

Spatial and temporal variability of rainfall intensity over the Mooi River catchment

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ABSTRACT

Rainfall is highly variable over space and time. The need for an improvement in the quality of rainfall estimates in Africa has never been greater. In this dissertation the variability of rainfall on the Highveld of South Africa will be explored. For this the Mooi River catchment area has been used to characterise rainfall in the area. The first objective was to characterize the rainfall intensity over the Mooi River catchment. Events were identified by a 15min gap between measurements and characterized by the rainfall intensity and duration of each event measured by a Parsivel disdrometer. It has been found that the majority of events in the Mooi River catchment is highly variable, isolated and has a short duration. These events can therefore be named as convective events. Stratiform events are far more evenly distributed and not that variable, has low rain rates and is longer in duration. These events are not that common in the catchment. The second objective involved developing an algorithm to measure rain rates using a siphon tipping-bucket rain gauge. Measuring rain rates with a siphon poses unique challenges. The newly developed algorithm solves two of the biggest problems associated with siphon gauges. Firstly the rain rate for the first 0.2mm of rain is calculated and added before the first tip of an event. Secondly, double tips were identified, the second tip was deleted and the amount of rainfall of that tip was added to the first tip. A 93% correlation was observed using the new algorithm between the tipping-bucket rain gauge and the Parsivel disdrometer at a time scale resampled to 15minutes. The last objective of this study was to improve single-parameter weather radar data in the catchment. For this objective weather radars, rain gauges and the Parsivel disdrometer was used. It is important to firstly fully understand the variability of the rainfall intensity under the coverage area of a radar to implement new innovative methods which can improve radar rainfall estimates. In the Mooi River catchment when using the theoretical Z-R relation to measure rainfall with radar data events with low rain rates are overestimated and events with high rain rates are underestimated. It has been found that the theoretical Z-R relation used by SAWS is relatively well suited for stratiform events in the Mooi River catchment. However the majority of events in the area are convective which the theoretical Z-R relation does not accurately represent. It is recommended that the Z-R relation used by SAWS should be adjusted to suite the majority of convective events in the catchment situated on the Highveld of South Africa more. Instead of using an A coefficient of 200 and a b coefficient of 1.6, Marshall and Palmer relation, the events will be more represented by a Z-R relation with an A coefficient of 179 and a b coefficient of 1.5.

Keywords: Rain rates, Variability, Parsivel Disdrometer, Weather radar, Siphon, Tipping-Bucket Rain Gauge

DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Magister Scientiae in Environmental Sciences at the Potchefstroom Campus of the North-West University. It has not been submitted before for any degree or examination in any other University.



Jaun van Loggerenberg

15th day of Augustus 2016.

DEDICATION

I dedicate this M.Sc. to the Heavenly Father to honor His guidance and love.

I will be forever grateful to my parents

Hennie van Loggerenberg

and

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Your constant support throughout my studies will always be one of the greatest gifts I have ever received.

PREFACE

The climate of the world is a dynamic and complex system. Research in the past has shown that South Africa is either drying up or undergoing large-scale cyclic rainfall variations (Tyson et al., 1975). This rainfall variation is specifically associated with the variability of the rainfall rates. Small-scale changes in the climate may have large-scale negative effects on the day-to-day weather of a region.

Rainfall intensity is the main contributing factor in natural disasters such as flash floods, landslides, erosion, sinkholes, etc. There has been an increase in flash floods and other natural disasters in the late 1990's (Trenberth, 1998). The same trend has also been observed in other parts of the world. Studies in the United States of America have shown increased rain rates for the biggest part of the twentieth century (Nicholls & Kariko, 1993; Karl & Knight, 1998). Because of climate change the character of rainfall has been changing over the last couple of decades. South Africa, being a developing country is extremely vulnerable to increasing rain rates due to the high density over populated townships with people living in extreme poverty. Developing countries are usually extremely susceptible to flooding because residents from townships normally settle within floodplains. Rainfall events with high rain rates occur from time to time over the Highveld of South Africa and can cause large-scale damage to infrastructure and in some cases human casualties (Easterling *et al.*, 2000; Dyson, 2009; Lennard *et al.*, 2013). Understanding the trends and characteristics of variations in rainfall can improve predictions and forecasting. A previous study has shown that over 70% of the country has seen an increase in rainfall intensity over much of the twentieth century (Mason et al., 1999).

