observations*. World Meteorological Organization, Technical Note no. 143, WMO no 415.

Some'e, B.S. Ezani, A. and Tabari, H. (2013). Spatiotemporal trend of aridity index in arid and semi-arid regions of Iran. *Theory and Applied Climatology*, 111: 149–160.

Song, X., Zhang, Z., Chen, Y., Wang, P., Xiang, M., Shi, P. and Tao, F. (2014). Spatiotemporal changes of global extreme temperature events (ETEs) since 1981 and the meteorological causes. *Natural Hazards*, 70(2): 975–994.

Sousa, P.M., Blamey, R.C., Reason, C.J.C., Ramos, A.M. and Trigo, R.M. (2018). The 'Day Zero' Cape Town drought and the poleward migration of moisture corridors. *Environmental Research Letters*, 13. DOI: 10.1008/1748-9326/aaebc7.

Sparks, T. and Braslavská, O. (2001). The effects of temperature, altitude and latitude on the arrival and departure dates of the swallow Hirundo rustica in the Slovak Republic. *International Journal of Biometeorology*, 45: 212–216.

Spearman, C. (1904). General intelligence objectively determined and measured. *The American Journal of Psychology*, 15(2): 201–292. DOI: 10.2307/1412107.

Stander, J.H. (2013). Synoptic circulation patterns and atmospheric variables associated with significant snowfall over South Africa in winter [Thesis]. University of Pretoria.

Stander, J.H., Dyson, L. and Engelbrecht, C.J. (2016). A snow forecasting decision tree for significant snowfall over the interior of South Africa. *South African Journal of Science*. http://dx.doi.org/10.17159/sajs.2016/20160221.

Stott, P.A., Christidis, N., Otto, F.E.L., Sun, Y., Vanderlinden, J-P., van Oldenborgh, G.J., Vautard, R., von Storch, R., Walton, P., Yiou, P. and Zwiers, F.W. (2016). Attribution of extreme weather and climate related events. *WIREs Climate Change*, 7(1): 23–41.

Tabari, H. and Talaee, P.H. (2011). Temporal variability of precipitation over Iran: 1966-2005. *Journal of Hydrology*, 396(3): 313–320.

Tank, A.M.G.K., Zwiers, F.W. & Zhang, X. (2009). Guidelines on Analysis of extremes in a changing climate in support of informed decision adaptation. *World Meteorological Organization*, WMO-TD No. 1500.

Tennant, W.J. and Hewitson, B.C. (2002). Intra-seasonal rainfall characteristics and their importance to the season prediction problem. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 22: 1033–1048.

Thibault, K.M. and Brown, J.H. (2008). Impact of an extreme climatic event on community assembly. *Proceedings of National Academy of Science*, 105 (9): 3410–3415.

Thorton, P.K., Ericksen, P.J., Herrero, M. and Challinor, A.J. (2014). Climate variability and vulnerability to climate change: A Global review. *Global Change Biology*, 20: 3313–3328. DOI:10.1111/gcb.12581.

Tiengrod, P. and Wongseree, W. (2013). A comparison of spatial interpolation methods for surface temperature in Thailand. *International Computer Science and Engineering Conference* (ICSEC): ICSEC 2013.

Toreti, A. and Desiato, F. (2008). Changes in temperature extremes over Italy in the last 44 years. *International Journal of Climatology*, 28: 733–745.

Trenbreth, K.E. (1983) What are seasons? *Bulletin of American Meteorological Society*. 64(11):1276–1282.

Trewin, B. (2010). Exposure, instrumentation, and observing practice effects on land temperature measurements. *Wiley Interdisciplinary Reviews: Climate Change*, 1: 490–506.

Tshiala, M.F., Olwoch, J.M & Engelbrecht F.A. (2011). Analysis of temperature trends over Limpopo Province, South Africa. *Journal of Geography and Geology*, 3(1), 13—21.

Tuller, S.E. (1990). Standard seasons. *International Journal of Biometeorology*, 34: 181–188.

Tyson, P.D. and Preston-Whyte, R.A. (2000). *The atmosphere and weather of southern Africa*. 2nd Ed. Cape Town: Oxford University Press Southern Africa. DOI: 10.1002/joc.725.

Unal, Y., Kindap, T. and Karaca, M. (2003). Redefining the climate zones of turkey using cluster analysis. *International Journal of Climatology*, 23: 1045–1055.

Van der Walt, A.J. and Fitchett, J.M. (2020). Statistical classification of South African seasonal divisions on the basis of daily temperature data. *South African Journal of Science*, 116(9/10): #7614. DOI:10.17159/sajs.2020/7614.

Van Hyssteen, E., Le Roux, A. and van Niekerk, W. (2013). Analysing risk and vulnerability of South African settlements: Attempts, explorations, and reflections. Jàmbá: *Journal of Disaster Risk Studies*, 5(2): 1–8. DOI: 10.4102/jamba.v5i2.80.

Van Huyssteen, C.W., Du Preez, C.C. and Holmes, P.J. (2018). Agriculture and a changing biophysicial environment. In: Holmes, P.J. and Boardman J. (eds.). *Southern African landscapes and environmental change. Earthscan Studies in Natural Resource Management*. Routledge, pp. 228-248.

Van Wilgen, N.J., Goodall, V., Holness, S., Chown, S.L. and McGeoch, M.A. (2016). Rising temperatures and changing rainfall patterns in South Africa's national parks. *International Journal of Climatology*, 36: 706–721.

Vardoulakis, S., Dear, K., Hajat, S., Heaviside, C., Eggen, B. and Mchael, A.J. (2014). Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. *Environmental Health Perspectives*, 122(12): 1285–1292.

Varghese, B.M., Barnett, A., Hansen, A.L., Bi, P., Hanson-Easey, S., Heyworth, J.S., Sirn, M.R. and Pisaniello, D.L. (2019). The effects of ambient temperatures on the risk of work-related injuries and illnesses: Evidence from Adelaide, Australia 2003-2013. *Environmental Research*, 170: 101–109. DOI:10.1016/j.envres.2018.12.024.

Vigaud, N., Pohl, B. and Crétat, J. (2012). Tropical-temperate interactions over southern Africa simulated by a regional climate model. *Climate Dynamics*, 39: 2895–2916.

Vincent, L.A., Zhang, X., Bonsal, B.R. and Hogg, W.D. (2002). Homogenization of daily temperatures over Canada. *Journal of Climate*, 15: 1332–1334

Vincent, L.A., Wang, X.L., Milewska, E.J., Wan, H, Feng, Y. and Swail, V. (2012). A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis. *Journal of Geophysical Research Atmospheres*, 117: D18110. DOI: 10.1029/2012JD017859.

Vogel, E., Donat, M.G., Alexander, L.V., Meinshausen, M., Deepak, K.R., Karoly, D., Meinshausen, N. and Frieler K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, 14.

Vose, R.S. and Menne, M.J. (2004). A method to determine station density requirements for climate observing networks. *Journal of Climate*, 17: 2961–2971.

Wang, X.L. (2003). Comments on “Detection of undocumented change points: a revision of the two-phase regression model”. *Journal of Climate*, 16: 3383–3385.

Wang, X.L., Wen, Q.H. and Wu, Y. (2007). Penalized maximum *t* test for detecting und undocumented mean change in climate data series. *Journal of Applied and Meteorological Climatology*, 46(6): 916–931.

Wang, X.L. (2008a). Accounting for autocorrelation in detecting mean shifts in climate data series using penalized maximal *t* and *F* test. *Journal of Applied Meteorology and Climatology*, 47: 2423–2444.

Wang, X.L. (2008b). Penalized maximal F-test for detecting undocumented mean-shifts without trend-change. *Journal of Atmospheric and Oceanic Technology,* 25(3): 368–384. DOI: 10.1175/2008/JTECHA982.1.

Wang, X.L., Chen, H., Wu, Y., Feng, Y. and Pu, Q. (2010). New techniques for detection and adjustment of shifts in daily precipitation data series. *Bulletin of American Meteorological Society*, 49: 2416–2436.

Wang, X.L. and Feng, Y. (2013). *RHtestsV4 User Manual*. Climate Research Division, Atmospheric Science and Technology Directorate, Science and Technology Branch, Environment Canada. [Online] Available from: https://github.com/ECCC-CDAS/RHtests/blob/master/V4_files/RHtestsV4_UserManual_10Dec2014.pdf.

Wang, X., Liu, H., Gu, M-B., Boucek, R., Wu, Z-M. and Zhou, G-Y. (2016). Greater impacts from extreme cold spell on tropical than temperate butterflies in south China. *Ecosphere*, 7(5). DOI:10.1002/ecs2.1315.

Wang, B., Liu, D.L., Macadam, I., Alexander, L.V., Abramowitz, G. and Yu, Q. (2016). Multi-model ensemble projections of future extreme temperature changes using statistical downscaling method in south eastern Australia. *Climatic Change*, 138: 85–98.

Ward, J.H. (1963). Hierarchical grouping to optimize an objective evaluation. *Journal of American Statistical Association*, 58(301): 236–244.

Wilks, D.S. (2011). Cluster analysis. *International Geophysics*, 100: 603–616.

Wenal, G., Keqin, D. and Shuangshuang, L. (2019). Spatial-temporal variations in cold surge events in northern China during the period 1960-2016. *Journal of Geographical Sciences*, 29(6): 971–983. DOI:0.1007/s11442-019-1668-0.

Whang, X.L. and Feng, Y. (2013). *RHtestV4 Manual*. Climate Research Division, Atmospheric Science and Technology Branch, Environment Canada. [Online] Available from:

https://github.com/ECCC-CDAS/RHtests/blob/master/V4_files/RHtestsV4_UserManual_10Dec2014.pdf. [Accessed: 03 September 2020].

Whitecross, M.A., Witkowski, E.T.F. and Archibald, S. (2017). Savanna tree-grass interactions: A phenological investigation of green-up in relation to water availability. *South African Journal of Botany*, 108: 29–40.

WMO. (2000). *Detecting trends and other changes in hydrological data.* [Online] Available from: https://water.usgs.gov/osw/wcp-water/detecting-trends.pdf. [Accessed: 3 August 2020].

WMO. (2011). *Guide to climatological practices*. Geneva: WMO. WMO No. 100.

WMO. (2016). *Guidelines on the definition and monitoring of extreme weather and climate events*. [Online] Available from: https://www.wmo.int/pages/prog/wcp/ccl/opace/opace2/documents/DraftversionoftheGuidelinesontheDefinitionandMonitoringofExtremeWeatherandClimateEvents.pdf. [Accessed: 23 July 2020].

WMO. (2017). *WMO Guidelines on the calculation of climate normal*. Geneva: WMO. WCDP No 10, WMO-No, 1203.

Wright, C., Norval, M. and Albers, P. (2015). Climate change, public health and COP21 – a South African perspective. *South African Medical Journal*, 105(12): 997–998.

Yang, Q., Zheng, J. and Liu, Z. (2016). Which one is the best: the interpolation method comparison on average annual temperature in Xinjiang from 1951 to 2013. *IEEE International Geoscience and Remote Sensing Symposium* (IGRSS). Beijing: IEEE.

Yin, H. and Sun, Y. (2018). Detection of Anthropogenic influence on fixed threshold indices of extreme temperature. *American Meteorological Society*, 31: 6341—6352.

Yosef, Y., Aguilar, E. and Alpert, P. (2019). Changes in extreme temperature and precipitation indices: Using an innovative daily homogenized database in Israel. *International Journal of Climatology*, 39: 5022–5045.

You, Q., Ren, G., Fraedrich, K., Kang, S., Ren, Y. and Wang, P. (2013). Winter temperature extremes in China and their possible causes. *International Journal Climatology*, 33: 1444–1455.

Yu, Z. and Li, X. 2015. Recent trends in daily temperature extremes over northeastern China (1960-2011). *Quaternary International*, 380-381: 35–48.

Yue, S., Pilon, P. and Cavadias, G. (2002). Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology*, 259: 254–271.

Zhang, Y. and Yang, F. (2004). *RClimDex (1.0): Manual*. Environmental Canada: Ontario, Canada.

Zhang, X., Feng, Y. and Chan, R. (2018). *Introduction to RClimDex v1.9*. Climate Research Division, Environment Canada, Downsview, Ontario. [Online] Available from: https://github.com/ECCC-CDAS/.

Zhang, P., Bassil, K., Gower, S., Katic, M., Kiss, A., Gogosis, E. & Hwang, S.W. (2018a). Cold-related injuries in a cohort of homeless adults. *Journal of Social Distress and the Homeless*.

Zhao, Q., Zhao, Y., Li, S., Zhang, Y., Wang, Q., Zhang, H., Qiao, H., Li, W., Huxley, R., Williams, G., Zhang, Y. and Guo, Y. (2017). Impact of ambient temperature on clinical visits for cardio-respiratory diseases in rural villages in northwest China. *Science of the Total Environment,* 612: 379–385. DOI:10.1016/j.scitotenv.2017.08.244.

Zhou, Y. and Zhang, J. (2014). Application of GIS in downscaling regional climate model results over the province of Ontario. *Environmental Systems Research*, 3(1):8.

Zhou, M.G., Wang, L.J., Lui, T., Zhang, Y.H., Lin, H.L., Luo, Y., Xiao, J.P., Zeng, W.L., Zhang, Y.W., Wang, X.F., Gu, X., Rutherford, S., Chu, C. & Ma, W.J. (2014). Health impact of the 2008 cold spell on mortality in the subtropical China: the climate and health impact national assessment study (CHINAs). *Environmental Health*, 13: 60.

Ziervogel, G., New, M., van Garderen E.A., Midgley, G., Taylor, A., Hamann, R., Stuart-Hill, S., Myers, J. & Warburton M. (2014). Climate change impacts and adaption in South Africa. *Wiley Interdisciplinary Reviews of Climatic Change*, 5: 605—620.

Zwiers, F.W., Alexander, L.V., Hegerl, C., Knutson, T.R., Kossin, J.P., Naveau, P., Nicholls, N., Schär, C., Seneviratne, S.I. and Zhang, X. (2013). Climate extremes: challenges in estimating and understanding recent changes in the frequency and intensity of extreme climate and weather events. In: Asrar, G.R. and Hurrell, J.W. (eds.). *Climate Science for Serving Society: Research, Modeling and Prediction Priorities*. Dordrecht: Springer. DOI: 10.1007/978-94-007-6692-1_13.

Supplementary Material (Draft Article):

Extreme Temperature Events: African Vulnerability in the Global Context

Adriaan van der Walt[1,2], Jennifer M. Fitchett[1]*

[1] School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, South Africa

[2]Department of Geography, Faculty of Natural and Agricultural Sciences, University of the Free State

* Corresponding author: Jennifer.Fitchett@wits.ac.za

Abstract

Extreme temperature events, exceeding thresholds on the cold or warm boundaries, receive considerable media attention. There is consensus among scientists that these events are occurring more frequently now than in the early 20th century. The frequency and intensity of extreme temperature events is projected to increase in future decades under anthropogenic climate change. Given this background, it is notable that academic literature exploring the longitudinal occurrence of these events is limited in both number and geographical reach. Studies are largely restricted to individual events, and thus limited to a geographic focal region which is often as small as a single city. This paucity of scientific knowledge is worsened by the limited availability of long-term continuous climate records. The vulnerability of African societies and ecosystems is critical. The expected increases in weather-related disasters, in particular extreme temperature events, pose significant challenges for risk management and are expected to negatively impact climate-sensitive sectors such as infrastructure, transportation, agriculture, health and tourism. This paper reviews the literature on extreme temperature events from a global to continental scale and emphasises the vulnerability of African countries to these events.

Keywords: Heatwave, cold snap, temperature thresholds, heat stress, review

Introduction

Climate extremes, by definition, are rare and often difficult to define (Seneviratne and Zwiers, 2015; Walthall, 2015; Ebi and Brown, 2016; Easterling *et al*., 2016). While storm events including tropical cyclones and tornadoes are temporally and spatially discrete, extreme temperatures and periods of drought are often more difficult to delineate. The lack of consensus on definition for extreme temperature events makes the comparison of results between studies difficult (Klein and Können, 2003; Easterling *et al*., 2016).

Extreme climatic events have significant impacts on society (Jahn, 2015). The very survival of early civilisations was challenged by periods of severe climate and extreme climatic events (Heim, 2015; Conner, 2016). Most recently, the most severe heatwave on record occurred in June 2019 over Europe, claiming approximately 1,500 lives in France alone (Osborne, 2019). Projections of an increased severity and frequency of extreme climatic events are now widely accepted by scientists over many regions globally (Nicholls *et al*., 2012; Boero *et al*., 2015; Ebi and Bowen; 2016; IPCC, 2018; Vogel *et al*., 2019), and locally (Engelbrecht *et al*., 2015; Nangombe *et al*., 2019; Akinyemi and Abiodun, 2019). The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Nicholls *et al*., 2012; Hartman *et al*., 2013) and 2018 Special Report affirm that climate change has resulted in an increase in the intensity and frequency of climatic extremes which will continue into the future (Smith, 2011; Mueller and Seneviratne, 2012; Nicholls *et al*., 2012; Hartmann *et al*., 2013; Kharin *et al*., 2013; IPCC 2018, Akinyemi and Abiodun, 2019).

The risks associated with extreme events are expected to increase in the future, particularly in low-income countries where adaptive capacity is low (Herold *et al*., 2017; Filho *et al*., 2018). Landscape use, social infrastructure changes and demographic variables often further increase this vulnerability (Ebi and Bowen, 2016). The risks of extreme climatic events pose a heightened threat to societies that are dependent on natural resources which are sensitive to changes in climate; including agriculture (Vogel *et al*., 2019), fishing (Serdeczny *et al*., 2016), and tourism (Hoogendoorn and Fitchett, 2016). These threats are also heightened for countries that have more pressing immediate needs than the long-term development of adaptive infrastructure (Herold *et al*., 2017). These risks in low-income countries are exacerbated where agriculture and food security constitute the livelihood of populations, as in most African countries (Herold *et al*., 2017; Akinyemi and Abiodun, 2019). There is little doubt that both human society and the natural environment have become more vulnerable to extreme weather and climatic events (Easterling *et al*., 2016). The Centre for Research on Epidemiology of Disasters (CRED), in its EM-DAT (International Disaster Database), analysed 281 events recorded in 2018 and reported that no part of the globe was spared; earthquakes and tsunamis accounted for the majority of the 10, 373 lives lost. Extreme events accounted for most of 61.7 million people affected by natural disasters (UNISDR, 2019; CRED, 2019).

There is consensus regarding the likelihood of an increase in extreme climatic events (Khan *et al*., 2015; IPCC 2018, Akinyemi and Abiodun, 2019), and recent findings have suggested that widespread persistent changes to temperature extremes have already occurred earlier than predicted, over large parts of the earth (Li *et al*., 2018). But research into the frequency of occurrence of extreme temperatures and casualties caused over recent decades is sparsely distributed, and neglects many of the less developed regions (Sheridan and Allen, 2015; CRED, 2019) on which such events are likely to have a significant impact (Mirza, 2003; Thornton *et al*., 2014; Nangombe *et al*., 2019). The few review papers on extreme climate events provide broad overviews often for the global North (Easterling *et al*., 2000; Coumou and Rahmstorf, 2012), in the context of vulnerability to climate change (Thornton *et al*., 2014), attribution of extreme events (Stott *et al*., 2016), and modelling of extreme events (Bellprat, 2019). This paper presents a review of extreme temperature events, with a particular focus on the African continent.

Defining Extreme Temperature Events

Extreme climatic events can be defined as rare, infrequent, unpredictable climate phenomena, characterised either by the meteorological characteristics or the consequent impacts (Easterling *et al*., 2016; Stott *et al*., 2016; Vogel *et al*., 2019). There is little consensus in the published literature regarding the classification process for extreme temperature events (Radovic and Ilglesias, 2019). The weather for many days could be considered an extreme event depending on both the definition of 'extreme' and the method used to determine mean conditions (Drijfhout *et al*., 2015). The most widely used accepted definition of an extreme event, proposed by the IPCC, is an event in the 10th and 90th percentile of the probability density function estimated from the observations (Radovic and Ilglesias, 2019). However, weather or climate events, even if not classified as extreme in a statistical sense, can still lead to extreme conditions or impacts, either by crossing a critical threshold in a social, ecological, or physical system, or by occurring simultaneously with another event (Vose *et al*., 2014). However, temperatures which are considered to be extreme events in one location may fall within the normal seasonal range in another. This heightens the importance of recorded archives and the verification of extreme record events, as the frequency and severity of extreme climatic events increases (Table 1; Khan *et al*., 2015; IPCC 2018, Akinyemi and Abiodun, 2019). Currently, insufficient reporting from droughts and extreme temperature events hinders better understanding of these events worldwide (UNISDR, 2019).

The lack of a consistent definition or classification process poses considerable challenges in the characterisation of these events, in particular the threshold for extreme temperatures (Seneviratne and Zwiers, 2015). The literature highlights different approaches to classifying and defining extreme temperature events. ETEs can be defined in terms of the extent of the deviation from the statistical mean daily, monthly or annual temperatures for a given location or region (Easterling *et al*., 2000; Lewis and King, 2017). The threshold for which a deviation is considered to be indicative of an 'extreme event', however, is largely debated (Lewis and King, 2017). Another distinction concerns definitions based on absolute temperatures versus percentiles (Horton *et al*., 2016). Absolute temperatures are of central importance to societal and environmental impacts such as resilience of infrastructure, whereas percentiles facilitate comparisons across locations, relative to the local climatology (Horton *et al*., 2016). This, together with the importance of climate-risk management and decision-oriented approaches, has expanded the number of heat event indices used in research (Russo *et al*., 2010; Russo *et al*., 2014). Alternative approaches classify events on the basis of the societal impact such as deaths resulting from extreme heat events (Easterling *et al*., 2000; Luber and McGeehin, 2008; Lewis and King, 2017). In these instances, the human thermal threshold plays an enormous role in classifying an extreme temperature event (Lougan *et al*., 2010; Vardoulakis *et al*., 2014; Napoli *et al*., 2018). Recent approaches such as the Universal Thermal Climate Index (UTCI) attempt to explore thermal comfort as a measure of extreme temperature events, coupling the temperature with a wider range of meteorological parameters such as humidity and windspeed (Napoli *et al*., 2018). These allow for extreme temperature events to be classified on the basis of the biometeorological impact without deaths necessarily occurring, which standardises for the impact of varied levels of healthcare (Pappenberger *et al*., 2015; Napoli *et al*., 2018).

There are 27 internationally agreed indices of climate extremes that form the core indices and are recommended by the World Meteorological Organisation (WMO) CCI/CLIVAR Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI; (Vincent and Mekis, 2005; Ren *et al*., 2018), which describe characteristics of extremes that include the frequency, amplitude and persistence (Tank *et al*., 2009; Christidis and Stott, 2016). The key approach of indices is the calculation of the number of days in a year that exceed a specific threshold (Tank *et al*., 2009; Yu and Li, 2015). Many of the indices are based on percentiles with thresholds to assess moderate extremes that typically occur a few times every year rather than high impact, one-in-a-decade weather events (Yu and Li, 2015). Most studies focus on changes in the intensity and frequency of extreme temperatures, because of the high representativeness of these indices (Tank *et al*., 2009, Yin and Sun, 2018). Percentile thresholds are more evenly distributed in space than fixed thresholds and are arguably meaningful in every climatic region (Tank *et al*., 2009; Nicholls *et al*., 2012; Yin and Sun, 2018).

The more severe extreme events are often investigated by using an Extreme Value Theory (EVT) approach (Cheng *et al*., 2013). More researchers are using EVT to fit non-stationary generalised extreme value (GEV) distributions to temperature data to explore relationships with large-scale climate drivers (Whan *et al*., 2015). This approach for the estimation of extreme values aims at deriving a probability distribution of events from the tail of the probability distribution (Whan *et al*., 2015). The EVT approach derives a complete probability distribution for very rare events, which can facilitate the analysis of the probability of occurrence of events outside the observed data range, using an extreme value analysis rather than to model the distribution (Nicholls *et al*., 2012; Whan *et al*., 2015).

Table 1: List of extreme warm and cold temperature events, 2000-2020.

	Year	Region	Extreme temperature event	Impact/Magnitude
Warm events	2003	France, Germany, Italy (Stott *et al*., 2004).	Heatwave	Heat related fatalities 70,000.
	2004	Brisbane, Australia (Tong *et al*., 2010).	Warm spells	Highest temperature recorded 42°C
	2006/2007	Western and eastern Europe (Luterbacher *et al*., 2007).	Warm spells	Autumn and winter warmest on record.
	2009	South eastern Australia (Perkins, 2015)	Heatwave	347 fatalities
	2010	Moscow, Russia (Barriopedro *et al*., 2011; Otto *et al*., 2012; Ragone *et al*., 2018; Simmonds, 2018).	Heatwave	55,000 fatalities, annual crop production dropped by 25%, more than 15 billion US dollars loss
		Texas, America (Coumou *et al*., 2013b).	Heatwave	
	2012	USA (Khandekar, 2013)	Heatwave	Exceptionally dry summer
	2013	Australia (Lewis and Karoly, 2013)	Heat extremes	Record summer temperatures
	2015	Europe (Luterbacher *et al*., 2016)	Heatwave	
	2019	Europe (The Independent, 2019)	Heatwave	Approximately 1,500 fatalities

	Year	Region	Extreme temperature event	Impact/Magnitude
Cold events	2002/2003	South Asia, Vietnam and Bangladesh (Kandekar, 2013)	Cold extremes	Hundreds of people died due to exposure to colder weather.
		North America (Khandkar, 2013)	Cold extremes	Colder and snowier than normal.
	2005/2006	European continent	Cold extremes	Severe winters
	2007/2008	European continent	Cold extremes	Severe winters
		North America (Khandekar, 2013)	Cold extremes	Colder and snowier than normal.
		China (Ponjoan *et al*., 2017)	Cold spell	140,000 related fatalities
	2009/2010	North America (Khandekar, 2013)	Cold extremes	Colder and snowier than normal.
	2011/2012	Europe (Khandekar, 2013)	Cold spell	Minimum temperature plummeted to -40°C, leading to hundreds of deaths.
	2012/2013	UK, Berlin and parts of eastern Germany (Khandekar, 2013)	Colder than normal	Record-breaking low temperatures
		North India	Winter severity	Several hundred deaths, due to no heat or insulation.

Research on Extreme Temperature Events in the Global North

A number of high-impact ETEs have occurred over the last two decades in the Global North (Mckinnon *et al*., 2016; Simmonds, 2018, Vogel *et al*., 2019). Europe experienced a pronounced warm summer accompanied by severe heatwaves in 2003, 2010, 2015, 2017, 2018 and 2019 (Luterbacher *et al*., 2016; Few *et al*., 2019; WMO, 2019). The exceptional summer heatwave of 2003 caused ~70,000 heat-related deaths which had significant impacts on agriculture, ecosystems, economy, and infrastructure (Stott *et al*., 2004; Barriopedro *et al*., 2011; Yu and Li, 2015). The worst heat wave event in Europe since the 1950s occurred in Russia in 2010. It left 55,000 people dead, more than 1 million ha of burned land, a 25% decrease in annual crop yields and a total economic loss of 15 billion US$ (Barriopedro *et al*., 2011; Otto *et al*., 2012; Ragone *et al*., 2018; Simmonds, 2018). These high-profile events, together with the most recent extreme temperature events, have led to considerable public concern regarding the possible increase in frequency and intensity of extremely hot weather under climate change (Ding *et al*., 2010; Easterling *et al*., 2016). This concern has encouraged both methodological developments such as the Universal Thermal Climate Index (UTCI) and an increase in research outputs.

