An investigation of the impacts of intra-seasonal rainfall variability on the maize growing season in Limpopo Province, South Africa from 1990-2014

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Plagiarism declaration

I know the meaning of plagiarism and declare that all the work in this dissertation, save for that which is properly acknowledged is my own.

Signature: …Signed by candidate……………………………………………………

Dedication

In memory of my late mother Roselet Ramugondo.

For her unwavering love and the many great wishes she had for me!

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Abstract

Rain fed maize is an important staple food crop for rural communities in Southern Africa as it plays a major role in ensuring food security and improving livelihoods. Rainfall consistency and intensity is an essential requirement for successful maize growing seasons. The variability of intra-seasonal rainfall characteristics such as onset, cessation and wet and dry spells threatens maize yields in Southern Africa. Previous studies have focused on the impacts of seasonal rainfall totals on maize yields. The aim of this study is to investigate the impacts of intra-seasonal rainfall variability on the maize growing season of Limpopo Province, South Africa from 1990 to 2014. A Self-Organizing Map (SOM) is used to identify and distinguish synoptic states and patterns that are conducive for growing maize in the province from those that are not. The SOM is trained using daily mean Geopotential height reanalysis data, composites for rainfall and moisture are then analysed to understand surface responses. CHIRPS daily rainfall data is used to analyse the variability of rainfall characteristics. The relationship between these rainfall characteristics and maize yield is evaluated to assess the impacts of variability on maize yields.

The SOM shows that summer maize growing season is characterised by low pressure systems over the mainland which act as tropical sources of moisture and the formation of cloud-bands associated with Tropical Temperate Troughs. There is a trend in late rainfall onset and earlier cessation leading to a shift and shortening of the rainy season. The shifted and shortened rainy seasons are characterised by dry spells and high intensity rainfall events and are potentially more suitable for planting the shorter season maize cultivars. Regardless of these agrometeorological conditions being detrimental to yields, district level and provincially averaged maize yields show an overall increasing trend. This is a result of improved farming methods such as planting drought resistant short season yellow maize cultivars which can withstand dry spells.

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List of abbreviations

CDD	Consecutive Dry days
CHIRPS	Climate Hazards Group Infrared Precipitation with Station data
CSAG	Climate System Analysis Group
CWD	Consecutive Wet Days
DAFF	Department of Agriculture Forest and Fisheries
ENSO	El Niño Southern Oscillation Index
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
LRB	Limpopo River Basin
NCAR	National Centre for Atmospheric Research
NCEP	National Centre for Environmental Prediction
SAH	South Atlantic High-pressure system
SAWS	South African Weather Services
SIOCZ	South Indian Ocean Convergence Zone
SIH	South Indian High-pressure system
TTTs	Tropical Temperate Troughs
WRC	Water Research Commission

Chapter 1

Introduction

1.1. Background

Climate variability and crop production in Southern Africa

Rainfed agriculture plays a significant role in economic growth, creation of jobs and food security in Southern Africa. Food security, however, remains a major concern throughout the subcontinent as most staple food agricultural systems are predominantly rainfed (Syampungani et al., 2010, Rockström et al., 2010). It is estimated that over 70% of people in Southern Africa rely on rainfed agriculture and face food insecurity (Mabhaudhi et al., 2018). Over the past 2 decades, climate has been changing drastically in Southern Africa, rainfall has become erratic and temperature has increased drastically (Kusangaya et al., 2014, Jury, 2013, MacKellar et al., 2014). These changes in the climate system threaten the yield potential of staple food crops such as wheat, millet, sorghum and maize leading to food insecurity. Future projections show that the food insecurity challenge will persist resulting from the shrinking of areas suitable for staple food crop farming (Schlenker and Lobell, 2010). A shift in the rainy season resulting to changes in rainfall onset has been observed for greater parts of Africa including Southern Africa (Dunning et al., 2016a, Liebmann et al., 2012a). Mean temperatures are projected to increase by 2°C and possibly 3 - 4°C in Southern Africa by 2065 (James and Washington, 2013). Climate variability has been attributed as one of the main causes of reduced yields across the subcontinent (Ramirez-Villegas and Thornton, 2015).

For Southern Africa, studies show that global warming has led to changes in the climate system leading to increased frequency and intensity of heavy rainfall events (Thornton et al., 2014, Trenberth, 2011). Southern Africa is dominated by summer rainfall regions and the summer rains are essential for subsistence agriculture. The complex topography, geographic location and the varying impacts of the surrounding ocean currents make Southern Africa particularly vulnerable to climate change and variability (Xulu et al., 2020, Dedekind et al., 2016). Changes in the climate system are evident through extreme heavy rainfall events and prolonged droughts (Jury, 2013, Baudoin et al., 2017). For example, in February 2000, parts of Southern Africa including Mozambique, Zimbabwe and South Africa experienced extreme rainfall leading to floods which damaged infrastructure (Cairncross and Alvarinho, 2013). At interannual and decadal scales, the sub-continent has experienced prolonged El Niño induced droughts such as the 1982/83, 1997/98 and the 2014-2016 (Rouault and Richard, 2005, Blamey et al., 2018). These droughts had significant impact on livestock and crop production in the region. Warm anomalous Sea-surface temperatures in the Pacific Ocean and the intensification of surface winds associated with the El Niño Southern Oscillation (ENSO) modulate precipitation on the subcontinent (Hoell et al., 2017). Alternating wet and dry years induced by the ENSO have had significant impacts on different sectors which are important for economic growth such as the agricultural sector. Some studies have found that the strength and position of significant large climate modes such as the Inter-Tropical Convergence Zone (ITCZ) and features such as the Angola Low play significant roles in influencing rainfall variability in Southern Africa (Quagraine et al., 2019, Nicholson, 2017, Munday and Washington, 2017). The seasonal shifting and intensification of the ITCZ influences convection processes and the formation of Tropical Temperate Troughs and cloud bands which contribute the most to summer rainfall in the region (Suzuki, 2011, Baumberg et al., 2015). At seasonal scales, significant changes in intensity of wet and dry spells, number of rainy days and daily patterns of rainfall distribution have been observed (Mupangwa et al., 2011a, Crétat et al., 2011). Rainy seasons have shifted and shortened as a result of late rainfall onset, these short seasons are often characterized by high intensity rainy days and mid-summer dry spells. These local scale rainfall changes are associated with changes in dynamics of large synoptic features like the Tropical Temperate Troughs (Hart et al., 2010, Suzuki, 2011). These studies indicate the need to investigate the variability in rainfall characteristics which are critical for the crop growing season.

Staple food agricultural systems are essential for household food security and improving livelihoods in Southern Africa. Staple crops such as maize, millet, sorghum and wheat are important for rainfed smallholder farms as they are used for consumption, livestock feeds and for small-scale commercial gain (Rurinda et al., 2014, Mukarumbwa and Mushunje, 2010). Of these crops, maize is the dominant crop planted in the subcontinent (Langyintuo et al., 2010). Agricultural success and yield of maize is driven by many factors including the timing and intensity of seasonal rainfall, availability of seeds and land. For smallholder farmers of rainfed maize, changes in rainfall patterns have significant impacts as they may impact phenology and lead to reduced crop yields (Moeletsi et al., 2011b, Cairns et al., 2013). Maize is particularly more sensitive to water deficits and is mostly planted on drylands in most parts of Southern Africa (Zinyengere et al., 2014).

Given the importance of maize in maintaining livelihoods and combating food insecurity, there is a need to investigate the impacts of climate variability on yield potential and quality. Rurinda et al. (2014) demonstrated the need to improve cropping systems to curb impacts of climate change using planting dates and maize cultivars. Zinyengere et al. (2013) estimated that maize yields are expected to decline by 18% on average in Southern Africa in the mid-century. This decline in yield threatens food security for farmers with low adaptive capacity in Southern Africa hence there is a need to investigate the impact of climate variability on yield output.

1.2. Rationale of the study

In South Africa, maize is a significant crop for economic growth and is mainly grown in the dryland areas of Free State, Gauteng, North west and Limpopo Province. Commercial maize accounts for 95-96% of the total maize produced in the country whilst subsistence maize accounts for the rest (Schulze, 2016). Akpalu et al. (2008a) estimated that on average, maize requires 450 mm to 600 mm per season for optimal growth. In South Africa, maize yield may vary annually with variability in rainfall (Akpalu et al., 2008b). The spatio-temporal variability of rainfall in the country is dependent amongst other factors on ocean-atmospheric interactions, topography and the varying strength and location of regional rainfall drivers (Botai et al., 2018).

Although the impacts of rainfall variability have been well documented in most regional studies, crop failure and reduced yields resulting from late onset, dry spells within the rainy season and high intensity rainfall events persist (Moeletsi and Walker, 2012). There is still high uncertainty on suitable planting dates for different crop varieties in South Africa particularly in Limpopo Province. The maize growing season coincides with different rainfall characteristics which may threaten or enhance yield depending on the timing in relation to the crop cycle (Tadross et al., 2009). Given the importance of maize and the variability of summer rainfall in South Africa, it is essential to investigate the impacts of intra-seasonal rainfall variability on the maize growing season of Limpopo Province. Although the province is not the largest maize growing region in the country, a large population in the province depends on maize for subsistence.

1.3. Study aim and specific objectives

The aim of this study is to investigate the impacts of intra-seasonal rainfall variability on the maize growing season of Limpopo Province, South Africa between 1990-2014.

Specific objectives

- To review the sensitivity of maize phenology to intra-seasonal rainfall variability.
- To identify and analyse large scale drivers of rainfall variability over Limpopo Province.

- To analyse maize crop-specific intra-seasonal rainfall characteristics over Limpopo Province.
- To relate the impacts of intra-seasonal rainfall characteristics with maize growth characteristics

1.4. Thesis outline

This thesis is composed of five chapters and each chapter adds value to the understanding of rainfall variability and the impacts on maize yield in Limpopo Province, South Africa. Chapter 1 is an introductory chapter and it provides a broader context from which the study stems. This chapter also describes the study aim and objectives. Chapter 2 analyses and reviews the relevant literature that informs this study. Chapter 3 describes the material and methods adopted in this study and how they are applied to best achieve the objectives of the study. Chapter 4 presents and discusses the results of this study through graphs, tables and maps. Chapter 5 provides an overview based on the key findings and explains the contribution of this study to the understanding of the impacts of intra-seasonal rainfall variability on maize yields. The approach of this study links rainfall characteristics with the maize growing season and yield output by analysing the impact of intra-seasonal rainfall indices on maize yield variability.

Chapter 2

Literature review

2.1. Introduction

Maize sensitivity to rainfall variability

Maize plays an essential role as a staple food crop for subsistence and boosting of the economy in Africa. In Southern Africa, maize is mostly rainfed and is mainly grown between October and April. This growing period coincides with the main austral summer rainfall period which is from October to April in most parts of the subcontinent. Studies have shown that the yield and quality of maize partly depends on the timing of rainfall with respect to maize phenology (Tadross et al., 2009, Mupangwa et al., 2011a). As most Southern African countries are impoverished and depend on maize for subsistence, understanding the sensitivity of maize phenology to rainfall variability and water stress is critical for various socio-economic sectors (Mulungu and Ng'ombe, 2019). Although some studies have covered aspects of maize and rainfall variability such as dry spell probability, daily rainfall distribution and suitable planting dates (Duffy and Masere, 2015, Moeletsi and Walker, 2012), there is a need to explore further on the water stress sensitivity of reproductive stages of maize phenology particularly in Limpopo Province, South Africa where maize is mainly grown on drylands. With a focus on germination, pollination and physiological maturity stages of maize, this section reviews available literature on the sensitivity of maize phenology to water stress induced by intra-seasonal rainfall characteristics such as late onset, dry spells and shorter length of rainy season. To a lesser extent, the section highlights how factors such as temperature variability, slope type and farming practices such as planting depths can influence maize phenology and yield. The selection of critical phenological stages was aided using a summary table (**Table 1**) designed to show critical maize stages and their stress sensitivity to various rainfall characteristics and other geographical factors.

2.2. Maize production and growth requirements in South Africa

Many aspects have been studied to quantify the impact of climate variability on maize, for example, production. Estimations show that in the year 2000, maize accounted for 40% of the cultivated area in South Africa and yielded over 15% of the gross value of all agricultural products (Statistics, 2008). The main production regions for maize in South Africa include; North West, the Orange Free State, Gauteng, Mpumalanga and Limpopo. Greyling and Pardey (2019) established that commercial farmers accounted for about 94.6% of all the maize produced in South Africa in 2015 and for this, white maize accounted for 49.6%. In earlier studies, for shorter and drier growing seasons, yellow maize production was found to be higher than white maize, this is because white maize requires longer rainy seasons for optimal growth in areas like the Free State Province (Moeletsi et al., 2011a). Given the trend of increased variability in white and yellow maize production with varying seasonal climate, it is important to understand how the main production regions are impacted. For example, the 2015/16 El Niño induced drought resulted in the poorest white maize harvest for Free State and North-West (53%) due to extended dry spells within the growing season (Botai et al., 2016). Although maize production and estimate studies have provided insight on the impact of climate variability on maize, most are limited to understanding yield responses hence they do not directly contribute to the scope of this section which focuses on specific phenology responses to different rainfall characteristics. **Figure 1** below shows the annual commercial and smallholder farm maize yields in South Africa from 1936-2017.

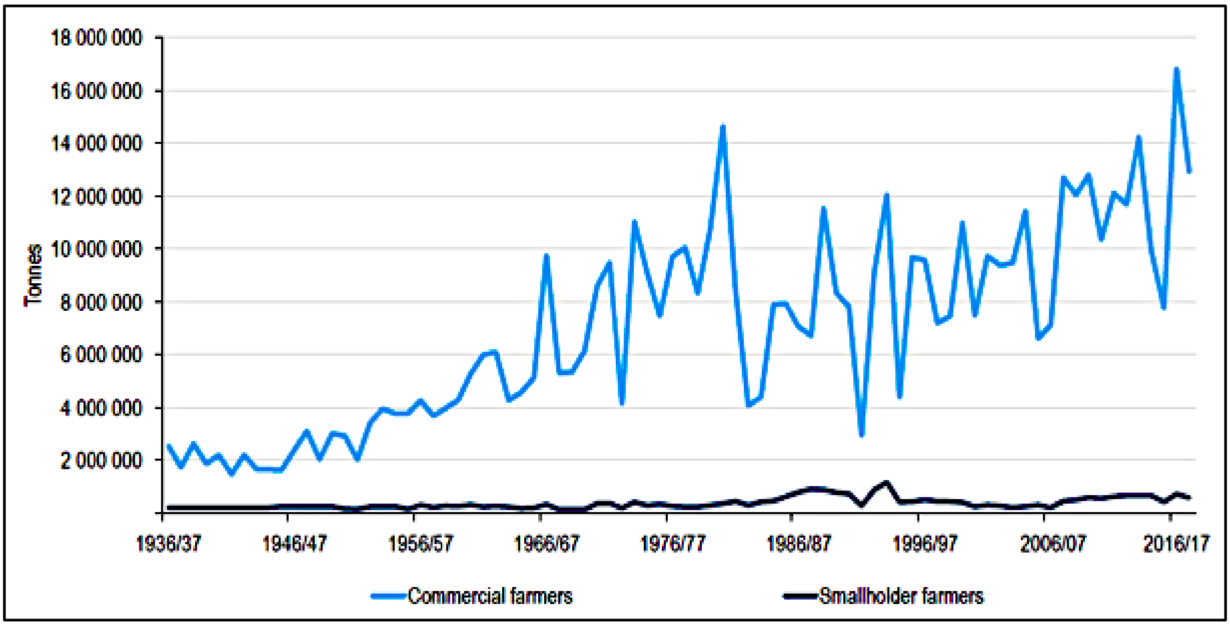


Figure 1 :Commercial and small-holder farmer maize yield in South Africa from 1936-2017. The blue line graph represents commercial maize yield (ton/ha) and the black line represents smallholder farm maize yield (ton/ha).

Source:(Greyling and Pardey, 2019).

It is estimated that at full maturity each maize plant would have used a minimum of 250 Litres of water in the absence of water stress. A yield of 3152 kg/ha would require approximately 350 to 450mm of rainfall per year and each millimeter (mm) of water used can produce around 15-16 kg (Baloyi, 2012, Du Plessis, 2003). Many studies also argue that the reproductive stages of maize are more water stress sensitive than the vegetative stages because of higher moisture requirements (Mtongori et al., 2015a, Mupangwa et al., 2011b). Bergamaschi et al. (2007) defined the reproductive stage as a 45-day period comprising of flowering and grain-filling. **Figure 2** shows maize growth stages and the critical moisture requirement periods. This provides insight on the water stress sensitive stages of maize growth and management techniques to use to maximize yield. The first two weeks before and after pollination are more water-stress sensitive than the rest of the growing season. As the optimal temperature for growth is 20-30°C, temperature exceeding 30°C and 5 to 10-day dry spells below 2 mm mean daily rainfall can lead to irreversible yield losses due to reduced maize ear receptivity to pollen (Le Roux, 2009). Long and short duration heavy rainfall may wash away the pollen before fertilization occurs. The required growing season length depends on the maize cultivar planted, for the Limpopo and Free State regions, the 120 day and 140 day maize cultivars are mostly planted (Moeletsi and Walker, 2012). It is important for conditions to be optimal during germination, reproduction and a few weeks before harvesting. It is critical to understand the growth requirements of maize in the eastern and temperate growing region of Limpopo given the spatio-temporal variability of rainfall characteristics and the need to improve farming methods used.

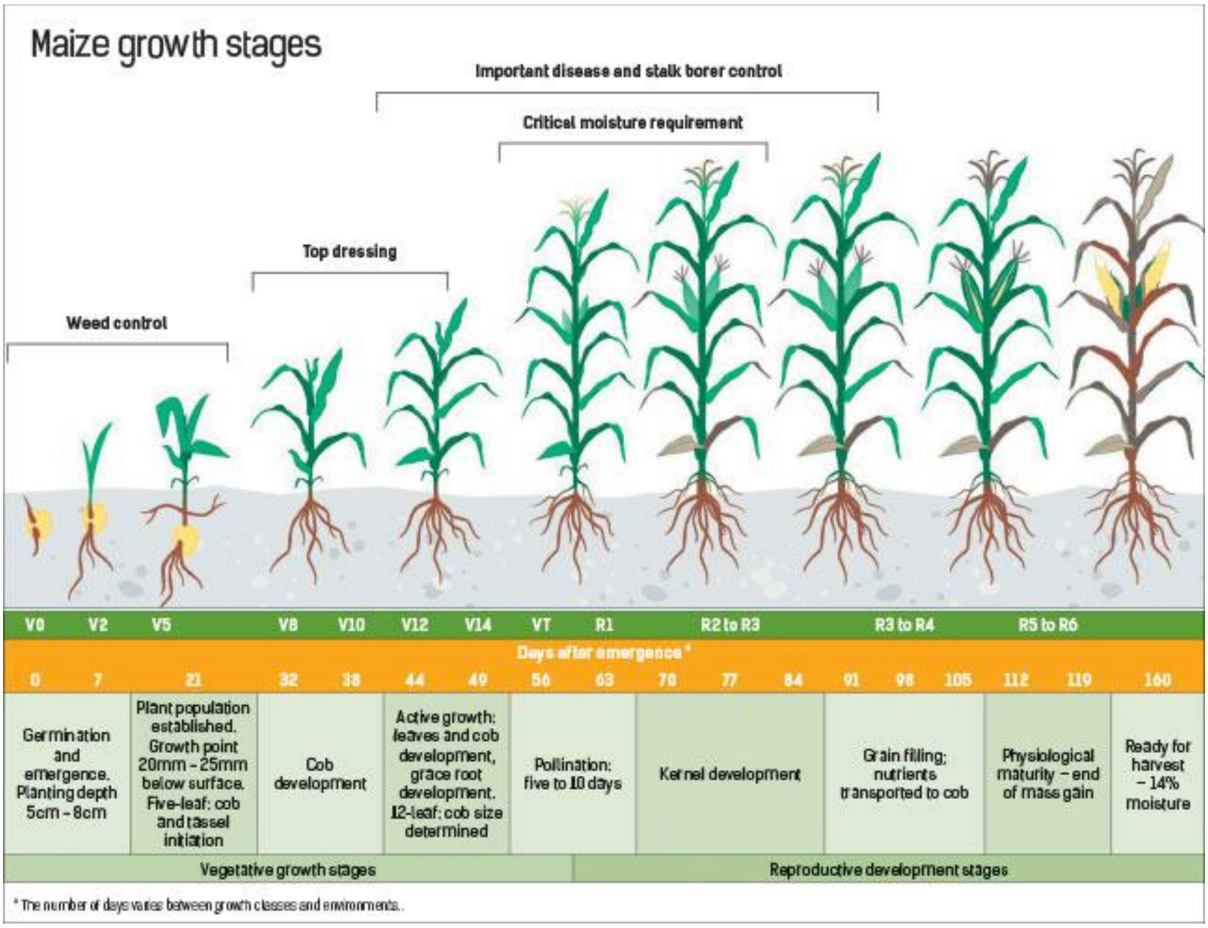


Figure 2: An illustration of maize growth stages from vegetative(V0-VT) to reproductive (R1-R6) phase. The management techniques for each stage are also shown above. Source: (Darby and Lauer, 2004)

2.3. Sensitivity of maize phenology to rainfall characteristics

Table 1 below provides a summary for critical maize phenology stages, their sensitivity index to different rainfall characteristics, thresholds and the literature sources. A bulk of the thresholds are based on studies conducted in South Africa and Southern Africa. Whilst all critical stages of maize phenology are sensitive to variability in rainfall characteristics and temperature, some stages are more sensitive than others, for example the pollination stage is more sensitive to moisture deficits than the other stages shown below.

Table 1: Tabulated summary of maize phenology stages and their water stress sensitivity index.

Maize stage of growth	**Sensitivity & Index**	**Threshold estimates & scale of impact**	**Reference**

Germination stage	• Extended dry spells: Slowed seedling growth. • Water stress stops the expansion and elongation of seedling growth cells. • Cold and dry conditions: Delayed germination by up to 2 weeks. • Excess rainfall before and after sowing leads to waterlogging which also slows seedling growth.	• Prolonged dry spells = 10-20 consecutive dry days. • Rainfall below 84.06 mm during DJF affects overall yield in South Africa. • Optimum temperature for germination: 20 - 30˚C. • Minimum temperature required for germination: 10˚C.	(Le Roux, 2009) (Du Plessis, 2003) (Aslam et al., 2013)
Tasselling stage	• Dry spells lead to tassel desiccation. • Water stress also reduces plant height. • Maize planted late receives low rainfall from tasselling to maturity. • Extreme wet spells result in lack of oxygen which restricts respiration and ion absorption.	• About 96 mm of rainfall could increase yield potential. • Late Planting in Limpopo: Late December to January. • Wet spells of 5 - 8 days with mean daily rainfall below 10 mm can restrict ion absorption.	(Tshililo, 2017) (Mzezewa et al., 2010b).
Silking stage	• Mid-summer dry spells greater than or equal to 10 days: Delayed silking, pollination failure & shorter grain-filling period. • Delayed silking.	• Mid-December to Mid-January. • One week before silking is the beginning of the stress-susceptible period.	(Mtongori et al., 2015b) (Mupangwa et al., 2011a)

Pollination	• Persistent heavy rainfall may wash away pollen off the silks before fertilization occurs: Pollination failure. • Water stress also reduces maize ear receptivity to pollen. • Poor pollination: Reduced number of Kernels.	• Pollination takes about 5-10 days. • Intermediate Wet spells ranging between 5 – 8 days coincide with pollination and may wash away pollen. • High intensity rainfall events exceeding 80 mm/day may also wash away pollen and damage the plant.	(Lauer, 2003) (Mugalavai et al., 2012)
Grain-filling	• Shorter day lengths can delay grain-filling. • Droughts can shorten grain filling stage. • Extended dry spells that reach the kernel development stage can cause abortion of developing kernels. • Extreme heavy rainfall causes cobs to rot. • Yield losses at grain-filling are often irreversible as it is too late to re-plant.	• Rainfall more than 60 and 80 mm/day cause the rotting of maize cobs. • Water stress reduces yield by 2.5 to 5.8% with each day of stress. • Intermediate water stress: 70% Grain yield reduction. • Severe water stress: 90% grain yield reduction through reduced kernel set.	(Lauer, 2003) (Ghooshchi et al., 2008)

Roots development	• Extremely dry conditions: Roots shoot deeper for water thus affecting the plant structure. • Extremely wet conditions: Adventitious roots fail to develop leading to the plant solely depending on the primary roots for water and nutrients.	• Drought reduces the fresh and dry shoot and root weight by about 40 and 58% respectively.	(Le Roux, 2009)
Physiological maturity	• At kernel maturity, moisture content must be reduced to about 35% if not, maize bacteria and fungi proliferate. • The kernels dry at a rate of 5% per week. • Short term water stress: Reduced dry matter accumulation rate. • Heavy rainfall prevents ripening and affect harvest.	• Short duration dry spells (2-3 days) can cause loss of final dry matter weight (20-38%).	(Otegui et al., 1995) (Çakir, 2004)

2.3.1. Germination, rainfall onset and planting dates

The germination of different maize crop varieties such as the 120-Day variety depend on amongst other factors soil temperature, planting dates and rainfall onset. Early summer rainfall onset has been mostly associated with longer rainfall durations whilst late onset leads to shorter growing seasons in South Africa and Southern parts of Zimbabwe (Moeletsi and Walker, 2012, Mupangwa et al., 2011a, Tongwane and Moeletsi, 2015). To avoid the agricultural implications of false rainfall onset, farmers around the Limpopo River Basin use the first October onset for land preparation and then plant after the second onset in November and December (Masupha et al., 2016b). During El

Niño seasons where onset is often delayed, the planted seeds usually die off due to water stress if farmers have planted early (Moeletsi et al., 2011a). Hachigonta et al. (2008) established that the summer rainfall onset over Zambia is between October and November with great interannual variability. The shifting of rainfall onset dates shifts the suitable planting dates for maize, this impacts the length and the timing of the growing season. Delayed onset changes the crop cycle timing hence causing the germination stage to coincide with high water stress.

Several definitions of rainfall onset have been used depending on the mean annual rainfall of a location and the sector to which the study is contributing. Tadross et al. (2009) defined onset as 25 mm of rainfall in 10 days followed by 20 mm of rainfall in the following 20 days. The first 25 mm of rainfall adds moisture to the surface for planting to commence and the 20 mm that follows in two weeks maintains the germination stage. When 10 -15% of the mean annual rainfall has fallen, it is assumed that the rainy season has commenced. In studies linked with circulation drivers, the most relevant definition to apply is one suggested by Tadross et al. (2009) as it is directly linked to the number of rainfall days and the life cycle of certain synoptic features such as the Tropical Temperate Troughs. Although onset and germination are an extensively researched area, for Limpopo province there are several important areas that are yet to be explored. For example, given the high spatio-temporal variability of rainfall onset, suitable planting dates for different maize cultivars are yet to be determined for most production districts. Also, the impacts of onset on germination are not clearly elucidated as most studies have focused on rainfall total and maize yield.

2.3.2. Impact of dry spells on pollination

Most agricultural drought studies indicate that maize plants are more sensitive to drought during silking and pollination compared to the vegetative stage, this is because of differences in moisture requirements during the different stages (Masupha et al., 2016a). The duration and intensity of dry spells occurring at this stage are important aspects of this study as Limpopo Province is very prone to mid-summer droughts. Extended droughts with mean daily rainfall less than or equal to 3 mm can impact pollen viability and at this stage the impacts are irreversible because farmers cannot re-plant (Tshililo, 2017). Dry spells have been regarded as the most important determinant of maize yield and when they coincide with water stress stages of the maize crop cycle, yields can be reduced by up to 90% (Mzezewa et al., 2010a).The number of kernels can be determined by the rate of pollination, poor pollination reduces kernel weight and number. Mtongori et al. (2015a) found that intensified dry spells that last 5 to 10 days with daily mean rainfall of less than 3 mm are more detrimental because they are of the same length as the pollination period which is about 5 to 10 days. Understanding the drivers of extreme dry spells can aid understanding of the length and intensity of the spells which impact pollination and grain filling.

2.3.3. Maize phenology response to high intensity rainfall events

Generally, for maize to thrive, consistent rainfall is required in the form of showers. Depending on the geographical location, per season the accumulated rainfall for good yield must be at least between 450 and 650 mm. The manifestation of rainfall within the season is critical, although seasonal rainfall total may be enough for growing maize, if it is in the form of high intensity rainy days it may be detrimental to the crop depending on the period at which it occurs (Duffy and Masere, 2015). Daily rainfall events with rainfall greater than or equal to 10 mm have been found to be detrimental to maize yield (Beyer et al., 2016). When these high intensity rainy days occur during germination they may lead to waterlogging and the planted seed may accumulate excess water and germination will not occur (Tadross et al., 2009). When these high intensity rainfall events occur during the mid-season, they coincide with the water sensitive pollination stage and may wash away the pollen before it fertilizes thus leading to pollination failure. In cases where these extreme days occur during harvest, they increase the moisture content leading to the proliferation of maize bacteria and fungi. Excess moisture content on the crop affects the final dry mass output leading to poor yields.

2.3.4. Maize kernel sensitivity to dry spells and wet spells

The grain-filling stage determines the kernel weight and number of kernel rows. Shorter day lengths and dry spells can shorten the grain-filling stage. Water stress has been found to reduce yield by 2.5 to 5.8 % with each day of stress. Depending on the frequency, dry spells can cause kernel abortion, this is a process where the development of kernels stops due to moisture stress (Ghooshchi et al., 2008).Intermediate dry spells can reduce yield by about 70% depending on management techniques adopted and severe dry spells of 10 - 15 days with less than 2 mm mean daily rainfall can reduce yield by up to 90% (Le Roux, 2009). Wet spells of more than 5 days can reduce the amount of dry matter and reduce the quality of the kernels and promote the proliferation of fungi during harvest times (Darby and Lauer, 2004).

Advancing understanding on the sensitivity of maize kernel to water stress is critical as the kernels define the quality of the yield and the quantity. To understand this, rainfall characteristics before and during the grain filing stage need to be studied closely for Limpopo Province. Maize is rain fed in

Limpopo and most farmers do not have alternative irrigation to boost kernel weight and size during droughts, therefore it is essential to understand kernel sensitivity to dry spells for the region.

