

Exploring variability of drought events for the western region of South Africa

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PREFACE

Drought is a naturally occurring phenomenon and is viewed as a climatic extreme because it can lead to severe socio-economic consequences. Its impacts include but are not limited to, increased water scarcity, wildfire risk, decrease in agricultural productivity, increased food prices, and increased health impacts. Provinces located in South Africa, namely the Western Cape, Northern Cape, Free State, North West, and Eastern Cape were declared disaster regions in 2015 - 2019 and endured socio-economic impacts because of prolonged drought. Drought on the district level in the western region of South Africa has not yet been examined in other studies. In this study, the western region refers to the entire region of South Africa, west to the Kalahari Dryline. The aim of this study was to investigate changes in drought variability from the past and future and link the past results to changes in vegetation in the Western region of South Africa. This aim was achieved by completing the following objectives:

- 1.)** Explore the changes in the frequency, intensity, and duration of drought events in the western region of South Africa.
- 2.)** Investigate the extent to which drought events impacted vegetation density in the provinces within the study area of South Africa.
- 3.)** Examine the characteristics of future drought events in the western region of South Africa and compare them to historical events.

An extensive literature review was conducted in this study which covered topics in relation to drought in South and southern Africa. Several categories of drought were first examined, and natural and anthropogenic climate change was discussed as background information in relation to drought. Rainfall, a distinctive variable relating to drought, was also extensively covered. This includes rainfall variability, history of past droughts, trends, and circulation patterns in South/southern Africa. Drought variability and drought cycles were then examined, leading up to factors causing drought. The literature review ends with the economic, environmental, and social impacts of drought. Overall, the literature review provides insightful information in relation to drought in South Africa. It emphasises the consequences of drought and how drought conditions could potentially worsen over time, which justifies the importance of this study.

In conducting the objectives of the research, multiple data sources were utilised. Firstly, rainfall and near-surface temperature (hereafter “temperature”) data were collected from sources such as the South African Weather Service (SAWS), the Global Surface Summary of the Day (GSOD), the Normalised Difference Vegetation Index (NDVI), the Coupled Model Intercomparison Project (CMIP), and the ECMWF Reanalysis v5 gridded data. The data was processed using the Standardised Precipitation Evaporation Index (SPEI) in order to analyse

drought from the past (1962-2022) and for the future (2050-2100) of the Western region. Numerical climate data was used to analyse projected future drought conditions. The SPEI was the main tool used to achieve Objectives 1 and 3. Objective 2 focused on whether the drought events, observed in Objective 1, were reflected in NDVI values and, therefore, vegetation density in the Western region. The study concludes with a summary of the findings and specifically directs the information to stakeholders of the district municipalities who should proactively be aware of the potential drought variabilities.

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I declare that this dissertation was completed entirely on my own, except where referenced or acknowledged otherwise.



Signature

ABSTRACT

The occurrence of drought in South Africa is inevitable, as it is a naturally occurring phenomenon. What makes this phenomenon extreme is its creeping nature, which could unravel into prolonged, socio-economic drought. Socio-economic drought imposes the greatest threat to agriculture and the economy. Examples of this type of drought recently (at the time of this study) occurred in the Northern Cape, Western Cape, North West, Free State, and Eastern Cape provinces. Most of these provinces were declared disaster regions because of prolonged drought and/or underwent socio-economic impacts. Parts of these provinces are located in the western region of South Africa, which is the area of interest in this study due to its dry nature. The standardised precipitation evapotranspiration index (SPEI) was used to analyse the potential changes in the drought frequency, duration, and intensity of district municipalities. Those findings were linked to potential changes in vegetation, by examining the normalized difference vegetation index (NDVI) trends. The SPEI was then used to examine future drought events from 2050-2100 using Coupled Model Intercomparison Project (CMIP6) data, which was compared to the data from 1962-2022. The 1962-2022 findings showed that the frequency, duration, and intensity of drought had worsened in all district municipalities in the second half of the study period. During the extensive drought period of 2012-2022, a decrease in the NDVI values is present. Yet, the NDVI trends showed an overall increase in all five provinces, meaning that the worsened drought conditions, observed in the SPEI, did not reflect on the NDVI to the same degree. Only 4/17 district municipalities are predicted to have worsened drought conditions in 2050-2100 in comparison to the 1962-2022 results. Overall, this study provides insight into the intensities, frequencies, and duration of past and future drought events in the district municipalities. This information can enable stakeholders, policymakers, mayors, etc. of the district municipalities to proactively prepare for worsening drought conditions.

Keywords: *Drought, Climate, SPEI, NDVI, CMIP6, Western region*

LIST OF ACRONYMS

AO	Antarctic Oscillation
ARS	Automatic Rainfall Stations
AVHRR	Advanced Very High-Resolution Radiometer
AWS	Automatic Weather Stations
CCD	Cold Cloud Duration
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CHPclim	Climate Hazards Group Precipitation Climatology
CMIP	Coupled Model Intercomparison Project
CoL	Cut-off Low
C3S	Copernicus Climate Change Service
DJF	December, January, February
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation
ERA5	ECMWF Reanalysis v5
FAO	Food and Agricultural Organisation
GCM	Global Climate Modelling
GHG	Greenhouse Gas
GSOD	Global Surface Summary of the Day
GWL	Global Warming Level
IFS	Integrated Forecasting System
IOD	Indian Ocean Dipole

IPCC	Intergovernmental Panel on Climate Change
KD	Kalahari Discontinuity/Dryline
LST	Land surface temperature
MK	Mann-Kendall
MODIS	Moderate Resolution Imaging Spectroradiometer
OLR	Outgoing Longwave Radiation
NDVI	Normalised Difference Vegetation Index
NIR	Near-infrared
NOAA	National Oceanic and Atmospheric Administration
PDSI	Palmer Drought Severity Index
PET	Potential Evapotranspiration
QBO	Quasi-biennial Oscillation
RCP	Representative Concentration Pathway
SADC	Southern African Development Community
SAWS	South African Weather Service
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SSP	Shared Socioeconomic Pathway
SST	Sea Surface Temperature
TTT	Tropical Temperate Troughs
VIS	Visible
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation

4D-VAR

Four-dimensional Variational

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Background and problem statement

Two major extremes of precipitation variability include drought and flood events (Dai *et al.*, 1997). The occurrence of drought is inevitable (Jordaan *et al.*, 2013) and the consequences thereof are often accelerated through climate change. Depending on the region, if dry conditions are persistent in naturally arid areas, water scarcity becomes aggravated, enhancing the consequences and severity of drought (Mukherjee *et al.*, 2018). One of the infamous characteristics of drought is its creeping nature (Botai *et al.*, 2017). Implying that it commences without significant impact, yet it slowly progresses with time, eventually leading to serious socio-economic consequences (Botai *et al.*, 2017; Malherbe *et al.*, 2016). The impacts of a drought become more problematic if it persists for periods longer than 12 months (Malherbe *et al.*, 2016).

Dai (2011) highlights that drought conditions and aridity have increased globally since the 1970s. Regions such as Africa, southern Europe, eastern Australia, and southern and eastern Asia serve as examples. The El Niño-Southern Oscillation (ENSO) phenomenon and Sea Surface Temperatures (SSTs) form part of the reasons contributing to drought events globally. However, anthropogenic influences, such as increasing greenhouse gases (GHGs), have contributed to the warming, especially in the Indian Ocean. In turn, the atmospheric moisture demand increases with the enhanced warming, which plausibly alters atmospheric circulation patterns (Dai, 2011). Drought is arguably one of, if not *the* worst natural hazards because of the potentially severe economic and environmental disruption it is able to inflict on society (Dai, 2011; Tyson & Preston-Whyte, 2000; Wilhite, 2000).

Observations from the Intergovernmental Panel on Climate Change (IPCC) have found that mean annual temperatures have increased over southern Africa ranging between 1.04°C-1.44°C from 1961-2015 (IPCC, 2022). Temperature observations in southern Africa have showed that in the last four decades (1980-2020) hot days have increased, while heat stress is increasingly impacting agriculture. Previous observations from the IPCC in 2014 have found that a large fraction of increased warming is accounted for from 1990 onwards (Collins, 2011; IPCC, 2014). Projections show that mean annual temperatures in southern Africa will be 1.2°C, 2.3°C, and 3.3°C warmer in comparison to averages from 1994-2005 at global warming levels (GWLs) of 1.5°C, 2°C, and 3°C (above pre-industrial levels) respectively. As a result of increasing temperatures, heat waves are also projected to increase in numbers under increasing GWLs (Engelbrecht, *et al.*, 2015b; IPCC, 2022). Projections from one of the previous IPCC reports

found that in the 21st century, African temperatures will increase at a greater pace than the global average. These temperatures surpass the effect of natural climate variability (IPCC, 2014; Moise & Hudson, 2008), highlighting the possible anthropogenic influences.

IPCC observations found, with high confidence, that the winter rainfall region of South Africa (which forms part of the western region) has endured decreasing precipitation trends since the 1960s (IPCC, 2022). As a result, agricultural drought and the frequency of dry spells have increased from 1961-2016 (Yuan *et al.*, 2018). In the southwestern Cape, the probability of a multi-year drought occurring has increased by three times as a result of anthropogenic climate change (IPCC, 2022; Otto *et al.*, 2018). This coincides with past IPCC reports which found that downward trends in rainfall were detected for western parts of South Africa (IPCC, 2014). Projections in precipitation, under the Representative Concentration Pathway (RCP), have estimated that mean annual rainfall, in the summer rainfall region of southern Africa, will decrease by 10-20%, with increasing consecutive dry days (RCP8.5). Furthermore, there is high confidence that under RCP8.5, the western parts of southern Africa are projected to become drier because of factors such as increasing frequency, intensity, and duration of drought (Engelbrecht, *et al.*, 2015b; IPCC, 2022).

It is overall projected that dryness will increase in the summer rainfall region of southern Africa, which will strengthen evaporation. The increasing dryness will lead to increasing drought frequencies and duration, which will increase the duration of meteorological drought from lasting for 2 months to 4 months from the mid-21st century (under RCP8.5) (IPCC, 2022). Past IPCC reports found that southern Africa will experience an increase in extreme hot days, nights, and hottest days, while a decrease in extreme cold days and nights is estimated (IPCC, 2014; Kruger & Sekele, 2013). The findings are specifically significant to the western half of the country which places emphasis on the importance of the study area being investigated.

The aforementioned information placed an emphasis on the reduction in rainfall in western South Africa and increasing temperatures in southern Africa. Thus, the occurrence of increased, intensified droughts in southern Africa become a greater possibility. Consequences of drought are usually associated with socio-economic impacts. These include increased water scarcity, increased wildfire risk, damage to agriculture (loss of crops and livestock), increased food prices, and the risk of impacts on health (to name a few) (Mukherjee *et al.*, 2018). Moreover, with water scarcity increasing, especially available surface water, considerable strain is put on groundwater resources during times of drought. The use of groundwater resources is increasing through greater use of wells and boreholes which raises the pressure of available water resources for future generations (Archer *et al.*, 2018; Calow *et al.*, 1997; Mukheibir, 2007).

Significant droughts with impacts taking place in southern Africa alone and/or globally occurred in 1991-1992, 1993, 1995, 1997-1998, 2002-2003, 2009-2010, 2015-2016 (Lakhraj-Govender & Grab, 2018; Rouault & Richard, 2003). In South Africa, droughts have impacts on different regions. In the Northern Cape province, 20 million hectares of farmland were impacted by prolonged drought up until 2019 (Agri-SA, 2019). As a consequence, the Northern Cape economy and the livelihoods of farmers, particularly smallholder farmers, were negatively impacted (Maltou & Bahta, 2019). It is projected that by the end of the century, the Kalahari region (within the Northern Cape) will be subject to rising temperatures and decreased annual rainfall (Archer *et al.*, 2018). Between 2014-2017 the Western Cape province experienced what is declared its worst drought since 1904, labelling it a 'disaster region'. In addition, the Western Cape endured its worst water shortage in over a century because of the drought and dry conditions influencing the water resources (Botai *et al.*, 2017). Just like the Western Cape, both the Free State- and North West provinces were also declared disaster regions in 2016 due to drought (Botai *et al.*, 2016). Since both provinces greatly contribute to South Africa's agricultural production, the country's economy was negatively impacted (Botai *et al.*, 2016). In the Eastern Cape province, severe drought conditions have occurred since 2015. This affected the vulnerable rural populations within the province due to the consequential socio-economic effects (Mahlalela *et al.*, 2020).

Increasing warm temperatures and changes in rainfall patterns over South Africa (IPCC, 2014, 2022) (Figure 1); as well as the recent disaster status declarations (Botai *et al.*, 2016, 2017), have made it necessary to investigate drought conditions further. Drought can further have an effect on vegetation and agriculture (loss of crops and livestock) (Mukherjee *et al.*, 2018) which also makes it necessary to investigate the effect thereof. Drought studies have been conducted in the provinces in South Africa as well as for South and southern Africa as a whole (Malherbe *et al.*, 2016; Wainwright *et al.*, 2021). However, no study (to the best of the authors' knowledge) has investigated western South Africa as a whole. This study intends to fill that research gap. The study area for this research covers the region that falls west of the 'Kalahari discontinuity' (KD) as discussed in later Chapters.

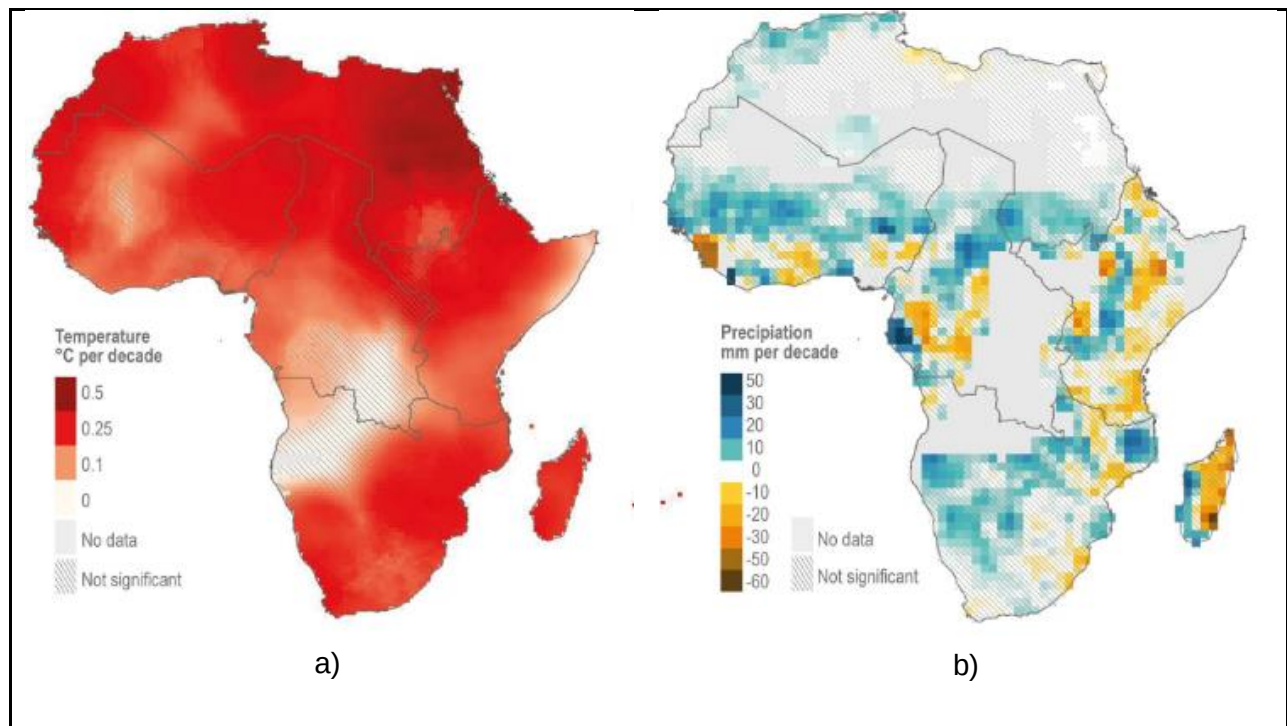


Figure 1: The 1980-2015 (a) mean average temperature (°C per decade) and (b) mean average precipitation in (mm per decade) (IPCC, 2022).

1.2 Aim and objectives

1.2.1 Aim

To investigate past and future changes in drought variability over the western region of South Africa and link past results to changes in vegetation.

1.2.2 Research questions

- 1.) How did the frequency, intensity, and duration of drought events change over the western region of South Africa?
- 2.) To what extent did drought events impact vegetation density in the provinces within the study area of South Africa?
- 3.) Are future drought events projected to worsen when compared to drought events from the past in the western region of South Africa?

1.2.3 Objectives

To accomplish the aim of the study, the following set of objectives have been considered:

- 1.)** Explore the changes in the frequency, intensity, and duration of drought events in the western region of South Africa.

To accomplish objective one, the Standardised Precipitation Evapotranspiration Index (SPEI) was used. The SPEI assisted in determining a possible change in the frequency, intensity, and spatial distribution of drought events from the years 1962 to 2022.

2.) Investigate the extent to which drought events impacted vegetation density in the provinces within the study area of South Africa.

To accomplish objective two, the Normalised Difference Vegetation Index (NDVI) anomaly values were used to examine the impact of drought events on vegetation density from 1984-2021. The NDVI data is also used to compare to the SPEI results, from the previous objective, over the given period.

3.) Examine the characteristics of future drought events in the western region of South Africa and compare them to historical events.

Future drought events in the western region were analysed using CMIP6 data. The data was used to produce SPEI graphs to interpret severe to extreme drought events of the study area. A comparison was made between 1962-2022 and 2050-2100.

1.3 Dissertation structure

This dissertation has a total of 7 Chapters.

Chapter 1 consisted of the introduction and background of the study. This included a discussion of previous drought events that have occurred in South Africa, as well as future projections of warming trends that the country might endure. The research gap, aim, objectives, and research questions were identified.

Chapter 2 entails a detailed literature review. Firstly, the types of droughts were discussed; natural and anthropogenic climate change and/or variability were distinguished and examined; rainfall trends and circulation patterns that prevail in South Africa were reviewed; South African drought trends and variability were discussed; The chapter ends with discussing factors that cause drought, and the impacts of drought.

Chapter 3 provides the data and methodologies used in this study. The temperature and rainfall data are derived from the South African Weather Service (SAWS), Global Surface Summary of the Day (GSOD), and ECMWF Reanalysis v5 (ERA5). NDVI data is also used to analyse the vegetation density trends. The future rainfall and temperature data is derived from the CMIP6. The statistical processes used in this study include the SPEI and the Mann-Kendall trend analysis.

Chapter 4 provides the results of the SPEI from 1962-2022. Depending on the availability of SAWS, ERA5, and GSOD data of the district municipalities, the data was split into two sets. They were termed dataset 1 (SAWS and GSOD) and dataset 2 (SAWS, GSOD, and ERA5). The 1962-2022 period was split into two halves, termed period 1 (1962-1991) and period 2 (1992-2022). The frequency, duration, and intensity of drought of the two periods were compared.

Chapter 5 provides the results of NDVI from 1984-2021. The trends of the NDVI from the five provinces within the western region were examined. This includes the Western-, Northern-, and Eastern Cape, the North West and Free State. Connections between the drought periods that were identified in Chapter 4 were compared to the NDVI trends in Chapter 5 to examine whether an effect in vegetation density is present.

Chapter 6 shows the future SPEI of the district municipalities from 2050-2100 under the SSP2-4.5 scenario. The results were compared to the results from 1962-2022 to examine whether drought conditions will worsen.

Chapter 7 provides a detailed summary of the results from Chapters 5-7 in relation to the objectives. The dissertation ends with a detailed conclusion of the findings and shows that the aim and objectives were achieved.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The following literature review consists of defining the drought phenomenon, examining the climatology of rainfall in South Africa, and discussing the circulation patterns of the country. This includes examining the changing rainfall and drought trends. This chapter will end with factors causing drought and the impacts thereof.

2.2 Defining drought

No universal definition of drought exists (Lloyd-Hughes, 2014; Wilhite, 1993, 2000; Wilhite & Glantz, 1985; Wilhite *et al.*, 2007). The lack of a universally acceptable definition stems from drought's uniqueness as a natural hazard. This is because the impact of drought varies over different spatial and temporal scales, where it ideally should be applied to the characteristics of the region of interest (Wilhite *et al.*, 2007). Drought is frequently outlined as a natural hazard that 'creeps' on society since it is complex to determine the onset and end of a drought event. Its impacts also occur slowly over time (Wilhite, 2000).

Dai, (2011) highlights that drought is often viewed as a recurring event that can last from months to years. It is characterised as a period that temporarily consists of dry conditions yet should not be mistaken with already arid-prone conditions in permanent arid areas. It should also be noted that drought occurs globally and is even present in wet, humid areas. This is because drought presents itself as a dry spell that deviates from the local meteorological norm, in possibly any given region. In contrast to wet and humid areas, arid regions are more susceptible to drought since the limited amount of rainfall usually received is dependent on only a few rainfall events (Dai, 2011). Meaning, that if these critical rainfall events do not occur, arid areas are more likely to suffer greater from droughts.

Drought can also be the evidential shortage of precipitation over a specified period. Moreover, it is also expressed as the occurrence of a water deficit in comparison to 'normal conditions' (Van Loon, 2015; Mishra & Singh, 2010; Rouault & Richard, 2003; Wilhite & Glantz, 1985). The common ground in various definitions is the lack of precipitation (Wilhite & Glantz, 1985). Evaporation and transpiration (Lloyd-Hughes, 2014) are factors that also play a role in drought events. In this study, rainfall, as well as temperature data, will be considered when analysing drought.

Time scale, intensity, and extent are prominent factors that influence the impact of drought (Malherbe *et al.*, 2016). In the context of this study, the definition of drought is narrowed down

by firstly examining the types of droughts. This includes the meteorological-, agricultural-, hydrological- and socio-economic disciplines of drought (Van Loon, 2015; Sheffield & Wood, 2012; Wang *et al.*, 2016) and are discussed hereafter.

2.2.1 Meteorological drought

Meteorological drought is most commonly evident when there is a deficiency in precipitation, combined with increased evapotranspiration (Van Loon, 2015). The deficiency is apparent when there is a negative variance from the long-term-annual average rainfall (Sheffield & Wood, 2012). Although a meteorological drought is recurrent, it is normally only temporary in nature (Smakhtin & Hughes, 2007). This type of drought is often regionally based, meaning that a meteorological drought is said to occur under different circumstances for each region (Wilhite & Glantz, 1985).

Libya can serve as an example of a region that has a specific meteorological drought definition; namely, when less than 180mm of annual precipitation falls, a meteorological drought is occurring (Wilhite & Glantz, 1985). On the other hand, a meteorological drought in the United States is defined as a region that is experiencing less than 2.5mm of rainfall over 48 hours (Wilhite & Glantz, 1985). From these two examples, it is seen that a meteorological drought is different for regions across the world. A broad definition of drought in South Africa is when less than 70% of the anticipated seasonal long-term average rainfall has occurred (Boken *et al.*, 2005; Bruwer, 1993). Since this definition takes seasonality into account, reinforcing that it is temporary, it can be labelled as a meteorological drought. This definition is also similar to the previous regional-specific examples provided (Wilhite & Glantz, 1985).

2.2.2 Agricultural drought

Once the effects of a meteorological drought persist, an agricultural drought eventually occurs. This is when the drought starts to affect crop yield, caused by the reduction of soil moisture. Crop yield usually declines by 5% during an agricultural drought (Boken *et al.*, 2005). Dryland farming is mostly affected by agricultural drought types due to its reliance on rain (Edossa *et al.*, 2014). Southern Africa (and Africa as a whole) is greatly affected by agricultural drought, especially rural areas that depend on rain (Reason *et al.*, 2006). A worsened state of meteorological drought (below-average precipitation) results in an agricultural drought which causes decreasing soil moisture resulting in inadequate maintenance of average crop yields (Botai *et al.*, 2017).

2.2.3 Hydrological drought

Extended meteorological drought features can lead to a hydrological drought as the hydrological cycle becomes affected (Boken *et al.*, 2005). Thus, the different drought types are connected and derives from a meteorological drought (Boken *et al.*, 2005; Huang *et al.*, 2017). A hydrological drought occurs after the impacts of an agricultural drought and groundwater sources become depleted. A hydrological drought reinforces the last biophysical effects of a drought event. The timespan of a hydrological drought occurring (when groundwater is impacted), could occur from months to years (Tallaksen & van Lanen, 2004).

Hydrological drought events also inflict a deficiency on other forms of water on land and not just groundwater, including streamflow, lakes, and reservoirs. A hydrological drought affecting the streamflow of an area is considered an important variable to look at due to the effect imposed on the water availability (Nalbantis & Tsakiris, 2009).

2.2.4 Socio-economic drought

As an effect of the meteorological-, agricultural-, and hydrological drought types, the socio-economic drought is seen as the resulting consequence because of the effects of the drought inflicted on populations (Ziolkowska, 2016). A socio-economic drought implies that unfavourable social and economic consequences are imposed on society (Sheffield & Wood, 2012). There is thus an imbalance between the demand (from agriculture) and supply (from precipitation) (Wilhite & Glantz, 1985). Table 1 provides a summary of the characteristics of the categories of drought.

Table 1: Table summarising the categories of drought.

Meteorological drought	Agricultural drought	Hydrological drought	Socio-economic drought
• Deficiency in precipitation (negative variance from long-term annual rainfall) (Van Loon, 2015). • Temporary in nature (Smakhtin & Hughes, 2007). • Regionally based (Wilhite & Glantz, 1985).	• Persistent effects from meteorological drought (Wilhite & Glantz, 1985). • The reduction of soil moisture which affects crop yield (Botai <i>et al.</i>, 2017). • Affects rain-fed agriculture (Edossa <i>et al.</i>, 2014).	• Extended effects of a meteorological and agricultural drought (Boken <i>et al.</i>, 2005). • Months to years (Tallaksen & van Lanen, 2004). • Groundwater storage and availability (and other forms of water) become affected (Tallaksen & van Lanen, 2004).	• Combined effects from meteorological, agricultural, and hydrological drought (Ziolkowska, 2016). • Unfavourable social and economic consequences affect society (Sheffield & Wood, 2012). • The imbalance between demand (agriculture) and supply (precipitation) (Wilhite & Glantz, 1985).

2.3 Natural climate variability and spatial-temporal scales

Climatic variables naturally vary and undergo change at different time scales (Figure 2) (Muller & Yates, 2006). The natural changing of climate modes and variables are independent of human-induced factors. Factors within the climate system drive natural variability. These factors include oceanic components, solar activity, and volcanic eruptions (Verner *et al.*, 2018). Moreover, the natural variability of the Earth's climate system is also influenced by positive and negative feedbacks, instabilities, interactions between clouds and radiation, and the rotation of the Earth and gravity (Ghil & Lucarini, 2020). Drought occurs as a result of natural variability of the Earth's climate system and the interactions within.

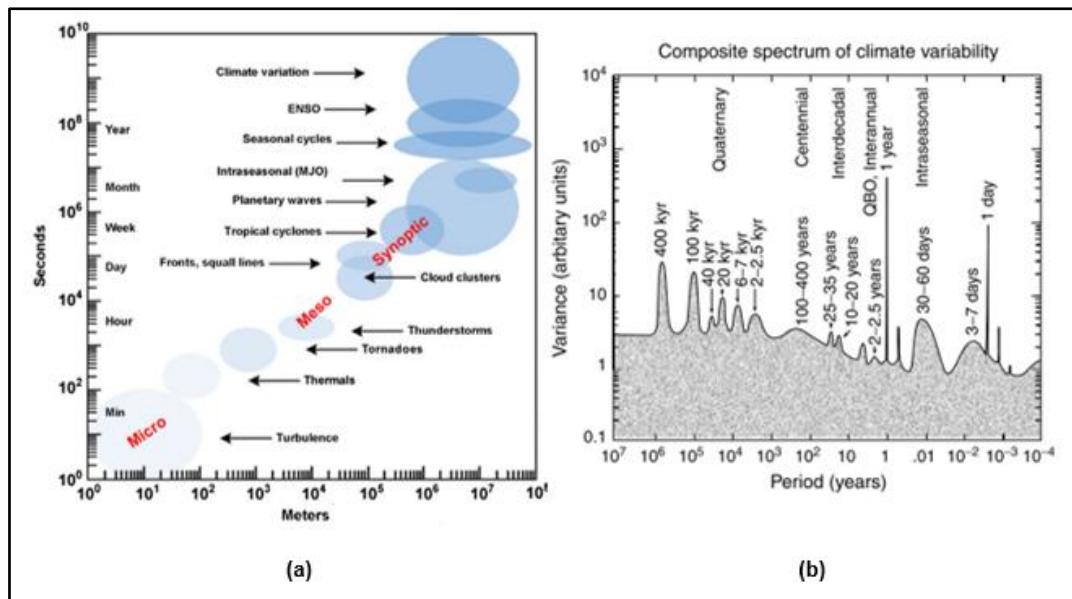


Figure 2: Natural climate variability (scales) and spatial-temporal scales (Ghil & Lucarini, 2020).

Ghil & Lucarini, (2020) highlight that different scales exist in the climate system, ranging from micro to meso, to synoptic and/or macro as shown in the Stommel diagram (Stommel, 1963) (Figure 2a). The microscale represents turbulence in the atmosphere. Larger-scale thunderstorms and greater frontal disturbances fall under the mesoscale. Tropical cyclones, larger seasonal cycles, ENSO, and climate variability are represented by the synoptic/macro scale. Ghil, (2002), describes the terms for periods of climate variability (Figure 2b). At a synoptic scale, variability ranges between one day to one year, which is also where intra-seasonal variability takes place (1-3 months). An ocean-atmosphere interaction such as the Madden-Julian oscillation takes place during that time scale. Furthermore, on an interannual and interdecadal time scale, phenomena such as ENSO and the quasi-biennial oscillation (QBO) occur (Ghil, 2002).

It is important to understand natural variability of the climate and the time scales at which these phenomena occur. The factors influencing drought usually occur within the larger synoptic scales where climate variability occurs over longer periods. Anthropogenic factors also influence the climate system.

2.4 Anthropogenic climate change

Anthropogenic climate change is caused by human activity which creates greenhouse gases (GHG) and aerosols (IPCC, 2007). The main GHGs associated with climate change include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), among others. Due to increasing human activities from the 20th century onwards, these gases have increased (Figure 3)

(Solomon *et al.*, 2010). Examples of these human activities include fossil fuel burning by industries, generation of electricity, emissions from motor vehicles and airplanes, and deforestation (Trenberth, 2018).