This study is focused on the Mooi River catchment which is in the Highveld of South Africa. Understanding the character of rain in the Mooi River catchment would also improve the understanding of the rainfall character for the entire Highveld as the radars used in this study covers the Gauteng region. This area is extremely important because of the importance of this region to the whole of South Africa. Its importance lies in the fact that

- (a) the economical hub, the Gauteng province, is situated in this area;
- (b) the area is one of the largest food production areas in the country and the effect of rainfall on the Highveld subsequently affects the whole country;
- (c) the area is densely populated and includes residents who often settle within floodplains because of socio-economical reasons.

An improved understanding of the characteristics of rainfall may therefore help in the areas of disaster management, water resource management and agricultural management.

The aim of this study is to improve single-parameter radar rainfall estimates in the Mooi River catchment. The objectives are to:

1. characterise the variability of rainfall intensity in the Mooi River catchment
2. estimate rain rates using a siphon tipping-bucket rain gauge
3. improve single-parameter weather radar rainfall estimates

This study uses the dissertation model as stipulated in the General Rules of the North-West University, Potchefstroom Campus. Chapter One is an introduction which includes a background, problem statement, aims and objectives and literature study. The methodology and data used in this study are set out in Chapter Two. Chapters Three to Five discuss the results and findings. Chapter Three explains the variability of rainfall in the Mooi River catchment. Chapter Four a newly-developed algorithm for the measurement of rain rates using a siphon tipping-bucket rain gauge will be discussed and, lastly, these findings are implemented to improve single-parameter radar rainfall estimates in the Mooi River catchment.

Sections of the thesis have been published, presented orally/poster, or are currently under consideration for publication. Papers have been published and submitted for review in a paper titled “Evaluating radar data by using a ground-based Parsivel disdrometer” that was peer-reviewed and presented at the 10th International Conference of the African Association of Remote Sensing of the Environment (Johannesburg, South Africa, 27 – 31 October 2014)

A peer-reviewed paper was also presented at the 31st South African Society of Atmospheric Sciences Conference (Pretoria, South Africa, 21-22 September 2015) titled “Microstructure of rainfall events on the southern African Highveld”. A poster was presented at the South Africa Society for Atmospheric Sciences (Potchefstroom, South Africa, 1-2 October 2014).

Radar data used in this study was obtained through the tireless help of Mr. Erik Becker from SAWS. Parsivel disdrometer and tipping-bucket rain gauge data operated by the North-West University were measured under the guidance of the author.

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LIST OF ABBREVIATIONS

cappi

Constant Altitude Plan Position Indicator, xviii, 10, 38, 39, 40, 50

CRG

Climatology Research Group, ii

DSD

Drop Size Distribution, ii, 8, 12, 28, 29, 61, 51, 79, 68

ENSO

El Niño Southern Oscillation, 17

FABMS

Bethlehem S- band weather radar, 46

FACTC

Cape Town C- band weather radar, 46

FADNS

Durban S- band weather radar, 46

FADYC

De Aar C- band weather radar, 46

FAELS

East London S- band weather radar, 46

FAEOS

Ermelo S- band weather radar, 46

FAGGS

George S- band weather radar, 46

FAIRS

Irene S- band weather radar, 46

FAOTS

Ottosdal S- band weather radar, 46

FAPES

Port Elizabeth S- band weather radar, 46

FAPPS

Polokwane S- band weather radar, 46

FASZS

Skukuza S- band weather radar, 46

FAUTS

Umtata S- band weather radar, 46

MDV

Meteorological Data Volume, 50, 53

NWU

North-West University, xii, xviii, xx, 35, 38, 40, 44, 45, 46, 55

SAWS

South African Weather Service, ii, viii, xii, xviii, 4, 30, 38, 40, 45, 46, 48, 52, 54, 62, 69