2.3.5. Impact of rainy season duration on phenology

The average duration of the maize growing season in most parts of Southern Africa is between 90 and 140 days (Tadross et al., 2009, Beyer et al., 2016, Hachigonta et al., 2008). Farmers require information about the duration of the growing season, the information is mostly used for deciding the type of maize cultivar to plant. Onset and cessation of rainfall have great influence on the length of the growing season, although heat units may also increase the length of the growing season (Moeletsi et al., 2011a, Cairns et al., 2013). The duration of the season determines the time period at which conditions remain suitable for optimal maize plant growth. These studies highlight the importance of understanding the impact of climate variability on the length of maize growth stages. The mid-season dry spells are associated with early cessation of rainfall at critical phenological stages. It is estimated that white maize requires longer seasons of 140 days for optimal growth and high yields whilst yellow maize can grow well in short to intermediate season lengths. Frequent wet spells can increase the length of the growing season; however, this is likely to coincide with the harvesting period which requires the least amount of moisture for the kernels to dry (Masupha et al., 2016b).

In Limpopo where both onset and cessation vary from place to place, it is essential to define the suitable length of the maize growing season. Despite water stress during sensitive phenological stages of maize plant growth being a major contributor of yield and quality loss, there are several factors which can be attributed to yield loss and sensitivity. These include geographical factors such as soil type, slope type, the effect of temperature and farming practices such as planting spaces, land preparation and fertilizer application.

2.4. Effect of temperature and geographical significance on phenology

The role of temperature in influencing maize growth and determining growing season characteristics cannot be overemphasized especially in South Africa where maize is grown on drylands. Harrison et al. (2011) emphasized that temperature increase shortens the length of the growing periods which are essential for yield and grain size in Mozambique. By speeding phenological development, temperature alters the timing of plant water demand. Hatfield and Dold (2018) found that temperature increases the phenological development during the vegetative stage through increased heat units but extreme temperatures during pollination and grain filling reduce yields. The estimated optimum temperatures for maize growth in South Africa are between 20-30°C, temperatures above 30°C and heatwaves lead to pollen receptivity thus affecting pollination. Heat stress has a great potential of limiting maize production. Harrison et al. (2011) observed that extreme temperatures prevented grain filling entirely in Mozambique between 1979 and 2008. Despite its influence on the growing season length, temperature is more uniform as compared to within season rainfall changes in South Africa hence rainfall characteristics are better linked with change in maize phenology. Temperature and maize are a widely investigated study area but contributes less the scope of this study.

Slope steepness and soil factors such as texture and water holding capacity have an impact of maize phenology response. For example, soil compaction impacts root growth in maize. Singh (2014) emphasized that increased soil strength and increased slope steepness lead to increased run-off which limits plant available water and promotes the erosion of nutrients in the soil. In addition Nazmi et al. (2012) observed yield reductions with slope increase and alternating slope positions. Soil properties are significant in maintaining the maize seed and controlling germination and emergence. Sub-soil compaction delays germination by up to 10 days whilst in soils with no compaction it may take only 3 days (Singh, 2014). Despite these factors not being in the scope of the study, it is important to note their potential role in determining the seasonal maize phenology and the time it takes to advance from one phenological stage to another. Moeletsi (2017) established that at altitudes above 1300 m in the Free State, the number of days it takes to reach heat units sufficient for growing maize increases. Although altitude is an important determinant of maize yield and phenology, it contributes less in this study as the study locations are of similar elevation in the lowveld of Limpopo.

2.5. Sensitivity to farming practices

Farming and establishment practices are critical for maize phenology and final yield. The soil must be prepared before planting commences, the depth to which it is tilled affects soil properties such as water holding capacity and texture thus determining conditions for the seed (Mtongori et al., 2015a).The ability of the seed to thrive depends on the cultivar type, drought tolerance and its capacity to hold water and expand. Management practices such as fertilizer application and alternative irrigation during droughts can improve phenology growth and final yield, other phenology specific management practices are illustrated on **Figure 2**. Duffy and Masere (2015) argued that for seasons with low rainfall and unpredictable daily distribution, fertilizer application can increase yield by up to 46%. It is important to understand the effect of management techniques on phenology especially in areas where rainfall varies significantly. It is also argued that row spacings have an impact on maize growth as the individual plants compete for factors such as sunlight and water. Du

Plessis (2003) argued that closely planted maize may have higher yields due to easier cross pollination. Weeds may compete with the maize plants for water; therefore, it is essential to remove them especially during stages before silking when the plant is still physiologically weak.

It is important to understand maize sensitivity to varying factors especially rainfall which is often erratic from area to area in Limpopo. Information on phenology sensitivity enhances decision making on planting dates, management techniques to adopt and cultivar to plant based on growing season length. Studies linking maize and rainfall that have been conducted in Limpopo have primarily focused on the final yield output therefore excluding the critical phenological details and sensitivity indices (Mzezewa et al., 2010a, Akpalu et al., 2011).

2.6. Synoptic drivers of rainfall variability in Limpopo Province

The South African summer rainfall season is from October to April, however, December to February is the period marked by a peak in rainfall events. Rainfall varies on both inter-annual and intra-seasonal scales and is influenced by regional synoptics and mechanisms. The aim of this section is to highlight and explain the variability of large- and small-scale synoptic features and the associated intra-seasonal rainfall characteristics in Limpopo Province, South Africa. The synthesis is aided with the use of a summary table which is designed to show large scale synoptic drivers, influence of geographical location and rainfall characteristics as observed by other authors. Variability is mainly driven by changes in circulation dynamics of large-scale climate modes such as the El Niño Southern Oscillation (ENSO) at an inter-annual scale via regional Sea Surface Temperature changes and the seasonal southward shifting of the ITCZ (Dedekind et al., 2016, Crétat et al., 2011). Changes in the dynamics of these features also affect convection processes and cloud bands (Tropical Temperate Troughs) at an intra-seasonal scale. To understand intra-seasonal rainfall variability in Limpopo Province, this section explores the dynamics and mechanisms of large-scale climate modes and synoptic drivers and their impact on intra-seasonal rainfall characteristics such as onset, length of the rainy season and cessation.

2.6.1. The climate of South Africa

South Africa has a semi-arid climate influenced by its subtropical location, topography and the Cold Benguela and Warm Agulhas currents (Jury, 2018). There is an evident spatial variability in rainfall between the east and the western areas, generally rainfall decreases from east to west (Kruger and Nxumalo, 2017). South Africa is divided into three main rainfall regions; the summer rainfall region (early and late summer), the all-year rainfall region and the winter rainfall region which is influenced by a Mediterranean climate (Roffe et al., 2019). These main rainfall zones are illustrated in **Figure 3** below. The mean annual rainfall of South Africa ranges from below 200 mm in the Northern Cape Karoo to 975 mm in KwaZulu Natal(Kruger and Nxumalo, 2017). Due to its subtropical location, South Africa's rainfall is mainly sourced from tropical temperate troughs, however, occasional waves and tropical cyclones have been found to produce extreme rainfall for the region. As a result of these tropical systems, there has been an observed increase in the intensity and amount of summer rainfall except for northern and north-eastern areas of South Africa (Kruger and Nxumalo, 2017, MacKellar et al., 2014).

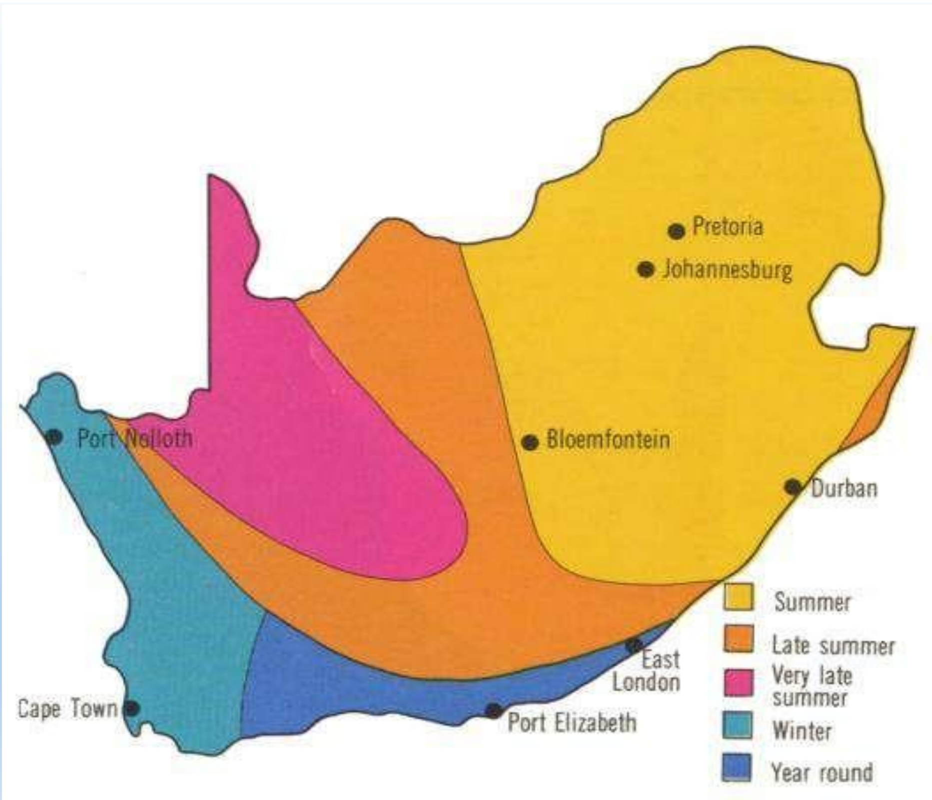


Figure 3: The seasonality of rainfall in the main rainfall regions of South Africa. The three main regions are the summer rainfall region, the winter rainfall region and the year-round rainfall region. *Source:(Roffe et al., 2019)*.

The spatio-temporal heterogeneity of rainfall in South Africa is evident through changes in rainfall onset, intensity, rainy season length and the distribution of wet spells as emphasized in some studies (Kruger and Nxumalo, 2017, MacKellar et al., 2014, Thomas et al., 2007). Although rainfall characteristics in South Africa have been widely investigated, there is a need to explicitly show the impacts of these characteristics for different sectors such as the agricultural and water management sectors as the rainy season coincides with activities which contribute greatly to the economy.

2.6.2. Interannual variability of rainfall in South Africa

At an inter-annual scale, variability of rainfall in South Africa is mainly attributed to the El Niño Southern Oscillation (ENSO). ENSO is the main mode of climate variability in 2 to 7-year time scales involving ocean-atmosphere interactions. The negative phase of known as El Niño involves the intensification of Sea-Surface temperatures and winds in the Eastern Pacific Ocean and a fall in pressure. El Niño through increased regional Sea Surface Temperatures results in drier than normal conditions due to the suppression of convection in South Africa (Pohl et al., 2009). Major droughts that occurred in the South African rainfall cycle in 1982/83, 1997/98 and recently in 2015/16 are strongly linked with El Niño occurrence through regional sea surface temperature forcing (Kane, 2009, Archer et al., 2017). ENSO has been found to modulate rainfall in Southern Africa by determining the location of major cloud bands. During the El Niño phase in South Africa, North-West cloud bands are pushed offshore towards Madagascar resulting in suppressed convection in the eastern rainfall regions of South Africa (Pohl et al., 2009, Hart et al., 2010). During the positive La Nina phase of ENSO, cloud bands are located on the continent resulting in higher rainfall often leading to flooding.

The ENSO has also been found to impact the periodicity of the annual rainfall cycle in South Africa. Kane (2009) found abnormally high year to year fluctuations in rainfall with a variance of 50% to 200% of the mean in South Africa. This high variance suggested a strong influence of El Niño phase on year to year scales. Usman and Reason (2004) found that the occurrence of an El Niño increased dry spell frequencies between 1979 and 2002. Circulation anomalies of dry seasons tend to be ENSO induced in South-eastern parts of South Africa (Limpopo and Mpumalanga). This was later supported by Tadross et al. (2009) who observed a strong link between ENSO and the number of dry days, length of dry spells and onset variability during the maize growing season.

During strong El Niño seasons, the probability of late onset and early cessation is greater (Moeletsi et al., 2011a). Given that El Niño is strongly linked to the interannual fluctuations in dry spell intensity and frequency which pose a threat to agriculture, it is critical to understand the impacts of El Niño on the rainfall cycle of South Africa. Moeletsi et al. (2011a) analysed the impacts of ENSO on rainfall characteristics and maize production in the Free State Province, results show that El Niño years are associated with shorter rainy seasons resulting in shorter maize growing seasons. This was evident during the recent 2015/16 El Niño induced drought that shortened the growing season and led to a decline in maize production in South Africa.

Although the links between ENSO and some rainfall characteristics have been established and cannot be overlooked, the links such as the location of cloud bands with alternating La Nina and El Niño phases vary at the interannual scale and is not in the scope of this study. However, it is important to understand ENSO as it explains the year to year and quasi-biennial fluctuations of rainfall characteristics such as wet and dry spells and rainfall totals.

2.6.3. Main synoptic drivers of rainfall variability

Large-scale modes of variability and synoptic features are key in modulating the intra-seasonal manifestations of rainfall in Southern Africa. **Table 2** below summarizes the development, occurrence and contribution of large-scale climate modes such as ITCZ and ENSO and synoptic features such as the Angola low and Tropical Temperate Troughs to intra-seasonal rainfall variability in Southern Africa. The key literature sources are also listed on the table.

Table 2: Tabulated summary of synoptic features and associated rainfall characteristics.

AL- Angola low, **LRB-** Limpopo River Basin, **TTTs**- Tropical Temperate Troughs, **TCs**- Tropical Cyclones, **ENSO**- El Niño Southern Oscillation, **ITCZ**- Inter-tropical Convergence Zone, **SIOCZ**- South Indian Ocean Convergence Zone, **IO-** Indian Ocean, **SAH**-South Atlantic High-pressure system, **SIH**-South Indian high-pressure system.

Synoptic features	**Characteristics & associated rainfall characteristics**	**Geographical significance & scale of impact**	**Reference**
TTTs	• Contributes 60% of summer rainfall in Southern Africa. • When TTTs lie over the Mozambican channel and Madagascar, little/no rainfall occurs for South Africa. • Late summer rainfall systems. • TTTs associated with extreme rainfall occur in late summer in South Africa.	• Cloud bands are positioned in the SIOCZ linking the Tropics to mid-latitude circulation. • Extreme rainfall TTTs: (January-February-March). • Only 45 TTTs associated with extreme rainfall in SA from 1980-1998 between October and March.	(Macron et al., 2014) (Ratna et al., 2013) (Hart et al., 2010) (Hart et al., 2013b**)**
ITCZ	• The ITCZ coupled with the Angola low form a convergence Zone associated with TTTs formation.	• Shits Southward during the Austral summer (DJF) to form a north-	(Dedekind et al., 2016) (New et al., 2006)

	• Associated with major latent heat release in Southern Africa. • Its oscillation determines the duration of dry and wet seasons.	easterly flow of low-level moisture (15˚S). • Forms a convergence zone of low-level moisture in combination with the Angola Low.	(Nicholson, 2009) (Suzuki, 2011)
AL	• Develops from October-March. • It is driven by dry convection processes (Heat low). • Moves Southward over Kalahari during austral summer.	• Zonal displacement influences daily rainfall anomalies in subtropical Southern Africa. • Position can be modulated by ENSO. • Higher AL intensity = larger rainfall amounts.	(Howard and Washington, 2018) (Munday and Washington, 2017) (Crétat et al., 2019)
ENSO	• Regional SSTs influence continental precipitation by modifying synoptic scale circulation. • Above normal SSTs South of Madagascar are strongly correlated to summer rainfall over eastern South Africa. • Summer dry spell frequency and onset in Limpopo are related to ENSO through regional circulation changes. • In non-ENSO dry summers, high pressure anomalies suppress convection and make it unfavourable for Cloud bands to form.	• Associated with regional scale impacts. • ENSO mature phase: January to March. • La Nina conditions increase TTTs occurrence. • Upper tropospheric westerlies make rain-bearing unfavourable in North-eastern parts of South Africa (Limpopo).	(Ratnam et al., 2012) (Pohl et al., 2009) (Reason et al., 2005)

MJO	• Dominant modulator of moisture supply within the seasonal cycle in Southern Africa.	• Influences rainfall in the east and south of Southern Africa. • Occurs on a scale of 30-60 days in the tropics. • Associated with the eastward movement of convective & circulation anomalies. • Influences the occurrence of wet and dry spells	• (Oettli et al., 2014) • (Hart et al., 2013a)

2.6.3.1. Tropical Temperate Troughs (TTTs)

Tropical Temperate Troughs (TTTs) are the main synoptic rain-bearing systems in Southern African contributing approximately 60% of the summer rainfall (Macron et al., 2014). Given their contribution to summer rainfall in Southern Africa, it is crucial to understand their formation, propagation and their influence on rainfall characteristics. A notable contribution to the understanding of TTTs formation and propagation is that by Hart et al. (2013a), they found that these cloud bands extend from northwest to Southeast forming a link between the tropics and the mid-latitude zone. Fauchereau et al. (2009) found that these systems form on the subcontinent and propagate eastward as they reach a state of maturity. When they lie further east in the Mozambican channel and Madagascar, little or no rainfall occurs over South Africa. They are predominantly late summer systems and they occur between December and January in South Africa. TTTs were found to represent 29% of the total rainy days between 1971 and 1999. Macron et al. (2014) emphasized that mid-latitude baroclinic waves were a requirement for the development of TTTs. Hart et al. (2018) investigated the likelihood of tropical temperate troughs occurring in the South Indian Convergence Zone during ENSO events. Results show that more TTT cloud bands occur during the La Nina phase of ENSO over Southern Africa.

Ratnam et al. (2012) found that more TTT events occur during La Nina years than during El Niño years. In an attempt to understand the number of wet days (>10 mm) associated with TTTs in South Africa, Hart et al. (2013a) found that TTTs are responsible for 30-60% of wet days increasing from east to west. For extreme rainfall, only 30 out of 52 TTTs were found to be associated with extreme rainfall in South Africa between 1979 and 1999 (Hart et al., 2013b). Stronger TTTs are most likely to produce heavier cloud bands and extreme rainfall. The possible influence of TTT cloud bands on rainfall onset and distribution is not understood.

2.6.3.2. Intertropical Convergence Zone (ITCZ)

The ITCZ is regarded as a large climate mode in Southern Africa. This is a zone where north-eastern and South-eastern trade winds converge, it is characterized by convergence, convection and latent heat release (Crétat et al., 2011). The seasonal cycle of precipitation over continental Africa is largely influenced by the movement of the ITCZ and significant rain belts in relation to the maximum incoming solar radiation (Dunning et al., 2016a). Nicholson (2017) emphasized that during the austral summer (December to February), the ITCZ is located across Southern Africa centred at about 12° S and less than 50 m in Mozambique and 10° pole ward. As the movement and position of the ITCZ influences other small disturbances and synoptic circulations, it is essential to understand the influence of the ITCZ on the characteristics of rainfall in South Africa. Dedekind et al. (2016) argued that the duration and alternation of wet and dry spells is influenced by the oscillation of the ITCZ. The frequent dry spells in South Africa and Zimbabwe result from the Botswana High pressure system pushing the ITCZ further away from the Southern areas. The ITCZ coupled with the Angola low form a convergence zone for TTTs which contribute to more than 60% of rainfall in Southern Africa (Dedekind et al., 2016). Given the ITCZ's influence on other rain bearing systems in Southern Africa, it is essential to understand its variability and potential impacts on moisture sources and rainfall characteristics.

2.6.3.3. Madden-Julian Oscillation (MJO)

For intra-seasonal rainfall variability, the Madden-Julian Oscillation is dominant in modulating moisture supply for Southern Africa (Pohl et al., 2010). It is associated with eastward propagating convective and circulation anomalies from Indian Ocean to the Western pacific and influences rainfall in the east and south of Southern Africa (Oettli et al., 2014). This mode of climate has been found to lead to significant intra-seasonal fluctuations at 30-60 day timescales in tropical Southern Africa from October to April (Pohl et al., 2007). In determining the interactions between synoptics at intra-seasonal scale, Pohl et al. (2009) argued that regardless of TTTs being partially influenced by MJO activity, they are an independent mode of variability in South Africa. The link between Madden-Julian Oscillation phases and the intensity of Tropical Temperate Troughs is unclear. Furthermore, MJO has been found to influence wet and dry spells in Southern Africa. Understanding the MJO as an intra-seasonal scale mode of variability provides insight on rainfall characteristics such as wet and dry spells that are modulated by the MJO.

2.6.3.4. Angola low

The Angola low is a key synoptic feature for the Southern African austral summer as it influences precipitation across the subcontinent (Howard and Washington, 2018). This low-pressure system is a combination of dry heat lows and tropical lows and develops between October and March over eastern Angola at about 13° S. Crétat et al. (2019) identified three preferential states of the Angola Low (AL); Near-climatological AL state, anomalously weak AL and anomalously strong AL. Results show that the near-climatological state is associated with wet daily rainfall anomalies over eastern subtropical Southern Africa. Cook et al. (2004) found that intense AL result in larger summer rainfall amounts over Southern Africa. The intensification of the low is marked with increased local convection and westerly moisture flux from the south east Atlantic Ocean. When coupled with a passing easterly wave, this low can promote the formation of northwest cloud bands (Macron et al., 2014). An evaluation of the synoptic expression reveals that this tropical low exhibits a semi-stationary behaviour around Angola instead of moving offshore (Howard and Washington, 2018). This behaviour is influenced by a sea breeze which enhances convection and vorticity.

At an interannual scale, the strength of the Angola low varies with wet and dry years (Cook et al., 2004). ENSO has been found to modulate the seasonal occurrence of the Angola low for most of its states (Crétat et al., 2019). Given the different states of the AL, its role and contribution to the austral summer rainfall in Southern Africa, it is important to understand how this low-pressure system influences the characterization of summer rainfall.

2.6.3.5. The influence of Sea Surface Temperatures on rainfall variability

Sea-Surface Temperatures (SSTs) play a major role in the ocean-atmosphere interactions which controls the availability and intensity of rainfall on the subcontinent. The adjacent Atlantic and Indian Oceans contribute largely to the variability of rainfall in South Africa via the SSTs (Reason and Rouault, 2006). Washington and Preston (2006) found that above-normal rainfall years in the twentieth century are associated with SST patterns that are independent of ENSO and play a major role in extreme rainfall conditions. These conditions are characterised by warm anomalies in the sub-tropical Indian Ocean and cool anomalies in the northern Indian Ocean. SST anomalies and winds have been found to influence moisture fluxes and cloud bands in Southern Africa (Reason and Rouault, 2006). Further investigations by Reason and Rouault (2006) show that onset and dry spell frequencies in Southern Africa are correlated with ENSO through the warming of upper ocean surface temperatures. Although not in the scope of this study, the ocean-atmosphere interactions play a significant role in modulating rainfall characteristics.

2.7. Intra-seasonal rainfall characteristics

2.7.1. The variability of wet and dry spells

The impact of wet and dry spells on the crop growing season cannot be overemphasized. It is important to understand the duration, frequency of occurrence and scale of impact of the spells which occur between December and March in Limpopo Province. Masupha et al. (2016b) found high probabilities (≥ 80%) of short dry spells occurring near the Luvuvhu River Catchment during the maize growing season. A previous study, Mzezewa et al. (2010a) recorded the lowest probabilities of dry spell occurrences in December with probabilities varying from month to month for the semi-arid ecotope of Limpopo (Thohoyandou). Usman and Reason (2004) found that the frequency of dry spells is strongly correlated to ENSO for the December-January-February (DJF) season via regional circulation changes. On average, a dry spell for the DJF season in Limpopo can be defined as a 5-Day period (Pentad) with rainfall less than 5 mm and a wet spell as a 5-Day period with at least 10 mm of rainfall (Beyer et al., 2016). Dry spells in El Niño seasons are likely to be more intense than those for normal seasons.

Some extreme wet spells in the region can be attributed to heavy rainfall producing Tropical Temperate Troughs which form from north-easterly moisture which is diverted south into the Semi-arid regions of Southern Africa including South Africa (Hart et al., 2010). Occasional waves and tropical cyclones from the Indian Ocean are also associated with wet spells resulting from heavy rains.

2.7.2. Defining seasonal rainfall onset and cessation

The onset of seasonal rainfall is critical for determining farmer's planting decisions. Planting dates for different maize crop cultivars depend on the first rains of the season in Limpopo. Tadross et al. (2009) observed that false rainfall onset is linked with El Niño occurrence, this was confirmed in the 2015/16 El Niño induced drought season which impacted the planting dates and led to most farmers planting late in the semi-arid region of Limpopo. Planting dates vary from place to place with response to onset of rainfall which may also vary with topography and ENSO phases. (**Figure 4**) shows the estimated plating dates during the neutral phase of ENSO in South Africa.

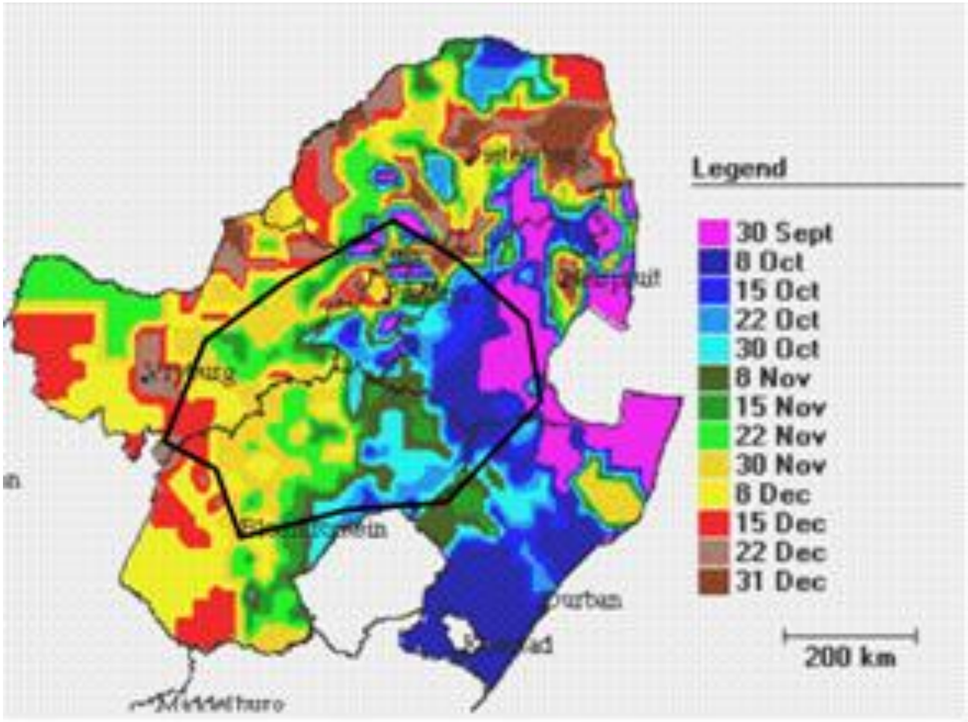


Figure 4: Estimated optimal maize planting dates over Northern parts of South Africa during the neutral phase of the El Niño Southern Oscillation (ENSO). Source:(Johnston, 2008).

Multiple definitions of rainfall onset have been utilized depending on onset dates, mean annual precipitation and the nature of the study. Although rainfall in the region may be associated with similar synoptic features, it varies from place to place. It has been observed that synoptics associated with early and late rainfall onset in Limpopo province vary considerably (Tadross et al., 2005). Impacts of rainfall onset variability may vary from location to location owing to the daily distribution of rainfall after onset. Tadross et al. (2009) defined rainfall onset as 25 mm of rainfall occurring in 10 days followed by 20 mm of rainfall in 20 days. This is a suitable definition which links well with agriculture, the first 25 mm is essential to prepare the soil for planting and the 20 mm in the following 20 days maintains the germination phase. Dunning et al. (2016a) defined the climatological onset based on fluctuations points where daily rainfall exceeds its annual mean. For this method, onset for each year is calculated by checking where cumulative rainfall is at its minimum starting from 50 days prior to the defined climatological onset. In this method, the annual mean rainfall and daily mean rainfall are computed, the rainfall anomaly is acquired by subtracting the annual mean from the daily mean and this is summed to get the Cumulative Rainfall Anomaly (CRA). From this, the 1st day after the minima is described as the onset and the 1st day after the maxima is described as the cessation. This is considered onset as it is the 1st day after daily precipitation exceeds its annual mean.

Understanding and defining the cessation of seasonal rainfall is difficult due to the occasional breaks (Dry spells) that occur during the mid-season which can be mistaken for cessation of rainfall. The dissipation of synoptic features contributing to the seasonal rainfall result in the cessation of seasonal rainfall, however some synoptic features are replaced by others during the growing season making it difficult to define rainfall cessation. Beyer et al. (2016) defined cessation as occurring when 3 consecutive 10-day periods (dekads) each with total rainfall less than 20 mm after the 1st of February occur. Based on the Liebmann et al. (2012b) cessation method, cessation is computed based on cumulative rainfall anomaly where 1 day after the maximum cumulative rainfall anomaly is observed. This is cessation as it is the point where cumulative rainfall anomaly starts to decrease below its annual mean.

2.7.3. Number of high intensity rainfall events

High intensity rainfall events exceeding 10,20,40,60 and 80 mm have been observed as an important determinant of yield output. Such rainfall manifestations often result from larger drivers such as cut-off lows, Tropical Temperate Troughs and mid-latitude cyclones (Hart et al., 2010, Lennard and Hegerl, 2015). Depending on the period of the season at which they occur, these extreme rainy days can be detrimental to the crop growth. Extreme rainfall has been found to wash away pollen before fertilization, lead to waterlogging at germination stage and increase crop available moisture content during harvest periods (Tadross et al., 2009). Beyer et al. (2016) investigated the impact of rainy days exceeding 10 mm and their impact on agricultural success. The 10 mm threshold was defined as the "productive rainfall" threshold as it is essential for plant growth and is associated with less damage to the crops. Understanding synoptic environments associated with these high intensity rainfall events and their variability is essential for the maize growing season as certain maize growing stages are particularly vulnerable to high intensity rainfall events.