Globally, the release of emissions from GHGs cause heat to accumulate due to being trapped in the atmosphere (Trenberth, 2018). The accumulated heat alters the climate through increased temperatures (Mukherjee *et al.*, 2018; Trenberth, 2018), which cause variability in climatic extremes such as drought. Global mean annual surface temperatures have increased (compared to average temperatures in the 1900s) in relation to CO₂ concentrations (Figure 3). It is noticeable that as CO₂ concentrations start increasing from the mid-20th century (due to human activities) the average temperature also increases (Trenberth, 2018). This supports the notion that greater emissions lead to rising temperatures, which in effect leads to greater drought variability. Since the 1950s, changing temperature trends have been linked to human-induced causes/climate change (IPCC, 2022).

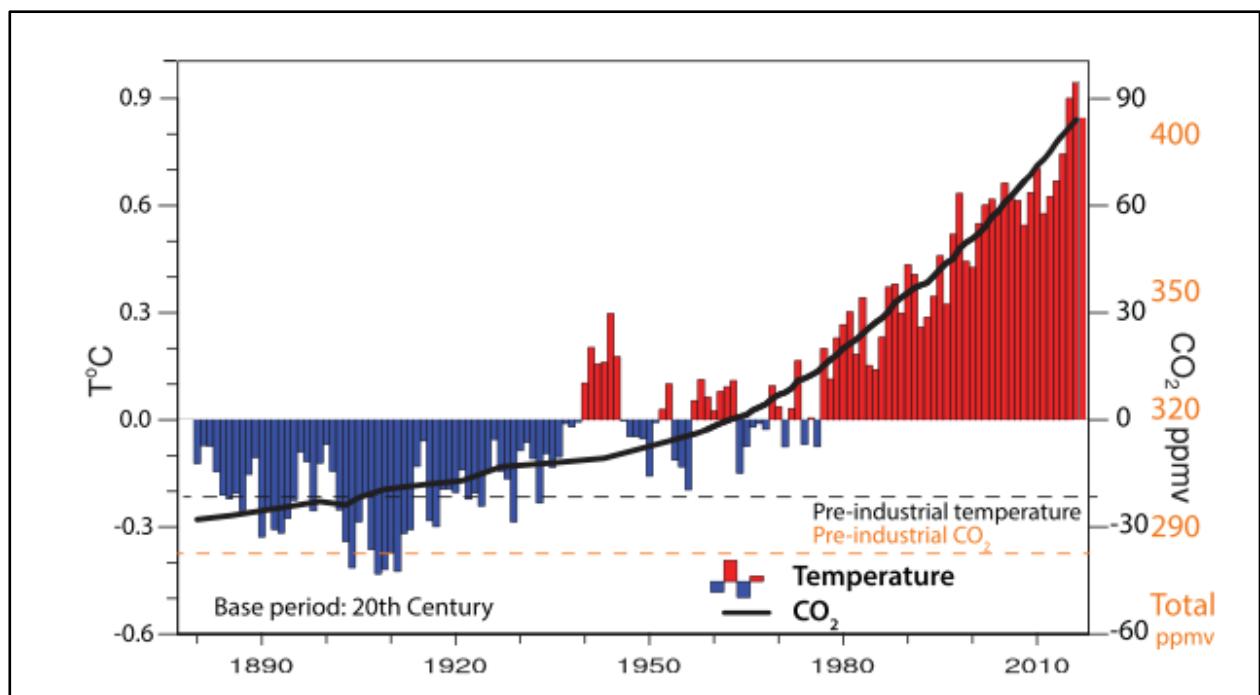


Figure 3: Global average annual surface temperatures alongside CO₂ concentrations from 1890-2010 with a base period of the 20th century (Trenberth, 2018).

Anthropogenic climate change is influencing hydrological processes (Trenberth, 2011). This is because of the increase in temperature and heating of the Earth's surface caused by the greenhouse effect, which leads to greater evapotranspiration of soil moisture (Jury, 2013; Trenberth, 2011; Trenberth *et al.*, 2014). One should also consider that although the greenhouse effect plays a role, dry conditions also occur because of compound events (Kautz *et al.*, 2022). This is where the interaction between the atmosphere and soil moisture can

exacerbate dry conditions. For example, trapped shortwave radiation leads to warming, increased temperatures, and, therefore, dry conditions (Kautz *et al.*, 2022). As a result of the increasing temperatures, the hydrological cycle becomes altered and intense climatic extremes (such as drought) become more widespread (Mukherjee *et al.*, 2018).

Although natural climate variability contributes to the warming through cycles, anthropogenic global warming is causing surplus warming to accumulate (Trenberth, 2018). As previously mentioned, one of the effects of anthropogenic warming is the increasing instance of drought events. The following section examines the climatology of rainfall in South Africa which considers the link between the atmosphere and drought.

2.5 The climatology of rainfall in South Africa

This section considers South Africa's seasonal rainfall areas and climatology by examining rainfall trends. Examining the common rainfall trends and variability provides insight into determining any possible changes when analysing the data.

South Africa has a semi-arid to arid climate with four distinguishable seasons, summer, autumn, winter, and spring. These seasons occur in the months December to February, March to May, June to August, and September to November, respectively (Botai *et al.*, 2018). Most of the rainfall occurs in summer, however the western/southwestern areas have Mediterranean climate conditions characterised by winter rainfall. The southern coastal areas experience rainfall year-round, while the central to northern areas have rainfall occurring from late summer to very late summer (autumn). The eastern region experiences early to mid-summer rainfall (Botai *et al.*, 2018) (Figure 4).

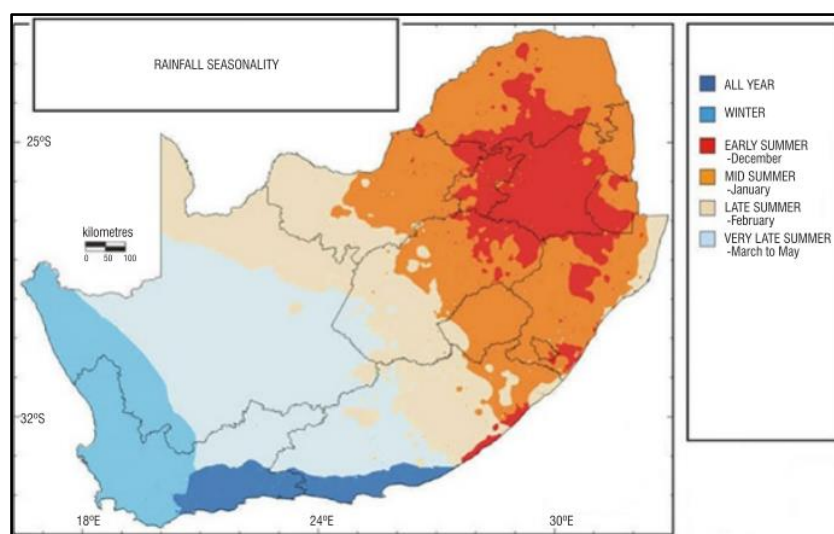


Figure 4: Different seasonal rainfall areas in South Africa (Botai *et al.*, 2018; EUMETSAT, n.d.).

2.5.1 Rainfall variability

Variability in rainfall is affected by the changing frequency, intensity, and extent of weather systems that bring significant rainfall days. This is often confused with the rainfall season's length or the number of rainfall days (Mason & Jury, 1997). South Africa's total average rainfall annually is approximately 450 mm, which is below the yearly global average of 860 mm, highlighting the country's aridity. Rainfall also varies spatially and temporally across the country which also affects the annual average. Wetter areas can receive an average of up to 1000 mm, while areas more prone to aridity typically receive less than 250 mm per annum (Botai *et al.*, 2019). Southern Africa's rainfall variability and arid climate cause water resources to be limited. This adds to the problematic effects of poor water resource management issues (Mason & Joubert, 1997).

Mason & Jury, (1997) found that eastern South African rainfall shows quasi-periodicities where a rainfall cycle of 18 years is evident (where summer rainfall is prominent). This is said to be influenced by the inter-decadal variability of SSTs in the adjacent oceans. Other cycles over southern Africa encompass 3.5-6 years where ENSO has the dominant contributing effect (Mason & Jury, 1997). More recently, it was found that South African rainfall exhibited a 12-year periodicity between 1960 and 2010 (Jury, 2015). Other studies have shown that rainfall variability in southern Africa has also exhibited an 18-year cycle of variability (Tyson *et al.*, 2002). Rainfall variability is also characterised by El Niño and La Niña events. For southern Africa, dry (wet) spells are identified through high (low)-pressure anomalies which are El Niño (La Niña) events that influence rainfall variability (Malherbe *et al.*, 2016; Reason & Rouault, 2002). Examples of such events occurred during 1938/39, 1942/42 (La Niña), and 1940-1942 (El Niño). A more recent El Niño event occurred in 2015-2016 (Lakhraj-Govender & Grab, 2018). There is some evidence in these examples that events occasionally occur consecutively, which highlights the interannual rainfall variability present. The timing of when rainfall occurs also varies across regions and due to seasons within South Africa.

2.5.2 South African circulation patterns

This section will outline the most important synoptic scale/atmospheric circulation that form around South Africa. These patterns include fine to mildly disturbed weather and temperate mid-latitude disturbances (Tyson & Preston-Whyte, 2000) (Figure 5 - Figure 6).

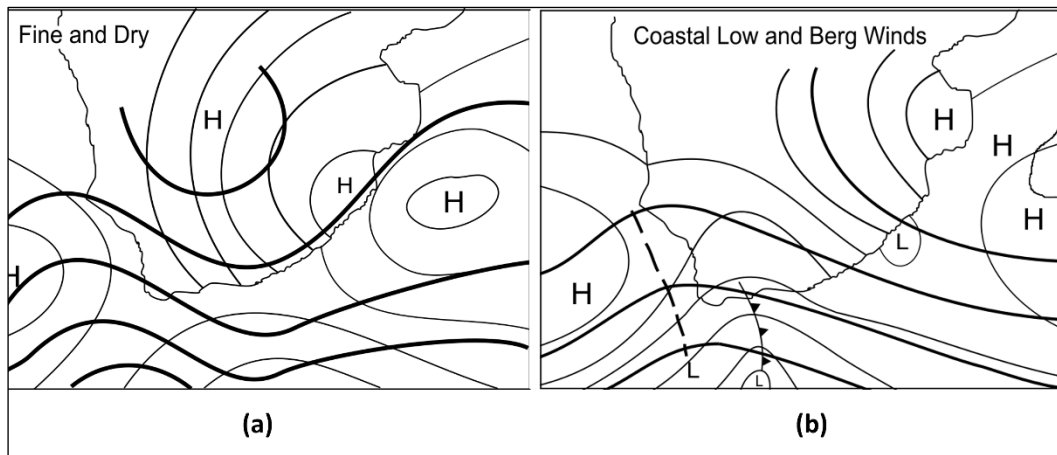


Figure 5: Fine, dry, and mildly disturbed weather patterns (Tyson & Preston-Whyte, 2000).

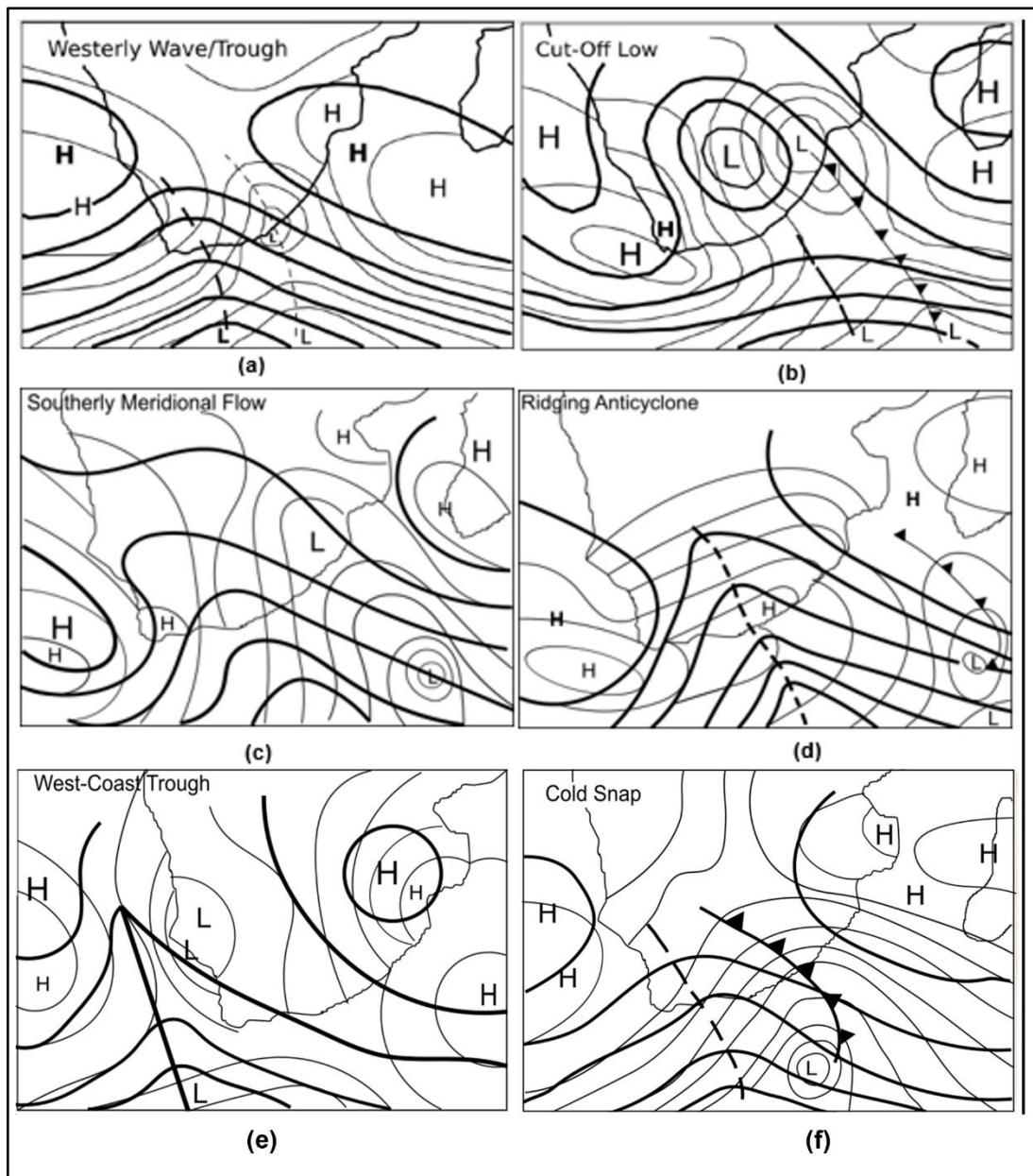


Figure 6: Westerly temperate disturbed weather patterns (Tyson & Preston-Whyte, 2000).

The schematic representations of the circulation patterns were adapted from Tyson & Preston-Whyte, (2000). A detailed description of the different circulation patterns contributing to western South African weather follows.

Table 2: Circulation patterns that constitute of fine or mildly disturbed weather.

Fine or mildly disturbed weather	Impact on rainfall in South Africa	Sources
Continental highs/Subtropical anticyclones (Figure 5 (a))	Anticyclonic weather originates from a high-pressure belt where divergence occurs near the surface wind field, while accompanied by subsidence. Inversions take place, leading to fine conditions with clear skies and, seldom to no rainfall.	(Taljaard, 1967; Tyson <i>et al.</i> , 1996; Tyson &

		Preston-Whyte, 2000)
Coastal lows and Berg winds (Figure 5 (b))	Coastal lows occur along the South African coast and are characterised as shallow, low-pressure disturbances, formed from the interaction between anticyclone ridging and the local topography. Berg winds usually cause surface temperatures to rise and once the coastal low arrives, surface temperatures tend to decline and increase the dew point. Coastal lows and Berg winds can either cause fine to mildly disturbed weather, ranging from no rain to stratus clouds or either showers or storms.	(Bonnardot <i>et al.</i> , 2005; Gill, 1977; Kamstra, 1987; Reason & Jury, 1990; Torrance, 1995)

Table 3: Temperate disturbances from westerly weather patterns.

Temperate disturbances in the westerlies	Impact on rainfall in South Africa	Sources
Westerly wave (Figure 6 (a))	Westerly waves are baroclinic disturbances that are also viewed as Rossby waves and influence cut-off lows. At the surface of the waves, cyclonic vorticity is exhibited which slopes towards the west of the system. They are associated with heavy rainfall as they travel across the south coast of South Africa.	(Dyson <i>et al.</i> , 2015; Kelbe, 1988; Tyson <i>et al.</i> , 1996; Tyson & Preston-Whyte, 2000)
Cut-off low (Figure 6 (b))	A CoL (closed low) can cause copious amounts of rainfall over small periods, which can result in flash flooding. This is partly because these systems are associated with deep moist convection and take part in stratosphere-troposphere exchange. Rainfall along the western coast of South Africa mainly receives rainfall from CoL systems.	(Baray <i>et al.</i> , 2003; Favre <i>et al.</i> , 2013; Muller <i>et al.</i> , 2008; Porcù <i>et al.</i> , 2007; Singleton & Reason, 2007)
Southerly meridional flow (Figure 6 (c))	This type of circulation pattern involves airflow along the southern coast of South Africa and is linked to cyclonic curvature. This airflow is associated with a powerful zonal pressure gradient which exhibits a high pressure to the west of South Africa and a low pressure to the east. This circulation type also produces light spring rainfall, while causing decreasing temperatures.	(Tyson, 1984; Tyson & Preston-Whyte, 2000)
Ridging anticyclone (Figure 6 (d))	Ridging anticyclones (or ridging highs) form over a 5-day period. As ridging anticyclones are linked to CoL systems in the upper atmosphere or other low-pressure systems, extensive rainfall can occur. It is estimated that 46% of South Africa's annual rainfall stems from ridging	(Engelbrecht <i>et al.</i> , 2015a; Ndarana <i>et al.</i> , 2018, 2022;

	anticyclones.	Weldon & Reason, 2014)
West-coast trough (Figure 6 (e))	Extensive rainfall over the western region of South Africa is caused by a low-pressure surface trough and westerly waves found in the upper troposphere. The west coast trough can form onshore (during late summer) or offshore (during spring). In front of the west-coast trough, convergence occurs at the surface and divergence aloft which helps create the factors needed for upward vertical motion, leading to rainfall.	(Reason, 1996; Tyson & Preston-Whyte, 2000)
Cold front/ snap (Figure 6 (f))	Cold fronts replace warm air with a mass of cold air. As a result, temperatures can rapidly decline and changes in moisture and winds also occur across regions. Cold fronts are associated with bringing widespread rainfall, especially over the south-western coastal regions.	(Crimp & Mason, 1999; Kumar <i>et al.</i> , 2014; Sakai <i>et al.</i> , 2005; van der Walt & Fitchett, 2021)

This section examined the dominant circulation patterns that contribute towards South Africa's rainfall. It was necessary to consider these patterns to examine the background influences towards rainfall variability and drought. Many of these circulation patterns originate from the west and influence weather over western South Africa, specifically over the coastal regions. The following section discusses drought variability and trends in South Africa.

2.6 Drought trends and variability in South Africa

In South and southern Africa, drought is viewed as a regular climate feature. The southern African subcontinent has experienced severe droughts since the 1970s (Richard *et al.*, 2001; Rouault & Richard, 2005) and have become more common and intense (Joubert *et al.*, 1996; Richard *et al.*, 2001; Rouault & Richard, 2003).

Drought indices that are commonly used to analyse drought events include the Standardised Precipitation Index (SPI) and the Standardised Precipitation Evaporation Index (SPEI). The SPI serves as a tool, developed by McKee *et al.*, (1993) to identify rainfall deficits. The SPI analyses drought events in a standardised manner as it is related to probability (Blain & Meschiatti, 2015). The SPEI is similar to the SPI but considers temperature data to take evapotranspiration into account when analysing drought (Beguería *et al.*, 2014). Researchers have made use of the SPI (and SPEI) to examine drought intensity and spatiality in South Africa (Adisa *et al.*,

2021; Botai *et al.*, 2016, 2017; Hoffman *et al.*, 2009; Malherbe *et al.*, 2016; Mbiriri & Mukwada, 2018; Nkamisa *et al.*, 2021; Rouault & Richard, 2003).

Malherbe *et al.*, 's (2016) record of dry periods (Table 4) in South Africa were analysed at 24 and 60-month SPI time scales. Furthermore, Rouault & Richard, (2005) also recorded severe drought years in South Africa (Table 4) which were also analysed at a 24-month SPI time scale. Most of these years were attributed to being El Niño years. Multiple severe drought events were also recorded at different time scales during 2001-2004. Due to this, the spatial extent of drought has been said to have increased since the 1970s (Rouault & Richard, 2005). ENSO is said to have a strong influence on southern African rainfall, affecting the extent of drought (Chikoore & Jury, 2021; Rouault & Richard, 2005).

Table 4: Recorded dry years in South Africa from the early 20th century to the early 21st century.

Dry Years recorded in South Africa (Malherbe <i>et al.</i> , 2016).	Severe drought years ending in [year] over a 24-month SPI time scale in South Africa (Rouault & Richard, 2005).	ENSO Phase droughts in South Africa (Rouault & Richard, 2005).
1926-1933	1906	1906
1946-1952	1933	1933
1965-1973	1983	1983
1983-1994	1984	1992
2003-2007	1992	1993
	1993	1995
	1995	1996
	1996	

Within the dry periods recorded for South Africa by Malherbe *et al.*, (2016) (at a 24-month SPI time scale) three drought cycles were identified namely, 4-7, 10-12, and 17-20 years. The 17–20-year drought cycle corresponds with the global recurring drought cycle of 18.6 years that was introduced by Currie, (1982) and Cook *et al.*, (1997). Malherbe *et al.*, (2016) highlight that extensive and intense drought events in South Africa can occur as a result of what is termed “multi-years” of dry conditions (low rainfall periods). Drought years can range from multi-years to multi-decadal (McCabe & Palecki, 2006). Negative impacts caused by drought are exacerbated as a result of the extended length over multiple years. Furthermore, multi-year droughts can

also occur as a result from a series of consecutive short extreme drought periods (1-2 years) (Malherbe *et al.*, 2016).

From these drought events recorded in southern- and South Africa, this study aimed to investigate the prevalence of drought events and their severity over the western region of South Africa. It is generally considered that the spatial extent of drought events has expanded since the 1970s. It, therefore, becomes important to investigate if the prevalence of drought events is increasing.

2.7 Factors linked to climate variability

The following subsections will discuss some of the most prominent factors linked to drought. These include SSTs and ENSO, Indian Ocean Dipole (IOD), Antarctic Oscillation (AO), soil moisture (lack thereof), and finally, surface-, land- and air temperatures.

2.7.1 SSTs and ENSO

Several previous studies have studied SSTs and their effect on rainfall worldwide (Fauchereau *et al.*, 2003; Hirst & Hastenrath, 1983; Mason, 1995; Lamb, 1978; Phillips, 1992; Rowell *et al.*, 1992; Walker, 1990). The studies have found SSTs to be useful predictors of seasonal rainfall (Phillips, 1992). Heat and moisture are transferred at the air-sea boundary and affect the surrounding continental regions (Walker, 1990). In Angola researchers have seen that high rainfall years have correlated with warm oceanic surface waters (Hirst & Hastenrath, 1983). Around South Africa, SSTs (originating from adjacent oceans) have been found to be connected to the country's interannual and interdecadal rainfall variability (Hansingo & Reason, 2009).

Several main oceanic currents exist surrounding the southern African region and should be noted as possible sources affecting South Africa's rainfall variability. This includes the Agulhas current which surrounds South Africa's east and south coasts (Figure 7). Along the west coast, the Benguela current is found, and thirdly the Subtropical Convergence (38°-42°S) is present and also plays a role (Walker, 1990). The southern Benguela- and southern Agulhas currents are the nearest currents to western South Africa.

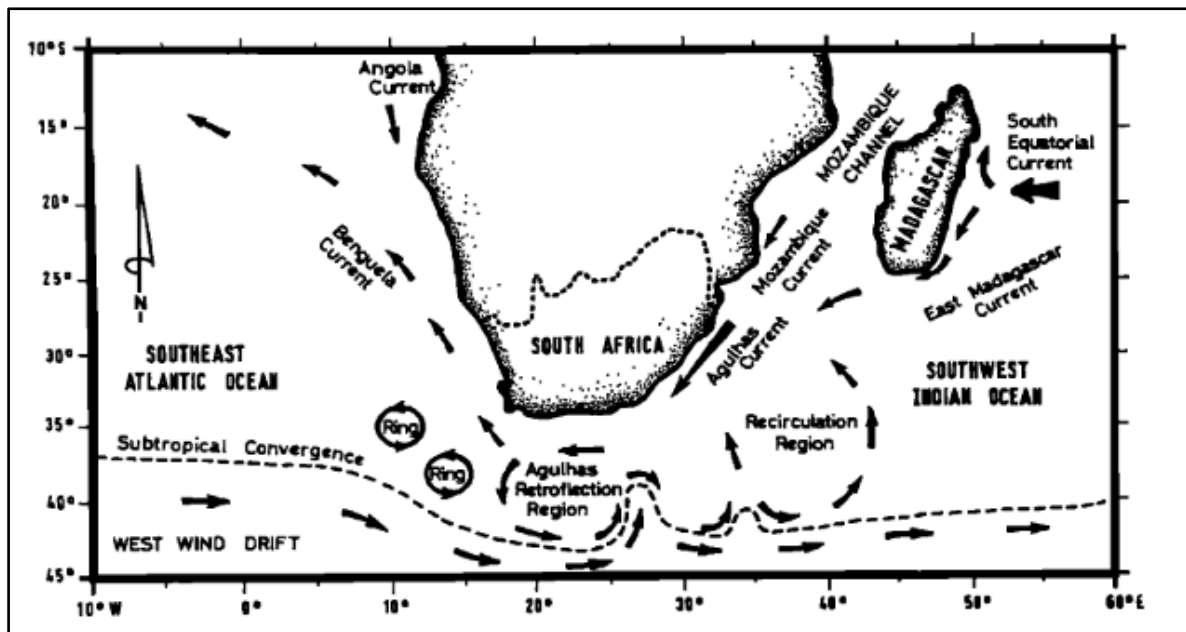


Figure 7: Diagram displaying the ocean currents of southern Africa (Walker, 1990).

The southern Benguela Current lies closest to western South Africa (Figure 7). For both the northern and southern Benguela, warm and cool events were documented during the 20th century. The earliest recorded example of how the Benguela Current influenced rainfall was during the summer of 1933-1934 when warm waters (termed 'Benguela Niños') were observed with consequential high rainfall over Namibia's interior (Shannon *et al.*, 1986). The monthly SSTs during this event were recorded to be 2-3°C above the 15-year monthly averages from March-July (Shannon *et al.*, 1986). The Benguela Current influences Angola's- and Namibia's rainfall more so than western South Africa, where the southern Benguela is present (Hansingo & Reason, 2009; Shannon *et al.*, 1986).

Anomalous SSTs can influence western portions of South Africa's rainfall area as outlined by Walker, (1990). The winter rainfall region often experiences increasing summer rainfall due to the Southern Oscillation that increases SSTs in the South Atlantic Ocean rather than the Benguela Current itself (Mason, 1995). The majority of southern Africa receives its moisture from the western Indian Ocean for summer rainfall (Rouault *et al.*, 2003). Therefore, emphasising the importance of the Agulhas Current as a catalyst for rainfall over the subcontinent. Overall, when dry (wet) conditions are present in South Africa, sea surface temperatures are said to have fallen (increased) in the Agulhas Current system (Mason, 1995).

El Niño is present when there is a rise (above normal) in SSTs in the South Pacific. When SSTs decrease (below normal) in the South Pacific, conditions of La Niña occur (Glantz, 2001; Kim, 2019). The terms 'El Niño' and 'Southern Oscillation' were combined (Behera & Yamagata, 2003; McPhaden, 2002) (ENSO), describing the changing atmospheric sea level pressure and

fluctuation of SSTs. This is the most dominant factor that influences local weather and the global climate (Behera & Yamagata, 2003).

Numerous articles have found that southern Africa's rainfall variability is increasingly influenced and affected by ENSO (Dieppois *et al.*, 2015; Fauchereau *et al.*, 2003; Van Heerden *et al.*, 1988; Kane, 2009; Makarau & Jury, 1998; Mason, 2001; Mason & Jury, 1997; Reason & Rouault, 2002; Richard *et al.*, 2001; Ropelewski & Halpert, 1996). The high interannual climate variability is related to South Africa's location within the sub-tropical high-pressure belt. This is because the high-pressure systems found west over the Atlantic Ocean and east over the Indian Ocean influence the strength of the rainy season (Jury, 1996; Malherbe *et al.*, 2016; Tyson, 1981). Variability in rainfall has been increasing over southern Africa since the 1970s (Jury, 1996, 2013).

El Niño is associated with the occurrence of the most severe droughts in southern Africa (Rouault & Richard, 2005). When El Niño is at its most mature phase, severe drought events often occur, while La Niña is associated with rain-bearing wet summers in southern Africa (Rouault *et al.*, 2010; Rouault & Richard, 2005). Significant summer rainfall over the northern and eastern regions of South Africa is usually associated with ascending Walker Circulation (cells). During the El Niño phase, the ascending local Walker cell (associated with rain) can be influenced by an offshore shift which displaces the cell to then lie over the western Indian Ocean (Reason *et al.*, 2000). Once it has been displaced over the western Indian Ocean, less rain falls over southern Africa. Dry conditions then occur, since the tropical-extratropical cloud bands have shifted. It should also be noted that dry summers in southern Africa do not solely derive from El Niño (ENSO) events (Mulenga *et al.*, 2003).

Mulenga *et al.*, (2003) outline examples of such events which took place during December, January, and February (DJF) of 1951/52, 1967/68, and 1981/82. During these events, mid-latitude circulation patterns over South Africa brought anticyclonic (stable) conditions. These circulation patterns also cause cool, dry South Atlantic Ocean air to flow over western South Africa. Hindering onshore flow of moisture for rain-bearing events (Mulenga *et al.*, 2003).

