THE ANALYSIS OF TROPICAL TEMPERATE TROUGH-ASSOCIATED RAINFALL ONSETS AND THEIR INFLUENCE ON MAIZE YIELDS IN THE MAIZE TRIANGLE, SOUTH AFRICA

by

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Submitted in fulfilment of the requirements for the degree

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SUMMARY

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Keywords: Tropical temperate troughs, outgoing longwave radiation, rainfall onsets, planting dates, maize triangle

This study investigated the association of tropical temperate troughs (TTTs) with rainfall onsets, as well as the bearing this association had on subsequent maize yields in the Maize Triangle during the period 1979 to 2018. It intended to expand the detailed knowledge and understanding of the relationship between these variables and contribute useful information towards the atmospheric sciences and decision-making processes. Finally, the study envisages to advance the development of relevant and efficient climate change mitigation tools for application, particularly in the agriculture and agrometeorology fields. Various data sets (including observed TTT centres, outgoing longwave radiation (OLR), district rainfall and maize yields) were analysed and the subsequent results were plotted using different methods.

The analysis of TTT climatology over the subcontinent, which was done through the computation of daily OLR anomaly composites, confirmed that TTTs were an austral summer phenomenon, who's prominent and fully developed structure was visible from September to December when these systems were positioned to the most southwest section of the subcontinent. From December, TTTs began shrinking in size and deforming in structure, while propagating northeastward until their negative OLR limb merged with the zonal tropical belt in February. The study further examined the relationship between the identified TTTs and their association with rainfall onsets in the Maize Triangle, and found that approximately 90% of the investigated austral summer seasons that constitute the study record had rainfall onsets occurring concurrently with TTTs, while less than 3% of rainfall seasons consisted of rainfall onsets that were not associated with TTTs during the same study period. The 7% that was unaccounted for consisted of missing rainfall onset data. Furthermore, rainfall districts that constitute the Maize Triangle had between 74% and 97% of their rainfall seasons characterised by TTT-associated rainfall onsets.

Seasonal trends analyses of TTT-associated rainfall onsets and subsequent maize yields suggested that there was no temporal consistency between these variables during the study period. Spatial analyses showed that the majority of rainfall districts had increasing trends and slopes that were relatively stronger for seasonal maize yields when compared to trends and slopes of rainfall amounts produced by TTT-associated rainfall onsets, while the seasonal frequency of rainfall district based TTTs that occurred during the rainfall onset periods was declining. The regression analysis between rainfall amounts from TTT-associated rainfall onsets and subsequent maize yields revealed an insignificant relationship with a regression coefficient of 0.0004. Correlation analyses between rainfall amounts from TTT-associated rainfall onsets and subsequent maize yields, as well as rainfall amounts from post-TTT-associated rainfall onsets (120 days afterwards) showed that there were weak positive correlations in both sets for the majority (82%) of rainfall districts. This study therefore concluded that while TTTs played a crucial role in the initiation and sustainability of rainfall onsets, their impact on the resulting maize yields was not as significant, possibly owing to numerous other factors that are typically employed in maize cultivation in the Maize Triangle.

RESEARCH OUTPUTS

Conference presentation

Oral presentations

1. Conference: SAEON GSN Indibano

   Presentation title: The climatology of tropical temperate troughs occurring over South Africa during the summer rainfall onset period

   Date: 16–21 October 2022

   Location: Sol Plaatje University, Kimberley, Northern Cape, South Africa

LIST OF ABBREVIATIONS

ARID:	Agricultural Reference Index for Drought
CCWR	Computing Centre for Water Research
CMAP:	Climate Merged Analysis of Precipitation
CMI:	Crop Moisture Index
CoCA:	Census of Commercial Agriculture
COL:	Cut-off Low
COPs:	Conference of the Parties
CPC:	Climate Prediction Centre
CSIS:	Centre for Strategic and International Studies
DAFF:	Department of Agriculture, Forestry and Fisheries
DALRRD:	Department of Agriculture, Land Reform and Rural Development
DEA:	Department of Environmental Affairs
DJF:	December-January-February
ECMWF:	European Centre for Medium-Range Weather Forecasts
EDI:	Effective Drought Index
ENSO:	El Niño Southern Oscillation
ESRL:	Earth System Research Laboratories
ETCCDI:	Expert Team on Climate Change Detection and Indices
FAO:	Food and Agriculture Organization
GDD:	Growing Degree Day
GDP:	Gross Domestic Product
GIS:	Geographic Information System
GIZ:	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
IOH:	Indian Ocean High
IPCC:	Intergovernmental Panel on Climate Change
IRI:	International Research Institute
ITCZ:	Intertropical Convergence Zone
JJA:	June-July-August
KNMI:	Koninklijk Netherlands Meteorological Institute

LD:	Limits of Detection
MAKESENS:	Mann-Kendall test for trend and Sen's slope estimates
MAM:	March-April-May
MATLAB:	Matrix Laboratory
MJO:	Madden-Julian Oscillation
MK:	Mann-Kendall
MS:	Microsoft
NCEP:	National Centre for Environmental Prediction
NDVI:	Normalized Difference Vegetation Index
NOAA:	National Oceanic and Atmospheric Administration
OLR:	Outgoing Longwave Radiation
ONI:	Oceanic Niño Index
PDSI:	Palmer Drought Severity Index
PET:	Potential Evapotranspiration
QBO:	Quasi-Biennial Oscillation
SADC:	Southern African Development Community
SAH:	South Atlantic High
SANBI:	South African National Biodiversity Institute
SAWB:	South African Weather Bureau
SAWS:	South African Weather Service
SICZ:	South Indian Convergence Zone
SEAO:	Southeast Atlantic Ocean
SIH:	South Indian High
SMDI:	Soil Moisture Drought Index
SON:	September-October-November
SPEI:	Standardised Precipitation Evapotranspiration Index
SPI:	Standardised Precipitation Index
SST:	Sea-Surface Temperature
StatsSA:	Statistics South Africa
SWIO:	Southwest Indian Ocean
TE:	Tropical-Extratropical

TP: Tropical Plumes

TTT: Tropical Temperate Trough

UNEP: United Nations Environmental Program

USAID: United States Agency for International Development

VHI: Vegetation Health Index

WMO: World Meteorological Organization

DECLARATION

I, Mthobisi P. Nxumalo, declare, that the thesis, which I hereby submit for the master's degree in Environmental Management (MSc) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution

ETHICS STATEMENT

The author, whose name appears on the title page of this thesis, has obtained the applicable research ethics approval for the research described in this work.

The author declares that he has observed the ethical standards required in terms of the University of Pretoria's Code of Ethics for Researchers and the Policy Guidelines for responsible research.

Signature:

Student name: Mthobisi Percival Nxumalo

Month Year: February 2024

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Climate change is arguably the biggest global threat the world is currently facing. In its State of the Global Climate 2022 (WMO, 2023), the World Meteorological Organization (WMO) reported an increasing temperature trend, the steepness of which was more pronounced from the late 1900s (Figure 1-1). While the historical behaviour of temperature trends as an indicator of climate change has been well documented using various models, future predictions, as well as its subsequent impacts (IPCC, 2007a; IPCC, 2018; Kruger and Shongwe, 2004; Lindsey and Dahlman, 2024), are not yet well understood. Furthermore, there is notable evidence of agreements between these authors about the future of the world in a warming climate. However, inconsistencies and, to a certain extent, disagreements still exist in future climate predictions, particularly predictions in developing regions where there is insufficient infrastructure and data to draw plausible conclusions (WMO, 2023). The State of the Global Climate 2022 (WMO, 2023) reiterated that climate change impacts are wide and variable, with their effects felt across all socio-economic sectors around the world. This difficulty is exacerbated by conflicts in these sectors, which typically lead to poor decision making, which, in turn, contributes negatively to societies (WMO, 2023). In addition, the report pointed out that resource distribution was arguably the principal cause of society's lack of resilience to climate change, particularly in poor countries that are ravaged by political conflicts.

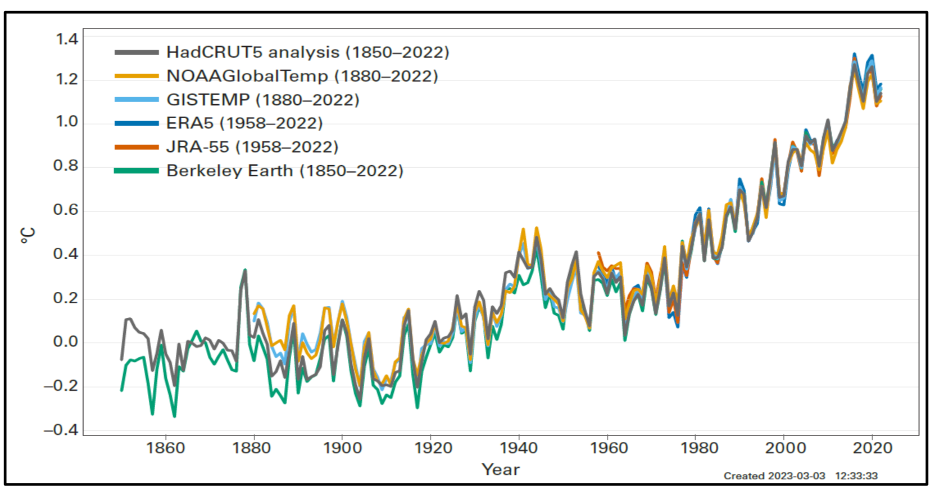

Figure 1-1 Global annual mean temperature anomalies with respect to pre-industrial conditions (1850–1900) for six global temperature data sets (1850–2022). Source: WMO, 2023.

While this study acknowledges that there is a variety of socio-economic sectors that are critical for societies to thrive, such as health, environment and finance, it views the agricultural sector as the basis of all sectors, since no society can exist without food. Furthermore, the agricultural sector is extremely sensitive – with impacts that are visible within a short space of time – to significant changes to the climate system. A constant supply of agricultural products that meets societal demands is critical in ensuring food security for communities. Food security is complex, dependent on numerous factors and, as a result, varies from one region to another, making it difficult for researchers to fully comprehend and provide common solutions. Climate change is regarded as one of the main issues that pose a major threat to food security (Bwalya, 2013). Various researchers from different parts of the world have observed the negative impacts of climate change on agricultural land degradation. These are projected to continue in the future (Masipa, 2017). The lack of adequate research, particularly in developing countries, leads to limited knowledge and understanding of how climate change will impact future livelihoods, as well as fundamental socio-economic sectors such as agriculture, which ultimately hinders the satisfactory planning and implementation of critical decisions.

Humanity's strong dependency on agriculture – as one of the core socio-economic sectors – creates a significant need for in-depth understanding of this sector, along with other related sectors. Although the agricultural sector can generally be divided into two main types – commercial and subsistence – it is a wide and diverse industry that comprises two basic classes – livestock and crops – that vary considerably. The same variability is notable in the extensively diverse societies the agricultural sector serves. These range from the poor and marginalised to the wealthy. It is, however, noteworthy that the dependency of poor societies on this sector is relatively stronger and more sensitive since they usually lack access to sufficient resources, including scientific knowledge and infrastructure, and rely heavily on indigenous knowledge and weather patterns. While the diversity within this sector is well acknowledged, it is, unfortunately, further complicated by external drivers, such as the climate, hydrology, soil types and the economy, which are also complex. The dependency of the agricultural sector on external factors such as rainfall patterns creates the need to intensify research that interrogates the nature of relationships between agricultural practices and associated external sectors, such as patterns in rainfall-producing systems and economic variations, to gain a more comprehensive understanding of the issue at hand.

This study has therefore followed the approach of investigating the interaction between one of the major rainfall-producing systems and the agricultural yields of one of the key crops in southern Africa, maize. The key variables investigated in this study were tropical temperate troughs (TTTs) and rainfall onsets to establish an understanding of their interactions, as well as the impacts of their interactions on subsequent maize yields, which serve as an indicator for the nature of the resulting relationship.

1.2 PROBLEM STATEMENT

Numerous researchers are actively investigating various aspects of the environment, with the intention of crafting solutions to many of the problems we face today. With climate change arguably being the biggest issue that is spatially and temporarily variable, much of the research in the environmental sciences revolves around it. It has been noted that the bulk of these investigations has been focused on the analysis of a single factor or aspect of the environmental system at a time. Not much research is focused on establishing relations and interactions between two or more distinct aspects of the environmental system that are related in one way or another. Additionally, many of the environmental factors that are under scientific scrutiny are made up of other aspects. Although these are typically smaller in scale, resulting in them being ignored by researchers, they still need to be understood to better understand the bigger system. These gaps may contribute to the observed difficulty in accurately predicting the behaviour of the environmental system. This study therefore proposes a methodology of research that investigates the relationship between two distinct, but related environmental processes and the impacts of these relations on agricultural production. In order to bridge the identified gap, the study will analyse the interaction of one of the major austral summer rainfall-producing systems, tropical temperate troughs, with one of the agricultural aspects that is a requirement of planting, i.e. rainfall onsets. The study will further investigate the impact of this interaction on the resulting yields of the main crop in South Africa, i.e. maize. Results from this study are envisaged to contribute meaningfully to understanding trends and variables of the investigated environmental processes, and advance the knowledge of the relationship that exists between the two primary aspects that are researched and their resultant influence on crop production. This work will contribute to the available literature, and improve existing forecasting techniques and decision making. Some of the limiting factors of this research include data availability and quality. However, there are possibilities of new research topics emanating from this work.

1.3 NEED FOR THE STUDY

The need for this study is embedded in expanding knowledge and understanding the relationship between TTTs and rainfall onsets as well as to determine the impact of their relationship on subsequent maize yields. Its need is even more important during this time in which climate change has brought puzzling variations and shifts to various environmental processes, thus introducing significant uncertainties in predicting the behaviour of these processes. The semi-holistic approach employed in this study has the advantage of gaining a comprehensive understanding of interactions that exist between tropical temperate troughs and rainfall onsets, as well as how these interactions affect resultant production. As a result, this study will not only provide an additional understanding of the investigated systems individually, but will also address how they interact, as well as the outcomes of their interactions. Climate change – among other factors – necessitates rigorous research to be conducted using different approaches, particularly in the environmental field. This includes agriculture, which supports life. The focus on maize as an indicator was motivated by the role maize plays – particularly in the developing regions – as a food source for both humans and animals, as well as its useful applications in other sectors. Valuable information that can be of use for multiple purposes is expected from this work.

1.4 RESEARCH QUESTIONS

- What is the climatology of tropical temperate troughs in southern Africa?
- What is the nature of the relationship between tropical temperate troughs and rainfall onsets in the Maize Triangle?
- How do tropical temperate trough-associated rainfall onsets influence subsequent maize yields in the Maize Triangle?

1.5 AIM AND OBJECTIVES

1.5.1 Aim

The aim of this study is to investigate the influence rainfall onsets that are associated with tropical temperate troughs have on subsequent maize yields in the Maize Triangle, South Africa.

1.5.2 Objectives

(i) Investigate the climatology of tropical temperate troughs that occurred over southern Africa during the period from 1979 to 2018.

(ii) Explore the nature of the relationship between tropical temperate troughs and rainfall onsets in the Maize Triangle.

(iii) Assess the influence of tropical temperate trough-associated rainfall onsets on subsequent maize yields in the Maize Triangle.

1.6 HYPOTHESES

This study puts the following hypotheses forward:

Null hypothesis (H_0): Rainfall onsets associated with tropical temperate troughs have no impact on subsequent maize yields in the Maize Triangle.

Alternative hypothesis (H_a): Rainfall onsets associated with tropical temperate troughs have a positive impact on subsequent maize yields in the Maize Triangle.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

A literature review related to this study is presented in this chapter. It is largely comprised of recent research conducted by researchers from various places and covers numerous topics related to concepts investigated in this study. These include the climate and its implications, rainfall variability – in the form of droughts and floods – and the El Niño Southern Oscillation (ENSO) as the driver, tropical temperate troughs, agriculture, maize cultivation and the relevant rainfall timing aspects. This chapter is a continuation of the background and therefore references the climate change issues with which the world is currently faced. It will also update the reader on this and other topics listed above. Some of the important highlights this chapter intends to demonstrate include the progress that climate and related sciences have made in recent years, as well as some of the existing challenges and gaps. This chapter should paint a comprehensive picture of the state of recent research.

2.2 THE CLIMATE OF SOUTH AFRICA

While several definitions of climate are available in the literature, this study adopted that of Goose et al. (2010), who define climate as the mean and variability of relevant atmospheric variables such as temperature, precipitation and wind. The climate of South Africa is semi-arid, highly variable and strongly seasonal (Tyson, 1986; Tyson and Preston-Whyte, 2000). It is characterised by frequent extreme events such as flash floods and severe droughts, which typically result in loss of property and even lives (Landman et al., 2015). ENSO is a major factor that influences the climate of South Africa on seasonal time scales (Tyson and Preston-Whyte, 2000). The country's climate comprises four seasons: winter, spring, summer and autumn. During winter (June to August), the South African atmosphere is largely dominated by the subtropical pressure belt, which displaces rainfall over much of the country, leading to only the southern parts of the country receiving rainfall from cold fronts, although cut-off low pressure systems have a tendency to enhance rainfall over summer rainfall regions during winter (Landman et al., 2015).

Spring (September to November) is characterised by the development of a thermal low over the western parts of southern Africa as a result of enhanced solar radiation on a poorly vegetated surface (Landman et al., 2015). This thermal low is responsible for triggering the formation of thunderstorms to the east of the subcontinent from spring to autumn (Tyson and Preston-Whyte, 2000; Landman et al., 2015). Furthermore, the onset of the rainy season in South Africa occurs in spring and results in the occurrence of the first significant rains east of the country, typically over KwaZulu-Natal, before spreading to the interior. Rains that occur in the interior parts of the country during spring are typically produced by weather systems of the westerly wind regime known as the "westerly waves" when they occur in combination with ridging high-pressure systems in the lower levels of the atmosphere (Landman et al., 2015).

Summer (December to February) is the period when the Intertropical Convergence Zone (ITCZ) is at its southernmost location, bringing tropical moisture southwards. This is regarded as the most important period for rainfall in the central and northern interior of the country (Landman et al., 2015). During this season, most rainfall occurs through TTT events, which occur as a result of a westerly wave, combining with a tropical trough or low-pressure system, leading to the development of an extended cloud band formation, which results in the occurrence of widespread rainfall over the subcontinent that lasts for several days (Landman et al., 2015). This season is also characterised by heat-induced thunderstorms that frequently occur over the central interior of the country, particularly over the eastern escarpment and Highveld areas, as well as a high prevalence of tropical cyclones making landfall from the Southwest Indian Ocean (SWIO). In autumn (March to April), the ITCZ propagates northwards, allowing subsidence to set over much of the subcontinent, leading to reduced rainfall over much of the region (Landman et al., 2015). The adverse diversion from the normal long-term weather conditions in a particular area is referred to as climate change (DAFF, 2011; IPCC, 2006; Kurukulasuriya and Rosenthal, 2003). Changes in the climate can lead to notable shifts in trends and variability of environmental systems that are linked to the climate, such as rainfall and temperature patterns. Sectors that are heavily dependent on these systems, such as agriculture, can be severely negatively affected by the changing climate. There is a global agreement among researchers that climate change and variability are a reality (Botai et al., 2018) with several scientific publications from different fields confirming climate change (IPCC, 2007a; Meehl et al., 2006; Mora et al., 2013; Rouault et al., 2013).

Kruger and Nxumalo (2016) reported that analyses of historical temperature trends had all shown a generally increasing trend in both mean and extreme values over recent decades. Moreover, Kruger and Nxumalo (2016) observed an upward trend in warm events accompanied by a general decrease in extreme cold events across the country, with the austral summer showing the strongest warming. The analysis of heatwaves conducted by Mbokodo et al. (2020) demonstrated that weather and climate extremes such as heatwaves had become more frequent due to climate change around the world, and were expected to increase in South Africa. In agreement with the latter findings, the South African Weather Service (SAWS, 2023) updated the country's mean annual temperature anomalies to demonstrate that there is a countrywide changing climate to be noted from the observed warming trend of 0.16 °C per decade, which occurred during the period 1951–2022, as shown in Figure 2-1. Temperature increases in parts of the country were also noted by Van Wilgen et al. (2016), who observed changes in temperature and rainfall in South African national parks during the past few decades, with their results exhibiting significantly increasing temperatures in most parks, while most rapid increases were noted over the arid parts of the country. Van Wilgen et al. (2016) also demonstrated that increases in the frequency of extreme high temperatures were more pronounced in these regions. They further stated that their findings were consistent with previous climate studies conducted on these regions.

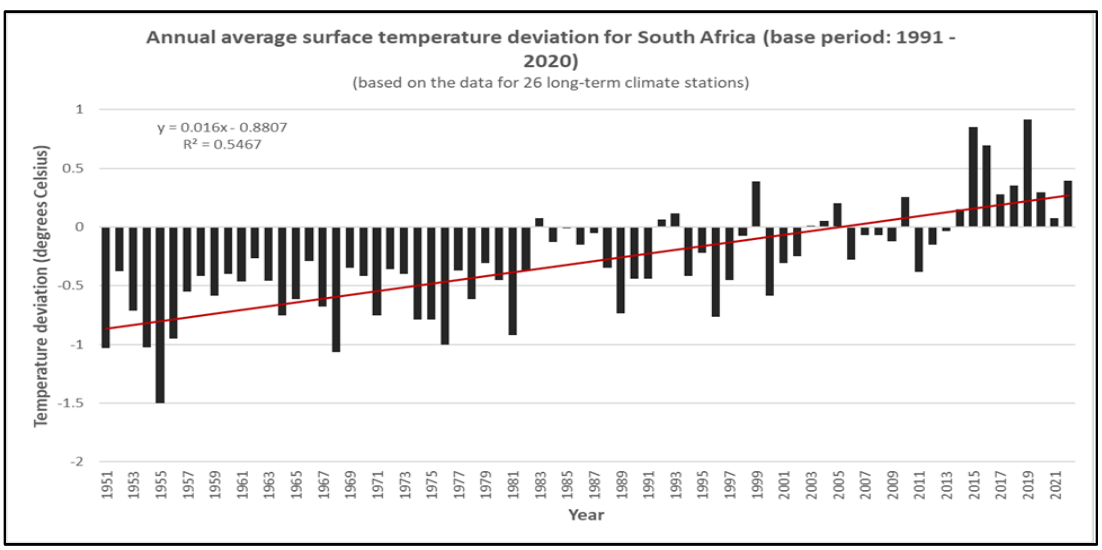

Figure 2-1 Mean annual temperature anomalies calculated from 26 climate stations in South Africa for the period 1951–2022, using the base period 1991–2020. Source: SAWS, 2023.

South Africa is additionally divided into three main climatic regions: the summer rainfall region, the winter rainfall region and the all-year rainfall region (Roffe et al., 2019). Hart et al. (2012) described South Africa as a country that is characterised by steep spatio-temporal rainfall gradients, which can be attributed to its subtropical location and complex topography. Rainfall over the southwestern part of the country predominantly originates from cold fronts associated with mid-latitude cyclones, which are high in activity during the austral winter (Mahlalela et al., 2019; Weldon and Reason, 2014). The northeastern region receives much of its rainfall from convective activity that is dominant during the austral summer (Blamey and Reason, 2012; Blignaut et al., 2009). The northwestern region receives annual rainfall below 200 mm, while the eastern Highveld receives between 500 mm and 900 mm of rainfall – occasionally exceeding 2 000 mm per annum. The northeastern parts of South Africa receive approximately 30% of their annual rainfall between January and February (De Coning et al., 1998). A number of atmospheric systems at different scales are responsible for interannual climate variability in southern Africa. Mason and Jury (1997) compiled a list of some of these systems which are presented on Table 2.1.

Table 2.1 Atmospheric systems that drive interannual climate variability over southern Africa.

System	Description
El Niño Southern Oscillation (ENSO)	ENSO warm (cool) events are typically associated with drought (floods) over much of southern Africa. Warm (cool) ENSO periods are referred to as El Niño (La Niña) periods.
The quasi-biennial oscillation	The quasi-biennial oscillation (QBO) is an atmospheric system that is thought to interact with the Walker circulation over the western Indian Ocean. It happens when the lower stratospheric easterly zonal winds provide upper tropospheric wind stress that would enhance the Walker cell overturning with a descending limb over southern Africa and a rising limb over the ocean to the east. During westerly phase years, the Walker cell is reversed with a rising limb over southern Africa, resulting in enhanced convection and rainfall over the subcontinent.
Sea-surface temperature anomalies	When the sea surface temperatures in the central equatorial Indian Ocean are higher than average, dry conditions prevail over southern Africa.
Atmospheric temperature variability	Temperature variations over southern Africa are a response to changes in advection, adiabatic heating and cooling, turbulent mixing and changes in radiation.

A climate risk assessment study for South Africa, conducted by the World Bank Group (2021), demonstrated that the temporal variations of rainfall and temperature in South Africa follow a similar pattern, as shown in Figures 2-2 and 2-3 displayed in the following page. However, spatial variability tends to be the opposite. Figure 2-2 shows that higher temperatures and rainfall are largely experienced during the austral summer months. The two variables are relatively low during the austral winter months in South Africa. On the other hand, Figure 2-3 illustrates that the spatial distribution of high temperatures is restricted over much of the western half of the country, while higher rainfall is restricted to the eastern half of the country. Several factors are responsible for this state of the country's climate, some of which this study shall report on.

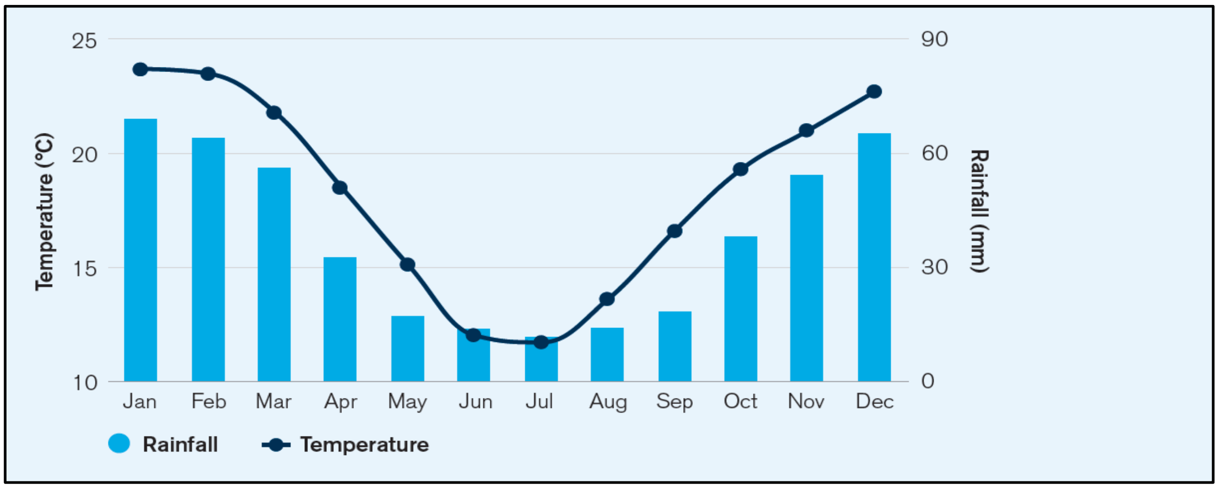

Figure 2-2 Average monthly temperature and rainfall for South Africa: 1991–2020. Source: World Bank Group, 2021.

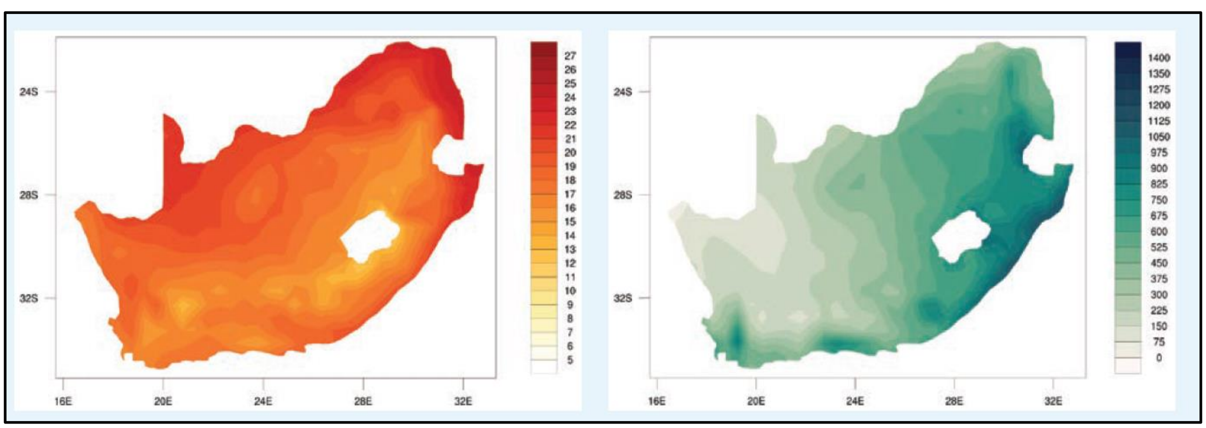

Figure 2-3 Mean annual temperature (°C) (left) and annual precipitation (mm) (right) for South Africa: 1991–2020. Source: World Bank Group, 2021.

The South African rainfall is predominantly an austral summer phenomenon (November to March), with exceptions of the south coast, which receives rainfall throughout the year, as well as the southwestern coast, which receives much of its rain during the austral winter (Blamely and Reason, 2013; Crétat et al., 2019; Mulenga, 1998; Taljaard, 1986). Page 11 of this thesis consists of the seasonality of rainfall in South Africa that was developed by Schulze (2007) and is presented in Figure 2-4 on page 12. This figure revealed that rainfall is typically received during the early and middle summer periods over the eastern half of South Africa while it is received during the latter half of the austral summer over the central to the west of the country.

In addition, the western region of the country receives much of its rainfall in winter, while the southern tip receives rainfall throughout the year. Austral summer rains are brought about by the southward migration of the ITCZ, as well as the accompanying weather systems that are responsible for the occurrence of austral summer rainfall in South Africa such as thunderstorms and tropical cyclones (Berry and Reeder, 2014; Dedekind et al., 2016; Zagar et al., 2011). Austral winter in southern Africa occurs during the months of June to August and is characterised by the northward location of the ITCZ, leading to the prevalence of large-scale subsidence over much of the country, which, in turn, suppresses the occurrence of rainfall over much of the country (Dedekind et al., 2016). During this period, a semi-permanent high-pressure belt migrates northwards and is located over much of the country, restricting cold fronts that sweep over much of the south and southwestern areas of the country. As a result, it is only the extreme southern parts of the southwestern Cape and Cape south coast of South Africa that are regularly affected by cold fronts and thus receive winter rainfall (Dedekind et al., 2016). The north/south migration of the ITCZ as it follows the sun is the main driver of seasonal rainfall variations in South Africa and gives rise to four main seasons: summer (December-January-February (DJF)), autumn (March-April-May (MAM)), winter (June-July-August (JJA)) and spring (September-October-November (SON)).

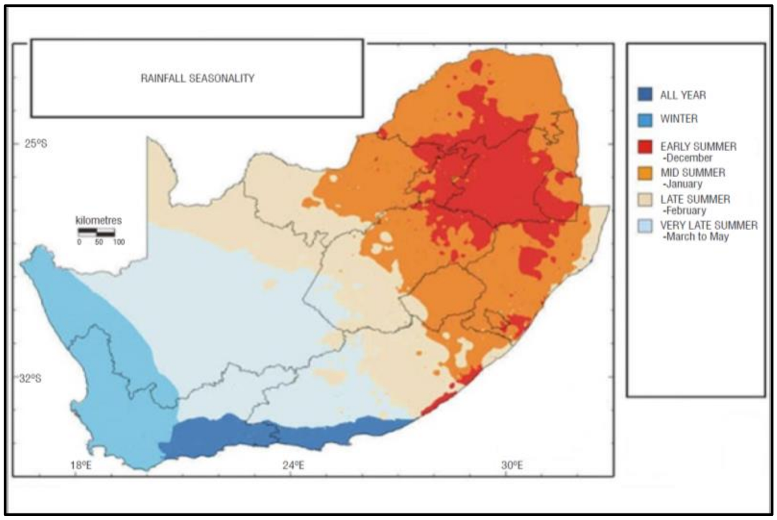

Figure 2-4 Rainfall seasonality over South Africa. Source: Schulze, 2007.

From a regional domain perspective, the location of southern Africa between latitudes 0°S and 30°S exposes the region to various rainfall-bearing systems, which are either tropical, e.g. monsoons, the ITCZ and easterly flow, or midlatitude, e.g. westerly waves and fronts (Preston-Whyte and Tyson, 1988). During the austral summer, the southward shift of the high-pressure belt allows for the broad deepening of the continental trough in the lower levels, making the atmosphere of the region conducive for the development and transportation of energy and moisture, and signalling the beginning of the austral summer that will typically last from September to February (Tyson and Preston-Whyte, 2000). The structure and typical location of the ITCZ, defined as an area of low pressure around the planet that resides along the equator, are the main characteristics that make its southward migration important to the southern hemispheric regions as it contributes large amounts of rainfall over these regions (Harrison, 1986; Taljaard, 1994), and supports other summer rainfall-bearing systems (Karoly and Vincent, 1998). Some of the systems that are supported by the ITCZ include the Angola low (Mulenga, 1998; Williams et al., 1984), which is defined by Reason et al. (2006) as a shallow thermal low that typically develops over the region north of Namibia and south of Angola around October. TTTs are one of the major rainfall-bearing systems of the subcontinent (Harrison, 1986; Van den Heever et al., 1997) and are typically associated with the Angola low (Crimp et al., 1998; Washington and Todd, 1999).

The ITCZ is predominantly responsible for driving tropical rainfall (Reason et al., 2006). During the southward displacement of the ITCZ in austral summer, when the northeasterly flow of low-level moisture from the Indian Ocean High (IOH) converges with moisture flow from the Angola low, increased rainfall is typically received over southern Africa (Reason et al., 2006). Some of the important features that are responsible for rainfall over southern Africa are illustrated in Figure 2-5. The eastern part of South Africa is bordered by this region, which is responsible for housing the southern tip of the cloud bands. It is referred to as the South Indian Convergence Zone (SICZ) (Hart et al., 2010). The exception exists for the southwestern Cape and the Cape south coast regions, which receive rainfall during the austral winter months and all year round, respectively (Jury, 2012; Taljaard, 1996; Weldon and Reason, 2014). There is a strong west to east rainfall gradient from the Northern Cape in the west to Lesotho in the east (Jury, 2012), as well as the dry slot that extends zonally from southern Namibia over Botswana into the Limpopo river basin of Zimbabwe, South Africa and Mozambique (Engelbrecht et al., 2002, 2009).

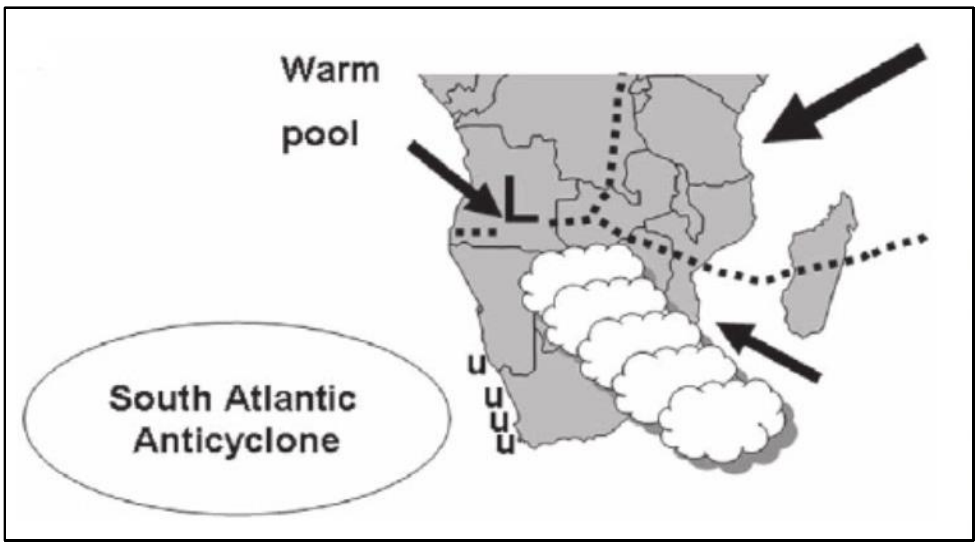

Figure 2-5 Important circulation and other features in southern Africa during the austral summer. Source: Reason et al., 2006.

A number of researchers have recently reported observed changes in the country's precipitation as a result of climate change. For instance, McBride et al. (2022) analysed extreme daily rainfall using 70 weather stations during the period 1921–2020 and noted that most weather stations experienced an increase in the probability of receiving daily rainfall that exceeds 50 mm in the latter half of the analysis period. Moreover, most weather stations exhibited increased 1:50- and 1:100-year return period values, as well as a notable increase in the probability of heavy rainfall (>75 mm) and very heavy rainfall (>115 mm) during the latter half of the study period.

2.3 CLIMATE CHANGE IMPLICATIONS IN SOUTH AFRICA

Climate change has widely been described as arguably the greatest environmental challenge facing the world in this century (Hougton, 2002). Oduniyi (2013) added that climate change is regarded as one of the most important environmental challenges the world of today faces. Concerns about climate change implications have resulted in a rise in the interest to find solutions for climate change-related environmental issues through means such as research, conferences, campaigns and shared data sets. The emergence of these initiatives is largely driven by the quest to investigate the observed climate change consequences and develop solutions, adaptation strategies, relevant policies and regulations (e.g. the Conference of the Parties (COPs), Agenda 21 of the Rio Declaration of 1992, the Intergovernmental Panel on Climate Change (IPCC) of 2001 and the Copenhagen Agreement of 2009). In addition, various researchers have investigated the impacts of climate change on different fields, such as agriculture, hydrology and the environment (Che Ros et al., 2016; Gajbhiye et al., 2016; Ndebele et al., 2020). In some instances, research efforts have been focused more on how climate change-impacted systems can affect related socio-economic sectors, for example, how increasing trends in the number of surface runoffs, fires, pests and longer dry periods are expected to affect the agricultural sector (Peprah, 2014).

It has been reported that sub-Saharan Africa is more likely to be severely affected by climate change compared to other regions because of its high exposure to climate risks and limited capacity for adaptation (Niang et al., 2014). The climate of southern Africa is semi-arid with a high spatial (Karoly and Vincent, 1998; Kotir, 2010; Tyson, 1986) and temporal (Botai et al., 2018; Tyson, 1986; USAID, 2015; Vogel, 1994) rainfall variability. This makes the subcontinent particularly sensitive to changes in climate (Crétat et al., 2019 Richard et al., 2001).

As a result, impacts of climate change on food production, agricultural livelihoods and food security in South Africa were regarded by Midgley (2013) as significant national policy concerns. The IPCC (2013) reported that rising temperatures and changing precipitation patterns will most likely restrict yields of rain-fed agriculture in most developing countries, including South Africa. Akpalu et al. (2008) added that climate change could have a significant impact on South African maize production, which is the most important staple food in South Africa and around the world. Ala-Kokko et al. (2021) also reported that food security is an ongoing concern for a large segment of South Africa's population. As a result, the World Bank has classified the country as an upper-middle income country. Apart from threatening food security, climate change is expected to negatively affect the South African economy through various means, which include revenue and the availability of jobs (FAO, 2019). Furthermore, the impacts of climate change in South Africa are expected to be exacerbated by the already existing dire economic state, where 11% of individuals and 10% of households in South Africa are already vulnerable to hunger. The prevalence of undernourishment increased from 5% (2.8 million people) in 2014 to 6% (3.5 million people) in 2017 (FAO, 2019).

Average temperatures that continue to increase (e.g. Kruger and Shongwe, 2004) and average rainfall that is gradually declining (e.g. Durand, 2006; Hewitson, 1999) in South Africa are clear signals that the country's climate is already changing. Various authors (e.g. Dube and Jury, 2000; Jury, 2002; Vogel, 1994; Washington and Downing, 1999) have raised concerns about the existing high risk of relying heavily on subsistence agriculture that is prevalent in the subcontinent, particularly in the majority of poverty stricken and marginalised communities. Warnatzsch and Reay (2019) concurred by reporting that climate change was also expected to intensify the current food insecurity, health challenges, poverty and development challenges in sub-Saharan Africa. On a regional scale, the tropics are predicted to decrease under unfavourable climatic conditions with food production that relies on rain-fed agriculture projected to decline by about 50% in Africa (Affholder et al., 2013; IPCC, 2007a). Evidence of projected climate change (e.g. IPCC, 2007a) calls for everyone to take part in curbing the impacts of climate change, particularly in regions where adaptation and resilience are difficult to achieve. Agricultural activities are expected to be the most impacted, particularly South Africa's rain-fed agriculture, because the country's climate is already semi-arid and consists of a strongly variable spatio-temporal rainfall (Akpalu et al., 2008; Blignaut et al., 2009; Johnson, 2019).

2.4 RAINFALL PATTERNS IN SOUTH AFRICA

It has been widely documented that the South African seasonal rainfall is predominantly influenced by ENSO (Odiyo et al., 2019; Tfwala et al., 2018), a phenomenon described as the oscillation of sea surface temperatures (SSTs) from warm phases (El Niño, which is typically associated with predominantly dry conditions over the subcontinent) to cold phases (La Niña, which is typically associated with predominantly wet conditions over the subcontinent) over the equatorial Pacific Ocean region called Niño 3.4 (Crétat et al., 2019; Ganguli and Reddy, 2013; Saunders et al., 2017). Other systems, such as regional SSTs, can also influence rainfall occurring over the country (Landman and Beraki, 2010). As a result, the climate of South Africa is occasionally characterised by flooding and droughts that are driven by the intensity of the prevailing climate systems (Mason and Joubert, 1997). According to Taljaard (1989) and Harrison (1983), rainfall variability is caused by changes in the frequency, duration and intensity of large-scale weather systems that are responsible for the number of days with significant rainfall rather than the number of rain days (Harrison, 1983; Rubin, 1956) or the length of the rainfall season (Nicholson and Chervin, 1983) over the subcontinent.

Kibii (2021) updated the spatial distribution of annual rainfall over South Africa and demonstrated east/west and north/south spatial rainfall distribution variation (Figure 2-6 on page 17). Kibii (2021) also highlighted that, although the average annual rainfall received over central South Africa is 450 mm/year, the eastern parts receive an annual average rainfall that exceeds 600 mm/year, while the western parts only receive up to 250 mm/year. However, the total mean annual rainfall received by South Africa is still below the world's average and, as a result, the country is regarded as a semi-arid country (Tyson, 1986) that receives an average of 450 mm of rainfall per annum (Tyson, 1986). Other authors, such as Botai et al. (2018), reported an average rainfall of 500 mm/year, which is still much less when compared to the global average of 800 mm/year. In a study by Blignaut et al. (2009), South African provinces were grouped into three clusters based on temperature and rainfall data sets with percentage changes between 1970–1979 and 1997–2006. For rainfall, in particular, these clusters were <550 mm (North West was classified under this cluster), 500–700 mm (Free State was classified under this cluster) and >700 mm (Mpumalanga was classified under this cluster).

The observed rainfall variation from wet (averaging between 500 and 900 mm and occasionally exceeding 2 000 mm per annum) over the east coast to semi-desert and desert (averaging below 200 mm per annum) over the west coast, as well as the central interior that receives an average of 400 mm of rainfall per annum, is not enough to consider the country as having a wet climate (Botai et al., 2018; Dinar et al., 2012). The semi-arid climate state of South Africa is in line with the study of rainfall variability and trends over the African continent conducted by Alahacoon et al. (2022), who suggested that countries around the globe located above 15°N and below 15°S do not receive significant rainfall in any month. According to the Department of Environmental Affairs (DEA) (2013) and the United States Agency for International Development (USAID) (2015), analyses of South Africa's historical rainfall revealed a high interannual variability during the period 1960–2010 when the annual rainfall exceeded the average during the 1970s, late 1980s and early 2000s, and dropped below the average towards 2010.

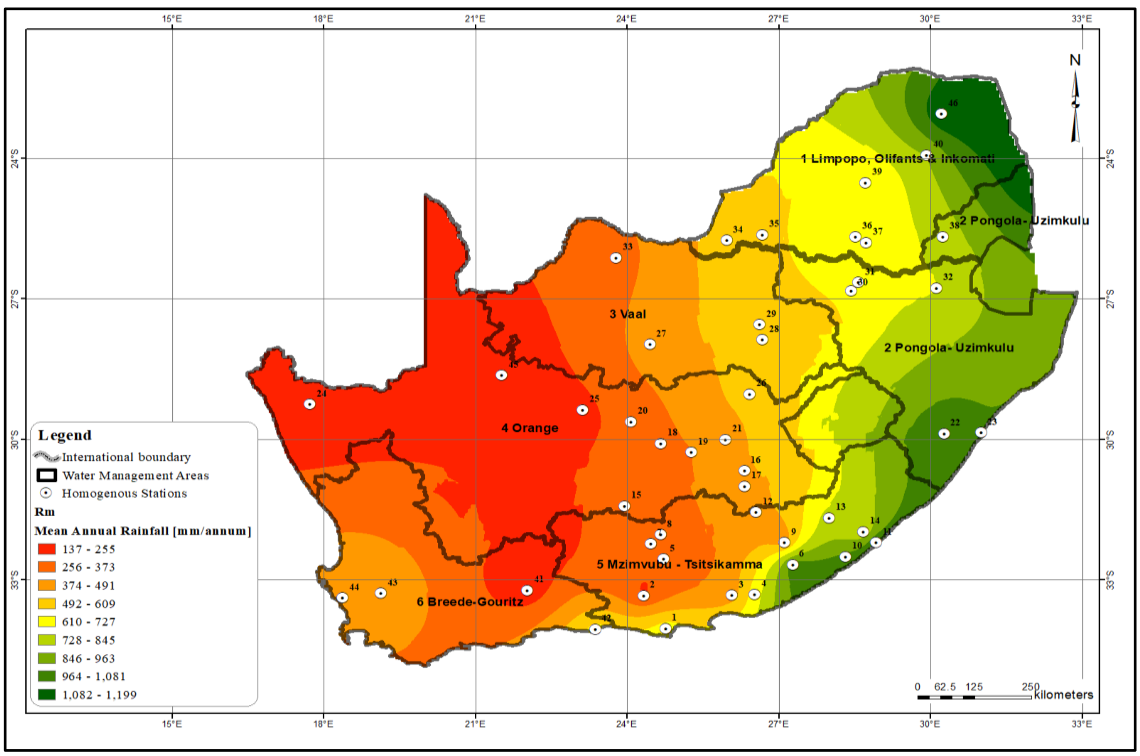

Figure 2-6 Long-term mean annual rainfall over South Africa during the period 1900–2019. Source: Kibii, 2021.

Mean annual rainfall that was analysed by Kibii (2021) for three four-decade periods from 1900 to 2019 (Figure 2-7), showed spatial variations, particularly for the northwest spatial rainfall distribution where the low rainfall seemed to be expanding towards the east during the most recent four-decade period, thus reducing the spatial distribution of high rainfall over the east. Another study by the DEA (2013) reported that there was an increase in extreme annual rainfall events, particularly during spring and summer, while these events displayed decreasing trends during autumn. Groisman et al. (2005) noted an increase in the annual frequency of extreme rainfall over the eastern parts of South Africa from 1906 to 1997, while Kruger (2006) identified increasing trends in extreme rainfall indices over the eastern parts of the country from 1910 to 2004. Mason et al. (1999) reported that there was an increase in the intensity of strong rainfall events during the period 1961–1990 compared to 1931–1960 over much of South Africa. A study by McBride et al. (2022) also noted a staggering increase in return period values, with the eastern part of the country exhibiting return period values that exceed the 1:100-year return period value. These findings were in agreement with those of Donat et al. (2013), who suggested that extreme daily rainfall generally made an increased contribution to annual rainfall totals. They also suggested that there was a significantly increasing trend in the intensity of daily rainfall received in the country.