2.7.4. Number of wet days and rainy season duration

The length of the rainy season is determined by the setup of synoptic features and moisture sources. Seasons where synoptics are stronger, there is higher rate of convection to frequently form clouds for rainfall to progress throughout the season. For example, in seasons where it is conducive for Tropical Temperate Troughs to produce extreme rainfall, which is often between January and March, there are higher possibilities of a longer rainy season (Cook, 2000). Seasons with early onset and fewer interrupting dry spells are likely longer than seasons with late onset and mid-season dry spells. The number of consecutive rainy days within the season is of great significance as it can also be a direct reflection of the duration of synoptic drivers (Macron et al., 2014). For example Macron et al.

(2014) found a link between number of seasonal rainy days and TTTs occurrences in South Africa. The number of consecutive rainy days vary from season to season depending on the strength of the driving synoptics and convection processes.

Given the unpredictable nature and importance of rainfall for agriculture in Limpopo, it is critical to understand the implications of its variability on the sector. Building on the existing knowledge of synoptic drivers, this section has highlighted and explained some of the main synoptic drivers associated with intra-seasonal rainfall characteristics within the seasonal rainfall cycle. Although more than one rainfall characteristic may be associated with one synoptic driver such as in the case of TTTs which may result in extreme rainfall and normal light showers depending on their formation and movement, it is important to understand the rainfall conditions which are more prevalent in the Limpopo Province seasonal rainfall cycle.

2.8. Summary

This chapter reviewed available literature on the sensitivity of maize phenology to different rainfall indices, large scale synoptic drivers of intra-seasonal rainfall and factors such as temperature and topography which influence maize yield and phenology in Southern Africa. Most studies show that large scale modes of climate such as the ITCZ modulate rainfall characteristics. Summary tables were used to show large scale synoptic drivers and their contributions to intra-seasonal variability and the response of maize phenology to different intra-seasonal rainfall characteristics. There is a consensus in maize phenology literature, most studies indicate that the reproductive stages of maize are more sensitive to moisture stress than the vegetative stages. The available literature suggests a need to further investigate the response of maize yields and phenology to variability in rainfall characteristics such as wet and dry spells and high intensity rainy days.

Chapter 3

Data and methods

3.1. Introduction

This chapter summarizes the datasets and methods used in this study to analyse the large synoptic drivers of intra-seasonal rainfall variability and the implications on the maize growing season in Limpopo Province. The chapter also provides a justification for the selection of the study domain, rainfall datasets and the Self-Organizing Map (SOM) training parameters. The methods and data used for computing trends and correlation analysis for rainfall characteristics such as onset, cessation, wet and dry spells and high intensity rainfall are summarized in a table and discussed. The long-term maize yield data used from three maize production districts in the province to evaluate the impact of rainfall variability on long-term maize yields is also described.

3.2. Study domain selection

For analysing large scale synoptic features, the domain selected for this study is Southern Africa, 5°, 45° E and - 40°, -15° S including the South Indian and South Atlantic Oceans. The domain is subject to great variability of climate and weather owing to tropical low-pressure systems, sub-tropical high-pressure systems on either side of the sub-continent and a complex topography. Some prominent synoptic features in the domain such as the ITCZ, Angola Low (AL) and Tropical Temperate Troughs (TTTs) are shown in **Figure 5**. For local scale rainfall characteristics and maize districts, Limpopo Province is the selected study area. The map in **Figure 6** shows the selected study area of Limpopo Province, the South African Weather Service station locations and the selected maize growing districts.

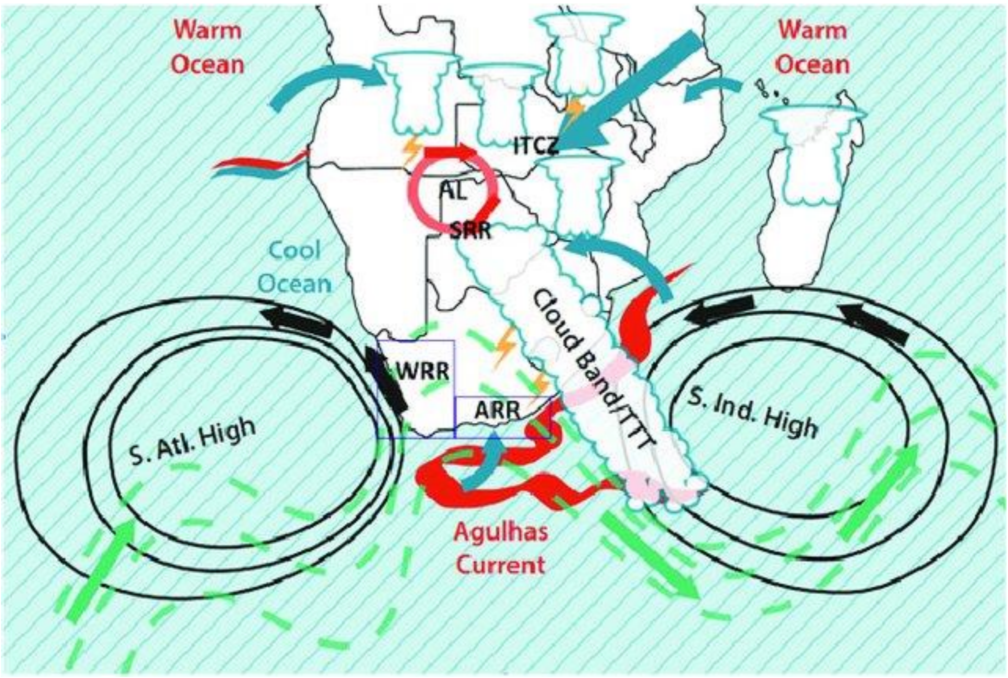


Figure 5: A map illustrating major atmospheric and oceanic circulation systems and convergence zones in Southern Africa. The Intertropical Convergence Zone (ITCZ), Angola Low (AL) and Tropical Temperate Troughs (TTTs) and The Summer Rainfall Region (SRR), Winter Rainfall Region (WRR) and the All-year Rainfall Region (ARR) are also illustrated. Source:(Hart et al., 2010).

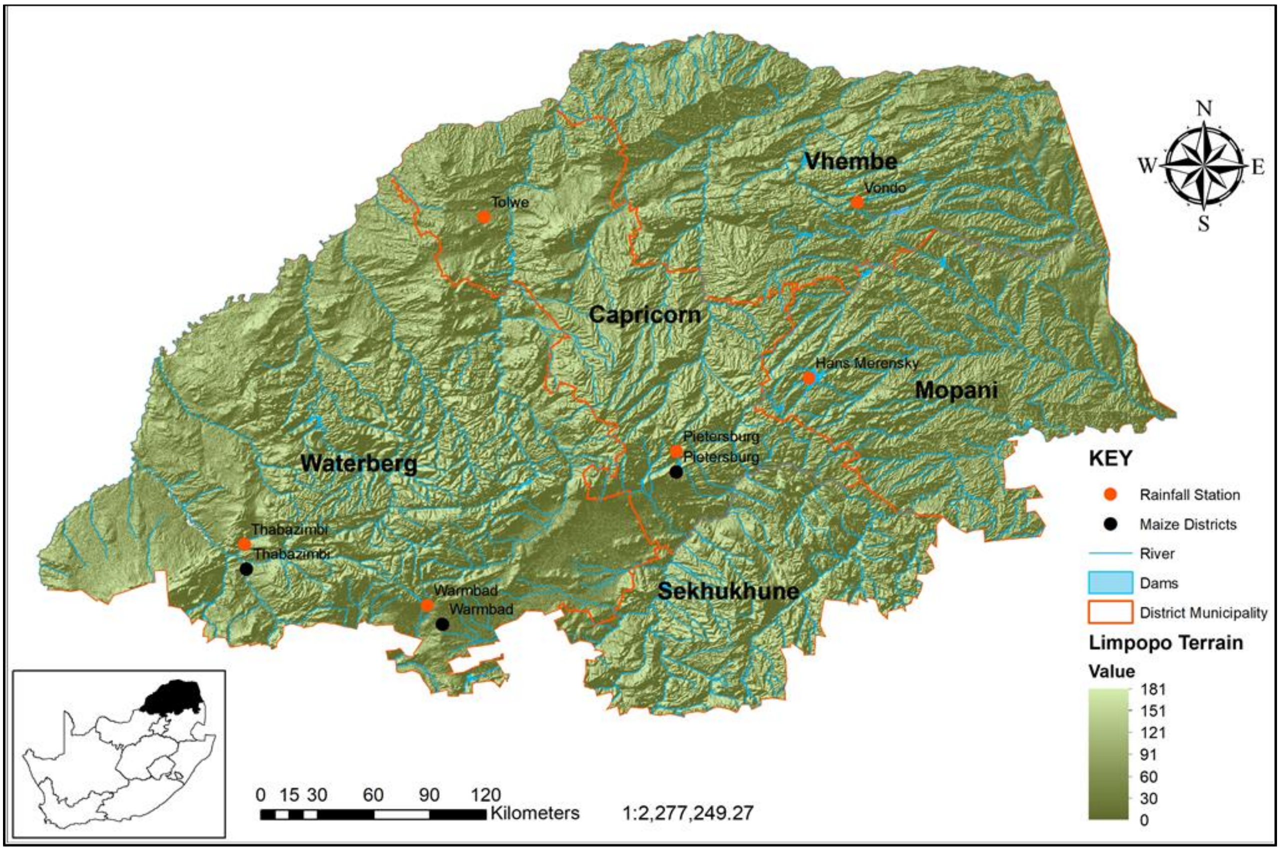


Figure 6: A map showing rainfall stations, maize districts and rivers in Limpopo province.

Figure 6 shows the locations of the selected stations. The selection of the stations for this study is based on availability of long-term consistent data at least spanning the years 1990-2014. The selected stations are positioned such that they provide a meaningful spatial account for both rainfall and maize yield variability. Pietersburg station is located centrally in the Capricorn District, Warmbad and Thabazimbi are in the Western most parts in the Waterberg District. Vondo station is in the north most parts of the province, the Hans Merensky station on the eastern-most side and Tolwe on the north-western side. The spatial set up of the stations also links well to the position and movement of synoptic features influencing rainfall in the area. The stations on the eastern side of the province are potentially more subject to the South Indian Ocean High pressure system. The period of observation for the study is from 1990 to 2014 and the frequency of observations is daily. **Figure 7** shows the annual rainfall at the three selected maize growing districts, the annual rainfall does not vary greatly from district to district.

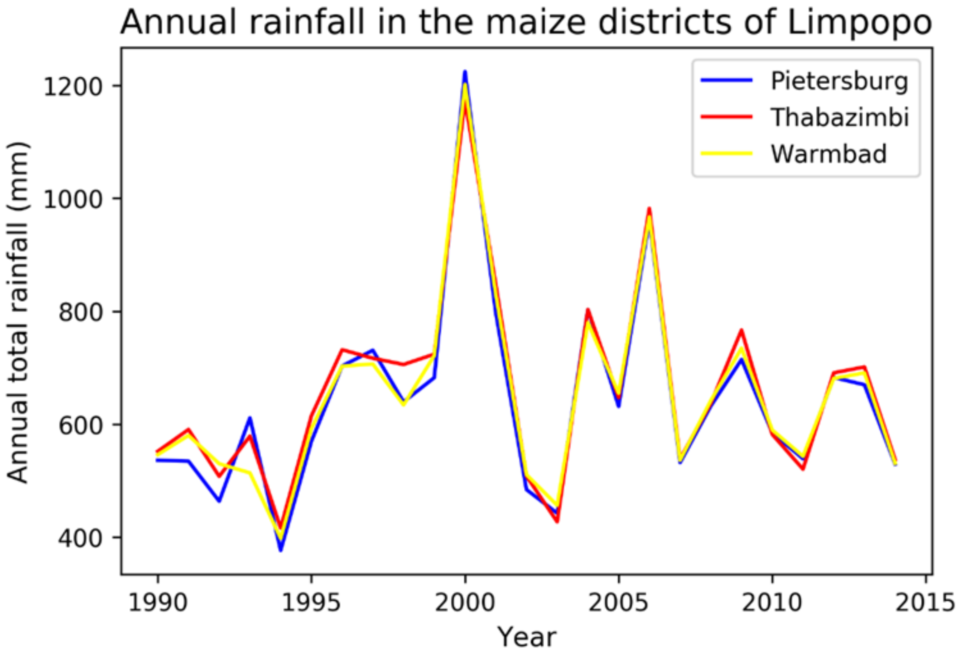


Figure 7: Annual rainfall in the selected maize districts of Limpopo from 1990-2014.

3.3. Data

3.3.1. SOMs and composites input data

1. Geopotential height data (500 hPa and 850 hPa)

Mean daily Geopotential height reanalysis data was acquired from the National Centre for Environmental Prediction (NCEP/NCAR reanalysis 1) for years from 1948 to 2019. The data has a spatial coverage of 2.5° X 2.5° and 17 pressure levels. Using the Climate Data Operators (CDO) functions, years from 1990-2014 were selected as well as two pressure levels; 850 hPa and 500 hPa for the study domain. Anomalies at 500 hPa have been found to be associated with variability in onset of seasonal rainfall and at 850 hPa essential synoptic drivers of seasonal rainfall can be identified (Tadross et al., 2005). The data was standardised to compensate for variance between the two selected pressure levels, this is done by subtracting the mean from each grid point and dividing by the standard deviation. The two selected pressure levels were merged and the output file was used to train the SOM. **Table 3** summarizes the details of the datasets used in this study and the sources of the data.

Table 3: A table showing the SOMs and composites input data including the variables, the data and the sources.

Data	**Variables**	**Source**
Daily mean Geopotential height data	**Levels:** 850 hPa and 500 hPa **Spatial coverage:** 2.5° X 2.5° **Period:** 1990-2014	NCEP/NCAR reanalysis 1
Moisture flux data	**Variables:** Specific humidity, Zonal wind, Meridional wind. **Level:** 850 hPa **Spatial coverage:** 2.5° X 2.5° **Period:** 1990-2014	NCEP/NCAR reanalysis 1
Daily rainfall data	**Level:** Surface **Period:** 1990-2014 **Spatial coverage:** 0.5° X 0.5 °	CHIRPS
Maize yield data	**Level:** District **Period:** 1990-2013	South African Department of Agriculture Forest and Fisheries

2. Moisture flux

For this study, moisture flux was derived from three data variables, namely; Specific humidity (Q), Meridional (U) and Zonal (V) winds. The reanalysis data spanning the years from 1990 to 2014 was acquired from NCEP/NCAR reanalysis 1. The Southern Africa domain and level 850 hPa were selected. This level is considered as a dominant layer of moisture over the study area (Dyson, 2015). Wind anomalies at 850 hPa have also been highlighted as a strong indicator of rainy season onset in Southern Africa. The data is used for moisture flux composites using the days from the trained SOM.

3. Daily rainfall

Mean daily rainfall data was acquired from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS). CHIRPS is a 30+ year global dataset which incorporates 0.05° resolution satellite imagery with station data to create a gridded rainfall time-series (Funk et al., 2015). The CHIRPS rainfall data from 1990-2014 was used to compute composites for indices such as Simple Daily precipitation Intensity Index and consecutive wet and dry days mapping to nodes in the trained SOM. From the CHIRPS data, daily rainfall time-series were extracted using actual locations of the South African Weather Service stations for all days from 1990-2014 for six stations. These time-series were used to compute onset of rainfall, cessation, duration and wet and dry spells. CHIRPS data was preferred as it has a greater spatial coverage and has no missing data values in the main rainy season. The data is also found to be accurate in analysing trends although it may underestimate extreme rainfall (Funk et al., 2015, Dinku et al., 2018). The consistent CHIRPS data is useful for the accurate determination of the consistency of rainfall after onset (within-season wet and dry spells). Dunning et al. (2016b) found that the CHIRPS data was good for representing rainfall regimes on the sub-continent.

4. District maize yield data

Long-term maize yield data (ton/ha) from 1990-2013 for Thabazimbi, Warmbad and Pietersburg was acquired from the Department of Agriculture, Forests and Fisheries. The areas selected consist of long-term data and contribute largely to the district yield totals. The data is averaged from maize grain silos in the district areas. This data is used for correlation with different rainfall indices to understand the relationship between rainfall characteristics and maize yield in the three districts.

3.4. Methods

3.4.1. Self-Organizing Maps (SOMs)

Self-Organizing Maps are a widely used approach in synoptic climatology to cluster synoptic patterns. These unsupervised artificial neural networks were first introduced by Teuvo Kohonen in the 1980s (Kohonen, 1989). The SOM methodology differs from other cluster analysis in that it is not primarily concerned with grouping data; instead it attempts to locate points in the physical space that are representative of nearby observations and updates the neighbour nodes (Hewitson and Crane, 2002). Lennard and Hegerl (2015) used SOMs to relate atmospheric circulation processes to seasonal surface precipitation response. In this study, the method is applied to assess the surface response of different rainfall characteristics to atmospheric changes. The response is assessed from the onset of the rainy season to cessation to understand how atmospheric circulation changes throughout the season influence rainfall changes. From this, synoptic states associated with "good" rainy seasons which are suitable for growing maize can be distinguished from those that are not suitable for growing maize.

The SOM training process

The SOM was trained using the SOMPak software package. The SOM was trained through two iterations using 4 rows X 5 columns grid consisting of 4 rows and 5 columns at a learning rate of 0.1 for the first iteration using a rectangular topology and a radius of 5. For the second iteration, the learning rate was reduced to 0.05 as well as the radius to 3, this is done to fine tune the training process. The SOM grid selected for this study is 4 rows X 5 columns resulting in 20 nodes, this grid captures synoptic scale variability well over the domain from the beginning to the end of the rainy season. Larger SOM grids have been found to result in overgeneralization of synoptic patterns whilst smaller grids may not capture all significant patterns (Lennard and Hegerl, 2015).

3.4.2. Node frequency analysis

Seasonal patterns are analysed by finding the frequency of node occurrence. The node and occurrence count are an output data file of the second iteration of the SOM training process. The nodes are disaggregated into different seasons, namely; summer (DJF), autumn (MAM), winter (JJA) and spring (SON) for all days from 1990-2014 in each of the 20 cells in the SOM grid. The peak in node frequency determines the season which is dominant for each cell and the frequency of occurrence is computed in percentage. Based on the frequency bar graph and the SOM maps, dominant synoptic drivers for each season can be identified.

3.4.3. Composite analysis

Using days from the trained SOM, moisture flux and daily rainfall composites are created. From the CHIRPS mean daily rainfall, the days in the trained SOM are extracted using CDO functions to select the timesteps and compute the mean, this is done to understand daily moisture and rainfall response to changing seasonal atmospheric processes. Composites for the consecutive wet days, consecutive dry days and Simple daily rainfall intensity mapping to the trained SOM are also computed and this provides insight on the spatial variability of rainfall intensity across the domain.

3.4.4. Rainfall characteristics

Table 4 shows the computed rainfall characteristics and the definitions adopted for this study. These definitions are based on thresholds that are relevant for both the maize crop and the rainy season. The duration characteristics include onset, cessation and rainy season duration and the rainfall intensity indices include the wet and dry spells and extreme rainy days. Sources for the adopted definitions are also listed below.

Table 4: A table showing the computed rainfall indices, definitions adopted and the sources.

Indices	**Definition**	**Reference**
Duration indices Onset, cessation and rainy season duration	**Onset:** First 10 days >25 mm, no 10 consecutive dry days in next 20 days **Cessation:** 3 consecutive 10-day periods each with less than 20 mm (after Feb 1st). **Duration:** Cessation date - Onset date.	(Beyer et al., 2016) (Hachigonta et al., 2008) (Tadross et al., 2005)
Wet and dry spells	**Wet day:** Rain > 2 mm. **Dry day:** Rain < 2 mm. **Wet spell:** 5-day sum > 10 mm and less than 3 days with no rain. **Dry spell:** 5-day sum < 5 mm. **Mean/Maximum wet/dry spell duration:** Number of consecutive days with wet/dry spell criteria satisfied.	(Hachigonta et al., 2008) (Usman and Reason, 2004) (Reason et al., 2005)

Extreme rainfall indices	**Simple Daily intensity index** = Total seasonal rainfall / Number of season rainy days. **No. of rainfall events** above the 10/20/40/60 and 80 mm threshold	(Beyer et al., 2016) (Karl et al., 1999)

3.4.5. Rainfall characteristics, trends and correlation analysis

Onset, cessation and rainy season durations are computed for each year in the period of observation. Long-term trends in onset, cessation and rainy season duration are observed for the period between 1990-2014 for the six stations. This period is selected as it coincides with the longest period for which there is consistent maize yield data in Limpopo Province. Mean variability in onset, cessation and rainy season duration are computed. A non-parametric Mann-Kendall test was used to assess observed trends in onset, duration, cessation and total rainfall for the rainy season. The Mann-Kendall test does not set any assumptions about the distribution of the data and is not affected by the length of the time-series. Correlation analysis is performed using the Pearson's correlation method to capture the relationships between the different rainfall characteristics such as the rainy season duration and the total seasonal rainfall. These characteristics are also correlated with maize yield to assess their potential impact on maize yield variability.

Onset, Cessation and rainy season duration

Onset is determined when 25 mm of rainfall has been accumulated in 10 days and no 10 consecutive dry days occur in the following 20 days. By checking the following 20 days to ensure that there are no dry days, this method accounts for the possibility of false rainfall onset and isolated showers. This method accounts for moisture requirements to ensure germination of the maize seed in the first month after planting. Cessation occurs when 3 consecutive 10-day periods (dekads) each with less than 20 mm after the 1st of February is observed. The duration of the rainy season is defined as: (Date of cessation - Date of onset). For all the computed rainfall characteristics, a rainy day is defined as any day with rainfall greater than or equal to 2 mm (Rainfall ≥ 2 mm). The definitions for onset, cessation and duration adopted in this study have been widely used in many agro-meteorological studies in the country and regionally (Beyer et al., 2016, Tadross et al., 2009, Tadross et al., 2005). The criteria used for all the indices define thresholds and conditions suitable for planting and ensuring optimal maize growth. These methods used here for defining onset and cessation are useful for understanding large rainfall drivers as the number of days are used. Using rainfall threshold over several days may improve the understanding of the span of certain rainfall features such as Tropical Temperate Troughs and other convective systems.

Wet and dry spells

Understanding the within-season wet and dry spells is critical as these spells coincide with maize during critical stages of growth such as the flowering stage. These alternating wet and dry periods determine the consistency of rainfall from onset to cessation. In this study, a wet spell is defined as a 5-day sum with rainfall greater than 10 mm and less than 3 days with no rain. A dry spell is defined as a 5-day sum of rainfall less than 5 mm (Beyer et al., 2016). These spells are computed using daily rainfall data for all the selected stations from the onset date of each year to the cessation date of each year. The impact of these dry spells is often irreversible as they occur at a period in which it is too late for farmers to re-plant. The mean and maximum dry spell durations are also computed to get the mean and maximum number of days within the season for which the dry spell criteria is met.

High intensity rainfall events

A count of rainfall events with rainfall greater than or equal to 10 mm, 20 mm,40 mm, 60 mm and 80 mm is computed to assess rainfall intensity and extremes. These thresholds are selected based on their potential impact on the maize growing season. The spatial variability of the high intensity rainfall events mapping to nodes in the trained SOM is also assessed. Extreme wet days, depending on the period of the season at which they occur, may result in waterlogging after planting and excess moisture at harvesting periods leading to the proliferation of maize fungi and bacteria. These rainfall events are counted from the defined rainfall onset period to the defined cessation period for each year.

Simple Daily Intensity Index (SDII)

The Simple Daily Precipitation Intensity Index is defined as the sum of precipitation for wet days in a season divided by the number of rainy days in that season. In this study a rainy day is defined as any day with rainfall greater than or equal to 2 mm. The SDII is useful for detecting trends in daily rainfall intensity. This index provides insight on the average daily intensity over rainy days within a season. High intensity rainfall can be detrimental to the crop depending on its timing in the crop cycle. Maps for Simple Daily precipitation Index based on the trained SOM are also produced to understand the spatial extent of daily rainfall intensity.

3.5. Summary

This chapter highlighted and explained the data and methods used to analyse the impacts of intra-seasonal rainfall drivers on rainfall characteristics such as onset, wet and dry spells, duration of seasonal rainfall and cessation. Furthermore, the methods and data used for analysing trends in variability of intra-seasonal rainfall characteristics were explained and summarized in tabular form. The connection and impacts of these characteristics on the maize growing season were analysed using maize yield data and the methods and data sources were highlighted.

Chapter 4

Results and discussions

4.1. Introduction

With the aid of maps and graphs, this chapter presents the results of the investigation of the impacts of intra-seasonal rainfall variability on the maize growing season of Limpopo province, South Africa. The first section presents results for the large synoptic features influencing rainfall variability in Southern Africa observed on SOMs, the second section shows results for variability in rainfall characteristics such as onset, cessation and duration over six stations in Limpopo. The third section of the results shows the relationships between the rainfall characteristics and maize yields. This chapter also discusses the links between synoptic scale atmospheric features, their role and influence on rainfall characteristics and how the maize growing season, yield and phenology is impacted by the timing and intensity of rainfall in Limpopo Province, South Africa.

4.2. Variability of synoptic circulation types

Figure 8 illustrates synoptic circulation types identified in Southern Africa on a 2-dimensional Self-Organizing Map using daily mean Geopotential height at 850 hPa for all days from 1990-2014. The nodes are organized from 1 to 20 from top left to bottom right. The strength and position of high- and low-pressure systems which drive rainfall variability in the region are mapped to the nodes.

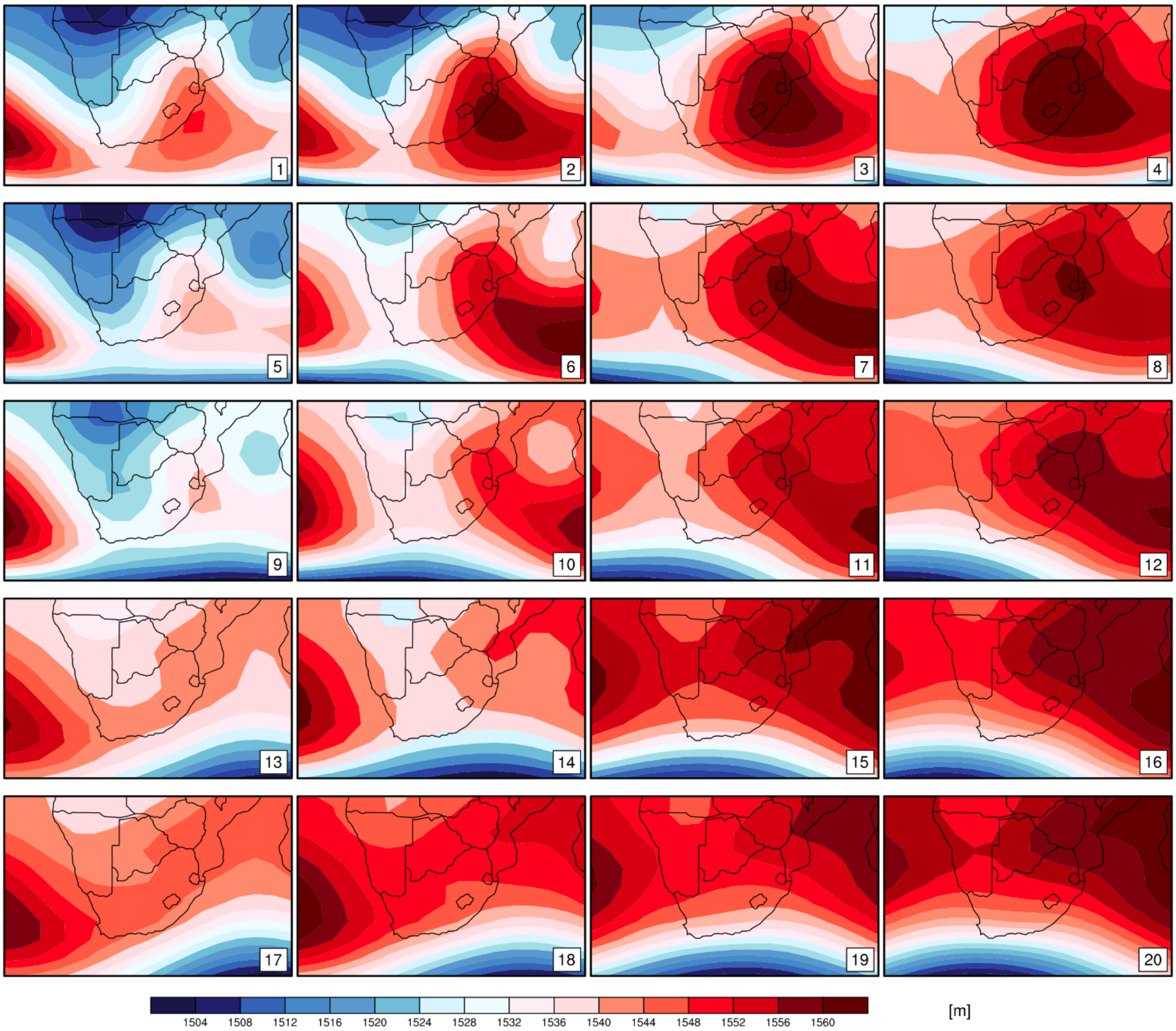


Figure 8: A 4 rows X 5 columns SOM showing daily mean NCEP Geopotential height at 850 hPa from 1990-2014. Node numbers are shown on the bottom right corner.

In **Figure 8** above, there is a clear distinction in the alignment of winter and summer nodes such that typical winter nodes 3, 4, 8, 12, 16 and 20 are found on the right of the SOM and summer nodes 1, 5, 9, 10, 14 are on the left of the SOM. There is evidence of a ridging high-pressure system from the South Indian Ocean in nodes 3 and 4 suggesting subsidence, this subsidence weakens to the left and bottom of the SOM. Atmospheric conditions that prevail during this synoptic state are cool and dry particularly in the South-eastern parts of the sub-continent including Mpumalanga and Limpopo Province. The South-western parts of South Africa are characterised by cold frontal systems which contribute to the winter rainfall for the region as depicted in nodes 7-8, 11-12 and 15-16. The summer rainfall is driven by a deep low-pressure system over the sub-continent which acts as a source of moisture for the convection of cloud bands, these conditions prevail more evidently in nodes 1, 5, 6, 9 and 10. Node 5 is typical of a mid-summer situation characterised by a tropical low-pressure system over Angola and parts of Mozambique (Angola low) and a heat low between Botswana and South Africa. Circulations in nodes 5 and 9 suggest a linkage between mid-latitudes and sub-tropical low-pressure systems, these conditions are favourable for the formation of TTTs which contribute to a great proportion of the summer rainfall in the region (Hart et al., 2010). Summer rainfall onset is dependent upon the strength and location of these synoptic features (Tadross et al., 2005). Seasons with late summer rainfall onset are often associated with high intensity rainfall as synoptics are well developed to produce heavy rainfall during that time of the season over the sub-continent (Archer et al., 2017). The high-pressure system located in the South west of the region in summer nodes 10, 13 and 14 displaces frontal systems poleward leading to dry summers in Western parts of South Africa.