2.7.2 Indian Ocean Dipole

In addition to ENSO, the IOD (Saji *et al.*, 1999) also influences southern Africa's rainfall variability (Kulkarni *et al.*, 2007; Manatsa *et al.*, 2008). The IOD is seen as a periodic climate mode, exhibiting interannual variability, that produces changes in the interactions between the ocean and atmosphere within the Indian Ocean (Manatsa *et al.*, 2007). The IOD is characterised as the difference in SST anomalies located between the eastern and western

Indian Ocean (Saji *et al.*, 1999). It should be of note that although ENSO- and IOD events can occur during the same time, IOD events can still take place independent of ENSO (Saji & Yamagata, 2003a,b). Saji & Yamagata, (2003b) note that when ENSO and IOD events coincide, the impact and variability of the ENSO event is amplified. Furthermore, IOD events were more prominent in causing rainfall variability during the 1960s and 1990s, while ENSO events were more notable during the 1970s-80s (Saji & Yamagata, 2003a).

A positive IOD tends to take place during an El Niño event, while a negative IOD tends to occur during La Niña (Saji & Yamagata, 2003b). When a positive (negative) IOD event takes place, the effect thereof on southern Africa's rainfall variability is similar to the effect of El Niño (La Niña) and triggers dry (wet) conditions (Figure 8 (a) and (b)). An example of this was also highlighted by Manatsa *et al.*, (2008) where Zimbabwe experienced deficiencies in rainfall seasons during positive IOD events, independent of or either co-occurring with El Niño.

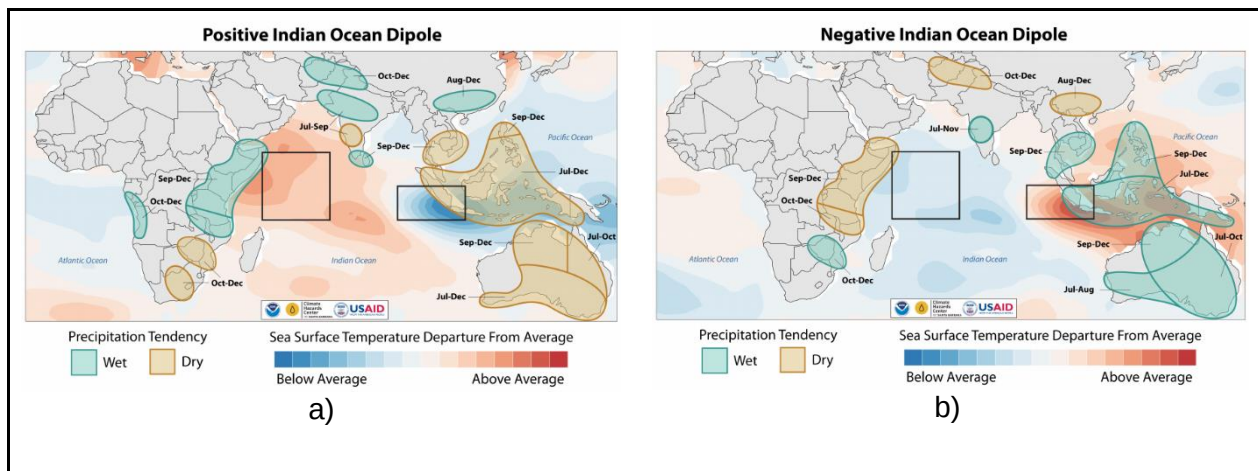


Figure 8: a) positive IOD and b) negative IOD (FEWS NET, 2021)

2.7.3 Antarctic Oscillation

The AO (Thompson & Wallace, 2000) is a climate mode of atmospheric low-pressure variability, located south of 20°S. As with ENSO, a seesaw in atmospheric pressure results from the AO affecting the areas between the Antarctic and mid-latitudes (Pohl *et al.*, 2010). Depending on whether the AO is in a positive (negative) phase, westerly winds located in the mid-latitudes, as well as the subtropical high-level jet shift poleward (equatorward) due to pressure changes (Pohl *et al.*, 2010; Rouault *et al.*, 2010).

Reason & Rouault, (2005) investigated the possible effect of the AO on winter rainfall variability of the western region of South Africa. It was found that when rainfall was abundant in winter, the AO was in a negative phase and vice versa for dry winters. Pohl *et al.*, (2010) on the other hand, found that the opposite occurs over central South Africa, where greater rainfall occurs during

the positive AO phase at an intra-seasonal time scale. It is evident that AO is another key factor that can influence rainfall variability within western South Africa.

2.7.4 Soil moisture

Soil moisture is a measure of the amount of water available in the ground which can evaporate after rainfall and consequently affect the surface energy budget (Oglesby & Erickson, 1989). Soil moisture is typically the first factor to be affected by dry conditions (Byun & Wilhite, 1999). Cook *et al.*, (2006) explain that soil moisture influences rainfall through initiating a positive feedback cycle, termed precipitation recycling. Thus, wetter soils increase the moisture flux in the atmosphere, which generates more humidity, and eventually cloud cover and possibly enhances rainfall. Moisture convergence is also enhanced from the surface moisture flux (Cook *et al.*, 2006; Douville *et al.*, 2001).

There is, however, contradicting views on the exact relationship between soil moisture and precipitation. New *et al.*, (2003) argues that in southern Africa, a negative feedback cycle of precipitation is present. This is because with wetter soils, sensible heating is actually reduced, consequently causing the lower atmosphere to experience increased stability, which results in less precipitation. Cook *et al.*, (2006) also explain that increased soil moisture can decrease precipitation through two processes. The first method is through the enhancement of atmospheric stability and subsidence which inhibits the formation of precipitation, while the second method is caused by a decline in moisture convergence, subsequently lessening moisture supply in the atmosphere (Cook *et al.*, 2006).

2.7.5 Surface, land, and air temperatures

Greater than average surface- and air temperatures, alongside below normal precipitation, are associated with the onset of drought (Chang & Wallace, 1987; Dai, 2011; Engelbrecht *et al.*, 2015b). Thus, the increase in surface, land, and air temperatures are associated with the onset of drought, it can be deduced as one of the causes contributing to drought. Projected increasing average global temperatures of 3°C will affect the hot desert zone in southern Africa, which might expand and affect southern Northern Cape, and northern parts of southwestern Cape. Thus, these areas might be affected by desertification stemming from the surrounding hot and arid desert zones (Engelbrecht & Engelbrecht, 2016).

Land surface temperatures (LSTs) are also one of the critical factors to consider when examining drought as the increase thereof is correlated to dry conditions (Sruthi & Aslam, 2015). A negative correlation exists between LST and the Normalized Difference Vegetation Index (NDVI) (Yue *et al.*, 2007). It was observed at different scales, ranging from 25 m² to 1.2

km² that LSTs increase when soil moisture and vegetation cover decrease, or experiences change (Goetz, 1997; Wan *et al.*, 2004).

2.7.6 Link between heat waves and drought

According to the South African Weather Service (SAWS) (Mbokodo *et al.*, 2020), heat waves occur when a certain region's maximum temperature is more than 5°C warmer than the average mean of the hottest month or that station for three days in a row (or longer).

Heat waves and drought events can occur simultaneously, which exacerbates the consequential impacts of drought (Albright *et al.*, 2010; Lyon, 2009). The added effect of heat waves (high surface and air temperatures) contribute to crop and agricultural losses, as well as increasing livestock mortality rates (Lyon, 2009) because of dehydration (Kay, 1997).

During heat waves, rainfall tends to be scarce, and during droughts, surface and air temperatures tend to be high. What is distinguishable, however, is the time scale at which they occur. Drought events persist for months or years, whereas heat waves occur over a few days or a week (Chang & Wallace, 1987). The two phenomena are also connected through a lack of soil moisture. This is because low soil moisture (resulting from drought) causes an increased Bowen ratio (sensible-to-latent heat). Consequently, surface and air temperatures increase which is when heat waves arise (Albright *et al.*, 2010). Moreover, there exists a positive feedback cycle between the two phenomena. This is because greater evapotranspiration, and an increased moisture deficit rate, are associated with high temperatures (He *et al.*, 2022). However, evaporative (adiabatic) cooling can cause the sensible heat flux to increase which, in turn, increases surface air temperatures (He *et al.*, 2022; Seneviratne *et al.*, 2010). Hence, this positive feedback cycle can cause or intensify heat waves (He *et al.*, 2022).

This section examined the factors that contribute towards causing drought. Most of the factors were regionally based i.e., prominent factors playing a role to southern and South Africa. Heat waves were considered to emphasise how they exacerbate the consequences of drought. The final section outlines the impacts that drought inflicts on the economy, environment, and society.

2.8 Impacts of drought

Drought can have a wide range of effects within economic, environmental, and social domains, classified as either direct or indirect (Byun & Wilhite, 1999). Farmers livelihoods and the local economy is most directly affected by drought. Other effects may include mental stress due to the loss of productivity, crops and animals. Moreover, population growth might be affected as lives might be lost (Edwards *et al.*, 2019). An example of the effect of drought to local

communities in the Western Cape was that farmers and locals had to prepare for “day zero” without water during the 2018 drought. The agricultural sector in the province contributed to 2% of South Africa’s Gross Domestic Product. Behavioural changes (i.e. social effects) were also observed in farmers as they began to hoard water when it became available. Job losses also became more prominent as less workers were needed on farms (Johnston, 2018). Direct effects, as the term suggests, inflict harm directly onto the subject. Indirect effects, on the other hand, are the consequential effects resulting from the direct effects (Ding *et al.*, 2011; Wilhite *et al.*, 2007). The following table describes some of the economic, environmental, and social direct and indirect effects associated with drought (Table 5).

Table 5: Summary of some of the most prominent impacts of drought.

Domains	Economic	Environmental	Social
Direct	- Failures of crop production and pastures (Ding <i>et al.</i>, 2011; Wilhite <i>et al.</i>, 2007). - High costs to obtain water for livestock and/or unavailability thereof (Wilhite, 1992, 1993; Edwards <i>et al.</i>, 2019). - High costs to obtain feed for livestock and/or the unavailability thereof (Wilhite, 1992, 1993). - Mortality rates of livestock may increase, resulting in direct economic loss (Wilhite, 1993; Ziolkowska, 2016).	- Increase in wildfires and increase in animal (wildlife and livestock) mortalities (Wilhite <i>et al.</i>, 2007). - Reduction of water availability (Wilhite <i>et al.</i>, 2007). - Various animal species undergo harm due to a decline in water and/or food. (Wilhite, 1993; Ding <i>et al.</i>, 2011). - The quality of water (Ding <i>et al.</i>, 2011) and air is reduced (Wilhite, 1993). - Fish habitat is reduced because of a decline in water flow, which causes an increase in fish mortality rate (Wilhite, 1992, 1993).	- Increase in famine due to food shortages from crop failures (Wilhite, 1993). - Increase in heat and famine leads to an increase in the loss of human lives (Wilhite, 1993). - Mental-health consequences of dealing with loss of crops and animals (Edwards <i>et al.</i>, 2019)
Indirect	- Decrease in economic growth and delay in economic development (Wilhite, 1993; Ding <i>et al.</i>, 2011). - Farmers and others in	- Animals undergo harm from an increase in diseases and a decline in habitat (Wilhite, 1992, 1993). - Animals that are prey	- Rise in poverty (Wilhite, 1993). - Rise in social unrest due to conflict relating to water shortage

	agribusiness who rely on agricultural production have a loss in income (Wilhite, 1993). • Food prices may increase due to the increased importation of food (Wilhite, 1993). • Increase in unemployment in the agricultural sector (Wilhite, 1992, 1993; Ziolkowska, 2016). • Upstream and downstream stakeholders will be affected by farmers with crop losses (reduction in production and supplies) (Ding <i>et al.</i>, 2011).	become more susceptible to predators due to the loss of habitat. For example, the increase in gathering of species near available water (Wilhite, 1992, 1993).	(Wilhite, 1993). • Increasing in-migration from rural to urban areas (Wilhite, 1993). • Reduction in quality of life (Wilhite, 1993; Edwards <i>et al.</i>, 2019).
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2.9 Chapter summary

This literature review started with examining the different disciplines of drought. This includes the meteorological-, agricultural-, hydrological- and socio-economic drought types. From these disciplines of drought, drought was defined within the context of this study. Natural climate variability was discussed as well as anthropogenic factors that contribute towards climate change. This included factors such as increasing GHGs that have contributed towards higher global average annual surface temperatures.

The climatology of rainfall in South Africa was then examined which included the predominant rainfall cycles and circulation patterns surrounding southern/South Africa. These circulation patterns form part of the main weather systems that influence the country's rainfall. South Africa's drought cycles and variability were then considered. This is where the main drought cycles of 4-7, 10-12 and 17-20 years for South Africa were identified. Factors causing drought was an extensive section that ranged from global factors such as SSTs, ENSO, IOD, AO to more local influences of soil moisture, surface, land, and air temperatures. The economic, environmental, and social impacts of drought were also considered.

This literature review provided insights into the background of rainfall and drought cycles specific to South Africa. It also laid emphasis on the factors causing drought and its impacts.

This is important to consider as the causes and impacts justify the importance of studying drought.

CHAPTER 3: DATA AND METHODS

3.1 Introduction

The data and methodology chapter introduces the study area and provides an overview of the data sources that were obtained and used for the statistical analysis. The weather stations and their available data is discussed. Data quality control was executed to refine the data. The statistical methods used for analysing the data included the SPEI and the Mann-Kendall (MK) trend test. An overview of the use of these methods were provided. The chapter ends with a review of the limitations of the current study.

3.2 Study Area

The study area (Figure 9) is based on the Kalahari discontinuity dryline (KD) (Howard & Washington, 2019) and is also termed the moisture front and/or moisture discontinuity by Tyson & Preston-Whyte, (2000). The KD is a dryline present southeast-to-northwest of the Kalahari Desert. Based on Howard & Washington, (2019) the KD is formed between the Congo Air Boundary (CAD) and the Eastern Low Pressure Systems, such as the easterly wave. It influences southern Africa's interannual rainfall variability, where the dryline forms a west-to-east border over the subcontinent (Howard & Washington, 2019). Storms tend to build up along the moisture discontinuity (and/or KD). This is because ahead of this moisture discontinuity (north-east direction), warm, moist, anticyclonic weather is found; whereas south-west of the front, cool and drier airflow is present (Tyson & Preston-Whyte, 2000).

The study area is allocated based on the south-west, drier region west of the KD (Figure 9). The KD changes its position between spring and summer seasons (Howard & Washington, 2019). The study area is termed the 'western region' of South Africa and includes the entire region (five different provinces) located west of the KD. The five different provinces comprise the entire Northern Cape, the entire Western Cape, the western region of the North West, the western Free State, and the western Eastern Cape. The study area contains different climates and seasonal rainfall patterns which is outlined for each province hereafter.

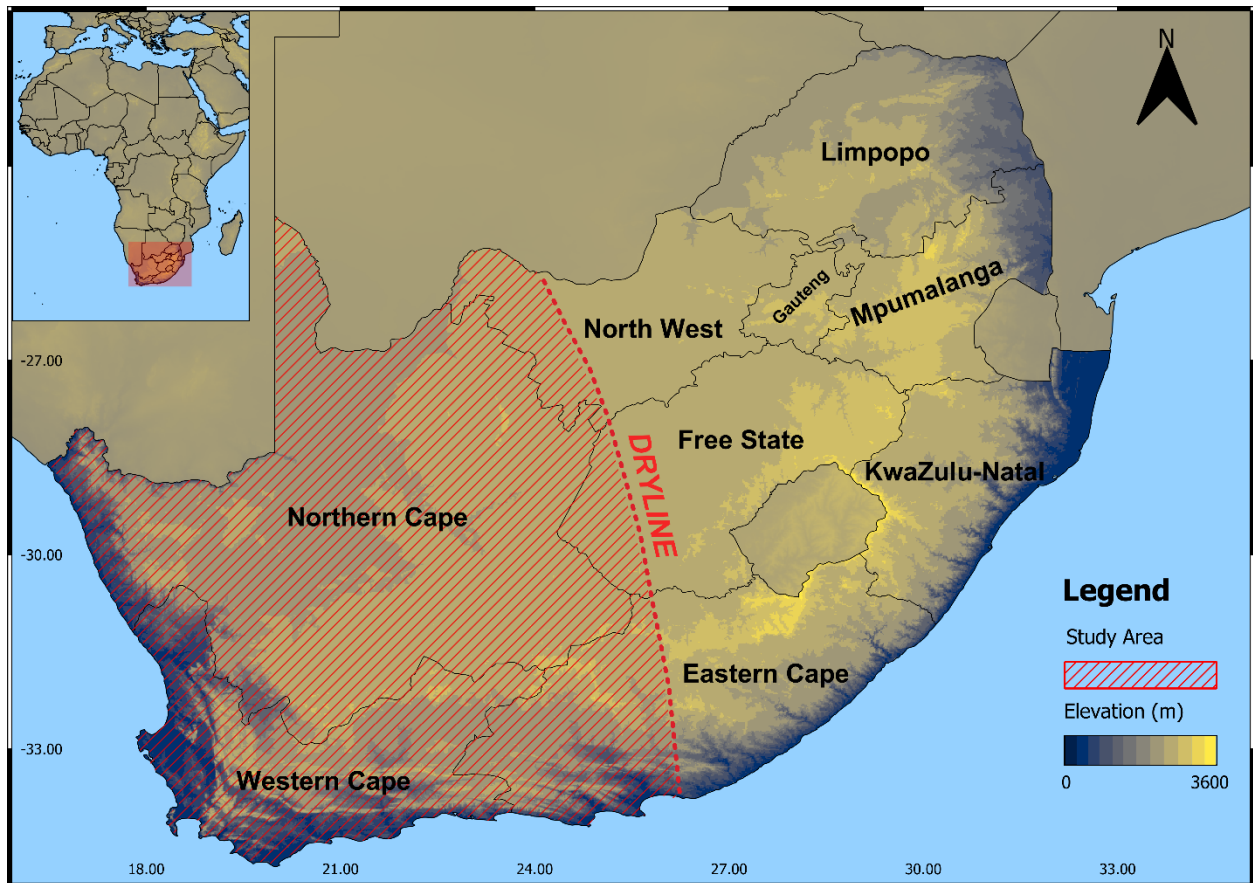


Figure 9: Study area displaying the western region. The study area includes all regions west of the KD boundary (Howard & Washington, 2019) displayed in red.

The Northern Cape occupies 30.5% of South Africa's land area, at 372 889 km², making it the largest province (Stats SA, 2011). The Northern Cape is naturally arid as it experiences low rainfall while frequently experiencing severe drought events. A strong east to west precipitation gradient exists as the eastern region receives up to 540 mm per annum of rainfall, while the western region receives as little as 20 mm per annum of rainfall. The province's climate is mostly subject to summer rainfall except for areas along the south western coastline which receive winter rainfall (Jordaan *et al.*, 2013).

The Western Cape is the fourth largest province in SA occupying 129 462 km² of land (Tizora *et al.*, 2016). The province's climate is dominated by a warm Mediterranean climate usually alongside the coastal region. Summer temperatures average between 15°C and 27°C where winter temperatures average between 5°C and 22°C. Different rainfall regimes exist across the Western Cape. Areas dominated by winter-rainfall and warm, dry summers include the Peninsula and Boland regions. The Great Karoo area is dominated by summer rainfall, while the south-coastal region is characterised by persistent, year-round rainfall. Rainfall varies between ~300 mm to more than 900 mm per annum. Rainfall in certain areas of the Western Cape can receive as little as 60 mm and as much as 3345 mm (Botai *et al.*, 2017).

Located towards the north-western region of South Africa, the North West province is landlocked between the Limpopo-, Gauteng-, Free State- and the Northern Cape province, as well as the neighbouring country, Botswana. It covers 9.5% of the country's surface area at 116 320 km². Urban areas and activity (such as agriculture) accounts for 35%, yet it is mainly rural at 65% (Botai *et al.*, 2016). The North West's western region is characteristically semi-arid, where xerophytic vegetation is present. The eastern region has greater rainfall and a more temperate climate and greater vegetation diversity in comparison to the western region. Rainfall ranges between 200 mm and 650 mm per annum where months between October to March are considered the wet season (Thorn *et al.*, 2012).

The third largest province is the Free State. It covers 10.6% of South Africa's surface area (Moeletsi *et al.*, 2011). Most of the province's climate (including parts of the western region) is semi-arid since the eastern and north-eastern region is more humid and subtropical (Moeletsi, 2010; Moeletsi *et al.*, 2011). Within the western region of the province, warmer minimum and maximum temperatures prevail (in comparison to the eastern region) with summer rainfall. 70% of the annual rainfall occurs during the months of September/October throughout April/May ranging between 300 mm to more than 900 mm (Moeletsi, 2010).

The Eastern Cape province is the second largest province in the country, rounding up to an area of 169 000 sq. km². It borders the Western Cape, Northern Cape, Free State and KwaZulu-Natal provinces, as well as the neighbouring country, Lesotho. The Indian Ocean lies south and south-east to the province. The Eastern Cape is positioned on the south-eastern part of South Africa. In the Karoo (western region of the province), long, hot summers prevail with modest winters, exhibiting Mediterranean characteristics due to winter rainfall. However, constant (year-round) rainfall in the western region is also prevalent. The average annual rainfall consists between 100 mm and 520 mm per annum (Botai *et al.*, 2020). The western region and coast, which is located near Port Elizabeth at 34°S, experiences greater drought conditions because of the arid conditions of the Karoo semidesert (Mahlalela *et al.*, 2020).

3.3 Data sources

The following section includes a brief overview of the sources of data used in this study. This includes data from the SAWS, the Global Surface Summary of the Day (GSOD), the Normalised Difference Vegetation Index (NDVI), the Coupled Model Intercomparison Project (CMIP), and the ECMWF Reanalysis v5 (ERA5) gridded data.

3.3.1 South African Weather Service data

SAWS is the country's main meteorological service provider (Bezuidenhout & Schulze, 2006; Bopape *et al.*, 2021). It has the responsibility of supplying weather forecasts and information regarding the weather and meteorological services to the public of South Africa and the Southern African Development Community (SADC) and the surrounding oceans. SAWS maintains Automatic Weather Stations (AWSs) (Sinclair & Pegram, 2010) and Automatic Rainfall Systems (ARSs) (De Coning & Poolman, 2011). There exists a network of AWSs, providing meteorological information (Sinclair & Pegram, 2010). Parameters recorded by the AWSs include temperature, rainfall, humidity, atmospheric pressure, cloud cover, wind speed and direction, to name a few. These parameters are recorded in hourly format (Brighton *et al.*, 2018). Across South Africa, 164 AWSs exist within 1.2 million km² (Sinclair & Pegram, 2010). Open-source data was utilised to supplement the SAWS' supplied datasets. This includes the GSOD consolidated dataset.

3.3.2 Global Surface Summary of the Day data

The GSOD provides a dataset of over 9000 certified in-situ (ground) weather stations situated around the world. Daily meteorological parameters are provided for the weather stations selected at the following web address: <https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00516> (Data.GOV, 2021; Lavigne & Liu, 2022). The GSOD contains arguably the largest dataset of worldwide meteorological stations (Kilibarda *et al.*, 2014, 2015). Every day the GSOD provides meteorological measurements of 11 parameters (Kilibarda *et al.*, 2014). This includes measurements of daily minimum and maximum temperatures, as well as precipitation (rainfall) of that particular day, which is of interest for the current study. Other meteorological parameters include the occurrence of fog, snow, hail, thunder, tornado, relative humidity, mean visibility, mean wind speed, and others (Data.GOV, 2021; Kilibarda *et al.*, 2014; Lavigne & Liu, 2022). One of the limitations of the data is that information concerning the type of instrumentation used for data collection is not specified. Furthermore, changes in instrumentation over the data collection period is, therefore, also not specified (Lavigne & Liu, 2022). Data from 1973 and subsequent years are the most complete (Data.GOV, 2021).

Within this study, the maximum- and minimum temperatures, as well as precipitation data was obtained from 87 stations situated across the western region of South Africa from 1962-2022. The GSOD stations' data was combined with the SAWS data. The total available data percentage and the respective available years were calculated for the GSOD and SAWS stations situated in the study area (Table 6).

The provinces within the study area were divided into district municipalities (Figure 11). The districts were represented by the respective SAWS and GSOD weather stations that it fell under. This method of representing the weather stations was executed to gain a closer perspective of drought within the provinces of the western region. The temperature and precipitation data of each SAWS and GSOD weather station, that fell under each respective district, was averaged between the stations to represent the district. It should be noted that averaging the data within each district presents its own set of limitations as the data is averaged across different landscapes and rainfall-receiving areas. Therefore, the averaged data per district might not accurately represent different regions within a district. Smaller districts should have a better representation of the data.

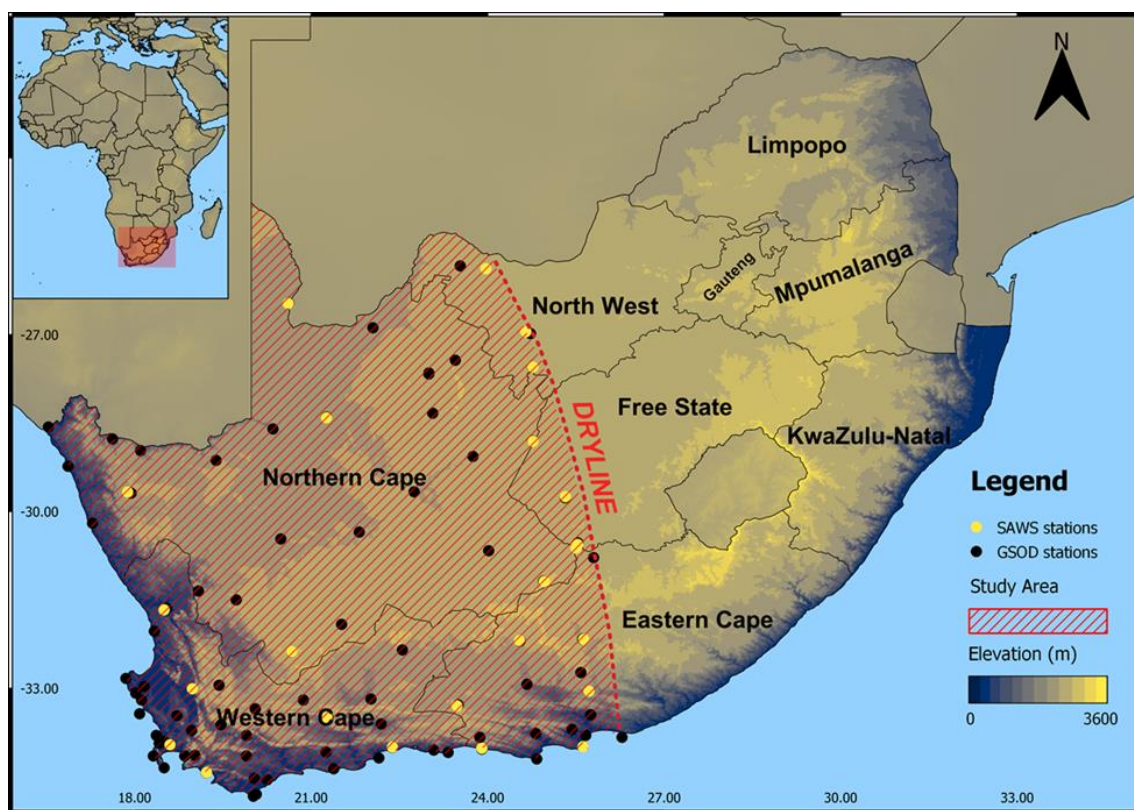


Figure 10: SAWS and GSOD weather stations within the western region of South Africa.

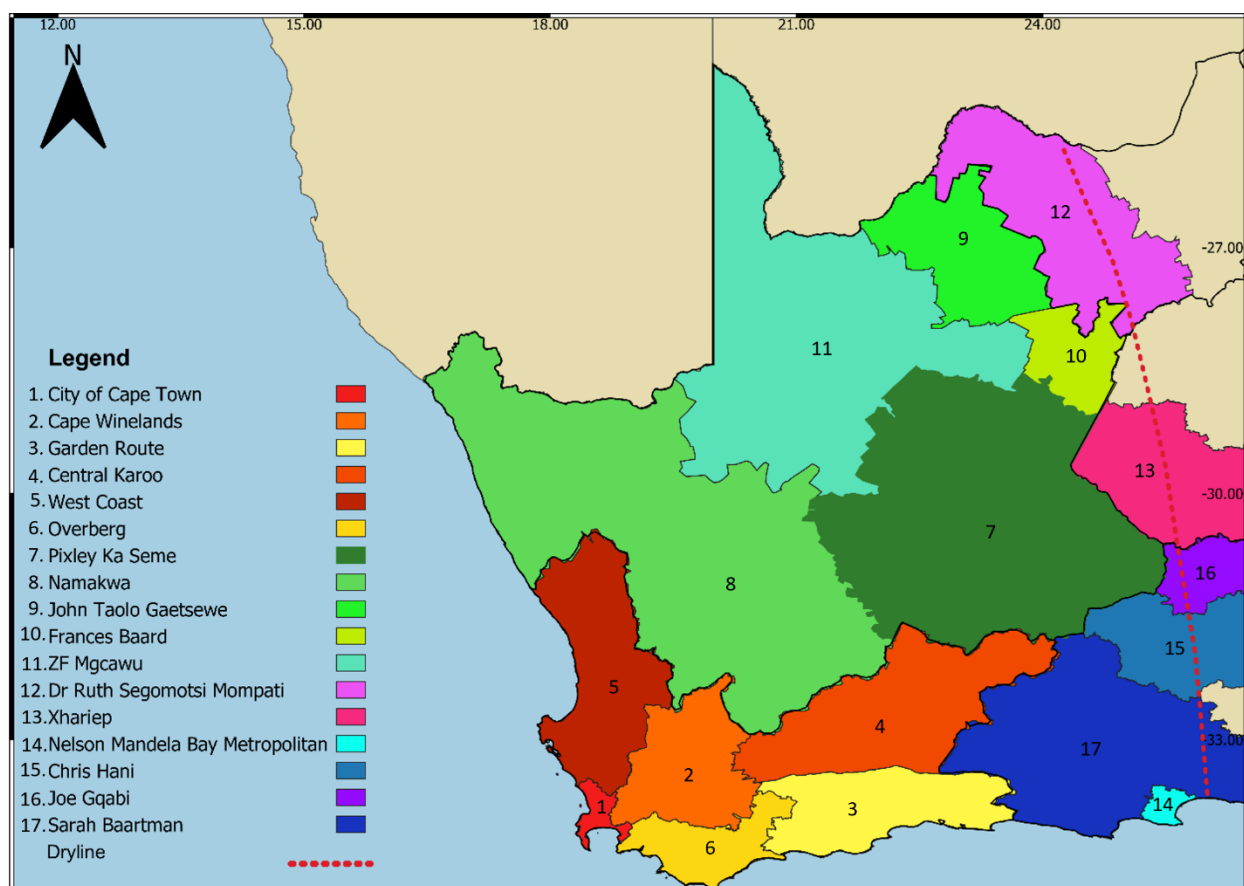


Figure 11: District municipalities within the study area

The percentage available data, and their start and end dates, of the SAWS and GSOD weather stations (when averaged within their respective districts) is shown in Table 6. 11 out of the 17 districts had above 90% available data. An SPEI graph (discussed later) was not generated from SAWS and GSOD data alone if the data was below 90% availability for a district.