Recent global analysis of trends in extreme temperatures illustrates that increases (decreases) are found in most regions, in warm (cold) extreme indices since 1900 (Irannezhad *et al*., 2019). Alexander *et al*. (2006) similarly reported that there is a significant increase (decrease) in the annual occurrence of warm (cold) nights over 70% of land regions, with data from 1950-2003 (Alexander *et al*., 2006). A reduction in cold days and nights was observed for central North America, the eastern United States, southern Greenland and the southern half of South America (Alexander *et al*., 2006). Notably, almost no analyses were reported for the African continent due a lack of available data (Alexander *et al*., 2006). A similar global study spanning the years between 1950-2004 found that minimum temperatures increased more rapidly than maximum temperatures, resulting in a significant diurnal temperature decrease, except for some regions e.g southern Argentina, eastern Africa, southeastern Australia (Vose *et al*., 2005). Furthermore, global studies exploring extreme daily temperatures (Alexander *et al*., 2006; Brown *et al*., 2008; Donat *et al*., 2013) and regional studies for North America (Easterling, 2002; Peterson *et al*., 2008), South America (Rusticucci, 2012) Central- Western Europe (Moberg and Jones, 2005), the eastern Mediterranean region (Kostopoulou and Jones, 2005), Australia (Caloierio, 2017) report an increase in warm days and nights and a reduction in cold days and nights.

Numerous regional- and local-scale studies report an increase (decrease) in warm (cold) temperature extremes over the past four decades across the Global North, using a wide range of different temperature indices; percentile-based indices, annual maximum and minimum value of daily annual temperature and also fixed threshold-based indices. The United States is recorded to have experienced a decline in the occurrence of cold extremes over the 20th century, and an increase in warm extremes since the 1960s (Peterson *et al*., 2008; Kunkel *et al*., 2013), revealing a significant increasing trend in the length and number of occurrences in warm events (Furrer *et al*., 2010; Schoof and Robeson, 2016). The increasing trend was observed in various other countries, among them Finland (Irannezhad *et al*., 2019), Canada (Mallet *et al*., 2018), Australia (Steffen *et al*., 2014; Caloiero, 2017), New Zealand (Caloiero, 2017) Spain (El Kenway *et al*., 2011), Austria (Nemec *et al*., 2013), Portugal (Espirito Santo *et al*., 2014) and Romania (Dumitrescu *et al*., 2015).

There is strong statistical evidence that extremely warm monthly and seasonal temperatures associated with persistent heat waves can now be attributed to the observed climatic continental warming trend over the last 50 years (Christides *et al*., 2005; Luterbacher *et al*., 2007; Coumou and Robinson, 2013). In the 1960s, extreme heat events during summer seasons spanned less than 1% of the Earth's land surface, whereas extremely hot seasonal temperatures today cover about 10% of the earth's land surface area (Coumou and Robinson, 2013). Simultaneously, the incidence of record-breaking monthly temperatures has increased significantly (Coumou and Robinson, 2013). Additionally, it has been found that the distribution of the seasonal mean temperature has shifted toward higher temperatures and the range of anomalies has increased for many regions worldwide (Hansen *et al*., 2012). The importance of a seasonal perspective on warm and cold extreme temperatures is highlighted due to evidence of adverse effects. These include; timing and crop harvest yield, phenological cues for many plant and animal species, as well as melting periods for glaciers depending on the length of temperature exceedance (Orlowsky and Seneviratne, 2012; Harrington *et al*., 2017). An increasing trend in unprecedented hot extreme temperatures during summer was observed in 2013 and 2018 in South Korea (Im *et al*., 2018). The summers of the Mediterranean, over the period 1960-2006, are reported to have experienced an increase in intensity, number and duration of heatwaves (Kuglitsch *et al*., 2009). Several studies report high-impact and costly summer temperature extremes in various regions with significant impacts caused, including the 2003 heatwave in Europe (Kew *et al*., 2019), 2010 Russian heat wave (Johnson *et al*., 2018), 2011 heat wave in the United States (Coumou *et al*., 2013; Johnson *et al*., 2018), the 2009 Victorian heatwave in Australia that killed over 370 people (Perkins-Kirkpatrick *et al*., 2016), the Japan summer heatwave in 2010, as well as the most recent heat wave in Europe that claimed nearly 1,500 people's lives (Independent, 2019). In contrast to extreme summer temperatures, extremely high temperatures in winters have been observed in Romania, which led to a decrease in winter snow depth in the years between 1961-2000 (Dumitrescu *et al*., 2014). Researchers identified similar winter warming trends in Canada (Mallet *et al*., 2018) and New Zealand with temperatures increasing in the autumn-winter period (Caloierio, 2017). Studies also indicate that Argentina and Chile were colder in the winters of 2007 and 2010; some locals recorded temperatures as low as -25°C and some snow fell in Buenos Aires for the first time since 1918 (Khandekar, 2013).

The news media tends to place a disproportionate focus on hot extremes and seldom reports on cold weather extremes and their adverse effects (Khandekar, 2013). Several Northern Hemisphere countries witnessed severe winters during 2002/2003, 2005/2006, 2009/2010, 2011/2012 and 2013/2014 (Khandekar, 2013; Messori *et al*., 2016; De Perez *et al*., 2018; Johnson *et al*., 2018). During January and February 2012, temperatures plummeted in central Europe to -40°C; this led to hundreds of deaths (Khandekar, 2013). The severity of the winter of 2002/2003 was felt equatorward to south Asia as far as Vietnam, Bangladesh and northern India. Furthermore, the cold wave in 2003 killed more than 900 people in India, due to long exposure to cold weather (De Prerez *et al*., 2018). The winters of 2002/2003, 2007/2008 and 2009/2010 were significantly colder and snowier over portions of North America and Eurasia (Cattiaux *et al*., 2010; Johnson *et al*., 2018). China, located in the subtropical zone (25-40° latitude), witnessed a cold spell in 2008 that caused an estimated economic loss of more than US $22.3 billion (Zhou *et al*., 2014), 140 000 deaths (Ponjoan *et al*., 2017), losses of 40% of wintertime crops, the deaths of 75 million livestock, as well as the deaths of 30% of bee colonies and 0.45 million tons of aquacultured fish (Boucek *et al*., 2016). The most recent cold wave in the United States led to over 20 reported deaths (Van Oldenborgh *et al*., 2019). The occurrence of these cold extremes has been ascribed to large-scale modes of variability including the Pacific Decadal Oscillation, North Atlantic Oscillation, Artic Oscillation and El Niño-Southern Oscillation (ENSO; Khandekar, 2013; Zhou *et al*., 2014; Messori *et al*., 2016), as well as changes in midlatitude planetary wave activity (Messori *et al*., 2016). This poses a great threat to populations that are not acclimatised to cold extremes and are unprepared for such cold events - it could lead to loss of life (Zhou *et al*., 2014; Ponjoan *et al*., 2017; De Prerez *et al*., 2018; Van Oldenborgh *et al*., 2019).

In addition, the increase in the frequencies of unusually high annual mean temperatures has been attributed in part to human influence (Jones *et al*., 2008). Attribution studies focusing on individual extreme events in different countries found that anthropogenic forcing clearly increases the occurrence probability of extreme events associated with high temperatures (Christidis and Stott, 2016; Yin and Sun, 2018), using either intensity-based (Kim *et al*., 2016), frequency-based (Morak *et al*., 2013), fixed threshold (Yin and Sun, 2018) or the fingerprint method (Christidis and Stott, 2016). Traditionally, detection and attribution studies focused on mean changes; however, in the past decade climate extremes have become the predominant focus (Morak *et al*., 2013; Easterling *et al*., 2016). Detection and attribution studies aim to determine whether the observed changes can be explained by internal natural climate variability or whether external factors (for example anthropogenic influences) also contribute (Morak *et al*., 2013; Bellprat *et al*., 2019). A significant improvement in the simulation of changing extremes in temperature can be seen with the inclusion of anthropogenic effects in climate models (Kiktev *et al*., 2003). Greenhouse emissions are found to play a key role in the increase of warm minimum temperature extremes and concurrent decrease in cold minimum temperature extremes over the Northern Hemisphere (Kiktev *et al*., 2003).

Increases in the frequency of seasonal temperatures that are significantly higher than the norm, not just in the Northern Hemisphere summers but also in other regions and seasons, can be directly linked to anthropogenic influence on atmospheric chemistry (Stott *et al*., 2010). Anthropogenic influences have been detected in regional temperatures across the

Northern Hemisphere (Vogel *et al*., 2019). Other continental and regional studies of anthropogenic influences include observations and model simulations of the North American temperature changes from 1950-1999 (Karoly *et al*., 2003a); the European heatwave of 2003 as well as the 2010 Russian heatwave (Stott *et al*., 2003; Vogel *et al*., 2019), Indian heatwave in 2015 (Vogel *et al*., 2019), and Australia's record summer temperatures of 2013 (Lewis and Karoly, 2013).

Global scale drivers of extreme temperature events

Studies seeking to attribute extreme temperature events to natural variability have suggested that both explosive volcanism and solar variability are important in forcing climate variations over the past several centuries (Zhou ad Tung, 2013). Statistically significant correlations have been found with annual and decadal variations of solar activities (Haigh, 2011). However, a non-uniform response to these drivers is detected across the globe (Knutson *et al*., 2013), with the largest impacts recorded for the mid-latitudes (Haigh, 2011). Simulated climate models have shown that the radiative cooling signal in high European latitudes is stronger during the summer season compared to lower latitudes (Fischer *et al*., 2007; Esper *et al*., 2013). This cooling is only dominant in the summer half, whereas anomalously warm conditions prevail during the boreal winter (Fischer *et al*., 2007).

A growing body of evidence indicates that modes of variability of the large-scale circulations have a global-scale teleconnection effect on temperature extremes (e.g Khandekar, 2013; Zhou *et al*., 2014; Messori *et al*., 2016). It has been well established that the large-scale circulation patterns of ENSO have a global effect (Kenyon and Hegerl, 2008; Messori *et al*., 2016). These deviations from normal surface temperatures can have large-scale impacts on the weather and climate, and often affect cold and warm extremes differently (Johnston *et* *al*., 2004; Conway, 2008; Sithole and Murewi, 2009; Jury, 2012; Arblaster and Alexander, 2012). ENSO can cause seasonal temperature increases that, in combination with background warming (Coumou *et al*., 2012), have strong influences on temperature extremes over different regions e.g. United States and Canada (Ning and Bradley, 2015).

El Niño episodes, bring warmer than normal conditions to southeastern Asia and India during December to February (Kenyon and Hegerl, 2008). In South America during the months of June to August, the relationship between extreme temperatures closely matches that of ENSO (Kenyon and Hegerl, 2008; Loikith *et al*., 2017). Regionally, El Niño events also contribute to warmer wintertime temperatures over northwestern United States, western Canada and southern Alaska, whereas the southeastern United States experiences wetter and cooler conditions (Kenyon and Hegerl, 2008; Ning and Bradley, 2015). During the La Niña phase, west equatorial Africa and Japan experience cooler than normal temperatures (Kenyon and Hegerl, 2008). West equatorial Africa is also cooler during the boreal summer (Kenyon and Hegerl, 2008).

Several studies report that other natural modes of variability have been related to extreme climatic events, in particular cold and warm extreme temperatures include the North Atlantic Oscillation (NAO), the Southern Annular Mode (SAM), the Madden-Julian Oscillation (MJO), the Artic Oscillation (AO), the Indian Ocean Dipole (IOD), and the Pacific Decadal Oscillation (PDO) in various regions (e.g. Nicholls *et al*., 2012; You *et al*., 2013; Ning and Bradley, 2015; Matsueda and Takaya *et al*., 2015; He *et al*., 2017; Loikith *et al*., 2017; Liu *et al*., 2018). The effects of the NAO are confined to the Northern Hemisphere; however, anomalous temperature variations associated with these fluctuations can cause cooling over North Africa (Stenseth *et al*., 2003; Nicholls *et al*., 2012; Hanna and Cropper, 2017). The SAM dominates atmospheric circulation of the extratropical Southern Hemisphere, characterised by a north-south shift in atmospheric mass between the middle and high latitudes, in turn driving regional climate variability (Stenseth *et al*., 2003; Nicholls *et al*., 2012; Lim *et al*., 2016). Zonally symmetric anomalies of reduced rainfall and higher temperature in the mid-latitudes and enhanced rainfall and lower temperature in the high latitudes are observed during positive SAM periods, and the converse with a negative SAM condition (Lim *et al*., 2016). The SAM is associated with cooler than normal temperatures over most of Antarctica and South America, and southern New Zealand, whereas dry anomalous conditions are experienced over southern America, New Zealand and Tasmania, and wet anomalies over much of Australia and South Africa (Gillett *et al*., 2006). Reason and Rouault (2005) document evidence of links between the AO/SAM and winter rainfall regions in southern Africa (Malherbe *et al*., 2014). This phenomenon tends to be stronger during La Niña events (Mackeller *et al*., 2014).

The IOD is a natural ocean-atmosphere coupled mode in the Indian Ocean that plays an important role in seasonal and inter-annual climate variations over regions (Yamagata *et al*., 2004). A positive IOD event is associated with anomalous cooling in SSTs in the southeastern equatorial Indian Ocean and anomalous warming in SSTs in the western equatorial Indian Ocean (Behera *et al*., 2008). The IOD affects many parts of the world, in particular Indian Ocean rim countries and East Africa, where the IOD has an important impact (Behera *et al*., 2008).

The links between extreme temperature events and natural variability drivers are, in cases, critiqued due to the small signal-to-noise ratios, modelling deficiencies, and uncertainties in the effects of climate forcing on circulations (Collins, 2011; Stot *et al*., 2016). At regional scales and for individual extreme events, global statistics and thermodynamic arguments may not apply if the occurrence and evolution of climate extremes in a particular place is influenced by the atmospheric or oceanic circulation, or unexpected changes in large external forcing on regional climate (Collins, 2011; Stott *et al*., 2016). While climate models appear to successfully capture thermodynamic changes, they can struggle to simulate circulation changes (Trenbreth *et al*., 2015; Stott *et al*., 2016).

African vulnerability

Africa is often considered to be the most vulnerable continent to climate variability and climatic extremes, due to its high exposure and low adaptive capacity (Otto *et al*., 2015; Russo *et al*., 2016; Harrington and Otto, 2020). Africa experienced 1,560 weather-related catastrophes, which included drought, heatwaves, storms and floods, together with 614,250 fatalities, over a span of 1950-2015 (Russo *et al*., 2016). It is projected that the frequency and intensity of these extreme climatic events may change, increasing the vulnerability of those already exposed and sensitive, especially farmers and rural communities (Nkemelang *et al*., 2018; Engelbrecht, *et al*., 2015). However, there remains a paucity of research on climatic extremes, in particular temperature related extreme events, in Africa (New *et al*., 2006; Collins, 2011; Otto *et al*., 2015). This is primarily due to the lack of easily available, continuous, high resolution climate data (Harrington and Otto, 2020). Large regions are without readily and freely available digital infrastructure, have sparsely distributed meteorological station networks, and do not often have daily data for analysis (Collins, 2011; Harrington and Otto, 2020). Weather station networks in developing countries are often poorly resolved spatially and are plagued by large gaps in records (Collins, 2011; Scovronick *et al*., 2018; Harrington and Otto, 2020). This could be because the continent is plagued by e.g. civil war, extensive poverty, demographic change and political instability (Scovronick *et al*., 2018; Collins, 2011). Another challenge is the lack of multi-decadal meteorological observations which are needed to identify extreme events, to define crucial thresholds, and to help validate the modelled data (Otto *et al*., 2015).

The most prominent climate research that has been done in Africa focuses on certain high-profile events that impact agriculture, health and water resources: droughts (Hellmuth *et al*., 2007; Gan *et al*., 2016), floods and tropical cyclones (Hellmuth *et al*., 2007; Rapolaki and Reason, 2018) and rainfall this, due to the importance of rainfall over temperature in Africa) (Nicholson, 2001; Collins, 2011; Ongoma and Chen, 2017). Temperature studies are less focused on and are limited to individual countries or regions (Collins, 2011; Ongoma and Chen, 2017; Abatan *et al*., 2018). Furthermore, little work has been done on extreme temperature events and health related issues, particularly in developing countries such as those in Africa (Harrington and Otto, 2020). Knowledge on resilience to extreme temperatures is required to guide development and awareness to reduce heat-related morbidity and mortality (Kwapata *et al*., 2018; Scovronick *et al*., 2018).

Africa is a rapidly developing continent with a population of approximately 1,031,084,000; it has a wide variety of ecological and climatic regions and cultural diversity (UN DESA Population Division, 2013). Part of Africa's vulnerability to climate extremes and ETEs lies in the fact that recent development has been in climate-sensitive sectors (Ngiang *et al*., 2014). Many Africans depend on the agricultural and fishing sector for food and income, which will be significantly affected by increasing temperatures, extreme rainfall events and ETEs. The demand for resources e.g. water will be greatly impacted with an increase in the population and during prolonged drought periods, which will additionally put pressure on crop yields. Regions in Africa already suffer from recurring risks to food production (Taylor *et al*., 2009). Without adaptive measures these risks could become more intense under current climate change projections.

In recent decades numerous southern African countries have experienced severe droughts, with one of the most significant drought events in 1991/1992 (Harrington and Otto, 2020). During this event, many regions experienced <75% of the mean annual rainfall, and 70% of crops failed in the region. It is estimated that 86 million people were affected, with 20 million at risk of starvation (Harrington and Otto, 2020). The Intergovernmental Panel on Climate Change Fifth Assessment (IPCC AR5) report indicates that, under current climate change projections, it is very likely that the crop yield will be negatively impacted across Africa (Roudier *et al*., 2011; Berg *et al*., 2013; Niang *et al*., 2014). The estimated yield loss at mid-century range is between 18% for southern Africa to 22% combined across sub-Saharan Africa, with a yield loss of >30% expected for South Africa and Zimbabwe (Zinyengere *et al*., 2013; Schlenker and Lobell, 2010). The cropping areas across Africa are expected to become unviable if the world's temperatures increase above 4°C. This would not only impact agriculture, but livestock, fisheries, tourism, health, water and energy (Niang *et al*., 2014) as well. However, it is difficult to estimate the impacts of climate change on the economy although there is evidence that the irregular economic growth in sub-Saharan Africa can be linked to the increasing drought and increased frequency of heat events (Niang *et al*., 2014). Many livelihoods (e.g. subsistence farmers) and the economy depend directly on weather patterns; thus, the additional changes would have direct implications (Godfray *et al*., 2010; Kumar and Quisumbing, 2011).

Climatic changes pose a significant risk to African countries' health sectors. People across the continent already have insufficient access to drinkable water, good sanitation and adequate health care. In 2010, between 429,000 and 772,000 deaths as a result of malaria were recorded in Africa (WHO, 2012). Studies suggest that climatic changes may exacerbate vulnerability to vector and water-borne diseases (Olago *et al*., 2007; Murray *et al*., 2012). For instance, an increase in floods in regions with poor waste management could spread diseases. In addition, warmer days and nights will allow disease-carrying insects to spread to new regions and latitudes (Murray *et al*., 2012). Climatic changes could increase the vulnerability and undermine the progress that African populations already have made in fighting diseases, malnutrition and early death rates, together with gains in the agricultural sector.

Conclusion

There is a strong evidence that the frequency of climatic extremes, in particular ETEs, will increase in the near future. The African continent is especially vulnerable to these increases due to the additional risk to water resources, the threat of reduced crop productivity, changes in the frequency and geographic range of vector- and water-borne diseases. Adaption strategies may reduce these risks; however even with significant resources and institutional investments in adaptation, for the most vulnerable there may be lingering risks to food security, access to water and proper sanitation and health (Ngiang *et al*., 2014).

References

Abatan, A.A., Osayomi, T., Akande, S.O., Abiodun, B.J. and Gutowski Jr, W.J. (2018). Trends in mean and extreme temperatures over Ibadan, Southwest Nigeria. *Theory Applied Climatology*, 131: 1261–1272, DOI: 10.1007/s00704-017-2049-1.

Akinyemi, F.O. and Abiodun, B.J. (2019). Potential impacts of global warming levels 1.5°C and above on climate extremes in Botswana. *Climatic Change*, 154: 384–400, https://doi.org/10.1007/s10584-019-02446-1.

Alexander, L.V. (2016). Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond. *Weather and Climate Extremes*, 11: 4–16.

Arblaster, J.M. and Alexander, L.V. (2012). The impact of the EL Niño-Southern Oscillation on maximum temperature extremes. *Geophysical Research Letters*, 39. DOI: 10.1029/2012GL053409.

Bellprat, O., Guemas, V., Doblas-Reyes, F. and Donat, M.G. (2019). Towards reliable extreme weather and climate event attribution. *Nature Communications*, 10. DOI: 10.1038/s41467-019-09729-2.

Berg, A., De Noblet-Ducoudre, N., Sultan, B., Lengaigne, M., and Guimberteau, M. (2013). Projections of climate change impacts on potential C4 crop productivity over tropical regions. *Agricultural and Forest Meteorology*, 170: 89–102.

Boero, R., Bianchini, L. and Pasqualini, D. (2015). Vulnerability and adaption to severe weather events in the American southwest. *Weather and Climate Extremes*, 8: 12–25.

Boucek, R.E., Gaiser, E.E., Liu, H. and Rehage, J.S. (2016). A review of subtropical community resistance and resilience to extreme cold spells. *Ecosphere*, 7(10). DOI: 10.1002/ecs2.1455.

Caloiero, T. (2017). Trend of monthly temperature and daily extreme temperature during 1951-2012 in New Zealand. *Theoretical and Applied Climatology*, 129(1-2), 111–127.

Cattiaux, J., Vautard, R., Cassou, C., Yiou, P., Masson-Delmotte, V., & Codron, F. (2010). Winter 2010 in Europe: A cold extreme in a warming climate. *Geophysical Research Letters*, 37: 1–6.

Ceccherini, G., Russo. S., Ameztoy, I., Marchese, A.F., Moreno,-C. (2017). Heatwaves in Africa 1984-2015, observations and reanalysis. *Natural Hazards and Earth System Sciences*, 171: 115–125.

Centre for Research on Epidemiology of Disasters (CRED), (2019). *2018 Review of disaster events*, Brussels, 24 January 2019, ttps://www.emdat.be/publications.

Cheng, L., AghaKouchak, A., Gilleland, E. and Katz, R.W. (2013). Non-stationary extreme value analysis in a changing climate. *Climatic Change*, 127: 353–366. DOI: 10.1007/s10584-014-1254-5.

Christidis, N. and Stott, S. (2016). Attribution analysis of temperature extremes using a set of 16 indices. *Weather and Climate Extremes*, 14: 24–35.

Christidis, N., Jones, G.S. and Stott, P.A. (2015). Dramatically increasing change of extremely hot summers since the 2003 European Heatwave. *Nature Climate Change*, 5: 46–50.

Christidis, N., Stott, P.A., Brown, S., Hegerl, G.C. and Caesar, J. (2005). Detection of changes in temperature extremes during the second half of the 20th century. *Geophysical Research Letters*, 3. DOIi: 10.1029/2005GL023885.

Collins, J.M. (2011). Temperature variability over Africa. *Journal of Climate*, 24: 3649–3666, DOI: 10.1175/2011JCLI3753.1

Conner, L.H. (2016). Climate change and Anthropos: planet, people and places. Routledge. New York, 222.

Coumou, D. and Rahmstorf, S. (2012). A decade of extreme weather, *Nature Climate Change*. DOI: 10.1038/NCLIMATE1452.

De Perez, E.C., Van Aalst, M., Bishiniotis, K., Mason, S., Nissan, H., Pappenberger, F., Stephens, E., Zsoster, E. and Van den Hurk B. (2018). Global predictability of temperature extremes. *Environmental Research Letters*, 13.

Donat, M.G., Alexander, L.V., Yang, H., Durre, I., Vose, R. and Caeser, J. (2013). Global land-based datasets for monitoring climatic extremes. *Bulletin of the American Meteorological Society*, 96: 997–1006.

Drijfhout, S., Bathiany, S., Beaulieu, C., Brovkin, V., Claussen, M., Huntingforf, C., Scheffer, M., Sgubin, G. and Swingedouw, D. (2015). Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. *Proceedings of the National Academy of Sciences of the United States of America*, 122: E5777–E7586, DOI: 10.1073/pnas.1511451112.

Dumitrescu, A., Bojariu, R., Brisan, M. V., Marin, L. and Manea, A. (2015). Recent climatic changes in Romania from observational data (1961-2013). *Theoretical and Applied Climatology*, 122 (1-2): 111–119.

Easterling D.R., Evans J.L., Groisman, P.Ya. Karl, T.R., Kunkel, K.E. and Ambenje, P. (2000). Observed variability and trends in extreme climate events: a brief review. *Bulletin of the American Meteorological Society*, 81(3): 417–425.

Easterling D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R. and Mearns, L.O. (2000) Climate Extremes: Observations, modeling and impacts. *Science*, 289: 2068–2074.

Easterling, D.R., Kunkel, K.E., Wehner, M.F. and Sun, L. (2016). Detection and attribution of climate extremes in the observed record. *Weather and Climate Extremes*, 11: 17–27.

Ebi, K.L. and Bowen, K. (2016). Extreme events as sources of health vulnerability: Drought as an example. *Weather and Climate Extremes*, 11: 95–102.

El Kenway, A., López-Moreno, J.I. and Vincente-Serrano, S.M. (2011). Recent trend in daily temperature extremes over northeastern Spain (1960-2006). *Natural Hazards and Earth System and Sciences*, 11: 2583–2603.

Engelbrecht, F., Adegoke, J., Bopape, M.J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. and Gatebe, C. (2015). Projections of rapidly rising temperatures over Africa under low mitigation. *Environmental Research Letters*, 10. DOI:10.1088/1748-936/10/8/085004.

Esper, J., Schneider, L., Krusic, P.J., Luterbacher, J., Büntgen, U., Timonen, M., Sirocko, F. and Zorita, E. (2013). European summer temperature response to annually dated volcanic eruptions over the past nine centuries. *Bulletin of Volcanology*, 75(736): 1–14, DOI: 10.1007/s00445-013-0736-z.

Espirito Santo, F., De Lima, M.I.P., Ramos, A.M. and Trigo, R.M. (2014). Trends in seasonal surface air temperature in mainland Portugal, since 1941. *International Journal of Climatology*, 34(6): 1814–1837.

Few, S.F., Philip, S.Y., Van Olenborgh, G.J., Otto, F.E.L., Vautard, R. and Van der Schrier, G. (2019). The exceptional summer heatwave in southern Europe [in "Explaining extremes of 2017 from a climate perspective"]. *Bulletin of the American Meteorological Society*, 100(1): s49–s53.

Filho, W.L., Al-Amin, A.Q., Nagy, G.J., Azeiterio, U.M., Wiesböck, L., Ayal, D.Y., Morgan, E.A., Mugabe, P., Aparicio-Effen, M., Fudjumdjum, H. and Jabbour, C.J.C. (2018). A comparative analysis of climate-risk and extreme event-related impacts on well-being and health: Policy Implications. *International Journal of Environmental Research and Public Health*, 15: 331. DOI:10.3390/ijerph15020331.

Gan T.Y., Ito M., Hulsmann S., Qin X., Lu, X.X., Liong, S.Y., Rutschman, P., Disse, M. and Koivusalo, H. (2016). Possible climate change/variability and human impacts, vulnerability of drought-prone regions, water resources and capacity building for Africa. *Hydrological Sciences Journal*, 61(7): 1209–1226.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., and Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *Science*, 327(5967): 812–818.

Guirguis, K., Gershunov, A., Schwartz, R. and Bennet, S. (2011). Recent warm and cold daily winter temperature extremes in the Northern Hemisphere. *Geophysical Research Letters*, 38. DOI: 10.1029/2011GL048762.

Harrington, L.J., Frame, D.J., Hawkins, E. and Joshi, M. (2017). Seasonal cycles enhance disparities between low- and high-income countries in exposure to monthly temperature emergence with future warming. *Environmental Research Letters*, 12: 114039.

