A synoptic climatology of Continental Tropical Low pressure systems over southern Africa and their contribution to rainfall over South Africa

By

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DECLARATION

I, Elizabeth May Webster, declare that the dissertation which I hereby submit for the degree Master of Science (Meteorology) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: ________________

DATE: January 2019

SUMMARY

A synoptic climatology of Continental Tropical Low pressure systems over southern Africa and their contribution to rainfall over South Africa

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Tropical weather systems are known to cause havoc due to heavy rain which leads to flooding. Continental Tropical Low pressures (CTLs) are one of such systems. Very little research has been dedicated to tropical weather over southern Africa, with even less literature available on CTLs. As a result, there is little understanding of these weather systems and the potential danger associated with them. Using NCEP reanalysis data, an objective identification method which consists of four criteria is created to recognize CTLs by detecting atmospheric conditions that are conducive to the development of CTLs. These conditions include, the presence of an upright standing low pressure with a high pressure aloft, warm column temperatures, high precipitable water and high total energy values.

These results are used to create a climatology of CTLs over southern Africa where it is found that CTLs occur most frequently over southern Zambia and Angola. CTLs do not often reach the central interior of South Africa, with a return period of 78 years, however, they occur more frequently over the northern parts of Limpopo province with a return period of 5 years. It is uncommon for CTLs to extend south of 22.5°S (South Africa) during December months, however by March there is a westward shift in the preferred CTL location. January has the highest number of CTL events (36%), followed very closely by February (34%). The average lifespan of a CTL is up to three days, but reaching 13 to 16 days on rare occasions.

The rainfall contribution of CTLs to South Africa is calculated using daily observed rainfall station data from the South African Weather Service. It is found that the average rainfall associated with a CTL is far higher than the total rainfall of the region. CTLs are associated with extreme rainfall events and it is seen that there is an average of 110 occurrences per year where at least 50 mm is measured in a 24 hour period and 29 per year where at least 100 mm is recorded. The general rainfall distribution around a CTL largely occurs to the east of it, while the extreme rainfall amounts are found to the south of the CTL. It is also established that topography plays an important role in the rainfall distribution with higher rainfall amounts occurring along the escarpment.

A case study is used to demonstrate the objective identification method presented in this dissertation. The CTL was accurately identified, however the NCEP data slightly misplaced the position of the low pressure when compared to the satellite image. The case study highlighted that due to the slow movement, broad extent of the rain bands and the possible long lifespan, CTLs can result in widespread impacts. It also demonstrated that using the criteria developed in this dissertation, a forecaster can accurately identify a CTL.

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- EUMETSAT for the satellite imagery;

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LIST OF SYMBOLS AND ABBREVIATIONS

COL	Cut-off low pressure
Cp	Specific heat of dry air
CTL	Continental Tropical Low pressure
ENSO	El Niño-Southern Oscillation
FTE	Favourable Tropical Environment
g	Magnitude of gravity constant, 9.8 $m.s^{-2}$
ITCZ	Inter-Tropical Convergence Zone
L	latent heat of condensation
MCC	Mesoscale Convective Complex
MITS	Model for the Identification of Tropical weather Systems
MRE	Major Rain Event
NCEP	National Centre for Environmental Prediction
NWP	Numerical Weather Prediction
ONI	Oceanic Index
q	Water vapour mixing ratio
Quad	Quadrant
RGB	Red-Green-Blue colour combination
SAST	South African Standard Time
SAWS	South African Weather Service
T	Temperature
TSE	Total Static Energy
TTT	Tropical Temperate Trough
u	Zonal wind
v	Meridional wind
$\overline{V}_T$	Thermal wind
$\overline{V}_g$	Geostrophic wind
W	Precipitable water

Z	Zulu Time Zone
z	Geopotential height in meter
ζ	Relative vorticity

Chapter 1
Introduction

1.1 Background

Tropical weather systems occupy the northern parts of South Africa during the late summer months and are often associated with heavy rainfall and flooding (Dyson and van Heerden, 2002). Tropical disturbances hardly ever occur between April and October, but rather have a peak between December and February (Preston-Whyte and Tyson, 1993). Dyson and van Heerden (2002) stated that due to the high frequency of heavy rainfall events that occur in summer over the eastern and north-eastern parts of South Africa, it is important to develop better forecasting techniques that can identify and predict tropical weather systems.

Dyson and van Heerden (2002) also stated that due to tropical weather systems only affecting South Africa three or four times a year, forecasters often do not have the necessary skill to identify these systems ahead of time. Nevertheless, Poolman, contributing to Dyson *et al.,* (2002) found that the contribution of heavy rainfall days that occur during the summer months and the weather systems that are responsible for them are far more important for the South African hydrology than the heavy rainfall days that occur in the winter months and their associated weather systems. Tropical weather systems play an important role in southern Africa's weather and there is therefore a need to accurately identify tropical weather systems and with a fair amount of lead-time in order for weather alerts to be sent out in a timeous manner and to be acted upon.

1.2 Motivation

Southern Africa is often affected by devastating floods that are a result of Continental Tropical Low pressures (CTLs) (February 1988, February 2000 and January 2013). Research results show that tropical weather systems mainly occur in late summer.

Recently, during January 2017, a well-developed CTL developed over southern Africa, causing flooding of houses and roads. However, even though this synoptic scale weather system was clearly identifiable on satellite imagery (Fig. 1.2), forecasters failed to classify this system as a CTL (SAWS, 2017). It is clear that there is a need to enhance the understanding and identification of these synoptic scale weather systems over southern Africa.

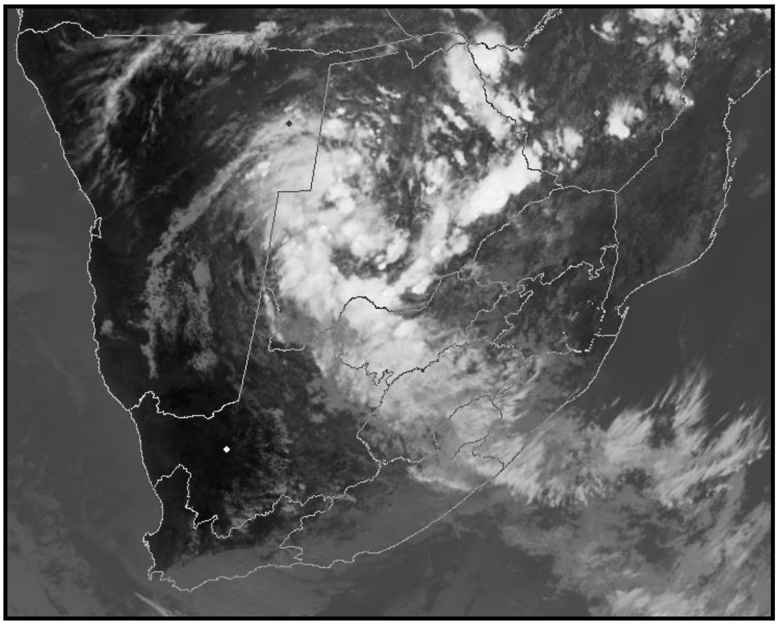


Figure 1.2: Infra-Red 10.8 satellite image on 6 January 2017 at 12:00Z, clearly indicating the presence of a well-developed CTL over southern Africa with cloud bands extending into South Africa. (© EUMETSAT, 2018)

As CTLs are rarely identified in operational environments there is a lack of knowledge of the frequency of occurrence of these low pressure systems and their impact on the weather in South Africa. By creating a climatology of these systems, it can be seen how often CTLs occur over southern Africa and how regularly they extend into South Africa. There is also a need to understand the rainfall associated with CTLs on daily rainfall over South Africa as well as the contribution of rainfall CTLs have to the annual rainfall over South Africa. Creating a synoptic climatology and investigating the impact on rainfall over South Africa the significance of these weather systems can be established.

1.3 Research Questions

Numerical Weather Prediction (NWP) models are used to predict the location and movement of CTLs, however weather forecasters have little knowledge themselves of the actual identification and climatology of these low pressures. There is also limited understanding of the potentially enormous impacts these weather systems have due to the rainfall produced by CTLs. The questions that are needing to be answered in this study include;

- How can forecasters easily identify CTLs?
- What is the frequency of occurrence of CTLs over southern Africa?
- What contribution CTLs have to the rainfall of South Africa during the summer months?

1.4 Aims and objectives of the research

The main focus of this dissertation is developing a synoptic climatology of CTLs over southern Africa, using these results the rainfall contribution is investigated. There are three main aims that are set out in this research:

1. Create an objective identification method for CTLs.
2. Develop a synoptic climatology of CTLs over southern Africa.
3. Determine the rainfall contribution CTLs have to South Africa.

In order to achieve these aims, the following objectives need to be met:

- Set criteria that can be used to identify CTLs
- Determine the occurrence of CTLs over southern Africa during December, January, February and March for the period 1979 to 2018;
- Establish the spatial and temporal characteristics of CTLs using the climatology results;
- Using rainfall data from the South African Weather Service (SAWS), determine the rainfall contribution these systems have to the annual rainfall over South Africa.

1.5 Chapter Overview

This dissertation consists of eight chapters. Outlines of each of the chapters are provided below.

Chapter 1 provides a background and introduction into the study with a motivation for undertaking the research of CTLs. The aims and objectives are also presented as well as the research question.

Chapter 2 provides a literature review which contains a background on the study area including the topography and the rainfall distribution. It also incorporates a discussion on tropical weather systems as well as other synoptic scale rainfall bearing weather systems that affect southern Africa. Discussion on methods that have used been to objectively identify other synoptic scale weather systems is included in this chapter.

Chapter 3 starts by describing the dynamics that are associated with a tropical atmosphere. It then continues by demonstrating the methodology that was applied to objectively identify CTLs over southern Africa. The final section of the chapter explains how the rainfall and atmospheric circulation data were used in the study to develop a climatology of CTLs over southern Africa and calculate the rainfall contribution to South Africa.

Chapter 4 is the first of three result chapters with this chapter documenting the climatology results. A geographical distribution of CTLs over southern Africa is presented as well as the seasonal distribution of CTLs.

Chapter 5 builds on from Chapter 4 as the rainfall results are revealed. These results are restricted to the rainfall contribution CTLs have to South Africa due to the limited availability of rainfall data for the neighbouring countries. Rainfall extremes associated with CTLs are demonstrated and the general distribution of rainfall around the central point of a CTL is discussed.

Chapter 6 presents a case study of a CTL that occurred in January 2013. This CTL is investigated in terms of tracking the position of the CTL during its lifespan and investing the rainfall distribution around the CTL. The impacts caused by the CTL over South Africa are also discussed.

Chapter 7 is the final chapter which merges all the components of the study. This chapter contains the concluding remarks and recommendations for future research to be conducted. It also demonstrates the importance of the research presented and explains the value this research will have to forecasting.

Chapter 8 is a list of the references that are referred to in this dissertation.

1.6 Summary

This chapter provides a fundamental introduction into the research that is to be undertaken in the proceeding chapters. It outlines the need for this study to be conducted including the motivation and offers background information on CTLs. The aims and objectives of the dissertation are presented as well as the research question. This chapter concludes with a summary of the chapters that will be presented.

Chapter 2

Literature Review

The purpose of this chapter is to provide an overview of the literature that is related to the tropical region and the main tropical weather systems that occur over southern Africa. Particular attention is placed on the weather systems affecting South Africa as well as the rainfall contribution large synoptic scale systems have to the Republic. This chapter also provides an introduction on objective identification methods that have been used in other studies to identify synoptic scale weather systems.

2.1 Background

Taljaard (1994) stated that there are six main features that govern the climate of South Africa. The first feature is the latitude, as there is less direct short-wave radiation at higher latitudes when compared to areas closer to the equator. The second feature is the position in relation to the distribution of land and sea. The height above sea level and the general topography of the area is the third feature, while the fourth is the overall circulation and perturbations of the atmosphere. The sea temperature is the fifth feature, which is influenced by the ocean currents and the final feature that governs the climate of South Africa is the underlying surface. Adding to this, Crimp *et al.,* (1997) stated that the geographical position southern Africa has with respect to the mid-latitude, sub-tropical and tropical pressure systems is another key feature that affects the climate of the region.

The tropical region can generally be defined as the area demarcated between the Tropic of Cancer (23.5°N) and the Tropic of Capricorn (23.5°S) (Asnani, 2005) and is said to be the source of most of the heat and momentum in the atmosphere (Riehl, 1979). Tropical weather systems, however, are not bounded by these latitudes, but rather follow the position of the sun (Asnani, 2005).

The tropics are dominated by general rising air while over the subtropics there is sinking air, this causes the formation of the Hadley cell (Laing and Evans, 2016). The Hadley cell causes the meridional circulation in the tropics, which then transports heat and momentum to higher latitudes (Asnani, 2005). The equatorial zone is dominated by a low pressure belt, called the equatorial trough, with an area of high pressure found over the subtropics, known as the subtropical high pressure belt (Riehl, 1979). In the area between these two belts, lies a region that is dominated by easterly winds, which have become known as the trade winds (Riehl, 1979).

The weather that occurs in tropical areas ranges from sunshine during the dry season to severe rain and winds associated with tropical cyclones (Ramage, 1995). Worldwide, tropical weather systems are known to result in devastating floods, but are also responsible for providing vital rainfall to many regions (Anthes, 1982) which often determines the success of crops (Riehl, 1979).

South Africa is positioned such that the Tropic of Capricorn tracks through the extreme north-eastern parts of the country. Tropical weather systems therefore extend into the northern parts of the republic during the summer months and may be accompanied by heavy rainfall which could lead to flooding (Dyson and van Heerden, 2002). Over southern Africa, January to March is generally the season with the highest rainfall and is also the period that is mainly linked to tropical circulation (Richard *et al.,* 2001). Southern Africa, broadly defined here as the African countries south of approximately 10°S and represented in figure 2.1.1, is generally regarded as a semi-arid region that has great variability in rainfall (Blamely and Reason, 2012).

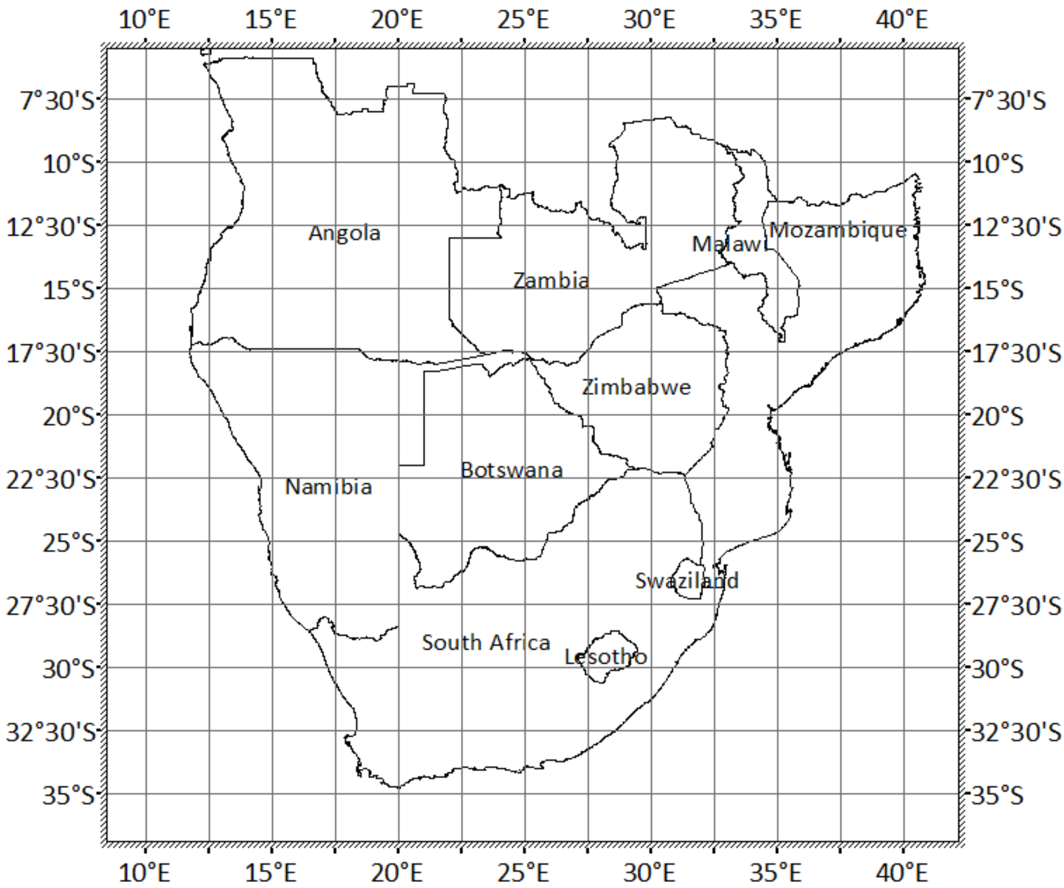


Figure 2.1.1: Geographical representation of the countries forming part of southern Africa.

The topography of southern Africa consists of an extended plateau that lies 1000 to 1500 m above sea level, covering most parts of the region (Fig. 2.1.2). Along the coastal region, an escarpment lies 200-300 km from the coast at an elevation of 1000 m (Taljaard, 1994). The Kalahari, which is a broad generally-flat region, is located over the north-western parts of South Africa, into Botswana and Namibia (Taljaard, 1994).

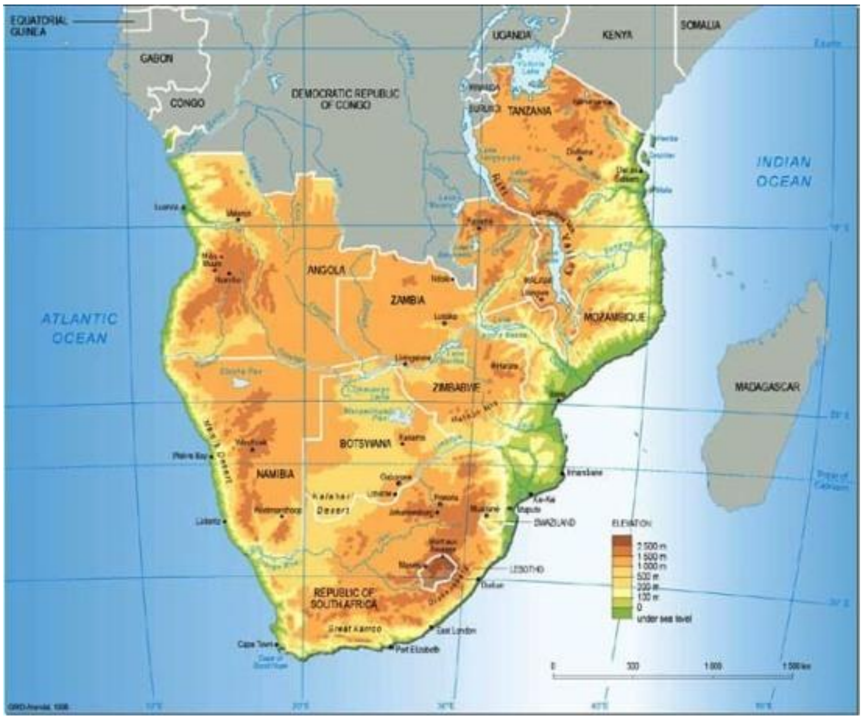


Figure 2.1.2: Topographical map of southern Africa (After Rekacewicz and Bournay, 2005).

Southern Africa can be classified as a semi-arid region that is particularly exposed to changes in the climate (Crétat *et al.,* 2018). The rainfall across the region is also very variable each year with wet and dry periods a regular occurrence (Richard *et al.,* 2001). Southern Africa generally receives rainfall over the summer months, from November to March, except for the south-west and south coasts (Mulenga, 1998, Crétat *et al.,* 2018 and Taljaard, 1986). Southern Africa area can be divided into three main rainfall regions, firstly, the east coast and most of the interior which is a primarily summer rainfall region, the west coast and adjacent interior is a winter rainfall area and lastly the south coast generally receives rainfall throughout the year (Blamely and Reason, 2012). There is a prominent east to west variation in the rainfall (van Heerden and Taljaard, contributing to Karoly and Vincent, 1998), with the western parts of Namibia and South Africa only receiving an average of less than 200 mm rainfall per annum (Fig. 2.1.3.), while central and northern Mozambique as well as Angola and Zambia receiving more than 1000 mm each year. There is also a clear dry area over the Limpopo River Valley along the South Africa/Zimbabwe border (van Heerden and Taljaard, contributing to Karoly and Vincent, 1998). Richard *et al*., (2001) explains that the rainfall contribution of the late summer months (January to March) is regularly more than 40% of the annual rainfall for southern Africa.

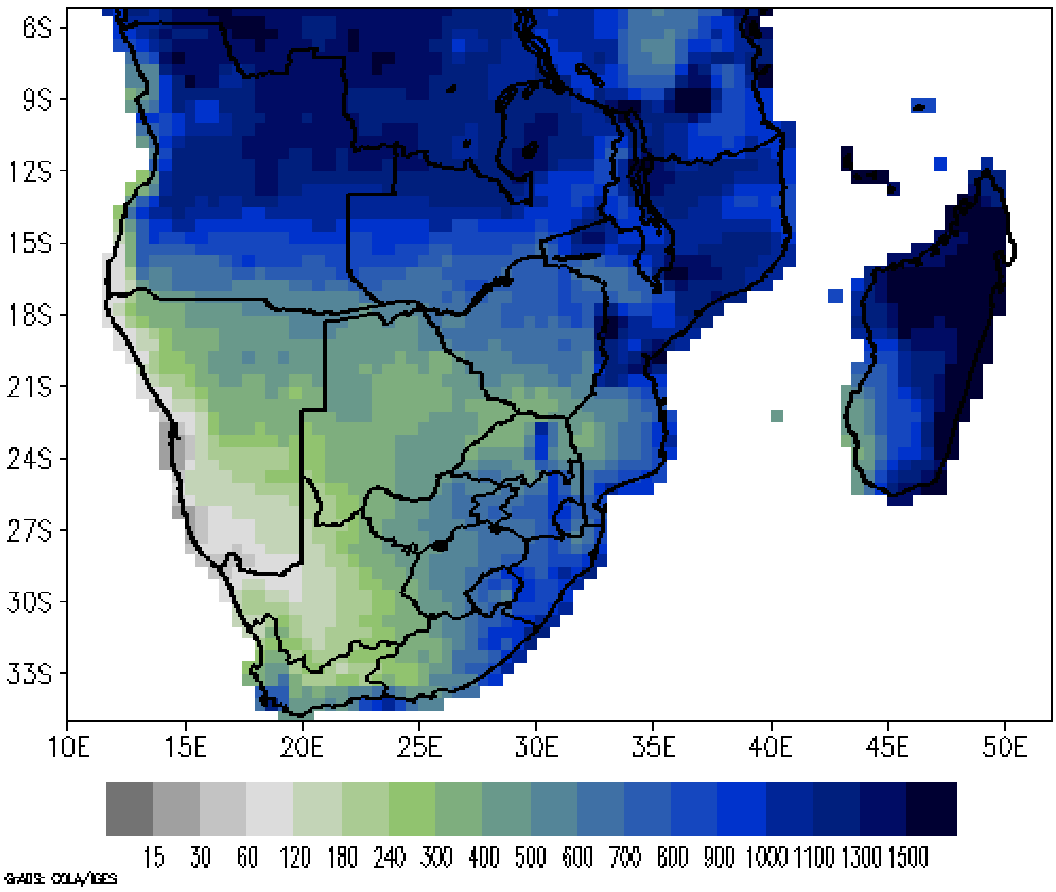


Figure 2.1.3: Annual rainfall across southern Africa (mm) (Schneider, et al., 2011).

The variability of rainfall over southern Africa has been studied extensively (Nicholson *et al.,* 2018 and Crimp *et al.,* 1997). However, very little research has been dedicated solely to tropical weather systems over southern Africa, even though these systems are known to cause extreme rainfall and often result in extensive damage due to flooding (Dyson *et al.,* 2002; de Villiers *et al.*, 2000, Chikoore *et al.,* 2015). Overall, the advancement of forecasting in tropical regions has been very slow due to restricted data as well as a limited knowledge of these weather systems (Ramage, 1995). There is therefore a clear need for comprehensive research on tropical weather systems, especially over southern Africa.

This research focuses on firstly the identification of CTLs over southern Africa. Secondly, it also intends to create a climatology of these weather systems and finally quantify their contribution to the rainfall over South Africa.

2.2 Tropical weather systems of the Southern Hemisphere

In this section, the main tropical weather systems that affect southern Africa are discussed. These weather systems are tropical cyclones, tropical temperate troughs, tropical low pressures and the inter-tropical convergence zone.

Tropical cyclones are warm-cored cyclonic vortices (Kepert, contributing to Chan and Kepert, 2010), that develop over warm tropical oceans (Anthes, 1982). There has been substantial growth in the understanding of tropical cyclones (Kepert, contributing to Chan and Kepert, 2010) as most of the research on tropical meteorology is directed towards these weather systems (Ramage, 1995). This could be attributed to the notion that intense tropical cyclones are the tropics' most prominent weather systems (Ramage, 1995). These weather systems are the most destructive of all natural disasters, responsible for the deaths of hundreds of thousands of people and are able to completely destroy coastal towns (Anthes, 1982). A single tropical cyclone has the capability of affecting many different countries in the course of its lifespan (Anthes, 1982).

Tropical cyclones are classified according to the wind speeds they produce. In the south-west Indian Ocean, a tropical disturbance is classified as a tropical depression once the maximum wind speed reaches between 34-63 knots (Ramage, 1995). There is an average of eleven tropical disturbances that reach tropical depression intensity in the south-west Indian Ocean each summer season (Jury and Pathack, 1991). These systems do not make landfall every year (Malherbe *et al.,* 2012) in fact, less than 5% of tropical cyclones that occur in the south-west Indian Ocean make landfall over southern Africa (Reason and Keibel, 2004, Chikoore *et al.,* 2015). Nevertheless, when these systems do make landfall over southern Africa, they tend to move over areas where large river basins are situated, resulting in enormous impacts downstream due to flooding (Malherbe *et al.,* 2012).

One of the key climatological components of the global atmosphere is the Inter-Tropical Convergence Zone (ITCZ) (Zagar *et al.,* 2011) and is said to be one of the most vital mechanisms of the climate system (Berry and Reeder, 2013). The ITCZ is an area of low pressure that extends around the globe in close proximity to the equator (Taljaard, 1994). The positioning of the ITCZ has a major effect on the annual rainfall over southern Africa (Harrison,

1986) and the overall weather conditions in South Africa (Taljaard, 1994). The position of the ITCZ and the inter-ocean convergence zone troughs during summer are the average locations of zones of convergence as well as zones of active weather (van Heerden and Taljaard, contributing to Karoly and Vincent, 1998). In the northern hemisphere summer, the ITCZ reaches 20°N and in the southern hemisphere summer, it extends to 17°S (Taljaard, 1994).

During these summer months in southern Africa, when the ITCZ is furthest south, there is generally a low-level tropical/subtropical low pressure that extends a trough southwards across the continent reaching South Africa (Williams *et al*., 1984). Mulenga (1998) named this the Angola low pressure while Reason *et al.,* (2006) defined the Angola low as a shallow heat low that starts to develop over northern Namibia and southern Angola around October, strengthening in January and February. The Angola low pressure has been recognised as a cyclonic moisture convergence area that is one of the governing features of rainfall of southern Africa (Mulenga, 1998).

In some instances, the tropical low pressure will interact with a temperate westerly trough and form a cloud band across the subcontinent (Washington and Todd, 1999). These long bands of clouds are one of the major distinguishing features of the southern hemisphere circulation that can be seen on satellite imagery (Harrison, 1986) and represent tropical temperate troughs (TTTs) (Crimp *et al.,* 1997).

Tropical temperate troughs can be described as areas of increased convergence that connect tropical and temperate systems (Crimp *et al.,* 1997), which transport energy, moisture and momentum from tropical to temperate regions (Harrison, 1986; van den Heever *et al.,* 1997). TTTs are not unique to southern Africa, but can be found in many regions, including Australia and South America (Hart *et al.,* 2010, Hart *et al.,* 2012, Hart *et al.,* 2013 and van den Heever *et al.,* 1997).

Limited emphasis has been placed on researching tropical low pressure systems over southern Africa as well as in Australia (Tang *et al.,* 2016) in recent years even though these low pressures have been one of the main weather systems responsible for many flooding incidents. Known cases in southern Africa are the February 1988 flooding event that occurred over the Free State (Triegaardt *et al.,* 1991) and February 2000, where the central parts of Mozambique and the Northern Province of South Africa were affected by devastating floods (Dyson and van Heerden, 2001).

van Heerden and Taljaard, contributing to Karoly and Vincent (1998) stated that tropical low pressures are one of the three low pressure systems that prevail at low latitudes with the other two being tropical cyclones and heat lows. CTLs are generally defined as having a cool core in the lowest 3-4 km of the low pressure with a warm core aloft (van Heerden and Taljaard, contributing to Karoly and Vincent, 1998). These weather systems have a typical scale of 500-1000 km (Engelbrecht *et al.*, 2013) with convergence to the east of the low pressure that is accompanied by divergence in the upper air (Preston-Whyte and Tyson, 1993 and Triegaardt *et al.*, 1991). van Heerden and Taljaard, contributing to Karoly and Vincent (1998) also stated that tropical low pressures can be identified on satellite imagery with the low level circulation being cyclonic and anti-cyclonic in the upper troposphere.

More recently Dyson and van Heerden (2002) developed a Model for the Identification of Tropical Weather Systems (MITS) which assists forecasters in identifying tropical weather systems as well as detecting areas where tropical convection can occur. There are five components of MITS which are focused on the atmospheric dynamics that are necessary for the development of convective rainfall caused by tropical systems. Further details on MITS will be discussed in Chapter 3.

2.3 Major rainfall producing synoptic scale weather systems of South Africa

The main weather systems that result in substantial rainfall over South Africa are discussed in this section, focussing particularly on weather systems that are not of a tropical nature. Rainfall and temperature are the two most important factors in the weather and climate in most parts of the world, with rainfall outweighing temperature in South Africa (Taljaard, 1996). Cut-off low pressures, cold fronts and ridging high pressures are a few of the most favourable rainfall-producing weather systems in South Africa (Taljaard, 1996) with cold-core cut-off low pressures being one of the main rainfall contributors of southern Africa (Engelbrecht *et al.,* 2013). These weather systems may be responsible for widespread flood events over South Africa. On average, 11 cut-off low pressures affect South Africa each year

(Taljaard, 1985) with the most common occurrence being in late summer and into autumn (Favre *et al.,* 2012), and least common occurrence in January and July (Taljaard, 1996). Cut-off low pressures often result in extreme rainfall over the southern and eastern coastal regions of South Africa (Singleton and Reason, 2006; Engelbrecht *et al.,* 2014).

The southern parts of South Africa generally receives rainfall from structured synoptic-scale weather systems, particularly cold fronts (Singleton and Reason, 2006) with the south-western parts mainly being affected by passing mid-latitude low pressure systems in the winter months which result in the bulk of the rainfall for the region (Landman *et al.,* 2016). These weather systems substantially contribute to rainfall across South Africa, especially along the east and south coasts (Favre *et al.,* 2013), however, the amount of rainfall received from cold fronts is strongly dependant on the orographic uplift across South Africa (Taljaard, 1996).

2.4 Rainfall contribution of tropical weather systems over southern Africa

In this section, the focus is directed on tropical weather systems that affect southern Africa and the contribution they have to rainfall. During the summer months, the northern parts of South Africa are typically affected by tropical weather systems (Tennant and Hewitson, 2002). The heavy rainfall that is caused by these tropical weather systems is far more important for the South African hydrology than the rainfall that occurs in the winter months and the weather systems during that period (Poolman, contributing to Dyson *et al.,* 2002).