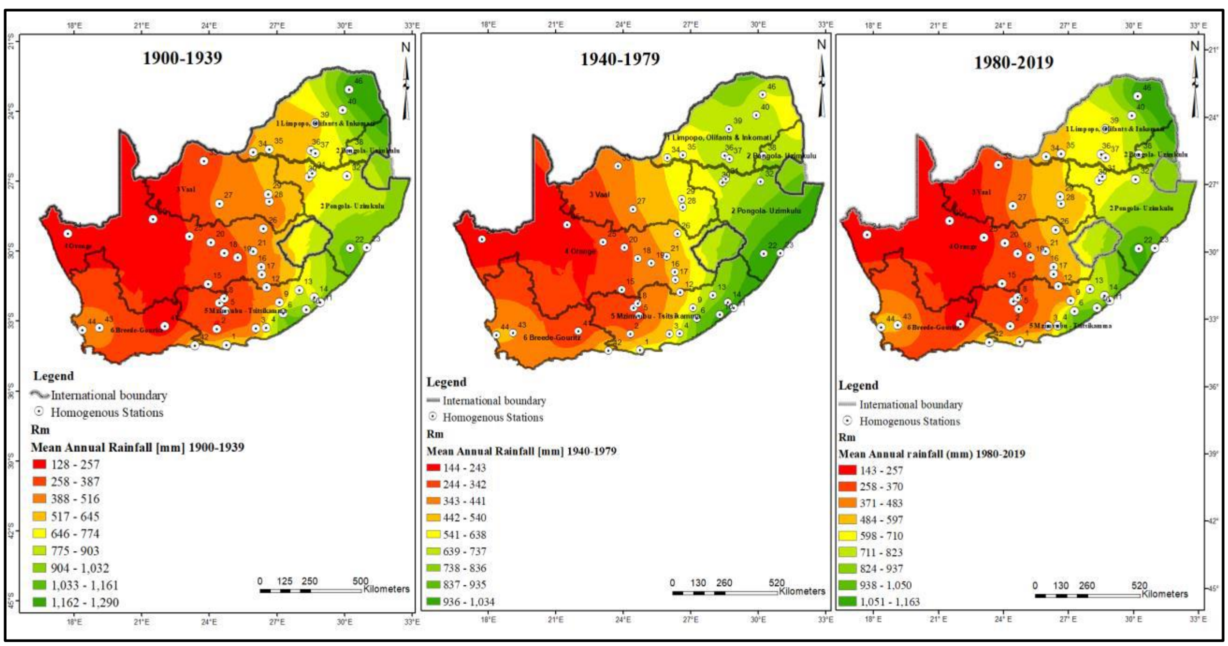

Figure 2-7 Mean annual rainfall distribution for three four-decade periods over South Africa. Source: Kibii, 2021.

Average rainfall trends for the world were reported to exhibit generally decreasing trends (Donat et al., 2013). Rainfall trends observed in the southern African region show similar patterns to global trends and are further confirmed by studies such as those conducted by Alahacoon et al. (2022), which suggested that rainfall trends were generally decreasing in the country. Using the WMO Expert Team on Climate Change Detection and Indices (ETCCDI), as well as rainfall districts for South Africa, Kruger and Nxumalo (2017) found that the majority of weather stations located over the western half of the country displayed increasing trends in rainfall (mm/decade), while those located over the eastern half were characterised by high spatial variability during the period 1921–2015 as depicted on Figure 2-8. Furthermore, the district map showed that the southern interior of the country was getting wetter, while the extreme north was becoming drier for the same period. Seasonal analyses conducted by Kruger and Nxumalo (2017) also investigated seasonal rainfall, which displayed a notable increase during summer, while during autumn, a non-significant declining trend of rainfall over the whole country was observed. These findings were partially in agreement with those of the World Bank Group (2021), which reported that the western and interior parts of the country were likely to become drier, while the eastern parts were likely to get wetter for all four emission scenarios over all four projected time periods.

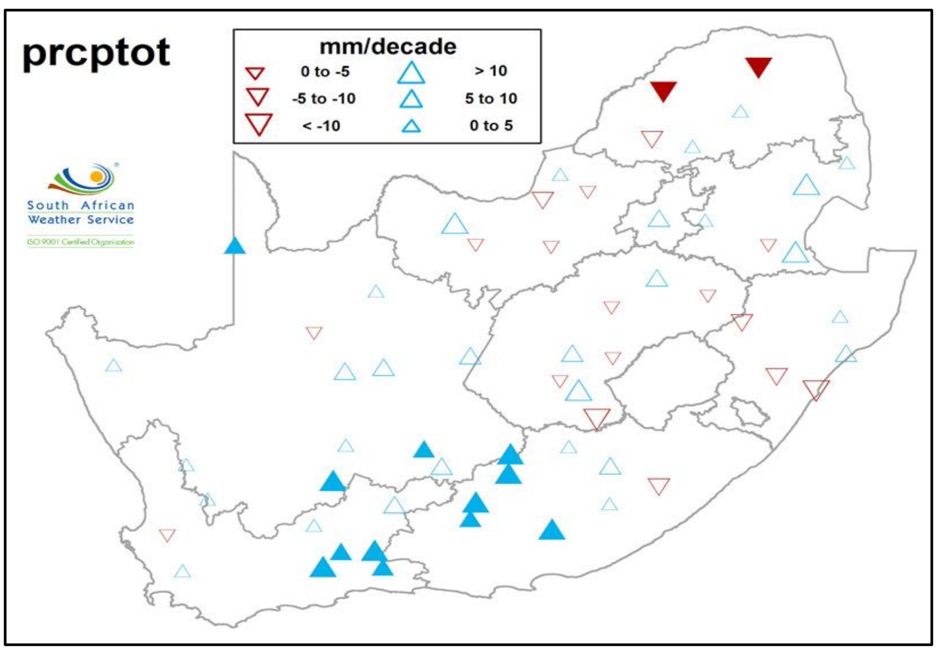

Figure 2-8 Trends in total annual rainfall in wet days for individual stations for the period 1921–2015. Shaded symbols indicate significant trends at the 5% level. Source: Kruger and Nxumalo, 2017.

The analysis of extreme rainfall events also demonstrated notable increases in extreme rainfall trends in South Africa (Donat et al., 2013). Likewise, studies conducted by various researchers suggested that there were notable increases in the annual frequency of extreme rainfall events such as the very heavy rainfall events in the eastern parts of South Africa from 1906 to 1997 (Groisman et al., 2005), the increased intensity of high rainfall events during 1961–1990, compared to 1931–1960, over much of the country (Mason et al., 1999) and the increased extreme rainfall index values during 1910–2004 over the eastern parts of South Africa (Kruger, 2006). A fact sheet series produced by the South African National Biodiversity Institute (SANBI), DEA and the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ) in 2014 downscaled rainfall projections for six South African hydrological zones. While this fact sheet is in agreement with DEA (2013) about the reduced autumn rains, it further states that there was an increase in annual extreme rainfall events, particularly during spring and summer, while these events decreased in autumn. Easterling et al. (2000) noted significant increases in rainfall over KwaZulu-Natal and the southwestern parts of the country during 1926–1997 and 1901–1997.

Groisman et al. (2005) noted the increased annual frequency of extreme rainfall over the eastern parts of South Africa from 1906 to 1997, while Mason et al. (1999) demonstrated that there was an increase in the intensity of strong rainfall events in 1961–1990, compared to 1931–1960, over much of South Africa. Kruger (2006) identified the increased extreme rainfall index values over the eastern parts of the country from 1910 to 2004. These findings are in agreement with those of Donat et al. (2013), who suggested that there was a general increase of the contribution of extreme daily rainfall to annual totals and a strong upward trend of the intensity of daily rainfall. Similar historical rainfall observations were made by Mason et al. (1999) and Groisman et al. (2005), who reported an increasing frequency of extreme rainfall events along the eastern coast of the country. Similar results were noted by other researchers, such as Richard et al. (2001), Rouault et al. (2003) and New et al. (2006). Rainfall in southern Africa is expected to decrease as the climate continues to change (Mpandeli et al., 2005; Nhemachena, 2008).

Pittock (1983) suggested that rainfall belts would extend further south and the summer rains may begin earlier in spring and last longer in autumn, leading to reduced winter rains in southern African Mediterranean climate regions (Manabe et al., 1981). The examination of rainfall variability and changes in southern Africa, as well as their potential links to global warming by Fauchereau et al. (2003), suggested that some regions have experienced a shift towards more extreme rainfall over recent decades. Mason and Joubert (1997) indicated that southern Africa would experience a significant increase in the frequency of intense daily rainfall events, which would be coupled by a decrease in the number of rain days, and also proposed that rainfall variability had increased since the 1960s, with droughts that had turned out to be more intense and widespread. These outcomes were in agreement with the proposal made by Joubert et al. (1996), who stated an increase in the probability of dry years in the tropics towards the southwest of the subcontinent, as well as the western and eastern parts of South Africa and southern Mozambique.

2.5 DROUGHT AND FLOOD EFFECTS IN SOUTH AFRICA

The climate of South Africa is characterised by the occasional occurrence of droughts and floods (Abubar et al., 2020; Chapman, 1994; Deo et al., 2016; Latif et al., 2016; Tirivarombo et al., 2018). Both droughts and floods share rainfall as the key factor, i.e. the climate state when rainfall does not meet the minimum requirements (such as meteorological, hydrological and agricultural) is generally regarded as a drought, while that which far exceeds the water-carrying capacity of a certain area is referred to as a flood (Blum, 2005; Heim, 2002; Mishra and Singh, 2010). Small-scale farmers across southern Africa – who commonly have limited access to advanced irrigation systems – generally struggle to maintain crop production during droughts, and, as a result, have to incur considerable losses while waiting for sufficient rains to resume cropping (Mkuhlani et al., 2019; Ntombela et al., 2017). Some are forced to leave their barren farms (Figure 2-9 on page 22) to look for alternative ways to generate an income for sustainability.

Recent (2016–2018) droughts that have affected both agricultural production and water resources have been well documented by Botai et al. (2016; 2017). Adisa et al. (2019) reported that the 2016–2018 droughts were widely distributed, affecting at least five provinces in South Africa. According to Statistics South Africa (StatsSA) (2019), 22% of South African households experienced food insecurity between 2014 and 2015 as a result of a severe drought, which led to increased staple food prices. For example, the price of white maize more than doubled between January and December 2015 (Stoddard, 2016). Hoerling et al. (2006) raised concerns about the increased likelihood of a greater frequency and intensity of sustained drought in future, which is anticipated to increase the vulnerability of this region. Understanding drought requires research on its key features, particularly agricultural drought, which includes drought onset, duration, intensity, magnitude and spatial extent (Adisa et al., 2019). A thorough understanding of drought enables information users to be better prepared and to properly manage their activities, ultimately guiding their decision making in an objective and efficient manner (Kurniasih et al., 2017).

Figure 2-9 One of the many farms that were left barren due to the 2015 drought. Source: BBC, 2023.

In order to investigate drought, various researchers and agencies employ different tools in the form of drought indices. These include the Palmer Drought Severity Index (PDSI) (Palmer, 1968), the Crop Moisture Index (CMI) (Palmer, 1968), the Soil Moisture Drought Index (SMDI) (Hollinger et al., 1993), the Standardised Precipitation Index (SPI) (McKee et al., 1993), the Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010), the Effective Drought Index (EDI) (Byun and Wilhite, 1999), the Agricultural Reference Index for Drought (ARID) (Woli et al., 2013) and the Vegetation Health Index (VHI) (Dalezios et al., 2014). All these methods are mainly applied in drought assessment, monitoring, analysis and alerts to derive effective early warning drought monitoring systems to detect and respond to potential future drought risks (Adisa et al., 2019). The selection of the most suitable method is dependent on various factors, such as the hydro-climatology of the region, the type of drought considered, the purpose of the study and the available data (Morid et al., 2006). However, many researchers tend to use the SPI since it is recommended by the WMO (Chen et al., 2013; Potop et al., 2012) and is considered a flexible method for monitoring all three types of drought: meteorological, agricultural and hydrological (Adisa et al., 2019). While the SPI is capable of detecting and depicting drought on multi-temporal scales and only requires precipitation data, its closest counterpart – the SPEI – is said to have similar capabilities, although the SPEI additionally requires potential evapotranspiration (PET) data, which is computed from minimum and maximum temperatures (Adisa et al., 2019). While many drought assessment and monitoring studies in South Africa do not directly link drought to agriculture, Masupha and Moeletsi (2017) conducted a study that specifically established and analysed this link.

Floods occur over a much shorter period when compared to droughts, and are severely destructive, with impacts that are quick and severe, and can cause destruction to a wide variety of sectors, including infrastructure and agriculture. They can even claim lives as they occur and are notoriously destructive to both commercial and subsistence farmers, although the consequences are largely felt by subsistence farmers who are usually small scale and lack advanced cultivation technologies and ample resources (Newton et al., 2011). These small-scale farmers would typically suffer considerable losses during floods, which destroy crop fields and kill livestock, a situation with consequences that can be felt long after the flood event has passed (Newton et al., 2011; Serdeczny et al., 2017).

One of the notable flood events occurred in 2000 and destroyed parts of Limpopo and Mpumalanga, resulting in a 1% drop in the gross domestic product (GDP)'s growth as it led to a significant reduction in yields (Mazibuko et al., 2021). A study by Mazibuko et al. (2021) reported that the agricultural seasons 1980/81, 1984/85, 1987/88, 1998/99, 1999/00, 2008/09, 2010/11 and 2013/14 were extremely wet, with the agricultural seasons of 1998/99 and 1999/00 characterised as having the most devastating impacts on agricultural production. The April 2022 floods shown in Figure 2-10 on page 24, which occurred in KwaZulu-Natal were regarded as being the most catastrophic natural disaster yet recorded in KwaZulu-Natal when collectively considering lives lost, homes and infrastructure damaged or destroyed, as well as economic impact (Grab and Nash, 2023). This study suggested that the frequency of flooding in Durban, KwaZulu-Natal, has likely doubled over the last century based on the findings that the period 1850–1899 had an average of about 1.1 significant floods per annum, while the period 1900–2022 had an average of about 1.7 significant floods per annum.

Figure 2-10 Flooding of shops in an area called The Field as a result of floods that hit Durban, KwaZulu-Natal, on 12 April 2022. Source: eNCA, 2023.

2.6 EL NIÑO SOUTHERN OSCILLATION

Seasonal variations in South African rainfall are largely influenced by the ENSO (Goddard et al., 2001; MacKellar et al., 2014; Mulenga, 1998), which is generally described as a recurring, coupled climate phenomenon that consists of three states: the El Niño, La Niña and neutral states (NOAA, 2014). In detail, El Niño refers to a warming (by between 1 °C and 3 °C from normal) of the ocean surface or above average SSTs in the central and eastern tropical Pacific Ocean. This state is usually associated with drier atmospheric conditions over southern Africa (MacKellar et al., 2014). For example, during the El Niño phase, rainfall onsets are usually delayed, leading to the water stress suffering and death of planted seeds (Moeletsi et al., 2011). La Niña is a cooling (by between 1 °C and 3 °C from normal) of the ocean surface or below average SSTs in the central and eastern tropical Pacific Ocean. Wet atmospheric conditions over the subcontinent are typically associated with the presence of the La Niña phase (MacKellar et al., 2014). The neutral state is when neither El Niño nor La Niña states are dominant and SSTs are close to average. The average atmospheric state of the subcontinent is usually normal during this ENSO state (MacKellar et al., 2014). In Figure 2-11 which is shown on page 25, examples of equatorial Pacific Ocean SSTs during the two opposing ENSO phases are displayed.

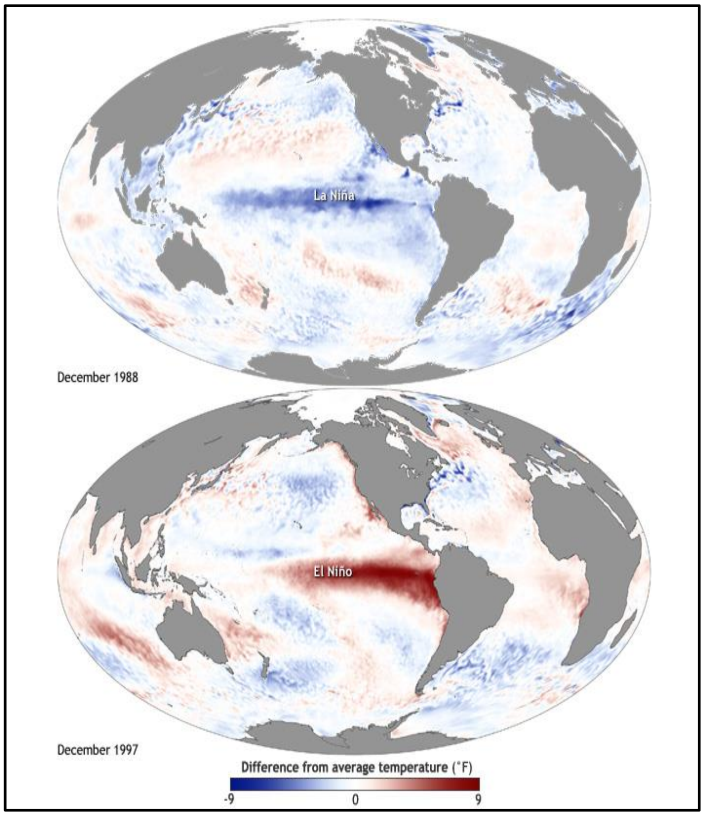

Figure 2-11 Maps of the sea surface temperature anomaly in the Pacific Ocean during a strong La Niña (top, December 1988) and El Niño (bottom, December 1997). Source: NOAA, 2014.

According to Mulenga (1998), ENSO has a major influence on the African climate and explains about 36% of the total variance of seasonal (DJF) 500 hPa geopotential height anomalies and 16% of the total variance of seasonal (DJF) outgoing longwave radiation (OLR) anomalies. Atmospheric states of various regions during different ENSO phases are presented in Figures 2-12A and B on page 26. According to this figure, the climate state of southern Africa is drier than normal during the El Niño phase (A) and wetter than normal when the La Niña phase prevails (B).

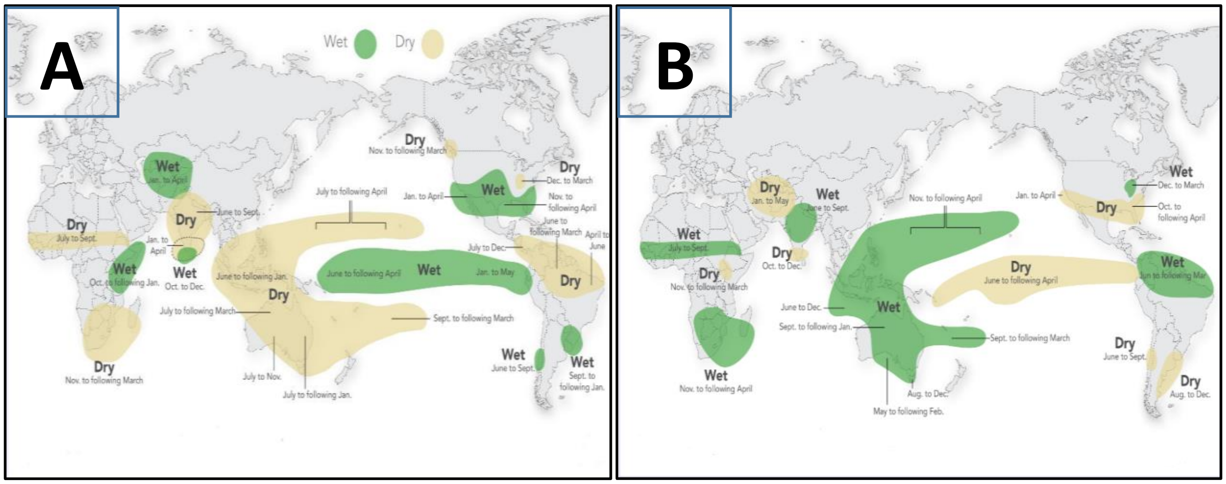

Figure 2-12 Climate conditions demonstrated as dry or wet conditions around the world during an El Niño phase. The left hand side image (A) represents an El Niño phase while the right hand side image shows a La Niña phase. Source: Lenssen et al., 2020.

Shikwambana et al. (2023) demonstrated seasonal precipitation variations between the 2010/11 La Niña, the 2013/14 neutral and the 2015/16 El Niño periods for all seasons in South Africa as shown on page 26 in Figure 2-13 on page 27. The figure displays clear precipitation variations during different ENSO phases, which, in turn, vary for each season during a particular ENSO phase. Shikwambana et al. (2023) vividly demonstrated that South Africa receives much of its rainfall during the austral summer of a La Niña phase. This rainfall is largely located over the eastern parts of the country, a notion that is consistent with that of the Lenssen et al. (2019). The least precipitation is received during the austral winter of a neutral phase. In addition, the difference between a La Niña and an El Niño phase is most distinguishable during the austral summer.

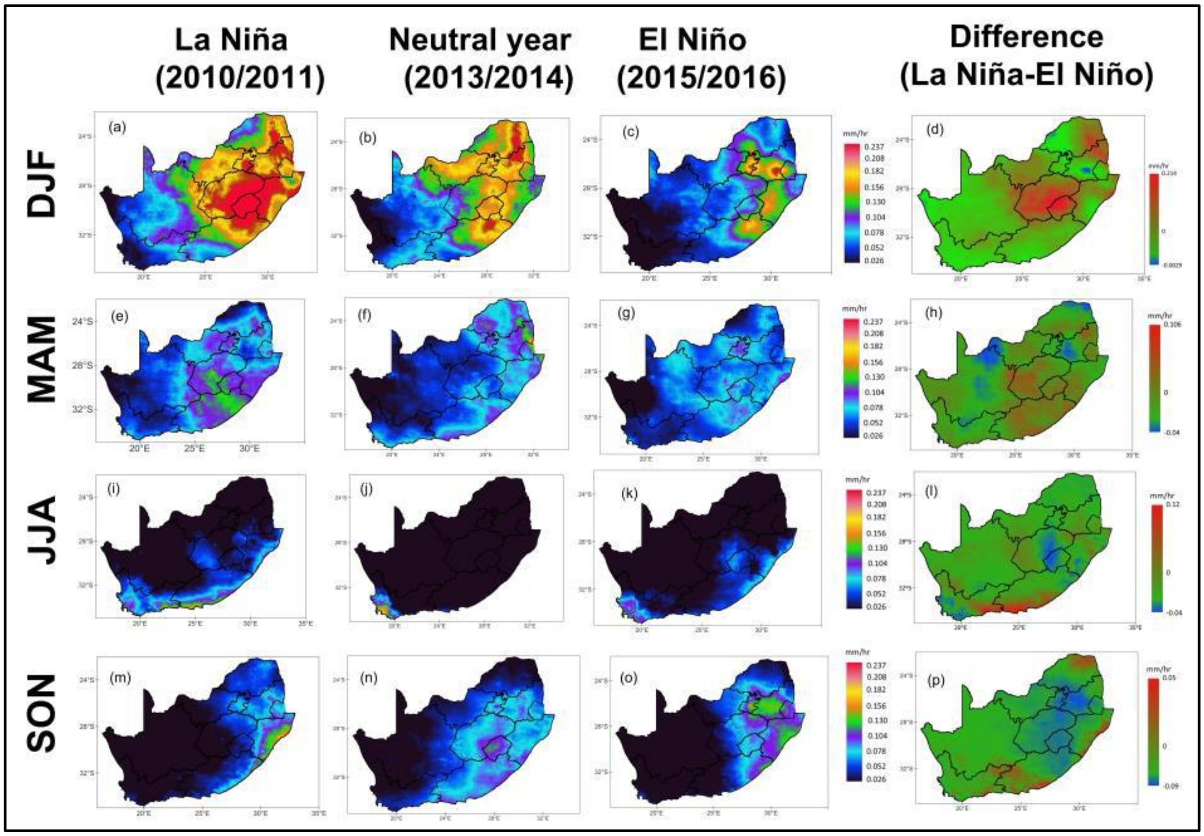

Figure 2-13 Seasonal mean spatial distribution of precipitation during La Niña (a, e, i, m), neutral (b, f, j, n) and El Niño (c, g, k, o) periods, as well as the difference between La Niña and El Niño (d, h, l, p). Source: Shikwambana et al., 2023.

Shikwambana et al. (2023) also showed temperature variations for similar ENSO phases and seasons as shown in Figure 2-14 on page 28. This figure suggested that the austral summer of an El Niño phase was the hottest, while the coldest temperatures were observed during the austral winter season. However, temperature variations during the austral winter seasons did not vary significantly from one phase to another.

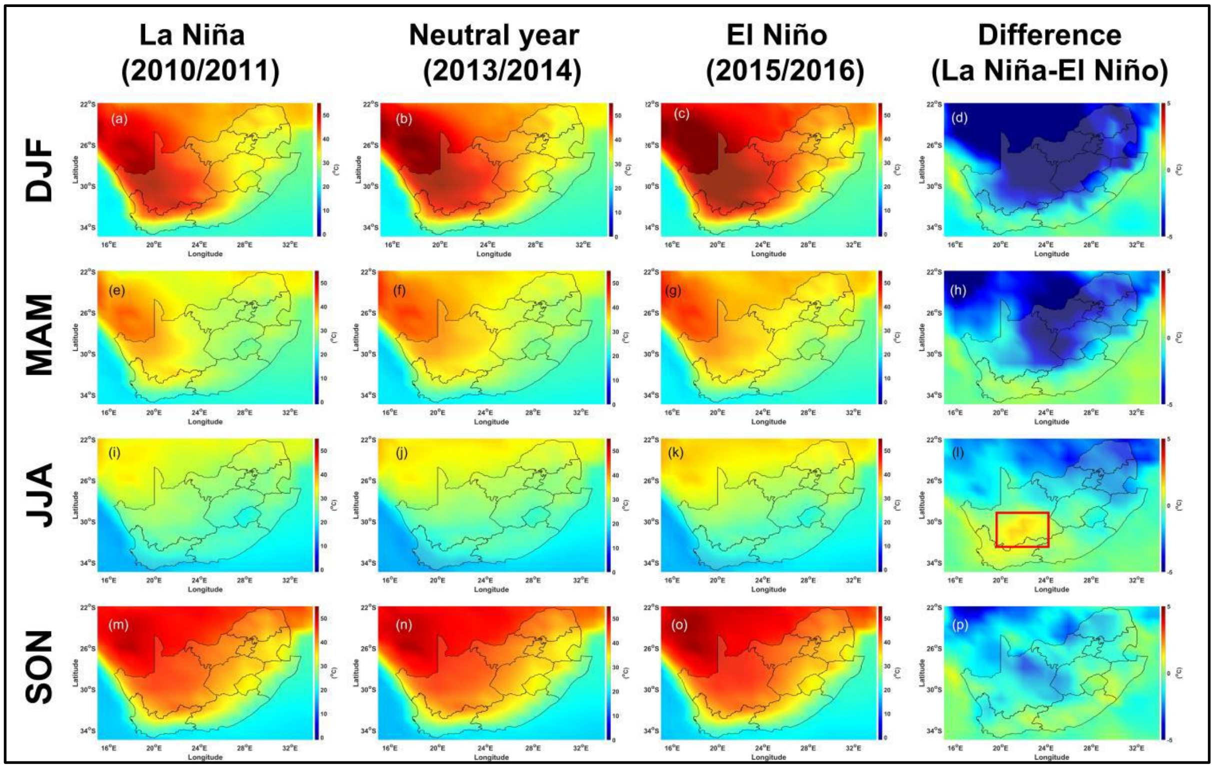

Figure 2-14 Seasonal mean spatial distribution of temperature during La Niña (a, e, i, m), neutral (b, f, j, n) and El Niño (c, g, k, o) periods, as well as the difference between La Niña and El Niño (d, h, l, p). Source: Shikwambana et al., 2023.

Shikwambana et al. (2023) further compared the Normalised Difference Vegetation Index (NDVI) values using the same procedure applied in the last two analyses, as shown in Figure 2-15 on page 29. According to this figure, the austral summer consists of the largest distribution of high NDVI values, although these are largely restricted to the eastern part of the country. Furthermore, the austral summer of the La Niña phase stood out as the most spatially distributed values of high NDVI. NDVI values for both austral winter and spring displayed the lowest distribution of high NDVI for all ENSO phases when compared to the other two seasons when NDVI values were relatively higher. No particular season of any phase displayed the lowest distribution of high NDVI values.

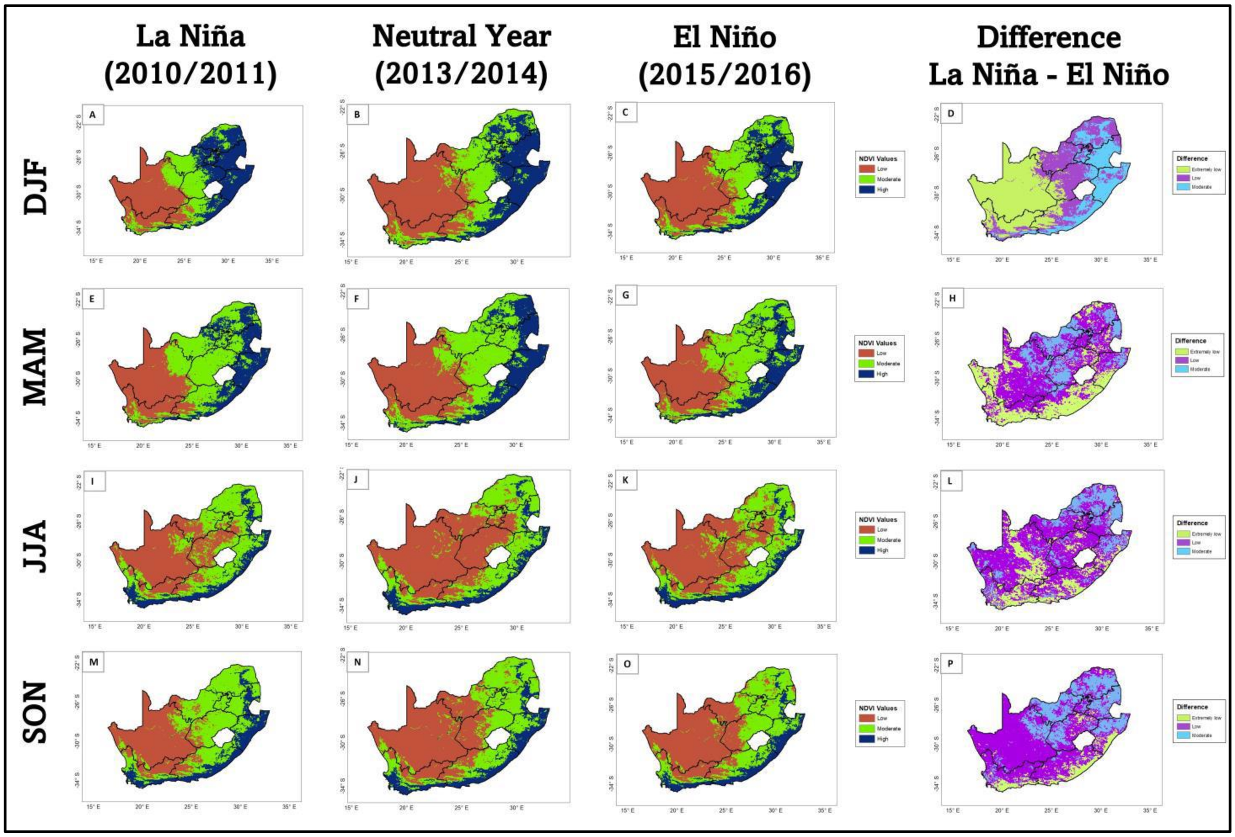

Figure 2-15 Seasonal mean spatial distribution of NDVI during La Niña (a, e, i, m), neutral (b, f, j, n) and El Niño (c, g, k, o) periods, as well as the difference between La Niña and El Niño (d, h, l, p). Source: Shikwambana et al., 2023.

Finally, Shikwambana et al. (2023) exhibited the spatial distribution of winds for similar seasons and ENSO phases as demonstrated in Figure 2-16 on page 30. This analysis suggests that austral winter and spring had relatively stronger winds, which were widely distributed, particularly over much of the western part of the country, for all ENSO phases when compared to the austral summer and autumn seasons. Although there is a large variation of wind direction over most of the western half of the country during all seasons and ENSO phases, a notable easterly flow tends to follow an anticyclonic motion for all seasons and all ENSO phases over the eastern half of the country.

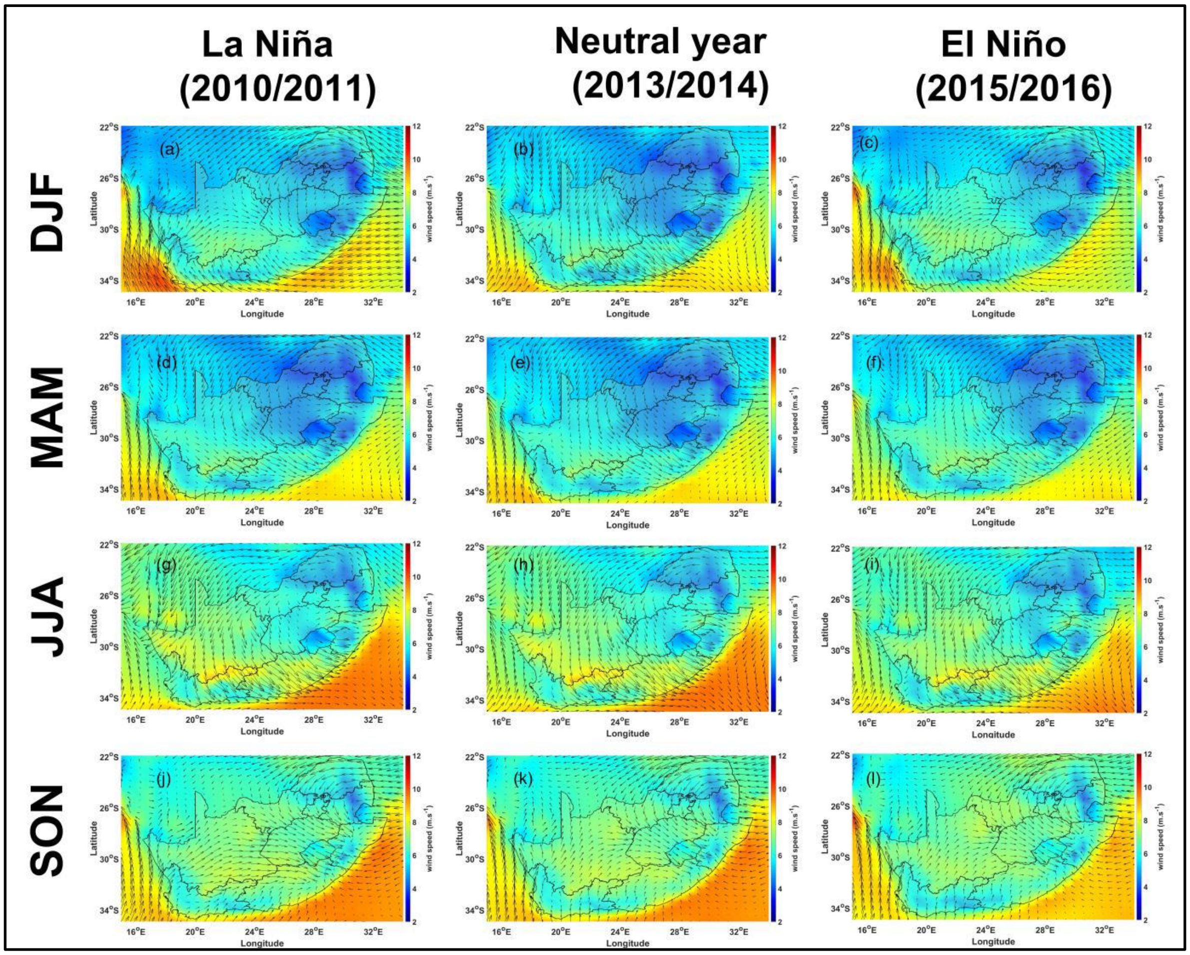

Figure 2-16 Seasonal mean spatial distribution of winds during the La Niña (a, e, i, m), neutral (b, f, j, n) and El Niño (c, g, k, o) periods, as well as the difference between La Niña and El Niño (d, h, l, p). Source: Shikwambana et al., 2023.

2.7 TROPICAL TEMPERATE TROUGHS IN SOUTHERN AFRICA

Tropical temperate troughs are cloud bands from the northwest to the southeast, which link the tropics to the midlatitude circulation (Harangozo and Harrison, 1983). The first identification of TTTs originated in the late 1900s when they were observed from satellite imagery by Thepenier and Cruette (1981), who referred to them as tropical plumes (Figure 2-17 on page 31). The structure of these systems is an elongated cloud band that stretches from western central Africa to the east of southern Africa, enabling heat and moisture exchange through tropical-extratropical interactions over the subcontinent (Harangozo and Harrison, 1983; Thepenier and Cruette, 1981).

Moreover, these cloud bands are typically between 4 000 and 16 000 km in length, approximately 400 to 1 200 km wide and have a lifespan that typically ranges from three to nine days. They are most active between November and April with a peak in activity in December (Harangozo and Harrison, 1983; Thepenier and Cruette, 1981). When viewed using the OLR anomaly method, TTTs appear as a dual OLR structure in which a positive OLR is located on the northern side and a negative OLR is located on the southern side of the structure (Harrison, 1984; Todd et al., 2004; Todd and Washington, 1999; Washington and Todd, 1999). Thus, they can be visually displayed using the spatial variability of OLR anomalies (Fauchereau et al., 2009). According to Streten (1973) and Hart et al. (2010), southern Africa, along with the SWIO, is one of three known regions in the southern hemisphere to experience the occurrence of such cloud bands namely Australia and South America while in the northern hemisphere, cloud bands can be found in the North Pacific, North Atlantic and North Africa. However, unlike other regions, the occurrence of these bands is restricted to the austral summer in southern Africa and the SWIO.

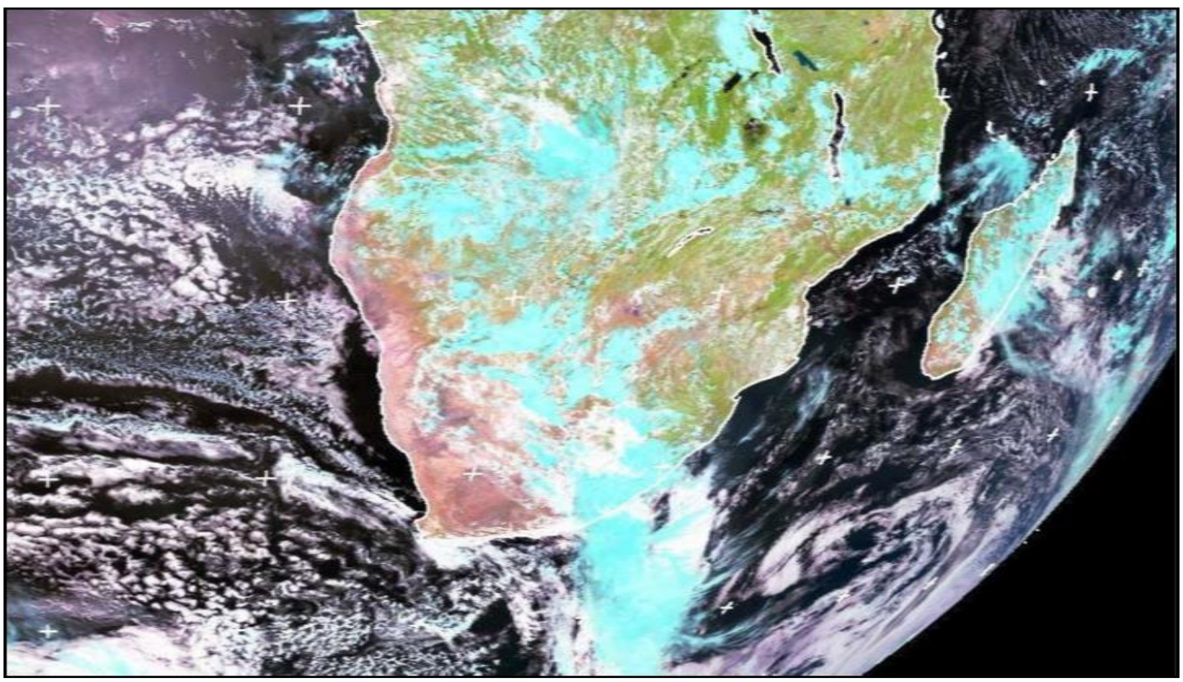

Figure 2-17 Satellite image showing a typical TTT cloud band across southern Africa, taken on 19 January 2010 at 12:00 UTC using a Meteosat SEVIRI RGD composite 3, 2, 1. Source: NERC, 2010.

A number of atmospheric features plays a role in the development of TTTs, for example, the upper westerly waves that contribute to the poleward transportation of moisture, the Angola low, a surface high over southern Mozambique and the SWIO, continental thermal lows over the Kalahari Desert, the South Atlantic High (SAH) and the South Indian High (SIH) (Harangozo and Harrison, 1983; Hart et al., 2010; Macron et al., 2014). Figure 2-18 on page 33 shows some of these atmospheric features, as well as their location over the subcontinent. The development process of a TTT is initiated by the Angola low that is located in the lower to mid-troposphere as a semi-permanent feature of the tropical southern African circulation during summer (Hart et al., 2010; Reason et al., 2006; Todd et al., 2004). This is accompanied by a weak surface high that is often located over the southern parts of Mozambique and the SWIO, which enhances the pressure gradient across Botswana and Zimbabwe. This, in turn, sets up a strong low-level northeasterly flow across the central subcontinent region, promoting the flow of tropical easterlies north of Madagascar deep into the subcontinent (Hart et al., 2010; Reason et al., 2006; Todd and Washington, 1999). According to Harrison (1984) and Knippertz (2007), upper tropospheric troughs, which are associated with a band of divergence east of their leading edge, also play an essential role in the development of TTTs. Continental thermal lows often form over the central Kalahari Desert and contribute to inducing weak cyclonic circulation, which can divert the low-level north-easterlies farther south (Hart et al., 2010).

The eastward ridging of the SAH often induces onshore flow and coastal showers along the south coast and sometimes up the east coast. The northwestern extension of the SIH, coupled with a surface depression in the Mozambique Channel, then produces an easterly wave flow into Mozambique and eastern South Africa (Hart et al., 2010; Ratna et al., 2013). The resulting cloud band then propagates eastwards, leading to the transportation of moisture, energy and momentum from the tropics towards the subtropics (D'Abreton and Tyson, 1995; Ratna et al., 2013; Todd et al., 2004). Moisture transported through the TTTs is initially northwesterly from the tropical Atlantic Ocean (Viguad et al., 2007). However, at a later stage, moisture influx results from ridging high-pressure systems from the SWIO (Ndarana et al., 2019). During the mature stage of TTTs, moisture is transported off the continent along the axis of a band of moisture convergence, rising from near 800 hPa over the land mass into the mid-level flow between 700 and 650 hPa in the mid-latitudes (D'Aberton and Tyson, 1996; Todd et al., 2004).

During this process, precipitation is received along the cloud band over the subcontinent, as well as over the eastern coast of the subcontinent to which the band extends. These systems tend to move eastwards from southern Africa to the Mozambique Channel and southern Madagascar (Fauchereau et al., 2009; Pohl et al., 2009). Ratna et al. (2013) simplified the lifecycle of TTTs by classifying their temporal evolutions into three stages: the developing stage (from several days to one day prior to the event), the mature stage (the day of the event) and the decaying stage (two days after the event).

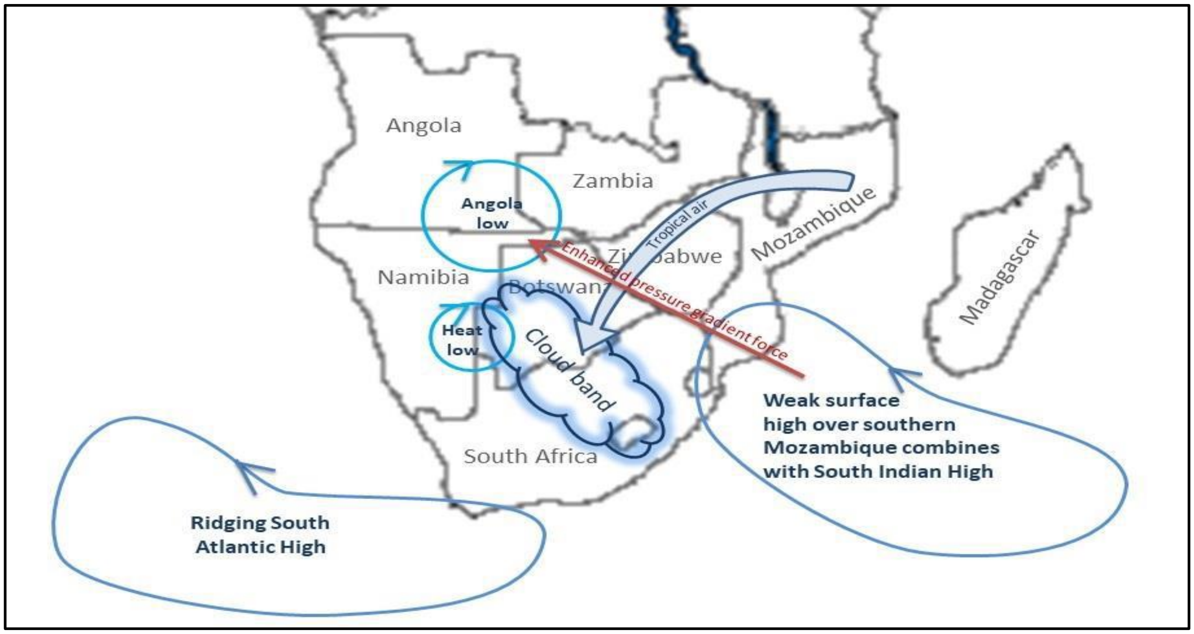

Figure 2-18 Various atmospheric circulation features that play a role in the development of tropical temperate troughs over southern Africa. Source: Erasmus, 2019.

A TTT is one of the major synoptic austral summer rainfall-producing systems in the subcontinent (Harrison, 1984; Ratna et al., 2013). Some researchers regard it as the dominant rainfall-producing synoptic-scale system over the subcontinent, also responsible for the poleward transportation of energy, water vapour and momentum (Harrison, 1986; Palmer et al., 2004; Todd et al., 2004; Todd and Washington, 1998; Washington and Todd, 1999). Harrison (1984) reported that a TTT occurs over the subcontinent at least once in seven days during the austral summer. Its maximum activity is between November and February (Harrison, 1984; Hart et al., 2010; Ratna et al., 2013; Vigaud et al., 2012), a period that coincides with the austral summer in southern Africa.

Rainfall from these systems can occasionally be destructive, particularly when their occurrence is coupled with another rainfall-producing system, such as a cut-off low (COL) (Muller et al., 2008). A classic example of the combination of two rainfall-producing systems occurring at the same time was when a TTT was coupled with a COL from the 16th to the 22nd of April 2006 is depicted in Figure 2-19. This resulted in an accumulated rainfall of more than 100 mm (about six times more than the annual average rainfall of the country) within a seven-day period, causing flooding in Lüderitz, a town in Namibia (Muller et al., 2008). Hart et al. (2012) reiterated that some of the most severe floods in South Africa have been associated with COL events co-occurring with TTTs. A study by Lindesay and Jury (1991) suggested that the weather system responsible for heavy rainfall over the South African central interior in February 1988 resulted from a TTT. This was in agreement with various researchers (e.g. Walker and Lindesay, 1989), who also attributed some extreme rainfall events to TTTs. A study by Macron et al. (2014) concluded that TTTs associated with Rossby waves tended to be stronger than those that occurred without Rossby waves.

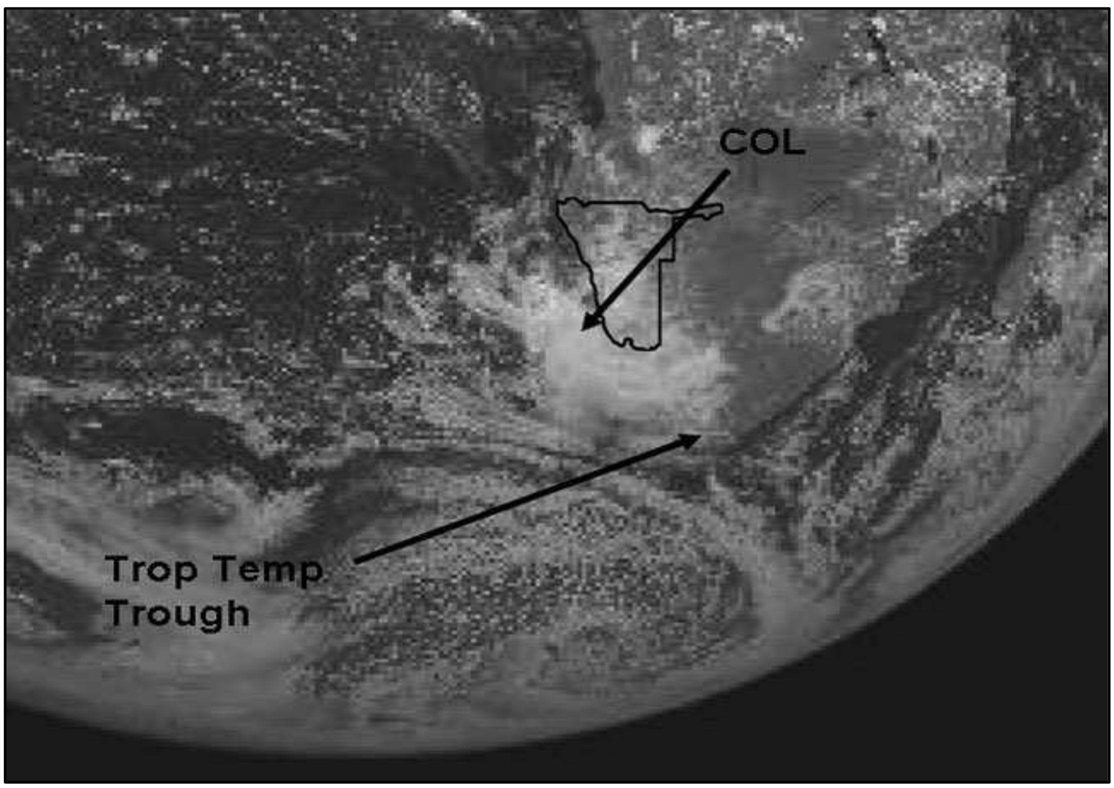

Figure 2-19 A satellite image taken during the co-occurrence of a TTT and a COL over southern Africa on 16 April 2006. Source: EUMETSAT, 2006.