Table 6: Percentage temperature and precipitation data availability from SAWS and GSOD of the districts

District	Percentage data available	Start and end date
<i>Northern Cape province</i>		
Frances Baard	99.55%	1962-2022
John Taolo Gaetsewe	49.51%	1977-2022
Namakwa	97.95%	1962-2022
Pixley Ka Seme	70.57%	1968-2022
ZF Mgcawu	99.94%	1962-2022
<i>North West province</i>		
Dr. Ruth Segomotsi Mompati	99.70%	1962-2022
<i>Free State province</i>		
Xhariep	77.89%	1964-2022
<i>Eastern Cape province</i>		

Chris Hani	96.10%	1985-2022
Joe Gqabi	78.46%	1998-2003
Nelson Mandela Bay Metropolitan	99.95%	1962-2022
Sarah Baartman	98.78%	1962-2022
Western Cape province		
Cape Winelands	49.42%	1977-2022
Central Karoo	68.44%	1973-2022
City of Cape Town	99.98%	1962-2022
Garden Route	98.22%	1962-2022
Overberg	90.14%	1973-2022
West Coast	99.92%	1962-2022

3.3.3 Coupled Model Intercomparison Project 6 data

The CMIP is an analysis of the global climate modelling (GCM) data which is organised by the World Climate Research Programme (WCRP) (Meehl *et al.*, 1997). The CMIP exists in order to better grasp the past, present, and future climate. Specifically, the change in the climate is observed via natural variability or radiative forcings. The CMIP has had five previous phases and the CMIP6 is the latest phase (Eyring *et al.*, 2016). It differs from the previous phases in terms of the forcing scenarios and carbon emissions by applying new Shared Socioeconomic Pathway (SSP) scenarios (Sian *et al.*, 2021). The scenarios include the SSP1-2.6 (low forcing pathway), SSP2-4.5 (medium forcing pathway), SSP3-7.0 (medium to high forcing pathway), and lastly the SSP5-8.5 (high forcing pathway). These SSPs depict different future scenarios, ranging from GHG emissions to land use changes, economic assumptions, and climate mitigation measures (Cook *et al.*, 2020).

In this study the SSP2-4.5 scenario was chosen as it is the intermediate path of radiative forcing (Riahi *et al.*, 2017), meaning that it represents what is currently executed by nations in an effort to mitigate GHG emissions (Sian *et al.*, 2021). Therefore, this scenario was selected as the future representation of drought as it uses the data of what is most likely to happen given current efforts. Furthermore, multiple GCMs exist to provide data. Sian *et al.*, (2021) found the FGOALS-g3 model to be one of the best performing GCMs for South Africa in comparison to other models and was thus used in this study. Monthly maximum- and monthly minimum temperature, as well as monthly precipitation data from 2050-2100 was extracted from the Copernicus website (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=form>). The horizontal resolution of the model is 2.25° x 2.25° (latitude x longitude) (Sian *et al.*, 2021). The data was used to process the future (2050-2100) SPEI values/graphs to compare to the past (1962-2022) SPEI values/graphs of the districts.

3.3.4 ECMWF Reanalysis v5 gridded data

ERA5 denotes that it is the fifth generation of atmospheric Reanalysis data, provided by the ECMWF. The product was developed by the European Union's Copernicus Climate Change Service (C3S) and its datasets date back to 1950-present (Bell *et al.*, 2021). Using four-dimensional variational (4D-Var) (Jiang *et al.*, 2021), ERA5 is assembled and stems from the Integrated Forecasting System (IFS) Cy41r2 (Hersbach *et al.*, 2020).

Reanalysis precipitation tools, such as the ERA5, provide important datasets for areas where stations are sparsely located (as is the case with this study area) (Jiang *et al.*, 2021). The term 'Reanalysis' signifies that the tool integrates observations and models to produce "maps without gaps" (Hersbach *et al.*, 2020). Furthermore, Reanalysis operates by collecting observations and combining it with forecasts to provide newly created datasets of previous years. These datasets are more refined than original data observations (Hersbach *et al.*, 2018).

Different precipitation data are produced in different ways in ERA5. Convective precipitation is generated through the convection scheme and large-scale precipitation via the cloud scheme. Both types of precipitation consider rainfall and snow (Jiang *et al.*, 2021). Daily maximum-, daily minimum temperature, and daily large-scale precipitation data was collected from 1962-2021. The horizontal resolution of ERA5 is roughly 30 km (Tarek *et al.*, 2020).

3.3.5 Normalised Difference Vegetation Index data

The NDVI is one of the most commonly used tools based on satellite remote sensing regarding measurements of vegetation (Chikoore & Jury, 2010; Eastman *et al.*, 2013). Its parameters are based on red and near-infrared wavelengths of sunlight reflections (Eastman *et al.*, 2013). The NDVI is calculated through the following (Eidenshink, 1992; Wang *et al.*, 2003):

$$NDVI = \frac{(NIR - VIS)}{(NIR + VIS)} \quad (2)$$

The NDVI is determined through the difference between the near-infrared (NIR) and visible (VIS) reflectance values, which are divided by the summation of the two values (Eidenshink, 1992; Wang *et al.*, 2003). It is measured through satellites operated by the National Oceanic and Atmospheric Administration (NOAA) (Anyamba *et al.*, 2001). The instrument that specifically measures the NDVI values is the Advanced Very High-Resolution Radiometer (AVHRR) (Anyamba *et al.*, 2001) which has 5 channels (Tarpley *et al.*, 1984). As outlined by Tarpley *et al.*, (1984), this instrument measures the VIS band, which ranges between 0.58-0.68

μm , on Channel 1, while Channel 2 measures NIR band, ranging between 0.73-1.10 μm (Tarpley *et al.*, 1984).

The values shown by the NDVI range between -1.0 and 1.0 (Wang *et al.*, 2003). The greater the positive values, the greater the indication is of denser vegetation (Tarpley *et al.*, 1984; Wang *et al.*, 2003). When values are negative, there could be an indication of elements such as water, deserted land, snow, clouds, or ice (Wang *et al.*, 2003). Elements such as snow, clouds, and water have higher reflectivity in the VIS band, resulting in negative NDVI values (Tarpley *et al.*, 1984).

Since the NDVI can take measurements over time, several climatic variables, which include rainfall, are correlated with the NDVI. The tool can be used to detect the effect of climate variability to land surface and biosphere changes (Anyamba *et al.*, 2001). In this study, the NDVI can be used for detecting and monitoring drought, as well as examining the frequency and extent thereof (Anyamba & Tucker, 2012; Peters *et al.*, 2002). NDVI datasets were used to examine changes in vegetation of provinces within the study area from 1984-2021 (early 2021). Data derived from the Food and Agricultural Organisation (FAO) ("Food and Agriculture Organization of the United Nations", 2023).

The Northern Cape and Western Cape are the only two provinces that fall within the study area in their entirety. The remaining provinces fall only partly within the western region (Figure 9). NDVI values were analysed as a whole for provinces in the study area. Analysing at provincial level presents a limitation of masking the NDVI trends that are present across at smaller scales, as averaging at the provincial level would average-out different topographies, vegetation classes, and landscapes.

3.4 Statistical methods

The SPEI is used as a tool to process the precipitation and temperature data. Thereafter, the Mann-Kendall trend analysis is executed to analyse the trends in the SPEI and NDVI data. This section discusses the statistical methods in greater depth.

3.4.1 Standardised Precipitation Evaporation Index

The SPEI was developed by Vicente-Serrano *et al.*, (2010). The SPEI is calculated using precipitation data and the potential evapotranspiration (PET) (through the use of temperature data) (Vicente-Serrano *et al.*, 2010). It is calculated by deducting potential evapotranspiration from precipitation (Vicente-Serrano *et al.*, 2013). PET includes the advantages of the Palmer drought severity index (PDSI) and the SPI. The PDSI considers the fluctuations in temperature

trends, which considers changes in evaporation demand. The SPI is advantageous in the sense that it is multitemporal and is calculated in a simple manner (Beguería *et al.*, 2014; Vicente-Serrano *et al.*, 2010). As the SPEI incorporates both of these advantages, it is beneficial in detecting and monitoring dry/drought conditions (Vicente-Serrano *et al.*, 2010). Temperature variability is also included, which helps to consider the effect of global warming and the severity of drought (Beguería *et al.*, 2014; Vicente-Serrano *et al.*, 2010).

There are several formulations used to calculate the SPEI, the formula used in this study is based on Hargreaves & Samani, (1985), as it requires a limited number of different data variables. Apart from precipitation, the Hargreaves equation (Hg) is only in need of the minimum and maximum temperatures (Beguería *et al.*, 2014).

The SPEI values within the following drought scale is utilised to interpret the values qualitatively (Guttman, 1999):

Table 7: Qualitative classification of SPEI values (Guttman, 1999).

SPEI	Classification
2.0+	Extremely wet
1.5 to < 2.0	Very wet
1.0 to < 1.5	Moderately wet
> -1.0 to < 1.0	Near normal
-1.0 to > -1.5	Moderately dry
-1.5 to > -2.0	Severely dry
< -2.0	Extremely dry

The SPEI is calculated through the following (Vicente-Serrano *et al.*, 2010):

$$SPEI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3}, \quad (1)$$

where

$$W = \sqrt{-2\ln(P)} \quad \text{for} \quad P \geq 0.5$$

P refers to the probability of exceeding a determined value for the difference in precipitation and potential evapotranspiration. C_0 , C_1 , d_1 , d_2 , and d_3 are defined as constants (Vicente-Serrano *et al.*, 2010).

The frequency, duration, and intensity of the drought events were analysed by splitting the examined period (1962-2022) into equal periods which were termed 'period 1' (1962-1991) and

'period 2' (1992-2022). The periods were split based on the 60-year data record. Period 1 of each district started at the available date of the data, leading up to 1991. Period 2 of all the districts ranged from 1992-2021/22 (It ended in 2021 when ERA5 data was substituted and ended in 2022 when data included SAWS and GSOD alone). Districts that had starting dates that were later than 1962 consequently had a shorter period 1. Splitting the data into two periods allowed for easier comparison of the drought characteristics in order to examine change over the years. The decision to keep period 2 the same length was to maintain consistency and more accurate comparisons (by comparing the same years) between the districts to capture climate variability.

Furthermore, two separate datasets were used to generate the SPEI graphs for each district. The 'first dataset' was generated based only on the SAWS and GSOD data if 90% or more was available, therefore including missing values. The 'second dataset' (for the same respective district municipality) was generated by including all the data sources (SAWS, GSOD, and ERA5) to cater for 100% data in the results. SPEI graphs of each dataset were presented to ensure all possible outcomes of the data is shown. If the data availability from SAWS and GSOD was below 90%, only one SPEI graph was generated based on the second dataset alone.

Drought events of -1.0 to -2.0 SPEI values and less are considered moderate to extreme drought events (Table 7). For both period 1 and 2 of each district, every drought event with an SPEI value of -1.0 or less was documented. During each event, that an SPEI value of -1.0 and less occurred, was recorded until conditions were normal (between -1.0 and +1.0). This would represent one 'event', therefore obtaining the *frequency* of events occurring during each period. The time that the events would last (in months and years) was also recorded, which represented the *duration*. The *intensity* of the drought events was recorded by averaging the SPEI values of the given events. Examples of this are depicted in the next Chapter (Table 9). This method was executed extensively in Chapter 4, where past drought conditions were examined. The future drought conditions were analysed using the same concept, but in a briefer manner. The frequency, duration, and intensity were compared between the past and future.

3.4.2 Mann-Kendall trend analysis

The Mann-Kendall test (Kendall, 1955; Mann, 1945) is a non-parametric, robust, trend analysis, without requiring normally distributed data (Abbas *et al.*, 2018; van der Walt & Fitchett, 2021). It can be used to determine whether a trend is present in data (Hoffman *et al.*, 2009). The Mann-Kendall trend analysis was used in many SPI/SPEI and/or NDVI based studies before (e.g. Hoffman *et al.*, 2009; Xulu *et al.*, 2018; Zhang *et al.*, 2012). Within this study it was used to

determine whether positive or negative trends exist within the SPEI and NDVI trends. A trend was considered to be statistically significant at 5% (0.05) level (van der Walt & Fitchett, 2021), meaning that when the p-value was less than 0.05, the null-hypothesis can be rejected and a trend was present (Buhairi, 2010). The Kendall tau (τ) test was used to examine the consistency of the SPEI and NDVI values over the given period. The test shows the difference in probability of two variables that are in order compared to different orders (Mahoney & Schaefer, 2002).

3.5 Data quality control

In order to ensure that quality data is used, a data percentage threshold was applied to each district. If the SAWS and GSOD temperature and precipitation data was less than 90% available (Table 6), then the SPEI graphs for those districts were not processed. The ERA5 data was introduced to fill in the missing values of the SAWS and GSOD data, which would give 100% data availability. Each district either had two SPEI graphs, the first being SAWS and GSOD data alone (if the data availability was above 90%) or only one SPEI graph of the SAWS, GSOD and ERA5 data.

The SPI, and therefore the SPEI, should realistically have a data range of 30+ years (Mckee *et al.*, 1993). Considering this, if the district data was only available from 1993 onwards, it could not have been used. Fortunately, all districts had more than 30 years of available data (Table 7), which would provide a more realistic time frame to analyse the data.

To guarantee quality data, the data was inspected to fall within a certain range so that unrealistic values could be removed from the dataset. For example, rainfall could not contain any negative values and maximum and minimum temperatures were assessed to not contain unrealistic values. Each district's temperature and rainfall data were thoroughly examined from 1962-2022, including the future data of 2050-2100. The NDVI data was also examined to fall within -1 and +1. It was found that no district had unrealistic temperature or rainfall values and the NDVI values were within the correct range.

Daily rainfall, daily maximum- and daily minimum temperatures of the SAWS, GSOD and ERA5 data of the western region from 1962-2021 were used in this study. Data of the western region includes all the weather stations from all the districts, which were averaged to represent the values of the entire study area. The daily maximum and daily minimum temperatures (in °C) fall within a suitable range, indicating that no unrealistic values were present (Figure 12). Daily rainfall (in mm) (Figure 12c) appears different from the temperature, as the median values are between 0-2 mm. The outliers are also shown ranging beyond 25 mm, which is coherent with realistic daily rainfall values.

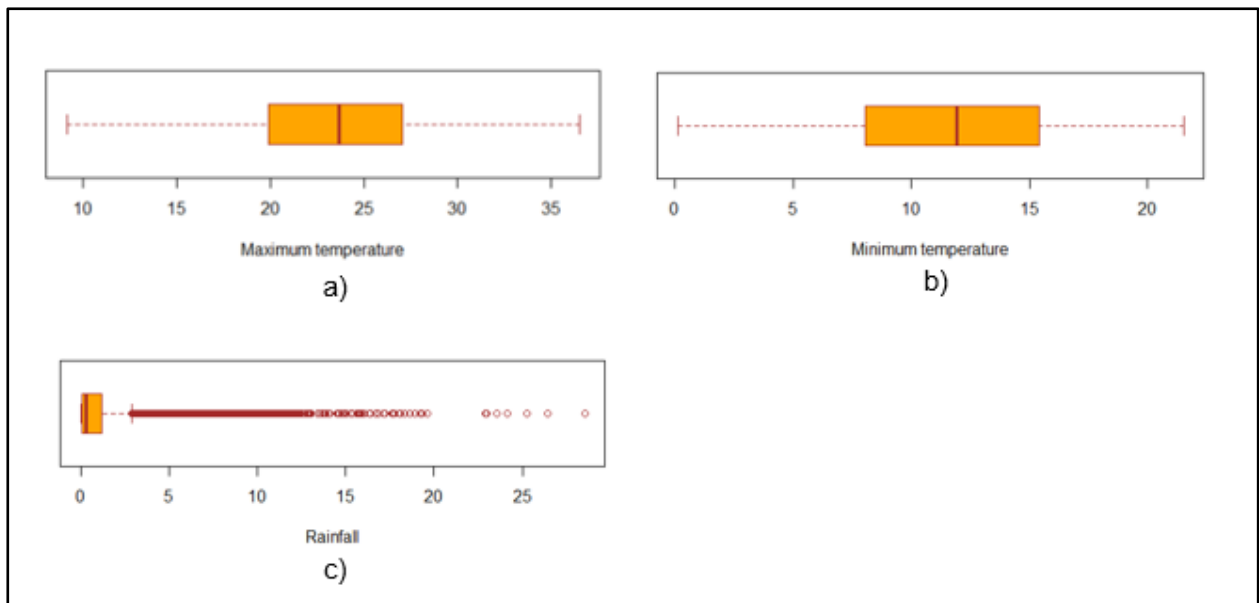


Figure 12: Quartile values of the maximum and minimum temperatures and rainfall of the SAWS, GSOD, and ERA5 data of the western region.

3.6 Limitations of the current study

The SAWS and GSOD weather stations (Figure 10) are not spatially and equally distributed between the provinces. At a local scale, some areas within the provinces have less weather stations than others. Consequently, data of large areas are more generalised based on the results of fewer in-situ weather stations. In order to lessen the impact of this, the GSOD weather stations were also included, in addition to the SAWS weather stations, which would enable more coverage of the areas.

Moreover, the number of stations representing the data of the district municipalities (Figure 10) is not an even amount and is not spread equally. Therefore, some districts, usually smaller, will have a better representation of data than larger districts. Splitting the districts into their local municipalities would have provided a better representation of that area than averaging all of the weather stations under one district. However, there would have been too many local municipalities per province. The scope thereof would have been too lengthy, which is why the decision was made to represent a province via the larger district municipalities.

The instruments used to capture the temperature and precipitation data present limitations themselves. Over the study period (1962-2022), the instruments plausibly underwent change. As such, in earlier years, data was most likely captured via simple human operative rain gauges and then switched to automatic tipping buckets. The simple rain gauge and tipping bucket present their own set of uncertainties which are discussed by Villarini *et al.*, (2008) and Habib *et al.*, (2001) (respectively) in greater detail.

Another limitation that is often present in studies, including this one, is missing values. Out of the 17 districts, 6 had under 90% available SAWS and GSOD data. To combat this, the missing values were substituted with ERA5 data to obtain a 100% dataset for each district. It is known that gridded Reanalysis data (including ERA5) possesses its own set of limitations, such as not capturing at the fine-scale resolution that good ground weather stations can (Tarek *et al.*, 2020). Thus, there is a possibility that the ERA5 data can skew the results as it does not have the same resolution as ground weather stations.

Only 9/17 districts had sufficient data to start in 1962 (Table 6). The remaining districts had less data to analyse in period 1 compared to period 2. This causes a limitation in analysing the data as the possibility to accurately compare the two periods of those districts decreases. The decision was made to keep period 2 the same range between the districts to maintain consistency in comparisons.

The CMIP6 (FGOALS-g3) data was chosen to represent the potential future drought of the western region in this study (objective 3). The model was seen as best-fit for the study as it is the latest model, while similarities were found in results between CMIP5 and CMIP6, indicating accuracy (Cook *et al.*, 2020). Improved performance of the CMIP6 was found by the Land Model Benchmarking Project (Cook *et al.*, 2020). Furthermore, the best-fit model for projections over South Africa was chosen (FGOALS-g3) in order to reduce discrepancies (Sian *et al.*, 2021). Limitations in the use of the CMIP6 in this study was that the extraction of its data was limited to the weather station's locations. As a result, weather stations that were fewer in a district, and districts that were in proximity with one another (Figure 11), projected similar results.

3.7 Chapter summary

In this section, the study area, as the 'western region' was introduced, alongside the districts and the weather stations that are located therein (Figure 9 - Figure 11). The sources of data were introduced, which includes the SAWS, GSOD, ERA5, NDVI, and CMIP6. The statistical methods of processing the data were discussed, which included the SPEI and Mann-Kendall analysis. The limitations pertaining to the data and methods of this study were outlined extensively. The steps and methods taken to present quality results were also discussed. The data and methods outlined in this section have aided in achieving the aim and objectives of the study.

CHAPTER 4: CHARACTERISTICS OF DROUGHT IN THE WESTERN REGION

4.1 Introduction

South Africa is a drought-prone country where the most recent drought conditions (at the time of this study) were experienced in combination with an El Niño event in 2015-16 (Baudoin *et al.*, 2017). As a result, several areas in South Africa have been declared disaster regions in 2016 (Botai *et al.*, 2016, 2017) and are still recovering from the effects. These regions fall mainly within the study area, in which droughts are expected to occur more frequently.

The extent to which a drought impacts a region is influenced by the intensity and duration thereof (Rouault & Richard, 2003). The duration of the event also paves way for different types of droughts to occur. At first, short-term droughts occur without significant impact. Yet, as they potentially intensify (at a slow-moving pace), drought events can last for several years. This is why drought is referred to as having a 'creeping nature' (Malherbe *et al.*, 2016).

This Chapter aimed to characterise drought events in the western region by exploring the frequency, intensity, and duration thereof. This was accomplished by using the SPEI to analyse the characteristics of the drought periods that took place within the region from 1962-2021/2. As a drought event could last for several years, the SPEI for each district was calculated at a 24-month scale (two-year drought period). In addition, the Mann-Kendall test was used to determine whether a trend within the SPEI exists. The seasonal rainfall patterns within the study area were examined to provide insight into the climate variability of the study area.

4.2 Annual rainfall patterns within the western region

The onset of rainfall in the study area is experienced at four seasonal timeframes. The western region of South Africa is characterised by winter rainfall, all-year rainfall, late-summer rainfall, and very late summer rainfall (Botai *et al.*, 2018). The winter rainfall receiving area, commonly designated as the western and southwestern areas of the Western Cape, showed a stark decrease in rainfall from 1962 based on the combined data from SAWS, GSOD, and ERA5. Each district was categorised within a seasonal rainfall receiving area, where the rainfall data from every rainfall receiving area was averaged to compile Figures Figure 13-Figure 16. The annual rainfall trends serve as background information of the rainfall patterns of the western region from 1962-2021, without the influence of temperature data. The total annual rainfall was at its highest in 1962 (751.5 mm), its lowest in 2017 with 68.04 mm, and averaged at 336 mm per annum (Figure 13).

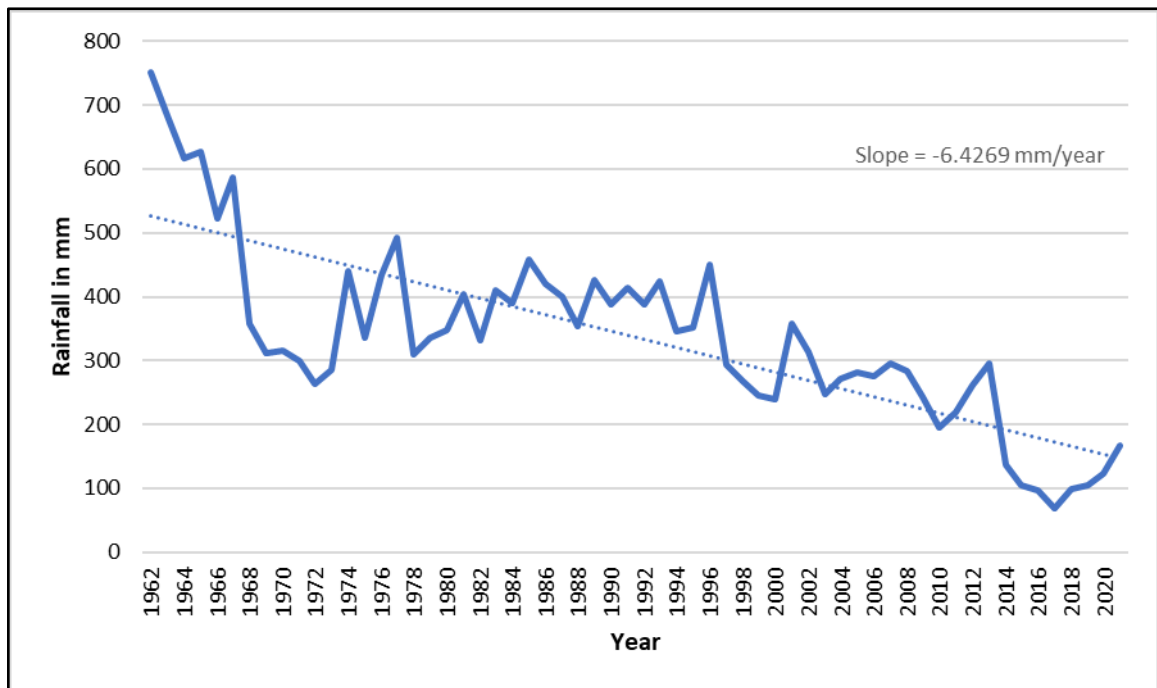


Figure 13: Area average total annual rainfall (in mm) in the winter rainfall area of the western region study area for 1962-2021.

The all-year rainfall receiving area include areas of the south coast within the western region. The data also displayed a decline in rainfall from 1962. The highest total rainfall per annum was 1155 mm which occurred in 1963, with its lowest taking place in 2019, having only 70 mm. Total rainfall per annum from 1962-2021 averaged at 468.6 mm (Figure 14).

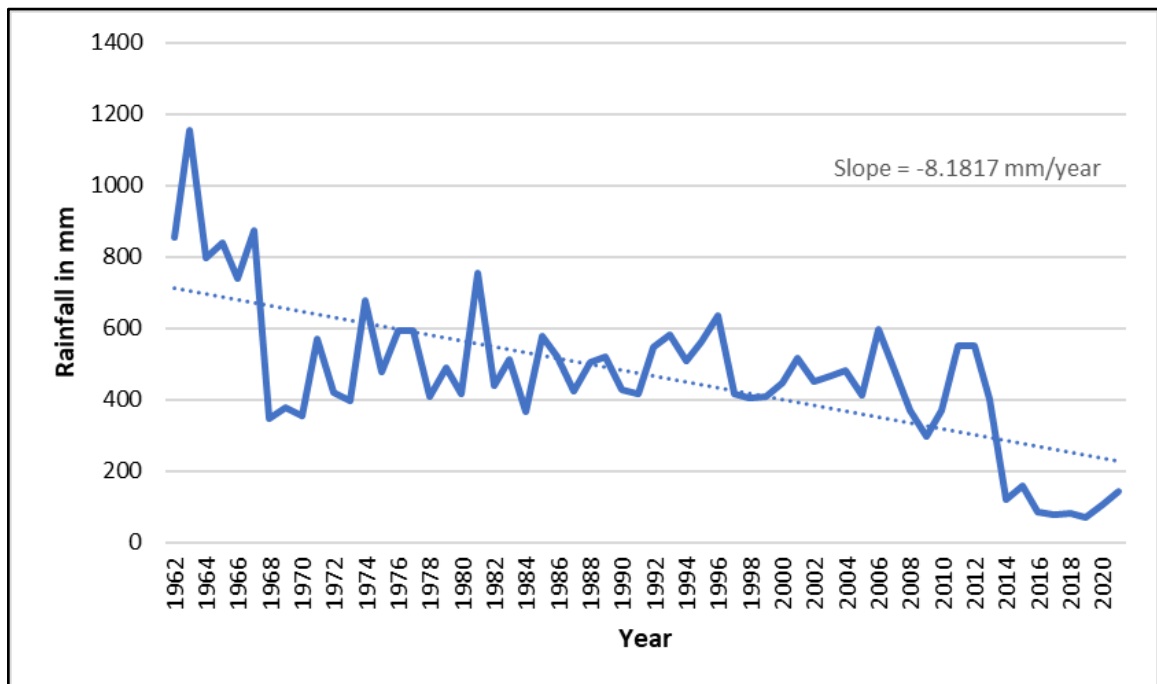


Figure 14: Area average total annual rainfall (in mm) in the all-year rainfall area of the western region study area for 1962-2021.

The late-summer rainfall receiving area include the eastern regions of the study area border, namely parts of the Northern Cape, North-West, Free State, and Eastern Cape. Late summer rainfall is characterised by areas that only receive rainfall from February (Botai *et al.*, 2018). The late-summer rainfall area showed a decline in rainfall from 1962. The highest total rainfall per annum was 1208.3 mm which occurred in 1963, with its lowest occurring in 1992 at 210.8 mm. Total annual rainfall from 1962-2021 averaged at 471.7 mm (Figure 15).

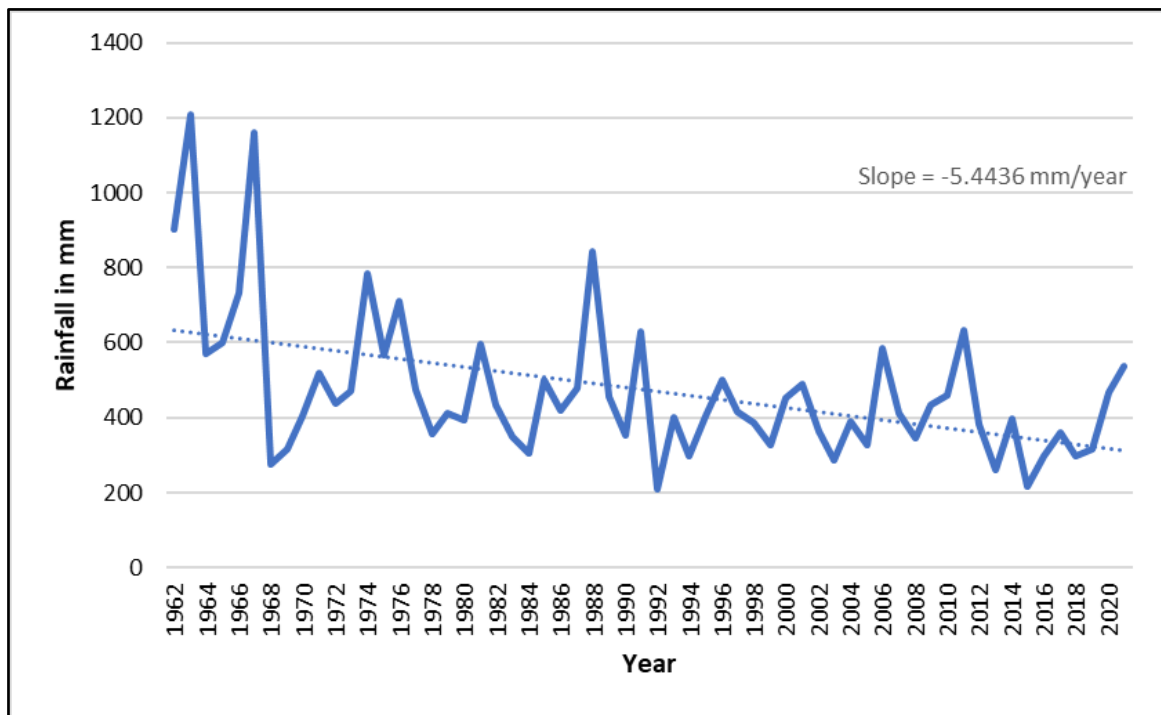


Figure 15: Area average total annual rainfall (in mm) in the late-summer rainfall area of the western region study area for 1962-2021.