In a recent study, Crétat *et al.,* (2018) found that a slight change in the position of the Angola Low pressure, either a north-south or east-west displacement, can have a significant impact on the placement of the rainfall associated with these weather systems. Harrison (1984) found that the most important contributors to rainfall over South Africa are as a result of cloud bands that link the tropics to temperate areas, contributing more than 35% of the annual rainfall over the central interior of South Africa (Harrison, 1986). More recently, Hart *et al.,* (2010) and Washington and Todd (1999) supported this finding but added that in South Africa, TTTs are the major rain producing systems during summer.

Another tropical weather system that affects the rainfall over South Africa are tropical cyclones. Generally, tropical cyclones situated over the coastal regions to the east of southern Africa result in rainfall conditions being suppressed over the interior of the sub-continent and are rarely a source of rainfall for South Africa in particular (Harrison, 1986). More recently, further research has shown that tropical cyclones from the south-west Indian Ocean that do make landfall, contribute to less than 10% of the annual rainfall over the eastern interior of southern Africa (Malherbe *et al.,* 2012). However, even though the contribution to the annual rainfall is not excessive, these weather systems are found to result in about 50% of the widespread heavy rainfall events that occur over the north-eastern parts of South Africa, specifically within the Limpopo Basin (Malherbe *et al.,* 2012). Tropical cyclones are also known to cause extensive damage due to flooding (Poolman and Terblanche, 1984; de Villiers *et al.*, 2000, Chikoore *et al.,* 2015). One such particularly extreme system was tropical cyclone Domoina that was responsible for the highest daily rainfall ever recorded in South Africa, where 597 mm was recorded in St Lucia, KwaZulu-Natal on 31 January 1984 (Weather Bureau, 1991).

Overall, tropical weather systems play an important role in heavy rainfall events over South Africa (Poolman contributing to Dyson *et al.,* 2002) and therefore there is clear need for better understanding of these weather systems. However, the rainfall contribution CTLs have to South Africa is not known and therefore this is one of the main focuses of this research.

2.5 Objective identification of synoptic scale weather systems

In the following section, objective identification methods will be investigated and the use of these methods will be discussed. Objective identification of synoptic scale weather systems in an operational environment could assist forecasters with the prediction of these weather systems in a timeous manner. This could in turn result in more accurate forecasts and increase the lead time in which authorities can receive information about potentially hazardous and life-threatening weather systems. The ultimate accomplishment would be to prevent the loss of lives and livelihood. Furthermore, the objective identification of weather systems makes researching these weather systems more probable for instance by creating climatologies (Malherbe *et al.,* 2012) and understanding processes and movement of these systems better (Engelbrecht *et al.,* 2014). Objective identification methods have been used to identify synoptic scale weather systems over South Africa (Engelbrecht *et al.,* 2014; Malherbe *et al.,* 2012) and in other parts of the world (Knaff *et al.,* 2008).

An objective identification method has also been created to detect the location of the ITCZ whereby layer- and time-averaged winds in the lower troposphere were used to identify the position of the ITCZ (Berry and Reeder, 2013). This is an automated method that was then used to create a climatology of the ITCZ for the period 1979-2009. It was found that the ITCZ most commonly occurs over the eastern Pacific Ocean, where it is limited to a narrow latitudinal band throughout the year (Berry and Reeder, 2013). Hart *et al.,* (2012) developed an automated objective method to identify TTT events over southern Africa. In their study, they created a climatology of cloud band positions and found that TTTs have two preferred areas of location.

In a study on synoptic decomposition of rainfall over the Cape south coast of South Africa, it was found that cut-off low pressures (COLs) are significant rainfall producing weather systems over the region and therefore an objective algorithm was created in order to investigate the effects of these weather systems (Engelbrecht *et al.,* 2014). COLs were objectively identified as a closed-low pressure (having a minimum geopotential height at 500 hPa) that exhibit a cold core for a period of at least 24 hours (Engelbrecht *et al.,* 2013). Earlier, Singleton and Reason (2007) also objectively identified COLs over southern Africa with slightly different criteria. They classified a COL as a low pressure that is closed at 300 hPa and also exists for at least 24 hours.

Malherbe *et al.,* (2012), objectively identified landfalling westward moving tropical systems in the south-west Indian Ocean using four criteria. The first criteria was that there needed to be a closed low pressure at heights 700 and 500 hPa, that had to exist for 24 hours and needed to be replaced by either a high pressure system at 250 hPa or at least have an absence of a low pressure. The next criteria was that the closed low had to be identified while over the south-west Indian Ocean, but not necessarily required to exist overland. The third criteria was that the centre of the low pressure had to move over land in either the low or middle parts of the atmosphere, however it was not required for the low pressure to be in closed-low form when making landfall. The final criteria was that this tropical low pressure needed to be responsible for rainfall over the eastern interior of South Africa or Zimbabwe. The purpose of objectively identifying this weather system was to gain an understanding of the rainfall contribution these weather systems have over the north-eastern interior of southern Africa.

Recently, Crétat *et al.,* (2018) objectively identified the Angola low pressure over Angola and the surrounding countries. In their study, they found that there are three low pressures over southern Africa. In order to identify the Angola low and to distinguish it from the other two low pressures, daily anomalies of vorticity at 700 hPa were used.

In this dissertation an objective identification method will also be used for CTLs. These weather systems will be objectively classified and their contribution to rainfall over South Africa determined. A comprehensive discussion on the methodology used to develop an objective identification of CTLs will be provided in Chapter 3.

2.6 Summary

This chapter provides a background of the tropical region, including the topography and annual rainfall. A discussion on tropical weather systems that affect southern Africa is supplied, these include tropical cyclones, tropical temperate troughs and tropical low pressures. Cold fronts and cut-off low pressures are presented introduced as major rainfall producing weather systems of southern Africa.

A summary of tropical weather systems that contribute to the rainfall over southern Africa is provided. This includes weather systems such as landfalling tropical cyclones as well as the main contributor to the rainfall which is tropical temperate troughs. Finally, objective identification methods that have been used to identify other synoptic-scale weather systems are also discussed.

Chapter 3
Data and Methodology

This chapter starts off with a discussion on the characteristics of the tropical region. These characteristics are then applied to identify CTLs, using reanalysis data from the National Centers for Environmental Prediction (NCEP) (Kalnay *et al*., 1996). Daily observed rainfall station data from the South African Weather Service (SAWS) was used in this dissertation. The methodology employed to create a climatology of CTLs and the process of calculating the rainfall contribution these systems have to South Africa is described.

3.1 Characteristics of a Tropical Atmosphere

In order to accurately develop an objective identification method for CTLs, the characteristics which govern the tropical region need to be understood. However, the dynamics of the tropics in terms of the circulation is notoriously complex (Holton, 2004). The main atmospheric components that will be focused on in this study are relative vorticity, total static energy, precipitable water and average column temperatures. This section attempts to discuss why these components are important in the tropical region.

The tropics can be defined as the region where the atmospheric processes vary distinctly from those at higher latitudes (Riehl, 1979). Asnani (2005) describes a few of these differences by explaining that temperature and pressure gradients are very weak in the tropics with temporal changes of only 1 hPa per day often occurring. Another unique feature of the tropics is the very weak or even negligible Coriolis force (Laing and Evans, 2016). It is due to these unique features of the tropics that relative humidity and wind discontinuities are of utmost importance when forecasting in a tropical environment (Riehl, 1979).

The tropical atmosphere is warmer than the extra-tropics (Asnani, 2005) and has the highest surface water vapour content (Laing and Evans, 2016). There is generally an upper high pressure present during the summer months (Taljaard, 1995) that is largely associated with above normal column temperatures (Dyson and van Heerden, 2002). These three measurements (moisture, temperature and upper high) are key features of the atmospheric conditions found in a tropical region. Therefore, in order to easily identify a tropical atmosphere, a variable that encompasses all three of these features (high temperatures and moisture as well as an upper high pressure) is needed.

Total static energy (TSE) contains all three variables which can thus be used to identify a tropical atmosphere. In addition, Dyson *et al.,* (2015) found that during late summer, there is an increase in temperature throughout the troposphere and the decrease in wind shear; the temperature lapse rate under such conditions is very small which makes commonly used instability indices, such as total of totals not very useful in a tropical environment. A vertical profile of TSE will however identify an unstable tropical atmosphere by indicating convective instability (Riehl, 1979) (Fig. 3.1). Agreeing with this, Harrison (1988) added that TSE can also be used as a measure of rainfall totals. The typical vertical profile of TSE in a tropical atmosphere (Fig. 3.1), which is used to determine the conditional instability in the atmosphere (Triegaardt *et al.,* 1991) has an isentropic layer just above the surface, from there the TSE reaches a minimum around 500 hPa and then increases higher up, at lower pressure levels (Harrison, 1988). The high TSE values at the surface which extend into the lower atmosphere are caused by the direct heating of the surface which in turn heats up the boundary layer (Harrison, 1988). The dashed line in figure 3.1 represents the TSE value at the surface which is once again reached at approximately 200 hPa, this shows that in such cases, the atmosphere is conditionally unstable and deep cumulus convection is probable up to 200 hPa (Dyson *et al.,* 2002).

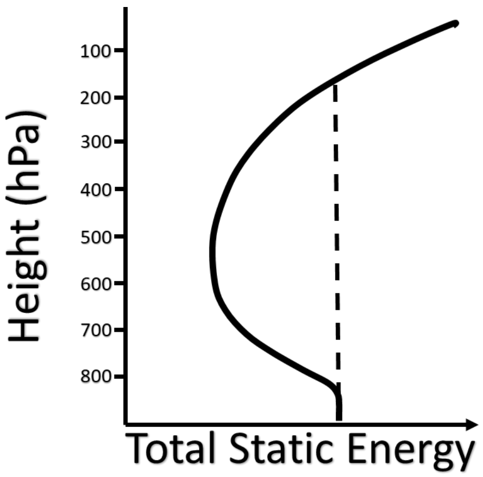


Figure 3.1: An illustration of the typical vertical profile of total static energy that is associated with deep convection (After Harrison, 1988).

TSE is given by:

$$TSE = C_p T + gz + Lq \qquad (1)$$

Where, Cp = the specific heat of dry air, T = temperature, g = magnitude of gravity constant, 9.8m.s^{-2}, z = the geopotential height in meter (gpm), L = the latent heat of condensation, q = the water vapour mixing ratio. The terms on the right of the equation represent enthalpy, geopotential and latent heat (Triegaardt *et al.,* 1991). Dyson *et al.,* (2015) stated that the upper tropospheric temperatures increase during summer months therefore the enthalpy will increase which will also increase the TSE. In tropical weather systems, there is generally an upper tropospheric high pressure that exists, this too will further increase the TSE. Using the latent heat term, there is high moisture content in the lower troposphere of tropical weather systems which will in turn also increase the TSE (Dyson and van Heerden, 2002).

The high moisture content that is generally found in a tropical airmass can be measured using the precipitable water (W) values in the atmosphere (Dyson and van Heerden, 2002 and Harrison, 1988). Precipitable water is defined as the amount of water vapour available within a given column of the atmosphere such that if all the water vapour in that column were condensed (Huschke, 1959). Precipitable water is given by:

$$W = \frac{1}{g}\int_{p_1}^{p_2} q \, dp \qquad (2)$$

Where, p_1 = 850 hPa and p_2 = 300 hPa.

The circulation in a tropical atmosphere is close to being barotropic (Dyson and van Heerden, 2002). Holton (2004) states that in a barotropic atmosphere, density is only a function of pressure, such that isobaric surfaces display constant density. In a barotropic atmosphere, the isobaric surfaces will also be isothermal in an ideal gas, resulting in:

$$\overline{\nabla}_p T = 0, \qquad (3)$$

Where, $\overline{\nabla}_p = \bar{i}\frac{\partial}{\partial x} + \bar{j}\frac{\partial}{\partial y}$.

This means that if the horizontal gradient vector of the average column temperature is zero, the thermal wind will be zero as well. Thermal wind is the relationship of the vertical wind shear which is defined as the vector difference between geostrophic winds at two levels (Holton, 2004). Thermal wind is given by:

$$\overline{V}_T = \overline{V}_g(p_1) - \overline{V}_g(p_0) \qquad (4)$$

Where, $\overline{V}_T$ = thermal wind and $\overline{V}_g$ = geostrophic wind at pressure levels p_1 and p_0 ($p_1 < p_0$).

Therefore, when the thermal wind equals zero, there will be no change in the geostrophic wind with height. This further means that the horizontal component of the gradient vector of geopotential does not change with height in a barotropic atmosphere and there is no temperature gradient on a pressure level (Dyson and van Heerden, 2002). Which ultimately demonstrates that in this perfect environment, synoptic-scale low pressures will stand upright with height (Dyson and van Heerden, 2002).

Dyson and van Heerden (2002) state that in a real tropical atmosphere, an upright low pressure system contains strong surface and mid-level convergence (i.e. the wind is not geostrophic). Holton (2004) stated that the level of the zero convergence is usually at 500 hPa in the mid-latitudes, but in a tropical atmosphere, it occurs at pressures even lower than 400 hPa. Riehl (1979) explains that this convergence in the boundary layer causes the moisture flux to be transported upward and makes the necessary release of latent heat available that will warm the atmosphere above the boundary layer. Riehl (1979) also describes how hot towers transport heat from the surface to the upper levels in the troposphere which is then horizontally dispersed through upper air divergence (Dyson and van Heerden, 2002). Above normal upper tropospheric temperatures (i.e. 500-300 hPa) will thus exist due to the release of latent heat and are able to maintain an upper high pressure (Triegaardt *et al.,* 1991).

Relative vorticity can be used to demonstrate an upright standing low pressure (Holton, 2004). By convention, in the Southern Hemisphere, low pressures (cyclonic rotation) can be identified as areas with negative values of relative vorticity with high pressures (anti-cyclones) represented by positive values (Holton, 2004). Relative vorticity is given by:

$$\zeta = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \qquad (5)$$

where, v is the meridional wind and u is the zonal wind component.

Due to the release of latent heat which results in above normal tropospheric temperatures in the tropical region (Riehl, 1979) an additional key identification feature of tropical weather systems is the average temperature in the 500 to 300 hPa layer (Dyson and van Heerden, 2002). Therefore, a tropical weather system can broadly be recognised as an upright standing low pressure with above normal tropospheric temperatures and a high pressure in the upper air. The low pressure can be identified by areas of negative relative vorticity and a high pressure as areas with positive relative vorticity values.

The characteristics of a tropical atmosphere explained above are used to create the objective identification method for CTLs that will be discussed in section 3.3. It is important to understand the complex atmospheric features of a tropical atmosphere so that all the necessary components can be included in the objective identification method.

3.2 Model for the identification of tropical weather systems

Using the atmospheric dynamics that are vital for the development of convective rainfall as a result of tropical weather systems, Dyson and van Heerden (2002) developed the model for the identification of tropical weather systems (MITS). MITS is used to identify tropical weather systems as well as to detect areas of tropical convection. It was therefore decided that this is an excellent starting point from which to build on further. MITS has five components based on the atmospheric mechanisms of a tropical atmosphere which is illustrated in figure 3.2.1.

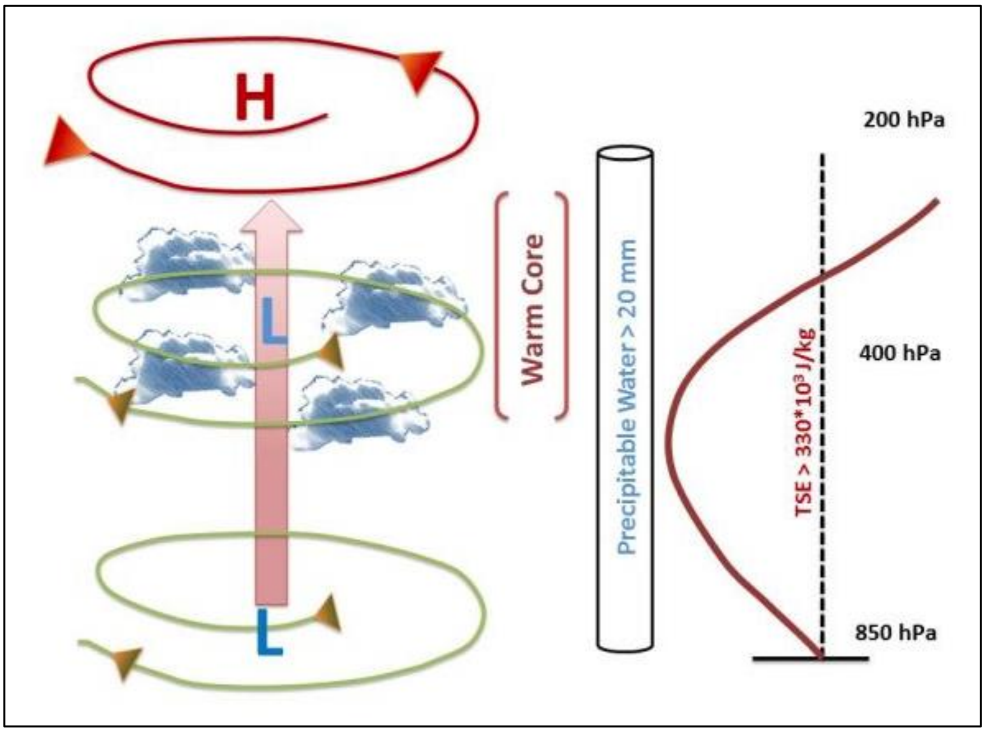


Figure 3.2.1: Graphical representation of MITS, displaying the components MITS uses to identify a tropical weather systems and areas of tropical convection (After CMSH, 2015).

The first component of MITS states that a low pressure must stand upright from 850 to 400 hPa with a ridge of high pressure at 200 hPa. This is demonstrated in figure 3.2.1 by displaying a low pressure at the lower levels (850 hPa) in the atmosphere through to the mid-levels (400 hPa) with cyclonic circulation. A high pressure is present in the upper air with anti-cyclonic rotation. This illustrates the upright low pressure with a ridge in the upper levels.

The second component is that in the 500 to 300 hPa layer, a core of high average column temperatures should be above or in close proximity to the low pressure. Dyson and van Heerden (2002) found that in order to identify a warm cored tropical system, no specific temperature threshold is used, instead the temperatures are required to be warmer than the surrounding areas.

The third component is that the precipitable water values should be more than 20 mm in the 850 to 300 hPa layer and this should be in the same area as the ridge of high pressure at 200 hPa, which all needs to exist with upper tropospheric wind divergence. In figure 3.2.1, a column is used to illustrate that precipitable water values within such a column need to exceed 20 mm.

The fourth component states that in the 850 to 300 hPa layer, the average total static energy should be greater than $330x10^3$ Jkg^{-1}. This is graphically represented in figure 3.2.1 on the far right side in the image which displays a vertical profile of TSE showing deep convection. The final component which helps identify rainfall from tropical lows is that the atmosphere should be conditionally unstable up to 400 hPa, upward motion should be present from 700 to 400 hPa and that precipitable water values should exceed 20 mm.

3.3 Methodology used to objectively identify Continental Tropical Low pressures

In order to accurately create a climatology of CTLs over southern Africa as well as to quantify the rainfall contribution of CTLs to South Africa, an objective identification method is created. The objective identification method in this study, is broadly based on MITS which is a subjective tool that was developed by Dyson and van Heerden (2002). Using MITS as a starting point as well as the characteristics described in 3.1, the following section provides a detailed description of the process whereby CTLs are objectively identified over southern Africa for this dissertation.

While using the components stated in MITS and identifying upright standing low pressures by means of geopotential heights, it was found that the Angola low pressure often meets this requirement during late summer. The Angola low pressure is a shallow heat low that develops over southern Angola and northern Namibia during the summer months (Reason *et al.,* 2006 and Mulenga, 1998) which can be identified using relative vorticity at 700 hPa (Cretat *et al.,* 2018). The CTL as defined in this dissertation is a deeper low which should have significant cyclonic circulation throughout the troposphere. Therefore to identify upright standing low pressures, it was decided to use relative vorticity (ζ), with a low pressure identified as an area of negative relative vorticity given by equation (5) at levels 850 and 500 hPa and positive values at 300 hPa to represent an upper high pressure.

In a further attempt to distinguish CTLs from the semi-permanent Angola low pressure, deviations of instantaneous values of certain parameters from the long term mean for the individual months are applied. A similar approach was used by Engelbrecht and Landman (2015) who used standardized anomalies to identify rare and thus severe events over South Africa. In this study, the deviations from the norm were applied to vorticity, TSE, column temperature and precipitable water, where each of these components are required to be stronger/higher than the norm for the specific month.

While identifying tropical environments, Dyson (2000) established that in order to sustain a tropical thermal high pressure in the upper atmosphere, precipitable water values of at least 20 mm are required. Therefore this is also a requirement in this study.

The subject method to identify the existence of a CTL has *four* criteria that need to be met. A graphical illustration of this process through the use of a flow chart is provided in figure 3.3.2. The *first* criteria is to detect **a favourable tropical environment (FTE)**. A grid point is positively identified as an FTE if the following conditions are met:

- Negative relative vorticity values are present at 850 and 500 hPa, and are replaced by positive values at 300 hPa;
- The cyclonic circulation at the surface and in the mid-troposphere is stronger than normal while the high pressure dominates near the tropopause. Therefore it is required that the deviation from the normal vorticity values for the month under investigation show this anomalous circulation;
- Average tropospheric total static energy (TSE) values should be higher than the long term average for that month;
- The average 500-300 hPa temperatures should be higher than the long term average value for that month;
- The precipitable water from 850-300 hPa should be greater than 20 mm;
- The precipitable water values should also be higher than the long term average value for that month.

The *second* criteria is that **a closed 500 hPa geopotential low with a warm core of 500-300 hPa temperatures are present.** This is seen in figure 3.3.2 as a two-fold requirement which leads to the next requirement of the 500 hPa low being within a two grid points from the warm core. This is then referred to as a warm low (first orange block in figure 3.3.2)**.** A closed low pressure (warm core) is identified when the surrounding eight grid points have higher geopotential heights (lower temperatures) than the grid point under investigation. Figure 3.3.1 is an illustration of this process, with X representing the grid point that has lower geopotential heights (warmer temperatures) than the 8 grid points surrounding it.

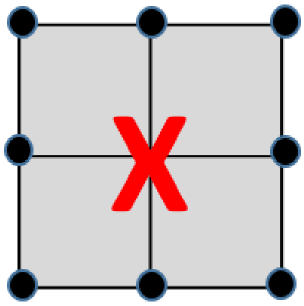


Figure 3.3.1: Illustration of a closed low pressure and/or a warm core, where X indicates the lowest geopotential height or warmest temperature of the surrounding eight grid points, within the grey area.

The *third* criteria is that the **FTE and warm low are within two grid points of each other**. If this requirement is met, the low pressure is then termed a warm FTE low pressure (second orange block in figure 3.3.2). The *fourth* criteria is two-fold and is related to time. It is required that **the current warm FTE low has another warm FTE low either 18 hours before or after *and* lies within two grid points of the current warm FTE low**. The time requirement is illustrated by using the following example; if the current warm FTE low is at time step t=4, with each time step six hours apart, then another warm FTE low is required to be present at one of the following time steps t=1, t=2, t=3, t=5, t=6 or t=7. In addition, the second part of the fourth criteria, which states that the current warm FTE low pressure is required to be within two grid points of another warm FTE low.

If all of these four criteria are met, then the warm FTE low is now classified as a CTL. The position of the closed low pressure, identified in the second criteria is used as the position of the CTL.

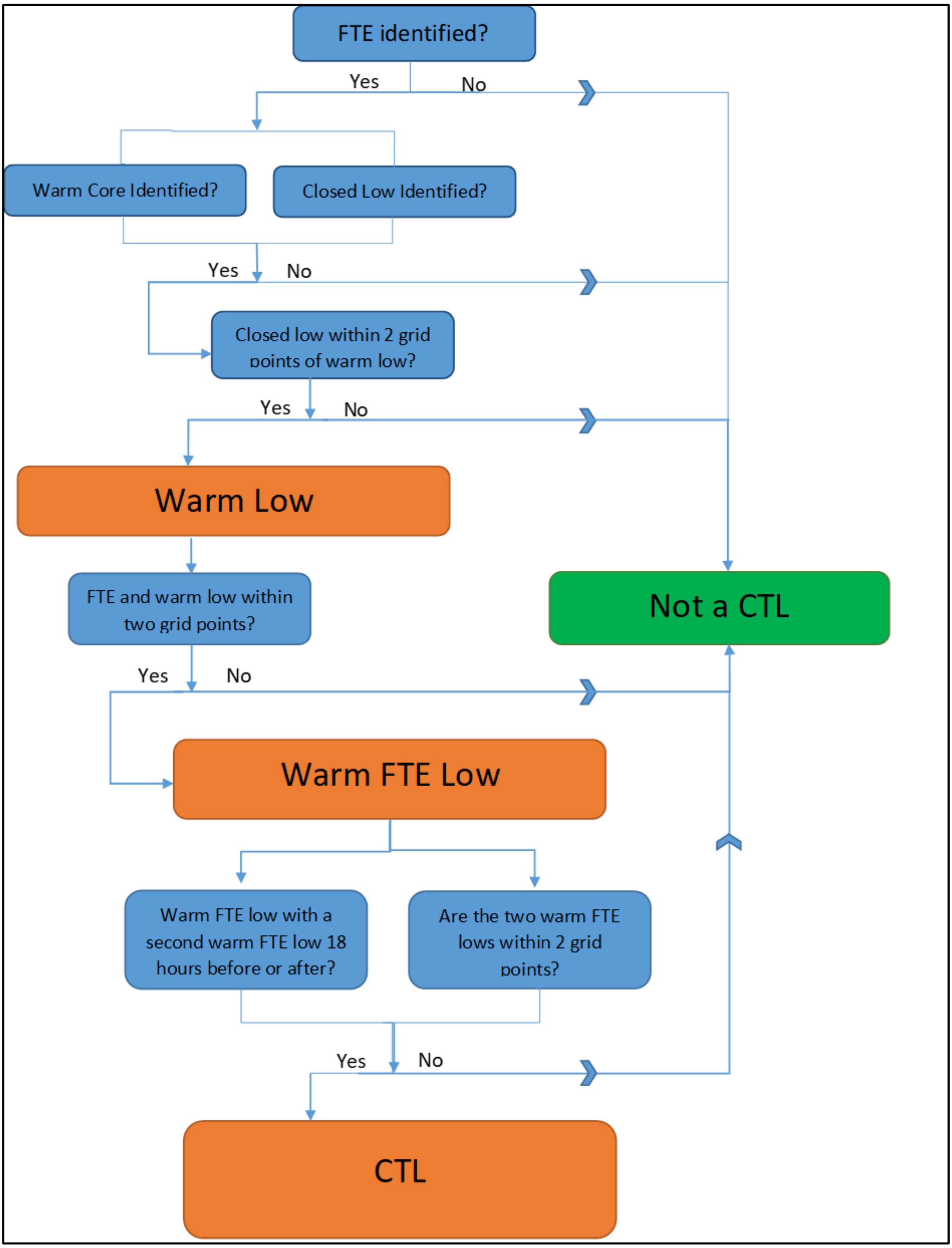


Figure 3.3.2: Flow diagram illustrating the procedure used to identify a CTL over southern Africa.

For this research a landmask is used to identify CTLs over land within the domain 17.5 to 32.5°S and 12.5 to 35°E. This domain is illustrated using the grey block in figure 3.3.3, and only CTLs within this region are considered in the study.

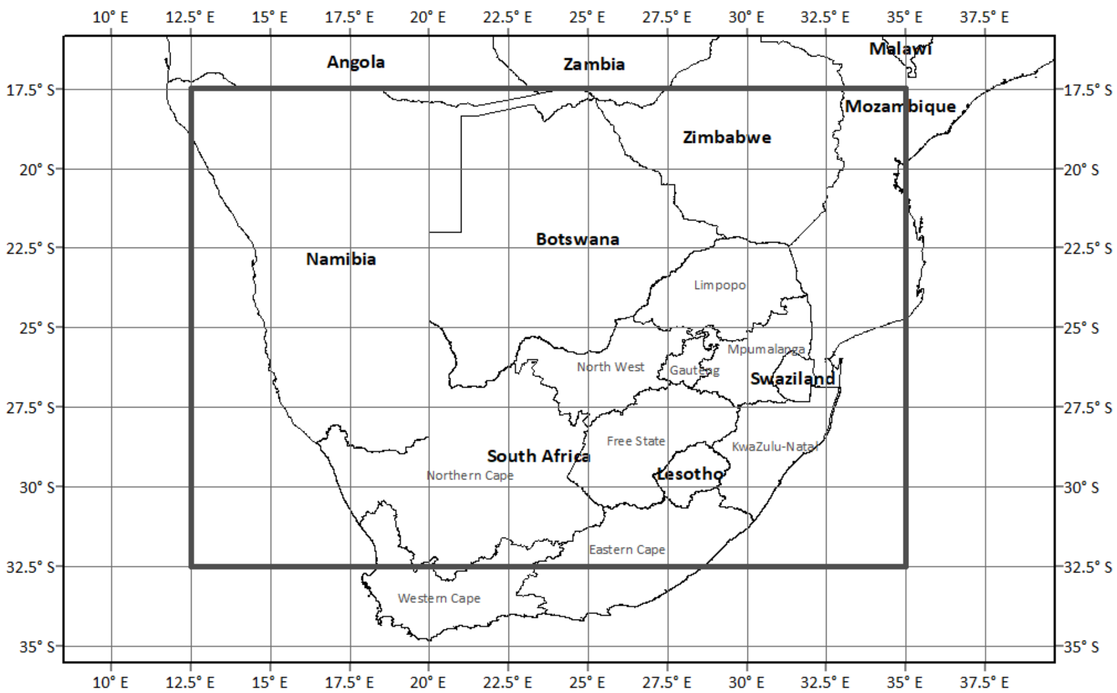


Figure 3.3.3: Illustration of research area depicted by region within the bold block. Country names given in bold with the provinces of South Africa in italics grey.

3.4 Gridded Rainfall

Daily observed rainfall station data supplied by SAWS was used to determine the rainfall contribution of CTLs to South Africa. This rainfall was converted to 0.5° grids so that a relative homogeneous density network can be obtained and to find a rainfall figure representative of synoptic scale rainfall. This is a similar method employed by Engelbrecht *et al*., (2013) when investigating the contribution of closed upper tropospheric lows to rainfall.

Tropical low pressures have a general scale of 500 to 1000 km (Engelbrecht, *et al.,* 2013), therefore a 21 by 21 point, 0.5° grid is assigned to every NCEP grid point (Fig. 3.4.1). This results in a 10° area representing the rainfall in every NCEP grid point which is located in the centre. This represents an area of approximately 1000 by 1000 km, which is in fact a very large area. In figure 3.4.1, “a” represents each 0.5° area and “B” the centre of the NCEP grid point. The maximum rainfall amount measured by any of the rainfall stations in each area “a” are then used as the representative value for that specific grid. Figure 3.4.2 shows the NCEP grid points where the 5° radius around the grid point falls into the borders of South Africa and rainfall data is available. For some of the grid points (red stars in Fig. 3.4.2) only the southern extremes of the 10° area falls into the borders of South Africa and a limited number of rainfall stations are available for analysis. Only grid points that had at least ten days with rainfall were considered.

	0.5°	1°	1.5°	2°	2.5°	3°	3.5°	4°	4.5°	5°	5.5°	6°	6.5°	7°	7.5°	8°	8.5°	9°	9.5°	10°
0.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
1°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
1.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
2°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
2.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
3°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
3.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
4°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
4.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
5.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
6°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
6.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
7°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
7.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
8°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
8.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
9°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
9.5°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a
10°	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a	a

B

Figure 3.4.1: A 21 by 21 point grid illustrating the rainfall data distribution around each NCEP grid point (represented by the orange block) point with a 5° area surrounding the point at an interval of 0.5°. "a" denotes the area where the maximum daily rainfall found in the 0.5° block represents the rainfall for that area, while "B" represents the position of the NCEP grid point in the centre of the NCEP rain area.