Hartmann, D.L., Klein Tank, A.M.G, Rusticucci, M., Alexander, L.V., Brönnimann, S., Charabi, Y., Dentener, F.J., Dlugokencky, E.J., Easterling, D.R., Kaplan, A., Soden, B.J., Thorne, P.W., Wild, M and Zhai, P.M. (2013). Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V and Midgley, P.M. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

He, S., Goa, Y., Li, F., Wang, H. and He, Y. (2017). Impact of Artic Oscillation on the East Asian climate: A review. *Earth-Science Reviews*, 164: 48–62.

Heim., R.R. (2015). An overview of weather and climate extremes – Products and trends. *Weather and Climate Extremes*, 10: 1-9.

Hellmuth, M.E., Moorhead, A., Thomson, M.C. and Williams, J., (eds) (2007). *Climate Risk in Africa: Learning from Practices*. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA.

Herold, N., Alexander, L., Green, D. and Donat, M. (2017). Greater increase in temperature extremes in low versus high income countries. *Environmental Research Letters*, 12: 1–3. DOI.org/10.1088/1748- 9326/aa5c43.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K.L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S.I., Thomas, A., Warren, R. and Zhou, G. (2018). Impacts of 1.5ºC Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. *An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I.Gomis, E. Lonnoy, T.Maycock, M.Tignor, and T. Waterfield (eds.)]. In Press.

Hoogendoorn G. and Fitchett, J.M. (2016). Tourism and climate change: a w of threats and adaption strategies for Africa. *Current issues in Tourism*, 21(7): 742–759. DOI: 10.1080/13683500.2016.1188893.

Horton, R.M., Mankin, J.S., Lesk, C., Coffel, E. and Raymond, C. (2016). A review of recent advances in research on extreme heat events. *Current Climate Change Report*, 2: 242–259, DOI: 10.1007/s40641-016-0042-x.

Im, E., Thanh, N., Kim, Y. and Ahn, J. (2019) 2018 summer extreme temperatures in South Korea and their intensification under 3°C global warming. *Environmental Research Letters*, 4: 094020.

IPCC (2018). Summary for Policymakers. In: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press.

IPCC (2019). IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, Summary for Policy Makers, approved draft.

Irannezhad, M., Moradkhani, H. and Kløve, B. (2019). Corrigendum to "Spatio-temporal variability and trends in extreme temperature events in Finland over the recent decades: Influence of Northern Hemisphere teleconnection patterns". *Advances in Meteorology*, 1–17.

Jahn, M. (2015). Economics of extreme weather events: Terminology and regional impact models. *Weather and Climate Extremes*, 10: 29–39.

Johnson, N.C., Xie, S., Kosaka, Y. and Li, X. (2018). Increasing occurrence of cold and warm extremes during the recent global warming slowdown. *Nature Communications*, 9: 1–12.

Khan, S.J., Deere, D., Leusch, F.D.L., Humpage, H., Jenkins, M. and Cunliffe, D. (2015). Extreme weather events: Should drinking water quality management systems adapt to changing risk profiles? *Water Research*, 85: 124–136.

Kharin, V.V., Zwiers, F.W., Zhang, X. and Wehner, M. (2013). Changes in temperature and precipitation extremes in the CMIP5 ensemble. *Climate Change*, 119: 345–357.

Kim, Y.-H., Min, S.-K., Zhang, X.B., Zwiers, F., Alexander, L.V., Donat, M.K. and Tung, Y.-S. (2016). Attribution of extreme temperature changes during 1951-2000. *Climate Dynamics*, 46: 1769–1782.

Klein Tank, A.G.M. and Können, G.P. (2003). Trends in indices of daily temperature and precipitation extremes in Europe 1946-99. *American Meteorological Society*, 16: 3665–3680.

Knutson, T.R., Zeng, F. and Wittenberg, A.T. (2013). Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth-century simulations. *Journal of Climate*, 26: 8709–8743. DOI: 10.1175/JCLI-D-12-000567.1.

Kodra, E., Ganguly, A.R. (2014). Asymmetry of projected increases in extreme temperature distributions. *Science Report*. 4: 1–8. http://dx.doi.org/10.1038/srep05884.

Kostopoulou, E. and Jones, P.D. (2005). Assessment of climate extremes in the Eastern Mediterranean. *Meteorology and Atmospheric Physics*, 89: 69–85.

Kruger, A.C. and Shongwe, S. (2004). Temperature trends in South Africa: 1960-2003. *International Journal of Climatology*, 24: 1929–1945.

Kruger, A.C. and Nxumalo, M. (2017). Surface temperature trends from homogenized time series in South Africa: 1931-2015. *International Journal of Climatology*, 37 (5): 2364–2377.

Kumar, N. and Quisumbing, A.R. (2011) *Gendered Impacts of the 2007-08 Food Price Crisis: Evidence Using Panel Data from Rural Ethiopia*. IFPRI Discussion Paper 01093, International Food Policy Research Institute (IFPRI), Poverty, Health, and Nutrition Division, Washington, DC, USA, 24 pp.

Kunkel, K.E., Stevens, L.E., Stevens, S.E., Sun, L., Janssen, E., Wuebbles, D., Dobson, J. G. 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. Climate of the Contiguous United States. NOAA Technical Report NESDIS 142-9. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C., 85 pp.

Lewis, S.C. and King, A.D., 2017. Evolution of mean, variance and extremes in the 21st century temperatures. *Weather and Climate Extremes*, 15, 1-10.

Li, C., Fang, Y., Caldeira, K., Zhang, X., Diffenbaugh, N.S. and Michalak, A.M. (2018). Widespread persistent changes to temperature extremes occurred earlier than predicted. *Scientific Reports*, 8: 1007.

Liu, X., Xu, Z., Peng, D. and Wu, G. (2018). Influences of the North Atlantic Oscillation on extreme temperature during the cold period in China. *International Journal of Climatology*, 39: 43–49.

Loikith, P.C., Detzer, J., Mechoso, C.R., Lee, H. and Barkhordarian, A. (2017). The influence of recurrent modes of climate variability on the occurrence of monthly temperature extremes over South America. Journal of Geophysical Research: *Atmospheres*, 122: 10,197–10,297.

Loughnan, M.E., Nicholls, N. and Tapper, N.J. (2010). When the heat is on: Threshold temperatures for AMI admissions to hospital in Melbourne Australia. *Applied Geography*. 30: 63–69.

Luber, G and McGeehin, M. (2008). Climate change and extreme heat events. *American Journal of Preventative Medicine*, 35(5): 429–435.

Luterbacher, J., Dietricj, D., Xoplaki, E., Grosjean, M. and Wanner, H. (2004). European seasonal and annual temperature variblity, trends, and extremes since 1500. *Science*, 303: 1499–1503.

Mahmood, R. and Babel, M.S. (2014). Future changes in extreme temperature events using the statistical downscaling model (SDSM) in the trans-boundary region of the Jhelum river basin. *Weather and Climate Extremes*, 5(6): 56–66.

Mallet, J., Fortin, G. and Germain, D. (2018). Extreme weather events in northeastern New Brunswick (Canada) for the period 1950-2012: Comparison of newspaper archive and weather station data. *The Canadian Geographer*, 62(2): 130–143.

Marigi, S., Njogu, A.K. and Githungo, W.N. (2016). Trends of extreme temperature and rainfall indices for arid and semi-arid lands of South Eastern Kenya. *Journal of Geoscience and Environment Protection*, 4: 158–171, http://dx.doi.org/10.4236/gep.2016.412012.

Matsueda, S. and Takaya, Y. (2015). The global influence of the Madden-Julian Oscillation on extreme temperature events. *American Meteorological Society*, 28: 4141–4151.

Maúre, G., Pinto, I., Ndebele-Murisa, M., Muthige, M., Lennard, C., Nikulin, G., Doiso, A. and Meque, A. (2018). The southern African climate under 1.5°C and 2°C of global warming as simulated by CORDEX regional climate models. *Environmental Research Letters*, 13. DOI:10.10088/1748-9326/aab190.

Mckinnon, K.A., Rhines, A., Tingley, M.P. and Huybers, P. (2016). The changing shape of Northern Hemisphere summer temperature distributions. *Journal of Geophysical Research*, 121: 8849–8868.

Messori, G., Caballero, R. and Gaetani, M. (2016). On cold spells in North America and storminess in western Europe. *Geophysical Research Letters*, 43: 6620–6628.

Mirza, M.M.Q. (2003). Climate change and extreme weather events: can developing countries adapt? *Climate Policy*, 3(3): 233–248.

Mirza, M.M.Q. (2011). Climate change, flooding in south Asia and implications. *Regional Environmental Change*, 11: S95–S107.

Morak, S., Hegerl, G.C. and Christidis, N. (2013). Detectable changes in the frequency of temperature extremes. *Journal of Climate*, 26: 1561–1574.

Mueller, B. and Seneviratne, S.I. (2012). Hot days induced by precipitation deficits at the global scale. *National Academy of Science*, 109 (31): 12398–12403.

Murray, V., McBean, G., Bhatt, M., Borsch, S., Cheong, T.S., Erian, W.F., Llosa, S., Nadim, F., Nunez, M., Oyun, R., and Suarez A.G. (2012). Case studies. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., and Midgley P.M. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 487-542.

Nangombe, S., Zhou, T., Zhang, W., Zou., L. and Li, D. (2019). High-Temperature extreme events over Africa under 1.5 and 2°C of global warming. *Journal of Geophysical Research*, 124 (8). https://doi.org/10.1029/2018JD029747.

Napoli C.D., Pappenberger, F. and Cloke, H.L. (2018). Assessing heat-related health risk in Europe via the Universal Climate Index (UTCI), *International Journal of Biometeorology*, 62, 1155–1165.

Nemec, J., Gruber, C., Chimani, B. and Auer, I. (2013). Trends in extreme temperature indices in Australia based on a new homogenized dataset. *International Journal of Climatology*, 33(6): 1538–1550.

New, M., Hewitson B., Stephenson, D.B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B., Coelho, A.A.S., Masis, D.N., Kululanga, E., Mbambalala, E., Adesina, F., Saleh, H., Kanyanga, J., Adosi, J., Bulane, L., Fortunata, L., Mdoka, M.L. and Lajoie, R. (2006). Evidence of trend in daily climate extremes over southern and west Africa, *Journal of Geophysical Research*, 111: D14102. DOI: 10.1029/2005JD006289.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. and Urquhart, P. (2014) Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White L.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nicholls, S.I., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C. and Zhang, X. (2012). Changes in climate extremes and their impcats on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaption* [Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastranda, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M. and Midgley, P.M. (eds.)]. A special report on working groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press. Cambridge. UK. New York, USA, 109-230.

Nicholson, S.E. (2001). Climatic and environmental change in Africa during the last two centuries. *Climate Research*, 17: 123–144.

Ning, L. and Bradley, R.S. (2015). Winter climate extremes over the northeastern United States and southeastern Canada and telecommunications with large-scale modes of climate variability. *American Meteorological Society*, 28: 2475–2493.

Nkemelang, T., New, M. and Zaroug, M. (2018). Temperate and precipitation extremes under current, 1.5°C and 2.0°C global warming above pre-industrial levels over Botswana, and implications for climate change vulnerability. *Environmental Research Letters*, 13: 065016.

Olago, D., Marshall, M., Wandiga, S.O., Opondo, M., Yanda, P.Z., Kanalawe, R., Githeko, A.K., Downs, T., Opere, A., Kavumvuli, R., Kirumira, E., Ogallo, L., Mugambi, P., Apindi, E., Githui, F., Kathuri, J., Olaka, L., Sigalla, R., Nanyunja, R., Baguma, T., and Achola, P. (2007) Climatic, socio-economic, and health factors affecting human vulnerability to cholera in the Lake Victoria basin, East Africa. *Ambio*, 36(4): 350–358.

Ongoma, V. and Chen, H. (2015). Temporal and Spatial variability of temperature and precipitation over East Africa from 1951 to 2010. *Meteorology and Atmospheric Physics*, 129: 131-144.

Orlowsky, B. and Seneviatne, S.I. (2012). Global changes in extreme events: regional and seasonal dimension. *Climatic Change*, 110: 669–696.

Osborne, S. (2019). France's summer heatwave killed 1,500 people, health minister announces. Independent. https://www.independent.co.uk/news/world/europe/france-heatwave-summer-dead-death-toll-europe-a9096806.html. Accessed 14 April 2020.

Otto, F.E.L., Boyd, E., Jones, R.G., Cornforth, R.J., James R., Parker, H.R. and Allen, M.R. (2012) Attribution of extreme weather events in Africa: a preliminary exploration of the science and policy implications. *Climate Change*, 132, 531-543.

Pappenberger, F., Jendritzky, G., Staiger, H., Dutra, E., Giuseppe, F.D., Richardson, D.S. and Coke, H.L. (2015). Global forecasting of thermal health hazards: the skill of probabilistic predictions of the Universal Thermal Climate Index (UTCI). *International Journal of Biometeorology*, 59, 311–323: DOI 10.1007/s00484-014-0843-3.

Perkins, S.E. (2015). A review of the understanding of heatwaves – Their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research*, 164-165: 242–267.

Perkins-Kirkpatrick, S.E., White, C.J., Alexander, L.V., Argüeso, D., Boschat, G., Cowan, T., Evans, J.P., Ekström M., Oliver, E.C.J., Phatak, A. and Purich, A. (2016). Natural hazards in Australia: heatwaves. *Climate Change*, 139: 101–114.

Peterson, T.C., Zhang, X., Brunet-India, M. and Vázquez-Aguirre, J.L. (2008). Changes in North American extremes derived from daily weather data. *Journal of Geophysical Research*, 113: 07113.

Radovic, V. and Iglesias, I. (2019). Extreme weather events: Definition, classification and guidelines towards vulnerability reduction and adaption management, In Climate Action. Encyclopaedia of the UN Sustainable Development Goals. Springer Nature Switzerland, DOI: 10.1007/978-3-319-71063-1_68-1.

Ragone, F., Wouters, J. and Bouchet, F. (2018). Computation of extreme heat waves in climate models using a large deviation algorithm. *Proceedings of the National Academy of Sciences of the United States of America*, 115: 24–29.

Rapolaki, R.S. and Reason, C.J.C. (2018). Tropical storm Chedza and associated floods over south-eastern Africa. *Natural Hazards*, 93: 189–217.

Ren, F.M., Trewin, B., Brunet, M., Dushmanta, P., Walter, A., Baddour, O. and Korber, M. (2018). A research progress review on regional extreme events. *Advances in Climate Change Research*, 9: 161–169.

Roudier, P., Sultan, B., Quirion, P., and Berg A. (2011). The impact of future climate change on West African crop yields: what does the recent literature say? *Global Environmental Change*, 21(3): 1073–1083.

Russo, S., Dosio, A., Graversen, R.G., Sillman, J., Carrao, J. and Dubar, M.B. (2014). Magnitude of extreme heat waves in present climate and their projection in a warming world, Journal Geophysical Research Atmospheric: *Atmospheres*, 119(12): 500–512. DOI: 10.1002/2014JD022098.

Russo, S., Marchese, A., Silmann, J. and Immé, G. (2016). When will unusual heat waves become normal in a warming Africa?, *Environmental Research Letters*, 11: 054016 DOI:10.1088/1748-9326/11/5/054016.

Rusticucci, M. (2012). Observed and simulated variability of extreme temperature events over South America. *Atmospheric Research*, 106: 1–17.

Save the Children (SC), 2019. 2019: Climate shocks claim more than 1 200 lives across east and southern Africa. Accessed on 09 December 2019, https://www.savethechildren.net/news/2019-climate-shocks-claim-more-1200-lives-across-east-and-southern-africa

Schlenker, W. and Lobell, D.B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1): 014010, doi:10.1088/ 1748-9326/5/1/014010.

Schoof, J.T. and Robeson, S.M. (2016). Projecting changes in regional temperature and precipitation extremes in the United States. *Weather and Climate Extremes*, 11: 28–40.

Seneviratine S.I., Donat, M.G., Mueller, B. and Axexander, L.V. (2014). No pause in the increase of the hot temperature extremes. *Natural Climate Change*, 4: 161–163.

Seneviratne S.I. and Zwiers, F.W. (2015). Attribution and prediction of extreme events: Editorial on special issue. *Weather and Climate Extremes*, 9: 2–5.

Serdeczny, O., Adams, S., Baarsch, F., Coumou, D., Roberson, A., Hare, W., Schaeffer, M., Perrette, M. and Reinhardt, J. (2016). Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, 15(8): DOI: 10.1007/s10113-015-0910-2.

Sheridan, S.C. and Allen, M.J. (2015). Changes in the frequency and intensity of extreme temperature events and human health concerns. *Current Climate Change Report*, 1: 155—162. DOI: 10.1007/s40641-015-0017-3.

Simmonds, I. (2018). What causes extreme hot days in Europe. *Environmental Research Letters*, 13. DOI: 10.1088/1748-9326/aacc78.

Smith, M.D. (2011). An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *Journal of Ecology*, 99: 656–663.

Steffen W., Hughes, L. and Perkins, S.E. (2014). Heatwaves: Hotter, longer, more often. Special Report by the Climate Council of Australia, Sydney, Australia, 62 [Available online at http://www.climatecouncil.org.au/heatwaves-report.

Stott, P.A., Stone, D.A. and Allen, M.R. (2004). Human contribution to the European heatwave of 2003. *Nature*, 432: 610–614.

Stott, P.S., Christidis, N., Otto, F.E.L., Sun, Y., Vanderlinden, J.-P., Van Oldenborgh, G.J., Vautard, R., Von Storch, H., Walto, P., Yiou, P. and Zwiers, F.W. (2016). Attribution of extreme weather and climate-related extremes. *WIREs Climate Change*, 7: 23–41. DOI:10.1002/wcc.380.

Tank, A.M.G.K., Zwiers, F.W. and Zhang, X. (2009). Guidelines on Analysis of extremes in a changing climate in support of informed decision adaptation. *World Meteorological Organization*, WMO-TD No. 1500.

The Independent news, 2019, Samuel Osborne, https://www.independent.co.uk/news/world/europe/france-heatwave-summer-dead-death-toll-europe-a9096806.html

Thorton, P.K., Ericksen, P.J., Herrero, M. and Challinor, A.J. (2014). Climate variability and vulnerability to climate change: A Global review. *Global Change Biology*, 20: 3313–3328. DOI: 10.1111/gcb.12581.

UN DESA Population Division (2013). *World Population Prospects: The 2012 Revision. Excel Tables – Population Data*. United Nations Department of Economic and Social Affairs (UN DESA) Population Division, United Nations, New York, NY, USA, esa.un.org/unpd/wpp/Excel-Data/population.htm.

United Nationals Office for Disaster Risk Reduction (UNISDR), 2019. *2018: Extreme weather events affected 60 million people*, Press release: EMBARGO 11.00 CET, Geneva, Switzerland, 24 January 2019, https://www.emdat.be/publications.

Van Oldenborgh, G.J., Mitchell-Larson, E., Veccchi, G.A., De Vries, H., Vautard, R. and Otto, F. (2019). Cold waves are getting milder in the northern midlatitudes. *Environmental Research Letters*, 14. DOI: 10.1088/1748-9326/ab4867.

Vardoulakis, S., Dear, K., Hajat, S., Heaviside, C., Eggen, B. and Mchael, A.J. (2014). Comparative assessment of the effects of climate change on heat- and cold-related mortality in the United Kingdom and Australia. *Environmental Health Perspectives*. 122 (12): 1285–1292.

Vincent, A. and Mekis, E. (2005). Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. *Atmosphere-Ocean*, 44(2),: 177–193. DOI: 10.3137/ao.440205.

Vogel, E., Donat, M., Alexander, L.V., Meinshausen, M., Ray, D.K., Karoly, D., Meinshausen, N. and Frieler, K. (2019). The effects of climate extremes on global agricultural yields. *Environmental Research Letters*, 14. DOI: 10.1088/1748-9326/ab154b.

Vogel, M.M., Zscheischler, J., Wartenburger, R., Dee, D. and Seneviratne, S.I. (2019). Concurrent 2018 hot extremes across Northern Hemisphere due to human-induced climate change. *Earth's Future*, 7: 692–703.

Vose, R.S., Applequist, S., Bourassa, M.A., Pryor, S.C., Barthelmie, R.J., Blanton, B., Bromirski, P.D., Brooks, H.E., DeGaetano, A.T., Dole, R.M., Easterling, D.R., Jensen, R.E., Karl, T R., Katz, R.W., Klink, K., Kruk, M.C., Kunkel, K.E., MacCracken, M.C., Peterson, T.C., Shein, K., Thomas, B.R., Walsh, J.E., Wang, X.L., Wehner, M.F., Wuebbles, D.J. and Young, R.S., (2014). Monitoring and understanding changes in extremes: extratropical storms, winds, and waves. *Bulletin of the American Meteorological Society*, 95: 377–386.

Walthall, C.L. (2015). Foreword. *Weather and Climate Extremes*, 10, 1.

Whan, K., Zscheischler, J., Orth, R., Shongwe, M., Rahimi, M., Asare, E.O. and Seneviratne, S.I. (2015). Impact of soil moisture on extreme maximum temperatures in Europe. *Weather and Climate Extremes*, 9: 57–67. DOI: 10.1016/j.wace.2015.05.001.

WHO, (2012). *World Malaria Report 2012*. World Health Organization (WHO), Geneva, Switzerland, pp 195.

World Meteorological Organisation (WMO). 2019. July matched, and maybe broke, the record for the hottest month since analysis began, Published 1 August 2019. Retrieved from https://public.wmo.int/en/media/news/july-matched-and-maybe-broke-record-hottest-month-analysis-began.

Yin, H. and Sun, Y. (2018). Detection of Anthropogenic influence on fixed threshold indices of extreme temperature. *American Meteorological Society*, 31: 6341–6352.

You, Q., Ren, G., Fraedrich, K., Kang, S., Ren, Y. and Wang, P. (2013). Winter temperature extremes in China and their possible causes. *International Journal Climatology*, 33: 1444–1455.

Yu, Z. and Li, X. (2015). Recent trends in daily temperature extremes over northeastern China (1960-2011). *Quaternary International*, 380-381: 35–35.

Zhou, J. and Tung, K.-K. (2013). Deducing multidecadal anthropogenic global warming trends using multiple regression analysis. *Journal of the Atmospheric Sciences*, 70: 3–8, DOI: 10.1175/JAS-D-12-0208.1.

Zinyengere, N., Crespo, O., and Hachigonta, S. (2013). Crop response to climate change in southern Africa: a comprehensive review. *Global and Planetary Change*, 111: 118–126.

Supplement Material (Chapter 5)

Supplement material 1: ETCCDI climate indices (Adapted from Zang *et al*., 2018a).

Indices	Long name	Definitions	Units
SU	Summer days	Count of days where TX (daily maximum temperature) >25°C	days
TXx	Max TX (Warmest day)	The monthly maximum value of daily maximum temperature (TXx = max)	°C
TNx	Min TX (Warmest night)	The monthly minimum value of daily minimum temperatures (TNx = max)	°C
TX90p	Warm days	Count of days where TX>90th percentile	%
TN90p	Warm nights	Count of days where TN>90th percentile	%
WSDI	Warm spell duration indicator	Count of days in a span of at least six days where TX>90th percentile	days
FD	Frost days	Annual number of days when TN<0°C	days
ID	Ice days	Annual count when TX<10°C	days
TR	Tropical nights	Annual count of days when TN>20°C	days
TNn	Max TN (Coldest night)	Monthly maximum value of daily minimum temperature (TNn = max)	°C
TXn	Max TX (Coldest day)	Monthly minimum value of daily minimum temperature (TXn = max)	°C
TN10p	Cool nights	Count of days where TN<10th percentile	%
TX10p	Cool days	Count of days where TN<10th percentile	%
CDSI	Cold spell duration indicator	Count of days of at least six days where TN<10th percentile	days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C

Supplement material 2: Temperature indices used in the analysis of ETEs and ETs (Adapted from Kruger and Shongwe, 2004).

TX extreme indices	TN extreme indices
Very hot days: TX≥35°C	*Hot nights: TN≥20°C*
Hot days: 30°C≤TX<35°C	*Warm nights: 15°C≤TN<20°C*
Hot-day events: TX≥30°C for 3–5 days	Warm-night events: TN≥15°C for 3–5 days
Cold days: TX≤15°C	Very cold nights: TN≤0°C
Cool days: 15°C<TX≤19°C	Cold nights: 0°C<TN≤5°C
Cool-day events: TX≤19°C for 3–5 days	Cold-night events: TN≤5°C for 3–5 days

Supplement material 3: Temperature indices used by Mackellar *et al*. (2014) (Adapted from Mackellar *et al*., 2014)

Index	**Description**	**Units**
Hot days	Number of days with TX>25°C	Days
Cold days	Number of days with TN<0°C	Days
Warm nights	Number of days with TN>20°C	Days
Dtr	Difference between TX and TN	°C
TX 90th	Number of days with TX>90th percentile of 1960-2010 daily TX	Days
TX 10th	Number of days with TX<10th percentile of 1960-2010 daily TX	Days
TN 90th	Number of days with TN>90th percentile of 1960-2010 daily TN	Days
TN 10th	Number of days with TN<10th percentile of 1960-2010 daily TN	Days

Supplement material 4: Meteorological stations compiled from publications.

Province	Station	Latitude (°S)	Longitude (°E)
Eastern Cape	Addo	*-33.97*	25.70
	Cape St.Francis	-34.20	24.83
	Cradock-MUN	-32.16	25.61
	East London	-24.98	31.60
	Mthatha	*-29.10*	26.30
	Port Elizabeth	-33.98	25.60
	Queenstown	-31.91	26.95
	Willowmore	-29.02	29.87
Free State	Bethlehem	-28.24	28.31
	Bloemfontein	-33.30	23.48
	Bothaville	-25.73	28.18
	Frankfort	-28.80	24.77
	Glen College	-28.95	26.33
	Wepener	-29.72	27.02
Gauteng	Johannesburg International	-26.13	28.23
	Pretoria	-25.73	28.18
	Pretoria PUR	-25.73	28.17
	Pretoria UP	-25.75	28.27
	Zuurbekom	-26.30	27.80
KwaZulu-Natal	Cape St.Lucia	-28.50	32.40
	Cedara	-29.53	30.28
	Durban	-30.30	27.83
	Emarald Dale	-29.93	29.95
	Escourt	-29.25	16.87
	Mount Edgecombe	-29.70	31.05
	Richardsbay	-28.78	32.03
Limpopo	Lephalale	-23.66	27.74
	Mara	-23.11	29.63
	Musina	-22.27	29.90
	Phalaborwa	-23.94	31.14
	Polokwane	-33.98	25.61
Mpumalanga	Punda Maria	-22.69	31.01
	Lydenburg	-31.67	18.50
	Skukuza	-25.11	30.48
Northern Cape	Agterkop	-32.11	20.11
	Calvinia	-31.48	19.77
	De Aar	-27.37	29.88
	Fraserburg	-31.91	21.51
	Henkries	-28.97	18.09
	Kimberley	-26.47	20.61
	Pofadder	-30.67	24.00
	Port Nolloth	-30.35	21.82
	Springbok	-29.66	17.88
	Twee Rivieren	-28.41	21.26
	Upington	-28.45	21.25
	Vanwyksvlei	-30.35	21.82
North-West	Armoedsvlakte	-26.95	24.63
	Buffelspoort	-25.75	27.48
	Marico	-31.53	28.67
	Volksrust	-25.50	26.35
	Vryburg	-26.30	24.63
Western Cape	Beaufort Wes	-32.35	22.60
	Cape Agulhas	-34.83	20.20
	Cape Columbine	-32.83	18.70
	Cape Point	-34.35	18.50
	Cape St. Blaze/Mosselbay	-34.18	22.15
	Cape Town	-26.95	24.63
	Cape Town International	-33.18	18.60
	Cape Town Slangkop	-34.14	18.31
	Jonkershoek	-33.97	18.93
	Langebaanweg Wo	-32.96	18.16
	Langegewens	-33.28	18.70
	Vredendal	-27.27	28.50

Supplement Material (Chapter 7)

Supporting Table 1: Number of inhomogeneities of long-term temperature stations data over the period 1950-2016.