SST

Sea Surface Temperature, 17

TBR

Tipping-bucket rain gauges, xv, xvi, xix, xxii, 12, 13, 15, 16, 37, 40, 1, 2, 50, 51, 58, 59, 74, 77, 78, 79, 61, 62, 63, 64, 62, 63, 64, 66, 67

TITAN

Thunderstorm Identification, Tracking, Analysis and Nowcasting, 50

TTT

Tropical Temperate Trough, 27

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CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

The Highveld of South Africa in which the Mooi River catchment is situated is extremely important for the well-being of the country because of the large scale of agricultural activities in the region; the inclusion of the economical hub of South Africa (Gauteng) and residents living in densely populated townships. A number of different instruments were used in this study namely a Parsivel disdrometer, weather radars and siphon tipping-bucket rain gauges. These three instruments all measure different aspects of rainfall at different scales. An improved understanding of rainfall can help in the management of disasters, of agriculture and water resources as well as the formulation of climate models and the validation of satellite data. Characterizing the variability of rainfall is very important and can help improve the accuracy and reliability of data.

The Parsivel disdrometer is an optical rain gauge that measures each particle's size and velocity as it moves through the sampling area. One of the greatest advantages of the use of this instrument is that it has the ability to measure the rain rate (R) and reflectivity (Z) on the ground simultaneously at a resolution of 10s. The Z - R relation is a direct measurement of the drop size distribution (DSD) and the use of this measurement may improve the quality of radar rainfall estimation.

The South African Weather Service (SAWS) currently uses a generic Z - R relation to extend the Z measurement made in the atmosphere by the radar-to rain-rate on the ground. However, the rain rates of rainfall events in this region are highly variable and using this theoretical relation can create inconsistencies in the radar rainfall estimates. Measurements made by the disdrometer were used to determine new Z - R relations for different rainfall events which included mixed, convective and stratiform precipitation. South Africa has an extensive network of weather radars. It includes nine single polarised S-band radars, one dual-polarised S-band weather radar, two mobile dual-polarised X-band radars and 5 C-band radars. Maintaining the network with limited funds presents unique challenges in a developing country. The main radar used in this study is the Irene weather radar. This radar covers the Mooi River catchment and also the Highveld of South Africa. Therefore, findings made on the rainfall characteristics in the catchment can be implemented on the radar to improve the rainfall estimates for the entire Highveld region. In this context, optimized algorithms for precipitation estimation in this setting are shown.

Despite it being one of the oldest types of measuring instruments, the use of tipping-bucket rain gauges is still very common, because of its simplicity and ruggedness. Rain gauges have the tendency to overestimate events with high rain rates. Therefore newer models are developed

with a siphon. The siphon controls the flow of water into the buckets which eliminates over-estimation errors. This, in turn, creates irregularities in the rain rate measurement. SAWS operate over 600 of these rain gauges across South Africa. The Climatology Research Group (CRG) also operates a high-density rain-gauge network in the Mooi River catchment which consists of twenty of these instruments. This rain gauge network is considered as a high-density network compared to other networks across the country as it is the densest per m^2 . The high number of rain gauges in South Africa has the ability to provide accurate and reliable data of rainfall intensity on a spatial extent. These rain gauges all use a siphon to eliminate overestimation at high rain rates. It will therefore be very beneficial to develop an algorithm which could be used to measure rain rates with a siphon tipping-bucket rain gauge.

