# Characterization of rainfall over the Limpopo province, South Africa, for the period 1990 to 2020

by

Peter Lesiba Moumakwe

Submitted in fulfilment of the academic requirements of

Master of Science

in Geography and Environmental Science
School of Agricultural, Earth and Environmental Science
College of Agriculture, Engineering and Science
University of KwaZulu-Natal
Pietermaritzburg
South Africa

August 2024

## PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Geography and Environmental sciences, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg campus, South Africa. The research was financially supported by the Agricultural Research Council (ARC) and the National Research Fund (NRF).

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

[redacted]

Signed: Dr. Dube LT

Date: 28/08/2024

**DECLARATION 1: PLAGIARISM**

I, Peter Lesiba Moumakwe, declare that

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

(iii) This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) This dissertation does not contain other persons' writing unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) Their words have been re-written but the general information attributed to them has been referenced;

b) Where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) Where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) This dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) This dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

[redacted]

_______________________

Signed: Peter Moumakwe

Date: 28/08/2024

## DECLARATION 2: PUBLICATIONS

The following papers were presented at the following conferences

1. The paper titled "Investigating long-term rainfall trends and variability over the Limpopo province, South Africa from 1990-2020" was presented at the 36th annual conference of the South African Society for Atmospheric Sciences (SASAS) on the 31st – 1st November 2022 at Global change institute at University of Witwatersrand, under the theme "Climate change tipping points in southern Africa".

2. The paper titled "Assessing the spatial and temporal variability and trends of wet days and dry spells over the Limpopo province for the period 1990 to 2021", was presented at the at the Society of South African Geographers Conference on the 2-4 October 2023, at University of Free State, Qwaqwa Campus.

[redacted]

Signed: Moumakwe PL

Date: 28/08/2024

## ABSTRACT

The Limpopo Province is home to a large rural population which is highly dependent on rain-fed agriculture. Although extensive research has been undertaken to understand rainfall variability over South Africa, a better understanding of the localized rainfall characteristics and variability remains crucial for decision-makers and the livelihoods of the local community. The study aims to investigate rainfall variability and trends over the Limpopo province, understand the distribution (both spatial and temporal) of seasonal rainfall characteristics, and also establish the relationship between seasonal rainfall characteristics with larger modes of climate variability (i.e. El Niño Southern Oscillation (ENSO), and Southern Indian Ocean Dipole (SIOD)).

High-resolution Climate Hazard Group Infrared Precipitation with Station Data (CHIRPS) 0.05° gridded data spanning the duration 1990-2020 was employed to analyze the spatial distribution of rainfall over the Limpopo province. In this study dry spells (pentads with < 5 mm rainfall), moderate (rainfall ranging from 10-30 mm per day) and heavy wet days (rainfall > 30 mm per day) were analyzed. Standardized Anomaly Index (SAI) was used to understand the relationship between rainfall characteristics and anomalies. The Mann-Kendall test was also used to determine the trends of seasonal rainfall characteristics over the province. The Pearson correlation was used to establish the association between seasonal rainfall characteristics (dry spells, moderate and heavy wet days) and large modes of variability (ENSO and SIOD).

The results of this study show that seasonal rainfall exhibits high spatial and temporal variability over the study period. Throughout the extended summer season (October-March (ONDJFM)), dry spells migrate from the north of Vhembe and Capricorn to the northeast of Mopani, with their frequency and extent increasing from early summer (October-November) to late summer (February-March). The distribution of these rainfall characteristics follows that of mean annual rainfall. Of all periods, December-January (DJ) receives the highest frequency of moderate wet days with a larger spatial extend ranging from 6-13 days in the high-lying escarpment of Vhembe, west of Mopani, south-east of Capricorn, Waterberg, and Greater Sekhukhune. The

highest heavy wet day frequency is also observed in the DJ period, over the high-lying escarpment of Vhembe, west of Mopani, south-east Capricorn and north of Greater Sekhukhune records heavy wet days ranging from 3-7 days.

The results of the Mann-Kendall trend test revealed a statistically significant decreasing trend in dry spells during DJ and February-March (FM) over the entire Limpopo province. Statistically significant moderate wet day trends were observed during ON over north and east of Mopani, south-east of Capricorn, and west of Mopani district, whereas during the DJ periods, statistically significant increasing trends are recorded over the south-east of Vhembe and north-west of Mopani. During DJ, statistically significant increasing heavy wet day trends are observed over Vhembe, Greater Sekhukhune, and west of Waterberg.

The relationship between seasonal rainfall characteristics and rainfall anomalies was observed. The results show that the inter-annual variability of seasonal rainfall characteristics does not always reflect in seasonal rainfall totals/anomalies. This shows that anomalies overlook the isolated impact of seasonal rainfall characteristics. The relationship between seasonal rainfall characteristics and large modes of variability was observed. A strong negative correlation with moderate wet days over the high-lying escarpment in the Vhembe district and south of the Mopani district. However, a complex relationship was observed between the inter-annual rainfall characteristics and large modes of variability. The results showed that not all La Nina years or positive phase SIOD phase equate to wet seasons. Furthermore, years with neutral ENSO and SIOD phases still exhibited above-average wet days.

## ACKNOWLEDGMENTS

- First and foremost, I would like to extend my thanks to the Almighty for granting me the gift of life, talent, and the wonderful people who have surrounded me throughout this journey.
- I owe a great debt of gratitude to my supervisors, Dr. Lawrence Dube and Dr. Mokhele Moeletsi, for their exceptional guidance and unwavering support. Your constructive comments and encouragement have been a driving force behind this study.
- I extend my heartfelt thanks to Dr. Ramontsheng Rapolaki for his pivotal role in my research. Your guidance, patience, and assistance with technical questions, as well as helping me with my Python scripts, have been indispensable. You instilled confidence in me, and for that, I am truly grateful. Modimo ke oo!!!
- To my beloved parents, Betty and Nico Moumakwe, your unwavering support, encouragement, and the confidence you instilled in me during my years of study have been instrumental in my success. I am profoundly grateful. I also want to express my appreciation to my little brother, Modikwe Moumakwe, for his support and understanding.
- I would like to express my appreciation to the Agro-meteorology staff at the ARC and fellow students for their company and thoughtful inputs throughout this academic journey.
- Special thanks are reserved for Mr. Marks Sebaiwa, whose unwavering support and advice have been with me from the very first day until the completion of this thesis. Your dedication has made a significant difference, and I am thankful.
- Lastly, I extend my gratitude to the University of KwaZulu-Natal (UKZN) for granting a fee remission in my first year, and to the Agricultural Research Council (ARC) and the National Research Funding (NRF) for their financial support for this project.


"I can do all things through Christ who strengthens me." (Philippians 4:13)

**TABLE OF CONTENTS**

**LIST OF FIGURES**

**LIST OF TABLES**

**LIST OF ACRONYMS**

Here is the list organized alphabetically:

AL - Angola Low

ARC - Agricultural Research Council

BH - Botswana High

CDF - Cumulative Distribution Frequency

CHIRPS - Climate Hazard Group Infrared Precipitation with Station Data

COL - Cut-Off Low

CV - Coefficient of Variability

DJF - December-January-February

ENSO - El Niño Southern Oscillation

GHG - Greenhouse Gas

IWRM - Intergraded Water Resource Management

ITCZ - Inter-tropical convergence zone

JFM - January-February-March

KNP - Kruger National Park

LRB - Limpopo River Basin

LULC - Land-use land Cover

MAE - Mean Absolute Error

MCS - Mesoscale Convective System

MCT - Mozambique Channel Trough

MJO - Madden-Julian Oscillation

MSE - Mean Squared Error

NDP - National Development Goal.

OLR - Outgoing longwave Radiation
OND - October-November-December
QBO - Quasi-Biennial Oscillation
RMSE - Root Mean Square Error
RVF - Rift Valley Fever
SAI - Standardized Anomaly Index
SAM - South Annular Mode
SDG - Sustainable Development Goal
SI - Seasonality Index
SIOD - Southern Indian Ocean Dipole
SST - Sea Surface Temperature
SWIO - South-Western Indian Ocean
TTT - Tropical Temperate troughs

# 1 INTRODUCTION

## 1.1 Background

Southern Africa is characterized by significant intra-seasonal and long-term rainfall variability, making it prone to droughts and floods (Reason *et al.*, 2005). Rainfall variability affects many socioeconomic activities in South Africa, including food security, livelihoods, and farming (Atiah *et al.,* 2019). Climate models suggest that no area will be immune to the impacts posed by climate change in the present and future (Ngoma *et al.*, 2021). Africa as a continent is one of the most vulnerable continents in the world (Jansen and Schulz, 2006). Studies show that southern Africa is warming faster than the global average (Fauchereau *et al.,* 2003; Phaduli, 2018). The IPCC reported that from 2011 to 2020 global surface temperature was 1.1º C higher than from 1850 to 1900 (IPCC, 2022). This increase is close to the threshold of 1.5 and 2ºC, which is defined as “dangerous climate change” (IPCC, 2022). However, decreases in rainfall and extreme temperature events are projected to be frequent under the 1.5ºC of global warming (Engelbrecht and Monteiro, 2021). The dangerous climate change threshold is likely to be reached by the early 2030s (Engelbrecht and Monteiro, 2021).

Understanding how rainfall patterns have changed over time is crucial for grasping the complex aspects of climate change and variability. This knowledge forms the foundation for effective planning (Masupha *et al.,* 2016). As more and more evidence shows that climate change and variability have a significant impact on the environment (Bartzke *et al.*, 2018) and agricultural production (Moeletsi *et al.*, 2013), it is important to carefully analyzech the specific ways in which these changes happen in different places and times. This detailed understanding is essential for creating targeted strategies to adapt to these changes. The practical effects of extreme weather events like floods, droughts, hailstorms, or frost—whether they occur on their own or together have far-reaching consequences for agriculture. These effects have a profound influence on both food security and the lives of local communities (Lestari *et al.,* 2019; Walker and Schulze, 2008)

Since the Limpopo province comprises a large rural population (Rapolaki *et al.,* 2020), with limited economic adaptability and insufficient scientific comprehension. The region is vulnerable to extreme climate events, which threaten agricultural production and food security (Dlamini *et al.*, 2011; Landman and Mason, 1999). A study by Chikosi *et al.* (2019) highlighted the climate change and variability perceptions of rural communities in the Limpopo province. The findings show that community members are aware of the devastating changes in their living conditions, such as floods and droughts although they do not have much evidence on adaptation and mitigation strategies for these climate hazards. To cope with increasing rainfall variability and drought frequency, tools that assist with rainfall forecasting at a finer spatial resolution are needed (Jury and Dube, 2000).

The province is facing mounting pressures from factors such as population growth, urbanization, industrial expansion, and increasing agricultural practices (Dag Heward-Mills, 2004). These challenges are compounded by issues of climate change and variability (Botai *et al.*, 2020). The consequences of climate change and variability are anticipated to manifest as higher temperatures, increased evaporation demands, shifts in rainfall patterns, and a heightened occurrence of both flooding and drought (Masupha *et al.*, 2016; Mosase and Ahiablame, 2018). However, it is important to note that these patterns are projected to exhibit variability across different parts of the Limpopo province (Mosase and Ahiablame, 2018). This suggests that distinct regions within the province might encounter varying degrees of climate-related issues in the future.

Rainfall variability is influenced by meteorological drivers. These drivers include Sea Surface Temperature (SST), El Niño Southern Oscillation (ENSO), and land-atmosphere feedback (Nicholson 2000; Nkuna and Odiyo, 2016). At the inter-annual scale, the variability of rainfall has been predominantly attributed to the ENSO (Hoell and Cheng, 2018). This is in line with the findings of Kane (2009), who discovered pronounced year-to-year fluctuations in rainfall with variances ranging from 50% to 200% of the mean in South Africa. Notable episodes of extreme weather events in the form of major droughts and floods have been associated with the occurrence of ENSO.

Studies have highlighted that during El Niño (La Niña) events, rainfall decreases (increases) over the south-eastern region of Africa (Rouault and Richard, 2005; Trenberth and Hoar, 1997; Zhao *et al.,* 2019). This results in dry (wet) conditions. Rainfall anomalies can also be attributed to varying positions of synoptic features such as tropical cyclones (Kuleshov *et al.*, 2008), Tropical Temperate Troughs (TTTs: Reason and Jagadheesha, 2005; Pohl *et al.,* 2009; Ratna *et al.,* 2013), Angola Low (AL: Nicholson and Selato, 2000) and walker circulation (Gore *et al.,* 2020). Rapolaki. *et al.* (2019) have also reported that, on an inter-annual timescale, the majority of summers exhibiting above-average extreme rainfall events within the Limpopo Basin coincide with La Niña phases. Additionally, Reason *et al.* (2005) have also shown that La Niña events are correlated with below-average occurrences of dry spells.

Impacts of extreme climate are severe, more especially in regions that consist of a relatively large, poorly resourced rural subsistence population and several large parks, including the Kruger National Park (KNP)(Malherbe *et al.*, 2020; Mathivha *et al.*, 2017; Zambatis and Biggs, 1995). Drought events that occurred in 1982/83, 1997/98, 2002/03, and 2015/16 were strongly linked to El Niño occurrences (Blamey *et al.*, 2018; Monyela, 2017; Ndlovu and Demlie, 2020; Nicholson and Entekhabi, 1987; Reason and Jagadheesha, 2005). The Limpopo province has been severely affected by droughts (2001-2004) and, extreme rainfall in February 2000 (Dyson and Van Heerden, 2001), which caused floods in the north-eastern South Africa and southern Mozambique.

The population of the province is expected to increase in the future. This will add pressure to the already scarce water resources and agricultural production (Machete *et al.*, 2024; Ntombani, 2019; Statistics South Africa, 2021). However, understanding the spatiotemporal distribution of rainfall characteristics may aid in informed decision-making, improved monitoring plans, and focused management tasks (Kumar and Kumar, 2020). As a result, much emphasis in this dissertation is placed on understanding rainfall characteristics and extremes, as well as their spatial and temporal attributes, to better understand rainfall in the area and help with the allocation of resources for sectors such as agriculture and tourism.

### 1.2 Research problem statement

Climate change and variability are attributed to have dire impacts on socio-economic sectors such as water resources, energy, agriculture, and health services (Botai *et al.*, 2020). Consequently, this forced government institutions to revise the existing mitigation and adaptation strategies and further reduce the vulnerability of rural exposed communities (Botai *et al.*, 2020). Agriculture and tourism in the province are some of the sectors that contribute significantly to the economy and employment (Maponya *et al.*, 2016; Maponya *et al.*, 2013; Nyoni *et al.*, 2022). Several studies have worked on the perception of farmers on climate change in the Limpopo province. Most studies found that subsistence farmers in the Limpopo province are aware of climate change, although they lack capital, scientific knowledge, and resources to better adapt. This further makes them vulnerable to any impact and threats associated with the changing and variable climate.

Investigating the spatial and temporal distribution of inter-annual and seasonal rainfall will play a vast role in assisting decision-makers to properly allocate resources and establish areas that need attention in terms of managing impacts associated with droughts and floods. Therefore, a comprehensive analysis of seasonal and temporal rainfall characteristics across the Limpopo province is crucial for providing a detailed understanding of the nature of rainfall in the area. This plays a fundamental role in enhancing local interpretation of rainfall as well as resource allocation to promote sustainability in the province.

Numerous studies ( Mupangwa *et al.,* 2011; Maponya and Mpandeli, 2012; Kephe *et al.,* 2016; Masupha *et al.,* 2016; Kruger and Nxumalo, 2017; Masupha and Moeletsi, 2017; Gebrechorkos *et al.,* 2021; Shikwambana *et al,* 2021; Mazibuko *et al.,* 2021; Roffe *et al.,* 2021) have been conducted to understand the spatial and temporal distribution of rainfall over the Limpopo province. This studies used weather station data that is sparsely distributed and consists of gaps (Chikosi *et al.,* 2019; Dube *et al.,* 2020; Garidzirai *et al.,* 2019; Mafunzwaini and Hugo, 2005; Nyoni *et al.,* 2022). This limits our ability to synthesize rainfall in the area and deeply understand its distribution and characteristics. This study will bridge that gap by using high-resolution gridded data to understand rainfall distribution. The use of satellite-derived rainfall has found limited application in climate studies, particularly in the Limpopo province.

The relationship between large-scale climate models and seasonal rainfall characteristics such as dry spells and wet day frequencies will be investigated. This will help forecasters improve and understand if there is any predictability that exists between the large-scale modes of climate variability and seasonal rainfall characteristics (Dube and Jury, 2003).

## 1.3 Research questions

Understanding the spatial distribution of different rainfall characteristics can assist with understanding the implications of rainfall on agriculture and resource allocation in the province. Previous studies have focused more on anomalies in seasonal totals, rather than characteristics that constitute seasonal rainfall. Cumulative rainfall overlooks the impact of isolated rainfall events (i.e. heavy rainfall) on agriculture (Reason *et al.*, 2005). Therefore, understanding the spatial and temporal distribution of rainfall anomalies and cumulative rainfall can give a false impression that a rainfall season was good to support agriculture, whereas the rainfall constitutes of few extreme rainfall events and consecutive dry spells. Crop production can be negatively affected as hot, dry conditions prevail, despite the cumulative rainfall or anomalies being favorable (Reason *et al.*, 2005; Tadross *et al.*, 2005; Tennant and Hewitson, 2002). Understanding the frequency and duration of rainfall characteristics such as dry spells also serve a significant role as they indicate the degree of stress plants are exposed to (Masupha *et al.*, 2016; Reason *et al.*, 2005).

Furthermore, although the overall amount of rainfall may remain relatively constant over time, alterations in the distribution of wet and dry events within the season can have severe implications for people's livelihoods (Hachigonta and Reason, 2006; Tadross *et al.*, 2009). Therefore, gaining an understanding of the general teleconnection associated with these wet and dry events can drive a deeper understanding of the mechanisms behind these inter and intra-seasonal rainfall characteristics variability. It is worth noting that a season with above-average rainfall is not necessarily better than a below-average season if the rainfall is not well distributed (Thoithi *et al.*, 2021). Consistency in receiving the minimum required rainfall at various crop stages is more critical for crop growth and production than the total amount of rainfall received (Matimolane *et al.*, 2022). Uniformly distributed "light and moderate" rains are more favorable for crops than a few heavy rainy days interrupted by dry periods (Hachigonta *et al.*, 2008; Tadross *et al.*, 2005; Taljaard, 1986).

Rainy seasons tend to be made up of a combination of wet and dry spells occurring after and before the defined onsets and cessation dates that directly influence human activity. Therefore, rainfall characteristics provide more useful information about rainfall to user groups and stakeholders, for instance, increased dry spell duration has been associated with drought and a decrease in growing season duration. Understanding the spatial and temporal patterns of rainfall characteristics will assist in identifying regions with more susceptible to climate extremes and areas experiencing

This study seeks to address the following research questions:

- What is the nature of rainfall variability in the Limpopo province from 1990 to 2020?
- What are the seasonal rainfall trends during this period?
- What are the seasonal rainfall characteristics for this period?
- What is the relationship between the larger modes of climate variability and seasonal rainfall characteristics?

### 1.4 Aim

The study aims to investigate the spatial and temporal distribution of seasonal rainfall characteristics as well as their relationship with large modes of climate variability over the Limpopo province for the period 1990-2020.

### 1.5 Specific objectives

The objectives of this study are to:

- Determine the annual rainfall variability and trends in the Limpopo province.
- Determine seasonal rainfall characteristics in the region.
- Establish the relationship between the seasonal rainfall characteristics and large modes of climate variability.

### 1.6 Outline of the dissertation

This dissertation consists of five chapters that significantly contribute to the understanding of seasonal rainfall characteristics over the Limpopo province for the period 1990 to 2020:

Chapter 1 serves as an introduction, providing background information on the study. This chapter also outlines the objectives and aims of the research.
Chapter 2: A review of a variety of relevant literature that informs this study.
Chapter 3: A description of data and methods used in this study and how they are applied to best achieve the objectives of the study used in this study.
Chapter 4 presents the results and discussions of this study.

Chapter 5 offers an overview of the study's findings, highlighting key results, explaining the contributions of the research, providing recommendations, and suggesting possible future research areas to explore.

# 2 LITERATURE REVIEW

## 2.1 Introduction

Southern Africa is predominantly a semi-arid region characterized by high inter-annual rainfall variability and a distinct seasonal rainfall cycle. Rainfall variability in the region is influenced by topography, large ocean-atmosphere interactions, and its geographic position between the tropics and mid-latitudes (de Souza *et al.*, 2021; Dedekind *et al.*, 2016; Kibii *et al.*, 2021; Mason and Joubert, 1997; Mason and Jury, 1997; Nicholson *et al.*, 2014). The inter-annual variability in southern Africa is further affected by Sea Surface Temperatures (SST) in the Atlantic, Indian, and Pacific Oceans (Dieppois *et al.*, 2019; Rayner *et al.*, 2003; Reason, 2017), with El Niño-southern Oscillation (ENSO: Hoell *et al.*, 2014; Kane, 2009; Philippon *et al.*, 2012) being a critical climate mode. Additionally, studies indicate that the Subtropical Indian Ocean Dipole (SIOD: Behera and Yamagata, 2001; Hoell and Cheng, 2018), the Southern Annular Mode (SAM: Holz *et al.*, 2017; Lim *et al.*, 2016; Malherbe *et al.*, 2014), and the Benguela Niño (Hoell *et al.*, 2023) also exert substantial influences on inter-annual scales in specific parts of the region.

In recent years, population expansion, economic growth, growing urbanization, and shifting weather patterns have placed pressure on the region's already restricted water resources and agricultural production (Jansen and Schulz, 2006; Masupha and Moeletsi, 2017). In spite of occasional water restrictions, water use in this region has more than quadrupled in the past 30 years (Jansen and Schulz, 2006; van Koppen *et al.*, 2020). The persistence of dry conditions in southern Africa increases the demand for water resources (Dube and Jury, 2003; Mason and Jury, 1997). The inability of water as a resource to meet the demands will pose both direct and indirect devastating impacts on the socio-economic and biophysical environments.

Rain-fed agriculture is important for providing food and livelihoods to the exponentially increasing population (Rockström *et al.*, 2010). To address the increasing demand for water and food, there is an urgent need to improve Integrated Water Resource Management (IWRM), more especially in regions where rainfall is regarded as the entry point for the governance of freshwater. Given the region's high inter-annual variability, highly accurate seasonal forecasts are essential for effective water resource planning and mitigating the impacts of droughts and floods (Mason and Jury, 1997).

Understanding the atmospheric interactions and characteristics that drive wet and dry conditions is crucial for optimizing water resources and enhancing agricultural productivity (Jury and Dube, 2000). This chapter seeks to understand the atmospheric patterns influencing rainfall variability in southern Africa.

## 2.2 Climate change

Climate change poses a risk to the existence of humanity and the ecosystem. Although climate change can occur naturally, anthropogenic activities have exacerbated the rate at which Greenhouse gases (GHGs) are emitted to the atmosphere (Alley *et al.*, 2003; Rahman and Lateh, 2017; van der Bank and Karsten, 2020). This has subsequently increased the rate at which climate changes over time. The unequal historical and ongoing human contribution to global emissions will continue to increase (Ongoma and Chen, 2017). This occurs as a result of unsustainable energy use and Land Use Land-Cover Change, which directly results from human activities that support livelihoods (LULC: IPCC, 2022). This has led to an increase in the atmospheric concentration of several GHGs [CO2, CH4, and N2O](IPCC, 2022) (**Figure 2.1**).

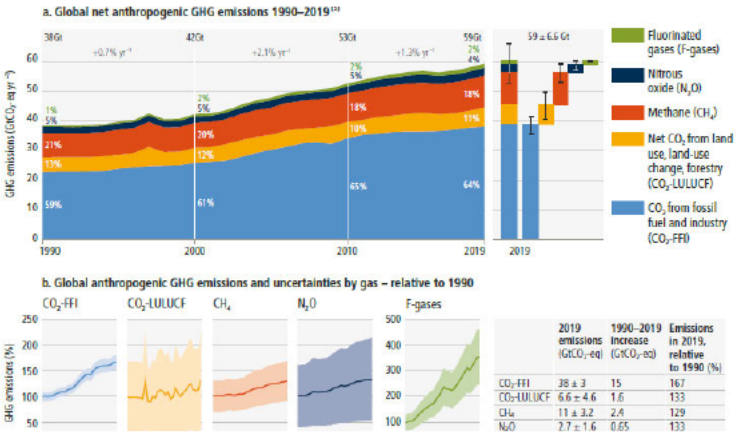


Figure 2.1: Global net anthropogenic Greenhouse Gas (GHGs) emissions from 1990-2019 (IPCC, 2021).

Global temperatures have already warmed by 0.5ºC over the past century (Collier *et al.*, 2008; Mccarty *et al.*, 2021). Following the Paris Agreement of December 2015 (UNFCCC, 2015), there is an international effort to limit global warming to below 2ºC above pre-industrial levels. Research indicates that exceeding the 1.5ºC and 2ºC thresholds will result in increased climate extremes. The relatively low economic development of Africa exacerbates its vulnerability to the adverse impacts of climate change (IPCC, 2022; Nangombe *et al.*, 2018).

Exacerbating rates of heating might increase the evapotranspiration rate and cause the surface to dry as a consequence (Green *et al.*, 2011; Trenberth, 2011). Bates *et al.* (2008) and Kunreuther *et al.* (2013) maintain that semi-arid and arid regions (i.e. western USA, northern Brazil, and southern Africa) are exposed to possible climate change impacts and they are further projected to suffer a substantial deficit of water resources. In South Africa, the arid interior and the moist northern eastern region are projected to experience increased rates of evapotranspiration, stress, and persistent droughts (van Jaarsveld and Chown, 2001; Lian *et al.*, 2021). Furthermore, the winter rainfall region (south-western region) of the country is likely to be subjected to increased early winter frontal and orographic rainfall (van Jaarsveld and Chown, 2001).

### 2.3 Global impacts of the changing climate

The acceleration of GHGs has rapidly aided the progression of the changing climate and further influenced extreme weather events (Green *et al.*, 2011). Climate change impacts affect both developed and developing countries (van der Bank and Karsten, 2020). Exposure to extreme climatic hazards increases the vulnerability of Africa as compared to other nations (Leichenko and O'Brien, 2002; Collier *et al.*, 2008; Hosu *et al.*, 2016; Jagarnath *et al.*, 2020; Samuels *et al.*, 2022; Mutengwa *et al.*, 2023). Impacts of climate change are unevenly distributed within different sectors, other sectors in some regions will benefit from climate change, whereas others may suffer (Downing *et al.,* 1997; Gbetibouo e*t al.,* 2010; Gössling and Humpe, 2020; Naik and Abiodun, 2020).

Global climate impacts threaten human health, the environment, economy, and stress existing social arrangements (**Figure 2.2**)(Linares *et al.*, 2020; Taye *et al.*, 2018). Climatic changes will bring changes in crop growth and affect annual average income through agriculture (Love *et* *al.*, 2010; Mupangwa *et al.*, 2011; Lemi and Hailu, 2019; Nhemachena *et al.*, 2020; Maja and Ayano, 2021). Food security and malnutrition will pose devastating social impacts (Mzezewa *et al.*, 2010), All impacts could be traced back to the primary importance of fossil fuels for energy, transportation, and manufacturing (Armah *et al.*, 2011; Gökmen and Temiz, 2015).

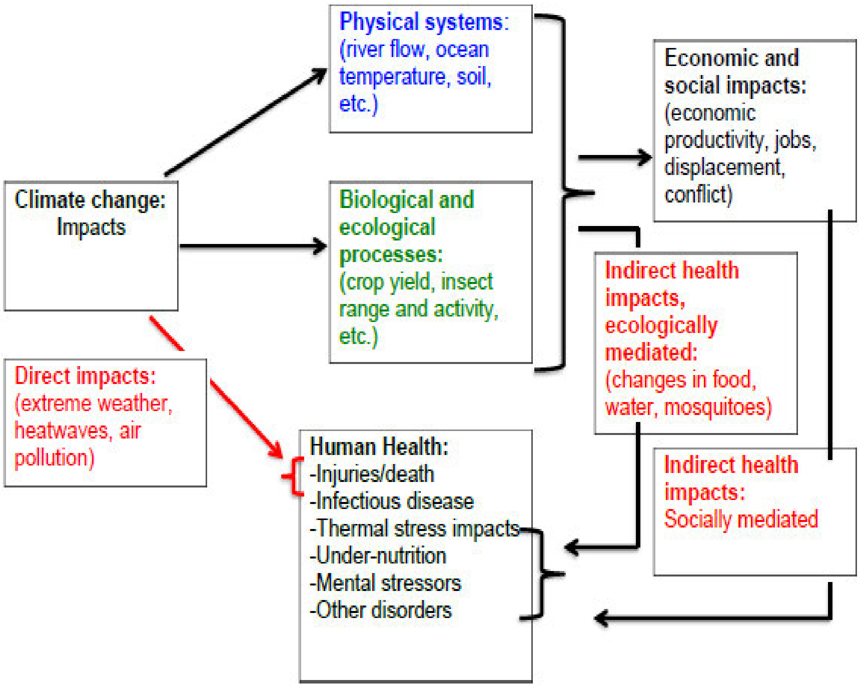


Figure 2.2: Climate change impacts on social, biological, and health systems pathways (Lipsett, 2017).

### 2.3.1 Environmental Impacts

Consequences of climate change are already visible (Calzadilla *et al.*, 2013; Gebrechorkos *et al.*, 2021; Malik *et al.*, 2019; Nhamo *et al.*, 2019; Zinyengere *et al.*, 2014). For instance, temperatures are rising (Bates *et al.*, 2008), sea levels are rising (Manatsa *et al.*, 2008; Mather and Stretch, 2012), polar caps are melting (Adedeji *et al.*, 2014; Bates *et al.*, 2008), winters in Europe are forever wet (the Gulf stream influences the climatic conditions) and desertification is increasing as well (Adedeji *et al.*, 2014; O'Reilly *et al.*, 2020). Observations also demonstrated that Mount Kilimanjaro in Tanzania is currently experiencing less snow because of global warming. However, Scientists do not know whether or not Mount Kilimanjaro will be covered with snow soon (Adedeji *et al.*, 2014). Wet areas will become wetter and dry areas will become drier (Trenberth, 2011). This simply implies that the frequency and intensity of hydrological extreme events (droughts and floods) will increase as compared to past times (Whitehead *et al.*, 2009; Adedeji *et al.*, 2014; Thomas *et al.*, 2022).

Li and Fang (2016) reported that extreme rainfall events, (higher rainfall amounts and rainfall intensity) could directly elevate soil erosion. The following effects of extreme rainfall are exhibited in several studies: Loss of land availability, enhanced drainage and accelerated aridification processes, increased occurrence of floods, decreased water recharge, and suspended sediments in streams (Dlamini *et al.*, 2011; Kakembo and Rowntree, 2003; Le Barbé *et al.*, 2002; Le Roux *et al.*, 2013; Valentin *et al.*, 2005). Vegetation loss reduces infiltration rates, reduces the ability of roots to capture water, and further increases runoff (Alley *et al.*, 2003). Seven existing biomes in South Africa are expected to shrink by at least 40% (van Jaarsveld and Chown, 2001). Grasslands are susceptible to invasion by Savannah tree species (van Jaarsveld and Chown, 2001). This will result in the enlargement of the savannah biome and will probably amount to an increase in bush encroachment.

The predominantly rain-fed agriculture in Africa will remain the victim of climate change and experience a substantial burden of climate change impacts. Agronomists have long highlighted the vulnerability of developing countries to the warming climate in contrast to developed countries (Mendelsohn, 2008; Mpandeli, 2014). The impacts of climate change on agriculture are not uniformly distributed. Abrupt extreme weather conditions undoubtedly pose a threat to agricultural water and production (Lu *et al.*, 2019). High evaporation will decrease soil moisture, resulting in crop drought and reducing yield production (Lu *et al.*, 2019). According to Lu *et al*. (2019) and Adams *et al.*, (1998) climate change has negatively affected rice yield. High temperatures in semi-arid areas will shorten the crop cycle and reduce crop and livestock yield (Adams *et al.*, 1998; Calzadilla *et al.*, 2013). Flooding will also become a significant problem in some flood-prone regions (Aydinalp *et al.*, 2008). Adverse impacts of heavy rainfall on food security are already felt in Southern Africa (Calzadilla *et al.*, 2013). Temperature and precipitation are likely to influence crop management practices (Lu *et al.*, 2019).

### 2.3.2 Health impacts

The effects of climate change are heavily dependent on the ability of humans and health systems to adapt (Khasnis and Nettleman, 2005). Increased exposure to extreme weather events poses health impacts to animals, plants, and humans (Adedeji *et al.*, 2014). Collier *et al.* (2008) maintain that extreme temperatures (above 30$^{o}$C) will have a tremendous effect on health. Linares *et al.* (2020) reported that old people and those with chronic diseases are faced with health risks because of climate change. The most vulnerable individuals include those with pre-existing diseases especially those with pulmonary illness (Javadikasgari *et al.*, 2018; Khasnis and Nettleman, 2005).

Warmer climates and changing rainfall patterns create a suitable environment for vector-borne diseases, vector-pathogen interaction, and pathogen replication (Adedeji *et al.*, 2014; Khasnis and Nettleman, 2005; Tabachnick, 2010). Owing to the increase in disease-carrying insects, the effects of vector-borne diseases will be substantial (Collier *et al.*, 2008). In the Horn of Africa, the ENSO and satellite imagery were used to predict the outbreak of Rift Valley Fever (RVF) (Nicholas *et al.*, 2016; Tabachnick, 2010). The results show that an outbreak of RVF is closely linked with excessive rainfall. This further highlights the importance of climate variables in vector-borne disease surveillance and risk management.

Climate change also increases the threat of food insecurity. For instance, high temperatures influence the survival and multiplication of *Salmonellosis* (food-borne disease)(Linares *et al.*, 2020). It was observed that temperature played a vital role in influencing 35% of *Salmonellosis* infections (Kovats *et al.*, 2004). If temperatures continue to rise as projected, the risk of food-borne diseases will be eminent (Grjibovski *et al.*, 2014; Milazzo *et al.*, 2016; Shmeleva, 2020; Kynčl *et al.*, 2021; Morgado *et al.*, 2021).

### 2.3.3 Economic impacts of climate change

Global climate change enormously threatens nature as well as the economy. Although the IPCC has not yet produced a tangible estimation of the costs of global change to the economy (Adedeji *et al.*, 2014), they have managed to produce costs of limiting further climate change. It is projected that taking action on climate change will slightly boost global economic income compared to a scenario where no action is taken (Adedeji *et al.*, 2014).

The shift in supply and demand will tremendously affect the global price of traded agricultural commodities (Winters *et al.*, 1998). The linkage between the agricultural sector and other sectors will lead to changes in yield and prices (Winters *et al.*, 1998). Economic shocks will manifest based on the relative importance of different crops (Winters *et al.*, 1998). A decline in the supply of goods as a result of extreme weather events might cause inflationary pressures (Dell *et al.*, 2008).

Extreme weather events can be liable for the destruction of buildings and infrastructure, and reduce production in manufacturing, construction, and energy sector and the service sectors (transport, tourism, financial services, and telecommunications) (Heidari *et al.*, 2020; Iqbal *et al.*, 2021). Demand shock side caused by extreme weather events of climate change constitutes of reduction in household wealth, and thereby affects investments and business, leading to the deterioration of financial assets (Oh and Reuveny, 2010). Supply-side shock is represented by damage to capital stock and infrastructure. This will affect imported inputs, more especially commodities (i.e. food and energy), resulting in shortages which in turn result in volatility in prices (Gassebner *et al.*, 2010).

Extreme climatic events (such as rising sea levels, droughts, floods, and storms) pose a huge financial risk, with an estimated annual loss of billions of US dollars (Trenberth, 2011; Eckstein *et al.,* 2021). These events can also pose a significant threat to insurance companies and can affect the value of physical assets. Khan *et al*. (2022) studied the long-term macroeconomic effects of climate change. The study stipulated that volatile weather events, changes in precipitation, and high temperatures tend to have long-term effects on macroeconomics and affect labour production (Khan *et al.*, 2022). The study also emphasized that temperatures below 2ºC will reduce global income by 1% by the year 2100. Predictions using the RCP 8.5 scenario show that an increase in temperature by 0.04ºC will reduce the world's GDP per capita by 7% by the year 2100 (Khan *et al.*, 2022).

## 2.4 Implications of southern African climate on agriculture and water resource

The connection between climate water resources and agriculture in southern Africa has been recognized by climate experts for a long time. As a result, the geographical community has experienced increases in hydro-climatological research, with climatologists and hydrologists adopting an integrated approach to comprehending hydrological phenomena within a climatological context. Hydro-climatologists examine hydrological events within the spatial context of changing ocean, atmosphere, and land surface conditions to develop models for the improved explanation and prediction of water-related hazards, water resource availability, and consequently the management of water supply and demand.

Climate change studies show evidence of intensification of the global water cycle, with extreme events expected to become more frequent (Kusangaya *et al.*, 2014; Manatsa *et al.*, 2011; Trambauer *et al.*, 2015). For instance, the ENSO effects have continued to strengthen in the recent decades resulting in severe droughts and floods. However, drought conditions are likely to increase the frequency of extremely low flow and low storage episodes and inevitably affect water supply, irrigation, and hydro-generation (Kusangaya *et al.*, 2014). Since the mid-1970s, dam levels have been decreasing in Namibia (Jury and Engert, 1999) and in South Africa since the early 1980s as a result of a sustained rainfall deficit in the 1980s and early 1990s (Mason, 1995). In September 2016, the level of the Vaal Dam in South Africa fell to about 26% at the end of a 4-year drought (Engelbrecht and Monteiro, 2021). Jury and Dube (2000) also ascribed the fall in inflow levels of the Midmar Dam and Pongolapoort reservoir in 1992/93 to KwaZulu-Natal drought episodes.

A study by Hoell *et al.* (2017)) reported that the ENSO and Southern Indian Ocean Dipole (SIOD) are linked with the reduction of runoffs in southern Africa and follow a fairly similar pattern with the contemporaneous precipitation anomalies. Alemaw and Chaoka (2016) evaluated the implications of the warm phase of ENSO events on river flow variability in southern Africa. The study reported that there is a decline in annual rainfall in parts of Zambia, Namibia, Mozambique, and Lowveld South Africa, and this is due to the high frequency of drought-related to warm ENSO. Although drought is primarily associated with a lack of consistent precipitation, recent research suggests that temperature plays a significant role in explaining recent trends in water supplies (Cai and Cowan, 2008; Gerten *et al.*, 2008; Lorenzo-Lacruz *et al.*, 2010).

Extremely high evapotranspiration rates and variability in the intensity of precipitation can result in significant water level fluctuations in shallow reservoirs. Simulated surface water resulting from precipitation is distributed to runoff and evapotranspiration. Arnell (2018) predicted a run-off of 26-40% in the Zambezi River system, as a result of reduced rainfall and increased evaporation. Evaporative increases of 40% could result in reduced outflow from reservoirs. The difference between runoff and evaporation allocations is attributable to climatology. In rainy or wetland regions, an increase in precipitation is devoted primarily to runoff rather than evaporation, because the amount of evaporation is almost constant due to the saturated land surface. The variability and changes in runoff reflect not only the patterns of precipitation but also the general increase in potential evaporation (Arnell, 2018)

Some areas in southern Africa are projected to experience an increase in the frequency and magnitude of heavy precipitation. The formation of TTTs in South Africa is associated with extended periods of heavy rainfall (Mason and Jury, 1997), particularly in the north and east of South Africa. Botai *et al.* (2020) report that such extremes are also attributed to the vulnerability of groundwater resource systems as well as the sensitivity of such systems to natural disasters through impacts on the changes in climatic variables such as precipitation, evapotranspiration, and streamflow. However, during this period, perennial rivers in parts of the southern and eastern cape reach their peak flow (Utete *et al.*, 2019). Under projected climate changes, intense tropical cyclones are likely to occur more frequently, and the possibility exists that these systems can follow more poleward trajectories.

As far as agriculture is concerned, the Limpopo province is predominantly inhabited by a rural population that relies on rain-fed agriculture for subsistence farming (Moeletsi *et al.*, 2013; Rapolaki *et al.*, 2019). Rainfall variability in this area is a complex issue with far-reaching consequences for agriculture (Adeola *et al.*, 2019; Gbetibouo *et al.*, 2010; Toté *et al.*, 2015). However, the low adaptive capacity of the region makes agricultural activities and management more challenging (Maponya and Mpandeli 2012). Due to the variability and inconsistencies in intra-annual, intra-seasonal, and inter-seasonal rainfall, drought and flood occurrences have become more frequent, intense, and persistent, and have caused socio-economic and agricultural disruptions (Ndlovu *et al.*, 2021). For instance, Mpandeli, (2014) reported that frequent droughts affect agricultural production in the Limpopo province. The severe drought of 1991-1992, which had traumatic impacts on smallholder farmers, was the most severe drought in the history of South Africa's droughts (Dube and Jury, 2002). The impacts of drought on agricultural yield and production have been highlighted by studies conducted by (Masupha and Moeletsi, 2017). Flood risks and events are also major concerns, resulting in noticeable impacts such as loss of life, destruction of infrastructure, and loss of property and livestock (Mosase and Ahiablame, 2018; Musyoki *et al.*, 2016).