Province	Station Name	Climate Number	Abbreviation	No. of inhomogeneities	
				TX	TN
Eastern Cape	Dohne	00798116	DH	3	3
	East London	00595729	EL	2	1
	Port Elizabeth	00351795	PE	1	1
Free State	Bloemfontein JBM Hertzog	02615161	BFN	1	0
Gauteng	Johannesburg Int	*04763990*	JHB	4	4
	Zuurbekom	04755288	ZB	1	0
KwaZulu-Natal	Cedara	02394820	CD	0	3
	Durban	0240808A2	DBN	2	2
Limpopo	Mara	072200991	MR	3	1
	Warmbad Towoomba	05895941	WBT	1	1
Mpumalanga	Skukuza	05961793	SK	2	3
Northern Cape	Kimberley	02904684	KB	4	5
	Upington	03174765	UP	0	0
	Vanwyksvlei	01935613	VW	4	2
North-West	Vryburg	04322383	VB	0	0
Western Cape	Cape Agulhas	00030204	CA	2	0
	Cape Columbine	00606209	CC	6	0
	Mosselbay	0012215	MB	4	3
	Cape Town	0021178A3	CPT	0	6
	Vredendal	0106880A2	VL	1	1

Supporting Table 2: Annual trends of ETCCDI and ET-SCI indices during 1960-2016.

Station	TNMean			**TXn**			**TNn**			**FD**			**tnLtm2**			TX10P			**TN10P**			TXb2TNb2		
	ETCCDI			*ETCCDI*			*ETCCDI*			*ETCCDI*			*ET-SCI*			*ETCCDI*			*ETCCDI*			*ET-SCI*		
	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*
Dohne	**0.31**	**0.35**	0.02	**0.16**	0.22	0.02	0.08	0.10	-	0.08	0.10	-	0.20	0.24	-	**-0.28**	**-0.41**	-0.07	**-0.28**	**-0.37**	-0.09	-0.02	-0.03	-
East London	0.06	0.08	-	-0.15	-0.22	-0.01	**0.11**	0	0.01	-	-	-	-0.13	-0.16	-	**-0.35**	**-0.51**	-0.08	-0.02	-0.04	-0.01	-	-	-
Port Elizabeth	-0.14	**-0.29**	-0.01	0.04	0.03	-	**-0.04**	-0.08	-	-0.22	-0.26	-	-	-	-	**-0.32**	**-0.48**	-0.08	0.10	0.21	0.04	-0.19	-0.23	-
Bloemfontein	0.01	0.04	-	0.06	0.07	0.01	**0.07**	0.09	0.01	-0.10	-0.16	-	-0.04	-0.06	-	**-0.26**	**-0.37**	-0.07	-0.10	-0.14	-0.05	-0.15	-0.18	-
Johannesburg Int	**0.19**	**0.27**	0.01	**0.20**	**0.28**	0.02	**-0.03**	-0.04	-	0.05	0.12	-	-	0.02	-	**-0.30**	**-0.43**	-0.08	-0.15	-0.23	-0.06	**0.03**	0.03	-
Zuurbekom	**0.46**	**0.65**	0.03	**0.25**	**0.37**	0.03	**0.53**	**0.73**	0.06	**-0.48**	**-0.70**	**-**	**-0.51**	**-0.71**	-0.84	**-0.25**	**-0.36**	-0.10	**-0.44**	**-0.63**	-0.20	**-0.13**	-0.16	-
Cedara	**0.22**	0.23	0.01	0.10	0.12	0.01	**-0.03**	-0.04	-	-0.03	-0.01	-	0.03	0.07	-	**-0.24**	**-0.36**	-0.05	**-0.25**	**-0.30**	-0.08	-	-	-
Durban	**0.30**	**0.48**	0.02	-0.04	-0.06	-	**0.18**	0.25	0.02	-	-	-	-	-	-	**-0.20**	**-0.31**	-0.05	**-0.38**	**-0.56**	-0.19	**0.07**	0.08	-
Mara	-0.02	-	-	-0.12	-0.17	-0.01	**-0.07**	-0.09	-0.01	-0.05	-0.06	-	0.06	0.07	-	**-0.38**	**-0.54**	-0.11	-0.04	-0.09	-0.01	-	-	-
Warmbad Towoomba	0.15	0.22	0.01	-0.02	-0.04	-	**-0.03**	-0.03	-0.01	-0.10	-0.13	-	-0.02	-	-	**-0.34**	**-0.49**	-0.13	-0.18	-0.26	-0.08	-	-	-
Skukuza	**0.25**	**0.36**	0.01	-0.17	-0.23	-0.01	**0.13**	0.18	0.02	-0.10	-0.13	-	0.01	0.02	-	**-0.29**	**-0.40**	-0.08	**-0.26**	**-0.35**	-0.10	-	-	-
Vryburg	-0.11	-0.16	-0.01	-0.07	-0.09	-0.01	**-0.09**	-0.13	-0.01	0.06	0.10	-	0.09	0.14	0.08	**-0.30**	**-0.42**	-0.08	0.12	0.18	0.04	**0.04**	0.05	-
Kimberley	**-0.37**	**-0.54**	-0.03	-0.16	-0.24	-0.02	**-0.43**	**-0.62**	-0.05	**0.46**	**0.64**	**-**	**0.46**	**0.64**	0.32	**-0.32**	**-0.45**	-0.08	**0.37**	**0.55**	0.15	**-0.06**	-0.07	-
Upington	0.07	0.10	0.01	-0.04	-0.05	-	**0.08**	0.11	0.01	-0.02	-0.01	-	-0.11	-0.16	-	**-0.40**	**-0.57**	-0.10	-0.13	-0.19	-0.05	**-0.20**	-0.24	-
Vanwyksvlei	0.16	0.24	0.01	0.04	0.05	-	0.10	0.14	0.01	-0.01	-0.02	-	-0.14	-0.20	-0.08	**-0.44**	**-0.62**	-0.13	**-0.24**	**-0.33**	**-0.07**	**-0.31**	**-0.37**	**-**
Cape Agulhas	**0.44**	**0.62**	0.01	**0.29**	**0.40**	0.02	**0.25**	**0.36**	0.02	-	-	-	-	-	-	**-0.42**	**-0.63**	-0.13	**-0.45**	**-0.65**	-0.13	-0.19	-0.23	-
Cape Columbine	**0.39**	**0.57**	0.02	-0.04	**-0.03**	-0.01	**0.34**	**0.52**	0.02	-	-	-	-	-	-	**-0.33**	**-0.45**	-0.14	**-0.46**	**-0.69**	-0.20	-	-	-
Mosselbay	-0.02	-0.11	-	0.07	0.09	-	-0.05	-0.09	-	-	-	-	-	-	-	**-0.45**	**-0.65**	-0.17	0.04	0.13	0.01	-0.10	-	-
Cape Town	**0.54**	**0.72**	0.03	**0.19**	**0.30**	0.02	**0.43**	**0.61**	0.03	**-0.32**	**-0.40**	-	-	-	-	**-0.43**	**-0.62**	-0.12	**-0.56**	**-0.73**	-0.23	-	-	-
Vredendal	**0.35**	**0.51**	0.01	0.11	0.16	0.03	0.12	0.18	0.01	-0.12	-0.15	-	-0.13	-0.16	-	**-0.64**	**-0.84**	-0.21	**-0.37**	**-0.53**	-0.11	-0.14	-	-
Average trend	*0.16*	*0.22*	*0.01*	*0.03*	*0.04*	-	*0.08*	*0.12*	*0.01*	*-0.05*	*-0.06*	-	*-0.02*	*-0.03*	-	*-0.35*	*-0.49*	*-0.10*	*-0.18*	*-0.25*	*-0.07*	*-0.09*	*-0.12*	-

**Values in bold are different from 0 with a significance level alpha = 0.05.*

Supporting Table 3: Cold duration days and cold wave trends for the period 1960-2016.

Station	CDSI				$CDSI_3$				CWN				CWD			
	ETCCDI				*ET-SCI*				*ET-SCI*				*ET-SCI*			
	MK	ρ	*SS*	LT	MK	ρ	*SS*	LT	MK	ρ	*SS*	LT	MK	ρ	*SS*	LT
Dohne	0.22	0.27	-	0.05	-0.12	-0.16	-0.06	-	0.01	0.01	-	-0.01	-0.04	-0.05	-	-
East London	-	-	-	-	0.06	0.11	-	0.05	-0.18	-0.22	-0.02	-0.01	-0.19	-0.24	-0.05	-0.01
Port Elizabeth	0.09	0.40	-	0.01	0.18	**0.29**	0.03	0.08	-0.06	-0.07	-	-	0.06	0.13	-	0.01
Bloemfontein	-0.05	-0.06	-	-0.01	-0.06	-0.07	-0.04	-0.06	-	-0.01	-	-0.02	0.09	0.12	-0.03	-0.03
Johannesburg Int	**-0.04**	-0.05	-	-	**-0.16**	-0.21	-0.14	-0.11	**0.01**	0.01	-	-	**-0.04**	-0.07	-0.07	-0.01
Zuurbekom	**-0.08**	-0.11	-	-0.03	**-0.35**	**-0.52**	-0.36	-0.31	**-0.24**	**-0.31**	-0.05	-0.04	**-0.15**	-0.19	-0.07	-0.09
Cedara	**-0.11**	-0.14	-	-0.04	**-0.22**	**-0.29**	-0.20	-0.15	**0.01**	0.01	-	-	-	-0.01	-	-
Durban	**-0.32**	**-0.40**	-	-0.09	**-0.34**	**-0.48**	-0.29	-0.45	**-0.34**	**-0.42**	-0.04	-0.04	**-0.25**	**-0.34**	-0.07	-0.10
Mara	**0.06**	0.07	-	-	**-0.04**	-0.09	-0.03	-0.02	**-0.15**	-0.20	-	-0.01	**-0.27**	**-0.40**	-0.08	-0.1
Warmbad Towoomba	**0.01**	0.02	-	-0.03	**-0.18**	-0.28	-0.13	-0.15	**-0.20**	**-0.27**	-	-0.02	**-0.18**	-0.24	-0.05	-0.09
Skukuza	**-0.16**	-0.20	-	-0.08	**-0.15**	-0.21	-0.13	-0.15	**-0.26**	**-0.33**	-	-0.03	**-0.13**	-0.21	-0.03	-0.07
Vryburg	**0.03**	0.03	-	0.03	**0.13**	0.19	0.09	0.11	**-0.01**	-0.02	-	-0.01	**0.02**	0.03	-	-0.01
Kimberley	**0.27**	**0.33**	-	0.07	**0.33**	**0.49**	0.24	0.29	**0.20**	0.26	-	0.02	**0.19**	0.18	-	0.01
Upington	**-0.13**	-0.16	-	-0.03	**-0.11**	-0.16	-0.08	-0.07	**-0.08**	-0.10	-	-0.02	**-0.08**	-0.10	-	-0.02
Vanwyksvlei	-0.14	-0.18	-	-0.03	-0.15	-0.22	-0.15	-0.20	-0.18	-0.23	-	-0.03	-0.03	-0.04	-	-0.03
Cape Agulhas	-0.08	-0.09	-	-	-0.17	-0.25	-0.09	-0.10	-0.21	**-0.30**	-	-0.03	-0.19	-0.27	-	-0.01
Cape Columbine	-0.19	**-0.23**	-	-0.02	**-0.36**	**-0.52**	-0.18	-0.19	-0.19	-0.27	-	-0.04	-	-	-	0.01
Mosselbay	0.16	0.19	-	0.05	0.05	0.10	-	0.10	-0.11	-0.13	-	-	-0.09	-0.10	-	0.03
Cape Town	-0.13	**-0.15**	-	-0.01	**-0.29**	**-0.40**	-0.09	-0.15	**-0.30**	**-0.40**	-	-0.04	-0.15	-0.19	-	-0.03
Vredendal	-0.19	**-0.23**	-	-0.02	**-0.35**	**-0.48**	-0.19	-0.20	-0.16	-0.21	-	-0.04	-0.04	-0.07	-	-0.02
Average trends	*-0.03*	*-0.03*	-	*-0.01*	*-0.12*	*-0.16*	*-0.10*	*-0.09*	*-0.12*	*-0.15*	-	*-0.02*	*-0.07*	*-0.10*	-	*-0.03*

**Values in bold are different from 0 with a significance level alpha = 0.05.*

Supporting Table 4: Seasonal trends of minimum temperatures (TNMean) for the period 1960-2016.

Stations	TNMean											
	Summer			Autumn			Winter			Spring		
	MK	ρ	SS	MK	ρ	SS	MK	ρ	SS	MK	ρ	SS
Dohne	**0.43**	**0.56**	0.03	**0.26**	**0.29**	0.02	**0.27**	**0.33**	0.02	0.15	0.19	0.01
East London	0.11	0.18	-	0.17	0.23	0.01	0.04	0.06	-	-0.06	-0.09	-
Port Elizabeth	-0.01	-0.04	-	-0.14	-0.24	-0.01	-0.14	**-0.27**	-0.01	-0.13	-0.21	-0.01
Bloemfontein	0.06	0.10	-	-0.03	-0.05	-	0.08	0.13	0.01	0.02	0.03	-
Johannesburg Int	**0.29**	**0.43**	0.02	**0.21**	**0.29**	0.02	0.05	0.06	-	**0.19**	**0.29**	0.01
Zuurbekom	**0.35**	**0.50**	0.02	**0.29**	**0.42**	0.03	**0.49**	**0.70**	0.02	**0.20**	**0.32**	0.20
Cedara	**0.21**	**0.29**	0.01	0.09	0.13	0.01	0.11	0.12	0.01	0.05	0.06	-
Durban	**0.31**	**0.46**	0.02	**0.22**	**0.35**	0.02	**0.27**	**0.44**	0.03	0.10	0.17	-
Mara	0.09	0.13	0.01	-0.02	-	-	-0.02	-0.03	-	0.03	0.05	-
Warmbad Towoomba	**0.25**	**0.34**	0.02	0.04	0.08	-	0.06	0.08	0.01	0.13	0.21	0.01
Skukuza	**0.31**	**0.42**	0.02	0.15	0.21	0.03	0.18	0.26	0.02	0.19	0.26	0.01
Vryburg	0.04	0.05	-	-0.09	-0.15	-0.01	-0.02	-0.04	-	-0.14	-0.16	-0.01
Kimberley	**-0.23**	**-0.33**	-0.02	**-0.26**	**-0.40**	-0.03	**0.44**	**-0.60**	-0.05	**-0.33**	**-0.49**	-0.03
Upington	0.16	0.23	0.01	0.14	0.17	0.01	-0.04	-0.04	-	0.01	0.03	-
Vanwyksvlei	**0.32**	**0.46**	0.02	**0.21**	**0.30**	0.01	0.01	0.01	-	0.05	0.10	-
Cape Agulhas	**0.39**	**0.57**	0.02	**0.23**	**0.35**	0.01	**0.26**	**0.38**	0.01	**0.33**	**0.47**	0.02
Cape Columbine	**0.34**	**0.50**	0.02	**0.25**	**0.40**	0.01	**0.29**	**0.43**	0.01	**0.34**	**0.49**	0.02
Mosselbay	0.10	0.15	-	-0.11	-0.18	-0.01	-0.15	-0.26	-0.01	0.07	0.05	-
Cape Town	**0.55**	**0.73**	0.03	**0.45**	**0.63**	0.02	**0.29**	**0.41**	0.02	**0.37**	**0.53**	0.02
Vredendal	**0.46**	**0.65**	0.03	**0.25**	**0.36**	0.01	0.05	0.08	-	0.15	0.25	0.01
Average trend	*0.23*	*0.32*	*0.01*	*0.12*	*0.16*	*0.01*	*0.08*	*0.11*	*0.01*	*0.09*	*0.13*	-

**Values in bold are different from 0 with a significance level alpha = 0.05*

Supporting Table 5: Seasonal trends of coldest daytime temperatures (TXn) for the period 1960-2016.

Stations	**TXn**											
	Summer			Autumn			Winter			Spring		
	MK	ρ	SS	MK	ρ	SS	MK	ρ	SS	MK	ρ	SS
Dohne	0.14	0.18	0.02	0.10	0.11	0.01	**0.29**	**0.41**	0.04	-0.03	-0.07	-
East London	-0.07	-0.09	-	-0.06	-0.09	-0.01	-0.10	-0.13	-0.02	0.04	0.07	-
Port Elizabeth	0.07	0.08	**0.01**	**-0.26**	**-0.38**	-0.02	-0.05	-0.07	-	-0.07	-0.09	-0.01
Bloemfontein	-	-	-	-0.11	-0.15	-0.01	0.02	0.05	-	-0.08	-0.11	-0.01
Johannesburg Int	**0.20**	**0.28**	0.02	0.05	0.05	0.01	0.16	0.23	0.02	0.15	0.21	0.02
Zuurbekom	**0.24**	**0.36**	0.03	**-0.01**	-0.01	-	0.12	0.18	0.02	0.01	0.01	-
Cedara	**0.09**	0.12	-	**-0.05**	-0.05	-	0.04	0.04	-	-0.12	-0.16	-0.02
Durban	**-0.02**	-0.04	-	**0.06**	0.05	-	0.08	0.12	0.01	-0.01	-	-
Mara	**-0.09**	-0.14	-0.01	**0.07**	0.11	0.01	-0.06	-0.13	-0.01	-0.05	-0.08	-0.01
Warmbad Towoomba	**0.04**	0.06	-	**0.04**	0.04	-	0.03	0.05	0.01	-0.06	-0.09	-0.01
Skukuza	**-0.18**	-0.22	-0.01	**0.08**	0.13	0.01	0.06	0.09	0.01	0.06	0.08	0.01
Vryburg	**0.06**	-0.08	-0.01	**-0.17**	-0.26	-0.02	0.09	0.13	0.02	-0.08	-0.12	-0.01
Kimberley	**-0.16**	-0.22	-0.02	**-0.06**	-0.08	-0.01	0.14	0.20	0.02	-0.07	-0.11	-0.01
Upington	**-0.03**	-0.04	-	**-0.01**	-0.03	-	**0.20**	**0.29**	0.03	-0.05	-0.08	-0.01
Vanwyksvlei	**0.06**	0.09	0.01	**-0.07**	-0.11	-0.01	0.10	0.13	0.02	0.06	0.08	0.01
Cape Agulhas	**0.25**	**0.36**	0.01	0.01	0.01	-	0.05	0.08	0.01	**0.36**	**0.51**	0.02
Cape Columbine	0.08	0.10	0.01	-0.06	-0.08	-0.01	0.04	0.05	0.01	0.06	0.09	0.01
Mosselbay	0.17	0.21	0.01	-0.05	-0.07	-	-0.11	-0.16	-0.02	0.08	0.12	0.01
Cape Town	0.16	0.24	0.01	0.18	0.26	0.02	-	-	-	0.09	0.10	0.01
Vredendal	0.19	**0.27**	0.05	-0.05	-0.07	-0.01	-0.14	-0.20	-0.01	-0.13	-0.17	-0.04
Average trend	*0.05*	*0.08*	*0.01*	*-0.02*	*-0.03*	-	*0.05*	*0.07*	*0.01*	*0.01*	*0.01*	-

**Values in bold are different from 0 with a significance level alpha = 0.05*

Supporting Table 6: Seasonal trends of night-time temperatures (TNn) for the period 1960-2016.

Stations	TNn											
	Summer			Autumn			Winter			Spring		
	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*
Dohne	**0.23**	**0.33**	0.03	0.04	0.09	0.01	0.03	0.04	-	0.18	0.31	0.03
East London	-	-	-	0.11	0.16	0.01	0.08	0.09	0.01	0.10	0.13	0.01
Port Elizabeth	-0.11	-0.19	-0.01	0.03	0.02	-	-0.02	-0.06	-	-0.05	-0.08	-
Bloemfontein	0.17	0.25	0.03	-0.02	-0.02	-	0.07	0.09	0.01	0.05	0.09	0.01
Johannesburg Int	**0.28**	**0.40**	0.04	0.01	0.02	-	-0.01	-0.02	-	0.10	0.16	0.02
Zuurbekom	**0.26**	**0.37**	0.05	**0.29**	**0.44**	**0.07**	**0.56**	**0.77**	0.02	**0.34**	**0.52**	0.08
Cedara	**0.21**	**0.32**	0.04	0.10	0.13	0.02	-0.02	-0.02	**-**	**0.19**	**0.29**	0.04
Durban	0.13	0.19	0.01	**0.27**	**0.38**	0.04	0.17	0.25	0.02	0.14	0.21	0.02
Mara	0.16	0.20	0.02	-	-0.01	-	-0.04	-0.06	-0.01	-	-0.02	-
Warmbad Towoomba	**0.30**	**0.41**	0.05	0.05	0.08	0.01	-0.02	-0.02	-	0.15	0.23	0.04
Skukuza	**0.22**	**0.32**	0.03	0.07	0.09	0.01	0.15	0.20	0.02	0.06	0.10	0.01
Vryburg	0.11	0.15	0.02	-0.01	-0.01	-	-0.07	-0.10	-0.01	-0.05	-0.08	-0.01
Kimberley	0.09	0.12	0.01	**-0.27**	**-0.38**	**-0.05**	**-0.43**	**-0.61**	-0.05	-0.13	-0.17	-0.02
Upington	0.08	0.13	0.01	0.07	0.11	0.02	0.10	0.14	0.01	-0.05	-0.04	-0.01
Vanwyksvlei	**0.24**	**0.35**	0.04	0.01	0.01	-	0.10	0.15	0.01	-0.01	0.01	-
Cape Agulhas	**0.30**	**0.44**	0.04	**0.23**	**0.34**	**0.02**	**0.25**	**0.35**	0.02	0.13	0.18	0.02
Cape Columbine	**0.41**	**0.57**	0.02	**0.39**	**0.55**	**0.03**	**0.27**	**0.42**	0.02	**0.23**	**0.34**	0.02
Mosselbay	0.09	0.13	0.01	-	-	-	-0.04	-0.10	-	-0.02	-0.05	-
Cape Town	**0.29**	**0.41**	0.04	**0.44**	**0.62**	**0.05**	**0.36**	**0.51**	0.03	**0.45**	**0.63**	0.05
Vredendal	0.12	0.17	0.01	0.13	0.19	0.02	0.09	0.14	0.01	**0.19**	**0.28**	0.02
Average trend	*0.18*	*0.25*	*0.03*	*0.10*	*0.14*	*0.01*	*0.08*	*0.11*	*0.01*	*0.10*	*0.15*	*0.02*

**Values in bold are different from 0 with a significance level alpha = 0.05.*

Supporting Table 7: Seasonal trends of days below -2°C ($tnLtm_2$), for the period 1960-2016.

Stations	$tnLtm_2$											
	Summer			Autumn			Winter			Spring		
	MK	*ρ*	*SS*	MK	*ρ*	*SS*	MK	*ρ*	*SS*	MK	*ρ*	*SS*
Dohne	-	-	-	-	-	-	0.20	0.24	-	-	-	-
East London	-	-0.16	-	-	-	-	-	-	-	-	-	-
Port Elizabeth	-	-	-	-	-	-	-	-	-	-	-	-
Bloemfontein	-	-	-	-0.01	-0.01	-	-0.04	-0.06	-	-0.06	-0.10	-
Johannesburg Int	-	-	-	0.08	0.10	-	-	0.01	-	-	-0.07	-
Zuurbekom	-	-		**-0.28**	**-0.39**	-0.06	**-0.51**	**-0.72**	-0.08	**-0.26**	**-0.34**	-
Cedara	-	-	-	**-0.03**	-0.03	-	0.06	0.10	-	-	-	-
Durban	-	-	-	-	-	-	-	-	-	-	-	-
Mara	-	-	-	-	-	-	0.06	0.07	-	-	-	-
Warmbad Towoomba	-	-	-	**0.15**	0.18	-	-0.03	-0.01	-	-0.07	-0.08	-
Skukuza	-	-	-	-	-	-	0.01	0.02	-	-	-	-
Vryburg	-	-	-	**-0.13**	-0.16	-	0.10	0.15	0.09	0.02	0.02	-
Kimberley	-	-	-	**0.23**	**0.29**	-	**0.45**	**0.62**	0.03	0.13	0.16	-
Upington	-	-	-	**-0.02**	-0.02	-	-0.11	-0.16	-	-	-	-
Vanwyksvlei	-	-	-	**-0.05**	-0.06	-	-0.13	-0.19	-0.07	-0.05	-0.05	-
Cape Agulhas	-	-	-	-	-	-	-	-	-	-	-	-
Cape Columbine	-	-	-	-	-	-	-	-	-	-	-	-
Mosselbay	-	-	-	-	-	-	-	-	-	-	-	-
Cape Town	-	-	-	-	-	-	-	-	-	-	-	-
Vredendal	-	-	-	-	-	-	-0.13	-0.16	-	-	-	-
Average trend	-	-	-	-	*-0.01*	-	*-0.01*	*-0.01*	-	*-0.05*	*-0.07*	-

**Values in bold are different from 0 with a significance level alpha = 0.05*

Supporting Table 8: Seasonal of cold days (TX10p) for the period of 1960-2016.

Stations	**TX10p**											
	Summer			Autumn			Winter			Spring		
	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*
Dohne	**-0.27**	**-0.37**	-0.09	**-0.28**	**-0.41**	-0.10	-0.13	-0.18	-0.05	-0.13	-0.16	-0.07
East London	-0.15	-0.23	-0.05	**-0.29**	**-0.40**	-0.13	**-0.21**	**-0.29**	-0.10	**-0.20**	**-0.28**	-0.08
Port Elizabeth	**-0.26**	**-0.38**	-0.09	**-0.26**	**-0.37**	-0.09	-0.16	-0.24	-0.06	-0.16	-0.24	-0.07
Bloemfontein	0.02	0.03	0.01	**-0.26**	**-0.39**	-0.12	-0.08	-0.12	-0.04	**-0.25**	**-0.36**	-0.12
Johannesburg Int	-0.11	-0.16	-0.06	**-0.21**	**-0.33**	-0.10	**-0.18**	**-0.27**	-0.08	-0.17	-0.24	-0.08
Zuurbekom	-0.13	-0.18	-0.06	**-0.26**	**-0.37**	-0.12	-0.17	-0.24	-0.07	**-0.22**	**-0.33**	-0.12
Cedara	**-0.35**	**-0.48**	-0.11	**-0.21**	**-0.34**	-0.07	-0.14	-0.20	-0.05	-0.02	-0.01	-
Durban	**-0.21**	**-0.30**	-0.08	-0.14	-0.21	-0.06	**-0.19**	**-0.27**	-0.07	-0.02	-0.02	-0.01
Mara	**-0.20**	**-0.29**	-0.13	**-0.19**	**-0.29**	-0.15	**-0.28**	**-0.37**	-0.21	**-0.24**	**-0.35**	-0.09
Warmbad Towoomba	**-0.25**	**-0.38**	-0.12	**-0.24**	**-0.35**	-0.11	**-0.29**	**-0.41**	-0.13	**-0.22**	**-0.32**	-0.10
Skukuza	-0.12	-0.17	-0.06	-0.15	-0.23	-0.09	-0.17	-0.26	-0.07	-0.19	-0.26	-0.08
Vryburg	-0.04	-0.04	-0.03	**-0.31**	**-0.46**	-0.14	**-0.20**	**-0.29**	-0.08	**-0.24**	**-0.34**	-0.09
Kimberley	0.01	0.03	-	**-0.33**	**-0.48**	-0.14	**-0.18**	**-0.27**	-0.07	**-0.27**	**-0.36**	-0.10
Upington	**-0.36**	**-0.52**	-0.15	**-0.31**	**-0.43**	-0.13	-0.13	-0.20	-0.05	-0.08	-0.11	-0.04
Vanwyksvlei	**-0.36**	**-0.51**	-0.16	**-0.35**	**-0.51**	-0.16	**-0.22**	**-0.35**	-0.09	**-0.23**	**-0.35**	-0.08
Cape Agulhas	-0.18	-0.27	-0.07	**-0.33**	**-0.48**	-0.16	**-0.29**	**-0.44**	-0.14	**-0.28**	**-0.39**	-0.16
Cape Columbine	-0.20	-0.27	-0.12	-0.16	-0.22	-0.08	-0.16	-0.24	-0.09	-0.38	-0.53	-0.21
Mosselbay	**-0.35**	**-0.50**	-0.17	**-0.36**	**-0.51**	-0.20	-0.14	-0.21	-0.07	**-0.42**	**-0.58**	-0.24
Cape Town	**-0.42**	**-0.60**	-0.18	**-0.33**	**-0.45**	-0.13	-0.13	-0.17	-0.06	**-0.22**	**-0.30**	-0.11
Vredendal	**-0.55**	**-0.75**	-0.28	**-0.49**	**-0.68**	-0.21	**-0.35**	**-0.50**	-0.14	**-0.40**	**-0.55**	-0.21
Average trend	*-0.22*	*-0.32*	*-0.10*	*-0.27*	*-0.40*	*-0.13*	*-0.19*	*-0.28*	*-0.09*	*-0.22*	*-0.30*	*-0.10*

****Values in bold are different from 0 with a significance level alpha = 0.05***

Supporting Table 9: Seasonal trends of cold nights (TN10p) for the period of 1960-2016.