At 500 hPa (**Figure 9**), there is a dominant mid-tropospheric ridge over the sub-continent on most of the top nodes such as node 5. This ridge weakens to bottom right of the SOM. This anti-cyclone inhibits the transport of moisture from the Indian Ocean into the sub-continent. The winter nodes on the far right are characterised by a mid-latitude trough to the south-west of the sub-continent in nodes 8, 12, 16 and 20. This trough shifts to the south-east in summer as depicted in the summer nodes. Circulation anomalies at 500 hPa have been found to influence differences in early and late summer rainfall onset. In the South east of the sub-continent including South of Zimbabwe and northern parts of South Africa; late rainfall onset is associated with heavy rainfall and positive geopotential height anomalies (Tadross et al., 2005). The early start to the rainy season is associated with negative geopotential height anomalies, decreased subsidence and convective activity.

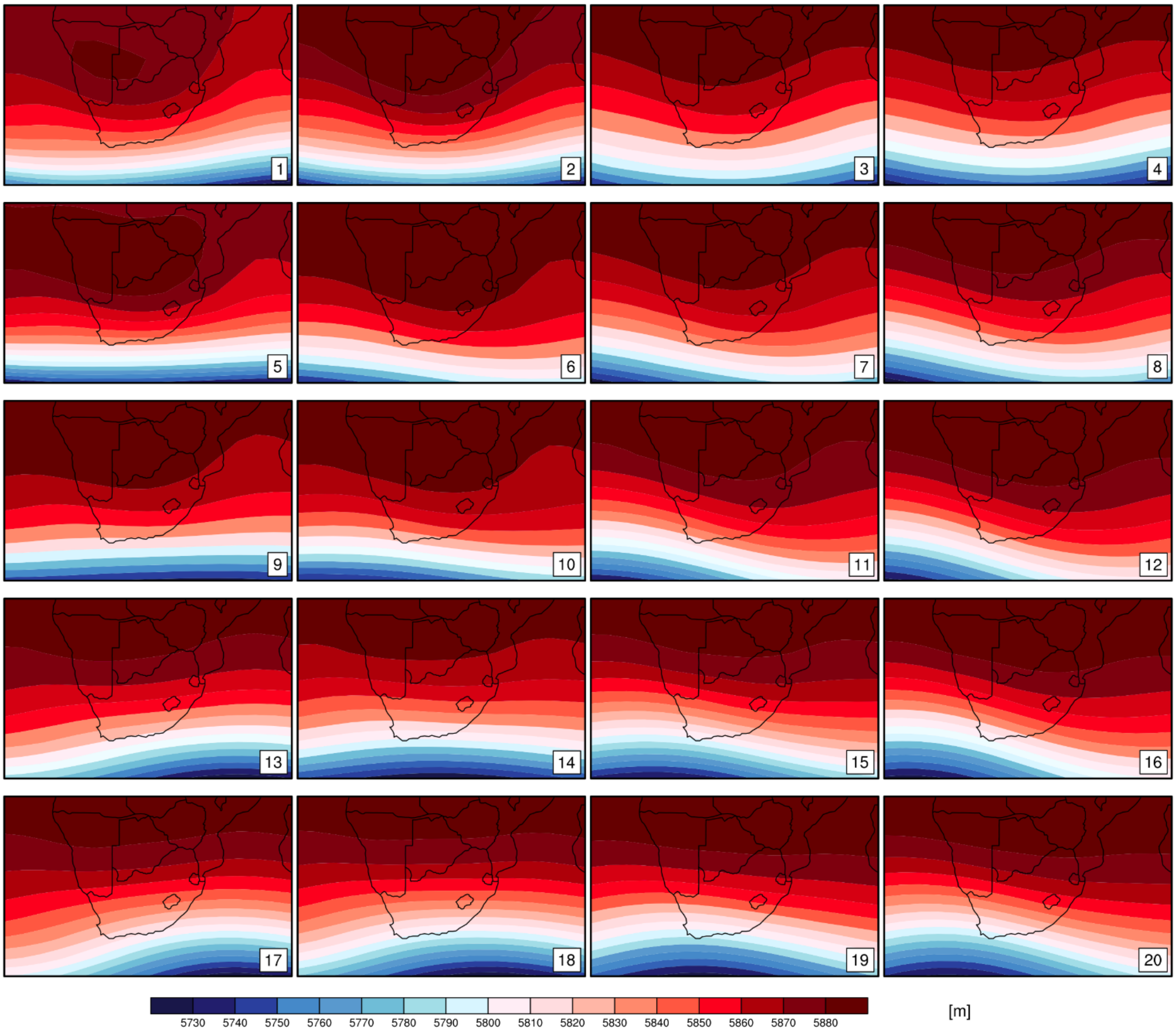


Figure 9: A 4 rows X 5 columns SOM showing daily NCEP Geopotential height at 500 hPa from 1990-2014.

The frequency distribution of seasonal and annual circulation patterns is shown below in (**Figure 10**). Nodes dominated by winter (JJA) patterns are nodes 3, 4, 8, 12, 16 and 20 with the highest frequency of occurrence of 20% for node 4 and 15% for node 8. Nodes typical of summer circulations are 1, 5, 6, 9, 10 and 14 with the highest frequency of 17% of the total days of occurrence for node 10 and second highest 15.5% for node 9. Node 11, 13 and 15 are dominated by spring circulations with the highest frequency of occurrence of 10 % for node 13. This is the period where the first summer rains often occur. Autumn circulations are frequent at the top of the SOM in node 2-3 with a frequency of occurrence of 10 % of the total days of node occurrence for node 2 and 9 % of the total days of node occurrence for node 3.

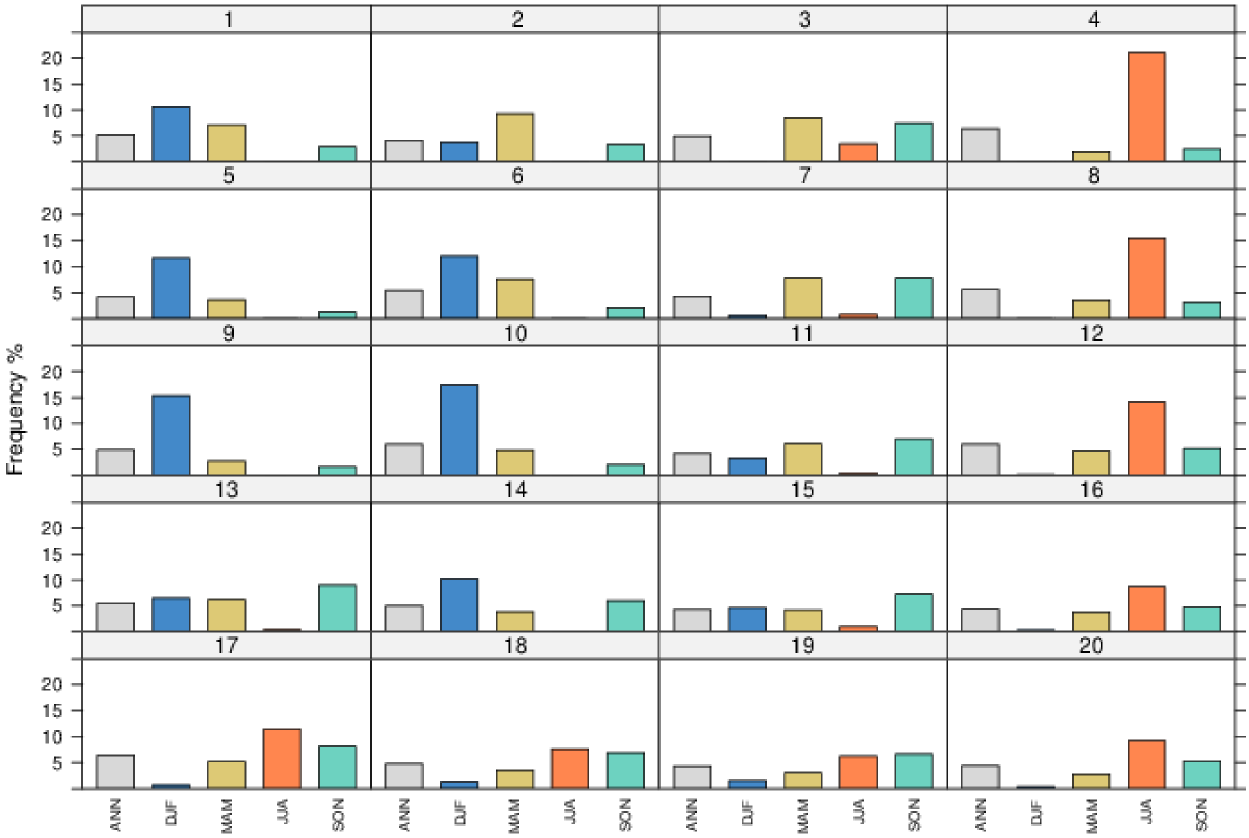


Figure 10: Annual and seasonal variation of the frequency of occurrence (%) for each node from 1990-2014 for Geopotential height at 850 hPa and 500 hPa. The blue represents summer nodes (DJF), orange winter nodes (JJA), green spring nodes (SON) and the yellow autumn nodes (MAM) and the grey is annual nodes (ANN).

4.3. Variability in moisture flux

The moisture flux vector illustrated in **Figure 11** shows long-term moisture transport across the study domain from 1990-2014. The 850 hPa dominant moisture layer is used, the long arrows represent high moisture transport and the short arrows represent low moisture transport. The South west Indian Ocean is the main source of moisture for late summer rainfall. This moisture is transported by South-East trade winds which blow the warm moist air into the sub-continent. This is evident in the typical summer situation presented in nodes 5, 9 and 10 in **Figure 11**. The South Atlantic Ocean is a secondary source of moisture which advects cool dry air into parts of Namibia and South Africa. The Angola low increases the rate of moisture flux in the central parts of the study domain as illustrated in nodes 5, 9, 10 and 14. This high moisture content is associated with an increase in rainfall per day rather than the number of rainy days.

The winter nodes are characterised by subsidence from the South Indian high-pressure system, this ridging high pressure system evident in nodes 3, 4 and 8 inhibits moisture transport into the sub-continent. Moisture transport in the winter rainfall region of South Africa is westerly as opposed to the easterly transport in most of the summer rainfall regions of the country. The austral winter rainfall is mainly sourced from cold frontal systems associated with westerly waves nodes 16 and 20.

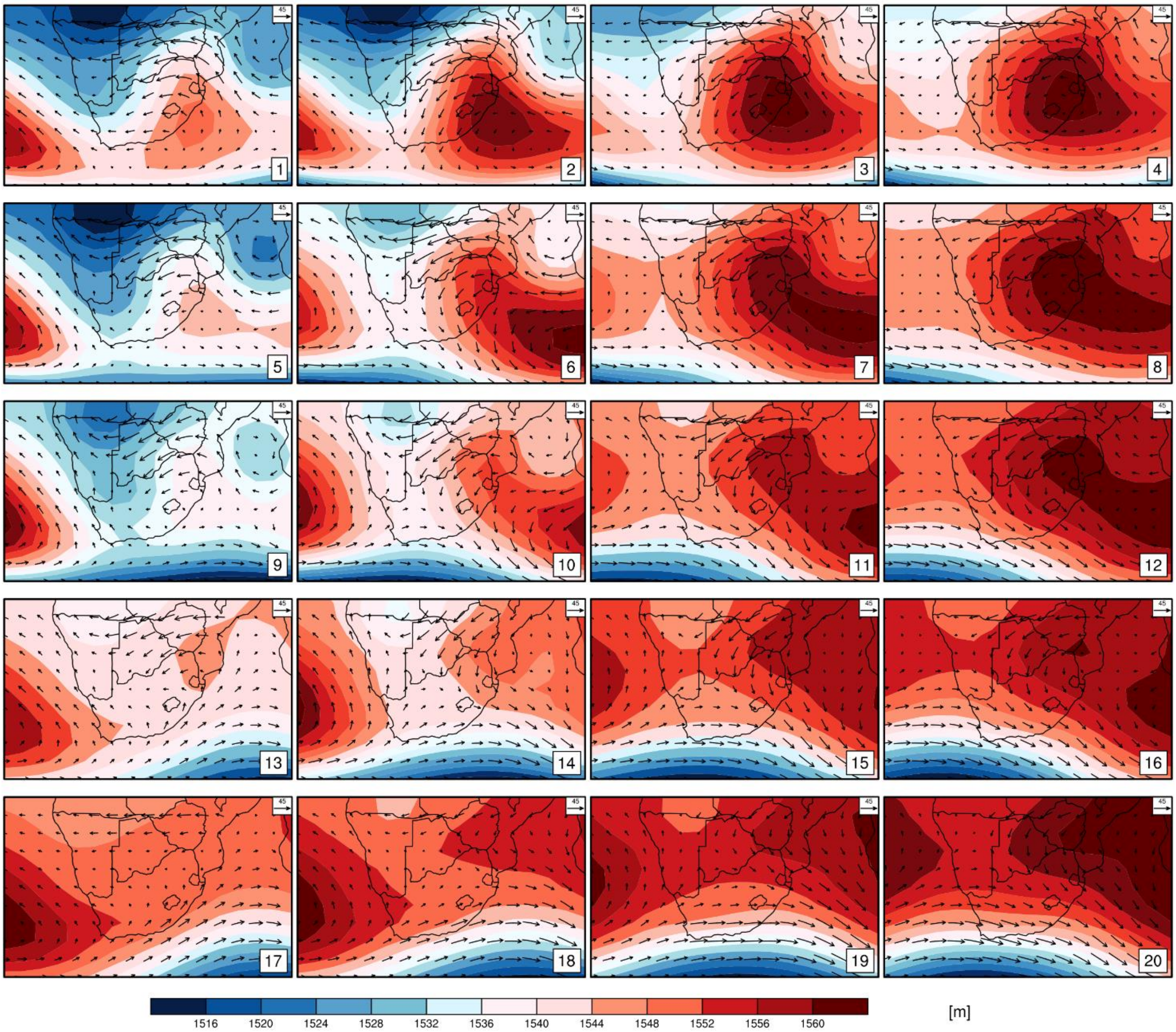


Figure 11: Composite for a moisture flux vector, Geopotential height 850 hPa (shaded).The vectors represent moisture flux ($g.kg^{-1}\ m\ .s^{-1}$) mapping to each node in the trained SOM.

4.4. Seasonal daily mean rainfall

The mean daily rainfall mapping to the trained SOM nodes for all the days from 1990-2014 is illustrated below in **Figure 12**. There is a distinct variation in mean daily rainfall, typical summer rainfall nodes are on the far left and winter rainfall nodes are on the right of the grid. Daily mean rainfall increases from the bottom right to the top left with the main rainy season for Southern Africa occurring on the top left of the grid in nodes 1, 5, 6, 9, 10 and 14. Over the study domain, nodes 5, 9 and 10 are dominant with mean daily rainfall ranging between 6 and 7 mm/day in the north-eastern parts of the sub-continent and up to 10 mm/day further north into Mozambique and the Mozambique channel. The winter rainfall region is well represented in the nodes on the far right particularly node 16, 19 and 20 and the daily mean rainfall here ranges between 8 and 10 mm/day. In the study area of Limpopo, the mean daily rainfall of 6 to 7mm/day is enough to maintain activities such as maize planting which coincides with this main rainy season. However, there is great variability in the early and late summer rainfall conditions depending on the dominant rain-producing synoptic features.

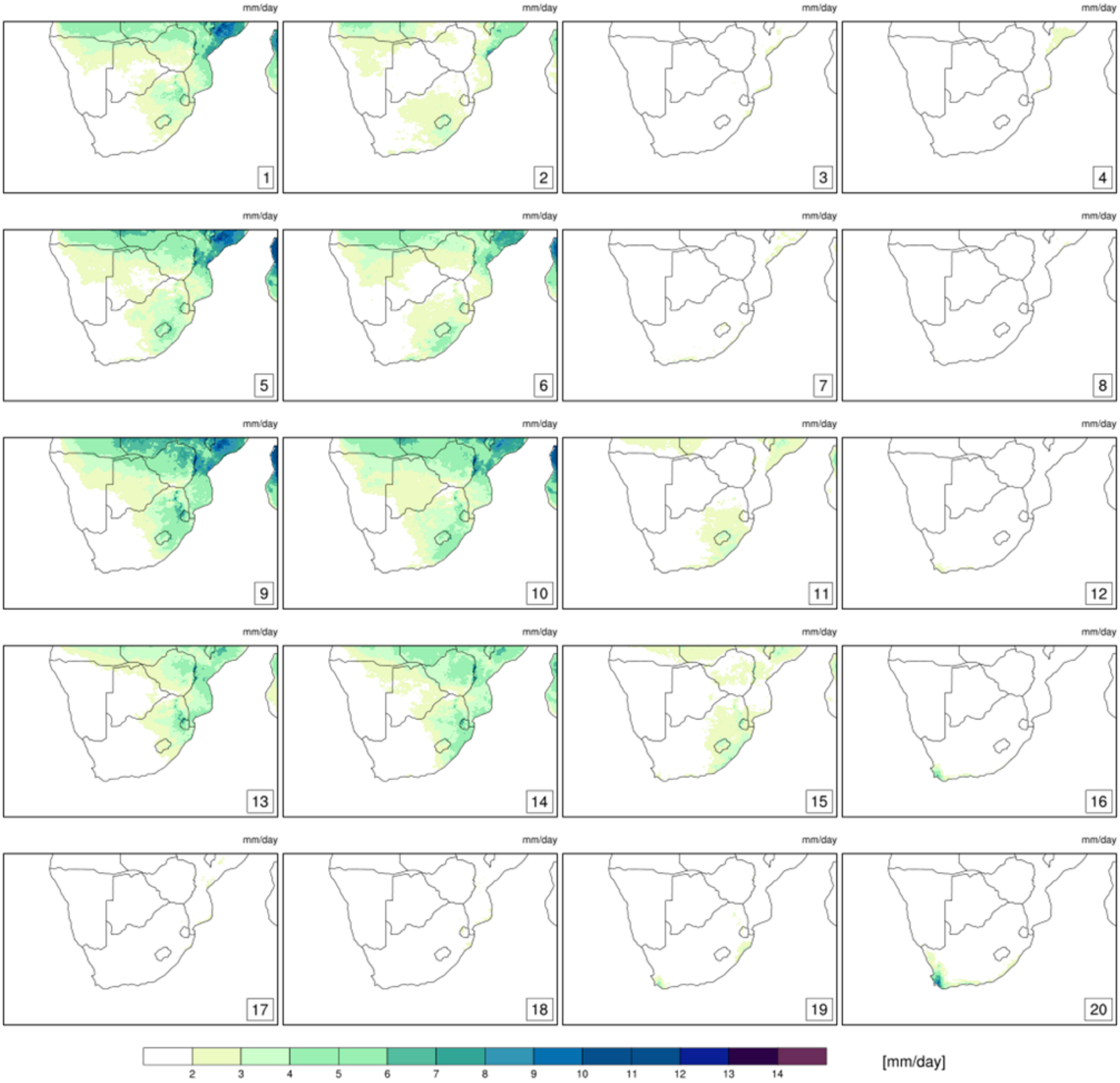


Figure 12: Spatial variability of daily mean rainfall for all days in years from 1990-2014 mapping to the trained SOM nodes using CHIRPS satellite derived data.

4.5. Trends in rainfall characteristics

4.5.1 Trends of seasonal onset, cessation and rainy season duration

In the study area, the climatology of onset varies between August and December with October being the mean onset month from year to year. In the observed stations, on average, the month of October is the rainfall onset month. This may vary depending on large climate modes, for example El Niño years may delay the start to the rainy season (Moeletsi et al., 2011a). Cessation varies between February and April with March being the mean cessation month. There is little variability in the climatology of onset and cessation from station to station.

Trends in onset occurrence

There is evidence that onset does not vary significantly from station to station for some years across the province as illustrated in **Figure 13** below. **Table 4** shows the definitions adopted for computing rainfall onset and other rainfall indices for this study. For five of the six stations (Thabazimbi, Vondo, Pietersburg, Tolwe and Hans Merensky), onset shows an increasing trend as an indication that onset is occurring later in the years on average. The Warmbad station situated South-west of the province is the only station showing a slightly decreasing trend in rainfall onset. The mean onset for this station occurs on day 294 (20th of October). Stations located further north in Limpopo Province such as Vondo and Pietersburg experience later onset, this is an indication that on average rainfall onset occurs later in stations further north in the province as compared to stations in the Southern parts of the province. Seasonally, there is high variability of onset around the mean onset for all the stations with years below the mean observing earlier onset and years above the mean observing later onset. The mean onset for all stations occurs in the 3rd week of October between day 291 and 296.

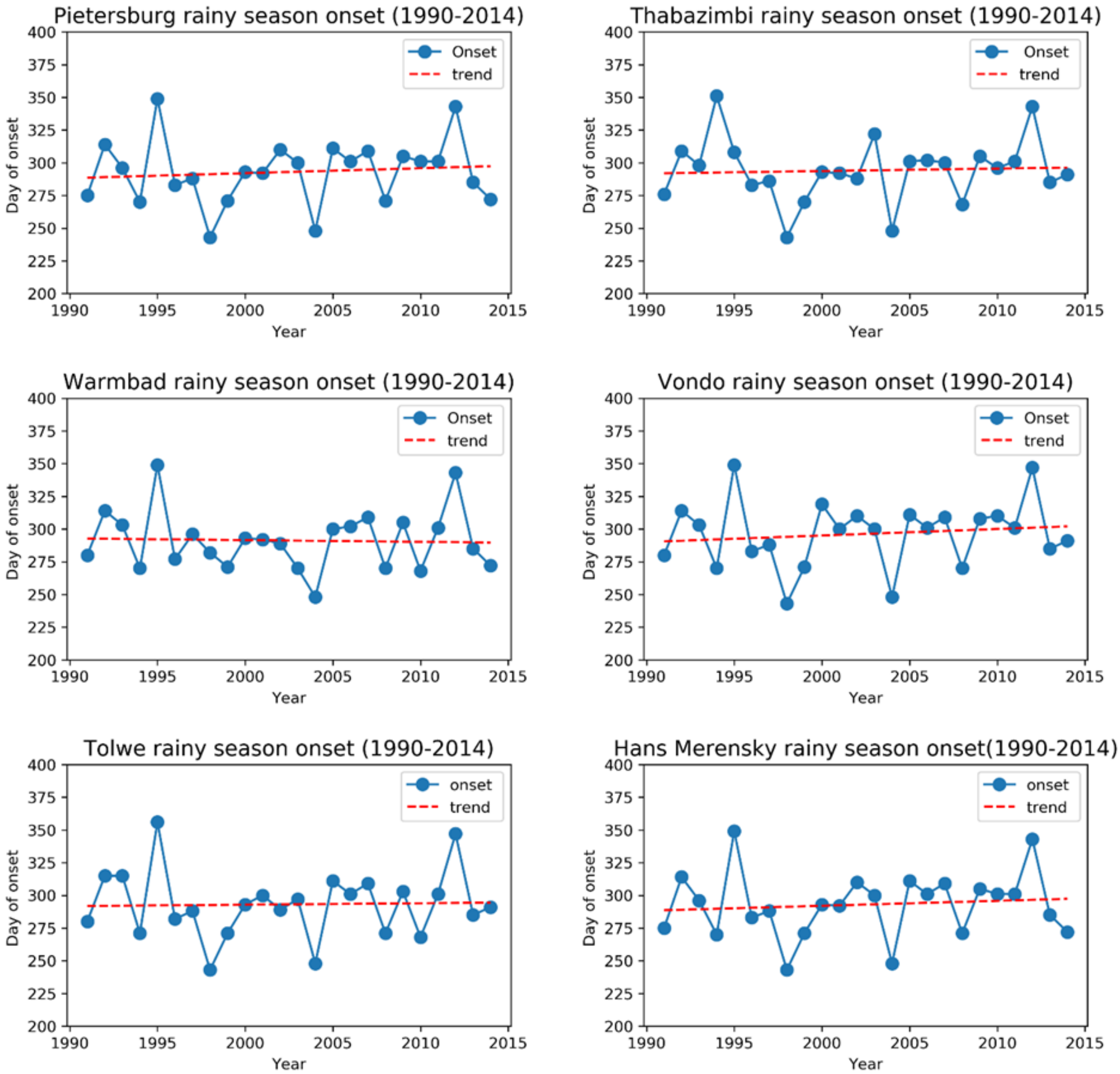


Figure 13: Trends in rainfall onset for Warmbad, Vondo, Tolwe, Pietersburg, Thabazimbi and Hans Merensky in Limpopo from 1990-2014 in Limpopo using CHIRPS daily rainfall data.

On the observed record of the study, the latest onset day is the 22nd of December (Day 356) for Tolwe station and the earliest on the 31st of August (Day 243) for Pietersburg, Vondo, Tolwe, Hans Merensky and Thabazimbi in the 1997/1998 El Niño season. Between 1994 and 1995, a large fluctuation in onset days was observed, onset in 1995 occurred 85 days later than onset in 1994 for Tolwe station and 79 days later for Hans Merensky, Pietersburg and Warmbad stations. The year to year fluctuations in onset suggest the likelihood of different drivers influencing onset variability. Late rainfall onset may also indicate the likelihood of dominant high-pressure systems inhibiting moisture transport from the Warm Indian Ocean and cloud convection. Late rainfall onset is mainly associated with rainfall of higher intensity as the continental features that drive summer rainfall are well developed and well positioned during this period. These features include the heat low over the continent which acts as a conduit for moisture convergence.

A late start to the rainy season can shift the maize growing season to the mid-summer periods which are often characterised by mid-season dry spells in Limpopo, especially if cessation is early. For individual years experiencing late rainfall onset, a shift in the maize growing season alters the maize planting dates for the 120 and 140-day cultivar in Limpopo depending on farmer's planting decisions. On late onset years with early rainfall cessation, these maize cultivars which require longer seasons for optimal growth will be subjected to shorter growing seasons which will impact the yield adversely.

Trends in cessation occurrence

There is a decreasing trend in rainfall cessation which is more clearly defined for Thabazimbi, Tolwe and Vondo stations shown in **Figure 14**. The mean cessation date for all the stations is between the first and the 2nd week of March (Day 62 to day 70). The earliest cessation for all stations on record is on day 33 (2nd of February) for all six stations and the latest cessation on day 111 (21st of April) for all stations except Thabazimbi. A closer investigation of individual years shows that years associated with El Niño experience earlier cessation of rainfall. For example, 1997/1998 season has recorded the earliest cessation for four (Pietersburg, Tolwe, Warmbad and Hans Merensky) of the six stations. This indicates the likelihood of the El Niño influencing variability in rainfall cessation. Strong El Niño years are often characterized by a false start to the rainy season and early rainfall cessation. When this occurs, the first few days are characterised by heavy rains then the rest of the season is characterised by consecutive dry spells. The 1994 season, although not an El Niño year, recorded the earliest cessation of all stations and it appears to be a relatively drier year. The greatest year to year fluctuation was observed between 1993 and 1994, in 1994 cessation occurred 78 days earlier than 1993 for all stations. Between 2010 and 2011, the shortest year to year fluctuation in cessation of 3 days was observed for five of the six stations excluding Warmbad.

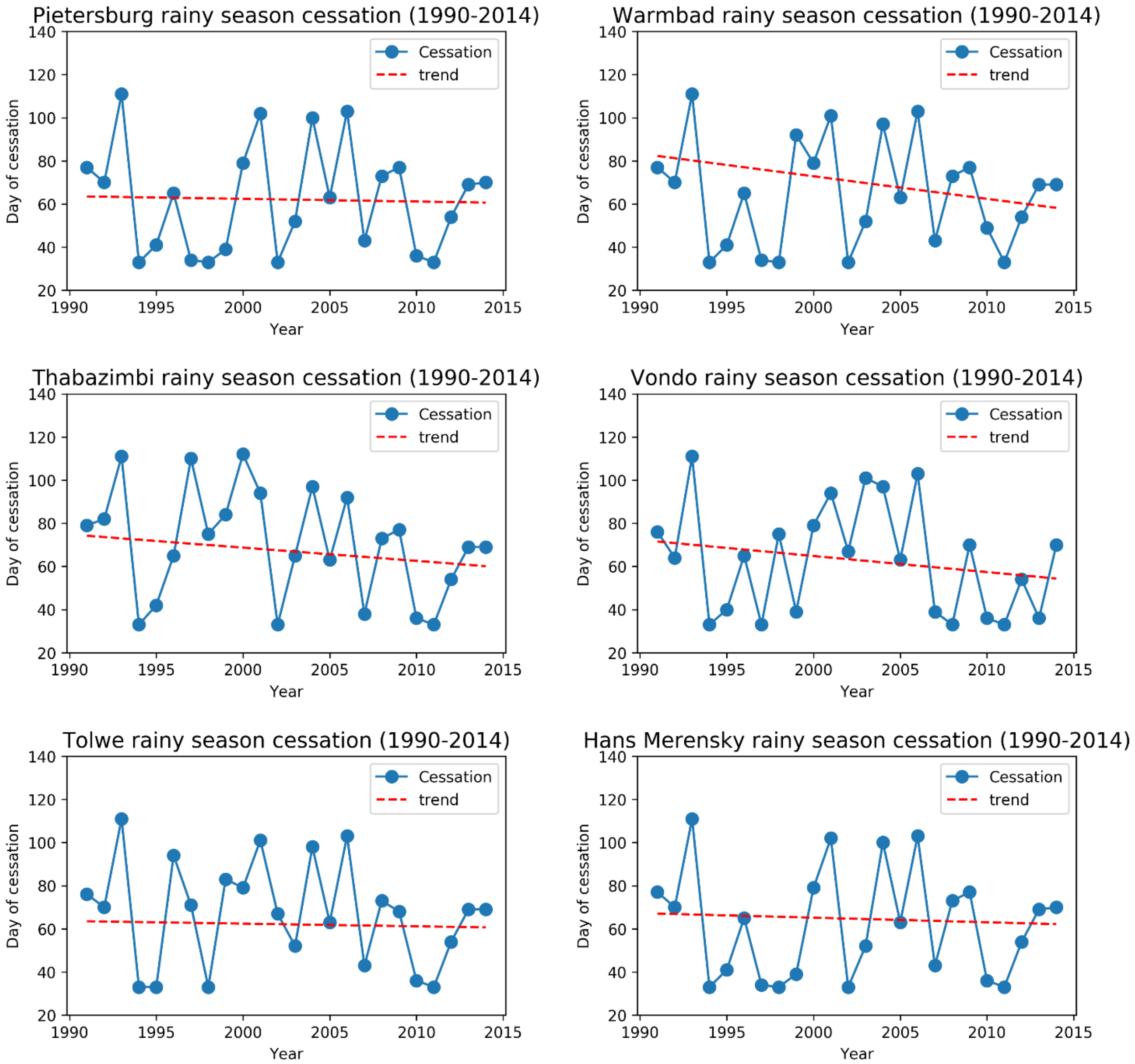


Figure 14: Rainfall cessation trends for Warmbad, Vondo, Tolwe, Pietersburg, Thabazimbi and Hans Merensky in Limpopo from 1990-2014, all cessation dates are computed after the 1st of February.