Additional major rainfall-producing systems that are responsible for rainfall during the rainfall season in South Africa include cut-off low pressure systems, upper air westerly troughs, tropical cyclones and ridging South Atlantic Ocean anticyclones (Engelbrecht et al., 2015; Fauchereau et al., 2009; Macron et al., 2014; Malherbe et al., 2014; Ndarana et al., 2018; Ratna et al., 2013; Singleton and Reason, 2007; Tyson and Preston-Whyte, 2000; Van Heerden and Taljaard, 1998). Ridging anticyclones can also influence systems such as COLs, resulting in relatively increased rainfall from such systems by transporting moisture influx from the SWIO as they ridge over the southeastern coast of southern Africa, causing a northerly to northeasterly influx of moisture towards the east coast of the subcontinent (Ndarana et al., 2018). Other synoptic and larger-scale systems that influence rainfall in southern Africa include the well-documented ENSO (Ashok et al., 2007; Horel and Wallace, 1981; Izumo et al., 2010; Matthews, 2000), ITCZ (Cook et al., 2004; Crétat et al., 2012; Takana et al., 2004; Todd et al., 2004), Madden-Julian Oscillation (MJO) (Jones et al., 2004; Pohl et al., 2007; Sultan et al., 2009; Wang et al., 2011) and Atlantic and Indian Ocean SSTs (Crétat et al., 2012; Washington and Preston, 2006; Williams et al., 2008). Todd et al. (2004) added that TTTs are associated with an increase in the intensity of the African Walker cell with enhanced moisture convergence over tropical southern Africa, as well as poleward moisture transported along the cloud bands. Furthermore, Ndarana et al. (2019) demonstrated that about 20% of ridging high-pressure systems are associated with TTTs, while almost all TTTs are followed by ridging high-pressure systems.

Harangozo and Harrison (1983) pointed out that a significant portion of austral summer rainfall over southern Africa can be attributed to TTTs. Washington and Todd (1999) added that, during the period of November to March, the leading mode of daily rainfall variability is a TTT, with the exception of February, where these structures display a parallel structure. Harrison (1984) proposed that TTTs produce most of the rainfall (approximately 60%) that is received over the subcontinent between spring and autumn. However, Hart et al. (2010) argued that, while TTTs contribute a substantial amount of rainfall in South Africa, the amount is lower (30 to 50%) than the 60% usually cited in the literature. On the other hand, Crimp et al. (1997) estimated that approximately 39% of the mean annual rainfall received over South Africa originates from TTTs, while Crétat et al. (2010) added that 30 to 60% of the subcontinent's summer rainfall originates from TTTs. Factors influencing rainfall's spatial and temporal variability are complex and are still being debated by scientists.

Barclay et al. (1993) reported that the heaviest rainfall associated with TTTs occurs when the propagation speed of the mid-latitude disturbance is slower, along with a greater wavelength and amplitude of the westerly wave. According to various authors (e.g. Harrison, 1984, 1986; Todd and Washington, 1999; Washington and Todd, 1999), the location of TTTs strongly influences rainfall variability on intraseasonal and even interannual time scales. For example, the occurrence of TTTs farther east of the subcontinent results in significantly low rainfall over the subcontinent, leading to summers over the subcontinent that are drier than normal (Usman and Reason, 2004). This is caused by a suppression of convection over the subcontinent and its proliferation over the SWIO, east of Madagascar (Jury and Pathack, 1991; Jury et al., 1993). This is typically caused by an eastward shift of the large-scale atmospheric circulation from its favourable location of surface convergence in the tropics, which controls TTT development (Harangozo and Harrison, 1983; Harrison, 1986; Tyson, 1986). Mason and Jury (1997) concluded that this longitudinal shift in convection is partially linked to changes in SSTs in the equatorial Pacific, Indian and Atlantic oceans. Furthermore, it was found that, in this parallel structure, if the band off the east coast of the subcontinent is enhanced, moisture over the subcontinent is suppressed, and vice-versa (Washington and Todd, 1999).

The importance of TTTs as a major source of rainfall in southern Africa and the SWIO (Hart et al., 2012), including their role as a mechanism for the poleward transportation of energy, moisture and momentum (Todd et al., 2004; Todd and Washington, 1999; Washington and Todd, 1999), has been emphasised. Various researchers have conducted substantial research with the aim of improving the understanding of TTTs for multiple uses, such as predicting them (e.g. Fauchereau et al., 2009; Tyson, 1986; Washington and Todd, 1999; Williams et al., 2007). Although the latter work has been done, Ratna et al. (2013) argued that their physical and dynamic characteristics, including frequencies of occurrence, were not well understood and, as a result, it was difficult to accurately predict them. Therefore, more rigorous research was required. As a result, various researchers continue to conduct further research. This includes research by Pohl et al. (2009), who argued that no clear interaction was identified between TTTs and the MJO. Hart et al. (2012) developed a methodology that explicitly captures the evolution of TTTs at the synoptic scale through a comprehensive assessment of the seasonal cycle and rainfall contribution of TTTs using a novel object-based strategy that tracks TTTs' full life cycle. Ratna et al. (2013) developed one of the methods to objectively identify TTTs using the following equation:

$$OLR = \left(\left(\frac{OLR_{E1} + OLR_{E2}}{2.0}\right) \times 0.4\right) - \left(\left(\frac{OLR_{W1} + OLR_{W2}}{2.0}\right) \times 0.6\right) \quad \text{Equation 0.1}$$

$$Wind = V_W - V_E \quad \text{Equation 0.2}$$

The condition for defining a TTT event is that standard deviations of OLR and wind exceed 1.5 and 0.5, respectively. The 1 standard deviation values for OLR and wind are 16.37 and 4.99, respectively. The subscript in Equation 0.1 represents the area-averaged OLR anomaly over each of the regions shown in Figure 2-20 (i.e. E1 (37°E to 42°E; 17°S to 12°S), E2 (45°E to 50°E; 23°S to 15°S), W1 (22°E to 32°E; 24°S to 18°S) and W2 (32°E to 42°E; 36°S to 28°S), respectively). These four boxes were picked for OLR due to the dipolar structure of convection orientated in the north-west/south-east direction in the case of TTT events. The values 0.4 and 0.6 in Equation 0.1 are the weighting factors for the eastern and western regions, respectively. The subscript in Equation 0.2 represents the area-averaged meridional wind anomaly over each of the regions W (0°E to 15°E; 38°S – 27°S) and E (34°E to 46°E; 38°S to 27°S), respectively. Figure 2-20 depicts the method of identifying TTTs and subsequent results from a study by Ratna et al. (2013).

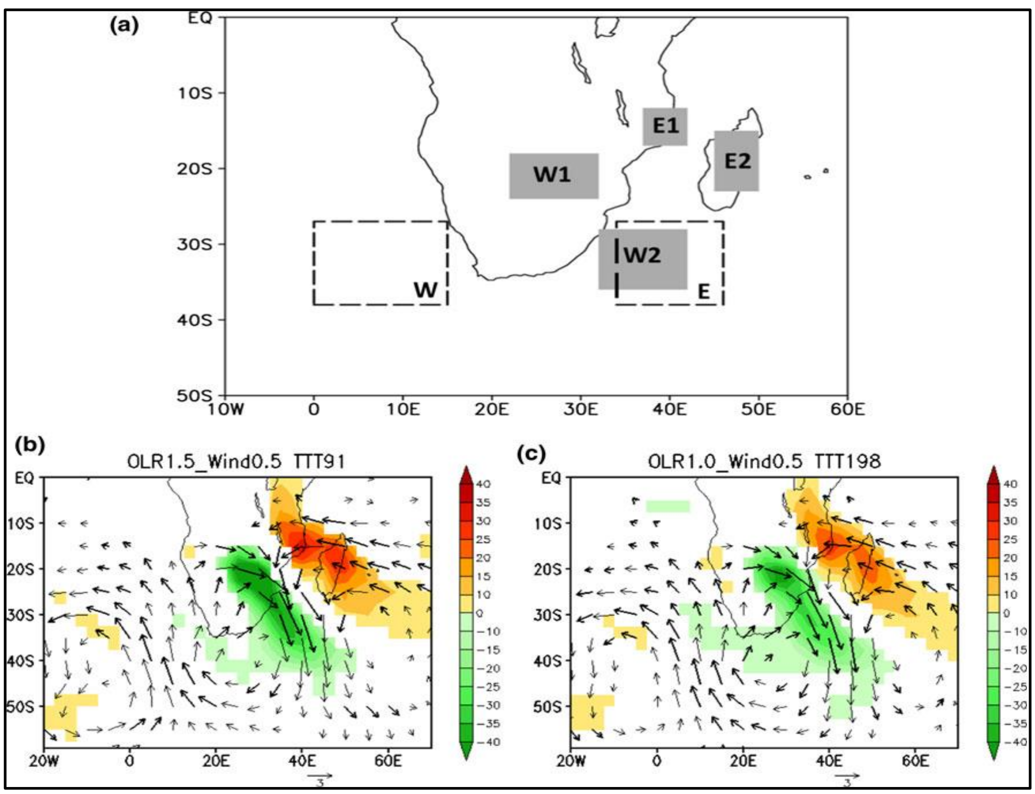

Figure 2-20 A method to identify TTTs using regions (E1, E2 and E3 for OLR and W and E for wind) in (a), as well as the examples of TTTs identified using OLR anomaly composites in (b) and (c). Source: Ratna et al., 2013.

TTT events were noted to increase during La Niña conditions (Fauchereau et al., 2009; Hart et al., 2010; Manhique et al., 2011; Pohl et al., 2009; Ratna et al., 2012). In a study that intended to understand the impact of ENSO events on TTT likelihood in the SICZ, it was concluded that La Niña events are associated with two to three more cloud bands per month over mainland southern Africa and the SWIO, with particular reference to December and February, while El Niño events reduced the likelihood of TTTs with one to two fewer events per month, particularly in November and February (Hart et al., 2018), while La Niña seasons increased seasonal TTTs by 150 to 200%. Moreover, El Niño events that occurred over the SWIO seemed to be associated with an increase in TTT activity between three and four events per month. In January, both the negative and positive ENSO events were associated with a decrease in TTT activity (Hart et al., 2018).

2.8 AGRICULTURE

The agricultural sector plays a significant role in developing and maintaining many economies in the subcontinent (Acquah and Kyei, 2012). According to the report of the World Food Programme (2016), the global average crop production per hectare has been increasing at a rate below the global population growth, implying that the global demand for food in the near future may not be met, exacerbating the threat of food shortage already facing the world. The global agricultural sector is expected to increase its food production by up to 68% by 2050 to meet the projected growing demand (Marr, 2022). In order to achieve this, the sector will have to adapt and embrace new farming methods. While the old methods were largely influenced by factors such as mechanical improvements (bigger and better machinery), genetic advancements (improved seeds) and the green revolution (more effective fertilizers), the future of the sector is envisaged to be largely driven by digital tools, lifestyle changes and recent pandemics (Okole et al., 2022). Agriculture is interconnected with many other industries and their operations (Quantec, 2020). It was estimated that over 70% of people in southern Africa rely on rain-fed agriculture and face the risk of food insecurity (Mabhaudhi et al. 2018). In order to achieve the desired food security goals, productivity and the sustainability of food production must be achieved (Asare and Amoatey, 2001). Achieving the latter is challenging, particularly in sub-Saharan Africa where 97% of agricultural land is rain fed, due to the high vulnerability of the agricultural sector to the negative impacts of climate change and variability (Rockström et al., 2004).

Okole et al. (2022) reported that humanity's food systems and consumption practices are the major contributors to climate change, nature and biodiversity loss, as well as pollution and waste. They added that up to 10% of greenhouse gas emissions can be attributed to food losses and waste. Furthermore, Okole et al. (2022) pointed out that 931 million tons of food waste was generated in 2019 globally, 61% of which was from households, while 26% was from food service and 13% from retail. In South Africa, the generated waste was estimated to be in the order of 10.3 million tons in 2021. Oelofse et al. (2021) reported that the cost of food losses and waste to society was R61.5 billion in 2013, a figure equivalent to 2.1% of South Africa's GDP.

Agriculture in many countries of sub-Saharan Africa is practised by smallholder farmers. It is widely rain fed and mostly dependent on the soil's inherent fertility since fertilizers are very costly (Edreira et al., 2018; Masupha and Moeletsi, 2018). The agricultural sector contributes significantly to the South African economy and is deeply interconnected and central to many other industries and their operations. South Africa is a major exporter of a variety of agricultural products (Okole et al., 2022). However, South African agriculture is prone to high rainfall variability, both intra- and inter-seasonal, which subsequently affects rainfall onset, duration and cessation, leading to crop failure (Kumar et al., 2009). In South Africa, the agricultural sector contributes about 1.9% to the GDP, employs about 30% of the labour sector (Chamuka, 2011) and plays a significant role in foreign exchange through the export of raw agricultural materials. Trends in South African agricultural export, import and trade balance between 2010 and 2020 are presented in Figure 2-21 on page 40. With agricultural exports amounting to USD10.2 billion in 2020, South Africa's agricultural sector is considered to be a major producer and exporter of agricultural products (Sihlobo, 2021). South Africa comprises a dual agriculture economy, made up of well-developed commercial farmers that occupy 87% of agricultural land, and smallholder subsistence farmers that occupy the remaining 13% (Johnson, 2019). According to the US International Trade and Administration (2022), approximately 32 000 commercial farmers dominate the South African agricultural sector, of which between 5 000 and 7 000 are responsible for approximately 80% of the country's agricultural production. Smallholder farmers, in particular, are usually constrained by a lack of access to finance, challenges regarding land governance in communal areas, access to water, the need for effective extension services, poor infrastructure (roads and electricity) and access to markets (Johnson, 2019).

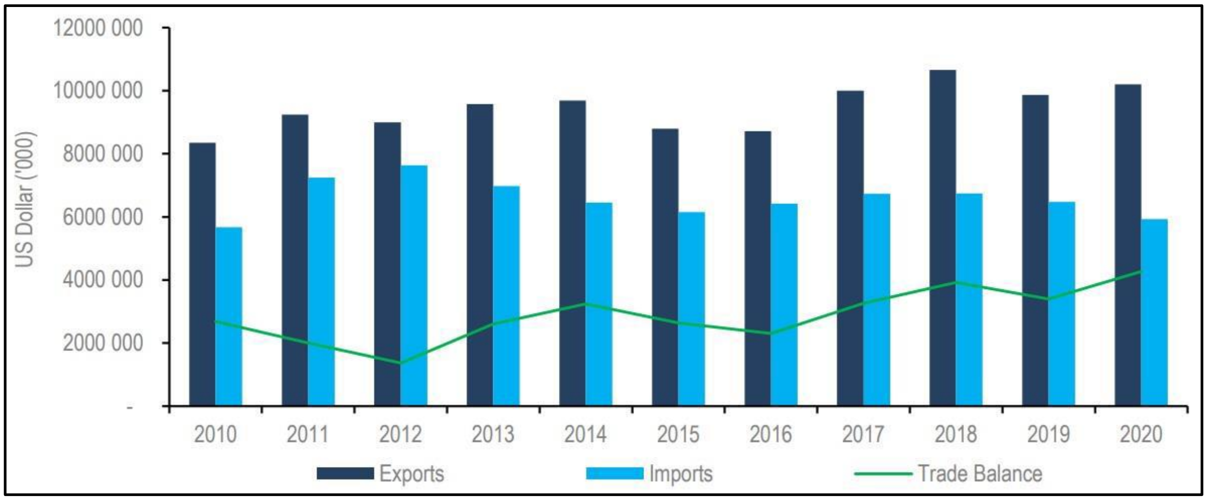

Figure 2-21 South Africa's agricultural trade for the period 2010–2020. Source: Sihlobo, 2021.

According to the Census of Commercial Agriculture (CoCA) (2020), South Africa has more than 40 000 commercial farms, which generate more than R332 billion in income. The farming of animals contributes up to 36% of this income. The Western Cape generates the most income from commercial agriculture, with the Free State following in second place (CoCA, 2020). The main crops cultivated in South Africa include maize, barley, wheat, sunflower, potatoes, sugarcane, soybeans and sorghum. Maize is the most cultivated crop, using approximately 2.8 million hectares of land (CoCA, 2020). South Africa's largest crop outputs by volume are maize, sugarcane and potatoes. The Free State has the most commercial farms, while animals and animal products generate over half the total farming income (Figure 2-22A on page 41) (CoCA, 2020). Figure 2.22B on page 41 shows that maize was by far the most produced crop in 2017, with more than 10 million metric tons produced in the country, while cattle topped the production scales in animal production (excluding chickens), with more than 3.5 million heads of cattle sold (CoCA, 2020).

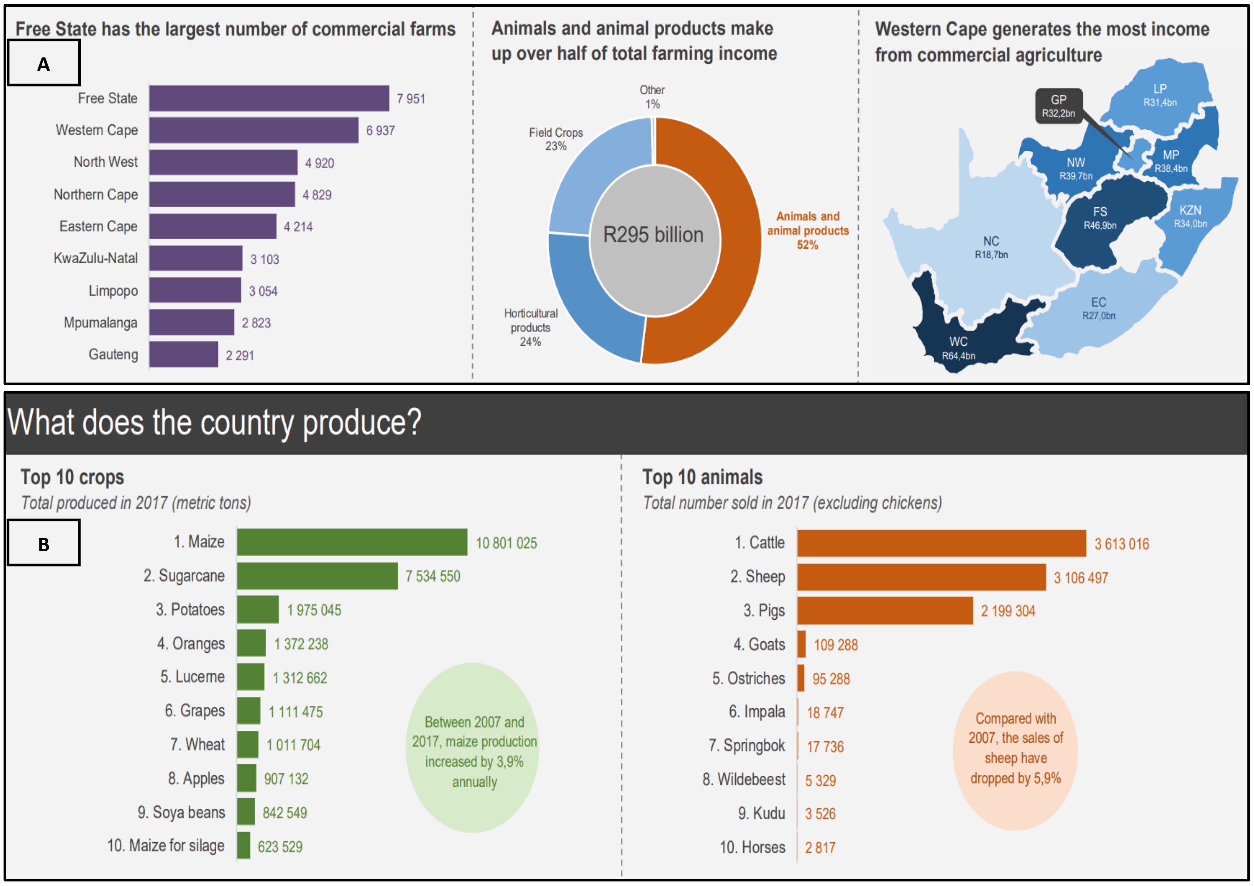

Figure 2-22 Agricultural production and associated revenue records for South Africa during 2017. Countrywide distribution of commercial farms, percentage of farmed products and income generated (A) and Top 10 crop and animal types produced in the country (B). Source: CoCA, 2020.

The country's spatial crop production in 2017 is presented on page 42 in Figure 2-23A and shows that the three provinces that are major producers of maize and make up the Maize Triangle also contribute to the production of all other crops except sugarcane, the production of which is restricted to the far eastern provinces of the country (Mpumalanga and KwaZulu-Natal). Field crops account for the largest portion of cultivated land in South Africa, with the major crops in planted areas being maize, soya beans, sunflower seeds, wheat and sugarcane in 2007 and 2017, employing more than 120 000 employees and generating close to R70 billion in 2017, while accounting for 23% of total farming income in 2017, as shown in Figure 2-23B on page 42 (CoCA, 2020).

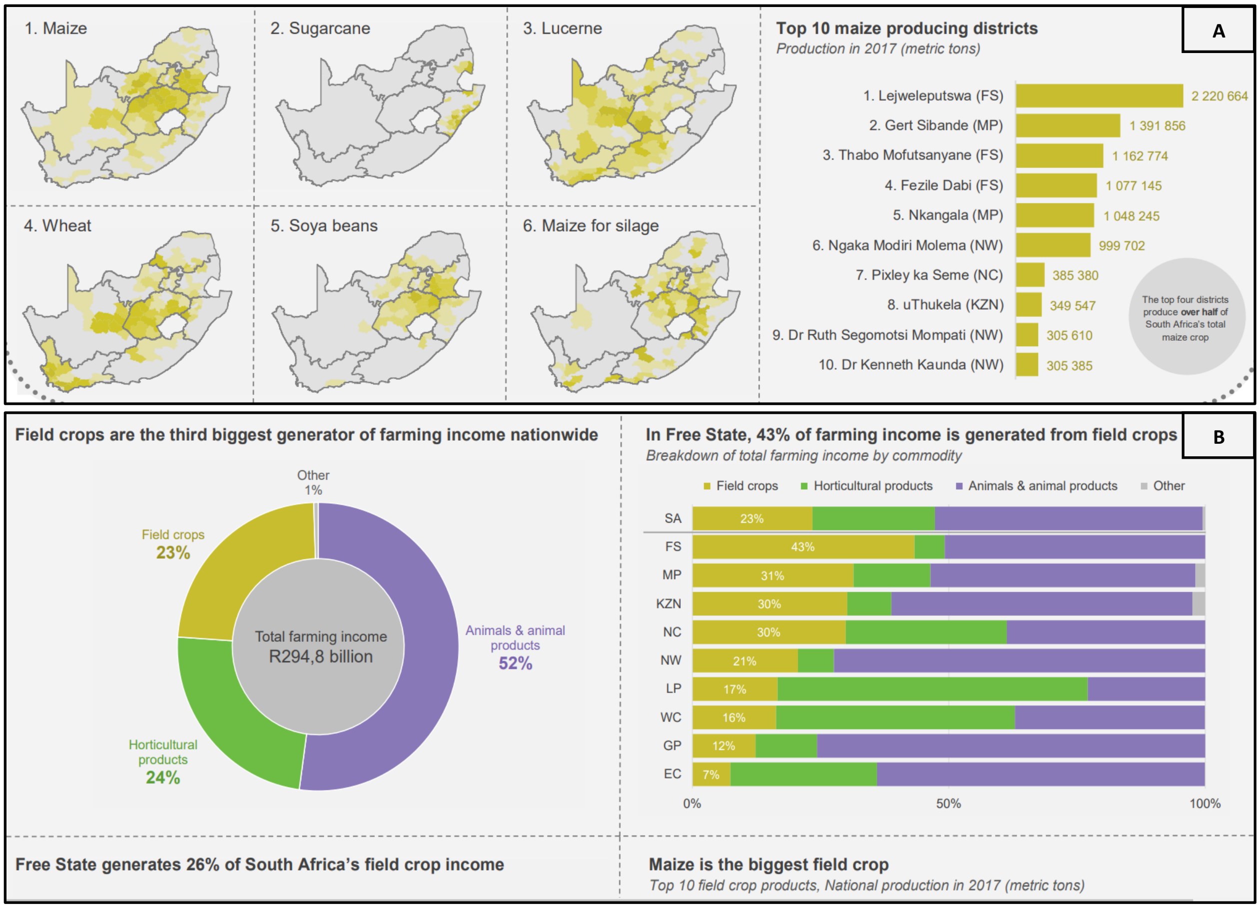

Figure 2-23 Spatial distribution of the various crops and production records, as well as maize revenue generation during 2017. Crop production concentration in South Africa (A) and income from different types of farming in South Africa (B). Source: CoCA, 2020.

Several threats can potentially affect the South African agricultural sector. These include climate change, urban migration and land degradation, which could result in a high usage of chemical fertilizers, high input costs, monocropping, water scarcity, high costs and unreliable energy supplies, biodiversity loss, as well as geopolitics and wars, which could lead to reduced supplies and excessively high prices (CSIS, 2022). Affholder et al. (2013) and Fischer (1985) argued that crop yield is influenced more by farming practices than by climate. According to Johnson (2019), many crops can endure exposure to high temperatures. However, it is the increase in extremely hot days (and warm nights) that can cause damage to crops. On the other hand, changing rainfall seasons leads to shifts in rainfall dates, thus confusing planting dates and crop management practices (Johnson, 2019).

2.9 MAIZE CULTIVATION IN SOUTH AFRICA

Maize (*Zea mays.*) is a cereal crop grown widely throughout the world in a range of agro-ecological environments (Oduniyi, 2013). According to the FAO (2009), maize has about 50 species, which are characterised by different colours, textures and grain shapes and sizes. The white, yellow and red maize are the most common varieties. Based on a report by Kriel (2022), maize was first introduced to South Africa in 1655 and has since accounted for approximately two thirds of the country's commercial area under field crops. Two types of maize, white and yellow, are produced for human consumption and animal feed, respectively. While there has been notable variation in the area planted by maize in the country, a steady decline has prevailed over the years. Despite this decline, maize yields have been gradually increasing (Kriel, 2022). Figure 2-24 illustrates mature maize crops in the field.

Figure 2-24 Image of mature maize crops in the field. Source: Alamy, 2023.

Maize is regarded as the most valued grain crop in South Africa (Johnson, 2019) and the most important cereal worldwide with the largest global production (Du Plessis, 2003; Fischer et al., 2014). The Department of Agriculture, Forestry and Fisheries (DAFF, 2011) reported that maize accounts for approximately 46.2% of the gross value of field crops in South Africa, a notion that makes it the most important grain crop in the country.

White maize, in particular, serves as the staple food for the majority of South Africa's population, especially low-income households (Abidoye and Mabaya, 2014; Gouse, 2013). In South Africa, the agricultural sector contributes about 1.9% to the GDP, employs about 30% of the labour sector (Chamuka, 2011) and plays a significant role in foreign exchange through the export of raw agricultural materials. The importance of this crop goes beyond South Africa's borders, since it is regarded as a major crop in sub-Saharan Africa due to its wide and diverse consumption capabilities, which range from being consumed as a staple food for people and animals, to its utilisation as a raw material for some manufactured products, such as paper, paint, textiles and food (Macaskill, 2017). According to Du Plessis (2003), maize requires 450 to 600 mm of rainfall per season to grow and reach a fully developed stage. This consists of a tassel, ear, leaves, stem, brace roots and roots. Furthermore, Du Plessis (2003) reported that 10 growth stages are defined for a maize crop to be regarded as a mature plant. These are Stage 0 (from planting to seed emergence), Stage 1 (four leaves completely unfolded), Stage 2 (eight leaves completely unfolded), Stage 3 (twelve leaves completely unfolded), Stage 4 (sixteen leaves completely unfolded), Stage 5 (silk appearance and pollen shedding), Stage 6 (green mealie stage), Stage 7 (soft dough stage), Stage 8 (hard dough stage), Stage 9 (physiological maturity) and Stage 10 (drying of kernels, which marks biological maturity). In order to fully attain all these stages, maize must be grown in areas with a mean daily temperature of no less than 19 °C or where the mean temperature of all summer months is less than 23 °C, while the critical maximum temperature that is detrimental is 32 °C. An illustration of different parts of a maize crop is given in Figure 2-25.

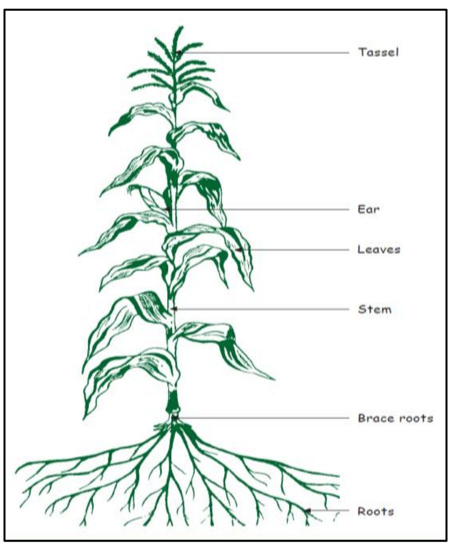

Figure 2-25 A depiction of a fully developed maize plant. Source: Du Plessis, 2003.

Different growth stages of the maize crop were provided by PANNAR (2022) and are displayed in Figure 2-26. The phenology of the maize crop is generally influenced by seasonal and inter-annual climate variations, habitat factors, as well as management practices (Abubakar et al., 2020). The crop is reported to be very sensitive to water availability during the stages of germination, silking, pollen shedding and grain filling (Jain et al., 2019). The typically accepted total seasonal rainfall for good yields must range from 450 to 650 mm. Insufficient moisture within two weeks of planting negatively affects maize germination, while insufficient water availability at later growth stages affects grain quality and quantity (Jain et al., 2019). On the other hand, daily rainfall equal to or more than 10 mm was found to be detrimental to maize yield (Beyer et al., 2016). According to Tadross et al. (2009), the occurrence of rainfall equal to or exceeding 10 mm during germination may lead to waterlogging, and the planted seed may accumulate excess water that hinders germination. Furthermore, the occurrence of such rainfall events during the middle of the maize growth season when the maize crop is at the pollination stage may lead to the washing away of pollen before it fertilizes, resulting in pollination and, ultimately, crop failure. Lastly, the occurrence of such rainfall events during the harvesting stage can result in the development of maize bacteria and fungi, while excessive moisture content on the crop affects the final dry mass output, leading to poor yields.

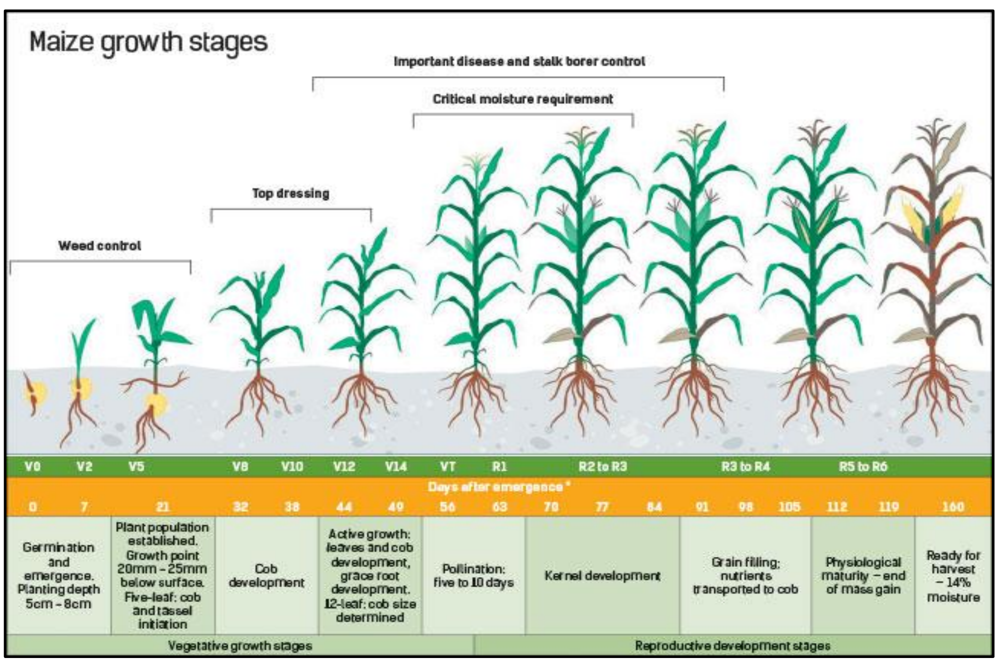

Figure 2-26 Maize growth stages with stage-relevant management techniques. Source: PANNAR, 2022.

Beiragi et al. (2011) stated that rainfall and other associated weather patterns, such as solar radiation and temperature (Mqadi, 2005), have a direct effect on maize cultivation, particularly planting dates, development period and harvesting dates. Blignaut et al. (2009) further indicated that South Africa is likely to experience a 1.1% decline in maize production with every 1% reduction in rainfall. Limited knowledge on future patterns of rainfall drivers restricts our understanding of rainfall behaviour in the future and thus threatens food security, among other things, in a climate that is said to be changing. The dates of the rainfall onset or cessation play a critical role in defining the start and end of the growing season (Moeletsi et al., 2011). Research shows that farmers who can correctly align their planting dates with rainfall onset are able to maximise their yields (Akinnuoye-Adelabu and Modi, 2017; Ati et al., 2002). Maize growers often find it challenging to accurately predict the planting window for various planting seasons (Du Plessis, 2003). Planting date is the most important management tool in rain-fed maize cultivation (Du Plessis, 2003) and is fundamentally linked to the long-term climatic conditions of a particular region (Abraha and Savage, 2006). The importance of the correct timing of a planting date stems from the strong influence it has on the timing and duration of the vegetative and reproductive stages of a maize plant (Abraha and Savage, 2006). As a result, changing the planting date is considered to be one of the critical adaptation strategies employed by farmers to cope with the changing climate. Walker and Schulze (2006) identified potential planting dates for rain-fed maize cultivation as October for the eastern and December for the western parts of the country that receives much of its rainfall during the austral summer.

According to a report by Kriel (2022), maize is planted from October to December after sufficient rain has fallen to allow the seeds to germinate. Substantial variation in planting times is notable in the country and ranges from the eastern to western regions. This can be attributed to differences in temperatures, rainfall and the duration of the growing season (Kriel, 2022). In contrast, Blignaut et al. (2009) states that since South Africa had been approximately 2% hotter and at least 6% drier over the decade between 1997 and 2006, compared to the 1970s, a 1% countrywide drop in rainfall could lead to a 1.1% decline in the production of maize. Temperatures have also been reported to play a role in maize crop growth and the resulting yield. The optimum temperatures for maize growth are between 20 and 30 °C. According to Harrison et al. (2011), temperature increases shorten the length of the growing period, which is essential for yield and grain size.

Temperature increases the phenological development through increased heat units during the vegetative stage, but extreme temperatures during pollination and grain filling reduce yields (Hatfield and Dold, 2018). Harvesting of maize is done when moisture percentages range from 12.5% to 14%, although harvesting can also be done with a dry matter content of 30 to 48% if maize is used to make maize silage (Kriel, 2022), which is regarded as the most valuable forage for ruminant livestock (Roth and Heinrich, 2001). However, temperatures exceeding 30 °C can lead to pollen receptivity, which negatively affects pollination.

South Africa is among the ten top maize producers in the world, accounting from up to 12 million tonnes in annual production (FAO, 2015). It is considered the main producer in the Southern African Development Community (SADC) region with more than 9 000 commercial maize farmers, as well as thousands of subsistence maize farmers (RSA, 2016). Furthermore, maize is said to occupy the largest farmland in the country, followed by wheat, sugarcane and sunflower. Three major maize-producing provinces in South Africa (Mpumalanga, the Free State and North West) receive less than 600 mm of annual rainfall (Adisa et al., 2019). These three maize-producing provinces accounted for 87% of the total maize produced in South Africa during the 2017 season (Adisa et al., 2019). The location of these provinces (in addition to KwaZulu-Natal) is displayed in Figure 2-27 and is superimposed with elevation, South African Weather Service (SAWS) climate districts and centroids of the climatic districts in the proximity of weather stations with provincial borders.

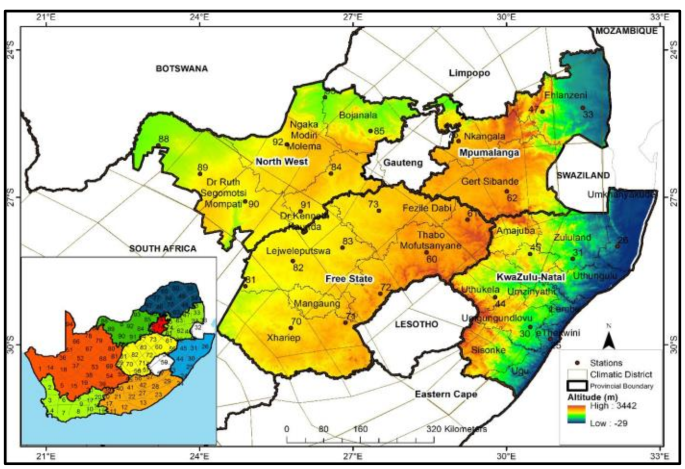

Figure 2-27 The three major maize-producing provinces in South Africa, superimposed with their elevation, SAWS climate districts and centroids of their climatic districts in the proximity of weather stations with provincial borders. Source: Adisa et al., 2019.

2.10 RAINFALL ONSETS, PLANTING DATES AND CESSATION RELATED TO MAIZE CULTIVATION IN SOUTHERN AFRICA

Oruonye et al. (2016) define rainfall onset as the time when a region receives an accumulated amount of rainfall that is sufficient for the growing of crops. It does not necessarily refer to the first day of rainfall. Agroclimatologists typically define the onset and cessation of rainfall using rainfall thresholds that are defined particularly for the crop under investigation, as well as the local climatic conditions (Phakula, 2016). Rainfall cessation was defined as the termination of effective rainfall, which does not necessarily refer to the last day of rainfall (Oruonye et al., 2016). Many studies of agricultural users indicated that the information of most interest to users is not the total rainfall, but the start and end dates of the wet season (Ingram et al., 2003; Ziervogel and Calder, 2003). Furthermore, various researchers regard rainfall onset and cessation as the most critical rainfall characteristics in the agricultural process, with the onset typically occurring towards the end of October and cessation at the beginning of November during the austral season over southern Africa, although there is considerable variation across various areas over the subcontinent (Ati et al., 2002; Camberlin and Mbeye, 2003; Kniveton et al., 2008; Majisola, 2010; Marengo et al., 2001).

Rainfall onset is regarded as being particularly fundamental in the agricultural sector since it determines the planting dates that are important to avoid planting too early or too late in the season, the length of the growing season, which is crucial in choosing the best cultivars, as well as the harvesting dates, which are important for proper planning, among other aspects (Dodd and Jolliffe, 2001). Late rainfall onset is said to lead to poor seasonal rainfall distribution, even when the total rainfall received for that particular season is normal (Otun and Adewuni, 2009), while a combination of late onset and early cessation may lead to drought, resulting in loss of property and sometimes lives (Cheruiyot and Osunmakinde, 2010). On the other hand, early rainfall onset and late rainfall cessation are likely to cause flooding, which is typically damaging to property and can lead to loss of lives. This demands a huge need to be able to understand trends in the start and end of the wet season, as well as to accurately predict these periods (Kniveton et al., 2008).

Various definitions of rainfall onset exist. They usually depend on an area's mean annual rainfall, as well as the sector involved. For example, Tadross et al. (2005) calculated rainfall onset over South Africa and Zimbabwe using rainfall data from the Climate Prediction Centre (CPC)'s Merged Analysis of Precipitation (CMAP) and the Computing Centre for Water Research

(CCWR). Some time later, Tadross et al. (2009) defined rainfall onset as 25 mm of rainfall in 10 days, which provides moisture for planting, followed by 20 mm of rainfall in the following 20 days, which is responsible for maintaining the germination stage of maize. Early summer rainfall onset has been associated with a longer rainfall season duration in South Africa (Moeletsi and Walker, 2012; Tongwane and Moeletsi, 2015). One of the strategies practiced by farmers in the Limpopo river basin to avoid the agricultural implications of false rainfall onset is to use the first October onset for land preparation and then plant after the second onset in November and December (Masupha et al., 2016).

According to Kniveton et al. (2008), there is no definitive answer to the question of the quantity and period of rainfall that must occur to define the start of the rainfall season. As a result, this phenomenon has not yet been widely and robustly investigated. Furthermore, the occurrence of a dry spell after an initial period of rainfall is regarded as a false rainfall onset. What adds to this confusion is the fact there is also no conclusive definition of what constitutes a dry spell. A number of authors have, however, proposed various definitions of rainfall onset (Benoit, 1977; Hulme, 1987; Stern et al., 1982). Kniveton et al. (2008) argued that the most used definition was documented by Stern et al. (1982) and is as follows:

a) The start of the wet season is not considered until after a particular date, ‘d’.
b) The potential start date is defined as the first occurrence of at least ‘x’ mm totaled over ‘t’ consecutive days.
c) The potential start could be a false start if a dry spell of ‘n’ or more days in the next ‘m’ days occurs afterwards.

The advantages of this method are that the variables d, x, t, n and m can be defined locally according to user requirements, which allows this type of definition to be tailored to suit a particular crop’s water requirements (Kniveton et al., 2008).

A number of authors regard rainfall onset and cessation as the most critical rainfall characteristics in the agricultural sector (Ati et al., 2002; Camberlin and Mbeye, 2003; Kniveton et al., 2008; Majisola, 2010; Marengo et al., 2001). Regions of southern Africa that receive rainfall during austral summer usually have their rainfall onset during the period between the end of October and the beginning of November. While the latter is well established, a considerably high variability in specific rainfall onset dates still poses a huge challenge to accurately determine rainfall onset.

An early rainfall onset was deemed by Moeletsi et al. (2011) to be the main cause of a longer than normal duration of the rainfall season, while Otun and Adewuni (2009) stated that the delay in rainfall onset may lead to poor and unusual seasonal rainfall distribution, thus contributing more confusion to rain-dependent activities. The timing of these phenomena is of crucial importance since a late onset and an early cessation of rainfall may lead to severe drought, and an early onset and a late cessation may lead to strong floods. In addition, crops planted too early or too late in relation to rainfall onset may be lost due to moisture deprivation (Kniveton et al., 2008).

A study conducted by Olaniran (1984) found that rainfall onset and cessation in the area of this study occurred during the September/October and March/April periods, respectively. The study further suggested that rainfall onset can be identified during wet, dry and normal years. The years with rainfall onset dates between 17 and 27 September are regarded as wet years, while those with rainfall onset dates after September are classified as dry years (Olaniran, 1984). An assessment of the relationship between total annual rainfall and associated maize yield showed that the relationship between rainfall and maize yield was insignificant (Figure 2-28), a result that can be attributed to the influence of various non-meteorologically related agricultural practices that influence maize yields (Matimole, 2018).

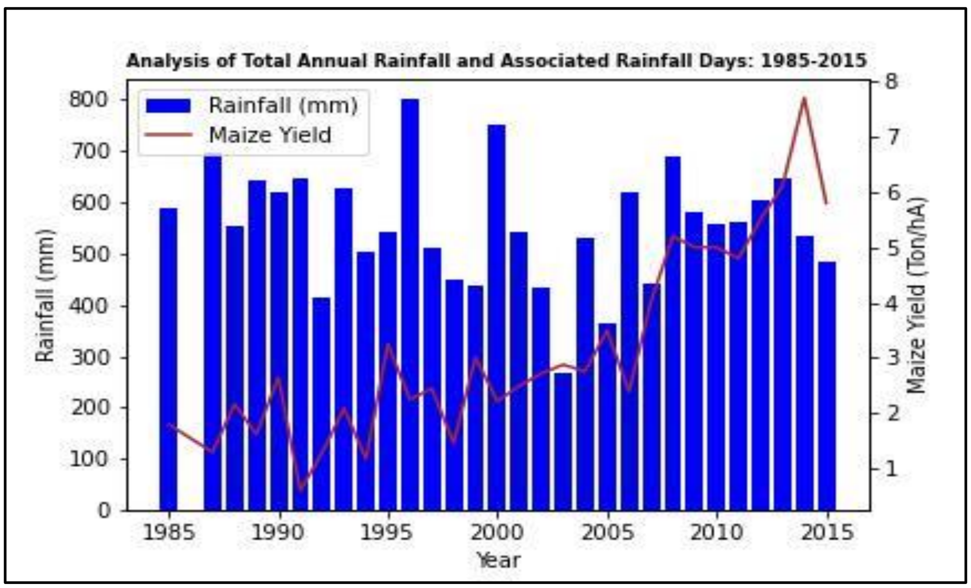

Figure 2-28 The analysis of the relationship between rainfall and maize yield. Source: Matimole, 2018.

Akinnuoye-Adelabu and Modi (2017) regard planting date as one of the most important management practices, since it influences the resultant crop yield through seedling establishment and development. In a study conducted by Beiragi et al. (2011), it was concluded that planting date also has a significant effect on maize hybrids, where some hybrids (e.g. EXP1 and KDC370) demonstrated the best production under early planting conditions, while others (EXP1 and KDC370) showed the best behaviour under late planting conditions. The latter study also concluded that delaying the planting date reduced yields and their components (e.g. kernel weight, kernel number, ear length and kernel depth). More specifically, planting data has a direct influence on day and night temperature, light intensity, photo period and soil moisture. While different areas have varying optimal planting dates, maize yield response to planting date is very similar in different years and locations (Hoegemeyer, 2013). This is because the number of growing degree days (GDDs) required by maize crops to reach various developmental stages is fairly uniform across different environments (Hoegemeyer, 2013). Additionally, maize hybrids respond differently to planting dates, with each hybrid having its own optimum planting date. Deviation from the optimal planting date could negatively affect growth duration and yield. A study conducted in Pietermaritzburg, KwaZulu-Natal, by Akinnuoye-Adelabu and Modi (2017) indicated that early planting dates were in November, mid-season planting dates were in December, while late planting dates were in January.

Water requirements for different crops vary, based on the type of crop, period of crop growth and micro-environmental factors (Altieri, 2018). Environmental changes associated with different sowing dates, such as sunshine and temperature, have a modifying effect on the growth and development of maize (Beiragi et al., 2011). Maize growers often find it challenging to accurately predict the planting window for various planting seasons (Du Plessis, 2003). Planting date is the most important management tool in rain-fed maize cultivation (Du Plessis, 2003) and is fundamentally linked to the long-term climatic conditions of a particular region (Abraha and Savage, 2006). The importance of the correct timing of a planting date stems from the strong influence it has on the timing and duration of the vegetative and reproductive stages of a maize plant (Abraha and Savage, 2006). As a result, changing the planting date is considered to be one of the critical adaptation strategies employed by farmers to cope with the changing climate. Walker and Schulze (2006) identified potential planting dates for rain-fed maize cultivation as October for the eastern and December for the western parts of the country that receives much of its rainfall during the austral summer season. Agribiz Research of Grain SA (Agricultural Economics Today, 2019) mapped optimal maize planting dates in South Africa, as shown in Figure 2-29.