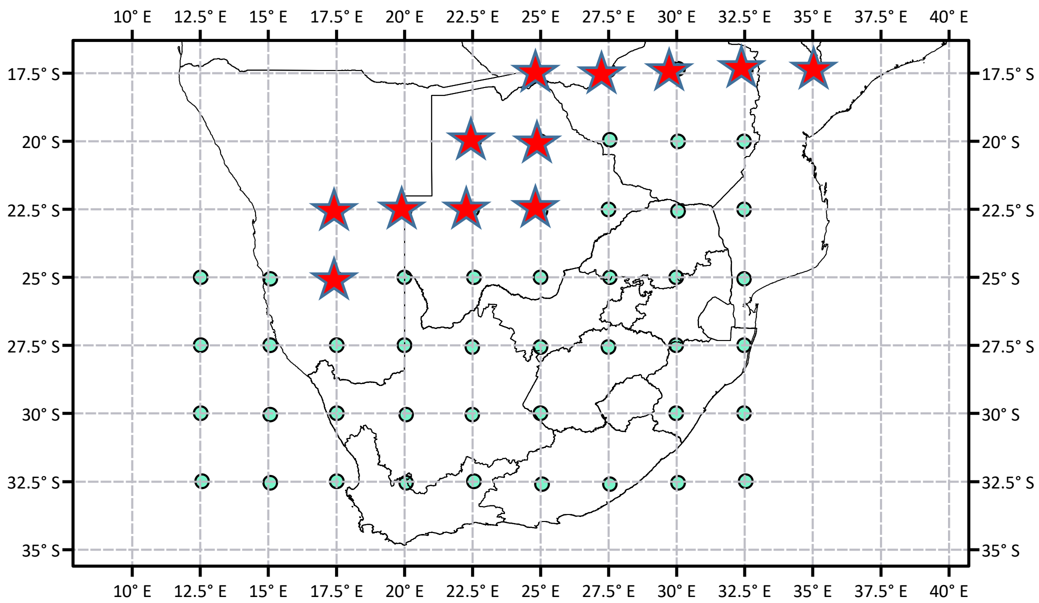


Figure 3.4.2: NCEP grid points for which rainfall data from the South African Weather Service is available. Blue circles indicate the NCEP grid points where there is an adequate amount of rainfall data available, while the red stars indicate the NCEP grid points where the rainfall data availability is limited.

The NCEP data used to identify CTLs are available in 6-hr intervals (see Section 3.5) and 4 possible CTLs could be identified for every grid point in a 24-hr period (referred to as a CTL event). Rainfall data is only available once a day at 08:00 SAST and the temporal resolution of the two data sets had to be consolidated. The CTL events were grouped per day with each day starting at 08:00 SAST (day 1) and continuing until 08:00 SAST on the following day (day 2). The CTL events that occur in a 24-hr period prior to 08:00 SAST on day 2 are grouped together and termed a CTL day. There could be a number of CTL events that form part of one CTL day. The location of the CTL is assigned to the relevant NCEP grid point and the rainfall value for each area "a" (Fig. 3.4.1) is then obtained for each CTL day.

The rainfall for each CTL day is calculated. The average rainfall per NCEP grid point for all CTL days was calculated as well as the maximum rainfall recorded at each grid point for any CTL day. Rainfall extremes are calculated and compared to the long term rainfall extremes. A detailed discussion on the rainfall characteristics of CTLs is provided in Chapter 5.

3.5 Atmospheric Circulation Data

CTLs generally have a scale of 500-1000km (Engelbrecht *et al*., 2013) and NCEP reanalysis data (Kalnay *et* al., 1996), which has a horizontal grid resolution of 2.5° (approximately 250km) and a vertical resolution of 17 levels, adequately resolves these synoptic weather systems. NCEP reanalysis data has previously been used to describe synoptic scale weather systems over South Africa. Engelbrecht *et al*., (2015) used this data to identify synoptic weather patterns that affect the Cape South coast while Malherbe *et al*., (2012) identified landfalling tropical cyclones over southern Africa.

In this dissertation, daily, six-hourly NCEP data for the period December 1979 to March 2018 (only December to March months) was used in order to objectively identify CTLs. The variables used were zonal and meridional wind, temperature and geopotential and specific humidity was used to calculate precipitable water as per equation (2). Other variables calculated were relative vorticity using equation (5), average column temperature and TSE using equation (1).

3.6 Summary

In the section above, a brief explanation of the data that is used in this study is provided. Also, a comprehensive description detailing the process of determining the climatology of CTLs is given. This is a process that consists of four main criteria that need to be met. Once all of the criteria are met for a certain grid point, the grid point under investigation is recognised as being the position of a CTL. The method in which the rainfall contribution of CTLs to South Africa is also briefly discussed in this section.

Chapter 4

Climatology Results

The methodology used to objectively identify CTLs over southern Africa is thoroughly discussed in Chapter 3. In this section, the results of the objective identification method are used to create a climatology of these weather systems over southern Africa. Forming part of these results will include a discussion of the geographical distribution, seasonal distribution as well as some statistical analysis on the seasonal climatology.

4.1 Geographical distribution of Continental Tropical Low pressures

Using reanalysis data from the National Centre for Environmental Prediction (NCEP) (Kalnay *et al*., 1996), a total number of 2929 time steps (every six hours) satisfied the criteria and were identified as CTL events. This was calculated for the period December 1979 to March 2018 over the area of interest (10-40°S and 10-40°E) and only overland.

The geographical distribution of the total number of CTL events over the entire period for each grid point covering the study area is displayed in Fig. 4.1.1. CTLs occur most frequently over southern Angola and Zambia, where more than 300 events were identified at two NCEP grid point. The number of CTL events steadily decreases further southwards with less than 60 events observed over the South Africa region (south of 22.5°S indicated with a blue block in Fig. 5.1.1). The total number of CTL events over the SA region is 342, with the highest number recorded at a single grid point being 55, over south-western Mozambique/north-eastern Limpopo. The furthest south a CTL ever occurred was 32.5°S, this only took place once on 23 January 2011.

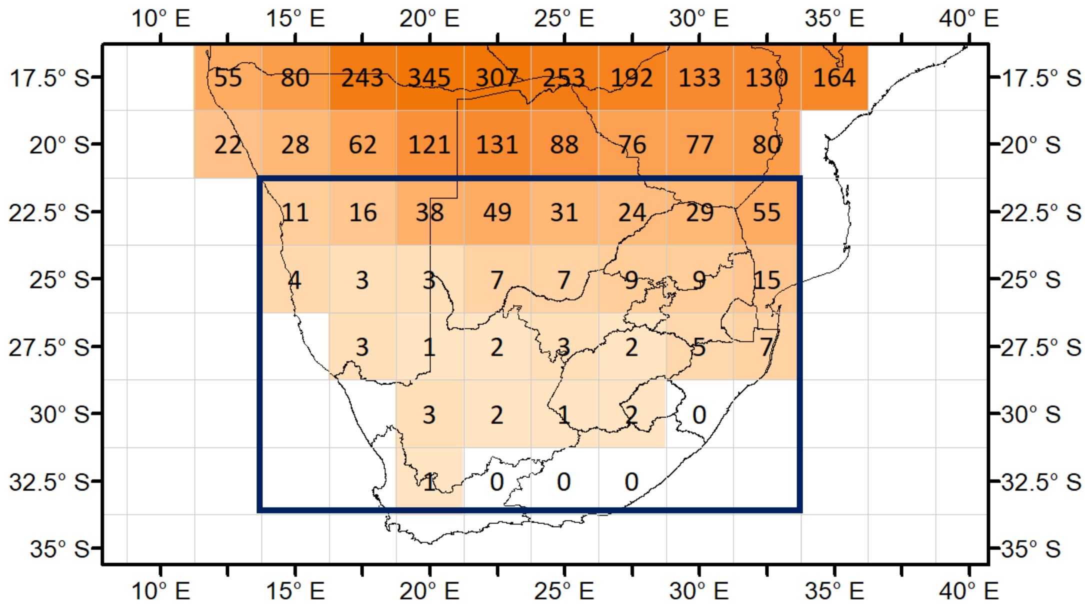


Figure 4.1.1: Geographical distribution of the total number of CTLs identified over southern Africa with the block illustrating the area defined as the South Africa region, below 22.5°S.

Considering the entire domain in figure 4.1.1 and the complete period, a total number of 2929 events were identified. This is an average of approximately 732 CTL days (see Section 3.4 for an explanation of a CTL day) which translates to 19 CTL days per year (Table 4.1). For the South Africa region, the area south of 22.5°S, a total number of 342 time steps satisfied the criteria, which represents two CTL days per year. This is considerably less than the contribution further north. There are 19 CTL days per year over the entire region but only 2 over the South African region (Table 4.1).

Table 4.1: CTL events per year for the entire region as well as for the South African region

	Entire Region	**South Africa (south of 22.5°S)**
Total events	2929	342
CTL days	732	85
CTL days per year	19	2

From these results, it is clear that CTLs are rare over the Republic of South Africa and are even less likely to reach the central interior of the country. Instead, these weather systems seem to rather favour the north-eastern parts of the country. When tropical cyclones invade Mozambique from the east and weaken overland they will be identified as CTLs over land and the high occurrence of CTLs in this area is most likely due to weakening tropical cyclones. The average return period of CTLs over the central interior of the country is 78 years, whereas over the northern parts of Limpopo province the return period is a lot lower at five years.

The geographical distribution of CTL events vary slightly per month (Fig. 4.1.2). CTL events occur a lot more frequently over Gauteng from January, while during December months there are very few CTL events and they are more confined to the eastern parts of South Africa (Fig. 4.1.2). These results in echoed in research by Dyson *et al.,* (2015) who also found that between December and January, the atmospheric circulation over Gauteng becomes noticeably tropical. It is uncommon for CTLs to extend south of 22.5°S during December months (Fig. 4.1.2a), while from January (Fig. 4.1.2b), there is a clear increase in events reaching the southern and western interior of South Africa.

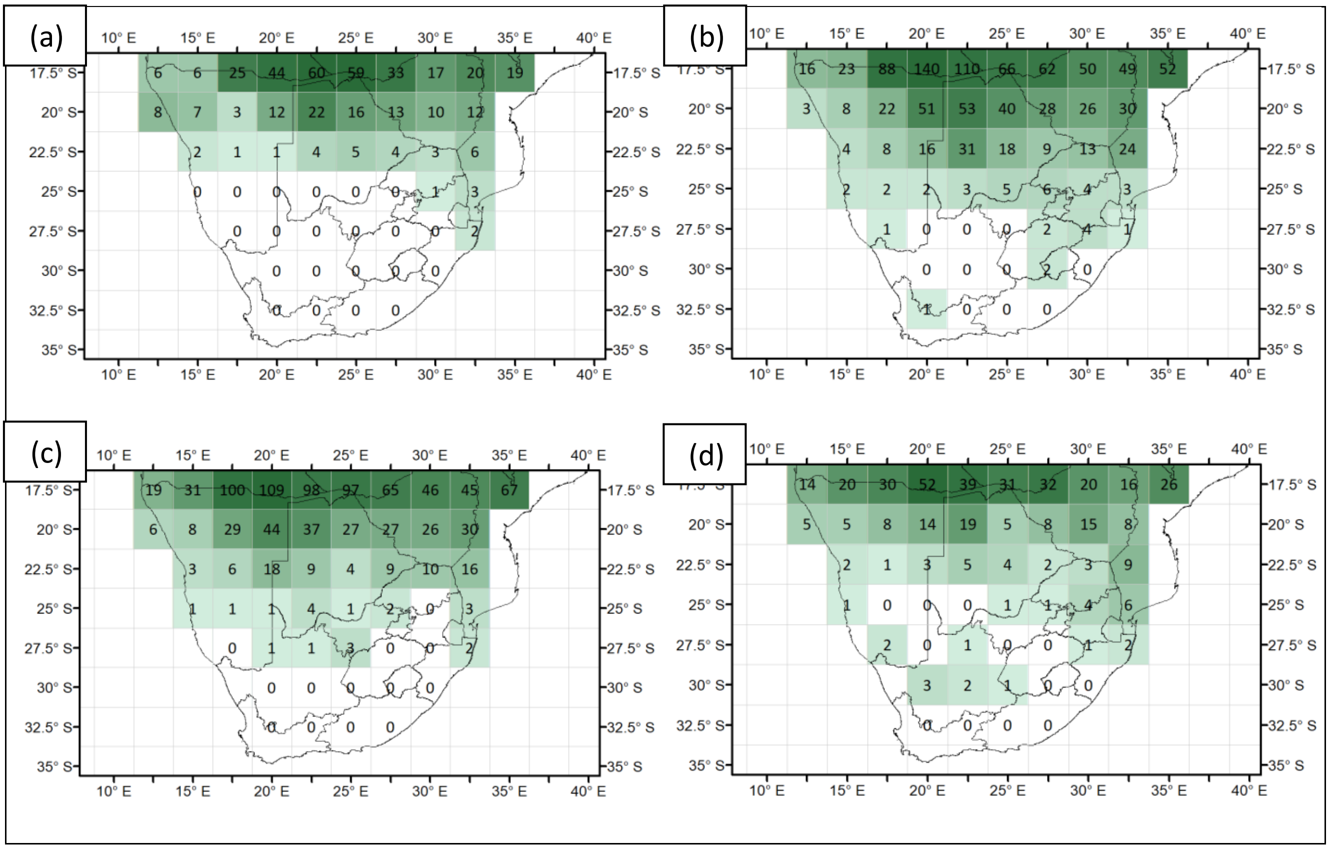


Figure 4.1.2: Geographical distribution of the total number of CTLs identified over southern Africa during (a) December, (b) January, (c) February and (d) March.

During February, CTLs spread further westwards into the northern parts of the Northern Cape in South Africa. A few CTLs still occur over northern KwaZulu-Natal and into southern Mozambique, but the number of events decrease from January months. By March, (Fig. 4.1.2c), the number of CTL events decrease further in the north-eastern parts of southern Africa, while there is an additional increase in events over the western interior of South Africa. This coincides with Taljaard (1996) which indicated how the 50 mm isohyet moved westward over South Africa during the summer rainfall season from the western parts of the Free State in December to the Northern Cape Province by March.

January has the highest number of CTL events (Fig. 4.1.3), with 36% of CTL events occurring during this month, followed very closely by February with 34%. CTL events seldom occur in December (only 15%), and are even less frequent in March with only 14% CTL events occurring during this month.

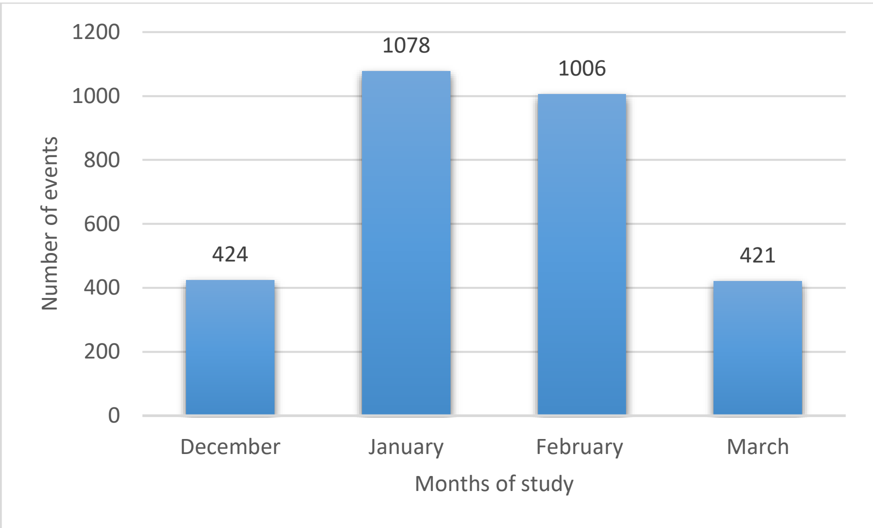


Figure 4.1.3: Graph displaying the total occurrence of CTLs per month (December, January, February and March).

4.2 Temporal characteristics of Continental Tropical Low pressures

Further analysis on the temporal characteristics of CTLs were investigated by calculating the number of CTL events per time step (Fig. 4.2.1). If there was more than one CTL at a certain time step, that time step would only be counted once. It was found that the highest frequency of CTLs occurs at 18Z, followed closely by 00Z. However, unlike mesoscale convective complexes (MCCs), that display nocturnal characteristics (Laing and Fritsch, 1993), these results show that CTLs have no noteworthy difference in the time step frequencies.

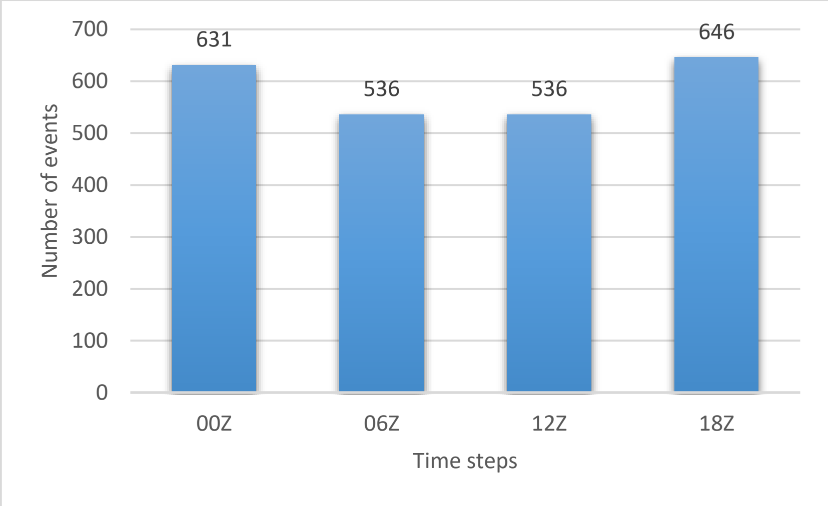


Figure 4.2.1: Graph showing the frequency of occurrence of CTLs at time steps 00, 06, 12 and 18Z.

The life span of CTLs was calculated using the total number of consecutive days a CTL exists. There were 410 days when CTLs lasted for more than one day and the average life span is 2.8 days. By far, the majority of CTLs exist for less than 3 days (Fig. 4.2.2), with only three existing for more than 13 consecutive days. The highest number of days a CTL existed for was 19, this was a recent event that occurred between 3 and 21 January 2017. The other two cases where a CTL existed for more than 13 days were February 2000 and January/February 2014 where each of these CTL cases lasted for 16 days.

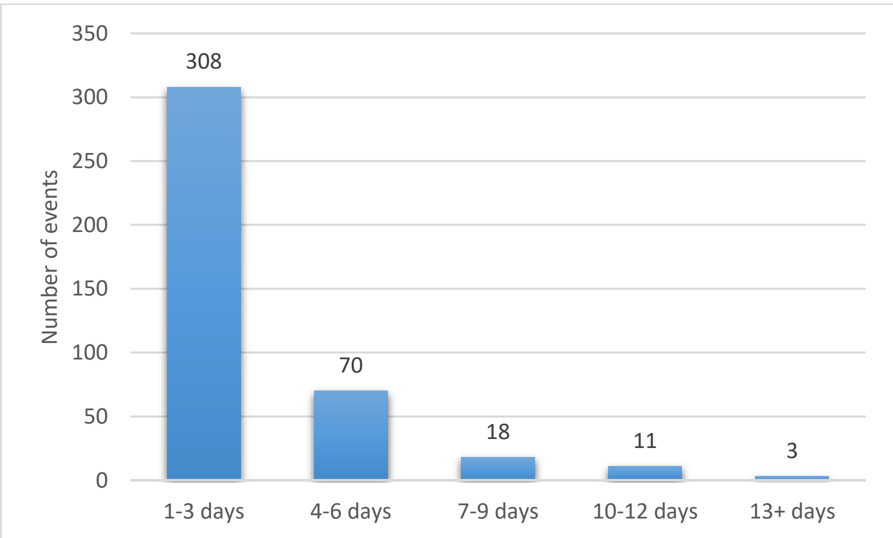


Figure 4.2.2: Graph showing the number of consecutive days a CTLs existed per threshold of 1 to 3 days, 4 to 6 days, 7 to 9 days, 10 to 12 days and more than 13 days.

4.3 Seasonal Distribution of Continental Tropical Low pressures

Table 4.3.1 shows the CTL events per season over the entire domain, with each season from December to March. On average, 75 CTL events occur each season. The majority of these events transpire during January with an average of 28 CTL events, followed very closey by February with 26 events. December and March have the same average number of events of 11.

The 1999/2000 season had the highest number of CTL events with 197. Every month during that season, except December, had an above average number of CTL events, most of which occurred in February (100). In February 2000 floods occurred over north-eastern South Africa, when tropical weather systems moved over Mozambique and into the north-eastern parts of South Africa, causing devasting floods on two separate occasions during the month (Dyson and van Heerden, 2002). The previous season 1998/99 had the 2nd highest number of CTL events and in this instance all the months had an above normal number of events but the number of events more evenly distributed through the season. Another season with an exceptionally high number of CTL events were 2016/17 when 145 events occurred. This season followed the exeptionally dry 2014/15 and 2015/16 seasons over the summer rainfall areas of South Africa (Botai *et al.,* 2016). During 2016/17 only March had a below normal number of events with January month receiving 87 CTLs.

The lowest number of CTL events in a season occurred during the 1985/1986 season with only 4 events and according to Richard *et al.,* (2001) rainfall over the summer rainfall areas of South Africa was well below normal during this season. During the drought of 2014/15 and 2015/16 (Botai *et al.,* 2016) the number of CTL events were far below normal with all the months in these seasons receiving below normal number of events. From the 1983/1984 season to the 1986/1987 season, three of the lowest CTL event seasons occurred. These seasons coincided with below normal rainfall over southern Africa (Richard *et al.,* 2001). Overall, there is an average of 75 CTL events per season.

Table 4.3.1: The number of CTL events from the 1979/1980 season to the 2017/2018 season. The totals and averages for each month are provided as well as the total for the season. Yellow blocks indicate the lowest three CTL seasons with the green blocks indicating the highest three CTL seasons.

Season	December	January	February	March	Seasonal Total
1979/1980	7	2	9	10	28
1980/1981	6	19	31	3	59
1981/1982	8	15	19	0	42
1982/1983	6	17	21	0	44
1983/1984	8	9	0	3	20
1984/1985	20	25	4	8	57
1985/1986	0	3	1	0	4
1986/1987	4	10	0	1	15
1987/1988	19	6	36	7	68
1988/1989	0	25	62	19	106
1989/1990	7	28	4	4	43
1990/1991	2	47	36	11	96
1991/1992	30	5	0	13	48
1992/1993	32	14	43	14	103
1993/1994	3	51	8	2	64
1994/1995	14	9	39	7	69
1995/1996	7	63	31	12	113
1996/1997	10	59	39	13	121
1997/1998	10	50	39	14	113
1998/1999	32	51	50	20	153
1999/2000	9	44	100	44	197
2000/2001	13	8	35	18	74
2001/2002	7	7	11	10	35
2002/2003	6	17	50	35	108
2003/2004	3	29	44	38	114
2004/2005	13	21	8	3	45
2005/2006	19	47	55	23	144
2006/2007	6	14	29	10	59
2007/2008	35	59	1	6	101
2008/2009	23	30	11	9	73
2009/2010	0	28	29	6	63
2010/2011	2	32	0	4	38
2011/2012	7	43	7	10	67
2012/2013	9	50	16	3	78
2013/2014	14	35	43	10	102
2014/2015	1	19	9	4	33
2015/2016	5	0	12	8	25
2016/2017	19	87	29	10	145
2017/2018	8	0	45	9	62
Average	**11**	**28**	**26**	**11**	**75**

The 2002/2003 season started off with both December and January experiencing far below the average CTL events for those months, however from February, the average CTL events were far above the monthly average for the respective months. During the recent very dry 2015/2016 season (Botai *et al., 2016*), there were only a total 25 CTL events with no events occuring during January. Even more recently, the 2017/2018 season mainly had below normal number of CTL events, however during February, there were almost double the number of average CTL events for that specific month which resulted in the seasonal CTL events only being slightly below the seasonal average.

After further analysis (Table 4.3.2), it has been found that February is the month with the highest number of times when zero events occurred in a season and that overall, February is also the month that had the highest occurrence of CTL events, which was 100 events in a single month. Overall, February also has the highest variation with a standard devation of 21.6. There is an average of 28 and 26 CTL events that occur during January and February months repectively each season, while December and March months both have the same average of 11 CTL events per season. December and March also have the lowest variability with a standard deviation of less than 10 for both months.

Table 4.3.2: The number of CTL extremes per month, including the number of zero CTL events, the highest number of events and the average CTL events per month.

	December	January	February	March
Number of zero CTL events	3	2	4	3
Highest number of CTL events (season)	35 (07/08)	87 (16/17)	100 (99/00)	44 (99/00)
Average CTL events	11	28	26	11
Standard Deviation	9.2	20.7	21.6	9.9

Further analysis on the CTL events per season were conducted where the data was standardized using the long term average and standard deviation. These results are depicted in figure 4.3.1 for the total CTLs per season and in figure 4.3.2 for the individual months. From Table 4.3.1 and figure 4.3.1 it is seen that during the 1980s there was generally a below normal occurence of CTL events. During the late 1990s there was an above normal occurrence of CTL events with their occurences becoming quite variable after that. During the early part of the period, before the 1988/1989 season, there were nine below normal CTL seasons identified (Fig. 4.3.1). However, from the 1995/1996 season, there were five consecutive seasons of above normal CTL events which included the 1999/2000 extreme season. There is nevertheless a clear increase in the number of CTL events during the period 1979 to 2018, as shown by the trend line in Fig. 4.3.1. The individual months also show an increasing trend overall (trend lines in Fig. 4.3.2). The Mann-Kendall Test for Significance (Wilks, 2011) was used, with a significance level of 95% and it was shown that these increasing trends were not significant.

In figure 4.3.1, the colour of the bars describe the El Niño-Southern Oscillation (ENSO) phase during the December-January-Febraury period, with the red bar colours indicating warm periods (El Niño) and blue indicating cold periods (La Niña) (Climate Prediction Centre Internet Team, 2018). The black coloured bars indicate the neutral phases. During the entire period, there were a total of 13 El Niño seasons, with 11 of these coinciding with below normal CTL event seasons and only two El Niño seasons occurring during above normal CTL event seasons. There were a total of 13 La Niña seasons, of which 6 corresponded with above normal CTL events.

The effect ENSO has on southern Africa is that usually during El Niño events, below normal rainfall amounts occur while during La Niña events, above normal rainfall is received (Lyon and Mason, 2007 and Crétat *et al.,* 2018). This is not always true as is the case of the 1997/1998 season which was a strong El Niño event that landed up being a season where near or even above normal rainfall occurred (Lyon and Mason, 2007). Figure 4.3.1 shows that during this strong El Niño, an above normal amount of CTL events also occurred.

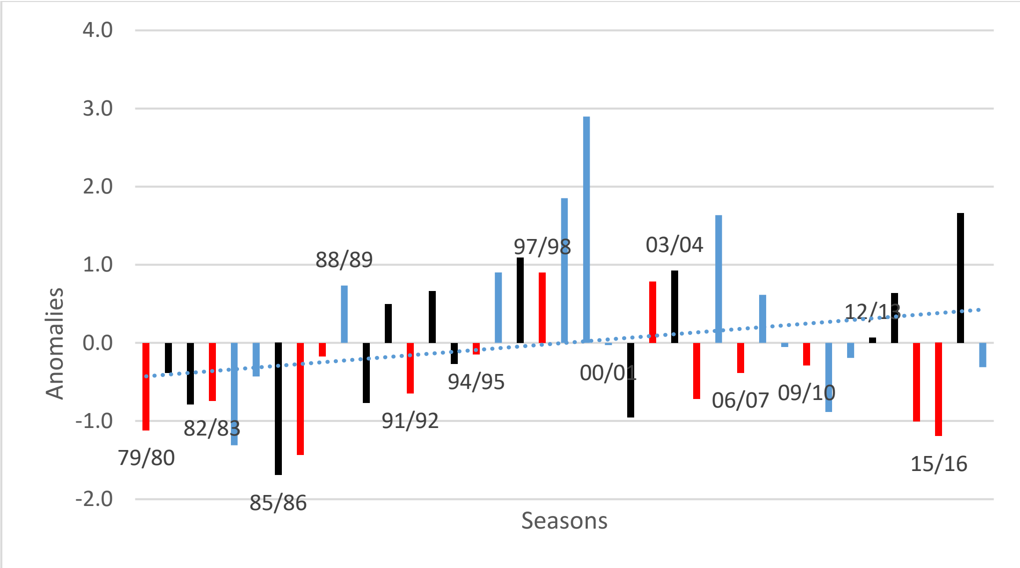


Figure 4.3.1: Standardized CTL event anomalies per season, with the dotted line indicating a trend line. Red bars indicate a warm ENSO period while a blue bar indicates a cold periods.

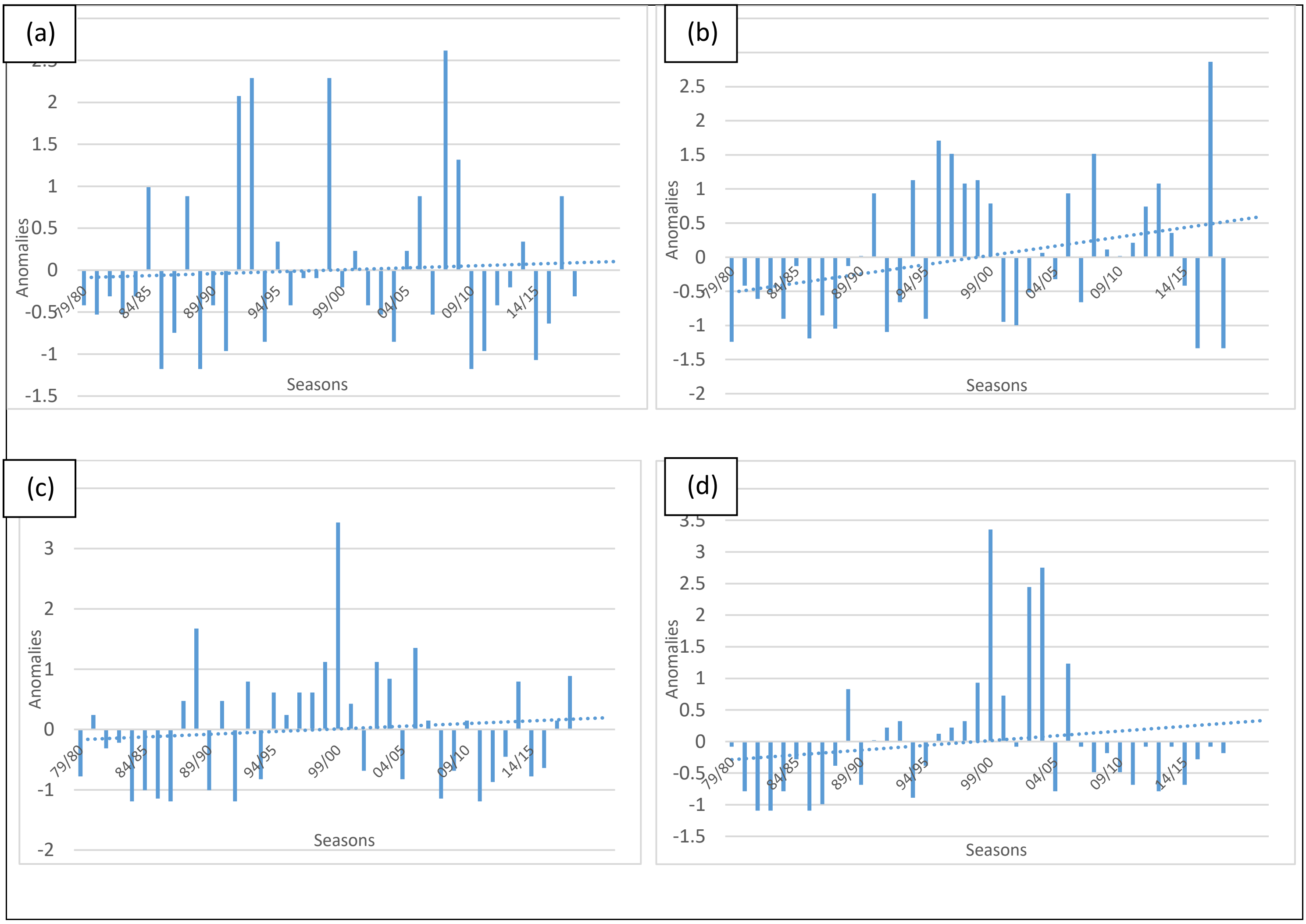


Figure 4.3.2: Standardized anomalies of the CTL events for each season for (a) December, (b) January, (c) February and (d) March.