Early rainfall cessation is associated with shorter growing seasons for years experiencing late rainfall onset, this shortens the length of the maize growing season. Although growing seasons may be short, within-season conditions such as wet and dry spells may determine the final yield output. Maize is particularly sensitive to moisture deficits and the withdrawal of seasonal rains at critical stages of maize growth may lead to pollination failure and reduce the final yield output. On average, it is estimated that a maize plant requires 450 mm to 600 mm per season for optimal growth, early withdrawal of rains may occur before there is enough moisture accumulated to meet the required threshold for optimal maize growth and given that maize in Limpopo province is grown on drylands, this may affect the total yield output on seasons experiencing early cessation such as 1994,1998 and 2011.

Trends in rainy season lengths

The length of the rainy season is important as it determines the length of the period for which agro-meteorological conditions are suitable for maintaining crop growth. Duration of the rainy season shows a decreasing trend as an indication of the shortening of rainy seasons. The shortest duration for all observed stations is 43 days for Tolwe station in 1995 which is 85 days shorter than the previous year (1994) and 135 days shorter than the following year (1996). The longest rainy season durations for all stations occurred in 2004 and spanned 218 days for Pietersburg and Hans Merensky Hoerskool, 216 days for Tolwe station and 215 days for Warmbad, Thabazimbi and Vondo (**Figure 15**). Stations located south (Thabazimbi and Warmbad) have higher mean durations compared to stations in the far north. Thabazimbi recorded a mean duration of 142 days, Warmbad 140 days, Vondo station (132 days), and Pietersburg (135 days). There is great variability in the rainy season durations from year to year and this suggests that the maize cultivars planted from year to year may differ. Seasons such as 1991, 1993, 2001 and 2004 are suitable for longer season cultivars(140-days) and seasons such as 1992, 1994, 1997 and 2005 are suitable for shorter season maize cultivars(120-days) and some seasons such as 1995, 2011 and 2012 are too short for either cultivar. The decreasing trend in duration is a result of the late onset of rainfall and earlier cessation which in turn shifts and shortens the rainy season.

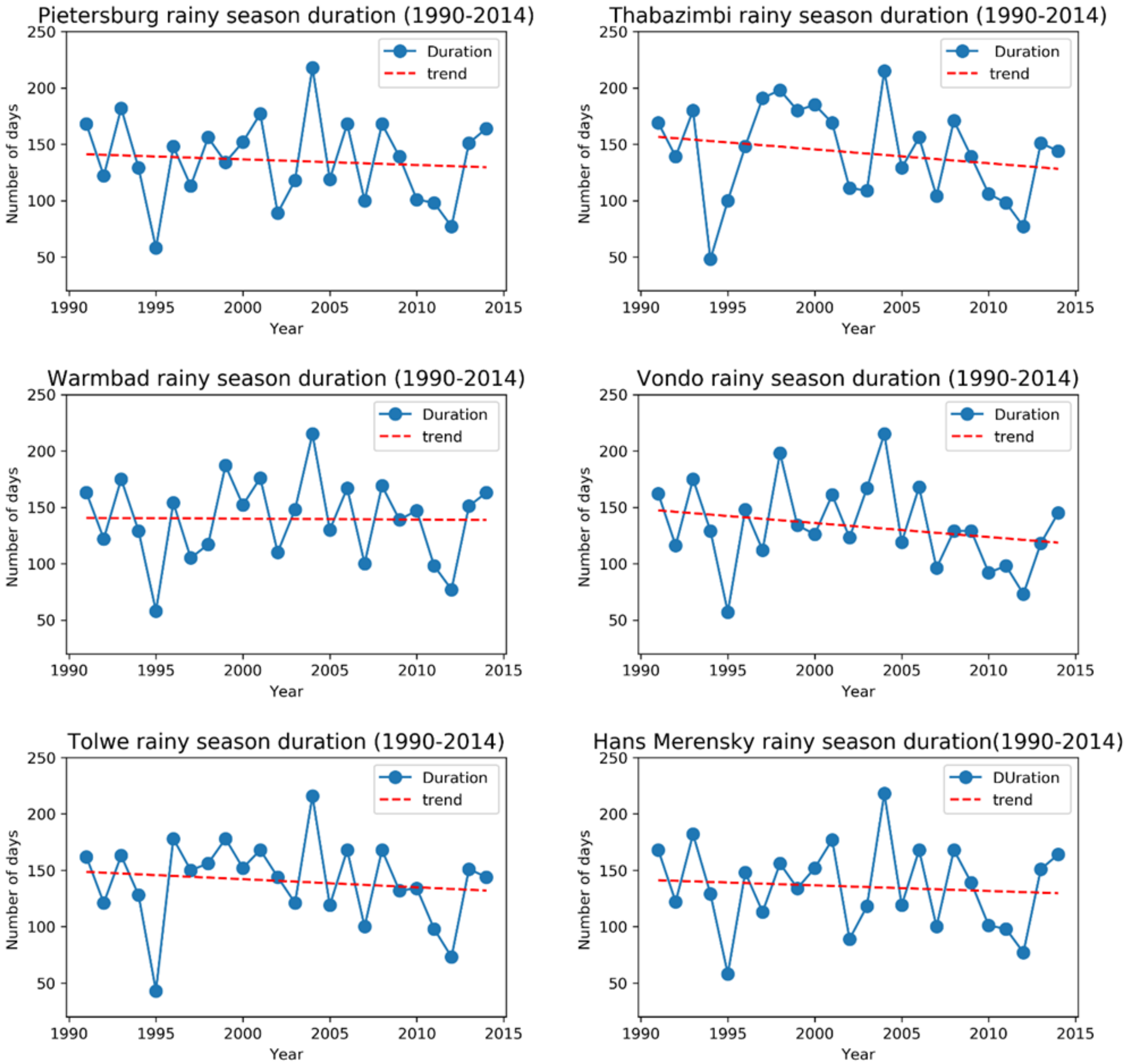


Figure 15: Trends in rainy season duration for Warmbad, Vondo, Tolwe, Pietersburg, Thabazimbi and Hans Merensky in Limpopo from 1990-2014. Duration is computed as: (Onset date-cessation date) for each season.

Rainy season length does not necessarily determine seasonal rainfall totals as there is an interplay of several other rainfall characteristics such as dry spells. Depending on the geographical area, maize requires at least 120 days for optimal growth, however the characterization of rainfall within that period is essential as it determines conditions that are suitable for the maize crop. Some short seasons can be characterized by short-duration high intensity rainfall which may enhance or be detrimental to the crop and some long seasons may be characterised by dry spells which deprive the maize crop of moisture. Normal seasons with consistent rains are often associated with synoptic features that are well developed to provide consistent rains to maintain the growing season and meet the required growing thresholds.

Total seasonal rainfall trends

Three of the six stations (Warmbad, Pietersburg and Hans Merensky) show an increasing trend in the total rainfall. For some individual years the total rainfall is associated with rainy season durations for all stations, for example, the 2012 season recorded the shortest season durations and the lowest seasonal totals. The mean rainfall for the Pietersburg, Warmbad and Thabazimbi maize growing districts over the study period suggests that rainfall was enough for optimal growth of maize although its characterization and distribution per season may determine the final yield output. The Thabazimbi and Warmbad stations in the Highveld recorded a higher mean seasonal totals and this may be attributed to the potential influence of the Modimolle mountain range and orographic rainfall processes (**Figure 16**). For individual years, the year 2000 recorded the highest seasonal total which caused flooding in February 2000 which affected Mozambique, Zimbabwe and northern parts of South Africa. The highest recorded seasonal total is 1072 mm for Thabazimbi in 2000 and the lowest seasonal total is 140 mm for Thabazimbi in 1994. There is no clear spatial pattern in the variability of the season totals although stations in the Highveld have higher season totals and means.

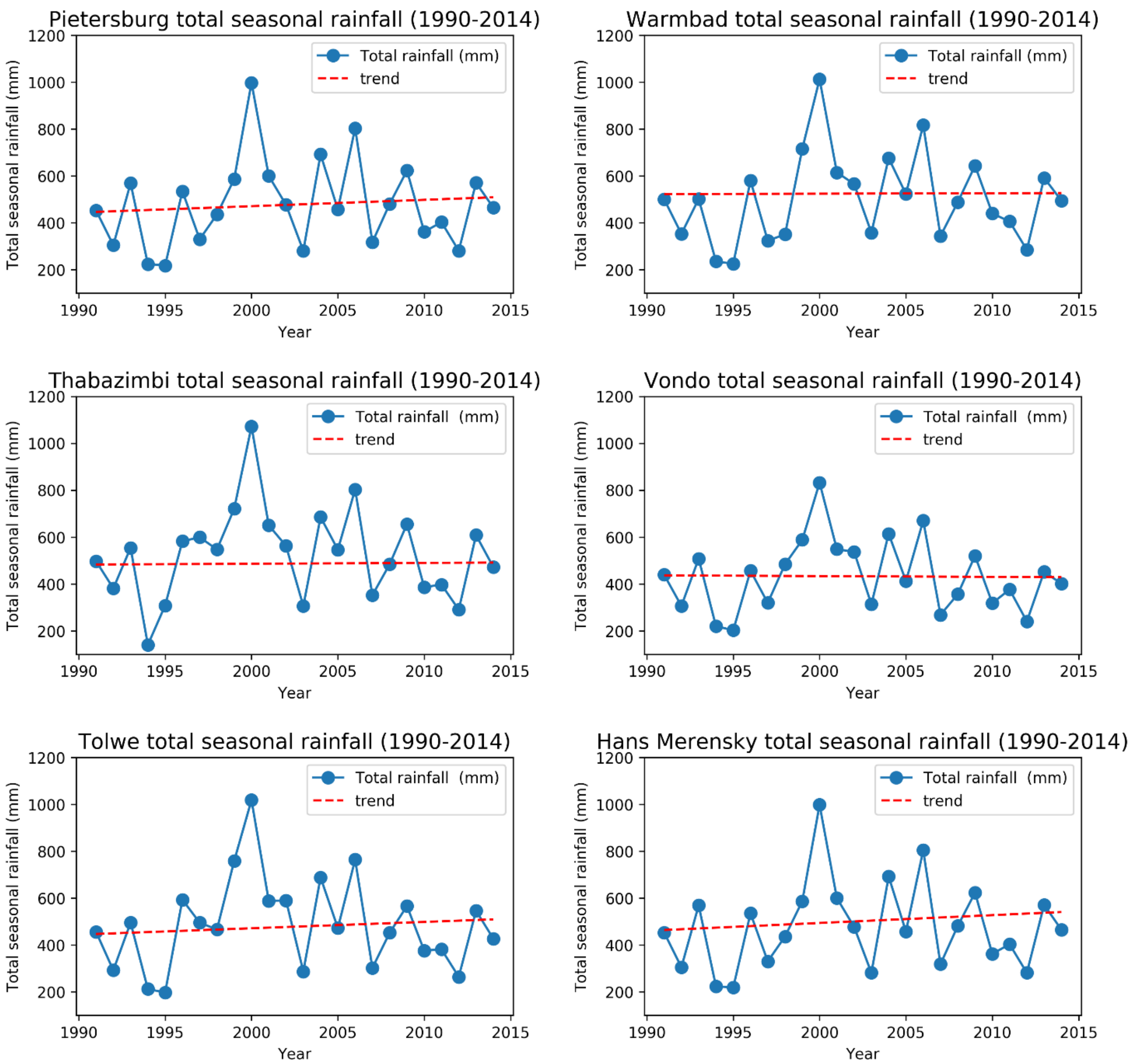


Figure 16: Total seasonal rainfall trends for Vondo, Tolwe, Pietersburg, Thabazimbi and Hans Merensky in Limpopo from 1990-2014 using CHIRPS daily rainfall data. This is the total accumulated rainfall between the defined onset and cessation.

4.5.2. Rainy season duration and total seasonal rainfall changes

The relationship between rainy season duration and the total seasonal rainfall accumulated is investigated to understand if longer seasons experience a higher seasonal total or if shorter seasons are characterised by lower seasonal totals. This relationship also provides insight on the nature of rainfall during the season. For example, shorter seasons with high seasonal totals could translate into a narrower and more intense distribution of rainfall events in the season increasing chances of heavy showers while longer seasons with low rainfall totals could arise from wider and less intense rainfall event distribution increasing the possibility of dry spells.

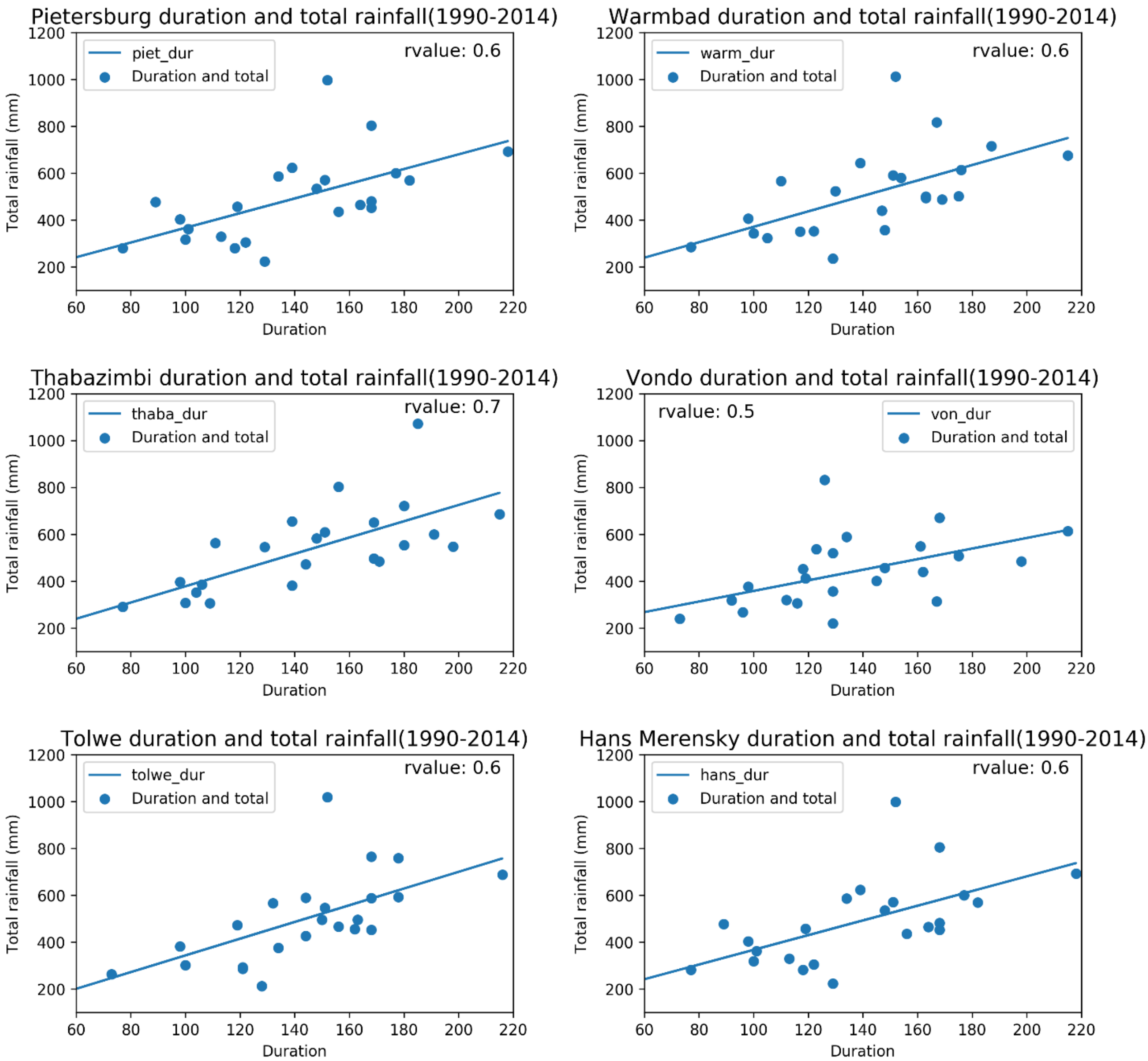


Figure 17: The relationship between the rainy season duration and total seasonal rainfall for Warmbad, Vondo, Tolwe, Pietersburg, Thabazimbi and Hans Merensky in Limpopo Province from 1990-2014.

Figure 17 shows that there is a positive linear relationship between rainy season duration and total seasonal rainfall for all the six stations and the strength of the relationship varies from station to station. As the rainy season duration increases, so does the total seasonal rainfall all the stations. This relationship is strongest in Thabazimbi with a correlation of 0.7 and Tolwe, Hans Merensky and Pietersburg with correlation of 0.6. Vondo station in the north has a moderate correlation of 0.5 as it recorded the lowest mean rainfall total. For Limpopo, longer growing seasons are associated with enough total rainfall which meets the maize growing thresholds for 140-day maize varieties. On average, over the study period, season durations have been shortening but the total seasonal rainfall meets the maize growing threshold. The Vondo station is an exception as it has recorded a lower mean for rainfall totals showing that for some seasons only short (120-day) and drought tolerant varieties can be planted. There is no clear evidence of spatial variability in the strength of the relationship between rainy season duration and total seasonal rainfall, with all five stations in the Lowveld, Highveld and Bushveld of the province apart from Vondo, observing moderate to strong positive correlations. Year to year variability in durations and rainfall total shows that for individual dry years such as 1992, 2003, 2007 and 2012, the maize growing rainfall threshold was not met. For these years, farmers who planted long duration cultivars that are not drought resistant potentially suffered losses. Although total rainfall and duration could be enough for optimal maize growth in some years, the potential impact of wet and dry spells and high intensity rainy days within the season should not be overlooked.

4.5.3. Number of wet days, rainfall onset and rainy season duration.

Appendix A illustrates the number of wet and dry days within the defined rainy seasons for the six stations. These number of wet and dry days are significant in determining the wet and dry spell lengths shown in **Figure 18**. There is greater annual variability in the seasonal number of wet and dry days with the year 2004 having a having the highest number of dry days (160 days) for all stations. This year as also been found to be one of the driest for the study period. The number of wet days vary between 5 and 55 days for all stations.

Understanding the relationship between onset and duration provides insight on whether later rainfall onset is associated with shorter rainy seasons or longer rainy seasons. **Appendix B** shows that as day of onset increases, duration of the rainy season decreases. Later rainfall onsets with early cessation are associated with shorter growing seasons. There is a strong negative relationship between rainfall onset and rainy season duration, this relationship is stronger for Tolwe, Thabazimbi and Warmbad. For the three selected maize growing districts (Thabazimbi, Warmbad and Pietersburg), maize that is planted late following the late rainfall onset, will most likely experience short growing seasons. The mid-season conditions determine the final yield output even if the maize growing seasons are short. These crops are most likely to coincide with mid-season dry spells. The mid-season consecutive dry days lead to water-stress for the maize crops through higher evapo-transpiration. For farmers who plant earlier around the 15th of October regardless of rainfall onset occurring late, yield depends on the cultivar planted. If the cultivar is drought-resistant, the seeds can withstand dry spells and grow with little rainfall required. If the cultivar is not drought resistant, seedling growth can be delayed. The damage caused dry spells occurring during pollination is often irreversible even if agro-meteorological conditions improve towards the end of the season.

The relationship between rainy season duration and number of wet days reveals that there is a linear positive correlation, as rainy season duration increases so does the number of wet days in the rainy season. The strength of this relationship may change from year to year depending on the length of the rainy season (**Appendix C**). In the three selected maize growing regions (Thabazimbi, Warmbad and Pietersburg), rainy season durations between 120-140 days often experience between 30 and 40 wet days. For Thabazimbi, a strong correlation of 0.8 was observed, and 0.7 for Warmbad and Pietersburg. The intensity of rainfall on these wet days may determine yield response for the three maize growing districts. The year to year variability in rainy season duration translates to variability in number of wet days for each season. Warmbad with higher mean duration are expected to have a higher number of wet days, however this does not directly translate to higher yield as the wet days may be characterised by high intensity rainfall events which may be detrimental to maize growth and yield.

4.6. Variability of wet and dry spells

Wet and dry spells provide an account of the consistency of rainfall from onset to cessation. **Table 4** shows the agro-meteorological definitions adopted for computing wet and dry spells in this study. All stations are characterised by high number dry spells resulting from a higher number of consecutive dry days within the defined rainy season. All stations including those with high seasonal rainfall totals like Warmbad and Hans Merensky have high number of dry spells (**Figure 18**). Given that fewer wet spells have been observed, the total rainfall accumulated in each of the stations is mainly from isolated high intensity rainfall events rather than wet spells. There is a great variability in the number of dry spells from year to year with a mean number of 9 dry spells for all stations. The highest number of dry spells is 16 spells observed for Pietersburg, Warmbad, Tolwe and Hans Merensky for 1993 and 2004. The highest number of dry spells recorded for Vondo and Thabazimbi is 15 spells in 1993 and 2004 respectively.

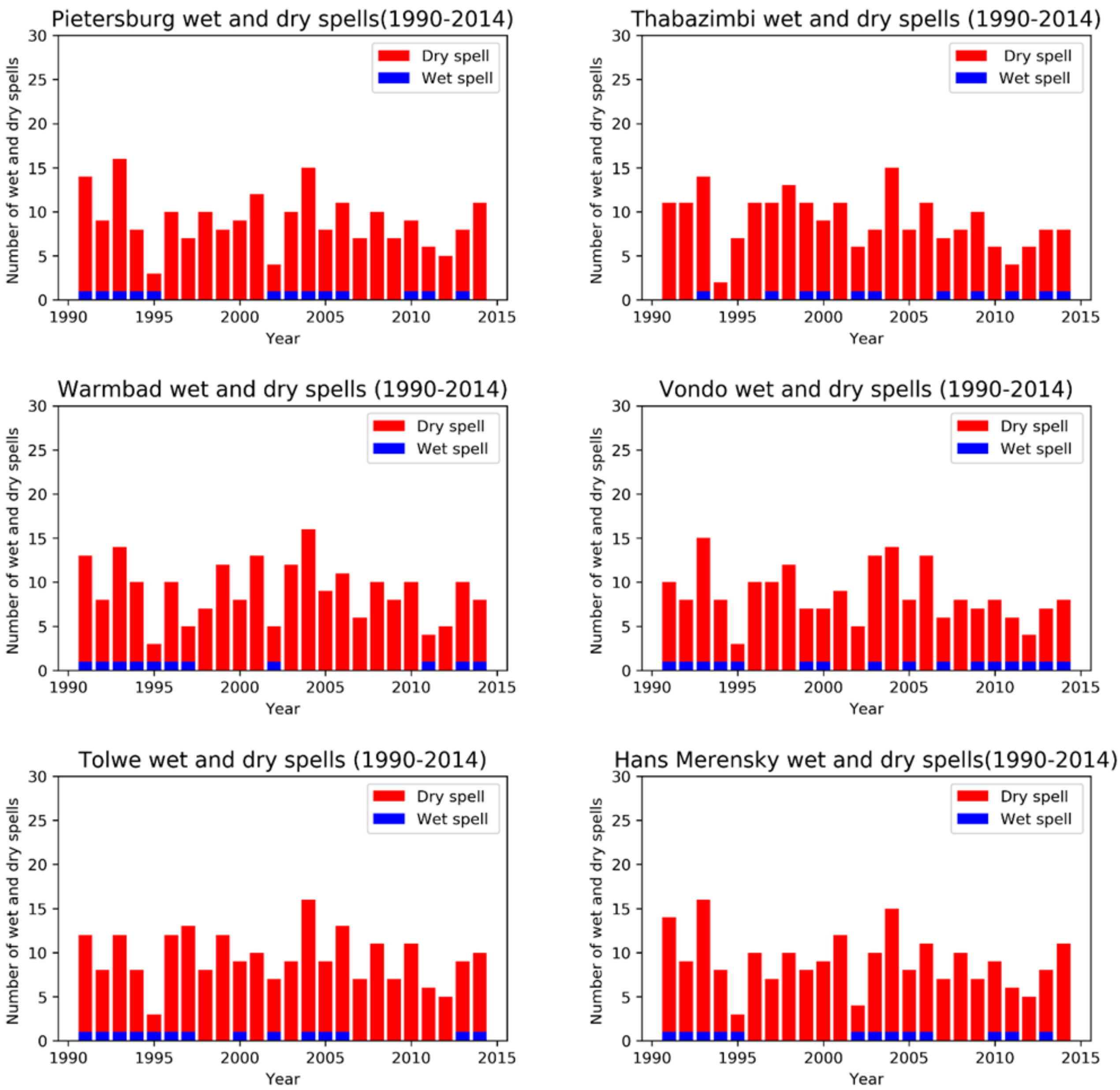


Figure 18: Wet and dry spells for Warmbad, Vondo, Pietersburg, Thabazimbi, Tolwe and Hans Merensky in Limpopo Province from 1990-2014.

The consecutive wet days (CWD) and consecutive dry days (CDD) mapping to each node in the trained SOM where computed to understand the spatial extent of the wet and dry patterns using the defined wet and dry spell criteria (**Figure 19** and **Figure 20**). During the mid-summer, in nodes 9 and 10 CWD predominantly occur in the north-eastern parts of the domain. These consecutive wet days increase in a north-easterly direction with a number of days ranging between 6 and 13 days,

Figure 20. These consecutive wet days such as those observed in node 10, exhibit a north-easterly inflow of moisture from the Tropical Western Indian Ocean (**Figure 11**). The winter nodes on the right, are characterised by consecutive wet days over the Western Cape region in nodes 16 and 20 with between 10 and 12 consecutive wet days. The consecutive dry days are, however, predominant over the domain during the main summer rainy season. Consecutive dry days range between 13 and 14 days even in typical mid-summer nodes such as 5, 6, 9 and 10, **Figure 19**. This is an indication that the season is characterised by high number of dry spells and individual-high intensity rainy days. These consecutive wet and dry days are essential determinants of soil moisture during the growing period.

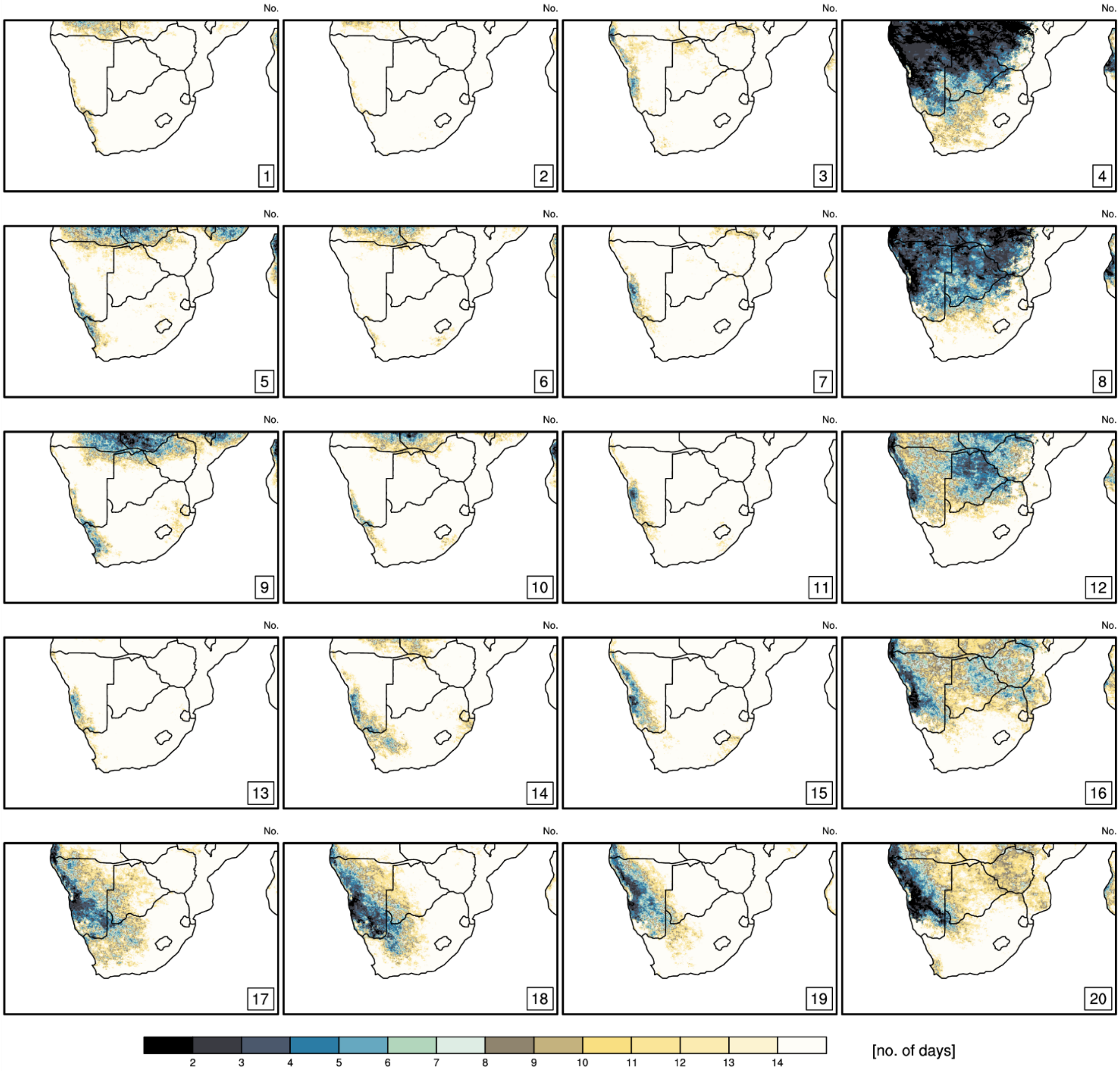


Figure 19: Number of consecutive dry days mapping to each SOM node in the study domain from 1990-2014.