Over the years, the number of consecutive dry days has been increasing together with daily extreme events (Ndlovu *et al.*, 2021; Ndlovu and Demlie, 2020). Late onsets and cessation, and changes in rainfall duration, are also characteristics affected by rainfall variability (Fiwa *et al.*, 2014). The study shows year-to-year variability of rainfall, with onsets being delayed. These adverse changes threaten the livelihoods of the already vulnerable population and indicate that rainfall variability results in shifts in areas and times suitable for the growth of many crops (Shikwambana *et al.*, 2021). Promoting sustainable agriculture and crop production and livelihoods, by developing and investing in adaption and livelihoods strategies, considering environmentally sound technology and feasible local adaptation strategies, and improving adaptive capacity, is essential (Gwambene *et al.*, 2023). This stresses the need for systematic measures to deal with stressors affecting agricultural production

## 2.5 Rainfall variability in southern Africa

The relationship between southern Africa's considerable climate variability on multiple scales and regional circulation systems is still poorly understood (Driver and Reason, 2017; Dube, and Jury, 2003; Nicholson *et al.*, 2014; Philippon *et al.*, 2012; Reason, 2017; Richard *et al.*, 2001). South Africa receives most of its rainfall during the summer season (ranging from October to March (ONDJFM)) (Reason, 2017) except for a winter rainfall region in the southwest (Philippon *et al.*, 2012; Malherbe *et al.*, 2016; Mahlalela *et al.*, 2019). The late summer season (January–March) often represents more than 40% of the annual rainfall amount (Rapolaki *et al.*, 2019; Richard *et al.*, 2001)

Precipitation in this region has a strong correlation with the Botswana High (Driver and Reason, 2017). The Botswana High develops in August and migrates southward over southern Africa as it strengthens during spring and summer (Driver and Reason, 2017), influencing droughts, heatwaves, and high temperatures (Singo *et al.*, 2023). Its position is always to the south and southeast of the Inter Tropical Convergence Zone (ITCZ) and its meridional arm, which flows over the eastern Congo Basin. As the ITCZ reaches its southernmost location across central Madagascar and Mozambique in January-February-March (JFM), southern tropical Africa and the south-west Indian Ocean islands (Madagascar, Mauritius, and Reunion)is subjected to wetter conditions (Reason, 2017).

The south-west JFM is drier than the October-November-December (OND) (**Figure 2.3**) due to the southern movement of the mid-latitude frontal system during summer. On the seasonal scale, linking regional circulation patterns to those of rainfall requires consideration of the large-scale moisture fluxes. In addition to moisture recycling over the Congo basin, there are three major oceanic sources of moisture for precipitation over southern Africa. The most important is the tropical western Indian Ocean. The subtropical southwest Indian Ocean is also a substantial contributor of moisture for rain over subtropical southern Africa, whereas the south Atlantic has been traditionally regarded as a secondary source of summer rainfall (D'Abreton and Lindesay, 1993; Reason *et al.*, 2006).

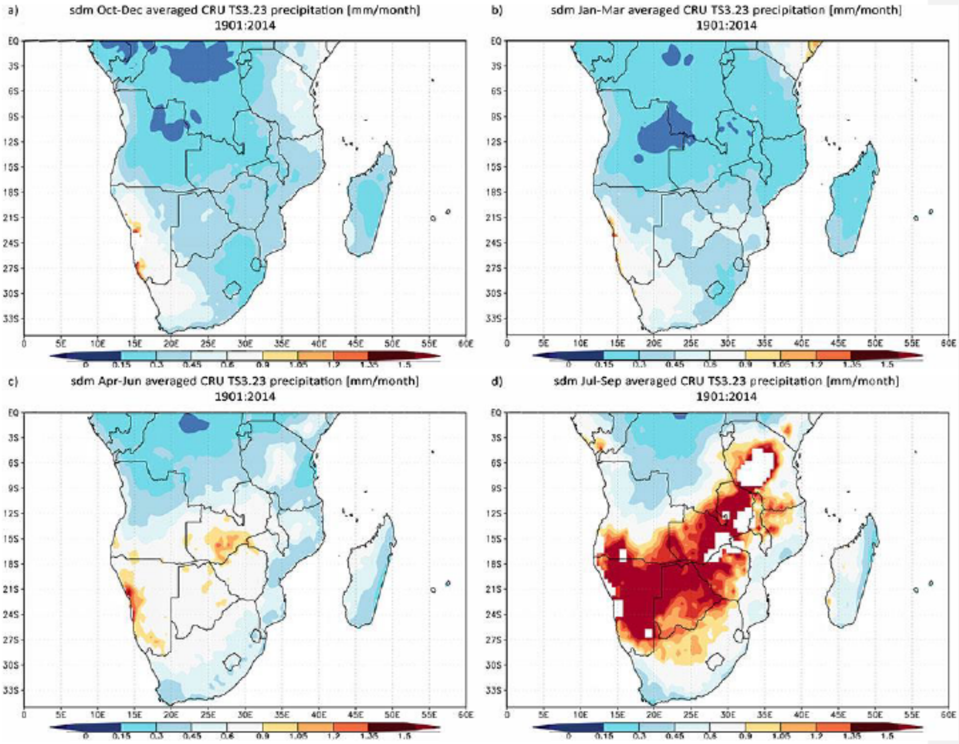


Figure 2.3: Seasonal rainfall averages (mm/month) over southern Africa (calculated from 1901-2014). The data is derived from CRU TS3.23. Frame (a) shows early summer rainfall, (b) Late summer, (c) early winter, (d) late winter rainfall. Source: (Reason, 2017).

ENSO significantly accounts for about 30% of rainfall variability in South Africa (Dube and Jury, 2002). ENSO is the most predictable source of natural variability on earth's climate on an annual scale (Hao *et al.*, 2020). The magnitude and duration of individual ENSO events are influenced by the combination of Bjerknes and equatorial wave feedbacks (Mcphaden *et al.*, 2006)). Cane (2005)referred to the Bjerkness feedback as the positive feedback between trade winds intensity and zonal SST contrasts. Trade winds weaken along the equator during El Niño as the atmospheric pressure in the western Pacific rises and declines in the eastern Pacific (Manatsa and Reason, 2017; Manatsa *et al.*, 2018). The El Niño (La Niño) year favours dry (wet) conditions during the austral summer in southern Africa (Meque and Abiodun, 2015; Richard *et al.*, 2001). During El Niño (La Niña), the speed of wind is weaker (stronger) than normal in the subcontinent (Philippon *et al.*, 2012). ENSO controls about 25% of wet seasons (JFM) rainfall variability (Lizcano and Todd, 2005). The AL promotes the relationship between ENSO and the southern African precipitation (Reason *et al.*, 2006).

The Quasi-Biennial Oscillation (QBO) in its westerly or easterly phase, modulates the effects of the ENSO over southern Africa in a manner still to be fully understood. When the QBO is westerly, over large areas of the summer rainfall region of southern Africa, more than 36% of the inter-annual variability in the late summer (JFM) may be ascribed to the ENSO (Reason and Mulenga, 1999). The modulation of the ENSO response over southern Africa by a westerly QBO is a result of its enhancement of the convergence field (Jury *et al.*, 1994). Conversely, when the QBO is easterly, the ENSO-rainfall association over the summer rainfall region weakens to a maximum of 16% of the variability and ceases to be statistically significant (Lau and Sheu, 1988). The modulation of the ENSO response over southern Africa at this time is a result of its enhancement of the divergence field at the surface (Jury *et al.*, 1994).

## 2.6 Atmospheric circulations responsible for wet and dry conditions in southern Africa

Variability in the number of days with significant rainfall in South Africa is caused by changes in the frequency, length, and intensity of large-scale meteorological systems. Both tropical and mid-latitude weather systems, as well as their interactions, are capable of producing significant precipitation across a major portion of southern Africa. For instance, the interaction between the tropical disturbance over southern Africa at the low latitude and a westerly system traveling south of the continent is responsible for the formation of Tropical-Temperate Troughs (TTT: Harrison, 1984; Hart *et al.*, 2010). Strong easterly (westerly) flow from the tropical Indian (mid-latitude South Atlantic) Ocean facilitates moisture convergence and subsequent advection from the tropics to the mid-latitudes in the TTT (Harrison, 1984; Hart *et al.*, 2010; Reason, 2017).

TTTs contribute about 30% of October-December precipitation and 60% of January precipitation in southern Africa (Hart *et al.,* 2013; Macron *et al.*, 2014), as well as approximately 40% of the total annual precipitation (Van Den Heever *et al.*, 1997). Tyson (1984) reported that cloud bands in Africa are associated with the formation of linked TTTs and have a strong correlation with wet conditions in South Africa. Cloud band development is triggered by the movement of the upper-tropospheric westerly trough over southern Africa (Hart *et al.*, 2010; Macron *et al.*, 2014). About 48% of the extreme rainfall events in the Limpopo River Basin in southern Africa are closely associated with cloud bands (Rapolaki *et al.*, 2019). Given their significant contribution to summer rainfall in South Africa, it is crucial to comprehend the mechanisms involved in their formation, dissemination, and influence on rainfall features. The Angola Low (AL) determines the availability of moisture essential for cloud bands (**Figure 2.4**) (Ndarana *et al.*, 2020). Wetter months (JFM) demonstrate an enhanced moisture over the Mozambique Channel and easterly flux anomaly over the region, with little intensification of the Angola/Namibia low (Cook *et al.*, 2004). During the JFM, the AL strengthens with an area of low convergence stretching along the ITCZ across southern Africa (Reason and Jagadheesha, 2005).

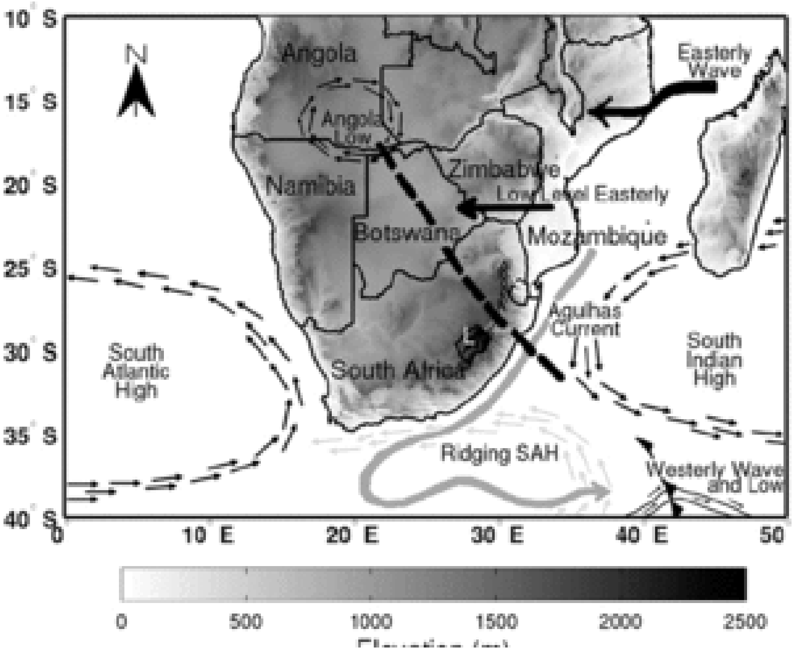


Figure 2.4: Important regional oceanic and atmospheric features for summer precipitation in southern Africa (Blamey and Reason, 2013).

The significant association between southern African precipitation and SST patterns in the South Indian Ocean indicates that SST patterns play a crucial role in determining the severity and positions of TTTs (Manhique *et al.*, 2011; Mason, 1995). High SST to the north of Madagascar promotes the development of tropical easterly disturbances over the western equatorial Indian Ocean rather than over the interior of the subcontinent, hence producing dry conditions over the land (Mason, 1995). Furthermore, high SST throughout the majority of the Agulhas current region and the Mozambique Channel is coupled with rainy conditions in the summer rainfall zone (Mason, 1995). TTT events can further result in major floods with devastating impacts, especially when they occur simultaneously with Cut-Off Lows (COLs).

When the Botswana high-pressure system pushes the ITCZ away from the southern areas, South Africa and Zimbabwe experience frequent dry spells (Driver and Reason, 2017; Kenabatho *et al.*, 2012). Unganai and Mason (2002) reported that the 1982-1984 and the 1991-1992 were strongly correlated with the Botswana High (BH). This pressure system is an important component of the regional circulation over southern Africa (Reason, 2019). The BH forms around August, strengthens throughout spring, and peaks in the austral summer (Maoyi and Abiodun, 2021; Moses *et al.,* 2023). The BH weakens in March and dissipates around April (Driver and Reason, 2017; Maoyi and Abiodun, 2022). Furthermore, during the summer season, the stronger BH is characterized by warmer temperatures, reduced cloud cover, and a greater diurnal temperature range (Maoyi and Abiodun, 2022). Driver and Reason, (2017) also reported a strong correlation between dry spells and the Botswana High index.

Most southern Africa's floods are caused by Cut-Off Lows (COL: Reason, 2017). COLs form when upper troposphere troughs become cut off from westerly waves (Abba and Abiodun, 2020; Favre *et al.*, 2012). Barnes *et al.* (2021) report that about 89% of COLs occurring in the southern hemisphere are associated with the Rossby waves breaking, usually upstream, on or before the day of the cut-off low formation. Singleton and Reason (2007) maintained that COLs occur in the middle/upper troposphere when a pre-existing cold trough extends equatorward. The air inside COLs is colder than its surroundings (Singleton and Reason, 2007), and this often encourages deep convection as the relatively cold air in the middle/upper troposphere assists in destabilizing the atmosphere (Baray *et al.*, 2003; Barnes *et al.,* 2021; Singleton and Reason, 2007).

When upper-level COLs move over potentially unstable air at low-level air, they provide the dynamical forcing that triggers rapid and severe surface cyclogeneses, resulting in heavy rainfall (Fuenzalida *et al.*, 2005). Occasional COLs can also contribute significantly to winter precipitation in some years (Favre *et al.*, 2012; Molekwa *et al.*, 2014) and spring precipitation along the south coast of South Africa (Engelbrecht *et al.*, 2015; Favre *et al.*, 2012; Molekwa *et al.*, 2014; Weldon and Reason, 2014). When there is a substantial meridional component to the upper-level westerly flow, post-frontal ridging can result in cold air outbreaks across South Africa, with the source of the low-level air being the deep southern Ocean (Barnes *et al.*, 2021). Such winter storms may bring heavy snowfall to the higher mountains of southern and eastern South Africa/Lesotho (Barnes *et al.,* 2021). Their contribution to rainfall is high during the OND. The coastal regions witness the highest contribution during July-August-September (JAS: Molekwa *et al.*, 2014).

The Angola Low (AL) plays a vast role in instigating precipitation in southern Africa. The AL is a semi-permanent low-pressure system that affects the convergence of low-level moisture fluxes into southern Africa (Howard and Washington, 2018). This low pressure occurs as a result of the combination of dry heat lows and tropical lows (Ramugondo, 2020). The AL is responsible for modulating moisture transport into the subcontinent and it has a relationship with the convergence of moisture flux from the western Indian and south-eastern Atlantic Ocean (Howard and Washington, 2018). Cook *et al.* (2004) reported that a stronger AL is closely correlated to wet spells. The ability of the AL to enable southward movement of atmospheric water from the tropics suggests that it plays an essential role in the development TTTs. The strong AL minimizes the occurrence of forecasted drought and when the AL is weak, lower rainfall records in history were experienced (Pascale *et al.*, 2019). The contribution of the tropical lows to the AL influences the relationship between rainfall and ENSO (Howard *et al.*, 2019).

The South Annular Mode (SAM), also well known as an Antarctic Oscillation (Gillett *et al.*, 2006; Gupta and England, 2006), is a central mode for tropospheric circulation variability in the mid- and high-latitudes of the southern hemisphere (south of about 30$^{o}$C) (Holz *et al.*, 2017; Mahlalela, 2018; Reason, 2017). It poses a great deal of influence on the distribution of rainfall and temperatures from the subtropics to the south pole (Mahlalela, 2018). Negative (positive) SAM has a relative correlation with wet conditions (dry) in western South Africa (Mahlalela *et al.*, 2020; Reason and Rouault, 2005). Precipitation in south-eastern Africa is also closely correlated with SAMs (Malherbe *et al.*, 2014). The positive phase of ENSO which is reliable for the increment of global mean SST influences the negative phase of SAM (Ibebuchi, 2021).

Cyclone activity depends on natural cycles such as ENSO. For instance, El Niño propagates cyclonic activity in the South Pacific region (Mavume *et al.*, 2009). In southern Africa, Madagascar and Mozambique are heavily affected by tropical cyclones. The Sofala province in Mozambique is the most affected region by tropical cyclone activity (Charrua *et al.*, 2021; Macamo *et al.*, 2016). The South African coastlines are protected by Madagascar from tropical cyclones. About 95% of tropical cyclones on the east coast of southern Africa have failed to make their landfall (Fitchett and Grab, 2014; Reason and Keibel, 2004), whereas the remaining 5% is characterized by tropical storms over southern Africa that made landfall in Mozambique (Reason, 2017), For instance, ex-tropical cyclone Eline made its landfall in central Mozambique in the late February 2000 and travelled over to northern Namibia as a tropical storm causing severe rainfall in eastern Zimbabwe, north-eastern South Africa and some parts of the Kalahari (Macamo *et al.,* 2016; Reason and Keibel, 2004)

The Madden–Julian Oscillation (MJO) regulates moisture supply for intra-seasonal rainfall variability in southern Africa (Pohl *et al.*, 2010). It is characterized by its slow eastward propagation of convective clusters (~10 000 km across) along the Indian Ocean to the western Pacific (Pohl *et al.*, 2007). It is believed that the MJO triggers the southern Africa Southwest Indian Ocean (SWIO) convection dipole, hence it significantly affects the rainfall field over southern Africa (Salby and Hendon, 1994). Furthermore, significant statistical associations are found during the austral summer seasons which expand from October to April (Pohl *et al.*, 2007). A study by Pohl *et al*. (2007) concluded that about 30-40% of MJO events account for the overall intra-seasonal variance of the Outgoing Longwave Radiation (OLR) field over the region. Much is not yet known about the relationship between the synoptic-scale TTT and the MJO cycle. In addition, (Pohl *et al.*, 2009) maintained that although TTTs are partially influenced by MJO, they are an independent mode of variability in southern Africa. Therefore, it is very important to understand MJO on an intra-seasonal scale mode of variability. This will provide meaningful insight into rainfall characteristics (i.e., wet and dry spells modulated by the MJO).

## 2.7 Seasonal rainfall characteristics over the Limpopo province

The economy of the Limpopo province relies much on agriculture, which depends deeply on the temporal and spatial variability of rainfall, especially during the six months of the rainy season from October to March (ONDJFM). However, studies of the spatial and temporal distribution of seasonal rainfall characteristics over the Limpopo province have great relevance in the context of planning, management, and policy formulation, especially in the context of global climate change and warming.

Changes in rainfall characteristics have been associated with negative implications on agricultural productivity. For instance, crops may be destroyed by hot, dry periods despite the seasonal rainfall total being favorable (Reason, *et al.*, 2005; Tadross *et al.*, 2005; Tennant and Hewitson, 2002), and this is because the frequency and duration of dry spells indicate a degree of stress that plants are exposed too (Masupha *et al.*, 2016; Reason *et al.*, 2005). Furthermore, although the overall amount of rainfall may remain relatively constant over time, alterations in the distribution of wet and dry events within the season can have severe implications for people’s livelihoods (Hachigonta and Reason, 2006; Tadross *et al.*, 2009).

Seasons with above-average rainfall are not necessarily better than below-average seasons if the rainfall is not well distributed (Thoithi *et al.*, 2021). Consistency in receiving the minimum required rainfall at various crop stages is more critical for crop growth and production than the total amount of rainfall received (Matimolane *et al.*, 2022). Uniformly distributed "light and moderate" rains are more favorable for crops than a few heavy rainy days interrupted by dry periods (Hachigonta *et al.*, 2008; Tadross *et al.*, 2005; Taljaard, 1986).

The year-to-year variability of rainfall in southern Africa is driven by the interplay between the atmosphere, the underlying ocean, and land surfaces across various regions. The spatial patterns of SST also play a very significant role in the interaction (Cook *et al.*, 2004). A strong correlation between SST and southern African precipitation is also observed, whereas some studies highlight the role played by the SST pattern in influencing the locations and intensity of TTTs (Mason, 1995). Increasing SSTs in the north of Madagascar promote the development of tropical easterly disturbances over the western equatorial Indian Ocean rather than over land, hence producing dry conditions over land. However, high SST in the Agulhas current and the Mozambique Channel is correlated with rainfall in the summer rainfall zone (Mason, 1995)

Seasonal rainfall characteristics variability in South Africa is attributable to the shifts in the duration, intensity, and frequency of large-scale meteorological systems. The tropical and mid-latitude weather systems, coupled with their interaction can generate precipitation with significant expanse of southern Africa. For instance, the interaction between the tropical disturbance over southern Africa at the low latitude and the westerly system travelling south of the continent is responsible for the formation of TTTs (Hart *et al.*, 2010).

## 2.8 Summary

This chapter has provided a summary of atmospheric circulations across southern Africa and their effects on water resources and agriculture. Focus has been placed on the water resource's response to both the below and above rainfall scenarios. Droughts and floods in southern Africa and the necessity for precise forecasting and prediction have been highlighted. The potential wide-ranging effects of the climate of southern Africa on water resources and agriculture, as discussed above, make it imperative to develop integrated water resource management institutions in each southern African nation, assisting the goals of WMO's Global Framework on Climate Services. Improving the reliability of hydrological models is reliant on a thorough comprehension of changing ocean, atmosphere, and land surface conditions.

# 3 METHODOLOGY

## 3.1 Overview of the study area

The Limpopo province is located in the north-eastern part of South Africa, along the latitudes 22-25º S and longitudes 26-32º E. The province shares borders with Mozambique, Zimbabwe and Botswana. It is geographically diverse and comprises of a variable range of lands, from mountainous areas to flat land, with an altitude ranging from a minimum 100msl to greater than 1600msl (**Figure 3.1**). The total area of land covered by the Limpopo province is approximately 129 910 $km^2$(Maluleke *et al.*, 2019; Singo *et al.*, 2023)

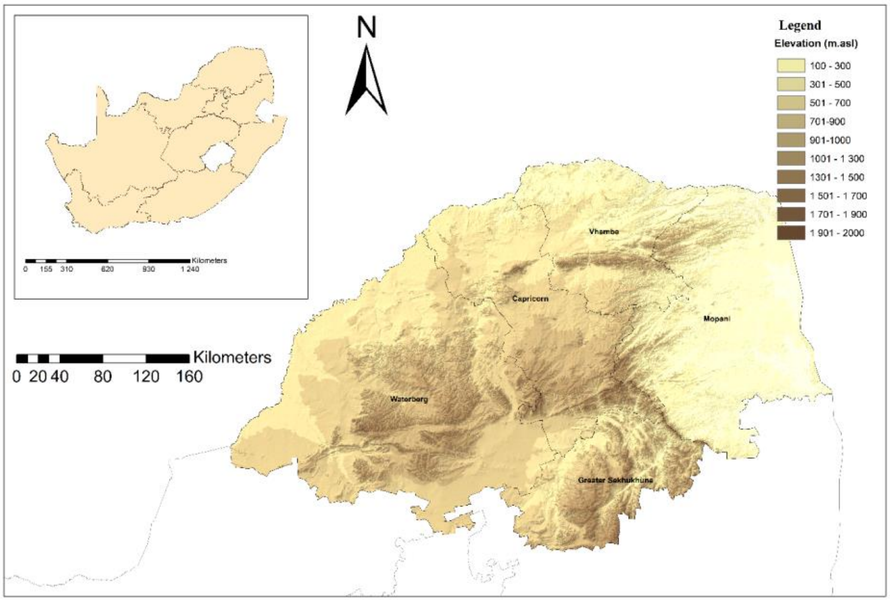


Figure 3.1: Map of the Limpopo province showing the 5 districts and the topography.

The Limpopo province is characterized by hot summers with an average maximum temperature of 27º C (Dzurume *et al.*, 2022). Winters in the province are mild with an average minimum temperature of 18ºC (Maluleke *et al.*, 2019). High rainfall variability, makes the region prone to drought and floods. The majority of the rainfall is accumulated during the austral summer months, ranging from 200 to 1600mm (Maluleke *et al.*, 2019; Singo *et al.*, 2023). According to the Koppen Geiger climate classification, the climate of Limpopo province is variable. The dominant climate type is semi-arid, followed by humid subtropical climates and arid (**Figure 3.2**). The variable climate classification highlighted the variability of environmental conditions in the Limpopo province.

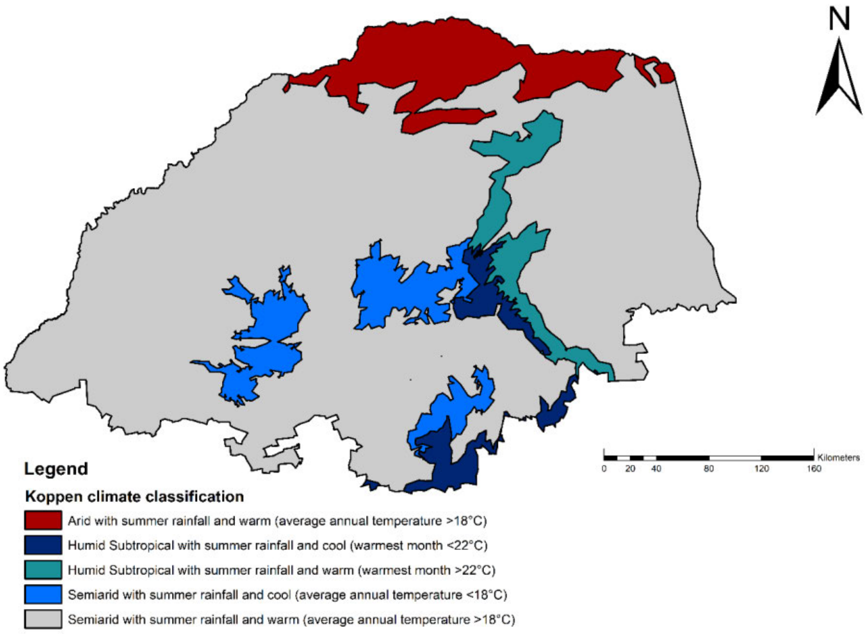


Figure 3.2: Map showing the the Koppen classification of the Limpopo province climate zone.

The province also consist(s) of large national parks (i.e. Kruger National Park), which contribute significantly to the economy through tourism (Mateyisi *et al.*, 2021). Approximately 73% of the province is in its natural state (not transformed), with the majority of it being used for grazing. However, 27% of the remaining land is undergoing transformation due to various land uses. Of this, 6% is used for commercial farming, and 6% is used for subsistence farming (Gibson *et al.*, 2006). Subsistence farming is widely spread all over communal lands in the province, whereas commercial farming is distributed all over the province, with much concentration being in the south of Limpopo (Gibson *et al.*, 2006). The major river systems responsible for supporting agricultural practices in the region include the Mokoko, Lephalale, Mogolakwena, Sands, Luvhuvhu, Letaba, and Olifants (Gibson *et al.*, 2006).

## 3.2 Data

### 3.2.1 Station Data

Rainfall data used in this study was sourced from the Agricultural Research Council (ARC). **Table 3.1** indicates the geographical distribution of nine weather stations, comprising of dataset ≥ 30 years, with more than 90% of data availability. For data quality, the climate data was inspected and the ARC stand-alone patching tool, which uses inverse distance weighting and multiple linear regression methods using neighbouring stations, was used to fill in missing values (Moeletsi *et al.*, 2016; Shabalala *et al.*, 2019). In this study, the station data was used to evaluate the performance of Climate Hazard Group Infrared Precipitation with Station Data (CHIRPS) over the Limpopo province. The evaluation was performed based on a point-to-pixel analysis, disregarding the location of the station within the pixel. The evaluation was done on 9 stations over the Limpopo province, taking into consideration the variable nature of the Limpopo province.

Table 3.1 Weather station over the Limpopo province and their geographic coordinates

| Station | Latitude (ºE) | Longitude(ºS) | Time |
|---|---|---|---|
| De Groot | -24.75 | 30.33333 | 1991-2020 |
| Koedoeskop | 24.8822 | 27.52116 | 1989-2020 |
| Kwaggahoek | 24.3333 | 28.66667 | 1992-2020 |
| Letaba Letsitete | 23.8667 | 30.31667 | 1973-2020 |
| Marble Hall | 25.0167 | 29.41667 | 1981-2020 |
| Polokwane | -23.9 | 29.46667 | 1984-2020 |
| Rabali | 22.8703 | 30.0811 | 1986-2020 |
| Sigonde | 22.3965 | 30.713 | 1983-2020 |
| Lephalale | -23.68 | 27.71 | 1989-2020 |

### 3.2.2 Climate Hazard Group Infrared Precipitation with Station Data (CHIRPS)

Daily rainfall data is obtained from the Climate Hazard Group Infrared Precipitation with Station Data (CHIRPS). This global dataset spans over 30 years and utilizes 0.05° resolution satellite imagery and station data to create a gridded rainfall time series (Dinku *et al.*, 2018; Funk *et al.*, 2015). The dataset was developed by the U.S Geological Survey Earth Resources Observation and Science Centre in collaboration with the Climate Hazard Group at the University of California, Santa Barbara (Dinku *et al.,* 2018; Alemu and Bawoke, 2020). Precipitation data is of paramount importance for diverse applications such as crop modelling, hydrometeorology, water resource management, and climatological studies (Kidd *et al.*, 2017). The availability of long-term precipitation estimates with high spatial and temporal resolution provides meaningful information, more especially in areas with complex topography such as South Africa, specifically the Limpopo province (Prakash, 2019)

According to Funk *et al*. (2015), CHIRPS data can be employed to understand trends, seasonal drought, and flood monitoring. Numerous validation studies have been conducted all over the world such as Argentina (Rivera *et al.*, 2018), Italy (Duan *et al.*, 2016), Mozambique (Toté *et al.*, 2015), China (Bai *et al.*, 2018; Gao *et al.*, 2018; Lai *et al.*, 2019; Zhong *et al.*, 2019), Ethiopia (Bayissa *et al.*, 2017), Burkina Faso (Dembélé and Zwart, 2016), India (Prakash, 2019) and many more. Satellite-derived rainfall products provide an alternative to better understanding rainfall patterns at varying temporal and spatial resolutions.

### 3.2.3 Large modes of rainfall variability

The interconnection of seasonal rainfall characteristics and large modes of variability, the El Niño-Southern Oscillation (ENSO) and Southern Indian Ocean Dipole (SIOD) were examined. The Monthly Nino3.4 index was obtained from the Hadley Centre Sea and Sea Surface Temperature (HadlSST1) version 1.1 anomalies dataset at 1º x 1º grids (Rayner *et al.*, 2003). The dataset is developed by the Met Office center in the United Kingdom UK. The data spanning from 1990 to 2020 was sourced from climexp.knmi.nl/data/ihadisst1_nino3.4a.dat [last accessed 20 August 2023]. According to Rayner *et al.* (2003), the data consists of a carefully quality-controlled blend of satellite and in-situ ship and buoy SST data and is made globally complete through the use of statistical interpolation techniques. The seasonal anomalies (ON, DJ, and FM) averages in the Nino 3.4 SST index above (below) 0.05º C (-0.05º) are defined as El Niño (La Niña), while averages between 0.05º C and -0.05º are considered as neutral. The SIOD index is defined as the difference in SST anomalies between the eastern Indian Ocean and the southwestern Indian Ocean (Behera and Yamagata, 2001). In this study, the SIOD index was sourced from http://www.jamstec.go.jp/virtualearth/data/SINTEX/SINTEX SIOD.csv [last accessed 20 August 2023].

## 3.3 Methods

### 3.3.1 Performance evaluation

Statistical metrics were used to quantify overall performance and systematic errors of CHIRPS dataset using station data. In this study, the Pearson Correlation Coefficient (PCC), Root Mean Square Error (RMSE), Mean Square Error (MSE), and Mean Absolute Error (MAE) were computed to evaluate the performance of CHIRPS. The correlation coefficient is a statistical measure used to evaluate the similarity between two data sets (station data and CHIRPS data). The root mean square error is a popular statistic measuring the accuracy of a product's predictions compared to actual data. In other words, the root-mean square error is a metric for comparing two datasets disparity in error rates. The MAE is a measure of the mean magnitude error of the absolute error. The formulae and other descriptions of the evaluation statistics are given in **Table 3.2**. The Cumulative Distribution Function (CDF) was used to determine the proportion of both CHIRPS and the weather station.

Table 3.2: Descriptions of statistical metrics used to validate CHIRPS.

| **Parameter** | **Expression** | **Perfect Value** | **Range** |
|---|---|---|---|
| Pearson correlation coefficient (r) | $r = \frac{\sum_{i=1}^{n}(G_i - G)(S_i - S)}{\sqrt{(G_i - G)(S_i - S)}}$ | 1 | -1 to 1 |
| Root mean square error | $RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - G_{i)}}{n}}$ | **0** | 0 to ∞ |
| Mean square error | $MSE = \frac{\sum(S_i - G_i)^2}{n}$ | 0 | |
| Mean absolute error | $MAE = \frac{1}{N}\sum \vert (S - G)$ | 0 | 0 to ∞ |

| |
|---|
| Where<br>G= observed precipitation from gauge measurements<br><br>S= CHIRPS rainfall data |

### 3.3.2 Climatological mean

In this study, long-term climatological means were used to investigate the climatology of rainfall over the Limpopo province. The climatological mean serves as a fundamental measure of average annual rainfall over an extended period, providing a baseline for understanding climatological conditions over the area. This comprehensive analysis will assist in trend detection, seasonal rainfall patterns, and regimes. The descriptive basic statics were computed on a monthly and annual time scale to understand the temporal and spatial variability of rainfall. The following formula was used to calculate the arithmetic mean:

$$\overline{x} = \frac{1}{n}\sum_{i=n}^{n} x_i$$

In this study $x_i$ represent the ith observation and n denotes the total number of observations.

The rainfall mean was calculated using monthly and annual rainfall recorded over the study period. A similar approach was employed by (Kruger and Nxumalo, 2017).

### 3.3.3 Coefficient of variation

The coefficient of variation measures the overall variability of climate data in the study area. CV is defined as the ratio of standard deviations to mean in percentages where the mean and standard deviation values are estimated in rainfall data. A higher value of CV indicates a rainfall greater variability and vice versa.

$$\text{CV} = \frac{\sigma}{\mu} \times 100$$

Where$\sigma$is the standard deviation and $\mu$ is the mean annual rainfall for the chosen temporal scale. Generally, CV is used to classify the degree of variability of rainfall events into three: low (CV < 20), moderate (20 < CV > 30), and high (CV > 30) (Alemu and Bawoke, 2020; Asfaw *et al.,* 2018).

### 3.3.4 Seasonality Index (SI)

The Seasonality Index (SI), as proposed by Walsh and Lawler (1981), quantifies annual rainfall regimes based on the distribution of monthly rainfall throughout the year. In this study, the relative seasonality index (SI) of rainfall series was used to classify the climate of Limpopo province. Due to the high variability of rainfall in this region, some areas may experience high total annual rainfall, but the monthly distribution is often uneven. Consequently, this index is used to identify patterns of rainfall. The SI is defined as the sum of the absolute deviations of mean monthly rainfall from the overall monthly mean, divided by the mean annual rainfall. This provides a measure that highlights the variability in rainfall distribution and aids in understanding the seasonal characteristics of the region's climate.

$$\overline{SI} = \frac{1}{\overline{\overline{R}}} \sum_{n=1}^{n=12} \left| \overline{X}_n - \frac{\overline{\overline{R}}}{12} \right|$$

Where $\overline{X}_n$ is the mean rainfall of month n and $\overline{R}$ the mean annual rainfall. This index varies from zero (when all months share the same amount of rainfall) to 1.83 (when all rainfall incidence occurs in a single month). A classification of SI is shown in **Table 3.3.**

Table 3.3. Classification of seasonality index (SI) according to Walsh and Lawler (1981).

| Rainfall regime | $\overline{SI}$ |
|---|---|
| Very equable | ≤ 0.19 |
| Equable with a definite wetter season | 0.20-0.39 |
| Rather seasonal with short drier season | 0.4-0.59 |
| Seasonal | 0.60-0.79 |
| Markedly seasonal with long drier season | 0.80-0.99 |
| Most rain in 3 months or less | 1.00-1.19 |
| Extreme, almost all rain in 1 to 2 months | ≥1.20 |

### 3.3.5 Standardized Anomaly Index

To investigate the temporal nature of rainfall, Standardized Anomaly Index (SAI) was calculated. This index calculates the standardized deviation of rainfall from the annual and monthly timescale, allowing for the determination of dry and wet years at different intensity levels. In this study, this index is utilized to measure if the seasonal rainfall totals reflect wet days and dry spell characteristics. The main advantage of using this index is its procedural simplicity, as it only requires the calculation of rainfall data. It is computed as:

$$SAI = \frac{x_1 - \overline{x}}{\sigma}$$

Where $x_1$ represents the annual rainfall of the particular year, $\overline{x}$ the long-term mean over the period of observation. The negative value of SAI indicates dry years compared to the reference point ($\overline{x}$), while the positive value represents wet years. The SAI was calculated for each year from 1990-2021, using the high-resolution CHIRPS rainfall data. The results were used to detect temporal rainfall variability over the Limpopo province.

## 3.4 Wet days and dry spells characteristics.

Seasonal rainfall characteristics were selected to address common user needs, particularly in agriculture. Since rainfall distribution is often uneven throughout the rainy season, it is crucial to understand the distribution and contribution of different types of rainfall. Specifically, this study considered the following seasonal rainfall characteristics:

- Dry spells (pentads with < 5 mm rainfall)

The definition of dry spells by Beyer *et al.* (2016), Mengistu *et al.* (2021), Thoithi *et al.* (2021), and Usman and Mamman (2022) is adopted in this study. The authors define a dry spell as a pentad (5-day period) with rainfall less than 5 mm. A pentad with less than 5 mm represents an extended period of dry conditions that could disrupt crop growth if it occurs at a high frequency.

In defining moderate and heavy wet days, multiple factors are considered to ensure accuracy. For example, a threshold of 30mm of rainfall per day is chosen to classify heavy rainy days, as such conditions are detrimental to crop growth, leading to water logging and reduced yields (Hachigonta *et al.*, 2008; Zwiers *et al.*, 2013). On the other hand, moderate wet days are deemed beneficial, as they provide adequate rainfall necessary for the germination and growth phases of maize.

- Moderate wet days (rainfall ranging from 10-30 mm per day)
- Heavy wet days (rainfall greater than 30 mm per day)

Moderate wet days were considered to be those containing 10-30 mm of rainfall, whereas heavy wet days were taken to be days containing rainfall greater than 30 mm of rainfall (Gong *et al.*, 2004; Thoithi *et al.*, 2021). Rainfall is unlikely to have an even distribution throughout the season, therefore, wet days having both low and high thresholds are considered to aid an in-depth understanding of accumulated rainfall needed for each growing phase (Hachigonta and Reason, 2006; Pohl *et al.*, 2017). High-resolution CHIRPS pentads and daily data were used to generate time series for dry spells, moderate wet days, and heavy wet days in the Limpopo province from 1990 to 2020, during the ON (early summer), DJ (Mid-summer) and FM (late summer) seasons.

### 3.5 Analysis of trends

In this study, The Mann-Kendall test will be employed to analyze the monotonic trends of total annual rainfall. This statistical method is widely recognized for its ability to assess monotonically significant trends, both increasing and decreasing, in meteorological and hydrological time series data (Alemu and Bawoke, 2020). To determine the significance of detected trends, a significance level of 0.05 was used in this study (Rahmat *et al.*, 2015). The Mann-Kendall test is denoted as (Rahmat *et al.*, 2015):

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

$$sign(x_j - x_i) \begin{Bmatrix} +1 & if\ (x_j - x_i) > 0 \\ 0 & if(x_j - x_i) = 0 \\ -1 & if(x_j - x_i) < 0 \end{Bmatrix}$$

Where,

n= number of data

x=data points at times $i \wedge j$ (j>i)

The equation of variance of S is as follows:

$$var(S) = \left[ n(n-1)(2n+5) - \sum_{i=1}^{m} t_i \,(i-1)\,(2i+5)/18 \right]$$

Where,

$t_i$ = the number of ties of the extent

$i$And $m$ = the number of tied groups. For n larger than 10, the standard test is estimated as the Mann-Kendall test as denoted:

$$Z = \begin{Bmatrix} \frac{s-1}{\sqrt{var(s)}} if & S > 0 \\ 0 if & S = 0 \\ \frac{s+1}{\sqrt{var(s)}} if & s < 0 \end{Bmatrix}$$

Statistically significant trends are estimated using the value Z. Positive Z values signify an increasing trend while negative Z values signify a decreasing trend. The trend is statistically significant at a 90% confidence interval if Z >1.65 and significant at a 95% interval if Z >2.58.

### 3.6 Large modes of rainfall variability

Considering the high variability nature of precipitation patterns in southern Africa, particularly in the Limpopo province, this study focuses on the influence of ENSO (El Niño-Southern Oscillation) and SIOD (Southern Indian Ocean Dipole), on rainfall during the extended summer season. The relationship between dry spells frequency, moderate wet days frequency, and heavy wet days and Niño 3.4 (Rayner *et al.*, 2003) and SIOD (Behera and Yamagata, 2001)) was assessed by calculating the Pearson correlation coefficient. Pearson correlation was computed using the following equation:

$$r = \frac{S_{XY}}{\sqrt{S_{XX}S_{YY}}}$$

The Pearson correlation was developed by Karl Pearson in 1896, using the concept developed by Galton, (1889). This concept was developed to establish the association between two variables or more. The r values range between -1 and +1, with values closer to -1 and +1 representing a very strong correlation, whereas r values closer to represents very weak correlation (**Table 3.4**) (Asuero *et al.*, 2006; Pearson, 1896)

Table 3.4: Strength of correlation (Pearson, 1896).

| Size of r | Interpretation |
|---|---|
| 0.8-1 | Very Strong |
| 0.6-0.799 | Strong |
| 0.40-0.599 | Moderate |
| 0.20-0.599 | Weak |
| 0.00-0.0199 | Very Weak |

# 4 RESULTS AND DISCUSSIONS

## 4.1 Performance evaluation of CHIRPS data

Cumulative distribution function (CDF) of CHIRPS and weather station rainfall at selected points are shown in **Figure 4.1**. In De Groot, CDF of CHIRPS rainfall estimates are below those of weather stations. This shows that CHIRPS underestimates rainfall events between 50-250 mm. In Koedoeskop, CDFs of CHIRPS show close proportion to weather stations, except for a slight overestimation around 100 to 160 mm. In Sigonde, Lephalale, Marble Hall and Kwaggahoek, a close proportion of CHIRPS rainfall estimates and weather stations is exhibited. In Letaba Letsitele and Marble Hall, CHIRPS shows a slight overestimation of rainfall. In Letaba Letsitele, the CHIRPS CDF is above the weather station CDF from 100 mm to 310 mm. Polokwane and Rabali also show that CHIRPS underestimates rainfall. However, the overall CDFs show that the distribution of rainfall is well estimated by CHIRPS and relatively performs better in most stations.