1.1 Background

The need for improved radar rainfall estimates has never been greater in South Africa. The changing character of rainfall justifies the need to explore new methods to measure rainfall more accurately and reliably. The South African Weather Service has an extensive network of weather radar across South Africa. These are cutting-edge top-of-the-range weather radars equipped with 21st-century technology. However these radars use old strategies to measure and estimate rainfall. Inconsistencies exist in weather radar data because of the highly variable nature of rainfall on the Highveld of South Africa. Understanding the rainfall variability will help in developing new ways of calculating rainfall

To improve the accuracy of radar rainfall estimates it is extremely important for high-resolution reliable data to be available. Tipping-bucket rain gauges are often deployed in large networks to study the spatial variability of rainfall. These rain gauges measure the volume of rainfall at a resolution depending on the size of the bucket. Measuring rain rates is however a problem and in this dissertation a new method is developed to measure rain rates with these rain gauges equipped with a siphon (Maksimović et al., 1991; Sieck et al., 2007; Wang et al., 2008).

Rainfall on the Highveld is highly variable over space and time (Tyson *et al.*, 1975; Janowiak, 1988; Walker, 1990; Lindesay & Jury, 1991; Matarira & Jury, 1992; Levey & Jury, 1996; Mason & Jury, 1997; Reason & Mulenga, 1999; Landman *et al.*, 2001; Cook *et al.*, 2004; Reason *et al.*, 2005; Rouault, 2014). This makes the measurement of rainfall intensity very challenging. Understanding these variations and the small-scale changes in the drop-size distribution between different storms can help to develop new methods of measuring rainfall using weather radars. It is very important to develop methods for estimating rain rates considering the type of

event and the climate. These methods can differ between events and climates and therefore using the same methods for all events and climates can create inconsistencies in data.

When striving to improve radar rainfall estimates it is important to consider two aspects that could influence the accuracy and reliability of data (Ulbrich & Miller, 2001). Firstly, the Z-R relation between storms is highly variable. Because of the difference in storm structure between stratiform and convective events the Z-R relation differs significantly (Houghton, 1968; Batten, 1973:68; Steiner & Houze Jr, 1997; Biggerstaff & Listemaa, 2000). Methods used to estimate rain rates in convective storms cannot be utilized in the same way for stratiform precipitation because of the large discrepancies in storm structure. Secondly, the performance of the radar must also be taken into considerations. Weather radars often tend to overestimate events with low rain rates and underestimate events with high rain rates. Comparing weather radar data to data measured on the ground can improve the accuracy of the data by calculating the calibration offset and applying a bias measurement (Ulbrich & Miller, 2001).

A detailed discussion of the factors that influence the variability of rainfall over space and time will be discussed in this chapter. The increase in greenhouse gasses around the world may result in an increase in surface temperature and the enhancement of the hydrological cycle. This increased temperature may accelerate evaporation and lead to a rise in moisture within the atmosphere. The frequency of events with higher rain rates may increase in the next few decades (Trenberth, 1998). The research goals and research design are also outlined in the chapter.

1.2 Problem Statement

The character of rainfall differs between different climates and locations. This causes challenges in the measurement of rain rates. The rainfall in the Mooi River catchment on the Highveld of South Africa poses unique challenges in the measurement thereof. This is because of the high variability over space and time. To improve radar rainfall estimates one needs to fully understand the character of rainfall and how changes.

It is also very important that ground truth measurements of rain rates must be made to validate measurements made by the radar aloft. For reliable measurements to be made on the ground tipping-bucket rain gauges are used. Because these rain gauges are prone to errors at high rain rates they are fitted with a siphon which regulates the flow of water into the buckets. This creates another problem as it makes it difficult to measure rain rates. In this dissertation a new algorithm is developed to measure rain rates using these siphon tipping-bucket rain gauges.

Improving radar rainfall estimates involves understanding the character of the rainfall in the region. This includes the spatial and temporal variability and the relationship between the reflectivity and the rain rate. Once this is understood parameters can be set on the radar for optimal performance for a specific climate which includes parameters such as the Z-R relationship, bias measurements and offsets which is derived when investigating the character of rainfall.