The autumn rainfall receiving area include the central regions of the study area, namely parts of the Northern Cape, Western Cape, and Eastern Cape. Autumn rainfall denotes rainfall occurring from March to May (Botai *et al.*, 2018). As with the other rainfall areas, a decline in rainfall is seen from 1962. The highest total rainfall per annum was 944.6 mm which occurred in 1963, with its lowest occurring in 2019 at 94.2 mm. Total annual rainfall from 1962-2021 averaged at 333.6 mm (Figure 16).

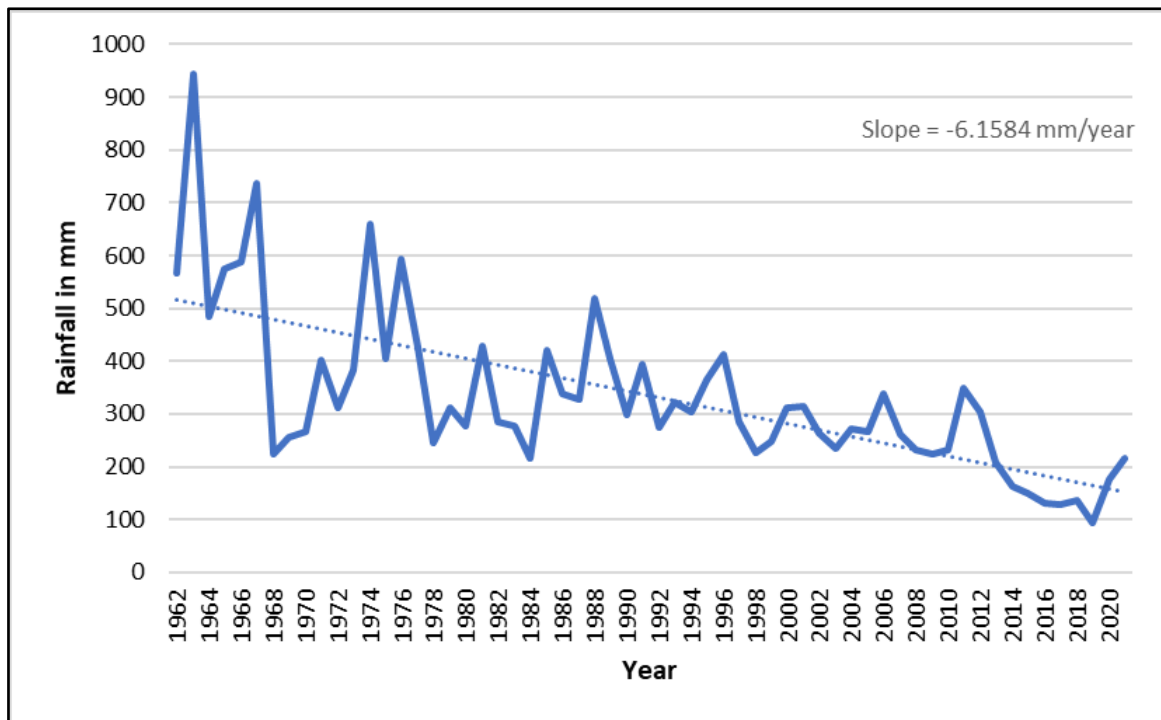


Figure 16: Area average total annual rainfall (in mm) in the autumn rainfall area of the western region study area for 1962-2021.

There are four seasonal rainfall regimes within the study area, each with different timeframes of onset for rainfall. The SPEI analysis will provide greater insight into the drought of the western region. It is examined at a finer scale (district municipal-scale) than the rainfall regimes to analyse the potential changing characteristics of drought in greater detail.

4.3 SPEI results of district municipalities

A meteorological drought is typically analysed at an SPEI time scale of 1-3 months, an agricultural drought at 3-6 months, and a hydrological drought at 12-24 months (Dikshit *et al.*, 2021; Mishra & Singh, 2010). 12–24-month time scales are viewed as long-term droughts (Svoboda *et al.*, 2012). The SPEI for each district was calculated at a 24-month scale, as 2-year, long-term droughts form part of decadal variability (Malherbe *et al.*, 2016). Longer time scales, such as 36 and/or 48-month time scales were not used in this study. This is because a bias may form when fitting the probability distribution due to a limit in the data length (Mishra & Singh, 2010). Even though data over a period of 60 years were used in this study, and is, therefore not limited, a 24-month time scale was deemed fit as a long-term period for analysing drought, without the possible bias when using 36 or 48-month time scales.

4.3.1 SPEI results of the Northern Cape

Six district municipalities are present within the Northern Cape. Frances Baard, which lies towards the North-eastern region of the study area (Figure 11), is the only district municipality of the province to have experienced drought events during period 1 (Table 8). This is evident in both SPEI graphs derived from the first and second datasets (Figure 17a.1 and Figure 17a.2). The drought events during period 1 mostly occurred during 1984, with an average SPEI range of -1.14 to -1.15. These are moderately dry events according to the drought scale (Table 7). Frances Baard displays fluctuating dry- and wet conditions throughout the entire period, yet conditions remain 'near normal' (SPEI -1 to 1) for most of the years. The driest conditions of Frances Baard transpired during 2013-2020, which led to a 'severe' drought average SPEI of -1.51 to -1.55 (Table 8).

When comparing Frances Baard to the other district municipalities, less fluctuation takes place. Within Namakwa, a clear change is seen between the two periods. Period 1 presents conditions that are wetter, while period 2 displays drier conditions. Similarly, ZF Mgcawu, John Taolo Gaetsewe, and Pixley Ka Seme exhibit drier years in the second period, while the first period shows wetter years (Figure 17b.1, Figure 17b.2, Figure 17c.1, Figure 17c.2, Figure 17d, and Figure 17e). Parallel to Frances Baard, most district municipalities endured one large drought event that started continuously in 2013/14 for the remainder of the data period. Therefore, the duration of dry conditions of all the district municipalities is lengthier during the second period than the first period if present at all.

The SPEI graphs of both datasets concur that the duration of the drought events/dry conditions altogether was the longest in Namakwa (ranging at an average of 13-18 years). Both datasets also show that ZF Mgcawu endured the most intense drought conditions (average SPEI of 1.76/7) in the province, resulting in severely dry circumstances. ZF Mgcawu lies in the northernmost part of the study area (Figure 11), which is already arid (Jordaan *et al.*, 2013) and therefore vulnerable to prolonged drought (Dai, 2011). It was found that Namakwa and Frances Baard endured the most drought events, with six and four in total, respectively. The second dataset showed that Frances Baard encountered the most events, with four in total. The differences can be attributed to Namakwa having more missing values from the first dataset (Table 8).

Overall, it is evident from the six district municipalities that the Northern Cape province had greater wet years in period 1 (1962-1991) and greater dry years in period 2 (1992-2021/2). Little to no wet years were present in period 2, while Frances Baard was the only district municipality having drought events during period 1, mostly occurring during 1984. Most of the dry conditions

occurred continuously from 2013 onwards, causing severe drought events in districts of the province. These severe drought events can be associated with the impacts of the 2015/16 El Niño event (Baudoin *et al.*, 2017). The drought events occurring in period 2 explain why the Northern Cape had 20 million hectares of farmland affected by drought proceeding to 2019 (Agri-SA, 2019).

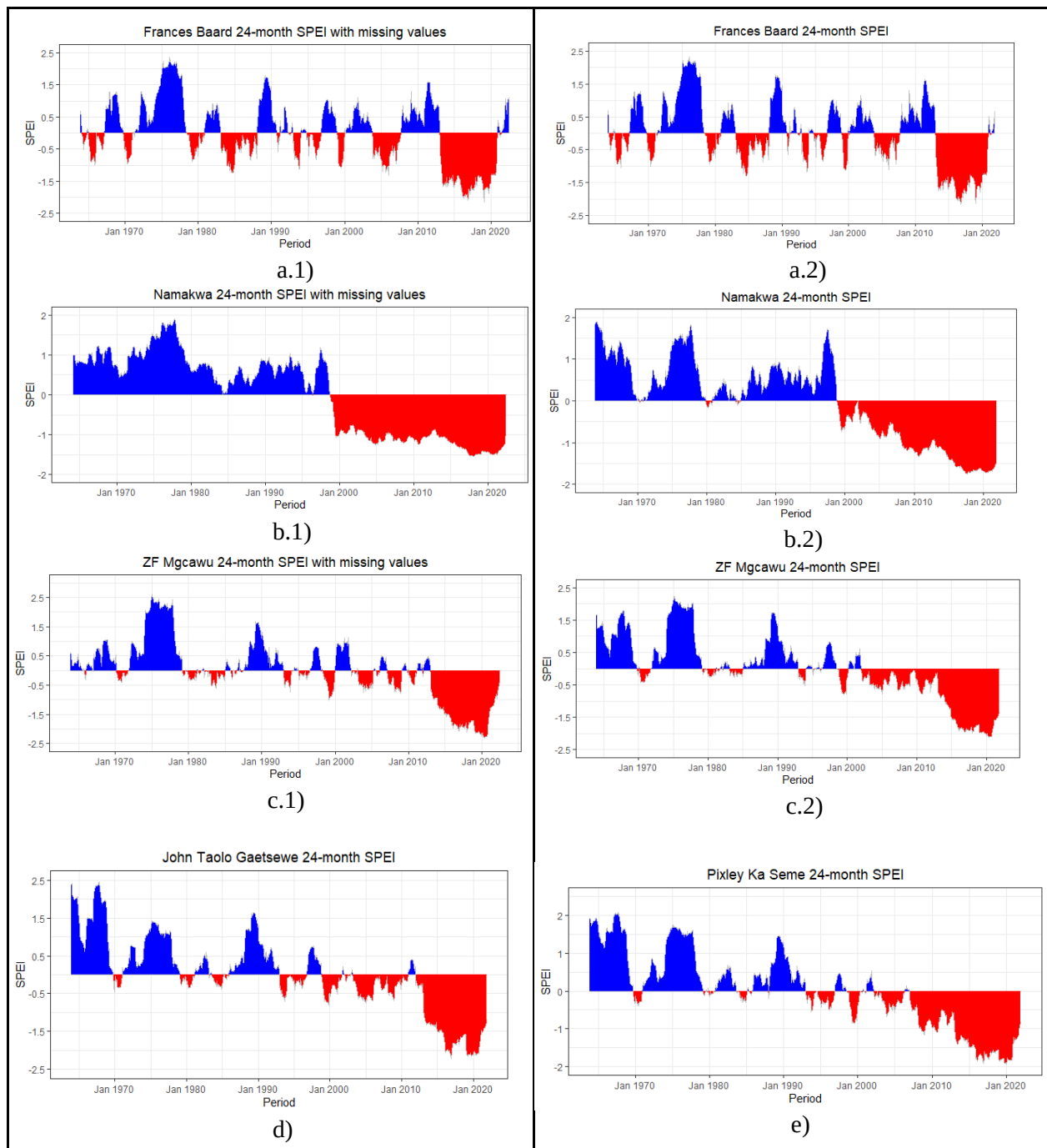


Figure 17: SPEI of the district municipalities within the Northern Cape province. Blue cycles represent wet years and red areas represent dry years. Frances Baard displays the fluctuating wet and dry years, while the other districts show dry years in period 2.

Table 8: Drought characteristics of Northern Cape district municipalities

SPEI derived from SAWS and GSOD data (First dataset)								
District Municipality	Period 1	Frequency of drought events (period 1)	Duration of drought events altogether (period 1)	Average SPEI intensity of drought events (period 1)	Period 2	Frequency of drought events (period 2)	Duration of drought events altogether (period 2)	Average SPEI intensity of drought events (period 2)
Frances Baard (Figure 17a.1)	1962-1991	3	10 months	-1.14	1992-2022	5	9 years	-1.51
Namakwa (Figure 17b.1)	1962-1991	0	n/a	n/a	1992-2022	6	18.08 years	-1.23
ZF Mgcawu (Figure 17c.1)	1962-1991	0	n/a	n/a	1992-2022	2	7.91 years	-1.77
SPEI derived from SAWS, GSOD and ERA5 data (Second dataset)								
Frances Baard (Figure 17a.2)	1962-1991	3	1.08 years	-1.15	1992-2021	4	8.33 years	-1.55
Namakwa (Figure 17b.2)	1962-1991	0	n/a	n/a	1992-2021	2	13.33 years	-1.41
ZF Mgcawu (Figure 17c.2)	1962-1991	0	n/a	n/a	1992-2021	1	7.83 years	-1.76
John Taolo Gaetsewe (Figure 17d)	1962-1991	0	n/a	n/a	1992-2021	1	8.83 years	-1.70
Pixley Ka Seme (Figure 17e)	1962-1991	0	n/a	n/a	1992-2021	3	9.83 years	-1.51

4.3.2 SPEI results of the North West

Two SPEI graphs were generated for one district municipality in the North West province, Dr. Ruth Segomotsi Mompati. The first graph displays results based solely on SAWS and GSOD data (first dataset), i.e., includes missing values (Figure 18a.1). The second graph includes data from all the sources (SAWS, GSOD, and ERA5 i.e., second dataset), therefore displaying SPEI results using 100% data availability (Figure 18a.2). Dr. Ruth Segomotsi Mompati is the only district municipality that falls under the study area within the North West province.

Some discrepancies are present between the two datasets. The first dataset depicts normal conditions from 1962-1970 (Figure 18a.1), however, wet conditions are seen within the same time frame in the results shown from the second dataset (Figure 18a.2). One drought event from period 1 (1962-1991) from the first dataset was noted, however, the SPEI graph derived from

the second dataset did not record this event. The drought noted in 1984 during the first period, was only at an SPEI value of -1.01, which borders close to normal conditions.

Furthermore, similarities are mostly present between the graphs of the two datasets. The district displays intense dry conditions from 2012/3-2017/8 and later again from 2017/8-2020. The total duration of these dry events amounted to eight years. The average SPEI value of these dry conditions ranged between -1.62 to -1.67 (Table 9), correlating to severe dry years. Overall, the time at which these severe dry years occurred (2013 onwards) correlates with the dry events/years of the districts within the Northern Cape. The similarity in timing of these dry years can be attributed to a combination of severe drought events and the strong El Niño event of 2015/16 (Baudoin *et al.*, 2017).

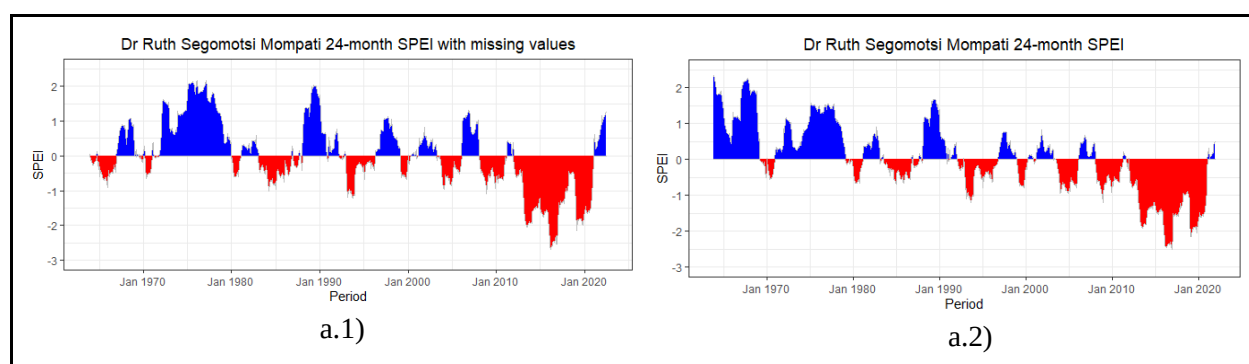


Figure 18: SPEI of the district municipality within the North West province. Wet (blue) to normal conditions are seen in period 1, while dry years (red) are present in period 2.

Table 9: Drought characteristics of North West district municipality.

SPEI derived from SAWS and GSOD data (First dataset)								
District Municipality	Period 1	Frequency of drought events (period 1)	Duration of drought events altogether (period 1)	Average SPEI intensity of drought events (period 1)	Period 2	Frequency of drought events (period 2)	Duration of drought events altogether (period 2)	Average SPEI intensity of drought events (period 2)
Dr Ruth Segomotsi Mompoti (Figure 18a.1)	1962-1991	1	1 month	-1.01	1992-2022	6	7.75 years	-1.67
SPEI derived from SAWS, GSOD, and ERA5 data (Second dataset)								
Dr Ruth Segomotsi Mompoti (Figure 18a.2)	1962-1991	0	n/a	n/a	1992-2021	6	8 years	-1.62

4.3.3 SPEI results of the Free State

Within the Free State, the Xhariep district municipality is the only district included in the study area. Since not enough data sufficed from the first dataset alone, only one SPEI graph was produced using the second dataset (Figure 19).

The Xhariep district also displays fluctuating wet and dry cycles like other districts. However, in this district, the conditions deviate more from the norm, causing multiple drought events in both periods. Period 2 exhibited more drought events (15 compared to 7), longer duration altogether (8 years compared to 1.83 years), and greater SPEI intensity (-1.35 compared to -1.20) (Table 10). The average SPEI of the drought events (of both periods) is not as intense and corresponds to moderately dry conditions. Yet, when viewing the graph, it is also worth noting that within both periods, the drought events peaked beyond moderately dry conditions (Figure 19). It is apparent that during period 1, the drought events peaked at a SPEI of -1.5 in 1970, as well as in 1984. The same intensity occurred during period 2, especially from 2013 onwards, when an SPEI value beyond -2.0 is reached in 2017. Although not for a long duration, these extremely dry conditions still took place, while the overall effect was only moderate.

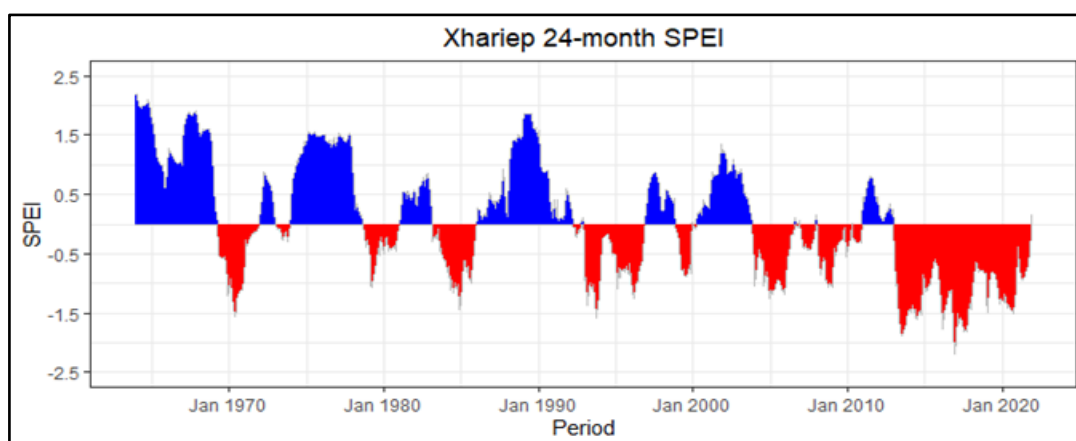


Figure 19: SPEI of the district municipality within the Free State province. Multiple dry years (red) occurred in period 1 and 2, yet it occurred more frequently and intensely in period 2.

Table 10: Drought characteristics of Free State district municipality

SPEI derived from SAWS, GSOD, and ERA5 data (Second dataset)								
District Municipality	Period 1	Frequency of drought events (period 1)	Duration of drought events altogether (period 1)	Average SPEI intensity of drought events (period 1)	Period 2	Frequency of drought events (period 2)	Duration of drought events altogether (period 2)	Average SPEI intensity of drought events (period 2)

Xhariep (Figure 19a.2)	1962- 1991	7	1.83 years	-1.20	1992- 2021	15	8 years	-1.35
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4.3.4 SPEI results of the Eastern Cape

The SPEI results of the Chris Hani-, Nelson Mandela Bay- and Sarah Baartman district municipalities (Figure 20a.1, Figure 20b.1, Figure 20c.1, respectively) were generated based only on the SAWS and GSOD data if 90% or more was available (first dataset). The second set of SPEI results of the same respective district municipalities included all the data sources (second dataset) (Figure 20a.2, Figure 20b.2, Figure 20c.2). Only one SPEI graph was generated for Joe Gqabi (Figure 20d) from the second dataset due to too many missing values from the first dataset.

Within the Eastern Cape, four district municipalities reside within the study area. It should be noted that data from the first dataset for Chris Hani was only available from 1985 onwards, therefore making period 1 short. Overall period 1 displays no drought events, yet 7-10 drought events occurred during period 2 (Table 11). These events remained moderately dry overall, however, both datasets showed values reaching less than -2.0 in 2020. Similar to the Xhariep district, although these extremely dry conditions did occur, the overall average SPEI represented moderately dry conditions only. The wet years are more intense from the results of the first dataset (Figure 20a.1) compared to the second dataset (Figure 20b.2). Both datasets display similar dry events occurring from 2017 onwards, where the most intense dry events occur.

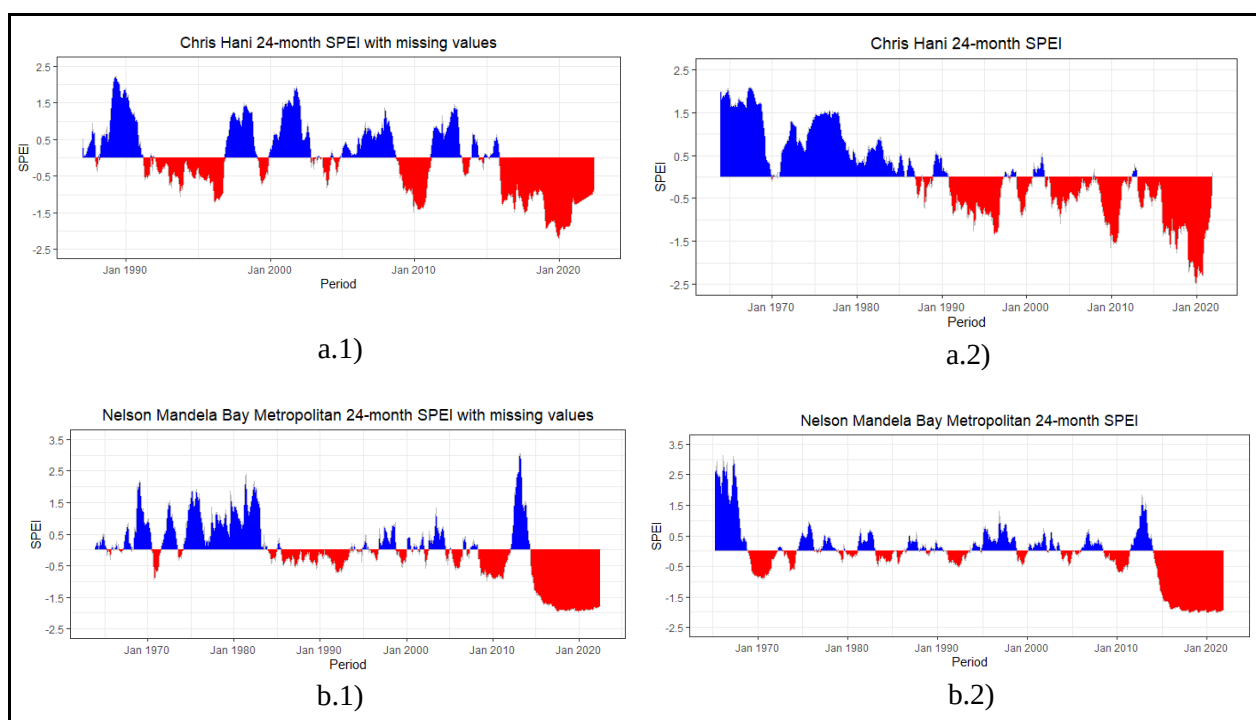
Nelson Mandela Bay Metropolitan displays the most similar patterns between the two datasets of the Eastern Cape (Figure 20b.1 and Figure 20b.2). Although differences in wet years are noticeable, the dry event from 2014 onwards is the only event noted from both datasets. This dry event corresponds to severely dry conditions and lasts continuously for over 7 years.

The Sarah Baartman district displays the most discrepancies between the two datasets. Major wet years are noted in period 2 of the first dataset (Figure 20c.1), while normal conditions are recorded during that time in from the second dataset (Figure 20c.2). Moreover, a total of 7 drought events are noted in period 1 from the first dataset, which is not noted in the second dataset. When solely turning to the first dataset, Sarah Baartman is one of the few districts, out of all the provinces, that displays more drought events in period 1 than in period 2. Since there is no consensus between the datasets, it is more beneficial to consider both results than only one. Nevertheless, both sets do note that four drought events occurred in period 2, ranging from

moderate to severely dry conditions. Similar to what was seen in other districts from other provinces, an incessant drought event is seen starting from 2014 onwards (Figure 20c.2).

For the Joe Gqabi district, it is seen that severe to extreme wet years were mainly present in period 1, while period 2 mostly presented severe to extreme dry years (Figure 20d). Only one moderate drought event occurred in 1984, while six drought events occurred in period 2, with an average SPEI of -1.77. This average is equivalent to severely dry conditions. What is notable about this district is that the long drought event that took place occurred earlier in period 2 (1999-2004). This is unlike the other districts in the Eastern Cape and other provinces, where a long continuous drought event was displayed taking place from 2014 onwards.

Districts in the Eastern Cape show fluctuating wet and dry cycles. Although discrepancies are present in each district between the two datasets, a similar pattern is seen in the later stages of period 2. From 2014 onwards, Nelson Mandela Bay Metropolitan and Sarah Baartman show one large dry event occurring. The Chris Hani district shows a similar event(s) occurring from 2017 onwards. Joe Gqabi shows an anomalous occurrence where a severe to extremely dry event is seen in the earlier stages of period 2 and not towards the end. Although it is anomalous compared to the other districts, this event can also be attributed to separate El Niño events taking place during that time (Lakhraj-Govender & Grab, 2018). Overall, more dry events have transpired during period 2 in comparison to period 1 in the Eastern Cape.



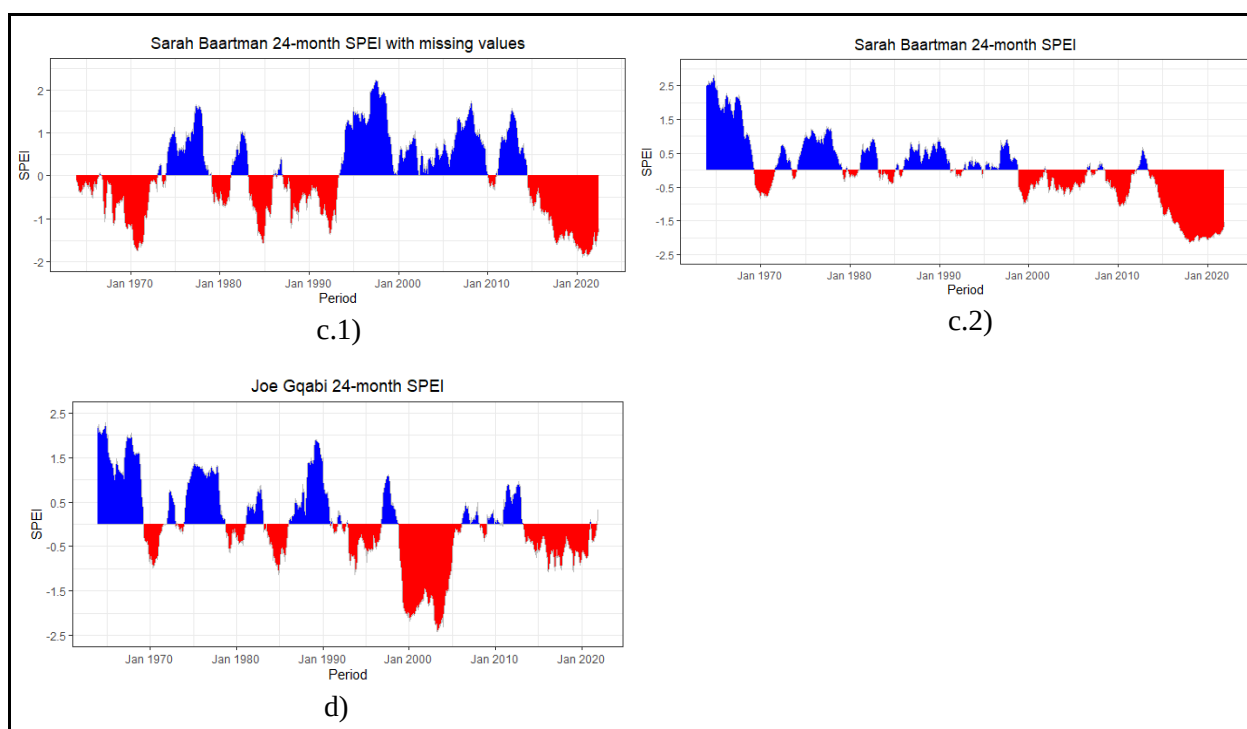


Figure 20: SPEI of the district municipalities within the Eastern Cape province. Fluctuating wet (blue) and dry (red) years are seen in all districts. More dry conditions are present in period 2 compared to period 1.