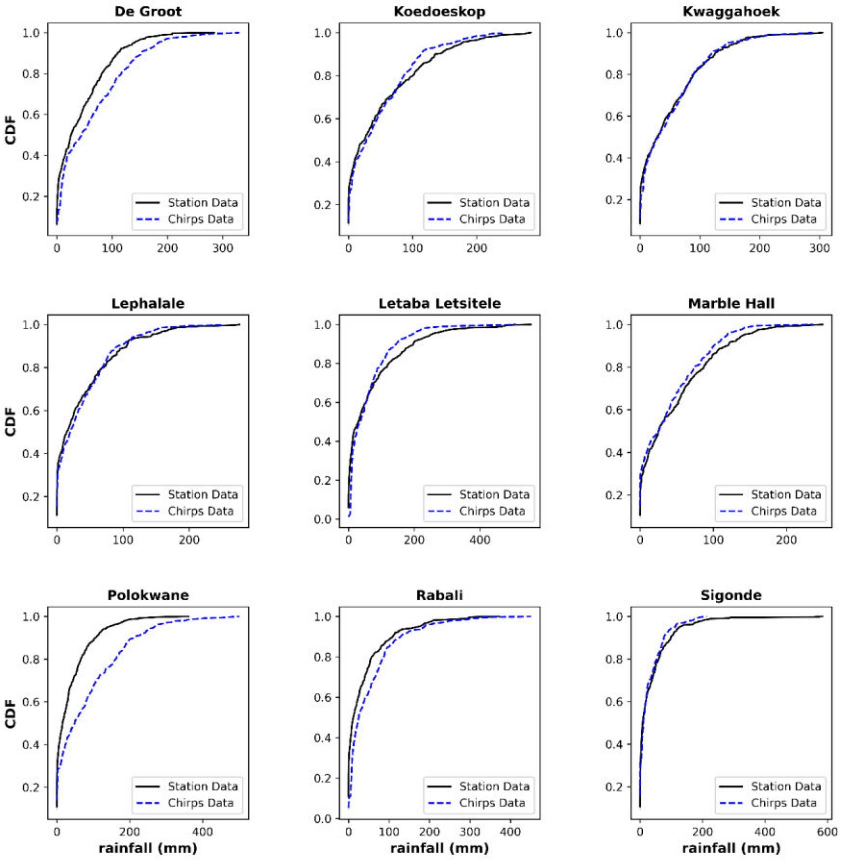


Figure 4.1: Monthly rainfall Cumulative Distribution Function (CDF) of CHIRPS estimated and weather station measurements.

**Figure 4.2** shows the performance evaluation of CHIRPS in comparison to weather station data using statistical matrices. The Pearson correlation coefficient (r), Root Mean Square Error (RMSE), Mean Squared Error (MSE) and Mean Absolute Error (MAE) were used as comparison statistics. The results suggest that CHIRPS dataset can better estimate rainfall from weather stations over the Limpopo province. Stations in the study region recorded the following performance when compared to CHIRPS: De Groot (RMSE =1.41, MSE =1.99, r =0.80, MAE =0.89), Koedoeskop (RMSE =0.94, MSE =0.88, r =0.89, MAE =0.58), Kwaggahoek (RMSE =0.96, MS E=0.94, r =0.86 and MAE =0.59), Letaba Letsitele (RMSE

=1.75, MSE =3.09, r =0.85, MAE =1.02), Marble hall (RMSE =0.99, MSE =0.99, r =0.80, MAE =0.62), Polokwane (RMSE =1.18, MSE =1.40, r =0.75, MAE =0.69), Rabali (RMSE =1.41, MSE =1.99, r =0.80, MAE =0.84), Lephalale (RMSE =0.87, MSE =0.75, r =0.85, MAE =0.48), Sigonde (RMSE =1.45, MSE =2.12, r =0.73, MAE =0.69). A strong positive linear relationship is recorded in all stations. The overall evaluation of CHIRPS shows that CHIRPS can adequately represent weather station data.

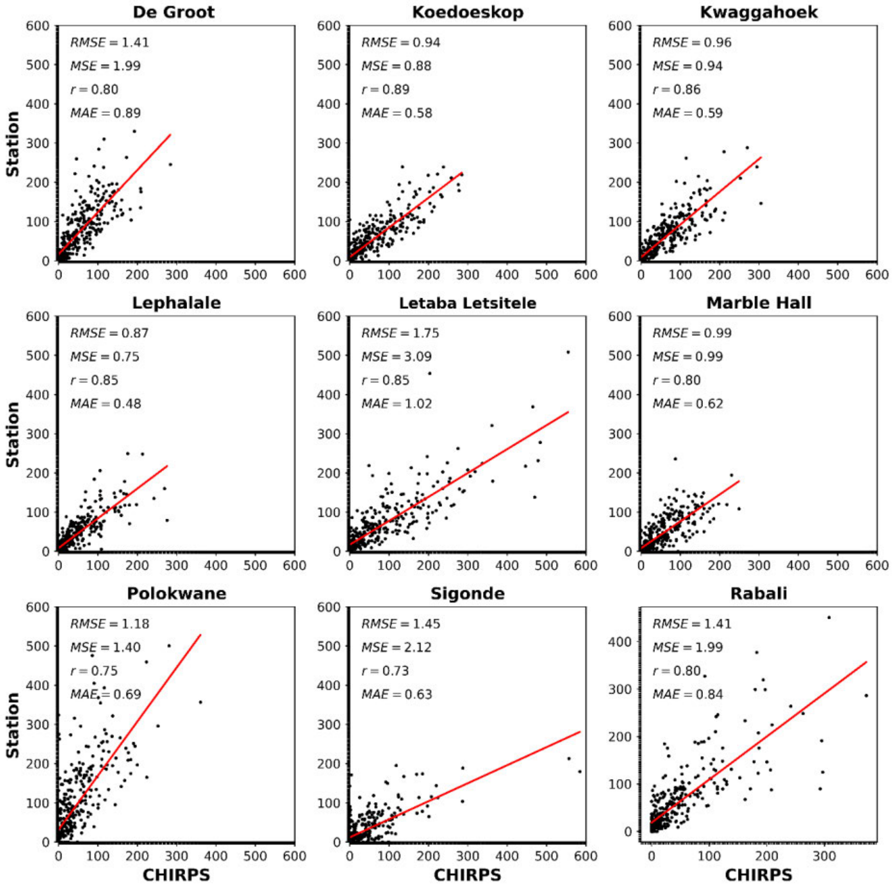


Figure 4.2: Scatter plot comparing monthly rainfall, between CHIRPS and weather station for 1990-2020.

## 4.2 Spatial and temporal rainfall variability over the Limpopo province for the period 1990 to 2020

### 4.2.1 Spatial distribution of annual rainfall cycle over the Limpopo province

The spatial distribution of monthly rainfall demonstrates high rainfall variability across the Limpopo province (**Figure 4.3**). This is consistent with the findings of Chikwiramakomo *et al* (2021) and Mzezewa *et al* (2010). In this study, high monthly rainfall totals are quantified for the months of October to March (Oct-Mar). These results are aligned with those of Mzezewa *et al* (2010) and Dedekind *et al* (2016). High rainfall during these months is induced by a number of rain-bearing systems like the semi-stationary subtropical easterly wave, tropical depressions, Angolan Low pressure system, Northwest cloud bands, and Cut Off Lows leading to convective rainfall during austral summer months (Roffe *et al.*, 2019; Nicholson and Selato, 2000; Reason and Jagadheesha, 2005; Pohl *et al.*, 2009; Kuleshov *et al.*, 2008; Favre *et al.*, 2012; Macamo *et al.*, 2016)

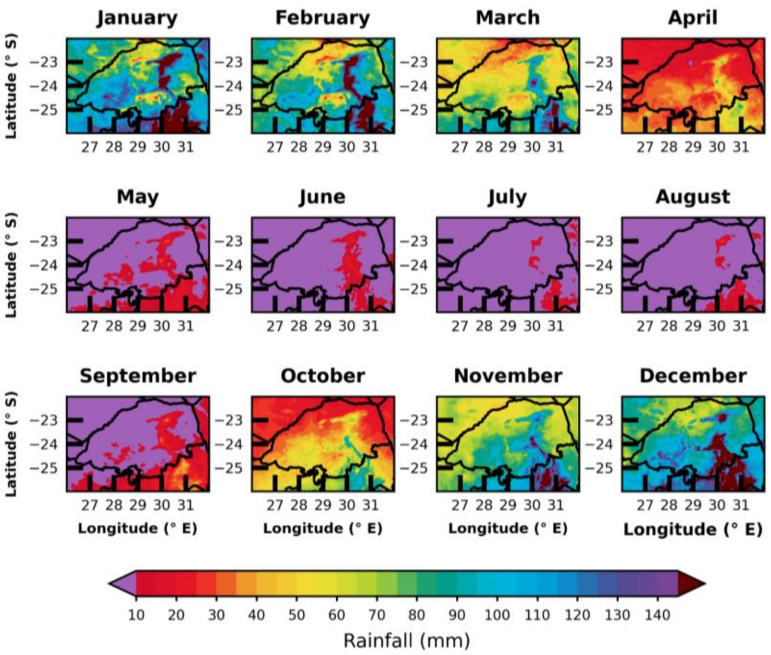


Figure 4.3: Annual rainfall cycle over the Limpopo province expressed in the form of monthly mean calculated over the period 1990-2020.

The highest rainfall is recorded during the December-January-February (DJF) period. A similar peak in rainfall in the Limpopo province during this period was observed by Mpandeli (2014) and Roffe *et al.* (2021). The highest number of extreme weather events are also recorded during these months (Rapolaki *et al.*, 2019; Tadross *et al*., 2005). Furthermore, Rapolaki *et al*, (2019) demonstrated that 45% of the top 200 extreme rainfall events in the Limpopo River Basin (LRB) from 1981-2016 were associated with cloud bands, 45% with tropical lows, and 10% linked with Mesoscale convective systems (MCSs). During the winter months (May to September), the entire province receives little to no rainfall. This dry period is attributed to the subtropical high-pressure systems which are displaced north due to the seasonal migration of the ITCZ (Musyoki *et al.*, 2016; Rapolaki *et al.*, 2019; Roffe *et al.*, 2021).

High-lying escarpment in the south of Vhembe, north and west of Mopani, south of Capricorn, Waterberg, and north of Greater Sekhukhune district is characterized by high rainfall. In contrast, Capricorn, Mopani, north of Vhembe district are characterised by lower rainfall. Dedekind *et al.* (2016) also reported that areas with high-lying topography experience maximum rainfall. These findings are also consistent with those of Shikwambana *et al*. (2021). Additionally, De Coning *et al.* (1998) and Mosase and Ahiablame (2018) have reported that the Drakensberg Mountain in the eastern part of the country plays a significant role in enhancing rainfall by triggering strong ascents of moist air.

### 4.2.2 Standardized Anomaly Index

Monthly standardized rainfall anomalies over the Limpopo province show the deviation in rainfall from the norm for 1990-2020 period (**Figure 4.4**). Positive (negative) anomalies indicate that rainfall recorded for a given month is above (below) the monthly average. The spatial distribution of these anomalies shows high spatial variability across the Limpopo province. The central high-lying escarpment in the south of Vhembe, north and west of Mopani, south of Capricorn, Waterberg, and north of Greater Sekhukhune during the month of NDJFM exhibits high rainfall.

The timing of wet and dry periods provides a classification of rainfall seasonality in the Limpopo province (Roffe *et al.,* 2019). The months of March and November exhibit the beginning and end of a rainy season, hence the reduced rainfall during these transition months.

Conversely, the months of April, May, June, August, and September are characterized by below-average rainfall, with the driest months being exhibited during July and August.

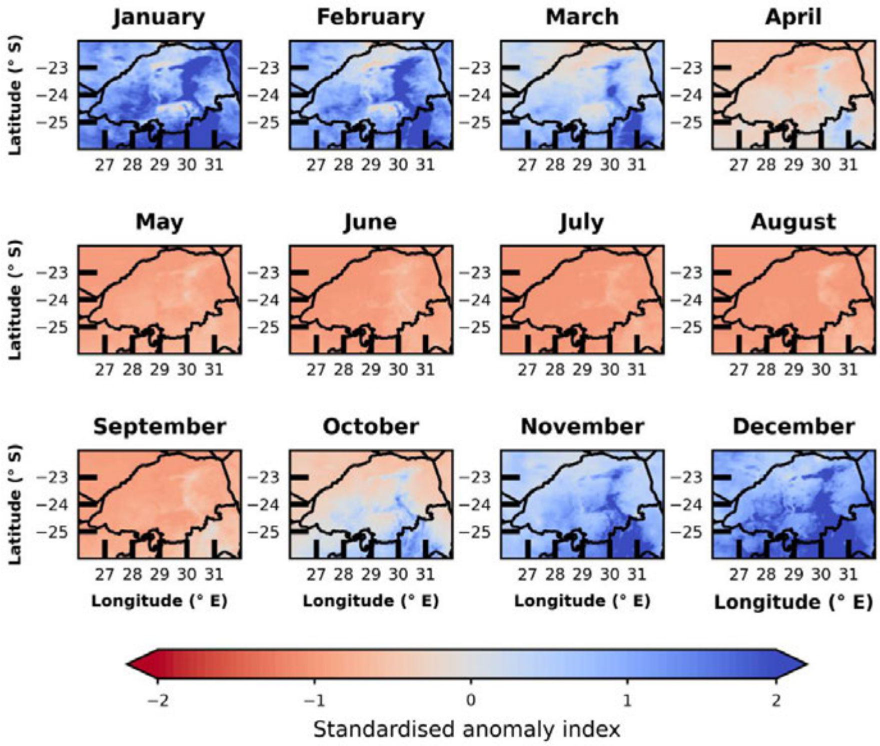


Figure 4.4: The temporal and temporal distribution of standardized rainfall anomalies over the Limpopo province.

### 4.2.3 Monthly rainfall trends

The spatial distribution of total monthly rainfall trends displays changes in rainfall over the study period, capturing both statistically significant and insignificant rainfall trends over the Limpopo province (**Figure 4.5**). However, months with statistically insignificant rainfall suggest that no changes or very small changes occurred in monthly rainfall. Despite this, such results remain important in the context of this study. This is because, over the long term, these trends might become significant. Such information will further help us understand the evolution of such trends and shifts in rainfall seasonality.

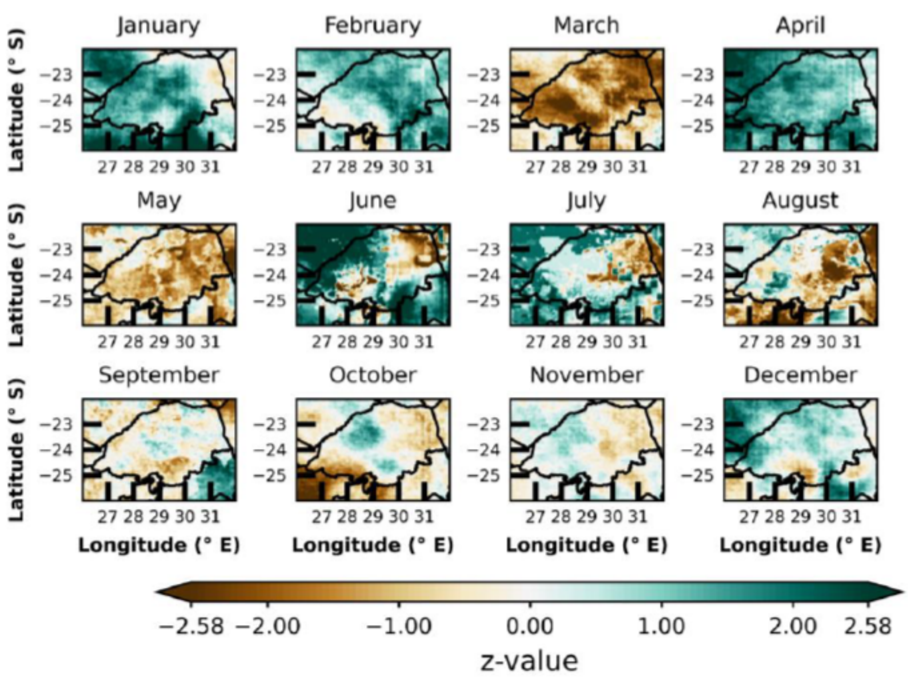


Figure 4.5: Changes in monthly rainfall over time for the period 1990 to 2020.

In January, increasing trends in mean monthly rainfall are observed over much of the Limpopo province, except for the eastern Mopani and north of Vhembe district. Statistically significant increasing trends were observed over the south-east of Greater Sekhukhune. Statistically insignificant decreasing trends were observed over the east of Mopani and north of Vhembe district, whereas statistically insignificant increasing trends were observed over Waterberg, Capricorn, and south-west of Greater Sekhukhune.

The month of February demonstrates increasing rainfall over much of the Limpopo province. Statistically significant increasing trends are recorded only in the south of Greater Sekhukhune. Statistically insignificant increasing trends are observed over the north of Waterberg, Capricorn, Vhembe, and Mopani, whereas the south of Waterberg demonstrated no changes in total rainfall during February. Kruger and Nxumalo (2017) identified decreasing trends in seasonal rainfall totals during DJF, which is considered the primary summer season. In contrast, this study reports increasing trends during the December-January (DJ) (**Appendix**

**A3**) period. The differences may be attributed to varying reference periods used in the studies. Furthermore, Kruger and Nxumalo (2017) used station data, which may limit the synthesis of the spatial component of the province.

The month of March demonstrates a decrease in mean monthly rainfall across the Limpopo province. Statistically significant decreasing rainfall was observed over the north-west of Capricorn, south of Waterberg, south-west of greater Sekhukhune district, west and north-east of Mopani, and south-east of Capricorn district. On the other hand, statistically insignificant trends were observed over Vhembe, north-east of Waterberg, and south-west of Capricorn, south of Waterberg, south-east of Greater Sekhukhune, and south of Mopani district.

In April, the entire Limpopo province records statistically insignificant increasing trends over the entire Limpopo province. In May, statistically significant decreasing trends are observed over a very small portion in the high-lying escarpment in Vhembe. No changes were observed over the north of Waterberg, north of Vhembe, and Capricorn. Whereas the remainder of the province records statistically insignificant decreasing trends.

During the month of June, both statistically significant increasing and decreasing trends were observed across the Limpopo province. Statistically significant decreasing trends were recorded in the north-east of the Mopani district, north-east of Vhembe, and the high-lying escarpment in the Waterberg district. Statistically significant increasing trends are recorded in the north-west of Capricorn, west of Waterberg, and south of Greater Sekhukhune district. Additionally, statistically insignificant decreasing trends are recorded in south-east of Mopani, north of Greater Sekhukhune, and a small portion in the high-lying escarpment in the Waterberg district.

No statistically significant trends were observed in July during the study period. Mopani, and south Capricorn district show statistically insignificant decreasing trends. The Greater Sekhukhune and Waterberg, Vhembe, and Capricorn records statistically insignificant increasing trends. The month of August shows that the south-east of Mopani records statistically significant decreasing rainfall. No changes were observed in the Vhembe and Capricorn districts. Statistically insignificant decreasing trends are observed in the Greater Sekhukhune, whereas the south of Waterberg records statistically insignificant increasing trends.

In September, no statistically significant trends were observed. Only the Greater Sekhukhune district records statistically insignificant decreasing trends, while the rest of the region shows no changes in rainfall. In October, similarly, no statistically significant trends were observed. Statistically insignificant decreasing trends were observed in Mopani and south of Waterberg districts, whereas south-west of Greater Sekhukhune and northwest of Capricorn districts record statistically insignificant increasing trends.

The month of November also records no statistically significant trends. Mopani and Vhembe districts recorded statistically insignificant decreasing trends, while the Waterberg, and Capricorn received statistically insignificant increasing trends. No changes were observed in Greater Sekhukhune. In December, no statistically significant trends were observed. The entirety of the Limpopo province received statistically insignificant increasing rainfall, except the south-west of the Greater Sekhukhune districts which received statistically insignificant decreasing rainfall.

## 4.3 **Seasonal rainfall characteristics and Trends**.

### 4.3.1 Seasonal rainfall climatology

The spatial distribution of the average seasonal rainfall in Limpopo province for the period 1990 and 2020 exhibits high rainfall variability (**Figure 4.6a**). Average seasonal rainfall over the Limpopo province ranges from a minimum of 200 mm to a maximum greater than 1000 mm. The high-lying escarpment in Vhembe, north and west of Mopani, south of Capricorn, and north of Greater Sekhukhune receives the highest total annual rainfall, ranging from 800 mm to greater than 1000 mm. Similar spatial patterns of rainfall were observed by several studies (Engelbrecht and Engelbrecht, 2016; Reason *et al.*, 2005b; Richard *et al.*, 2001; Roffe *et al.*, 2019). These findings are also consistent with those of Shikwambana *et al. (2021)*. The high-lying escarpment in the Waterberg district receives rainfall ranging from 400-750 mm. Mopani, south-west of Greater Sekhukhune, south-east and north of Waterberg, and Capricorn receive rainfall ranging from 350 mm to 600 mm. The lowest rainfall for the study period was recorded over the north of Vhembe district with rainfall less than 300 mm.

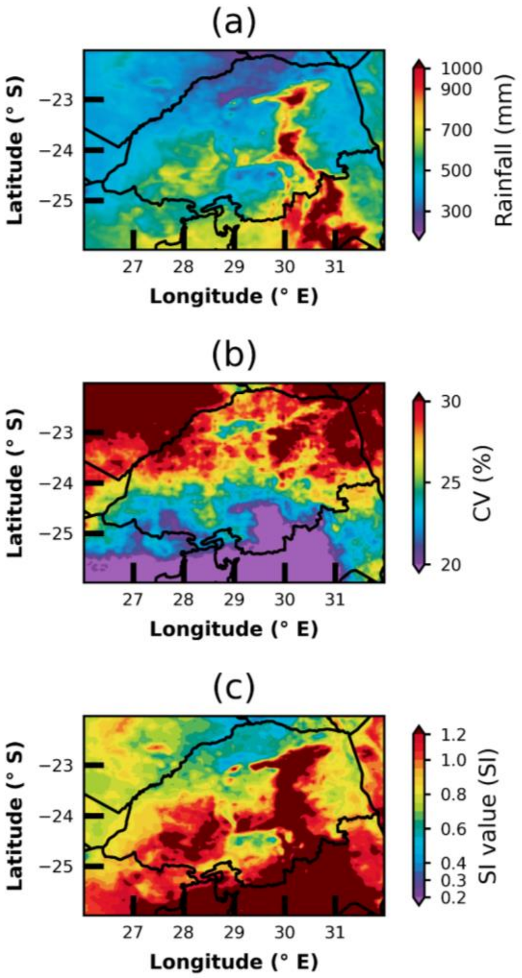


Figure 4.6: Rainfall patterns in the Limpopo province (a) Average annual distribution of seasonal rainfall in the region (b) the Coefficient of Variability (CV) and (c) the seasonality index (SI) during the study period (1990-2020).

**Figure 4.6b** shows that the highest CV (35.91%) was recorded in the Mopani and north of Capricorn district, whereas the lowest (14.69%) was recorded over the greater Sekhukhune district. The CV distribution shows that the Waterberg, Vhembe and Capricorn districts are moderately variable. This could be due to the fluctuating inter-annual rainfall. An inverse relationship between the topography of the area and the CV was also observed. The low elevations in the Mopani and north of Capricorn district are associated with the highest CV, whereas highly elevated areas are linked to moderate variability.

**Figure 4.6c** shows that the climate of the Limpopo province can be classified into different categories based on seasonality index values (SI). The high-lying escarpment in the Vhembe, west of Mopani, north-east of Greater Sekhukhune, south of Capricorn, and a small portion in the Waterberg districts, records the highest seasonality value of 1.20 or greater, suggesting that rainfall is extreme and mainly occurs in 1 to 2 months. In the high-lying escarpment over the Waterberg and west of Mopani district, an SI value of 1 to 1.19 is recorded, indicating that rainfall occurs in 3 months or less. The SI value in the north of Capricorn and Vhembe ranges from 0.4 to 0.6, implying that rainfall in the region is rather seasonal with a short dry season. In the east of Mopani district, the rainfall regime is notably seasonal with a long dry season with an SI value ranging from 0.80 to 0.99. The observed spatial patterns of mean seasonality index climatology emphasize that rainfall variability in the province is a product of rainfall duration and magnitude (Livada and Asimakopoulos, 2005).

### 4.2.2 Rainfall trend analysis in the Limpopo province.

The changes in total seasonal rainfall over time were observed in the Limpopo province for the period 1990 to 2020. **Figure 4.7** shows the shifts in total annual seasonal rainfall during the study period. The results showed statistically significant increasing trends over the Capricorn, Vhembe, north-west and south-west of Mopani, and south-east of Greater Sekhukhune. Statistically insignificant decreasing trends were observed east of Mopani, south-west of Greater Sekhukhune, and south of Waterberg. A statistically insignificant decrease of total seasonal rainfall in Mopani, south-west of Greater Sekhukhune, and south of Waterberg suggest that rainfall did not change or the changes were small and not impactful. However, it is still important to consider statistically insignificant rainfall trends over longer periods, as these trends could persist and become statistically significant over time.

Since increasing rainfall trends are being recorded over the Capricorn, Vhembe, north-west and south-west of Mopani, and south-east of Greater Sekhukhune. Food production and the livelihoods of these communities will be threatened, due to the area being prone to flood conditions. The gravity of this situation is reinforced by various sources, including (Maponya and Mpandeli, 2012; Mpandeli *et al.*, 2015; Nicholson *et al.,* 2014; Wetterhall *et al*., 2015). As such, proactive measures must be taken to mitigate the impact of floods on farming in communities in the region.

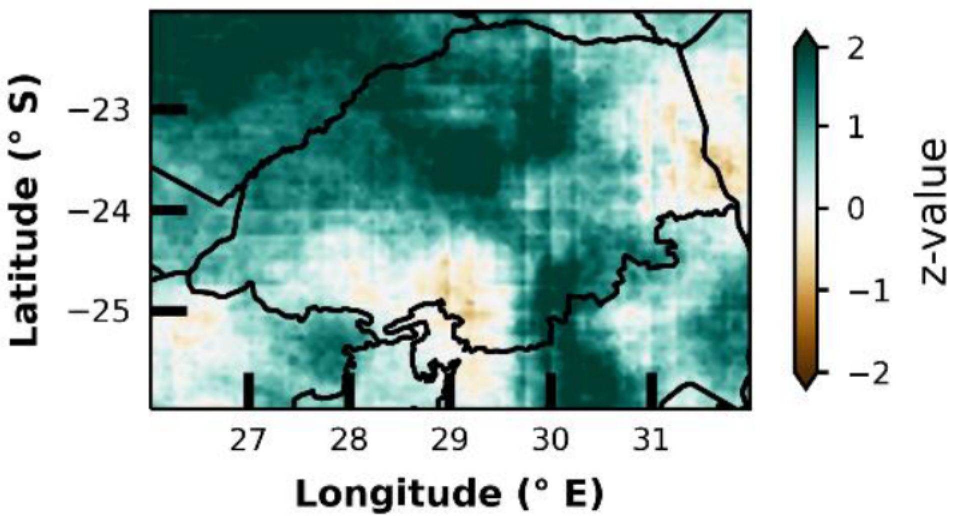


Figure 4.7: Changes in total seasonal rainfall (ONDJFM) over time for the period 1990-2021.

## 4.4 Wet days and dry spell frequencies

### 4.4.1 Mean frequency of dry spells

The authors define a dry spell as a pentad (5-day period) with rainfall less than 5 mm The mean frequency of dry-spells for the period 1990-2020 during the extended summer season which spans ON (early summer), DJ (mid-summer), FM (Late summer season) is shown (**Figure 4.8**). In this study, a dry spell is defined as a pentad (5-day period) with rainfall less than 5 mm. The uneven distribution and varying frequencies of dry spells throughout the extended summer periods are prominent features in the area. Throughout the extended summer season, migration and intensification of dry spells is observed from the north of Vhembe and Capricorn to the north-east of Mopani. The frequency and extent of dry spells increase from early summer to the late-summer. A study by Mengistu *et al*. (2020) reported that the Limpopo province records high episodes of dry spells.

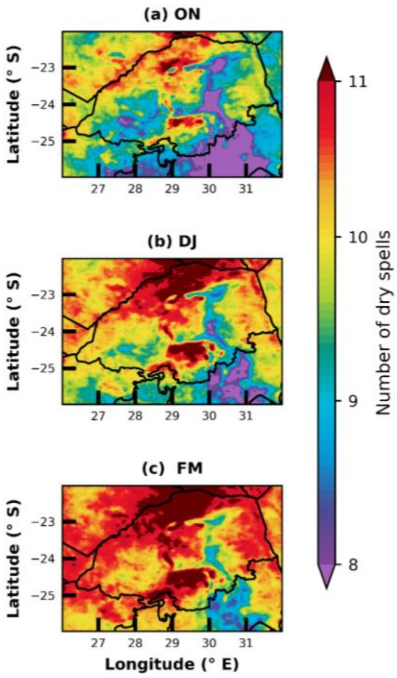


Figure 4.8: Dry-spell frequency climatology over the period 1990-2020 during (a) ON, (b) DJ, and (c) FM.

**Figure 4.8a** shows the spatial distribution of dry spells during ON, which is considered a transitional period. The highest dry-spell frequency with a range of 9-12 pentads is recorded over the north of Waterberg, Capricorn, and Vhembe, south-east of Waterberg, and south of Capricorn. The high-lying escarpment in the Vhembe, north-west and south-west Mopani, south-east of Capricorn and Waterberg districts records the lowest dry-spell frequency ranging from 6-9 pentads. During the DJ period (**Figure 4.8b**), the lowest dry-spell frequency ranging from 8-9 pentads is observed over the high-lying escarpment of Vhembe, west of Mopani, south-east Capricorn. The high-lying escarpment in Waterberg district records dry spells ranging from 9-10 pentads. In the north of Vhembe and Capricorn, south-west Waterberg, and north of Greater Sekhukhune and Mopani district dry spells ranging from 9-12 pentads are recorded. The FM period (**Figure 4.8c**), shows that the spatial extent of dry spell increases, with almost the entire province of Limpopo recording 9-12 pentads. The high-lying escarpment of Vhembe, west of Mopani, south-east Capricorn receives 8-10 pentads.

The highest frequencies of dry spells in this study are observed over the north of Vhembe, and Capricorn and Mopani districts throughout the periods. These observations are similar to the seasonal rainfall distribution, indicating minimal rainfall over these districts (**Appendix A1 and A2)**. These findings are in agreement with insights provided by Usman and Reason (2004), stating that these districts are located within the drought corridor, which is normally characterized by poor rainfall seasons and susceptibility to dry spells. The results of this study are similar to those of Thoithi *et al.* (2021) reinforcing the presence of the visible portion of the drought corridor as well as the frequency of dry spells within the region.

Although this area is located close to major moisture sources of the western and south-western Indian Ocean, the study area is still prone to multi-year droughts (Rapolaki *et al.*, 2019; Thoithi *et al.*, 2021), as evidenced by high occurrence of dry-spells frequencies. Cook *et al*. (2004) have attributed the dry spells to a decrease in the contribution of moisture from the tropical/subtropical southwest Indian Ocean (SWIO) into South Africa.

The Mozambique Channel plays a very critical role in influencing rainfall patterns over South Africa. Several studies show that a strong Mozambique Channel Trough (MCT) is associated with a decrease in rainfall over southern Africa and an increase in Madagascar, whereas a weak MCT shows the opposite effects (Matarira and Jury, 1992; Macron *et al.*, 2014; Barimalala *et al.*, 2021; Gebre and Getahun, 2016). According to Munday and Washington (2017), MCT can weaken the Angola low. The weakening of the Angola low can further affect the formation and position of the TTTs, which are known to play a critical role in rainfall patterns over southern Africa (Cook *et al.,* 2004; Reason and Mulenga, 1999).

### 4.4.2 Mean moderate wet days

The spatial distribution of mean moderate wet days is observed over the Limpopo province for the period 1990 to 2020. Moderate wet days exhibit high spatial and temporal variability over the study period. Of all periods, DJ receives the highest frequency of moderate wet days with a larger spatial extent over the Limpopo province.

**Figure 4.9a** displays the frequency of moderate wet days frequency over the Limpopo province during ON. Low moderate wet days are observed over Mopani, north of Vhembe, Capricorn, and north-west of Waterberg, south-west of Greater Sekhukhune, and south-east of Waterberg ranging from 1-3 days, whereas the high-lying escarpment of Vhembe, west of Mopani, south-east Capricorn and north of Greater Sekhukhune ranges from 4 to greater than 8 days. In contrast, moderate wet days during the DJ **(Figure 4.9b**) record 6 to greater than 8 days in the high-lying escarpment of Vhembe, west of Mopani, south-east Capricorn and Waterberg, and Greater Sekhukhune district. The north of Vhembe and Capricorn, Greater Sekhukhune, and south-east of Waterberg district records a minimum ranging from 1-5 days. During the FM period **(Figure 4.9c),** the Waterberg, south of Greater Sekhukhune and south of Mopani district records the highest frequency of moderate wet days ranging from 4-6 days. The north of Waterberg, Capricorn, Vhembe, and Mopani, and north of Greater Sekhukhune, and south-east of Waterberg records a range of 0-4 moderate wet days.

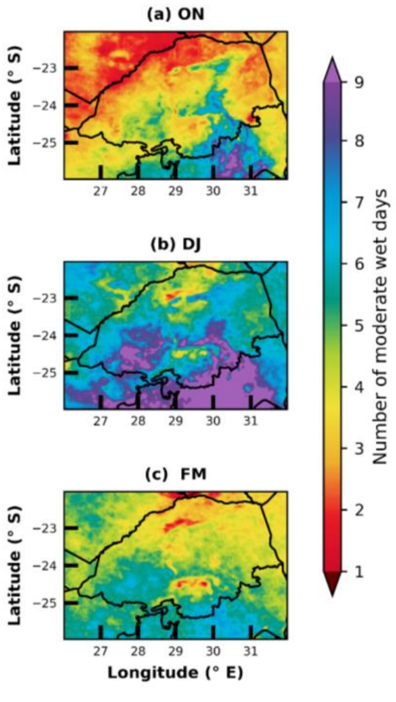


Figure 4.9: Moderate wet day frequency climatology over the period 1990-2020 during (a) ON, (b) DJ, and (c) FM.

The results show that Limpopo province exhibits a high frequency of moderate wet days during the DJ and FM seasons. Rapolaki *et al.* (2019) attribute this bias to cloud bands occurring mostly from October-March associated with almost half of high-intensity rainfall over the Limpopo River Basin. A study by Dunning *et al.* (2016) also showed that a large area of South Africa is projected to have later onset dates during the summer rainfall season. This might also be seen in fewer moderate wet days during the ON season, implying a delay in rainfall.

### 4.4.3 Mean heavy wet days

During the ON period (**Figure 4.10a**), the entirety of the province does not record any heavy wet days, except for a small portion in the high-lying escarpment in the Vhembe and west of Mopani district, which records 1-2 days. During the DJ period (**Figure 4.10b**), the high-lying escarpment of Vhembe, west of Mopani, south-east Capricorn, and north of Greater Sekhukhune records heavy wet days ranging from 3-7 days, whereas the Capricorn, north of Vhembe, west of Greater Sekhukhune and Waterberg records heavy wet days ranging from 0-2 days. The FM period (**Figure 4.10c**), shows that no heavy wet days were recorded in Capricorn, west of Waterberg, and north of Vhembe. The east of Mopani, south of Greater Sekhukhune, and high-lying escarpment in the Waterberg district record wet days ranging from

1-2 days. The highest frequency was recorded in the small portion in the high-lying escarpment in the Vhembe and west of Mopani district with a range of 3-7 days.

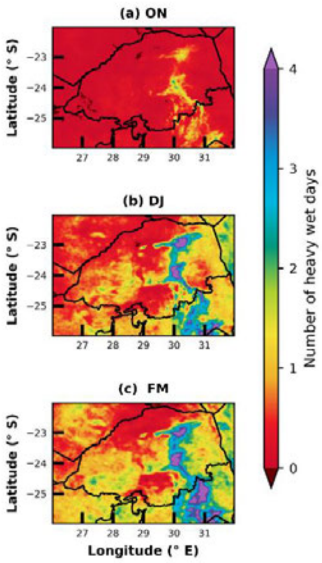


Figure 4.10: Heavy wet day's frequency over the period 1990-2020 during (a) ON, (b) DJ, and (c) MA.

### 4.5 Wet days and dry spells trends

#### 4.5.1 Dry-spell frequency trends

**Figure 4.11** shows the trend distribution of dry-spell frequency over the Limpopo province during the ON, DJ, and FM periods. Statistically insignificant trends of dry spells over the Limpopo province suggest that their frequency did not change or that the changes were small and not impactful. However, these results are still considered important in this study, as these trends could be significant in the long term.

During ON (**Figure 4.11a),** statistically significant decreasing trends at a 95% confidence interval are exhibited over the Greater Sekhukhune district. Statistically insignificant increasing trends are observed over Mopani and Waterberg. Statistically insignificant decreasing trends are recorded over the Vhembe and Capricorn districts. During the DJ period **(Figure 4.11b**), the province records decreasing trends. Statistically significant decreasing trends are observed over much of the Limpopo province except for the south of Waterberg and

Mopani. During FM (**Figure 4.11c**), the entirety of the region exhibits statistically significant decreasing trends over the whole of the Limpopo province. The DJ and FM show that the entirety of the region is characterized by statistically significant decreasing dry spells. The persistence of this trend is favorable for agricultural activities and further aids the attainment of the Sustainable Development Goals (SDGs) and objectives of the National Development Plan (NDP) within the province.

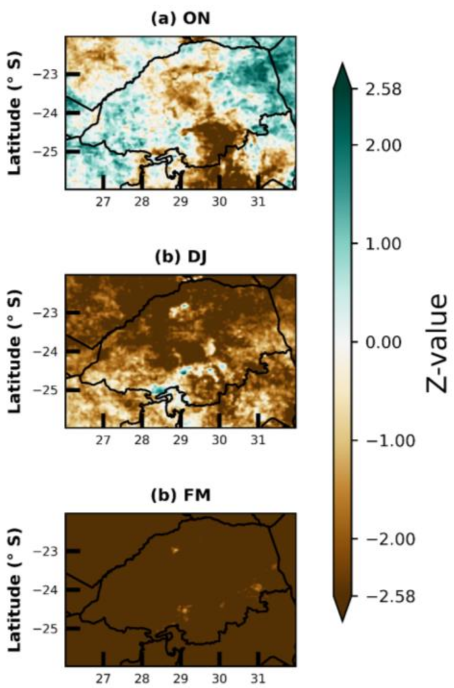


**Figure 4.11:** Spatial distribution of dry spell trends during (a) ON, (b). DJ and (c) FM.

4.5.2 Moderate wet day frequency trends.

Moderate wet day frequency trends are displayed in **Figure 4.12 (a to c)** for the extended summer season. During ON **(Figure 4.12a**), statistically significant decreasing trends were observed in the north and east of Mopani, south-east of Capricorn, and west of Mopani district. Furthermore, statistically insignificant increasing trends were observed over Capricorn, Waterberg, and Vhembe. During DJ **(Figure 4.12),** statistically significant decreasing trends were observed over a small portion in the south-east of Vhembe and north-west of Mopani district, whereas statistically insignificant decreasing trends were observed south of Capricorn and Greater Sekhukhune. Of these, statistically insignificant increasing trends are observed over the south-west of Vhembe and north of Capricorn district. The FM period (**Figure 4.12c**) records statistically insignificant decreasing trends over the Limpopo province except for a small portion lying between south-west Waterberg and south-east of Greater Sekhukhune. The entirety of the province records a mixture of both statistically insignificant decreasing and increasing moderate wet days.

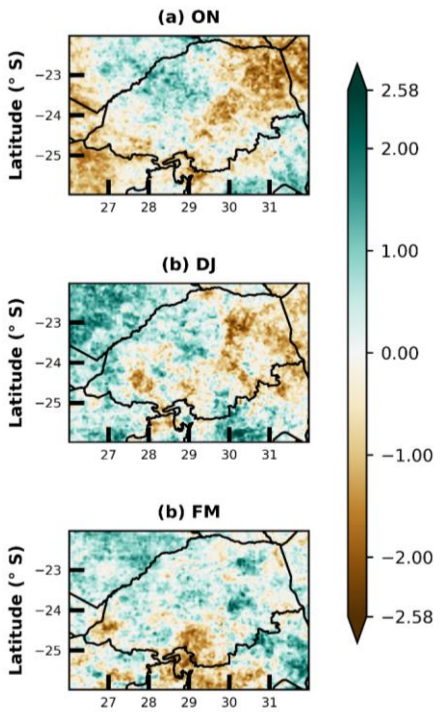


Figure 4.12: Spatial distribution of moderate wet day trends during (a) ON, (b). DJ and (c) FM.