Stations	TN10p											
	Summer			Autumn			Winter			Spring		
	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*	MK	ρ	*SS*
Dohne	**-0.36**	**-0.54**	-0.15	-0.19	-0.24	-0.09	-0.11	-0.14	-0.07	-0.11	-0.17	-0.04
East London	-0.11	-0.17	-0.04	-0.17	-0.24	-0.07	-0.03	-0.04	-0.01	0.01	-	-
Port Elizabeth	0.05	0.10	0.03	0.08	0.16	0.03	0.09	0.16	0.05	0.14	0.19	0.08
Bloemfontein	-0.16	-0.22	-0.09	-0.04	-0.06	-0.03	-0.03	-0.03	-0.02	-0.14	-0.20	-0.06
Johannesburg Int	**-0.40**	**-0.56**	-0.20	-0.16	-0.24	-0.07	0.10	0.18	0.05	-0.04	-0.05	-0.01
Zuurbekom	**-0.30**	**-0.44**	-0.16	**-0.24**	**-0.39**	-0.15	**-0.57**	**-0.78**	-0.38	**-0.25**	**-0.36**	-0.12
Cedara	**-0.19**	**-0.28**	-0.08	**-0.13**	-0.16	-0.07	-0.06	-0.05	-0.02	-0.12	-0.18	-0.06
Durban	**-0.39**	**-0.55**	-0.20	**-0.32**	**-0.45**	-0.18	**-0.31**	**-0.47**	-0.25	**-0.19**	**-0.28**	-0.10
Mara	-0.08	-0.11	-0.04	-	0.01	-	-0.04	-0.06	-0.02	-0.04	-0.05	-0.01
Warmbad Towoomba	**-0.28**	**-0.38**	-0.13	**-0.06**	-0.11	-0.03	-0.14	-0.19	-0.08	-0.14	-0.20	-0.07
Skukuza	**-0.28**	**-0.41**	-0.12	**-0.10**	-0.13	-0.05	-0.14	-0.22	-0.09	-0.12	-0.16	-0.08
Vryburg	-0.06	-0.08	-0.03	**0.09**	0.12	0.05	0.08	0.13	0.05	0.17	0.28	0.07
Kimberley	**0.18**	0.23	0.08	**0.29**	**0.44**	0.15	**0.41**	**0.58**	0.22	**0.29**	**0.41**	0.15
Upington	**-0.26**	**-0.38**	-0.11	**-0.10**	-0.13	-0.05	-0.01	-0.05	-	-0.01	-0.03	-0.01
Vanwyksvlei	**-0.36**	**-0.49**	-0.16	**-0.13**	-0.18	-0.07	-0.03	-0.05	-0.01	-0.11	-0.17	-0.06
Cape Agulhas	**-0.41**	**-0.58**	-0.16	**-0.27**	**-0.38**	0.12	**-0.29**	**-0.42**	-0.15	**-0.20**	-0.26	-0.10
Cape Columbine	**-0.42**	**-0.61**	-0.23	**-0.38**	**-0.61**	-0.18	**-0.33**	**-0.45**	-0.15	**-0.35**	**-0.49**	-0.19
Mosselbay	-	-0.01	-	0.06	0.10	0.03	0.15	0.26	0.11	-0.01	0.02	-
Cape Town	**-0.51**	**-0.69**	-0.23	**-0.43**	**-0.61**	-0.22	**-0.29**	**-0.42**	-0.13	**-0.48**	**-0.64**	-0.22
Vredendal	**-0.45**	**-0.64**	-0.21	**-0.27**	**-0.39**	-0.13	-0.11	-0.15	-0.05	-0.18	-0.26	-0.10
Average trend	*-0.24*	*-0.34*	*-0.11*	*-0.12*	*-0.17*	*-0.07*	*-0.08*	*-0.11*	*-0.05*	*-0.09*	*-0.13*	*-0.05*

**Values in bold are different from 0 with a significance level alpha = 0.05.*

Supplement Material (Chapter 8)

Theoretical and Applied Climatology
https://doi.org/10.1007/s00704-020-03479-8

ORIGINAL PAPER

Exploring extreme warm temperature trends in South Africa: 1960–2016

Adriaan J. van der Walt[1,2] · Jennifer M. Fitchett[2]

Received: 15 June 2020 / Accepted: 20 November 2020

Abstract
Warm extreme temperature events or 'heatwaves' have disastrous impacts. Several high-impact heatwave events have recently occurred in the Global North, resulting in significant losses of human life and dire effects on economies. The expected increases in the frequency and intensity of extreme heat events under climate change pose a significant threat to South Africa. South Africa, a developing country, with an increasing population, faces many socioeconomic challenges. This study presents the first comprehensive annual and seasonal, spatial and temporal trend analyses of daily maximum and minimum extreme temperature events recorded from 20 meteorological stations across South Africa, spanning 1960–2016. Trend results based on the World Meteorological Organization Expert Team on Climate Change Detection (ETCCDI) and the World Meteorological Organization Commission for Climatology and Indices Expert Team on Sector-Specific Climate Indices (ET-SCI). Indices describing the characteristics of warm extremes are calculated using RClimDex and ClimPACT, respectively. The non-parametric Mann-Kendall test, Spearman rank correlation coefficient and Sen's slope estimates were used to determine the statistical significance and magnitude of the calculated trend. Results show a general annual trend increase in maximum temperature at a rate of 0.02 °C year^{-1}. The majority of stations reveals statistically significant trends in warm days and nights; with the strongest, general annual trend increases experienced in warm days at a rate of 0.15% year^{-1}. Seasonally, the strongest increases of 0.11% days year^{-1} in warm days are evident for autumn, while increases of 0.07% days year^{-1} are calculated for summer. A general increasing trend in heatwave events is recorded at 0.03 events year^{-1} countrywide.

Keywords Extreme temperature events · ETCCDI indices · ET-SCI indices · Mann-Kendall test · Sen's slope

1 Introduction

Over the past two decades, several high-impact extreme temperature events occurred in the Global North, most notably the 2003 European and 2010 Russian heatwaves, which resulted in more than 70,000 and 10,000 human fatalities, respectively (Simmonds 2018; Ragone et al. 2018). These high-profile events garnered significant public attention due to the severe impacts on human health, ecosystems and socioeconomic development (Perkins et al. 2012; Simmonds 2018). More recently, less dramatic yet extraordinary extreme heat events have included the hottest heatwave in June 2019, resulting in 1500 fatalities in France (Osborne 2019). The global interest in these extreme heat events is growing, particularly under current climate change projections indicating a likely increase in frequency and duration of heatwaves and warm spells across both the Northern and Southern Hemispheres (Alexander et al. 2006; Perkins et al. 2012; Perkins-Kirkpatrick et al. 2017).

In South Africa, the South African Weather Service (SAWS) defines heatwaves as climatological events where maximum temperatures are at least 5 °C warmer than the recorded mean of the hottest month at a given location for a period of at least 3 days (Malherbe et al. 2020; SAWS 2020). By this definition, several heatwaves have been recorded over the past 5 years. The most recent involved record-high mean winter temperatures for the winter months (June, July and August) in the Eastern Cape in 2019, with mean daytime temperatures exceeding 20.9 °C, followed by unseasonably, record-high maximum temperatures exceeding 35 °C,

✉ Jennifer M. Fitchett
Jennifer.fitchett@wits.ac.za

[1] School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Johannesburg, South Africa

[2] Department of Geography, University of the Free State, Bloemfontein, South Africa

recorded in Cape Town on 7 September 2019 (Head 2019). It is estimated that the mean annual temperature in South Africa has increased by at least 1.5 times the global average, at an estimated 0.65 °C over the past five decades (Ziervogel et al. 2014). Extreme climatic events are projected to increase in frequency and severity throughout the twenty-first century (Davis-Reddy and Vincent 2017). Without significant efforts to reduce the vulnerability of the region, exposure to extreme climate events, including temperature events, will increase (Davis-Reddy and Vincent 2017).

The expected increases in extreme heat events pose a significant threat to developing countries (Abatan et al. 2016), including South Africa. South Africa faces many pressing socioeconomic development needs, compounded by environmental stressors and a growing and urbanizing population with greater exposure to these events (Pasquini et al. 2013; Davis-Reddy and Vincent 2017). Extreme temperatures have various impacts on ecosystems (Malherbe et al., 2020), agriculture (Mangani et al. 2018), water resources and energy (Lubega et al. 2018), infrastructure (Pasquini et al. 2013), tourism (Noome and Fitchett, 2019) and human health (Nana et al. 2019; Chersich and Wright, 2019). Regarding human health, exposure to abnormally high temperatures over a prolonged period (i.e. during warm spells and heatwaves) will result in heat stress (Lee 2014; Founda et al. 2019) which may lead to heat-related illnesses including cardiovascular disease, heatstroke, heat exhaustion and mortality (Ngwenya et al. 2018). Despite these considerable threats, heat stress and heat events are inadequately understood and sometimes ignored (Lee 2014; Pelling et al. 2017), particularly in developing countries (Ngwenya et al. 2018). Therefore, given the increased attention due to the vulnerability of the society and ecosystems in South Africa (Pasquini et al. 2013), it is important to understand the nature of changes in temperature extremes in South Africa at different spatial and temporal timescales, which is vital for adaptation.

Several metrics have been developed to quantify extreme heat events; however, no universal definition exists (Perkins-Kirkpatrick and Gibson 2017). For instance, heatwaves can be defined as a period of consecutive days where conditions are hotter than usual, which includes seasonally extreme events such as summertime heatwaves or seasonally anomalous warm spells occurring on an annual basis (Perkins et al. 2012). A set of metrics have been developed by the World Meteorological Organization (WMO) Expert Team on Climate Change Detection and Indices (ETCCDI; Zhang et al. 2018). These indices can be classified into duration indices, threshold indices, absolute indices and percentile indices (Klein Tank et al. 2009). Several studies have applied one or a combination of indices to examine trends in extreme temperature events globally (e.g. Alexander et al. 2006; Fischer and Shär 2010; Perkins et al. 2012; Perkins-Kirkpatrick and Gibson 2017), on the African continent (e.g. Abatan et al. 2016; Abatan et al. 2018), and specifically in South Africa (e.g. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017). Kruger and Sekele (2013), and Kruger and Nxumalo (2017) examined extreme temperature trends using a select few ETCCDI indices, for the periods 1962–2009 and 1931–2015, respectively. However, seasonal trends were not explored, and the time period of interest was limited. In the interests of global comparison, to explore the various facets of extreme temperature events, and to facilitate more precise attribution of the effects of these events, the WMO indices offer greater value than local definitions.

This study aims to provide updated trends of daily maximum and minimum temperature extremes on an annual and seasonal timescale for the period 1960 to 2016, for all indices, previously examined. Additionally, this study will make use of the extreme temperature indices developed by the Expert Team on Sector-Specific Climate Indices (ET-SCI) which was established by the WMO Commission for Climatology and Indices (CCI) (Alexander and Herold 2016; Yosef et al. 2019). The ET-SCI developed several sector-specific climate indices that consider health, water and agriculture derived from the ETCCDI (Alexander and Herold 2016; Yosef et al. 2019). This will be the first study using the ET-SCI to identify trends in warm events in South Africa, which is important in view of health, water and agricultural adaption strategies on a regional and national basis.

2 Study site

South Africa is located in the southern tip of Africa, spanning the subtropics and mid-latitudes between 22 and 35 °S and 17–33 °E, bordered by the Atlantic Ocean in the west and southwest, the Indian Ocean to the south and east (Fig. 1). The climate of South Africa is governed by the complex interaction between the subtropical location, the altitude of the interior plateau and proximity to, and temperatures of, the oceans. South Africa's latitudinal range results in pronounced seasonal difference in rainfall and temperature patterns over South Africa, together with the intra-annual migration of the Intertropical Convergence Zone (ITCZ; Lennard 2019). The high-pressure belt is situated over the southern tip of the subcontinent in summer, and over the interior during winter (Tyson and Preston-Whyte 2000). These high-pressure systems are interrupted by troughs associated with cold fronts. The influences of the subtropical high-pressure belt and the mid-latitude westerlies with associated cold fronts vary significantly interannually over the subcontinent. These interactions between tropical and temperate disturbances have significant consequences for the weather of the subcontinent (Tyson and Preston-Whyte 2000). The topography of South Africa is complex and predominantly characterized by the escarpment which influences the temperature distribution over the country

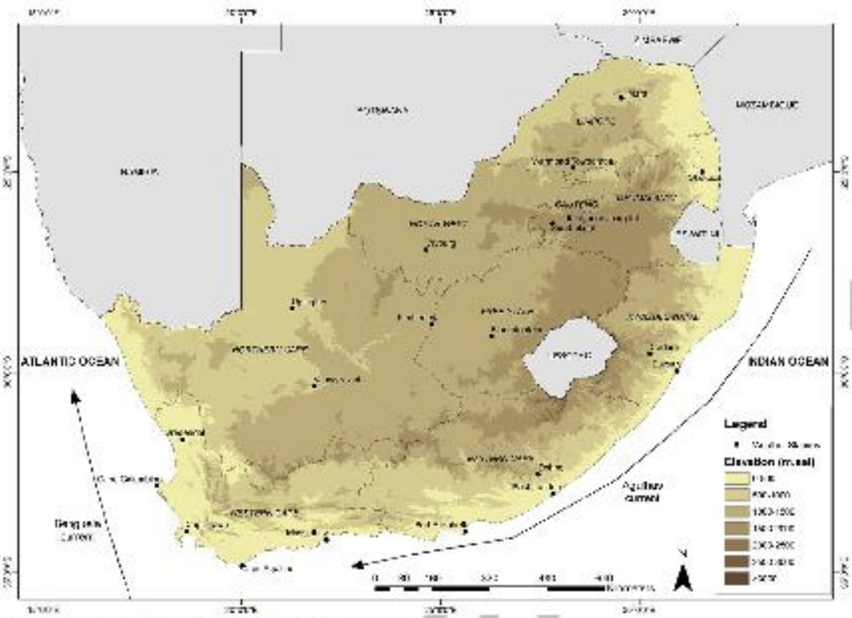


Fig. 1 Geographic location of selected meteorological stations

where the escarpment forms a climatic division between the high plateau and the low-lying coastal regions in the east and southeast and (Fig. 1; Grab and Knight 2018). The eastern and southern escarpments are the regions with the lowest temperatures, due to the decrease in temperature with altitude (Engelbrecht and Landman 2010; Grab and Knight 2018). The altitude ranges between the highest point of ~ 3000 m.asl in the Lesotho/KwaZulu-Natal border and ~ 2000 m.asl in the southern escarpment (Grab and Knight 2018).

3 Data and methodology

3.1 Data

For this study, daily maximum temperature (TX) and minimum temperature (TN) data for the period 1960–2016 are obtained from 20 selected SAWS meteorological stations (Fig. 1, Table 1), relatively evenly spatially distributed over South Africa. Only this discrete selection of weather stations was used to ensure consistency throughout the analysis period (cf. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017). Kruger and Nxumalo (2017) demonstrate that 20 stations are sufficient to define temperature variability to a reasonable degree across South Africa. The selection of the stations analysed in this study was based on the data quality length and homogeneity of the time series, spanning at least 50 years.

All of the climate data were subjected to thorough data quality controls to identify errors, missing data and outliers (Klein Tank et al. 2009; Salameh et al. 2018). All dates and times were checked, and two decimal point rounding was used to maintain consistency throughout. Missing TN and TX daily data were replaced with stations adjacent to the site within a 10 km radius and, if not possible, replaced with the 5-day running average (Klein Tank et al. 2009). If data were not available for more than five consecutive days, the period was excluded. Years with < 90% completeness were discarded from the data set (Mackellar et al. 2014; Abatan et al. 2016; Kruger and Nxumalo 2017; Kruger et al. 2019). Large data gaps in the time series were only found for three of the stations that were included in the study: Kimberley, Cedara and Dohne. However, 90% completeness could still be obtained through the aforementioned quality controls. The rest of the stations had only a few days of data missing for the full study period, which were replaced with the 5-day running average (Klein Tank et al. 2009). The selected stations used are similar to those used in previous studies (Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017), due to the completeness of the records.

Table 1 Selected meteorological stations information

Province	Station name	Climate num	Abbreviation	Lat	Long	Year period
Eastern Cape	Dohne	00798116	DH	−32.52	27.47	1960–2016
	East London	00595729	EL	−33.03	27.83	1960–2016
	Port Elizabeth	00351795	PE	−33.98	25.60	1960–2016
Free State	Bloemfontein	02615161	BFN	−29.10	26.30	1962–2016
Gauteng	Johannesburg International	04763990	JHB	−26.14	28.23	1959–2016
	Zuurbekom	04755288	ZB	−26.30	27.81	1959–2016
KwaZulu-Natal	Cedara	02394820	CD	−29.54	30.27	1959–2016
	Durban	0240808A2	DBN	−29.97	30.95	1960–2016
Limpopo	Mara	072200991	MR	−23.14	29.56	1959–2016
	Warmbad Towoomba	05895941	WBT	−24.90	28.32	1959–2016
Mpumalanga	Skukuza	05961793	SK	−24.99	31.59	1960–2016
Northern Cape	Kimberley	02904684	KB	−28.80	24.77	1959–2016
	Upington	03174765	UP	−28.43	21.27	1960–2016
	Vanwyksvlei	01935613	VW	−30.35	21.82	1961–2016
North West	Vryburg	04322383	VB	−26.95	24.65	1960–2015
Western Cape	Cape Agulhas	00030204	CA	−34.83	20.01	1959–2016
	Cape Columbine	00606209	CC	−32.83	17.86	1959–2016
	Mosselbay	0012215	MB	−34.18	22.15	1959–2016
	Cape Town	0021178A3	CPT	−33.96	18.60	1959–2016
	Vredendal	0106880A2	VL	−31.67	18.50	1959–2016

The statistical procedures in the R-based RClimDex v1.9 and ClimPACT v2 software package were used to flag missing values, identify outliers and aid with a visual inspection of the data series. It is important to note that the software does not calculate monthly indices if more than 3 days are missing in a month and if there are more than 15 missing days for the annual values (Zhang et al. 2018). The software allows the user to set the outlier threshold in terms of the standard deviation for the particular calendar day above the threshold; the default threshold of three standard deviations was used (Zhang and Yang 2004; Alexander and Herold 2006; Kruger and Nxumalo 2017; Zhang et al. 2018). Outliers in stations were compared to adjacent stations to determine whether an outlier was the result of systematic errors or natural factors. It is important to note that not all outliers are truly erroneous because their inclusion, exclusion or adjustment can significantly affect extreme analysis (Klein Tank et al. 2009).

The quality-controlled data time series were checked for non-climatic shifts that may exist in the data sets, which could result from changes in aspects such as observing site, instruments, station relocation, observing practices, time and automation of station during the period of data collection (Klein Tank et al. 2009; Aguilar et al. 2013; Kruger and Nxumalo 2017). Several methods have been used to examine and adjust non-climatic shifts in a data time series and often depend on the types and magnitude of the inhomogeneity to be detected and adjusted (e.g. Vincent et al. 2002, 2012; Wang 2008a; Nemec et al. 2013; Salameh et al. 2018). For the homogeneity analysis, the R-based software package, RhtestsV4, adopted by the (ETCCDI) was used (Wang and Feng 2013). The RhtestsV4 detects and adjusts for multiple change point in daily, monthly and annual time series. The statistical procedure is based on the penalized maximal *t* test (Wang 2008a) and the penalized maximal *F* test (Wang 2008b). Only the mean monthly time series was tested for inhomogeneities, due to the difficulty to test for non-climatic discontinuities in a daily time series (Wang and Feng 2013). The test was carried in this study without a reference series due to the difficulty in identifying and constructing an appropriate reference period, in particular for developing countries with a sparse distribution of long-term climate stations (Kruger and Nxumalo 2017). The necessary adjustments were applied to the daily data time series and loaded into the RClimDex and ClimPACT software to compute the extreme temperature indices.

3.2 Extreme temperature indices

This study examines and compares trends in extreme warm temperature indices on an annual and seasonal time scale. The seasonal scale was based on the astronomical divisions of South Africa: summer spanning December through February, autumn encompassing March through May, winter from June to August and spring from September to November

Table 2 ETCCDI and ET-SCI Temperature indices used in this study for the period 1960–2016 (Adapted from Alexander and Herold 2016; Zhang et al. 2018)

	Indices	Long name	Definitions	Units
ETCCDI indices	SU	Summer days	Count of days where TX (daily maximum temperature) > 25 °C	days
	TXx	Max TX (warmest day)	The maximum monthly value of daily maximum temperature (TXx = max)	°C
	TNx	Min TX (warmest night)	The monthly minimum value of daily maximum temperature (TNx = max)	°C
	TX90p	Warm days	Count of days where TX > 90th percentile	%
	TN90p	Warm night	Count of days where TX > 90th percentile	%
	WSDI	Warm spell duration indicator	Count of days in a span of at least 6 days where TX > 90th percentile	days
ET-SCI indices	Txge35	User-defined TX	Count of days where TX (daily maximum temperature) > 35 °C	days
	$WSDI_n$	User-defined WSDI	Count of number of days with at least n consecutive days where TX > 90th percentile	days
	TX_nTN_n	User-defined consecutive number of hot days and nights	The annual count of consecutive days where both TX > 95th percentile and TN > 95th percentile, where $n >= 2$ (and a max of 10)	Number of events
	HWN (EHF)	Heatwave number	The number of individual heatwaves that occur each summer (Nov–Mar in the southern hemisphere). A heatwave is defined as three or more days where either the Excess Heat Factor (EHF) is positive.	Events
	HWD (EHF	Heatwave duration	The length of the longest heatwave identified by the HWN	days

(Van der Walt and Fitchett, 2020). While there is a degree of spatial heterogeneity in the seasonal brackets of South Africa when determined quantitatively (Van der Walt and Fitchett 2020), the astronomical divisions facilitate regional analysis and comparison.

A core set of 27 descriptive extreme indices for temperature and rainfall have been developed by the WMO (CCl)/World Climate Programme (WRCP)/Joint Commission for Oceanography and Marine Meteorology (JCOMM) ETCCDI (Klein Tank et al. 2009; Alexander and Herold 2016; Zhang et al. 2018). The ETCCDI can be grouped into four categories: (1) absolute indices (e.g. warmest day TXx, warmest night TXn); (2) threshold indices (e.g. summer days; SU25); percentile indices (e.g. warm days TX90p, warm nights TN90p); and (4) duration indices (e.g. warm spell duration indicator; WSDI; Klein Tank et al. 2009; Zhang et al. 2018). These indices were designed to monitor the frequency and intensity of moderately extreme events, occurring several times per year rather than high-impact events (Klein Tank et al. 2009; Yosef et al. 2019). Only six extreme temperature ETCCDI are selected from the core set this study for purpose of comparison to previous studies (Table 2). In addition, five temperature indices are selected from the WMO CCl ECT-SCI, derived from the ETCCDI (Table 2). These indices have been developed for the use in sector applications, based on experts from agriculture, health and the water sector (Alexander and Herold 2016). These 11 extreme temperature indices were computed using the R software packages: RClimdex v1.9 for ETCCDI (Zhang et al. 2018) and ClimPACT v2 for the ET-SCI (Alexander and Herold 2016).

The ET-SCI user-defined warm spell duration index ($WSDI_n$) was set to three consecutive days where TX > 90th percentile (e.g. $WSDI_3$), as research has indicated that three consecutive days of temperatures exceeding the 90th percentile (or broadly very hot weather) are required for the mortality rate to rise significantly above the antecedent rate (Nairn and Fawcett 2015). The HWN and HWD indices were calculated based on the excess heat factor (EHF; cf. Perkens and Alexander 2013) with slight modifications to the EHF. Moreover, the user-defined TX_nTN_n indices were set to two consecutive days (e.g. TX_2TN_2). Shorter extreme warm events may affect many sectors, including health and infrastructure (Phanda et al. 2014). Detailed descriptions and definitions of the different indices used are recorded in Table 2. All the above-mentioned indices used were calculated for the base period of 1960–2016. ArcMap software was used to visually portray the trends, using the Mann-Kendall test as an identifier. The inverse distance weighting (IDW) tool within the software was used to spatially interpolate the annual TXMean.

3.3 Trend analysis and significance

Trend analyses for the various indices were performed for the period 1960–2016. To test whether the temperature series are non-stationary and to evaluate the magnitude of the trend, the non-parametric Spearman's rank correlation coefficient (ρ) and Kendall's tau correlation coefficient (τ) were used. The Kendall's tau coefficient has the advantage of having a low sensitivity to change points due to inhomogeneous time series (Tabari and Talaee, 2011; Abbas et al. 2018). The Spearman's rank correlation coefficient is calculated from ranks, while Kendall's tau represents probability (Allen et al. 2015). Since time is the dependent variable in this study, Kendall's tau correlation coefficient takes on a special case called the

Mann-Kendall test (MK) (cf. Allen et al. 2015). Sen's slope (SS) was used to quantify the magnitude of the trend for specific indices (Sen 1968). Tests for statistical significance are conducted at the 5% level (cf. Phanda et al. 2014; Caloiero et al. 2017; Karki et al. 2019; Yosef et al. 2019). The ClimPACT software calculates the linear trends which were used to assist in the analysis of the HWN and HWD. ArcMap software was used to display the trends visually, using the Mann-Kendall test values as an identifier.

4 Results

4.1 Mean maximum temperatures (TXMean)

There is a notable increase of > 8 °C in TXMean from the southwestern to the northeastern parts of the country over the period 1960–2016, with lower TXMean along the west and south coast (Fig. 2). The majority of the stations (19 of 20) has statistically significant increasing trends, with overall rate increases of 0.02 °C year^{-1} (Fig. 2; Table 3). The strongest statistically significant trend increase is evident in the Western Cape province at Vanwyksvlei, at a rate of increase of 0.05 °C year^{-1}. The interior stations calculate a stronger increase of 0.03 °C year^{-1}, compared to the coastal stations (0.02 °C year^{-1}).