Table 11: Drought characteristics of Eastern Cape district municipalities

SPEI derived from SAWS and GSOD data (First dataset)								
District Municipality	Period 1	Frequency of drought events (period 1)	Duration of drought events altogether (period 1)	Average SPEI intensity of drought events (period 1)	Period 2	Frequency of drought events (period 2)	Duration of drought events altogether (period 2)	Average SPEI intensity of drought events (period 2)
Chris Hani (Figure 20a.1)	1985-1991	0	n/a	n/a	1992-2022	10	4.66 years	-1.48
Nelson Mandela Bay Metropolitan (Figure 20b.1)	1962-1991	0	n/a	n/a	1992-2022	1	7.83 years	-1.79
Sarah Baartman (Figure 20c.1)	1962-1991	7	4 years	-1.34	1992-2022	4	6.16 years	-1.49
SPEI derived from SAWS, GSOD, and ERA5 data (Second dataset)								
Chris Hani (Figure 20a.2)	1962-1991	0	n/a	n/a	1992-2021	7	4.083 years	-1.28
Nelson Mandela Bay Metropolitan (Figure 20b.2)	1962-1991	0	n/a	n/a	1992-2021	1	7.25 years	-1.89

Sarah Baartman (Figure 20c.2)	1962-1991	0	n/a	n/a	1992-2021	4	7.92 years	-1.72
Joe Gqabi (Figure 20d)	1962-1991	1	3 months	-1.11	1992-2021	6	6.58 years	-1.77

4.3.5 SPEI results of the Western Cape

The SPEI results of the City of Cape Town-, Garden Route-, Overberg-, and West Coast district municipalities (Figure 21a.1, Figure 21b.1, Figure 21c.1, and Figure 21d.1, respectively) were derived from the SAWS and GSOD data since 90% or more was available (first dataset). The second set of SPEI results of the same respective district municipalities included all the data sources (second dataset) to cater for 100% data availability (Figure 21a.2, Figure 21b.2, Figure 21c.2, and Figure 21d.2). The Cape Winelands and Central Karoo (Figure 21e and Figure 21f, respectively) only have SPEI results from the second dataset due to too many missing values from the first dataset.

Fewer fluctuations are observed in the six district municipalities of the Western Cape when compared to the other provinces (Figure 21). Most of the SPEI graphs indicate that period 1 experienced greater wet events and little to no dry events while the opposite occurred during period 2. Greater similarities between the two datasets are observed in comparison to the Eastern Cape. When viewing the City of Cape Town, no dry years, alongside severe- to extreme wet years, and normal conditions occurred during period 1. During period 2, one long, severe (average SPEI of -1.6 and less) dry event occurred from 2014 onwards, which is a similar time frame to the other provinces.

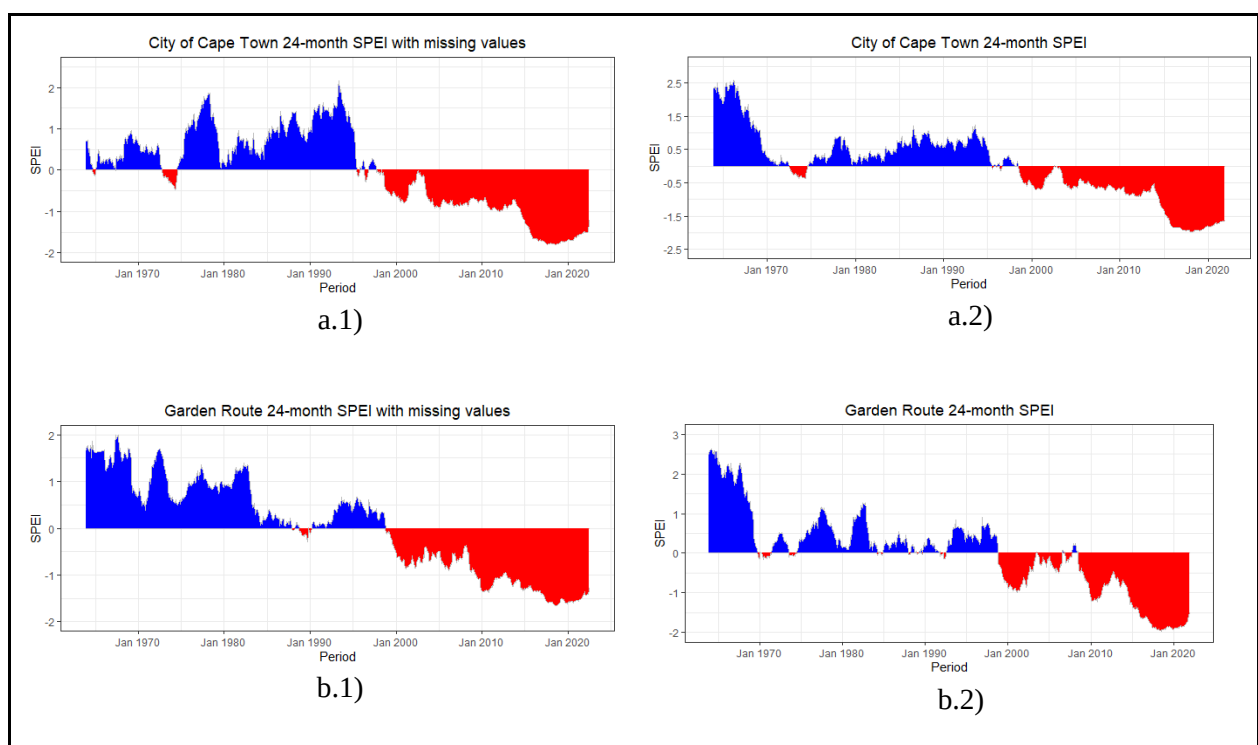
The Garden Route, differences in the duration are observed between the two datasets. The first dataset showed that the drought events endured overall for nearly 13 years, while the second dataset showed close to 9 years (Table 12). While the duration differs, both sets showed that two drought events occurred during period 2. The intensity of the drought events differs, ranging from moderate to severe drought conditions. Overberg also exhibits differences, as the results from the first dataset only started in 1973 (Figure 21b.1). More intense wet years are observed from 1994-1999, which is not present in the second dataset (Figure 21b.2). Yet, both highlight the continuous drought event that occurred from 2015 onwards, which corresponds to severely dry conditions.

The West Coast is the only district of the Western Cape to have experienced drought events in period 1 (Figure 21d.1). These events occurred in 1967, 1969-1971, and 1972-1974. On average, drought events only caused moderately dry conditions (Table 12). The opposite is recorded from the second dataset, where extreme wet years, to normal conditions occurred during that time frame (Figure 21d.2). Although these discrepancies are present, it is important

to consider both scenarios from the two different datasets. Both sets have established that period 2 was drier, with two to four dry events having occurred. The second dataset conveyed that the drought events occurred at a greater severity of -1.57 compared to -1.30 (Table 12).

The Cape Winelands and Central Karoo had insufficient data from SAWS/GSOD alone, thus generating results solely from the second dataset. Both districts follow a similar pattern because of their proximity (Figure 21e and Figure 21f). Period 1 (1962-1991) underwent severe to extreme wet events, which gradually decreased and developed into normal conditions. This eventually evolved into dry events in period 2 (1992-2021/22). The Cape Winelands experienced one long dry event, which lasted from 2015 onwards, correlating to great severity according to the drought scale. The Central Karoo endured a smaller drought event which peaked in 2010. The district then experienced a similar drought event developing from 2014 onwards. This event was still severe, but less intense than in the Cape Winelands.

The entire Western Cape followed a similar pattern, where period 1 displayed having greater wet years and period 2 had considerable dry years (Figure 21). The similarity thereof could arguably be because the stations and districts are in proximity and had similar weather patterns. Only the West Coast had dry events taking place in period 1 (according to first dataset), while no other district displayed any dry events with an SPEI less than -1.0 during period 1. All the districts endured at least one dry event during period 2, most being severe on average. These events commenced mainly in 2014 when most of the districts endured one large continuous dry event.



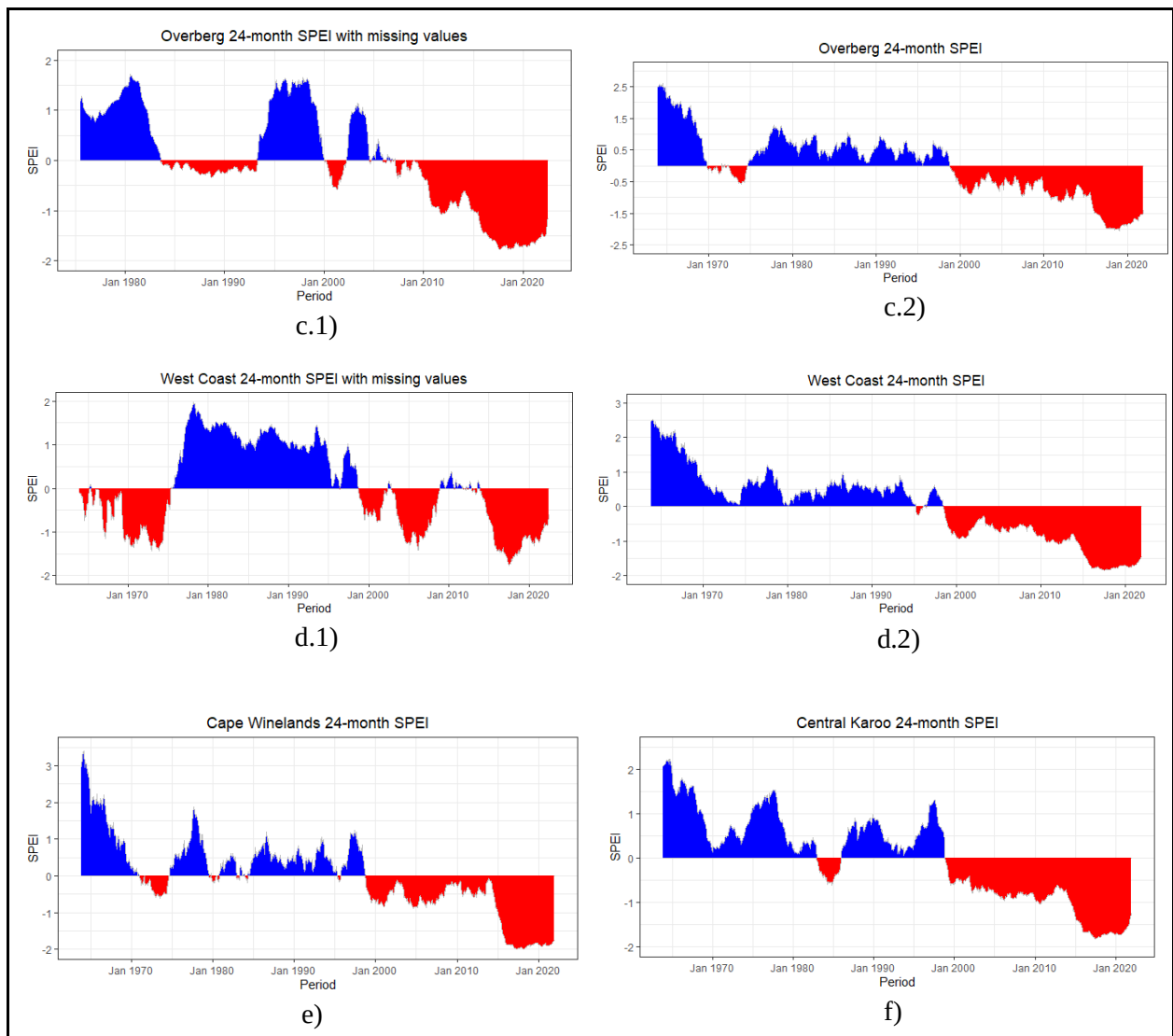


Figure 21: SPEI of district municipalities within the Western Cape province. Most districts display wet (blue) to normal conditions in period 1 and drier (red) conditions in period 2

Table 12: Drought characteristics of Western Cape district municipalities

SPEI derived from SAWS and GSOD data (First dataset)								
District Municipality	Period 1	Frequency of drought events (period 1)	Duration of drought events altogether (period 1)	Average SPEI intensity of drought events (period 1)	Period 2	Frequency of drought events (period 2)	Duration of drought events altogether (period 2)	Average SPEI intensity of drought events (period 2)
City of Cape Town (Figure 21a.1)	1962-1991	0	n/a	n/a	1992-2022	1	8 years	-1.62
Garden Route (Figure 21b.1)	1962-1991	0	n/a	n/a	1992-2022	2	12.83 years	-1.34
Overberg (Figure 21c.1)	1973-1991	0	n/a	n/a	1992-2022	4	8.5 years	-1.51
West Coast (Figure 21d.1)	1962-1991	3	4.33 years	-1.22	1992-2022	2	8.83 years	-1.30
SPEI derived from SAWS, GSOD, and ERA5 data (Second dataset)								
City of Cape Town (Figure 21a.2)	1962-1991	0	n/a	n/a	1992-2021	1	7.58 years	-1.76
Garden Route (Figure 21b.2)	1962-1991	0	n/a	n/a	1992-2021	2	8.92 years	-1.63
Overberg (Figure 21c.2)	1962-1991	0	n/a	n/a	1992-2021	7	7.92 years	-1.62
West Coast (Figure 21d.2)	1962-1991	0	n/a	n/a	1992-2021	4	9 years	-1.57
Cape Winelands (Figure 21e)	1962-1991	0	n/a	n/a	1992-2021	1	7 years	-1.83
Central Karoo (Figure 21f)	1962-1991	0	n/a	n/a	1992-2021	2	7.92 years	-1.59

4.3.6 SPEI of the western region of South Africa

The SPEI result for the western region was averaged from all the stations, from all the district municipalities, of the entire western region. The data derived from SAWS, GSOD, and ERA5 (second dataset) (Figure 22). This because not all districts have at least 90% or above from SAWS and GSOD data alone.

Parallel to the patterns seen in the SPEI graphs of the Western Cape, the western region presented severe- to extreme wet years during the beginning of period 1. Conditions then

stayed normal (SPEI of 1 to -1) from 1980 to 2013. From 2014, the western region endured dry conditions for 7.5 years, that led to a severe drought with an average SPEI of -1.75. Overall, all the stations, constituting the entire western region, conveyed wet- to normal conditions in period 1, while severe drought conditions unveiled in period 2. Causes behind these results are discussed in detail within the discussion section.

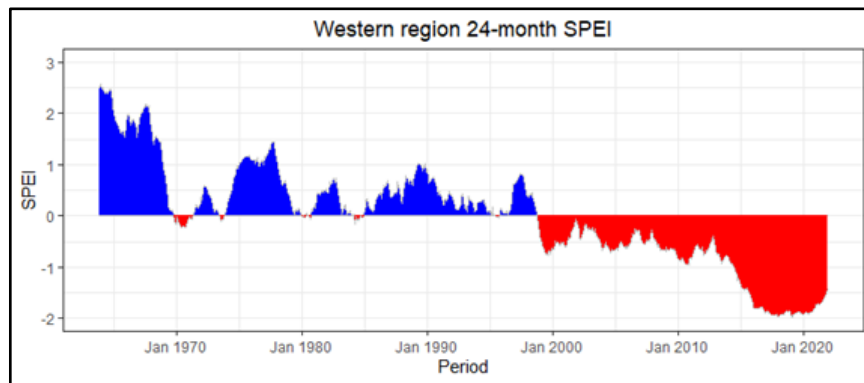


Figure 22: SPEI result of the entire western region. Wet years (blue) occurred in the beginning of period 1, with normal conditions present thereafter. Severe drought years occurred in period 2 from 2014 (red).

Table 13: Drought characteristics of the entire western region

SPEI derived from SAWS, GSOD, and ERA5 data (Second dataset)								
Region	Period 1	Frequency of drought events (period 1)	Duration of drought events altogether (period 1)	Average SPEI intensity of drought events (period 1)	Period 2	Frequency of drought events (period 2)	Duration of drought events altogether (period 2)	Average SPEI intensity of drought events (period 2)
Western region (Figure 22)	1962-1991	0	n/a	n/a	1992-2021	1	7.5 years	-1.75

4.4 Mann-Kendall trend test

All the districts, except for Sarah Baartman, had a p-value under 0.05 (Table 15). Therefore, the null hypothesis can be rejected, indicating that a trend is present in the SPEI data. Most districts also show negative Tao values, indicating that the data possesses a negative trend, supporting the observations made from the results. The negative trends reinforce that the conditions, from 1962-2021/22, were becoming drier, yet to different degrees. From the first dataset, the province with the greatest negative trends includes the Western Cape, where the Garden Route obtained a Tao value of -0.777. Namakwa also obtained a relatively strong negative trend of -0.681, indicating that some of the arid areas of the Northern Cape were becoming drier. Sarah Baartman is the only district that does not have a trend present in the data according to the p-

value. The Tao value is also the only positive trend, in comparison to the other districts, but is invalid to consider since no trend exists in the data. The district shows completely different results when turning to the second dataset, as a trend is indeed present, while a relatively strong negative Tao value is shown. The difference between the results could be due to the ERA5 data that serves as a substitution of missing values in the first dataset, which caused differences in results. Nevertheless, the second dataset of Sarah Baartman is more reliable according to the trend test.

The second dataset showed that all districts had a p-value under 0.05, meaning that a trend is present, while all Tao values are also negative. In coherence with the first dataset, the districts of the Western Cape in the second dataset also obtained the greatest negative trends, reinforcing that the province was becoming drier. Most districts of the Northern Cape also follow the drying negative trend, except for Frances Baard, which obtained a slight negative trend of -0.2 in both datasets. The extent of the negative trends varied for the districts of the Eastern Cape. The Dr. Ruth Segomotsi Mompati district of the North West obtained a stronger negative trend in the second dataset than the first. The Xhariep district did not obtain as a significant negative trend, meaning that conditions are drying to a lesser extent than other districts of the western region. The overall western region obtained a strong negative Tao value of -0.673, which is in coherence with the drying trend that was observed (Figure 21).

Table 14: Mann-Kendall trend test: Tao value and p-value of all the district municipalities

SPEI derived from SAWS and GSOD data (First dataset)		
District municipalities	Kendall Tao value	p-value
Frances Baard	-0.212	< 2.22e-16
Namakwa	-0.681	< 2.22e-16
ZF Mgcawu	-0.435	< 2.22e-16
Dr Ruth Segomotsi Mompati	-0.298	< 2.22e-16
Chris Hani	-0.281	< 2.22e-16
Nelson Mandela Bay Metropolitan	-0.394	< 2.22e-16
Sarah Baartman	0.0204	4.2e-1
City of Cape Town	-0.505	< 2.22e-16
Garden Route	-0.777	< 2.22e-16
Overberg	-0.515	< 2.22e-16
West coast	-0.279	< 2.22e-16
SPEI derived from SAWS, GSOD, and ERA5 data (Second dataset)		
Frances Baard	-0.211	< 2.22e-16
Namakwa	-0.628	< 2.22e-16
ZF Mgcawu	-0.588	< 2.22e-16
John Taolo Gaetsewe	-0.582	< 2.22e-16
Pixley Ka Seme	-0.674	< 2.22e-16
Dr Ruth Segomotsi Mompati	-0.51	< 2.22e-16
Xhariep	-0.393	< 2.22e-16
Chris Hani	-0.639	< 2.22e-16
Nelson Mandela Bay Metropolitan	-0.251	< 2.22e-16
Sarah Baartman	-0.538	< 2.22e-16
Joe Gqabi	-0.336	< 2.22e-16
City of Cape Town	-0.617	< 2.22e-16
Garden Route	-0.624	< 2.22e-16
Overberg	-0.64	< 2.22e-16
West Coast	-0.719	< 2.22e-16
Cape Winelands	-0.547	< 2.22e-16
Central Karoo	-0.674	< 2.22e-16
Western region (entire study area)	-0.673	< 2.22e-16

4.5 Discussion

The primary pattern of drought that emerges from the analysis is that most districts in South Africa, west of the dry line, encountered significantly more dry events in period 2 (1992-2021/22) than in period 1 (1962-1991). Sarah Baartman and the West Coast were the only

districts out of all the provinces to exhibit the opposite, where more dry events occurred during the first period. However, this was only noted by the results of the first dataset, yet as shown by the Mann-Kendall results, the first dataset of Sarah Baartman is less reliable as no trend is present. The second dataset, like the other districts, showed that Sarah Baartman and the West Coast endured more dry events in the second period. The average SPEI of the drought events was more intense for most district municipalities in period 2 than period 1. Nelson Mandela Bay Metropolitan displayed the most intense average SPEI, of -1.89 in period 2, which falls under the severe category, bordering on extreme dryness. Moreover, when taking the duration of the drought events into account, dry events of all the districts were longer in period 2 than period 1.

The dry years that were recorded for 6 out of the 17 districts in period 1 occurred in the years 1969-1971 (Sarah Baartman, West Coast, Xhariep), 1972-1974 (West Coast), and 1983-1985 (Frances Baard, Xhariep). These dry years pursued at an average cyclic duration of ~2 years. These cycles occurred at an average of every ~5 years (varying between 1-9 years). Single year droughts took place in 1965 (Frances Baard), 1966 (Sarah Baartman), 1967 (Sarah Baartman, West Coast), 1979 (Xhariep), 1984 (Sarah Baartman, Frances Baard, Dr. Ruth Segomotsi Mompati, Joe Gqabi), 1987, 1988, and 1991 (Sarah Baartman). Period 1 droughts were moderate when examining the average SPEI. The majority districts, where the drought events took place, are located towards the north-eastern and south-eastern regions of the study area, on the border of the KD (Figure 11).

The dry years from period 1 correspond to the drought years recorded by Malherbe *et al.*, (2016) for the entire country. Fauchereau *et al.*, (2003) highlights that the period 1970-1988 underwent extended droughts that were connected to peaks in the ENSO cycle. Ultimately, the drought events related to ENSO are mostly connected to rainfall variability in southern Africa (Fauchereau *et al.*, 2003). The 1983-1985 drought that took place in Frances Baard and Xhariep relates to the 1982-1984 drought that transpired on the plateau of southern Africa (Jury & Lyons, 1994). Several districts recorded a single year drought in 1984. During 1983, a low phase of ENSO caused increasing westerly winds over the plateau of southern Africa, which was attributed to the summer drought of 1983. Furthermore, as a consequence of the 1982-1984 droughts, outgoing longwave radiation (OLR) was above normal over the plateau, and summer rainfall was recorded as 60% below the average (Jury & Lyons, 1994).

Dry years occurred in period 2, most notably in the 2000s and 2010s. Most dry years took place in 1999-2004, 2004-2009, and 2012-2021/22. Numerous ranges transpired from the districts as some dry years started earlier or later than the ranges indicated. What is noticeable is that dry years in period 2 occurred more frequently than in period 1, which is why assigning dry periods in ranges is not as simple. These dry years occurred on an average cyclic duration of ~6.6

years. These dry spells typically lasted an average of ~1.5 years (varying between 1 and 3 years). Multiple single year droughts were also observable in period 2 within the districts, starting in 1992/93, 1995/96, 1999, 2004-2013, 2015-2019. The most distinguishable dry period is 2012-2021/22 since it was recorded taking place in all the districts except for Joe Gqabi. It should be noted that most districts record this dry period, although the onset thereof varied between 2012 and 2014. The Cape Winelands, Chris Hani, Overberg, and Xhariep recorded the dry period starting later (2015 and lasting until 2019). Therefore, the majority of the western region experienced a severe dry period, from about 2012 to 2022, except for Joe Gqabi in the Eastern Cape.

Southern Africa is well known to have experienced a severe drought in 1992-1993. These drought years (recorded as a single drought year in many districts) were driven by an El Niño event (Vogel & Van Zyl, 2016). El Niño events occurred during 1991-1992, 1997-1998, 2002-2003, 1993, 1995, 2009-2010, 2015-2016, with either climatic impacts over southern Africa alone or globally (Lakhraj-Govender & Grab, 2018; Rouault & Richard, 2005). It should be reiterated that drought events can occur without an El Niño event and/or co-occur with each other (Baudoin *et al.*, 2017). Many studies have highlighted the strong 2015-2016 El Niño event that affected South Africa (Baudoin *et al.*, 2017; Lakhraj-Govender & Grab, 2018; Yuan *et al.*, 2018). Baudoin *et al.*, (2017) noted that the 2015-2016 El Niño event co-occurred with a severe drought in South Africa. All the districts in this study, besides Joe Gqabi, took record of the 2015-2016 El Niño event. However, the results mostly show that the drought event took place for longer, lasting beyond 2016. This could be due to changes in the Indian Ocean SST variability, high pressure anomalies, increasing flash droughts, and ultimately a warming climate (Yuan *et al.*, 2018), causing the drought event to last longer.

In the Western Cape, the drought was considered to have lasted from 2015-2018. It was considered the worst drought since 1904, mainly caused by a series of below-average rainfall over three years (Burls *et al.*, 2019; Dube *et al.*, 2022; Theron *et al.*, 2021). Other reasons were due to record-breaking warm temperatures from 2015-2017 (Theron *et al.*, 2021), the influence of El Niño, a poleward shift in the moisture corridor, and a displacement in the jet stream (Dube *et al.*, 2022), influencing local weather. The results from this study showed that the drought events in the Western Cape mostly started in 2014/15 and ended in 2021/22. Due to the longevity of the drought and its effect on economic sectors, this severe drought was considered a socio-economic drought (Theron *et al.*, 2021).

Overall, the western region (as a whole) (Figure 22) experienced the severe drought event from 2014-2021. The Mann-Kendall results also confirm that a negative drying trend is present in the western region (Table 14). ENSO could have played an important role in lower observed rainfall

amounts within the summer rainfall region (Malherbe *et al.*, 2016). The winter-rainfall region (Western Cape) was influenced by below-average rainfall for three consecutive years, which were superimposed on an El Niño event (Dube *et al.*, 2022). The country is also susceptible to climate variability because of the incidence of high-pressure anomalies (Malherbe *et al.*, 2016; Mulenga *et al.*, 2003). Considering that in period 2, drought events endured on average about 6.6 years (for the entire region), decadal variability could be another factor playing a part in driving the drought cycles (Jury, 2015; Malherbe *et al.*, 2016). Drought events occurred more frequently and more intensely in period 2 than period 1. This finding is aligned with the IPCC findings in 2014 of downward trends in rainfall in the western parts of South Africa (IPCC, 2014). Overall, provinces within the western region were declared disaster regions from 2014-2017 (Botai *et al.*, 2016, 2017), which concur with the results of the drought event in the region.

4.6 Recommendations for district municipalities

Drought events occurred more intensively and for longer durations in the period 2 (1992-2021/22) than in period 1 (1962-1991) in the entire western region. Given that the drought conditions are worsening based on the results, it provides more reason for stakeholders to be better prepared for drought disasters. Since the results were analysed at district level, policy makers and local mayors can view the effect of drought of the associated districts more clearly. Oftentimes drought events are viewed as natural hazards to which the impacts thereof can only be dealt with after the occurrence of the drought (i.e., a reactive approach) (Baudoin *et al.*, 2017). However, it is best to approach the drought events in a proactive manner in order to manage a drought disaster before it takes place (Bruwer, 1993). This study provides a unique perspective of analysing drought at a finer scale (district level). It enables stakeholders, policy makers, mayors etc. to examine the past drought events through their intensity, duration, and frequency of their district of interest. The stakeholders can then better prepare for future drought events, through a proactive approach, by examining the past drought conditions that were outlined in this Chapter. This includes planning in the water, agricultural, and land use sectors (Malherbe *et al.*, 2016). All the districts of the western region should be aware of the increased drought frequency, duration, and intensity as the results indicated that drought conditions are worsening. All districts should proactively be prepared for worsened drought conditions.

CHAPTER 5 DROUGHT IMPACTS ON VEGETATION IN THE PROVINCES OF SOUTH AFRICA

5.1 Introduction

The NDVI is a widely used and efficient vegetation index as an indicator of drought. Drought conditions, examined via vegetation, is seen when a deviation in the temporal mean over an extended period is present in the NDVI values (Xulu *et al.*, 2018). Strong correlations exist between the NDVI and climatic variables, which include precipitation and temperature (Piao *et al.*, 2006), acting as an indicator of drought due to vegetation changes (Anyamba & Tucker, 2012; Lawal *et al.*, 2019; Peters *et al.*, 2002; Xulu *et al.*, 2018).

NDVI values, and variations within the trends thereof, can be used in conjunction with drought indices (Xulu *et al.*, 2018). In this study, the results of the drought conditions examined from the SPEI observations in the previous chapter is used as reference to the NDVI trends within this chapter. The NDVI corresponds to changes in rainfall and evapotranspiration (Jury & Gondwe, 1997), which are the variables used in the SPEI.

It should be noted that previous studies have explored the effect that drought has on vegetation in southern Africa (Jury & Gondwe, 1997; Lawal *et al.*, 2019). Yet, this study aimed to give a closer perspective on drought in the districts within the western region, as studies mostly focus on country- and/or southern African-level. However, in this chapter, the effect that drought had on vegetation were analysed at a larger, provincial level due to the data availability thereof. Although this is not a close, extensive, district-level examination of vegetation, the NDVI trends, analysed at a provincial level, still provide an adequate perspective of the effect that drought events had in the western region. Therefore, this chapter aimed to determine whether the drought characteristics identified in Chapter 4, affected vegetation within provinces in the western region during the associated drought periods. Thus, objective 2 of this study was achieved.

5.2 NDVI trends of the different provinces

The following section examines the NDVI trends and values from 1984-2021 (early 2021) of the five provinces (Northern Cape, North West, Free State, Eastern Cape, and Western Cape) that fall within the western region. It should be reiterated that the values can range between -1.0 and 1.0, where the level of denser vegetation is depicted by greater positive values. Negative values are usually an indication of snow, clouds, or ice (Tarpley *et al.*, 1984; Wang *et al.*, 2003). The data analysed represent areas containing vegetation.

5.2.1 NDVI trends of the Northern Cape

The long-term trend of the NDVI in the Northern Cape illustrates an overall increase from 1984-2021 (Figure 23a). Therefore, the density of the vegetation has increased and/or expanded over the period in the province. Low values, under 0.2, anomalously fall under the 25th percentile which occurred in 1994 and 2001 (Figure 23a and Figure 23b). A closer examination of the long-term trend is depicted by Figure 20b. In the 1980s and 1990s, the NDVI values gradually increased and escalated more drastically in the 2000s. However, from 2010-2021 the opposite occurred as the trend started drastically decreasing.