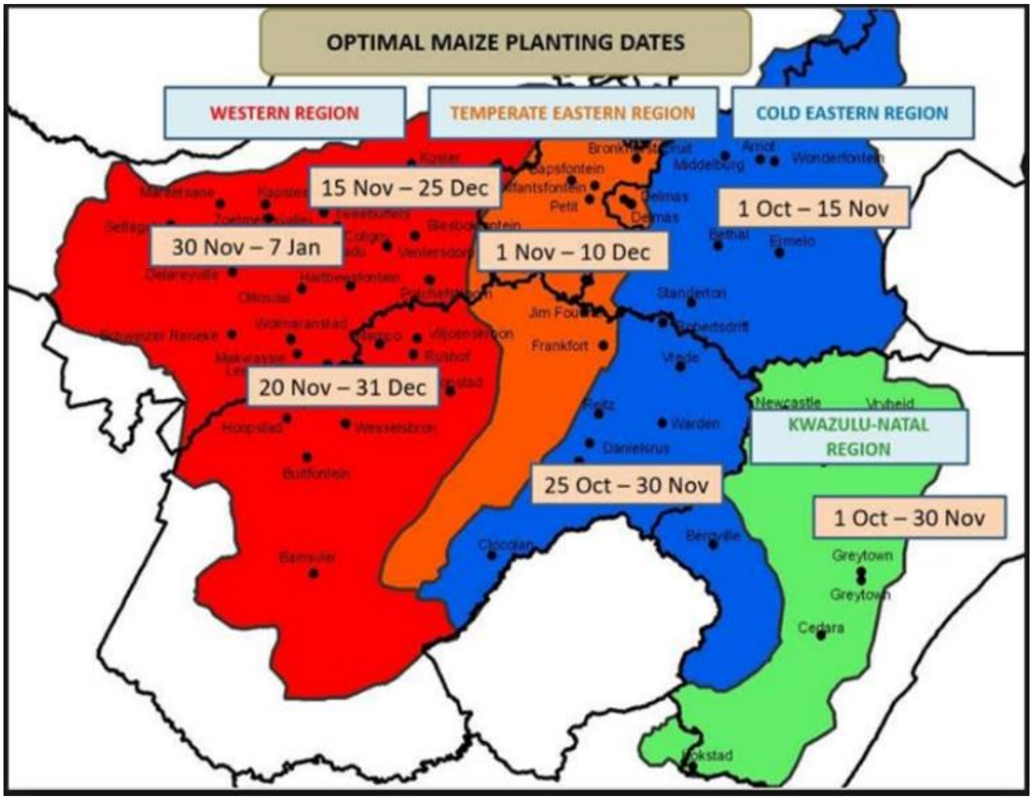

Figure 2-29 Optimal maize planting dates for different maize-growing regions in South Africa. Source: Agricultural Economics Today, 2019.

The average duration of the maize-growing season in most parts of the subcontinent is between 90 and 140 days (Beyer et al., 2016; Hachigonta et al., 2008; Tadross et al., 2009). However, each maize hybrid has its own optimal sowing date. The greater the deviation from this optimum (early or late) sowing date, the greater the yield loss (Berzsenyi and Lap, 2001; Sárvári and Futó, 2000). Accurately predicting planting dates has been a huge challenge for maize growers, since the window is narrow and variable, resulting in some farmers missing it and finding themselves planting either too early or too late (Nielson et al., 2002). According to Lauer et al. (1999), farmers who plant early pose their crops to the risk or frost, poor emergence and early plant growth, while those who plant late wonder what maturity hybrids to plant and how late planting might affect the final grain yield and grain moisture. Results from a study conducted by Beiragi et al. (2011) demonstrated that there were significant differences in yield among hybrids tested using sowing dates. Furthermore, the study found that delayed planting reduced cob percentage, physiological maturity, total leaf number, kernel weight, kernel number per row, kernel depth and ear length. Delayed planting also affected plant height, ear height and stem diameter. Total yield was reduced by -3.12%. Therefore, it is generally accepted that missing the correct planting window will lower the yield because the probability exists that unfavourable climatic conditions can occur after planting or during the growing season (Beiragi et al., 2011). As a way to safeguard against unfavourable climatic conditions negatively impacting the yield, Norwood (2001) proposed that farmers should plant on more than one planting date.

2.11 THE FUTURE OF MAIZE PRODUCTION UNDER CLIMATE CHANGE

The application of crop modelling in various cropping systems and environments as a means of projecting and upscaling agronomic decision making has increased over recent years (Kogo et al., 2019). Much of the recent work conducted (Basso et al., 2013; Deb et al., 2015; FAO, 2009) suggests that climate change has led to intra-seasonal yield variability and may alter crop production in the 21st century. Locally, Mapfumo (2020) suggested that climate change has led to drought, increased temperatures and subsequently decreased yields in some parts of South Africa. It is worth noting, however, that – as concluded by Mapfumo (2020) – while rainfall is a critical factor in maize production, it is not the only factor that must be managed with care. Other factors include pests, diseases and temperature.

Agriculture is a fundamentally important socio-economic sector in the world, particularly in Africa where it employs up 70% of Africans, while up to 80% of rural people in South Africa depend on agriculture to sustain themselves (African Agriculture Climate, 2002; Haggblade et al., 2002). In a study conducted by Kogo et al. (2019), it was found that models projected a decline of between 8 and 38% in maize yields under the RCP4.5 and RCP8.5 scenarios by the end of the 21st century. The study further recommended that major agro-adaptation – particularly in planting dates, cultivars and crop water management – is essential to alleviate the expected impacts of climate change. Zinyengere et al. (2013) added that climate change is envisaged to reduce maize yield by an average of 18%, putting a heavier burden on the already aggravated crop production and food availability.

Extreme weather events such as floods, drought and heat stress were deemed the most significant aspects of climate change (Bassu et al., 2014; IPCC, 2007a; Stocker et al., 2013). Other factors include water application, tillage, fertilizer application and seasonal changes in the magnitude and trend of temperature, precipitation and solar radiation (Ahmed et al., 2018; Kang et al., 2009). The United Nations Environmental Program (UNEP, 2002) reported that the African continent has been experiencing an increase in temperatures of approximately 0.05 °C per decade, while rainfall patterns have been altered in various parts of the continent, including southern Malawi, South Africa, Zimbabwe, western Mozambique and Zambia, over the 20th century. Akpalu et al. (2008) added that the scientific community established that the temperature in South Africa has increased by 0.13 °C between 1960 and 2003, and is expected to increase even further, with rainfall expected to also change in quantities and timing. According to a report by the IPCC (2018), the projected temperature increase of 1.5 °C is likely to reduce productivity in key cereals, including maize, rice and wheat, in sub-Saharan Africa, Southeast Asia, and Central and South America, possibly affecting over five million people in the world who are likely to be at risk of hunger by 2100 (Stocker et al., 2013). The Koninklijk Netherlands Meteorological Institute (KNMI) (2006) reported that extremely low rainfall conditions are expected over the subcontinent by 2100.

CHAPTER 3: DATA AND METHODS

3.1 INTRODUCTION

This chapter discusses data sets and methods that were employed to source and process data, and to represent findings. It includes information on various data sets and where they were sourced, and methods used to process data sets and execute the required computations, and present various results. It is worth pointing out that the nature of this study required the use of various data sets, which ultimately had to be merged together to paint a picture that shows which data sets interact with each other, when, how and why, in line with the study objectives. As a result, various sources and tools were used to obtain data, conduct analyses and display results.

3.2 STUDY AREA

Figure 3-1 on page 56 displays the study area on which this research is focused, presented in a spatially downscaled approach, where Africa is shown as the continent in which South Africa resides and the Maize Triangle as the specific study area, located in South Africa. The study area consists of three major maize-producing provinces: Mpumalanga, the Free State and North West. They are collectively referred to as the Maize Triangle and generally occupy parts of the central and east of the country. These are the three major maize-producing provinces of South Africa.

While KwaZulu-Natal is also considered a significant province in terms of maize production, it is not part of the Maize Triangle, and is therefore not included in this study. North West is predominantly flat in terrain and consists of vegetation comprising largely scattered trees and grasslands. The 2007 census reported that the province had a population slightly over 3 million. Just over 90% of the population was black, approximately 7% was white, close to 2% was coloured and less than 1% was Asian.

Mpumalanga is generally divided by the Drakensberg escarpment, which exceeds a height of 2 000 m in some places, into the Highveld and the Lowveld. The Highveld is the western part of the country, which is characterised by high altitude grassland, while the Lowveld is the eastern part of the country, which is low in altitude and is predominantly a savanna biome. The demographics of Mpumalanga indicate that it has a population of just over 4 million, with 90.65% being black, and 7.51% being white. The coloured and Indian/Asian population groups are less than 1% each.

The Free State is mainly high lying with some areas reaching over 2 000 m in altitude, and 32 000 km^2 of its land being used for cultivating crops, while 87 000 km^2 is natural veld that is used for grazing. The population of the Free State is approximately 3 million, with 88% of the population comprising black people.

Figure 3-1 The study area is the Maize Triangle, which comprises North West, the Free State and Mpumalanga, which are regarded as the major maize-producing provinces in South Africa.

3.3 SOUTH AFRICAN RAINFALL DISTRICTS

The South African Weather Service (at that time known as the South African Weather Bureau (SAWB)) delineated 94 rainfall districts for South Africa. These were delineated areas of homogeneous climate – particularly rainfall – in South Africa (SAWB, 1972). The delineation of these rainfall districts was based on the computation of annual rainfall totals and considered rainfall seasonality making use of boundaries between winter, the whole year and the summer rainfall regions. The SAWS has used its weather stations located in these districts to compute and update daily district rainfall data on a monthly basis since 1921 (SAWB, 1972). Figure 3-2 shows these rainfall districts with their numbers overlaid on a map of South Africa.

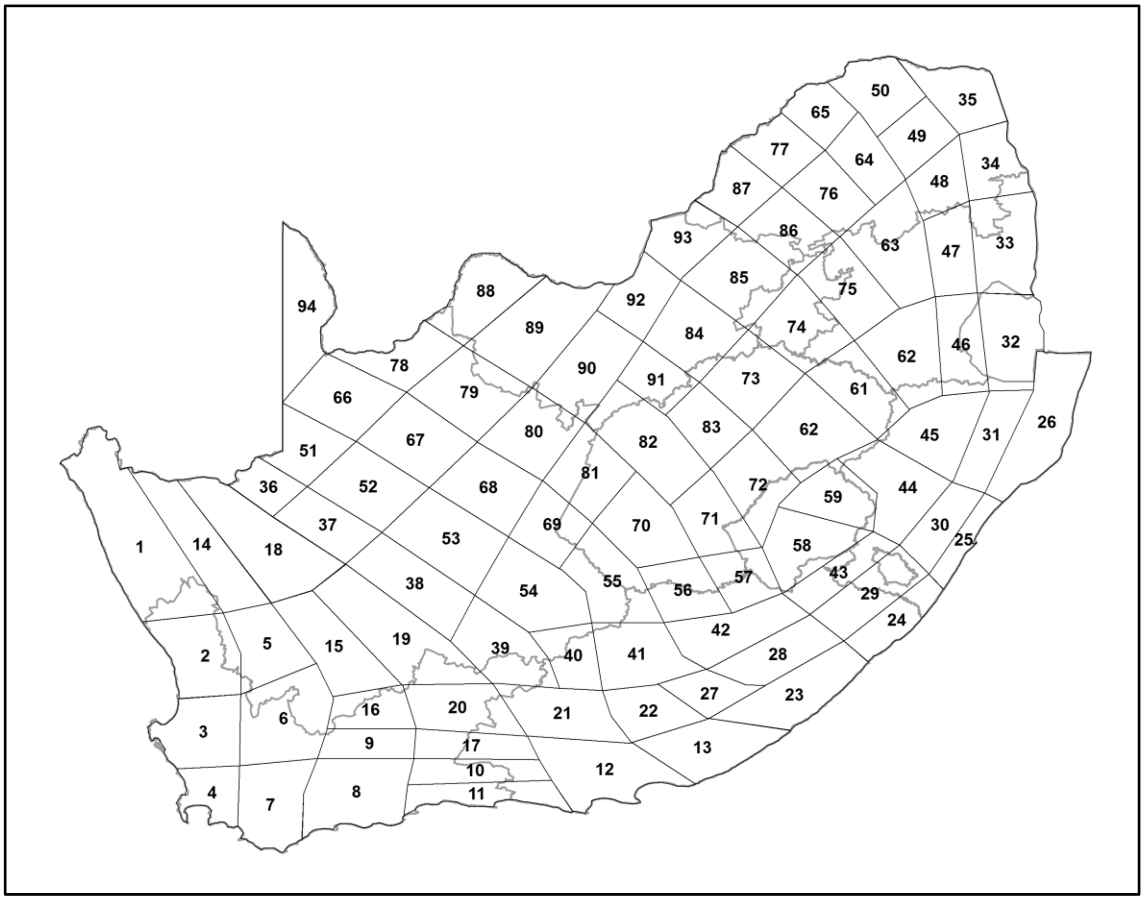

Figure 3-2 Rainfall districts of South Africa with their respective identification numbers developed by the SAWB (SAWS) plotted over a map of South Africa with provincial borders. Source: SAWB, 1972.

The Maize Triangle that was used as a study area for this research was further divided into 24 rainfall districts, which are spatially representative of the total Maize Triangle in South Africa and are depicted in Figure 3-3. Only 23 rainfall districts were coupled with a weather station that was used for rainfall data extraction which, in turn, represents the rainfall district in which it is located.

This was done because one rainfall district was located in Gauteng, which does not form part of the study area. Furthermore, a maize-producing region located within each of the selected rainfall districts was selected to represent maize yield from each rainfall district. The latter approach led to a decrease in the number of rainfall districts that was used for the study analyses from 23 to 17 districts, resulting from limitations in the available maize yield data. Therefore, Figure 3-3 displays the location of the weather stations (blue place marks) and their names (written in blue) that represent rainfall districts (demarcated by pink lines and marked by their numbers in pink), which are plotted over the three provinces (demarcated by black lines) that make up the Maize Triangle.

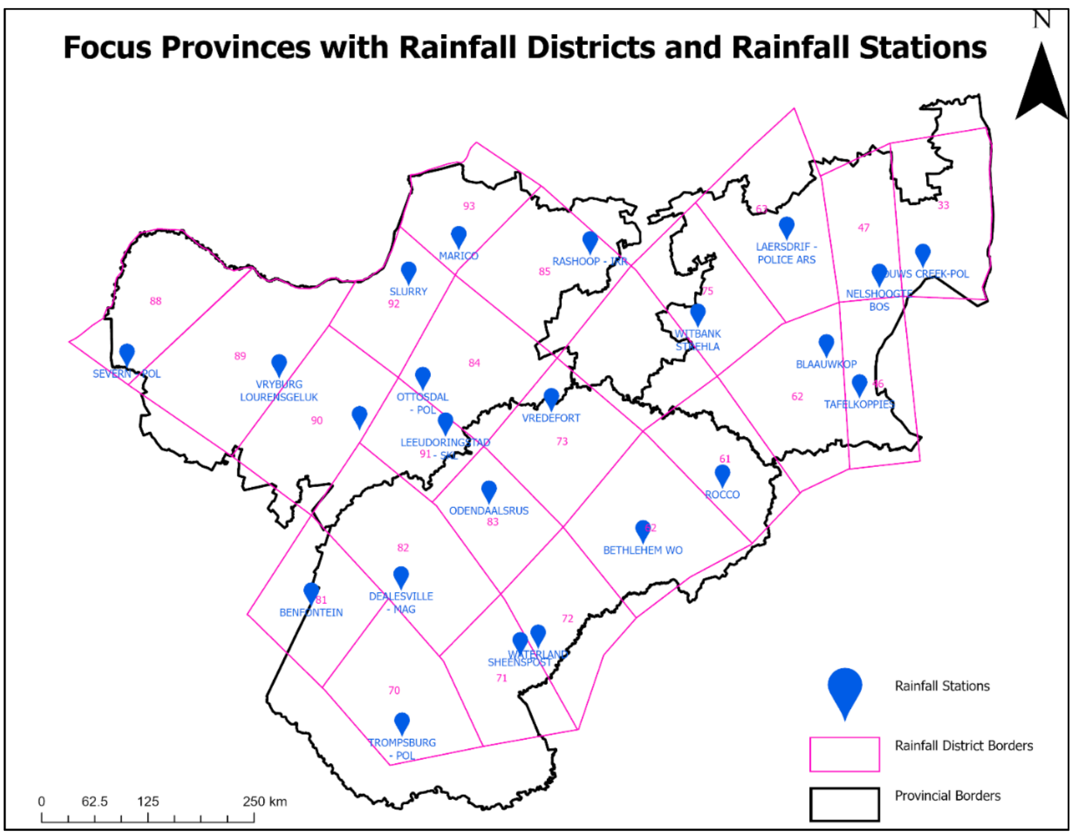

Figure 3-3 A map of the study showing 24 rainfall districts and district numbers, their representative weather station locations and names, as well as the three provinces that make up the Maize Triangle.

3.4 SOURCING, PREPARATION AND APPLICATION OF DATA SETS

The nature of this study required the use of five different data sets: the outgoing longwave radiation, tropical temperate troughs, monthly district rainfall, daily weather station rainfall and maize yield data sets. These were sourced from different providers. For this reason, data sets had to be synchronised by selecting common start and end dates for the study period, since some data sets start before others. Common time intervals also had to be selected. The latter considered the usability of the available (and selected) periods and intervals so that they could produce meaningful results for the study.

3.4.1 Outgoing longwave radiation data set

The National Oceanic and Atmospheric Administration (NOAA) OLR (Reanalysis II) data set was obtained as a NetCDF file from the Earth System Research Laboratories (ESRL) website (Liebmann and Smith, 1996). This is a global data set that comprises the daily mean interpolated OLR with four dimensions – latitude, longitude, time and variables – at the surface level and at a 2.5° spatial resolution. The selected data record spans 1979 to 2018, and consists of 14 610 time steps.

3.4.2 Tropical temperate trough case data set

Tropical temperate trough events, which were observed and recorded by Hart (2019), were obtained in the form of a text file for use in this study. A total of 1 161 cases was recorded over southern Africa and the surrounding oceans from 1979 to 2018. Each row of the TTT case data set comprised four columns, where the first contained the date of the event in the format YYYYMMDD. The second contained the longitude. The third contained the latitude, and the fourth contained the duration in days. For the purpose of this study, only 880 TTT cases located from the longitude of 0° to 40° were selected for use since these were deemed to have centres close enough to the study area for them to have an impact on it.

3.4.3 Monthly district rainfall data set

Monthly district rainfall data for rainfall districts that cover the study area were obtained from SAWS (2019). This data set was received in the form of an MS Excel spreadsheet with columns representing rainfall districts using district numbers and rows representing the months of each year.

3.4.4 Daily weather station rainfall data set

Daily rainfall data from multiple weather stations that are representative of the study area were obtained from SAWS and received in the form of an MS Excel spreadsheet (SAWS, 2019). Weather stations that met the data record criteria, i.e. those that had daily rainfall data recorded over the period 1979–2018, had the lowest percentage of missing data and were located within a chosen rainfall district, were selected to represent rainfall districts.

3.4.5 Seasonal maize yield data set

Maize yield data was obtained from the Department of Agriculture, Land Reform and Rural Development (DALRRD) (2020). The DALRRD collects this data from various pre-identified agricultural regions for different crops across the country and updates it on a seasonal basis. Regions that fell within the rainfall districts of the study area that contained data spanning the period 1980/81–2017/18 and had the most complete data record were selected for the analysis purposes of the study.

3.5 METHODS

3.5.1 Outgoing longwave radiation data set analyses methods

The OLR data file was downloaded and the data prepared for analysis using the Python programming language in Anaconda Navigator (anaconda3) in the Jupyter Notebook 6.4.8 environment. The sub-setting of the OLR data file was performed in Python to reduce the data file size from the global to the southern African domain. Thereafter, OLR monthly and seasonal averages were computed and plotted. Daily OLR anomaly composites were also computed by calculating an OLR seasonal average for September, October, November, December, January and February. Daily OLR averages for TTT cases that occurred during the said months were then calculated for each month. Anomaly composites for each of the said months were then computed by subtracting the daily OLR average from the seasonal OLR average. The OLR data file was also used to compute the monthly average OLR over the subcontinent using a Hovemöller diagram.

3.5.2 Tropical temperate trough case data set analysis methods

Using MS Excel spreadsheets, TTT cases were organised and merged with the identified rainfall onsets by considering their co-occurrence using dates. Because the TTT cases that occur immediately before rainfall onsets can contribute to the development and outcome of the subsequent rainfall onsets, TTT cases that occurred within a three-day period before the first day of the first dekad (10-day period) were considered. Furthermore, TTT cases that occurred on any day between the first day of the first dekad and the last day of the last dekad were considered and categorised accordingly. Additional details about dekads are provided in the section 3.5.4. MS Excel spreadsheets were also used to plot time series of TTTs with rainfall time series. TTT cases that occurred from September to February were further selected for spatial analyses using the ArcGIS program and a relevant shapefile, the projection of which was GCS_WGS_1984.

3.5.3 Rainfall districts and rainfall data set analysis methods

ArcGIS was used to select and plot rainfall districts that constitute the Maize Triangle. MS Excel spreadsheets were used to calculate the averages of monthly district rainfall for each of the rainfall districts that form part of the study to graphically represent the behaviour of district rainfall for each rainfall district. ArcGIS was also used to spatially display the various results on a map that shows variability from one rainfall district to another.

3.5.4 Daily weather station rainfall data set analysis methods

MS Excel spreadsheets were used to identify rainfall onsets for August to February during the seasons 1979/80 to 2017/18. Although August does not form part of the austral summer rainfall months (e.g. World Bank Group, 2021), it was included in the identification of rainfall onsets because the method used to identify rainfall onsets considered a 30-day period. As a result, rainfall onsets that occurred during much of September (i.e. on or before 29 September) would have had their genesis sometime during August. It should be noted, however, that rainfall onsets that occurred during August were excluded from this analysis.

The 30-day period approach that was followed to identify rainfall onset was adopted from Tadross et al. (2005) and stipulated that the rainfall onset is said to have occurred when daily rainfall is received over a period of 10 consecutive days (or dekad) with distribution over a minimum of two days and equals or exceeds 25 mm, and when the dekad is immediately followed by a period of 20 consecutive days where daily rainfall is received and equals or exceeds 20 mm over two or more days. Although the 30-day period used to identify rainfall onsets during the austral summer rainfall months used in this study is partly that of Tadross et al. (2005), this study extended the months under investigation to include August. The identified 30-day periods within the months of interest met the criteria of the first and second dekad, but had missing data, which was considered in the analysis. All seasons with the identified rainfall onsets were listed and associated with available TTT cases for relationship assessments between the two. Seasons with rainfall onsets that occurred without any association with a TTT, those that were not identified due to missing data, as well as those that had no rainfall onsets, were also listed for comparison purposes.

This study then linked the identified rainfall onsets to the spatial and temporal depiction of maize planting dates developed by Agricultural Economics Today (2019) and categorised as early, normal and late planting dates. The contents of this product allowed this study to categorise the identified rainfall onsets as early, normal and late rainfall onsets, following the already established rainfall onsets, and finally plot the timing of rainfall onsets. The close relationship between rainfall onsets and planting dates where planting must be timed with the occurrence of rainfall onset (Akinnuoye-Adelabu and Modi, 2017; Ati et al., 2002) permitted this study to link the two agricultural requirements. Following this categorisation, specific categorisations of the identified rainfall onsets, such as the timing variations between TTT-associated rainfall onsets and non-TTT associated rainfall onsets, were performed and analysed accordingly through the use of graphic and map depictions. Rainfall onsets associated with TTTs were tested for trends and slope using the Mann-Kendall Test and Sen's Slope Estimates for the Trend of Annual Data (MAKESENS 1.0) MS Excel model (Gocic and Trajkovic, 2012) for each rainfall district. Test Z values – one of the variables computed by MAKESENS) – for rainfall onsets were plotted against corresponding seasonal maize yield using MS Excel spreadsheet scatter plots for regression analyses. This was done for each rainfall district. Scatter plots were then performed to assess relationships.

3.5.5 Seasonal maize yield data set analysis methods

MS Excel spreadsheets were used to organise the maize yield data set to determine seasonal maize yield variations that correspond to the previously identified rainfall onset categories. Seasonal maize yield values were also plotted graphically for temporal variations using MS Excel spreadsheets. They were mapped for spatial analysis using ArcGIS. Mann-Kendall Test and Sen's slope estimates were used to detect and estimate trends in the time series of seasonal maize yields. Test Z values were used to plot regressions against Test Z values of rainfall onset amounts per district using an MS Excel spreadsheet scatter plot program. Seasonal maize yield values were also used to plot regressions against rainfall amounts produced by the identified rainfall onsets per district using MS Excel spreadsheet scatter plots.

3.5.6 Data and methods schematic

A diagram that shows raw data sets as inputs and the processed outputs, as well as how each of these processes addresses each study objective in a value chain form, is presented in Figure 3-4. The left side (in rectangles with a brown background) consists of the raw data sets, the middle (in ovals with a grey background) outlines the addressed objective, and the right side (in rectangles with a brown background) lists the resulting data outputs.

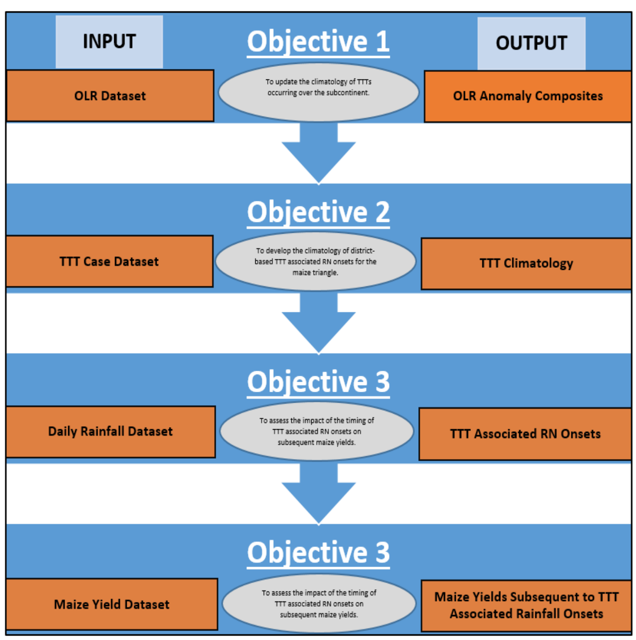

Figure 3-4 A diagram that illustrates the processing value chain of data sets used in this study, including the study objectives each process addresses.

3.6 MANN-KENDALL TEST FOR MONOTONIC TREND

The Mann-Kendall (MK) test is a statistics-based tool that is used to determine the presence and nature of trends (i.e. if the trend is monotonic upward or downward) in a long-term data set (Gilbert, 1987; Kendall, 1975; Mann, 1945). This is useful in understanding the behaviour of a variable over time. Visual Sample Plan (2022) defined a monotonic upward (downward) trend as that which the variable consistently increases (decreases) through time, but the trend may or may not be linear. The MK test can be used instead of a parametric linear regression analysis, which can be used to test if the slope of the estimated linear regression line differs from zero. The regression analysis requires that residuals from the fitted regression line to be normally distributed; an assumption not required by the MK test, i.e. the MK test is a non-parametric (distribution-free) test (Visual Sample Plan, 2022). Visual Sample Plan (2022) defines assumptions that underlie the MK test as follows:

- When no trend is present, the measurements (observations or data) obtained over time are independent and identically distributed. The assumption of independence means that the observations are not serially correlated over time.
- The observations obtained over time are representative of the true conditions at sampling times.
- The sample collection, handling and measurement methods provide unbiased and representative observations of the underlying populations over time.

The MK does not require the measurements to be normally distributed or for the trend, if present, to be linear. The MK test can be computed even if there are missing values and values below the one or more limits of detection (LD). However, the performance of the test will be adversely affected by such events.

MAKESENS 1.0 is an MS Excel spreadsheet-based model developed by the Finnish Meteorological Institute in 2002 (Salmi et al., 2002). It is used to detect and estimate trends in the time series of annual values of atmospheric chemistry. The method uses the non-parametric Mann-Kendall test to test the presence of the monotonic increasing or decreasing trend and the non-parametric Sen's method for estimating the slope of a linear trend. The template consists of four worksheets: About, Annual Data, Trend Statistics and Figure. The About worksheet gives general information about the template. The data of time series is entered into the Annual Data worksheet.

The calculation macro can be activated by using the button Calculate Trend Statistics, and the Trend Statistics worksheet contains the results. Finally, the original data and statistics can be viewed numerically and graphically in the Figure worksheet. Only one time series can be viewed at a time.

Test Z values were used to determine if there is a trend at the selected level of significance. A positive (negative) value of Z indicates an upward (downward) trend. The letter Q denotes Sen's slope estimate, which estimates the true slope of linear trend, i.e. change per unit time period (in this case, a year).

3.7 REGRESSION ANALYSIS USING SCATTER PLOTS

Regression analyses were performed for multiple variables using MS Excel spreadsheet scatter plots. This method was mainly used to investigate how TTT-associated rainfall onsets (rainfall amounts) affect subsequent maize yields. R^2 was displayed on the regression plots to determine the goodness-of-fit for the linear regression. The linear equation was also displayed on regression plots to determine the slope of the straight line.

CHAPTER 4: CLIMATOLOGY OF OLR AND TTT CASES OVER SOUTHERN AFRICA

4.1 INTRODUCTION

Climatological analyses of various relevant variables are conducted in this chapter, which is divided into two main sections: section 4.2 and section 4.3. Section 4.2 focuses on unpacking the fundamental factors that are relevant to the austral summer rainfall-bearing system of interest to this study. The purpose for these analyses stems from the need to establish a comprehensive background regarding TTTs and rainfall onsets over the southern African domain, as well as in the Maize Triangle. Therefore, this section will commence by exploring monthly rainfall patterns for rainfall districts that constitute the Maize Triangle, which is used as the study area in this work.

The analyses of the spatial distribution of OLR, as well as OLR anomalies over southern Africa, will also be performed to understand the link between TTTs and the OLR over the subcontinent during the study period. Focus will thereafter be granted to spatiotemporal variations of TTTs over southern Africa. The link between TTT variability and the ENSO over the subcontinent will finally be explored.

Section 4.3 mainly focuses on comparing properties and behaviour between rainfall onsets that were associated with TTTs and those that were not. This is done to advance an understanding of how TTTs influence rainfall onset in the Maize Triangle. Properties that will be explored for comparison include differences in frequency, spatiotemporal distribution, as well as differences in the contribution of rainfall between TTT-associated rainfall onsets and non-TTT-associated rainfall onsets in the study area during the study period.

4.2 UPDATING RAINFALL, OLR, TTTs AND ENSO PATTERNS IN THE SOUTHERN AFRICAN CONTEXT

This section addresses the first objective of this study, which is to define the climatology of TTTs that occurred over the subcontinent during the study period. The section commences by demonstrating rainfall patterns that were observed in the study area during the study period to establish if there is a consistency between the climate of the study area and that of the subcontinent.

It proceeds to explore OLR patterns, which are an indication of the ITCZ movements over the subcontinent. In addition, daily OLR anomaly patterns will be investigated for the months of the rainfall season over the subcontinent, since these serve as a proxy that is widely used for the identification of TTTs. The section will then conduct spatiotemporal analyses of TTTs over the subcontinent and finally assess their observed relationship with the ENSO phases in southern Africa during the study period.

4.2.1 Monthly rainfall distribution for rainfall districts that constitute the study area computed using district rainfall data for the period 1979–2018

Figure 4-1 shown on page 68 displays the monthly average rainfall for each of the rainfall districts that form the Maize Triangle, which was computed using district rainfall data that spanned the period 1979–2018. This figure shows that rainfall peaks during the austral summer months – from October to March – in all districts, with the highest rainfall received in January for most rainfall districts.

These rainfall patterns are consistent with the widely published literature on the general weather and climate of southern Africa, which are mainly attributed to the migration of the ITCZ that is typically located at its southernmost location during the DJF period, thus making the larger portion of the subcontinent's atmosphere conducive for rainfall development (Berry and Reeder, 2014; Dedekind et al., 2016; Zagar et al., 2011).

The austral summer season and its rains are critical to maize cultivation in the Maize Triangle since rainfall onset determines when to plant, and rainfall cessation determines when to harvest maize (Ati et al., 2002; Camberlin and Mbeye, 2003; Kniveton et al., 2008; Majisola, 2010; Marengo et al., 2001). The rainfall season also plays a significant role in the quantity and quality of maize crops, which is a prerequisite for good yields, particularly in rain-fed maize cultivation (Akinnuoye-Adelabu and Modi, 2017; Ati et al., 2002).

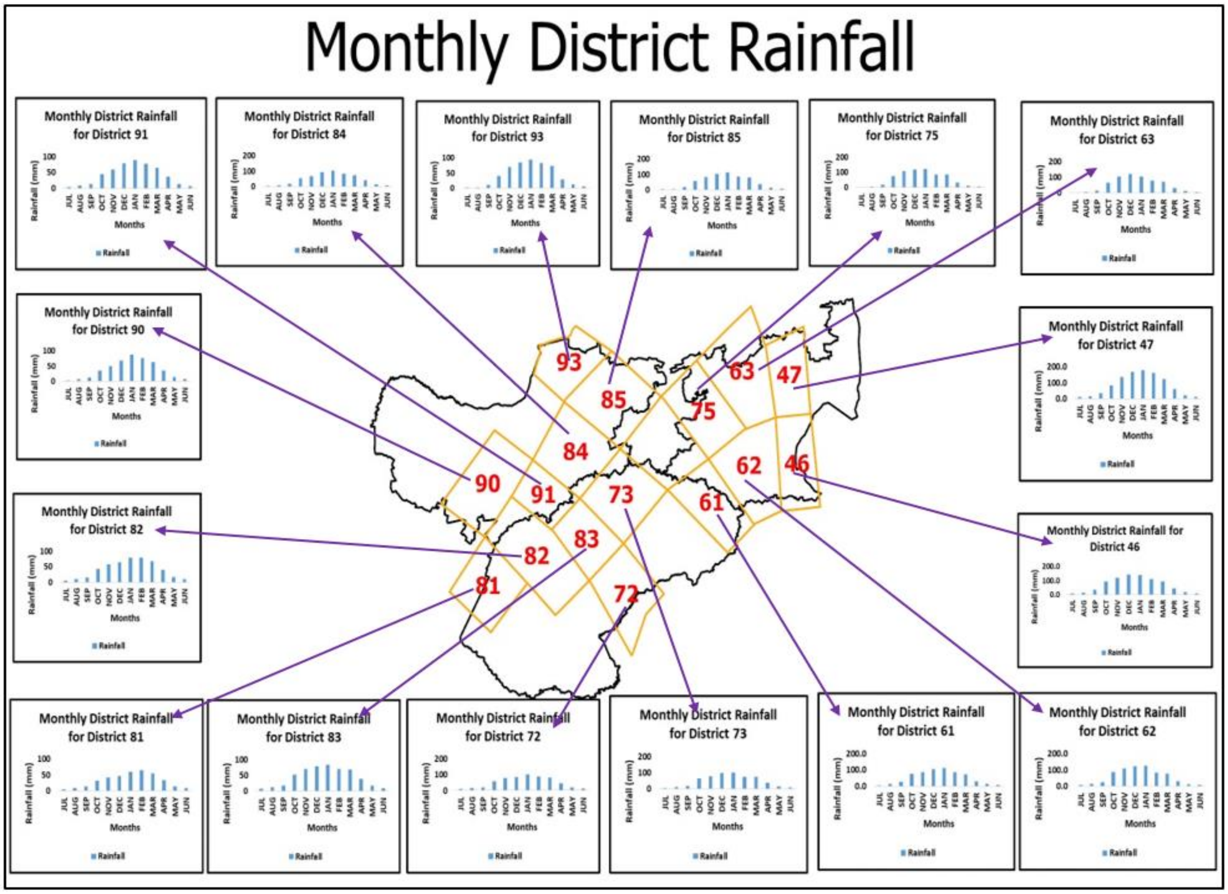

Figure 4-1 Monthly average rainfall distribution recorded from 17 rainfall districts that constitute the study area. Rainfall data was averaged over the period 1979–2018.

4.2.2 The spatial distribution of the OLR dipole structure as an indication of TTT positions over southern Africa

Monthly averaged OLR is displayed in Figure 4-2 on page 69 and demonstrates the prominent intrusion of a relatively low OLR region that extends from the deep tropics towards the southeast of the subcontinent. The appearance of this low OLR region starts during September when its location is in the deep tropics. It then stretches southeastward during the course of austral spring until it reaches its most southeastern location over Madagascar in the SWIO during the course of the austral summer. It then begins its retreat, which can be observed through the shrinking spatial extent that no longer reaches Madagascar during March. The retreat continues until the low OLR region disappears into the deep tropics during April and May.

During the DJF period known as the austral summer season, a relatively low OLR is prevalent over much of the northeastern half of southern Africa, stretching from the northwestern deep tropical part of the subcontinent (around Angola, as stipulated by researchers such as Reason et al. (2006)) until it reaches the southeast coast of Madagascar in the SWIO. This low OLR indicates an area of deep convection, which averages in the range of 200 W/m^2. On the other hand, a region with a notably high OLR (reaching above 280 W/m^2) develops over the southwestern tip of the subcontinent, covering the western parts of the Northern Cape and western, as well as the southern tip of Namibia.

These OLR patterns are consistent with those reported by Landman et al. (2015), who noted the development of a summer thermal low over the southwest of the subcontinent caused by enhanced solar radiation, which is responsible for triggering thunderstorm formation over the eastern parts of the continent. The subcontinent is generally dominated by a relatively high OLR during the austral winter months, a state that is consistent with the notions of researchers such as Tyson and Preston-Whyte (2000), who noted the predominantly dry austral winter season that is characterised by a high-pressure belt that suppresses convection, thus preventing the occurrence of rainfall over much of the subcontinent, except in the south and southwestern tips, which occasionally receive rainfall from passing cold fronts.

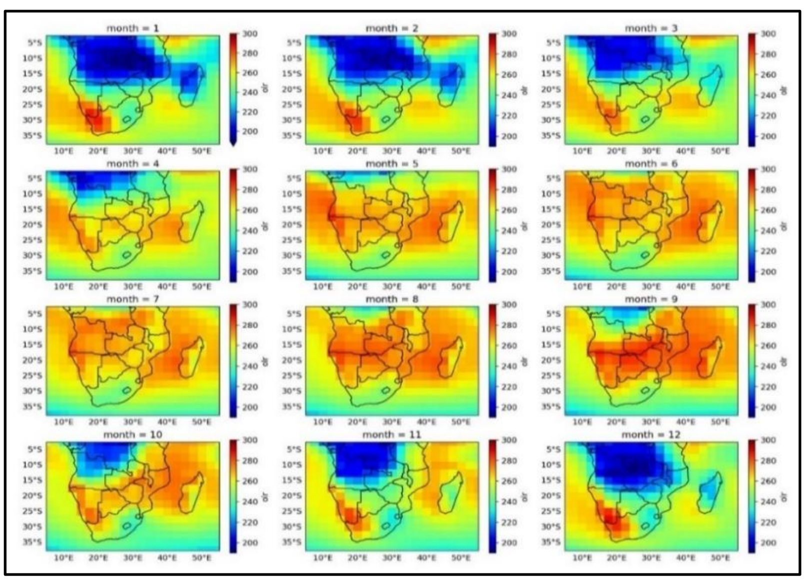

Figure 4-2 Monthly averaged variability of the OLR distribution over the subcontinent, computed using data from 1979 to 2018. Month = 1 is the first month of the calendar year (January) and month = 12 is the last month of the calendar year (December).

The seasonal variability of OLR over the subcontinent is displayed in Figure 4-3 where DJF refers to the December-January-February period, which is the austral summer season, MAM refers to the March-April-May period, which is the austral autumn season, JJA refers to the June-July-August period, which is the austral winter season, and SON refers to the September-October-November period, which is the austral spring season. In agreement with Figure 4-2, this figure demonstrates that the most prevalent low OLR region occurs during the DJF period, which is regarded as the austral summer season and is in agreement with findings from studies such as Mulenga (1998), Blamely and Reason (2013) and Crétat et al. (2018), who reported that the austral summer season occurs during the DJF months over southern Africa and is primarily driven by the southward migration of the ITCZ.

In contrast, the JJA period, which is regarded as the austral winter season over the subcontinent, is largely dominated by a vast region of high OLR that covers much of the subcontinent, particularly the region between approximately 5°S and 25°S. The low OLR abundance over the subcontinent during the austral summer is consistent with the southward migration of the ITCZ, which is a major driver of the moisture and energy that is required for the genesis of TTTs over the subcontinent, as well as its retreat during the austral winter months (Berry and Reeder, 2014; Dedekind et al., 2016; Zagar et al., 2011).

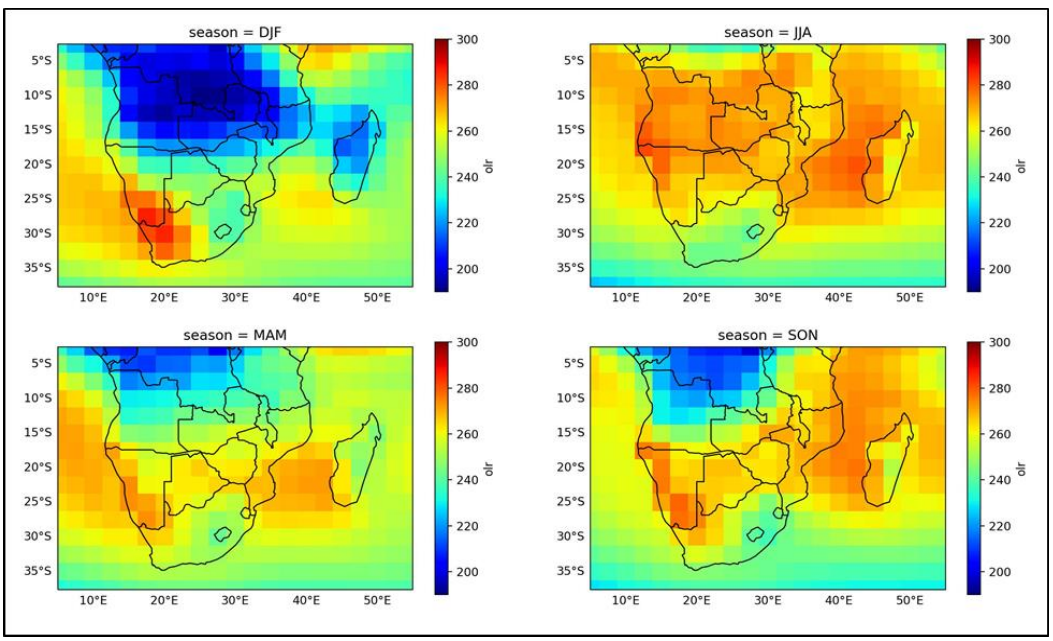

Figure 4-3 Seasonally averaged OLR variability over the subcontinent computed using data from 1979 to 2018.

A plot that demonstrates the monthly variation of OLR along the latitudinal axis over the subcontinent was prepared and presented in Figure 4-4 on page 72. In this figure, the y-axis indicates latitudes from 0 to -40°, while the x-axis indicates months from January on the far left to December on the far right. The figure confirms the presence of a relatively low OLR region over the subcontinent – as shown at the top left and top right sides of the figure.

This region dominates from the equator southward until approximately 20°S during the austral rainfall season months. The latter is consistent with the results in figures 4-2 and 4-3 (the DJF season), which demonstrated similar results.

Moreover, Figure 4-4 on the next page shows an anomalous extension of relatively high OLR, which is evident at the bottom left side of the figure, between 27°S and 31°S. This relatively high OLR region is also evident in Figures 4-2 and 4-3 (the DJF season) over similar latitudes where the southwestern tip of southern Africa is located.

The widespread high OLR region located in the middle of Figure 4-4 represents the prevalently dry atmospheric conditions that dominate the subcontinent during the austral dry season, and is in line with results shown in Figures 4-2 and 4-3 (the JJA season).

Additionally, the dry season period is characterised by two regions of excessively high OLR located between approximately 10°S and 24°S during the period from May to June, as well as the period from July to September. The low OLR region that is visible at the bottom of the figure during the austral winter months indicates the prevalence of moisture from cold fronts that sweep the south of the subcontinent and is in line with literature reports such as those of Tyson and Preston-Whyte (2000).

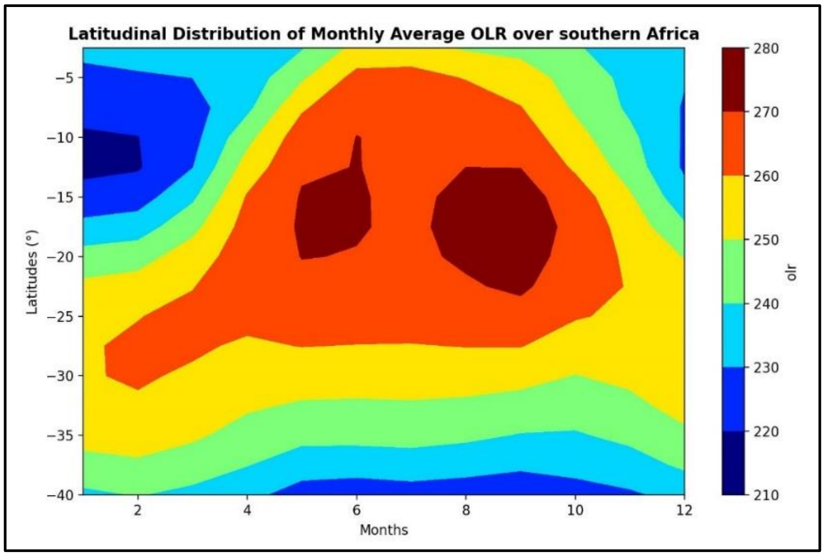

Figure 4-4 Latitudinal distribution of monthly averaged OLR over southern Africa during the period 1979–2018.

A method that is employed to visualise the structure and location of TTTs through the computation of daily anomalies, as demonstrated by various studies (Fauchereau et al., 2009; Macron et al., 2014; Ratna et al., 2013), was adopted. Daily OLR anomaly composites were computed for the rainfall season months (i.e. September to February) over southern Africa. Results are presented in Figure 4-5 which is on page 74 and confirm the northwest-southeast OLR dual structure, particularly for September to November, which show one distinct dual OLR structure.

These months display an OLR dipole structure that predominantly consists of a positive OLR located north of the band, while a negative OLR is located over the south. This structure is consistent with that identified by previous researchers (e.g. Hart et al., 2010; Ratna et al., 2013) and demonstrates the occurrence of a classical structure and position of TTTs over the subcontinent during the first half of the rainy season, otherwise known as austral spring.

Results presented in Figure 4-5 further suggest that the OLR dual structure that is exhibited during the TTT cases that occur in the first half of the rainfall season (SON) tends to perfectly match that previously described by various authors (e.g. Harrison, 1984; Hart et al., 2010; Ratna et al., 2013; Todd and Washington, 1999) as an elongated band of dual OLR anomalies that extend from the northwest to the southeast, with positive OLR anomalies towards the north and negative OLR anomalies towards the south. The difference between a positive and a negative OLR is also the largest during this period. However, this structure tends to be disrupted during the last half of the rainy season (DJF), thus weakening the dual structure. During the latter half of the rainy season, a negative OLR tends to be engulfed by a positive OLR from all directions, with a strong positive OLR developing south of the negative OLR from December.

This state progresses to divide the negative part of the main OLR dual structure into two limbs: the original northwest-southeast limb and the new limb that lies in a predominantly east-west direction. What is even more interesting is that the new limb tends to be stronger than the original limb, particularly during January and February, suggesting the halt of the northwest-southeast distribution of moisture, energy and momentum.

Lastly, results presented in Figure 4-5 show a gradual migration of the OLR dipole structure from the southwestern tip of the subcontinent towards the northeast. The dual structure is initially located at its southernmost position during September when the negative OLR stretches from the west coast of Angola to the east coasts of Mozambique and South Africa, and continues beyond the 45°E longitude.

During this month, both the positive and negative OLR anomalies cover the largest areas individually, and are characterised by the large difference in their polarity. They also maintain a clear and straight-line dual structure during this month. Although the northwest-southeast structure is still clearly visible and straight during October and November, the position of the dual system shifts north-eastward, while the spatial extent of each part of the dual system shrinks and its polarity weakens as a result of the reduced difference between the positive OLR and the negative OLR. However, the most evident changes begin during December when the negative OLR is restricted over land and the positive OLR stretches beyond Madagascar into the SWIO beyond 60°E. The negative OLR continues its onshore retreat as the secondary limb develops and replaces the positive OLR and attains its new position over Mozambique, through the Mozambique Channel and beyond Madagascar during January and February.