At a seasonal timescale (Table 4), the strongest trend and rates of increase are calculated for autumn, with a mean increase of 0.03 °C year^{-1}. The strongest increases in autumn are calculated for stations located in Limpopo, Northern Cape, Eastern Cape at Dohne, Free State at Bloemfontein, Gauteng at Zuurbekom and the Western Cape province at Vredendal, at > 0.04 °C year^{-1} (Table 4). The overall calculated rate of increase in winter and spring TXMean is 0.02 °C year^{-1}. The strongest increases in TXMean in winter are calculated for stations located in Limpopo, Northern Cape, Free State, Gauteng at Zuurbekom, Mpumalanga at Skukuza and Western Cape province at Vredendal at > 0.03 °C year^{-1} (Table 4). In spring, the strongest increase is experienced in the Free State, Gauteng, Limpopo, Mpumalanga, Northern Cape and the Western Cape province at Vredendal and Mosselbay with rate increases of > 0.03 °C year^{-1} (Table 4). In general, the calculated rate increase in TXMean is stronger in the interior stations for each season (> 0.02° year^{-1}), compared to the coastal stations (Table 4).

4.2 Warmest day (TXx) and warmest night (TNx)

At an annual scale, the warmest daytime (TXx; Fig. 3a) and warmest nighttime (TXn; Fig. 3b) temperatures demonstrate a general warming trend in terms of frequency and occurrence over many parts of the country, with stronger trends observed

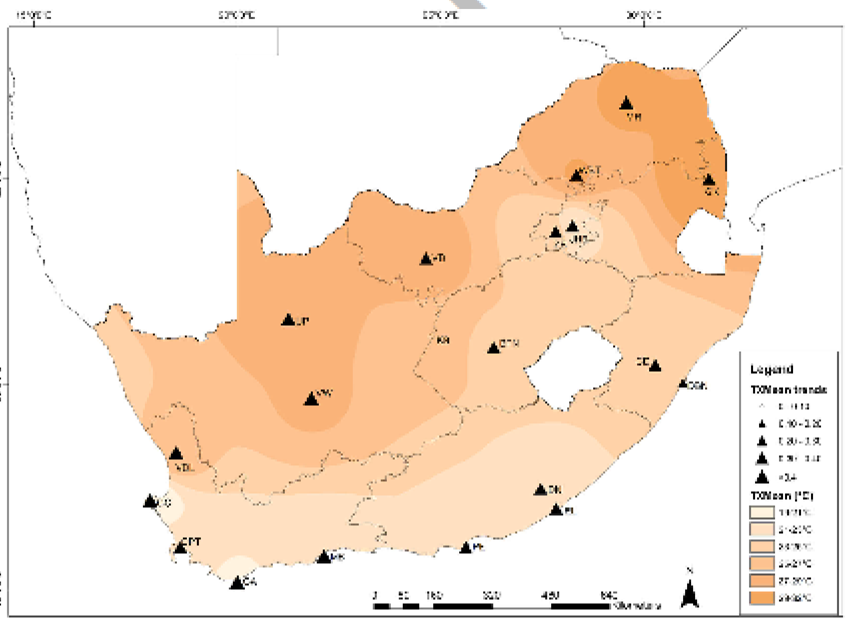


Fig. 2 Trends of TXMean over the period 1960–2016. Open downward and upward triangles indicate negative and positive trends. Solid upward triangles indicate trends that are statistically significant at the 5% level

Table 3 Increasing and decreasing trends in extreme warm temperature trends during 1960–2015

Station	TXMean	TXx	TNx	SU	TXge35	TX90p	TN90p	TX_2TN_2
Dohne	**0.34 (0.48;** 0.02)	0.03 (0.04; –)	−0.03 (− 0.04; –)	**0.31 (0.47;** 0.47)	0.06 (0.08; –)	**0.29 (0.40;** 0.10)	**0.23** (0.24; 0.13)	0.13 (0.15; –)
East London	**0.33 (0.51;** 0.01)	− 0.03 (−0.04; − 0.01)	- (0.01; –)	**0.20 (0.34;** 0.27)	0.01 (0.01; –)	**0.26 (0.40;** 0.05)	0.01 (0.03; –)	–
Port Elizabeth	**0.38 (0.53;** 0.01)	**0.20 (0.27;** 0.04)	0.06 (0.10; 0.01)	**0.29 (0.41;** 0.35)	**0.22 (0.30;** –; 0.02)	**0.23 (0.35;** 0.05)	**−0.19 (−0.30;** −0.06)	–
Bloemfontein	**0.37 (0.52;** 0.03)	0.18 (0.25; 0.03)	0.12 (0.18; 0.03)	**0.33 (0.48;** 0.57)	0.18 (0.25; 0.09)	**0.37 (0.51;** 0.22)	−0.17 (−0.23; −0.06)	0.20 (0.24; –)
Johannesburg Int	**0.35 (0.52;** 0.02)	0.14 (0.21; 0.01)	0.05 (0.08; 0.01)	**0.27 (0.41;** 0.56)	0.07 (0.09; –)	**0.30 (0.45;** 0.13)	**0.25 (0.36;** 0.13)	**0.23 (0.28;** –)
Zuurbekom	**0.35 (0.49;** 0.03)	**0.29 (0.41;** 0.05)	0.06 (0.09; 0.01)	**0.26 (0.38;** 0.82)	**0.30 (0.38;** –)	**0.38 (0.51;** 0.22)	**0.32 (0.45;** 0.12)	**0.30 (0.37;** –)
Cedara	**0.33 (0.47;** 0.02)	**0.19 (0.28;** 0.03)	0.10 (0.11; 0.01)	**0.34 (0.48;** 0.59)	0.16 (0.21; –)	**0.32 (0.45;** 0.12)	0.15 (0.14; 0.07)	0.04 (0.05; –)
Durban	**0.29 (0.43;** 0.01)	0.13 (0.18; 0.02)	0.04 (0.05; –)	**0.19 (0.28;** 0.30)	0.17 (0.21; –)	**0.31 (0.44;** 0.08)	0.17 (**0.29**; 0.06)	–
Mara	**0.49 (0.68;** 0.04)	**0.34 (0.50;** 0.04)	**0.25 (0.35;** 0.04)	**0.49 (0.67;** 0.84)	**0.34 (0.49;** 0.42)	**0.52 (0.70;** 0.21)	0.01 (0.01; –)	0.14 (0.17; –)
Warmbad Towoomba	**0.38 (0.55;** 0.04)	**0.33 (0.46;** 0.05)	0.08 (0.11; 0.02)	**0.41 (0.57;** 0.51)	**0.40 (0.52;** 0.40)	**0.37 (0.50;** 0.20)	0.10 (0.14; 0.06)	0.23 (0.27; –)
Skukuza	**0.32 (0.46;** 0.02)	0.11 (0.14; 0.01)	**0.28 (0.42;** 0.05)	**0.40 (0.40;** 0.56)	0.12 (0.16; 0.24)	**0.24 (0.34;** 0.10)	**0.22 (0.34;** 0.08)	–
Vryburg	**0.33 (0.46;** 0.03)	**0.19** (0.28; 0.02)	**0.22 (0.32;** 0.03)	**0.40 (0.55;** 0.78)	0.08 (0.10; 0.08)	**0.31 (0.45;** 0.17)	−0.10 (− 0.15; −0.04)	0.04 (–; –)
Kimberley	0.15 (**0.56;** 0.02)	**0.24 (0.34;** 0.02)	0.13 (0.18; 0.02)	**0.40 (0.58;** 0.51)	**0.26 (0.39;** 0.35)	**0.44 (0.65;** 0.18)	**−0.25 (− 0.37;** − 0.10)	**0.31 (0.37;** –)
Upington	**0.58 (0.58;** 0.03)	**0.32 (0.46;** 0.03)	0.07 (0.11; 0.01)	**0.55 (0.74;** 0.66)	**0.42 (0.61;** 0.65)	**0.52 (0.73;** 0.24)	0.04 (0.05; 0.02)	0.11 (0.13; –)
Vanwyksvlei	**0.59 (0.78;** 0.04)	**0.38 (0.55;** 0.03)	0.13 (0.19; 0.01)	**0.49 (0.68;** 0.59)	**0.53 (0.75;** 0.89)	**0.62 (0.82;** 0.27)	0.04 (0.05; 0.01)	0.18 (0.22; –)
Cape Agulhas	**0.43 (0.65;** 0.02)	0.15 (0.23; 0.03)	**0.28 (0.40;** 0.02)	**0.45 (0.65;** 0.40)	−0.10 (−0.12; –)	**0.47 (0.72;** 0.14)	**0.39 (0.57;** 0.14)	**0.32 (0.38;** 0.01)
Cape Columbine	**0.42 (0.58;** 0.02)	0.16 (0.23; 0.02)	0.30 (0.44; 0.02)	**0.27 (0.40;** 0.16)	−0.01 (−0.01; –)	**0.31 (0.47;** 0.08)	**0.26 (0.37;** 0.11)	**0.23 (0.28;** –)
Mosselbay	**0.49 (0.70;** 0.02)	0.08 (0.15; 0.02)	0.15 (0.24; 0.02)	**0.47 (0.68;** 0.52)	0.14 (0.18; –)	**0.49 (0.71;** 0.14)	0.03 (0.02; 0.01)	0.21 (0.26; –)
Cape Town	**0.38 (0.54;** 0.02)	0.04 (0.05; –)	0.11 (0.15; 0.01)	**0.40 (0.57;** 0.58)	0.17 (0.24; –)	**0.28 (0.43;** 0.06)	**0.38 (0.56;** 0.12)	0.07 (0.09; –)
Vredendal	**0.63 (0.81;** 0.05)	**0.47 (0.67;** 0.08)	**0.26 (0.39;** 0.02)	**0.57 (0.75;** 0.75)	**0.53 (0.74;** 0.57)	**0.57 (0.77;** 0.15)	**0.30 (0.41;** 0.07)	0.12 (0.14; –)
Averages	0.40 (0.57; 0.02)	0.20 (0.28; 0.03)	0.13 (0.19; 0.02)	0.37 (0.53; 0.54)	0.20 (0.28; 0.35)	0.38 (0.54; 0.15)	0.11 (0.15; 0.04)	0.19 (0.24; –)

*Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS)

Table 4 Trend analysis of seasonal mean maximum temperatures (TXMean) for the period 1960–2016

Stations	TXMean			
	Summer	Autumn	Winter	Spring
Dohne	0.10 (0.13; 0.01)	**0.37** (**0.53**; 0.04)	**0.20** (**0.30**; 0.02)	**0.30** (**0.38**; 0.03)
East London	0.16 (0.23; 0.01)	**0.33** (**0.48**; 0.02)	**0.20** (**0.29**; 0.01)	**0.28** (**0.40**; 0.01)
Port Elizabeth	**0.32** (**0.43**; 0.01)	**0.35** (**0.49**; 0.02)	0.14 (0.22; 0.01)	**0.23** (**0.32**; 0.01)
Bloemfontein	0.10 (0.16; 0.01)	**0.30** (**0.42**; 0.04)	**0.35** (**0.49**; 0.03)	**0.34** (**0.51**; 0.03)
Johannesburg Int	0.15 (0.21; 0.01)	**0.23** (**0.34**; 0.02)	**0.34** (**0.48**; 0.02)	**0.30** (**0.45**; 0.03)
Zuurbekom	0.19 (**0.28**; 0.02)	**0.32** (**0.45**; 0.04)	**0.32** (**0.45**; 0.03)	**0.27** (**0.41**; 0.03)
Cedara	**0.32** (**0.45**; 0.02)	**0.31** (**0.45**; 0.03)	**0.29** (**0.41**; 0.02)	**0.11** (0.15; 0.01)
Durban	**0.22** (**0.32**; 0.01)	**0.28** (**0.40**; 0.02)	**0.26** (**0.38**; 0.02)	**0.06** (0.07; –)
Mara	**0.23** (**0.35**; 0.02)	**0.28** (**0.41**; 0.04)	**0.51** (**0.69**; 0.04)	**0.43** (**0.59**; 0.04)
Warmbad Towoomba	**0.27** (**0.39**; 0.03)	**0.24** (**0.37**; 0.04)	**0.43** (**0.60**; 0.04)	**0.33** (**0.48**; 0.04)
Skukuza	0.06 (0.07; 0.01)	0.18 (0.26; 0.02)	**0.31** (**0.45**; 0.03)	**0.29** (**0.40**; 0.03)
Vryburg	0.07 (0.10; 0.01)	**0.27** (**0.38**; 0.04)	**0.37** (**0.53**; 0.03)	**0.26** (**0.37**; 0.03)
Kimberley	**0.32** (0.21; 0.02)	**0.28** (**0.48**; 0.04)	**0.30** (**0.40**; 0.02)	**0.29** (**0.42**; 0.02)
Upington	**0.44** (**0.44**; 0.03)	**0.47** (**0.47**; 0.05)	**0.33** (**0.33**; 0.03)	**0.31** (**0.31**; 0.03)
Vanwyksvlei	**0.51** (**0.72**; 0.04)	**0.49** (**0.67**; 0.06)	**0.34** (**0.52**; 0.03)	**0.40** (**0.58**; 0.04)
Cape Agulhas	**0.29** (**0.43**; 0.01)	**0.33** (**0.50**; 0.02)	**0.28** (**0.44**; 0.01)	**0.35** (**0.52**; 0.02)
Cape Columbine	**0.36** (**0.49**; 0.02)	**0.26** (**0.38**; 0.01)	**0.27** (**0.39**; 0.02)	**0.28** (**0.42**; 0.02)
Mosselbay	**0.41** (**0.59**; 0.02)	**0.47** (**0.63**; 0.03)	**0.21** (**0.29**; 0.01)	**0.37** (**0.53**; 0.03)
Cape Town	**0.42** (**0.59**; 0.03)	**0.29** (**0.42**; 0.02)	0.11 (0.17; 0.01)	0.16 (0.24; 0.01)
Vredendal	**0.55** (**0.75**; 0.06)	**0.58** (**0.77**; 0.05)	**0.29** (**0.43**; 0.03)	**0.40** (**0.56**; 0.04)
Averages	0.27 (0.37; 0.02)	0.33 (0.46; 0.03)	0.29 (0.41; 0.02)	0.29 (0.41; 0.02)

*Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS)

in TXx (Table 3). The majority of stations (19 of 20) displays an increasing trend (TXx; Fig. 3a; Table 3), except East London which experiences a decreasing trend, with a rate decrease of 0.01 °C year^{-1}. Overall, the TXx trends increased at a rate of 0.03 °C year^{-1}. Similar results are evident from the Spearman's rank correlation coefficient. The strongest statistically significant increase of TXx is experienced predominantly in the northern interior parts of the country, with increases of > 0.02 °C year^{-1} (Table 3).

In general, increasing trends are calculated for each season (Table 5). The strongest overall calculated rate of the increasing trend is evident in autumn (0.04 °C year^{-1}) (Table 5), followed by winter (0.03 °C year^{-1}). The lowest overall calculated increasing trend is evident in summer, with increases of 0.02 °C year^{-1}. Most of the stations which experience statistically significant increasing trends in summer are located in Limpopo, Gauteng, KwaZulu-Natal, Northern Cape and the Western Cape province, with increases of > 0.02 °C year^{-1} (Table 5). Decreasing trends are evident in East London and Skukuza in summer, at 0.01 °C year^{-1} (Table 5). In autumn, only five stations experience statistically significant increases, located in KwaZulu-Natal at Durban, Northern Cape and Western Cape province, with rate increases of > 0.03 °C year^{-1} (Table 5). Statistically significant increasing trends for winter are evident in 50% of the stations, at rates of > 0.03 °C year^{-1} (Table 5). For spring, statistically significant increasing trends are evident in stations located in Limpopo, Northern Cape at Vanwyksvlei and Upington and the Western Cape province at Vredendal, with rate increases of > 0.02 °C year^{-1}, while decreasing trends are calculated for stations located in KwaZulu-Natal at Durban and the Western Cape province at Cape Town, at rates of 0.02 °C year^{-1} and 0.01 °C year^{-1}, respectively (Table 5).

The TNx results (Fig. 3b) similarly reveal an increasing trend for the majority of stations, five of which are statistically significant. These stations are located in Limpopo, Mpumalanga, North West and Western Cape province with rate increases of > 0.02 °C year^{-1} (Fig. 3b; Table 3). Bloemfontein also exhibits a strong rate increase of 0.03 °C year^{-1}. In general, the overall calculated rate of the increasing trend over the country is 0.02 °C year^{-1} (Table 3).

At a seasonal timescale (Table 5), the strongest overall increasing trend and rate of the increasing trend are calculated for autumn, with an overall increase of 0.03 °C year^{-1}, followed by summer, spring and winter with rate increases of 0.02 °C year^{-1}, respectively (Table 5). Most of the stations (18 of 20) experience increasing trends in summer, of which seven are statistically significant (Table 5). These stations are

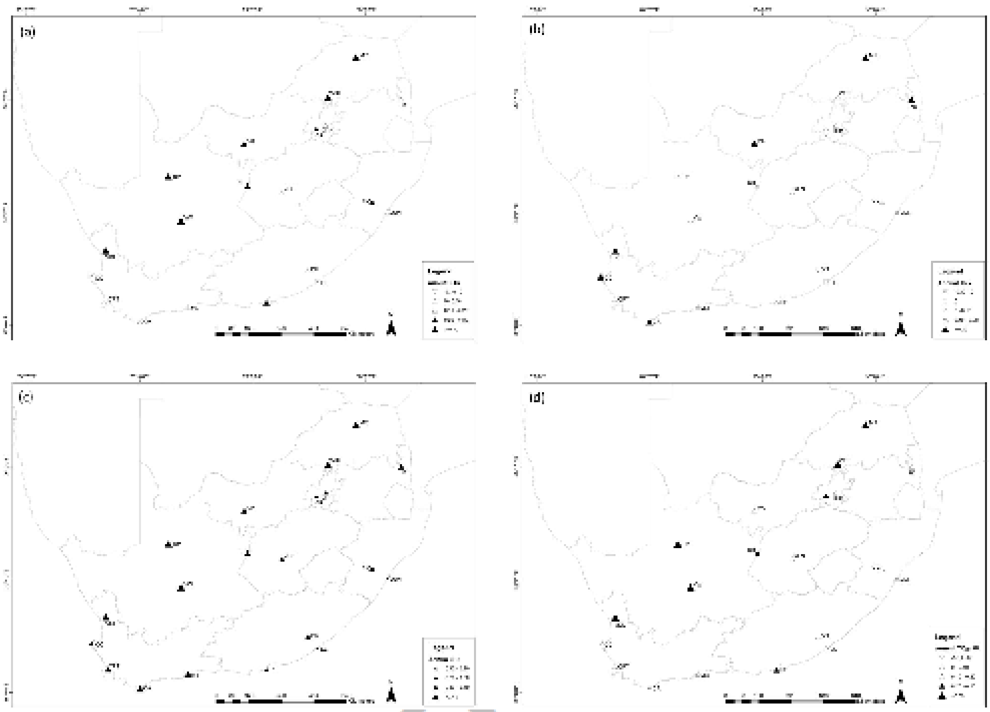


Fig. 3 Annual trends of (a) TXx, (b) TNx, (c) SU25 and (d) TXge35. Open downward and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level

located in KwaZulu-Natal, Limpopo, Northern Cape and Western Cape province, with rate increases of > 0.02 °C year^{-1} in TNx, while Bloemfontein in the Free State province exhibits a decreasing trend of 0.02 °C year^{-1}, for the period 1960–2016 (Table 5). Most of the stations (11 of 20) experience statistically significant increasing trends in autumn, which are located in the Eastern Cape, Gauteng at Zuurbekom, KwaZulu-Natal, Mpumalanga and Western Cape province, with rate increases of > 0.02 °C year^{-1} (Table 5). The strongest rate increases of 0.05 °C year^{-1} in TNx are experienced in Zuurbekom, Dohne and Skukuza (Table 5).

All the stations experience increasing trends in winter, with the strongest rate increases of > 0.03 °C year^{-1} evident in stations located in the Free State, Gauteng at Zuurbekom, Limpopo and North West province (Table 5). Most of the stations (19 of 20) experience increasing trends in spring, of which five being statistically significant (Table 5). The strongest rate increases of > 0.04 °C year^{-1} are evident in stations located in the Free State, Limpopo at Mara, Northern Cape at Kimberley and Vanwyksvlei and Cape Town province at Vredendal (Table 5).

In short, an increasing trend is calculated for the TXx and TNx temperatures countrywide. Seasonal timescale findings indicate stronger increasing trends and rates of increases in warmest TXx in winter and stronger TNx temperatures in autumn.

4.3 Summer days (SU and TXge35)

All the stations experience a statistically significant increase in the number of summer days above 25 °C (SU; Fig. 3c), with an overall calculated rate of 0.54 days year^{-1} (Table 3). Stations with rate increases > 0.54 days year^{-1} are located in the Free State, Gauteng, KwaZulu-Natal at Cedara, Limpopo at Mara, Mpumalanga, the North West, Northern Cape at Upington, Vanwyksvlei and Western Cape province at Cape Town and Vredendal (Fig. 3c; Table 3).

Most of the stations (18 of 20) experience increasing trends in days above 35 °C (TXge35; Fig. 3d), of which eight are statistically significant. These stations are located in Limpopo, Northern Cape, Eastern Cape at Port Elizabeth and Western Cape province at Vredendal, with rate increases of > 0.02 days year^{-1} (Table 3). The remaining two stations located

Table 5 Trend analysis of seasonal warmest daytime (TXx) and nighttime (TNx) temperatures for the period 1960–2016

Stations	TXx				TNx			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Dohne	0.03 (0.02; –)	0.18 (0.25; 0.04)	0.10 (0.14; 0.02)	0.23 (**0.31**; 0.04)	0.05 (0.06; 0.01)	**0.29** (**0.41**; 0.05)	0.10 (0.14; 0.01)	0.08 (0.14; 0.01)
East London	−0.03 (−0.08; −0.01)	0.15 (0.26; 0.03)	0.11 (0.16; 0.02)	0.06 (0.08; 0.03)	- (−0.02; –)	**0.19** (**0.30**; 0.03)	0.12 (0.18; 0.02)	0.08 (0.11; 0.01)
Port Elizabeth	- (–; –)	**0.27** (**0.35**; 0.06)	0.11 (0.16; 0.02)	0.02 (0.04; 0.01)	0.14 (0.20; 0.01)	**0.20** (**0.29**; 0.03)	0.07 (0.12; 0.01)	0.17 (0.25; 0.02)
Bloemfontein	0.16 (0.24; 0.03)	0.10 (0.14; 0.02)	**0.22** (**0.32**; 0.04)	0.11 (0.17; 0.01)	−0.02 (−0.01; –)	0.10 (0.16; 0.02)	0.11 (0.18; 0.03)	0.14 (0.21; 0.04)
Johannesburg Int	0.10 (0.14; 0.01)	0.11 (0.15; 0.02)	**0.22** (**0.30**; 0.03)	0.25 (**0.34**; 0.03)	0.12 (0.18; 0.02)	0.14 (0.19; 0.02)	0.04 (0.06; 0.01)	0.05 (0.07; 0.01)
Zuurbekom	**0.21** (**0.31**; 0.04)	0.19 (0.27; 0.04)	**0.35** (**0.49**; 0.05)	0.25 (**0.38**; 0.04)	0.09 (0.13; 0.02)	**0.21** (**0.30**; 0.05)	0.09 (0.13; 0.03)	0.05 (0.08; 0.01)
Cedara	**0.20** (**0.28**; 0.03)	0.17 (0.24; 0.03)	0.16 (0.23; 0.03)	0.12 (0.20; 0.02)	**0.21** (**0.31**; 0.02)	**0.26** (**0.38**; 0.04)	0.08 (0.10; 0.01)	0.11 (0.15; 0.02)
Durban	0.15 (0.22; 0.02)	**0.20** (**0.32**; 0.03)	0.07 (0.10; 0.01)	−0.10 (−0.13; −0.02)	0.09 (0.15; 0.01)	**0.24** (**0.35**; 0.03)	0.10 (0.15; 0.02)	0.05 (0.07; 0.01)
Mara	0.19 (**0.28**; 0.02)	0.22 (**0.32**; 0.04)	**0.36** (**0.50**; 0.04)	**0.34** (**0.49**; 0.04)	0.12 (0.17; 0.03)	0.15 (0.23; 0.03)	**0.29** (**0.40**; 0.06)	**0.20** (**0.29**; 0.04)
Warmbad Towoomba	**0.26** (**0.35**; 0.04)	0.10 (0.14; 0.02)	**0.21** (**0.32**; 0.03)	**0.35** (**0.50**; 0.04)	**0.19** (0.27; 0.04)	0.04 (0.05; 0.01)	0.14 (0.22; 0.03)	−0.02 (–; −0.01)
Skukuza	−0.08 (−0.12; −0.01)	0.04 (0.06; 0.01)	**0.21** (**0.29**; 0.04)	0.18 (0.26; 0.02)	0.06 (0.08; 0.01)	**0.22** (**0.32**; 0.05)	**0.24** (**0.35**; 0.05)	0.17 (0.25; 0.03)
Vryburg	0.10 (0.15; 0.01)	0.06 (0.11; 0.01)	0.17 (0.27; 0.03)	0.14 (0.19; 0.01)	0.08 (0.13; 0.02)	0.17 (0.26; 0.04)	**0.23** (**0.33**; 0.03)	0.05 (0.07; 0.01)
Kimberley	**0.20** (**0.29**; 0.02)	0.14 (0.22; 0.03)	0.14 (0.22; 0.02)	0.15 (0.22; 0.02)	0.11 (0.15; 0.03)	0.11 (0.16; 0.02)	0.13 (0.19; 0.02)	**0.24** (**0.35**; 0.05)
Upington	**0.32** (**0.46**; 0.03)	**0.25** (**0.36**; 0.04)	**0.30** (**0.41**; 0.05)	**0.26** (**0.36**; 0.02)	**0.32** (**0.46**; 0.08)	0.15 (0.21; 0.03)	0.10 (0.16; 0.01)	0.14 (0.19; 0.03)
Vanwyksvlei	**0.37** (0.54; 0.03)	**0.30** (**0.42**; 0.05)	**0.33** (**0.46**; 0.05)	**0.34** (**0.52**; 0.04)	**0.24** (**0.35**; 0.06)	0.16 (0.22; 0.03)	0.15 (0.20; 0.02)	0.17 (0.24; 0.04)
Cape Agulhas	**0.20** (0.27; 0.02)	**0.19** (**0.29**; 0.05)	0.09 (0.12; 0.02)	0.16 (0.24; 0.05)	**0.19** (**0.28**; 0.02)	**0.24** (**0.35**; 0.02)	**0.24** (**0.36**; 0.02)	**0.25** (**0.37**; 0.02)
Cape Columbine	0.21 (0.29; 0.05)	0.16 (0.23; 0.03)	0.14 (0.19; 0.02)	0.02 (0.03; 0.01)	0.16 (0.21; 0.01)	0.03 (0.04; –)	0.29 (0.43; 0.02)	0.23 (0.33; 0.02)
Mosselbay	0.16 (0.22; 0.03)	0.17 (0.25; 0.05)	0.15 (0.21; 0.02)	0.18 (0.26; 0.06)	0.09 (0.12; 0.01)	**0.25** (**0.34**; 0.02)	0.11 (0.16; 0.01)	**0.27** (**0.37**; 0.02)
Cape Town	0.10 (0.12; 0.02)	0.17 (0.24; 0.04)	0.01 (0.01; –)	−0.05 (−0.09; −0.01)	**0.24** (**0.34**; 0.03)	**0.18** (**0.29**; 0.02)	0.07 (0.10; 0.01)	0.09 (0.15; 0.01)
Vredendal	**0.43** (0.62; 0.08)	**0.32** (**0.44**; 0.06)	**0.21** (**0.30**; 0.03)	**0.36** (**0.50**; 0.07)	**0.35** (**0.47**; 0.05)	**0.22** (**0.33**; 0.03)	**0.24** (**0.37**; 0.02)	**0.29** (**0.40**; 0.04)
Averages	0.16 (0.23; 0.02)	0.17 (0.25; 0.04)	0.18 (0.26; 0.03)	0.17 (0.24; 0.03)	0.14 (0.20; 0.02)	0.18 (0.26; 0.03)	0.15 (0.22; 0.02)	0.14 (0.21; 0.02)

*Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS) in the Western Cape exhibit decreasing trends. Overall the calculated rate increase across the country is 0.35 days year^{-1}, for stations which exhibit rate increases (Table 3).