1.3 Research Questions

The overall aim of this research is to characterize the variability of rainfall intensity over space and time in the Mooi River catchment which is situated on the Highveld of South Africa. This was done to improve the accuracy and reliability of radar rainfall estimates which is so desperately needed especially in developing countries like South Africa. More specifically, the objectives are to:

1. characterise the variability of rainfall intensity in the Mooi River catchment
2. estimate rain rates using a siphon tipping-bucket rain gauge
3. improve single-parameter weather radar rainfall estimates

1.4 Research Design and Study Area

It is essential that data is as accurate as possible when investigating small-scale changes in rainfall. The Parsivel disdrometer can measure rainfall at a high resolution (10s) that enables it to measure microphysical processes within rainfall. Weather radar is also extremely important because it can measure rainfall at large distances with a small infrastructural footprint. SAWS has an extensive network of rain gauges over South Africa. The North-West University operates a high-density rain gauge network, which is considered high density in the South African context, in the Mooi River Catchment on the Highveld of South Africa (Figure 1-1). Comparing the data of these instruments to one another can improve the accuracy and reliability of data.

The weather radars used in this dissertation are operated by SAWS. This includes the Irene weather radar (FAIRS) which is a single-polarised S-band radar situated in Irene, Gauteng. The Bethlehem radar (FABMS) is a state-of-the-art dual-polarised S-band weather radar located in Bethlehem, Free State. Lastly, the Ottosdal weather radar (FAOTS) situated in Ottosdal, North West is, as the Irene radar a single-polarised S-band radar. The Parsivel disdrometer was placed outside of Potchefstroom in the North West Province.

The study area is mostly focused on a portion of the Mooi River catchment area situated within the Highveld of South Africa between Potchefstroom, North West and the Irene weather radar. This area has been chosen because of the location of different weather radars in the area, the Mooi River rain-gauge network which is located predominantly North-East of Potchefstroom between Potchefstroom and Gauteng and the presence of a number of SAWS rain-gauges. The area is also very important for the economy because of the large scale agricultural activities and dense population.