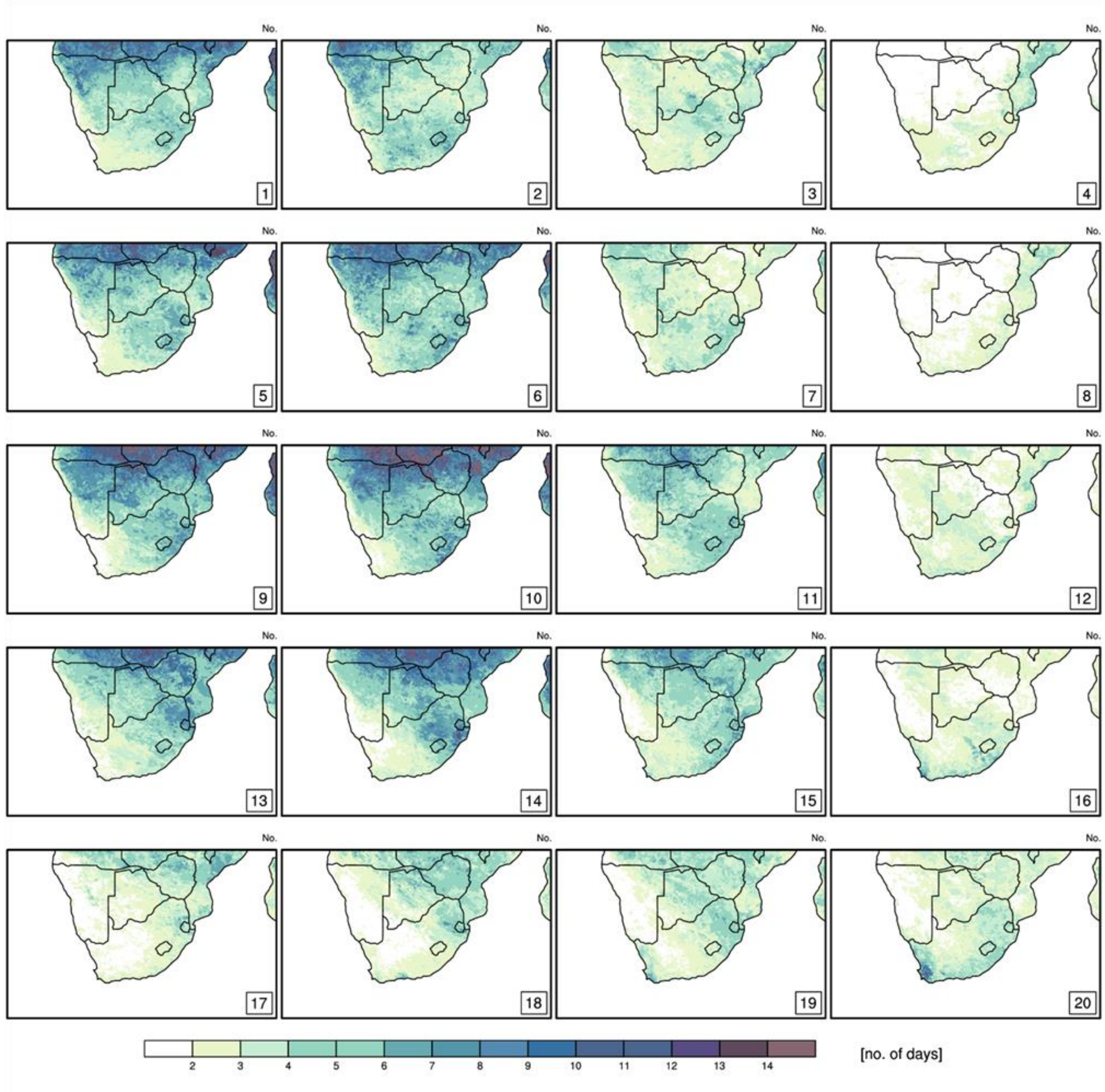


Figure 20: Number of consecutive wet days mapping to each SOM node in the study domain from 1990-2014.

4.7. High intensity rainfall events

The long-term wet conditions during the season are possibly determined by high intensity rainy events and not spell length as very few wet spells have been observed in this study. Rainfall events with rainfall greater than 10 mm, 20 mm, 40 mm, 60 mm and 80 mm were counted and computed for each year in all the stations from onset to cessation. These rainfall intensity thresholds have been found to have varying impacts on maize growth depending on the period of the growing season at which they coincide with maize crops. All the six stations are characterised by a high number of rainfall events accumulating rainfall greater than or equal to 10 mm/day, this signals at potential for productive seasons especially for stations such as Warmbad and Vondo with up to 29 rainfall events reaching 10 mm/day (**Figure 21**). The frequency of high intensity rainy days within the 10mm/day threshold varies from year to year with the lowest number of 4 events in 1994 for Tolwe station and 29 events for Vondo in 2006 and Warmbad in 1999. Rainfall events reaching the 10 mm threshold are often described as productive rainfall as they are associated with optimal maize growth and no adverse impacts on maize phenology. Maize producing districts with high number of events within this threshold such as Warmbad are expected to have more productive growing seasons compared to districts such as Pietersburg and Thabazimbi.

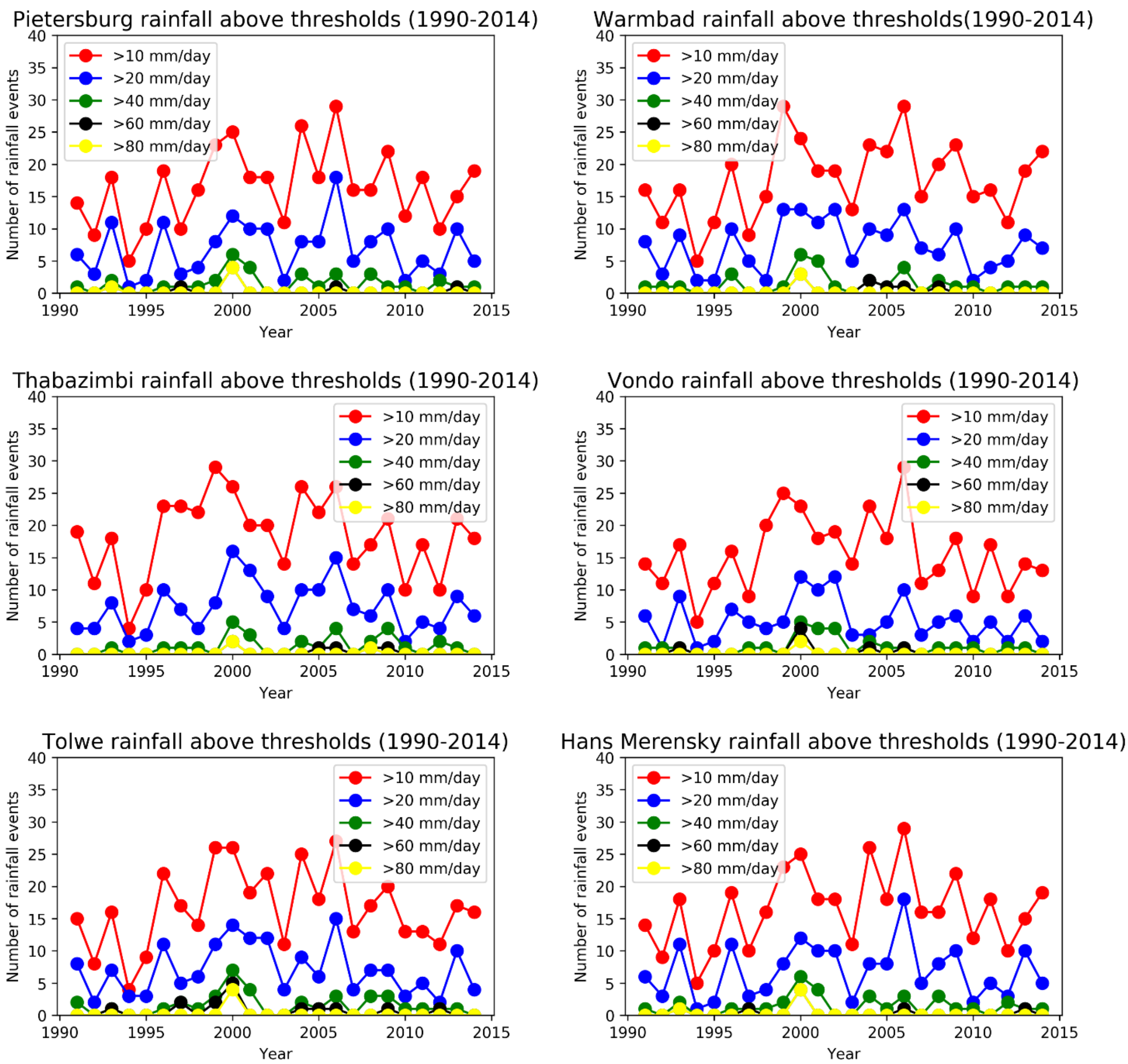


Figure 21: Number of rainfall events above the 10,20,40,60 and 80mm/day threshold in Limpopo Province from 1990-2014.

During the pollination stage, heavy rainfall events in the threshold of 80 mm/day can wash away the pollen before fertilization occurs thus reducing the rate of pollination leading to poor yields. These events are frequent in year 2000 for all the stations with the highest number of 4 events occurring in Pietersburg, Tolwe and Hans Merensky. These events appear to be associated with random extreme rainfall events such as the heavy rainfall event that occurred in February 2000 over north-eastern parts of South Africa and Mozambique. Towards the harvesting season, moisture in the crop must be reduced by 35-40% for the crop to dry out. Heavy rainfall during this period leads to excess moisture on the crop leading to the proliferation of maize bacteria and fungi. This reduces the yield quality and the weight of the dry mass; these events are dominant for the year 2000 for most stations. Consistent rainfall events above 40 mm a day during germination can lead to waterlogging leading to the seed being over-saturated by water thus delaying germination.

High intensity rainfall events are often associated with tropical temperate troughs, mid-latitude cyclones and other subtropical mesoscale convective systems. In the study region, extreme rainfall is predominant in late summer with January often appearing as the peak rainfall month. The ITCZ has been found to intensify over the continent before the occurrence of TTTs, cloud bands linked with these systems are aligned in a Northwest to Southeast and dissipate into the Indian Ocean after a few days. Their presence is often associated with heavy rainy days. The spatial distribution of rainfall events exceeding 10 mm/day and 20 mm/day mapping to the trained SOM is illustrated in **Appendix D** and **Appendix E**. For both the 10mm and 20mm thresholds, the number of high intensity rainfall events increases in a north-easterly direction into South of Zimbabwe and Mozambique.

4.8. Observed trends in daily rainfall intensity

The simple daily Intensity index (SDII) is computed by dividing the total rainfall by the number of wet days for each year. In this case, a wet day is defined as any day with rainfall greater than or equal to 2 mm. The SDII shows that the average daily rainfall intensity varies between 7 and 20 mm per day for all stations with an average of 13 mm/day, **Figure 22**. Stations with fewer (more) rainy days and higher (lower) seasonal totals are found to have higher (lower) rainfall intensity. This suggests that daily intensity is dependent on number of rainy days within which the rain has been accumulated rather than the total seasonal rain. When high rainfall total has been accumulated in a few days, it likely to be of high intensity.

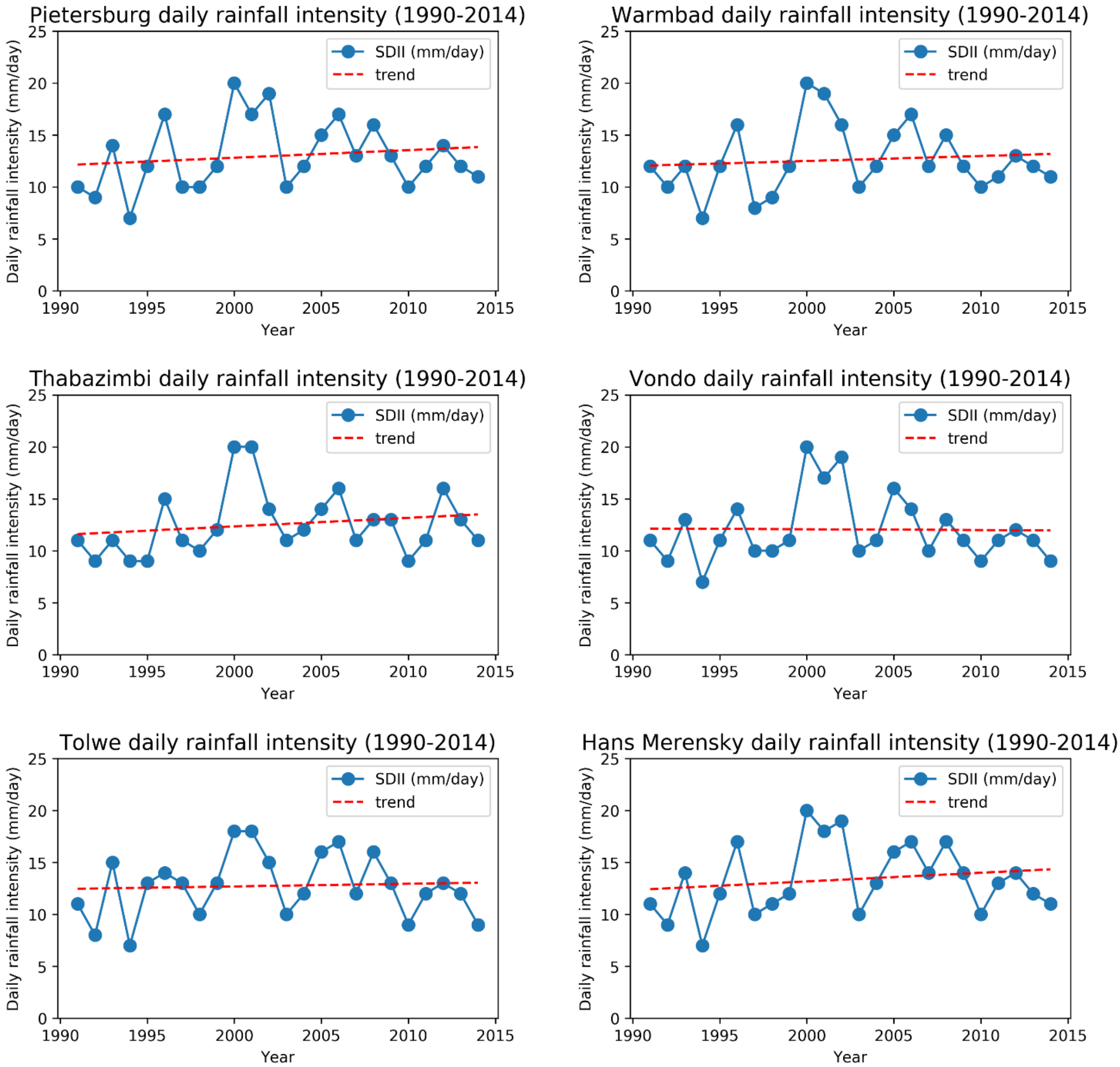


Figure 22: Simple daily intensity index for Warmbad, Vondo, Tolwe, Pietersburg, Thabazimbi and Hans Merensky in Limpopo Province from 1990-2014. The red dotted line represents the trend.

There is great annual variability in the intensity of daily rainfall across the six stations, however trends for five of the six stations excluding Vondo hint at an increase in the daily rainfall intensity during the main rainy season from onset to cessation for each year (**Figure 22**). This trend is more apparent at the Pietersburg and Hans Merensky stations. The year 1994 for all stations has recorded the lowest daily rainfall intensity of 7 mm/day and this year is one of the years that recorded the lowest total seasonal rainfall. The year 2000 which recorded the highest seasonal total, recorded the highest daily intensity of 20 mm/day in five (Warmbad, Thabazimbi, Hans Merensky, Pietersburg and Vondo) of the six stations. Although the total seasonal rainfall and the productive threshold for most of the stations reaches the requirements for maize growing in the region, the daily intensity of seasonal rainfall may be detrimental to maize crops depending on its timing relative to the crop cycle. Given that the daily rainfall intensity for the selected maize growing districts shows an increase on some years, it may have had a great impact on the agro-meteorological conditions and the overall yield on years such as 2000 and 2001.

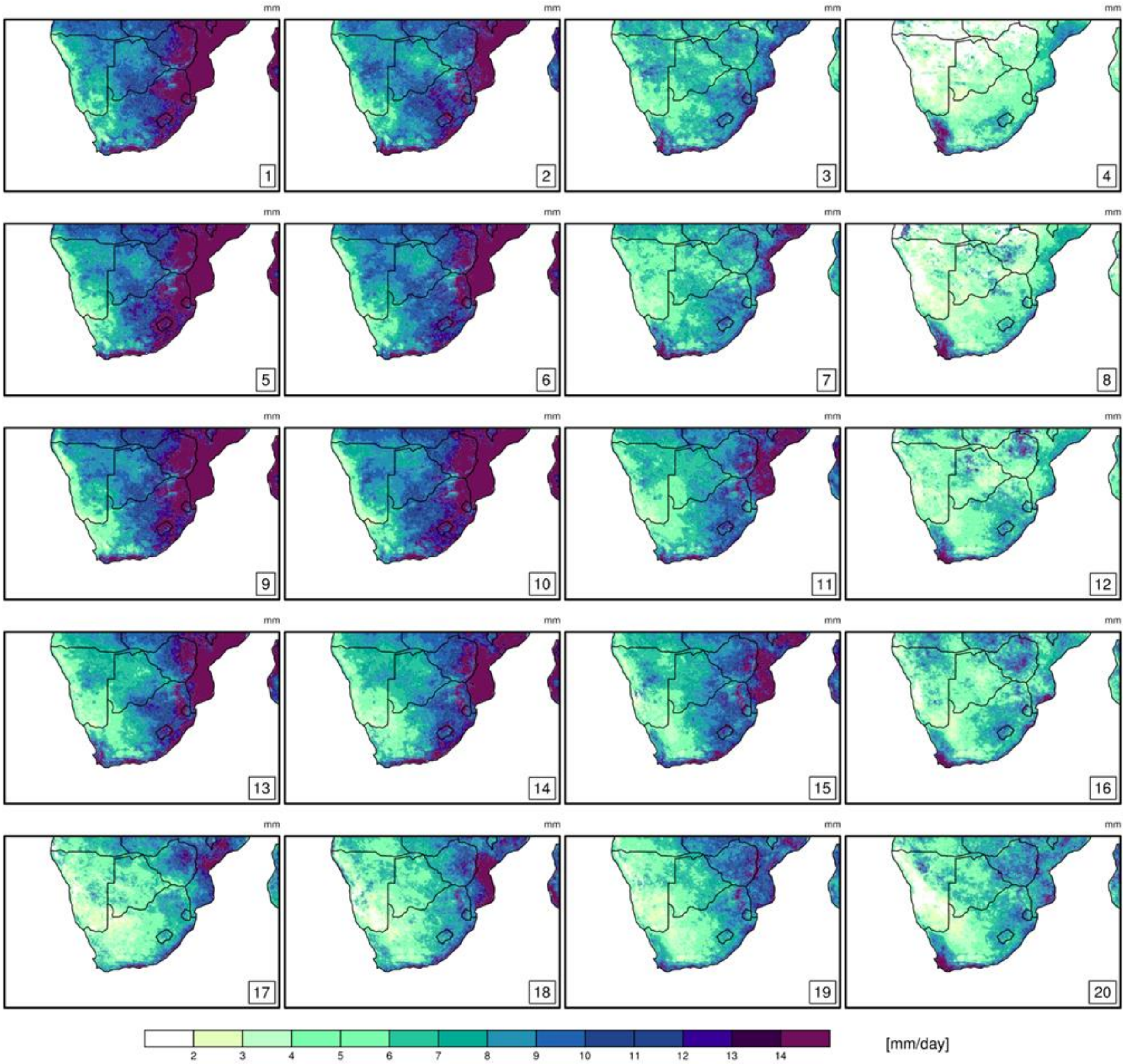


Figure 23: Spatial variability of daily rainfall intensity mapping to the trained SOM nodes over the study domain. Node numbers are indicated at the bottom right corner of each node.

Over the study domain during summer, rainfall shows high daily intensity particularly in node 1, 5, 9 and 10 over the selected maize planting districts as illustrated in (**Figure 23**). This intensity increases north-east into south of Mozambique. This shows that accumulated rainfall was mainly in the form of high intensity rainy events which had implications on the maize growing season. These high intensity rainfall events are predominant towards the end of the season in January over Limpopo

Province. Winter nodes 4, 8, 12, 16 and 20 are characterised with high daily rainfall intensity within the South-western region of South Africa owing to its Mediterranean climate. The daily rainfall intensity here is around 13mm/day. The all-year rainfall region in the Cape south coast of South Africa appears to have high rainfall intensity throughout all the grid except for nodes 17, 18 and 19. For this region, daily rainfall intensity is higher in summer nodes as compared to the winter nodes. Farmers who often plant very late in the season count on the January rains to sustain their maize crops into ripening, however when these rains become extreme, the yield is lost resulting from damage in the plant structure, poor pollination and the rotting of the maize cobs.

4.9. Maize yield variability and response to rainfall characteristics

The relationship between the computed rainfall characteristics and maize yield is evaluated using correlation analysis to understand the potential implications of rainfall variability on maize yield. Rainfall characteristics such as total seasonal rainfall, duration and wet and dry spells are key in determining growing conditions for maize. Ideally, for optimal maize growth in the common case of the 140-day growing maize cultivar, rainfall must be consistent in the form of light showers. Duration determines the length of the period for which conditions are suitable for growing maize and the wet and dry spells determine the consistency and distribution of the accumulated seasonal rainfall.

At district scale (**Figure 24**), maize yield (ton/ha) for Thabazimbi and Warmbad show great year to year variability. The Pietersburg district accumulated the highest yield on record of around 14 ton/ha in 2004 followed by Thabazimbi with a yield of 10 ton/ha in 2002. The highest yield for Pietersburg coincides with the longest rainy season duration of 218 days recorded for the Pietersburg district in 2004 (**Figure 15**). On record, the year 2000 is observed to be a year of high intensity rainfall events leading to flooding in February for South Africa and parts of Mozambique. **Figure 16** also shows that the year 2000 received the highest total seasonal rainfall, however, this year is one of the years with the lowest accumulated yield which is below the average yield for all the districts. The Warmbad maize district was mostly affected and accumulated yield of 1 ton/ha on that year although the season duration was 150 days. Although the total seasonal rainfall accumulated was enough to grow maize in the three districts, the year to year yield variability is a result of the impacts of high rainfall intensity on the maize phenology and yield.

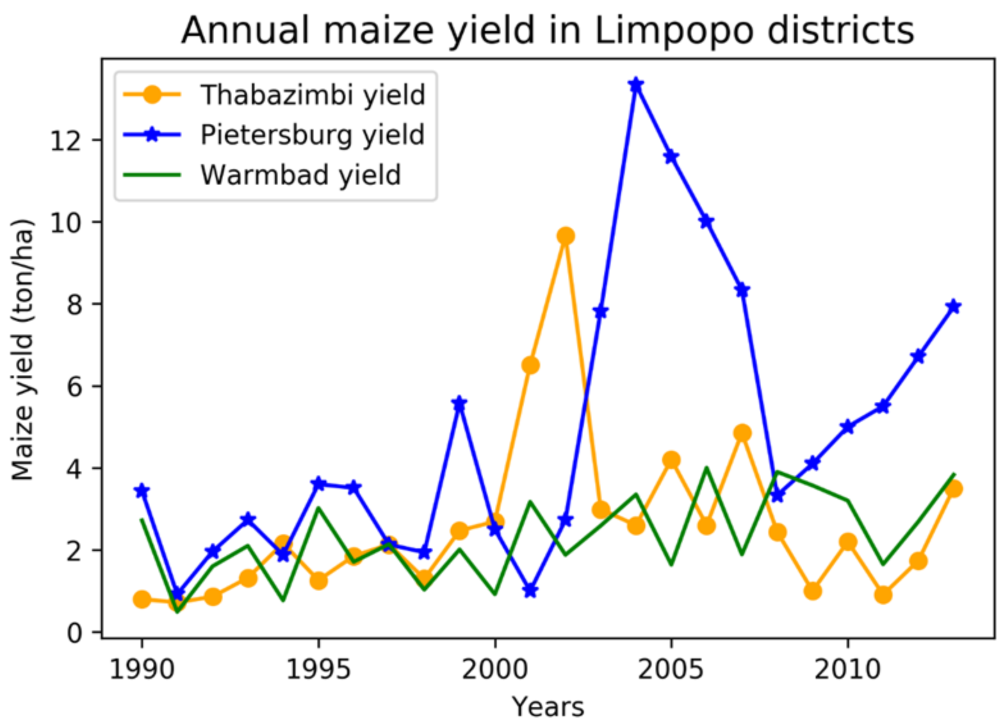


Figure 24: Long-term district annual maize yields (ton/ha) for Pietersburg, Thabazimbi and Warmbad from 1990-2013.

For this study, no long-term statistically significant linear relationship was found between maize yield and total rainfall and duration for the three maize growing districts. **Appendix G** illustrates the relationship between maize yield and total seasonal rainfall, this indicates that total seasonal rainfall had less impact on the yield and thus any variability in the yield could be a result of the characterization of rainfall within the season rather than the total rainfall accumulated. The same is true for the rainy season duration, **Appendix F**. Although in the long-term there is no significant correlation between maize and duration and total rainfall, the year to year variability in yield is a result of varying growing season lengths from year to year and variability in rainfall consistency. The variability in the choice of planting dates may be the cause of the lack of a significant relationship between rainy season duration and maize yield. The variability in maize yield may have been due to a combination of multiple rainfall characteristics and non-climatic factors.

For the eastern maize production region of South Africa, it has been previously found that white maize requires longer seasons to grow optimally and yellow maize can grow well under shorter drier seasons (Moeletsi and Walker, 2012, Walker and Schulze, 2008). In **Figure 25** below, a comparison of provincial averaged yellow and white maize for Limpopo Province shows that there is marginal yield variability from year to year. Both the yellow and white cultivars generally show an increase in annual yield (ton/ha) from 1990-2013. Farmer's choice between the yellow and white maize variety is mainly influenced by the length of the growing season. Yellow maize in the eastern maize growing region of South Africa in Limpopo can grow well in shorter seasons such as those illustrated in **Figure 15** for Vondo station. White maize requires longer growing seasons and thus would grow well in areas such as Warmbad growing district in Limpopo where the mean season duration is 140 days. This steady increase in yield for both cultivars regardless of seasons becoming shorter on average shows that farming methods and decisions such as cultivar choice have improved overtime.

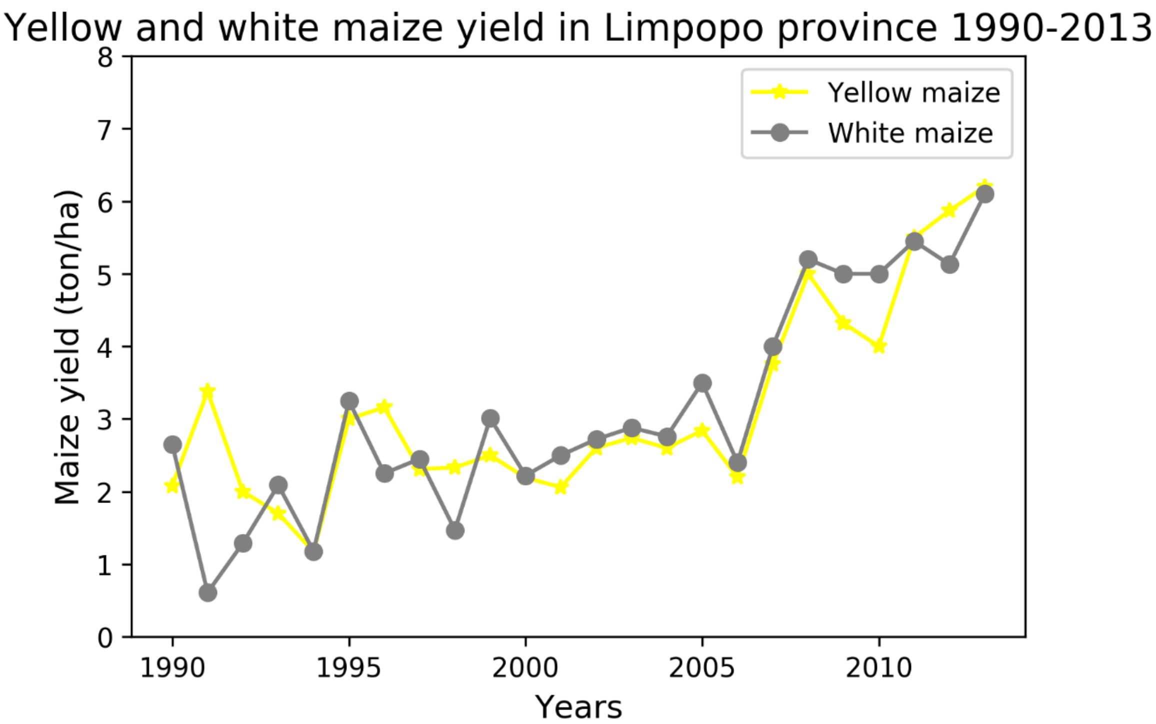


Figure 25: Provincial averaged yellow and white maize yield in Limpopo Province from 1990-2013.