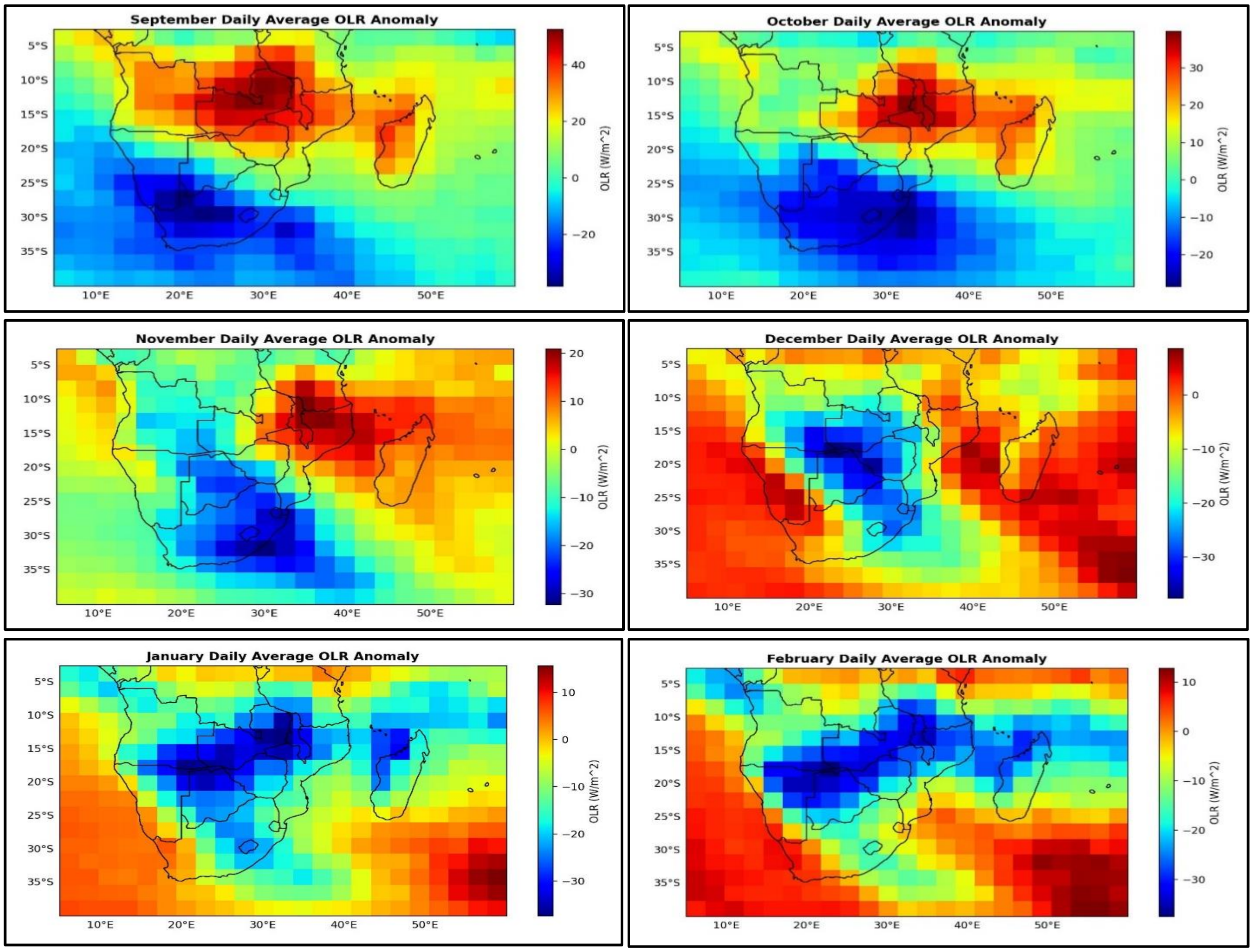

Figure 4-5 Daily averaged OLR anomalies computed for the austral rainfall months (September to February) over southern Africa using a daily OLR data record spanning 1979 to 2018.

4.2.3 Location of TTT centres during the austral rainfall months

Figure 4-6 on page 75 depicts centres of TTTs over the subcontinent that were recorded between 1979 and 2018. For the purpose of this study, only TTT centres located at 40° longitude and lower were investigated. What stands out is the distribution of these TTT centres over South Africa and the country's adjacent oceans, with a significantly high number of them found over the SWIO compared to the southeast Atlantic Ocean (SEAO).

In addition, the analysis of these TTT centres, which are represented as dots of varying colours, shows the northward migration of TTT centres as the austral summer season progresses. Centres of TTTs that occurred during the September-October period (yellow dots) are located relatively further south compared to those that occur later. TTT centres that occur during the November-December period (red dots) are shifted slightly north compared to the earlier-occurring TTT centres, while those that occur later, during the January-February period (green dots), tend to be distributed further north compared to those that precede them. The spatial distribution of TTT centres further indicates that they are relatively denser centres, and their spatial extent has a slightly higher density over land compared to over the surrounding oceans.

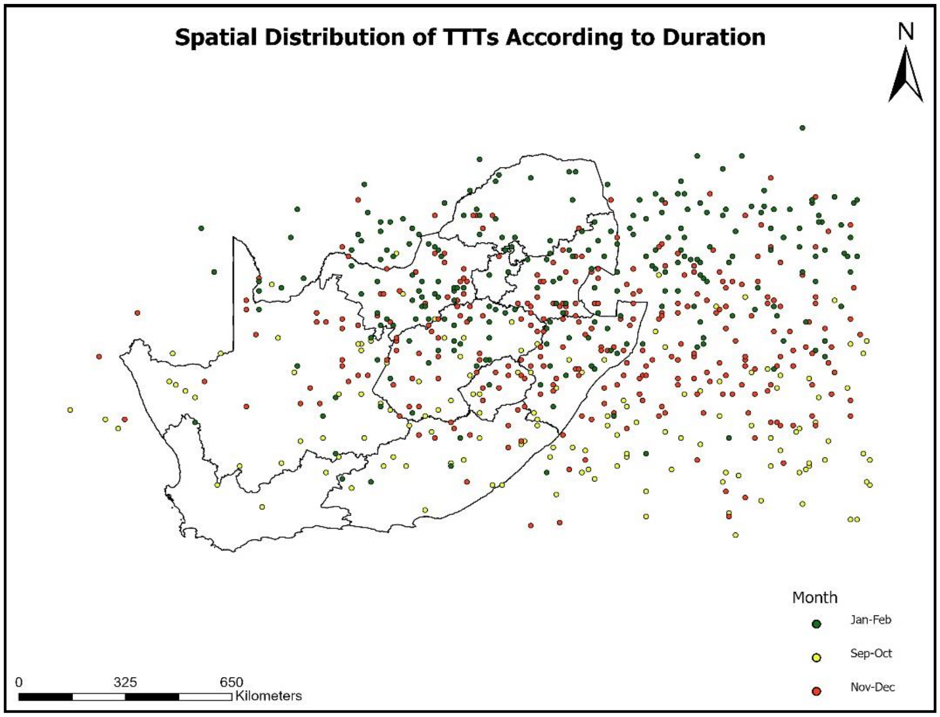

Figure 4-6 The spatial distribution of the TTT centres that occurred during the 1979–2018 rainfall seasons. These were grouped into two-month periods that divided the austral rainfall season into three phases and were plotted over South Africa and the adjacent oceans.

4.2.4 Spatial distribution of TTTs based on duration

The distribution of TTT centres with regard to their duration was also explored and is presented in Figure 4-7 on page 76. Data from the investigated TTTs suggests that a single TTT can last from one to ten days. TTTs were therefore divided into three categories: one to three days, four to six days, and seven to ten days. TTTs that lasted one to three days were the most abundant, and were followed by those that lasted between four and six days, while those that lasted between seven and ten days were the least abundant. There is no notable pattern in the spatial distribution of TTT centres, particularly for the first two categories. A characteristic of TTT centres that is evident in the last category is that they were only located over land.

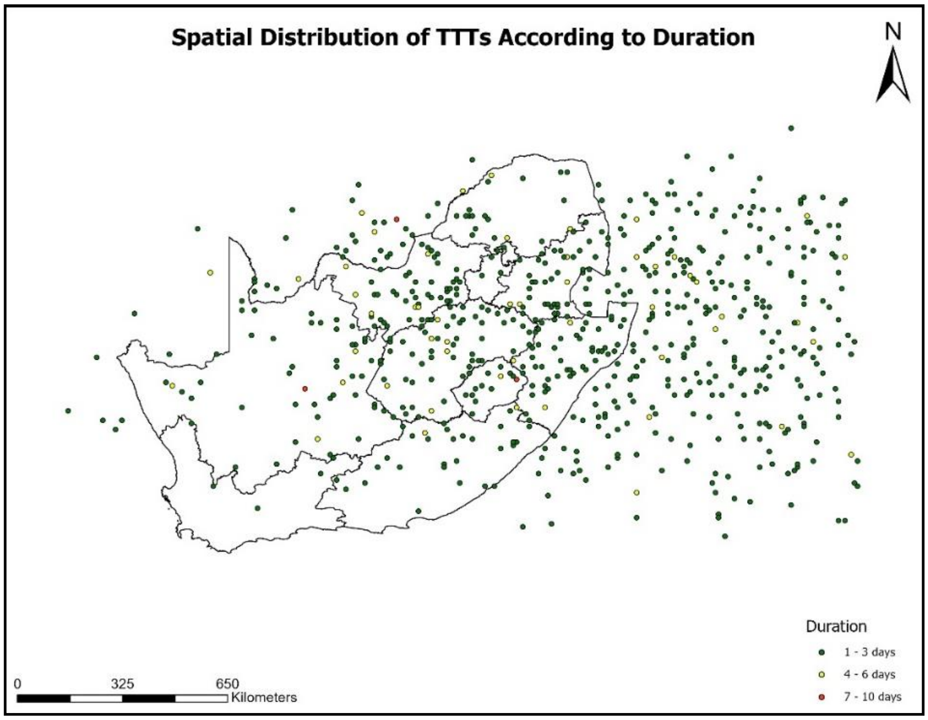

Figure 4-7 The spatial distribution of TTT centres that occurred during the 1979–2018 rainfall seasons. These were grouped according to their duration, which was divided into three categories, based on the lowest and highest number of days the recorded TTTs lasted, and plotted over South Africa and the adjacent oceans.

The graph in Figure 4-8 (top) on page 77 displays a combination of annual plots for TTT cases and rainfall. These were plotted together with the aim of assessing the relationship in the patterns of their occurrence between 1979 and 2018. Variability patterns of annual total TTT cases, annual average district rainfall for the study area's rainfall districts, as well as the annual average rainfall from South African rainfall districts, were more or less similar, suggesting that a strong interdependency exists between these variables.

These results also highlight the importance of TTTs to the contribution of rainfall in South Africa. The graph in Figure 4-8 (bottom) on page 77 shows the total number of TTT cases recorded per month plotted, and the monthly average district rainfall in the study area and in South Africa, which all follow a similar pattern. These results validate the strong interdependency between the two variables at monthly time intervals. Figure 4-8 (bottom) further suggests that the occurrence of TTT cases on a monthly basis, as well as the monthly rainfall patterns, peak from November to January – with the average district rainfall exceeding 80 mm and the highest total number of TTT cases per month peaking beyond 140 cases during December. This is South Africa's austral summer.

The direct relationship between rainfall and TTTs displayed in Figure 4-8 (top and bottom) is consistent with findings from research previously conducted by various researchers (Crétat et al., 2010; Harrison, 1984; Hart et al., 2010), who highlighted significantly positive relationships between rainfall and TTTs in southern Africa.

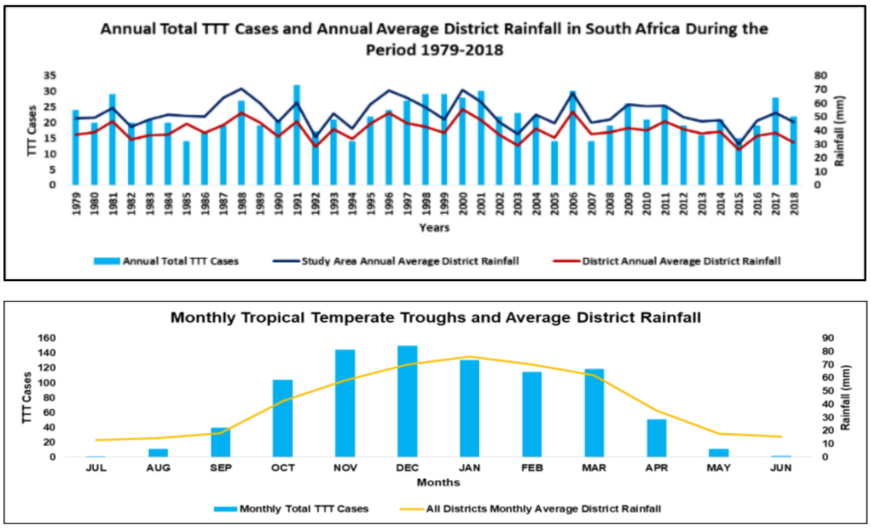

Figure 4-8 Top: Annual total TTT cases plotted as a bar graph with annual average rainfall computed for the study area's rainfall districts (dark blue) and South Africa (brown) during the period 1979 to 2018. Bottom: Total number of TTT cases per month and monthly average rainfall recorded in South Africa during the period 1979–2018.

4.2.5 Frequency distribution of TTT cases with duration and longitude over southern Africa

The frequency of TTT cases was also investigated based on their duration as shown on page 78 in Figure 4-9. According to this figure, TTT cases used in this study lasted between one and ten days. Furthermore, the most frequent TTT cases are those that lasted only one day – reaching above 450 cases. The frequency decreases the longer they last. The noted frequency reduction with increase in duration drops sharply from TTT cases that lasted two days, while the decreases are approximately uniform as the duration continues to increase. The longitudinal distribution of the frequency of TTT centres over the subcontinent was also examined and plotted in Figure 4-9 on page 78. It has been mentioned before that TTT centres that occurred between 0° and 40° were considered in this study because it is these centres that were close enough to the study area to be considered relevant.

According to Figure 4-9, the frequency of TTT centres increases from west to east, with the most TTT centres occurring between 31°E and 34°E, and reaching close to the 150 centres recorded during the study period. TTT centres are notable from as far west as 12°W. It is worth noting that no TTT centres were observed at the 19°E and 29°E longitudes.

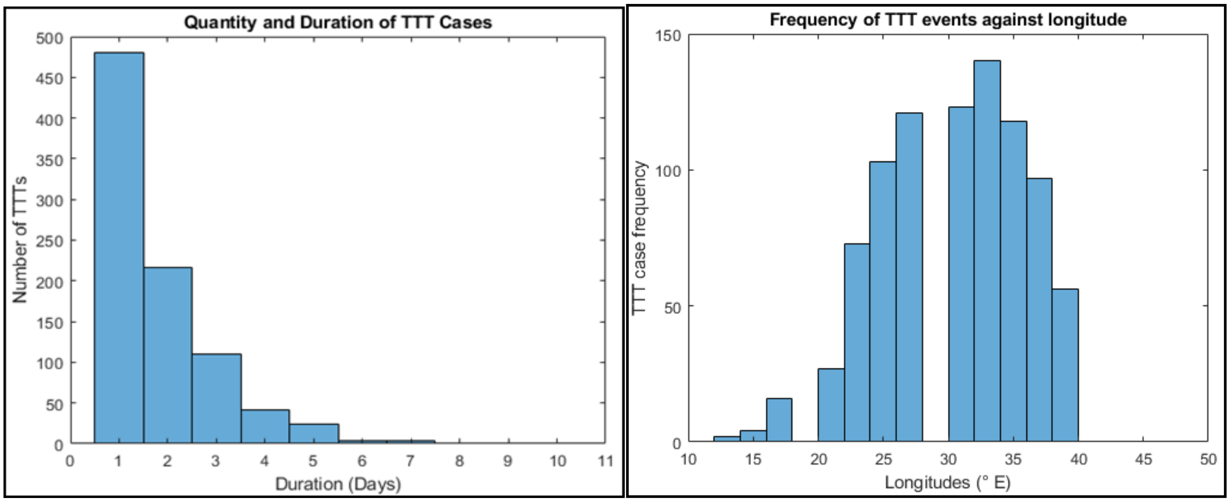

Figure 4-9 The frequency distribution of the total number of TTT cases against their duration in days, as well as their longitudinal distribution over southern Africa, during the 1979–2018 period.

4.2.6 TTT cases and ENSO temporal variability

Numerous researchers reported that ENSO phases have an effect on the behaviour of TTTs occurring over southern Africa during the austral summer (Goddard et al., 2001; MacKellar et al., 2014; Mulenga, 1998; Odiyo et al., 2019; Tfwala et al., 2018). For the purpose of this study, the relationship between seasonal ENSO variability and the variability in the total number of TTT cases observed during the 1979–2018 period over southern Africa was examined and presented in Figure 4-10 on page 79. Three seasons that were characterised by a strong El Niño (red ovals) and a strong La Niña (dark blue ovals) were identified and marked on the Oceanic Niño Index (ONI) (top) image. TTT cases that correspond to the identified ONI seasons (both El Niño and La Niña) were also marked using the same method. As a result, seasons that were selected for the El Niño phase were 1991/92, 1997/98 and 2015/16, and those that were selected for the La Niña phase were 1999/00, 2007/08 and 2010/11. These were published by Null (2023) on the Golden Gate Weather Services website. Results from Figure 4-10 suggest that the proposed relationship between ENSO and TTT activity is not consistent, particularly for the El Niño season, where, out of the three seasons that were selected, only one (1991/92) showed a decrease in the total number of TTT cases. This is not consistent with reports from various researchers that TTT activity is reduced by El Niño phases (Fauchereau et al., 2009; Hart et al., 2018; Manhique et al., 2011; Ratna et al., 2012). In fact, Hart et al. (2018) stated that the El Niño season is said to reduce the likelihood of TTTs with one to two fewer events per month during November and February. On the other hand, out of the three La Niña seasons that were selected, two (2007/08 and 2010/11) indicated an increase in the total number of TTT cases, thereby confirming literature findings that La Niña phases improve TTT activity (Hart et al., 2010; Pohl et al., 2009; Ratna et al., 2012). Moreover, Hart et al. (2018) pointed out that, during the La Niña season, cloud bands are increased by approximately 150 to 200%.

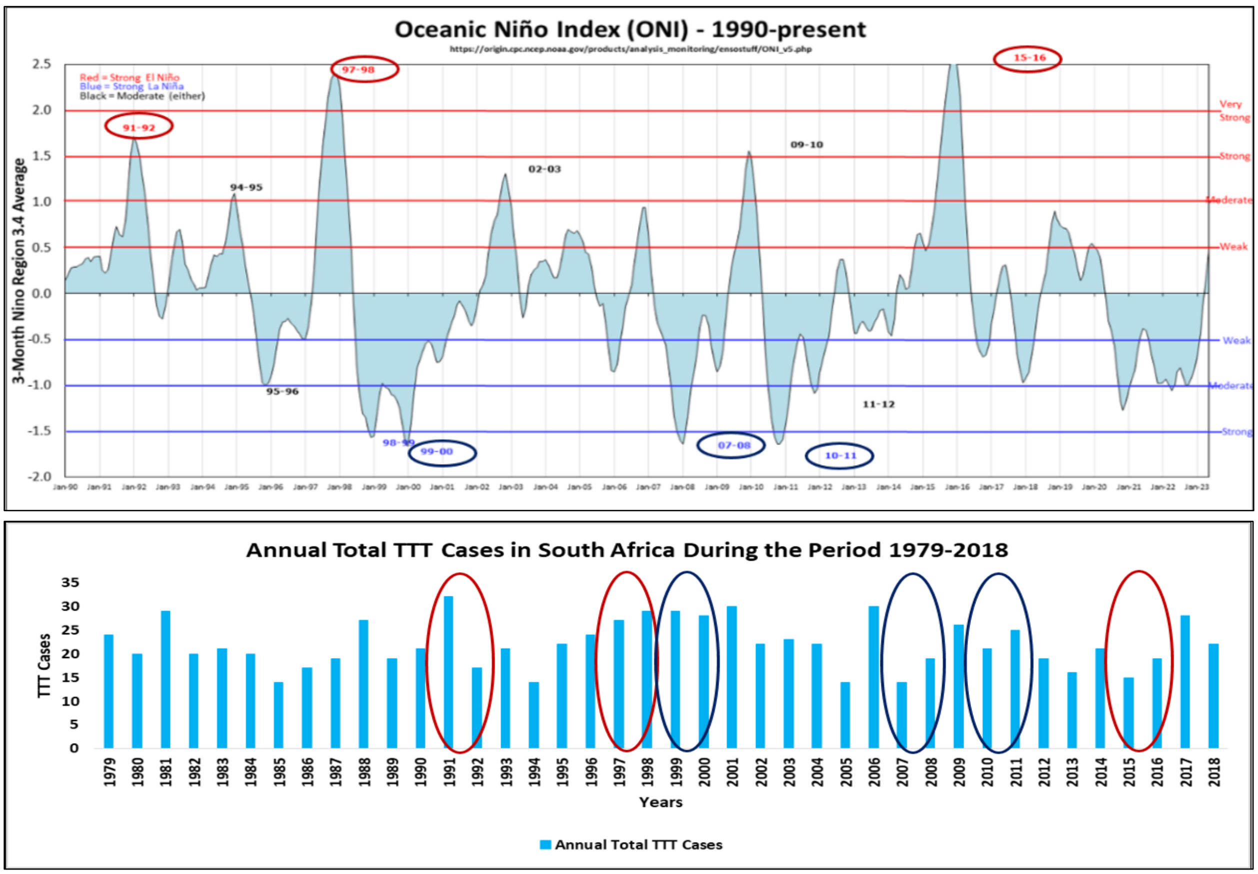

Figure 4-10 Top image: Oceanic Niño Index (ONI) obtained from a three-month Nino region 3.4 average. Bottom image: Total number of TTT cases per annum. Blue circles in both the top and bottom images are seasons when there were strong El Niño (red ovals) or La Niña (dark blue ovals) phases. Source: Null, 2023.

4.3 THE CLIMATOLOGY OF TROPICAL TEMPERATE TROUGHS AND RAINFALL ONSETS IN THE MAIZE TRIANGLE DURING THE 1979/80–2017/18 PERIOD

This section investigates the association of TTTs and rainfall onsets that occurs in the maize yield. It therefore addresses the second objective of this study. It commences by analysing the percentage distribution of total rainfall seasons based on whether they had rainfall onsets, and whether the identified rainfall onsets were associated with TTTs, as well as the total percentage of seasonal data that is missing.

The section further analyses the spatial distribution of rainfall districts that had percentages of rainfall seasons with rainfall onsets associated with TTTs, rainfall districts that had percentages of rainfall seasons with rainfall onsets that were not associated with TTTs, rainfall districts with percentages of rainfall seasons with missing seasonal data, and rainfall districts with percentages of rainfall seasons without rainfall onsets. This section intends to provide a basic understanding of the behaviour of various types of rainfall onsets that were identified in the study area during the period 1979/80–2017/18.

4.3.1 Percentage distribution of rainfall seasons with TTT-associated rainfall onsets and non-TTT rainfall onsets in the Maize Triangle during the 1979/80–2017/18 period

The association of TTTs with rainfall onsets during rainfall seasons over the Maize Triangle was analysed and results are shown in Figure 4-11 which is displayed on page 81. This was done by displaying the percentage of austral rainfall seasons with rainfall onsets that occurred in association with TTTs, the percentage of rainfall seasons with rainfall onsets that occurred without TTTs, the percentage of rainfall seasons without rainfall onsets, as well as the percentage of rainfall seasons with missing data that resulted in the inability of the study to compute rainfall onsets. The analysis was conducted for all rainfall districts that constitute the Maize Triangle for the period 1979/80–2017/18.

The analysis found that approximately 90% of the analysed rainfall seasons had rainfall onsets associated with TTTs. Less than 5% of the rainfall seasons had rainfall onsets that were not associated with TTTs, while just over 5% of the rainfall seasons did not have any rainfall onsets. The prevalence of rainfall seasons with TTT-associated rainfall onsets in the Maize Triangle suggests that there is a strong relationship between TTTs and rainfall onsets in the study area. These findings therefore require that the understanding and prediction of TTTs be advanced, an avenue that can lead to improved rainfall onset predictions in southern Africa.

It is worth noting that much of the literature emphasises the important role TTTs play in the general occurrence of rainfall during the austral rainfall period over the subcontinent. This study did not find much information on the direct influence TTTs have on rainfall onsets that occur over the subcontinent during austral spring, in particular. For example, Harrison (1984) proposed that TTTs produce approximately 60% of the austral summer and autumn rainfall over the subcontinent, while Crimp et al. (1997) indicated that TTTs are responsible for up to 39% of the austral rainfall over the subcontinent, and Hart et al. (2010) suggested that TTTs contribute between 30% and 50% of the austral summer rainfall over the subcontinent.

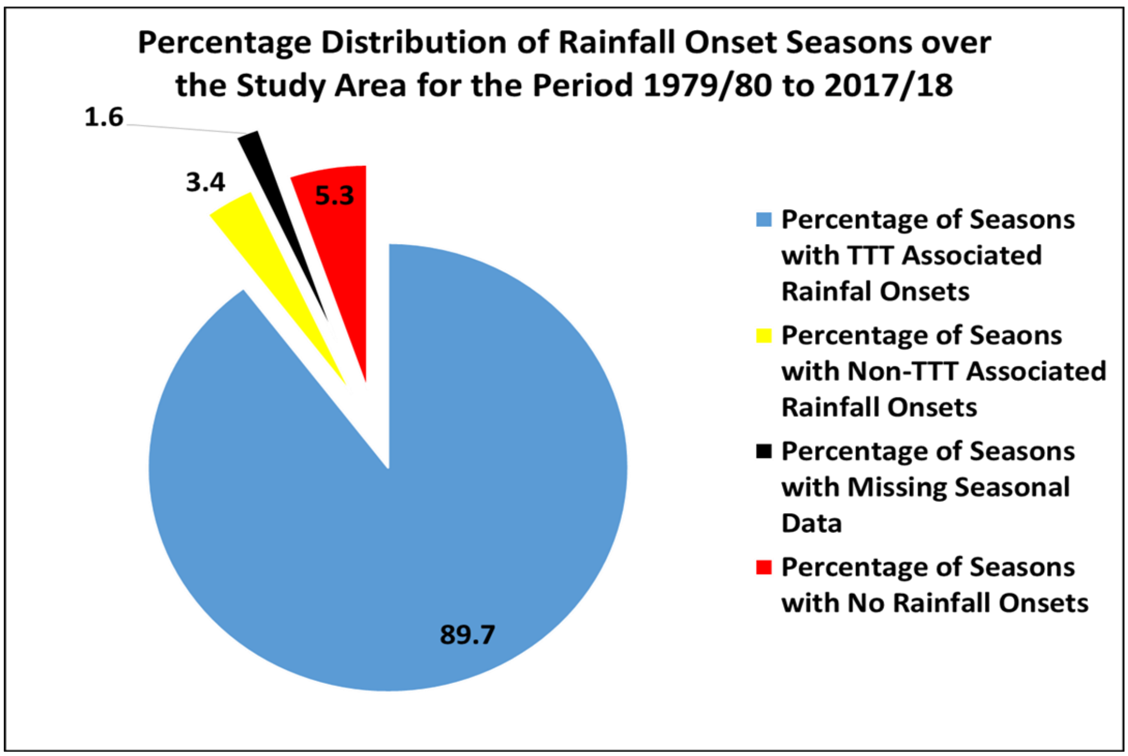

Figure 4-11 Percentage distribution of rainfall seasons with TTT-associated rainfall onsets, non-TTT-associated rainfall onsets, absent rainfall onsets and missing seasonal data in the Maize Triangle during the study period.

The study further made use of rainfall districts that constitute the study area, as well as the corresponding district rainfall data for the period 1979/80–2017/18 to investigate the spatial distribution of austral rainfall seasons with rainfall onsets that occurred with TTTs, seasons with rainfall onsets that occurred without TTTs, seasons with no seasonal data and seasons without rainfall onsets.

Displayed in Figure 4-12 on page 84, results from this investigation suggested that each rainfall district that forms the study area had at least 74% of its total rainfall seasons characterised by TTT-associated rainfall onsets, with the majority of rainfall districts located in the eastern half of the study area revealing high percentages (up to 97%) of such seasons (Figure 4-12 top left). These results highlight the importance of the presence of TTTs for the occurrence of rainfall onsets in the study area, and are in agreement with the notion of the general literature that TTTs play an important role in rainfall contribution over southern Africa during the austral rainfall season (e.g. Crétat et al., 2010; Crimp et al., 1997; Harrison, 1984), which proposes that the rainfall contributed by TTTs is up to 60% during the austral rainfall season over the subcontinent. Furthermore, Washington and Todd (1999) found that, between November and March, the leading mode of daily rainfall variability over the subcontinent is a TTT, while Landman et al. (2015) added that most of the rainfall that occurs during the austral summer period is from TTTs.

Figure 4-12 (top right) shows the spatial distribution of rainfall districts with rainfall seasons with rainfall onsets not associated with TTTs, and proposes that relatively high percentages of rainfall seasons with non-TTT-associated rainfall onsets were scattered approximately throughout the study area, although percentages of rainfall districts located at the extreme northeast and southwest of the study area showed relatively higher percentages (up to 8%), while many of the centrally located rainfall districts displayed relatively low percentages (up to 5%) during the investigated period.

These results suggest that the likelihood of having other rainfall-producing systems – other than TTTs – during rainfall seasons when rainfall onsets occur without TTTs is relatively higher in districts that are further northeast and southwest of the study area. The eastward location of high concentration of TTT-associated and non-TTT associated rainfall onsets presents a confusion which requires the investigation of the other rainfall producing system(s) that are responsible for rainfall that is not associated with TTTs. Nonetheless, the low range of percentages shown in Figure 4-12 (top right) confirms the relatively low percentage of total rainfall seasons with rainfall onsets not associated with TTTs in the study area during the period 1979/80–2017/18.

The bottom left section of Figure 4-12 was included with the intention of providing general insights into the completeness of the seasonal data set, which can be attributed to the missing daily district rainfall data that was used to compute rainfall onsets. Therefore, the bottom left section of Figure 4-12 shows that seasonal rainfall data was complete for more than 50% of the districts that were used in the analysis, while only 38% of the districts had up to 2.6% of missing seasonal rainfall data and only 6% of the districts had up to 14.7% of missing seasonal rainfall data.

The spatial distribution of districts with a complete seasonal data record was generally scattered across the study area, confirming the authenticity of findings from other sections of Figure 4-12 from a data completeness perspective. Finally, the percentage distribution of rainfall districts that had rainfall seasons with no rainfall onsets occurring in the study area during the investigated period is presented in Figure 4-12 (bottom right). According to this section, the rainfall seasons of the majority (more than 43%) of rainfall districts in the study area occurred with rainfall onsets, while 37.5% of rainfall districts had up to 8.3% of their rainfall seasons occurring without any rainfall onsets, and 18.8% of rainfall districts had up to 25.8% of their rainfall seasons occurring without any rainfall onsets during the study period.

The majority of rainfall districts that had some of their rainfall seasons occurring without rainfall onsets was located over much of the southwest of the study area. The westward location of the majority of rainfall districts with some rainfall seasons that lacked rainfall onsets may suggest an occasional failure of rainfall occurring from rainfall-producing systems (e.g. TTTs) to reach the far west of the study area during some rainfall seasons. No distinction was made between TTT-associated and non-TTT-associated rainfall onsets in Figure 4-12 (bottom right).

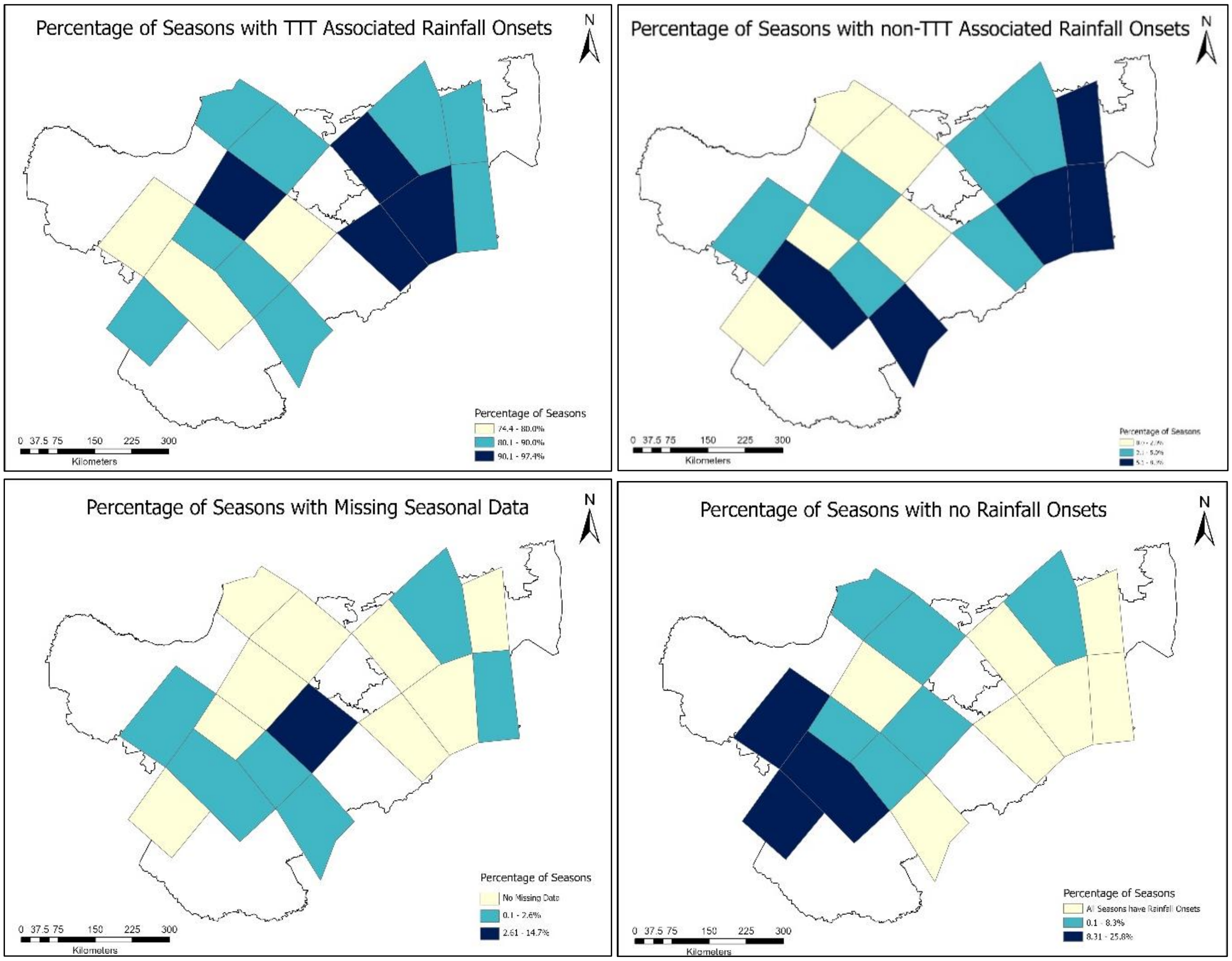

Figure 4-12 The spatial distribution of rainfall districts with percentages of various types of the identified seasons in the Maize Triangle during the 1979/80–2017/18 period.

4.3.2 Monthly distribution of TTT cases associated with rainfall onsets and those not associated with rainfall onsets in the study area over the period 1979/80–2017/18

Using TTT cases recorded over southern Africa from 1979/80 to 2017/18, a temporal distribution of two types of TTT cases that were distinguished by whether they were associated with rainfall onsets or not during their time of occurrence was explored and the subsequent results plotted in Figure 4-13 on page 85. This figure vividly displays the relatively high number of TTT cases associated with rainfall onsets particularly from September to February. These findings further suggest that even though non-TTT associated rainfall is concentrated towards the east of the Maize Triangle (see Figure 4-12 top right), TTT cases that occurred together with rainfall onsets outnumbered their counterparts by far, making TTT-associated rainfall onsets worth further investigations in order to improve rainfall onsets and lower the risk of farmers missing planting seasons. Although these results generally fall within those that are published in the literature from a seasonal peak point of view (e.g. Cretat et al., 2010; Harangozo and Harrison, 1983; Harrison, 1984; Thepenier and Cruette, 1981; Vigaud et al., 2012; Washington and Todd, 1999), no information was found that distinguishes between TTT cases that occurred together with rainfall onsets and those that did not.

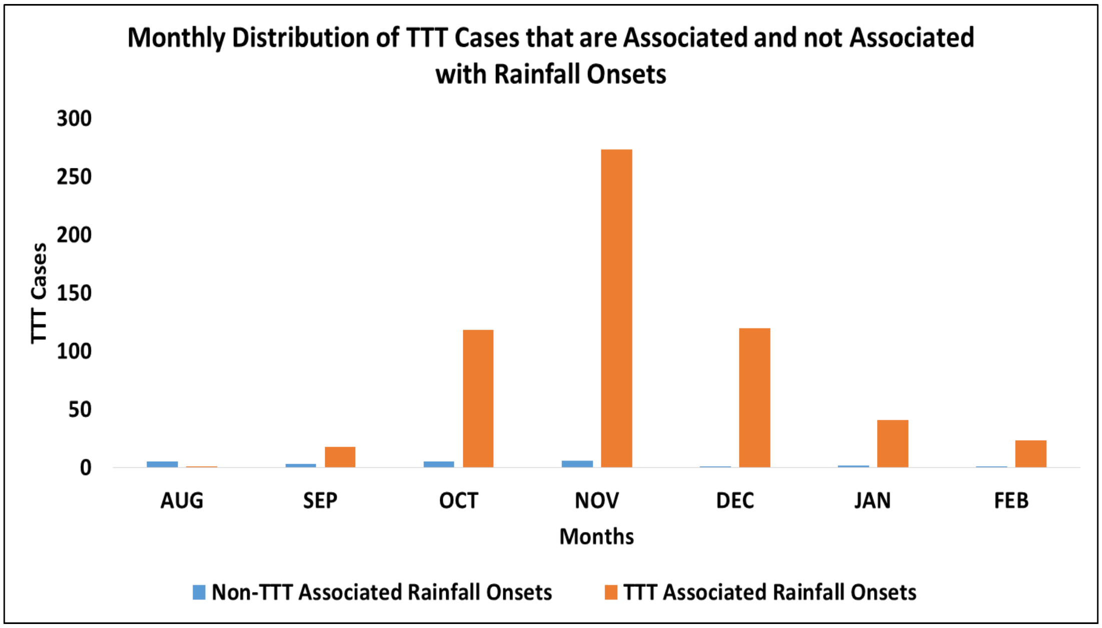

Figure 4-13 Monthly distribution of TTT cases associated and not associated with rainfall onsets in the Maize Triangle from 1979/80 to 2017/18.

4.3.3 Temporal and spatial distribution of the average, minimum and maximum number of TTTs associated with rainfall onsets in rainfall districts that constitute the study area during the seasonal rainfall period from 1979/80 to 2017/18

Results of the average, minimum and maximum number of TTT cases associated with rainfall onsets during the rainfall seasons 1979/80 to 2017/18 over the study area are displayed in Figure 4-14 (top) which is located on page 87, and those of the average, minimum and maximum number of TTT cases associated with rainfall onsets for the rainfall districts that constitute the study area are displayed in Figure 4-14 (bottom) on page 87. A remarkably large seasonal variation is exhibited by the average, minimum and maximum number of TTT-associated rainfall onsets, with the highest maximum number of TTTs reaching well beyond 10 in just one season (1982/83), as shown in Figure 4-14 (top).

While the observed high variability is consistent with the strong seasonality of the southern African climate that has been historically mentioned by various researchers, such as Tyson and Preston-Whyte (2000), the highest number of TTT-associated rainfall onsets is not in agreement with the strong El Niño phase that grabbed international attention (e.g. Hansen, 1990; Whilhite and Glantz, 1985) and was recently investigated by Mbokodo et al. (2023) since it induced a strong drought during the same season. There is a possibility that the recorded number of TTTs was shifted far east of the subcontinent, resulting in summer droughts in South Africa.

According to Usman and Reason (2004), the eastward shift in TTTs leads to summers over the subcontinent that are drier than normal. This can be attributed to an eastward shift of the large-scale atmospheric circulation from its typical location of surface convergence in the tropics that controls TTT development (Harangozo and Harrison, 1983; Harrison, 1986; Jury, 1993,1996; Tyson, 1986), thus reducing in convection over the subcontinent and enhancing it over the SWIO and east of Madagascar. The large variation in the climatology of TTTs that were associated with rainfall onsets make it difficult to identify meaningful pattern over the long term, thus somewhat inhibiting the ability to predicts the behavior of rainfall onsets as a result of the associated TTT activity.

The spatial variability of average, minimum and maximum TTT-associated rainfall onsets in rainfall districts that form part of the study area shown in Figure 4-14 (bottom) displayed no rigorous patterns, suggesting that there is not much variability in the frequency of TTT-associated rainfall onsets over the study area. This may be attributed to the large spatial area that is typically covered by a TTT, usually between 4 000 to 16 000 km long and 400 to 1 200 km wide according to various authors (e.g. Harangozo and Harrison, 1983; Thepenier and Cruette, 1981), meaning that rainfall districts in the study area cover an area that is small enough for all of them to be affected by a single TTT at any given time.

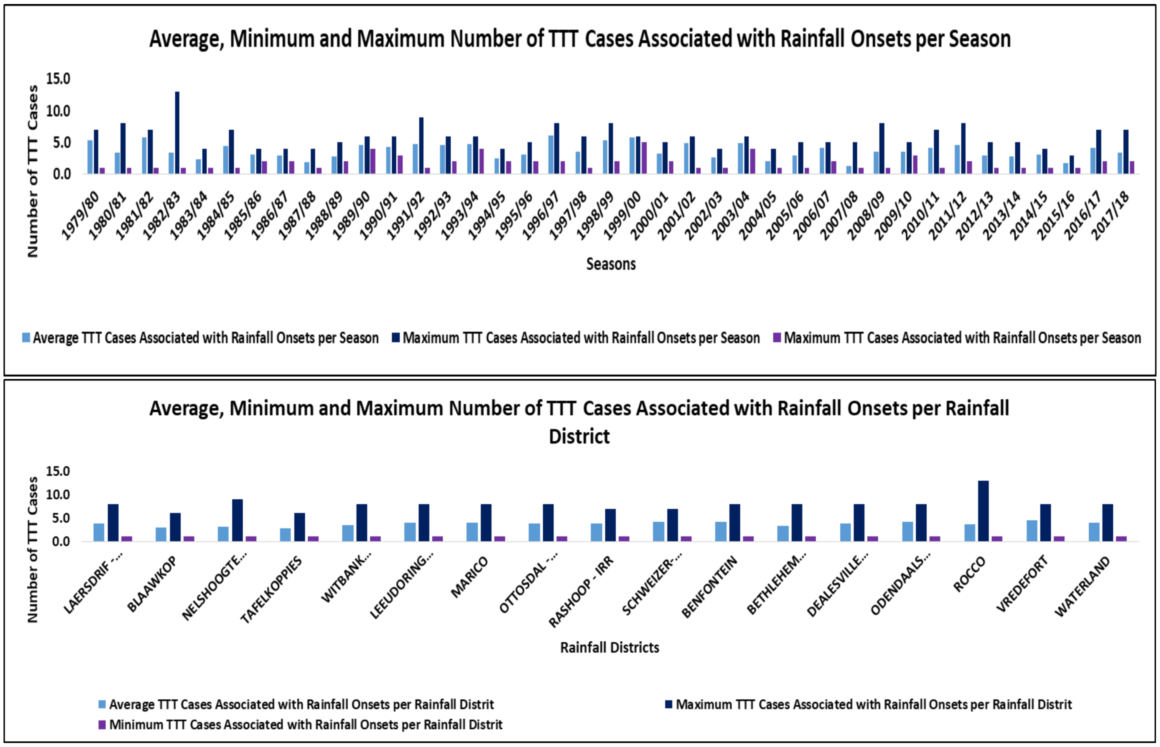

Figure 4-14 Average, minimum and maximum number of TTTs associated with rainfall onsets during the rainfall seasons 1979/80 to 2017/18 (top), and average, minimum and maximum number of TTTs associated with rainfall onsets for rainfall districts that constitute the study area (bottom).

4.3.4 Analysis of the temporal and spatial distribution of TTT-associated rainfall onsets that occurred in rainfall districts that constitute the study area

The austral rainfall season is typically described as starting from September and lasting until February. However, TTTs can occur beyond this period, with some differences in the literature regarding the months in which they start and the months in which they end. For the purpose of this study, the first notable appearance of TTTs during the study period was considered to be during August, and the last month in which they are significant was considered to be May.

However, because the focus of this study is on the interactions between TTTs and rainfall onsets, the period of TTT activity that was used was from August to February, a period considered favourable for maize planting in various maize-producing regions of South Africa (Agricultural Economics Today, 2019). Therefore, this study regarded early-occurring TTT-associated rainfall onsets as those that occurred between August and November, and late-occurring TTT-associated rainfall onsets as those that occurred between December and February.

In light of the above, Figure 4-15 presents findings of the location of rainfall districts that are typically characterised by TTTs that occur early in the austral rainfall season. This indicates that the earliest rainfall onsets (August and September) occur in rainfall districts located far east of the Maize Triangle (left frame), while TTT-associated rainfall onsets categorised as late were scattered approximately throughout the study area (right frame). It is worth noting that rainfall districts that exhibit TTT-associated rainfall onsets that occurred during much of the austral summer season are widely distributed over much of the Maize Triangle, confirming literature findings that TTT activity is at its peak during this period that generally coincides with maize planting dates in the Maize Triangle (Akinnuoye-Adelabu and Modi, 2017).

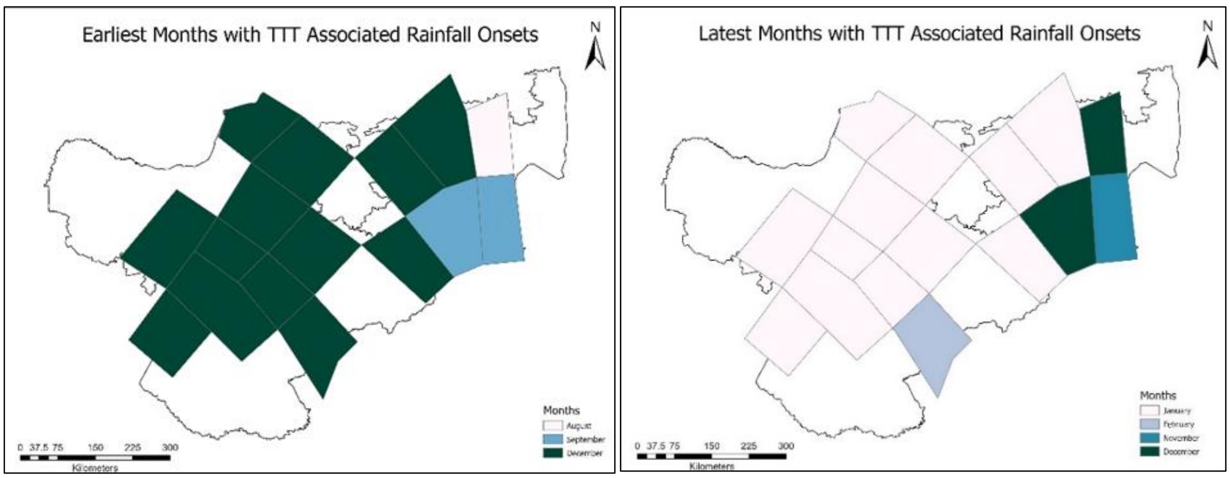

Figure 4-15 Spatial distribution of TTT-associated rainfall onsets that occur during the early (left) and late (right) months of the austral rainfall season in rainfall districts that make up the study area.

4.3.5 Temporal and spatial rainfall onset amounts over the study area during the period 1979/80–2017/18

Trends in seasonal average, as well as minimum and maximum rainfall amounts from TTT-associated rainfall onsets, are displayed in Figure 4-16 (top) on page 89 with the spatial variation of average, minimum and maximum rainfall amounts from TTT-associated rainfall onsets per rainfall district in the study area plotted in Figure 4-16 (bottom) on page 89. The seasonal average rainfall onset (top) and district average rainfall onset (bottom) are similar because similar data sets were used. Their inclusion was to set a guide to help identify values that are prominent. Approximately seven seasons (1985/86, 1986/87, 1996/97, 1999/00, 2006/07, 2007/08, 2010/11) stood out as seasons with the highest maximum rainfall amounts received during the occurrence of TTT-associated rainfall onsets in the Maize Triangle from the summer of 1979/80 to that of 2017/18. One of the interesting findings from Figure 4-16 (top) is that some of the seasons that were identified as having the highest maximum rainfall amounts (i.e. 1999/00, 2007/08 and 2010/11) coincided with the La Niña seasons that were published by Null (2023) on the Golden Gate Weather Services website. On the other hand, El Niño seasons published by the same source corresponded with some of the normal rainfall onset amounts (i.e. 1982/83, 1987/88, 1991/92, 1997/98 and 2015/16). While these results agree somewhat to literature findings regarding the tendency of La Niña seasons to enhance rainfall during the austral rainfall seasons over the subcontinent, indications that El Niño seasons tend to significantly reduce rainfall amounts are not evident in this analysis.