### 4.5.3 Heavy wet day frequency trends

**Figure 4.13** shows the distribution trends of heavy wet day frequency over the Limpopo province. During ON increasing trends are observed over much of the Limpopo province, with a small portion recording decreasing trends in the south of Waterberg district. Statistically significant increasing trends are observed over the north-east of Waterberg and north of Capricorn. During DJ **(Figure 4.13b)** statistically significant increasing trends are observed over Vhembe, Greater Sekhukhune, and west of Waterberg, whereas the south of Waterberg district exhibits statistically insignificant decreasing trends in heavy wet days. The east of Mopani district exhibits no changes. During the FM period **(Figure 4.13c),** statistically insignificant decreasing trends are observed over the south of Waterberg and north of Capricorn. Statistically insignificant decreasing trends are exhibited in Mopani and north of Capricorn. The north of Waterberg, south-west of Capricorn, Vhembe, and Greater Sekhukhune exhibit statistically insignificant increasing trends.

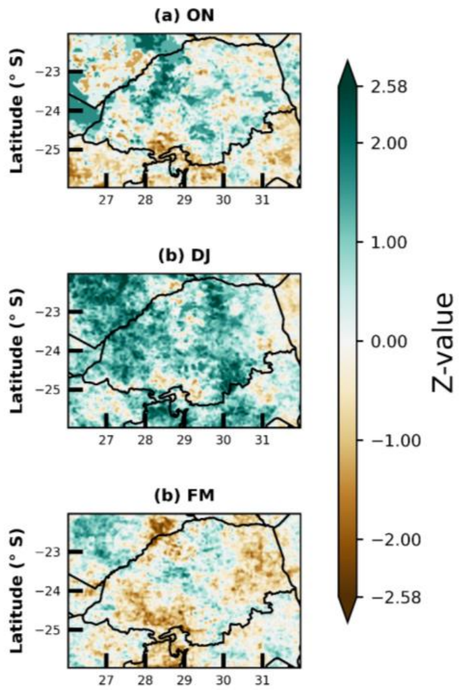


Figure 4.13: Spatial distribution of trends in heavy wet day frequency during (a) ON, (b). DJ and (c) FM.

## 4.6 Inter-annual variability of seasonal rainfall characteristics over the Limpopo province

### 4.6.1 Inter-annual seasonal rainfall characteristics variability during the ON period.

The relationship between standardized rainfall anomalies and seasonal rainfall characteristics was observed for the ON period. Positive (negative) rainfall anomalies are often associated with prevailing wet (dry) conditions. In this study, the results indicate that the relationship between seasonal rainfall characteristics and standardised rainfall anomalies is not always straightforward. For instance, in De Groot (**Figure 4.14**), the year 1997/98, 1998/99, 1999/00, 2001/02, 2007/08, and 2013/14 were characterized by positive anomalies. Although wet conditions prevail during positive anomalies, above-average dry spells were recorded in the years 1997/98, 1998/99, 1999/00, and 2001/02. Negative anomalies were recorded in the years 1991/92, 1992/93, 2002/03, 2004/05, 2015/16, and 2019/20. However, below-average dry spells were recorded in 1991/92, although dry conditions are expected to prevail.

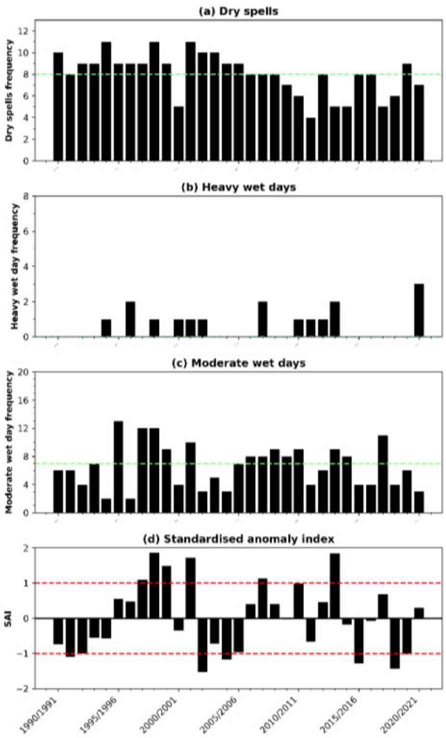

Figure 4.14: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in De Groot. The average is represented by green lines.

In Koedoeskop (**Figure 4.15**), positive anomalies were observed in 1993/94, 1998/99, 2000/01, 2007/08, and 2020/21. However, a complimentary relationship was observed between rainfall anomalies and seasonal rainfall characteristics. Negative rainfall anomalies were observed in the year 1990/91, 1999/00, 2002/03, 2004/05, 2015/16 and 2018/19. Of these years a complementary relationship between wet days and negative rainfall anomalies was observed. Although dry conditions are expected to prevail during these years, 1990/91 and 1999/00 recorded below-average dry spells. This therefore shows that seasonal rainfall anomalies overlook the impact of isolated rainfall events, especially on agriculture (Reason *et al.,* 2005).

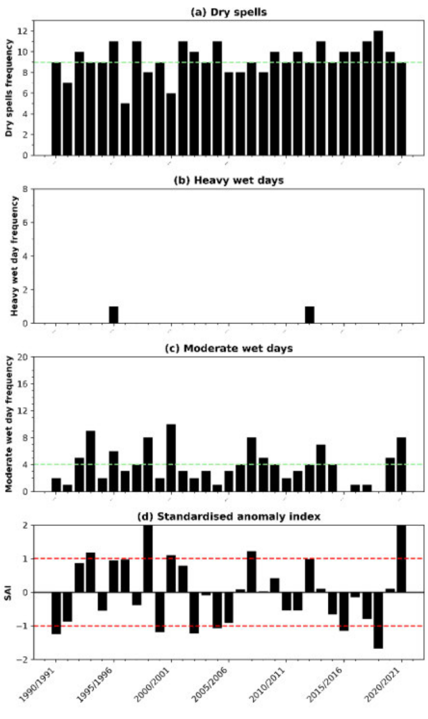


Figure 4.15: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in Koedoeskop. The average is represented by green lines.

In Kwaggahoek (**Figure 4.16),** positive rainfall anomalies were recorded in 1996/1997, 2001/02, and 2020/21. A complementary relationship was observed between positive rainfall anomalies and all seasonal rainfall characteristics. Furthermore, negative anomalies were recorded in 1991/92, 2002/03, 2005/06, 2014/15, 2018/19 and 2019/20. Although dry conditions are expected to prevail during these years, 2005/06 (1991/92, 2005/06, and 2014/15) recorded above-average moderate wet days (below average dry spells).

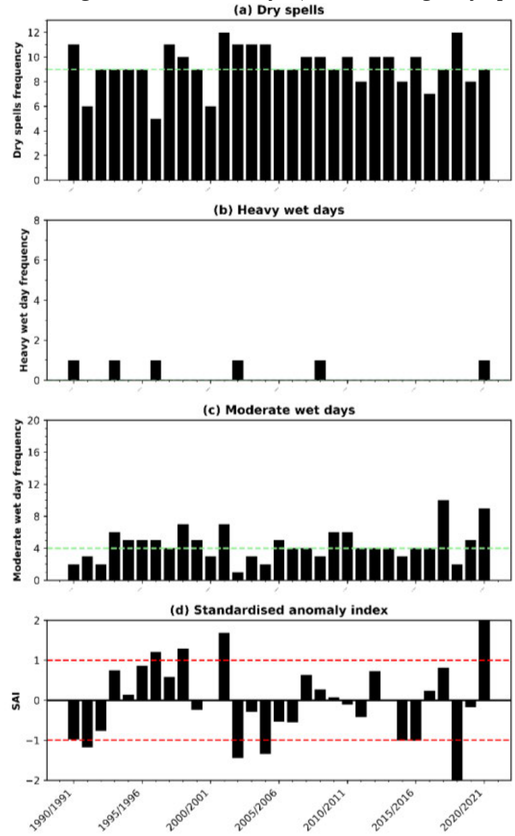


Figure 4.16: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in Kwaggahoek. The average is represented by green lines.

Lephalale (**Figure 4.17)** records positive anomalies in the years 1996/97, 1998/99, 2001/02, 2007/08, and 2020/21. Of these years a complementary relationship was exhibited between positive anomalies and moderate wet days, whereas above average dry spells were recorded in 1998/99, 2001/02, and 2007/08. Negative anomalies were exhibited in 1990/91, 2002/03, 2004/05, and 2018/19. Of these years, no year exhibited above-average moderate wet days and heavy wet days or below-average dry spells.

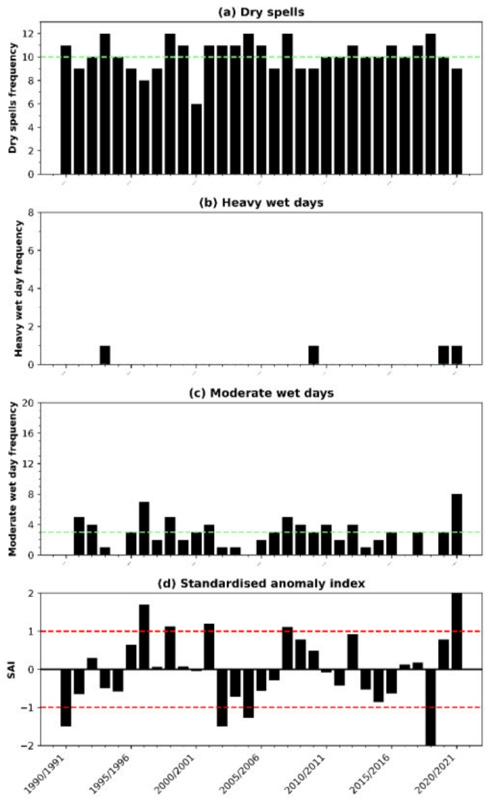


Figure 4.17: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in Lephalale. The average is represented by green lines.

Letaba Letsitele (**Figure 4.18)** recorded positive anomalies in 1998/99, 1999/00, 2001/02, 2007/08, and 2009/10. Of these years, only 2009/10 recorded below average moderate wet days. Above-average dry spells were recorded in 1998/99, 2001/02, and 2007/08. Negative anomalies were recorded in 1992/93, 2001/02, 2002/03, 2005/06 and 2014/15. Of these, 2014/15 recorded below-average dry spells were recorded, despite being characterized as an anomalously dry year.

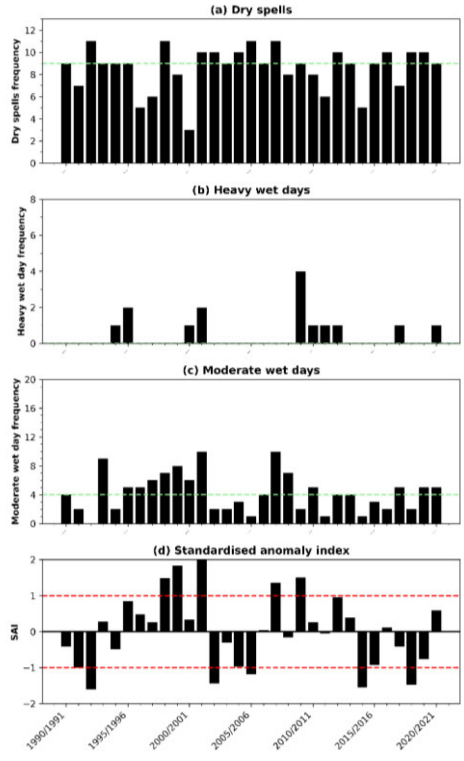


Figure 4.18: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in Letaba Letsitele. The average is represented by green lines.

Marble Hall (**Figure 4.19)** records positive anomalies in 1996/97, 1997/98, 1998/99, 2001/02, and 2020/21. Although wet conditions were expected to prevail, above-average were recorded in 1997/98, 1998/99, and 2001/02. Negative anomalies were exhibited in 1991/92, 2002/03, and 2008/09. Although dry conditions are expected to prevail, 1991/92 and 2018/2019 recorded below-average dry spells.

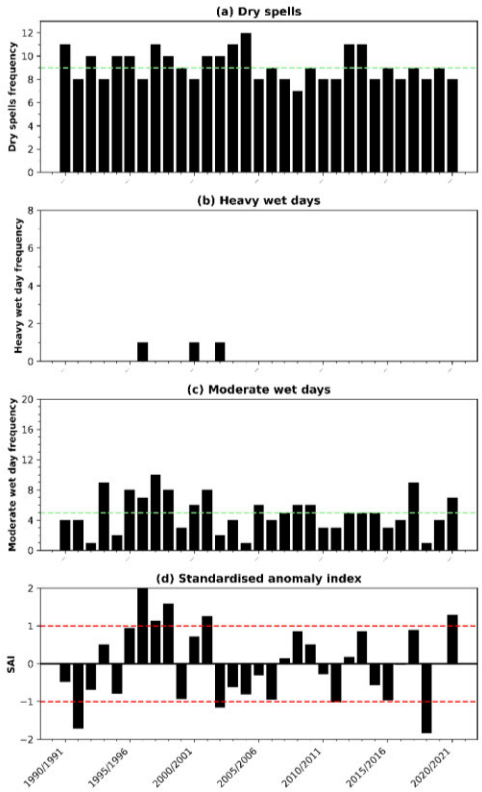


Figure 4.19: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in Marble Hall. The average is represented by green lines.

Polokwane (**Figure 4.20**) recorded positive anomalies in 1991/92, 2001/02 and 2007/08. Of all seasons, only 2001/02 recorded above (below) average moderate wet days (dry spells), despite the expectations of prevailing wet conditions. Negative anomalies were exhibited in 2002/03, 2004/05, 2005/06, 2014/15, and 2018/19. Only 2014/15 observed above-average dry spells, despite dry conditions being expected to prevail.

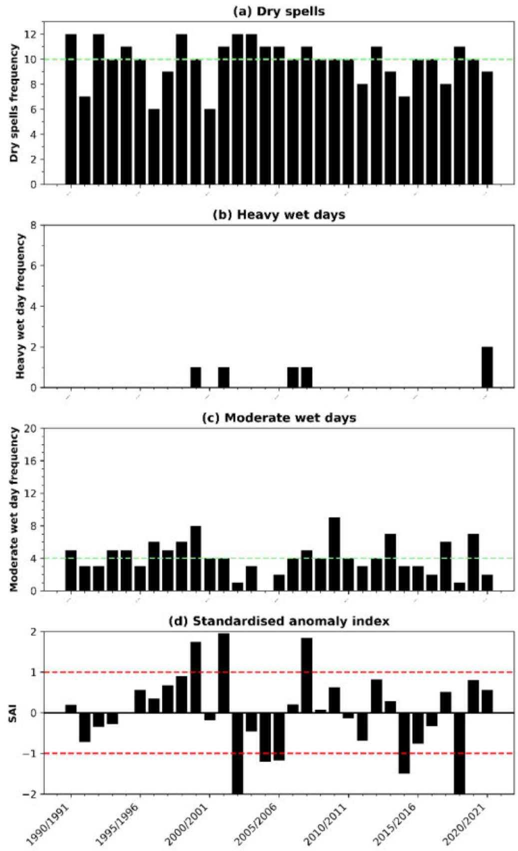


Figure 4.20: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index during the October to November (ON) period in Polokwane. The average is represented by green lines.

Sigonde (**Figure 4.21**) shows that positive anomalies were observed in 1993/94, 1998/99, 2000/01, 2007/08 and 2020/21. Not all years were characterized by prevailing wet conditions, for instance below (above) average moderate wet days (dry spells) were recorded in 2007/08 and 2020/21 (1993/94 and 1998/99). Negative anomalies were recorded in 1990/91, 1999/00, 2002/03, 2004/05, 2015/16 and 2018/19. Of these years above (below) average moderate wet days (dry spells) were recorded in 1991/92 and 2002/03 (1990/91, 1999/00, and 2004/05), despite dry conditions being expected to prevail.

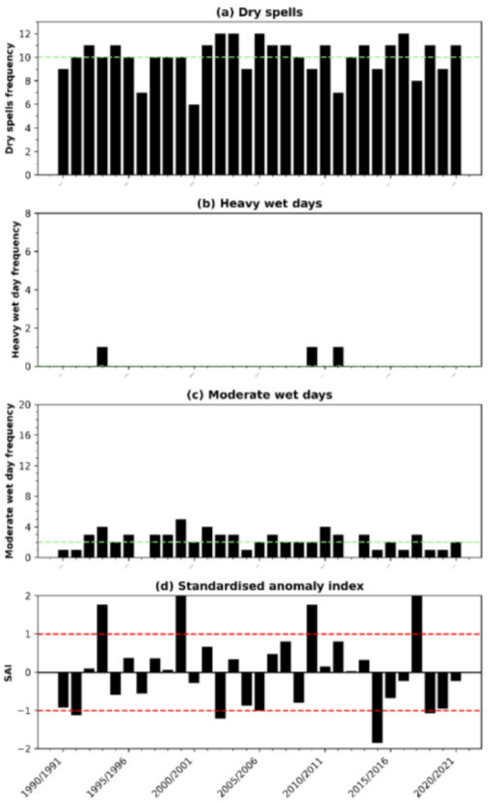


Figure 4.21: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in Sigonde. The average is represented by green lines.

In Rabali (**Figure 4.22**), positive anomalies were recorded in 1998/1999, 1999/00, 2007/08, 2009/10/, 2017/18. Moderate wet days (heavy wet days) were recorded below averages in 1998/99 and 2007/08 (1998/99/2009/10 and 2017/2018), while below-average dry spells were recorded in 2007/08. This suggests that the interplay between anomalously wet periods and dry spells is intricate and not solely determined by rainfall anomalies. Negative anomalies were recorded in the years 1991/1992, 1994/95, 2004/05, 2014/15 and 2018/19. However, below-average dry spells were recorded in 1994/95 and 2018/19 despite dry conditions being expected to prevail.

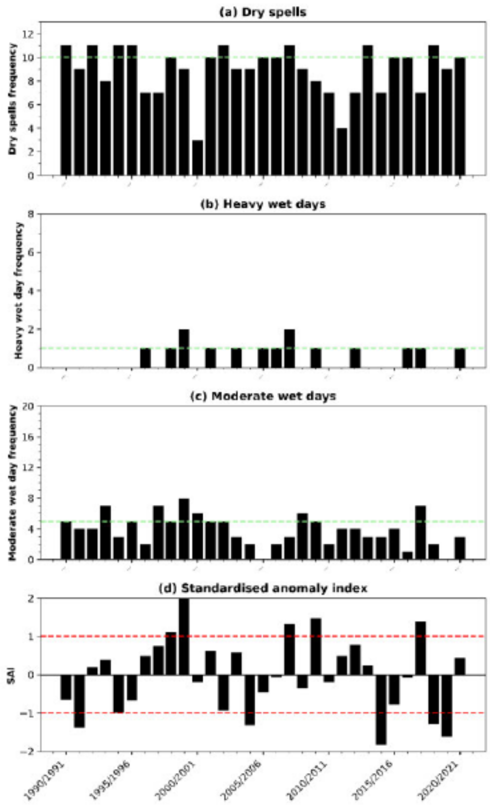


Figure 4.22: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the October to November (ON) period in Rabali. The average is represented by green lines.

### 4.6.2 Inter-annual seasonal rainfall characteristics variability during the DJ period.

In De Groot (**Figure 4.23**), positive anomalies were recorded in the year 2010/11, 2011/12, 2012/13, 2013/14, 2014/15, 2016/17, and 2017/18. Not all years are characterized by prevailing wet conditions during positive anomalies. For instance, below-average moderate (heavy) wet days were recorded in 2011/12, 2014/15, and 2017/18 (2017/18), while below-average dry spells were recorded in 2011/12. Negative anomalies were recorded in 1994/95, 2001/02, 2004/05, 2005/06 and 2007/08. Dry conditions prevailed during these years except for 2004/05, which recorded below-average dry spells.

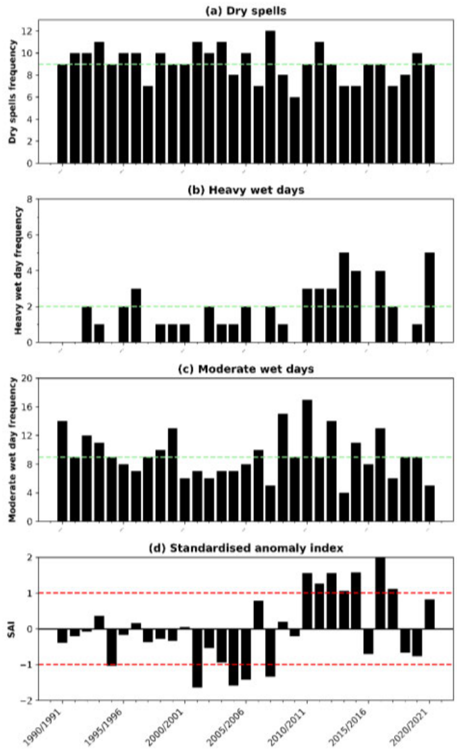


Figure 4.23: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in De Groot. The average is represented by green lines.

In Koedoeskop (**Figure 4.24**), the years 1991/92, 1998/99, 2006/07, 2008/09, 2009/10, 2010/11 and 2017/18 were characterized by positive anomalies. Despite wet conditions being expected to prevail, below-average moderate wet days (dry spells) were recorded in 1991/92, 2005/06, 2006/07, and 2009/10 (1998/99). Negative rainfall anomalies were recorded in 1993/94, 2002/03, 2003/04, 2007/08, and 2015/16. All the years recorded below (above) average moderate wet days (dry spells) except 2007/08 (1993/94).

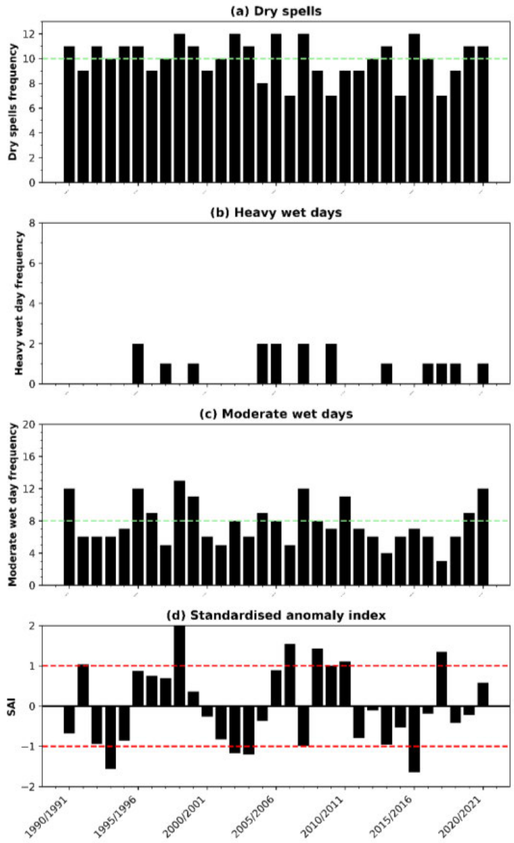


Figure 4.24: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly (SAI) Index during the December to January (DJ) period in Koedoeskop. The average is represented by green lines.

In Kwaggahoek (**Figure 4.25**), positive anomalies were recorded in 1996/97, 2006/07, 2009/10, 2017/18, and 2020/21. Since wet conditions are expected to prevail, all years recorded above-average moderate (heavy) wet days except the years 1996/97 and 2017/18 (1996/97, 2006/07, 2009/10, and 2017/18). Negative anomalies were recorded in 2001/02, 2002/03, 2003/04, 2005/06, and 2015/16. Although dry conditions are expected to prevail during negative anomalies, above-average moderate (heavy) wet days were recorded in 2001/02, 2005/06, and 2007/08 (2007/08), while below average dry spells are recorded in 2001/02, and 2003/04.

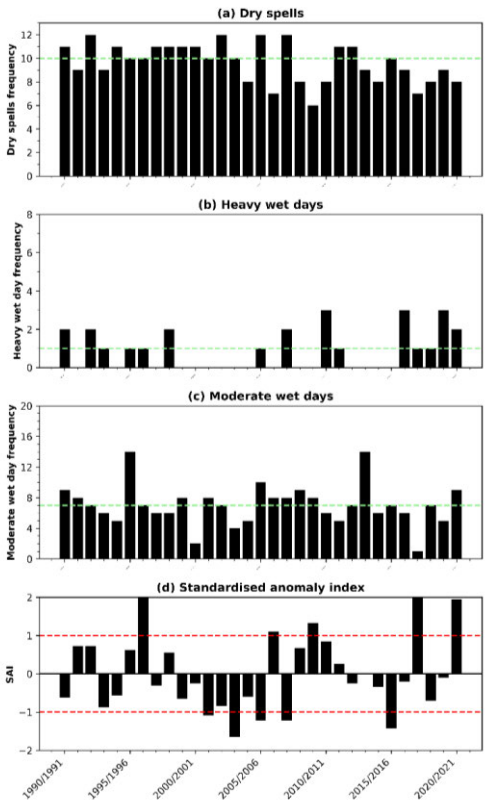


Figure 4.25: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in Kwaggahoek. The average is represented by green lines.

In Lephalale (**Figure 4.26**), positive anomalies were recorded in 1995/96, 2006/07, 2009/10, 2017/18, and 2020/21. During these years, most years except for 1995/96 recorded below average moderate wet days despite the expectations of wet conditions to prevail. Negative anomalies were recorded in 2001/02, 2002/03, 2003/04, 2005/06, and 2015/16. During these years above (below) average moderate wet days (dry spells) were recorded in 2005/06 (2001/02 and 2003/04), despite dry conditions being expected to prevail.

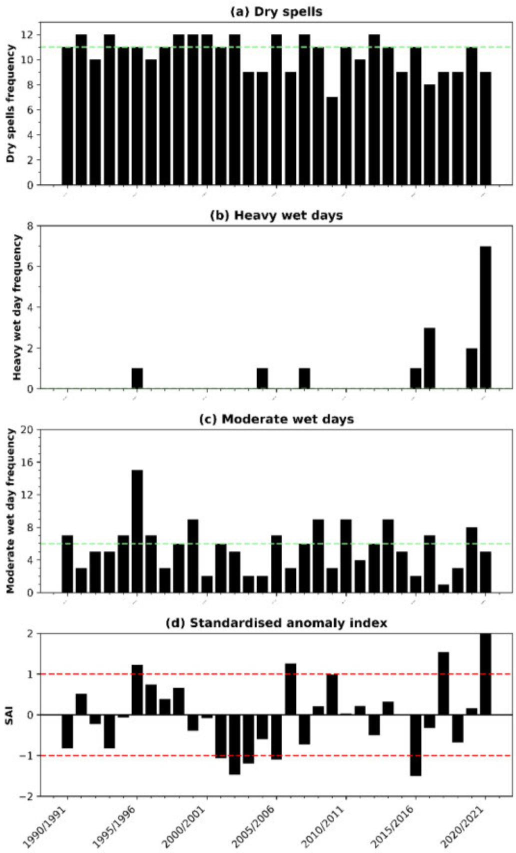


Figure 4.26: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in Lephalale. The average is represented by green lines.

Letaba Letsitele (**Figure 4.27**) shows that positive anomalies were recorded in 2010/11, 2013/14, 2014/15, and 2017/18. Although wet conditions are expected to prevail, below-average moderate (heavy) wet days were recorded in 2013/14 and 2017/18 (2014/15 and 2017/18). Negative anomalies are exhibited in the years 2001/02, 2002/03, 2005/06, 2007/08, 2015/16, 2018/18 and 2019/20. Of these years, above-average moderate wet days (dry spells) were recorded in 2005/06, 2015/16, and 2019/20 (2018/19 and 2019/20), despite dry conditions being expected to prevail.

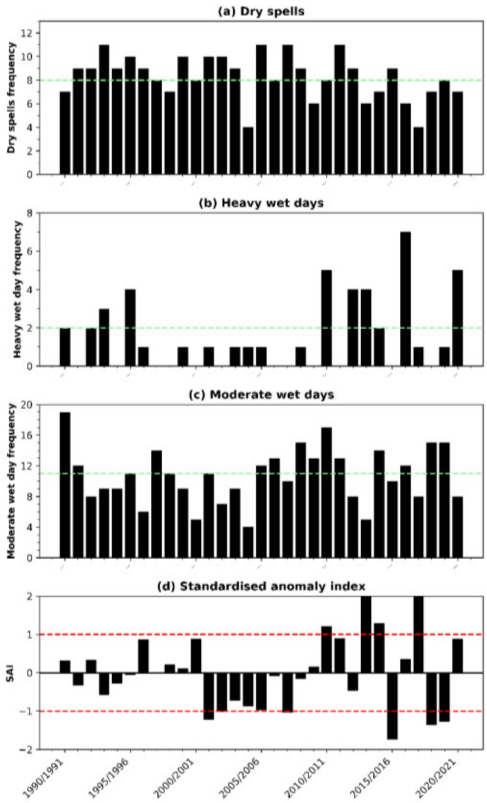


Figure 4.27: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in Letaba Letsitele. The average is represented by green lines.

Marble Hall (**Figure 4.28**) records positive anomalies in 2006/07, 2011/12, 2012/13, 2016/17, and 2017/18. All years recorded above (below) average moderate wet days (dry spells) except for 2011/12, 2012/13, and 2017/18 (2011/12 and 2012/13), despite the periods being associated with positive rainfall anomalies. Negative anomalies were exhibited in 1994/95, 2001/02, 2003/04, 2004/05, 2005/06 and 2007/08. Above (below) average moderate wet days (dry spells) were recorded in 1994/95 and 2005/06 (2003/04, 2004/05 and 2005/06), despite the expectation of dry conditions to prevail.

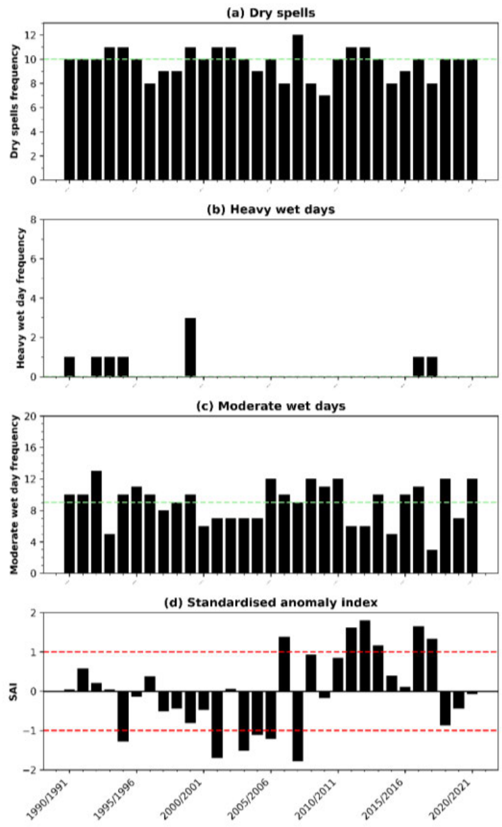


Figure 4.28: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in Marble Hall. The average is represented by green lines.

Polokwane (**Figure 4.29**) shows that the years 1996/97, 1997/98, 2013/14, 2017/18, and 2020/21, were characterized by positive anomalies. Although wet conditions are expected to prevail, all years recorded below-average moderate wet days, except for 2013/14, while above-average dry spells were recorded in 1997/98. Negative anomalies were exhibited in 2001/02, 2002/03, 2004/05, 2007/08 and 2015/16. Below-average dry spells were recorded in 2004/05, despite the expectation of dry conditions to prevail.

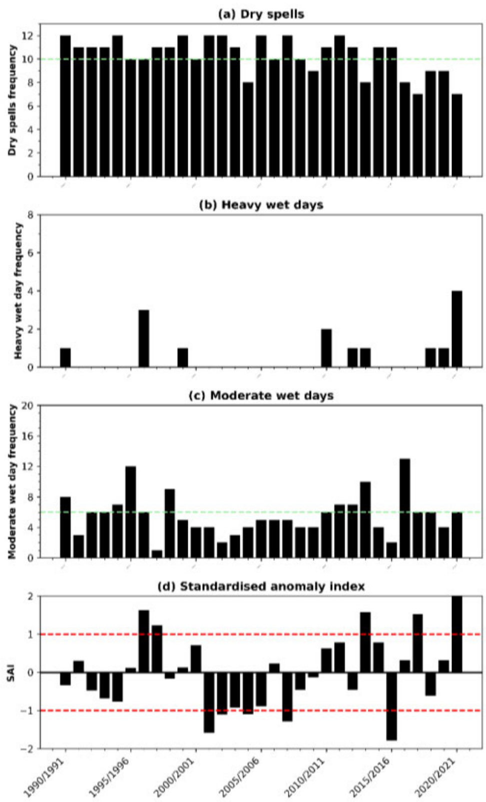


Figure 4.29: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in Polokwane. The average is represented by green lines.

In Rabali (**Figure 4.30),** positive anomalies were exhibited in 2000/01, 2010/11, 2011/12, 2013/14, 2014/15, and 2017/18. All years were characterized by below-average moderate (heavy) except for 2011/12 (2010/11, 2011/12, and 2013/14). This suggests that the relationship between seasonal rainfall characteristics and standardized anomaly index is not always linear. This further emphasizes the complex interplay between wet and dry periods within specific years. The findings underscore that positive anomalies do not necessarily equate to above-average moderate and heavy wet days or below-average dry spells (Rapolaki *et al.*, 2019). Negative anomalies were recorded in 2001/02, 2005/06, 2007/08, 2015/16, and 2018/19. Although dry conditions are expected to prevail, below (above) average dry spells (moderate wet days) were recorded in 2007/08 and 2018/19 (2005/06).

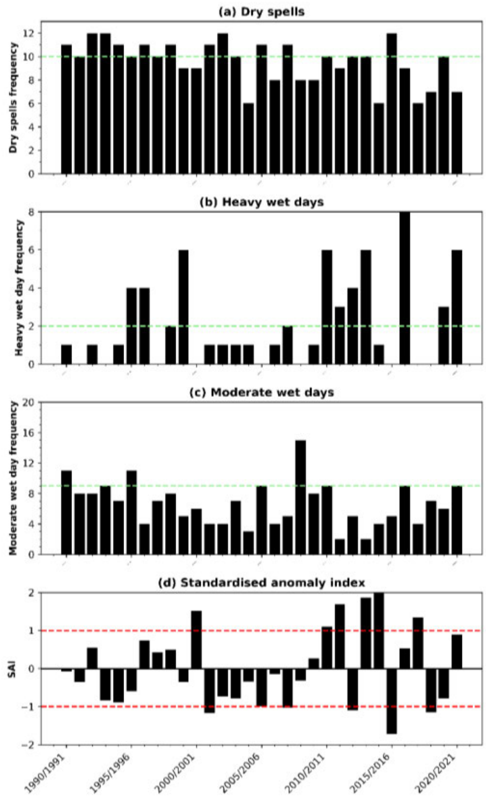


Figure 4.30: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in Rabali. The average is represented by green lines**.**

In Sigonde (**Figure 4.31**), the years 1996/97, 1998/99, 2000/01, 2010/11, and 2011/12 recorded positive anomalies. Below (above) average moderate wet days (dry spells) were recorded in 1996/97, 2000/01, and 2011/12 (1996/97, 1998/99, and 2000/01), despite years being characterized by positive anomalies. Negative anomalies were exhibited in 1995/96, 2001/02, 2002/03, 2005/06, 2012/13, and 2015/16. Of these years, above-average moderate (heavy) wet days were recorded in 2012/13 (1995/96 and 2012/13), while below-average dry spells were recorded in 1995/96, 2001/02, and 2012/13 despite dry conditions being expected to prevail during these years.

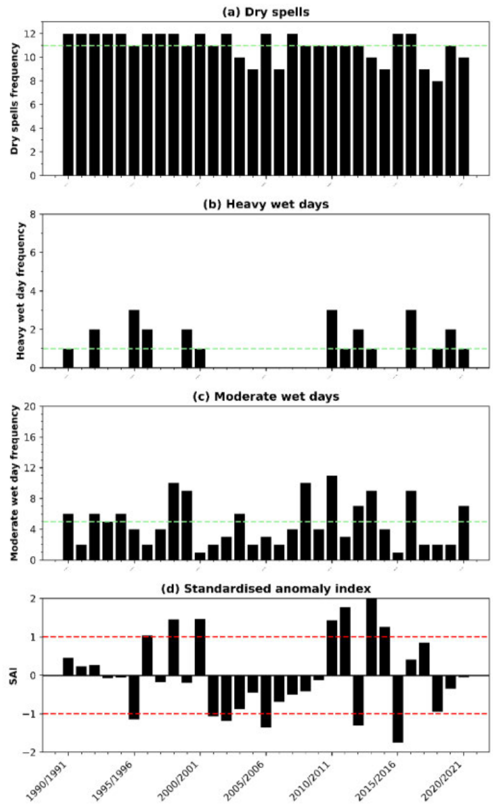


Figure 4.31: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the December to January (DJ) period in Sigonde. The average is represented by green lines.

4.6.3 Inter-annual seasonal rainfall characteristics variability during the FM period

During the FM period, De Groot (**Figure 4.32**) shows positive anomalies in 1996/97, 2000/01, 2006/07, 2014/15, 2017/18, and 2018/19. Of these years, below-average moderate (heavy) wet days were recorded in 2000/01 and 2014/15 (1996/97, 2006/07, and 2014/15), while dry spells show above average frequencies in 1996/97, despite the years being characterised by positive anomalies. Negative anomalies were exhibited in 1998/99, 2003/04, 2011/12. Although dry conditions are expected to prevail, above-average moderate (heavy) wet day were recorded in 1998/99 and 2003/04 (2003/04), and below-average dry spells in (2011/12).

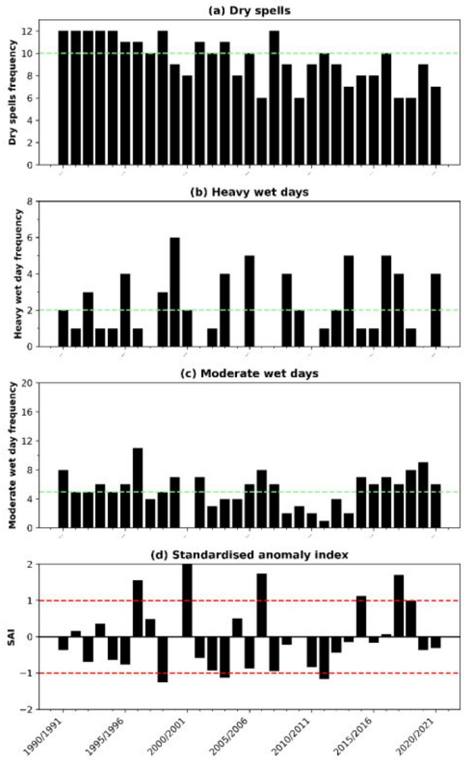


Figure 4.32: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the February to March (FM) period in De Groot. The average is represented by green lines.

In Koedoeskop (**Figure 4.33**), positive anomalies are recorded in 1996/97, 1997/98, 2000/01, 2004/05, 2006/07, and 2014/15. All years recorded below-average heavy wet days, while below average moderate wet days were recorded in 1997/98,2000/01, 2006/07, 2014/15. This further shows that positive rainfall anomalies do not necessarily imply that the season was characterized by frequent intense rainfall, sometimes they result from consistent light rainfall throughout the season (Thoithi *et al.*, 2021). Negative anomalies were observed in 1999/00, 2002/03, and 2007/08. Below-average dry spells were recorded in 2002/03 and 2007/08, despite the years being characterized by negative anomalies.

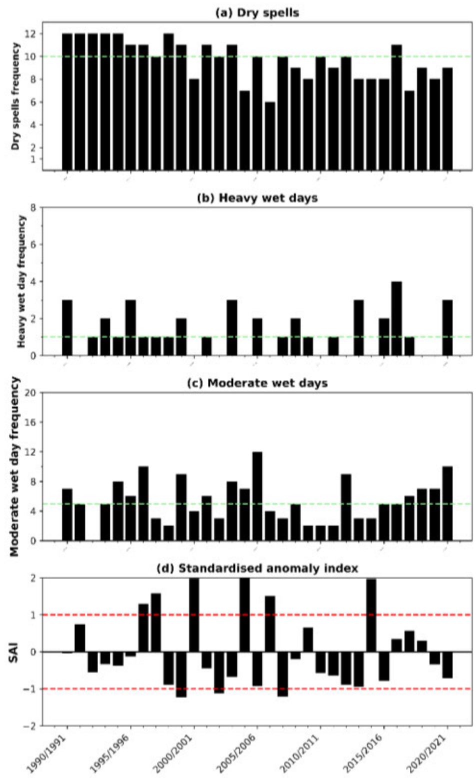


Figure 4.33: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the February to March (FM) period in Koedoeskop. The average is represented by green lines.

In Kwaggahoek (**Figure 4.34**), the years 1991/92, 1996/97, 2000/01, 2006/07, and 2019/20 recorded positive anomalies. Below-average moderate (heavy) wet days were recorded in 2000/01, 2006/07, and 2019/20 (1991/92, 2000/01, 2006/07, and 2019/20), while dry spells recorded above average frequencies in 1991/92, despite the years being characterized by positive anomalies. Negative anomalies were recorded in 2002/03, 2003/04, 2007/08, 2010/11 and 2011/12. Of these years above (below) average moderate (dry spells) were recorded in 2003/04 (2002/03, 2003/04, 2010/11, and 2011/12), despite years being characterized by negative anomalies.