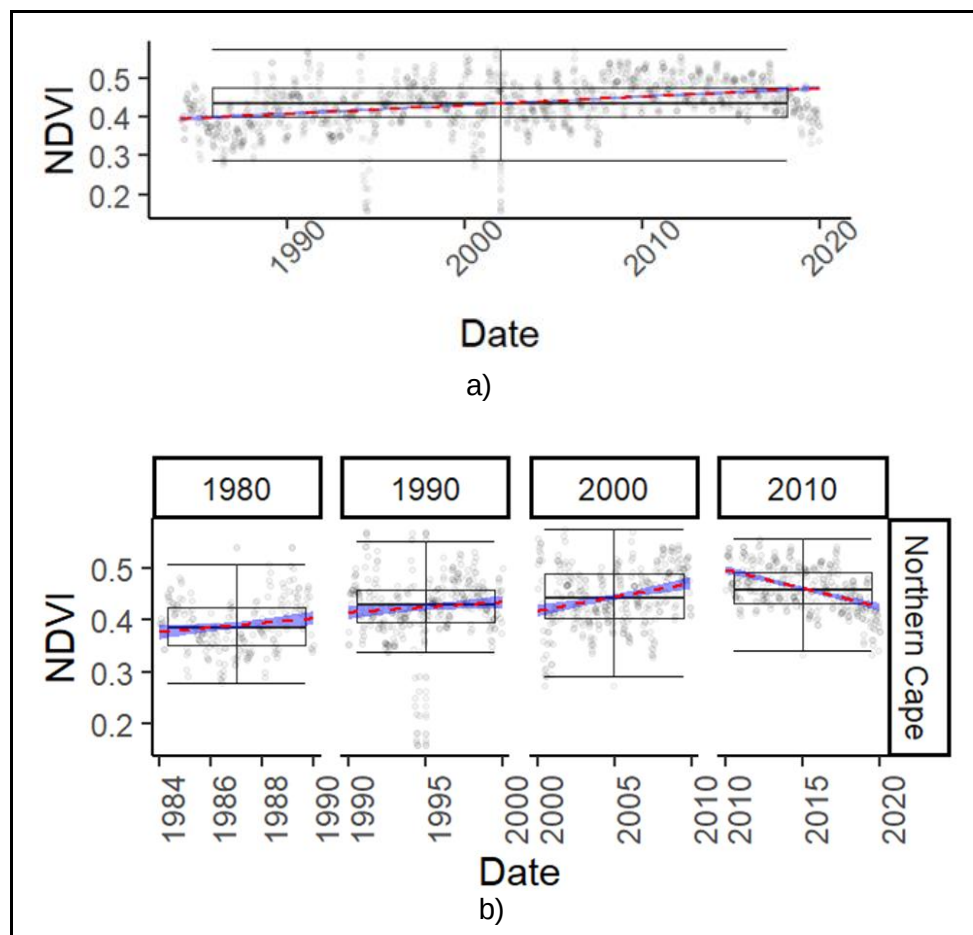


Figure 23: NDVI trends in the Northern Cape from 1984-2021. Figure 23a shows the overall trend, while 23b shows the trends split in decadal years. The blue area represents the trend margin, while the red dotted line shows the trend. The general NDVI trend is increasing in the Northern Cape but decreased from 2010.

5.2.2 NDVI trends of the North West

An increasing long-term trend is present in the North West from 1984-2021. More positive values are also examined, falling above 0.6, indicating denser vegetation than in the Northern Cape. The 1980s and 1990s had greater positive values and increasing trends, which started to

stagnate in the 2000s (Figure 24b). In the 2010s, the trend started to decrease, once again indicating the effect of drought. Although the trend decreases in the 2010s, greater lower values are present in the 1990s and 2000s, taking place in the 25th percentile. This indicates that greater extreme drought effects took place from 1990-2010 than in the 2010s.

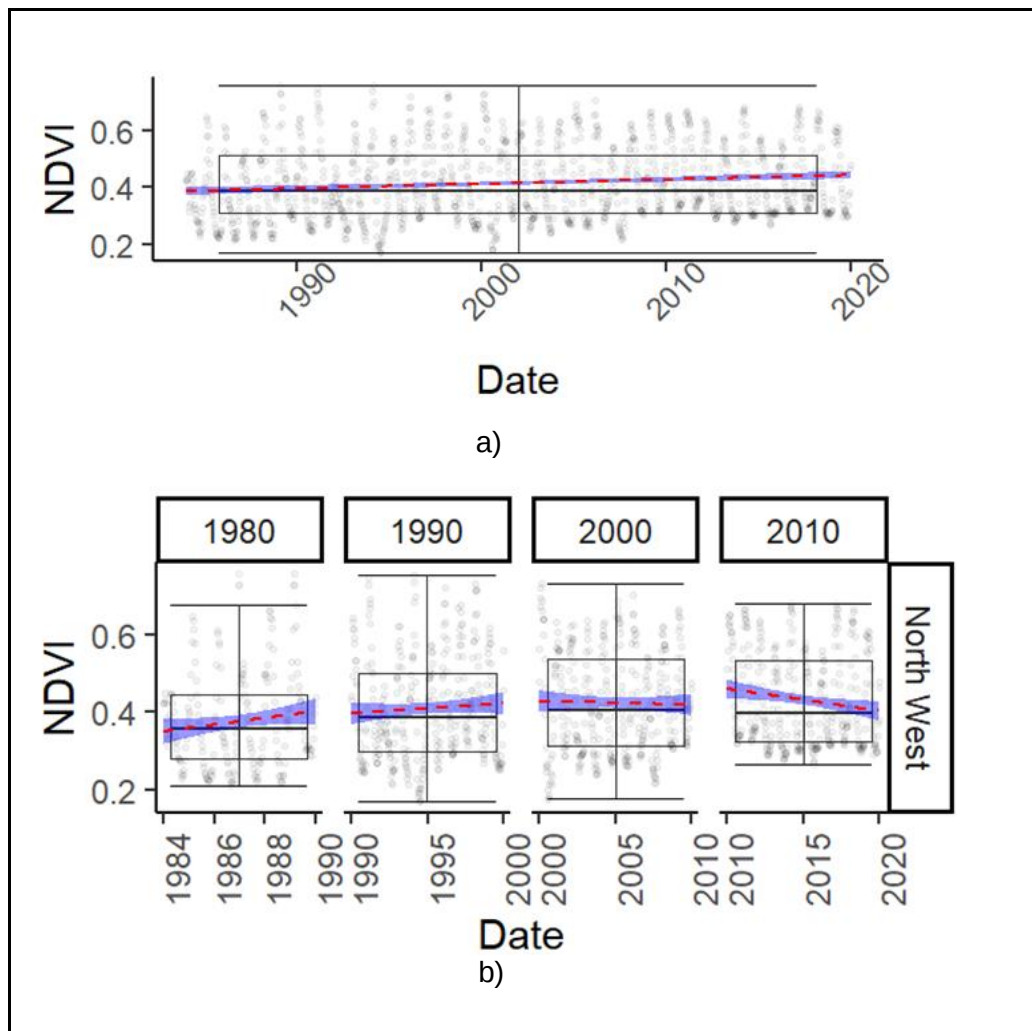


Figure 24: NDVI trends in the North West from 1984-2021. Figure 24a shows the overall trend, while 24b shows the trends split in decadal years. The blue area represents the trend margin, while the red dotted line shows the trend. The general NDVI trend is increasing in the North West but decreased from 2010.

5.2.3 NDVI trends of the Free State

The long-term trend of vegetation increased from 1984-2021 in the Free State (Figure 25a). The lowest values (i.e., reduced density of vegetation) are present in 1994. The 1990s were also where the highest values are present (Figure 25b), indicating that both dry and wet years occurred. In the 1980s and 1990s the density of vegetation slowly rose. In the 2000s the trend is seen slowly decreasing, which reduces even further in the 2010s. Considering this

decreasing trend, drought events mostly affected the vegetation in the Free State from 2010-2021, even though lower values are present in the 1990s.

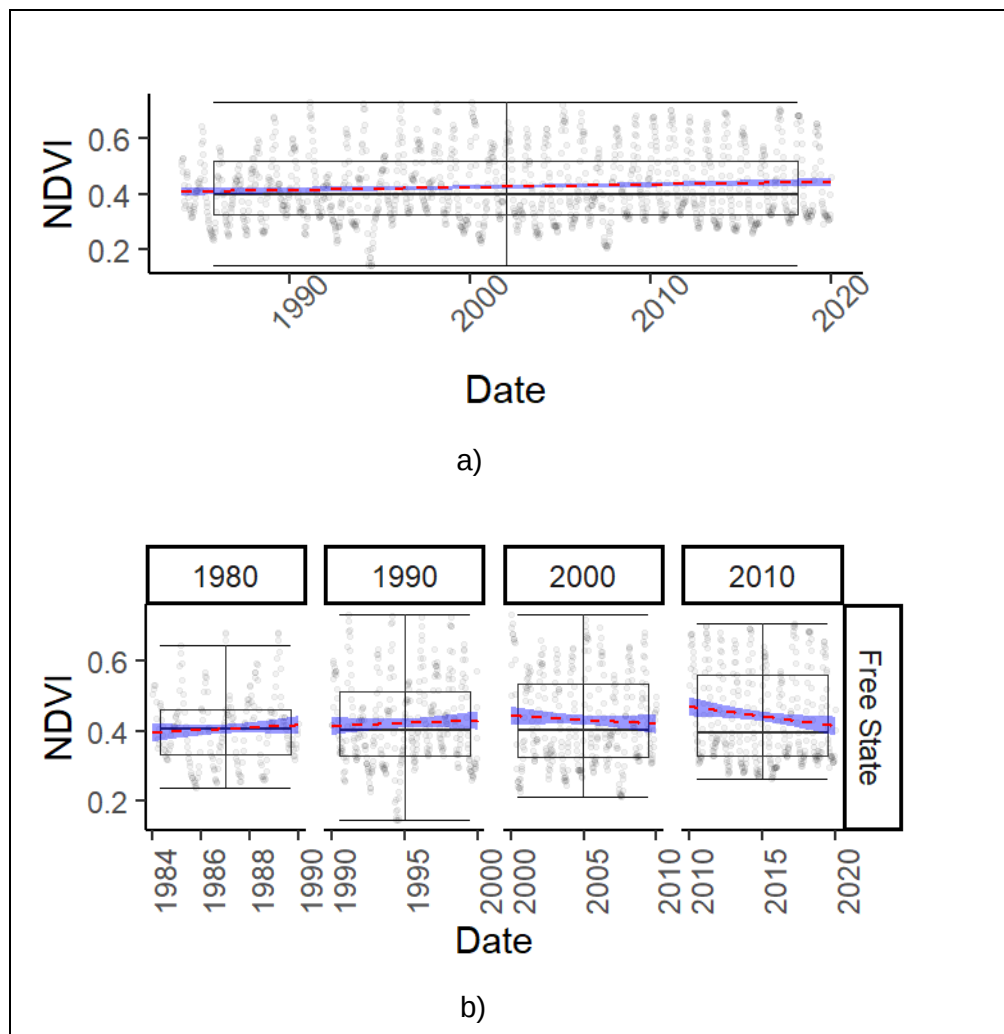


Figure 25: NDVI trends in the Free State from 1984-2021. Figure 25a shows the overall trend, while 25b shows the trends split in decadal years. The blue area represents the trend margin, while the red dotted line shows the trend. The general NDVI trend is increasing in the Free State but decreased from 2010.

5.2.4 NDVI trends of the Eastern Cape

In the Eastern Cape, the long-term NDVI trend increased over the period and is the province with overall highest median values. Similar to other provinces, low values (under 0.2 NDVI) occurred in 1994-1995, but also in 2005 (Figure 26a), signalling the effect of drought conditions. Like most of the other provinces, the 1990s showed the greatest variation in extremes in comparison to the other trends of the other decades. High NDVI values (up to 0.8) are present in all the decades, suggesting that multiple wet years were present to enhance the density of vegetation (Figure 26b). The 1980s only showed a slight increase in vegetation, while the 1990s showed the greatest escalation, followed by the 2000s. As examined in the previous discussed

provinces, the 2010s was a period of decreasing NDVI values, indicating the presence of drought conditions. Even though this period shows a decrease in vegetation density, the overall values are still higher in comparison to the previous decades and depicts no extreme low values as seen in the 1990s (Figure 26b).

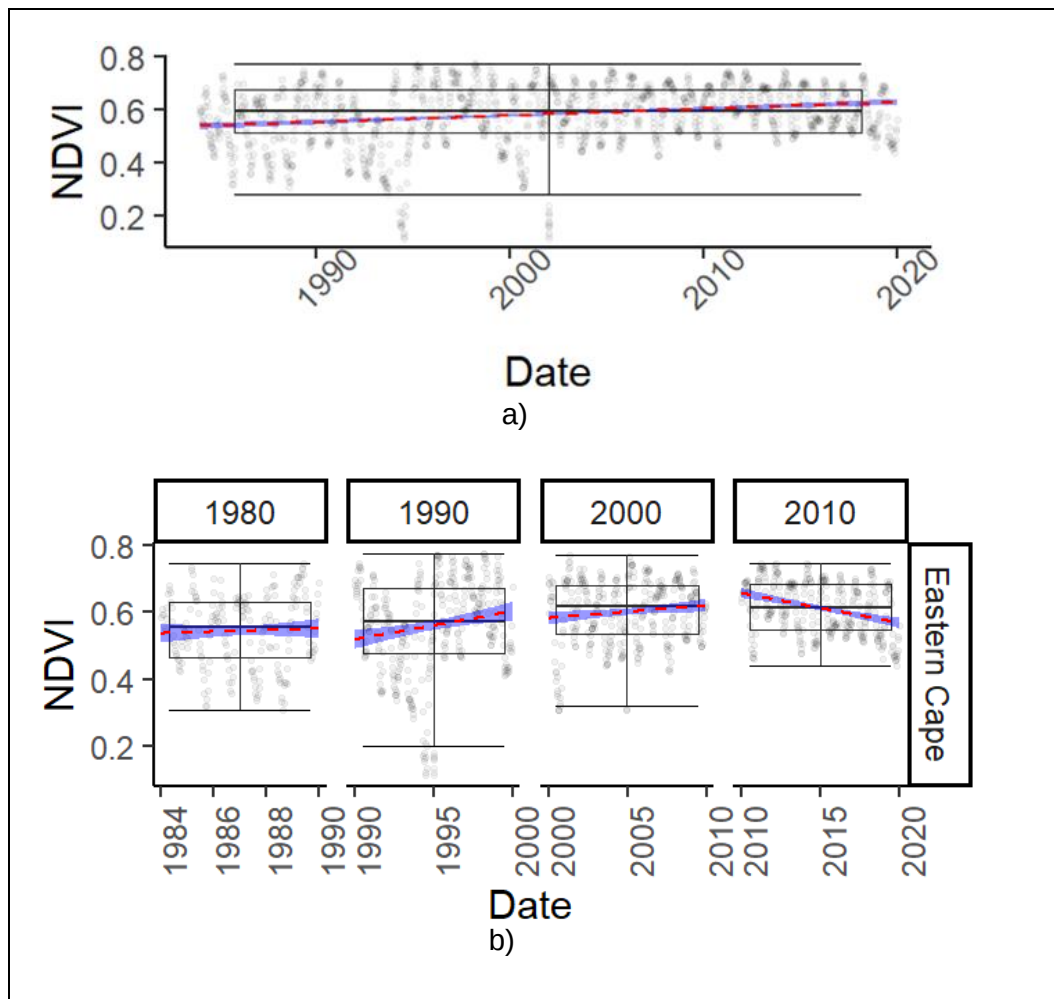


Figure 26: NDVI trends in the Eastern Cape from 1984-2021. Figure 26a shows the overall trend, while 26b shows the trends split in decadal years. The blue area represents the trend margin, while the red dotted line shows the trend. The general NDVI trend is increasing in the Eastern Cape but decreased from 2010.

5.2.5 NDVI trends of the Western Cape

The Western Cape also depicts an overall increasing NDVI trend in vegetation density from 1984-2021 (Figure 27a). The Western Cape shows high NDVI values, indicating greater vegetation density than the other provinces. As examined in the other provinces, the lowest values (below 0.2) were present in 1994 and ranged between 0.2-0.4 in 2001. The 1990s had the highest range of values, with low values present earlier- and higher values present later in the decade. In conjunction with the other provinces of the western region, the 1980s-2000s

showed increasing trends, which drastically decreased in the 2010s (Figure 27b). Even though the influence of drought is seen in the 2010s, values were at their highest in 2005-2015.

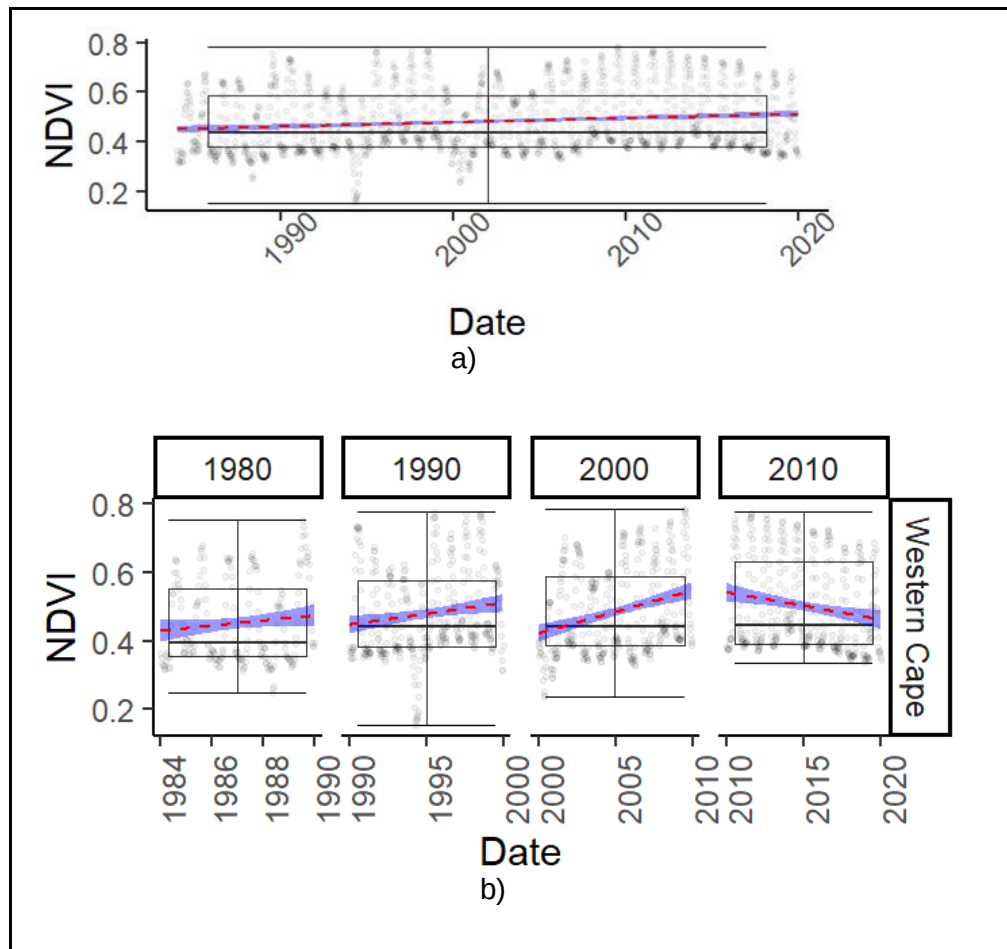


Figure 27: NDVI trends in the Western Cape from 1984-2021. Figure 23a shows the overall trend, while 23b shows the trends split in decadal years. The blue area represents the trend margin, while the red dotted line shows the trend. The general NDVI trend is increasing in the Western Cape but decreased from 2010.

5.3 Mann-Kendall trend test

All the provinces' NDVI data had a trend present since the null hypothesis could be rejected. Contrary to the negative trends seen in the SPEI data of the districts from 1962-2021/22, the NDVI Tao values showed positive trends. The positive trends correlate with the long-term trend lines that were depicted (Figure 23 - Figure 27). It should be noted that the Tao values are merely slightly positive and not as significant when compared to the SPEI data's Tao values of the previous Chapter. Thus, vegetation density has slightly increased from 1984-2021 in the five provinces that were investigated. Differences in the Mann-Kendall results are present when comparing Chapter 4 and 5 in relation to drought. Chapter 4 indicated that drought conditions have worsened, while Chapter 5 showed slight increased vegetation, therefore not displaying the effect of the drought.

Table 15 Mann-Kendall trend analysis of NDVI trends of the five provinces

Province	Kendall Tau value	p-value
Northern Cape	0.245	< 2.22e-16
North West	0.11	< 2.22e-16
Free State	0.0522	0.0041801
Eastern Cape	0.127	< 2.22e-16
Western Cape	0.0851	3.0994e-06

5.4 Discussion

All the provinces showed an overall increasing NDVI trend from 1984-2021. The increasing trend was also supported by the Mann-Kendall results, although it was only slightly positive. This suggests that all the provinces endured increased vegetation density over the period. When examining the long-term trends closer, most provinces depicted that the 1980s-2000s had increasing trends, except in the Free State. Although the trend increased in all provinces, the 2010s was a period where the trend decreased. This decreasing trend indicated that dry conditions/drought events were present from 2010-2021. This decreasing NDVI trend coincides with the findings in Chapter 4, where most districts in the western region recorded severe drought events taking place from 2012-2021/22. Therefore, one of the reasons for the decreasing vegetation from 2010-2021 is because of the severe drought events that occurred in the western region during that time.

Another commonality between the provinces' NDVI trends is the low NDVI values that are present in 1994 and 2001. Many single-year droughts were recorded in the western region in 1992/93, however none in 1994 itself. The notorious 1992/93 drought event that took place across South Africa because of El Niño (Vogel & Van Zyl, 2016) could serve as an explanation for the dip in the NDVI trend and low values recorded during this time. In Chapter 4, a range of multiple dry years were recorded occurring during period 2 from 1999-2004. The lower NDVI values recorded in the early 2000s could be as a result of those dry years that took place during that time.

The 1990s contained the highest and lowest NDVI values in all provinces. This could be because of the moderate to severe wet and dry years that occurred, as shown in Chapter 4. Moreover, although the 2010s in all the provinces had decreasing NDVI values, the values were still overall higher than values of the other decades. This suggests that the overall vegetation density was still greater in the 2010s than previous eras, even with the drought events occurring during that time. This is because although the 2010s showed decreasing trends, the overall median values were still higher, suggesting that the severe drought events did not have a great

effect on vegetation. The most water stress related conditions (values below 0.3) (Jury & Gondwe, 1997) were present in the 1990s and not in the 2010s. Considering that the most severe drought events were present during period 2 (as shown in Chapter 4), it explains why decreasing NDVI trends were examined in the 2010s. However, since Chapter 4 also showed that period 2 endured more droughts with greater severity than in period 1, the results of the NDVI trends disagree to an extent with the SPEI results. Reasons attributed to this could be an increase in techniques to combat drought and increase vegetation density and/or crop productivity. These techniques include, but are not limited to, greater seed varieties to tolerate drought, conservation agriculture, rain water harvesting etc. (Senyolo *et al.*, 2018). Thus, although an increase in drought intensity and frequency was found in Chapter 4, the results of the NDVI may not necessarily correlate to the same extent because of an increase in drought-resistant technologies.

CHAPTER 6 FUTURE DROUGHT OF THE WESTERN REGION

6.1 Introduction

The IPCC has predicted a warming trend to impact southern Africa, with emphasis on an increase in extreme hot days, nights, and a decrease in extreme cold days and nights (IPCC, 2014; Kruger & Sekele, 2013). Furthermore, an increase in austral summer heat waves is also predicted (IPCC, 2014; Lyon, 2009), alongside a medium confidence that droughts will increase in severity in some seasons in southern Africa (IPCC, 2014). Furthermore, the Kalahari region, which falls within the Northern Cape, runs risk of having a decrease in annual rainfall and an increase in temperatures by the end of the 21st century (Archer *et al.*, 2018). With climate change, South Africa is vulnerable because of its large population, poor economy, and low adaptability (Sian *et al.*, 2021). Thus, it becomes apparent for the need to assess the future climatic conditions of the western region in detail.

The CMIP provides the opportunity to obtain projected modelled data, using different SSP scenarios in order to analyse possible future climatic conditions (Sian *et al.*, 2021). The CMIP6 is the latest phase of the CMIP (Eyring *et al.*, 2016), where the GCM, FGOALS-g3 data, was used to analyse a projection of drought conditions in the western region from 2050-2100. Temperature and precipitation data was used to assess future drought using the SPEI. This chapter aimed to compare the future drought conditions to past drought conditions (examined in Chapter 4), therefore achieving objective 3 of this study.

6.2 Future SPEI results of the district municipalities

This section examines the future drought conditions in 2050-2100 of the districts in the western region using the SPEI. The modelled data was extracted under the SSP2-4.5, which is the medium forcing scenario (Cook *et al.*, 2020). The results were compared to the past conditions of 1962-2022 that were examined in Chapter 4.

6.2.1 Future SPEI of the Northern Cape

Under the SSP2-4.5 scenario, Frances Baard continues to have fluctuated wet and dry years, where the majority severe to extreme dry years are projected to occur between 2072-2082 (Figure 28a). In comparison to past conditions of Frances Baard (Figure 17a.1), normal conditions were more prevalent. Future drought conditions (going below -1.0 SPEI) are expected to occur more frequently, but for shorter durations than in the past and at a lesser intensity. In the past, Namakwa (Figure 17b.1 and Figure 17b.2) evidently endured wet to normal conditions in period 1 and dry conditions in period 2. However, results show that future

drought conditions in Namakwa fluctuate much more than in the past (Figure 28b). The average SPEI intensity is expected to also increase, and moderate to severe dry events are projected occur more frequently, yet one long-duration drought event is projected to not occur as it did in the past. Formerly, John Taolo Gaetsewe, Pixley Ka Seme, and ZF Mgcawu all experienced greater wetter conditions in period 1 and drier conditions in period 2, alongside normal conditions throughout the time series (Figure 17). All three districts now show that upcoming conditions also fluctuate more and remain present for only 1-3 years at a given time. The frequency of moderately dry conditions (less than -1.0 SPEI) occurs in each district at least 10 times, which is more than in the past. However, the total duration of the dry events is expected to be less (+/- 5 years) in comparison to 7+ years in the past. The average SPEI intensity was more severe in the past compared to future projections as it was -1.5 and less for all three districts.

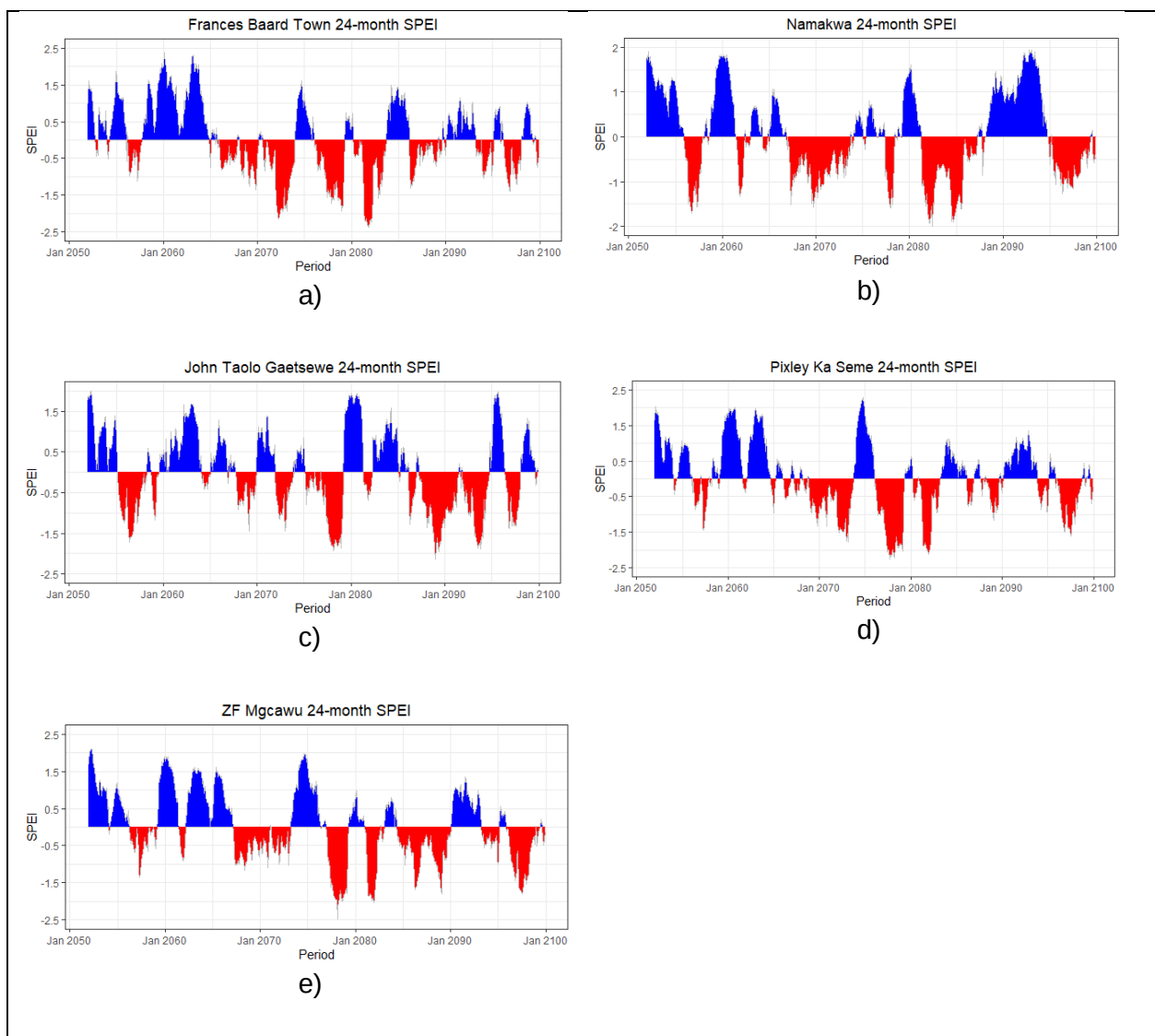


Figure 28: Future 24-month SPEI of the district municipalities within the Northern Cape. Fluctuating wet (blue) and dry (red) cycles are projected to occur.

6.2.2 Future SPEI of the North West

In the past, Dr. Ruth Segomotsi Mompati experienced fluctuating wet and dry conditions which appear to continue in the future under the SSP2-4.5 scenario. Wet conditions (beyond +1 SPEI) are expected to feature frequently and dry conditions are projected occur at least 9 times throughout the period. This is more times than in the past, however, the average SPEI intensity is estimated to be less. Once again, dry events in the past remained present for longer (7+ years) (Figure 18), while future dry events are projected occur for a slightly shorter duration altogether (+/-6 years) (Figure 29).