According to Figure 4-16 (bottom), rainfall onset amounts received per rainfall district in the study area during the 1979/8 to 2018/18 seasonal rainfall period showed that three rainfall districts (i.e. Laersdrift-Police ARS, Leeudoringstad-SKL and Benfontein) received a relatively higher maximum rainfall from rainfall onsets associated with TTTs compared to the rest of the rainfall districts. There is no deducible spatial pattern between these three rainfall districts.

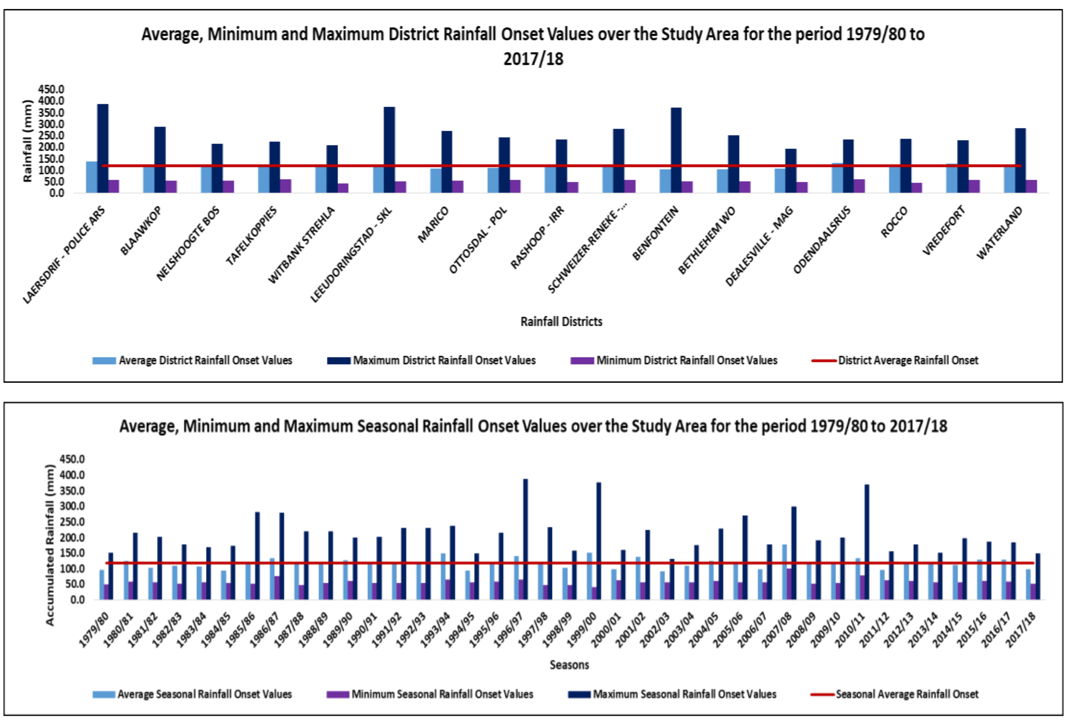

Figure 4-16 Average, minimum and maximum seasonal rainfall onset amounts (top) and average, minimum and maximum district rainfall onset rainfall amounts (bottom) associated with TTTs.

4.3.6 Comparison of rainfall contribution between TTTs associated with rainfall onsets and TTTs not associated with rainfall onsets in the study area during the period 1979/80–2017/18

A comparison was made between rainfall recorded from TTTs that occurred together with rainfall onsets, and rainfall recorded from TTTs that did not occur together with rainfall onsets per season (1979/80 to 2017/18), as well as per rainfall district (the study covers rainfall districts). The results are presented in Figure 4-17 on page 91. Figure 4-17 (top) on page 91 indicates that the majority (69.2%) of seasons received 100% of their rainfall from TTTs that occurred together with rainfall onsets. Only a few (30.8%) seasons consisted of both TTTs that occurred with rainfall onsets and those that did not.

Approximately five seasons (1981/82, 1994/95, 2006/07, 2015/16 and 2016/17) stood out as consisting of significant mixes of both types of TTTs. It is interesting to note that, out of the identified seasons with mixed TTT types, none coincided with the La Niña seasons, while only one season (2015/16) coincided with the El Niño season, as published by Null (2023).

Furthermore, Figure 4-17 (top) suggests that a significantly high percentage of rainfall was received from TTTs that occurred together with rainfall onsets during the seasons that there was activity from both types of TTTs, thus confirming that TTTs associated with rainfall onsets produced rainfall that is relatively higher when compared to their counterparts. These findings also validate the positive relationship between TTTs and rainfall onsets in southern Africa as stated in the literature previously cited in this body of work.

On the other hand, Figure 4-17 (bottom) presents results from a comparison between rainfall recorded from TTTs that occurred together with rainfall onsets and TTTs that occurred without TTTs from a spatial perspective using the rainfall districts of the study area and rainfall data for the study period. Results show that the majority (70.6%) of rainfall districts had at least one rainfall season that consisted of TTTs associated with rainfall onsets, while only a few (29.4%) consisted of TTTs that occurred without the co-occurrence of rainfall onsets. It is worth noting that about half of the rainfall districts that consisted of both types of TTTs were located further east of the study area.

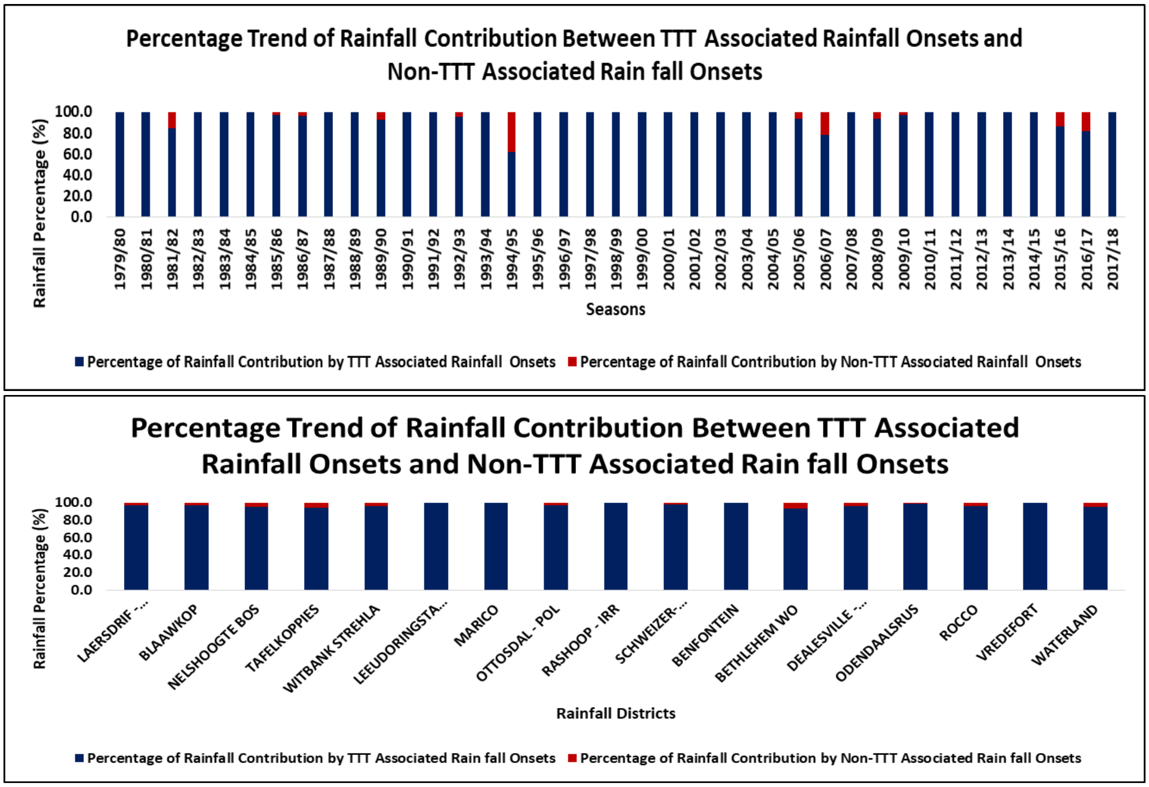

Figure 4-17 Temporal and spatial percentage comparison between rainfall recorded during the occurrence of TTT-associated rainfall onsets and non-TTT associated rainfall onsets.

This section was concluded by examining and presenting the spatial variability of rainfall percentages that were contributed by TTT-associated rainfall onsets as displayed in Figure 4-18 (left) on page 92, as well as the spatial variability of rainfall percentages that were contributed by non-TTT associated rainfall onsets which is depicted in Figure 4-18 (right) on page 92. The said analyses were performed using rainfall districts that constitute the study area and rainfall data that spans the period 1979/18 to 2017/18.

Figure 4-18 (left) illustrates that the majority of rainfall districts received more than 90% of their rainfall from TTT-associated rainfall onsets, from which those that had 100% rainfall from TTT-associated rainfall onsets were located centrally towards the west of the study area, while rainfall districts with mixed rainfall onsets were largely restricted to the northeast. This is in agreement with literature that was cited in previous sections of this work. These findings can be useful in understanding and predicting rainfall onsets at rainfall district level, thus amplifying the spatial accuracy of rainfall onset predictions.

It can be seen in Figure 4-18 (right) that the highest rainfall percentage exhibited by rainfall districts is only 6%, suggesting that non-TTT-associated rainfall onsets rarely occur without their counterparts in the study area. Moreover, rainfall districts that demonstrated relatively higher percentages of rainfall received from non-TTT-associated rainfall onsets were concentrated towards the northeast of the study area.

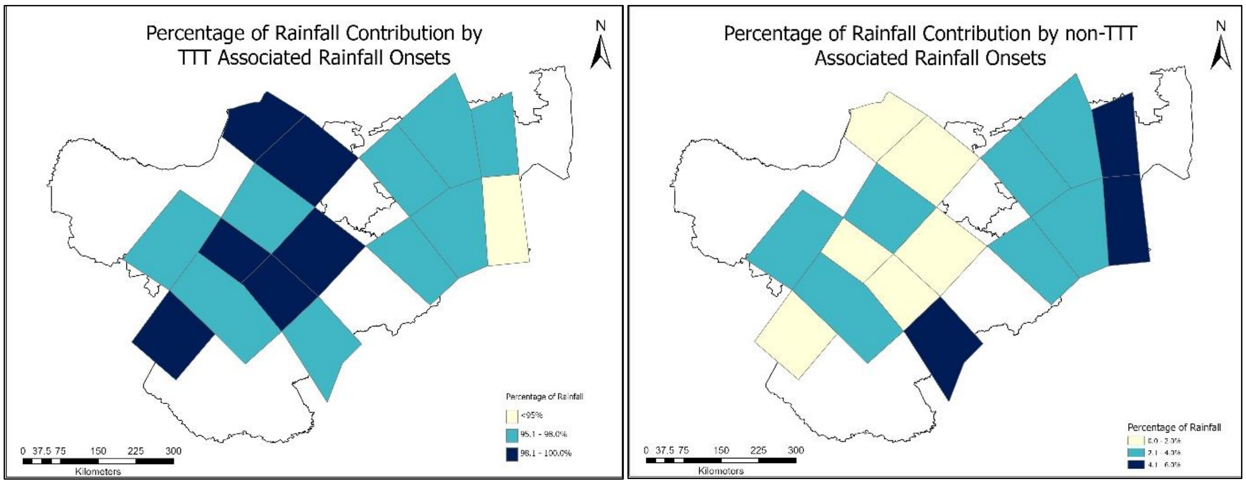

Figure 4-18 Spatial distribution of rainfall percentages contributed by TTT-associated rainfall onsets (left), as well as rainfall percentages contributed by non-TTT-associated rainfall onsets (right), using rainfall districts that constitute the study area and rainfall data spanning the study period 1979/80–2017/18.

CHAPTER 5: TTT-ASSOCIATED RAINFALL ONSETS AND MAIZE YIELD

5.1 INTRODUCTION

This chapter investigates the influence of TTT-associated rainfall onsets on subsequent maize yield. Maize yield data sets were used as an indicator to assess the influence of TTT-associated rainfall onsets on maize cultivation in the Maize Triangle. The maize yield data record that was used was from 1980/81 to 2017/18 since maize yield data for 1979/80 was not available.

This chapter starts off by exploring seasonal trends in maize yield, as well as the rainfall district variability of maize yields in the Maize Triangle. Trends and slopes between rainfall amounts recorded during the occurrence of TTT-associated rainfall onsets, the number of TTTs associated with rainfall onsets, as well as maize yields obtained from TTT-associated rainfall onsets are investigated, and Z-scores are regressed.

Further regressions are conducted between rainfall amounts from TTT-associated rainfall onsets against subsequent maize yields, and rainfall amounts recorded after TTT-associated rainfall onsets against subsequent maize yields. Further analyses are conducted of rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates.

5.1.1 The spatial and temporal distribution of maize yields between 1980/81 and 2017/18

Seasonal variations of average, minimum and maximum maize yield from 1980/81 to 2017/18 are plotted in Figure 5-1 (top) on page 94, while average, minimum and maximum variations of maize yield per district are plotted for rainfall districts that constitute the study area in Figure 5-1 (bottom) on the same page. A considerably increasing trend in average and maximum maize yield per season is notable in Figure 5-1 (top). This growth in maize yield is consistent with the general literature that also reports significant growth in maize production in South Africa (e.g. Sihlobo, 2019).

The literature notes a number of factors that contribute to this increasing trend, including soil properties and farm management practices (Ayoade, 2004; Munodowafa, 2011; Sihlobo, 2019), although rainfall is a crucial factor, particularly for rain-fed maize cultivation (Igwenagu, 2015; Tilahun, 2006). Maize yields per rainfall district are shown in Figure 5-1 (bottom) with the average maize yield at approximately 3 t/ha and no notable trend apart from the Nelshoogte and Tafelkoppies rainfall district that displays relatively higher maximum yields. Both these findings make it difficult to identify a particular relationship between any rainfall characteristic such as rainfall onsets and the maize yield and thus makes the yield an indicator that is challenging to use to test the activity of, in this case, rainfall onsets.

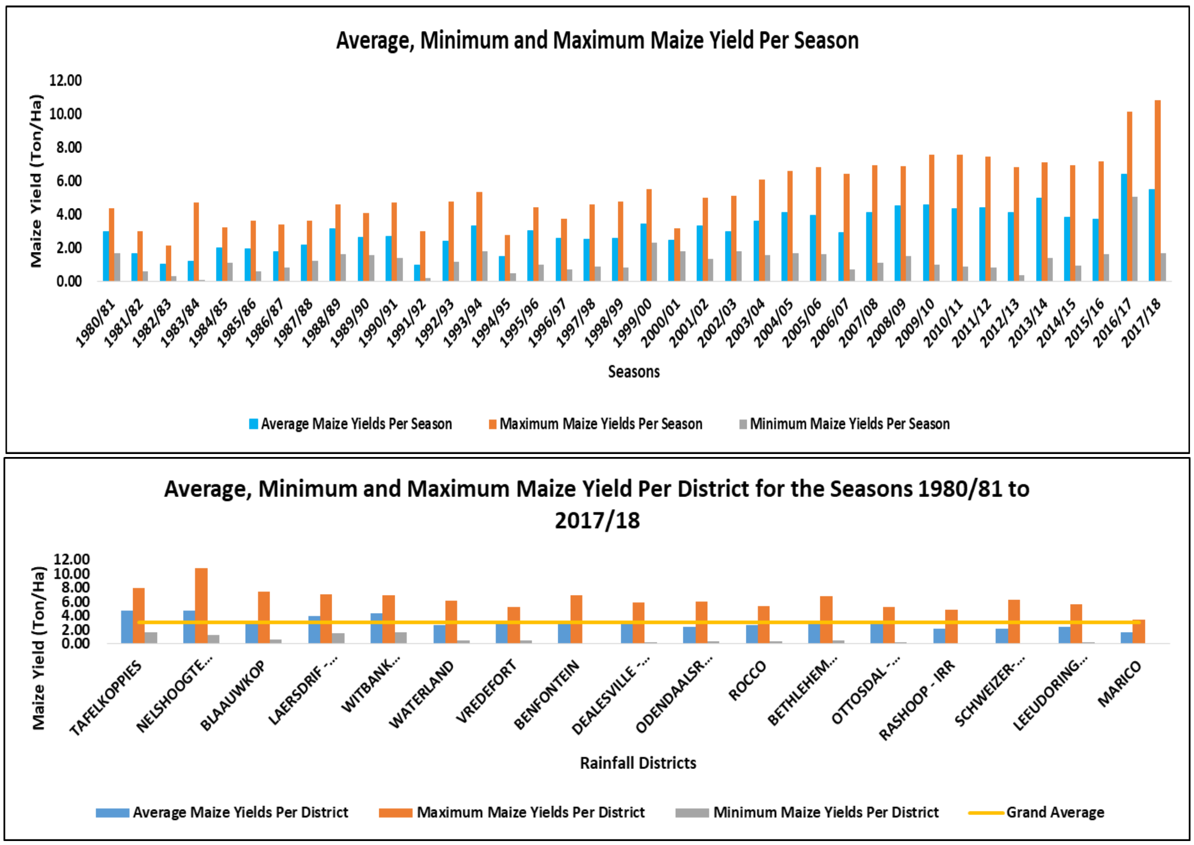

Figure 5-1 Average, minimum and maximum maize yield per season (top), as well as average, minimum and maximum maize yield per rainfall district (bottom) during the period 1980/81–2017/18 over the study area.

Figure 5-2 demonstrates the spatial variation in maize yield calculated for each rainfall district that is part of the study area. All average (top left), highest (top right) and lowest (bottom left) seasonal maize yield variables from 1980/81 to 2017/18 are the highest in the rainfall districts located at the north-easternmost edge of the study area, Nelshoogte, Tafelkoppies, Blaawukop, Laersdrift – Police ARS and Louws Creek – Pol. These rainfall districts are all in Mpumalanga. This spatial tendency follows the moisture distribution of the Maize Triangle, the spatial moisture distribution of which increases from west to east, just like South Africa and the subcontinent as a whole (Berry and Reeder, 2014; Dedekind et al., 2016; Zagar et al., 2011). These findings are consistent with those identified in Figure 4-12, suggesting that there is notable spatial consistency between rainfall onsets and maize yield, however, challenges such as whether this consistency is between TTT-associated rainfall onsets and maize yields, or between non-TTT associated rainfall onsets and maize yields, or between other rainfall producing systems and maize yields, or non-meteorological factors such as pesticides and manure etc., is still outstanding.

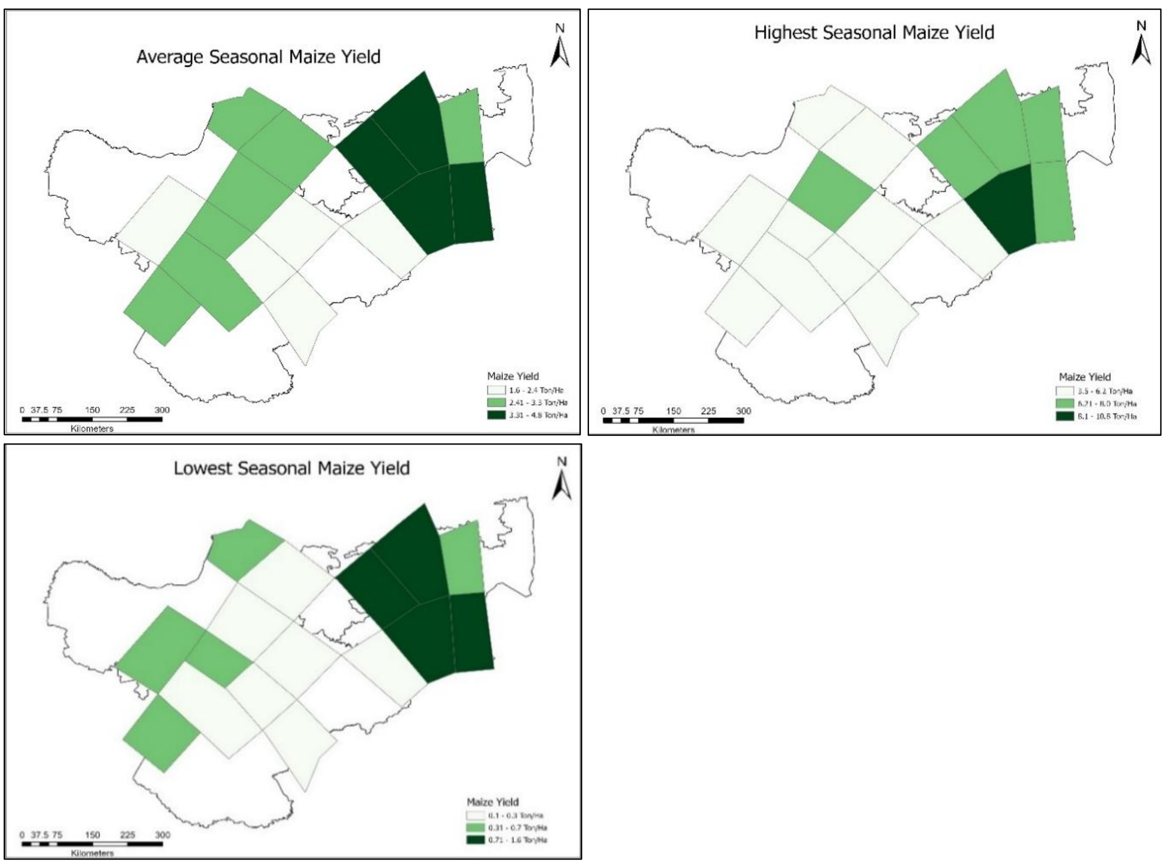

Figure 5-2 The spatial distribution of average, highest and lowest maize yield in rainfall districts that constitute the study area, calculated over the period 1980/81–2017/18.

5.1.2 Comparisons between seasonal TTT-associated rainfall onsets and subsequent maize yield for the study area rainfall districts

A heat map that displays the variability of TTT-associated rainfall onsets and subsequent maize yields in the Maize Triangle between 1980/81 and 2017/18 is plotted in Figure 5-3, and indicates that the majority of TTT-associated rainfall onsets that have occurred in the Maize Triangle were mainly during September and October, with the majority occurring in October. The figure also shows a gradually increasing trend in maize yields – from approximately 2 t/ha to approximately 7 t/ha – that is notable during both months. However, the increase in this maize yield tends to begin earlier in September, compared to October, signifying the association of earlier-occurring rainfall onsets with improved maize yields since it is easier for farmers to predict planting dates when rainfall onsets occur early and enable farmers to maximise their yields (Akinnuoye-Adelabu and Modi, 2017; Ati et al., 2002; Moeletsi et al., 2011). However, the general increasing displayed is not consistent with the climatological TTT activity which exhibited no discernable climatological trend.

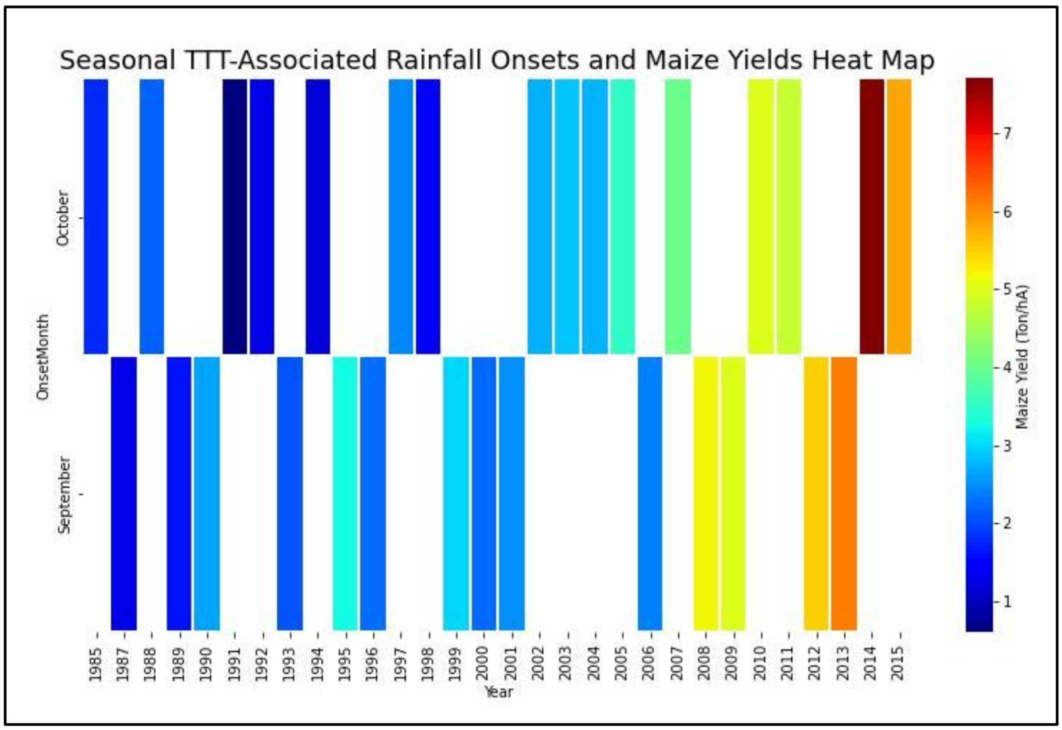

Figure 5-3 A heat map of TTT-associated rainfall onsets and subsequent maize yields in the Maize Triangle between 1980/81 and 2017/18.

Trends of average rainfall amounts obtained from TTT-associated rainfall onsets, average TTT cases associated with rainfall onsets, as well as average maize yields per season from 1980/81 to 2017/18 are presented in Figure 5-4. The plotted trends tend to consist of periods in which there is no visible consistency between the variables, as well as periods in which there is notable consistency. Periods of notable consistency were encircled with dotted lines, as shown in Figure 5-4. The periods during which this consistency was observed are approximately 1992/93–1995/96, 1998/99–2003/04 and 2016/17–2017/18. These periods do not coincide with any identified ENSO phase, making it difficult to formulate a theory on the cause of their consistency.

The link between TTTs and the ENSO is therefore unclear from Figure 5-4, since the majority of seasons do not show any consistency in the variability of these systems. A contributing factor for this ambiguity may be the relatively small size of the study area, which may hinder the ENSO effects from a size difference perspective. Another factor may be the fact that rainfall onsets were computed over a period of 30 days, which is only a fraction of the total austral summer season. This would possibly make it difficult to identify the impacts of a system that affects the entire austral summer season.

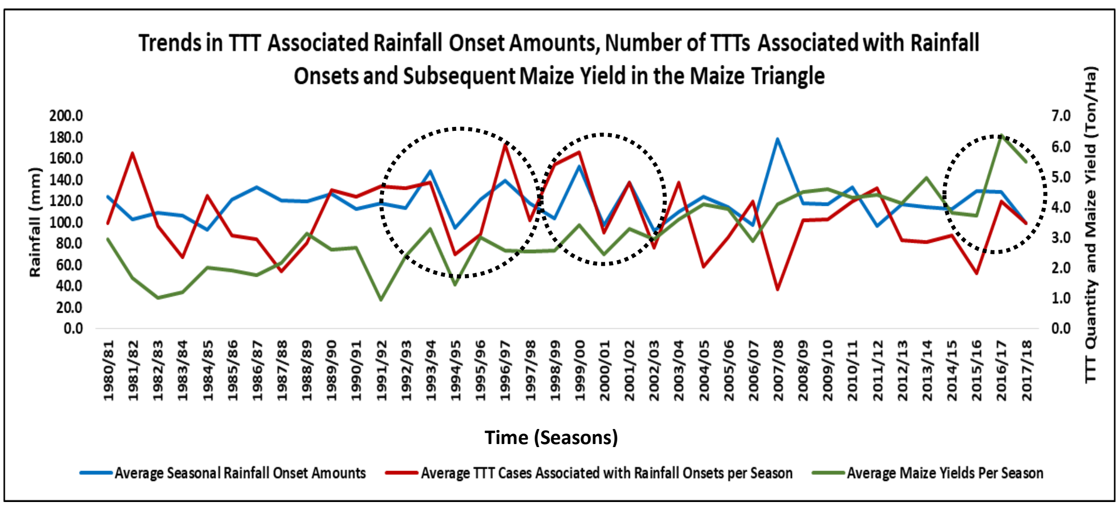

Figure 5-4 Trends of average TTT-associated rainfall onsets (rain amounts), average number of associated TTTs and average maize yields during seasons from 1980/81 to 2017/18 in the Maize Triangle. Dotted circles indicate periods of consistency between the three variables.

5.1.3 Trend and slope analyses for TTT-associated rainfall onsets (rainfall amounts), number of TTTs associated with rainfall onsets and subsequent maize yields for rainfall districts of the Maize Triangle during the period 1980/81–2017/18

Rainfall amounts that were recorded during the occurrence of the identified TTT-associated rainfall onsets were used to compute seasonal trends and slopes for rainfall districts that make up the study area, using the period 1980/81–2017/18, and plotted in Figure 5-5 on page 99.

These rainfall amounts were accumulated over a period of 30 consecutive days, which had accumulated a total minimum rainfall of 45 mm, following a method proposed by Tadross et al. (2005), which is used to identify rainfall onsets in southern Africa. Seasonal trends and slopes were computed using the MAKESENS model developed by Salmi et al. (2002). They were also used to determine the presence and nature of trends, as well as the slopes of the identified trends of input data. Sen's estimate is a line plotted by the MAKESENS model to indicate seasonal trends and slopes of the investigated data sets.

According to results displayed in Figure 5-5, the study found that approximately 65% of the rainfall districts that make up the Maize Triangle exhibited slightly increasing trends characterised by gentle slopes in the amount of rainfall produced by seasonal TTT-associated rainfall onsets. Furthermore, no spatial patterns of rainfall districts were identified that showed either increasing or decreasing trends in these rainfall amounts. The latter results therefore suggest that there has not been a significant increase in the amount of rainfall received from TTT-associated rainfall onsets over the investigated period.

However, there is strong seasonal variation in these rainfall amounts, which is shown in the results. This variation is in line with the nature of the southern African climate, which is said to be widely variable and strongly seasonal (Tyson and Preston-Whyte, 2000) and is driven by a number of climate drivers such as ENSO (MacKellar et al., 2014; Mulenga, 1998; Shikwambana et al., 2023), which, in turn, has an effect on the development of rainfall onsets over the subcontinent (Moeletsi et al., 2011).

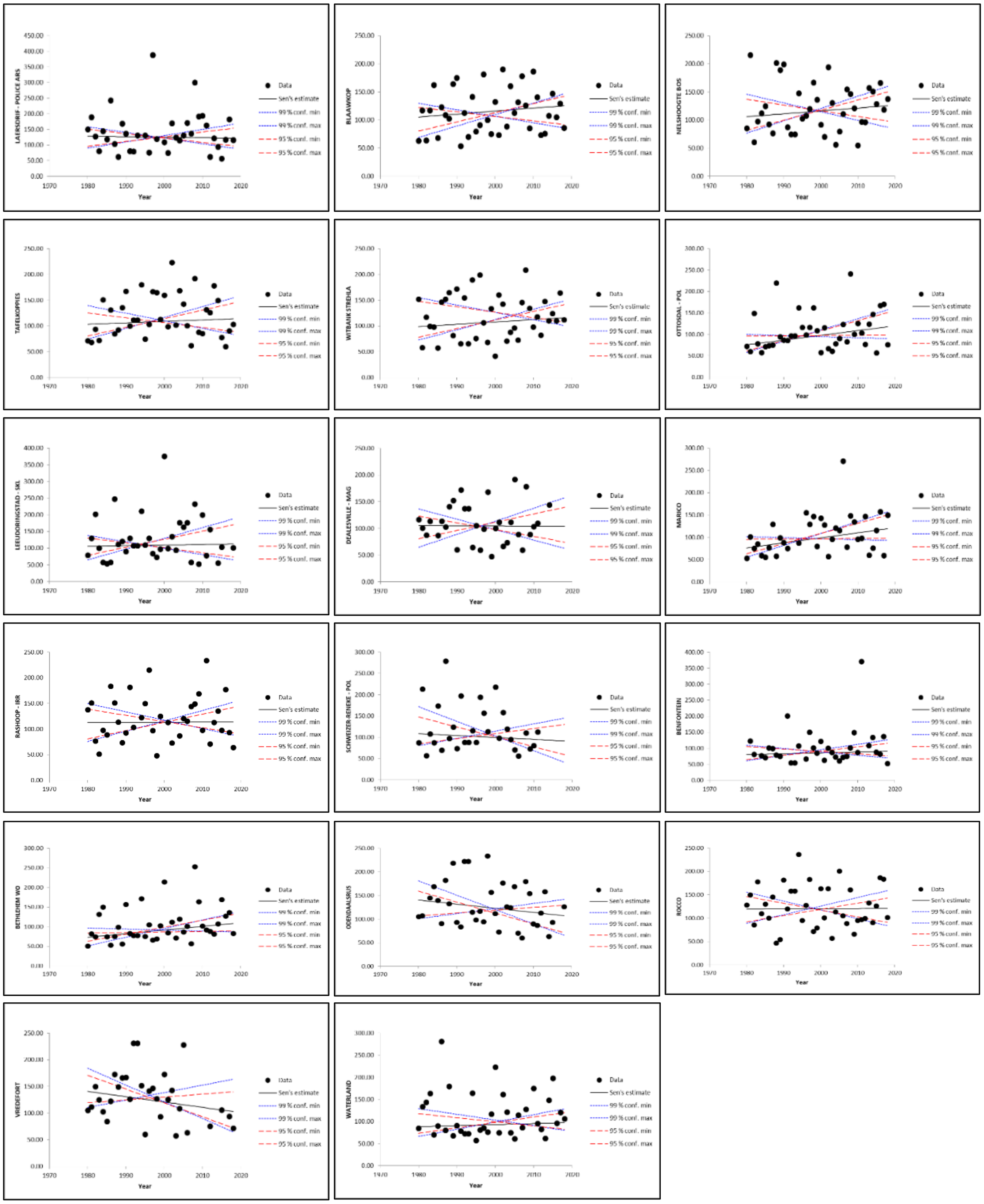

Figure 5-5 Trend and slope analyses for TTT-associated rainfall onsets (rainfall amounts) in the rainfall districts that constitute the Maize Triangle during the period 1980/81–2017/18.

A similar method to that used to obtain the results presented in Figure 5-5 was used to analyse trends and slopes of the number of TTTs associated with each rainfall onset during the 30-day period of the rainfall onset's development during the 1980/18–2017/18 period in the Maize Triangle. These are TTTs that occurred during the 30-day period of the rainfall onset development. The results of this analysis are presented in Figure 5-6 on page 101 and show a mixture of rainfall districts with the majority (approximately 70%) of rainfall districts exhibiting slightly decreasing trends in the number of TTTs associated with rainfall onsets, while approximately 20% of the districts show no trends. Although the percentage of rainfall districts with negative trends is significantly higher than the rest, most of the slopes exhibited by these trends are very gentle, with many of them extremely close to showing no trend. It is, however worth noting the significant variability in the number of TTTs associated with rainfall onsets from one season to another, which is consistent with the findings in Figure 5-5, as well as factors attributed to those findings.

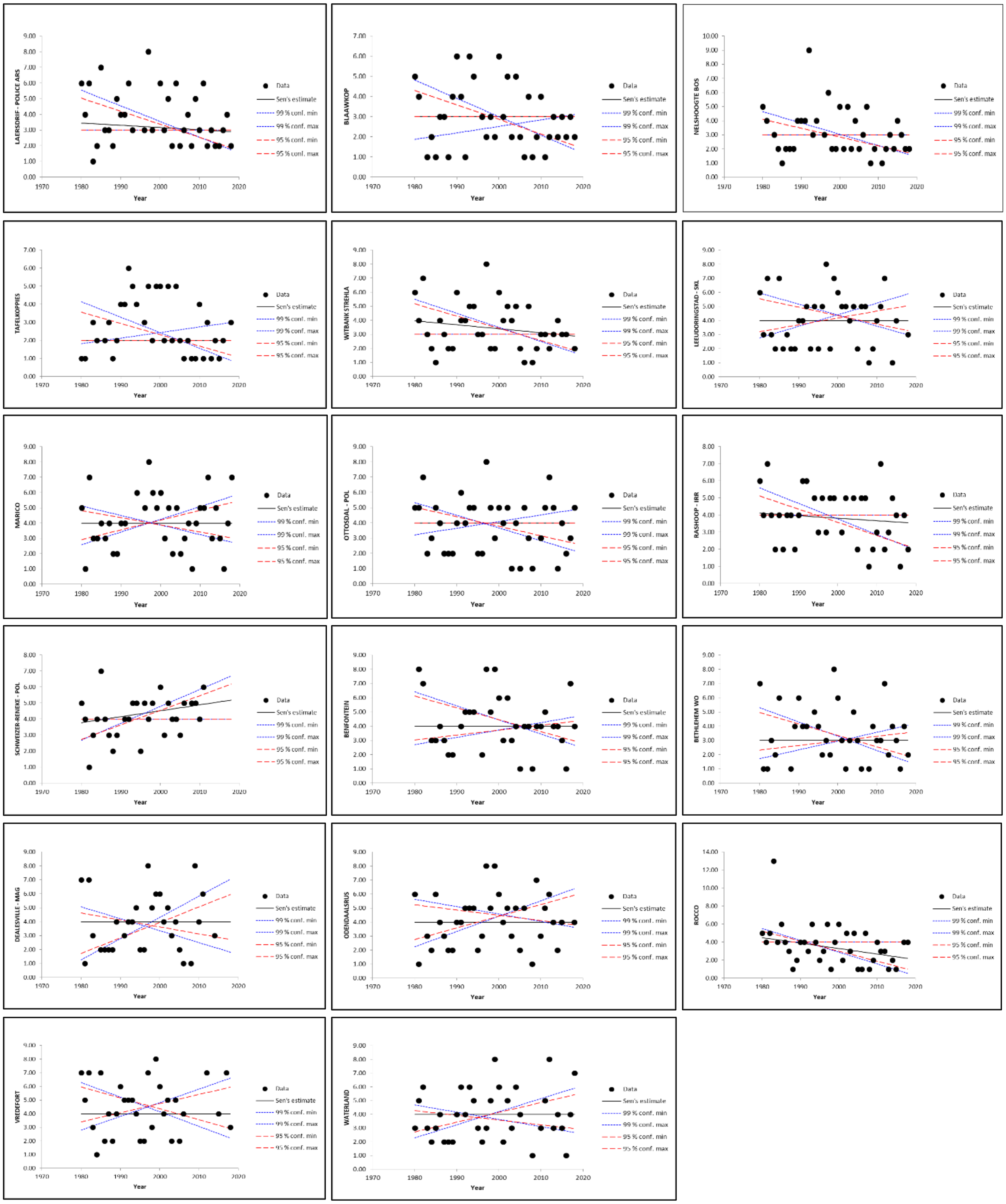

Figure 5-6 Trend and slope analyses for TTTs associated with rainfall onsets in the rainfall districts that constitute the Maize Triangle during the period 1980/81–2017/18.

Trends and slopes of yields from maize grown during the seasons when TTT-associated rainfall onsets were recorded in the Maize Triangle were also analysed using MAKESENS and presented in Figure 5-7 on page 103. The significance of including maize yield analyses in this study was to use it as an indicator of whether the co-occurrence of TTTs and rainfall onsets had any resulting impacts.

The majority (94%) of rainfall districts in the study area displayed increasing trends with strong slopes. Seasonal maize yields from these rainfall districts do not vary widely for the majority of rainfall districts. Marico – which is located at the northwestern edge of the study area – is the only rainfall district that exhibited a decreasing maize yield trend. The slope of this decreasing trend is, however, not very strong and the reason for the decreasing trend is not yet known to this study.

These findings confirm reports by various researchers, such as Sihlobo (2019), who observed a gradual increase in maize production over recent decades in South Africa. While rainfall onsets form an important part of the maize cultivation process, there are a number of other – non climatological – factors that contribute to this process, such as soil properties, hybrid varieties and farm management (Munodowafa, 2011).

Irrigation, when mixed with farm management and other agricultural practices, becomes the most crucial factor in agriculture since it negates the negative impacts of seasonal variations of climate (Tilahun, 2006). Therefore, the strongly rising trends observed in Figure 5-7 could be attributed to improved agricultural practices, which could be enhanced by recent technological advancements and coupled with efficient and effective irrigation systems.

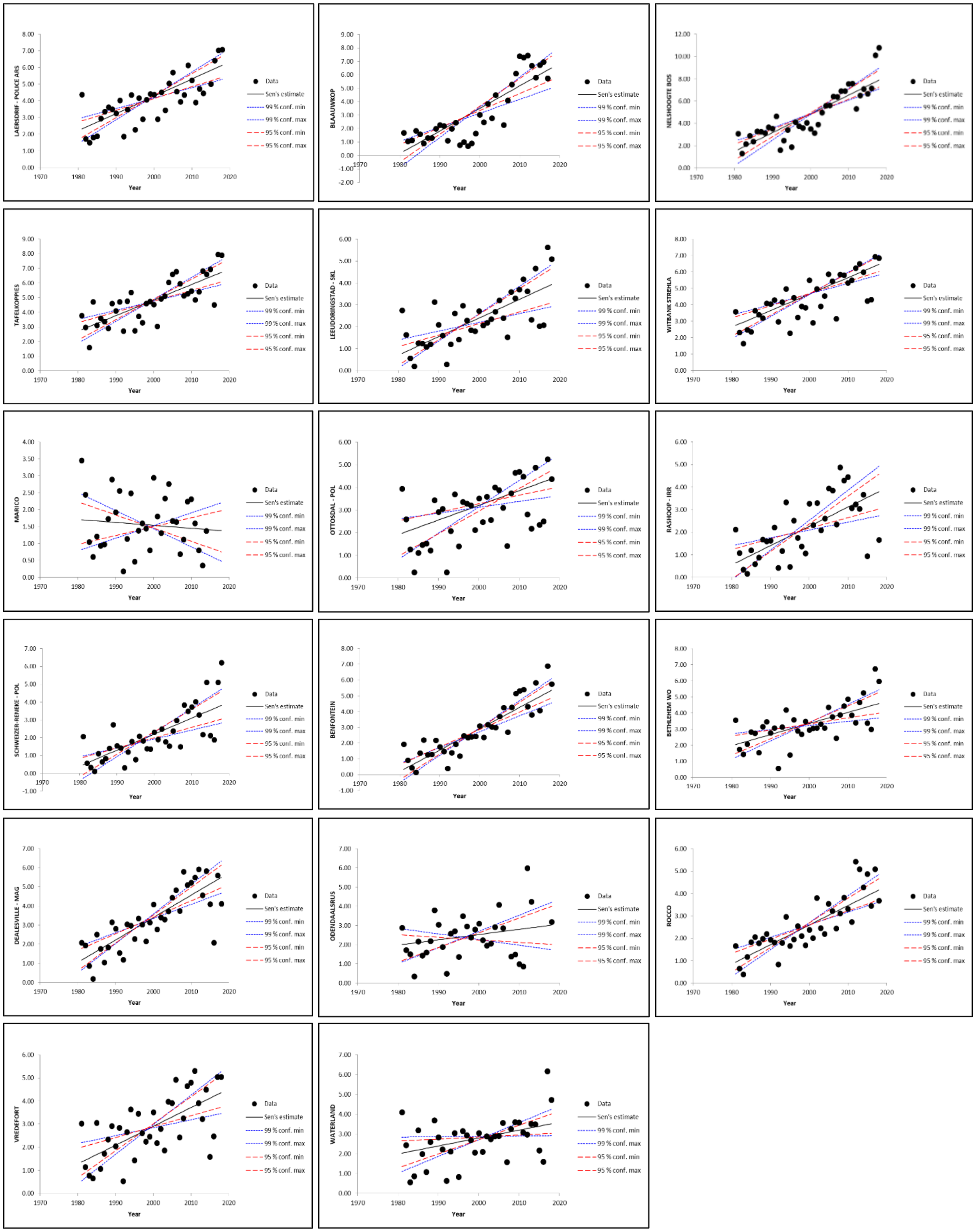

Figure 5-7 Trend and slope analyses for maize yields in the rainfall districts that constitute the Maize Triangle during the period 1980/81–2017/18.

The study ended this section by statistically investigating the relationship between the identified TTT-associated rainfall onsets (rainfall amounts) and maize yields produced during the same seasons using rainfall districts that make up the Maize Triangle.

Test Z values that resulted from MAKESENS computations of TTT-associated rainfall onsets and subsequent maize yields were statistically correlated and are displayed in Figure 5-8. These values are used to determine if there is a trend at a selected level of significance for the investigated data sets, where a positive (negative) value of Z indicates an upward (downward) trend. This analysis was performed to further the investigation on the influence of TTT-associated rainfall onsets in enhancing subsequent maize yields in the study area during the study period.

The results in Figure 5-8 suggest that there is no correlation between rainfall amounts obtained from TTT-associated rainfall onsets and subsequent maize yields during the 1980/81–2017/18 period in the Maize Triangle. These results provide little information to understand the relationship between the two variables. However, they shed some light on the nature of the agricultural sector that has evolved enough to limit its extensive dependency on climate, thereby reducing consequences resulting from extreme climate variability.

Findings from this analysis are particularly crucial, especially in a changing climate that is expected to increase the likelihood of greater frequency and intensity of rainfall and drought (Hoerling et al., 2006), bringing along with it much uncertainty about rainfall timing and the associated decision-making processes (Adisa et al., 2019; Kurniasih and Impron, 2017).

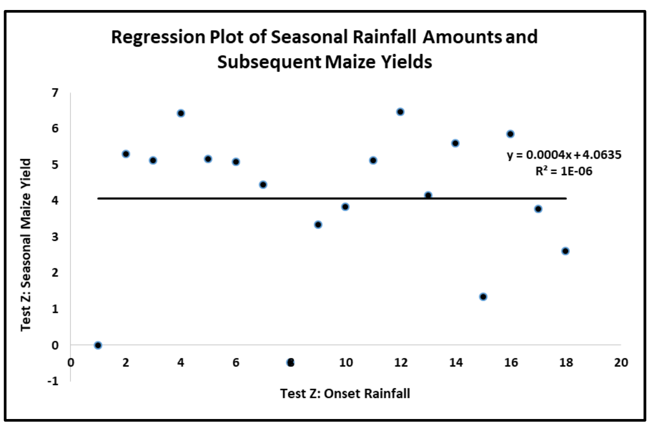

Figure 5-8 Correlation analysis between test Z scores of TTT-associated rainfall onsets and subsequent maize yields of rainfall districts that constitute the Maize Triangle between 1980/81 and 2017/18.

5.1.4 Correlation analyses of rainfall amounts recorded during and after the occurrence of TTT-associated rainfall onsets against subsequent maize yields for rainfall districts of the Maize Triangle during the period 1980/81–2017/18

The study continued the investigation of the relationship between TTT-associated rainfall onsets and subsequent maize yields for rainfall districts that make up the study area during the study period. Results from these analyses are presented in Figure 5-9, Figure 5-10 and Figure 5-11 which are displayed on pages 107, 108 and 109 respectively, and are comprised of two separate datasets that are correlated i.e. the first correlation analyses (left panel) were performed for the actual rainfall amounts recorded during the occurrence of TTT-associated rainfall onsets and subsequent maize yields, and the second correlation analyses (right panel) were performed for the actual rainfall amounts recorded after the occurrence of TTT-associated rainfall onsets and subsequent maize yields.

Rainfall amounts for TTT-associated rainfall onsets are actual amounts that were received during the 30-day period of the occurrence of rainfall onsets, and were recorded at a rainfall district level, while rainfall amounts for post-TTT-associated rainfall onsets are actual amounts received during the 120-day period immediately after the occurrence of the TTT-associated rainfall onsets. They were recorded at a rainfall district level. The 120-day period was selected because it is typically the number of days a maize crop takes to reach maturity (Akpalu et al., 2008). It was important for the study to investigate the rainfall that sustains the crops after the rainfall onset and throughout their growth period to compare between the impacts TTT-associated rainfall onsets have on subsequent yields and that of rainfall that sustains crop growth after the occurrence of TTT-associated rainfall onsets.

The results presented in Figure 5-9 to 5-11 were grouped according to rainfall districts that exhibited the strongest correlations between rainfall amounts which occurred after TTT-associated rainfall onsets and subsequent maize yields instead of correlations between rainfall amounts from TTT-associated rainfall onsets and subsequent maize yields. The adoption of this approach was motivated by the relatively large variance (0.019299733) in R^2 values of correlation analyses performed between rainfall amounts that occurred after TTT-associated rainfall onsets and subsequent maize yields compared to the relatively small variance (0.000639623) in R^2 values obtained from the correlation of rainfall amounts from TTT-associated rainfall onsets and subsequent maize yields.