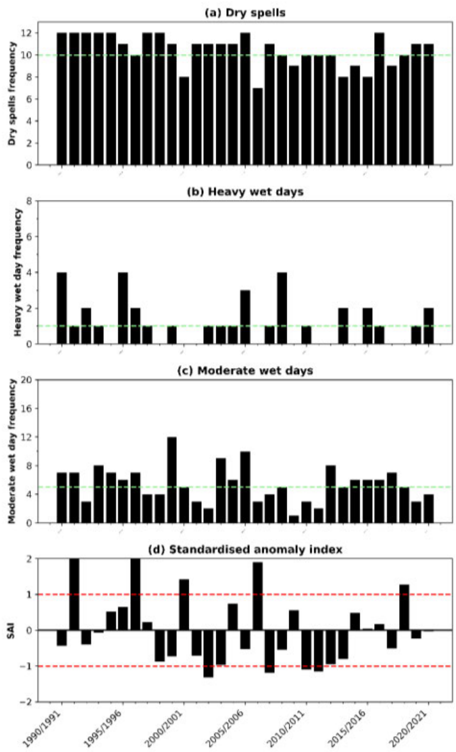


Figure 4.34: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the February to March (FM) period in Kwaggahoek. The average is represented by green lines.

Lephalale (**Figure 4.35**) records positive anomalies in 1996/97, 1997/98, 2000/01, 2006/07, 2014/15, 2016/17 and 2018/19. Although wet conditions are expected to prevail during positive anomalies, below (above) average moderate wet days (dry spells) were recorded in 1997/98, 2006/07, 2016/17, and 2018/19 (1996/97, 1997/98, 2016/17 and 2018/19). Negative rainfall anomalies were observed in 1998/99, 2002/01, 2005/06, 2007/08, 2011/12, 2012/16 and 2013/14. Although negative anomalies are associated with prevailing dry conditions, above-average heavy (moderate) wet days were recorded in 2013/14 (2005/06), while below-average dry spells were recorded in 2011/12, 2012/13, and 2013/14.

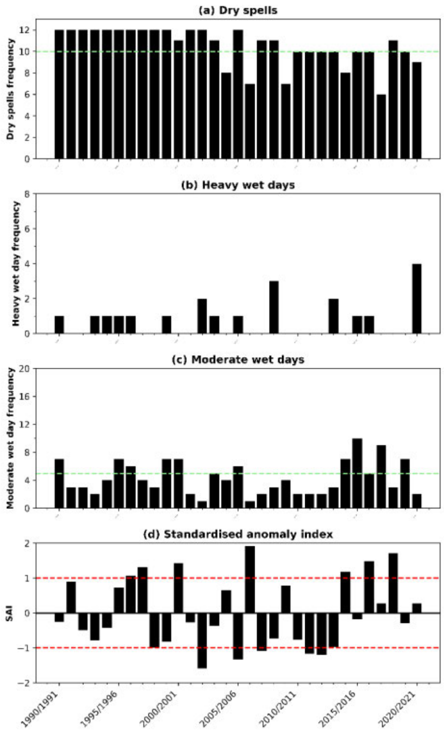


Figure 4.35: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the February to March (FM) period in Lephalale. The average is represented by green lines.

Letaba Letsitele (**Figure 4.36**) shows that the years 1996/97, 1997/98, 2000/01, 2004/05, 2006/07and 2018/19 were characterized by positive anomalies. Despite these years being characterized by positive rainfall anomalies, below-average moderate (heavy) wet days were exhibited in 1997/98, 2004/05, and 2006/07 (1997/98, 2000/01, 2004/05, and 2006/07), while above-average dry spells were recorded in 1996/97 and 1997/98. Negative rainfall anomalies were recorded in 1998/99, 2002/03 and 2011/12. Above (below) average moderate wet days (dry spells) were observed in 1998/99 and 2002/03 (2002/03 and 2011/12).

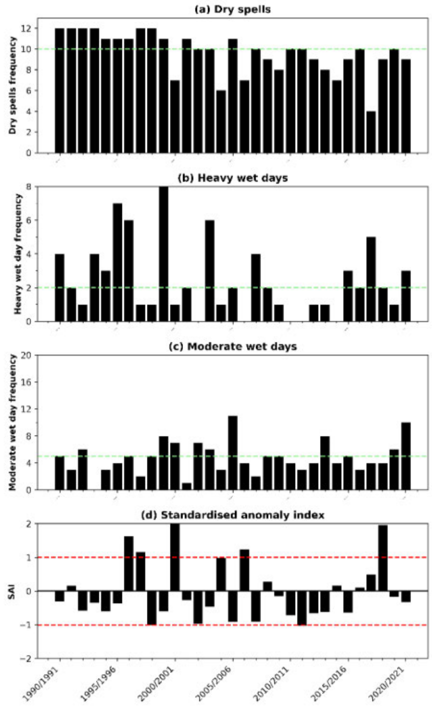


Figure 4.36: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the February to March (FM) period in Letaba Letsitele. The average is represented by green lines.

In Marble Hall (**Figure 4.37**), the years 1991/92, 1996/97, 2000/01, 2004/05, 2006/07, and 2009/10. Of these, all years recorded below-average moderate (heavy) wet days except for the years 1991/92 and 1996/97 (2000/01), while above average dry spells are recorded in 1991/92 and 1996/97. This further justifies that a year with a positive rainfall anomaly does not equate to a good agricultural season (Reason *et al.*, 2005). Negative anomalies were exhibited in 1998/99, 1999/00, 2003/04, 2007/08, 2010/11, 2011/12 and 2013/14. During this time, 1999/00, 2003/04, and 2013/05 (2003/04) were characterized by above-average moderate (heavy) wet days, while below-average dry spells were recorded in 2010/11 and 2013/14, despite the expectation of prevailing dry conditions during these years.

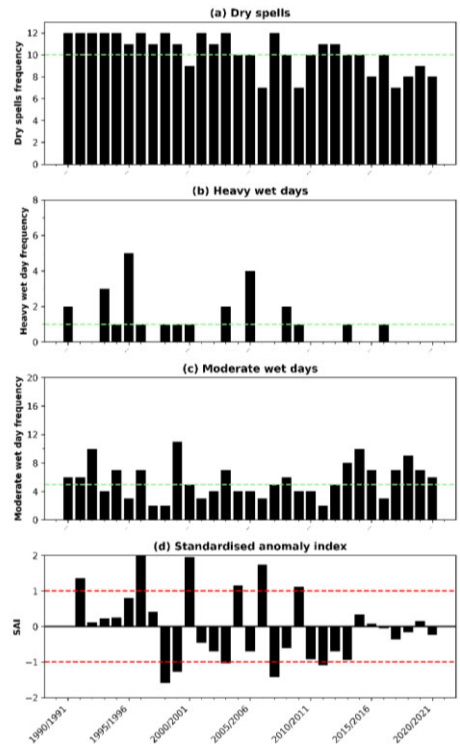


Figure 4.37: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the February to March (FM) period in Marble Hall. The average is represented by green lines.

In Polokwane (**Figure 4.38**), positive anomalies were exhibited in 1996/97, 2000/01, 2004/05, 2006/07, 2017/18 and 2018/19. Of these years the year 2000/01, 2004/05, 2006/07, 2017/18, and 2018/19 (1996/97, 2000/01, 2004/05, 2006/07 and 2018/19) were characterized by below average moderate (heavy) wet days. Negative anomalies were recorded in 1999/00, 2002/03, 2007/08 and 2011/12. Of these years, heavy and moderate wet days (dry spells) recorded above (below) average frequencies in 1999/00 (2007/08 and 2011/12).

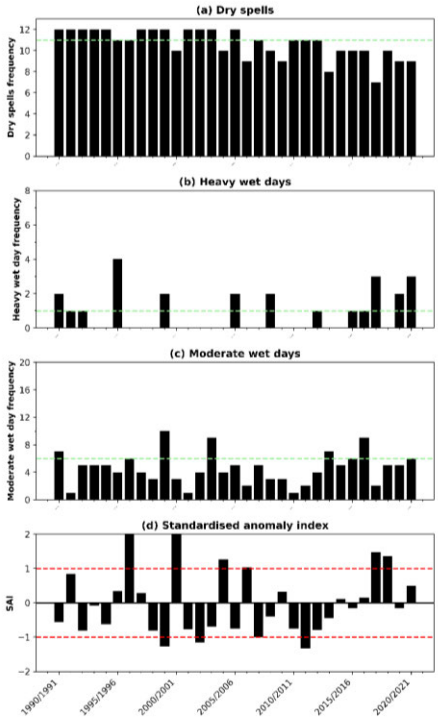


Figure 4.38: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardised Anomaly Index (SAI) during the February to March (FM) period in Polokwane. The average is represented by green lines.

Rabali (**Figure 4.39**) shows that the years 2000/01, 2002/03, 2007/08 and 2011/12 were characterised by positive anomalies. During these years, no above-average moderate wet days were recorded, although most of these years recorded above-average heavy wet days, except for 2002/03, while above-average dry spells were recorded in 2018/2019, despite the area being characterized by positive rainfall anomalies. Negative rainfall anomalies were recorded in the years 1994/95, 2002/03, and 1993/94. Although these years are expected to exhibit dry conditions, heavy wet days recorded above average frequencies in 1994/95 and 2002/03.

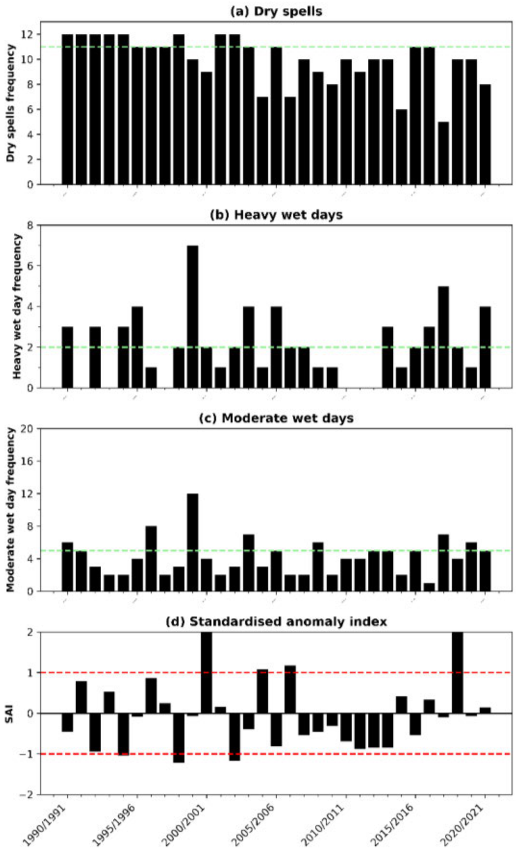


Figure 4.39: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardized Anomaly Index (SAI) during the February to March (FM) period in Rabali. The average is represented by green lines

In Sigonde (**Figure 4.40**), the years 1996/97, 1999/00, 2000/01, 2004/05, and 2018/19 show positive anomalies. However positive anomalies are often associated with prevailing wet conditions. During this year 1996/97, 2004/05, and 2018/19 (1996/97, 1999/00, 2000/01, and 2018/19) records below (above) average moderate wet days (dry spells). Negative rainfall anomalies were recorded in 1994/95, 1998/99, 2002/03, and 2011/12. Above (below) average moderate wet days (dry spells) were exhibited in 1998/99 and 2002/03 (2011/12).

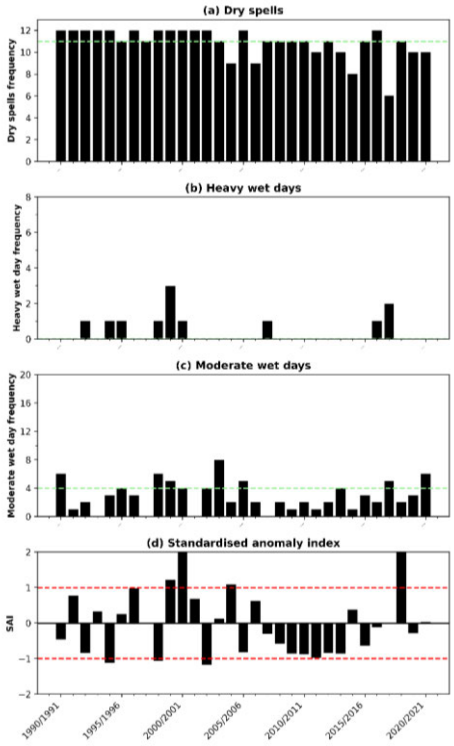


Figure 4.40: Comparison of (a) dry spells, (b) heavy wet days, (c) moderate wet days, and (d) Standardised Anomaly Index (SAI) during the February to March (FM) period in Sigonde. The average is represented by green lines.

## 4.7 Relationship between seasonal rainfall characteristics and ENSO

From the literature, it is known that ENSO plays a pivotal role in rainfall variability over southern Africa (Gaughan *et al.*, 2016). The warm phase ENSO (El Niño) is often associated with drier conditions and the cool phase of ENSO (La Niña) with wetter conditions over southern Africa (Jury *et al.*, 2004; Mason, 2001; Mason and Jury, 1997). Most above-average wet days align with La Niña. However, the results show that not all El Niño (La Niña) events are associated with dry (wet) conditions (**Figure 4.41 to 4.48**). The extent at which this phenomenon influences seasonal rainfall characteristics remains unclear.

A somewhat complex relationship exists between ENSO events and seasonal rainfall characteristics (Hoell *et al.*, 2021). It was shown that a La Niña (El Niño) season, does not always equate to an increase (decrease) in wet day frequency or a decrease (increase) in dry spell frequencies (Rapolaki *et al.*, 2019; Reason *et al.*, 2005). For instance, seasons showing above-average wet days and below-average dry spells were observed during El Niño season. Some seasons with the neutral phase of ENSO are characterized by above-average wet days. Jiménez-Muñoz *et al.* (2016) also demonstrated that the relationship between ENSO and the frequency of extreme rainfall events can be explained by other factors. For instance, Dube and Jury (2003) and Dedekind *et al*. (2016) showed the influence of local topographic circulations as other factors influencing seasonal rainfall characteristics and variability. Mulenga *et al.* ( 2003) demonstrated that the neutral season with anomalously high dry spell frequencies can be accounted for in terms of regional circulation anomalies. Mid-latitude anomalies leading to an increase in advection of relatively cool, dry south-Atlantic air appear to be important, similar to the severe none El Niño drought years analyzed in the region. The findings regarding the relationship between ENSO and seasonal rainfall patterns over the Limpopo province align with previous research that shows an association between ENSO and seasonal rainfall characteristics (Miron and Lindesay, 1983; Nicholson and Kim, 1997; Nicholson and Selato, 2000; Reason, 2007).

### 4.7.1 Relationship between dry spells and ENSO

During the ON period (**Figure 4.41**), the warm phase of ENSO was recorded in 1992/93, 1993/94, 1997/95, 1998/99, 2015/16, 2016/17 and 2019/20. Since this phase is associated with prevailing dry conditions, it was observed that not all years were characterized by above-average dry spells. For instance, the following years in the following station were characterized by below-average dry-spells, despite being characterized by the warm phase of ENSO. De Groot recorded below average dry-spells in 2016/17, Letaba Letsitele in 1993/94, 1997/98, Koedoeskop in 1993/94 and 1998/99, Kwaggahoek in 1992/93, 1993/94, 2016/17, and 2019/20, Polokwane in 1993/94, 1997/98, 2016/17 and 2019/20, Sigonde in 1993/94, 1997/98, 1998/99, and 2019/20, Rabali in 1993/94, 1997/98, 2015/16 and 2019/20, Lephalale in 1992/93, 1997/87, 2016/17 and 2019/20 and Marble hall in 1993/94, 2016/17 and 2019/20. The cool phase of ENSO was exhibited in 1999/00, 2000/01, 2008/09 and 2011/12. Since this year is associated with prevailing wet conditions, only Lephalale in 1999/00 recorded above-average dry spells.

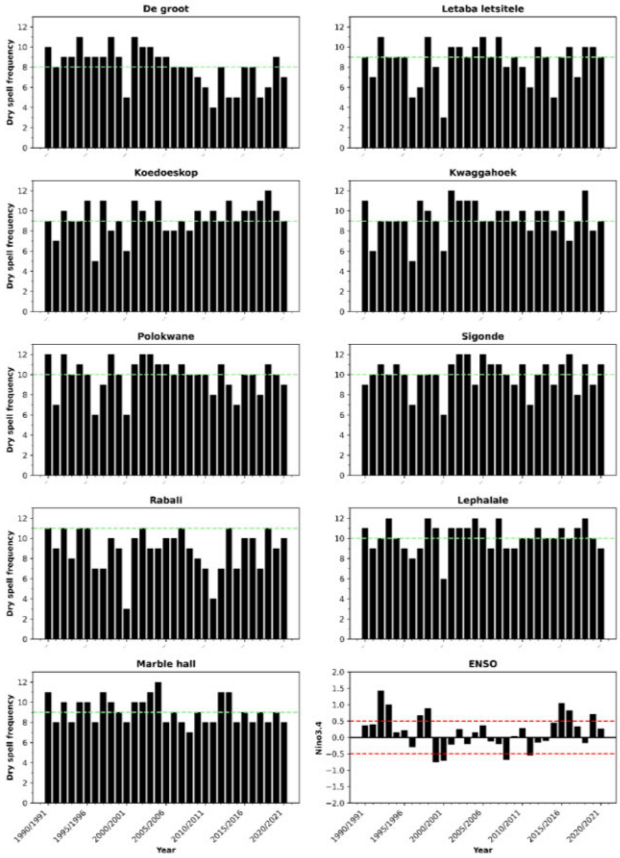


Figure 4.41: Comparison between the October to November (ON) dry-spell frequency and ENSO. The green dashes line denote the average dry spell frequency.

.

During the DJ period (**Figure 4.42**), the warm phase of ENSO was exhibited in 1991/92, 1992/93, 1993/94, 1997/98, 1998/99, 2015/16, 2016/17 and 2019/20. Despite the warm phase of ENSO being associated with prevailing dry conditions, below-average dry spells were recoded. For instance, De Groot recorded below average dry-spells in the years 1997/98, 2015/16 and 2016/17, Letaba Letsitele in 1997/98, 1998/99, 2016/17, and 2019/20, Koedoeskop in 1991/92, 1993/94, 1997/98 and 2016/17, Kwaggahoek in 1991/92, 1993/94, 2015/16, 2016/17, and 2019/20, Polokwane in 2016/17 and 2019/20, Sigonde in 2019/20, Rabali in 1991/92, 1997/98, 2015/16, 2016/17 and 2019/20, Marble Hall in 1992/93, 1997/98, 1998/9, 2015/16, 2016/17 and 2019/20. In contrast, the cool phase of ENSO was exhibited in 1999/00, 2000/01 and 2011/12. Of these years, not all years were characterized by prevailing wet conditions despite recording the cool phase of ENSO. Of all station, only Rabali did not record any above-average dry spell frequencies, while De groot (2011/12), Letaba Letsitele (1999/00 and 2011/12), Koedoeskop (1999/00), Kwaggahoek (1999/00, 2000/01 and 2011/12), Polokwane (1999/00 and 2011/12), Sigonde (2000/01) and Marble hall (1999/00 and 2011/12) recorded above average dry-spells during this phase.

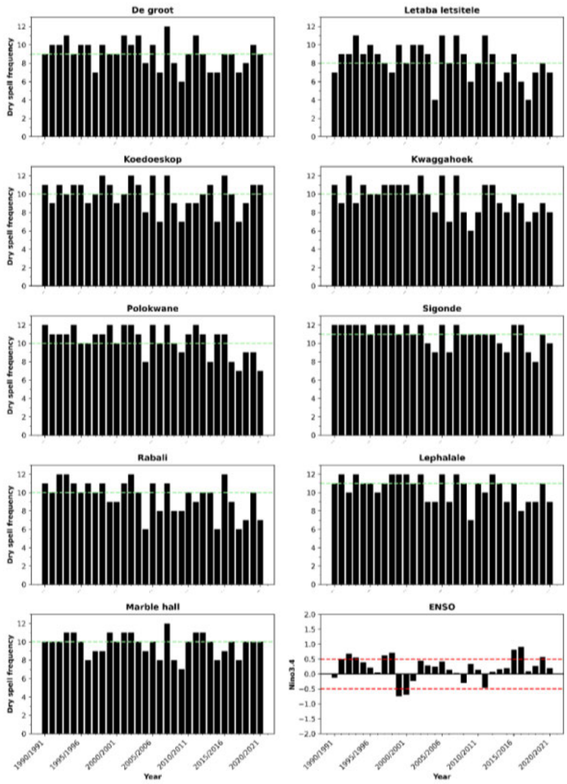


Figure 4.42: Comparison between the December to January (DJ) dry-spell frequency and ENSO. The green dash line denotes the average dry spell frequency.

The FM periods (**Figure 4.43**), show that the warm phase of ENSO was exhibited in 1995/96, 1998/99, 2003/04, 2005/06, 2007/08, 2010/11, 2013/14 and 2016/17. Although dry spells are expected to prevail, below-average dry spells were recorded in De Groot (2010/11 and

2013/14), Letaba Letsitele (2003/04, 2007/08, 2010/11, 2013/14 and 2016/17), Koedoeskop (2005/06, 2007/08, 2010/11, and 2013/14), Kwaggahoek (2010/11 and 2013/14), Polokwane (1995/96, 2007/08, 2010/11, 2013/14, and 2016/17), Sigonde (1995/96, 2003/04, 2007/08, 2010/11, and 2013/14), Rabali ( 2007/08, 2010/11 and 2013/14), Lephalale (2010/11, 2013/14 and 2016/17) and Marble hall (2005/06, 2010/11, 2013/14 and 2016/17). The cool phase of ENSO was recorded in 1999/00, 2000/01, 2009/10, 2011/12 and 2012/13. However, although this phase is associated with wet conditions, it was observed that above-average dry spells frequencies were observed in De Groot in 2011/12, Letaba, Letsitele, Koedoeskop, Kwaggahoek, Polokwane in 1999/00, Sigonde, and Lephalale in 1999/00 and 2000/01 and Marble Hall in 1999/00, 2011/12 and 2012/13. Of all stations, only Rabali did not record any above average dry spells during this phase.

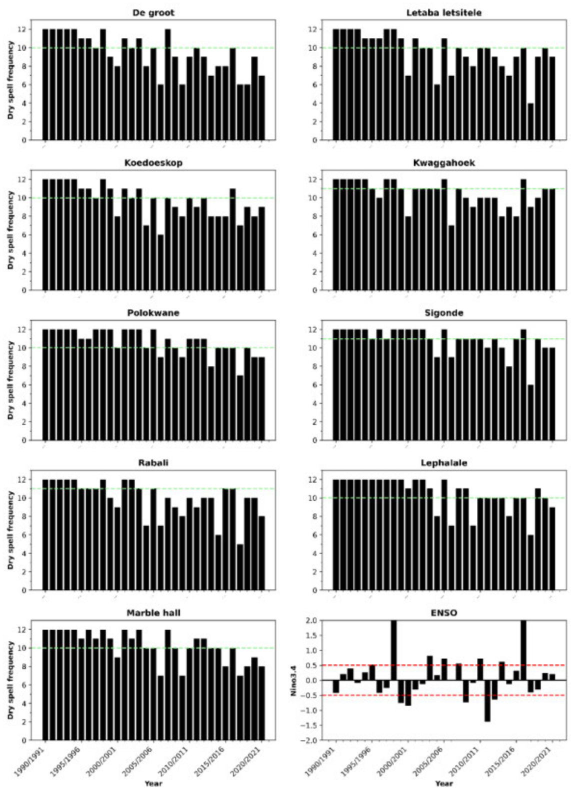


Figure 4.43: Comparison between the February-March (FM) dry-spell frequency and ENSO. The green dashes line denotes the average dry-spell frequency.

### 4.7.2 Relationship between moderate wet days and ENSO

During the ON period (**Figure 4.44**), the years 1992/93, 199394, 1997/98, 1998/99, 2015/16, 2016/17, and 2019/20 were characterized by the warm phase of ENSO. This phase is associated with dry conditions, however, some of the year's exhibit above average moderate wet days, despite the period being associated with dry conditions. For instance, in De Groot (1997/98 and 1998/99), Letaba Letsitele (1993/94, 1997/98, 1998/99, and 2019/20), Koedoeskop (1992/93, 1998/99 and 2019/2020), Kwaggahoek (1998/99 and 2019/20), Polokwane (1993/94, 1997/98, 1998/99, and 2019/20), Sigonde (1992/93, 1993/94, 1997/98, 1998/99), Rabali (1993/94, 1997/98 and 1998/99), Marble Hall (1993/94, 1997/98 and 1998/99), Lephalale (1992/93 and 1998/99), were characterized by above average moderate wet days. The cool phase of ENSO was exhibited in 1999/00, 2000/01, 2008/09, 2011/12. This phase is associated with wet conditions. Below average moderate wet days were, however, exhibited during years characterized by this phase. For instance, in De Groot (2000/01 and 2011/12), Letaba Letsitele and Rabali (2011/12), Koedoeskop (1999/00 and 2011/12), Kwaggahoek (2000/01, 2008/09 and 2011/12), Polokwane (2000/01, 2008/09 and 2011/12) and Sigonde (2008/09) below average moderate wet days were exhibited during this phase.

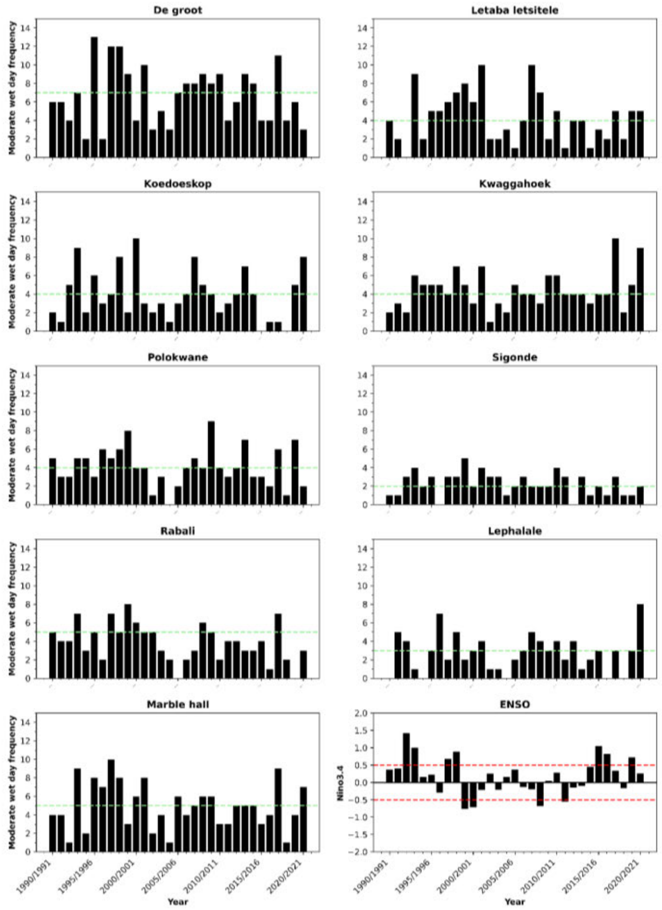


Figure 4.44: Comparison between the October to November (ON) moderate wet days frequency and ENSO. The green dash line denotes the moderate wet days frequency.

During DJ period (**Figure 4.45**), the warm phase of ENSO was exhibited in 1992/93, 1993/94, 1997/98, 1998/99, 2015/16, 2016/17, and 2019/20. Although dry conditions are expected to prevail, above-average moderate wet days were exhibited in some regions. Of these, the year 1992/93, 1993/94, 1997/98, 2016/17 (De Groot), 2016/17 and 2019/20 (Letaba Letsitele), 1998/99 and 2016/17 (Koedoeskop and Polokwane), 1992/93 and 2016/17 (Sigonde), 2016/17 and 2019/20 (Lephalalale), 1992/93, 1993/94, 1998/99 and 2016/17 (Rabali) and 1992/93, 2015/16, and 2016/17 (Marble hall) recorded above average moderate wet days, whereas in

Kwaggahoek no above average moderate wet day was recorded. The cool phase of ENSO was exhibited in the 1999/00, 2000/01, and 2011/12.Despite the expectation of wet conditions to prevail, below-average moderate wet days were exhibited in 2000/01 and 2011/12 in De Groot, Koedoeskop, Kwaggahoek, Sigonde, and Marble Hall. In Polokwane and Lephalale, below-average moderate rainfalls were exhibited in 1999/00 and 2000/01, whereas Rabali recorded below-average moderate wet spells in 1999/00, 2000/01, and 2011/12.

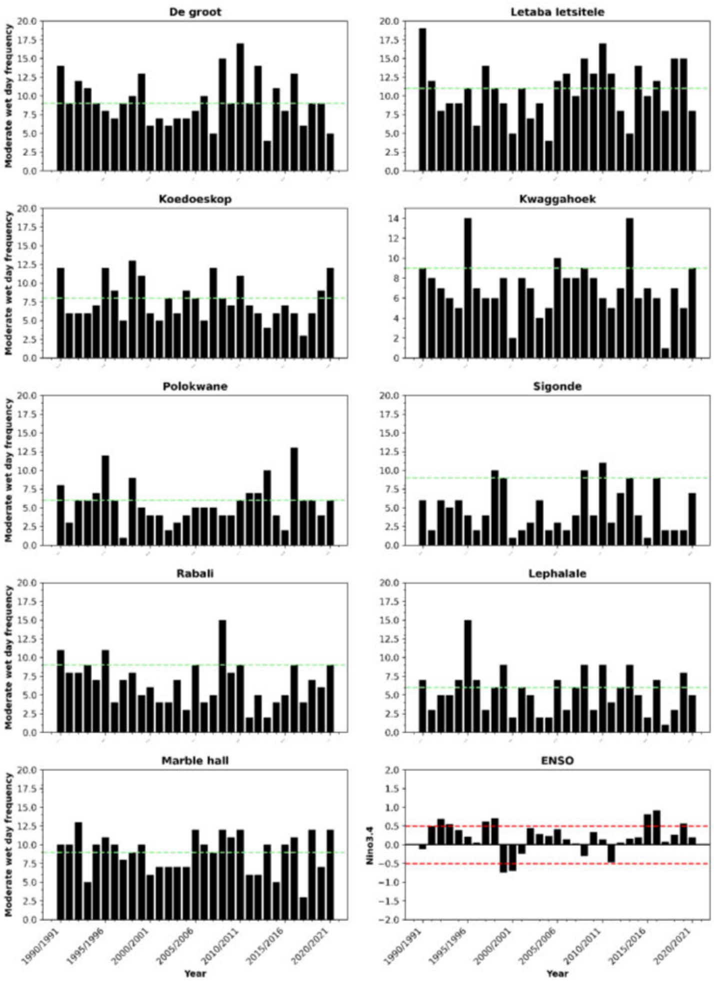


Figure 4.45: Comparison between the December to January (DJ) moderate wet days frequency and ENSO. The green dash line denotes the moderate wet days frequency.

During FM (**Figure 4.46**), the warm phase of ENSO is exhibited in the years 1995/96, 1998/99, 2003/04, 2005/06, 2007/08, 2010/11, 2013/14, and 2016/17. This phase of ENSO is characterized by prevailing dry conditions, However, above-average moderate wet days were exhibited in De Groot (1995/96, 1998/99, 2003/04, 2005/06, 2007/08, and 2016/17), Letaba Letsitele (1998/99, 2003/04 and 2005/06), Koedoeskop (1995/96, 2003/04 and 2005/06), Kwaggahoek (1995/96, 2003/04, 2005/06 and 2016/17), Polokwane (2003/04, 2013/14 and 2016/17), Sigonde (1998/99, 2003/04 and 2005/06), Rabali (2003/04), Lephalale (1995/96 and 2005/06) and Marble hall (2003/04 and 2013/14). In contrast, the cool phase of ENSO was recorded in 1999/00, 2000/01, 2008/09, 2011/12 and 2012/13. Of these years below average moderate wet days were recorded despite the expectation of wet conditions to prevail. The following weather stations recorded below-average years:  De Groot (2000/01, 2008/09, and 2011/12), Letaba Letsitele (2011/12 and 2012/13), Kwaggahoek and Koedoeskop (2000/01, 2008/09 and 2011/12), Polokwane (2000/01, 2008/09, 2011/12, 2012/13), Sigonde and Lephalale (2008/09, 2011/12, 2012/13), Rabali and Marble hall (2000/01, 2011/12 and 2012/13).

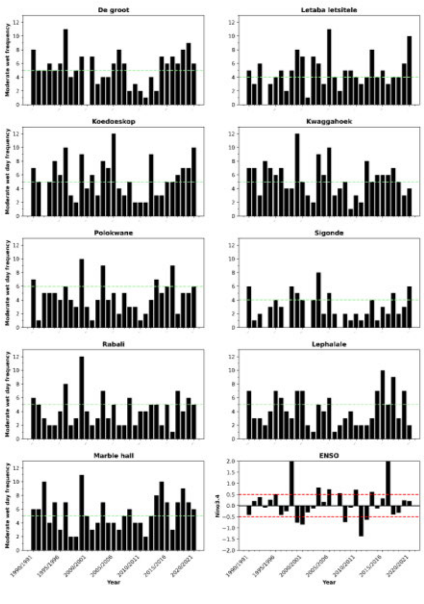


Figure 4.46: Comparison between the February to March (FM) moderate wet days frequency and ENSO. The green dash line denotes the moderate wet day's frequency.

### 4.7.3 Relationship between heavy wet days and ENSO

During the ON, no above-average heavy wet days were exhibited over all locations in the Limpopo province. During the DJ season (**Figure 4.47**), the years 1991/92, 1992/93, 1993/94, 1997/98, 1998/99, 2015/16, 2016/17 and 2019/20 are characterized by the warm phase of ENSO. Although this phase of ENSO is characterized by prevailing dry conditions, s above average heavy wet days were recorded in Letaba Letsitele (1993/94 and 2016/17), Kwaggahoek (1992/93, 1998/99 and 2016/17), Sigonde (1992/93, 2016/17 and 2019/20), Rabali (2016/17 and 2019/20) and Lephalale (2016/17 and 2019/20). No above-average heavy wet days were recorded in De Groot, Koedoeskop and Marble Hall. The year 1999/00, 2000/01 and 2011/12 is characterized by the cool phase of ENSO. During this phase, wet conditions are expected to prevail. However, below-average heavy wet days were recorded in all years in Letaba Letsitele, Koedoeskop, Kwaggahoek, Polokwane, Lephalale, and Marble Hall. De Groot recorded below-average heavy wet days in 1999/00 and 2000/01, Sigonde in 2000/01 and 2011/12 and Rabali in 2011/12.

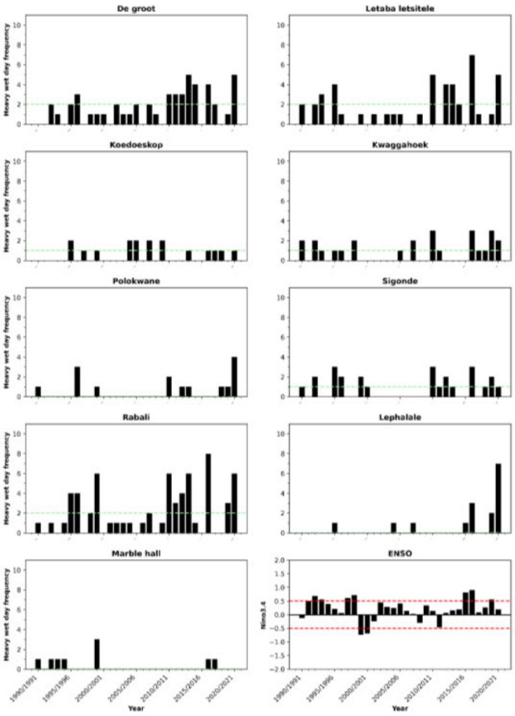


Figure 4.47: Comparison between the December to January (DJ) heavy wet days frequency and ENSO. The green dash line denotes the average heavy wet days frequency.

During FM (**Figure 4.48**), the warm phase of ENSO was recorded in 1995/96, 1998/99, 2003/04, 2005/06, 2007/08, 2010/11, 2013/14, and 2016/17. During this phase, dry conditions are expected to prevail. However, De Groot records above average heavy wet days in 1995/96, 1998/99, 2003/04, 2005/06, 2013/14 and 2016/17, Letaba Letsitele in 1995/96, 2003/04 and 2007/08, Koedoeskop in 1995/96, 2003/04, 2005/06, 2013/14 and 2016/17, Kwaggahoek and Polokwane in 1995/96 and 2005/06, Rabali in 1995/96, 2003/04, 2005/06, 2013/14 and 2016/18 and Marble hall in 1995/96, 2003/04 and 2005/06. In Sigonde and Lephalale none of the years recorded above-average heavy wet days during the warm phase of ENSO. The cool phase of ENSO was exhibited in 1999/00, 2000/01, 2008/09 and 2011/12. Of these years, not all stations were characterized by prevailing wet conditions. For instance, below average heavy wet days were exhibited in De Groot (2000/01 and 2012/13), Letaba Letsitele (2000/01, 2008/09, 2011/12 and 2012/13), Koedoeskop and Polokwane (2000/01 and 2011/12 and

2012/13), Kwaggahoek (1999/00, 2000/01, 2011/12 and 2012/13) and Rabali (2000/01, 2008/09, 2011/12 and 2012/13).

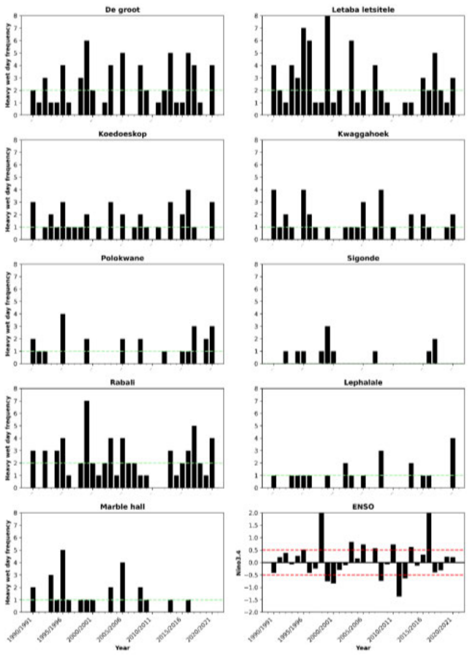


Figure 4.48: Comparison between the February to March (FM) heavy wet days frequency and ENSO. The green dash line denotes the average heavy wet day frequency.

## 4.8 Relationship between seasonal rainfall characteristics and SIOD.

### 4.8.1 Relationship between dry spells and SIOD

The inter-annual variability of seasonal rainfall characteristics and SIOD was observed in this study. Previous studies have highlighted the influence of SIOD on rainfall in southern Africa (Gaughan *et al.,* 2016; Hoell *et al.,* 2017; Gong *et al.,* 2019; Rapolaki *et al.,* 2019; Behera and Yamagata, 2001). This mode of variability fluctuates between the negative and positive phases. The positive (negative) phase of SIOD is associated with above (below) average rainfall (Behera and Yamagata, 2001).

During ON (**Figure 4.49**) positive SIOD was exhibited in 1990/91, 1992/93, 1995/94, 2004/05, 2008/09, and 2018/19. However, although wet conditions are expected to prevail during this years, above average dry spells were obtained in De Groot (1990/91, 1992/93, 1995/96, and 2004/05), Letaba Letsitele (1992/93, 2004/05 and 2018/19), Koedoeskop (1992/93, 1995/96, 2004/05 and 2018/19), Kwaggahoek (1990/91, 2004/05, 2008/09 and 2018/19), Polokwane (1990/91, 1992/93, 2004/05 and 2018/19), Sigonde (1992/93 and 2018/19), Rabali (1990/91, 1992/93, 1995/96 and 2018/2019), Lephalale (1990/92, 2004/05, and 2018/19) and Marble hall (1990/91, 1992/93 and 1995/96). The negative phase of SIOD was exhibited in 1994/95, 1997/98, 1999/00, 2013/14, 2014/15 and 2020/21. Although dry conditions are expected to prevail, below average dry spells were recorded in De Groot (2013/14, 2015/16, and 2020/21), Letaba Letsitele (1994/95, 1997/98, 1999/00, 2013/14, 2015/16 and 2020/21), Koedoeskop and Kwaggahoek (1994/95, 1999/00 and 2020/21), Polokwane (1997/98, 2013/14, 2015/16 and 2020/21), Sigonde and Rabali (1997/98 and 1999/00) and Marble Hall (1999/00, 2015/16 and 2020/21).

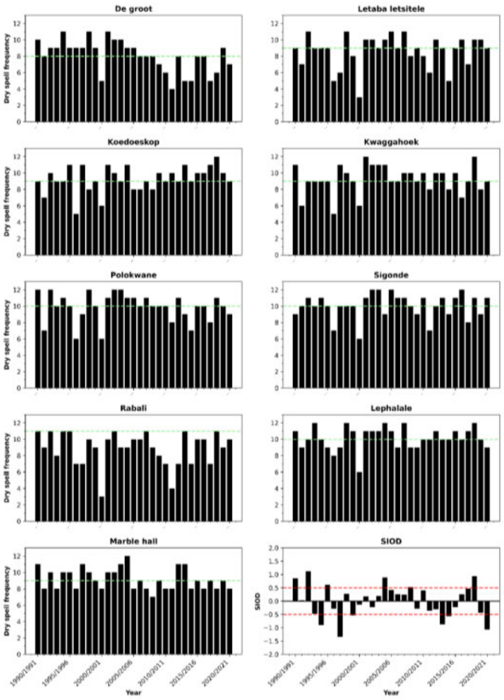


Figure 4.49: Comparison between the October to November (ON) dry spell frequency and SIOD. The green dash line denotes the average dry spell frequency.