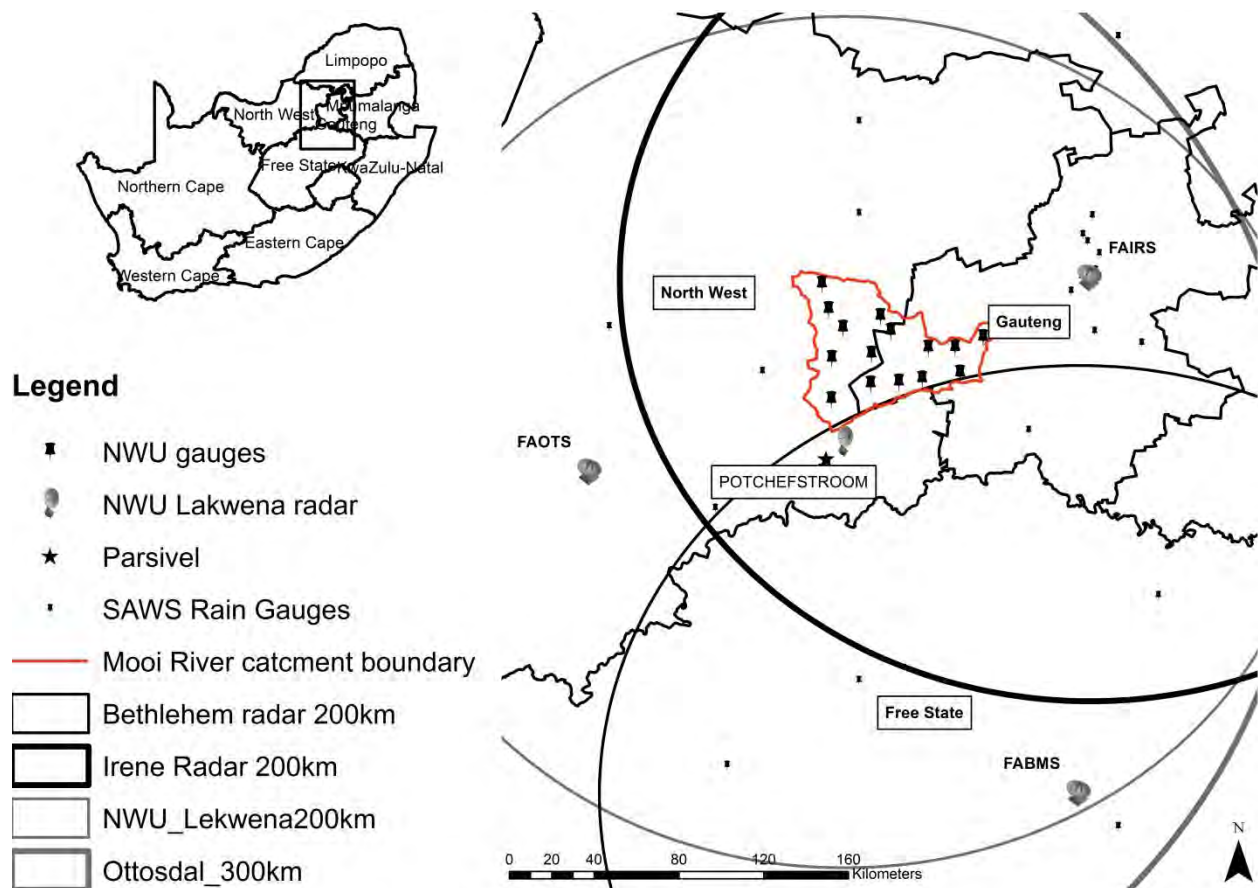


Figure 1-1: Study design, study area (Mooi River catchment) and instrument placement within the Highveld of South Africa. The study is focused in the Mooi River catchment. All the radars and the rain gauges covering the area are presented.

1.5 Introduction

Climate variability is a cause of concern as it impacts directly on human and environmental health. Predictions show that with climate variability and no adaption to these changes an additional 65000 deaths will occur due to heat exposure and flooding in the next few decades (Hales et al., 2014). This may have a devastating effect on a developing continent like Africa.

Research has shown that human activity is responsible for 95 percent of the observed warming of the earth's surface (IPCC, 2014). The warming of the atmosphere and ocean, the rising sea level, a decrease in snow and glacier formations and the increase in concentrations of greenhouse gases caused by anthropogenic influences are accelerating natural changes which is all a consequence of climate change (Stocker et al., 2013; Hales et al., 2014; IPCC, 2014; Neira, 2014). These small-scale changes in environmental processes can have a significant impact on the day-to-day weather of a region (IPCC, 2014).

The frequency and intensity of rainfall have been increasing globally over the last decade (Nicholls & Kariko, 1993; Karl & Knight, 1998). Rainfall intensity is one of the main triggers in natural disasters such as flash floods and landslides and, therefore, the shift in rainfall research from the amount to the intensity of rainfall is very important (Lanza & Stagi, 2002; Trenberth et al., 2003). Understanding rainfall intensity and the variability thereof will help in predicting flash floods and determining rainfall trends. Since 1950 there have been changes observed in extreme weather and climate (IPCC, 2014). The changes are mainly caused by an increase in surface temperatures which is directly proportionate to the amount of moist air that can be stored in the atmosphere. Increase in the moisture content in the air can have an impact on the hydrological cycle and cause variability in rainfall (Figure1-2) (IPCC, 2014). Studies have found that large parts of the United States of America experienced an increase in rain rates during the twentieth century (Nicholls & Kariko, 1993; Karl & Knight, 1998).

Researchers have found that South Africa is either drying up or undergoing large-scale cyclic rainfall variations (Tyson et al., 1975). Being a developing country these long-term changes is cause for concern because of the susceptibility to climate variability and a poverty-stricken society (Mason & Joubert, 1997; Engelbrecht et al., 2009). High-intensity rainfall with high rain rates often occurs on the Highveld of South Africa (Dyson, 2009). Small-scale changes in climate condition can have devastating effects on the day-to-day weather. An increase in rain rates have been observed in most parts of the country and this is particularly a problem because over 10 000 people in South Africa have settled in floodplains (Mason et al., 1999).