The correlation coefficient of the standardised CTL seasonal anomalies with the average Oceanic Index (ONI) anomalies (Climate Prediction Centre Internet Team, 2018) show that there is an general negative correlation (Table 4.3.3). The season with the strongest correlation between the CTL events and the ONI is January-February-March, with a correlation coefficient of -0.39. Overall, using an average of all the seasons, from September-October-November to March-April-May, a correlation of -0.36 was calculated. These results were also tested for statistical significance and it is shows that they are statistically significant. This signifies that during warm ENSO events there are fewer CTLs while cold events signifies an increase in CTLs.

Table 4.3.3: Correlation coefficient for the standardised CTL seasonal anomalies with the average SST anomalies for the entire period (overall) as well as for each of the rolling three-month seasons from September-October-November to January-February-March.

Season	Correlation
September-October-November	-0.32
October-November-December	-0.33
November-December-January	-0.37
December-January-February	-0.38
January-February-March	-0.39
Overall	-0.36

4.4 Summary

From the results presented above, it can be stated that overall, the highest occurrence of CTL events is found over southern Zambia and Angola. There is a rapid decrease in CTL events further south towards South Africa with a return period of 75 years over the central interior of the country. CTLs occur most frequently during January months and extend over the central interior of South Africa in March. There is an increasing trend of CTL events over southern Africa, however the trend is not significant. There is also a statistically significant correlation between the stardardised CTL seasonal anomalies and the average SST.

Chapter 5

The influence of Continental Tropical Low pressure on South Africa's rainfall

In the following section, the rainfall contribution CTLs have to South Africa will be presented. This is a continuation of the results given in Chapter 4, as the climatology of CTLs are used to quantify the rainfall contribution using daily rainfall station data supplied by SAWS for the period 1979-2017. Some CTL rainfall features are discussed in this chapter as well as comparisons made with the long term mean rainfall over the study area. In addition, the general rainfall distribution around a CTL is also provided.

5.1 Explanation of daily rainfall values

A total of 2929 CTL events were recognized in Chapter 4. These results provide the CTLs identified per 6 hourly time step, however the SAWS rainfall station data is only available once a day, with the measurement taken at 06Z, therefore the CTL events were grouped per day. A total of 1553 CTL days (CTL events grouped together per day) were identified and fell within the domain where rainfall data is available (Fig. 3.4.2).

As discussed in the methodology in Chapter 3, the rainfall per CTL day is calculated for a 10° region (rainfall area) with the central NCEP grid point being the position of the CTL (Fig. 5.1.1). This will be referred to as the NCEP rain area. One should consider that there is limited availability of rainfall data, especially towards the north of the study area. In figure 5.1.1, the green dots represent the NCEP grid points where some rainfall data is available in the 10° area representing the NCEP rain area (Fig. 3.4.2). Each NCEP rain area (red block) surrounding a NCEP grid point is divided into a 21 by 21 grid of 0.5° resolution, where the station with the highest daily rainfall in the geographical area represented by each 0.5° grid is used to represent the rainfall in that grid. Rainfall could be available in 441, 0.5° grid points in the NCEP rain area (if the rainfall distribution is adequate). The daily rainfall grid values are used to calculate the rainfall contribution of CTLs to South Africa. There is also an overlap of NCEP rain areas for different NCEP grid points as displayed in figure 5.1.1a, where the NCEP rain area with the centre at X_1 overlaps with NCEP rain area with the centre at X_2.

The CTLs that are positioned further south, as in figure 5.1.1a, will have more rainfall stations that contribute towards the total rainfall for each CTL day when compared to the CTL days positioned further north (Fig. 5.1.1b). Even though rainfall values in some of the NCEP grid points outside of South Africa are quite limited, it was decided to include these grids in order to investigate the influence of CTLs on South Africa's rainfall when the CTL is located outside of the borders of the republic. In Fig. 5.1.1b for instance a CTL located over Botswana could influence the rainfall over a vulnerable South African rainfall area bordering Botswana.

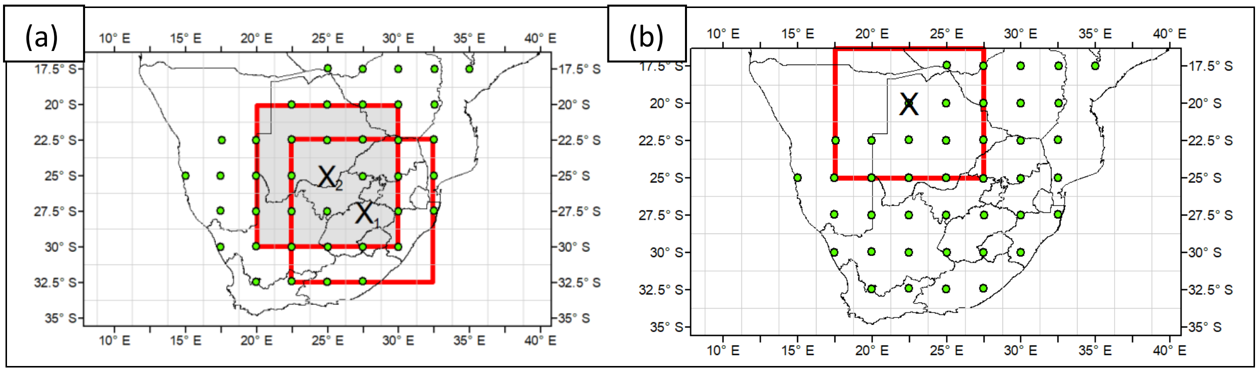


Figure 5.1.1: Red blocks indicate the 10° NCEP rain area for 3 different NCEP grid points. The green dots are NCEP grid points where some rainfall is available over South Africa in the NCEP rain area. NCEP grid points outside the borders of South Africa have rainfall values available only in a fraction of the NCEP rain area while grid points over South Africa have rainfall over the entire rainfall area (a). As an example in (b) only the extreme northern parts of North West Province and western Limpopo will have rainfall values for the particular NCEP grid point. There is an overlap of NCEP rain areas as X_1 represents the centre of a NCEP rain area that overlaps with that of X_2.

In figure 5.2.5 the distribution of the average rainfall of NCEP rain areas are shown as an illustration of the rainfall availability. The X shows that there is no rainfall data available for that specific 0.5° by 0.5° box. There is far less rainfall data available for NCEP rain areas in (h) compared to the NCEP rain areas in (v) and (z).

5.2 Rainfall contribution of Continental Tropical Low pressures to South Africa

a. Seasonal Continental Tropical Low pressure rainfall

The total rainfall for each season is provided in figure 5.2.1. The notoriously strong El Niño event (1997/1998) discussed in Section 4.3, where the rainfall was very close to or even above normal in places, also experienced CTL rainfall during that season that was reasonably high. The highest CTL day rainfall seasons that stand out are the 1987/1988, 1995/1996, 1999/2000, 2003/2004 and 2016/2017 seasons. A discussion of a few of these seasons will be given.

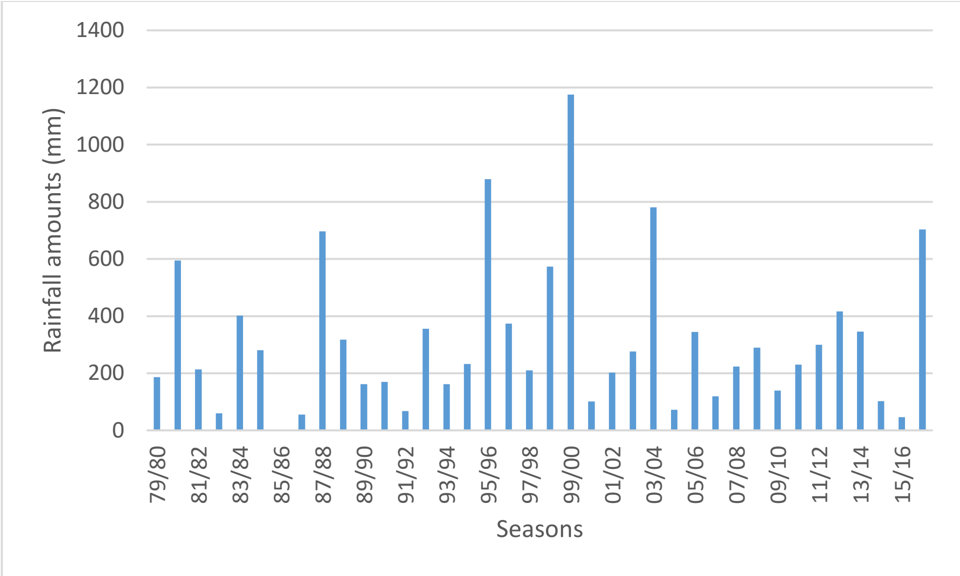


Figure 5.2.1: Seasonal rainfall totals (mm) for each NCEP rain area for every CTL day per season.

The 1999/2000 season was a very active CTL season with the highest number of CTL events ever recorded occurring during this season (Table 4.3.1). During February 2000, tropical cyclone Eline made landfall over Mozambique and moved westwards over the interior of the subcontinent. A CTL was first recognised on 4 February and continued until 19 February 2000. This CTL was the second longest lasting CTL which existed for a total of 16 days but was mainly situated around 17.5°S. The average number of CTL events for the month of February is 26, however during February 2000 an exceptional number of 100 CTL events (Table 4.3.1) occurring during this month. Earlier that year, in January, another long-lasting CTL (12 days) was present and also mainly persisted around the 17.5°S latitude. Even though these events were mainly situated quite far north, they have contributed to the high CTL day rainfall of this season. One can only imagine the true influence these CTLs had to the rainfall contribution over the areas further north of the study area, if this rainfall was available.

The 2003/04 season was a neutral period (Climate Prediction Centre Internet Team, 2018), however the graph in figure 5.2.1 shows that the CTL rainfall during this neutral phase was particularly high. This season had a very slow start in terms of the number of CTL events with December only having 3 events, which is far below the average of 11 (Table 4.3.1).

January had 29 which is very much in line with the norm, however, from February, the CTL events increased rapidly and into March with more than three times the average CTL events for March. The reason for the far above normal CTL rainfall could be that the CTL events were positioned further south during this season, extending in to the north-eastern parts of South Africa and will therefore have more rainfall data available.

The 2016/17 season started off with above normal number of CTL events for December, however, January was an exceptional month that season with more than triple the average number of CTL events for that month recorded. During this month the longest consecutive day CTL also existed, which lasted for 19 days.

Extremely high rainfall amounts occurred during February 1988 (Triegaardt *et al.,* 1991). This was as a result of a CTL which was first identified on 7 February using the objective identification method presented in this dissertation and continued to be observed intermittently until 29 February 1988. At that time, the floods caused by this CTL were considered to be the worst experienced in living memory (Quinn, 1988) with some areas over the central interior of southern Africa receiving between 400 and 600% of the monthly mean rainfall (Triegaardt *et al.,* 1991). The objective identification method for CTLs did not identify a CTL on each day throughout this period. This is due to the criteria that is used in the identification method being so strict.

*b. Monthly Continental Tropical Low pressure **rainfall***

The rainfall for each CTL day was used to calculate the monthly CTL rainfall in order to determine in which month the highest CTL rainfall occurs. The percentage contribution of each month towards the total CTL rainfall is shown in Fig. 5.2.2. The bulk of the CTL rainfall occur in January (Fig. 5.2.2), with 42% of the total CTL rainfall taking place during this month. This result is very much in line with the monthly climatology results (Fig. 4.1.3), which show that January has the highest number of CTL events. Also, similar to the climatology results, where December and March have the fewest CTL events, these months also have the least amount of CTL day rainfall compared to January and February.

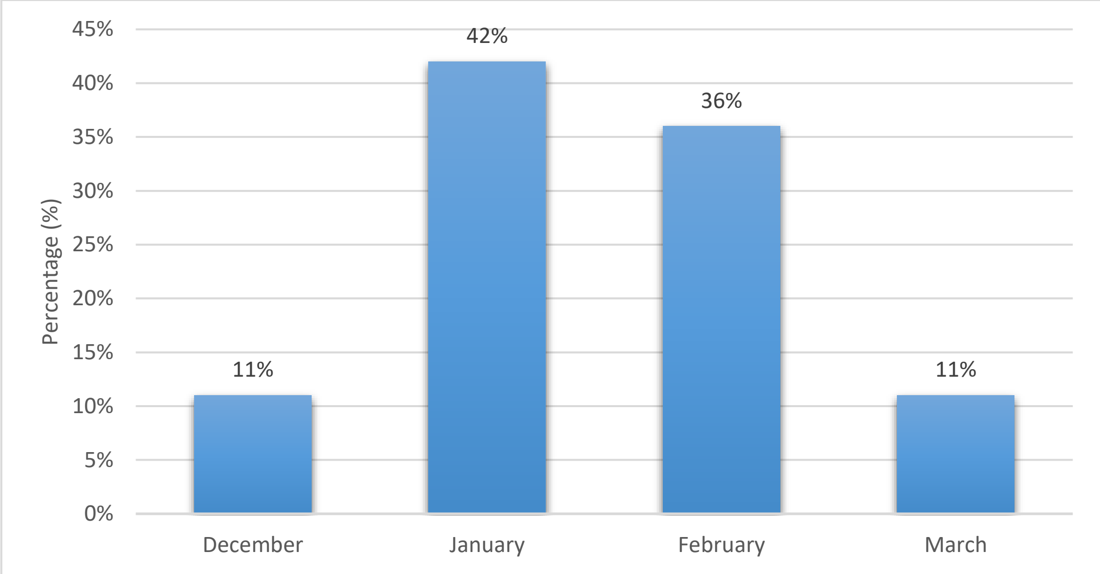


Figure 5.2.2: Frequency (%) of total CTL rainfall for each month.

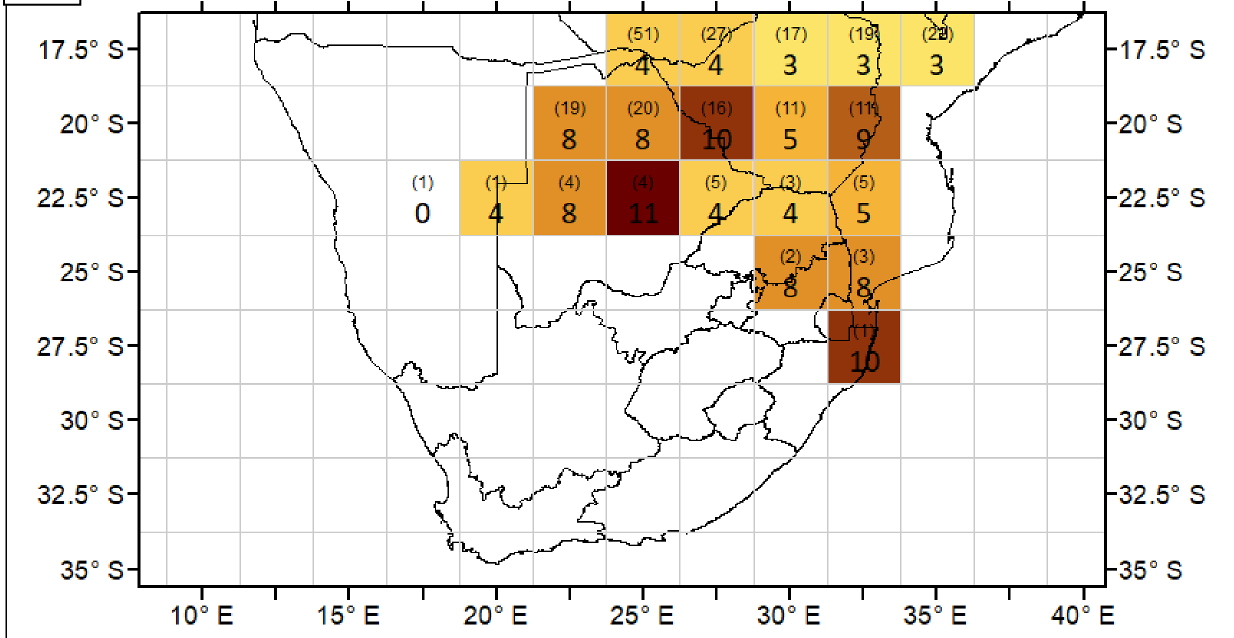
The average monthly CTL day rainfall was used to determine the variation in the geographical distribution of CTL rainfall for each of the months (Fig. 5.2.3). Over South Africa, (south of 22.5°S), the CTL rainfall during December (Fig. 5.2.3a) is very much restricted to the extreme north-eastern parts of the country. The highest average rainfall that transpired in December is 10 mm. This is the average rainfall for only one event, when a single CTL existed over northern KwaZulu-Natal. The NCEP rain area associated with this CTL day, includes a large part of the eastern half of South Africa (Fig. 5.2.5v).

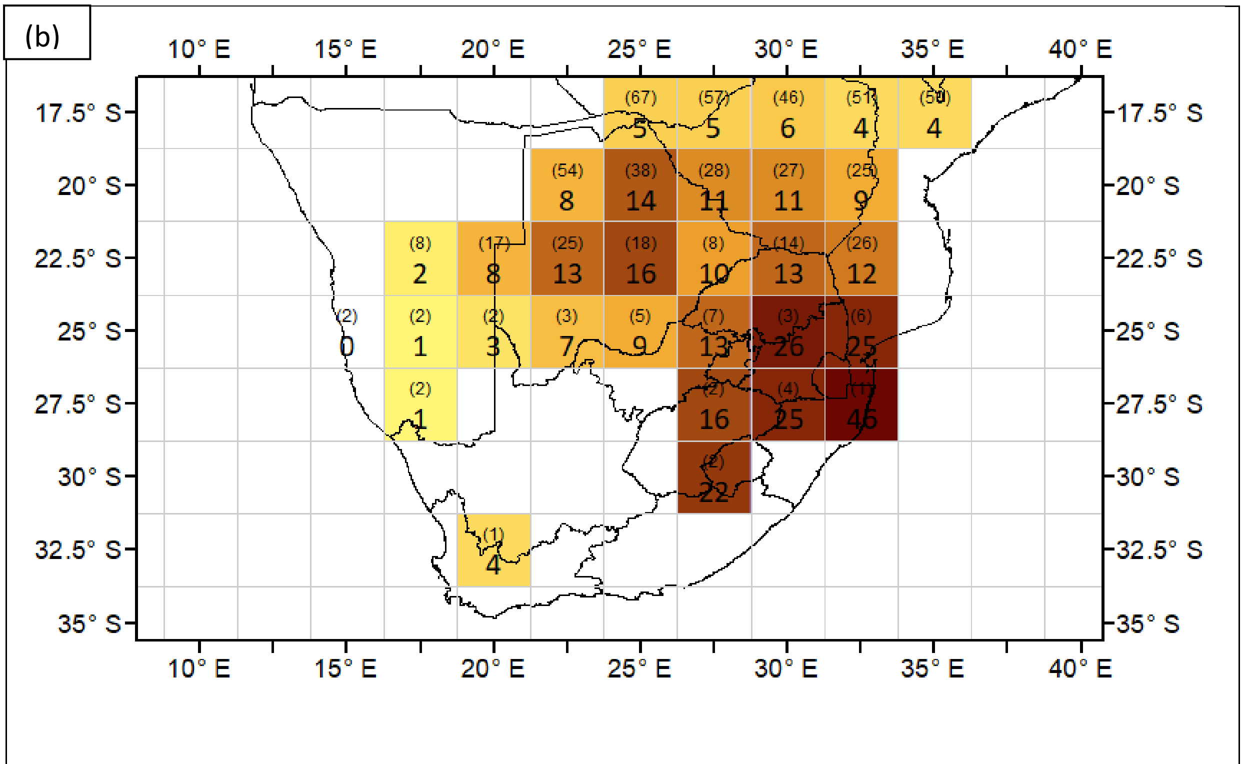
There is a clear change in the rainfall distribution from December to January (Fig. 5.2.3b), where the rainfall extends further south and westwards, however the highest rainfall is still associated with the NCEP grid point centred over northern KwaZulu-Natal. Once again, this was a single CTL day that resulted in the highest average rainfall for January, with an amount of 46 mm. The furthest southern CTL occurred during January, which was a single CTL day that existed over western interior of the Western Cape. This event resulted in an average of 4 mm across the NCEP rain area.

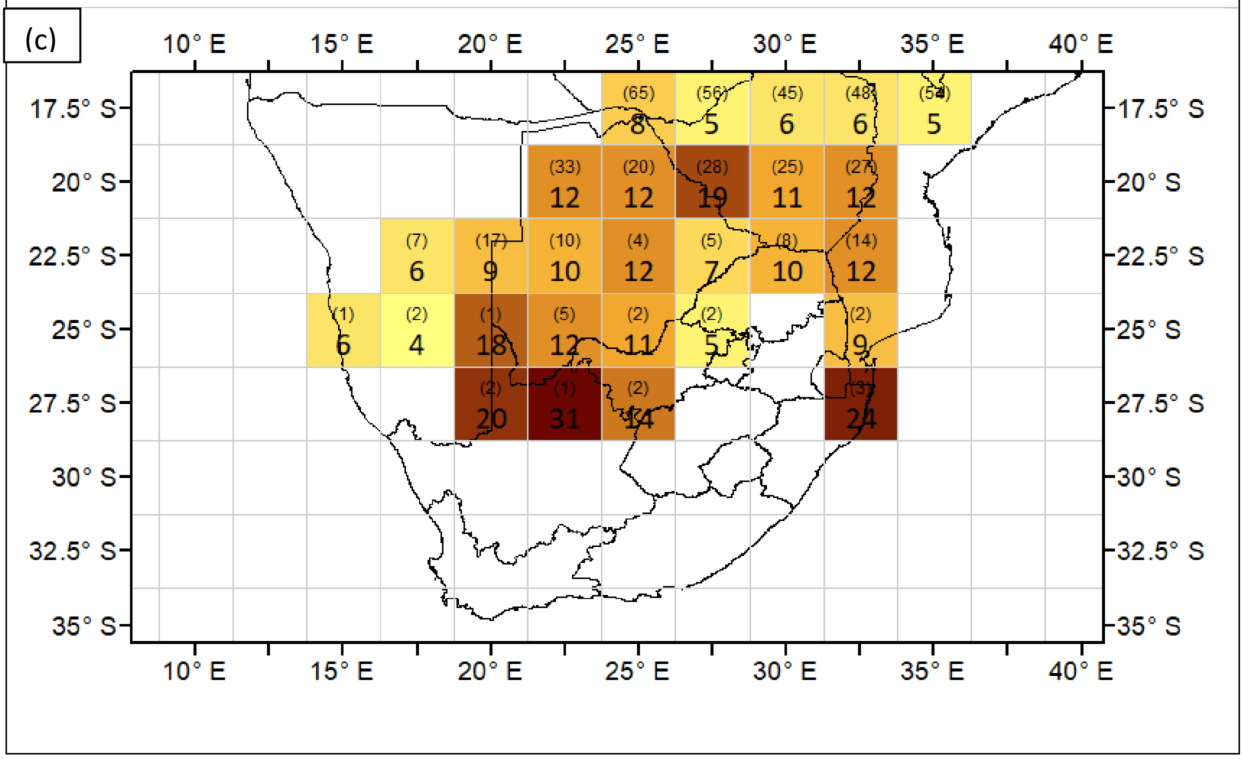
CTLs occur most frequently over the eastern parts of South Africa during January (Fig. 4.1.2b) and it is also noteworthy to mention that the average rainfall in the NCEP rain areas decreases from east to west. This is most probably due to the escarpment that is situated in the extreme eastern parts of the country, in a north-south orientation, which enhances rainfall along the area due to orographic uplift. A further consideration is the proximity to the warm Mozambique Channel which supplies ample moisture for precipitation to occur in the east.

By February (Fig. 5.2.3c), the highest rainfall values shift further westwards and are centred over the northern parts of the Northern Cape. Once again, the highest average rainfall (31 mm) is due to a single CTL day. CTLs are the furthest south during March (Fig. 4.1.2d) and therefore the average rainfall associated with CTLs during March is also far south. The rainfall as a result of CTLs during March stretches across most of South Africa covering the western and most of the eastern parts of the country. The westward shift of the monthly CTL rainfall pattern coincides with the westward advance of the 50 mm isohyet from December to March over South Africa (Taljaard, 1996) as well as with the maximum annual rainfall shift across South Africa (Rouault and Richard, 2003).

(a)




(b)
10° E
15° E
20° E
25° E
30° E
35° E
40° E
17.5° S
20° S
22.5° S
25° S
27.5° S
30° S
32.5° S
35° S


(c)
10° E
15° E
20° E
25° E
30° E
35° E
40° E
17.5° S
20° S
22.5° S
25° S
27.5° S
30° S
32.5° S
35° S

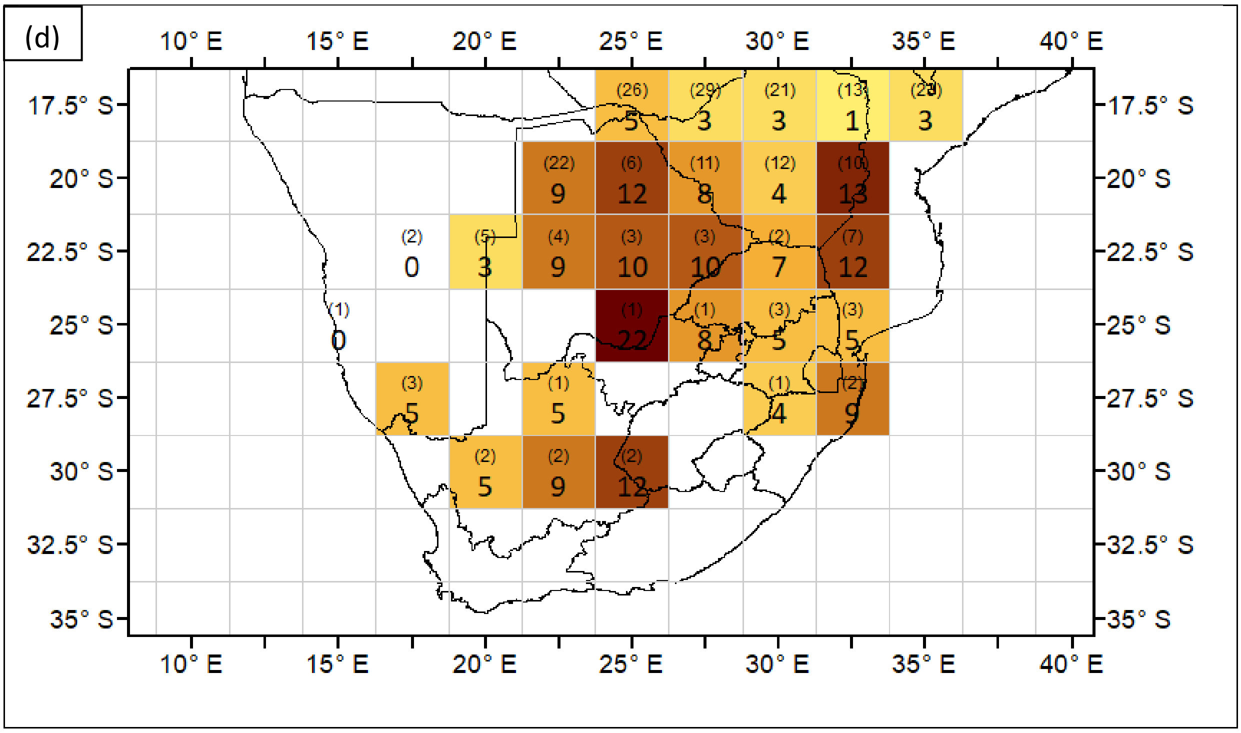


Figure 5.2.3: Geographical distribution of the average rainfall per CTL day with the number of CTL days in brackets above each value for (a) December, (b) January, (c) February and (d) March.

*c. **Average daily** Continental Tropical Low pressure **rainfall***

Over southern Africa (area south of 22.5°), the number of CTL days (amounts in brackets) decrease south and westwards while the average CTL rainfall increases southwards. This is most likely due to the limited rainfall in the areas further north (Fig. 5.2.5a).

In figure 5.2.4a the average daily rainfall for each grid point is shown. This is obtained by calculating the average rainfall for each of the NCEP rain areas per CTL day. For the areas over the southern and south-eastern parts of South Africa, these are left blank as no CTL events occurred at these grids points (Fig. 4.1.1). Over northern Namibia, however, these areas are blank due to there not being any rainfall data available in this area (Fig. 5.1.1).

The average daily CTL rainfall across South Africa is relatively evenly distributed (Fig. 5.2.4a), with the exception of the rapid decrease from east to west. Over the central interior of the country (region indicated with the block in Fig. 5.2.4a), these areas all only had two CTL days, however there is a great variation in the average rainfall across this area. The highest average rainfall amounts are in the northern and eastern parts of the block. This shows that the rainfall as a result of CTLs has a greater influence on the northern and eastern areas of South Africa and less of an effect further south-west, into the Western Cape.

In order to fully appreciate the significance of these results and understand the contribution CTLs have to the rainfall over South Africa, a comparison of the rainfall that occurs during CTLs is made to the long term mean rainfall per NCEP grid point (Fig. 5.2.4b). The long term mean rainfall is calculated in each NCEP rain area for every day during December, January, February and March from 1979 to 2017.