During DJ (**Figure 4.50**), positive SIOD was recorded in 1992/93, 1993/94, 2006/07, 2008/09, 2010/11, 2017/18 and 2018/19). This phase of SIOD is characterized by wet conditions. Despite this phase being characterized by wet conditions, above-average dry spells were exhibited in De Groot, Polokwane, Sigonde and Rabali (1992/93 and 1993/94), Letaba Letsitele (1992/93, 1993/94, and 2008/09), Koedoeskop and Kwaggahoek (1992/93), Lephalale and Marble Hall (1993/94). In contrast, the negative phase of SIOD was recorded in 1997/98, 2002/03, 2012/13, 2013/14 and 2020/21. Despite the expectation of dry conditions to prevail during this phase, below-average dry spells were recorded in De Groot and Rabali (1997/98, 2012/17, 2013/14 and 2020/21), Letaba Letsitele, Lephalale and Marble Hall (1997/98, 2013/14 and 2020/21), Koedoeskop (1997/98 and, 2012/13), Kwaggahoek and Polokwane (2013/14 and 2020/21) and Sigonde (2012/13, 2013/14 and 2020/21).

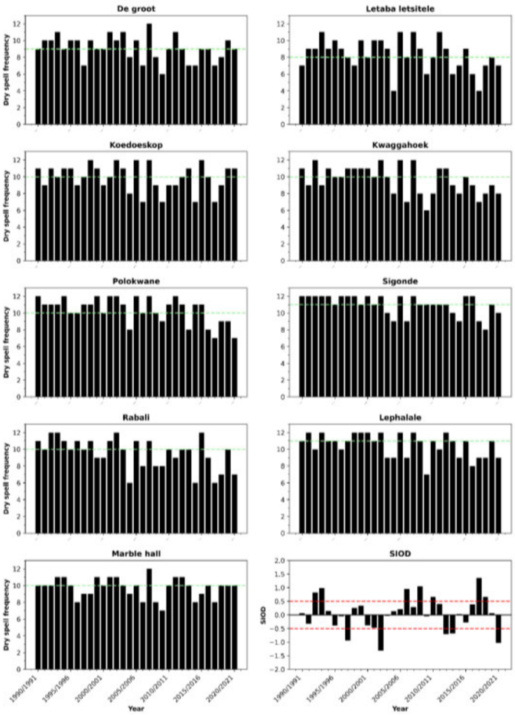


Figure 4.50: Comparison between the December to January (DJ) dry spell frequency and SIOD. The green dash line denotes the average dry spell frequency.

During FM (**Figure 4.51**), the positive phase of SIOD was exhibited in 1997/98, 1999/00, 2001/02, 2006/07, 2007/08, 2011/12 and 2017/18. Although this phase is characterized by wet conditions, above average dry spells were recorded in De Groot (2001/02 and 2007/08) , Letaba Letsitele (1997/98), Koedoeskop (1999/00 and 2001/02), Kwaggahoek, and Sigonde (1997/98, 1999/00, 2001/02 and 2007/08), Polokwane and Lephalale (1997/98, 1999/00 and 2001/02), Rabali (1997/98 and 2001/02) and Marble hall (1997/98, 1999/00, 2001/02, 2007/08 and 2011/12). The negative phase of SIOD was exhibited 1992/93, 1995/96, 1998/99, 2010/11, 2015/16, 2016/17, and 2020/21. This phase of SIOD is characterized by prevailing dry conditions. However, not all years reflect the prevalence of the dry conditions. For instance below-average dry spells were recorded in De Groot, Letaba Letsitele, Polokwane, Lephaplale and Marble Hall in 2010/11, 2015/16, 2016/17, 2020/19, Koedoeskop in 2010/11, 2015/16 and 2020/21, Kwaggahoek in 2010/11 and 2015/16, Sigonde in  2020/21 and Rabali in 2010/11 and 2020/21.

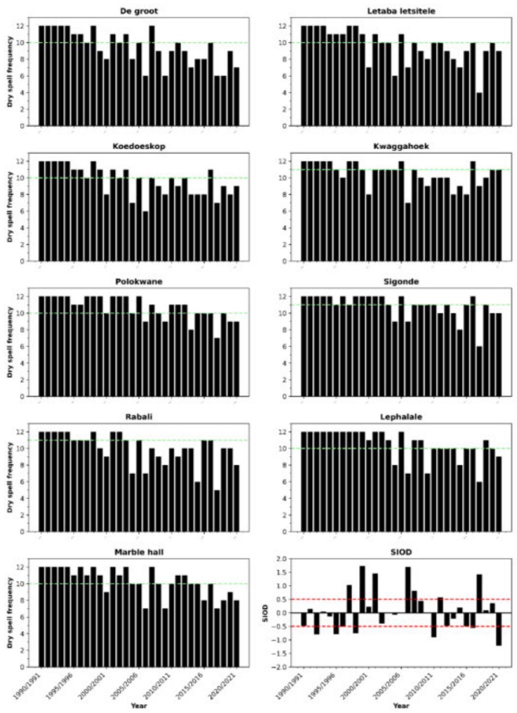


Figure 4.51: Comparison between the February to March (FM) dry spell frequency and SIOD. The green dash line denotes the average dry spell frequency.

### 4.8.2 Relationship between moderate wet days and SIOD

During ON (**Figure 4.52**) positive SIOD was exhibited in 1990/91, 1992/93, 1995/94, 2004/05, 2008/09, and 2018/19. During this phase wet conditions are expected to prevail. However, the prevalence of wet conditions does not reflect in all years. For instance below-average moderate wet days were exhibited in De Groot, Letaba Letsitele and Marble Hall (1990/91, 1992/93, 2004/05, and 2018), Koedoeskop (1990/91, 2004/05 and 2018/19), Kwaggahoek (1990/91, 1992/93, 2004/05, 2008/09 and 2018/19), Polokwane (1992/93, 1995/96, 2004/05, 2008/09 and 2018/19), Sigonde (1990/91, 2004/05, 2008/09 and 2018/19) Rabali (1992/93, 2004/05 and 2018/19) and Lephalale (1990/91, 1995/96, 2004/05 and 2018/19). The negative phase of

SIOD was exhibited in 1994/95, 1997/98, 1999/00, 2013/14, 2014/15 and 2020/21. This phase of SIOD is characterized by dry conditions. Despite the expectation for dry conditions to prevail during this phase, above-average moderate wet days were recorded in the following stations:  De Groot and Sigonde, (1997/98, 1999/00, and 2013/14), Letaba Letsitele (1997/98, 1999/00 and 2020/21), Koedoeskop (2013/14 and 2020/21), Kwaggahoek (1994/95, 1999/00 and 2020/91), Polokwane (1994/95, 1997/98, 1999/00 and 2013/14), Rabali (1997/98 and 1999/00), Lephalale (2020/21) and Marble hall (1997/98 and 2020/21).

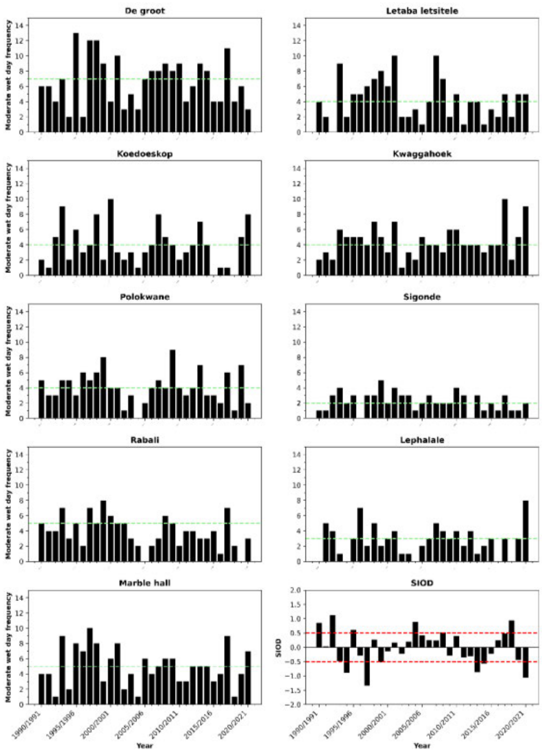


Figure 4.52: Comparison between the October to November (ON) moderate wet day frequency and SIOD. The green dashed line denotes the average moderate wet day frequency.

During the DJ period (**Figure 4.53**), positive SIOD was exhibited in 1992/93, 1993/94, 2006/07, 2008/09, 2010/11, 2017/18 and 2018/19. Wet conditions are common during this phase of SIOD. However, not all years exhibits the prevalence of wet conditions, for instance, below average moderate wet days were exhibited in De Groot (2017/18 and 2018/19), Letaba Letsitele (1992/93, 1993/94, 2017/18 and 2018/19), Koedoeskop (1992/93, 1993/94, 2006/07, 2016/17 and 2017/18), Polokwane (1992/93, 1993/94, 2006/07 and 2017/18), Sigonde (1993/94, 2006/07 and 2017/18), Rabali (2006/07 and 2007/08), Lephalale (1992/93, 1993/94, 2006/07 and 2017/18), Marble Hall (1993/94 and 2017/17). The negative SIOD was recorded in 1997/98, 2002/03, 2012/13, 2013/14 and 2020/21. Although dry conditions are common during this phase of SIOD, above-average moderate wet days were exhibited in De Groot (2012/13), Koedoeskop and Rabali (2020/21), Polokwane, Kwaggahoek and Marble hall (2013/14 and 2020/21), Koedoeskop (2020/21), Letaba (1997/98), Sigonde (2012/13, 2013/14 and 2020/21) and Lephalae (2013/14).

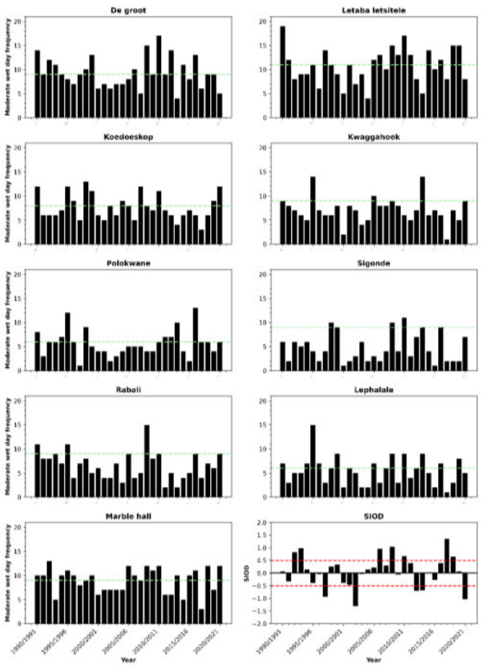


Figure 4.53: Comparison between the October to November moderate wet day frequency and SIOD. The green dashed line denotes the average moderate wet day frequency.

During the FM (**Figure 4.54**) period, positive SIOD were exhibited in 1997/98, 1999/00, 2001/02, 2006/07, 2007/08, 2011/12 and 2017/18. Of these years, not all years are characterized by wet conditions that prevail during this phase of SIOD. For instance, below-average moderate wet days were exhibited in De Groot (2011/12), Letaba Letsitele (1997/98, 2001/02, 2006/07, 2007/08, 2011/12 and 2017/18), Koedoeskop (1997/98, 2006/07, 2007/08 and 2011/12), Kwaggahoek (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12), Polokwane (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12), Sigonde (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12), Rabali (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12), Lephalale (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12) and Marble hall (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12). Negative SIOD anomalies were recorded in 1992/93, 1995/96, 1998/99, 2010/11, 2015/16, 2016/17 and 2020/21. This phase of SIOD is commonly characterized by dry conditions, however, above-average moderate wet days were exhibited in De Groot (1992/93, 1995/96, 1998/99, 2015/16, 2016/17, and 2020/21), Letaba Letsitele (1992/93, 1998/99, 2015/16, and 2020/21), Koedoskop (1995/96 and 2020/21), Kwaggahoek (1995/96, 2015/16 and 2016/17), Polokwane (2016/17), Lephalale (1995/96 and 2015/16) and Marble Hall (1992/93, 2015/16 and 2020/21). Rabali did not record any above-average moderate wet days during these years.

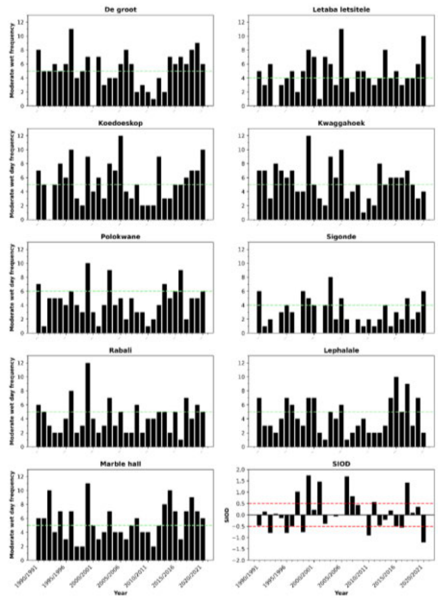


Figure 4.54: Comparison between the February to March (FM) moderate wet day frequency and SIOD. The green dashed line denotes the average moderate wet day frequency.

## 4.9 Relationship between heavy wet days and SIOD

There is no evident relationship between the SIOD and heavy wet day frequencies during the ON period. During the DJ period (**Figure 4.55**), a positive SIOD phase was recorded in 1992/93, 1993/94, 2006/07, 2008/09, 2010/11 and 2017/18. Below-average heavy wet days are evident during these years despite this phase of SIOD being characterized by prevailing wet conditions. Of these years, below-average wet days were exhibited in De Groot and Rabali in all years except for 2010/11. In Kwaggahoek and Sigonde, below-average heavy wet days were recorded for all years except for 1992/93 and 2010/11. Letaba also exhibited below-average heavy wet days for all years except for 1993/94 and 2010/11. In Koedoeskop, Polokwane, Lephalale, and Marble Hall, all years recorded below-average heavy wet days. Negative SIOD were recorded in, 1997/98, 2002/03, 2012/13, 2013/14 and 2020/21. Although dry conditions prevail during this phase of SIOD, above-average heavy wet days were recorded in De Groot, Letaba Letsitele and Rabali in 2012/13, 2013/14, and 2020/21. Kwgaahoek, Polokwane, and Lephalale reccorded above-average heavy wet days in 2020/21 and Sigonde in 2012/13. Koedoeskop and Marble Hall recorded no above-average heavy wet days.

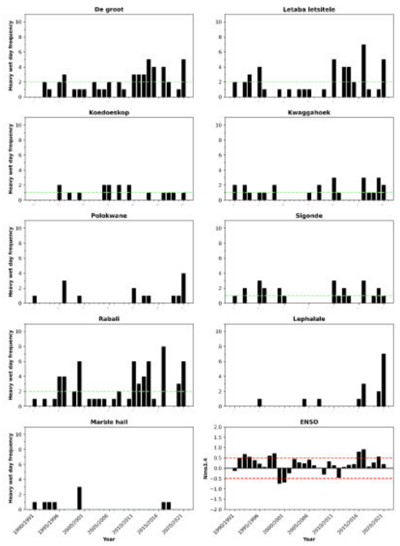


Figure 4.55: Comparison between the December to January (DJ) heavy wet day frequency and SIOD. The green dashed line denotes the average heavy wet day frequency.

During FM (**Figure 4.56**), positive SIOD were recorded in 1997/98, 1999/00, 2001/02, 2006/07, 2007/08, 2011/12 and 2017/18. Although wet conditions are common during this phase of ENSO, below-average heavy wet days during this season were exhibited in De Groot (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12), Letaba Letsitele (1997/98, 2001/02, 2006/07 and 2011/12), Koedoeskop (1997/98, 1999/00, 2001/02, 2006/07, 2007/08 and 2011/12), Kwaggahoek, Lephalale and Marble hall (1997/98, 1999/00, 2001/02, 2006/07, 2007/08, 2011/12 and 2017/18), Polokwane and Rabali (1997/98, 2001/02, 2006/07, 2007/08 and 2011/12). Negative SIOD was exhibited in 1992/93, 1995/96, 1996/97, 1998/99, 2010/11, 2015/16, 2016/17 and 2020/21. Despite this phase being characterized by prevailing dry conditions, above-average moderate wet days were exhibited in De Groot (1992/93, 1995/96, 1998/99, 2015/16, 2016/17, and 2020/21 ), Letaba Letsitele (1995/96, 2015/16 and 2020/21), Koedoeskop (1995/96, 2015/16, 2016/17 and 2020/21), Kwagahoek (1992/93, 1995/96, 1996/97, 2015/16, and 2020/21), Polokwane (1995/96 and 2020/21), Rabali (1992/93, 1995/96, 2016/17 and 2020/21) Lephalalae (2020/21) and Marble hall (1995/96).

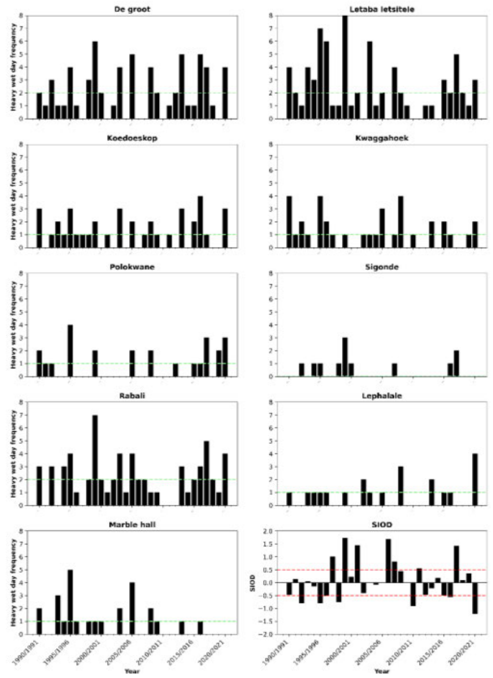


Figure 4.56: Comparison between the October to November (ON) heavy wet day frequency and SIOD. The green dashes line denotes the average heavy wet day frequency.

A somewhat complex relationship exists between ENSO, SIOD and seasonal rainfall characteristics. Previous studies have acknowledged the connection between SIOD and ENSO (Behera and Yamagata, 2001; Hoell *et al.*, 2017; Rapolaki *et al.*, 2019; Reason *et al.*, 2002). During years were SIOD and ENSO phases align, precipitation can be disrupted or enhanced over southern Africa (**Table 4.1, 4.2, 4.3**) (Hoell *et al.*, 2017). For example, in 1997/98 during the ON period, an alignment between the negative SIOD phase and warm phase of ENSO led to above-average moderate wet days and below-average dry spells in most stations. Lyon and Mason (2007) attributed this to internal atmospheric variability. During this season a strong Angola Low, exceptionally high SST, and eastern tropical and South Atlantic Ocean enhanced northerly moisture flux from the continental interior and western tropical ocean, minimizing the effects of El Niño during this season (Lyon and Mason, 2007). In 2008/09 during the ON period, positive SIOD and cool phase of ENSO aligned with above-average moderate wet days and below-average dry spells. These findings are consistent with the results of Gaughan *et al*.

(2016). In 1990/00 both ENSO and SIOD simultaneously recorded negative phases, this aligned with below-average dry spells and moderate wet days.

Table 4.1: The combination of ENSO and SIOD phases for October-to-November (ON) period during 1990-2020.

| | Negative ENSO | Positive ENSO |
|---|---|---|
| Negative SIOD | 1999/00 | 1997/98 |
| Positive SIOD | 2008/09 | |

Table 4.2: The combination of ENSO and SIOD phases for December-to-January (DJ) period during 1990-2020.

| | Negative ENSO | Positive ENSO |
|---|---|---|
| Negative SIOD | | 1997/98 |
| Positive SIOD | | 1992/93 |

Table 4.3: The combination of ENSO and SIOD phases for February-to-March (FM) period during 1990-2020.

| | Negative ENSO | Positive ENSO |
|---|---|---|
| Negative SIOD | | 1995/96, 1998/99, 2010/11 and 2016/17 |
| Positive SIOD | 1999/00, 2000/01 and 2011/12 | |

## 4.10 Correlations with climate modes

### 4.10.1 Correlation between ENSO and dry spells

In order to examine the relationship between ENSO and seasonal rainfall characteristics, correlation analysis was used to estimate the relationship during ON, DJ, and MA as shown in **Figure 4.57**. The relationship between ENSO and dry spells varies spatially over the rainy season. During ON (**Figure 4.57a)**, ENSO was found to have positive correlation over the Limpopo province except for a small portion in the south of Waterberg. Of these, statistically significant correlations were recorded in Mopani and Vhembe district (**Appendix 7**). A strong positive correlation is recorded in south-east of the Mopani district with r values greater than 0.5. A strong positive correlation between dry spells and ENSO during the ON period concurs with the result of Hoell and Cheng (2018) and Reason *et al.* (2005), suggesting that the positive phase of ENSO (El Niño) is associated with below average rainfall and frequent dry spells.

The DJ period **(Figure 4.57b**) shows that no strong correlation was recorded between dry spells and ENSO. The north of Waterberg, Capricorn, and Vhembe and greater Sekhukhune district recorded weak negative correlations, while weak positive correlations of dry spells and ENSO were recorded over the Mopani, Waterberg, and Vhembe districts. During the FM period **(Figure 4.57c)** weak positive correlations over the entire Limpopo province were recorded.

Munoz *et al.* (2015) demonstrated that the relationship between ENSO and seasonal rainfall characteristics can be explained by other factors, hence the weak and variable distribution of the association between ENSO and dry spells in Limpopo. For instance, Dube and Jury (2003) and Dedekind *et al*. (2016) showed the influence of local topographic circulations as other factors influencing seasonal rainfall characteristics and variability. Singleton and Reason (2006) and Blamey and Reason (2009) used numerical models to show how topography influences rainfall in eastern South Africa. The study showed that topography and local surface radiation flux play a role in determining the spatial and diurnal variation of rainfall events over southern Africa. However, this shows that the weak and spatially variable correlation observed over the Limpopo province may be attributed to the interplay between ENSO and these local factors, underscoring that ENSO's role is part of a complex interaction rather than an isolated determinant.

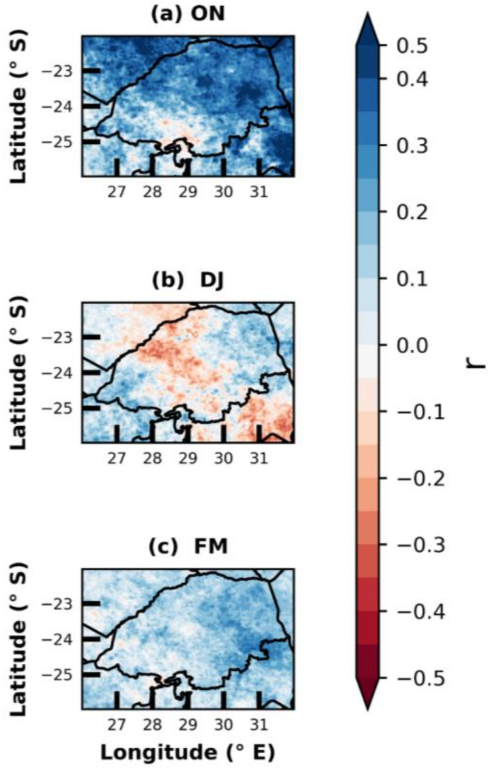


Figure 4.57: Correlation of ENSO with dry spells frequency during (a) October-November (ON), (b) December-January (DJ), and (c) February-March (FM).

### 4.10.2 Correlation between ENSO and moderate wet day

**Figure 4.58** shows the correlations between ENSO and moderate wet days. During ON, ENSO exhibits a strong negative correlation with moderate wet days over the high-lying escarpment in the Vhembe district (south of Vhembe) and south of Mopani district, with only small portions of the area recording statistically significant correlations (**Appendix 8**). Negative weak correlations are recorded over the Capricorn, west of Waterberg, north of Vhembe district, whereas weak positive correlations are recorded over the south of Waterberg and greater Sekhukhune. Of these correlations, a small portion of the Mopani and Vhembe district records statistically significant correlations The DJ and FM period does not show any definite spatial correlation. A combination of weak negative and positive correlations is distributed over the Limpopo province throughout the period.

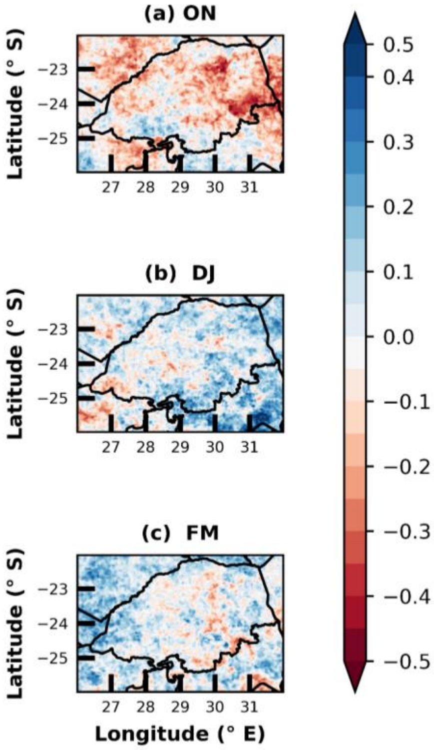


Figure 4.58: Correlation of ENSO with moderate wet day frequency during (a) October-November (ON), (b) December-January (DJ), and (c) February-March (FM).

### 4.10.3 Correlation between ENSO and heavy wet days.

**Figure 4.59** shows the association between heavy wet days and ENSO. During ON, heavy wet days show a weak positive correlation over Mopani, Vhembe, south-west of Waterberg, and north of Capricorn district, whereas, the south of Capricorn and the greater Sekhukhune records a weak negative correlation, with the Greater Sekhukhune recording strong negative correlation. During DJ, a statistically significant strong negative correlation is recorded over the north-west of Vhembe, and north of Capricorn, whereas the entirety of the region receives a weak positive correlation. During FM, weak positive correlations are recorded over the entirety of the province.

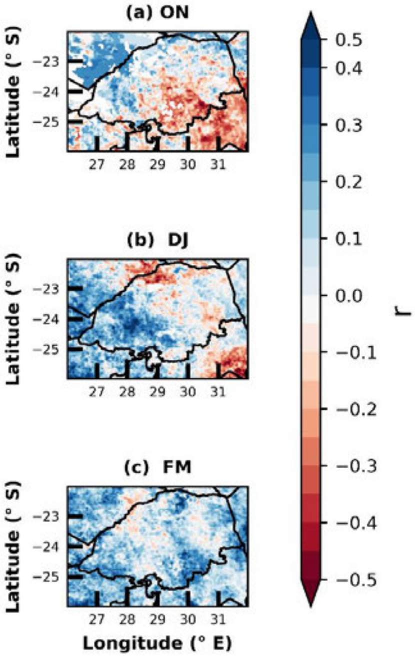


Figure 4.59: Correlation of ENSO with heavy wet day frequency during (a) October-November (ON), (b) December-January (DJ), and (c) February-March (FM).

#### 4.10.4 Correlation of SIOD and dry spells

A correlation of dry spells and SIOD was observed during ON, DJ, and MA (**Figure 4.60**). During ON, weak positive correlations are recorded over the entire Limpopo province between dry spells and SIOD. During the DJ period, the south of Waterberg records strong statistically significant negative correlations, whereas the Mopani, greater Sekhukhune, Capricorn, and Vhembe recorded weak negative correlations. During the FM period, strong negative correlations were exhibited over the Mopani district, while the entire province records weak positive correlations.

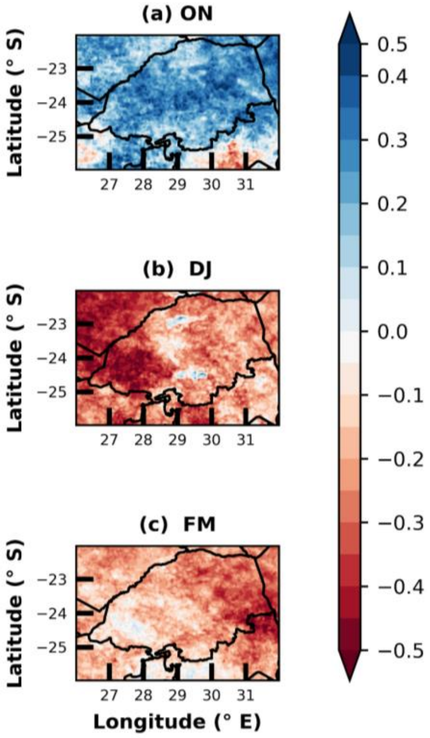


Figure 4.60: Correlation of SIOD with dry spells during (a) October-November (ON), (b) December-January (DJ), and (c) February-March (FM).

### 4.10.5 Correlation of SIOD and moderate wet day

The relationship between SIOD and moderate wet days was recorded (**Figure 4.61**). Results show that the entirety of the Limpopo province records a weak negative correlation during ON, except for the high-lying escarpment in the Waterberg and east of the Mopani district, which receives a strong, negative correlation, with small portions being statistically significant correlations (Appendix 12). During the DJ period, no strong correlation was recorded. However, the Capricorn, Greater Sekhukhune, Mopani, Vhembe, and north of Waterberg record weak positive correlation, while a small portion in the south-west of Waterberg records a weak negative correlation. The FM period records the combination of both weak positive and negative correlations.

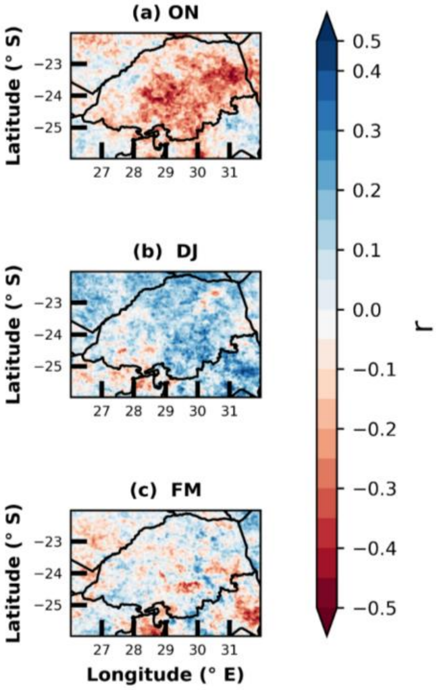


Figure 4.61: Correlation of SIOD with moderate wet days (a) October-November (ON), (b) December-January (DJ), and (c) February-March (FM).

### 4.10.6 Correlation of SIOD and heavy wet days

**Figure 4.62 (Appendix A12)** shows the relationship between heavy wet days and SIOD. A strong negative (statistically significant) correlation is recorded during the ON period over the south-west of Waterberg, whereas a weak positive correlation is recorded over the entire province. During the DJ period, weak positive correlations are distributed over the province. The FM periods exhibit a strong negative correlation over the south of Waterberg, while the remaining region is characterized by weak positive correlations.

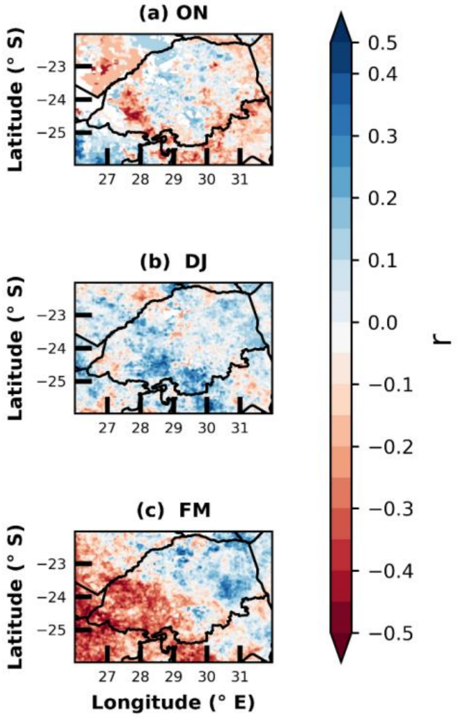


Figure 4.62: Correlation of SIOD with heavy wet days (a) October-November (ON), (b) December-January (DJ), and (c) February-March (FM).

### 4.11 Summary

In this study, the variability of rainfall in the period 1990 to 2020 over the Limpopo province was investigated. This study investigated the spatial and temporal distribution of seasonal rainfall characteristics over the Limpopo province. The results show that the province is characterized by high rainfall variability. A somewhat complex relationship was also observed between seasonal rainfall characteristics and rainfall anomalies. It was reported that not all positive anomalies suggest a good rainfall season. For instance, some seasons with positive anomalies were also characterized by above-average dry spells and below-average moderate and heavy days. This shows that anomalies overlook the isolated impact of seasonal rainfall characteristics. However, in the future, the isolated contribution of these rainfall characteristics should be fully understood to help with informed resource allocation over the province. A study on rainfall characteristics provides more useful information about rainfall to user groups and stakeholders. Increased dry spell duration has, for instance, been associated with drought and a decrease in growing season duration. Understanding the spatial and temporal patterns of rainfall characteristics will assist in identifying regions with more susceptibility and areas experiencing significant change. The relationship between seasonal rainfall characteristics and large modes of variability was observed. A complex relationship was observed between rainfall characteristics and large modes of variability. The results showed that not all La Niña years or positive phase SIOD phase equate to wet seasons. In conclusion, understanding rainfall variability over the Limpopo province is significant for improving management, risk reduction, and early warning systems for extreme events. The success or failure of agricultural output is mostly dependent on the distribution of seasonal rainfall characteristics throughout the growing season, rather than the total rainfall or deviation from the mean.

# 5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Introduction

The Limpopo province is subjected to severe floods and droughts due to its high rainfall variability (Mosase and Ahiablame, 2018). This poses a threat to the communities because of the predominance of rain-fed agriculture. The ability of these rural communities to adapt and mitigate these climate stresses is affected by extensive poverty, lack of scientific knowledge, political instability, and lack of capital. A better understanding of climate processes that influence rainfall variability over southern Africa may prove useful in adapting to future climates. This therefore necessitated the need to improve and initiate reliable forecasting of anomalous events, both of which could have positive implications for the quality of life and economic well-being of the rural population (Dube and Jury, 2000).

Several studies have attempted to understand the spatial and temporal rainfall characteristics over the Limpopo province, with varying methods and datasets at varying degrees of accuracy and usability. Most studies used sparsely weather stations with gaps. This limits the ability to understand spatial extends of rainfall distribution, more especially in high-lying areas and agriculturally-inactive regions such as the north of Vhembe and north and east of Mopani districts. To address this issue, CHIRPS was used to understand the spatial and temporal distribution of rainfall characteristics.

The first objective attempted to understand rainfall variability over the Limpopo province. Traditional methodologies such as CV, SAI, SI, and descriptive statistics were used to understand rainfall climatology over the area. The spatial distribution of changes in rainfall was observed using Mann-Kendall Trend test. The first objective aims to understand the spatial and temporal rainfall variability. The study found that the use of SAI to measure whether a season was wet or dry, exhibits some shortfalls as SAI relies on the deviation from the mean rather than the actual rainfall activity that took place. This simply implies that rainfall can distort the in-depth understanding of rainfall for a particular season. To address this gap the second objective, focused on seasonal rainfall characteristics, such as dry spells, moderate wet days, and heavy wet days. This further helps to understand the interplay between rainfall characteristics in the Limpopo region.  The third objective investigated the possible temporal and spatial relationship between seasonal rainfall characteristics and large modes of variability such as SIOD and ENSO.

## 5.2 Summary and conclusions

5.2.1 Determine the annual rainfall variability and trends in the Limpopo province.

- Overall the evaluation of CHIRPS with station data shows that CHIRPS can adequately represent weather station rainfall.
- The CDF shows that the distribution of rainfall is well estimated by CHIRPS and relatively performs better when compared to most weather stations.
- The spatial distribution of monthly rainfall demonstrates high rainfall variability across the Limpopo province.
- The highest rainfall is recorded during the DJF in the high-lying escarpment in the Vhembe district, north and west of Mopani, south of Capricorn, Waterberg, and north of Greater Sekhukhune.
- The standardised rainfall anomalies show that the period from November to March (NDJFM) exhibits positive rainfall anomalies over the central high-lying escarpment in the south of Vhembe, north and west of Mopani, south of Capricorn, Waterberg, and north of Greater Sekhukhune.
- Monthly rainfall trends show that the month of January, February, and April record statistically significant increasing trends, while March and August record statistically significant decreasing trends. The month of June records both statistically significant increasing and decreasing trends.
- Total seasonal rainfall over the Limpopo province also exhibits rainfall variability in space and magnitude. Rainfall in the region ranges from 200 to greater than 1000 $\mathrm{mm.yr^{-1}}$. There is more bias in the high-lying escarpment in the south of Vhembe, north and west of Mopani, south of Capricorn, Waterberg and north of Greater Sekhukhune (800 to greater than 1000 $\mathrm{mm.yr^{-1}}$), and the lowest bias is in Mopani, south-west of Greater Sekhukhune, south-east and north of Waterberg, and Capricorn ranging from 200-600 $\mathrm{mm.yr^{-1}}$).
- The CV of rainfall distribution shows that much of the region is moderately variable. The highest CV values are observed in the north-eastern region and the lowest in the southern region (ranging from 15% to 36%).

- Statistically significant increasing trends during the rainy season were observed in Capricorn, Vhembe, north-west and south-west of Mopani, and south-east of Greater Sekhukhune.

### 5.2.2 Objective 2: Determine seasonal rainfall characteristics in the region.

- The migration and intensification of dry spells is observed from the north of Vhembe and Capricorn to the north-east of Mopani.
- The frequency and extent of dry spells increase from early summer (ON) to the late summer (FM).
- Moderate wet days exhibit high spatial and temporal variability over the province. Of all periods, DJ receives the highest frequency of moderate wet days with a larger spatial extent over the province.
- Furthermore, heavy wet days exhibit high frequencies in the central high-lying escarpment in the south of Vhembe, north and west of Mopani, south of Capricorn, Waterberg, and north of Greater Sekhukhune during the DJ season.
- Dry spell analysis shows decreasing rainfall trends across the province over space and time. Statistically significant decreasing trends are recorded over the entire province during the DJ and FM period.
- Spatially variable statistically significant decreasing moderate wet day trends were observed throughout the ON to FM periods at varying spatial location and extents.
- DJ records statistically significant increasing heavy wet day trends with a larger spatial extent
- The relationship between seasonal rainfall anomalies and seasonal characteristics was observed. The relationship of seasonal rainfall characteristics emphasizes the complex interplay between wet and dry periods within specific years.
- The findings underscore that positive rainfall anomalies do not equate to above-average moderate or heavy wet days and below-average dry spells.
- Negative anomalies exhibit a complementary relationship between seasonal rainfall anomalies and moderate and heavy wet days. However, dry spells exhibit a complex relationship with negative rainfall anomalies. Not all negative anomalies are characterized by above average dry spells. This shows that anomalies overlook the isolated impact of seasonal rainfall.

### 5.2.3 Objective 3: Establish the relationship between the seasonal rainfall characteristics and large modes of climate variability.

- An inverse relationship is observed between ENSO and seasonal rainfall characteristics. The results indicate that a somewhat complex relationship exists between ENSO events and seasonal rainfall characteristics. For instance, not all seasons associated with La Niña were wet nor seasons associated with El Niño were dry.
- The scope of the study reveals that although ENSO plays an important role in rainfall variability, the ENSO alone is not liable for year-to year variability.
- The spatial correlation between ENSO and dry spells shows that during ON, the ENSO has a strong positive correlation with dry spells, whereas the FM and DJ period records a negative weak correlation.
- Moderate wet days also showed a strong negative correlation with ENSO during ON, whereas a weak positive correlation was observed during DJ and FM.
- During heavy wet days a strong negative correlation with ENSO is observed during the ON periods, a weak positive correlation in DJ, and a strong negative correlation was observed in FM.
- Although SIOD is also attributed to rainfall characteristics variability in this study, it is noted that negative SIOD coincides more with above-average dry spells, whereas positive coincides more with above-average moderate and heavy wet days.
- A somewhat complex relationship exists when SIOD and ENSO occur simultaneously. The combination of ENSO and SIOD disrupts or enhances precipitation when they occur simultaneously.
- The spatial relationship between seasonal rainfall characteristics and SIOD varies spatially and with periods.
- The correlation between dry spells and SIOD exhibits weak positive correlation during the ON, a strong negative correlation during the DJ and FM period
- The correlation between moderate wet days and SIOD exhibits a strong negative correlation during ON, whereas a weak positive correlation is exhibited during the FM and DJ periods.
- The spatial relationship between heavy wet days and SIOD exhibits a weak negative correlation during the ON and DJ periods, whereas a strong negative correlation was

observed during the FM periods.

In conclusion, this study will benefit research in South Africa, particularly research related to seasonal rainfall analysis and prediction. Understanding rainfall variability over the Limpopo province is significant for improving management, risk reduction, and early warning systems for extreme events. The success or failure of agricultural output is mostly dependent on the distribution of seasonal rainfall characteristics throughout the growing season, rather than the total rainfall or deviation from the mean. Furthermore, the implications of these results are important for the water budget of the province. This will provide information on rainfall variability information of different districts and may further be used for local planning and adaptation strategies.

### 5.3 Recommendations and future studies

This study was undertaken to understand seasonal rainfall characteristics over the Limpopo province. The findings of these studies are critical to the agricultural and water sectors for both district and individual farmer levels as they highlight the need for improving methods to adapt to changing rainfall characteristics. These findings also advance knowledge on aspects of decision-making in the agricultural sector under a changing climate. However, there is still a need for continued research following this study.

Although science plays an integral role in solving climate-related problems, it is also important that indigenous knowledge is perused to enhance efficiency and have a hybrid approach that includes every aspect of the environment. Furthermore, in the context of understanding or projecting future rainfall, the agricultural and water sector context must be considered in studies since much of Limpopo has a population that relies heavily on agriculture.

The findings of this study also indicated statistically significant increases or decreases in seasonal rainfall. However, the underlying causes of these significant changes have not been adequately addressed. Climate attribution studies are crucial for understanding the reasons behind these changes in seasonal rainfall. Determining whether climate change has contributed to these variations, and at what rate is very essential for developing effective strategies to mitigate and adapt to the effects of climate change. This will be instrumental in informing policymakers about the impact of climate change on seasonal rainfall characteristics.