The results of the correlation analyses presented in Figures 5-9 to 5-11 reveal that the majority (82%) of rainfall districts displayed positive correlations for both rainfall amounts of TTT-associated rainfall onsets, as well as rainfall amounts of post-TTT-associated rainfall onsets. It is interesting that the percentage of positive correlations was similar for both sets of correlations. However, patterns of these correlations differed in each set, i.e. up to 71% of rainfall districts had positive correlations for both sets of data investigated, while only 29% of rainfall districts exhibited positive trends in one set of correlations and negative trends in the other. There are no notable spatial patterns in rainfall districts that exhibited mixed correlations.

Figure 5-9 displays rainfall districts with R^2 values which range from 0.1 to 0.5, indicating a relatively higher proportion of the variance between the investigated variables. R^2 values shown in Figure 5-10 range from 0.01 to 0.09 and therefore sit in the moderate category of the total rainfall districts that are investigated while R^2 values shown in Figure 5-11 were the weakest, ranging from 0.0002 to 0.007. These findings suggest that rainfall that sustains crop growth has a relatively higher influence on subsequent maize yields compared to the influence rainfall from TTT-associated rainfall onsets has on subsequent maize yields. Furthermore, some rainfall districts displayed correlations than others, suggesting the existence of spatial variation in the investigated relationships in the Maize Triangle.

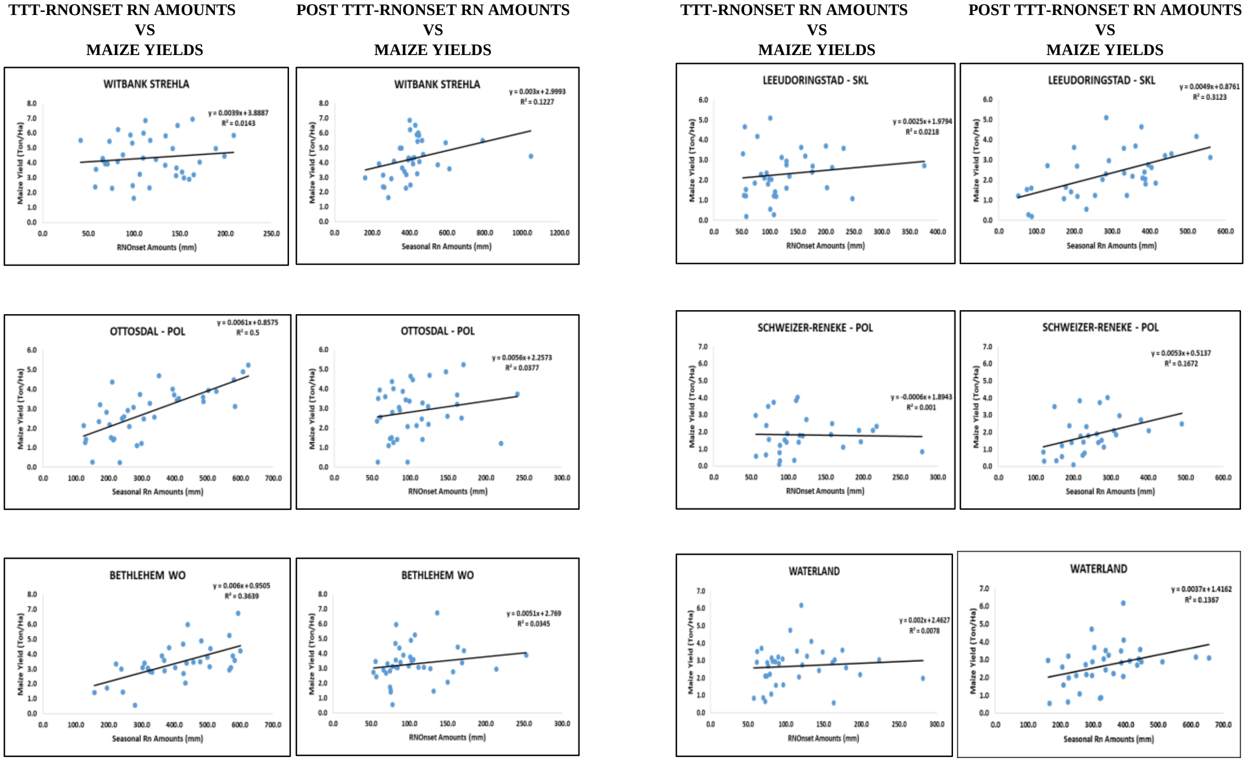

Figure 5-9 Correlation analyses with the highest R^2 values between rainfall amounts from TTT-associated rainfall onsets and associated maize yields, and between rainfall amounts from post-TTT-associated rainfall onset rainfall amounts and subsequent maize yields in the Maize Triangle rainfall districts.

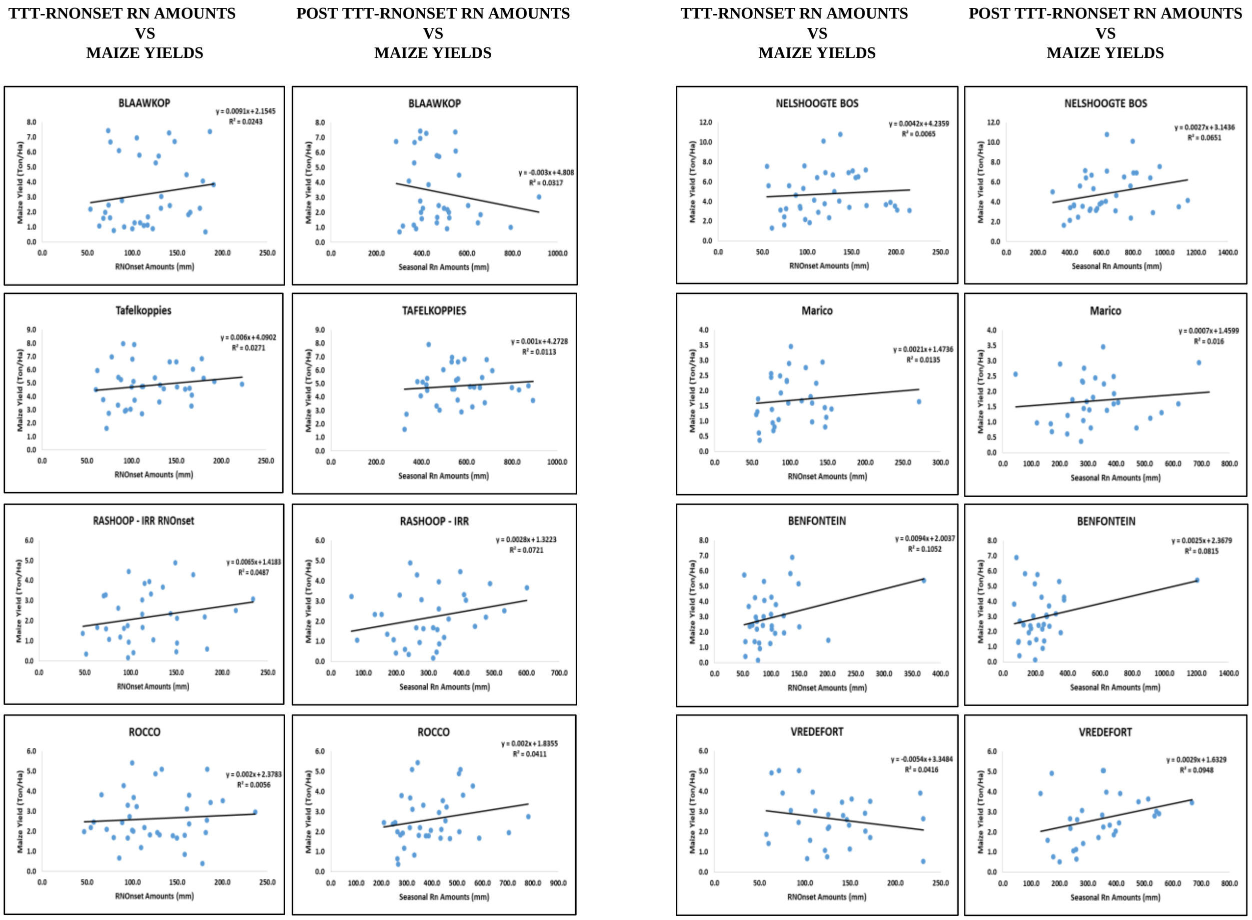

Figure 5-10 Correlation analyses with moderate R^2 values between rainfall amounts from TTT-associated rainfall onsets and associated maize yields, and between rainfall amounts from post-TTT-associated rainfall onset rainfall amounts and subsequent maize yields in the Maize Triangle rainfall districts.

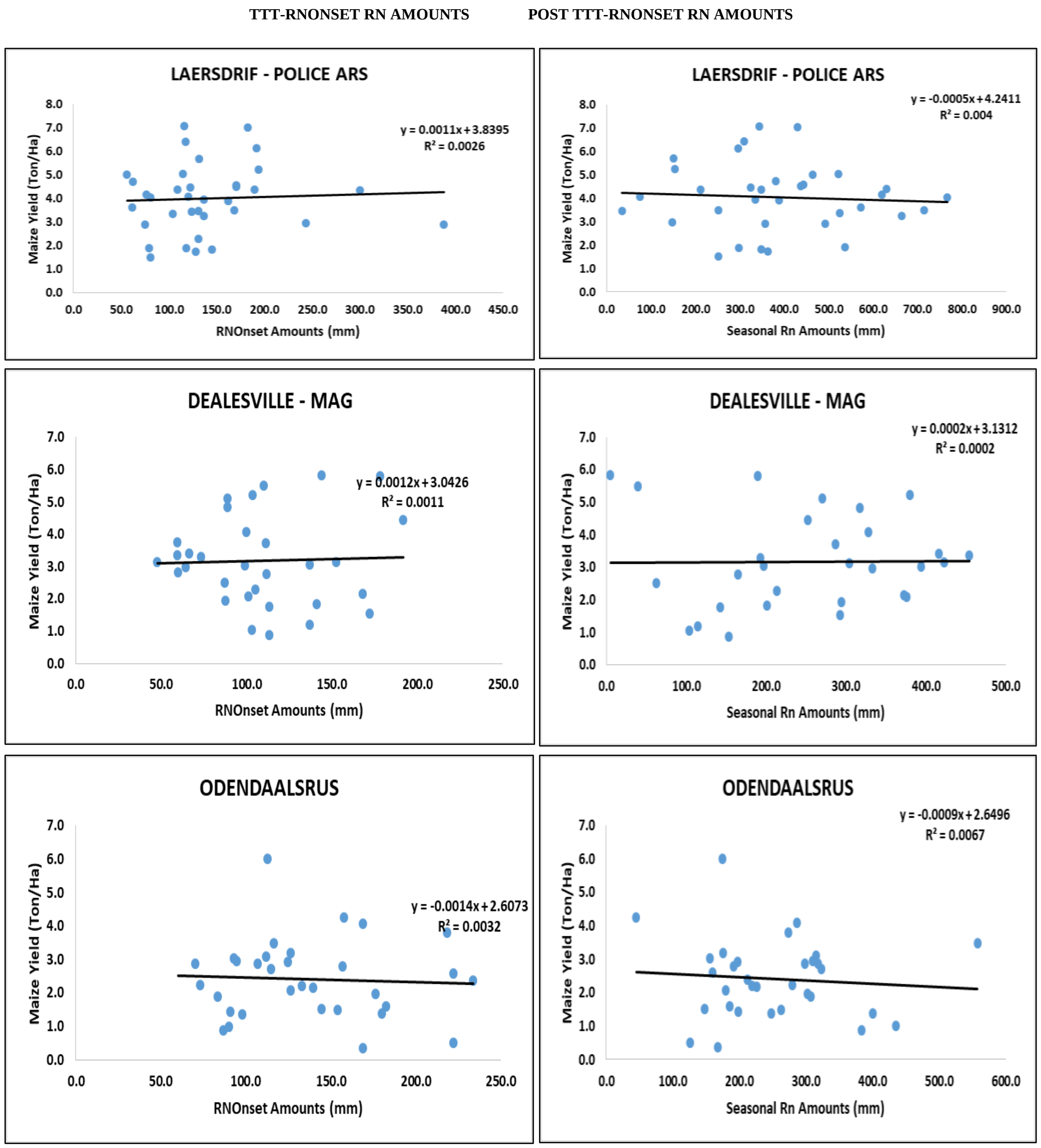

Figure 5-11 Correlation analyses with the lowest R^2 values between rainfall amounts from TTT-associated rainfall onsets and associated maize yields, and between rainfall amounts from post-TTT-associated rainfall onset rainfall amounts and subsequent maize yields in the Maize Triangle rainfall districts.

5.1.5 Seasonal rainfall patterns of post-TTT-associated rainfall onsets in the Maize Triangle during the period1980/81–2017/18

In this section, the spatial analysis of rainfall accumulated after the occurrence of TTT-associated rainfall onsets, throughout the maize crop growing period (120 days), in the Maize Triangle during the study period was conducted and the results presented in Figure 5-12 on page 111. The analyses considered the spatial distribution patterns for minimum, average and maximum rainfall using rainfall districts. The presented results suggested that there is a spatial transition that denotes low rainfall amounts over the western parts of the country, and higher rainfall amounts over the east. In addition, the significant rainfall amounts received in the study area after the occurrence of TTT-associated rainfall onsets are concentrated in the northeastern part of the study area. The latter is notable in all minimum, average and maximum rainfall categories.

These results are consistent with climatological patterns of rainfall in South Africa and the subcontinent, which is characterised by wetter conditions over the east, as previously cited in this work. These findings are also in agreement with some results found in previous sections.

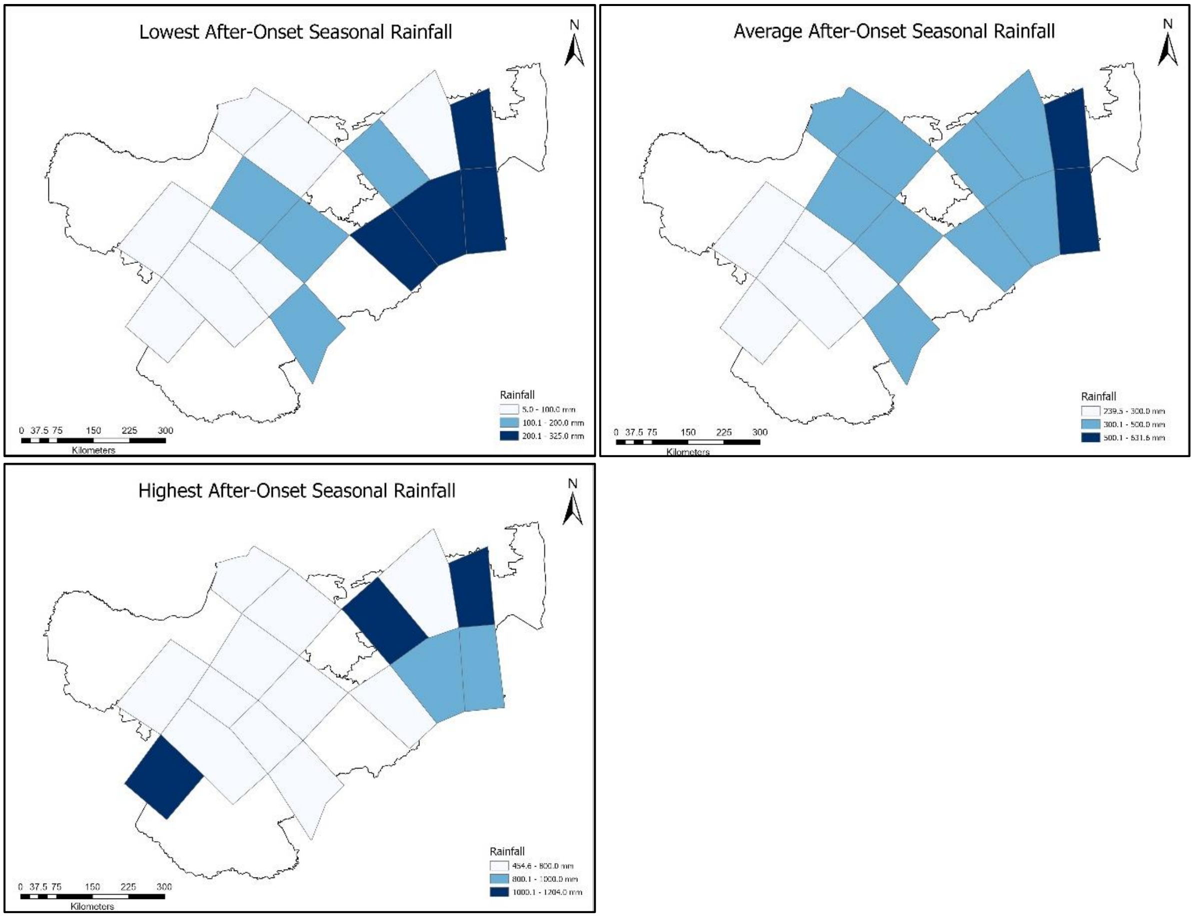

Figure 5-12 Spatial distribution of rainfall amounts received after TTT-associated rainfall onsets for rainfall districts that constitute the Maize Triangle during the period 1980/81–2017/18.

5.1.6 Analysis of TTT-associated rainfall onsets, as well as subsequent maize yields that occurred before, during and after planting dates in the study area during the study period

Agricultural Economics Today (2019) published a map that depicts optimal maize planting dates in the Maize Triangle (as well as KwaZulu-Natal). In this map, the investigated major maize-producing area in South Africa was categorised into four regions: KwaZulu-Natal, the cold eastern region, the temperate eastern region and the western region. These regions have different planting dates, with the eastern regions showing earlier planting dates compared to the western regions. The cold eastern region is the easternmost region (with KwaZulu-Natal excluded in the analysis) and covers the majority of Mpumalanga, as well as the far northeastern parts of the Free State. It consists of two parts: the northern part, characterised by earlier planting dates (1 to 15 November), and the southern part, characterised by later planting dates (25 October to 30 November).

The temperate eastern region is a narrow strip, covering much of Gauteng, as well as a part of the Free State. It is located towards the northeast and has planting dates from 1 November to 10 December. The western region extends over the largest area, covering much of North-West and approximately a quarter of the Free State. It consists of three sets of planting dates, with the northeastern part comprising the planting dates 15 November to 25 December and the northwestern part comprising the planting dates 30 November to 7 January. The planting dates of the southern part are from 20 November to 31 December.

Percentages of TTT-associated rainfall onsets that occurred before, during and after the planting dates for the rainfall districts that make up the study area between 1980/81 and 2017/18 were computed using the planting dates map of Agricultural Economics Today (2019), and the results presented in Figure 5-13 on page 113.

According to this figure, the TTT-associated rainfall onsets that occurred during the planting periods were dominant across the majority of the rainfall districts in the Maize Triangle with some rainfall onsets, such as Laersdrift – Police ARS, Blaauwkop, Nelshoogte – Bos, Tafelkoppies, Rocco and Vredefort, standing out. The highest percentages of TTT-associated rainfall onsets occurred during the planting dates. It is worth noting that the location of the latter rainfall districts is largely east of the study area, a pattern that follows the eastward distribution of much of the rain and maize yields that have been demonstrated in previous sections of this study.

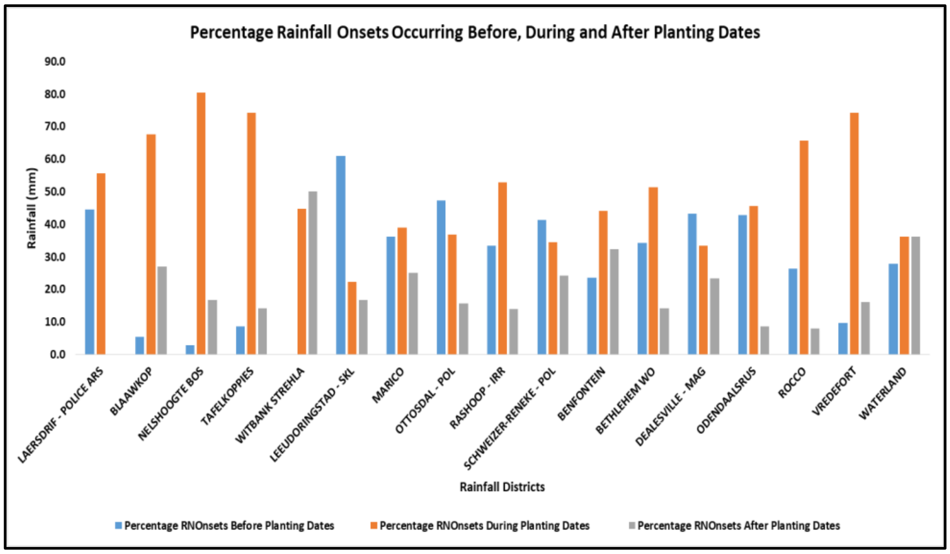

Figure 5-13 Percentages of TTT-associated rainfall onsets that occurred before, during and after the planting dates for rainfall districts that make up the study area between 1980/81 and 2017/18.

5.1.7 Correlation analyses of rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after planting dates and subsequent maize yields for rainfall districts that constituted the Maize Triangle between 1980/81 and 2017/18

Correlation analyses were conducted between rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates and subsequent maize yields in the study area during the study period. The results are presented in a format of three columns of graphs in figures from Figure 5-14 to Figure 5-18 which are presented from pages 115 to 118 respectively. The total investigated rainfall districts was divided into five figures based on similarities in characteristics which were R^2 values and data availability. R^2 variances for the "During Planting Dates" category and the "After Planting Dates" category were similar and as a result, the R^2 variance of the "During Planting Dates" was used for grouping rainfall districts since this category had the results dataset. The minimum data availability for a rainfall district's R^2 value to be accepted was the availability of at least five seasons with data for use during the correlation.

Figure 5-14 presents two rainfall districts with the highest R^2 values for the considered category which range from 0.246 to 0.4118. These R^2 values are higher than those found in the "Before Planting Dates" and "After Planting Dates" categories, suggesting that there was a relatively stronger correlation between rainfall received from TTT-associated rainfall onsets that occurred during the planting dates published by the Agricultural Economics Today (2019) and subsequent maize yields.

It is also worth noting that these two R^2 values are also the highest of all R^2 values of other rainfall districts. Three rainfall districts that ranked second to the highest had R^2 values ranging from 0.0298 to 0.0478 and these are displayed in Figure 5-15 while rainfall districts with R^2 values that ranked third are displayed in Figure 5-16 with R^2 values ranging between 0.0044 and 0.0062. Figures 5-17 and 5-18 consist of rainfall districts that had missing results for the "Before Planting Dates" and "After Planting Dates" categories respectively. Ranges of R^2 values for these groups were still lower than those of the first and second groups which are shown in Figures 5-14 and 5-15 with ranges between 0.0013 and 0.0509 as well as between 0.0264 and 0.0891 respectively. The overall results that are presented in Figures from 5-14 to 5-18 indicate that there was a relatively stronger correlation between rainfall onsets that occurred during the published planting dates, and subsequent maize yields.

These results are in agreement with the widely published dependency of maize yields on sufficiently high amounts of rainfall. Furthermore, the results demonstrate the importance of rainfall amounts recorded from TTT-associated rainfall onsets that occurred during planting dates on subsequent maize yields, thereby confirming the importance of TTTs as rainfall-bearing systems in maize yields in the Maize Triangle. Furthermore, these results emphasise the importance of the timing of TTTs, which initiate rainfall onsets and, subsequently, the planting dates.

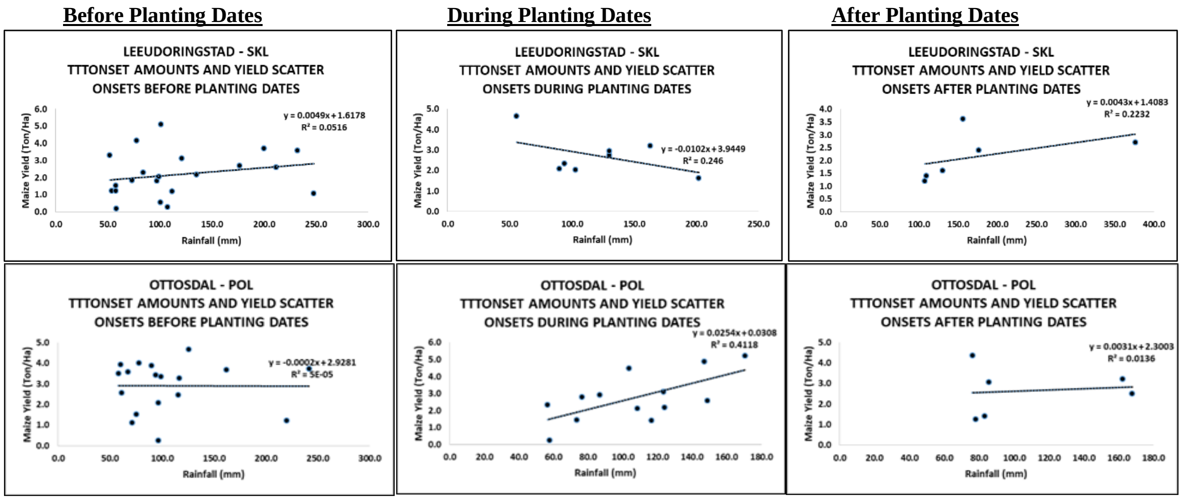

Figure 5-14 Rainfall districts with the highest R^2 values of correlation analyses between rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates, and subsequent maize yields for rainfall districts that constitute the Maize Triangle from 1980/81 to 2017/18.

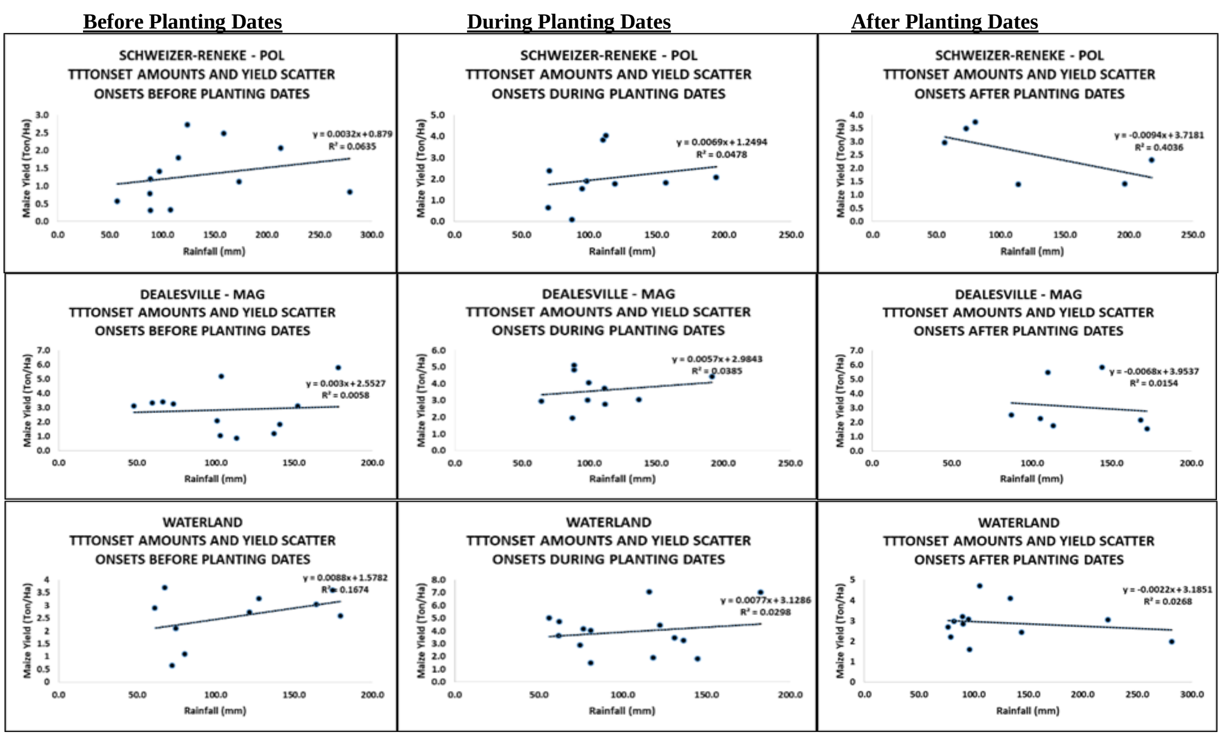

Figure 5-15 Rainfall districts with the moderate R^2 values of correlation analyses between rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates, and subsequent maize yields for rainfall districts that constitute the Maize Triangle between 1980/81 and 2017/18.

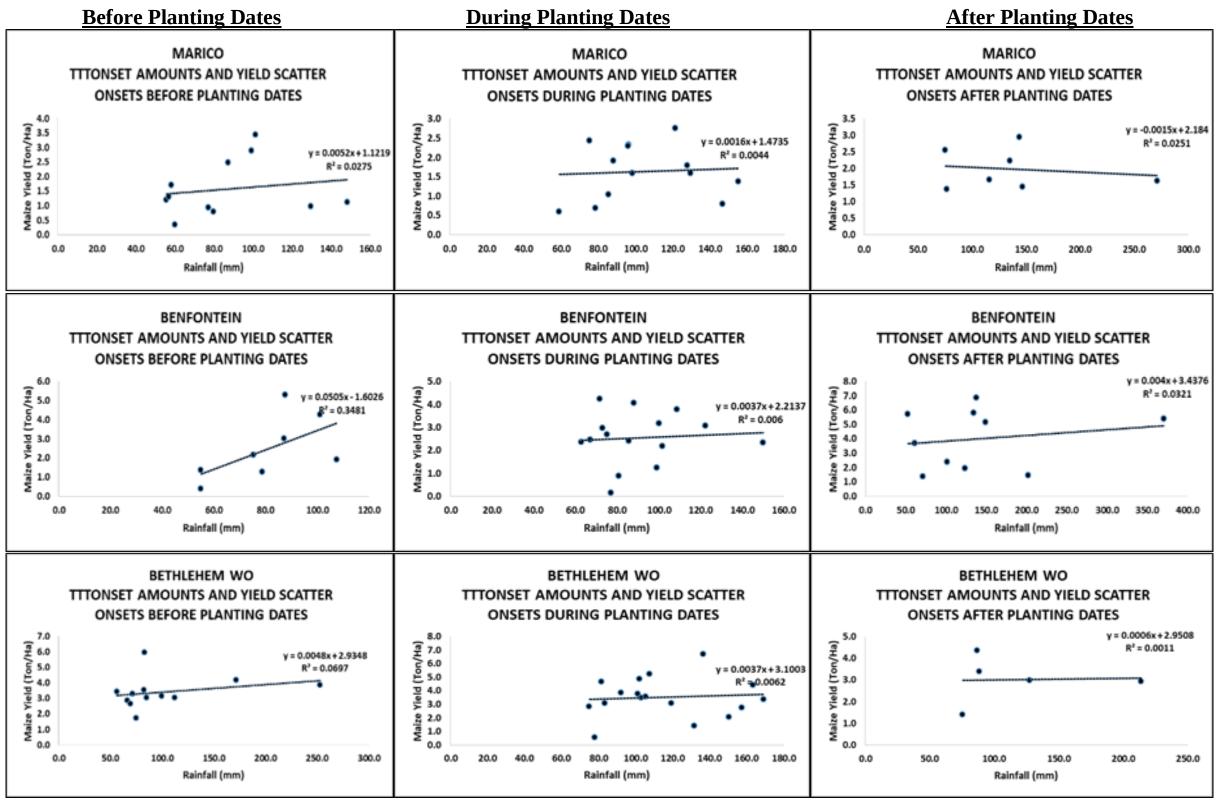

Figure 5-16 Rainfall districts with the lowest R^2 values of correlation analyses between rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates, and subsequent maize yields for rainfall districts that constitute the Maize Triangle between 1980/81 and 2017/18.

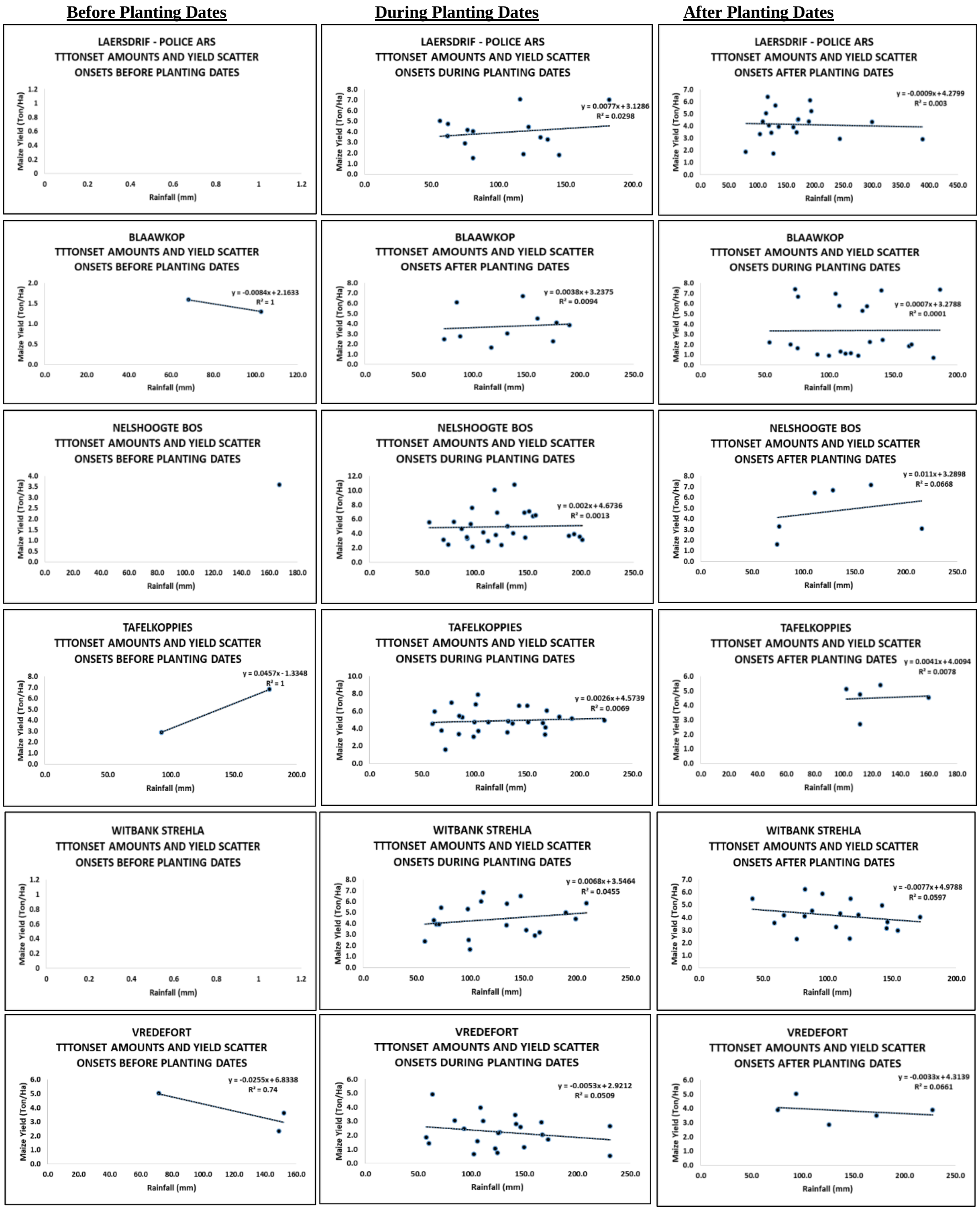

Figure 5-17 Rainfall districts with missing "Before Planting Dates" category during correlation analyses between rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates, and subsequent maize yields for rainfall districts that constitute the Maize Triangle between 1980/81 and 2017/18.

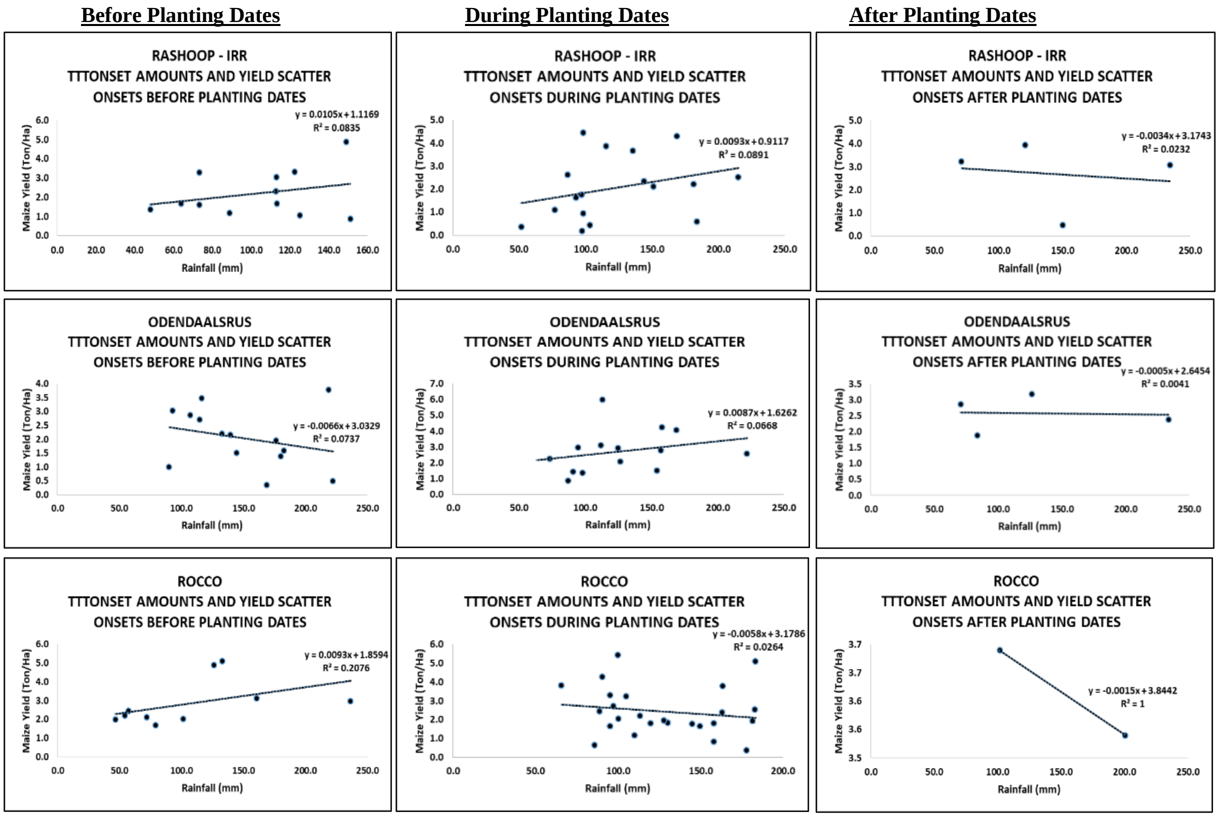

Figure 5-18. Rainfall districts with missing "After Planting Dates" category during correlation analyses between rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates, and subsequent maize yields for rainfall districts that constitute the Maize Triangle between 1980/81 and 2017/18.

5.1.8 Spatial analyses of rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates, and subsequent maize yields for rainfall districts that constituted the Maize Triangle between 1980/81 and 2017/18

The investigation on the timing of rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after the planting dates, as well as the subsequent maize yields in the study area during the study period, was continued in this section, where spatial analyses were conducted using rainfall districts and presented in Figure 5–19 on page 119.

The lowest average rainfall amounts recorded from TTT-associated rainfall onsets that occurred before, during and after the planting dates was approximately 80 mm, while the highest was approximately 176 mm. Rainfall amounts display an increase both spatially and in quantity from TTT-associated rainfall onsets before the planting dates compared to those that occur afterwards.

This increasing trend is widely distributed over the Maize Triangle, with the highest number of rainfall districts with average rainfall amounts below 100 mm being three for the TTT-associated rainfall onsets that occurred before the planting dates, and none for the TTT-associated rainfall onsets that occurred after the planting dates.

Subsequent maize yields follow similar patterns. The highest number of rainfall districts that displayed the lowest maize yields (1.3 to 2.0 t/ha) subsequent to TTT-associated rainfall onsets occurred before the planting dates, while the highest number of rainfall districts that showed the highest maize yields (3.1 to 4.7 t/ha) subsequent to TTT-associated rainfall onsets occurred after the planting dates.

In addition, the spatial patterns of maize yields indicate that maize yields were generally higher in rainfall districts located to the northeast of the Maize Triangle, following the wetter parts of the study area, as well as the country and subcontinent. The tendency of maize yields subsequent to TTT-associated rainfall onsets that occurred after the planting dates to be higher than the other two categories is not currently clearly understood by this study. However, it could be linked to several possible factors, such as the availability of sufficient soil moisture from irrigation, soil moisture that would have been received from previously occurring rains or the use of proper hybrids.

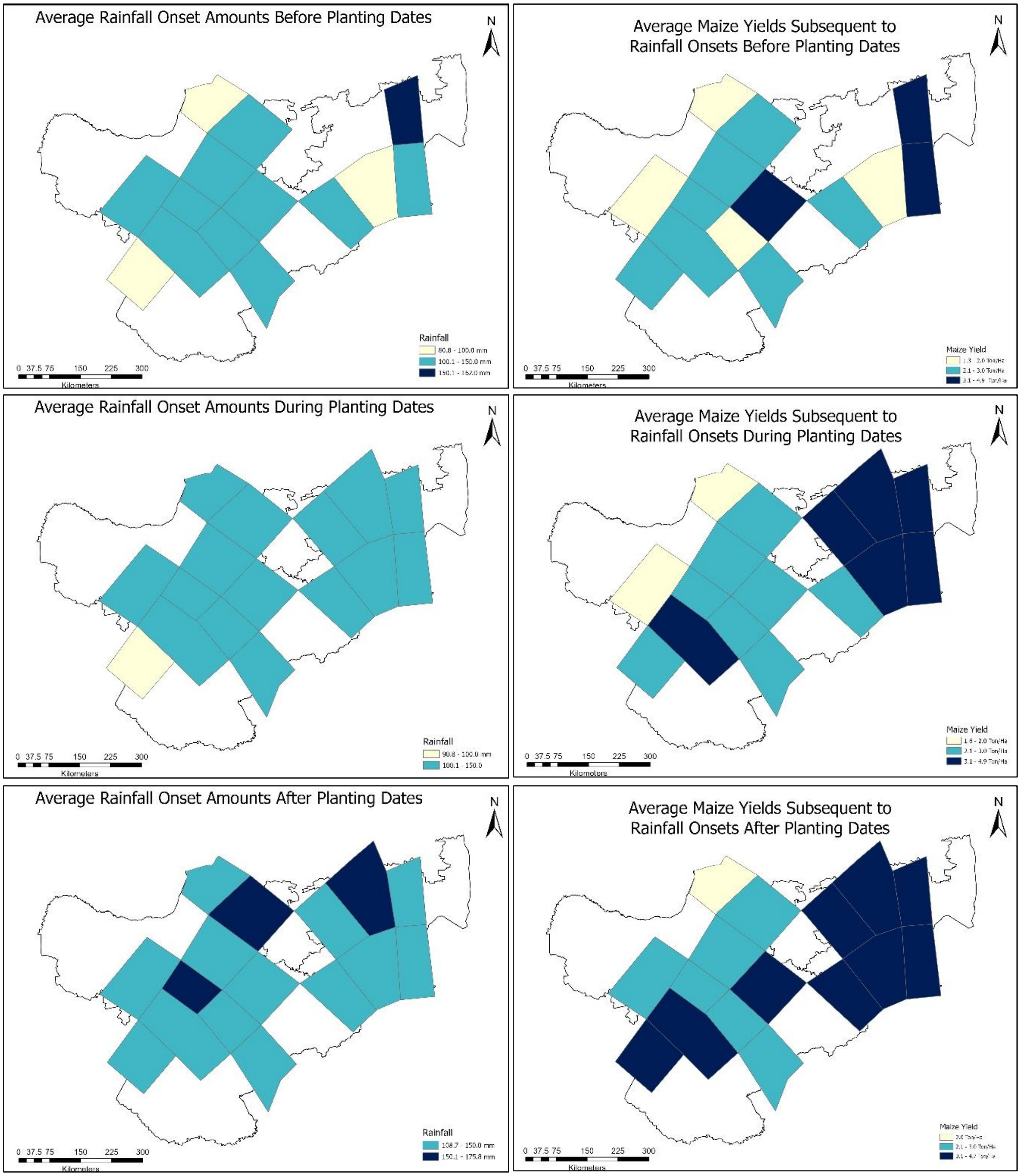

Figure 5-19 Spatial analyses of rainfall amounts from TTT-associated rainfall onsets that occurred before, during and after maize yields, as well as subsequent maize yields in the Maize Triangle between 1980/81 and 2017/18.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 INTRODUCTION

This study was guided by three research questions which asked the following:

- What is the climatology of TTTs in southern Africa?
- What is the nature of the relationship between TTTs and associated rainfall onsets?
- How do TTT-associated rainfall onsets influence subsequent maize yields in the Maize Triangle?

These research questions then shaped the structure of this work, which was designed in such a manner that the analyses and discussions topic of this study could be divided into two chapters: Chapter 4 and Chapter 5. Chapter 4 was divided into two main sections (sections 4.2 and 4.3), where section 4.2 focused on addressing the first objective, which was to define the climatology of TTTs that occurred over southern Africa, and section 4.3 addressed factors concerning the second objective of the study, which was to explore the relationship between TTTs and rainfall onsets that occurred in the Maize Triangle between 1979/80 and 2017/18. Chapter 5 examined the third and final objective of the study, which was to assess the influence TTT-associated rainfall onsets had on subsequent maize yields in the study area between 1980/81 and 2017/18. The difference in periods used by this study was a result of the unavailability of maize yield data for the 1979/80 season. The hypothesis of the study was that TTT-associated rainfall onsets have a significantly positive impact on subsequent maize yields in the Maize Triangle.

6.2 CONCLUSIONS

Analyses of the climatology of TTTs and related variables, as well as the relationship between TTTs and rainfall onsets, were conducted and presented in Chapter 4. This chapter was initiated by investigating climatological rainfall patterns that are representative of the rainfall districts that constitute the Maize Triangle, OLR and its anomalies that are used as a proxy to identify regions of high atmospheric moisture, including TTT activity, TTTs that are one of the major rainfall-producing systems in southern Africa, as well as ENSO variations in relation to TTT activity over the subcontinent. The climatological analysis of monthly rainfall patterns in the Maize Triangle confirmed that rainfall received in the rainfall districts peaks during the austral summer months, a pattern similar to rainfall patterns in South Africa and the subcontinent.

Rains peaked significantly in October until March, with January standing out as the month that received the highest rainfall in the majority of the rainfall districts. The analysis of monthly averaged OLR also confirmed that southern Africa received much of its rainfall in austral summer when the ITCZ migrates south, bringing along with it a region of significantly low OLR, which results from the cloud cover that was generated by the ITCZ moisture.

During the austral summer (DJF), when the ITCZ is at its highest latitude, a region of anomalously high OLR develops a thermal low over the southwestern tip of the subcontinent, which is responsible for triggering the formation of thunderstorms over the eastern parts of the subcontinent, while restricting rainfall occurrence over areas such as the Northern Cape and Namibia. This results in a west-east and south-north increasing rainfall trend over the subcontinent.

During the dry months, the region of low OLR retreats equatorward along with the ITCZ, leaving behind a region of relatively high OLR that prevails over much of the subcontinent, which suppresses the occurrence of rainfall in the process. The monthly variation of OLR on a latitudinal axis over the subcontinent also displayed a region of low OLR over the deep and subtropical regions of the subcontinent, while the temperate regions showed an extended high OLR area that lies in the latitudes where the southwestern tip of the subcontinent is located.

This analysis further displayed the occurrence of an anomalously high OLR region over the subtropics during the winter months, with two regions that stood out located between 10°S and 24°S between May and June, as well as between July and September. A narrow and zonal region of low OLR around the 40°S latitude that occurs almost throughout the year is indicative of the southernmost tip of the subcontinent that is characterised by an all-year rainfall that peaks during the austral winter months as a result of cold front activity.

OLR anomalies that were computed to identify TTT activity during the austral rainfall months demonstrated the presence of the northwest-southeast dual OLR structure that is fully developed from September to November, with a section of positive OLR north of the structure and negative OLR south of it. This dual OLR structure begins its deformation from December when the negative part of the structure develops a somewhat secondary limb. This develops zonally and lies in the subtropics, and gets stronger from January to February, while the original limb diminishes. This pattern suggests that TTTs are the strongest during the first half of the rainy season and deform, preparing to diminish during the second half of the rainfall season.