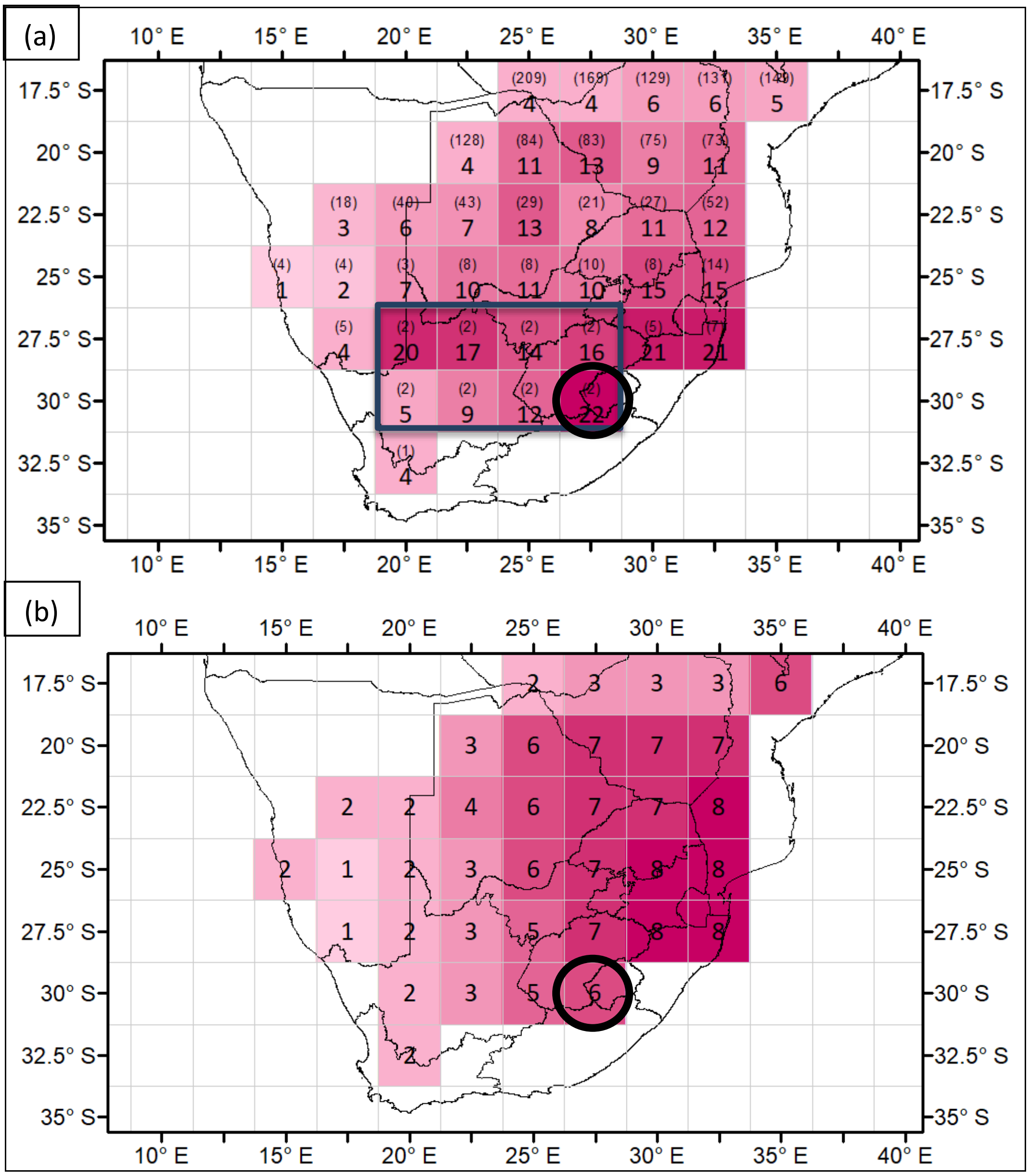


Figure 5.2.4: Geographical distribution of the (a) average rainfall per CTL day with the number of CTL days in brackets and (b) the long term mean rainfall across the region. The highest average CTL rainfall value of 22 mm is circled in (a) with the corresponding grid point also indicated in (b).

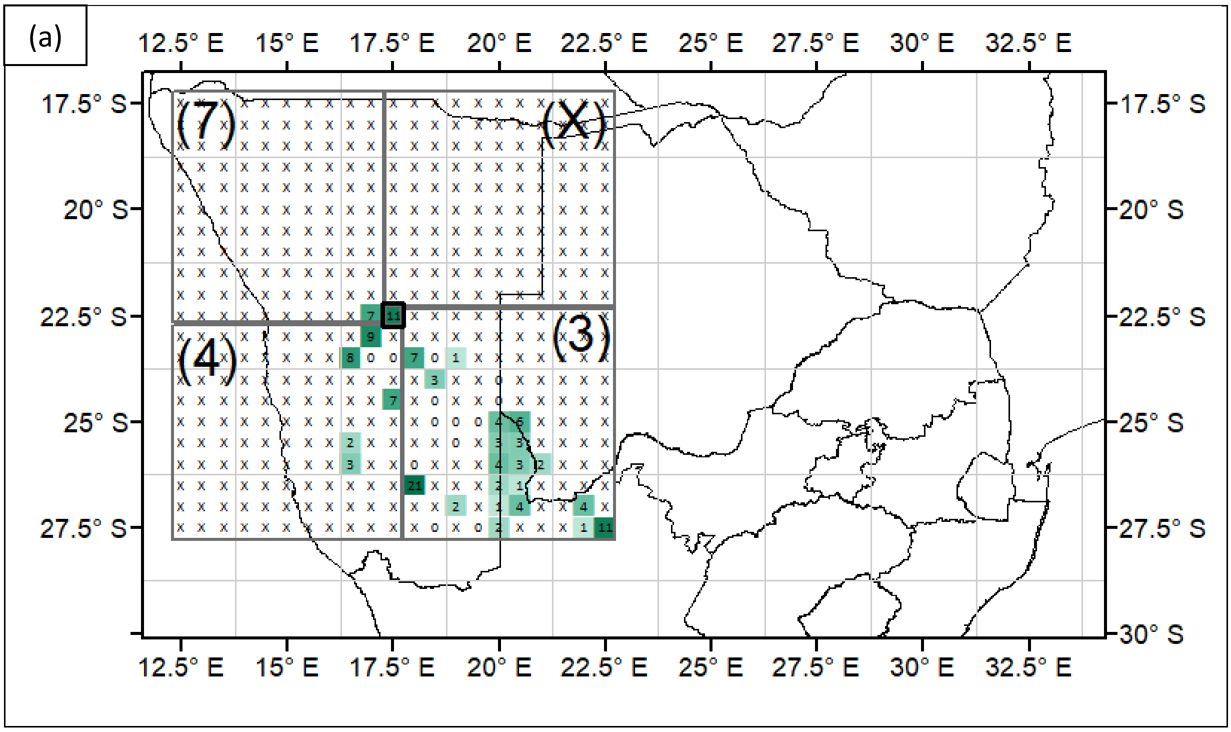
From visual inspection of figure 5.2.4a and b, it can be seen that the average rainfall during CTL days (a) is far higher than the long term mean rainfall (b). Over the entire study area, the average CTL day rainfall is 10 mm per grid point while the mean value is only 5 mm overall. This shows that the rainfall as a result of a CTL clearly contributes to the rainfall over the area.

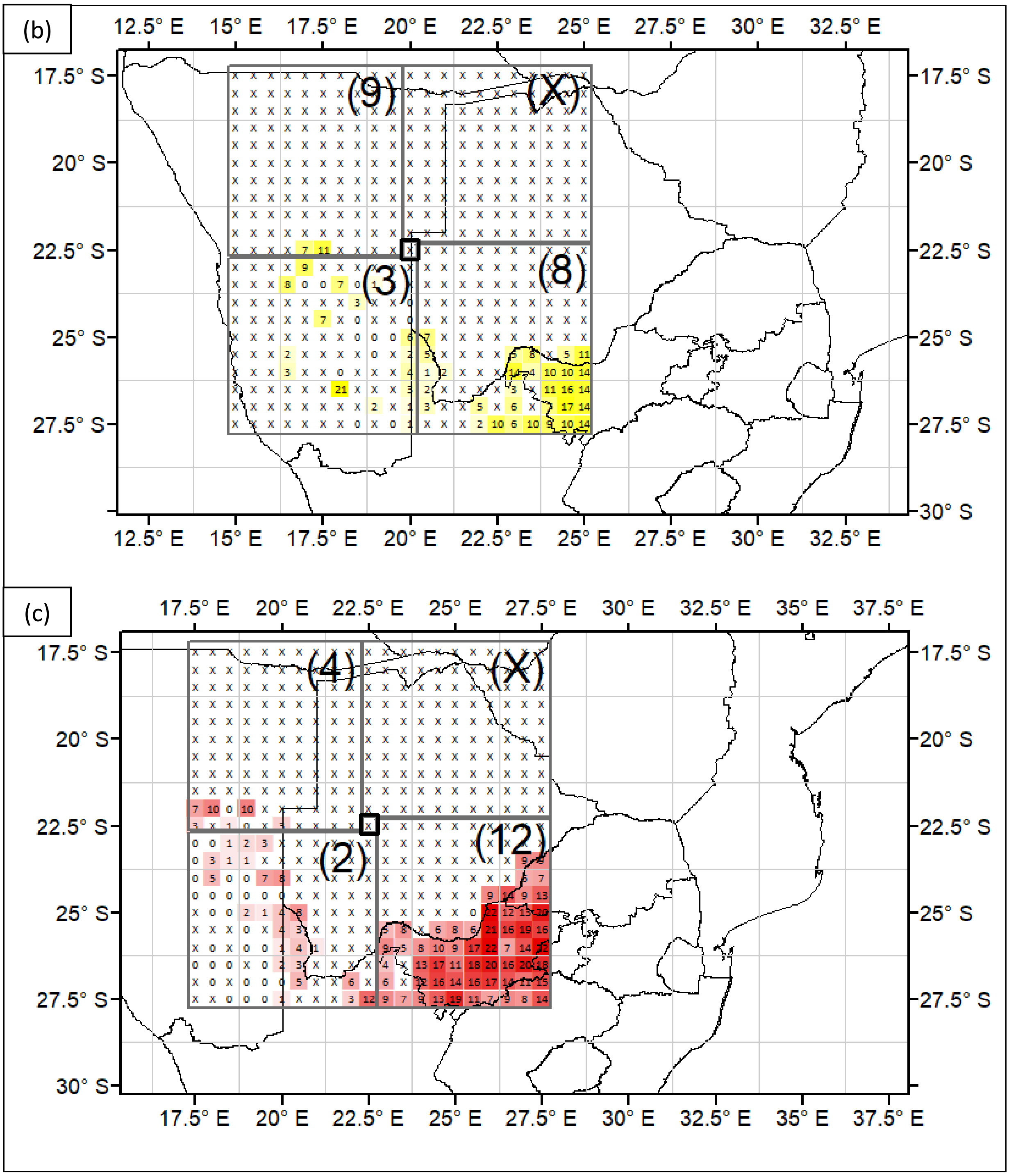
The highest average CTL day rainfall per NCEP rain area is 22 mm (circled), this value is more than 3.5 times higher than the long term mean value (circled in Fig. 5.2.4b) for the same position. The average NCEP rain for this specific point includes most of the eastern parts of South Africa with the distribution of the CTL day rainfall illustrated in figure 5.2.5z. However, one should consider than the average daily CTL rainfall at this grid point was calculated for two days only.

The distribution of the average rainfall varies considerably for each of the NCEP rain areas. It is clear from each of the distributions (Fig. 5.2.5) the moisture source is to the east of the CTL, as the average rainfall visibly decreases from east to west for each of the NCEP rain areas.

For the north-western most grid points (Fig. 5.2.5a-k) there is very limited rainfall data available for the northern quadrants. What is notable is that in figure 5.2.5c, a CTL that is positioned over western Botswana, results in an average of 12 mm of rain mainly across North-West Province in South Africa. What is even more interesting is that over the neighbouring NCEP grid point (Fig. 5.2.5d), situated over central Botswana, the rainfall as a result of a CTL positioned there, causes rainfall to extend all the way onto the Mpumalanga Highveld, approximately 650km away. The influence of topography on CTL rainfall is clearly demonstrated in figures 5.2.5 for the NCEP grid points east of 27.5°E where the higher rainfall amounts are visible along the eastern escarpment of South Africa. When a CTL is positioned over the central parts of southern Namibia, an average of 2 mm occurs over the north-western and central parts of the Northern Cape (Fig. 5.2.5i). There is a substantial increase in the average CTL rainfall over that same quadrant when a CTL is positioned just one grid point to the east (Fig. 5.2.5j). The average CTL rainfall then increases to 9 mm for the area. The rainfall influence as a result of a CTL when positioned over southern Botswana extends as far as the western interior of KwaZulu-Natal (Fig. 5.2.5l).

The highest CTL rainfall in one of the quadrants of the NCEP rain areas is 95 mm. This is for the south-eastern quadrant of NCEP rain area presented in figure 5.2.5u. It needs to be remembered however, that this average rainfall includes the extreme event when tropical cyclone Domoina made landfall in 1984 over northern KwaZulu-Natal. A very interesting observation is when a CTL is positioned over the extreme south-western parts of Limpopo, the rainfall distribution of that CTL includes the entire north-eastern parts of South Africa (Fig. 5.2.5m). The average rainfall as a result of a CTL starts to influence the rainfall of the Eastern Cape when a CTL is positioned from 27.5°S and reaching all the way to the Cape south Coast from 30°S.





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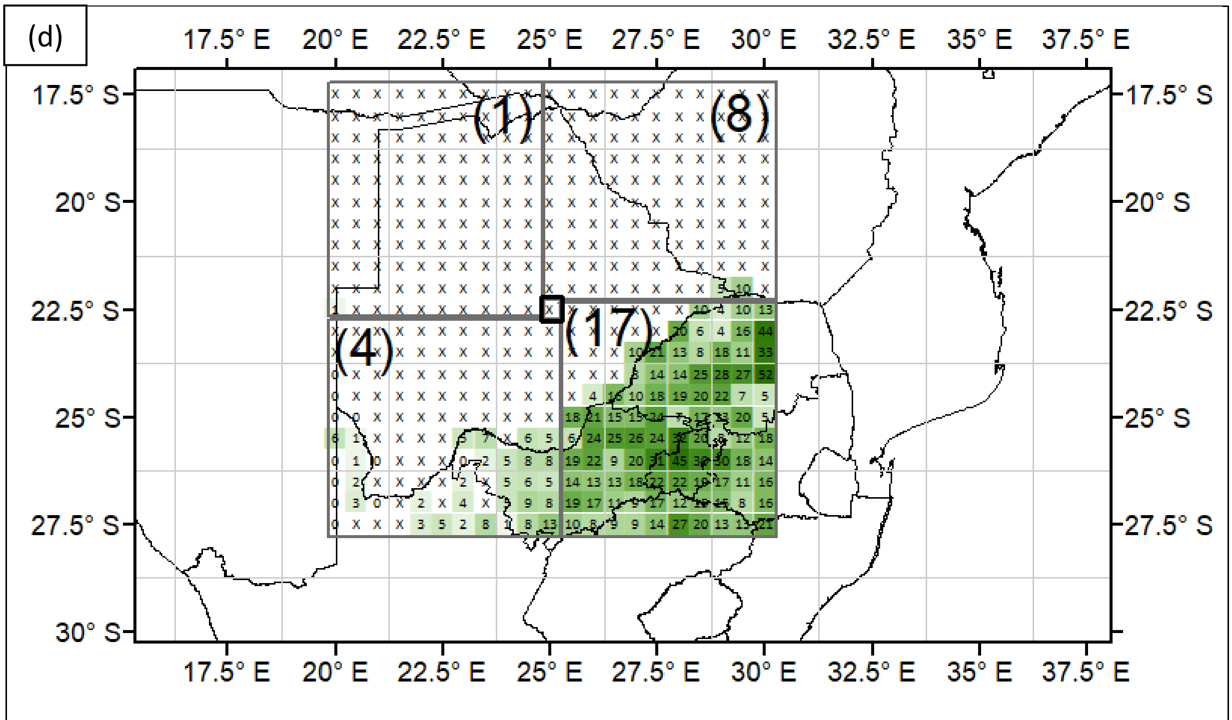
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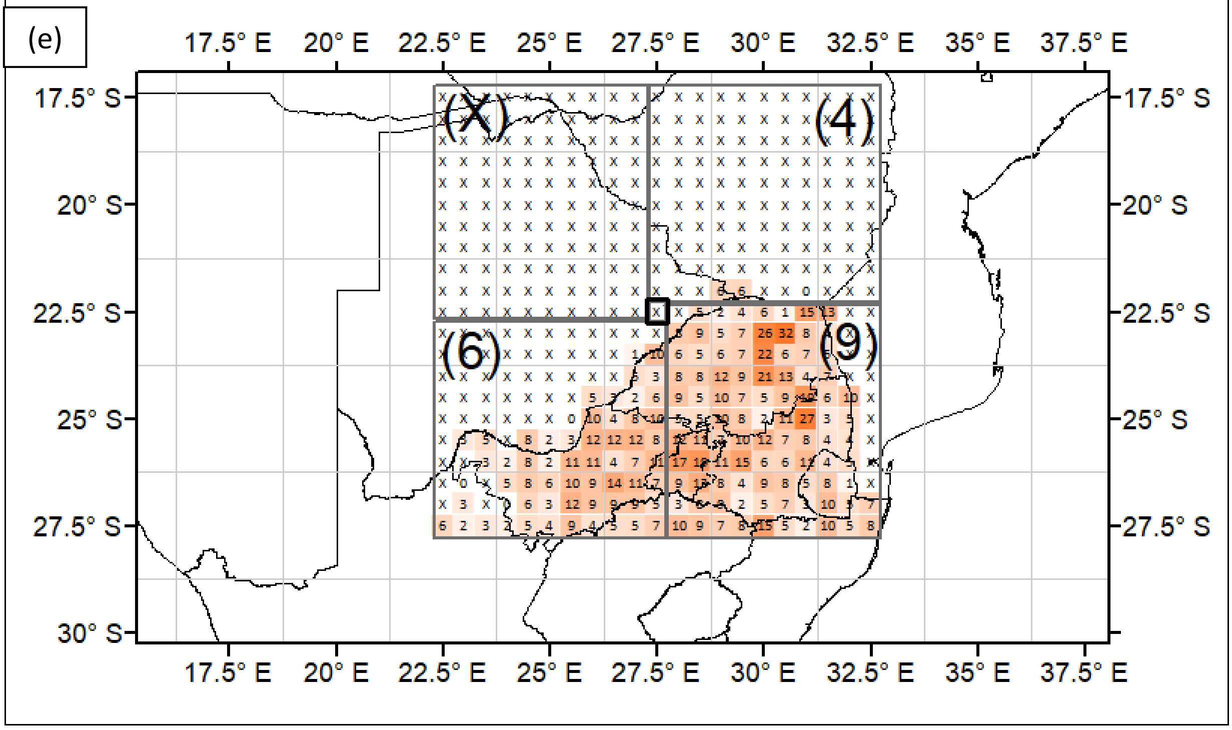
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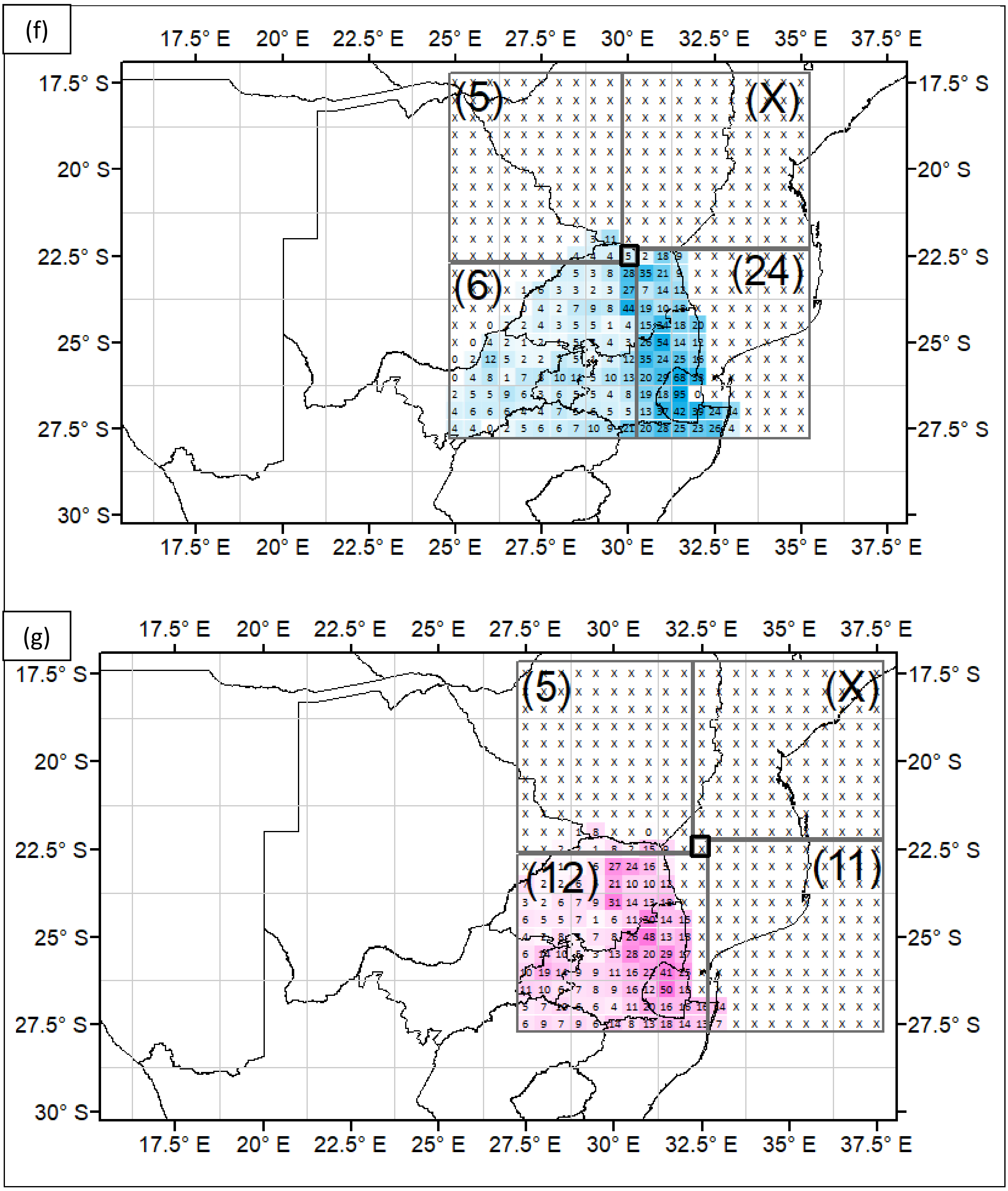