4.10. Synoptic states, rainfall characteristics and maize yield

4.10.1. Synoptic evaluation of the rainy season

The strength and position of large synoptic drivers that influence different rainfall responses in the region may vary from year to year. At an intra-seasonal scale, rainfall characteristics such as onset, rainy season duration, wet and dry spells and high intensity rainfall events vary with seasonal shift in subtropical high-pressure systems and changes in moisture sources. In typical summer synoptic states where most of the sub-continent's rainfall occurs, sub-tropical high-pressure systems retreat south into the ocean and are replaced by the heat low pressure systems in Spring and the tropical low-pressure system in summer (DJF). This period is also characterized by an increased rate of moisture flux influenced by the tropical low acting as a conduit for moisture flux convergence (**Figure 11**). The linkage between the mid-latitudes and subtropical low-pressure system in nodes 5 and 9 in **Figure 8** makes it conducive for Tropical Temperate Troughs to form. These troughs have been found to contribute up to 60% of the total rainfall in the region (Hart et al., 2013b). The drivers of early and late summer rainfall vary resulting in differences in rainfall intensity. The early summer rainfall is characterized by daily mean rainfall between 2 mm and 7 mm. Late summer rainfall is highly variable owing to different drivers and the daily mean rainfall varies between 0 mm/day and 3 mm/day. The high-altitude areas receive up to 5 mm/day (**Figure 12**).

4.10.2. The timing and intensity of seasonal rainfall in Limpopo Province

There is evidence of a shift in the timing of seasonal rainfall in Limpopo from 1990-2014. The rainfall onset occurs late and cessation occurs early leading to shorter rainy seasons. This shift presents difficulties in determining suitable planting dates and suitable maize cultivars to plant in the region. The shorter rainy seasons lead to shorter maize growing seasons, however, farmers who choose to plant regardless of the uncertainty often choose drought-resistant maize seeds that can withstand consecutive dry days and dry spells before the second and third rains. The first rains which often occur in mid-October on average are in the form of light showers and these alert farmers at the possibility of planting, most farmers use these rains to prepare the soil for planting.

High intensity rainfall indices such as the simple daily intensity index and rainfall events exceeding 10/20/40/60 and 80 mm per day show an increasing trend in the intensity of rainfall. These high intensity rainy days are not associated with wet spells as fewer wet spells were found during the period. This high intensity rainfall exceeding or equal to 10 mm per day is considered as productive rainfall and is essential for the optimal growth of maize. Rainfall exceeding 60 mm and 80 mm per day is detrimental to the crop phenology and total yield output.

Synoptic states and rainfall characteristics are grouped into classes to understand classes which are potentially more suitable for maize growth and those that are not. Surface responses to atmospheric changes are evident through the changes in timing and intensity of rainfall characteristics. The extent to which maize yield is impacted depends on the timing of rainfall relative to the crop cycle as some phenological stages are more sensitive to water-stress than others.

Table 5: Synoptic states and associated rainfall characteristics over Limpopo and Southern Africa.

Variable category	Synoptic state	Rainfall characteristics
• Onset	• Southward shift and intensification of ITCZ. • Displacement of Sub-tropical high-pressure systems into the ocean.	• Late rainfall onset
• Cessation	• Insufficient moisture transport into the mainland.	• Earlier cessation • Associated with shortened seasons
• Duration	• Synoptics not well developed and positioned to produce consistent rainfall	• Short season durations • Shifting of the rainy season
• High frequency of high intensity rainfall events	• TTTs • Mid-latitude lows • Convective storm systems • Well-developed synoptics (Angola and heat low)	• Extreme rainy days in the late summer • Increasing daily intensity of rainfall

Table 5 classifies observed synoptic states in this study and the associated rainfall characteristics. Geopotential height anomalies at 500 hPa have been found to be associated with both early and late rainfall onset of east Southern Africa including South Africa and South of Zimbabwe (Tadross et al., 2009). The Indian ocean is considered the main source of moisture for the sub-continent, as the main summer season approaches, the Southward shift and intensification of the ITCZ brings about additional sources of moisture and rain belts which ensure that conditions are suitable for continuous rains. Within the season, the distribution of wet and dry spells which sustain the rainy season is driven by convergent and divergent moisture respectively (Cook et al., 2004). Nodes that were found to be associated with high rainfall intensity were associated with the intensification of the Angola low and the presence of Tropical Temperate Troughs. This is in accordance with Lennard and Hegerl (2015) who found extremes and high intensity rainfall to be linked with a high frequency of Tropical Temperate Troughs, Mid-latitude cyclones and some convective storm system.

4.10.3. Variability in rainfall characteristics and maize response

Table 6: Observed rainfall characteristics and their implications on the maize growing season in Limpopo province.

Variable category	Observed rainfall characteristics	Implications on maize growing season and yield
Onset	Later onset trend	• Anticipated later maize planting dates.
Cessation	Earlier cessation trend	• Short growing seasons
Duration	Shorter season durations	• Shorter growing seasons • Suitable for the 120-day growing cultivar

High intensity rainfall events and daily intensity	• Increased daily rainfall intensity • Increased days with rainfall above 10 mm, 20 mm and 40 mm per day. • Fewer daily rainfall events exceeding 60 and 80mm/day.	• Daily rainfall events exceeding 60 and 80mm/day are detrimental to phenology. • Productive seasons are dominated by events in the 10mm/day threshold.

Table 6 above provides insight on rainfall characteristics suitable for maintaining a "good" maize growing season. The observed trend in later rainfall onset may potentially lead to later maize planting dates as planting is always preceded by the first rains and planting decisions are dependent on farmers' choice. Trends in earlier cessation suggest shorter-shifted growing seasons. The seasons have become shorter on average making them suitable for planting the 120-day maize cultivar. The shift in the rainy season means that the growing season may also shift pushing the growing season towards periods that prone to mid-season dry spells. The daily rainfall intensity has increased. Other high intensity rainfall indices such as rainfall events with rainfall exceeding 10, 20 and 40 mm per day have also increased. This evidence signals at an increase in heavy rainfall which can wash away pollen before fertilization and increase moisture content during the ripening stage of the maize. These high intensity rainfall events can also damage the maize plant structure. The variability of these selected rainfall characteristics from station to station are marginal as climate in the province is mainly driven by similar synoptic features. Spatially, the intensity increases north easterly into Mozambique and eastern parts of Zimbabwe, the maize planting districts further north like Pietersburg are potentially at higher risk of yield loss resulting from increased rainfall intensity.

Chapter 5

Conclusion

5.1. Overview

Livelihoods dependant on rainfed agricultural systems remain under threat in Southern Africa because of climate variability, particularly subsistence farmers of staple food crops such as sorghum, wheat and maize. This study aimed to investigate the impacts of intra-seasonal rainfall variability on the maize growing season in Limpopo Province, South Africa by reviewing the sensitivity of maize phenology to intra-seasonal rainfall characteristics, identifying and analysing large scale synoptic drivers of rainfall variability, analysing field-crop relevant intra-seasonal rainfall characteristics over Limpopo and relating the impacts of intra-seasonal rainfall characteristics with the maize growing season. The use of Self-Organizing Maps (SOMs) was an integral part in achieving the aim and objectives of this study. Although SOMs have been used widely in synoptic climatology over the study domain, not many studies have used it as a mechanism to identify and define synoptic states suitable for planting and growing maize. The added advantage of this clustering method is that the data can be disaggregated into seasons which enables the identification of changing synoptic states throughout the season. The use of this method allows for the results of this study to be useful in defining and distinguishing synoptic states and rainfall characteristics which are suitable for growing maize over the study region.

The limited choice of input datasets for training the SOM based on the scope of the study has limited the analysis approach. The datasets selected for this study such as Geopotential height and Moisture flux are useful in understanding the general circulation patterns and relating them to surface responses of variables such as rainfall intensity. The analysis of inter-annual variability and the role of ENSO in modulating the rainfall drivers and rainfall characteristics is not in the scope of this study hence it is not included in the analysis. This may limit the understanding of the role of ocean-atmospheric interactions in intra-seasonal rainfall variability. The study area of Limpopo Province is not the largest maize producing province and maize yield data availability is limited, this has had implications on the analysis of rainfall impacts on yield. Despite these limitations, important relationships can be drawn between synoptic circulation features and the response in the timing and intensity of seasonal rainfall and the potential impact on the maize growing season.

5.2. Key findings and conclusion

- **To review the sensitivity of maize phenology to intra-seasonal rainfall variability.**

The review on maize phenology and rainfall characteristics reveals that there is a consensus that high intensity rainfall events and consecutive dry days can impact seedling growth during emergence stage, leading to delayed silking during silking stage and poor pollination during pollination stage. The prevalence of dry summers threatens staple food crop productivity through phenology. Consecutive dry spells cause moisture stress by reducing plant-available moisture. Whilst staple food crops such as sorghum can withstand these dry spells, the yield of maize crops remains under threat as maize is highly sensitive to moisture stress and is mostly planted on drylands in Southern Africa. High intensity rainfall events are associated with damage to maize plants, washing away of pollen and fertile soil. These adverse impacts suggest the need to improve farming methods at district scale to get maximum yield output and to promote the use of drought resistant crops such as sorghum at small-scale farming scale.

- **To identify and analyse large scale drivers of rainfall variability over Limpopo Province.**

The analysis of synoptic features shows that the seasonal migration and intensification of synoptic features such as the Angola low modulate intra-seasonal rainfall responses at a regional scale. The variability in these large synoptic drivers is associated with different rainfall manifestations such as the late onset of the rainy season, high intensity rainfall events, consecutive dry spells and an early cessation to the rainy season. The variability in these rainfall manifestations may enhance or negatively impact agriculture in the province depending on the timing.

The SOM adequately captures prominent winter and summer rainfall synoptic features. High intensity rainfall events were found to be linked with a well-developed Angola low and Tropical Temperate Troughs which contribute the most to summer rainfall in the region. The tropical low pressure, weak and strong subsidence from the high-pressure systems and the Indian Ocean are found to play major roles in the availability and transport of moisture during wet and dry summers on the subcontinent. These findings are in accordance with findings by MacKellar et al. (2010) who observed different precipitation responses during weak and strong subsidence in Southern Africa. The findings show that the intensification of these synoptic features is often associated with enhanced rainfall response, for example, the intensification of the Angola Low is associated with more rainfall in the study region, Howard and Washington (2018) found similar results in relation to the synoptic expression of the Angola low and rainfall. Nodes with well-defined Angola low are associated with high daily mean rainfall. These results are useful in understanding maize specific synoptic conditions for rainfed maize farming in Southern Africa.

- **To analyse field crop relevant, intra-seasonal rainfall characteristics over Limpopo Province.**

Based on observed rainfall data (CHIRPS), analysis of the timing of rainfall in the region shows that there is great annual variability in onset and onset occurs later each year on average. Similar findings were observed by Tadross et al. (2005) in the Limpopo valley from 1979-1997. In the maize growing districts of Limpopo, planting dates are expected to be shifted as soil preparation and planting is often associated with the first seasonal rains. Rainy seasons have shortened and shifted resulting from late onset and early cessation of rains. The relationship between seasonal duration and total seasonal rainfall reveals that, as the season duration increases, the total seasonal rainfall increases as well. In a similar study, Beyer et al. (2016) found that in observed short rainy seasons there was interplay of different rainfall characteristics such as dry spells which determine agricultural success. The number of season wet days was also found to increase with increasing rainy season duration. The duration of dry spells shows great annual variability and seasons are characterised by high number of dry days and dry spells. Spatially, the consecutive dry days increase north-easterly during the main rainy season whilst the consecutive wet days are fewer and sparsely distributed over the domain. This shows that total rainfall was accumulated over fewer high intensity rainfall events rather than wet spells as there are few wet spells observed in the record.

The spatial extent of rainfall intensity shows that daily rainfall intensity has increased in the South-eastern parts of Southern Africa including South Africa, Zimbabwe and Southern parts of Mozambique. There is a high number of rainfall events within the 10 mm/day “productive” threshold for all the stations observed. The extreme rainfall days within the 80 mm/day threshold are fewer and are mostly associated with random rainfall events such as the February 2000 tropical cyclone and the January 2013 floods associated with an intense cloud band. The rainy seasons are late and have become more intense. These findings are consistent with Dunning et al. (2018) who observed a great tendency of later and more intense rainy seasons over Africa which are likely to persist into the far-future.

- **To relate the impacts of intra-seasonal rainfall characteristics with maize growth characteristics.**

The observed late onset of the rainy season is linked with shorter rainy seasons due to early withdrawal of rainfall producing synoptics leading to earlier cessation. As yellow maize requires shorter growing seasons, the short seasons are more suitable for growing yellow maize. Maize which is planted late in relation to late rainfall onset will coincide with consecutive dry spells which can potentially lead to pollination failure due to water-stress at the pollination stage which requires high rate of moisture. The high intensity rainfall events and daily rainfall intensity are linked with the intensification of the Angola low and the occurrence of Tropical Temperate Troughs. The TTTs are a typical late summer phenomenon thus the high intensity rainfall events resulting from these systems coincide with maize in the later stages of growth. When this occurs, moisture content on the maize crop increases and this has adverse impacts on the overall yield output. Although the pollination rate may have been high resulting in a good kernel size and set, excess moisture from rainfall events in the 60 mm/day and 80 mm/day threshold lead to rotting of the maize cob from maize bacteria. Most high intensity rainfall events in this study are within the “productive rainfall” threshold of 10 mm/day. Seasons with higher number of rainfall events in this threshold are productive maize growing seasons. The increase in the daily intensity of rainfall and the frequency of dry spells impact significant maize phenology stages thus impacting the yield output and food security. As most maize production systems are rainfed, the changes in the timing and intensity of rainfall response to changing synoptic features will impact productivity leading to heavy reliance on irrigation systems and machinery which may lead to job losses for commercial production.

There is no clear relationship established between maize yields and rainfall characteristics associated with the timing of seasonal rains such as onset and cessation, this indicates that the distribution and intensity of these rainfall characteristics is more determinant of the final yield output as compared to the timing. Also, farmers’ choices with regards to planting dates and maize cultivars to plant may be the determinant of total yield output. The lack of a positive linear correlation between maize yield and rainfall characteristics over the study locations shows the need for future studies to consider analysing factors such as evapotranspiration and soil moisture. Where long-term maize yield data is available, it would essential to study the relationship over a longer period.

The findings of this study are critical to the agricultural sector for both district scale and individual subsistence farmers as they highlight the need for improving farming methods. Understanding the nature and behaviour of large synoptic features will aid preparedness for both commercial and subsistence farmers thus improving crop yield output and challenging the food insecurity issue. The effects of a changing climatic system on staple food agricultural systems suggest the need to advance understanding on links between the changing climatic system and agricultural systems. These findings also advance knowledge on aspects of decision-making in the agricultural sector under a changing climate. These decisions include choice of planting dates of maize given changes in rainfall onset and maize cultivar given the shortening and shifting of the growing season.

List of references

Akpalu, W., Hassan, R. M. & Ringler, C. 2008b. Climate Variability and Maize Yield in South Africa: Results from GME and MELE Methods. *Food Policy*, 12.

Akpalu, W., Rashid, H. M. & Ringler, C. 2011. Climate variability and maize yield in the Limpopo region of South Africa: Results from GME and MELE methods. *J Climate,* 3**,** 114-122.

Archer, E. R. M., Landman, W. A., Tadross, M. A., Malherbe, J., Weepener, H., Maluleke, P. & Marumbwa, F. M. 2017. Understanding the evolution of the 2014–2016 summer rainfall seasons in southern Africa: Key lessons. *J Climate Risk Management,* 16**,** 22-28.

Aslam, M., Zamir, I., Afzal, I., Yaseen, M., Mubeen, M. & Shoaib, A. 2013. Drought tolerance in maize through Potassium: Drought stress, its effect on maize production and development of drought tolerance through potassium application. *Cercetări Agronomice în Moldova,* XLVI**,** 16.

Baloyi, T. C. 2012. *Evaluation of selected industrially manufactured biological amendments for maize production.* University of the Free State.

Baudoin, M.-A., Vogel, C., Nortje, K. & Naik, M. 2017. Living with drought in South Africa: lessons learnt from the recent El Niño drought period. *International Journal of Disaster Risk Reduction,* 23**,** 128-137.

Baumberg, V., Weber, T. & Helmschrot, J. Assessing the Change in Rainfall Characteristics and Trends for the Southern African ITCZ Region. EGU General Assembly Conference Abstracts, 2015.

Bergamaschi, H., Wheeler, T. R., Challinor, A. J., Comiran, F. & Heckler, B. M. M. 2007. Maize yield and rainfall on different spatial and temporal scales in Southern Brazil. *Pesquisa Agropecuaria Brasileira,* 42**,** 603-613.

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

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

Botai, C. M., Botai, J. O. & Adeola, A. M. 2018. Spatial distribution of temporal precipitation contrasts in South Africa. *South African Journal of Science,* 114**,** 70-78.

Botai, C. M., Botai, J. O., Dlamini, L. C., Zwane, N. S. & Phaduli, E. 2016. Characteristics of droughts in South Africa: a case study of free state and north west provinces. *J Water,* 8**,** 439.

Cairncross, S. & Alvarinho, M. 2013. The Mozambique floods of 2000: health impact and response. *Flood Hazards and Health.* Routledge.

Cairns, J. E., Hellin, J., Sonder, K., Araus, J. L., MacRobert, J. F., Thierfelder, C. & Prasanna, B. 2013. Adapting maize production to climate change in sub-Saharan Africa. *J Food Security,* 5**,** 345-360.

Çakir, R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research,* 89**,** 1-16.

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

Cook, K. H. 2000. The South Indian convergence zone and interannual rainfall variability over southern Africa. *Journal of Climate,* 13**,** 3789-3804.

Crétat, J., Macron, C., Pohl, B. & Richard, Y. 2011. Quantifying internal variability in a regional climate model: a case study for Southern Africa. *J Climate dynamics,* 37**,** 1335-1356.

Crétat, J., Pohl, B., Dieppois, B., Berthou, S. & Pergaud, J. 2019. The Angola Low: relationship with southern African rainfall and ENSO. *J Climate Dynamics,* 52**,** 1783-1803.

Darby, H. & Lauer, J. 2004. Plant physiology—critical stages in the life of a corn plant. Field Corn. Tech. Rep., 2004, http://www. mn. nrcs. USDA. gov/technical/ECS/pest.

Dedekind, Z., Engelbrecht, F. A. & Van Der Merwe, J. 2016. Model simulations of rainfall over southern africa and its eastern escarpment. *Water SA,* 42**,** 129-143.

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H. & Ceccato, P. 2018. Validation of the CHIRPS satellite rainfall estimates over eastern Africa. *Quarterly Journal of the Royal Meteorological Society,* 144**,** 292-312.

Du Plessis, J. 2003. *Maize production*, Department of Agriculture Pretoria, South Africa.

Duffy, K. J. & Masere, T. P. 2015. Effect of within-season daily rainfall distribution on maize crop yields. *Outlook on Agriculture,* 44**,** 267-271.

Dunning, C. M., Black, E. & Allan, R. P. 2018. Later wet seasons with more intense rainfall over Africa under future climate change. *Journal of Climate,* 31**,** 9719-9738.

Dunning, C. M., Black, E. C. & Allan, R. P. 2016a. The onset and cessation of seasonal rainfall over Africa. *J Journal of Geophysical Research,* 121**,** 11,405-11,424.

Dyson, L. L. 2015. A heavy rainfall sounding climatology over Gauteng, South Africa, using self-organising maps. *Climate Dynamics,* 45**,** 3051-3065.

Fauchereau, N., Pohl, B., Reason, C. J. C., Rouault, M. & Richard, Y. 2009. Recurrent daily OLR patterns in the Southern Africa/Southwest Indian ocean region, implications for South African rainfall and teleconnections. *Climate Dynamics,* 10.1007/s00382-008-0426-2.

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

Ghooshchi, F., Seilsepour, M. & Jafari, P. 2008. Effects of water stress on yield and some agronomic traits of maize (SC 301). *J Am-Eurasian J Agric Environ Sci,* 4**,** 302-305.

Greyling, J. C. & Pardey, P. G. 2019. Measuring Maize in South Africa: The Shifting Structure of Production During the Twentieth Century, 1904–2015. *Agrekon,* 58**,** 21-41.

Hachigonta, S., Reason, C. & Tadross, M. 2008. An analysis of onset date and rainy season duration over Zambia. *J Theoretical applied climatology,* 91**,** 229-243.

Harrison, L., Michaelsen, J., Funk, C. & Husak, G. 2011. Effects of temperature changes on maize production in Mozambique. *Climate Research,* 46**,** 211-222.

Hart, N. C., Reason, C. J. & Fauchereau, N. 2013a. Cloud bands over southern Africa: seasonality, contribution to rainfall variability and modulation by the MJO. *J Climate dynamics,* 41**,** 1199-1212.

Hart, N. C., Washington, R. & Reason, C. J. 2018. On the likelihood of tropical–extratropical cloud bands in the South Indian convergence zone during ENSO events. *Journal of Climate,* 31**,** 2797-2817.

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

Hatfield, J. L. & Dold, C. 2018. Climate Change Impacts on Corn Phenology and Productivity. *J Corn: Production Human Health in Changing Climate,* 10.5772/intechopen.76933**,** 95.

Hewitson, B. C. & Crane, R. G. 2002. Self-organizing maps: Applications to synoptic climatology. *Climate Research,* 22**,** 13-26.

Hoell, A., Funk, C., Zinke, J. & Harrison, L. 2017. Modulation of the Southern Africa precipitation response to the El Niño Southern Oscillation by the subtropical Indian Ocean Dipole. *J Climate Dynamics,* 48**,** 2529-2540.

Howard, E. & Washington, R. 2018. Characterizing the synoptic expression of the Angola low. *J Journal of Climate,* 31**,** 7147-7165.

James, R. & Washington, R. 2013. Changes in African temperature and precipitation associated with degrees of global warming. *J Climatic change,* 117**,** 859-872.

Johnston, P. 2008. *The uptake and utility of seasonal forecasting products for commercial maize farmers in South Africa.* University of Cape Town.

Jury, M. R. 2013. Climate trends in southern Africa. *South African Journal of Science,* 109**,** 1-11.

Jury, M. R. 2018. Climate trends across south africa since 1980. *Water SA,* 44**,** 297-307.

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

Karl, T. R., Nicholls, N. & Ghazi, A. 1999. Clivar/GCOS/WMO workshop on indices and indicators for climate extremes workshop summary. *Weather and Climate Extremes.* Springer.

Kohonen, T. 1989. Self-organizing feature maps. *Self-organization and associative memory.* Springer.

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

Kusangaya, S., Warburton, M. L., Van Garderen, E. A. & Jewitt, G. P. 2014. Impacts of climate change on water resources in southern Africa: A review. *J Physics Chemistry of the Earth,* 67**,** 47-54.

Langyintuo, A. S., Mwangi, W., Diallo, A. O., MacRobert, J., Dixon, J. & Bänziger, M. 2010. Challenges of the maize seed industry in eastern and southern Africa: A compelling case for private–public intervention to promote growth. *J Food Policy,* 35**,** 323-331.

Lauer, J. 2003. What happens within the corn plant when drought occurs. *J Corn Agronomist,* 10**,** 153-155.

Le Roux, N. 2009. *Seasonal Maize Yield Simulations for South Africa using a Multi-Model Ensemble System.* Master of Science, University of Pretoria.

Lennard, C. & Hegerl, G. 2015. Relating changes in synoptic circulation to the surface rainfall response using self-organising maps. *J Climate dynamics,* 44**,** 861-879.

Liebmann, B., Bladé, I., Kiladis, G. N., Carvalho, L. M., B. Senay, G., Allured, D., Leroux, S. & Funk, C. 2012a. Seasonality of African precipitation from 1996 to 2009. *Journal of Climate,* 25**,** 4304-4322.

Mabhaudhi, T., Mpandeli, S., Nhamo, L., Chimonyo, V. G., Nhemachena, C., Senzanje, A., Naidoo, D. & Modi, A. T. 2018. Prospects for improving irrigated agriculture in southern Africa: Linking water, energy and food. *Water,* 10**,** 1881.

MacKellar, N., New, M. & Jack, C. 2014. Observed and modelled trends in rainfall and temperature for South Africa: 1960-2010. *South African Journal of Science,* 110**,** 1-13.

MacKellar, N., Tadross, M. & Hewitson, B. 2010. Synoptic-based evaluation of climatic response to vegetation change over Southern Africa. *International Journal of Climatology,* 30**,** 774-789.

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

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

Moeletsi, M. E. 2017. Mapping of maize growing period over the free state province of South Africa: Heat units approach. *Advances in Meteorology,* 2017.

Moeletsi, M. E. & Walker, S. 2012. Rainy season characteristics of the Free State Province of South Africa with reference to rain-fed maize production. *Water SA,* 38**,** 775-782.

Moeletsi, M. E., Walker, S. & Landman, W. A. 2011a. ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa. *Physics and Chemistry of the Earth,* 36**,** 715-726.

Mtongori, H. I., Stordal, F., Benestad, R. E., Mourice, S. K., Justino, F. & Kikuu, C. 2015a. Impacts of climate and farming management on maize yield. *African Crop Science Journal,* 23**,** 399-417.

Mtongori, H. I., Stordal, F., Benestad, R. E., Mourice, S. K., Justino, F. & Kikuu, C. 2015b. IMPACTS OF CLIMATE AND FARMING MANAGEMENT ON MAIZE YIELD IN Among the major factors controlling agricultural productivity in Africa is climate (Sivakumar , 1988 ; Moore et al ., 2012). While total seasonal rainfall is important in crop production (Mati. *Meteorology, Applied Agricultural Water Management,* 23**,** 399-417.

Mugalavai, E. M., Kipkorir, E. & Songok, C. K. Evaluation of dry spells during sensitive growth stages for maize crop in Western Kenya. International Conference on Disaster Risk Reduction and Conflict Resolution for Sustainable Development, 2012. 18-20.

Mukarumbwa, P. & Mushunje, A. 2010. Potential of sorghum and finger millet to enhance household food security in Zimbabwe's semi-arid regions: A review.

Mulungu, K. & Ng'ombe, J. N. 2019. Climate Change Impacts on Sustainable Maize Production in Sub-Saharan Africa: A Review. *Maize-Production and Use.* IntechOpen.

Munday, C. & Washington, R. 2017. Circulation controls on southern African precipitation in coupled models: The role of the Angola Low. *Journal of Geophysical Research,* 122**,** 861-877.

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

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

Nazmi, L., Asadi, H., Manukyan, R. & Naderi, H. 2012. Influence of tillage displaced soil on the productivity and yield components of barley in northwest Iran. *Canadian Journal of soil science,* 92**,** 665-672.

New, M., Hewitson, B., Stephenson, D. B., Tsiga, A., Kruger, A., Manhique, A., Gomez, B., Coelho, C. A., Masisi, D. N. & Kululanga, E. 2006. Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research,* 111.

Nicholson, S. E. 2009. A revised picture of the structure of the "monsoon" and land ITCZ over West Africa. *Climate Dynamics,* 32**,** 1155-1171.

Nicholson, S. E. 2017. Climate and climatic variability of rainfall over eastern Africa. *Reviews of Geophysics,* 55**,** 590-635.

Oettli, P., Tozuka, T., Izumo, T., Engelbrecht, F. A. & Yamagata, T. 2014. The self-organizing map, a new approach to apprehend the Madden–Julian Oscillation influence on the intraseasonal variability of rainfall in the southern African region. *J Climate dynamics,* 43**,** 1557-1573.

Otegui, M. E., Andrade, F. H. & Suero, E. E. 1995. Growth, water use, and kernel abortion of maize subjected to drought at silking. *J Field Crops Research,* 40**,** 87-94.

Pohl, B., Fauchereau, N., Reason, C. J. C. & Rouault, M. 2010. Relationships between the Antarctic oscillation, the Madden-Julian oscillation, and ENSO, and consequences for rainfall analysis. *Journal of Climate,* 23**,** 238-254.

Pohl, B., Fauchereau, N., Richard, Y., Rouault, M. & Reason, C. J. C. 2009. Interactions between synoptic, intraseasonal and interannual convective variability over Southern Africa. *Climate Dynamics,* 10.1007/s00382-008-0485-4.

Pohl, B., Richard, Y. & Fauchereau, N. 2007. Influence of the Madden–Julian oscillation on southern African summer rainfall. *J Climate dynamics,* 20**,** 4227-4242.

Quagraine, K. A., Hewitson, B., Jack, C., Pinto, I. & Lennard, C. 2019. A methodological approach to assess the co-behavior of climate processes over Southern Africa. *Journal of Climate,* 32**,** 2483-2495.

Ramirez-Villegas, J. & Thornton, P. K. 2015. Climate change impacts on African crop production. *Working Paper No. 119***,** 1-27.

Ratna, S. B., Behera, S., Ratnam, J. V., Takahashi, K. & Yamagata, T. 2013. An index for tropical temperate troughs over southern Africa. *J Climate dynamics,* 41**,** 421-441.

Ratnam, J., Behera, S., Masumoto, Y., Takahashi, K. & Yamagata, T. 2012. A simple regional coupled model experiment for summer-time climate simulation over southern Africa. *J Climate dynamics,* 39**,** 2207-2217.

Reason, C. & Rouault, M. 2006. Sea surface temperature variability in the tropical southeast Atlantic Ocean and West African rainfall. *J Geophysical Research Letters,* 33.

Reason, C. J. C., Hachigonta, S. & Phaladi, R. F. 2005. Interannual variability in rainy season characteristics over the Limpopo region of southern Africa. *International Journal of Climatology,* 25**,** 1835-1853.

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

Roffe, S., Fitchett, J. & Curtis, C. 2019. Classifying and mapping rainfall seasonality in South Africa: A review. *J South African Geographical Journal,* 101**,** 158-174.

Rouault, M. & Richard, Y. 2005. Intensity and spatial extent of droughts in southern Africa. *J Geophysical research letters,* 32.

Rurinda, J., Mapfumo, P., Van Wijk, M., Mtambanengwe, F., Rufino, M. C., Chikowo, R. & Giller, K. E. 2014. Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. *J European Journal of Agronomy,* 55**,** 29-41.