Furthermore, the OLR dual structure that is typically positioned at its southernmost position and covers the largest area during September tends to shift in a northeastward direction during October and November. This shift is accompanied by shrinking spatial coverage and weakening polarity. The dual structure was at its northeasternmost location during December, when it started the deformation, which proceeded gradually throughout the end of the summer rainfall season.

The positions of TTTs during the austral summer months were also investigated using TTT centre information, which revealed that TTT centres that occurred between September and October were located further south of the subcontinent compared to those that occurred in November and December, when they are located slightly north, while those that occurred in January and February were located further north. Results from the analyses of TTT centres are consistent with those that were displayed by daily OLR anomalies, confirming that TTT activity occurs at the subcontinent's southernmost part, largely during the first half of the rainfall season.

Results from the duration analysis of the investigated TTTs proposed that the duration of TTTs that were recorded over the subcontinent during the study period lasted between one and ten days, with most of the TTTs lasted for a shorter period. Unlike the previous distribution base in the month of occurrence, the duration distribution does not reveal a spatial pattern, except that the centres of TTTs that lasted up to 10 days were located over land.

The annual variability of TTT cases and annual rainfall variability in the Maize Triangle between 1979/80 and 2017/18 displayed a close relationship in their annual variation, an indication that a close relationship exists between total annual TTT cases, annual average district rainfall for rainfall districts that constitute the study area, as well as annual average district rainfall for rainfall districts that constitute the whole of South Africa.

Results of the monthly variation between the number of TTT cases and average district rainfall in South Africa also showed a close relationship between the two variables and an austral summer activity that is in line with the climate of South Africa and southern Africa when rains initiate in austral spring, peak in austral spring and end in austral autumn. A further analysis of TTT variability pointed out that the frequency of TTTs is inversely proportional to the duration, with the TTTs that lasted for the shortest period having a frequency beyond 450 cases during the study period.

A longitudinal analysis revealed that, while the majority of TTTs occurred between 32°E and 34°E and reached closed to 150 in quantity during the study period, there are longitudes such as those between 18°E and 20°E, as well as between 28°E and 30°E, at which no TTT centre was recorded during the study period. The reason for this is not yet known to this study.

This section was ended by investigating relationships between TTT activity and ENSO variability. From the results, it was observed that, while the number of strong ENSO phases was too small to be statistically significant, there was no consistency in the co-occurrence of TTTs and ENSO on the available strong phases, particularly during a strong El Niño phase, where only one phase was consistent with a decline in TTTs that occurred during the same season. Therefore, the climatology of TTTs and other related variables that occurred over the subcontinent and in the Maize Triangle were explored and found to be consistent with the austral rainfall season, as widely published in the literature.

In order to investigate the influence of TTTs on rainfall onsets, section 4.3 explored comparative analyses between rainfall onsets that were associated with TTTs, as well as rainfall onsets that were not associated with TTTs. The study found that approximately 90% of the austral rainfall seasons that occurred over the Maize Triangle between 1979/80 and 2017/18 were associated with TTTs, proposing that TTTs play a role in almost all austral rainfall seasons in the study area.

The comparison between TTT-associated rainfall onsets and non-TTT associated rainfall onsets was further investigated through spatial analyses, using rainfall districts that make up the study area. Results from these analyses indicated that all the rainfall districts in the Maize Triangle had at least 74% of their rainfall seasons accompanied by TTT-associated rainfall onsets, with the rainfall districts located northeast of the Maize Triangle displaying that up to 97% of their rainfall seasons occurred with TTT-associated rainfall onsets.

The monthly distribution of TTT-associated rainfall onsets and non-TTT-associated rainfall onsets revealed that TTT-associated rainfall onsets significantly outnumber non-TTT-associated rainfall onsets in approximately all the months that showed TTT activity, with particularly large differences during October, November and December. The study also found that TTT-associated rainfall onsets that occur early were well distributed throughout the study area, suggesting that TTTs play a role in the early occurrence of rainfall onsets in the study area.

On the other hand, TTT-associated rainfall onsets that occur late were mainly restricted over the far eastern rainfall districts, a tendency that can be attributed to the north-eastward shifting of TTTs as the austral rainfall season progresses. This study was also able to demonstrate that the majority of rainfall seasons in the study area during the study period only received rainfall from onsets that were associated with TTTs, while during seasons when both types of rainfall onsets were present, TTT-rainfall onsets contributed the majority of the rainfall. Most of the rainfall districts had rainfall seasons that received rainfall from both TTT-associated and non-TTT-associated rainfall onset types. However, TTT-associated rainfall onsets contributed significantly higher amounts of rainfall when compared to their counterparts. Therefore, there is a significantly strong relationship between TTTs and rainfall onsets in the Maize Triangle.

The analyses of TTT-associated rainfall onsets and their influence on subsequent maize yields in the Maize Triangle during the study area was conducted in Chapter 5. Maize yield displayed an increasing trend during the study period, with the majority of maize yield obtained in rainfall districts located east of the Maize Triangle in Mpumalanga. The heat map analysis revealed that there have been more TTT-associated rainfall onsets during October than during September, as well as a gradually increasing trend of maize yield during the study period, with this increase in yield being notable during the earlier years in September compared to October.

A seasonal trend comparison between TTT-associated rainfall onsets, seasonal TTT totals and subsequent maize yields showed that there was no consistency between the three variables during the majority of the seasons comprising the study period. The study compared trends and slopes between rainfall amounts recorded during the occurrence of TTT-associated rainfall onsets, the number of TTTs that were associated with rainfall onsets, as well as maize yields obtained from the TTT-associated rainfall onsets.

The majority of rainfall districts exhibited increasing trends with gentle slopes for rainfall amounts recorded from TTT-associated rainfall onsets, while the majority of rainfall districts showed decreasing trends with gentle slopes in the number of TTTs that were associated with rainfall onsets. The majority of rainfall districts demonstrated strong increasing trends in maize yields.

Furthermore, there was no correlation between the Z scores of rainfall onset amounts obtained from TTT-associated rainfall onsets and subsequent maize yields. The inconsistencies in trends and no correlation between rainfall amounts obtained from TTT-associated rainfall onsets and subsequent maize yields suggest that TTT-associated rainfall onsets only play a certain and limited part in determining the maize yield. Other non-climatological factors, such as irrigation, hybrid varieties and farm management, also contribute considerably to maize yields.

Regression analyses between rainfall amounts obtained from TTT-associated rainfall onsets and maize yields, as well as rainfall amounts obtained from post TTT-associated rainfall onsets and maize yields for rainfall districts in the Maize Triangle, showed that the majority of rainfall districts displayed weak positive correlations for both sets of correlated variables, indicating that TTTs did not only contribute to the initiation of rainfall onsets, but also played a role in the sustainability of rainfall for months after the occurrence of the rainfall onsets in various rainfall districts of the Maize Triangle during the study period. Rainfall districts located east of the Maize Triangle received more rainfall during the four-month period after the occurrence of TTT-associated rainfall onsets. More TTT-associated rainfall onsets occurred during the planting dates for most rainfall districts.

The high number of observed rainfall districts which exhibited positive correlations between rainfall amounts from TTT-associated rainfall onsets that occurred during the published planting dates and subsequent maize yields was an indication maize yields are somewhat dependent on the TTT-associated rainfall onsets whose timing was synchronized with the published planting dates in the Maize Triangle during the study period. These findings suggests a somewhat dependency of maize yields on TTT-associated rainfall onsets and therefore validate the importance of understanding the behavior of TTTs on various time scales, including their drivers.

The spatial analyses using rainfall districts showed that both average rainfall amounts from TTT-associated rainfall onsets and subsequent average maize yields increased gradually in intensity and spatial extent when one compares them before, during and after the planting dates. Therefore, there is a somewhat notable influence of TTT-associated rainfall onsets on the cultivation of maize and the resulting maize yields in the Maize Triangle, although it is not very strong due to other strongly influential factors that play a role in the maize cultivation process.

The overall study conclusion is, therefore, that while TTTs play a fundamental role in initiating rainfall onsets and subsequently sustaining rainfall over the Maize Triangle, this role is largely limited to the first half of the rainfall season, and other rainfall-producing systems take over during the second half of the rainfall season. As a result of this and the activity of other numerous agricultural activities in maize cultivation, the influence TTTs have on the resulting maize yields is insignificant. These findings suggest that neither the null hypothesis nor the alternative hypothesis can be accepted fully since tropical temperate troughs associated with rainfall onsets are dominantly active during the start of the rainfall season and therefore provide rainfall that is sufficient for planting, but they retreat towards the middle of the rainfall season while other rainfall producing systems takeover for rainfall sustainability throughout the rainfall season and are coupled with relevant maize cultivation practices in order to maximise maize yields.

6.3 STUDY CHALLENGES AND RECOMMENDATIONS

The major challenges this study faced was the limited availability of data sets that were required to conduct this study. These include the relatively short data records of TTT cases and maize yield, as well as spatial limitations of the data. It would be recommended that this study be conducted using longer data records and at a southern African domain in future to allow a broader temporal and spatial analysis that can provide greater insights into spatial and temporal patterns of the investigated variables.

Work done on the interactions of TTTs and rainfall onsets was not readily and abundantly available in the literature. Therefore, more work on the relationship between these two variables is recommended. Various pieces of information were evaluated regarding the definition of rainfall onsets and planting dates in the literature. As a result, a recommendation was made to standardise the definition of rainfall onset, as well as planting dates in the Maize Triangle and South Africa.

There is also a lack of critical farming information, such as types of farming (commercial or subsistence), water resources (irrigation or rain-fed), as well as their locations, which can assist in interpreting some of the observed results. Finally, there is a gap in research that links two separate systems with the aim of understanding their relationship in the agrometeorology field. This study encourages conducting such studies with the aim of painting broader pictures that incorporate a variety of systems and the nature of their interactions.

6.4 FUTURE WORK

Results from this work are expected to contribute to the existing pool of knowledge regarding the understanding of TTTs, their drivers and patterns, as well as their implications, particularly on rainfall onset and planting dates in the maize-growing regions of South Africa. Further investigations on the gaps identified in this work – such as the unavailability of TTT centres at certain longitudes, the two regions of anomalously high OLR, the unclear link between TTT activity and ENSO in the subcontinent and the dominant type of farming (commercial/irrigated or subsistence/rain-fed) – are required to build on this work. There is potential to use this work to develop forecasting tools or methodologies, accompanied by indigenous knowledge systems, to contribute to the improved prediction of agrometeorological aspects such as rainfall onsets and planting dates, particularly for subsistence farming that typically have zero or limited resources to perform or access the available scientific methods, and rely heavily on indigenous knowledge.

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APPENDICES

APPENDIX 1 TOTAL RAINFALL ONSET AMOUNTS PER RAINFALL DISTRICT

ONSET RAINFALL TOTALS			1979/80	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	1987/88	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94
	1994/95	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11
	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18										
LAERSDRIF - POLICE ARS			150.6	189.5	128.0	81.0	145.0	118.5	243.5	104.0	62.0	168.5	136.5	81.0	79.5	131.3	
	131.3	76.7	388.0	120.1		109.0	74.8	170.5	124.0	115.0	131.4	171.0	137.0	300.0	192.0	194.0	162.5
	62.4	122.4	95.0	56.2	117.6	182.6	116.0										
BLAAWKOP		63.3	117.4	63.6	117.1	162.5	68.2	122.9	109.0	102.7	164.4	175.2	53.7	113.0	70.0	141.7	79.5
	91.0	181.5	100.0	75.5	132.5	73.7	190.5	88.5	160.5	113.0	132.0	178.5	126.0	85.5	186.5	141.0	73.5
	75.8	108.0	147.0	105.0	129.5	86.0											
NELSHOOGTE BOS		85.3	215.5	60.5	97.7	112.5	125.0	92.5	76.5	201.5	189.0	199.0	87.5	74.5	74.5	147.5	102.8
	107.8	119.6	167.0	136.2	92.1	70.0	194.0	130.6	56.5	80.0	111.2	154.9	146.8	120.8	54.8	97.1	96.0
	157.5	151.2	128.9	166.1	118.6	137.5											
TAFELKOPPIES		71.5	68.5	94.0	72.0	151.0		131.0	84.9	92.8	136.0	167.5	100.0	111.7	111.7	180.5	74.4
	103.5	166.9	165.0	113.0	160.1	98.8	223.5	102.2	168.5	142.5	101.0	62.0	192.5	88.3	85.5	132.0	126.1
	178.5	150.0	78.0	60.0	90.5	103.0											
WITBANK STREHLA			152.0	58.5	117.1	99.7	98.5	57.6	146.5	152.5	165.2	82.0	172.0	66.0	154.5	66.0	189.5
	76.0	199.0	106.5	68.5	134.0	41.5	160.5	142.5	71.0	88.0	96.0	73.0	146.0	209.0	134.5	98.0	118.0
	82.5	147.5	110.5	124.0	110.0	164.0	112.5										
LEEUDORINGSTAD - SKL			78.5	130.0	202.0	100.5	58.0	53.7	57.5	247.8	111.5	121.0	90.0	130.0	107.5	107.5	211.5
	109.5	130.0	84.0	73.0	97.0	376.0	99.0	135.0	94.0	176.5	163.0	176.0	57.5	232.0	52.0	200.0	77.5
	156.0		55.5	103.0			100.8										
MARICO	53.3	101.3	75.0	85.2	58.8	55.5	77.0	129.5	58.0	99.0	87.8	75.0			87.1		155.1
	129.4	146.5	79.7	143.4	127.7	56.7	96.0	121.1	115.8	271.3	78.3	148.2	134.8	95.9	98.0	146.6	60.0
	76.2	115.4	157.4	59.0	149.8												
OTTOSDAL - POL		72.0	60.0	149.0	78.0	57.5	71.5	73.5	75.5	220.0	94.0	86.5	85.5	96.5	96.5	162.0	116.5
	99.0	116.5	162.1	108.5	58.0	115.5	67.1	61.0	78.0	90.1	123.5	83.0	241.5	100.5	125.5	103.6	76.5
	124.1	147.2	56.5	167.8	170.5	76.0											
RASHOOP - IRR		137.9	151.1	76.7	51.5	97.5	88.9	183.7	151.1	113.4	73.3	92.8	181.3	103.2		122.5	150.0
	215.0	97.0	48.0	125.0		112.8	73.2		86.6	120.8	115.5	144.0	149.0	168.6	98.0	234.0	71.0
	113.0	135.5	98.0	177.0	93.0	64.0											
SCHWEIZER-RENEKE - POL			87.2	213.0	57.0	108.0	87.6	173.6	70.0	279.0	97.5	124.1	73.8	197.0	88.6	88.6	115.5
	88.3	194.6	157.0	113.7		218.0	98.4	158.7	119.5	95.0	70.5	56.5		110.3	73.2	80.4	112.5

BENFONTEIN			123.1	80.6		76.8	71.1	101.6	98.9	78.7	75.2		201.5	54.9	54.9	107.4	
	66.9	150.0	101.1	85.5	122.2	62.6	100.0	87.0	72.9	60.7	71.5	75.1	101.0	149.0	87.5	370.6	
	108.7	134.3	88.0	82.0	137.5	52.4											
BETHLEHEM WO		50.7	82.3	74.8	131.6	150.2	74.8	53.0	75.5	99.3	55.9	157.2	83.3	77.7	77.7	171.5	75.4
	105.3	66.1	69.3	102.9	214.0	84.7	112.1	71.2	119.2	86.7	101.1	56.9	252.8	163.4	102.1	91.9	88.3
	81.5	107.3	169.0	127.5	136.3	82.7											
DEALESVILLE - MAG			116.9	101.0	87.5	113.4		87.2	113.5	103.0	141.0	152.5	60.0	172.0	137.2	137.2	64.6
	105.2	59.7	99.0	168.0	47.8	100.0	111.8	66.5	73.3	111.5	191.7	88.7	59.5	178.3	89.0	103.6	110.1
		143.8															
ODENDAALSRUS		105.5	107.1		144.5	168.8	139.6	91.0	182.5	132.9	218.7	93.0	83.5	222.3	222.3	114.8	98.1
	116.6	94.7	233.9	157.0	111.8	73.1	176.5	126.6	124.6	168.9	70.5	60.2	180.0	154.0	90.1	87.0	113.0
	158.0	63.5	93.1			126.5											
ROCCO	128.1	149.6	85.7	177.8	109.9	130.2	100.1	145.1	46.7	54.2	181.5	119.8	158.2	158.2	236.4	95.2	127.8
	182.9	71.8	79.3	163.1	101.2	163.3	57.3	113.5	200.6	105.1	88.9	160.6	65.8	95.2	97.2	99.8	132.8
	90.5	126.0	186.8	183.4	101.7												
VREDEFORT		105.5	111.5	150.0	125.0	102.5	84.5	122.5	172.5	149.0	166.5	167.0	126.0	231.0	231.0	152.0	60.0
	141.4	146.7	126.9	93.4	172.5	125.8	142.6	57.5	108.7	227.8	63.5						75.5
		105.8		93.8	71.5												
WATERLAND		84.5	133.8	143.9	163.5	70.1	89.9	281.7	80.4	179.8	67.7	90.7	79.0	72.5	72.5	164.5	57.5
	81.0	85.9	76.7	117.2	223.4	74.7	161.7	121.6	75.1	61.4	114.7	86.6	127.8		174.8	95.5	82.2
	62.0	148.6	198.3	96.4	120.5	106.0											

APPENDIX 2 TOTAL RAINFALL ONSET DATES PER RAINFALL DISTRICT

ONSET MONTHS		1979/80	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	1987/88	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94	1994/95
	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12
	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18											
LAERSDRIF - POLICE ARS			13-Nov-79	19-Nov-80	21-Nov-81	25-Oct-82	7-Nov-83	2-Nov-84	23-Dec-85	26-Nov-86	7-Oct-87	21-Dec-88	5-Nov-89	4-Nov-90	22-Nov-91	26-Oct-92	
	11-Nov-94	3-Nov-95	20-Nov-96	8-Dec-97		24-Nov-99	28-Oct-00	16-Nov-01	6-Jan-03	28-Nov-03	1-Feb-05	3-Dec-05	16-Nov-06	6-Feb-08	18-Dec-08	18-Nov-09	16-Dec-10
	28-Oct-11	12-Nov-12	28-Oct-13	13-Nov-14	12-Dec-15	14-Nov-16	24-Oct-17										
BLAAWKOP		19-Oct-79	16-Nov-80	8-Oct-81	28-Oct-82	7-Nov-83	27-Sep-84	26-Oct-85	13-Nov-86	22-Sep-87	8-Nov-88	17-Nov-89	2-Nov-90	7-Nov-91	10-Nov-92	29-Oct-93	28-Oct-94
	4-Nov-95	3-Nov-96	6-Nov-97	7-Oct-98	19-Nov-99	18-Oct-00	16-Nov-01	19-Nov-02	16-Nov-03	10-Nov-04	5-Nov-05	11-Dec-06	26-Oct-07	20-Nov-08	29-Oct-09	2-Nov-10	29-Oct-11
	7-Nov-12	28-Oct-13	6-Dec-14	9-Nov-15	7-Nov-16	24-Oct-17											
NELSHOOGTE BOS		22-Oct-79	17-Nov-80	9-Oct-81	7-Nov-82	3-Nov-83	12-Oct-84	20-Oct-85	17-Nov-86	6-Oct-87	8-Nov-88	7-Nov-89	30-Oct-90	11-Dec-91	25-Oct-92	25-Oct-93	2-Nov-94
	27-Oct-95	10-Nov-96	29-Sep-97	9-Oct-98	15-Nov-99	11-Oct-00	11-Nov-01	5-Nov-02	10-Nov-03	8-Nov-04	26-Nov-05	13-Nov-06	24-Oct-07	12-Nov-08	30-Aug-09	2-Nov-10	20-Oct-11
	6-Nov-12	28-Oct-13	1-Dec-14	13-Dec-15	25-Oct-16	21-Oct-17											
TAFELKOPPIES		24-Sep-79	15-Oct-80	26-Sep-81	7-Nov-82	4-Nov-83		20-Oct-85	13-Nov-86	14-Sep-87	30-Oct-88	6-Nov-89	4-Nov-90	26-Nov-91	26-Nov-92	21-Oct-93	27-Oct-94
	1-Nov-95	11-Nov-96	1-Nov-97	25-Oct-98	18-Nov-99	12-Oct-00	10-Nov-01	17-Nov-02	14-Nov-03	15-Nov-04	2-Nov-05	15-Oct-06	22-Oct-07	11-Nov-08	6-Nov-09	3-Nov-10	26-Nov-11
	30-Sep-12	26-Oct-13	6-Nov-14	10-Nov-15	6-Nov-16	26-Oct-17											
WITBANK STREHLA			17-Nov-79	16-Nov-80	13-Dec-81	7-Nov-82	4-Nov-83	12-Oct-84	28-Dec-85	13-Nov-85	7-Oct-87	18-Nov-88	18-Nov-89	5-Nov-90	18-Dec-91	26-Nov-92	29-Oct-93
	15-Jan-95	3-Nov-95	20-Nov-96	6-Nov-97	9-Oct-98	5-Dec-99	26-Oct-00	16-Nov-01	4-Nov-02	1-Dec-03	16-Nov-04	8-Nov-05	27-Nov-06	26-Oct-07	15-Nov-08	27-Oct-09	25-Nov-10
	17-Nov-11	7-Nov-12	14-Nov-13	21-Nov-14	15-Dec-15	13-Nov-16	24-Oct-17										
LEEUDORINGSTAD - SKL			16-Nov-79	9-Dec-80	12-Dec-81	8-Nov-82	16-Nov-83	31-Oct-84	19-Nov-85	15-Nov-86	1-Oct-87	10-Nov-88	5-Dec-89	31-Jan-01	21-Oct-91	20-Feb-93	30-Oct-93
	10-Feb-95	16-Dec-95	23-Nov-96	10-Nov-97	5-Nov-98	16-Jan-00	20-Nov-00	13-Nov-01	5-Dec-02	16-Nov-03	26-Dec-04	20-Jan-06	29-Nov-06	25-Oct-07	17-Nov-08	2-Nov-09	7-Dec-10
	6-Jan-12	No Onset	12-Dec-13	1-Dec-14	No Onset	No Onset	28-Oct-17										
MARICO	26-Oct-79	7-Oct-80	11-Dec-81	21-Dec-82	21-Nov-83	12-Nov-84	10-Nov-85	7-Nov-86	6-Oct-87	10-Nov-88	30-Nov-89	31-Jan-91	No Onset	No Onset	12-Nov-93	No Onset	16-Dec-95
	20-Nov-96	10-Jan-98	26-Oct-98	30-Dec-99	23-Dec-00	17-Oct-01	21-Nov-02	2-Dec-03	26-Dec-04	15-Jan-06	16-Nov-22	25-Oct-07	13-Jan-09	15-Dec-09	29-Nov-10	16-Dec-11	7-Nov-12
	30-Dec-13	23-Nov-14	6-Feb-16	13-Nov-16	13-Feb-18												
OTTOSDAL - POL		10-Dec-79	23-Nov-80	10-Dec-81	28-Jan-83	6-Dec-83	21-Nov-84	26-Dec-85	18-Oct-86	1-Oct-87	17-Nov-88	30-Nov-89	8-Jan-91	22-Oct-91	26-Nov-92	29-Oct-93	26-Nov-94
	14-Nov-95	21-Nov-96	21-Jan-98	7-Jan-99	17-Nov-99	20-Nov-00	17-Oct-01	25-Nov-02	10-Nov-03	27-Dec-04	26-Dec-05	15-Jan-07	26-Oct-07	17-Oct-08	28-Oct-09	3-Dec-10	18-Dec-11
	24-Dec-12	23-Dec-13	2-Dec-14	17-Jan-16	12-Dec-16	8-Feb-18											
RASHOOP - IRR		17-Nov-79	30-Nov-80	13-Dec-81	25-Nov-82	15-Nov-83	14-Nov-84	27-Nov-85	6-Nov-86	4-Dec-87	10-Nov-88	30-Nov-89	24-Dec-90	8-Dec-91	No Onset	3-Nov-93	15-Jan-95
	16-Dec-95	16-Dec-96	27-Dec-97	25-Oct-98	No Onset	14-Nov-00	5-Nov-01	No Onset	16-Nov-03	26-Dec-04	18-Dec-05	24-Nov-06	24-Oct-07	22-Nov-08	15-Nov-09	3-Jan-11	2-Feb-12
	2-Nov-12	16-Nov-13	1-Dec-14	30-Jan-16	18-Dec-16	23-Oct-17											
SCHWEIZER-RENEKE - POL			19-Feb-80	29-Nov-80	19-Sep-81	8-Nov-82	23-Dec-83	31-Oct-84	26-Dec-85	13-Nov-86	1-Oct-87	6-Nov-88	20-Feb-90	4-Feb-91	22-Oct-91	21-Nov-92	31-Oct-93
	26-Nov-94	16-Dec-95	14-Dec-96	21-Jan-98	No Onset	17-Jan-00	16-Dec-00	13-Nov-01	27-Dec-02	3-Jan-04	20-Dec-04	29-Jan-06	No Onset	27-Dec-07	26-Jan-09	24-Jan-10	22-Dec-10
	No Onset	No Onset	No Onset	No Onset	No Onset	No Onset											
BENFONTEIN		No Onset	17-Feb-81	10-Dec-81	No Onset	16-Dec-83	20-Feb-85	25-Dec-85	23-Nov-86	1-Oct-87	10-Nov-88	No Onset	4-Feb-91	10-Nov-91	4-Nov-92	30-Oct-93	No Onset
	27-Nov-95	3-Dec-96	21-Jan-98	22-Nov-98	24-Dec-99	16-Dec-00	2-Dec-01	14-Sep-02	9-Dec-03	7-Jan-05	9-Dec-05	9-Nov-06	24-Oct-07	30-Jan-09	31-Oct-09	9-Jan-11	No Onset
	23-Dec-12	25-Feb-14	25-Nov-14	8-Feb-16	23-Jan-17	4-Jan-18											
BETHLEHEM WO		15-Nov-79	6-Oct-80	13-Sep-81	7-Nov-82	5-Nov-83	30-Oct-84	29-Nov-85	26-Sep-86	12-Sep-87	14-Oct-88	17-Nov-89	3-Nov-90	6-Nov-91	1-Sep-92	23-Oct-93	22-Feb-95
	14-Nov-95	16-Oct-96	1-Oct-97	6-Nov-98	30-Dec-99	15-Oct-00	28-Sep-01	15-Sep-02	23-Nov-03	18-Dec-04	3-Nov-05	30-Aug-06	24-Oct-07	30-Nov-08	22-Nov-09	12-Nov-10	19-Dec-11
	14-Nov-12	14-Nov-13	23-Nov-14	2-Feb-16	13-Nov-16	23-Oct-17											
DEALESVILLE - MAG			15-Nov-79	14-Oct-80	15-Dec-81	8-Nov-82	No Onset	23-Feb-85	12-Feb-86	17-Nov-86	1-Oct-87	8-Nov-88	8-Jan-90	18-Feb-91	22-Oct-91	30-Nov-92	1-Nov-93
	9-Feb-95	14-Nov-95	3-Dec-96	20-Jan-98	29-Oct-98	23-Dec-99	20-Nov-00	12-Nov-01	16-Sep-02	10-Dec-03	27-Dec-04	12-Dec-05	30-Aug-06	24-Oct-07	8-Dec-08	2-Nov-09	10-Jan-11
	No Onset	No Onset	27-Feb-14	No Onset	No Onset	No Onset											

ODENDAALSRUS		16-Nov-79	7-Oct-80		8-Nov-82	5-Nov-83	7-Nov-84	25-Dec-85	15-Nov-86	1-Oct-87	10-Nov-88	11-Nov-89	21-Jan-91	10-Nov-91	21-Nov-92	23-Oct-93	26-Nov-94
	5-Nov-95	21-Nov-96	20-Jan-98	22-Nov-98	27-Dec-99	19-Nov-00	13-Nov-01	31-Dec-02	3-Dec-03	27-Dec-04	27-Jan-06	30-Aug-06	25-Oct-07	7-Dec-08	29-Oct-09	7-Dec-10	21-Dec-11
	23-Dec-12	15-Dec-13	1-Dec-14	No Onset	No Onset	3-Jan-18											
ROCCO	10-Dec-79	30-Nov-80	19-Nov-81	8-Nov-82	30-Nov-03	30-Oct-84	6-Nov-85	13-Nov-86	13-Sep-87	26-Sep-88	14-Nov-89	2-Nov-90	5-Nov-91	25-Nov-92	22-Oct-93	26-Nov-94	2-Nov-95
	10-Nov-96	4-Oct-97	24-Oct-98	22-Dec-99	13-Oct-00	12-Nov-01	15-Sep-02	25-Nov-03	2-Jan-05	15-Nov-05	27-Nov-06	24-Oct-07	13-Nov-08	7-Nov-09	24-Nov-10	25-Nov-11	3-Oct-12
	13-Nov-13	24-Oct-14	22-Jan-16	12-Nov-16	6-Jan-18												
VREDEFORT		14-Nov-79	23-Nov-80	10-Dec-81	7-Nov-82	1-Nov-83	1-Nov-84	13-Nov-85	6-Nov-86	4-Oct-87	8-Nov-88	18-Nov-89	1-Jan-91	10-Nov-91	20-Nov-92	22-Oct-93	1-Dec-94
	13-Nov-95	19-Nov-96	8-Dec-97	2-Nov-98	22-Dec-99	18-Nov-00	13-Nov-01	18-Nov-02	25-Nov-03	26-Dec-04	8-Dec-05		No Onset				19-Dec-11
	No Onset	29-Nov-14	No Onset	11-Jan-17	30-Oct-17												
WATERLAND		16-Dec-79	3-Dec-80	20-Dec-81	8-Nov-82	6-Nov-83	27-Dec-84	26-Dec-85	28-Oct-86	1-Oct-87	26-Sep-88	1-Dec-89	30-Dec-90	22-Oct-91	6-Nov-92	30-Oct-93	9-Dec-94
	14-Nov-95	4-Nov-96	25-Dec-97	6-Nov-98	30-Dec-99	12-Oct-00	12-Nov-01	14-Sep-02	29-Nov-03	22-Oct-04	4-Nov-05	30-Aug-06	25-Oct-07		29-Oct-09	7-Dec-10	26-Dec-11
	8-Nov-12	22-Nov-13	24-Nov-14	9-Feb-16	16-Nov-16	12-Feb-18											

APPENDIX 3 TOTAL NUMBER OF TTTS PER RAINFALL ONSET

TOTAL NO. OF TTT CASES ASSOC WITH RN ONSETS						1979/80	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	1987/88	1988/89	1989/90	1990/91
	1991/92	1992/93	1993/94	1994/95	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08
	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18							
LAERSDRIF - POLICE ARS			6	4	6	1	2	7	3	3	2	5	4	4	6	3	
	3	8	3		6	3	5	2	6	2	3	4	2	5	3	6	2
	3	2	2	3	4	2											
BLAAWKOP		5	4		1	2	1	3	3	1	4	6	4	1	6	5	
	3	2	3	2	6	3	5	2	5	2	1	4	1	2	4	1	2
	3	2	3	2	3	2											
NELSHOOGTE BOS		5	4		3	2	1	2	2	2	4	4	4	9	3	4	
	3	6	2	2	5	2	5	2	4	2	3	5	1	2		1	2
	3	2	4	3	2	2											
TAFELKOPPIES		1	1		3	2		2	3	1	2	4	4	6	5	4	
	3	5	2	5	5	2	5	2	5	2	1	2	1	1	4	1	3
	1	2	1	2		3											
WITBANK STREHLA			6	4	7	3	2	1	4	3	2	2	6	4	4	5	5
	3	3	8	2	2	6	4	5	4	5	2	1	5	1	2	3	3
	2	3	4	3	3		2										
LEEUDORINGSTAD - SKL			6	3	7	3	2	7	2	3	2	2	4	4	5	2	5
	2	5	8	2	7	6	5	5	4	5	2	5	5	1	2	4	5
	7		1	4			3										
MARICO	5	1	7	3	3	4	3	4	2	2	4	4			6		5
	8	6	5	6	3	5	2	5	2	3	4	1	4	5	5	7	3
	5	3	1	4	7												
OTTOSDAL - POL		5	5	7	2	3	5	4	2	2	2	4	6	4	5	5	2
	2	8	5	3	5	4	5	1	4	1	5	3	1		3	5	7
	5	1	4	2	3	5											
RASHOOP - IRR		6	4	7	4	2	4	2	4	4	2	4	6	6		5	3
	5	3	5	5		3	5		5	2	5	5	1	2	3	7	2
	3	5	4	1	4	2											
SCHWEIZER-RENEKE - POL			5	4	1	3	4	7	4	3	2	3		4	4	5	5
	2	5	4	5		6	3	5	4	4	3	5		5	5	4	6
BENFONTEIN			8	7		3	3	4	3	2	2		4	5	5	5	
	2	8	5	8	6	3	6	3	4	1	4	4	1	4	4	5	
	4	4	3	1	7	4											
BETHLEHEM WO		7	1	1	3	2	6			1	4	6	4	4		5	4
	2	3	2	8	6	3	1	3	5	3	1		1	4	3	3	7
	2	4	3	1	4	2											
DEALESVILLE - MAG			7	1	7	3		2	2	2	2	4		3	4	4	5
	2	2	8	5	6	6	4	5	3	4	2	1		1	8	4	6
		3															

ODENDAALSRUS		6	1		3	2	6	4	3	2	2	4	4	5	5	5	2
	3	8	5	8	6	4	5	3	5	2	5		1	7	3	5	6
	4	2	4			4											
ROCCO	5	4	5	13	4	6	4	3	1	2	4	4	3	6	4	2	3
	6	1	4	6	2	5	3	5	1	1	5	1	2	4	3	3	1
	2	1		4	4												
VREDEFORT		7	5	7	3	1	7	2	4	2	4	6	5	5	5	4	2
	2	7	3	8	6	4	5	2	5	2	4						7
		4		7	3												
WATERLAND		3	5	6	3	2	3	4	2	2	2	4	6	4	6	5	3
	2	3	5	8	6	2	5	3	6	4			1		3	5	8
	3	4	3	1	4	7											

APPENDIX 4 AFTER-ONSET TOTAL RAINFALL AMOUNTS PER RAINFALL DISTRICT (UP TO 120 DAYS)

ONSET MONTHS		1979/80	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	1987/88	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94	1994/95
	1995/96	1996/97	1997/98	1998/99	1999/00	2000/01	2001/02	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12
	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18											
LAERSDRIF - POLICE ARS			588.6	348.0	362.9	251.4	348.1	537.1	148.5	525.0	572.5	251.5	665.0	767.5	298.5	715.3	
	288.4	620.5	357.3	74.9		630.7	491.8	437.0	35.0	522.5	150.8	442.8	335.0	211.7	296.5	154.5	388.0
	381.2	324.4	456.6	464.6	310.0	429.6	343.4										
BLAAWKOP		555.7	468.2	405.5	365.6	659.9	400.9	511.7	466.9	648.0	397.9	406.3	513.4	317.2	519.7	605.8	533.0
	793.0	302.7	376.5	522.5	917.5	475.0	430.5	393.5	565.6	585.0	499.5	343.5	367.5	549.9	549.4	420.8	393.5
	369.0	467.0	288.5	394.0	477.7	462.5											
NELSHOOGTE BOS		622.2	691.0	563.0	400.8	927.8	787.9	573.9	532.0	527.0	427.5	482.5	694.0	364.0	454.0	403.0	493.2
	1146.3	591.9	428.8	629.7	1089.8	567.8	603.5	293.4	784.3	465.6	909.0	503.3	822.9	802.7	678.7	968.8	550.3
	745.4	634.8	539.7	497.6	799.5	635.6											
TAFELKOPPIES		452.0	559.5	549.0	325.0	799.0		680.0	467.4	576.5	536.4	398.0	659.0	334.1	614.6	561.2	386.2
	893.3	624.7	545.5	632.6	830.6	480.3	422.6	405.3	496.5	562.0	687.5	713.0	382.0	553.7	669.0	872.6	425.6
	589.9	533.0	535.5	425.0	483.9	432.0											
WITBANK STREHLA			522.7	612.1	264.8	287.3	405.2	259.1	360.9	372.0	383.6	317.5	452.6	395.3	163.5	392.3	356.5
	380.0	1047.0	440.5	418.5	550.1	789.2	302.5	349.0	237.7	472.5	439.2	442.5	260.0	450.5	448.5	592.0	467.5
	403.5	431.5	447.5	413.0	425.5	451.0	401.0										
LEEUDORINGSTAD - SKL			273.8	395.2	177.4	232.0	88.0	255.0	338.5	172.5	208.5	559.5	380.5	86.5	78.5	51.5	404.5
	191.0	291.5	283.5	415.0	388.0	129.0	387.5	354.0	331.9	207.5	440.0	385.5	75.0	330.6	456.5	362.0	523.0
	199.5		377.5	274.5			285.0										
MARICO	532.8	353.5	326.1	284.7	227.7	228.3	169.8	120.0	245.6	201.9	392.6	45.3			390.8		305.0
	619.1	285.2	470.9	692.4	318.9	559.7	280.6	286.9	296.3	406.6	173.8	520.9	356.6	283.4	391.4	310.6	276.0
	366.8	245.6	214.0	728.4	350.4												
OTTOSDAL - POL		287.5	503.0	246.5	128.0	150.5	286.0	216.5	207.1	299.5	407.0	257.3	275.5	233.3	262.2	398.2	213.5
	488.0	324.5	173.6	123.4	412.7	306.5	486.1	338.6	394.5	526.5	583.0	130.5	295.0	505.0	352.1	579.5	193.1
	202.5	607.2	169.6	241.0	624.0	210.5											
RASHOOP - IRR		474.9	361.1	192.7	238.5	314.5	347.2	228.0	332.5	314.3	326.5	283.9	475.7	199.5		409.0	325.0
	532.5	442.1	173.0	80.8		156.2	211.2		331.5	331.0	488.0	135.0	243.9	264.1	397.0	278.3	63.0
	415.0	601.5	272.0	243.0	542.5	262.0											
SCHWEIZER-RENEKE - POL			79.4	308.2	169.5	154.6	200.5	281.4	224.7	120.0	267.1	380.8	172.0	227.0	122.1	170.0	240.0
	229.7	401.5	314.6	195.0		235.0	263.2	489.6	219.4	275.5	189.7	323.6		217.5	149.9	270.5	291.7
BENFONTEIN			160.7	244.9		198.5	97.7	173.1	164.0	94.2	243.8		205.4	100.9	256.2	358.5	
	253.3	286.7	221.0	126.2	269.7	168.7	328.0	187.4	272.5	284.7	377.7	103.5	238.5	197.5	347.5	1204.0	
	69.2	137.2	378.6	145.0	82.2	213.5											
BETHLEHEM WO		348.9	368.6	195.3	243.2	434.0	325.1	393.0	376.3	508.1	458.1	332.6	402.9	280.1	358.3	601.3	156.6
	584.0	370.2	428.1	478.4	568.1	319.4	572.1	222.0	303.1	509.6	500.6	365.5	362.7	383.7	482.2	578.7	309.4
	426.6	568.0	436.8	239.0	594.8	440.9											

DEALESVILLE - MAG			213.1	376.3	294.4	153.5		63.0	143.0	104.0	201.5	423.0	281.0	292.5	114.5	197.0	333.0
	213.5	454.6	394.5	372.7	304.3	328.5	164.6	416.1	192.8	286.8	252.4	317.7	115.3	189.6	270.1	379.9	39.9
		5.0															
ODENDAALSRUS		326.0	298.1		147.6	167.7	225.7	198.7	185.5	218.9	273.0	156.1	307.4	125.6	159.3	322.7	248.2
	557.4	310.0	212.1	191.5	314.7	279.6	302.2	179.1	197.2	286.0	317.6	220.2	399.8	262.6	435.0	383.4	174.4
	45.0	155.4	220.8			175.9											
ROCCO	413.4	471.4	263.5	267.7	290.3	276.4	396.8	387.2	509.5	352.6	285.5	349.6	331.4	376.6	429.4	435.4	704.6
	454.0	438.2	588.4	246.1	264.9	280.6	210.2	313.0	443.5	458.0	254.6	323.2	524.2	366.4	782.0	344.3	322.1
	562.2	507.1	216.4	513.3	314.9												
VREDEFORT		332.0	543.0	259.0	178.5	260.5	280.0	249.0	338.0	377.5	552.0	399.0	351.0	201.0	237.0	513.0	284.4
	668.5	262.8	355.6	409.9	479.5	238.3	535.9	392.1	365.7	414.7	173.1						133.5
		159.0		357.0	353.5												
WATERLAND		246.5	394.3	338.2	166.4	325.1	224.7	226.1	258.8	206.3	304.1	387.0	363.4	223.0	248.5	440.6	321.8
	615.8	413.1	435.4	392.5	333.0	297.3	513.6	277.7	298.4	447.9	559.6	193.8	348.3		445.1	656.2	162.4
	338.6	386.2	279.3	209.0	393.2	295.5											

APPENDIX 5 SEASONAL MAIZE YIELD PER MAIZE PRODUCTION DISTRICT

DISTRICT NO.S		46	47	62	63	75	72	73	81	82	83	61	62	84	85	90	91	93
MAIZE YIELD REGIONS			TAFELKOPPIES		NELSHOOGTE BOS		BLAAUWKOP		LAERSDRIF - POLICE ARS			WITBANK	STREHLA		WATERLAND			
	VREDEFORT		BENFONTEIN		DEALESVILLE - MAG			ODENDAALSRUS		ROCCO	BETHLEHEM WO		OTTOSDAL - POL		RASHOOP - IRR			
	SCHWEIZER-RENEKE - POL			LEEUDORINGSTAD - SKL			MARICO											
SEASONS	Piet Retief.	Lydenburg.		Amersfoort.		Belfast.	Witbank.	Clocolan.	Koppies.	Boshof.	Bultfontein.		Welkom.	Vrede.	Bethlehem.		Coligny.	
	Rustenburg.		Vryburg.		Wolmaransstad.		Marico.											
1980/81	3.78	3.09	1.68	4.38	3.58	4.10	3.03	1.94	2.09	2.88	1.66	3.57	3.94	2.12	2.08	2.76	3.46	
1981/82	2.99	1.32	1.06	1.73	2.33	2.44	1.14	0.91	1.94	1.72	0.66	1.74	2.60	1.09	0.58	1.64	2.45	
1982/83	1.60	2.16	1.14	1.51	1.64	0.56	0.77	0.45	0.87	1.52	0.39	1.45	1.27	0.35	0.33	0.56	1.05	
1983/84	4.72	2.91	1.84	1.82	2.49	0.87	0.66	0.16	0.20	0.36	1.18	2.07	0.26	0.17	0.11	0.20	0.61	
1984/85	3.11	2.38	1.59	1.90	2.37	3.20	3.06	1.37	2.51	2.17	1.83	2.84	1.11	1.20	1.12	1.25	1.21	
1985/86	3.59	3.31	0.90	2.96	3.65	1.99	1.07	2.20	1.77	1.44	2.06	2.74	1.46	0.60	0.65	1.23	0.94	
1986/87	3.36	3.27	1.30	3.36	3.40	1.09	1.72	1.27	1.05	1.60	1.79	1.54	1.52	0.89	0.84	1.09	0.98	
1987/88	2.91	3.13	1.30	3.62	3.19	2.60	2.34	1.29	1.84	2.20	1.99	3.16	1.22	1.68	1.41	1.20	1.73	
1988/89	4.60	3.68	2.00	3.50	4.10	3.70	2.92	2.19	3.15	3.80	2.20	3.47	3.44	1.60	2.73	3.14	2.90	
1989/90	4.10	3.54	2.27	3.26	4.05	2.84	2.04	1.76	2.82	3.04	1.94	2.78	2.92	1.64	1.55	2.10	1.93	
1990/91	4.72	4.63	2.20	4.04	4.31	2.22	2.85	1.48	1.54	1.89	1.82	3.08	3.06	2.21	1.42	1.61	2.56	
1991/92	2.72	1.62	1.10	1.88	2.98	0.64	0.53	0.41	1.20	0.50	0.84	0.56	0.25	0.43	0.32	0.29	0.18	
1992/93	4.77	2.47	1.99	3.48	4.17	2.12	2.66	1.39	3.05	2.59	1.8	3.13	2.08	1.17	1.21	1.21	1.14	
1993/94	5.36	3.42	2.45	4.36	4.98	3.04	3.64	1.93	2.97	2.71	2.96	4.20	3.70	3.33	1.80	2.62	2.49	
1994/95	2.75	1.88	0.77	2.28	2.28	0.84	1.43	1.18	2.28	1.37	1.67	1.41	1.41	0.47	0.79	1.42	0.47	
1995/96	3.74	4.13	1.01	4.17	4.44	3.15	3.46	2.47	3.36	3.49	1.95	3.59	3.37	2.52	2.09	2.96	1.39	
1996/97	3.29	3.76	0.69	2.91	3.24	2.94	2.61	2.35	3.03	2.96	2.55	2.89	3.28	1.76	1.84	2.30	1.60	
1997/98	4.61	3.60	0.90	4.07	3.92	2.70	2.24	2.42	2.16	2.38	2.11	2.69	3.21	1.37	1.39	1.85	1.45	
1998/99	4.74	4.05	1.63	4.43	3.84	2.07	2.46	2.44	3.13	2.80	1.69	3.49	2.13	1.07	1.38	1.81	0.80	
1999/00	4.54	3.51	3.04	4.39	5.50	3.05	3.51	3.09	4.08	3.10	2.38	2.95	3.52	3.27	2.32	2.72	2.95	
2000/01	3.04	3.14	2.47	2.91	2.91	2.11	2.18	2.38	2.78	2.24	2.01	3.05	2.47	2.33	1.91	2.07	1.80	
2001/02	4.92	3.92	3.85	4.52	4.97	2.89	2.80	3.18	3.41	1.96	3.80	3.08	3.60	3.30	2.49	2.19	1.31	
2002/03	5.12	4.99	2.77	3.45	3.92	2.74	1.87	3.03	3.29	2.07	2.46	3.32	2.56	2.09	1.78	2.36	2.34	
2003/04	6.06	5.58	4.50	5.05	4.55	2.88	3.97	3.00	3.72	2.93	2.20	3.08	4.01	2.62	1.54	2.69	2.76	
2004/05	6.61	5.61		5.70	5.87	2.90	3.92	3.70	4.45	4.08	3.54	4.37	3.89	3.95	2.38	3.21	1.67	
2005/06	6.79	6.43	2.27	4.57	5.44	3.56	4.92	4.26	4.83	2.87	3.23	3.78	3.11	3.86	2.97	2.4	1.64	
2006/07	5.96	6.40	4.09	3.95	3.15	1.58	2.43	2.71	3.75		2.45	2.44	1.42	2.35	1.50	1.53	0.69	
2007/08	5.14	6.91	5.30	4.36	5.86	3.26	3.25	4.28	5.80	1.39	3.12	3.89	3.74	4.88	3.84	3.59	1.12	
2008/09	5.27	6.90	6.11	6.13	5.82	3.60	4.65	5.16	5.11	1.50	3.83	4.44	4.65	4.30	3.49	3.31	2.24	
2009/10	5.45	7.54	7.39	5.24	5.34	3.59	4.80	5.32	5.22	1.00	3.31	4.88	4.69	4.45	3.74	3.70	2.31	
2010/11	4.86	7.58	7.29	3.91	5.50	3.09	5.31	5.40	5.50	0.87	2.74	3.88	4.48	3.08	4.03	4.17	1.60	
2011/12	5.41	5.33	7.44	4.73	6.23	2.97	3.92	4.32	5.92	6.00	5.43	3.40	2.81	3.24	3.29	3.63	0.80	
2012/13	6.83	6.51	6.69	4.46	6.51	3.52	3.23	3.81	4.56	4.25	5.10	4.67	2.19	3.04	2.18	2.33	0.36	
2013/14	6.61	7.10	5.80		6.00	3.49	4.50	5.83	5.83		4.28	5.26	4.88	3.67	5.11	4.66	1.38	
2014/15	6.96	6.68	6.73	5.01	4.23	2.18	1.59	4.08	4.11		4.88	3.38	2.35	0.95	2.13	2.04		
2015/16	4.51	7.17	6.96	6.42	4.33	1.60	2.47		2.08		3.45	2.99	2.51		1.89	2.08		
2016/17	7.96	10.11	5.75	7.03	6.93	6.18	5.05	6.90	5.60		5.10	6.74	5.24		5.11	5.63		
2017/18	7.91	10.79		7.07	6.85	4.73	5.04	5.75	4.12	3.19	3.69	5.97	4.37	1.67	6.23	5.10		