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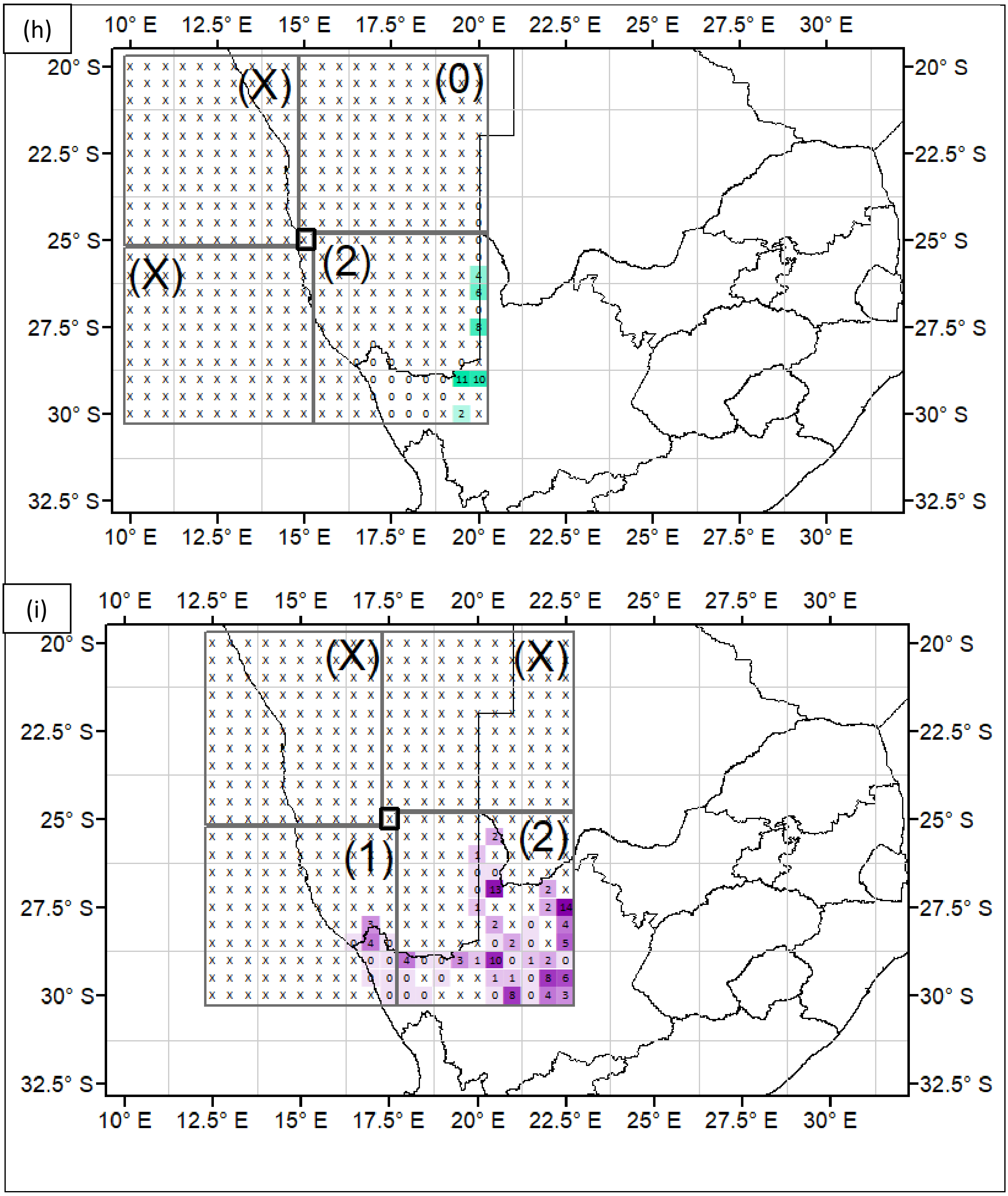
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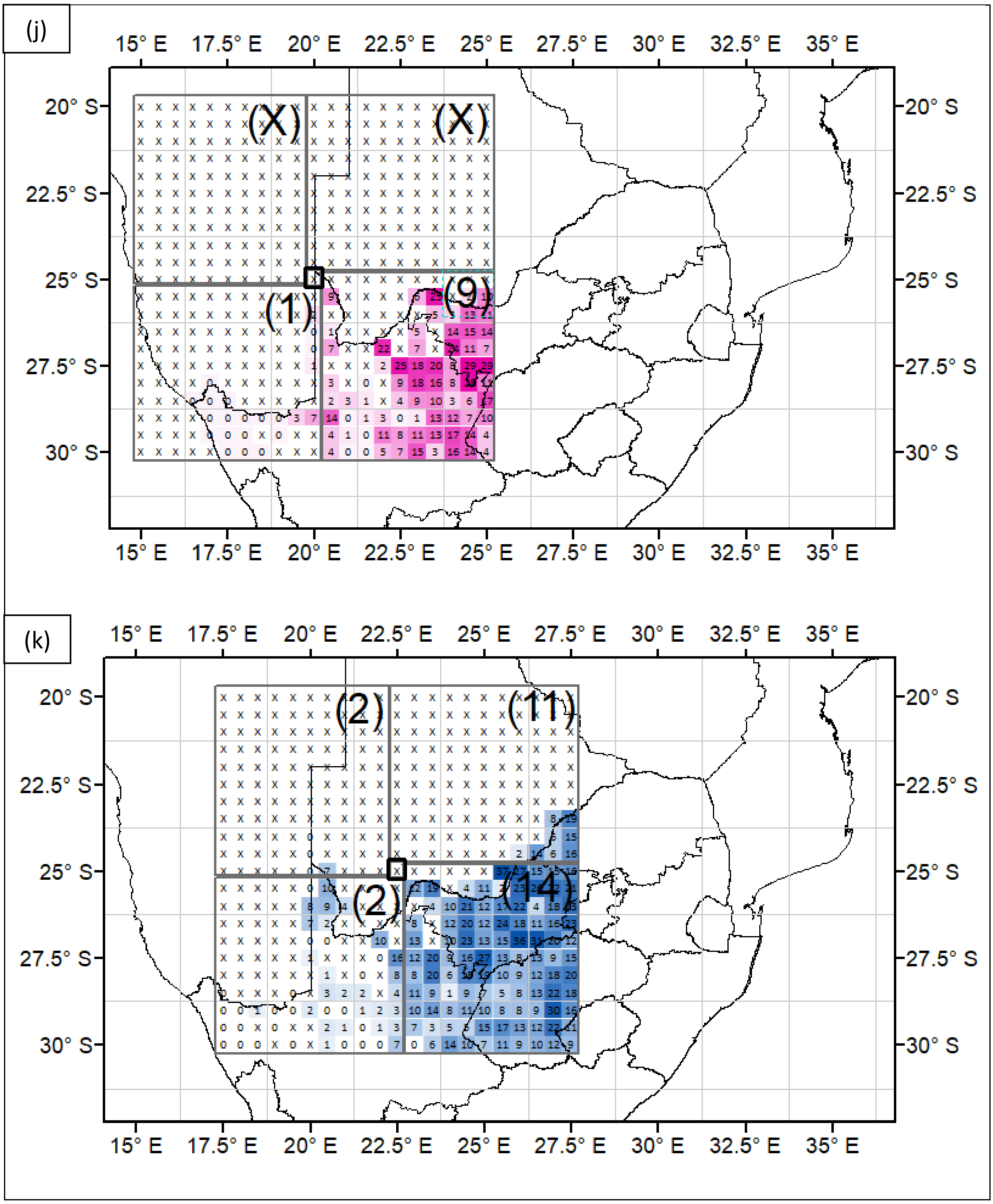
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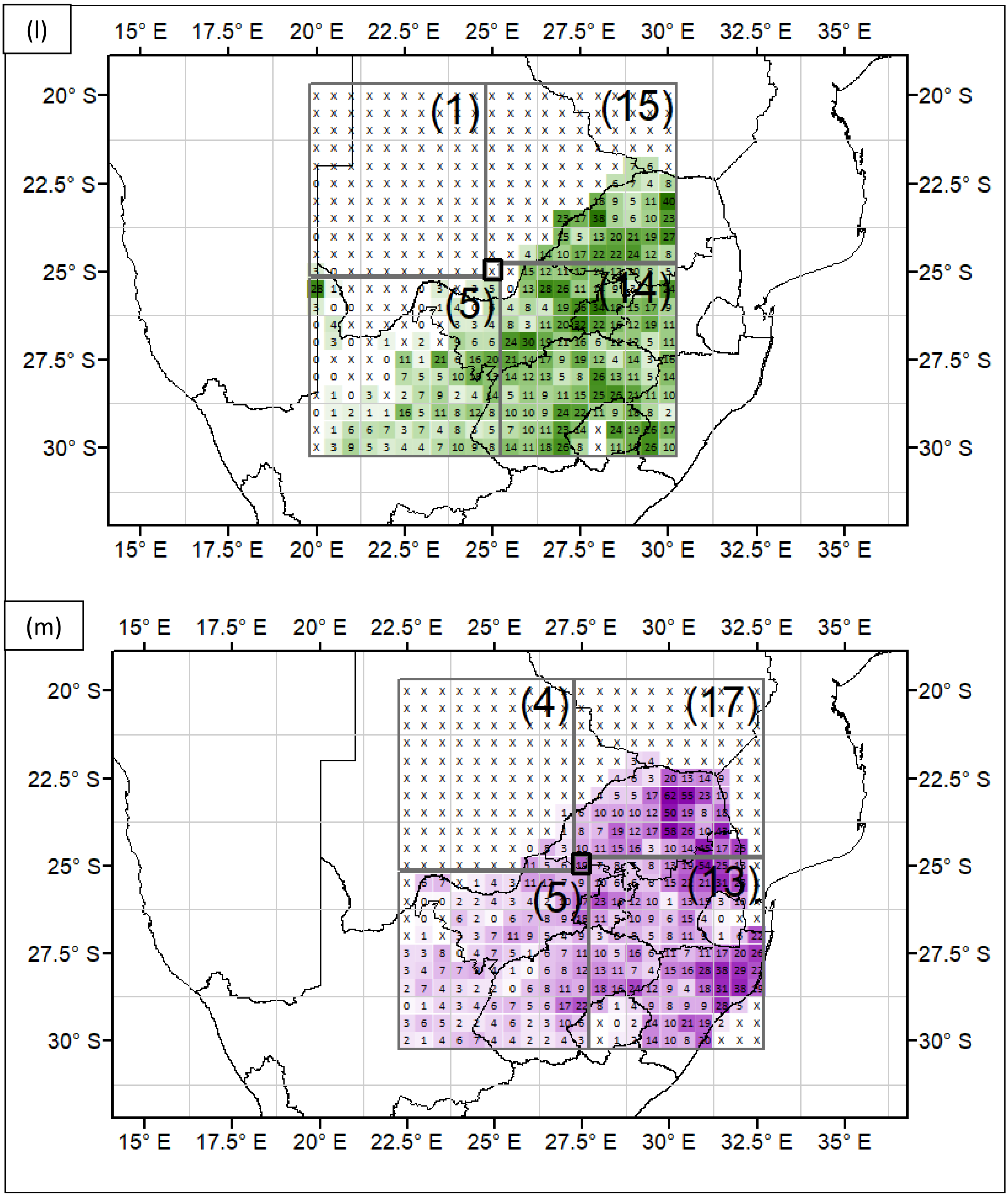
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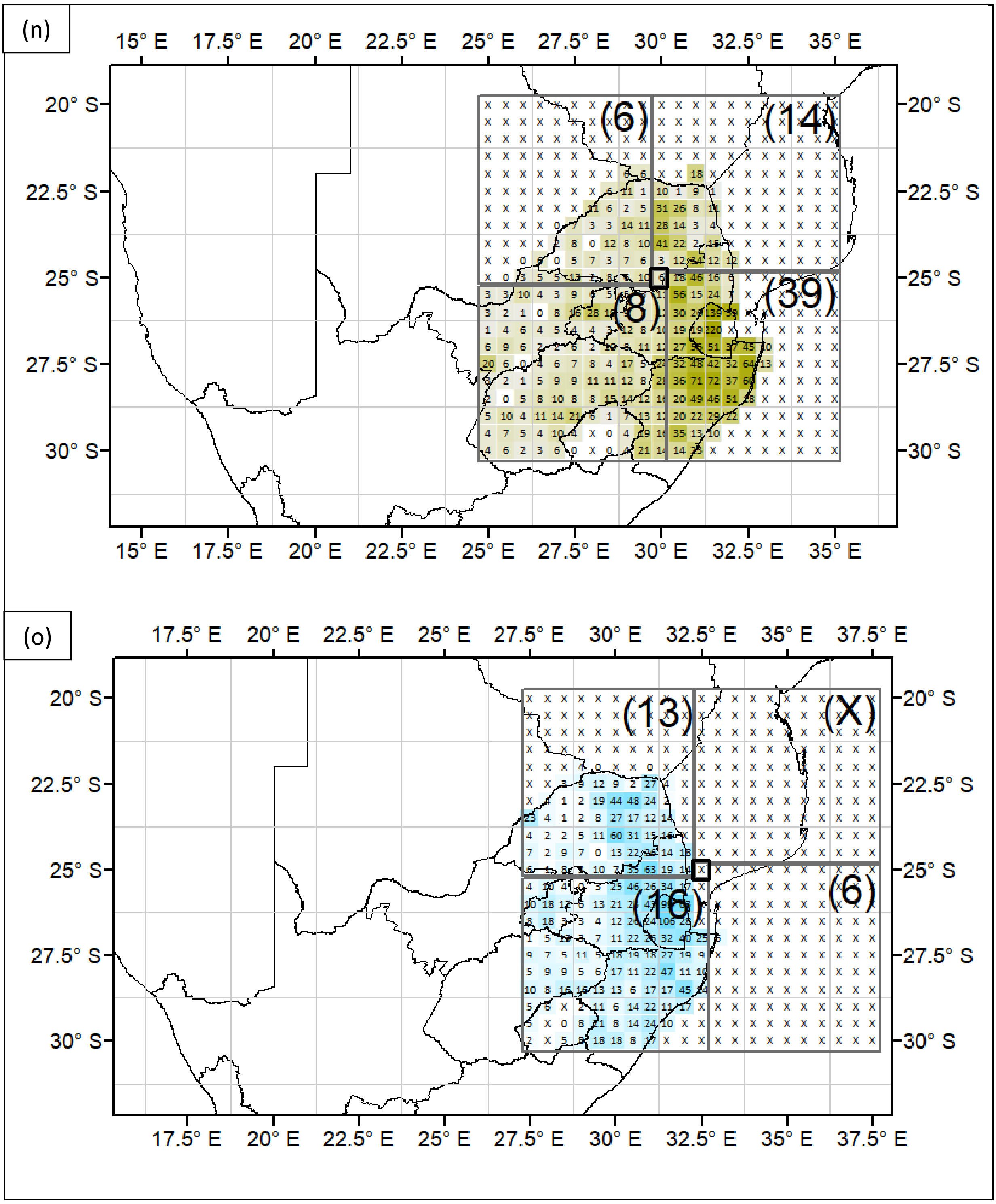
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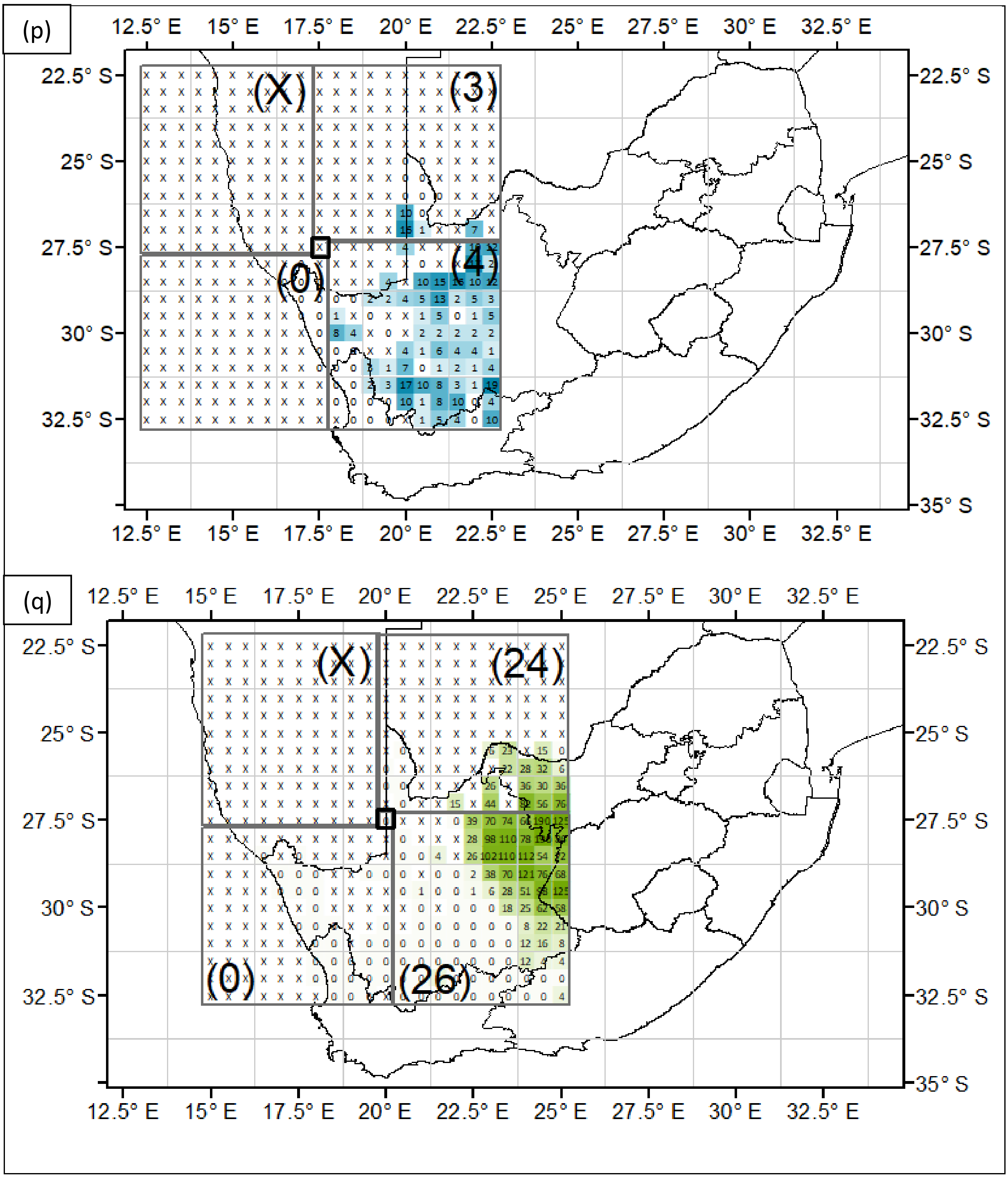
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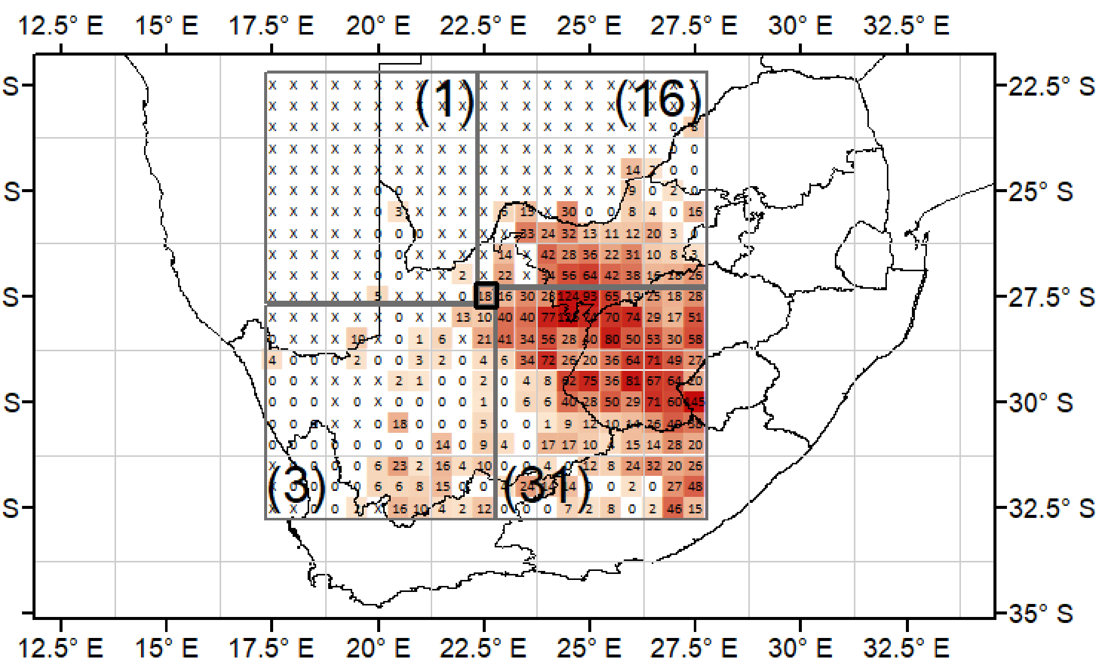
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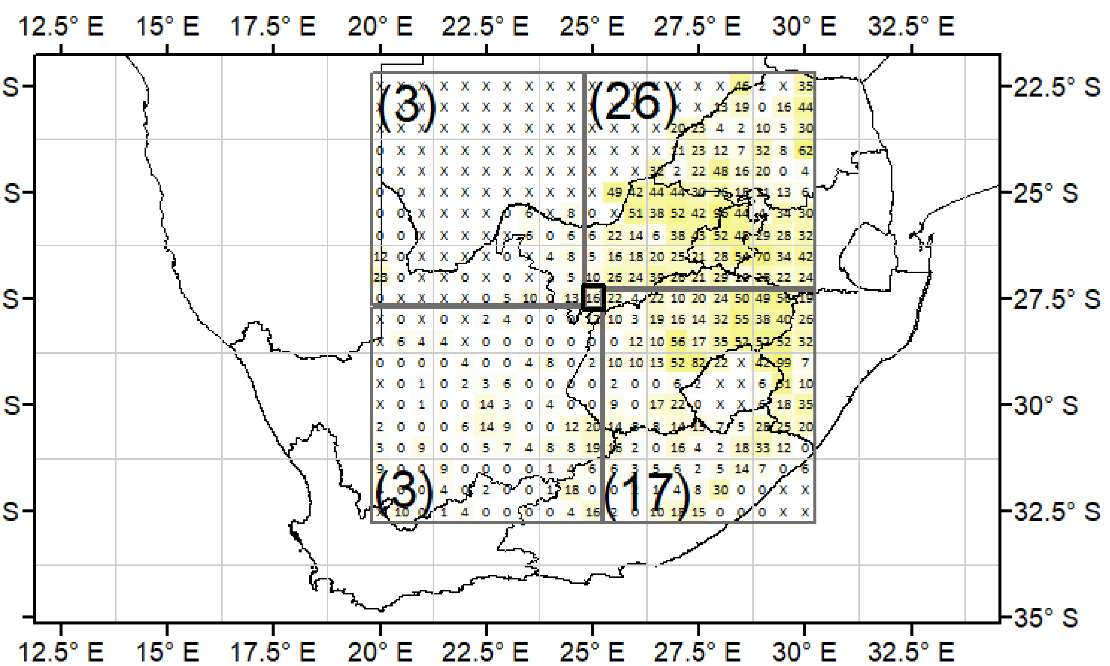
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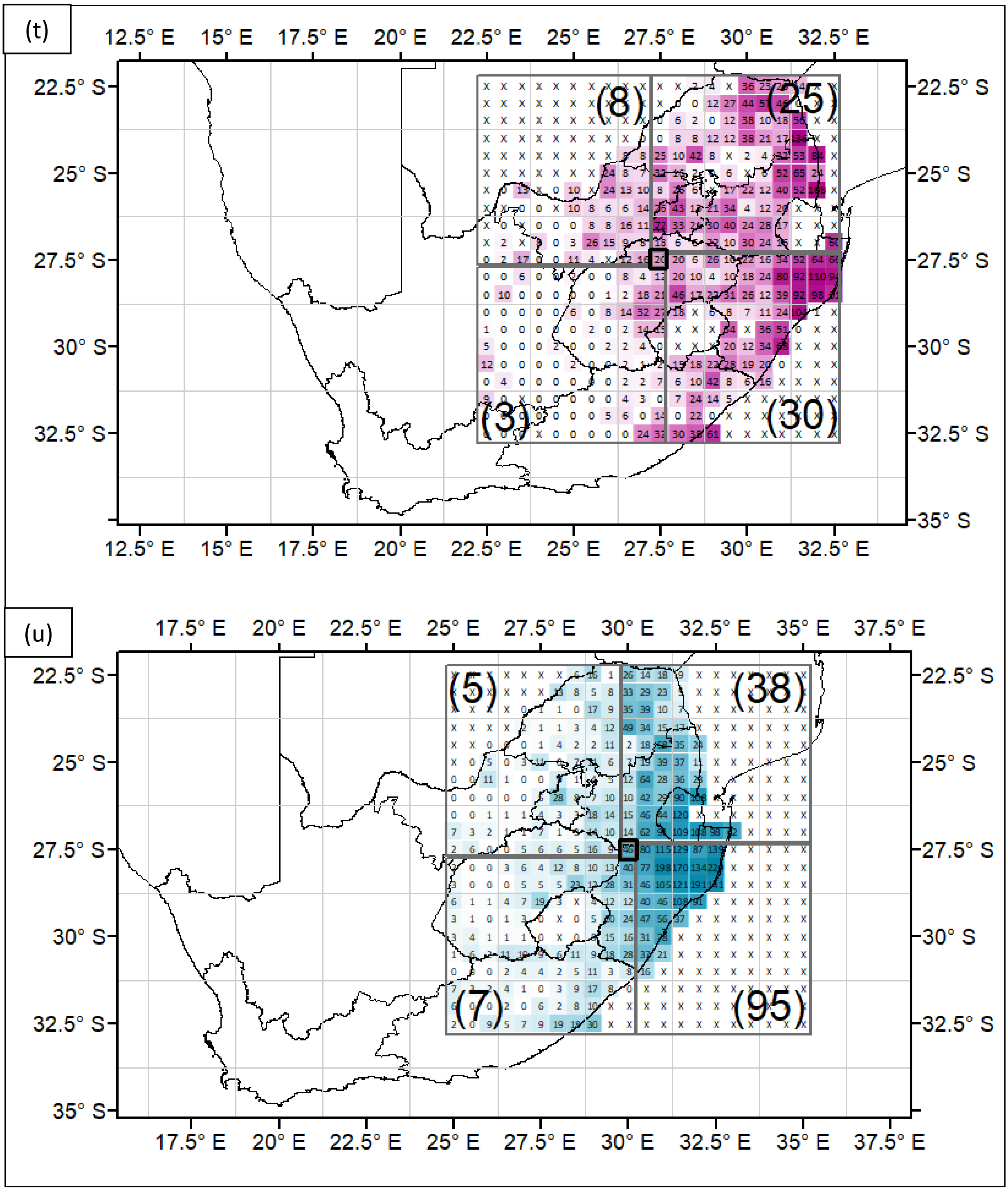
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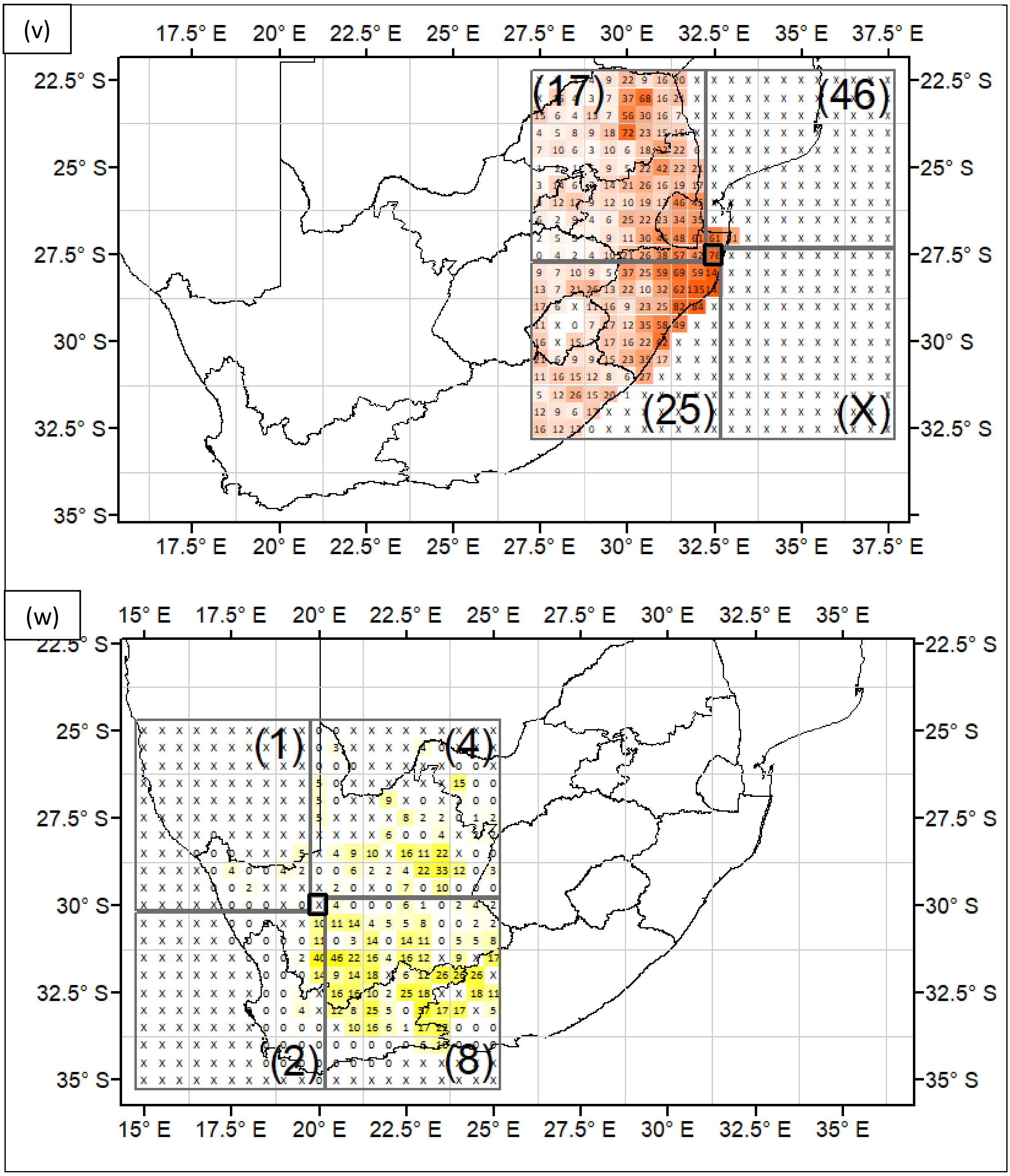
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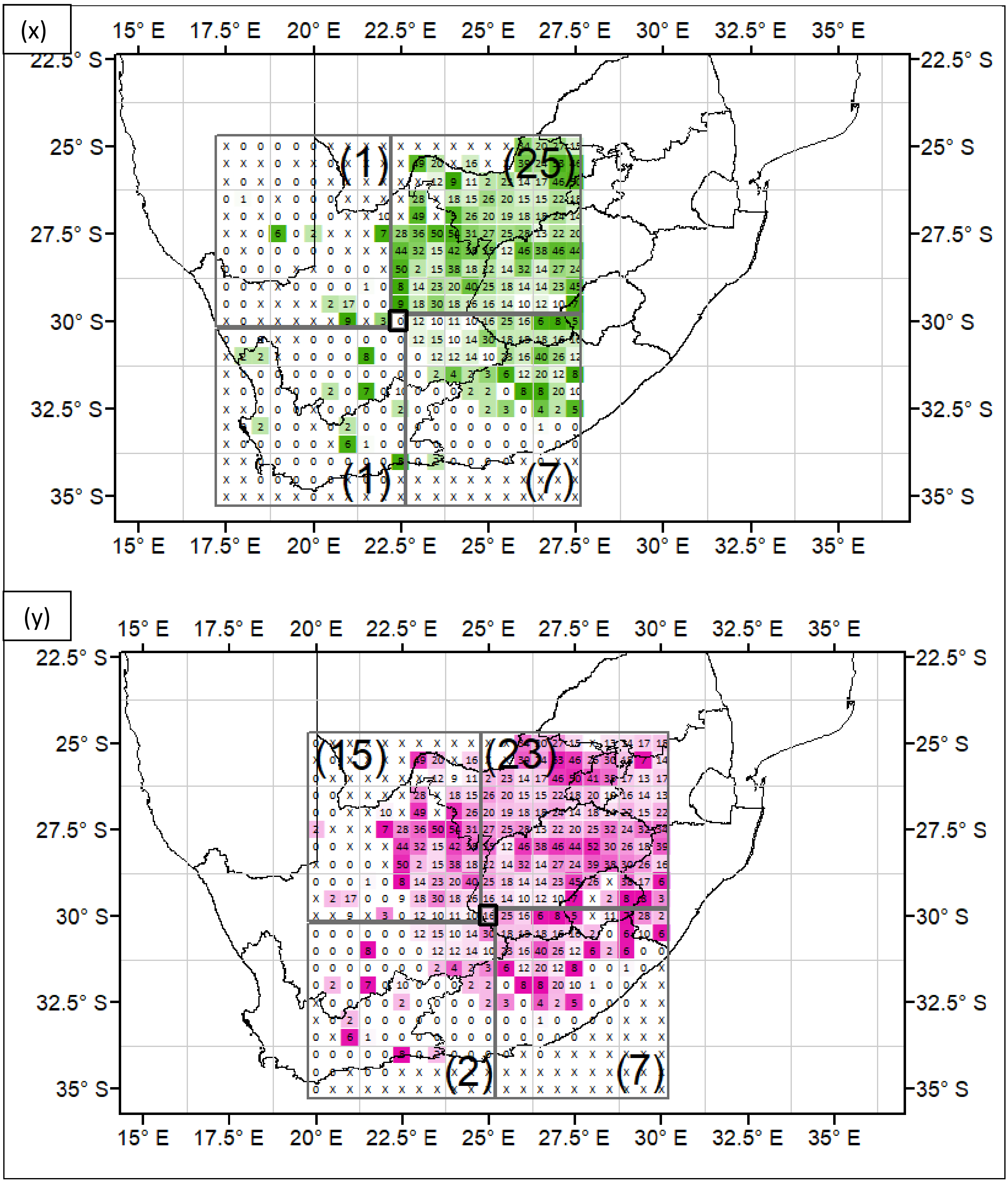
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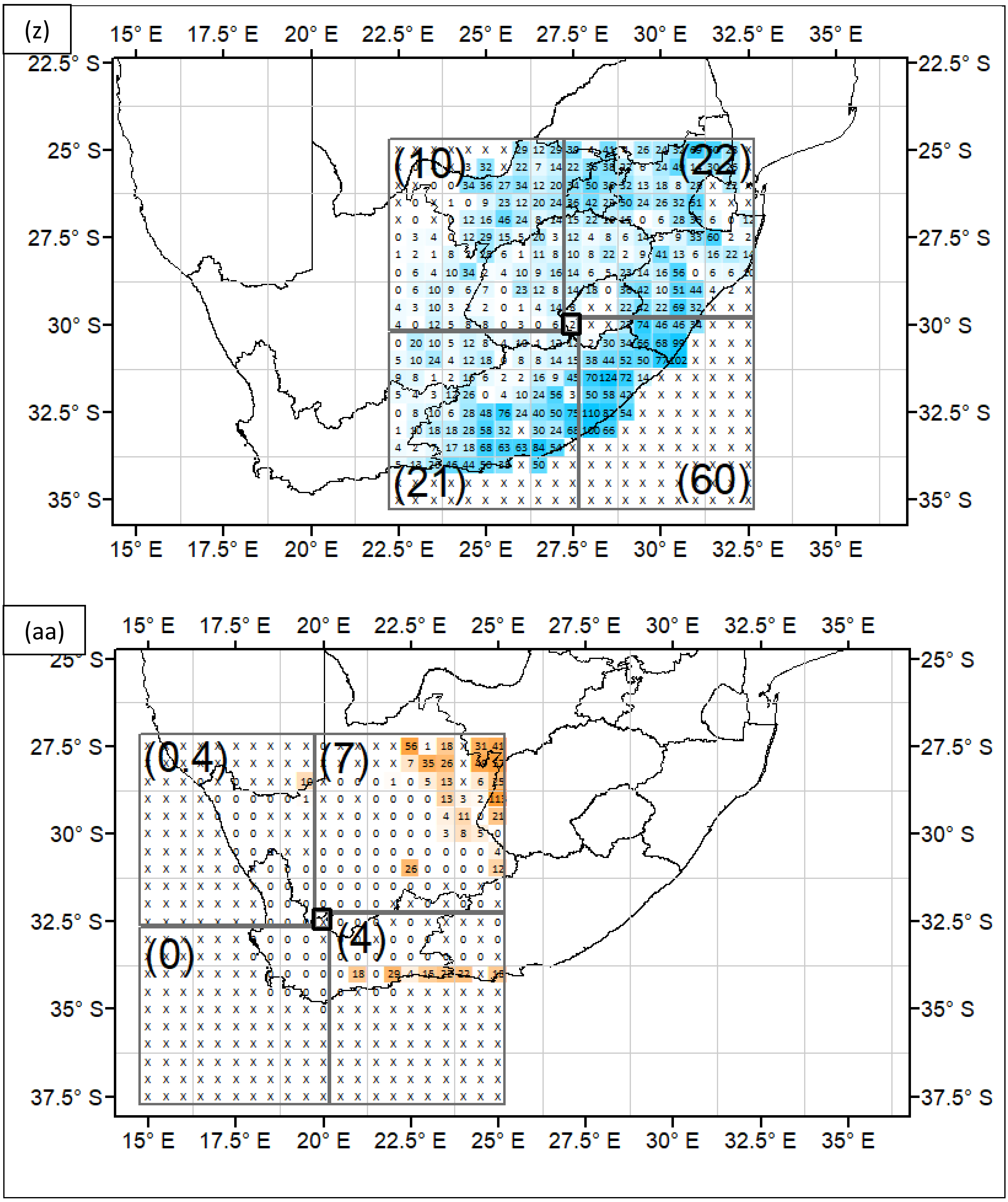

Figure 5.2.5: Average CTL rainfall distribution for all NCEP rainfall areas with the centre of each point in the small bold box circled. The value in brackets represents the average rainfall per quadrant.

The value of the information captured in figure 5.2.5 is of enormous significance to any operational forecaster. This demonstrates that an area positioned more than 600km away from the central point of a CTL, can still be affected by the rainfall as a result of that CTL.

5.3 General rainfall distribution around a Continental Tropical Low pressure

An arbitrary grid (Fig. 5.3.1) is created to display the distribution of rainfall around the central point of a CTL. This arbitrary grid consists of 441 0.5 by 0.5° grid boxes. This field is created by arranging the rainfall from all CTL days irrespective of their position.

In order to visualise the rainfall distribution, this grid is divided into four quadrants, Q1, Q2, Q3 and Q4. The central point (white block) is excluded from the calculations so that the quadrants can be equally distributed. The quadrant, Q4, has less data due to the north-western parts of the study area mainly falling outside of the South African borders with less rainfall data being available for this study. The purpose of creating an arbitrary grid is to assist forecasters by identifying the quadrant where the highest rainfall generally occurs during CTL events as well as the quadrant where the highest number of rainfall extremes are found. This information can be used by forecasters as a first guess as to where to expect the significant rainfall associated with a CTL.

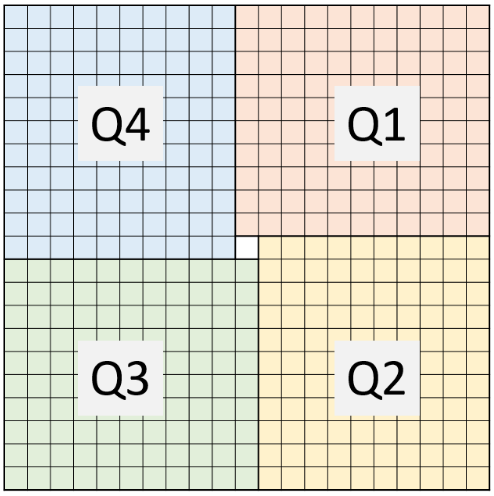

Figure 5.3.1: Arbitrary grid distribution with each quadrant divided into Q1, Q2, Q3 and Q4.

The average rainfall (Fig. 5.3.2) for each 0.5° grid is calculated. Furthermore, the maximum rainfall which occurred on any CTL day per grid is also identified per grid (Fig. 5.3.3). Upon visual inspection the highest average rainfall amounts (Fig. 5.3.2) during CTL days is mainly concentrated towards the eastern half (Q1 and Q2) of the central point of the CTL. While the distribution of the maximum (Fig. 5.3.3) rainfall values ever recorded during CTL events has the highest values (at least 300 mm) towards the south of the centre of the CTL (Q2 and Q3).