Schlenker, W. & Lobell, D. B. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letters,* 5**,** 014010.

Schulze, R. 2016. On observation, climate challenges, the South African agriculture sector and considerations for an adaption handbook. *Handbook for Farmers*.

Singh, J. 2014. Soil and maize response to compaction, slope steepness and nitrogen fertilization in coarse textured soil.

Statistics, A. 2008. Agricultural statistics. Pretoria, South Africa: National Department of Agriculture.

Suzuki, T. 2011. Seasonal variation of the ITCZ and its characteristics over central Africa. 103**,** 39-60.

Syampungani, S., Chirwa, P., Akinnifesi, F. & Ajayi, O. 2010. The potential of using agroforestry as a win-win solution to climate change mitigation and adaptation and meeting food security challenges in Southern Africa. *Agricultural Journal,* 5**,** 80-88.

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

Tadross, M. A., Hewitson, B. C. & Usman, M. T. 2005. The interannual variability on the onset of the maize growing season over South Africa and Zimbabwe. *Journal of Climate,* 18**,** 3356-3372.

Thomas, D. S. G., Twyman, C., Osbahr, H. & Hewitson, B. 2007. Adaptation to climate change and variability: Farmer responses to intra-seasonal precipitation trends in South Africa. *Climatic Change,* 83**,** 301-322.

Thornton, P. K., Ericksen, P. J., Herrero, M. & Challinor, A. J. 2014. Climate variability and vulnerability to climate change: a review. *J Global change biology,* 20**,** 3313-3328.

Tongwane, M. I. & Moeletsi, M. E. 2015. Intra-seasonal rainfall variability during the maize growing season in the northern lowlands of Lesotho. *J Theoretical applied climatology* 120**,** 575-585.

Trenberth, K. E. 2011. Changes in precipitation with climate change. *Climate Research,* 47**,** 123-138.

Tshililo, F. P. 2017. *Rainy season characteristics with reference to maize production for the Luvuvhu river catchment, Limpopo Province, South Africa.* Agrometeorology Doctoral Dissertation, University of KwaZulu-Natal.

Usman, M. T. & Reason, C. J. C. 2004. Dry spell frequencies and their variability over southern Africa. *Climate Research,* 26**,** 199-211.

Walker, N. & Schulze, R. 2008. Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. *J Agriculture, ecosystems & environment,* 124**,** 114-124.

Washington, R. & Preston, A. 2006. Extreme wet years over southern Africa: Role of Indian Ocean sea surface temperatures. *Journal of Geophysical Research,* 111.

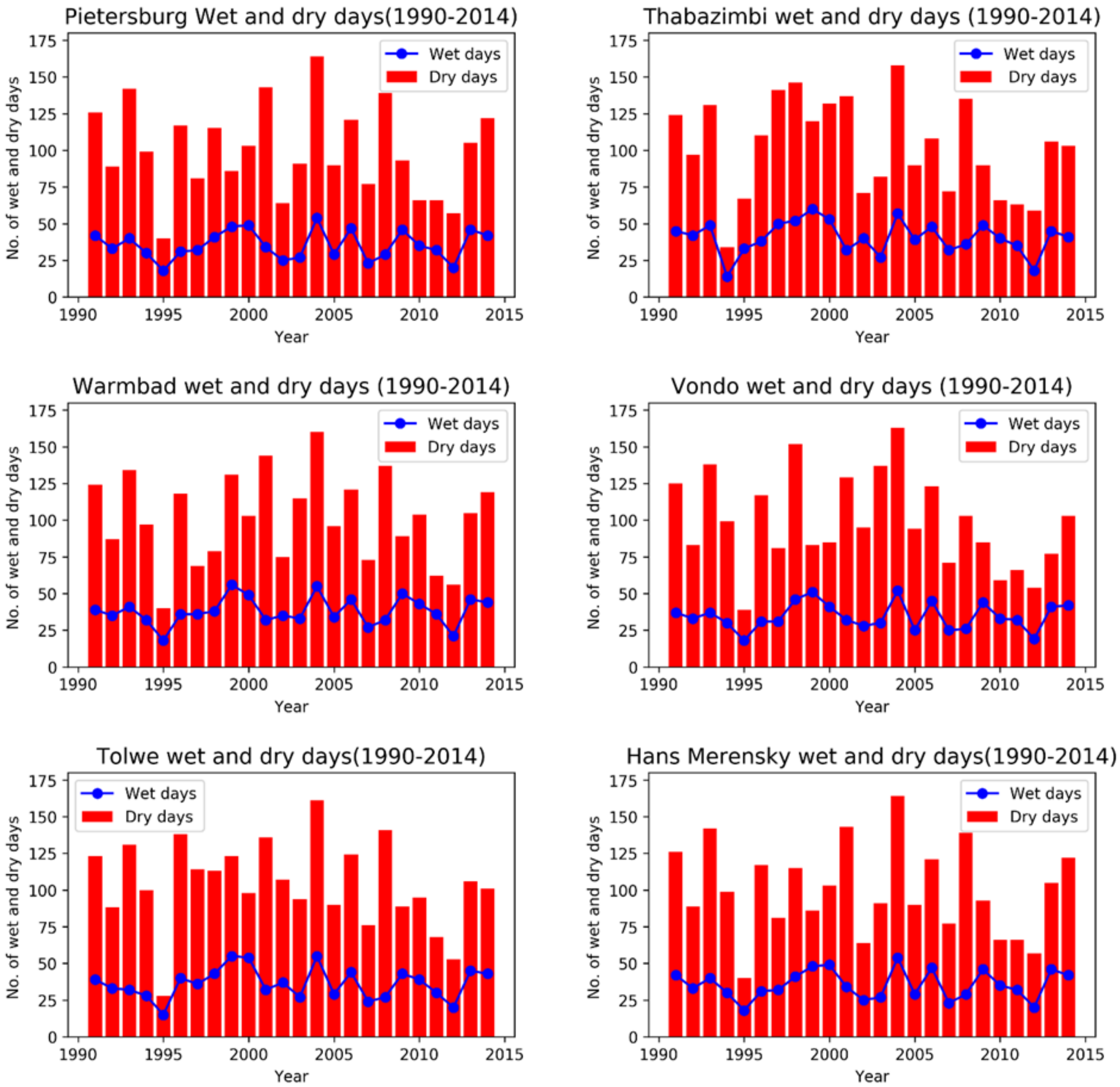
Xulu, N. G., Chikoore, H., Bopape, M.-J. M. & Nethengwe, N. S. 2020. Climatology of the Mascarene High and Its Influence on Weather and Climate over Southern Africa. *J Climate,* 8**,** 86.

Zinyengere, N., Crespo, O. & Hachigonta, S. 2013. Crop response to climate change in southern Africa: A comprehensive review. *J Global Planetary Change,* 111**,** 118-126.

Zinyengere, N., Crespo, O., Hachigonta, S. & Tadross, M. 2014. Local impacts of climate change and agronomic practices on dry land crops in Southern Africa. *J Agriculture,* 197**,** 1-10.

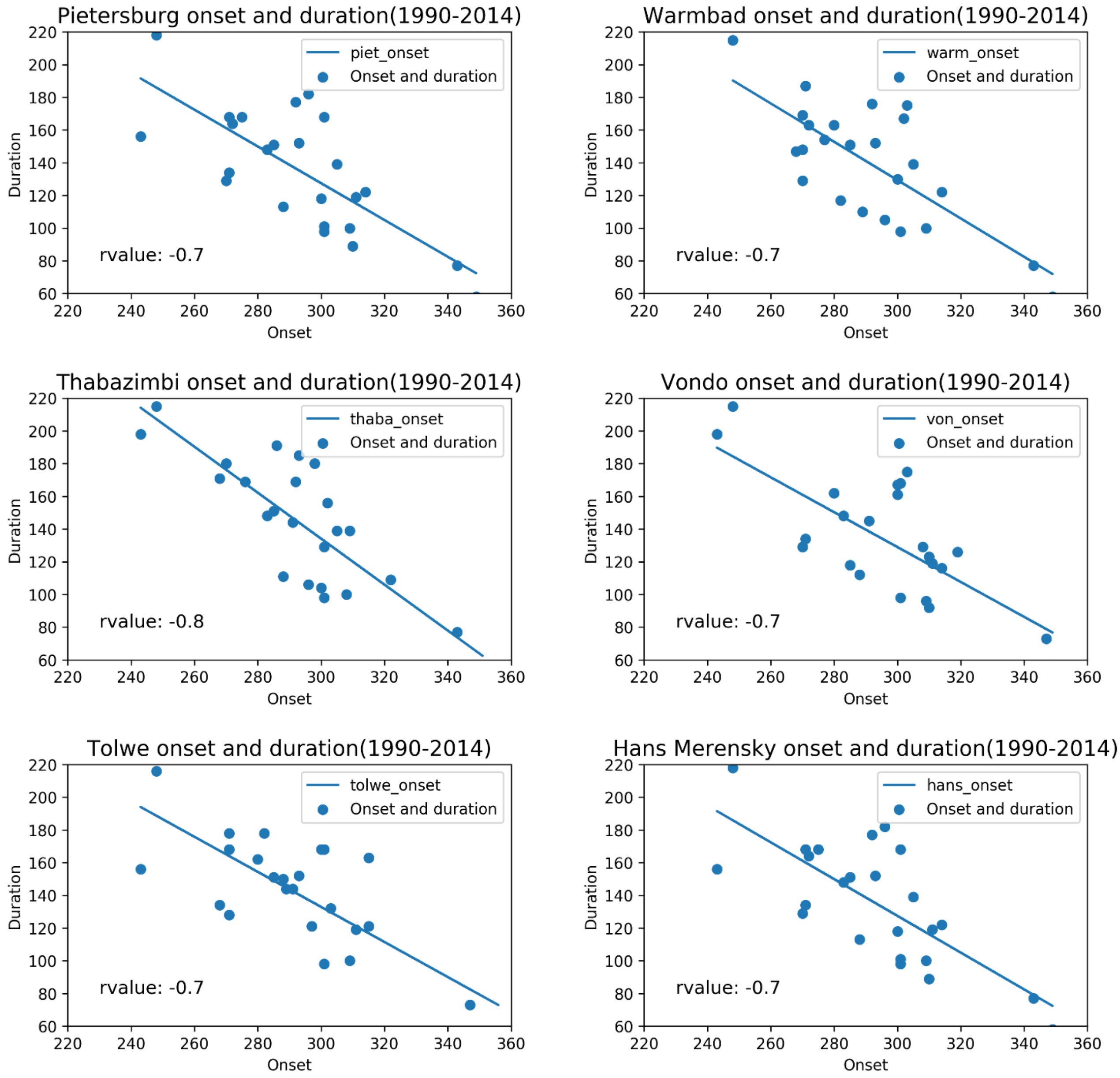
Appendix

Appendix A



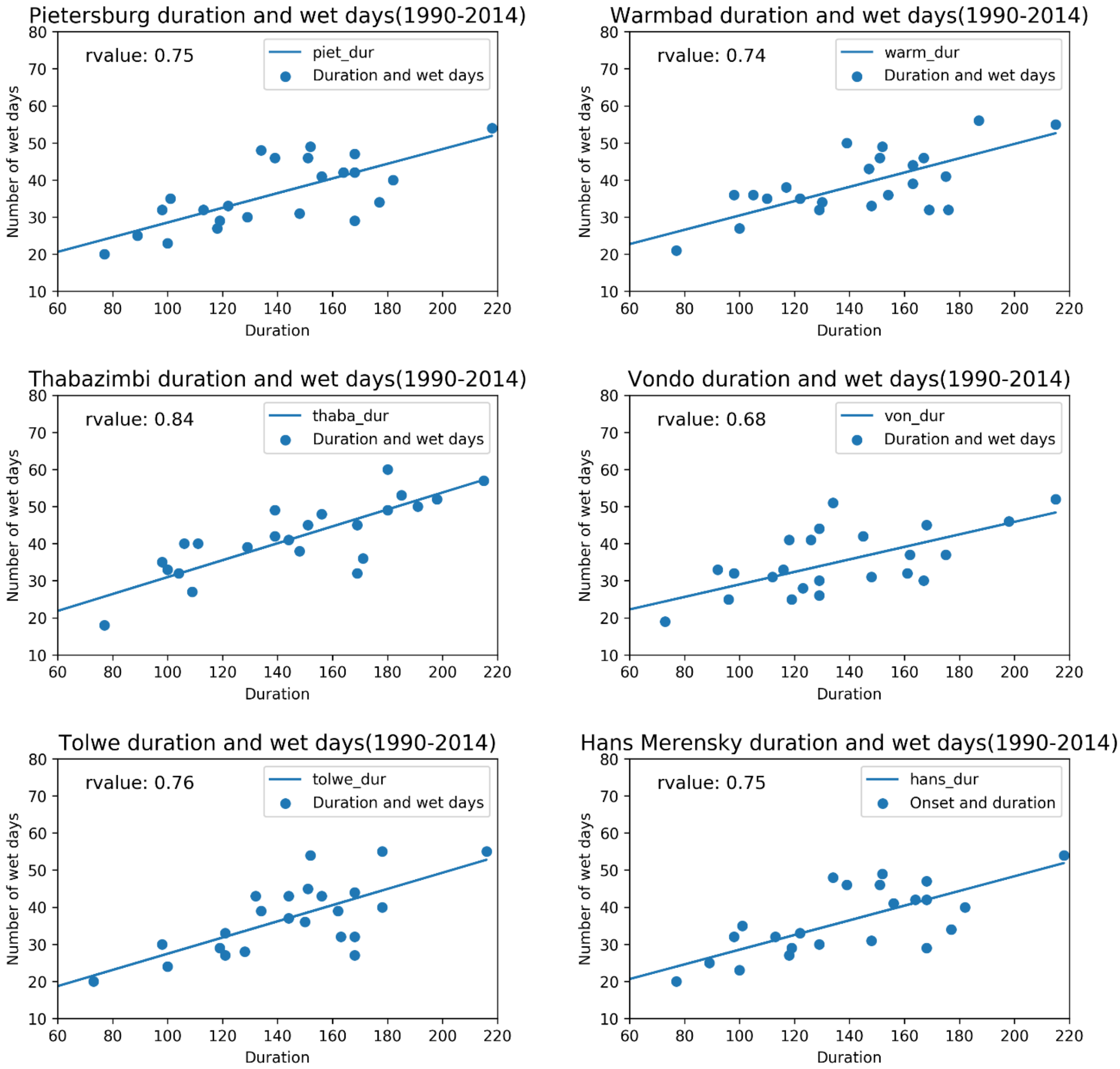
Appendix A : Seasonal wet and dry days for Pietersburg, Thabazimbi, Warmbad, Vondo, Tolwe and Hans Merensky from 1990-2014.

Appendix B



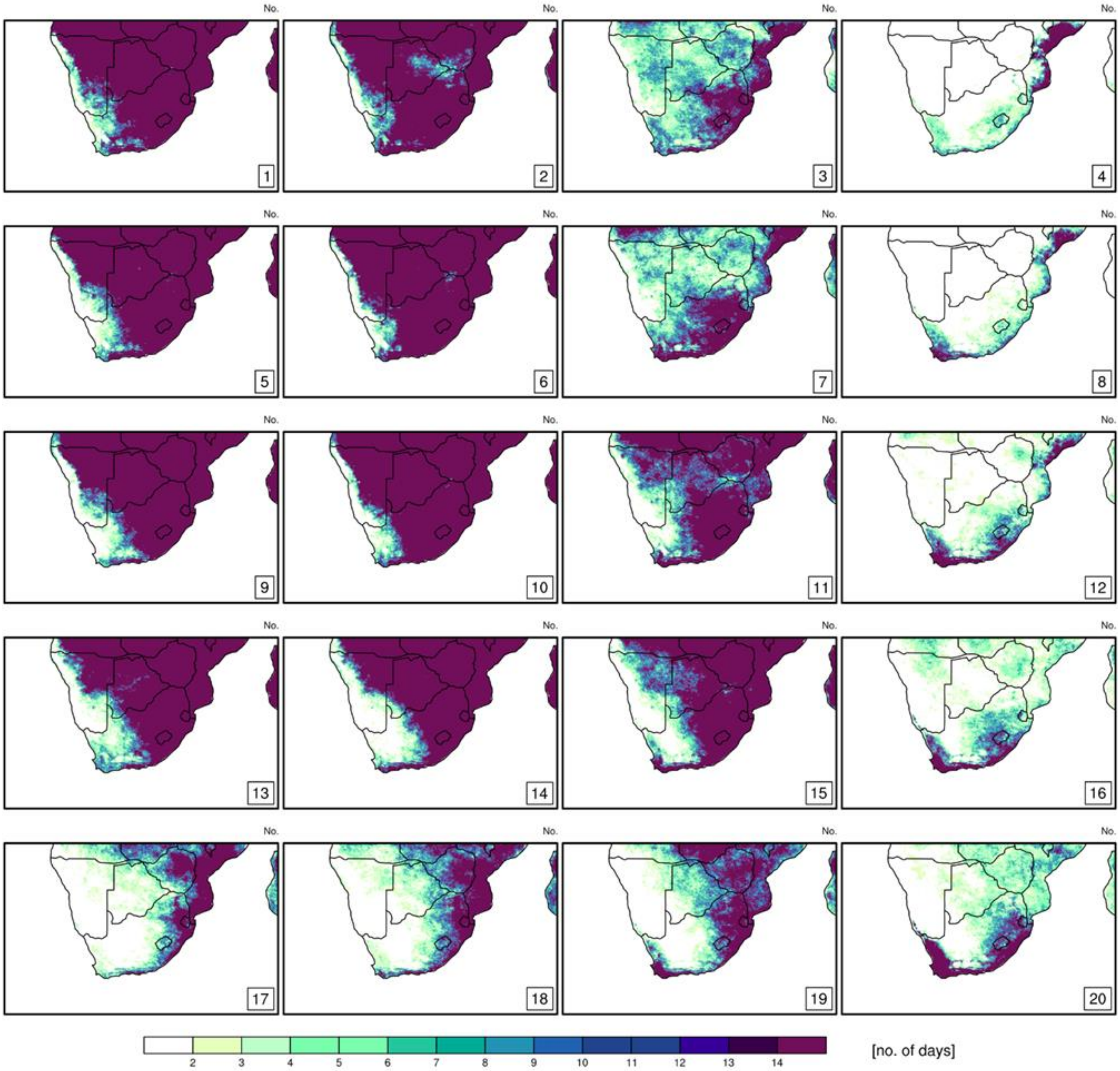
Appendix B: The relationship between seasonal rainfall onset and rainy season duration for Pietersburg, Warmbad, Vondo, Thabazimbi,Tolwe and Hans Merensky from 1990-2014.

Appendix C



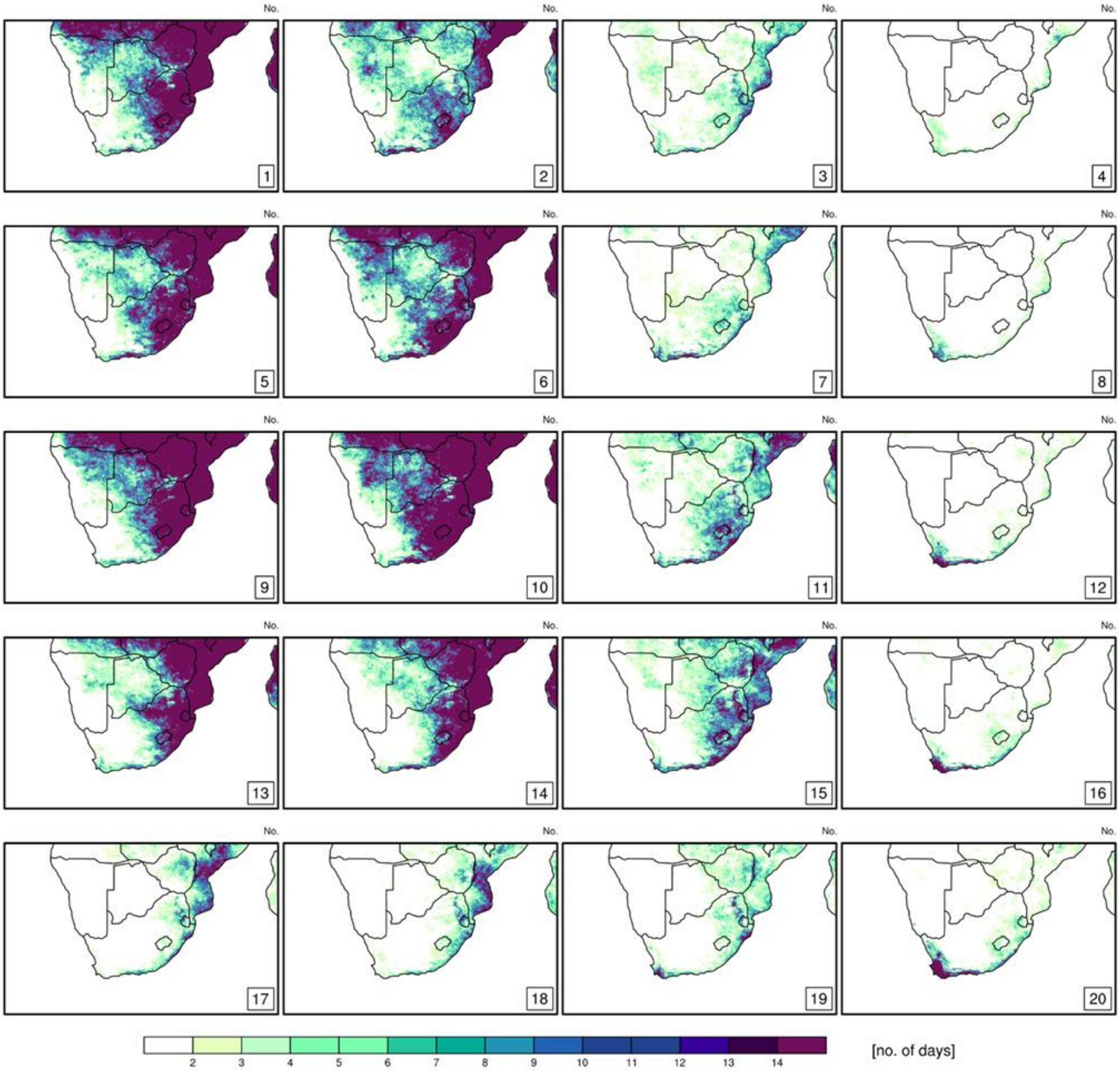
Appendix C: The relationship between rainy season duration and the number of wet days for Pietersburg, Warmbad, Thabazimbi,Vondo,Tolwe and Hans Merensky from 1990-2014.

Appendix D



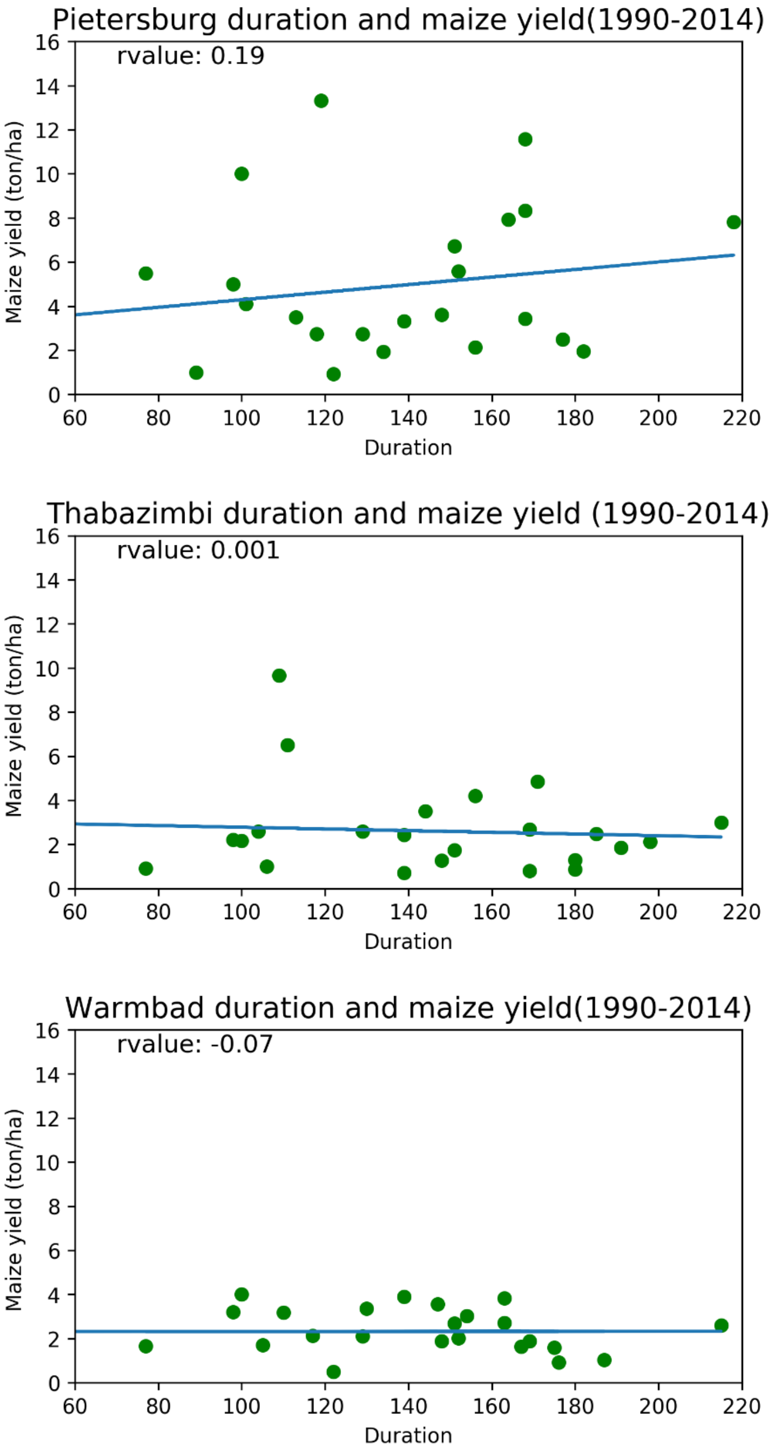
Appendix D: Number of rainfall events with rainfall greater than or equal to 10mm/day over the study domain from 1990-2014

Appendix E



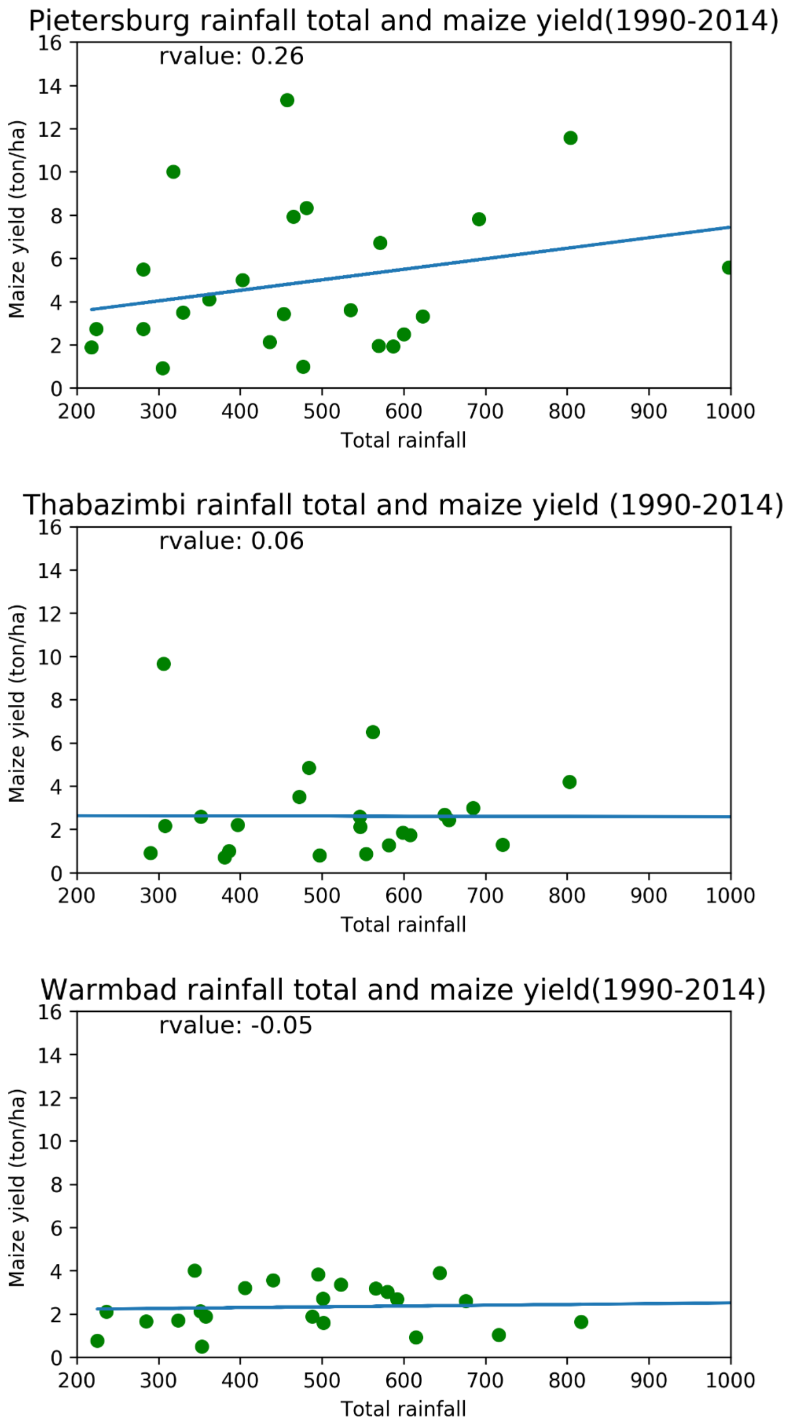
Appendix E: Number of rainfall events with rainfall greater than or equal to 20mm/day over the study domain from 1990-2014

Appendix F



Appendix F: The relationship between rainy season duration and maize yield for Pietersburg, Thabazimbi and Warmbad from 1990-2014

Appendix G



Appendix G: The relationship between total seasonal rainfall and maize yield (ton/ha) for Pietersburg, Thabazimbi and Warmbad from 1990-2014