## References


Abba O.S., and Abiodun, B. J. (2020) Characteristics of cut-off lows during the 2015–2017 drought in the Western Cape, South Africa. *Atmospheric Research* 235(November 2019): 104772.

Adams, R. M., Hurd, B., Lenhart, S., and Leary, N. (1998) Effects of global climate change on agriculture: an interpretative review. *Climate Research* 11: 19–30.

Adedeji, O., Reuben, O., and Olatoye, O. (2014) Global Climate Change. *Journal of Geoscience and Environment Protection* 02(02): 114–122.

Adeola, A., Ncongwane, K., Abiodun, G., Makgoale, T., Rautenbach, H., Botai, J., Adisa, O., and Botai, C. (2019) Rainfall trends and malaria occurrences in Limpopo province, South Africa. *International Journal of Environmental Research and Public Health* 16(24).

Alemaw, B. F., and Chaoka, R. T. (2016) Regionalization of Rainfall Intensity-Duration-Frequency (IDF) Curves in Botswana. *Journal of Water Resource and Protection* 08(12): 1128–1144.

Alemu, M. M., and Bawoke, G. T. (2020) Analysis of spatial variability and temporal trends of rainfall in Amhara Region, Ethiopia. *Journal of Water and Climate Change* 11(4): 1505–1520.

Alley, R.B., Marotzke, J., Nordhaus, W.D., Overpeck, J.T., Peteet, D.M., Pielke Jr, R.A., Pierrehumbert, R.T., Rhines, P.B., Stocker, T.F., Talley, L.D. and Wallace, J.M. (2003) Abrupt climate change. *science*, *299*(5615):2005-2010.

Armah, F. A., Odoi, J. O., Yengoh, G. T., Obiri, S., Yawson, D. O., and Afrifa, E. K. A. (2011) Food security and climate change in drought-sensitive savanna zones of Ghana. *Mitigation and Adaptation Strategies for Global Change* 16(3): 291–306.

Arnell, N.W. (2004) Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global environmental change*, *14*(1):31-52.

Asuero, A.G., Sayago, A. and González, A.G. (2006) The correlation coefficient: An overview. *Critical reviews in analytical chemistry*, *36*(1):41-59.

Aydinalp, C., Cresser, M. S., and Cresser, M. S. (2008) The Effects of Global Climate Change on Agriculture Agriculture Land use change (including biomass burning) The Effects of Global Climate Change on Agriculture. *Agric. & Environ. Sci* 3(5): 672–676.

Bai, L., Shi, C., Li, L., Yang, Y., and Wu, J. (2018) Accuracy of CHIRPS satellite-rainfall products over mainland China. *Remote Sensing* 10(3).

Baray, J. L., Baldy, S., Diab, R. D., and Cammas, J. P. (2003) Dynamical study of a tropical cut-off low over South Africa, and its impact on tropospheric ozone. *Atmospheric Environment* 37(11): 1475–1488.

Barimalala, R., Blamey, R. C., Desbiolles, F., and Reason, C. J. C. (2021) The influence of southeastern African river valley jets on regional rainfall. *Climate Dynamics* 57(9–10): 2905–2920.

Barnes, M. A., Turner, K., Ndarana, T., and Landman, W. A. (2021) Cape storm: A dynamical study of a cut-off low and its impact on South Africa. *Atmospheric Research* 249.

Bartzke, G. S., Ogutu, J. O., Mukhopadhyay, S., Mtui, D., Dublin, H. T., and Piepho, H. P. (2018) Rainfall trends and variation in the Maasai Mara ecosystem and their implications for animal population and biodiversity dynamics. *PLoS ONE* 13(9).

Bates, B.C. (2018) From prediction to scenario analysis: A brief review and commentary. *Bridging science and policy implication for managing climate extremes*.207-220.

Bayissa, Y., Tadesse, T., Demisse, G., and Shiferaw, A. (2017) Evaluation of satellite-based rainfall estimates and application to monitor meteorological drought for the Upper Blue Nile Basin, Ethiopia. *Remote Sensing* 9(7).

Behera, S. K., and Yamagata, T. (2001) Subtropical SST dipole events in the southern Indian Ocean. *Geophysical Research Letters* 28(2): 327–330.

Beyer, M., Wallner, M., Bahlmann, L., Thiemig, V., Dietrich, J., and Billib, M. (2016) Rainfall characteristics and their implications for rain-fed agriculture: a case study in the Upper Zambezi River Basin. *Hydrological Sciences Journal* 61(2): 321–343.

Blamey, R. C., Kolusu, S. R., Mahlalela, P., Todd, M. C., and Reason, C. J. C. (2018) The role of regional circulation features in regulating El Niño climate impacts over southern Africa: A comparison of the 2015/2016 drought with previous events. *International Journal of Climatology* 38(11): 4276–4295.

Blamey, R.C. and Reason, C.J.C. (2013) The role of mesoscale convective complexes in southern Africa summer rainfall. *Journal of climate*, *26*(5): 1654-1668.

Botai, C. M., Botai, J. O., Zwane, N. N., Hayombe, P., Wamiti, E. K., Makgoale, T., Murambadoro, M. D., Adeola, A. M., Ncongwane, K. P., de Wit, J. P., Mengistu, M. G., and Tazvinga, H. (2020) Hydroclimatic extremes in the limpopo river basin, south africa, under changing climate. *Water (Switzerland)* 12(12): 1–20.

Cai, W., and Cowan, T. (2008) Dynamics of late autumn rainfall reduction over southeastern Australia. *Geophysical Research Letters* 35(9): 1–5.

Calzadilla, A., Rehdanz, K., Betts, R., Falloon, P., Wiltshire, A., and Tol, R. S. J. (2013) Climate change impacts on global agriculture. *Climatic Change* 120(1–2): 357–374.

Cane, M. A. (2005) The evolution of El Niño, past and future. *Earth and Planetary Science Letters* 230(3–4): 227–240.

Charrua, A. B., Padmanaban, R., Cabral, P., Bandeira, S., and Romeiras, M. M. (2021) Impacts of the tropical cyclone idai in mozambique: A multi-temporal landsat satellite imagery analysis. *Remote Sensing* 13(2): 1–17.

Chikosi, E. S., Mugambiwa, S. S., Tirivangasi, H. M., and Rankoana, S. A. (2019) Climate change and variability perceptions in Ga-Dikgale community in Limpopo Province, South Africa. *International Journal of Climate Change Strategies and Management* 11(3): 392–405.

Chikwiramakomo, L., Gumindoga, W., Shekede, M. D., Gara, T. W., and Chuma, T. (2021) Modelling flood hazard in dry climates of southern africa: A case of beitbridge, limpopo basin, zimbabwe. *Water SA* 47(4): 488–497.

Collier, P., Conway, G., and Venables, T. (2008) Climate change and Africa. *Oxford Review of Economic Policy* 24(2): 337–353.

Cook, C., Reason, C. J. C., and Hewitson, B. C. (2004) Wet and dry spells within particularly wet and dry summers in the South African summer rainfall region. *Climate Research*. doi:10.3354/cr026017.

D. Melgoza, A. Hern´andez-Ram´ırez and J. M. Peralta-Hern´andez*Received 2nd October 2008, A. 12th D. 2008First published as an A. A. on the web 23rd J. 2009DOI: 10. 1039/b817287. (2008) No Title p . *Phys. Rev. E* (October): 6–11.

D'Abreton, P. C., and Lindesay, J. A. (1993) Water vapour transport over Southern Africa during wet and dry early and late summer months. *International Journal of Climatology*. doi:10.1002/joc.3370130203.

Dag Heward-Mills (2004) Limpopo province economic outlook review. *European University Institute* (2): 2–5.

de Souza, I. P., Andreoli, R. V., Kayano, M. T., Vargas, F. F., Cerón, W. L., Martins, J. A., Freitas, E., and de Souza, R. A. F. (2021) Seasonal precipitation variability modes over South America associated to El Niño-Southern Oscillation (ENSO) and non-ENSO components during the 1951–2016 period. *International Journal of Climatology* 41(8): 4321–4338.

Dedekind, Z., Engelbrecht, F.A. and Van der Merwe, J. (2016) Model simulations of rainfall over southern Africa and its eastern escarpment. *Water SA*, *42*(1):129-143.

Dell, M., Jones, B.F. and Olken, B.A. (2008) *Climate change and economic growth: Evidence from the last half century* (No. w14132). National Bureau of Economic Research.

Dembélé, M., and Zwart, S. J. (2016) Evaluation and comparison of satellite-based rainfall products in Burkina Faso, West Africa. *International Journal of Remote Sensing* 37(17): 3995–4014.

Dieppois, B., Pohl, B., Crétat, J., Eden, J., Sidibe, M., New, M., Rouault, M., and Lawler, D. (2019) Southern African summer-rainfall variability, and its teleconnections, on interannual to interdecadal timescales in CMIP5 models. *Climate Dynamics* 53(5–6): 3505–3527.

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., and Ceccato, P. (2018) Validation of the CHIRPS satellite rainfall estimates over eastern Africa. *Quarterly Journal of the Royal Meteorological Society*. doi:10.1002/qj.3244.

Dlamini, P., Orchard, C., Jewitt, G., Lorentz, S., Titshall, L., and Chaplot, V. (2011) Controlling factors of sheet erosion under degraded grasslands in the sloping lands of KwaZulu-Natal, South Africa. *Agricultural Water Management* 98(11): 1711–1718.

Downing, T.E., Ringius, L., Hulme, M. and Waughray, D. (1997) Adapting to climate change in Africa. *Mitigation and adaptation strategies for global change 2*:19-44.

Driver, P., and Reason, C. J. C. (2017a) Variability in the Botswana High and its relationships with rainfall and temperature characteristics over southern Africa. *International Journal of Climatology* 37: 570–581.

Duan, Z., Liu, J., Tuo, Y., Chiogna, G., and Disse, M. (2016) Evaluation of eight high spatial resolution gridded precipitation products in Adige Basin (Italy) at multiple temporal and spatial scales. *Science of the Total Environment* 573: 1536–1553.

Dube, K., Nhamo, G., and Chikodzi, D. (2020) Climate change-induced droughts and tourism: Impacts and responses of Western Cape province, South Africa. *Journal of Outdoor Recreation and Tourism*. doi:10.1016/j.jort.2020.100319.

Dube, L.T., and Jury, M. R. (2002) Meteorological structure of the 1992/93 drought over eastern south africa from ecmwf and satellite olr analyses. *South African Geographical Journal* 84(2): 170–181.

Dube, L.T., and Jury, M. R. (2003) Structure and precursors of the 1992/93 drought in KwaZulu-Natal, South Africa from NCEP reanalysis data. *Water SA* 29(2): 201–207.

Dunning, C. M., Black, E. C. L., and Allan, R. P. (2016) The onset and cessation of seasonal rainfall over Africa. *Journal of Geophysical Research* 121(19): 11405–11424.

Dyson, L. L., and Van Heerden, J. (2001) dyson-van-heerden-2001-the-heavy-rainfall-and-floods-over-the-northeastern-interior-of-south-africa-during-february. *South African Journal of science* 97(3): 80–86.

Dzurume, T., Dube, T., Thamaga, K. H., Shoko, C., and Mazvimavi, D. (2022) Use of multispectral satellite data to assess impacts of land management practices on wetlands in the Limpopo Transfrontier River Basin, South Africa. *South African Geographical Journal* 104(2): 193–212.

Eckstein, D., Künzel, V., and Schäfer, L. (2021) *Global climate risk index 2021: who suffers most from extreme weather events? Weather-related loss events in 2019 and 2000–2019. Germanwatch*.

Engelbrecht, C. J., and Engelbrecht, F. A. (2016) Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and Applied Climatology* 123(1–2): 247–261.

Engelbrecht, C. J., Landman, W. A., Engelbrecht, F. A., and 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.A. and Monteiro, P. (2021) The IPCC assessment report six working group 1 report and southern Africa: Reasons to take action. *South African Journal of Science*, *117*(11-12):1-7.

Favre, A., Hewitson, B., Tadross, M., Lennard, C., and Cerezo-Mota, R. (2012) Relationships between cut-off lows and the semiannual and southern oscillations. *Climate Dynamics* 38(7–8): 1473–1487.

Fitchett, J. M., and Grab, S. W. (2014) A 66-year tropical cyclone record for south-east Africa: Temporal trends in a global context. *International Journal of Climatology* 34(13): 3604–3615.

Fiwa, L., Vanuytrecht, E., Wiyo, K. A., and Raes, D. (2014) Effect of rainfall variability on the length of the crop growing period over the past three decades in central Malawi. *Climate Research* 62(1): 45–58.

Fuenzalida, H. A., Sánchez, R., and Garreaud, R. D. (2005) A climatology of cutoff lows in the Southern Hemisphere. *Journal of Geophysical Research D: Atmospheres* 110(18): 1–10.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. and Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific data*, *2*(1): 1-21.

Gao, F., Zhang, Y., Ren, X., Yao, Y., Hao, Z., and Cai, W. (2018) Evaluation of CHIRPS and its application for drought monitoring over the Haihe River Basin, China. *Natural Hazards* 92(1): 155–172.

Garidzirai, R., Meyer, D. F., and Muzindutsi, P. F. (2019) The impact of economic sectors on local economic development (LED): The case of the Capricorn Region, Limpopo Province, South Africa. *International Journal of Economics and Finance Studies* 11(2): 19–34.

Gassebner, M., Keck, A., and Teh, R. (2010) Shaken, not stirred: The impact of disasters on international trade. *Review of International Economics* 18(2): 351–368.

Gaughan, A.E., Staub, C.G., Hoell, A., Weaver, A. and Waylen, P.R. (2016) Inter-and Intra-annual precipitation variability and associated relationships to ENSO and the IOD in southern Africa. *International Journal of Climatology*, *36*(4).

Gbetibouo, G. A., Hassan, R. M., and Ringler, C. (2010) Modelling farmers' adaptation strategies for climate change and variability: The case of the limpopo basin, South Africa. *Agrekon* 49(2): 217–234.

Gebrechorkos, S. H., Hülsmann, S., Bernhofer, C., Mazibuko, S. M., Mukwada, G., Moeletsi, M. E., et al. (2021) Analysis of Temperature Trends over Limpopo Province, South Africa. *Scientific Reports* 11(1): 1–18.

Gerten, D., Rost, S., von Bloh, W., and Lucht, W. (2008) Causes of change in 20th century global river discharge. *Geophysical Research Letters* 35(20): 1–5.

Gibson, D.J. (2006) *Land degradation in the Limpopo province, South Africa* (Doctoral dissertation, University of the Witwatersrand).

Gillett, N. P., Kell, T. D., and Jones, P. D. (2006) Regional climate impacts of the Southern Annular Mode. *Geophysical Research Letters* 33(23).

Gökmen, A., and Temiz, D. (2015) The importance and impact of fossil and renewable energy sources in turkey on business and the economy. *Energy Sources, Part B: Economics, Planning and Policy* 10(1): 14–20.

Gong, D. Y., Shi, P. J., and Wang, J. A. (2004) Daily precipitation changes in the semi-arid region over northern China. *Journal of Arid Environments* 59(4): 771–784.

Gong, H., Zhou, W., Chen, W., Wang, L., Leung, M. Y. T., Cheung, P. K. Y., and Zhang, Y. (2019) Modulation of the southern Indian Ocean dipole on the impact of El Niño–Southern Oscillation on Australian summer rainfall. *International Journal of Climatology* 39(4): 2484–2490.

Gore, M., Abiodun, B. J., and Kucharski, F. (2020) Understanding the influence of ENSO patterns on drought over southern Africa using SPEEDY. *Climate Dynamics* 54(1–2): 307–327.

Gössling, S. and Humpe, A. (2020) The global scale, distribution and growth of aviation: Implications for climate change. *Global Environmental Change 65*:102194.

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., Treidel, H., and Aureli, A. (2011/5/August) Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology*.

Grjibovski, A. M., Kosbayeva, A., and Menne, B. (2014) The effect of ambient air temperature and precipitation on monthly counts of salmonellosis in four regions of Kazakhstan, Central Asia, in 2000-2010. *Epidemiology and Infection* 142(3): 608–615.

Gupta, A. and England, M.H. (2006) Coupled ocean–atmosphere–ice response to variations in the southern annular mode. *Journal of Climate*, *19*(18):4457-4486.

Gwambene, B., Liwenga, E., and Mung'ong'o, C. (2023) Climate Change and Variability Impacts on Agricultural Production and Food Security for the Smallholder Farmers in Rungwe, Tanzania. *Environmental Management* 71(1): 3–14.

Mulenga, H.M., Rouault, M. and Reason, C.J.C. (2003) Dry summers over northeastern South Africa and associated circulation anomalies. *Climate Research*, *25*(1):29-41.
Hachigonta, S., and Reason, C. J. C. (2006) Interannual variability in dry and wet spell characteristics over Zambia. *Handbook of Environmental Chemistry, Volume 5: Water Pollution*. doi:10.3354/cr032049.

Hachigonta, S., Reason, C. J. C., and Tadross, M. (2008) An analysis of onset date and rainy season duration over Zambia. *Theoretical and Applied Climatology* 91(1–4): 229–243.

Hao, Y., Hao, Z., Feng, S., Zhang, X., and Hao, F. (2020) Response of vegetation to El Niño-Southern Oscillation (ENSO) via compound dry and hot events in southern Africa. *Global and Planetary Change* 195(19): 103358.

Harrison, M.S.J. (1984) A generalized classification of South African summer rain-bearing synoptic systems. *Journal of Climatology*, *4*(5):547-560.

Hart, N. C.G., Reason, C. J. C., and Fauchereau, N. (2010) Tropical-extratropical interactions over southern Africa: Three cases of heavy summer season rainfall. *Monthly Weather Review* 138(7): 2608–2623.

Hart, N.C.G., Reason, C. J. C., and Fauchereau, N. (2013) Cloud bands over southern Africa: Seasonality, contribution to rainfall variability and modulation by the MJO. *Climate Dynamics* 41(5–6): 1199–1212.

Heidari, H., Arabi, M., Ghanbari, M., and Warziniack, T. (2020) A probabilistic approach for characterization of sub-annual socioeconomic drought intensity-duration-frequency (IDF) relationships in a changing environment. *Water (Switzerland)* 12(6).

Hoell, A., Barlow, M., Wheeler, M. C., and Funk, C. (2014) Disruptions of el niño-southern oscillation teleconnections by the madden-julian oscillation. *Geophysical Research Letters*. doi:10.1002/2013GL058648.

Hoell, A., and Cheng, L. (2018) Austral summer Southern Africa precipitation extremes forced by the El Niño-Southern oscillation and the subtropical Indian Ocean dipole. *Climate Dynamics* 50(9–10): 3219–3236.

Hoell, A., Funk, C., Zinke, J., and Harrison, L. (2017) Modulation of the Southern Africa precipitation response to the El Niño Southern Oscillation by the subtropical Indian Ocean Dipole. *Climate Dynamics* 48(7–8): 2529–2540.

Hoell, A., Gaughan, A. E., Shukla, S., and Magadzire, T. (2017) The hydrologic effects of synchronous El Niño-Southern Oscillation and subtropical Indian Ocean dipole events over southern Africa. *Journal of Hydrometeorology* 18(9): 2407–2424.

Hoell, A., Magadzire, T., McNally, A., and Eischeid, J. (2023) Multiyear dry periods in Southern Africa. *International Journal of Climatology* 43(7): 3225–3246.

Holz, A., Paritsis, J., Mundo, I. A., Veblen, T. T., Kitzberger, T., Williamson, G. J., Aráoz, E., Bustos-Schindler, C., González, M. E., Grau, H. R., and Quezada, J. M. (2017) Southern Annular Mode drives multicentury wildfire activity in southern South America. *Proceedings of the National Academy of Sciences of the United States of America* 114(36): 9552–9557.

Hosu, S. Y., Cishe, E. N., and Luswazi, P. N. (2016) Vulnerability to Climate Change in the Eastern Cape Province of South Africa: What Does the Future Holds for Smallholder Crop Farmers? *Agrekon* 55(1–2): 133–167.

Howard, E., and Washington, R. (2018) Characterizing the synoptic expression of the Angola low. *Journal of Climate* 31(17): 7147–7165.

Howard, E., Washington, R., and Hodges, K. I. (2019) Tropical Lows in Southern Africa: Tracks, Rainfall Contributions, and the Role of ENSO. *Journal of Geophysical Research: Atmospheres* 124(21): 11009–11032.

Ibebuchi, C. C. (2021) On the relationship between circulation patterns, the southern annular mode, and rainfall variability in western cape. *Atmosphere* 12(6).

IPCC (2022) *Summary for Policymakers Sixth Assessment Report (WG3)*. *Cambridge University Press*.

Iqbal, Z., Shahid, S., Ahmed, K., Ismail, T., Ziarh, G. F., Chung, E. S., and Wang, X. (2021) Evaluation of CMIP6 GCM rainfall in mainland Southeast Asia. *Atmospheric Research* 254(November 2020): 105525.

Jagarnath, M., Thambiran, T., and Gebreslasie, M. (2020) Heat stress risk and vulnerability under climate change in Durban metropolitan, South Africa—identifying urban planning priorities for adaptation. *Climatic Change* 163(2): 807–829.

Jansen, A. and Schulz, C.E. (2006) Water demand and the urban poor: a study of the factors influencing water consumption among households in Cape Town, South Africa. *South African Journal of Economics*, *74*(3):593-609.

Javadikasgari, H., Soltesz, E.G. and Gillinov, A.M., 2019. Surgery for Atrial Fibrillation. In *Atlas of Cardiac Surgical Techniques* (pp. 479-488). Elsevier.

Jiménez-Muñoz, J. C., Mattar, C., Barichivich, J., Santamaría-Artigas, A., Takahashi, K., Malhi, Y., Sobrino, J. A., and Schrier, G. Van Der (2016) Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015-2016. *Scientific Reports* 6(August): 1–7.

Jury, M. R., and Dube, L. T. (2000) The nature of climate variability and impacts of drought over kwazulu-natal, south africa. *South African Geographical Journal* 82(2): 44–53.

Jury, M.R. and Engert, S. (1999) Teleconnections modulating inter-annual climate variability over northern Namibia. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *19*(13):1459-1475..

Lau, K.M. and Sheu, P.J. (1988) Annual cycle, quasi-biennial oscillation, and southern oscillation in global precipitation. *Journal of Geophysical Research: Atmospheres*, *93*(D9):10975-10988.

Kakembo, V., and Rowntree, K. M. (2003) The relationship between land use and soil erosion in the communal lands near Peddie town, Eastern Cape, South Africa. *Land Degradation and Development* 14(1): 39–49.

Kane, R. P. (2009) Periodicities, ENSO effects and trends of some South African rainfall series: An update. *South African Journal of Science* 105(5–6): 199–207.

Kenabatho, P. K., McIntyre, N. R., Chandler, R. E., and Wheater, H. S. (2012) Stochastic simulation of rainfall in the semi-arid Limpopo basin, Botswana. *International Journal of Climatology* 32(7): 1113–1127.

Kephe, P. N., Petja, B. M., and Kabanda, T. A. (2016) Spatial and inter-seasonal behaviour of rainfall in the Soutpansberg region of South Africa as attributed to the changing climate. *Theoretical and Applied Climatology* 126(1–2): 233–245.

Khan, F., Ali, S., Mayer, C., Ullah, H., and Muhammad, S. (2022) Climate change and spatio-temporal trend analysis of climate extremes in the homogeneous climatic zones of Pakistan during 1962-2019. *PLoS ONE* 17(7 July).

Khasnis, A.A. and Nettleman, M.D. (2005) Global warming and infectious disease. *Archives of medical research*, *36*(6):689-696.

Kibii, J.K. (2021) *Assessment of seasonal and annual rainfall trends and variability in South Africa* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

Kidd, C., Becker, A., Huffman, G. J., Muller, C. L., Joe, P., Skofronick-Jackson, G., and Kirschbaum, D. B. (2017) So, how much of the Earth's surface is covered by rain gauges? *Bulletin of the American Meteorological Society* 98(1): 69–78.

Kovats, R. S., Edwards, S. J., Hajat, S., Armstrong, B. G., Ebi, K. L., Menne, B., Cowden, J., Gerner-Smidt, P., Hernández Pezzi, G., Kristufkova, Z., Kriz, B., Kutsar, K., Magdzik, W., O'Brien, S. J., Schmid, H., and van Pelth, W. (2004) The effect of temperature on food poisoning: A time-series analysis of salmonellosis in ten European countries. *Epidemiology and Infection* 132(3): 443–453.

Kruger, A. C., and Nxumalo, M. P. (2017) Historical rainfall trends in South Africa: 1921–2015. *Water SA* 43(2): 285–297.

Kuleshov, Y., Qi, L., Fawcett, R., and Jones, D. (2008) On tropical cyclone activity in the Southern Hemisphere: Trends and the ENSO connection. *Geophysical Research Letters* 35(14): 1–5.

Kumar, Y., and Kumar, A. (2020) Spatiotemporal analysis of trend using nonparametric tests for rainfall and rainy days in Jodhpur and Kota zones of Rajasthan (India). *Arabian Journal of Geosciences* 13(15).

Kunreuther, H., Heal, G., Allen, M., Edenhofer, O., Field, C.B. and Yohe, G. (2013) Risk management and climate change. *Nature climate change 3*(5):447-450.

Kusangaya, S., Warburton, M. L., Archer van Garderen, E., and Jewitt, G. P. W. (2014) Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth* 67–69: 47–54.

Kynčl, J., Špačková, M., Fialová, A., Kyselý, J., and Malý, M. (2021) Influence of air temperature and implemented veterinary measures on the incidence of human salmonellosis in the Czech Republic during 1998–2017. *BMC Public Health* 21(1): 1–7.

Lai, C., Zhong, R., Wang, Z., Wu, X., Chen, X., Wang, P., and Lian, Y. (2019) Monitoring hydrological drought using long-term satellite-based precipitation data. *Science of the Total Environment* 649: 1198–1208.

Landman, W. A., and Mason, S. J. (1999) Sea-Surface Temperatures and Summer Rainfall Over South Africa and Namibia. *International Journal of Climatology* 1492: 1477–1492.

Le Barbé, L., Lebel, T., and Tapsoba, D. (2002) *Rainfall Variability in West Africa during the Years 1950-90*.

Le Roux, P. C., Aalto, J., and Luoto, M. (2013) Soil moisture's underestimated role in climate change impact modelling in low-energy systems. *Global Change Biology* 19(10): 2965–2975.
Legesse Gebre, S., and Getahun, Y. S. (2016) Analysis of Climate Variability and Drought Frequency Events on Limpopo River Basin, South Africa. *Journal of Waste Water Treatment & Analysis* 7(3).

Leichenko, R.M. and O'brien, K.L. (2002) The dynamics of rural vulnerability to global change: the case of southern Africa. *Mitigation and adaptation strategies for global change*, *7*(1):1-18.

Lemi, T. (2019) Effects of Climate Change Variability on Agricultural Productivity. *International Journal of Environmental Sciences & Natural Resources* 17(1).

Lestari, S., King, A., Vincent, C., Karoly, D., and Protat, A. (2019) Seasonal dependence of rainfall extremes in and around Jakarta, Indonesia. *Weather and Climate Extremes* 24.

Li, Z. and Fang, H. (2016) Impacts of climate change on water erosion: A review. *Earth-Science Reviews 163*:94-117.

Lian, X., Piao, S., Chen, A., Huntingford, C., Fu, B., Li, L. Z. X., Huang, J., Sheffield, J., Berg, A. M., Keenan, T. F., McVicar, T. R., Wada, Y., Wang, X., Wang, T., Yang, Y., and Roderick, M. L. (2021) Multifaceted characteristics of dryland aridity changes in a warming world. *Nature Reviews Earth and Environment* 2(4): 232–250.

Lim, E. P., Hendon, H. H., Arblaster, J. M., Delage, F., Nguyen, H., Min, S. K., and Wheeler, M. C. (2016) The impact of the Southern Annular Mode on future changes in Southern Hemisphere rainfall. *Geophysical Research Letters* 43(13): 7160–7167.

Linares, C., Martinez, G. S., Kendrovski, V., and Diaz, J. (2020) A new integrative perspective on early warning systems for health in the context of climate change. *Environmental Research* 187.

Lipsett, A.S. (2017) Spatio-temporal effects of rainfall on stream/river flow in the Kruger National Park, South Africa (Doctoral dissertation, MSc Dissertation submitted to University of the Witwatersrand).

Livada, I., and Asimakopoulos, D. N. (2005) Individual seasonality index of rainfall regimes in Greece. *Climate Research* 28(2): 155–161.

Lizcano, G., and Todd, M. (2005) Non-ENSO control on southern Africa precipitation variability. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 363(1826): 61–62.

Lorenzo-Lacruz, J., Vicente-Serrano, S. M., López-Moreno, J. I., Beguería, S., García-Ruiz, J. M., and Cuadrat, J. M. (2010) The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *Journal of Hydrology* 386(1–4): 13–26.

Love, D., Uhlenbrook, S., Twomlow, S., and van Der Zaag, P. (2010) Changing hydroclimatic and discharge patterns in the northern Limpopo Basin, Zimbabwe. *Water SA* 36(3): 335–350.

Lu, S., Bai, X., Li, W., and Wang, N. (2019) Impacts of climate change on water resources and grain production. *Technological Forecasting and Social Change* 143(November 2018): 76–84.

Macamo, C. C. F., Massuanganhe, E., Nicolau, D. K., Bandeira, S. O., and Adams, J. B. (2016) Mangrove's response to cyclone Eline (2000): What is happening 14 years later. *Aquatic Botany* 134: 10–17.

Machete, K. C., Senyolo, M. P., and Gidi, L. S. (2024) Adaptation through Climate-Smart Agriculture: Socio-Economic Factors Influencing the Willingness to Adopt Climate-Smart Agriculture by Smallholder Maize Farmers in Limpopo Province. doi:10.20944/preprints202403.1019.v1.

Macron, C., Pohl, B., Richard, Y., and Bessafi, M. (2014) How do tropical temperate troughs form and develop over Southern Africa? *Journal of Climate* 27(4): 1633–1647.

Mafunzwaini, A. E., and Hugo, L. (2005) Unlocking the rural tourism potential of the Limpopo province of South Africa: Some strategic guidelines. *Development Southern Africa* 22(2): 251–265.

Mahlalela, P., 2018. Revisiting the links between the Southern Annular Mode and rainfall over the Western Cape region of South Africa (Masters Dissertation, University of Cape Town).

Mahlalela, P. T., Blamey, R. C., Hart, N. C. G., and Reason, C. J. C. (2020) Drought in the Eastern Cape region of South Africa and trends in rainfall characteristics. *Climate Dynamics* 55(9–10): 2743–2759.

Mahlalela, P. T., Blamey, R. C., and Reason, C. J. C. (2019) Mechanisms behind early winter rainfall variability in the southwestern Cape, South Africa. *Climate Dynamics* 53(1–2): 21–39.

Maja, M. M., and Ayano, S. F. (2021) The Impact of Population Growth on Natural Resources and Farmers' Capacity to Adapt to Climate Change in Low-Income Countries. *Earth Systems and Environment* 5(2): 271–283.

Malherbe, J., Dieppois, B., Maluleke, P., Van Staden, M., and Pillay, D. L. (2016) South African droughts and decadal variability. *Natural Hazards* 80(1): 657–681.

Malherbe, J., Engelbrecht, F. A., and Landman, W. A. (2014) Response of the southern annular mode to tidal forcing and the bidecadal rainfall cycle over subtropical Southern Africa. *Journal of Geophysical Research* 119(5): 2032–2049.

Malherbe, J., Landman, W. A., and Engelbrecht, F. A. (2014) The bi-decadal rainfall cycle, Southern Annular Mode and tropical cyclones over the Limpopo River Basin, southern Africa. *Climate Dynamics* 42(11–12): 3121–3138.

Malherbe, J., Smit, I. P. J., Wessels, K. J., and Beukes, P. J. (2020) Recent droughts in the Kruger National Park as reflected in the extreme climate index. *African Journal of Range and Forage Science* 37(1): 1–17.

Malik, A., Kumar, A., Guhathakurta, P., and Kisi, O. (2019) Spatial-temporal trend analysis of seasonal and annual rainfall (1966–2015) using innovative trend analysis method with significance test. *Arabian Journal of Geosciences* 12(10).

Maluleke, P., Landman, W. A., Malherbe, J., and Archer, E. (2019) Seasonal forecasts for the Limpopo Province in estimating deviations from grazing capacity. *Theoretical and Applied Climatology* 137(3–4): 1693–1702.

Manatsa, D., Matarira, C. H., and Mukwada, G. (2011) Relative impacts of ENSO and Indian Ocean dipole/zonal mode on east SADC rainfall. *International Journal of Climatology* 31(4): 558–577.

Manatsa, D., Mukwada, G., and Makaba, L. (2018) ENSO shifts and their link to Southern Africa surface air temperature in summer. *Theoretical and Applied Climatology* 132(3–4): 727–738.

Manatsa, D, Chingombe, W., and Matarira, C. H. (2008) The impact of the positive Indian Ocean dipole on Zimbabwe droughts Tropical climate is understood to be dominated by. *International Journal of Climatology* 2029(March 2008): 2011–2029.

Manatsa, Desmond, and Reason, C. (2017) ENSO–Kalahari Desert linkages on southern Africa summer surface air temperature variability. *International Journal of Climatology* 37(4): 1728–

1745.

Manhique, A. J., Reason, C. J. C., Rydberg, L., and Fauchereau, N. (2011) ENSO and Indian Ocean sea surface temperatures and their relationships with tropical temperate troughs over Mozambique and the Southwest Indian Ocean. *International Journal of Climatology* 31(1): 1–13.

Maoyi, M. L., and Abiodun, B. J. (2021) How well does MPAS-atmosphere simulate the characteristics of the Botswana High? *Climate Dynamics* 57(7–8): 2109–2128.

Maoyi, M. L., and Abiodun, B. J. (2022) Investigating the response of the Botswana High to El Niño Southern Oscillation using a variable resolution global climate model. *Theoretical and Applied Climatology* 147(3–4): 1601–1615.

Maponya, P., Venter, S. L., Plooy, C. P. Du, Modise, S. D., and Heever, E. Van Den (2016) Training Challenges Faced by Smallholder Farmers: A Case of Mopani District, Limpopo Province in South Africa. *Journal of Human Ecology* 56(3): 272–282.

Maponya, P., and Mpandeli, S. (2012) Climate Change Adaptation Strategies used by Limpopo Province Farmers in South Africa. *Journal of Agricultural Science* 4(12): 39–47.

Maponya, P., and Mpandeli, S. (2013) Perception of Farmers on Climate Change and Adaptation in Limpopo Province of South Africa. *Journal of Human Ecology* 42(3): 283–288.

Mason, S. J. (1995) Sea-Surface Temperature-south african rainfall associations, *1910-1989*. *International Journal Of Climatology* (Vol. 15) :1910-1989.

Mason, S.J. and Joubert, A.M. (1997) Simulated changes in extreme rainfall over southern Africa. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *17*(3):291-301.

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.

Masupha, T. E., and Moeletsi, M. E. (2017) Use of standardized precipitation evapotranspiration index to investigate drought relative to maize, in the Luvuvhu River catchment area, South Africa. *Physics and Chemistry of the Earth* 102: 1–9.

Masupha, T. E., Moeletsi, M. E., and Tsubo, M. (2016a) Dry spells assessment with reference to the maize crop in the Luvuvhu River catchment of South Africa. *Physics and Chemistry of the Earth* 92: 99–111.

Matarira, C.H. and Jury, M.R. (1992) Contrasting meteorological structure of intra-seasonal wet and dry spells in Zimbabwe. *International Journal of Climatology*, *12*(2):165-176.

Mateyisi, M. J., Maoela, M. A., Maluleke, A., Moeletsi, M. E., and Von Maltitz, G. (2021) Changes in annual extreme temperature and heat indices in Limpopo province: period 1941-2016. *Theoretical and Applied Climatology* 143: 1327–1339.

Mather, A. A., and Stretch, D. D. (2012) A Perspective on sea level rise and coastal storm surge from southern and eastern Africa: A case study near Durban, south Africa. *Water (Switzerland)* 4(1): 237–259.

Mathivha, F., Tshipala, N. and Nkuna, Z. (2017) The relationship between drought and tourist arrivals: A case study of Kruger National Park, South Africa. *Jàmbá: Journal of Disaster Risk Studies*, *9*(1):1-8..

Matimolane, S., Chikoore, H., Mathivha, F.I. and Kori, E. (2022) Maize producers' vulnerability to climate change: evidence from Makhuduthamaga Local Municipality, South Africa. *Jàmbá-Journal of Disaster Risk Studies*, *14*(1):1165.

Mavume, A.F., Rydberg, L., Rouault, M. and Lutjeharms, J.R., 2009. Climatology and landfall of tropical cyclones in the south-west Indian Ocean. *Western Indian Ocean Journal of Marine Science*, *8*(1).

Mazibuko, S. M., Mukwada, G., and Moeletsi, M. E. (2021) Assessing the frequency of drought/flood severity in the luvuvhu river catchment, limpopo province, south africa. *Water SA* 47(2): 172–184.

McCarty, J.L., Aalto, J., Paunu, V.V., Arnold, S.R., Eckhardt, S., Klimont, Z., Fain, J.J., Evangeliou, N., Venäläinen, A., Tchebakova, N.M. and Parfenova, E.I. (2021) Reviews & syntheses: arctic fire regimes and emissions in the 21st century. *Biogeosciences Discussions 2021*:1-59.

McPhaden, M.J., Zebiak, S.E. and Glantz, M.H. (2006) ENSO as an integrating concept in earth science. *science*, *314*(5806):1740-1745.

Mendelsohn, R. (2008) The impact of climate change on agriculture in developing countries. *Journal of Natural Resources Policy Research* 1(1): 5–19.

Meque, A., and Abiodun, B. J. (2015) Simulating the link between ENSO and summer drought in Southern Africa using regional climate models. *Climate Dynamics* 44(7–8): 1881–1900.

Milazzo, A., Giles, L. C., Zhang, Y., Koehler, A. P., Hiller, J. E., and Bi, P. (2016) The effect of temperature on different Salmonella serotypes during warm seasons in a Mediterranean climate city, Adelaide, Australia. *Epidemiology and Infection* 144(6): 1231–1240.

Moeletsi, M. E., Mellaart, E. A. R., Mpandeli, N. S., and Hamandawana, H. (2013) The Use of Rainfall Forecasts as a Decision Guide for Small-scale Farming in Limpopo Province, South Africa. *Journal of Agricultural Education and Extension* 19(2): 133–145.

Moeletsi, M.E., Phumlani Shabalala, Z., De Nysschen, G., and Walker, S. (2016) Evaluation of an inverse distance weighting method for patching daily and dekadal rainfall over the free state province, South Africa. *Water SA* 42(3): 466–474.

Molekwa, S., Engelbrecht, C. J., and Rautenbach, C. J. W. (2014) Attributes of cut-off low induced rainfall over the Eastern Cape Province of South Africa. *Theoretical and Applied Climatology* 118(1–2): 307–318.

Monyela, B. (2017) A two-year long drought in summer 2014/2015 and 2015/2016 over South Africa (Masters Dissertation, University of Cape Tow*n*).

Morgado, M. E., Jiang, C., Zambrana, J., Upperman, C. R., Mitchell, C., Boyle, M., Sapkota, A. R., and Sapkota, A. (2021) Climate change, extreme events, and increased risk of salmonellosis: foodborne diseases active surveillance network (FoodNet), 2004-2014. *Environmental Health: A Global Access Science Source* 20(1): 1–11.

Mosase, E., and Ahiablame, L. (2018) Rainfall and temperature in the Limpopo River Basin, Southern Africa: Means, variations, and trends from 1979 to 2013. *Water (Switzerland)* 10(4).

Moses, O., Blamey, R. C., and Reason, C. J. C. (2023) Drought metrics and temperature extremes over the Okavango River basin, southern Africa, and links with the Botswana high. *International Journal of Climatology* 43(14): 6463–6483.

Mpandeli, S. (2014) Managing climate risks using seasonal climate forecast information in Vhembe district in Limpopo province, South Africa. *Journal of Sustainable Development* 7(5):

68–81.

Mupangwa, W., Walker, S., and Twomlow, S. (2011) Start, end and dry spells of the growing season in semi-arid southern Zimbabwe. *Journal of Arid Environments* 75(11): 1097–1104.

Musyoki, A., Thifhulufhelwi, R., and Murungweni, F. M. (2016) The impact of and responses to flooding in Thulamela Municipality, Limpopo Province, South Africa. *Jamba: Journal of Disaster Risk Studies* 8(2).

Mutengwa, C. S., Mnkeni, P., and Kondwakwenda, A. (2023) Climate-Smart Agriculture and Food Security in Southern Africa: A Review of the Vulnerability of Smallholder Agriculture and Food Security to Climate Change. *Sustainability (Switzerland)* 15(4).

Mzezewa, J., Misi, T., and Van Rensburg, L. (2010) Characterisation of rainfall at a semi-arid ecotope in the Limpopo Province (South Africa) and its implications for sustainable crop production. 36(1).

Naik, M., and Abiodun, B. J. (2020) Projected changes in drought characteristics over the Western Cape, South Africa. *Meteorological Applications* 27(1): 1–14.

Nangombe, S., Zhou, T., Zhang, W., Wu, B., Hu, S., Zou, L., and Li, D. (2018) Record-breaking climate extremes in Africa under stabilized 1.5 °c and 2 °c global warming scenarios. *Nature Climate Change* 8(5): 375–380.

Ndarana, T., Rammopo, T. S., Chikoore, H., Barnes, M. A., and Bopape, M. J. (2020) A quasi-geostrophic diagnosis of the zonal flow associated with cut-off lows over South Africa and surrounding oceans. *Climate Dynamics* 55(9–10): 2631–2644.