							14	17		21			9				35	22		
	10					40	15	11			24	24	13			30	25	14		
			7	8	28	19	13	11	12	19	25	11	11	18	24	16	19	20	15	
2	3			8	31	14	9	12	12	29	23	15	20	15	24	19	19	39	9	27
5	5		3	4	4	18	18	10	10	11	19	34	14	13	12	18	20	14	14	10
1		3	6	8	10	10	22	14	12	14	14	17	15	13	17	14	16	16	11	9
1	5	4	3	11	26	24	14	9	11	21	20	16	18	22	39	28	20	14	23	27
12	5	4	3	7	14	13	9	14	14	16	17	13	17	26	25	24	15	15	13	17
3	1	4	4	5	24	14	13	14	10	19	18	16	23	21	26	20	22	29	15	20
6	3	6	3	3	8	14	15	10	14	16	20	26	19	20	29	25	24	14	15	19
3	2	4	2	5	8	10	17	11	11	20	16	20	15	20	26	16	21	14	22	17
5	4	3	2	5	20	17	14	13	12	31	24	24	24	23	37	24	17	15	24	32
6	5	5	6	6	14	9	12	12	17	24	14	17	19	25	25	19	15	17	15	19
4	4	5	6	6	15	9	11	18	12	17	14	13	22	16	15	15	17	21	19	22
4	4	4	4	4	5	9	19	8	10	9	13	23	13	13	15	13	18	12	12	13
5	3	5	3	4	7	13	16	8	9	9	13	17	12	11	17	9	14	10	14	16
4	6	6	4	6	18	15	11	12	10	17	17	15	14	13	26	22	13	11	15	27
4	7	7	5	6	10	8	9	7	10	13	11	11	11	12	19	16	13	13	11	19
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4	6	6	4	4	4	7	13	7	7	8	10	13	8	8	11	11	14	9	10	11
4	3	5	4	5	6	8	11	7	7	9	9	11	7	8	11	10	13	8	9	11

Figure 5.3.2: Average rainfall distribution around an arbitrary grid point during CTL days.

							79	116		52			38				106	89		
	49					280	60	55			83	60	42			99	76	42		
			40	67	182	99	65	75	22	92	99	44	36	60	58	59	46	101	60	
16	22			43	307	77	63	52	43	129	100	63	59	43	43	37	65	257	29	113
21	43		39	25	25	98	88	75	44	47	98	180	60	41	42	88	63	58	165	26
4		24	57	67	57	71	183	107	87	57	71	100	116	76	69	68	60	126	42	45
9	51	26	25	101	334	422	176	85	63	87	260	75	111	81	200	183	83	93	190	104
231	36	62	36	69	165	165	97	75	86	98	140	110	139	148	150	175	85	101	63	145
33	19	42	40	38	231	150	101	82	49	145	100	133	220	73	150	100	84	257	58	118
35	32	66	39	65	85	123	140	103	206	160	173	290	333	226	230	173	180	108	165	128
30	27	36	38	71	99	155	283	295	115	215	209	325	295	246	396	130	149	126	246	185
84	85	50	36	60	155	200	355	275	215	596	260	425	425	246	596	140	150	156	246	260
65	79	85	100	71	204	172	335	263	522	548	140	252	210	522	548	160	180	223	168	137
50	62	57	48	63	110	194	215	347	316	229	150	143	220	316	145	76	160	187	164	206
38	80	60	71	65	85	132	309	240	293	126	116	290	333	226	230	76	162	152	127	150
109	35	93	68	71	110	189	283	214	239	154	209	325	272	200	396	64	142	138	120	145
84	99	77	70	78	250	320	284	280	135	337	359	425	425	234	456	359	151	120	204	317
95	100	85	78	71	204	172	335	263	249	360	175	335	263	249	360	165	168	173	168	230
129	80	101	90	85	189	194	215	347	163	360	194	215	347	134	555	287	160	187	156	307
42	102	80	85	71	55	132	210	240	293	126	145	290	333	293	230	129	236	126	109	102
90	98	118	118	70	138	131	220	214	122	163	209	325	272	200	396	166	210	157	144	115

Figure 5.3.3: Maximum rainfall distribution around an arbitrary grid point during CTL days.

Table 5.3.1 displays a summary of the information in figure 5.3.2 for each of the four quadrants. Quadrants 1 and 2 have the highest amount of average rainfall with 34% and 32% of the average rainfall occurring in these two quadrants, respectively. Quadrants 1 and 2 also have the highest average rainfall per quadrant with 19 mm and 16 mm respectively. This indicates that the area to the east of the CTL is in fact, the area where the bulk of the rainfall occurs during CTL days. This rainfall distribution is similar to that produced by a COL where the bulk of the rainfall occurs to the east of the upper low pressure (Taljaard, 1985). In CTLs and COLs the bulk of the rainfall occurs to the east as this is where all the moisture is. However, the maximum rainfall distribution around a tropical cyclone is mainly found close to the centre of the storm (Anthes, 1982). It is very important to remember that local topography needs to be taken into account. For example, over KwaZulu-Natal, in South Africa, when a CTL is positioned over Richards Bay, the average rainfall distribution indicate that the highest amount of rainfall over South Africa occurs to the west of the low pressure (Fig. 5.2.5v). This is due to the influence of the escarpment, which lies in a north-south orientation, and enhances rainfall in that area.

It is also interesting to note that the fourth quadrant has the grid point where the highest average rainfall occurred, with an amount of 40 mm on average for that specific grid point. Overall, quadrant 1 had by far the most instances where an average more than 20 mm occurred and the least instances where an average of 20 mm was found to occur was in Q3 with only 3.

Table 5.3.1: Average rainfall of each grid point for all quadrants (Q1, Q2, Q3 and Q4) for all CTL days, with the percentage of average rainfall per quadrant as well as the highest average rainfall in each quadrant and finally, the number of grid points that had an average of at least 20 mm.

	% of total rain in each quad	**Average rain per quad (mm)**	**No. of points where average rain ≥20mm**
Q1	34%	19	42
Q2	32%	16	24
Q3	17%	9	3
Q4	17%	10	7

The percentage of maximum rainfall in each quadrant is notably different from the average rainfall as the highest amount of maximum rainfall occurred in Q2 and Q3 (Table 5.3.2). This shows that the maximum rainfall amounts generally occur towards the south of the CTL. The highest maximum rainfall amounts are found in Q2 and Q3, where 596 mm was recorded. This is a single event where the CTL was positioned over northern KwaZulu-Natal at two adjacent grid points on 31 January 1984 at 06Z and at 12Z. The highest number of 'extreme' rainfall amounts, where the maximum rainfall was at least 100 mm, 200 mm or 300 mm mainly occurred in Q2. The fewest of these 'extreme' incidents were found to occur in Q1 and Q4, which is to the north of the CTL.

Table 5.3.2: Maximum rainfall at each of the grid points per quadrant for all CTL days.

	% of total rain in each quad	Average maximum rain per quad	No. of points where maximum rain ≥100 mm	No. of points where maximum rain ≥200 mm	No. of points where maximum rain ≥300 mm
Q1	17%	107	44	9	1
Q2	41%	231	107	59	25
Q3	29%	165	66	38	14
Q4	13%	91	24	9	3

Further analysis of the rainfall distribution per quadrant was calculated for every 0.5° grid box (441 stations per NCEP grid point) for each CTL day. As can be seen in the results displayed in Table 5.3.3, it was found that overall, Q1 had the highest percentage of rainfall points that met the thresholds of at least 20 mm, 50 mm and 100 mm. In Q1, 42% of rainfall points measured at least 20 mm, 13% measured at least 50 mm and 3% measuring 100 mm. The rainfall extremes measured in Q3 and Q4 are very similar, with the same percentage of extremes measured in each of these quadrants. Overall, it is quite rare for any station to measure at least 100 mm during a CTL day as an average of only 2% of CTL days measured at least 100 mm. It is a lot more common for at least 20 mm to be measured, with 26% of stations measuring at least 20 mm during CTL days.

Table 5.3.3: Rainfall distribution per quadrant for every rainfall point for each CTL day.

	% of stations ≥20 mm during all CTL days	% of stations ≥50 mm during all CTL days	% of stations ≥100 mm during all CTL days
Q1	42%	13%	3%
Q2	27%	9%	2%
Q3	17%	5%	1%
Q4	17%	5%	1%
Average of all points	26%	8%	2%

5.4 Extreme daily rainfall

During CTL events the average daily rainfall, as discussed in section 5.1, across the region is 10 mm, compared to the long term mean rainfall which is 5 mm. In order to assess if the daily rainfall that occurs during CTL events is exceptional, the maximum daily rainfall per NCEP rain area is calculated for all CTL days (Fig. 5.4.1). This is the highest daily rainfall amount that ever occurred at every 0.5° grid in each of the NCEP rain areas for all CTL days. Once again, it needs to be noted that this is the maximum daily rainfall within a 5° radius around each NCEP grid point, therefore some grid points will have the same value which will be from the same event as the data that contributes to each grid point will overlap with a neighbouring NCEP grid point (Fig. 5.1.1a).

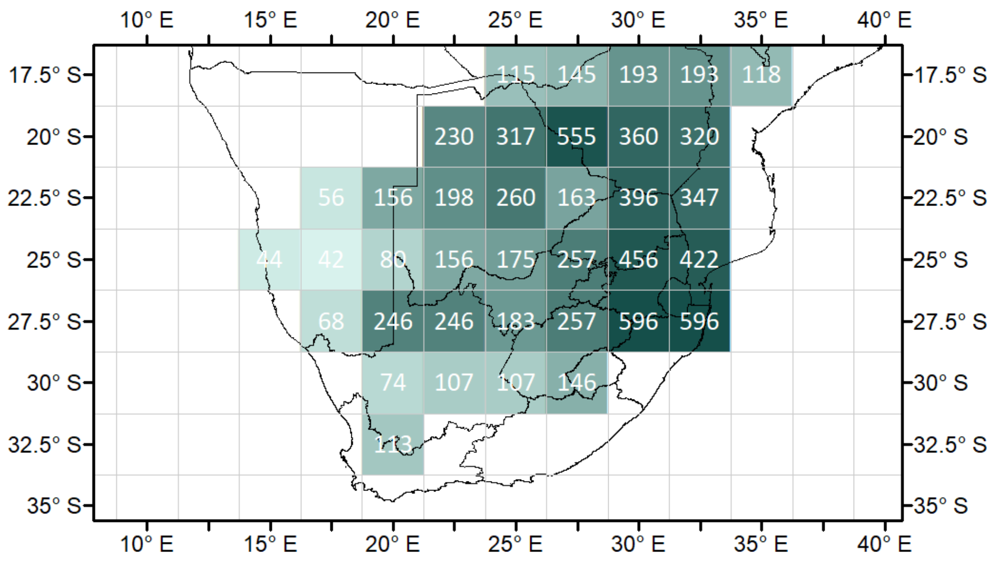


Figure 5.4.1: Geographical distribution of the maximum daily rainfall at a single station during a CTL day.

The maximum daily rainfall amounts generally decrease from the east to the west as well as from north to south. The highest daily rainfall that ever occurred during this period was centred over northern KwaZulu-Natal, where 596 mm was recorded in a 24 hour period. This occurred when tropical cyclone made landfall and changed into a CTL. The CTL was first identified over southern Mozambique on 29 January 1984 at 06Z, it then moved slightly northwards and then westwards into the extreme north-eastern parts of South Africa. On 30 January, the CTL moved slightly southwards, just east of Gauteng and into the north-western parts of KwaZulu-Natal. The final time step that the CTL was identified was on 31 January, when this extreme rainfall was measured. The adjacent grid point at 27.5°S has 596 mm as a maximum. This is because the rainfall measured at 06Z on the 31st was assigned to both the 30th and 31st to cover the rainfall observation period. This event only lasted for 3 days, which is very much an average length of time for CTLs to exist as discussed in section 4.2.

Another extreme rainfall maximum is found over south-western Zimbabwe. The exceptional amount of 555 mm occurred in February 2000, when tropical cyclone Eline made landfall over southern Africa and resulted in devastating damage to infrastructure and loss of lives (Dyson and van Heerden, 2001; Reason and Keibel, 2004).

Forecasters at SAWS are accustomed to defining a “heavy rainfall” event when more than 50 mm occurs in a 24 hour period at any given rainfall station. Therefore, this threshold with an additional two were used as extreme rainfall thresholds. These are, daily rainfall amounts measured at the 0.5° grid box of at least 20 mm, 50 mm and 100 mm. Daily rainfall extreme events were calculated for all NCEP rain areas for all CTL days. A single event is identified when rainfall at any of the 441 possible 0.5° grid boxes in each NCEP rain area meet the required threshold. During all CTL days, there were a total of 13 388 occurrences where at least 20 mm was measured at a single station in a 24 hour period, 4062 with at least 50 mm and 1080 occurrences where more than 100 mm was measured.

Table 5.4.1 shows the total number of grid boxes (possible 441 for each CTL day) where a maximum higher than each of the thresholds (daily rainfall measuring at least 20, 50 and 100 mm) during CTL days for each of the months are reached. There is an average of 362 grid boxes each year that measure at least 20 mm during CTL days, while only an average of 110 grid boxes measure at least 50 mm and even fewer with only an average of 29 grid boxes measuring 100 mm during CTL days.

Table 5.4.1: Extreme daily rainfall events for individual grid boxes per month for CTL days. The average per month is shown in the right hand column of each threshold (individual grid boxes measuring ≥20, 50 and 100 mm).

	Extreme Rainfall Events					
	Number of grid boxes ≥20 mm		**Number of grid boxes ≥50 mm**		**Number of grid boxes ≥100 mm**	
	Total	**Ave. per year**	**Total**	**Ave. per year**	**Total**	**Ave. per year**
December	1087	29	218	6	30	1
January	6584	178	2064	56	603	16
February	3973	107	1325	36	376	10
March	1744	47	455	12	71	2
Year	13 388	362	4 062	110	1 080	29

Overall, January has the highest number of extreme events with an average of 16 grid boxes per year measuring at least 100 mm during CTL days. December months have the least extreme rainfall events with an average of only 1 grid box measuring 100 mm per year. These results show that when CTLs exist during January and February months, it is more likely for heavy rainfall to occur.

A Major Rain Event (MRE), was defined by Dyson (2009) for Gauteng is when the average daily rainfall exceeds 10 mm and at least one station measuring at least 50 mm. Adapting the definition for this dissertation, a MRE is defined as an event where the average rainfall over a NCEP rain area exceeds 10 mm and one rainfall station measures at least 50 mm within the NCEP rain area.

Table 5.4.2: Total number of MREs per month with the average MREs per year for each of the months that occurred during CTL events.

	Major Rain Event (Average rain ≥10 mm and station rain ≥50 mm)	
	Total	**Average MRE days per year**
December	36	0.9
January	195	5.3
February	166	4.5
March	50	1.3
Total	447	12.1

During this study period, 447 MREs occurred during CTL days (Table 5.4.2). January had the highest number of MREs with 195, followed closely by February with 166. December had the least number of MREs with only 36. There is an average of 12.1 MREs per year that occur during CTL days across the study area, with 5.3 MREs during January and 4.5 during February. When comparing these results to those found by Dyson (2009) for rainfall over Gauteng, she found that January had 3.1 MREs and February 2.3. Overall for the entire summer season (October to March) over Gauteng, Dyson (2009) found that there is an average of 12.1 MREs, which is the exact result found in this study. This is most likely coincidental as the period and domain are very different for each of the studies.

5.5 Summary

Overall from the results above, it is clear that CTLs contribute significantly to the rainfall over South Africa. The average rainfall as a result of CTLs is far higher than the overall average rainfall, with the average rainfall per grid point during CTL days being double the overall average rainfall. January has the highest CTL day rainfall as well as the highest number of extreme rainfall events and MREs. Overall, February has very similar results to January with the results just being slightly less for all criteria. The highest average CTL day rainfall mainly occurs over the eastern parts of South Africa. From December to January, the average rainfall is mainly confined to the north-eastern parts of the country and by March, the rainfall distribution extends across most parts of South Africa. The general distribution of rainfall around a CTL is mainly found to occur to the east of the CTL, however, the extreme rainfall amounts generally occur towards the south. This information should be of substantial value to an operational forecaster as once a CTL is expected to develop over an area, the forecaster will then be able to delineate the area that is most likely to be affected by rain and therefore possible flooding as a result of a CTL. When a CTL exists, 26% of the time a forecaster can expect at least 20 mm of rain to be recorded at any given station, with more than 40% certainty that this rain will occur in Q1.

Chapter 6

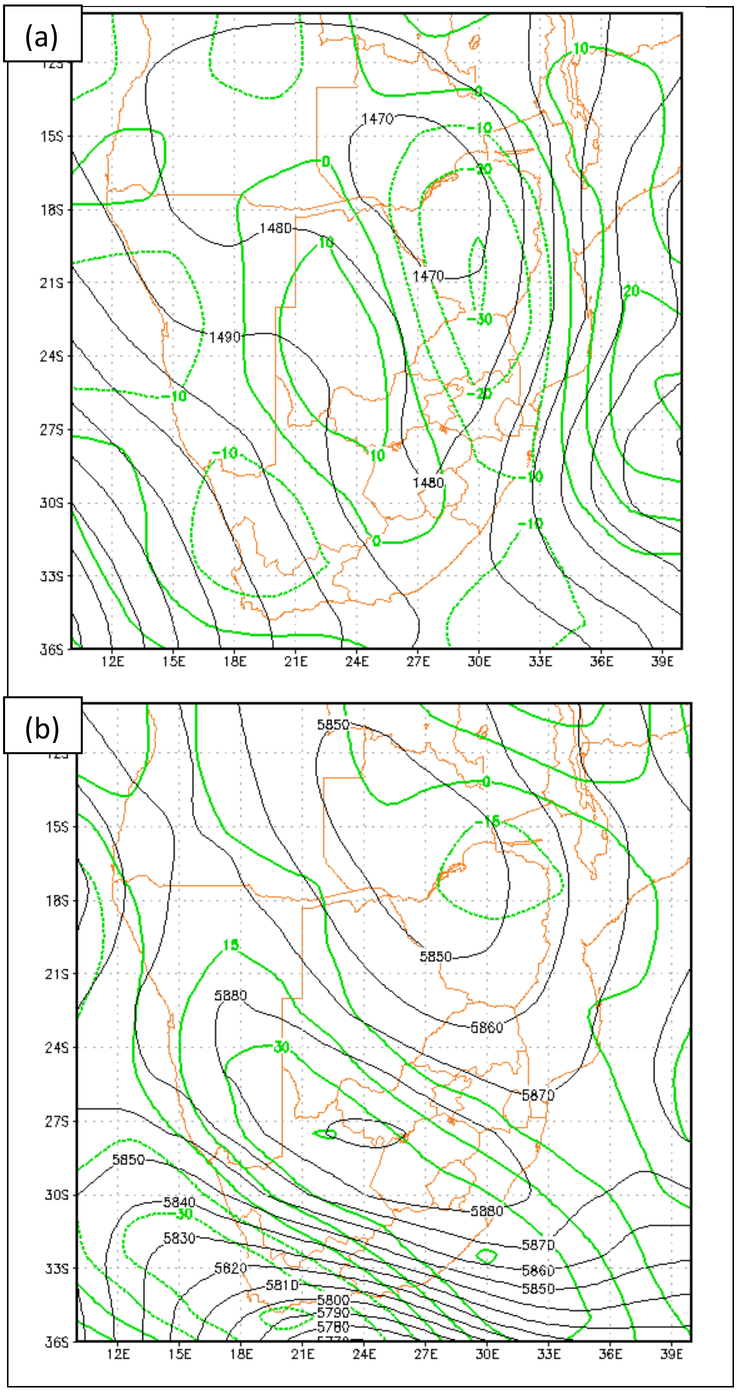
Continental Tropical Low pressure case study: January 2013

From 14 to 20 January 2013, devastating floods swept across Limpopo and Mpumalanga provinces resulting in the deaths of 12 people in South Africa and 9 in Mozambique (SAWS, 2017). This devastation was as a result of a CTL that developed over south-eastern Zimbabwe and advanced westwards. This chapter uses the CTL of January 2013 as a case study to demonstrate how the objective identification method can be utilized in identifying a CTL and to illustrate where rainfall occurs relative to the CTL.

6.1 Objective Identification of Continental Tropical Low pressure on 14 January 2013

Following the methodology presented in section 3.3, CTLs were accurately identified during January 2013 by meeting all four of the criteria for 49 time steps. To demonstrate the process that is followed when identifying a CTL, the event of 14 January 2013 at 12Z is used. In an operational environment, the long term mean would not be known, therefore using the variables presented in this dissertation that are readily available in a forecasting environment, will be used to identify the CTL.

On 14 January 2013, a low pressure is seen at 850 and at 500 hPa (black lines in Fig. 6.1.1a and b) with a high pressure aloft (300 hPa) (Fig. 6.1.1c). Coinciding with the surface low and upper high pressures, are areas of negative relative vorticity at 850 and 500 hPa and positive vorticity at 300 hPa (green lines in Fig. 6.1.1). Negative values of relative vorticity display areas of cyclonic rotation, while positive values show anti-cyclonic rotation in the southern hemisphere. This indicates that there is an upright low pressure in the lower and mid-levels of the atmosphere with a high pressure aloft.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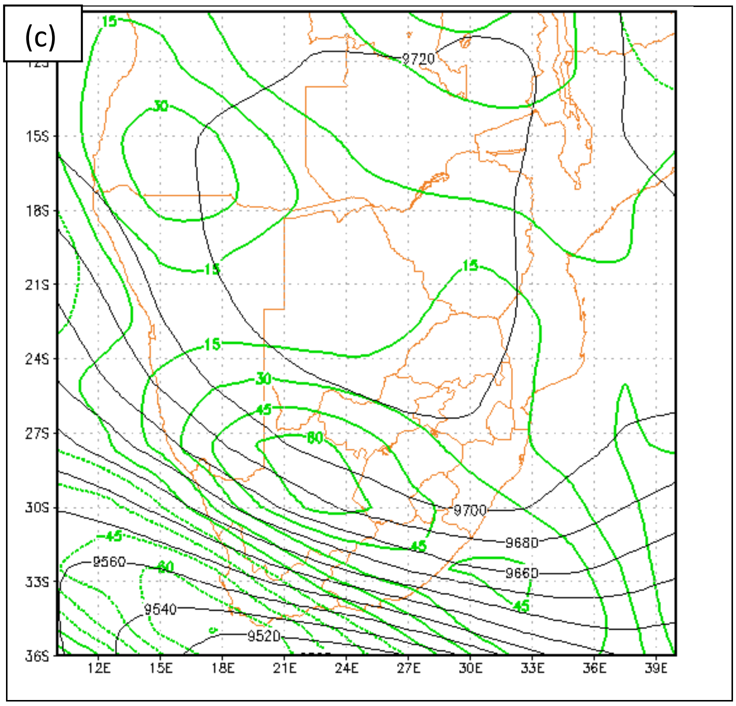

Figure 6.1.1: Relative vorticity (green lines in units of 10^{-5} s^{-1}) and geopotential heights (black lines) both at (a) 850 hPa, (b) 500 hPa and (c) 300 hPa on 14 January 2013.

There is a clear warm core in the 500-300 hPa column (shaded blue area in Fig. 6.1.2.) that is positioned over western Zimbabwe and north-eastern Botswana. The warm core is in very close proximity to the 500 hPa low pressure (black lines in Fig. 6.1.2).

There are two regions that stand out in figure 6.1.3 where very high TSE values occur. These regions are positioned over southern Zimbabwe where the CTL is located and eastern Namibia. A very broad area of TSE values higher than $330x10^3$ $J.kg^{-1}$ covers most of the region in figure 6.1.3, except for the small area in the extreme south-west, which have lower values.

The atmosphere is very moist on 14 January 2013 which is seen in the 850-300 hPa layer of precipitable water values on figure 6.1.4. The distribution of the precipitable water is strikingly similar to the TSE values (Fig. 6.1.3). There are also two areas of very high precipitable water values which correspond to the high TSE cores (Fig. 6.1.3). Precipitable values exceeding 20 mm cover most of the region, extending into the northern parts of South Africa. Values in the vicinity of the CTL are above 35 mm and above 25 mm over Limpopo and Mpumalanga Provinces where heavy rainfall occurred (Fig. 6.3.3)

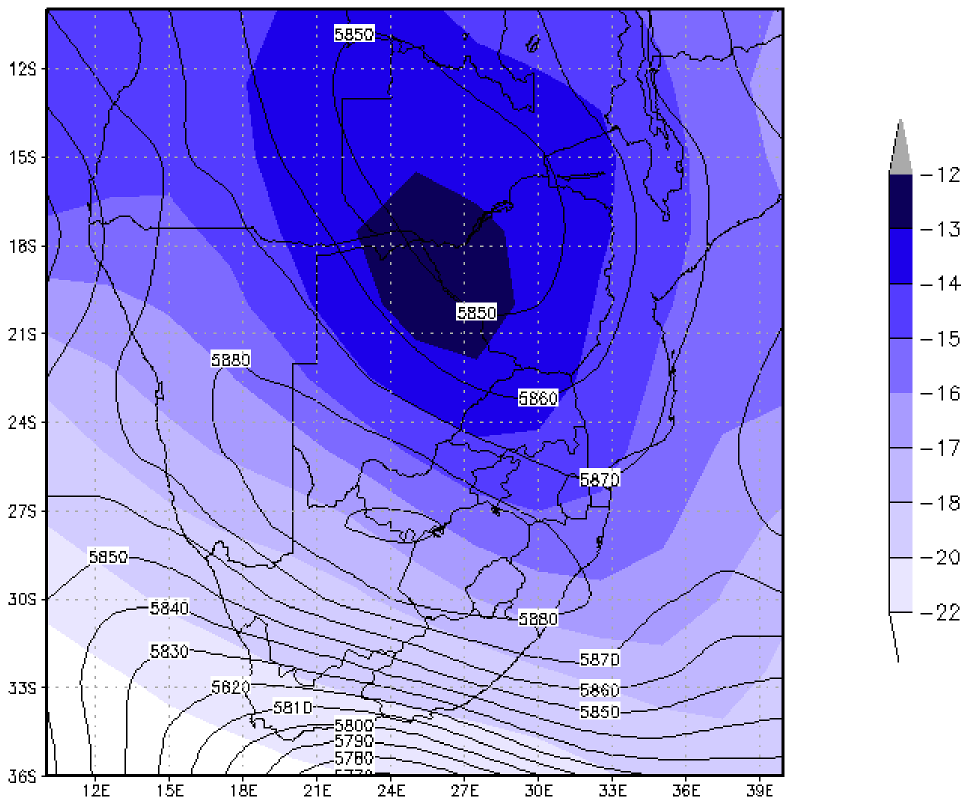

Figure 6.1.2: Average 500-300 hPa column temperatures on 14 January 2013. Temperatures are in °C. Black lines represent the geopotential heights at 500 hPa.

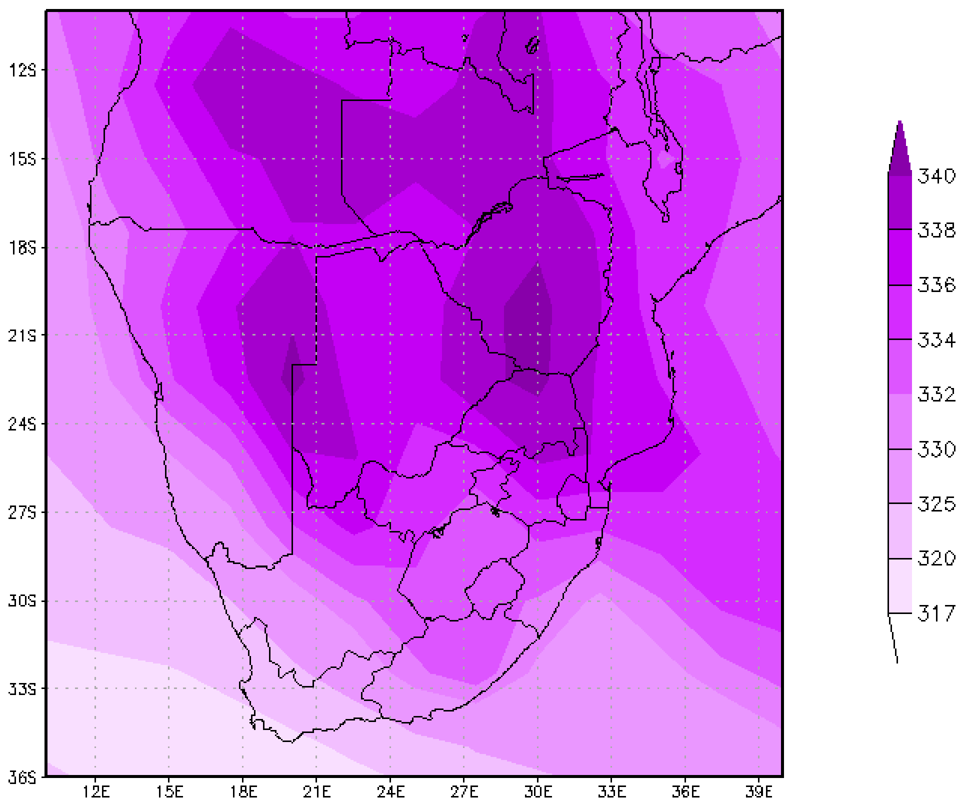

Figure 6.1.3: Average Total Static Energy in the 850-300 hPa column on 14 January 2013. Units in $10^3 J.kg^{-1}$.

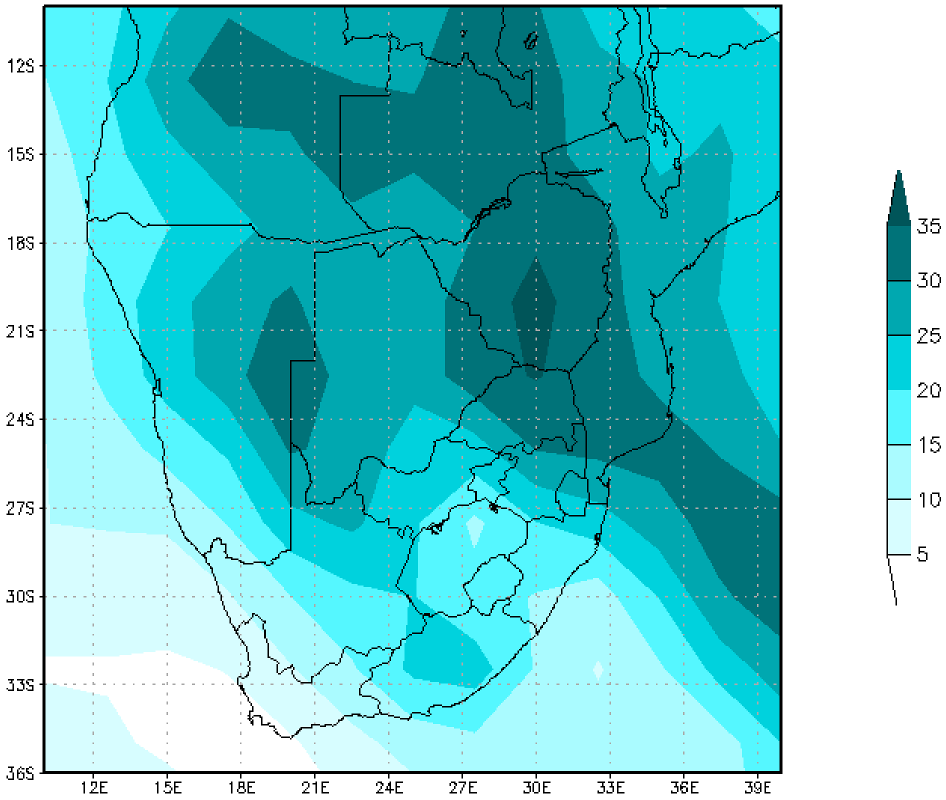

Figure 6.1.4: Precipitable water values in the 850-300 hPa column on 14 January 2013 in units of mm.

After examining the atmospheric conditions on 14 January 2013, it is clear that the dominant weather system is a CTL. The position of this low pressure is given by the location of the lowest pressure at 500 hPa (Fig. 6.1.1b), which is found at 17.5°S and 27.5°E (Fig. 6.2.1).