In summer, most of the stations (15 of 20) experience increasing trends in TXge35 (Table 6), of which four stations are statistically significant. These significant stations are located in the Northern Cape and Limpopo province at Warmbad Towoomba, at a rate increase of > 0.17 days year^{-1} (Table 6). Four stations experience decreasing trends, which are located in the Eastern Cape at Dohne and East London, North West at Vryburg and Mpumalanga province at Skukuza, with rate decreases of > 0.05 days/year^{-1} in the latter two stations (Table 6). Most of the station (18 of 20) experiences increasing trends in autumn (Table 6), of which six being statistically significant. Only four stations exhibit rate increases, which is located in Mpumalanga, the Northern Cape at Upington and Vanwyskvlei and the Western Cape province at Vredendal, with a rate increase of > 0.04 days year^{-1} (Table 6). Only six stations, Port Elizabeth Durban, Mara, Warmbad Towoomba, Skukuza and Vredenal, experience increasing trends in winter, with trend increases of > 0.08 days year^{-1} for the period 1960–2016 (Table 6).

Most of the stations (15 of 20) experience increasing trends in spring (Table 6), ten of which are statistically significant. Only seven of these statistically significant stations experience rate increases of > 0.10 days year^{-1}, which are located in Limpopo, Mpumalanga, Northern Cape and Western Cape province at Vredendal (Table 6). Of the remaining stations, four experience decreasing trends which are located in the Eastern Cape at East London, KwaZulu-Natal at Durban and the Western Cape province at Cape Agulhas and Cape Town, with trend decreases of > 0.02 days year^{-1} for the period 1960–2016 (Table 6).

4.4 Warm days (TX90p) and warm nights (TN90p)

In general, the frequency of annual TX90p is increasing across the country. All the stations experience statistically significant increasing trends (Fig. 4a), with an overall calculated rate increase of 0.15% days year^{-1}. Stations with rate increases > 0.20 days year^{-1} are located in the Free State, Limpopo, Gauteng at Zuurbekom and the Northern Cape province at Upington and Vanwyskvlei (Table 3). Generally, the interior stations show a stronger calculated rate increase of 0.18% days year^{-1}, compared to the coastal stations (0.10% days year^{-1}).

Table 6 Seasonal trend analysis of days above 35 °C (TXge35), for the period 1960–2016

Stations	TXge35			
	Summer	Autumn	Winter	Spring
Dohne	− 0.01 (− 0.01; –)	0.05 (0.06; –)	- (–; –)	**0.29** (**0.37**; –)
East London	− 0.04 (− 0.04; –)	0.06 (0.07; –)	- (–; –)	−0.02 (− 0.03; –)
Port Elizabeth	0.02 (0.02; –)	**0.24** (**0.31**; –)	0.19 (0.23; –)	0.10 (0.12; –)
Bloemfontein	0.15 (0.21; 0.06)	**0.25** (0.30; –)	- (–; –)	0.20 (0.25; –)
Johannesburg Int	0.07 (0.09; –)	- (–; –)	- (–; –)	- (–; –)
Zuurbekom	0.19 (0.25; –)	0.06 (0.07; –)	- (–; –)	**0.44** (**0.54**; –)
Cedara	0.13 (0.17; –)	**0.29** (**0.35**; –)	- (–; –)	0.02 (0.03; –)
Durban	0.18 (0.22; –)	**0.23** (**0.28**; –)	0.08 (0.09; –)	−0.10 (− 0.13; –)
Mara	0.19 (0.26; 0.13)	0.17 (0.24; –)	0.13 (0.16; –)	**0.44** (**0.58**; –)
Warmbad Towoomba	**0.31** (**0.43**; 0.17)	0.22 (**0.28**; –)	0.13 (0.16; –)	**0.36** (**0.47**; 0.19)
Skukuza	− 0.06 (− 0.07; −0.06)	0.07 (0.10; 0.04)	0.17 (0.22; –)	**0.29** (**0.39**; 0.21)
Vryburg	− 0.06 (− 0.08; −0.05)	0.04 (0.06; –)	- (–; –)	**0.23** (**0.32**; 0.13)
Kimberley	**0.21** (**0.29**; 0.24)	0.07 (0.10; –)	- (–; –)	**0.31** (**0.41**; 0.10)
Upington	**0.33** (**0.48**; 0.27)	**0.30** (**0.44**; 0.18)	- (–; –)	**0.34** (**0.48**; 0.20)
Vanwykskvlei	**0.50** (**0.70**; 0.55)	**0.33** (**0.49**; 0.13)	- (–; –)	**0.44** (**0.60**; 0.19)
Cape Agulhas	- (–; –)	0.05 (0.06; –)	- (–; –)	−0.18 (− 0.22; –)
Cape Columbine	0.08 (0.09; –)	− 0.01 (− 0.01; –)	- (–; –)	0.02 (0.02; –)
Mosselbay	0.03 (0.04; –)	0.15 (0.18; –)	- (–; –)	0.08 (0.10; –)
Cape Town	0.08 (0.12; –)	0.19 (0.25; –)	- (–; –)	−0.13 (− 0.15; –)
Vredendal	0.41 (**0.57**; 0.26)	**0.47** (**0.65**; 0.21)	0.18 (0.22; –)	**0.28** (**0.38**; 0.11)
Averages	0.14 (0.20; 0.16)	0.17 (0.23; 0.11)	0.13 (0.15; –)	0.18 (0.24; 0.14)

*Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(p; SS)

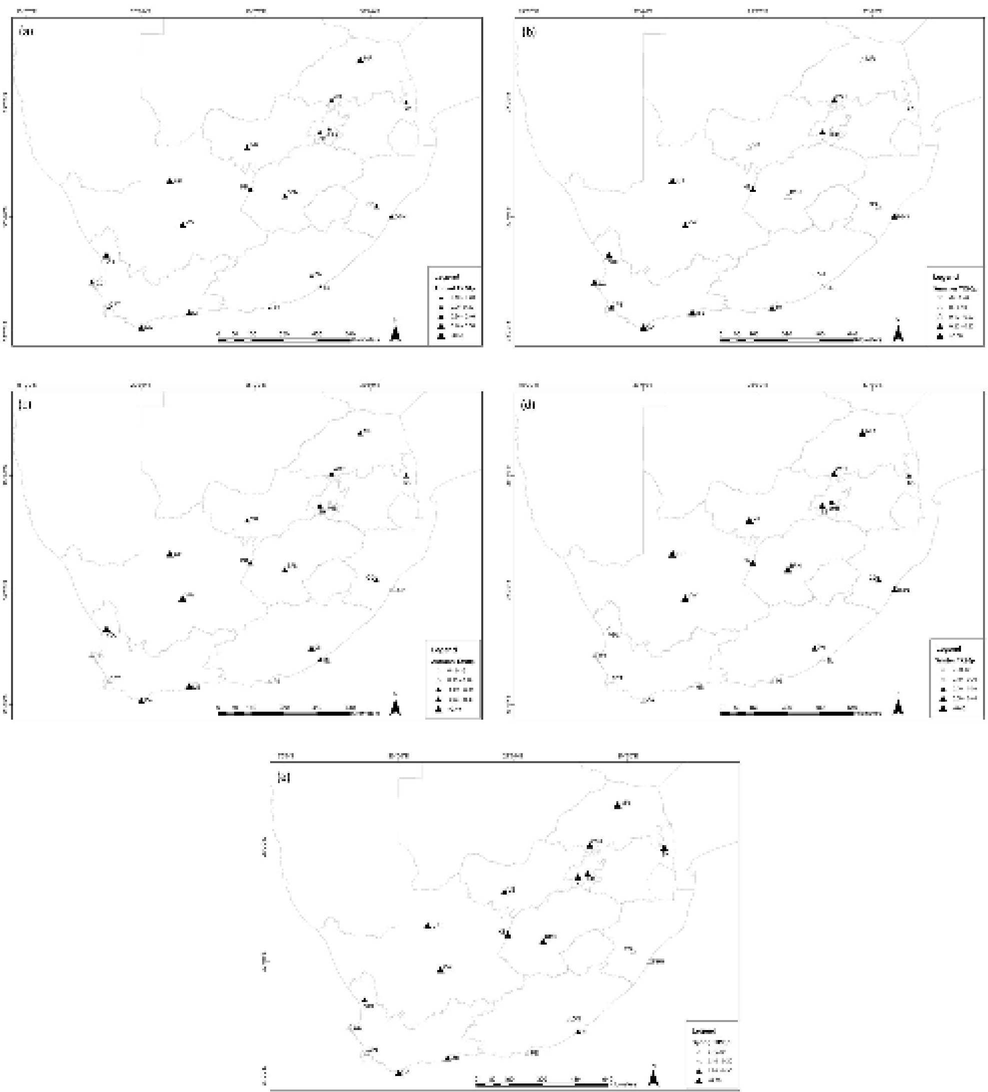


Fig. 4 Annual trends of (a) TX90p and mean seasonal temperature trends of (b) TX90p summer, (c) TX90p autumn, (d) TX90p winter and (e) TX90p spring. Open downward and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level

In summer, the majority of the stations (18 of 20) experiences an increasing trend in TX90p (Fig. 4b), of which ten being statistically significant. These statistically significant stations are located in the Eastern Cape, KwaZulu-Natal, Limpopo, Gauteng, Northern Cape and Western Cape (Fig. 4b), with rate increases of > 0.09% days year^{-1} (Table 7). The two remaining stations experience decreasing trends (Fig. 4b), at a rate decrease of 0.06% days year^{-1} evident only in Skukuza (Table 7). Overall, an increasing rate of 0.11% days year^{-1} in TX90p has been calculated in spring. All the

Table 7 Trend analysis of seasonal frequency of warm days (TX90p) and warm nights (TN90p) for the period 1960–2016

Stations	TX90p				TN90p			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Dohne	−0.01 (−0.03; −)	**0.35** (**0.47**; 0.23)	**0.29** (**0.40**; 0.17)	0.16 (0.24; 0.06)	**0.25** (**0.31**; 0.13)	**0.21** (0.24; 0.14)	0.11 (0.15; 0.05)	0.08 (0.06; 0.07)
East London	0.05 (0.08; 0.01)	**0.21** (**0.31**; 0.08)	0.11 (0.15; 0.03)	**0.21** (0.35; 0.08)	0.07 (0.08; 0.03)	−0.03 (−0.06; −0.01)	0.01 (0.01; −)	−0.03 (−0.05; −0.01)
Port Elizabeth	**0.23** (0.32; 0.09)	0.13 (0.19; 0.05)	0.08 (0.11; 0.03)	0.06 (0.09; 0.02)	0.08 (0.12; 0.05)	**−0.28** (**−0.42**; −0.13)	**−0.20** (**−0.34**; −0.09)	−0.05 (−0.08; −0.02)
Bloemfontein	0.14 (0.19; 0.09)	**0.26** (**0.37**; 0.20)	**0.46** (**0.63**; 0.28)	**0.38** (**0.55**; 0.22)	−0.13 (−0.18; −0.08)	−0.15 (−0.23; −0.09)	0.08 (0.12; 0.03)	−0.12 (−0.15; −0.08)
Johannesburg Int	0.08 (0.12; 0.06)	0.18 (0.27; 0.12)	**0.33** (0.49; 0.19)	**0.30** (0.44; 0.18)	**0.24** (**0.35**; 0.12)	**0.19** (**0.27**; 0.12)	0.15 (0.23; 0.08)	0.17 (0.24; 0.08)
Zuurbekom	**0.20** (**0.28**; 0.12)	**0.29** (**0.42**; 0.25)	**0.36** (**0.51**; 0.21)	**0.36** (**0.48**; 0.22)	**0.23** (**0.33**; 0.13)	0.16 (0.23; 0.11)	**0.22** (**0.33**; 0.13)	−0.01 (0.01; −)
Cedara	0.17 (0.23; 0.08)	**0.28** (**0.39**; 0.18)	**0.32** (**0.45**; 0.16)	0.18 (0.27; 0.07)	0.11 (0.15; 0.05)	0.06 (0.07; 0.03)	0.14 (0.18; 0.08)	−0.07 (−0.11; −0.03)
Durban	**0.20** (**0.29**; 0.09)	0.17 (0.25; 0.11)	**0.32** (**0.42**; 0.13)	0.17 (0.24; 0.06)	0.16 (0.22; 0.08)	0.15 (0.25; 0.07)	**0.19** (**0.29**; 0.09)	−0.08 (−0.11; −0.03)
Mara	0.18 (0.24; 0.11)	**0.28** (**0.42**; 0.21)	**0.50** (**0.68**; 0.25)	**0.54** (**0.72**; 0.26)	0.07 (0.10; 0.04)	0.02 (0.02; 0.01)	−0.05 (−0.09; −0.02)	0.01 (−0.03; −)
Warmbad Towoomba	**0.25** (**0.37**; 0.17)	**0.21** (**0.32**; 0.15)	**0.40** (**0.56**; 0.21)	**0.38** (**0.52**; 0.23)	0.14 (0.18; 0.08)	0.05 (0.06; 0.02)	0.11 (0.14; 0.04)	0.13 (0.17; 0.05)
Skukuza	−0.09 (−0.15; −0.06)	**0.23** (**0.33**; 0.14)	**0.23** (**0.33**; 0.11)	**0.37** (**0.50**; 0.15)	0.17 (0.27; 0.07)	0.13 (0.18; 0.08)	0.11 (0.15; 0.04)	0.11 (0.16; 0.06)
Vryburg	0.01 (−; −)	**0.27** (**0.40**; 0.18)	**0.42** (**0.55**; 0.23)	**0.34** (**0.47**; 0.20)	−0.13 (−0.20; −0.08)	−0.07 (−0.10; −0.04)	0.08 (0.10; 0.04)	−0.14 (−0.20; −0.06)
Kimberley	**0.20** (**0.30**; 0.14)	**0.28** (**0.41**; 0.20)	**0.37** (**0.53**; 0.20)	**0.43** (**0.64**; 0.20)	**−0.19** (**−0.27**; −0.12)	−0.17 (−0.23; −0.10)	**−0.20** (**−0.30**; −0.10)	**−0.28** (**−0.39**; −0.12)
Upington	**0.37** (**0.54**; 0.20)	**0.43** (**0.61**; 0.29)	**0.54** (**0.74**; 0.28)	**0.33** (**0.51**; 0.16)	−0.03 − 0.05; −0.01)	0.14 (0.21; 0.08)	−0.01 (−0.03; −)	−0.06 (−0.08; −0.03)
Vanwyksvlei	**0.48** (**0.67**; 0.26)	**0.44** (**0.62**; 0.34)	**0.54** (**0.74**; 0.26)	**0.41** (**0.59**; 0.21)	0.12 (0.15; 0.05)	0.13 (0.19; 0.05)	0.02 (0.04; 0.01)	−0.09 (−0.11; −0.06)
Cape Agulhas	**0.38** (**0.56**; 0.22)	**0.43** (**0.60**; 0.20)	0.13 (0.19; 0.06)	**0.34** (**0.49**; 0.19)	**0.31** (**0.46**; 0.20)	0.03 (0.05; 0.01)	**0.23** (**0.34**; 0.12)	**0.38** (**0.52**; 0.23)
Cape Columbine	0.30 (0.44; 0.14)	0.15 (0.23; 0.06)	0.19 (0.28; 0.08)	0.16 (0.23; 0.06)	**0.23** (0.33; 0.13)	0.11 (0.17; 0.05)	**0.22** (**0.32**; 0.11)	0.16 (0.19; 0.08)
Mosselbay	**0.46** (**0.66**; 0.19)	**0.47** (**0.63**; 0.17)	0.08 (0.12; 0.03)	**0.39** (**0.54**; 0.16)	0.16 (0.24; 0.08)	−0.14 (−0.21; −0.07)	**−0.19** (**−0.29**; −0.09)	0.14 (0.17; 0.09)
Cape Town	0.23 (0.36; 0.09)	0.11 (0.16; 0.04)	0.06 (0.09; 0.02)	0.14 (0.20; 0.07)	**0.40** (**0.56**; 0.21)	**0.21** (**0.30**; 0.10)	0.07 (0.12; 0.03)	**0.20** (**0.31**; 0.10)
Vredendal	**0.42** (**0.57**; 0.16)	**0.54** (**0.73**; 0.22)	**0.20** (**0.32**; 0.10)	**0.21** (**0.32**; 0.10)	**0.33** (**0.48**; 0.16)	0.11 (0.15; 0.04)	−.06 (−0.09; −0.02)	0.01 (0.03; −)
Averages	0.21 (0.30; 0.11)	0.29 (0.41; 0.17)	0.30 (0.41; 0.15)	0.29 (0.42; 0.14)	0.13 (0.18; 0.07)	0.04 (0.06; 0.02)	0.05 (0.07; 0.03)	0.02 (0.03; 0.02)

*Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS)

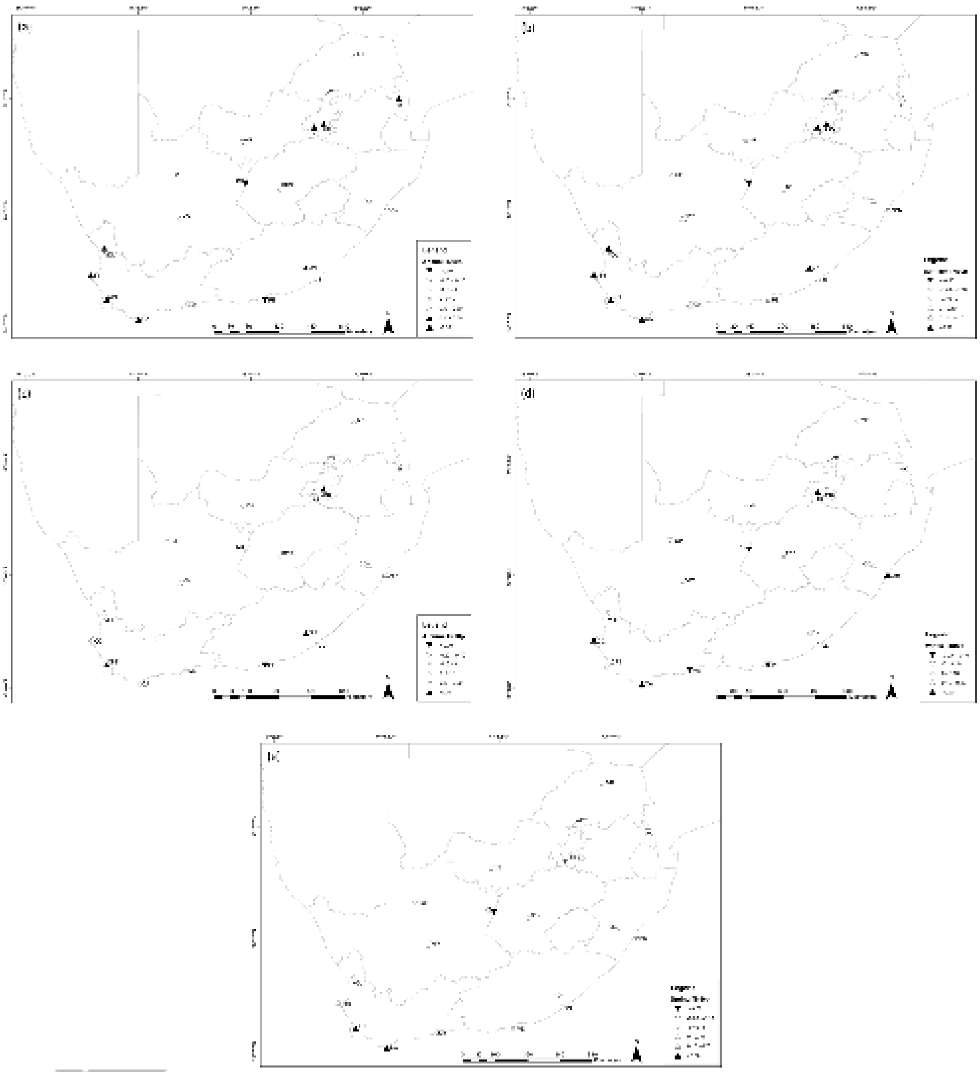


Fig. 5 Annual trends of (a) TN90p and mean seasonal temperature trend of (b) TN90p summer, (c) TN90p autumn, (d) TN90p winter and (e) TN90p spring. Open downward and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level

stations experience increasing trends in autumn (Fig. 4c), 15 of which are statistically significant. The strongest rate increases are experienced in stations located in the Northern Cape, with rate increases of >0.20% days year^{-1}. Overall, an increasing rate of 0.17% days year^{-1} in TX90p has been calculated (Table 7).

All the stations experience an increasing trend in winter (Fig. 4d), 14 of which are statistically significant (Fig. 4d). These stations are predominantly located in the northeastern interior parts of the country, with increases of >0.11% days year^{-1} in TX90p (Fig. 4d; Table 7). The south and west coast stations experience smaller insignificant trend increases, at a rate of > 0.02% days year^{-1} for TX90p (Fig. 4d; Table 7). The overall, calculated rate increase in TX90p in winter is 0.15% days year^{-1}. Similar to winter, all the stations in spring experience an increasing trend, with 14 trends statistically significant (Fig. 4e). These statistically significant stations are located in the Free State, Gauteng, Limpopo, Mpumalanga, North West, Northern Cape, Eastern Cape at East London and the Western Cape province at Cape Agulhas, Mosselbay and Vredendal, with rate increases of > 0.08% days year^{-1} (Fig. 4e; Table 7). Overall, a calculated rate increase is experienced in TX90p in spring of 0.14% days year^{-1}. In short, the strongest rate increase in TX90p is experienced in autumn, followed by winter (Table 7).

For annual TN90p, most of the stations (16 of 20) have experienced increasing trends (Fig. 5a; Table 3), of which eight are statistically significant. These stations are located in the Western Cape, Mpumalanga, Gauteng and Eastern Cape province at Dohne, which experience rate increases of > 0.08% days year^{-1} (Fig. 5a; Table 3). Decreasing trends of > 0.04% days year^{-1} are calculated for the remaining four stations: Bloemfontein, Vryburg, Port Elizabeth and Kimberley with the latter two being statistically significant. Overall, a calculated rate increase of 0.04% days year^{-1} has been found in TN90p countrywide.

For summer, increasing trends are calculated for the majority of the stations (16 of 20; Fig. 5b; Table 7), seven of which are statistically significant. These significant stations are located predominantly in the Western Cape, Gauteng and Eastern Cape at Dohne, with a rate increase of > 0.12% days year^{-1} (Table 7). The remaining four stations, which are located in the Free State and Northern Cape province, exhibit decreasing trends with rate decreases of > 0.01% days year^{-1}. Kimberley is the only station with a statistically significant decrease (Fig. 5b; Table 7). Overall, an increase of 0.07% days year^{-1} is calculated for TN90p in summer. Most of the stations (14 of 20) experience increasing trends for autumn (Fig. 5c), three of which are statistically significant. These stations, Dohne, Johannesburg Int and Cape Town experience increases of > 0.10% days year^{-1} in TN90p (Table 7). Decreasing trends in TN90 are evident in the remaining six stations at > 0.04% days year^{-1}; only Port Elizabeth has a calculated statistically significant decrease (Fig. 5c). Overall, a rate increase of 0.02% days year^{-1} has

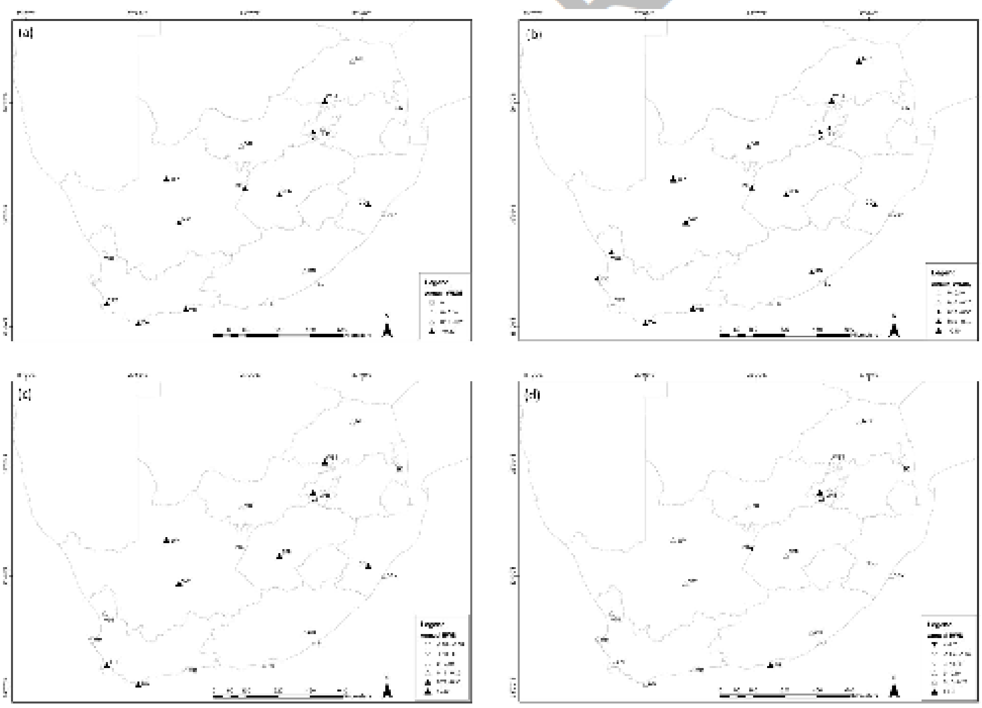


Fig. 6 Annual trends of (a) WSDI, (b) WSDI$_5$, (c) HWN and (d) HWD. Open downward and upward triangles indicate negative and positive trends. Squares indicate no trend. Solid upward triangles indicate trends that are statistically significant at the 5% level

Springer

Table 8 Increasing and decreasing trends in warm spell duration days and heatwaves during 1960–2015

Station	WSDI	$WSDI_3$	HWN	HWD
Dohne	0.21 (0.26; –)	**0.24 (0.31**; 0.09)	0.01 (–; –;0.02)	0.22 (0.32; –; 0.03)
East London	–	0.11 (0.13; –)	0.15 (0.19; –; –)	0.12 (0.15; –; 0.02)
Port Elizabeth	0.21 (0.25; –)	0.17 (0.23; –)	0.04 (0.06; –; 0.01)	**0.30 (0.37**; –; 0.03)
Bloemfontein	**0.24 (0.31**; –)	**0.39 (0.54**; 0.44)	**0.36 (0.45**; –; 0.03)	0.19 (0.26; 0.03; 0.03)
Johannesburg Int	0.16 (0.21; –)	**0.23 (0.33**; 0.25)	0.20 (0.24; –; 0.03)	0.06 (0.08; –; 0.06)
Zuurbekom	**0.28 (0.36**; –)	**0.27 (0.37**; 0.36)	**0.46 (0.59**; 0.06; 0.06)	**0.52 (0.69**; 0.14; 0.16)
Cedara	**0.30 (0.36**; –)	**0.23 (0.31**; –)	0.24 (0.31; –; 0.02)	– 0.03 (0.04; –; –)
Durban	–	0.17 (0.23; 0.08)	0.15 (0.21; –; 0.03)	0.24 (0.35; –; 0.05)
Mara	0.17 (0.21; –)	**0.51 (0.68**; 0.41)	0.19 (0.24; –; 0.05)	0.05 (0.05; –; 0.01)
Warmbad Towoomba	**0.30 (0.38**; –)	**0.35 (0.50**; 0.39)	**0.34 (0.45**; 0.03; 0.05)	**0.24** (0.32; 0.04; 0.10)
Skukuza	0.09 (0.12; –)	0.07 (0.11; –)	0.16 (0.20; –; 0.04)	0.08 (0.10; –; 0.02)
Vryburg	0.19 (0.24; –)	**0.27 (0.39**; 0.44)	0.12 (0.18; –; 0.03)	0.24 (0.30; 0.05; 0.05)
Kimberley	**0.24 (0.29**; –)	**0.36 (0.52**; 0.32)	– 0.14 (– 0.18; –; –)	– 0.23 (– 0.31; –; –0.01)
Upington	**0.31** (–; –)	**0.45 (0.64**; 0.44)	**0.31 (0.39**; –; 0.03)	0.05 (0.07; –; –)
Vanwyksvlei	**0.31 (0.39**; –)	**0.55 (0.75**; 0.54)	**0.31 (0.39**; –; 0.03)	0.19 (0.26; –; 0.04)
Cape Agulhas	**0.29 (0.36**; –)	**0.45 (0.62**; 0.25)	**0.27 (0.37**; 0.03; 0.05)	0.14 (0.18; –; 0.02)
Cape Columbine	0.02 (0.02; –)	**0.22 (0.32**; 0.09)	0.15 (0.20; –; 0.02)	0.10 (0.13; –; 0.02)
Mosselbay	**0.30 (0.37**; –)	**0.44 (0.57**; 0.14)	0.02 (0.03; –; –)	0.04 (0.03; –; 0.03)
Cape Town	**0.22 (0.27**; –)	0.08 (0.41; –)	**0.28 (0.37**; –; 0.02)	0.10 (0.14; –; 0.02)
Vredendal	0.18 (0.22; –)	**0.39 (0.54**; 0.25)	0.15 (0.20; –; 0.02)	0.20 (0.27; –; 0.02)
Average trend	0.20 (0.23; –)	0.30 (0.42; 0.30)	0.19 (0.25; –; 0.03)	0.14 (0.18; –; 0.04)

*Values in bold are different from 0 with a significance level alpha = 0.05. Trend values in the table are portrayed as follows: MK(ρ; SS; Linear trend)

been calculated for TN90p in autumn. Increasing trends are evident in most of the stations (14 of 20) in winter (Fig. 5d; Table 7), of which four are statistically significant. These stations, Zuurbekom, Durban, Cape Agulhas and Cape Columbine, experience rate increases of > 0.09% days year^{-1} in TN90p (Fig. 5d; Table 7). The remaining six stations experience decreasing trends with rate decreases of > 0.02% days year^{-1}, of which Port Elizabeth, Kimberley and Mosselbay being statistically significant (Fig. 5d; Table 7). An overall increase of 0.03% days year^{-1} in TN90p has been calculated for winter (Table 7). In general, an increase of 0.02% days year^{-1} in TN90p is calculated for spring, with 50% of the stations exhibiting increasing trends (Table 7). Most of the stations with increasing trends are located in the Limpopo, Mpumalanga and the Western Cape province, of which Cape Agulhas and Cape Town being statistically significant, with a rate increase of > 0.10% days year^{-1} (Fig. 5e; Table 7). Stations with decreasing trends, with rate decreases of > 0.01% days year^{-1}, are located in the Eastern Cape, Free State, KwaZulu-Natal, North West and Northern Cape province, of which Kimberley being statistically significant (Fig. 5e; Table 7). In short, the strongest rate of increase in TN90p is evident in summer, followed by winter.