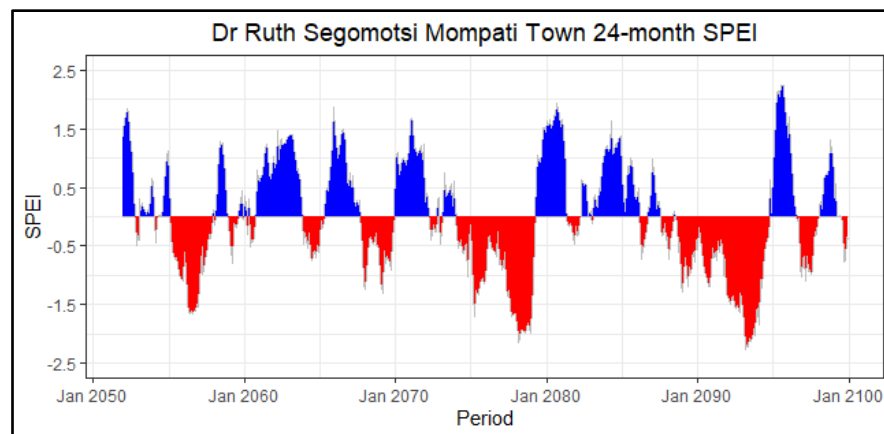


Figure 29: Future 24-month SPEI of the district municipality within the North West. Fluctuating wet (blue) and dry (red) cycles are projected to occur.

6.2.3 Future SPEI of the Free State

The Xhariep district is projected to continue to have fluctuating wet and dry conditions, under the SSP2-4.5 scenario (Figure 30), as examined in the past (Figure 19). Severe wet years are projected to continue to occur in the same amount, while +/- 9 dry events are expected to occur, which is less than the 22 events in the past. The longest dry event from the past occurred on and off from 2013, with dry years lasting 9+ years altogether. However, in the future, dry years are projected to last at least 12 years altogether. Most dry years are projected occur from the early 2070s-2080s. The average SPEI intensity is also projected to be more severe than in the past. The Xhariep is one of the few districts where the duration and average intensity of events is projected to increase, yet the frequency of events are expected decrease.

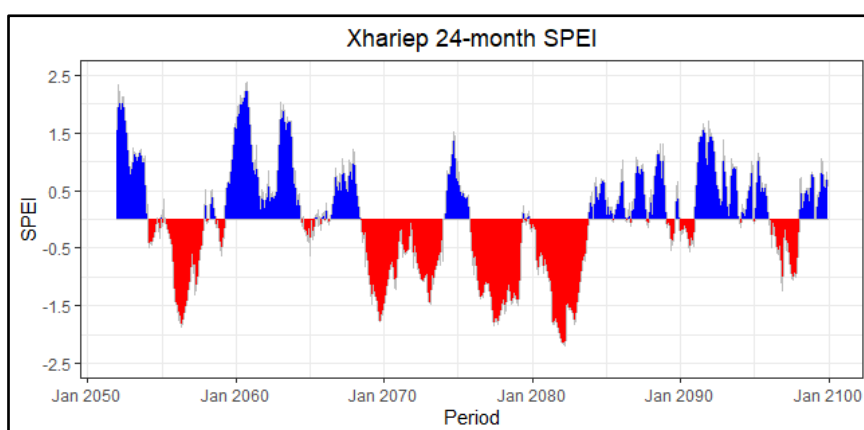


Figure 30 Future 24-month SPEI of the district municipality within the Free State. Fluctuating wet (blue) and dry (red) cycles are projected to occur.

6.2.4 Future SPEI of the Eastern Cape

Under the SSP2-4.5 scenario, Chris Hani and Joe Gqabi obtained the same results as the districts are located close to each other (Figure 31) and the data availability for that area was limited. Although this is not ideal and somewhat inaccurate, the possibility of the two districts having similar dry and wet periods is not impossible due to their proximity. From these results, it is seen that at least 13 dry periods are estimated to occur with an SPEI of -1 and less, which is more events compared to the past (Figure 31a and Figure 31b). The duration of the upcoming dry periods altogether for both districts is approximately 6 years. The duration of these periods remains roughly the same for Joe Gqabi in comparison to the past (Figure 20), however it is projected to increase for Chris Hani. The severity of the events is expected to remain roughly the same in Chris Hani, while it is projected to be less severe in Joe Gqabi compared to past conditions. The driest periods are projected to occur between 2076-2083. Nelson Mandela Bay Metropolitan continues to show fluctuating conditions (Figure 31c) as featured in the past (Figure 20b.1 and Figure 20b.2). However, conditions in the past remained more within the normal range (between 0.9 and -0.9 SPEI) than upcoming conditions. The frequency of moderate to extreme dry periods are estimated to increase, as at least 6 dry periods are predicted compared to only one large event in the past. The duration of the events altogether is expected remain similar (6-7 years), and the severity of the events was worse in past conditions.

Sarah Baartman also shows greater fluctuation (Figure 31d) than in the past, where conditions remained more within the normal ranges in Figure 20c.2 (second dataset). 11 dry periods were present in the first dataset (Figure 20c.1) which is more than the +/-6 predicted in upcoming conditions. However, the second dataset (Figure 20c.2) of Sarah Baartman features fewer dry periods in the past, therefore more dry years are predicted in the years to come (4 compared to

+/-6, respectively). Greater severity in dry conditions is predicted for Sarah Baartman in comparison to the first dataset, but the events are expected to be less severe than the second dataset. The duration of the events is projected to last approximately 7 years altogether which remains roughly the same in comparison to both datasets of the past. Overall, the frequency of dry events is projected to increase in most of the districts in the Eastern Cape, while no significant increase in intensity or duration is noted.

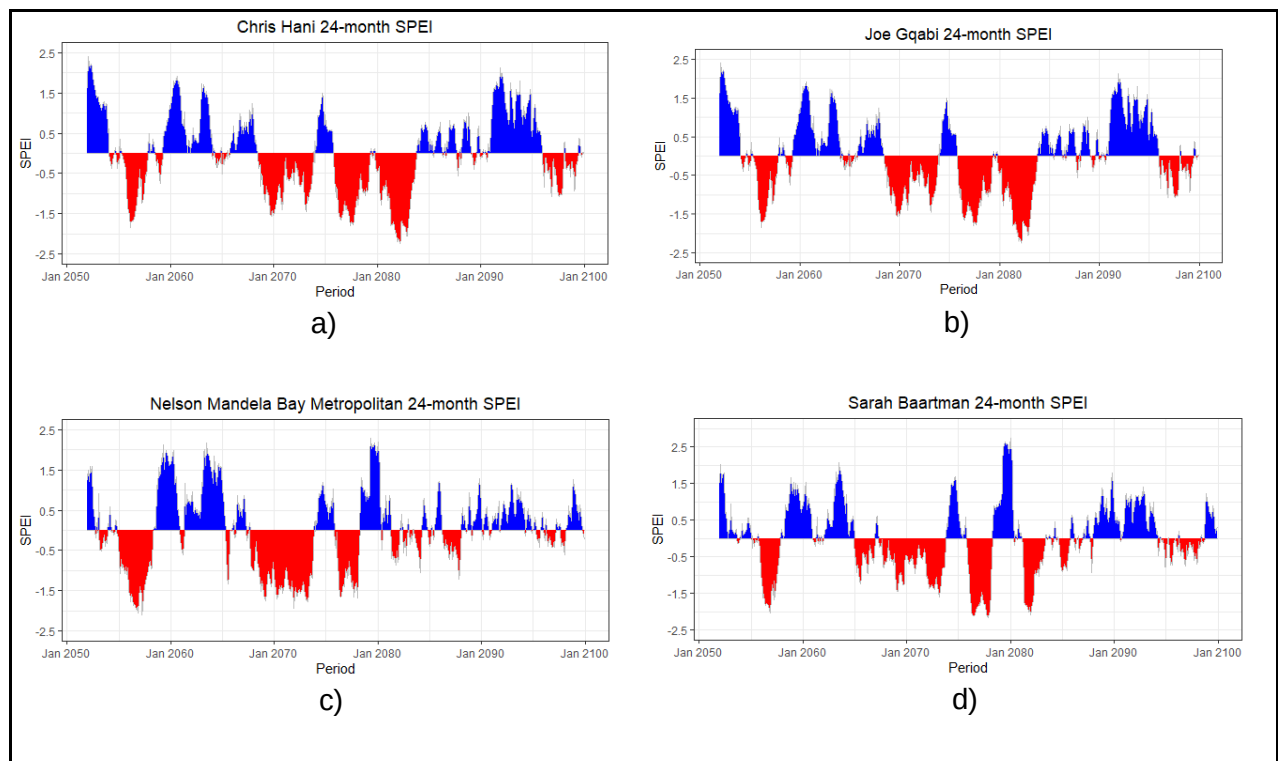


Figure 31 Future 24-month SPEI of the district municipality within the Eastern Cape. Fluctuating wet (blue) and dry (red) cycles are projected to occur.

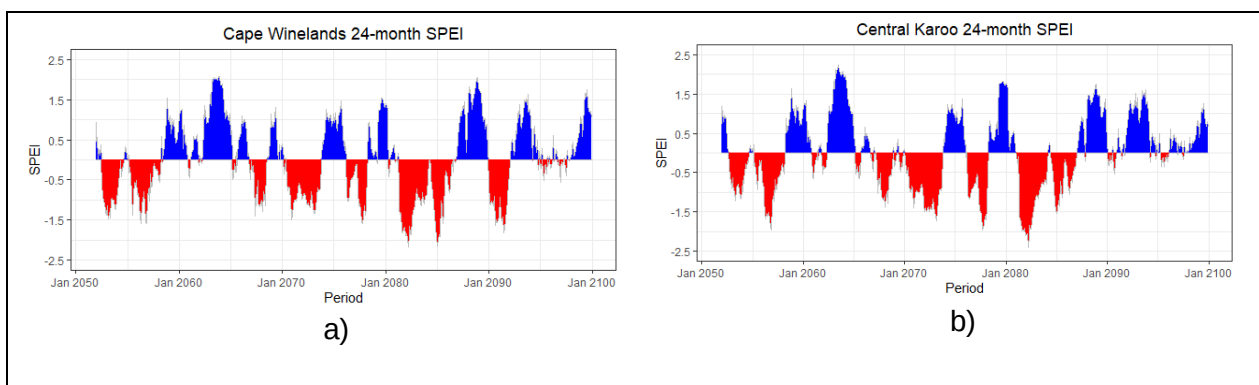
6.2.5 Future SPEI of the Western Cape

Under the SSP2-4.5 scenario, the districts of the Western Cape show much more fluctuating conditions (Figure 32) in comparison to past conditions (Figure 21). This gives an indication that the CMIP6 data is not entirely accurate when comparing it to the observations of SAWS' and GSOD data in Chapter 1. Nevertheless, the results can still provide an indication of the possible future drought scenarios. At least 19 future drought frequencies of an SPEI of less than -1 are predicted for the Cape Winelands (Figure 32a) in comparison to the single drought event of the past (Figure 21e). The duration and average SPEI severity of the events, however, are expected to decrease. The Central Karoo predicts that the district is expected to have at least 11 dry events (Figure 32b), which is much more than the 2 events in total of the past (Figure 21f). The average severity is estimated to be approximately the same as past, however future

conditions are projected to reach extreme intensity in 2082, which is more than it has reached in the past. The duration of the events altogether is also expected to be shorter.

The City of Cape Town district had only one large continuous drought event in the past (Figure 21a.1 and Figure 21a.2), while at least 9 events are projected in the future (Figure 32c). The overall severity of the events is projected to be less, however the most extreme event (less than -2.5 SPEI) of all the districts is predicted to occur in 2091. This event did not occur with such severity in the City of Cape Town in the past. The total duration of events is predicted to be shorter. When examining the Garden Route, dry events are estimated to also occur more frequently (at least 9 times) (Figure 32d). Only 2 past events occurred in the past (Figures 18b.1 and 18b.2), but for longer durations than upcoming events. Events are expected to be more severe on average than in comparison to the first dataset (Figure 21b.1), but roughly the same severity than the second dataset (Figure 21b.2).

In the past, Overberg was one of the districts that had the most frequent dry events (between 4-7) (Figure 21c.1 and Figure 21c.2) of the Western Cape, yet more dry events (at least 14) are predicted to occur. The upcoming dry events are expected to mostly be of short duration individually (Figure 32e) and shorter in total, than in comparison to the past. The severity is estimated to remain approximately the same. The West Coast underwent 4-5 dry events in the past (Figure 21d.1 and Figure 21d.2) but is projected to have at least 9 dry events in the future (Figure 32f). The duration of the events is projected to be much shorter altogether, but the average severity of the events is expected to increase in comparison to past events. Overall, the districts follow similar patterns in the SPEI graphs which is due to their proximity and the limited data. All the districts in the Western Cape are projected to have increased dry events, while the severity mostly remains the same and the duration is expected to become shorter.



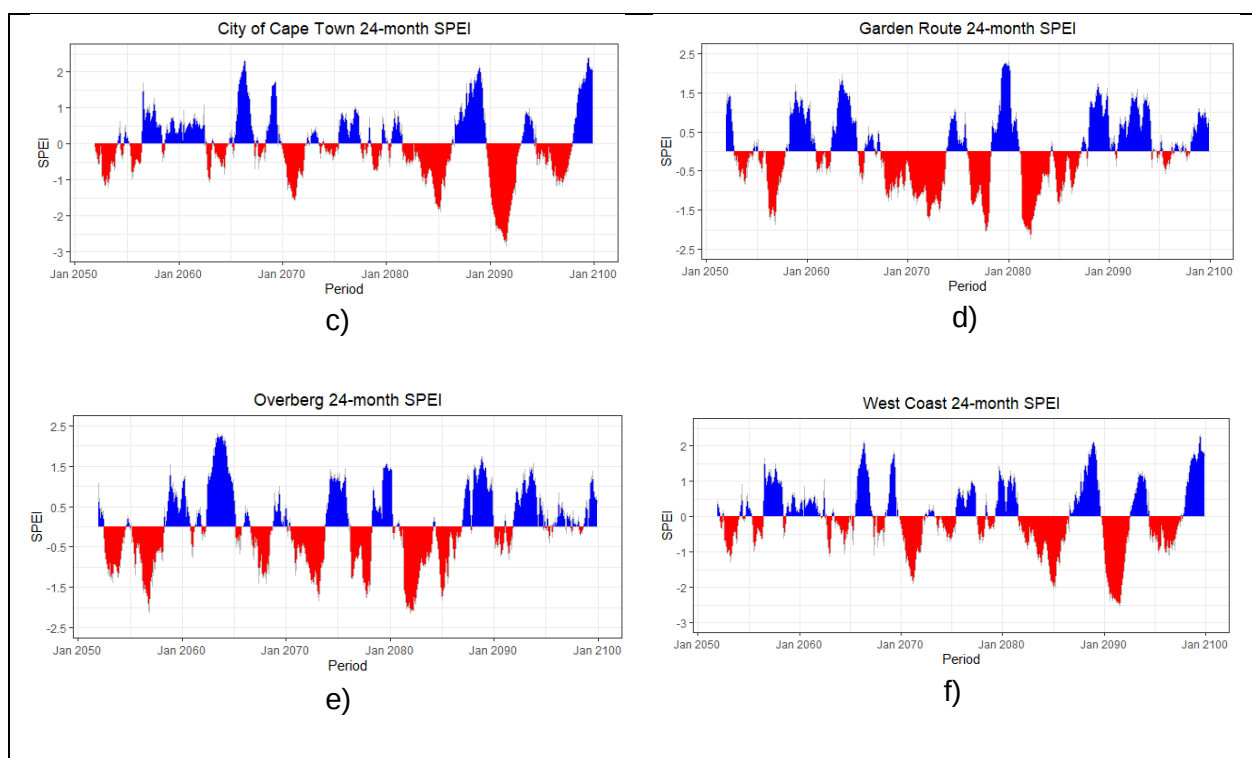


Figure 32 Future 24-month SPEI of the district municipality within the Western Cape. Fluctuating wet (blue) and dry (red) cycles are projected to occur.

6.3 Mann-Kendall trend test

From the CMIP6 results, more districts did not have a trend present (i.e. greater fluctuating results) in comparison to the previous SPEI and NDVI results. Districts with p-values greater than 0.05 were the Xhariep, Chris Hani, Sarah Baartman, and Joe Gqabi, and West Coast. Nevertheless, a trend was present in the other districts. The Tao values, on the other hand, yielded less significant results, ranging from weak positive to weak negative, but were close to zero. Therefore, the trends are not as strong, meaning future drought conditions are predicted to be less extreme in comparison to the past observations of Chapter 4. The SPEI graphs (Figure 28 - Figure 32), presented fluctuating conditions which is why the Tao values are weak. The district with the strongest Tao value was the ZF Mgacawu.

Table 16: Mann-Kendall trend test results of future districts' SPEI results.

District	Kendall Tao value	p-value
Frances Baard	-0.161	7.6371e-09
Namakwa	-0.0875	0.0016679
ZF Mgacawu	-0.244	< 2.22e-16
John Taolo Gaetsewe	-0.144	2.1671e-07
Pixley Ka Seme	-0.17	9.3837e-10
Dr Ruth Segomotsi Mompati	-0.106	0.00013728
Xhariep	-0.0117	0.67416

Chris Hani	-0.0232	0.40466
Nelson Mandela Bay Metropolitan	0.0563	0.043148
Sarah Baartman	0.0148	0.59443
Joe Gqabi	-0.0231	0.40759
City of Cape Town	-0.0576	0.038388
Garden Route	0.0797	0.0041885
Overberg	0.11	7.8678e-05
West Coast	-0.0346	0.21427
Cape Winelands	0.0554	0.04656
Central Karoo	0.108	0.00010061

6.4 Discussion

Most districts displayed greater fluctuating wet and dry conditions/years throughout the period compared to the past results seen in Chapter 4. Due to these fluctuations, most districts of the western region are projected to have an increasing number of dry events than the number of dry events in the past. The Xhariep district displayed the most anomalous conditions as the intensity and duration is predicted to be more severe and longer, while the occurrence of dry events is expected to be less. The other districts mostly have opposite predictions: a higher number of dry events, with a decrease in the average intensity and shorter durations.

Although a decreasing average intensity and shorter duration of dry events was the general result, some districts did show other predictions. In comparison to the past district results of Chapter 4, the Xhariep, Namakwa, Sarah Baartman (compared to the first dataset), Garden Route (compared to the first dataset), and West Coast are predicted to have increased average SPEI intensities in the future. Other than the Xhariep, the Chris Hani district is also predicted to have an overall longer duration of dry events than in the past. Sarah Baartman (compared to the second dataset), and the Xhariep, have projections that dry events are projected to not increase. Overall, this denotes that 15/17 districts are projected to have an increasing number of dry events, 5/17 districts are expected to have increased average drought intensities, and only 2/17 districts are estimated to have longer durations of dry events.

It can be argued that drought conditions are projected to worsen in the western region when solely taking the frequency of occurrence of dry events into account. However, since the intensity and duration also play a role, the effects of the drought events might not be long-lasting. Li *et al.*, (2021) found the opposite results for arid regions, including the whole of South Africa, under all the SSP scenarios. It was stated that the frequency of long-term drought events is expected to decrease, while the intensity and duration are estimated to increase. Despite having opposite results to this study, their findings were based on a global study and found that

arid areas (taking the entire country into account) are at a greater risk of desertification (Li *et al.*, 2021). Results may differ because this study analysed the western region (not the entire country) and at a smaller, and more localised scale. Another study by Sian *et al.*, (2021) who also used FGOALS-g3, among others, found that Western southern Africa (similar to the western region) are expected to have an increase in precipitation in each month except for April and November in the near future, while decreases are expected from 2045-2100. Their study found that South Africa is projected to endure an overall drying effect under the SSP2-4.5 scenario.

Overall, the future SPEI of the districts showed more fluctuations in the past, which is why most districts are predicted to have more dry events occur, but with lesser intensity and shorter durations. The Namakwa, Garden Route, and West Coast districts are the only districts predicted to have increased dry events with increasing intensities. Therefore, making them most likely to have worsened future drought events/conditions. These districts are found within the Northern Cape and Western Cape respectively, residing more towards the western coast of South Africa (Figure 11). The anomalous district, Xhariep, is projected to also have worsened future drought conditions due to the increasing duration and intensity. It is found towards the east of the western region, within the Free State. No district showed an increase in all three factors in comparison to the results from the past. Therefore, only 4/17 districts showed worsened conditions than past drought conditions (from Chapter 4). One could deduce that drought conditions may not worsen as much when comparing the past results to the future. This can be attributed to the increased fluctuations, but also be accredited to a certain amount of inaccuracy of the modelled data. Given that the districts' wet and dry conditions do not roughly have the same patterns in the future as in the past, the uncertainty associated with the results could be due to only using one model. Results were also not bias-corrected which could have influenced it.

6.5 Recommendations for future municipalities

Given that 15/17 districts are projected to have an increased frequency of drought events, mayors, policy makers, stakeholders, etc. can use this information to proactively plan for the upcoming drought events shown in the results. Furthermore, the stakeholders of the Namakwa, Garden Route, and West Coast districts can be aware that these districts are predicted to have increased drought intensities on top of increased frequencies. Since the Xhariep district's prediction is an increase in duration and intensity, stakeholders of this district can also proactively prepare for future drought effects.

CHAPTER 7 SUMMARY AND CONCLUSIONS

7.1 Summary

This study aimed to investigate changes in drought variability from the past and future and link past results to changes in vegetation in the western region of South Africa. The first chapter of the study included the introduction, aims, and objectives. Chapter 2 consisted of the literature review which incorporated topics related to drought in South/southern Africa. The third chapter consisted of the data and methodologies that were used to achieve the objectives of the study. Chapters 4-6 contained the results of the objectives in order to achieve the aim of the study. The findings of the results are discussed and summarised after each objective:

1.) Explore the changes in the frequency, intensity, and duration of drought events in the western region of South Africa.

Dry events in period 1 continued at an average cyclic duration of ~2 years, occurring at an average of every ~5 years (varying between 1-9 years). Multiple drought years took place in the early 1970s and middle 1980s, while single-year droughts also occurred. These drought events were connected to ENSO and ultimately rainfall variability. The overall average SPEI values of the districts in period 1 were merely moderate in intensity. Period 2 drought events occurred more frequently than in period 1, with an average duration of ~6.6 years, occurring every ~1.5 years (varying between 1-3 years). All districts, except for Joe Gqabi experienced a severe dry period that occurred within periods from 2012-2021/22. The Mann-Kendall results also indicated that drought conditions were worsening in all districts except for the first dataset of Sarah Baartman. Most of these events were linked to strong El Niño events. Overall, the SPEI results indicated that more dry events were present in period 2 (1992-2021/22) than in period 1 (1962-1991). The overall duration of dry events was also longer, and drought events were more severe in period 2. The first dataset of Sarah Baartman and the West Coast were the only two districts to have more drought events in period 1 than period 2, but their second datasets showed the opposite. Stakeholders, policymakers, mayors, etc. should therefore be aware of the worsening drought conditions in all districts of the western region. The limitations were thoroughly noted in the data and methodology chapter, yet a key limitation to note is that the weather stations were sparser in certain districts than others. Considering that the changes in characteristics of drought in the western region were thoroughly explored, objective 1 was thus achieved.

Findings from Objective 1 can be summarised as follows:

- The frequency of drought events has increased in period 2 (occurring every ~1.5 years) compared to period 1 (occurring every ~5 years).
- The average SPEI intensity of drought events were more severe in period 2 than in period 1 for most districts.
- The overall duration of drought events was longer in period 2 (~6.6 years) compared to period 1 (~2 years).

2.) Investigate the extent to which drought events were impacting vegetation density in the provinces within the study area of South Africa.

The NDVI values from all five provinces showed increasing trends from 1984-2021. This was also supported by the Mann-Kendall Tau values but was only slightly positive. The results suggested that the provinces endured vegetation growth. On closer inspection of the trends, all provinces showed a decrease in values from 2010-2021. This decreasing trend from 2010 coincides with the period of drought recorded by the results in Chapter 4. One reason for the decreasing NDVI values from 2010 can be associated with the severe drought events that occurred during that time and their effect on vegetation density. Low NDVI values were also recorded during the early 2000s, which also coincides with the multiple dry years recorded from 1999-2004 in Chapter 4. Even though the 2010s displayed decreasing NDVI trends in all provinces, the values were still overall higher than NDVI records from previous eras. More values below 0.3, relating to water stress, were present in the 1990s than 2010s. Results from Chapter 4 showed that worsened drought conditions were present in period 2 than in period 1. Therefore, the NDVI results disagreed with the SPEI results to a certain extent since the overall median NDVI values from the 2010s were still higher than previous decades. This suggests that although severe drought events were recorded in Chapter 4 from 2010 onwards, and a decrease was noted in the NDVI values, the intensity thereof did not reflect to the same degree. Reasons for this may be attributed to increasing drought resistant technologies, which results in a limitation in the use of the NDVI. Overall, the results indicated that the vegetation density of the provinces were only affected to a certain extent during the period of drought events, therefore achieving the second objective.

Findings from Objective 2 can be summarised as follows:

- Increasing trends were found in the NDVI values for all provinces from 1984-2021.
- All provinces displayed decreasing trends between 2010-2021, representing the increased drought events recorded in the SPEI graphs during period 2 from the first objective.

- The intensity of the drought events from period 2 did not reflect in the NDVI values (effect on vegetation density) to the same degree.

3.) Examine the characteristics of future drought events, in the western region of South Africa and compare them to historical events.

The SPEI data was extracted under the SSP2-4.5 scenario. The results showed that 15/17 districts are expected to have an increased number of dry events occur, 5/17 districts are expected to have increased average drought intensities, and 2/17 districts are projected to have longer durations of dry events in comparison to the past (Chapter 4). No district from the SPEI results has shown an increase in all three characteristics. The Mann-Kendall Tau values showed that most districts had either weak positive or weak negative trends and were not as significant as the results in Chapter 4. The Namakwa, Garden Route, and West Coast districts depicted that they would have both increasing dry events and increasing intensities. The Xhariep district was the only district to show an increase in duration and intensity, but not an increase in events. These four districts, located in the Northern Cape, Western Cape, and Free State (respectively) are most likely to have worsened drought events/conditions in comparison to the past. Stakeholders and mayors of these districts should proactively be aware of the possible upcoming drought events, including their duration, intensity, and frequency to be better equipped and prepared. Given that only 4/17 districts are predicted to have worsened drought conditions, one can state that conditions in the western region are predicted to be less intense and shorter than past results. However, any modelled data is limited to being a projection, therefore the accuracy thereof should be taken into consideration. Overall, the future SPEI of the districts showed greater fluctuations than in the past, which is why dry events were recorded more frequently, yet they are predicted to have weaker intensities and shorter durations. The characteristics of future drought events were examined and compared to past results, therefore, achieving the third objective.

Findings from Objective 3 can be summarised as follows:

- The Namakwa, Garden Route, West Coast, and Xhariep districts will have worsened drought conditions/events in comparison to the past SPEI results in Chapter 4.
- Greater fluctuations in SPEI results were present for the future than in past results, thus portraying weaker intensities and shorter durations.
- The Mann-Kendall Tau values for the future results showed weaker trends compared to the Mann-Kendall values from the past.

7.2 Conclusion

Drought is a climatic extreme that is arguably one of the worst natural hazards that can inflict socio-economic harm, especially when prolonged. Following the drought events up until 2019, 20 million hectares of farmland were impacted in the Northern Cape, because of prolonged drought. Around the same time, the Western Cape, North West, and Free State have been declared disaster regions because of prolonged drought impacts. Furthermore, rural communities in the Eastern Cape were left vulnerable after drought events started in 2015. Given the problematic socio-economic consequences of prolonged drought, it becomes important to investigate changes in drought variability over time. The western region of South Africa was chosen as the study area because of the recent impacts of drought inflicted on the aforementioned provinces. This region was not investigated, as a whole, in any other study, therefore filling a research gap. This study was unique as it broke the region down via its district municipalities so that stakeholders of those districts can be more aware and informed. As the frequency, duration, and intensity of drought events in every district was investigated, it became apparent which districts were under threat of changing drought variability in the past and in the future.

The SPEI results of the second dataset from Objective 1 indicated that a greater frequency of drought events, with greater intensities, and durations were present in period 2 (1992-2021/22) compared to period 1 (1962-1991). The Mann-Kendall Tau results supported the results and showed that all districts, except for the first dataset of Sarah Baartman, had moderate to significant negative Tau values. All districts, except for Joe Gqabi also displayed a long drought event(s) which occurred in 2012-2021/22. The drought event(s) recorded from 2012-2021/22 is the reason why so many provinces were declared disaster regions during that period as no other event for that duration and intensity was recorded in period 1. The worsening drought conditions of period 2 can lead to the assumption that drought events are projected to aggravate in the future. When taking these results of the first objective into account, one would assume it would reflect on the NDVI values. However, results from Objective 2 showed that the overall long-term NDVI trend was increasing in each province. Yet, upon closer inspection of the trends, each province showed decreasing NDVI values during the recorded 2012-2021/22 droughts. Therefore, indicating that the drought events did indeed have an impact on vegetation. Nevertheless, the overall NDVI results disagreed, to a certain extent, with the SPEI results, as the worsened drought events did not reflect on the NDVI values to the same degree. Objective 3 showed that only three districts, namely the Namakwa, Garden Route, and West Coast are predicted to have both increasing dry events and increasing intensities. The Xhariep is predicted to have an increase in the duration and intensity of drought events. Since the

results from the first objective indicated that all districts endured worsened conditions, it was assumed that future modelled data would indicate the same. However, in total, only 4/17 districts are predicted to have worsened drought conditions.

Overall, this study showed that changes in drought variability from the past did take place in all districts of the western region as worsened drought conditions were revealed in period 2 compared to period 1. The study discovered that NDVI values had decreased during the drought period of 2012-2021/22, but the long-term NDVI trends in all five provinces still increased overall. Modelled data showed that the drought events are expected to only worsen in 4/17 districts from 2050-2100. When taking the past and recent results of 1962-2022 into consideration, stakeholders, policymakers, mayors, etc. of all districts within the western region need to proactively be aware of the worsened drought conditions. The Namakwa, Garden Route, West Coast, and Xhariep districts' stakeholders should be aware of the future predictions of worsening drought events. This study, therefore, provided insight into drought variability in the past and future and changes in vegetation density of the western region, which provides valuable information for stakeholders. The study, therefore, achieved its aim and objectives.

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