6.2 Lifespan and movement of the Continental Tropical Low pressure

During January 2013, 49 6-hourly CTL events were identified. This case study focuses on the CTL that existed over the eastern parts of the study area. The CTL was first identified on 10 January 2013 at 06Z and continued until the 18th at 12Z. This is a total of nine days which is quite a long duration considering the average lifespan of a CTL is on 3 days or less (Fig. 4.2.2). The CTL initially developed over south-eastern Zimbabwe and followed a general westwards track (Fig. 6.2.1). The CTL remained stationary at 20°S and 32.5°E from 10 January at 06Z until 00Z on the 13th. It then headed north-westwards into northern Zimbabwe by the 14th at 00Z. The furthest south the CTL existed was at 25°S and 27.5°E on the 14th at 06Z. At this time, a CTL was identified at another grid point as well, 17.5°S and 30°E (not shown in Fig.

6.2.1). At 12Z on the 14th, the CTL was positioned at 17.5°S and 27.5°E (circled in Fig. 6.2.1), this is the time step that the objective identification method described in section 6.1 uses.

The CTL progressed further westwards, through the extreme southern parts of Zambia and into south-eastern Angola. On the 15th, the CTL moved to south-western Zimbabwe, but by the 16th at 18Z, it made its way back to the extreme south-eastern parts of Angola. The CTL headed southwards on the 17th, into western Botswana and eventually progressed north-eastwards on the 18th at 12Z which was the final CTL event identified for this system. It is clear the CTL retrogressed during its lifespan, which seems to be an usual track, however unusual tracks have been found in Australia too (Tang *et al.,* 2016). The objective identification method used in this study may also play a role in the location of the CTL.

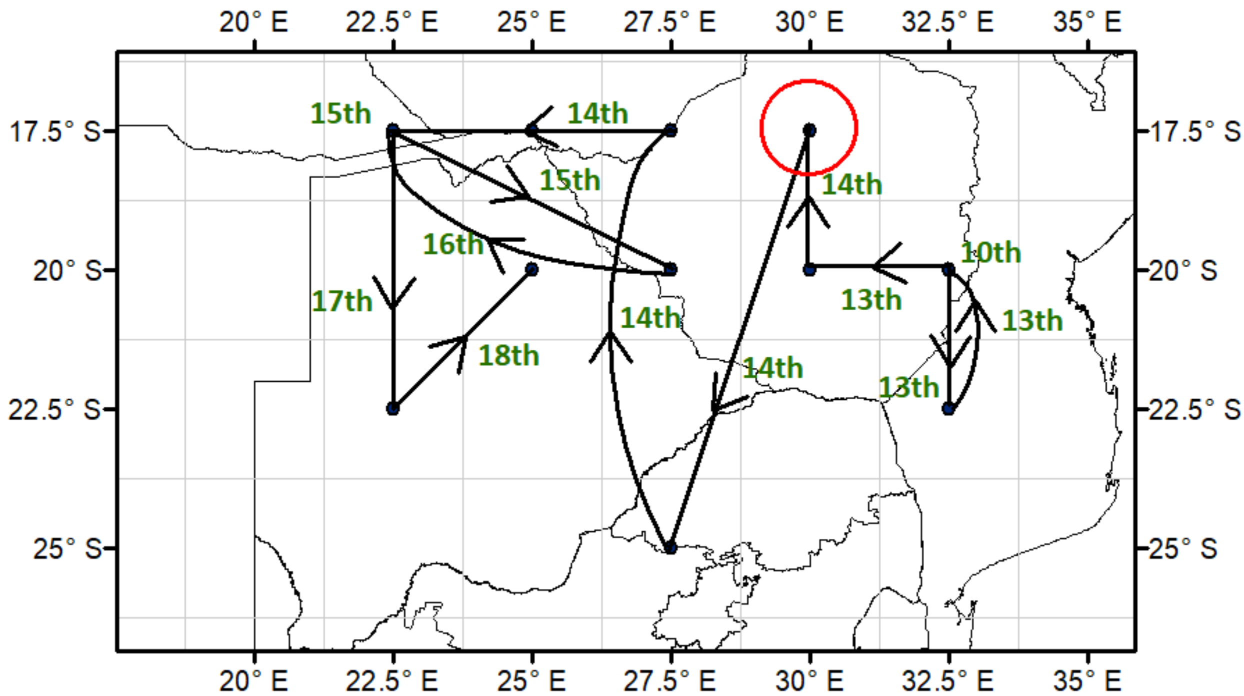

Figure 6.2.1: The path followed by the CTL from 10 January until 18 January 2013.The arrows indicate the direction of movement with a general westwards motion during the lifespan of the CTL. The red circle indicates the position of the low pressure identified in section 6.1.

6.3 Rainfall associated with the Continental Tropical Low pressure

Green colours on the airmass Red-Green-Blue colour combination (RGB) satellite image indicate a warm airmass with a high tropopause, blue show a cold airmass and red represents an advection jet (Kerkmann, 2005). On 14 January 2013, a warm airmass is clearly present over Zimbabwe, Botswana and Mozambique (green colour in Fig. 6.3.1). The objective identification method identified a CTL at the position indicated in figure 6.3.1, this is the centre of the 500 hPa low pressure.

On 14 January at 12Z, the main cloud masses were positioned over southern Mozambique (Fig. 6.3.1), by 18Z on the same day, the clouds started shifting to the west and were positioned over Zimbabwe (Fig. 6.3.2). The CTL also progressed westwards, positioned over the extreme southern parts of Zambia (Fig. 6.3.2). There appears to be a slight deviation in the position between the position of the NCEP CTL and the satellite image. Very high daily rainfall amounts were observed on the 14^{th} of January 2013 with 100-200 mm recorded in northern and central Limpopo (Fig. 6.3.3). High rainfall amounts (≥50 mm) are also observed along the Mpumalanga escarpment. This result reiterates what was presented in section 5.2 where the influence the escarpment has on the average CTL rainfall distribution is discussed.

The CTL then followed an anti-cyclonic motion with the final CTL location situated over north-eastern Botswana (Fig. 6.3.4). The cloud bands associated with this CTL extended all the way into the eastern interior of South Africa where rainfall amounts of more than 50 mm were recorded over KwaZulu-Natal (Fig. 6.3.5). The influence the topography has on the rainfall is clearly seen in figure 6.3.5 with higher rainfall amounts observed along the escarpment. Once again the position of the NCEP CTL (displayed as the L in Fig. 6.3.4) is not in the same position as where the spiral cloud bands indicate the low pressure to be in the satellite image.

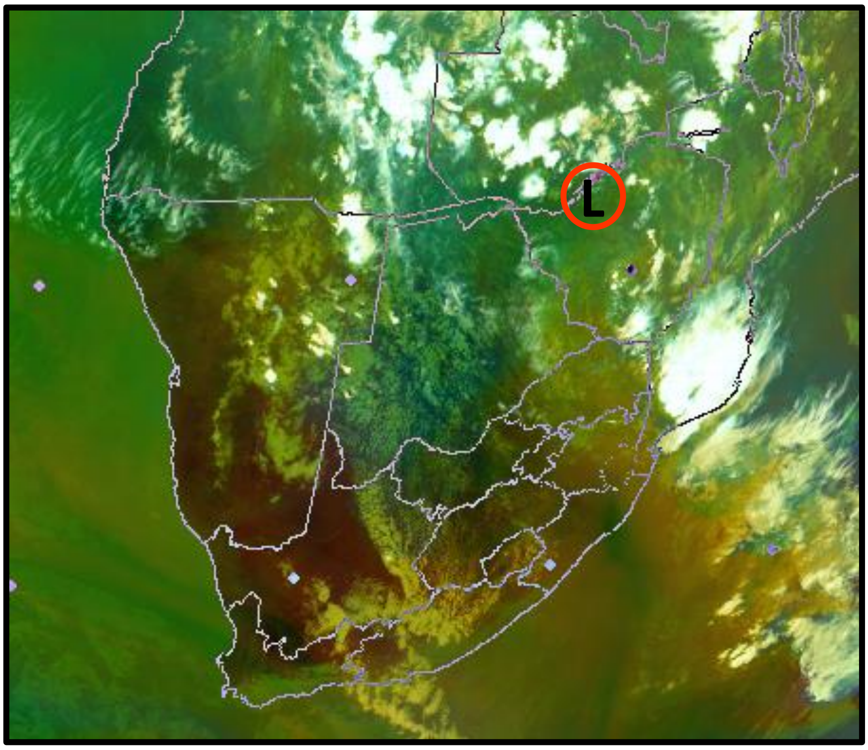

Figure 6.3.1: Airmass RGB satellite image on 14 January 2013 at 12Z with the "L" indicating the central position of the CTL that was identified using the objective identification method (© EUMETSAT, 2018)

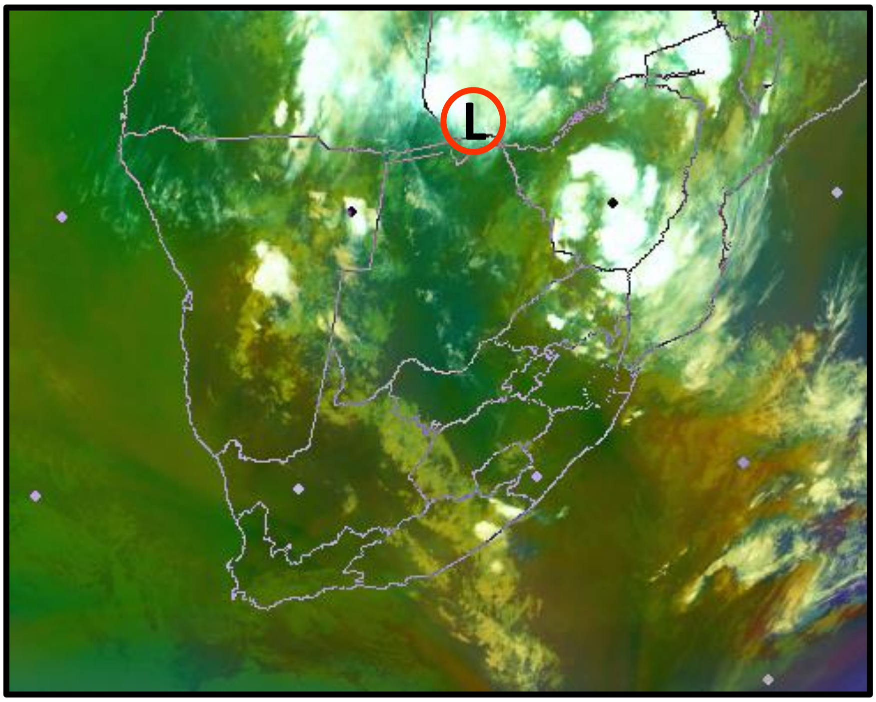

Figure 6.3.2: Same as Fig. 6.3.2 just at 18Z on 14 January 2013 (© EUMETSAT, 2018).

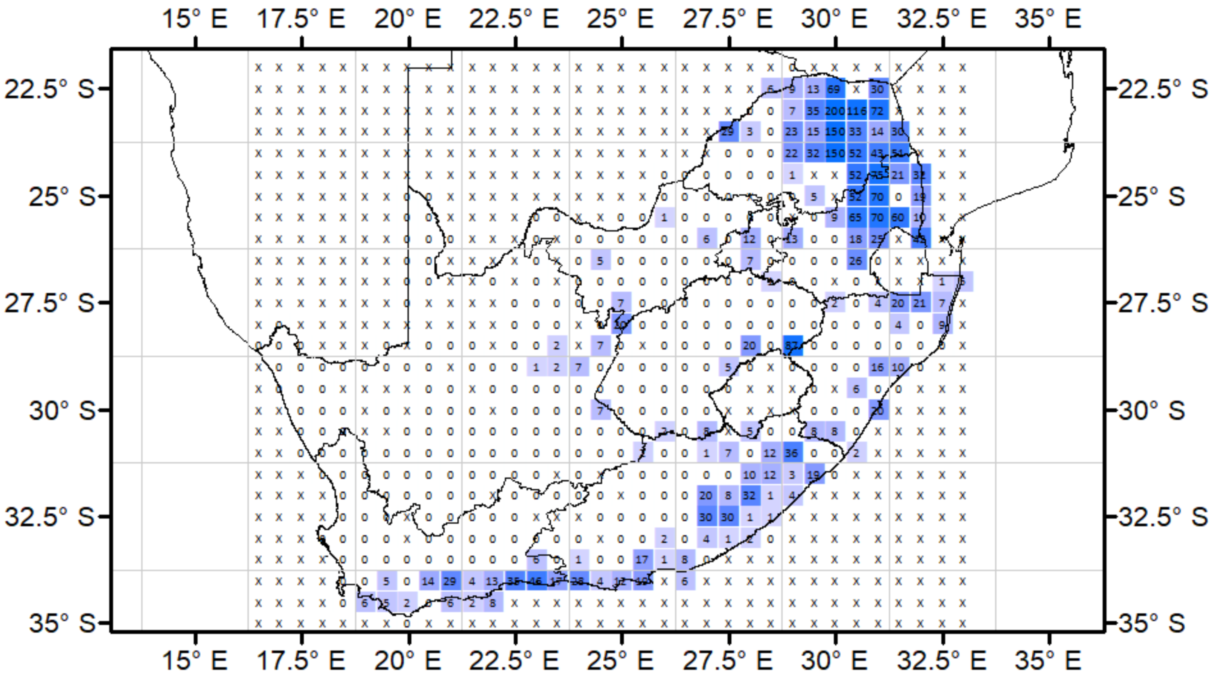

Figure 6.3.3: Geographical distribution of the CTL rainfall per 0.5° grid across South Africa on 14 January 2013.

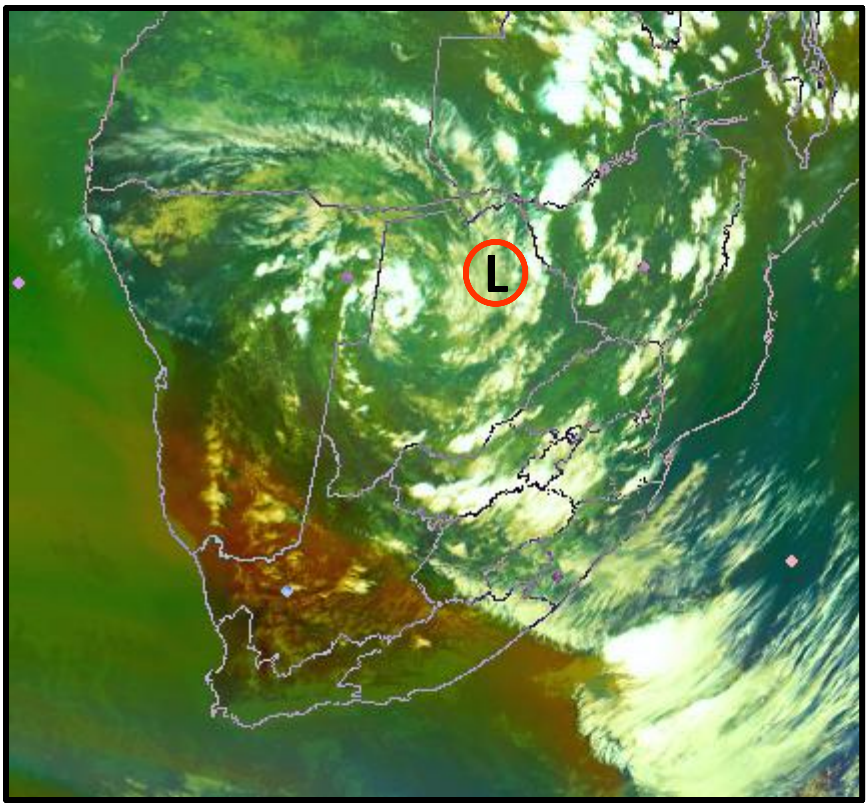

Figure 6.3.4: Same as Fig. 6.3.2 just for 18 January at 12Z (© EUMETSAT, 2018).

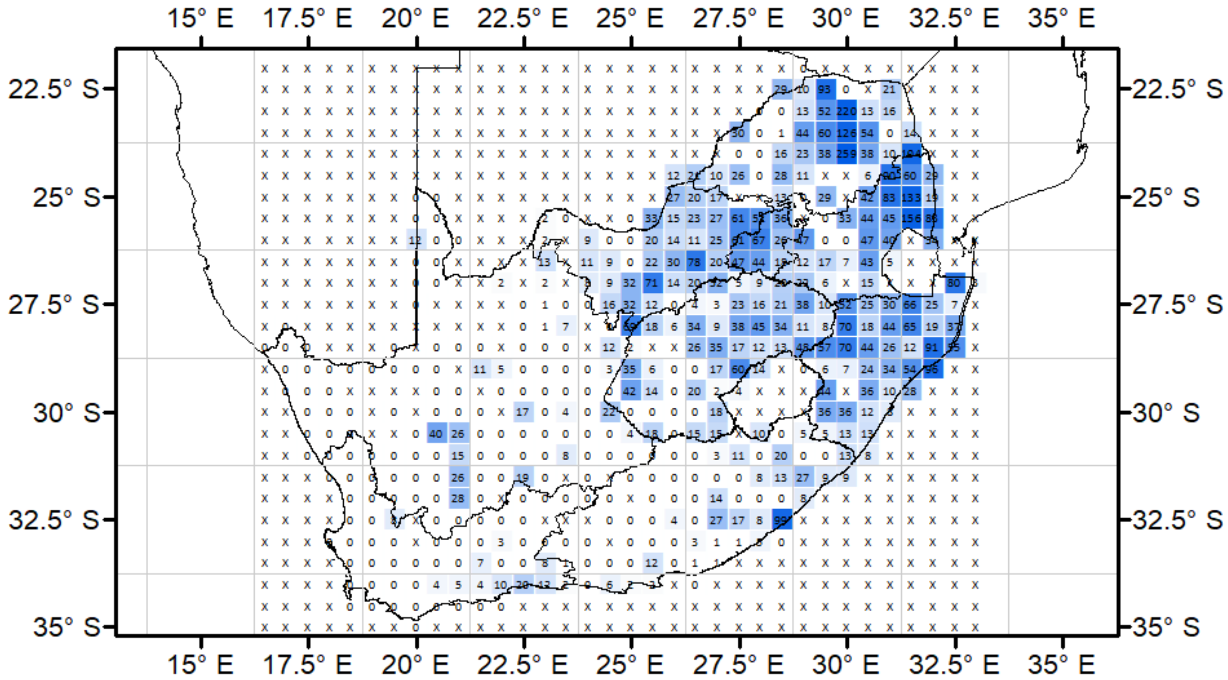

Figure 6.3.5: Geographical distribution of the CTL rainfall per 0.5° grid across South Africa on 18 January 2013.

6.4 Summary

The objective identification method presented in this dissertation accurately identified the CTL that occurred from 10-18 January 2013. The impact this CTL had on Limpopo and Mpumalanga Provinces was enormous (SAWS, 2017). Lives were lost and many homes were completely washed away. Flooding resulted in several thousand crocodiles escaping from a crocodile farm in Limpopo. The tourism industry was severely affected with many parks closed for two weeks. Three border posts between South Africa and Botswana were also closed as a result of the widespread flooding.

Even though the daily rainfall amounts as a result of a CTL are not as high as it could be from a tropical cyclone, it is the continual rainfall amounts in the order of 50-100 mm per day that result in the widespread adverse impacts. This case study demonstrates that due to the slow movement, long-lived lifespan of the CTL and the broad extent of the rain bands, these weather systems are capable of devastating effects causing prolonged disruptions to daily life.

Chapter 7

Summary and Conclusions

In this chapter, a summary as well as conclusions will be provided on the research undertaken in this dissertation. Recommendations will also be given as to what further work can be carried out in order to build onto this research and further contribute to the understanding of tropical weather systems that affect southern Africa. This section will also include information on how this research can contribute to science as well as to weather forecasting in southern Africa with a specific focus on rainfall over South Africa.

At the start of the dissertation, three aims were set out to be achieved in the study. The first aim was to create an objective identification method to recognise CTLs. The second aim was to develop a synoptic climatology of CTLs over southern Africa. The final aim was to determine the rainfall contribution CTLs have on the annual rainfall over South Africa.

7.1 Objective Identification of Continental Tropical Low pressures

The first aim was achieved by developing an objective identification method that can identify CTLs over southern Africa. This objective identification method has four main criteria with the process graphically displayed in figure 3.3.2.

The *first* criteria is to detect **a favourable tropical environment (FTE)**. The FTE is recognised by identifying grid points that meet the following requirements:

- Negative relative vorticity values be present at 850 and 500 hPa, and are replaced by positive values at 300 hPa
- The cyclonic circulation at the surface and in the mid-troposphere should be stronger than normal while the high should dominate near the tropopause. Therefore it is required that the deviation from the normal vorticity values for the month under investigation show this anomalous circulation
- Average tropospheric total static energy (TSE) values should be higher than the long term average for that month

- The average 500-300 hPa temperatures should be higher than the long term average value for that month
- The precipitable water from 850-300 hPa should be higher than 20 mm
- The precipitable water values should also be higher than the long term average value for that month

The *second* criteria is that **a closed 500 hPa geopotential low with a warm core of 500-300 hPa temperatures are present.** The *third* criteria is that the **FTE and warm low are within two grid points of each other**. If this requirement is met, the low pressure is then termed a warm FTE low pressure. The *fourth* criteria is two-fold and is related to time. It is required that **the current warm FTE low has another warm FTE low either 18 hours before or after *and* lies within two grid points of the current warm FTE low**. Once these four criteria are met the low pressure is classified as a CTL.

Very strict criteria were set in this dissertation to identify CTLs. This work builds on MITS (Dyson and van Heerden, 2002) but also incorporates ideas of Engelbrecht *et al.,* (2014), Berry and Reeder (2013), Hart *et al.,* (2012), Malherbe *et al.,* (2012) and Crétat *et al.,* (2018). Tropical weather systems were also identified by Malherbe *et al.,* (2012), Crétat *et al.,* (2018) and Berry and Reeder (2013), while authors such as Engelbrecht *et al.,* (2014) identified extra-tropical weather systems for example COLs and TTTs.

The case study demonstrated that the location of the NCEP CTL and the actual position as on the satellite image is not always the same, although it is in close proximity. Even though NCEP reanalysis data is of a high quality and have been used in similar studies, it remains an approximation of reality and therefore can misplace the position of the low. However I am convinced that the placement of the NCEP CTL is close enough to reality. Additionally, the objective identification method did not identify a CTL on each of the time steps during the 1988 event. This demonstrates that the objective identification method is not perfect, however in an operational environment, there is a forecaster, who has the ability to intervene and fill in gaps where necessary.

7.2 Synoptic Climatology of Continental Tropical Low pressures

Using the results of the objective identification method, the second aim was achieved by creating a climatology of CTLs (Fig. 4.1.1). The results show that CTLs events (CTLs per 6 hourly time step) most frequently occur over southern Angola and Zambia. There is an average of 19 CTL days per year across the domain, however, over the central interior of South Africa, the return period 78 years.

During the study it was found that CTLs occur most often during January with 36% of CTL events while CTLs seldom occur in December with only 15%. It was also found that CTL events do not show any real diurnal trends, however, they do occur most regularly at 18Z. The average life-span of a CTL is between 1-3 days, although there are rare occasions when they last for more than 13 days. The longest consecutive day CTL occurred in January 2017, where this specific CTL lasted for 19 days.

An additional study was compiled on the seasonal trends of CTLs by standardizing the data with respect to the average and standard deviation. These results show that there is an increasing trend in CTL events over southern Africa, however this trend is not significant. A negative correlation of CTL events exist with the Oceanic Index, suggesting that a warm ENSO event is associated with below normal CTL events and cold ENSO events increase the number of CTLs. Landman and Mason (1999) found that ENSO correlated best with rainfall over tropical Africa. The results in my research indicate that one of the synoptic drivers influenced by ENSO is CTLs and this in turn influences above and below normal rainfall events. It is more likely to have a below (above) normal number of CTLS events during warm (cold) ENSO events which can partly explain the below (above) normal rainfall over South Africa.

The results in this dissertation contribute to understanding the synoptic climatology of South Africa better. It builds on work done by Taljaard (1985) who developed a synoptic climatology of COLs which Singleton and Reason (2007) investigated further. Malherbe *et al.,* (2012) endeavoured to develop a climatology of westward moving lows in the south-west Indian Ocean. The contribution of my climatology is that a rare, but very significant rainfall producing weather system is introduced for the first time.

7.3 Rainfall contribution Continental Tropical Low pressures have to South Africa

The final aim was to calculate the rainfall contribution CTLs have to South Africa. This was achieved by using the climatology results and calculating the rainfall within a 10° area around the central point of the CTL. Only the rainfall over South Africa was considered due to the limited availability of data further north over neighbouring countries. The average CTL day rainfall over the study area is 10 mm per 10° grid area (NCEP grid area) while the long term mean value for the same area is only 5 mm. This shows that CTLs clearly do contribute significantly to rainfall over the region. It was found that the highest CTL rainfall occurred during January. This is very much in line with the climatology results which showed that January months had the highest number of CTL event occurrences. These results coincide with work presented by Taljaard (1996) which states that the north-eastern parts of South Africa, which is a primarily summer rainfall region, has a peak in annual rainfall during January and emphasises the importance of CTLs to the total rainfall budget in South Africa.

The geographical distribution of CTL rainfall was investigated for each of the months and it was found that the rainfall that occurs during December months is mainly confined to the north-eastern parts of South Africa with the highest rainfall recorded when a CTL is positioned over north-eastern KwaZulu-Natal. During January, the same grid point had the highest rainfall with an average of 46 mm. The rainfall area that surrounds this grid point includes most of the eastern parts of South Africa. By February, the CTL rainfall distribution spreads further towards the west and by March the rainfall reaches the western interior of the country. This demonstrates that the CTL rainfall has a clear westward shift from December to March which corresponds to the westward shift of the 50 mm isohyet during summer months (Taljaard, 1996).

Rainfall extremes for daily CTL rainfall were also calculated and it was found that the highest daily rainfall recorded by a single station due to a CTL was positioned over northern KwaZulu-Natal, where 596 mm was measured on 31 January 1984. During this investigation, extreme rainfall events were identified when a single grid box measured at least either 20, 50 or 100 mm in a 24 hour period. During CTL days, there is an average of 110 occurrences per year where at least 50 mm was measured and 29 per year where at least 100 mm was recorded. These extreme rainfall events mainly took place in January months.

Major rain events (MREs) are defined as an event where the average rainfall over a NCEP rain area exceeds 10 mm and at least one rainfall station measures at least 50 mm within the NCEP rain area. During the study period, a total of 447 MREs occurred with an average 12 per year. The results of the MREs during CTLs are exceptionally similar to the results found by Dyson (2009) when investigating heavy rainfall events over Gauteng province. She found that January had the highest number of MREs, with 3.1 events, followed closely by February, with 2.3. During this study, MREs also occurred most frequently in January where 5.3 events transpired while February had slightly less at 4.5 events.

The general distribution of rainfall around a CTL was also studied and it was found that the majority of rainfall associated with a CTL transpires in Q1 (Fig. 5.3.1) with the highest rainfall amounts mainly occurring in Q2. These results showed that the rainfall distribution around a CTL mainly occurs to the east of the CTL, with the extreme rainfall amounts occurring more towards the south.

7.4.1 Scientific contribution

On 6 January 2017, a CTL was positioned over Botswana with cloud bands extending into the north-eastern parts of South Africa. This CTL resulted in the loss of at least seven lives, damage to numerous households in Phalaborwa, closure of many roads in the Kruger National Park and several cars were swept away due to the flood waters in Mpumalanga (SAWS, 2017). Even though this was a clear CTL, which in fact was the longest consecutive day CTL during the study period, forecasters failed to acknowledge the presence of this weather system (SAWS, 2017). It is therefore evident that there is a lack of understanding and accurate identification of these weather systems over southern Africa even though the impacts caused as a result of the existence of a CTL are notoriously vast. The main contribution this research hopes to achieve is to create a better understanding of CTLs and the impacts they can have.

CTLs are not well recognised in southern African synoptic climatologies. The only exception being Taljaard (1996) and Dyson and van Heerden (2002). CTLs are unique over southern Africa and no documentation is available on similar weather systems elsewhere in the world. This research developed a unique and strict set of criteria to objectively identify

CTLs and then created a synoptic climatology of CTLs over southern Africa. In contrary, TTTs are well known and discussed over Africa and elsewhere around the globe (Hart *et al.,* 2010). The identification system developed in this research shows that CTLs can exist in isolation of TTTs and yet still contribute significantly to rainfall over South Africa. This is the first time such a study has been undertaken in southern Africa and provides information about a tropical low not previously available.

Rainfall which occurs from CTLs is heavy and widespread. Daily rainfall totals of more than 20 mm occurs regularly and more than 50 mm is also quite common. Rainfall along the eastern escarpment is excessive with more than 100 mm occurring, even if the CTL is located as far west as southern Botswana. CTLs are slow moving with an average life span of 1-3 days, this results in the floods that are associated with CTLs not necessarily occurring because of the rainfall in a single day, but rather due to continual rainfall that falls over the same area for several days.

7.4.2 Contribution to forecasting

By developing an objective identification method, this will assist forecasters to accurately recognise a CTL in a timeous manner. Forecasters will then be able to identify a possible CTL event in advance of the actual development. Necessary warnings can also be issued well ahead of time so that appropriate measures can be put in place before the anticipated flooding. In addition, by knowing the probable extreme rainfall amounts associated with these weather systems and the main distribution of the rainfall around the central point of the CTL, forecasters will be able to highlight areas to the east of the CTL that could receive the highest rainfall amounts.

7.5 Suggestions for future research

There are many opportunities for future research on this topic building on the work presented in this dissertation. A list of recommendations is provided:

1. The development of CTLs is not completely understood and therefore there is a definite need to fully appreciate the dynamics behind their development.
2. A rainfall contribution of CTLs on southern Africa can be completed by extending the rainfall area to include the entire southern Africa.

3. Another opportunity would be to examine the lifecycle of CTLs including the dynamics responsible for certain CTLs lasting for so much longer than others.

4. Research could be performed where CTL tracks are examined to identify if there is any preferred direction of movement.

5. Further analysis on the rainfall contribution CTLs have can also be conducted whereby the individual CTL events that exist intermittently can be grouped together and the rainfall can then be calculated for the entire period.

6. The objective identification method could also be incorporated into the numerical weather prediction models (NWP) at the South African Weather Service. The NWP could then display a single output field that will detect the position of the CTL. This will greatly assist forecasters as it will save time if the output is provided and it is hoped that this will result in a CTL over southern Africa never missed being again.

7. An investigation should be done on the connection CTLs have with TTTs.

8. Quantify the contribution of CTLs to the rainfall over South Africa.

7.6 Discussion of challenges

The main challenge encountered during this research was the lack of availability of rainfall data of neighbouring countries in southern Africa. This limited the extent of the research of the rainfall contribution CTLs have, however it does open opportunities for further research in this field.

7.7 Conclusion

In conclusion, from the research presented in this dissertation, it is clear that the rainfall caused by CTLs do contribute to South Africa. An objective identification method was created in order to develop a climatology of CTLs over southern Africa. The objective identification method consists of four criteria which incorporates the dynamical characteristics of a tropical atmosphere. These results show that CTLs mainly exist over southern Zambia and Angola. The furthest south a CTL existed was at 32.5°S which occurred on 23 January 2011. When CTLs do reach South Africa, they are found to occur more frequently over northern Limpopo province with a return period of 5 years while CTLs seldom reach the central interior of South Africa with a return period of 78 years.

Even though the existence of CTLs over South Africa is not an annual occurrence, the rainfall contribution these systems have to South Africa is noteworthy. Extreme rainfall amounts are a common occurrence with CTLs, with 29 grids measuring at least 100 mm and approximately 12 major rain events taking place each year.

From the literature review, it is evident that there is an overall limited research that is dedicated exclusively to tropical weather systems over southern Africa. This research hopes to fill in some of the gaps of tropical weather systems affecting southern Africa and the forecasting thereof. It is also hoped that this possibly be the start of future research in this very opportunity-vast field.

Chapter 8

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