In addition to TX90P and TN90p, TX_2TN_2 was calculated. Only 16 out of the 20 stations exhibit trends, of which four are statistically significant (Table 3). These stations are located in Gauteng and along the west coast, with increases of > 0.23 events year^{-1} for the period 1960–2016. Cape Agulhas exhibits the only rate increase of 0.01 events year^{-1} in TX_2TN_2 events.

4.5 Warm spell duration indicator and heatwaves

Most of the stations (18 of 20) experience increasing trends in WDSI, ten of which are statistically significant (Fig. 6a). These stations are located in the Free State, Gauteng, KwaZulu-Natal, Limpopo, Northern Cape and the Western Cape province, with increases of > 0.22 days year^{-1} for the period 1960–2016 (Table 8). The Spearman's rank correlation coefficient display similar results. No substantial rate of the increasing trends is found in the stations (Table 8).

All sampled stations experience an increasing trend in $WSDI_3$ (Fig. 6b; Table 8), 15 of which are statistically significant. These statistically significant stations are located in the Free State, Gauteng, Northern Cape, Limpopo, North West, Eastern Cape at Dohne, KwaZulu-Natal at Cedara and Western Cape province, which experience rate increases of > 0.09 days year^{-1} in $WSDI_3$ (Fig. 6b; Table 8). Smaller increasing trends are evident in the coastal stations, except for Cape Agulhas, Cape Columbine and Mosselbay with rate increases between 0.09 and 0.25 days year^{-1} (Table 8). The overall calculated rate increase is 0.30 days year^{-1} for the $WSDI_3$ index over the country (Table 8).

Most of the stations (19 of 20) experience an increasing trend in heatwave events (HWN; Fig. 6c), seven of which are statistically significant. These stations are located in the Free State, Gauteng, Limpopo, Northern Cape and Western Cape province, with linear rate increases of > 0.02 events year^{-1} (Table 8). Kimberley is the only station experiencing a decreasing trend. The strongest linear rate increases are evident in Limpopo, Gauteng at Zuurbekom and the Western Cape province at Cape Agulhas, with rate increases of > 0.05 events year^{-1} (Table 8). An overall, calculated linear rate increase of 0.03 events year^{-1} has been found for heatwave events across the country (Table 8).

The HWD index identifies the length (days) of the heatwaves identified by the HWN index. The results indicate that the number of days has increased, with an overall calculated linear rate increase of0.04 days year^{-1} (Table 8). Most of the stations (18 of 20) experience increasing trends in HWD, three of which are statistically significant (Fig. 6d). These significant stations are located in the Eastern Cape at Port Elizabeth, Gauteng at Zuurbekom and Limpopo province at Warmbad Towoomba, which experience linear rate increases between 0.03 and 0.16 days year^{-1} (Fig. 6d; Table 8). However, linear rate increases of > 0.05 days/year^{-1} are also evident in non-significant stations: Johannesburg Int, Durban and Vryburg (Fig. 6d; Table 8). Decreasing trends are calculated for the two remaining stations Cedara and Kimberley, with only the latter experiencing a linear rate decrease of 0.01 days year^{-1} (Table 8).

5 Discussion

This study is the first to apply the ET-SCI thermal stress indices to South Africa, exploring the incidence of warm extreme temperature events for the period 1960–2016. The general findings of the ETCCDI and ET-SCI indicate a warming trend and an increase in extreme warm temperature events on an annual and seasonal time scale over the study period. These findings are in agreement with the increasing global mean temperature trends (Yatim et al. 2019; NOAA 2020), increases in extreme warm temperature and increases in the frequency of incidence of hot days (Hartmann et al. 2013; Mueller et al. 2016).

Consistent with previous studies on extreme warm events in South Africa (e.g. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo 2017), most of our findings on an annual and seasonal time scale are in partial agreement. However, this study presents the first comprehensive seasonal trend analysis results of TXx, TNx, TX90p and TN90p. Observations on a seasonal timescale are very important. Unseasonably warmer temperatures may increase the risk of heat stress, due to an unprepared population (Lee 2014; Founda et al. 2019). Changes in seasonal temperatures may bring about shifts in the onset and length of growing seasons (Thorton et al. 2014) and contribute to a reduction in crop (Landman et al. 2017) and grape yields (Araujo et al. 2016) in particular in the Western Cape. The warmer temperature may delay and advance seasonal phenological events (Fitchett et al. 2019).

This study presents the first trend analysis of the frequency of annual hot days where TX is above 25 °C (SU25) and of seasonally hot days where TX is above 35 °C. These events, in terms of a positive anomaly, may be an important classifier of the degree of heat stress. The core body temperature in humans increases significantly from exposure to these high temperatures (Ngwenya et al. 2018), which may lead to higher risks in the mortality rate due to heat stress, caused by inadequate housing and infrastructure to cope with the intense heat (Pasquini et al. 2013; Nana et al. 2019; Chersich and Wright 2019).

Our results demonstrate a general increase in warm spell days (WSDI) over a 50-year period, providing an extension to the work of Kruger and Nxumalo (2017). Studies have found that the WSDI index is less effective to measure the frequency and intensity of heatwaves (Perkins et al. 2012; Panda et al. 2014), for the reason that 6-day consecutive warm spell events are rarely identified (see WSDI definition in Table 2). Therefore, $WSDI_3$, HWN and HWD indices were used to identify shorter warm spells (heatwaves). Together with the TX_2TN_2 index, which identify two consecutive warm days and night events. Research shows that it is not always daytime heat which is responsible for morbidity and mortality; humans need cooler night temperatures to recuperate to handle extreme heat the following day (Perkins 2015). A significant increase in $WSDI_3$ index was found, together with a general increase in heatwave events (HWN) and the number of heatwave days (HWD). Heatwaves can have significant impacts on many different sectors (Panda et al. 2014), in particular in a South African context. Extreme heat events disrupt agricultural practices and decrease crop yields (Mangani et al. 2018), which could have dire effects on the Free State's grain production and Western Cape's wine production. Heatwaves may devastate energy systems because with higher temperatures, the demand for electricity increases to supply air conditioners and fans (Lubega et al. 2018). Heatwaves also disrupt ecosystems; a study found that heatwaves induce fitness costs in birds which negatively impact their nesting growth and survival (Malherbe et al., 2016; Van Wilgen et al. 2016). Extreme heat can also contribute to and exacerbate wildfires—as has been seen in the 2019–2020 Australian fires (Ebbs, 2020). This poses significant threats to plantations and national parks, particularly in KwaZulu-Natal, Mpumalanga and the Western Cape (Davis-Reddy and Vincent 2017).

Heatwaves also have an impact on tourism; it has been found that temperatures play a significant role in outdoor tourism and tourist activities (Noome and Fitchett 2019). Tourist tends to stay indoors during heatwave events and is not always as accustomed to these warm events (Fitchett and Hoogendoorn 2018).

Extreme warm temperatures could have dire impacts and may result in human fatalities. An example of this are the health impacts and mortalities that resulted directly from the 2003 European and 2010 Russian heatwaves and the secondary impacts on ecosystems and socioeconomic development that persisted long after (Perkins et al. 2012; Ragone et al. 2018). The increase in the frequency, duration and intensity of these events may amplify these impacts, particularly in a developing country such as South Africa, with a low adaptive capacity (Davis-Reddy and Vincent 2017).

Our findings are in agreement with previous studies indicating a general increasing trend in extreme warm temperature and heatwaves (e.g. Kruger and Sekele 2013; Mackellar et al. 2014; Kruger and Nxumalo, 2017). Similar to the findings of Kruger and Sekele (2013) and Kruger and Nxumalo (2017), the majority of interior stations experienced a statistically significant increasing trend in frequency of warm days and warm spell duration days, compared to the coastal stations. These spatial patterns coincide with recent projection studies indicating that there is a notable increase in frequency of warm spells, but less so in the south eastern part of the country (Kruger et al. 2019).

Large-scale climate drivers, such as the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), affect the nature and timing of warm extreme temperatures events (Baudoin et al. 2017), together with local and regional synoptic circulation systems over the country. For instance, the decrease of warm days (TX90p) and nights (TN90p) in winter coincides broadly with the timing of movement of cold fronts over the subcontinent (Lennard, 2019). The increase in warm days in the interior stations can be linked to the subtropic high-pressure situated in the interior parts of the country during summer (Kruger et al. 2010). Furthermore, studies suggest that anthropogenic forces (Angélil et al. 2017) may play a role. However, less research is focused on understanding these relationships between extreme heat events and large-scale modes of climate variability and synoptic patterns in a South African context. This is an important avenue for future research.

As for any study, there are limitations. The ETCCDI and ET-SCI are far more robust approaches to assessing the occurrence of extreme temperature events, and preference should be given for these over ad-hoc local definitions. That said, when assessing the impact on human thermal comfort and stress, more complex indices such as the Universal Thermal Climate Index (UTCI) provide greater insight (Di Napoli et al. 2018). This forms an important avenue for future research. This study is the first to explore extreme temperature events at a seasonal scale for South Africa. Assessing extreme temperature relative to a period of lower homogeneity allows for aseasonally warm winter days and aseasonally cold summer days to be classified as extreme events, which is important in terms of preparedness relating to clothing, outdoor activity and indoor temperature control. The seasonal brackets selected facilitate spatial analysis across the country but overestimate the length and timing of the shoulder seasons (Van der Walt and Fitchett 2020). Recent findings suggest, based on temperature metrics, that the South African summer is longer extending from October to March (Van der Walt and Fitchett 2020). Finally, while the selection of 20 stations represent the full database with sufficient period of coverage and competeness, and has been deemed sufficient for the spatial coverage of South Africa (Kruger and Nxumalo 2017), it does limit the accuracy of the IDW spatial interpolation. Future work should seek to test the interpolation accuracy between stations, if even from records of shorter duration, and ongoing efforts to improve the climate monitoring in South Africa are welcomed.

6 Conclusion

This study provides one of the first comprehensive assessment on an annual and seasonal scale of extreme warm temperature events in South Africa, for the period 1960–2016. The findings of both the ETCCDI and ET-SCI indices produced significant results; however, the ET-SCI are more useful and can be applied in conjunction with many important sectors in a South African perspective. These findings have important implications on our natural system as well as society and set a precedent for likely future changes in extreme heat events resulting from further anthropogenic global warming. Furthermore, these results of extreme temperature events are crucial in order to frame mitigation and adaption strategies to counter the impacts of climate change, in an already vulnerable country.

Acknowledgements We acknowledge the financial and collegial support offered to Adriaan J van der Walt from the Faculty of the Natural and Agricultural Sciences and the Geography Department at the University of the Free State. Jenner M Fitchett received funding from the DST-NRF Centre of Excellence for Palaeoscience. The authors thank Professor Christopher Curtis for suggestions and advice on earlier stages of the project. The authors would also like to thank Yang Feng for assistance with the download and usage of RClimDex and RHtestV4 software.

Authors' contribution JF conceptualized and lead the project and was the principal supervisor. AvdW collected, curated and analysed the data and wrote the first draft. AvdW and JF developed the methodology, conducted the validation and wrote and revised the manuscript.

Funding JF receives operational support funding from the DSI-NRF Centre of Excellence for Palaeosciences.

Compliance with ethical standards

Conflict of interests The authors declare that they have no conflict of interest.

References

Abatan AA, Abiodun BJ, Lawal KA, Gutowski WJ (2016) Trends in extreme temperature over Nigeria from percentile-based threshold indices. Int J Climatol 36:2527–2540. https://doi.org/10.1002/joc.4510

Abbas F, Rehman I, Adrees M, Ibrahim M, Saleem F, Ali S, Rizwan M, Salik MR (2018) Prevailing trends of climate extremes across Indus-Delta of Sindh-Pakistan. Theor Appl Climatol 131:1101–1117. https://doi.org/10.1007/s0070-016-2028-y

Aguilar E, Vincent L, Zhang X (2013) Climate data homogenization theory. Toronto, Canada, Environmental Canada

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperatures and precipitation J Geophys Res 111. https://doi.org/10.1029/2005JD006290, Global observed changes in daily climate extremes of temperature and precipitation, 111

Alexander L, Herold N (2016) Climpact2 indices and software, the University of South Wales, Sidney, Australia. https://github.com/ARCCSSextremes/climpact2

Allen SMJ, Gough WA, Mohsin T (2015) Changes in the frequency of extreme temperature records for Toronto, Ontario, Canada. Theor Appl Climatol 119:481–491. https://doi.org/10.1007/s00704-014-1131-1

Angélil O, Stone D, Wehner M, Paciorek CJ, Krishnan H, Collins W (2017) An independent assessment of anthropogenic attribution statements for recent extreme temperature and rainfall events. Am Meteorol Soc 30:5-16. 101175/JCLI-D-16-0077.1

Araujo JA, Abiodun BJ, Crespo O (2016) Impacts of drought on grape yields in Western Cape, South Africa. Theor Appl Climatol 123:117–130. https://doi.org/10.1007/s00704-014-1336-3

Baudoin MA, Vogel C, Nortje K, Naik M (2017) Living with drought in South Africa: lessons learnt from the recent El Niño drought period. Int J Disaster Risk Reduct 23:128–137. https://doi.org/10.1016/j.ijdrr.2017.05.005

Caloiero T, Coscarelli R, Ferrari E, Sirangelo B (2017) Trend analysis of monthly mean values and extreme indices of daily temperature in a region of southern Italy. Int J Climatol 37:284–297. https://doi.org/10.1002/joc.5003

Davis-Reddy CL, Vincent K (2017) Climate risk and vulnerability: a handbook for southern Africa, 2nd edn. CSIR. Pretoria, South Africa

Di Napoli C, Pappenberger F, Cloke HL (2018) Assessing heat-related health risk in Europe via the universal thermal climate index (UTCI). Int J Biometeorol 62(7):1155–1165. https://doi.org/10.1007/s00484-018-1518-2

Engelbrecht F, Landman W (2010) South Africa's present-day climate. In: Southern Africa risk and vulnerability atlas. CPD Print, Pretoria, pp 2–5

Ebbs S (2020) Climate change can 'supercharge' wildfires in Australia through more extreme heat, drought. abcNews. https://abcnews.go.com/International/climate-change-supercharge-wildfires-australia-extreme-heat-drought/story?id=68096029.

Fischer EM, Shär S (2010) Consistent geographical patterns in high-impact European heatwaves. Nat Geosci 3:398–403. https://doi.org/10.1038/ngeo866

Fitchett JM, Grab SW, Portwig H (2019) Progressive delays in the timing of sardine migration in the Southwest Indian Ocean. S Afr J Sci. 2019 115(7/8):1-6. https://doi.org/10.17159/sajs.2019/5887

Founda D, Pierros F, Katavoutas G, Keramitsoglou I (2019) Observed trends in thermal stress at European cities with different background climates. Atmos 10(8):436. https://doi.org/10.3390/atmos10080436

Grab SW, Knight J (2018) Southern African montane environments. In: Holmes PJ, Boardman J (eds) Southern African landscape and environmental change. Routledge, Oxon

Head T (2019) Seven South African weather records that were broken in 2019. The South African. https://www.thesouthafrican.com/news/weather/hottest-day-in-south-africa-ever-weather-records/. Accessed 26 February 2020

Karki R, Hasson SU, Gerlitz L, Talchabhadel R, Schickhoff U, Scholten T, Böhner J (2019). Rising mean and extreme near-surface air temperature across Nepal. Int J Climatol 40(4):2445-2463. 1-19. https://doi.org/10.1002/joc.6344

Klein Tank AMG, Zwiers FW, Zhang X (2009) Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation (WCDMP no. 72, WMO-TD no. 1500). Switzerland: World Meteorological Organization, 54 pp.

Kruger AC, Sekele SS (2013) Trend in extreme temperature indices in South Africa: 1962-2009. Int J Climatol 33:661–676. https://doi.org/10.1002/joc.3455

Kruger AC, Nxumalo M (2017) Surface temperature trends from homogenized time series in South Africa: 1931-2015. Int J Climatol 37:2364–2377. https://doi.org/10.1002/joc.4851

Kruger AC, Rautenbach H, Mbatha S, Ngwenya S, Makgola TE (2019) Historical and projected trends in near surface temperature indices for 22 locations in South Africa. S Afr J Sci. 115(5/6). https://doi.org/10.17159/sajs.2019/4846

Landman WA, Malherbe J, Engelbrecht F, (2017) South Africa's present-day climate. In Mambo J, Faccer K, (eds). Understanding the social and environmental implication of global change, African Sun Media: Stellenbosch

Lee WV (2014) Historical global analysis of occurrences and human casualty of extreme temperature events (ETEs). Nat Hazards 70:1453–1505. https://doi.org/10.1007/s11069-0.13-0884-7

Lennard C (2019) Multi-scale drivers of the south African weather and climate. In: Knight J, Rogerson CM (eds) The geography of South Africa. Springer, Switzerland

MacKellar N, New M, Jack C (2014) Observed and modelled trends in rainfall and temperature for South Africa: 1960-2010. S Afr J Sci 110(7/8):51–63. https://doi.org/10.1590/sajs.2014/20130353

Malherbe J, Smit IPJ, Wessels KJ, Beukes PJ (2020) Recent droughts in the Kruger National Park as reflected in the extreme climate index. Afr J Ran For Sci 37(1):1–17. https://doi.org/10.2989/10220119.2020.1718755

Mangani R, Tesfamariam E, Bellocchi G, Hassen A (2018) Modelled impacts of extreme heat and drought on maize yield in South Africa. Crop Pas Sci 69:703–716. https://doi.org/10.1071/CP18117

Nairn JR, Fawcett RJB (2015) The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. Int J Environ Res Public Health 12:227–253. https://doi.org/10.3390/ijerph120100227

Nana M, Coetzer K, Vogel C (2019) Facing the heat: initial probing of the city of Johannesburg's heat-health planning. S Afr Geogr J 101(2):253–268. 1080/03736245.2019.1599412

Nemec J, Bruder C, Chimani B, Auer I (2013) Trends in extreme temperature indices in Austria based on a new homogenized dataset. Int J Climatol 33:1538–1550. https://doi.org/10.1002/joc.3532

Ngwenya B, Oosthuizen J, Cross M, Frimpong K, Chaibva CN (2018) A review of heat stress policies in the context of climate change and its impacts on outdoor workers: evidence from Zimbabwe. Int J Soc Ecol Sustain Dev 9(1):1–11. https://doi.org/10.4018/IJSESD.2018010101

Noome K, Fitchett J (2019) An assessment of the climate suitability of Afriski Mountain Resort for outdoor tourism using the tourism climate index (TCI). J Mount Sci 16(11):2453–2469

Osborne S (2019) France's summer heatwave killed 1,500 people, health minister announces. Independent. https://www.independent.co.uk/news/world/europe/france-heatwave-summer-dead-death-toll-europe-a9096806.html.

Panda K, Mishra A, Kumar A, Mandal KG, Thakur AK, Srivastava RC (2014) Spatiotemporal patterns in the mean and extreme temperature indices of India, 1971-2005. Int J Climatol 34:3585–3603. https://doi.org/10.1002/joc.3931

Pasquini L, Cowling RM, Ziervogel G (2013) Facing the heat: barriers to mainstreaming climate change adaption in local government in the Western Cape Province, South Africa. Habitat Int 40:225–232. https://doi.org/10.1016/j.habitatint.2013.05.003

Perkins SE, Alexander LV, Nairn JR (2012) Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophys Res Lett 39. https://doi.org/10.1029/2012GL053361

Perkins SE (2015) A review on the scientific understanding of heatwaves-their measurement, driving mechanisms, and changes at the global scale. Atmos Res 164-165:242–267. https://doi.org/10.1016/j.atmosres.2015.05.014

Perkins-Kirkpatrick SE, Gibson PB (2017) Changes in regional heatwave characteristics as a function of increasing global temperature. Sci Rep 7:12256. https://doi.org/10.1038/s41598-017-12520-2

Perkins-Kirkpatrick SE, Fischer EM, Angélil O, Gibson PB (2017) The influence of internal climate variability on heatwave frequency trends. Environ Res Lett 12. https://doi.org/10.1088/1748-9326/aa63fe

Ragone F, Wouters J, Bouchet F (2018) Computation of extreme heatwaves in climate models using a large deviation algorithm. Proc Natl Acad Sci U S A 115:24–29

Salameh AAM, Gámiz-Fortis SR, Castro-Díez Y, Hammad AA, Esteban-Parra MJ (2018) Spatial-temporal analysis for extreme temperature indices over the Levant region. Int J Climatol 39:5556–5582. https://doi.org/10.1002/joc.6171

Simmonds I (2018) What causes extreme hot days in Europe. Environ Res Let 13. https://doi.org/10.1088/1748-9326/aacc78

SAWS (2020) Weather questions. [available online at https://www.weathersa.co.za/home/weatherques.]

Tabari H, Talaee PH (2011) Temporal variability of precipitation over Iran: 1966-2005. J Hydrol 396(3):313–320

Thorton PK, Ericksen PJ, Herrero M, Challinor AJ (2014) Climate variability and vulnerability to climate change: a review. Glob Chan Bio 20:3313–3328. https://doi.org/10.1111/gcb.12581

Tyson PD, Preston-Whyte RA (2000) The atmosphere and weather of southern Africa. 2nd Ed. Cape Town: Oxford University Press Southern Africa. https://doi.org/10.1002/joc.725, The weather and climate of southern Africa by P. D. Tyson and R. A. Preston-Whyte. Oxford University Press Southern Africa, Cape Town, 2000. No. of pages: xii + 396. Price £32.50. ISBN 0-19-571806-2 (paperback)

Van der Walt AJ, Fitchett JM (2020) Statistical classification of south African seasonal divisions on the basis of daily temperature data. S Afr J Sci 116(9/10):1-15. 10.17159/ sajs.2020/7614

Van Wilgen NJ, Goodal V, Holness S, Chown SL, McGeoch MA (2016) Rising temperatures and changing rainfall patterns in South Africa's national parks. Int J Climatol 36:706–721. https://doi.org/10.1002/joc.4377

Vincent LA, Zhang X, Bonsl BR, Hogg WD (2002) Homogenization of daily temperatures over Canada. J Clim 15:1322–1334

Vincent L A, Wang XL, Milewska EJ, Wan H, Feng Y, Swail V (2012) A second generation of homogenized Canadian monthly surface air temperature of climate trend analysis J Geophys Res 117. https://doi.org/10.1029/2012JD017859, A second generation of homogenized Canadian monthly surface air temperature for climate trend analysis, 117

Wang XL (2008a) Accounting for autocorrelation in detecting mean shifts in climate data series using penalized maximal *t* and *F* test. J Appl Meteorol Climatol 47:2423–2444

Wang XL (2008b) Penalized maximal F-test for detecting undocumented mean-shifts without trend-change. J Atmos Ocean Technol 25(3): 368–384. https://doi.org/10.1175/2008JTECHA982.1

Wang XL, Feng Y (2013) RHtestsV4 user manual. Climate research division, atmospheric Science and Technology Directorate, science and technology branch, Environment Canada, 28pp. [available online at https://github.com/ECCC-CDAS/RHtests/blob/master/V4_files/RHtestsV4_UserManual_10Dec2014.pdf]

Yosef Y, Aguilar E, Alpert P (2019) Changes in extreme temperature and precipitation indices: using an innovative daily homogenized database in Israel. Int J Climatol 39:5022–5045

Zhang Y, Yang F (2004) RClimDex (1.0): Manual. Environmental Canada: Ontario, Canada

Zhang X, Feng Y, Chan R, (2018) Introduction to RClimDex v1.9, climate research division, Environment Canada, Downsview, Ontario, Available from https://github.com/ECCC-CDAS/

Ziervogel G, New M, Archer van Garderen E, Midgley G, Taylor A, Hamann R, Stuart-Hill S, Myers J, Warburton M (2014) Climate change impacts and adaption in South Africa. Wiley Interdiscip Rev Clim Chang 5:605–620. https://doi.org/10.1002/wcc.295