Ndlovu, M., Clulow, A. D., Savage, M. J., Nhamo, L., Magidi, J., and Mabhaudhi, T. (2021) An assessment of the impacts of climate variability and change in Kwazulu-Natal province, South Africa. *Atmosphere* 12(4).

Ndlovu, M. S., and Demlie, M. (2020) Assessment of meteorological drought and wet conditions using two drought indices across Kwazulu-Natal province, South Africa. *Atmosphere* 11(6).

Ngoma, H., Wen, W., Ojara, M., and Ayugi, B. (2021) Assessing current and future spatiotemporal precipitation variability and trends over Uganda, East Africa, based on CHIRPS and regional climate model datasets. *Meteorology and Atmospheric Physics* 133(3): 823–843.

Nhamo, L., Matchaya, G., Mabhaudhi, T., Nhlengethwa, S., Nhemachena, C., and Mpandeli, S. (2019) Cereal production trends under climate change: Impacts and adaptation strategies in Southern Africa. *Agriculture (Switzerland)* 9(2): 1–16.

Nhemachena, C., Nhamo, L., Matchaya, G., Nhemachena, C. R., Muchara, B., Karuaihe, S. T., and Mpandeli, S. (2020) Climate change impacts on water and agriculture sectors in southern africa: Threats and opportunities for sustainable development. *Water (Switzerland)* 12(10): 1–17.

Nicholas, D. E., Delamater, P. L., Waters, N. M., and Jacobsen, K. H. (2016) Geographically weighted discriminant analysis of environmental conditions associated with Rift Valley fever outbreaks in South Africa. *Spatial and Spatio-temporal Epidemiology* 17: 75–83.

Nicholson, S. E., Klotter, D., and Chavula, G. (2014) A detailed rainfall climatology for Malawi, Southern Africa. *International Journal of Climatology* 34(2): 315–325.

Nicholson, S.E. and Selato, J.C. (2000) The influence of La Nina on African rainfall. *International Journal of Climatology: A Journal of the Royal Meteorological*

*Society*, *20*(14):1761-1776.

Nicholson, S.E. and Entekhabi, D. (1987) Rainfall variability in equatorial and southern Africa: Relationships with sea surface temperatures along the southwestern coast of Africa. *Journal of Applied Meteorology and Climatology*, *26*(5):561-578.

Nicholson, S.E. (2000) The nature of rainfall variability over Africa on time scales of decades to millenia. *Global and planetary change*, *26*(1-3):137-158.

Nkuna, T.R. and Odiyo, J.O. (2016) The relationship between temperature and rainfall variability in the Levubu sub-catchment, South Africa. *International Journal of Education and Learning Systems*, *1*.

Ntombani, Z.N., 2019. Investigating the Influence of Present and Projected Climate on the Livelihood of Small-Scale Farmers in the Uthungulu District Municipality, Kwazulu Natal, South Africa (Master's thesis, University of Pretoria (South Africa)).

Nyoni, N. M. B., Grab, S., Archer, E., and Hetem, R. (2022) Perceived impacts of climate change on rural poultry production: a case study in Limpopo Province, South Africa. *Climate and Development* 14(4): 389–397.

O'reilly, J., Isenhour, C., Mcelwee, P., and Orlove, B. (2020) Downloaded from www.annualreviews.org Access provided by 197. *Annu. Rev. Anthropol. 2020* 49: 13–29.

Oh, C. H., and Reuveny, R. (2010) Climatic natural disasters, political risk, and international trade. *Global Environmental Change* 20(2): 243–254.

Ongoma, V., and Chen, H. (2017) Temporal and spatial variability of temperature and precipitation over East Africa from 1951 to 2010. *Meteorology and Atmospheric Physics* 129(2): 131–144.

Pascale, S., Pohl, B., Kapnick, S. B., and Zhang, H. (2019) On the Angola low interannual variability and its role in modulating ENSO effects in southern Africa. *Journal of Climate* 32(15): 4783–4803.

Pearson, K. (1896) Mathematical Contributions to the Theory of Evolution-III. Regression, Heredity, and Panmixia. *Philosophical Transactions of the Royal Society of London* 187: 254–318.

Philippon, N., Rouault, M., Richard, Y., and Favre, A. (2012) The influence of ENSO on winter rainfall in South Africa. *International Journal of Climatology* 32(15): 2333–2347.

Pohl, B., Fauchereau, N., Reason, C. J. C., and Rouault, M. (2010) Relationships between the Antarctic oscillation, the Madden-Julian oscillation, and ENSO, and consequences for rainfall analysis. *Journal of Climate*. doi:10.1175/2009JCLI2443.1.

Pohl, B., Fauchereau, N., Richard, Y., Rouault, M., and Reason, C. J. C. (2009) Interactions between synoptic, intraseasonal and interannual convective variability over Southern Africa. *Climate Dynamics* 33(7–8): 1033–1050.

Pohl, B., Janicot, S., Fontaine, B., and Marteau, R. (2009) Implication of the Madden-Julian oscillation in the 40-day variability of the West African monsoon. *Journal of Climate* 22(13): 3769–3785.

Pohl, B., Richard, Y., and Fauchereau, N. (2007) Influence of the Madden-Julian oscillation on southern African summer rainfall. *Journal of Climate* 20(16): 4227–4242.

Prakash, S. (2019) Performance assessment of CHIRPS, MSWEP, SM2RAIN-CCI, and TMPA precipitation products across India. *Journal of hydrology*, *571*:50-59.

Rahman, M. R., and Lateh, H. (2017) Climate change in Bangladesh: a spatio-temporal analysis and simulation of recent temperature and rainfall data using GIS and time series analysis model. *Theoretical and Applied Climatology* 128(1–2): 27–41.

Ramugondo, N. (2020) An investigation of the impacts of intra-seasonal rainfall variability on the maize growing season in Limpopo Province, South Africa from 1990-2014(Masters Dissertations, University of Cape Town).

Rapolaki, Ramontsheng S., Blamey, R. C., Hermes, J. C., and Reason, C. J. C. (2019) A classification of synoptic weather patterns linked to extreme rainfall over the Limpopo River Basin in southern Africa. *Climate Dynamics* 53(3–4): 2265–2279.

Rapolaki, Ramontsheng Sakia (2020) An analysis of heavy rainfall events over the Limpopo River Basin in southern Africa, their moisture sources and pathways (PhD Thesis, University of Cape Town).

Ratna, S. B., Behera, S., Ratnam, J. V., Takahashi, K., and Yamagata, T. (2013) An index for tropical temperate troughs over southern Africa. *Climate Dynamics* 41(2): 421–441.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., and Kaplan, A. (2003) Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres* 108(14).

Reason, C. J.C. (2019) Low-frequency variability in the Botswana High and southern African regional climate. *Theoretical and Applied Climatology* 137(1–2): 1321–1334.

Reason, C. J.C., Hachigonta, S., and Phaladi, R. F. (2005) Interannual variability in rainy season characteristics over the Limpopo region of southern Africa. *International Journal of Climatology* 25(14): 1835–1853.

Reason, C. J.C., and Jagadheesha, D. (2005) A model investigation of recent ENSO impacts over southern Africa. *Meteorology and Atmospheric Physics* 89(1–4): 181–205.

Reason, C. J.C., Landman, W., and Tennant, W. (2006) Seasonal to decadal prediction of southern African climate and its links with variability of the Atlantic ocean. *Bulletin of the American Meteorological Society* 87(7): 941–955.

Reason, C. J.C., and Mulenga, H. (1999) Relationships between South African rainfall and SST anomalies in the southwest Indian Ocean. *International Journal of Climatology* 19(15): 1651–1673.

Reason, C. J.C., and Rouault, M. (2005) Links between the Antarctic Oscillation and winter rainfall over western South Africa. *Geophysical Research Letters* 32(7): 1–4.

Reason, C.J.C. (2017) Climate of Southern Africa. In *Oxford Research Encyclopedia of Climate Science*. Oxford University Press doi:10.1093/acrefore/9780190228620.013.513.

Reason, C J C, Rouault, M., Melice, J.-L., and Jagadheesha, D. (2002) *Interannual winter rainfall variability in SW South Africa and large scale ocean±atmosphere interactions*. *Meteorol. Atmos. Phys* (Vol. 80).

Reason, C.J.C. and Keibel, A., 2004. Tropical cyclone Eline and its unusual penetration and impacts over the southern African mainland. *Weather and forecasting*, *19*(5), pp.789-805.

Richard, Y., Fauchereau, N., Poccard, I., Rouault, M., and Trzaska, S. (2001) 20th century droughts in Southern Africa: Spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. *International Journal of Climatology* 21(7): 873–885.

Rivera, J. A., Marianetti, G., and Hinrichs, S. (2018) Validation of CHIRPS precipitation dataset along the Central Andes of Argentina. *Atmospheric Research* 213: 437–449.

Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., and Qiang, Z. (2010) Managing water in rainfed agriculture-The need for a paradigm shift. *Agricultural Water Management* 97(4): 543–550.

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.

Roffe, S.J., Fitchett, J. M., and Curtis, C. J. (2021) Investigating changes in rainfall seasonality across South Africa: 1987–2016. *International Journal of Climatology* 41(S1): E2031–E2050.

Rouault, M., and Richard, Y. (2005) Intensity and spatial extent of droughts in southern Africa. *Geophysical Research Letters* 32(15).

Salby, M.L. and Hendon, H.H. (1994) Intraseasonal behavior of clouds, temperature, and motion in the tropics. *Journal of the Atmospheric Sciences*, *51*(15):2207-2224.

Samuels, M. I., Masubelele, M. L., Cupido, C. F., Swarts, M. B. V., Foster, J., De Wet, G., Links, A., Van Orsdol, K., and Lynes, L. S. (2022) Climate vulnerability and risks to an indigenous community in the arid zone of South Africa. *Journal of Arid Environments* 199(December 2021): 104718.

Shabalala, Z. P., Moeletsi, M. E., Tongwane, M. I., and Mazibuko, S. M. (2019) Evaluation of infilling methods for time series of daily temperature data: Case study of Limpopo Province, South Africa. *Climate* 7(7).

Shikwambana, S., Malaza, N. and Shale, K., 2021. Impacts of rainfall and temperature changes on smallholder agriculture in the Limpopo Province, South Africa. *Water*, *13*(20), p.2872.

Shmeleva, E. (2020) The influence of climate change on the spread of human salmonellosis (Mini-review). *Acta Agraria Kaposváriensis* 24(2): 89–107.

Singleton, A. T., and Reason, C. J. C. (2007) A numerical model study of an intense cutoff low pressure system over South Africa. *Monthly Weather Review* 135(3): 1128–1150.

Singo, M. V., Chikoore, H., Engelbrecht, F. A., Ndarana, T., Muofhe, T. P., Mbokodo, I. L., Murungweni, F. M., and Bopape, M. J. M. (2023) Projections of future fire risk under climate change over the South African savanna. *Stochastic Environmental Research and Risk Assessment* 37(7): 2677–2691.

Statistics South Africa (2021) Mid-Year population estimates 2021. *Statistical Release* P0302(July): 35.

Tabachnick, W. J. (2010) Challenges in predicting climate and environmental effects on vector-borne disease episystems in a changing world. *Journal of Experimental Biology* 213(6): 946–954.

Tadross, M.A., Hewitson, B.C. and Usman, M.T. (2005) The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. *Journal of climate*, *18*(16):3356-3372.

Tadross, M., Suarez, P., Lotsch, A., Hachigonta, S., Mdoka, M., Unganai, L., Lucio, F., Kamdonyo, D., and Muchinda, M. (2009) Growing-season rainfall and scenarios of future change in southeast Africa: Implications for cultivating maize. *Climate Research* 40(2–3): 147–161.

Taljaard, J.J., 1986. Change of rainfall distribution and circulation patterns over southern Africa in summer. *Journal of Climatology*, *6*(6):579-592.

Taye, M. T., Dyer, E., Hirpa, F. A., and Charles, K. (2018) Climate change impact on water resources in the Awash basin, Ethiopia. *Water (Switzerland)* 10(11).
Tennant, W. J., and Hewitson, B. C. (2002) Intra-seasonal rainfall characteristics and their importance to the seasonal prediction problem. *International Journal of Climatology* 22(9): 1033–1048.

Thoithi, W., Blamey, R. C., and Reason, C. J. C. (2021) Dry Spells, Wet Days, and Their Trends Across Southern Africa During the Summer Rainy Season. *Geophysical Research Letters* 48(5): 1–10.

Thomas, T. S., Schlosser, C. A., Strzepek, K., Robertson, R. D., and Arndt, C. (2022) Using a Large Climate Ensemble to Assess the Frequency and Intensity of Future Extreme Climate Events in Southern Africa. *Frontiers in Climate* 4(May): 1–16.

Toté, C., Patricio, D., Boogaard, H., van der Wijngaart, R., Tarnavsky, E., and Funk, C. (2015) Evaluation of satellite rainfall estimates for drought and flood monitoring in Mozambique. *Remote Sensing* 7(2): 1758–1776.

Trambauer, P., Werner, M., Winsemius, H. C., Maskey, S., Dutra, E., and Uhlenbrook, S. (2015) Hydrological drought forecasting and skill assessment for the Limpopo River basin, southern Africa. *Hydrology and Earth System Sciences* 19(4): 1695–1711.

Trenberth, K. E. (2011) Changes in precipitation with climate change. *Climate Research* 47(1–2): 123–138.

Trenberth, K. E., and Hoar, T. J. (1997) El Niño and climate change. *Geophysical Research Letters* 24(23): 3057–3060.

Tyson, P.D. (1984) The atmospheric modulation of extended wet and dry spells over South Africa, 1958–1978. *Journal of climatology*, *4*(6):621-635.

UNFCCC (2015) The Paris Observatory. *Nature* 127(3207): 600–601.

Unganai, L. S., and Mason, S. J. (2002) Long-range predictability of Zimbabwe summer rainfall. *International Journal of Climatology* 22(9): 1091–1103.

Usman, M.T. and Reason, C.J.C. (2004) Dry spell frequencies and their variability over southern Africa. *Climate research*, *26*(3):199-211.

Usman, A.A. and Mamman, M.B.A. (2022) Spatio-Temporal Analysis of Dry Spell for Agricultural Decision Support in North-Central Nigeria. *Environmental & Earth Sciences Research Journal*, *9*(1).

Utete, B., Nhiwatiwa, T., Kavhu, B., Kusangaya, S., Viriri, N., Mbauya, A. W., and Tsamba, J. (2019) Assessment of water levels and the effects of climatic factors and catchment dynamics in a shallow subtropical reservoir, Manjirenji Dam, Zimbabwe. *Journal of Water and Climate Change* 10(3): 580–590.

Valentin, C., Poesen, J. and Li, Y. (2005) Gully erosion: Impacts, factors and control. *Catena*, *63*(2-3):132-153.

Van Den Heever, S. C., D'Abreton, P. C., and Tyson, P. D. (1997) Numerical simulation of tropical-temperate troughs over southern Africa using the CSU RAMS model. *South African Journal of Science* 93(8): 359–365.

van der Bank, M., and Karsten, J. (2020) Climate Change and South Africa: A Critical Analysis of the Earthlife Africa Johannesburg and Another v Minister of Energy and Others 65662/16 (2017) Case and the Drive for Concrete Climate Practices. *Air, Soil and Water Research*. SAGE Publications Ltd.

Van Jaarsveld, A.S. and Chown, S.L., 2001. Climate change and its impacts in South Africa. *Trends in ecology & evolution*, *16*(1), pp.13-14.

van Koppen, B., Hofstetter, M., Nesamvuni, A. E., and Chiluwe, Q. (2020) Integrated management of multiple water sources for multiple uses: Rural communities in Limpopo province, South Africa. *Water SA* 46(1): 1–11.

Walker, N. J., and Schulze, R. E. (2008) Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *Agriculture, Ecosystems and Environment* 124(1–2): 114–124.

Weldon, D., and Reason, C. J. C. (2014) Variability of rainfall characteristics over the South Coast region of South Africa. *Theoretical and Applied Climatology* 115(1–2): 177–185.

Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., and Wade, A. J. (2009) A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*. IAHS Press.

Winters, P., Murgai, R., Sadoulet, E., de Janvry, A. and Frisvold, G. (1998) Economic and welfare impacts of climate change on developing countries. *Environmental and Resource Economics*, *12*:1-24.

Zambatis, N. and Biggs, H.C. (1995) Rainfall and temperatures during the 1991/92 drought in the Kruger National Park. *Koedoe*, *38*(1):1-16.

Zhao, M., Huang, S., Huang, Q., Wang, H., Leng, G., and Xie, Y. (2019) Assessing socio-economic drought evolution characteristics and their possible meteorological driving force. *Geomatics, Natural Hazards and Risk* 10(1): 1084–1101.

Zhong, R., Chen, X., Lai, C., Wang, Z., Lian, Y., Yu, H., and Wu, X. (2019) Drought monitoring utility of satellite-based precipitation products across mainland China. *Journal of Hydrology* 568: 343–359.

Zinyengere, N., Crespo, O., Hachigonta, S., and Tadross, M. (2014) Local impacts of climate change and agronomic practices on dry land crops in Southern Africa. *Agriculture, Ecosystems and Environment* 197: 1–10.

Zwiers, F. W., Alexander, L. V., Hegerl, G. 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 *Climate Science for Serving Society*. Springer Netherlands doi:10.1007/978-94-007-6692-1_13.

# 6 Appendix

Commented [LTD1]: The Appendix comes after references. It is the last thing on a scientific document.

## 6.1 Climatology of seasonal rainfall totals

Seasonal rainfall over the Limpopo province shows high variability in space and time (**Figure A1).** During ON, the south of Greater Sekhukhune and south-east Mopani record the highest rainfall greater than 200 mm. The high-lying escarpment in Vhembe and Waterberg district records rainfall ranging from 100-150 mm, whereas the lowest rainfall was observed over the north of Capricorn and Vhembe and east of Mopani ranging from 50-100 mm. During DJ, the entirety of the region records an increased spatial extend of rainfall. The high-lying escarpment of Vhembe, Mopani, and Greater Sekhukhune districts records the highest rainfall greater than 200 mm, while the north of Vhembe and Waterberg and a small portion in the north-east of Greater Sekhukhune record rainfall ranging from 100-150 mm. The FM season records the highest rainfall in the high-lying escarpment of Vhembe and Capricorn. The south and north-west records 50-100 mm whereas the eastern region records rainfall ranging from 110-150 mm. Throughout the season, negative SAI is observed over north of Vhembe and east of Mopani, whereas the high-lying escarpment of Vhembe, east of Mopani, north of Greater Sekhukhune and Waterberg district shows positive SAI (**Figure A2**).

### 6.2 Seasonal Rainfall Trends

Seasonal rainfall trends  show a variable distribution in the Limpopo province (**Figure A3**). During ON, the north of Capricorn shows statistically significant increasing rainfall trends, whereas the entirety region records statistically insignificant trends. During DJ, increasing trends are recorded in the Capricorn, Vhembe, and Waterberg, with the south region exhibiting statistically insignificant trends over Greater Sekhukhune and Mopan. During FM, no statistically significant trends were observed. Increasing trends are recorded over Greater Sekhukhune, Vhembe, and Capricorn, whereas decreasing trends are recorded over the south of Waterberg and Mopani.

### 6.3 Correlation of ENSO, SIOD, and seasonal rainfall totals

During ON, the total rainfall shows a strong negative correlation with ENSO in the south of Mopani with an r value greater than 0.5, whereas no correlation was observed between ENSO and seasonal rainfall totals in the south-west (**Figure A5**). During DJ and FM, no strong correlation was observed over the region. No strong correlations are recorded spatial correlation between rainfall and SIOD throughout all periods of all periods (**see Figure A6)**.

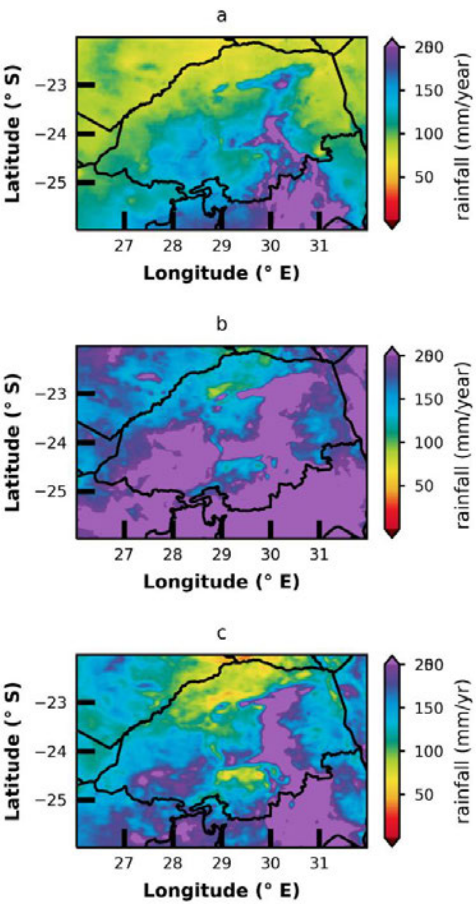


Figure A1: Distribution of annual rainfall pattern over the Limpopo province for the period 1990 to 2020

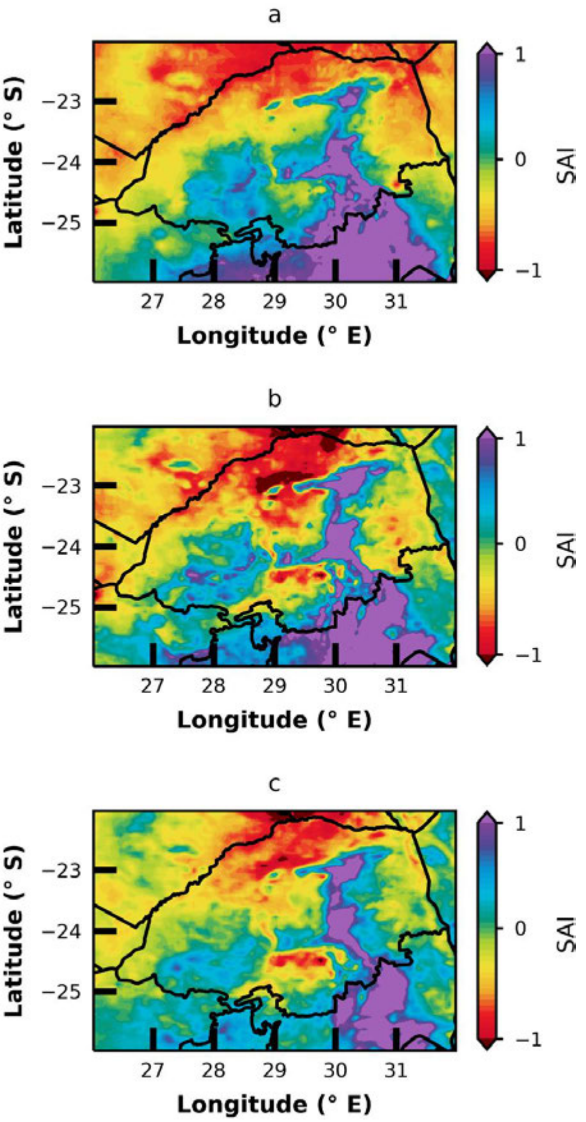


Figure A2: Standardised anomaly distribution over the Limpopo province.

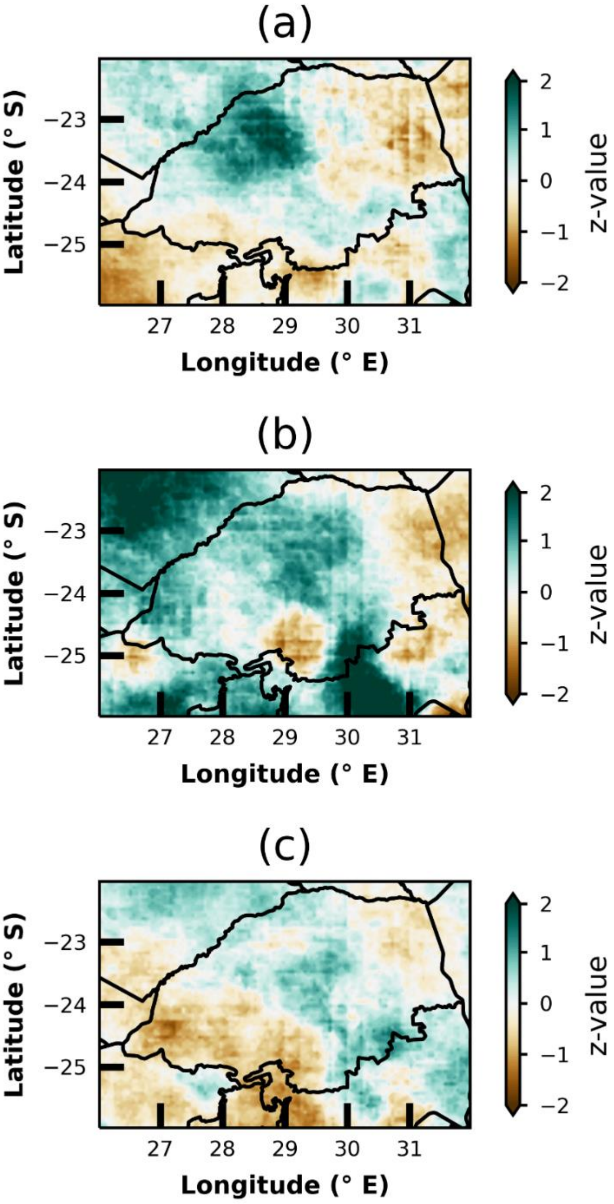


Figure A3: Changes in seasonal rainfall over time

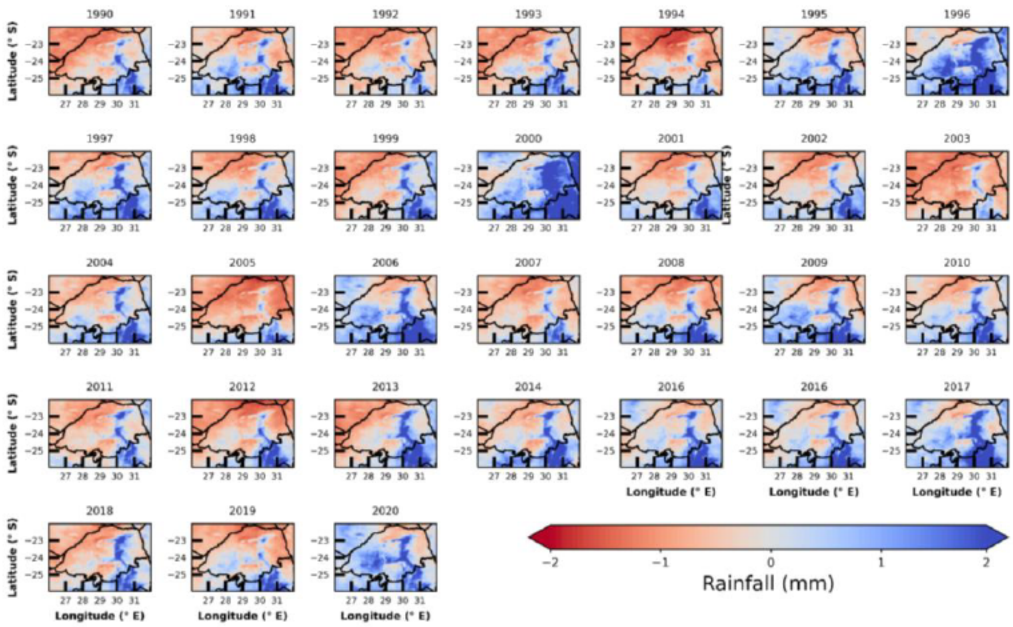


Figure A4: Spatial and temporal distribution of SAI over the Limpopo province for the period 1990 to 2020.

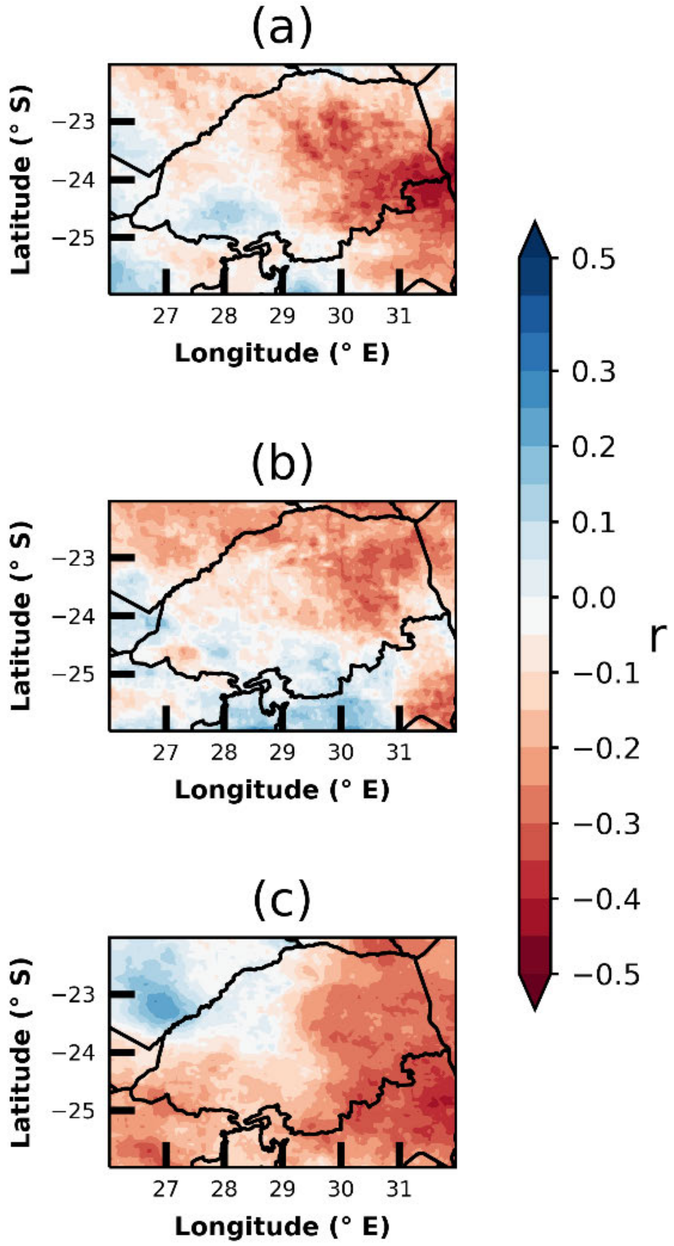


Figure A5: Correlation of ENSO and seasonal rainfall totals during (a) ON, (b) DJ and (c) FM.

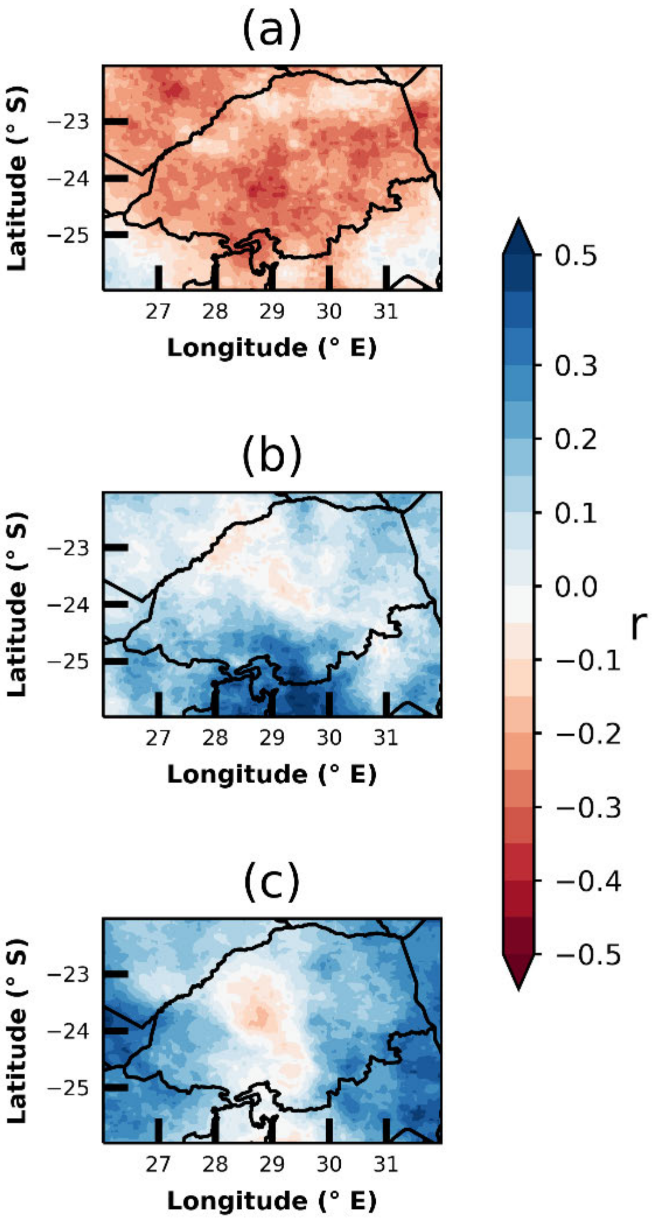


Figure A6: Correlation of SIOD and seasonal rainfall totals during (a) ON, (b) DJ and (c) FM.

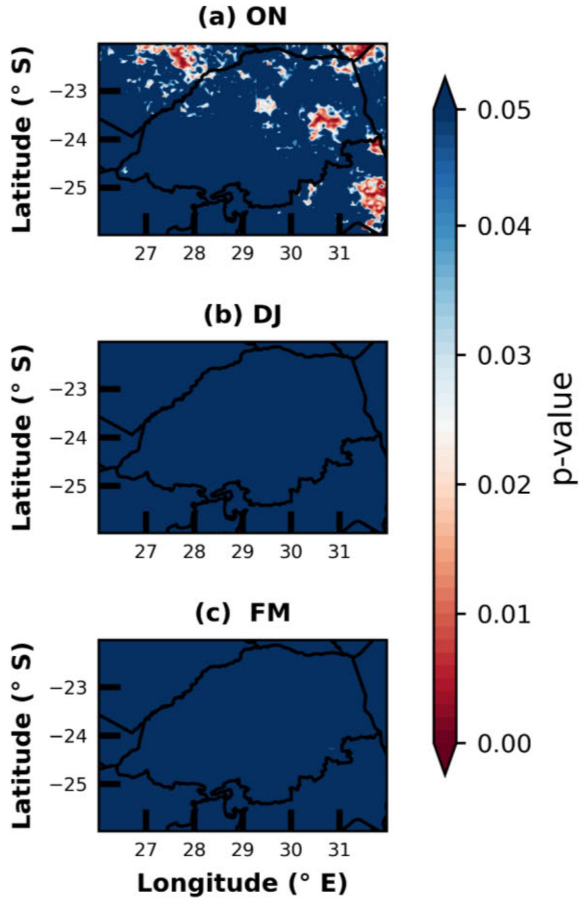


Figure A7: The statistical significance at a 95% confidence interval of the correlation between dry spells and ENSO.

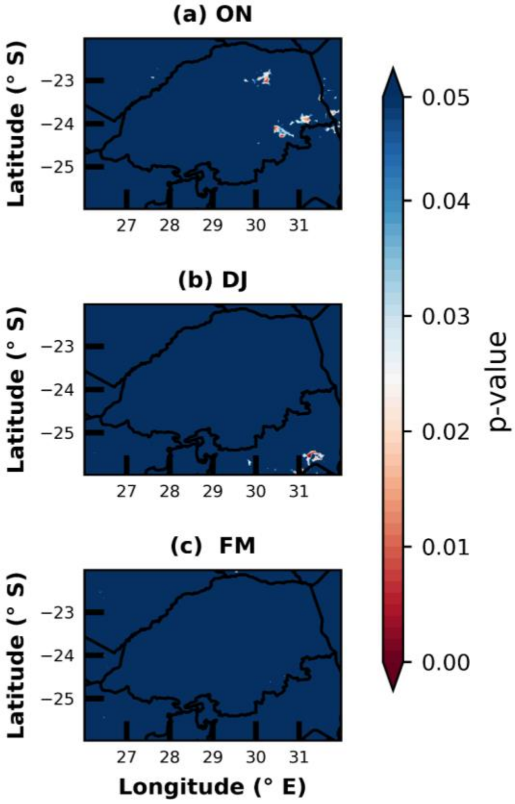


Figure A8: The statistical significance at a 95% confidence interval of the correlation between moderate wet days and ENSO.

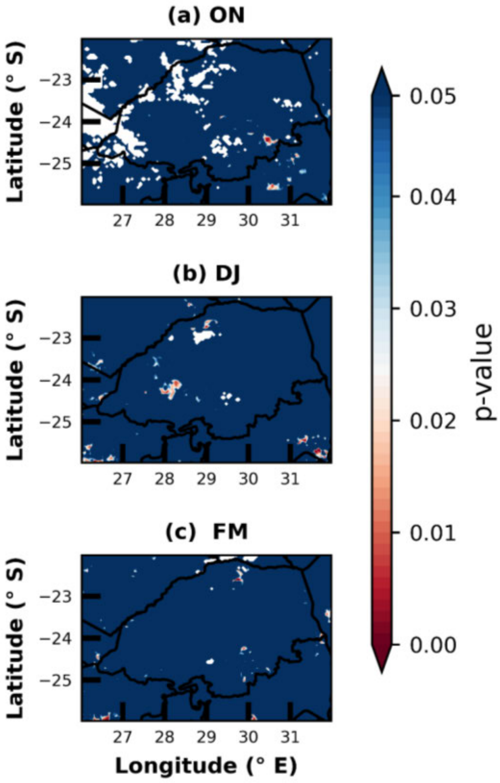


Figure A9: The statistical significance at a 95% confidence interval of the correlation between heavy wet day and ENSO.

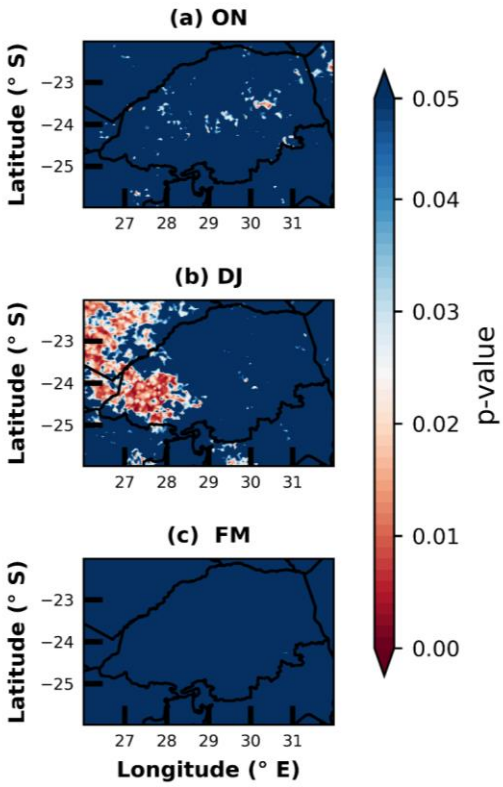


Figure A10: The statistical significance at a 95% confidence interval of the correlation between dry spells and SIOD.

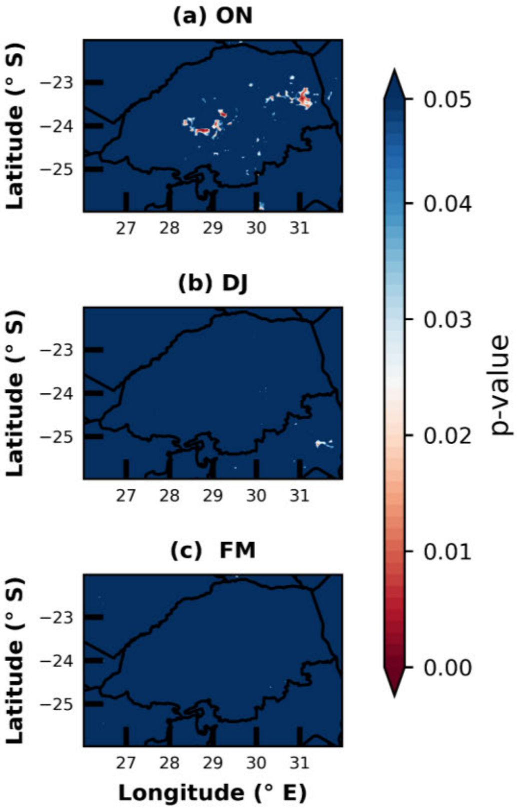


Figure A11: The statistical significance at a 95% confidence interval of the correlation between moderate wet days and SIOD.

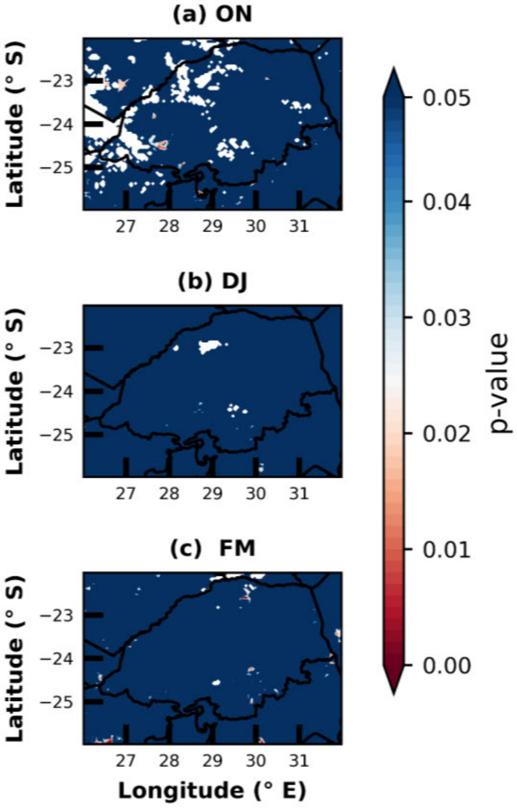


Figure A12: The statistical significance at a 95% confidence interval of the correlation between heavy wet day and SIOD.