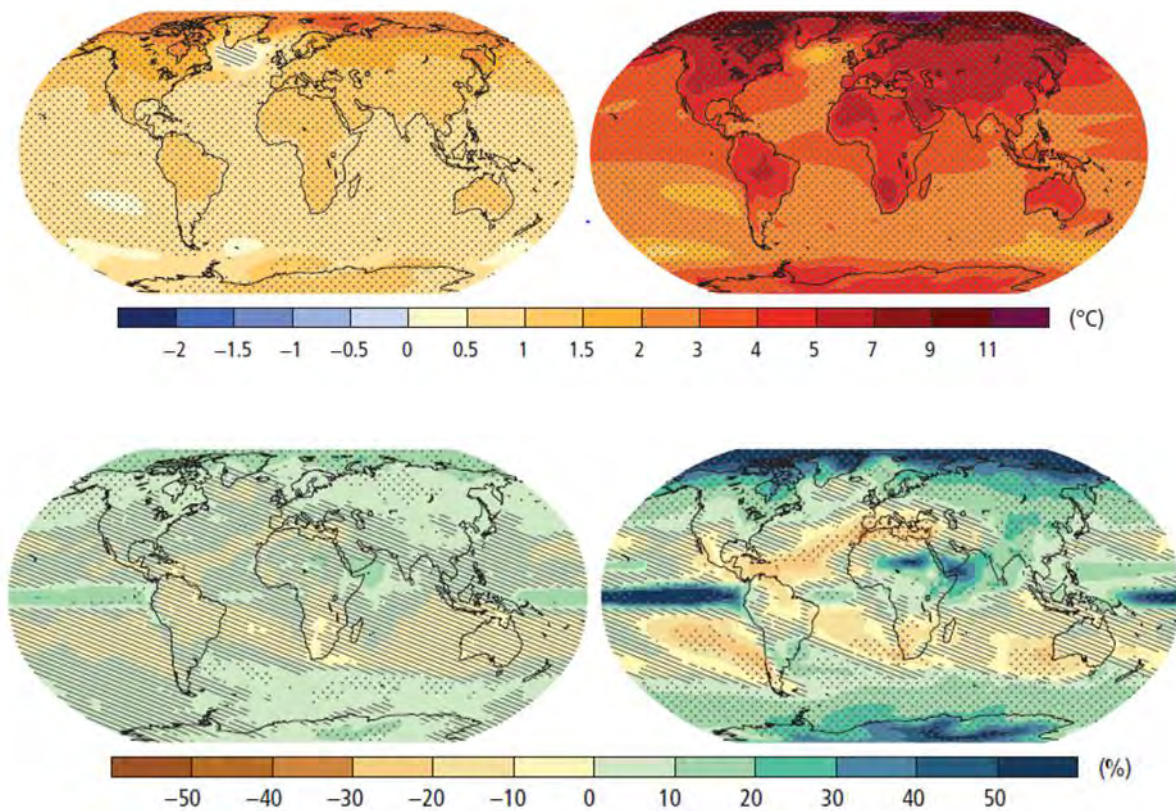


Figure1-2: Changes in the average surface temperature and average surface rainfall (1986-2005 to 2081-2100) (IPCC, 2014). The top image shows the changes in the temperature on the surface which causes evaporation to increase and therefore more moist air in the atmosphere. This can cause some changes in rainfall trends (bottom) (IPCC, 2014).

In this study changes within the environment, specifically related to the spatial and temporal variability of rainfall intensity will be discussed. Most of these changes are caused by anthropogenic impacts (IPCC, 2014). The entire climate system is extremely susceptible to small changes in the composition of the atmosphere. Microphysical processes within clouds and changes in the microstructure of the drop size distribution may give us a better understanding of the variability of rainfall on the ground. The change observed in rainfall intensity can be linked to variations in the microphysics of clouds that are caused by anthropogenic impacts. Rainfall intensities are extremely important to understand because it is a consequence of what happens within a cloud.

The need for improved rainfall estimates in Africa has never been greater (Lanza & Stagi, 2002). Understanding changes and linkages between different scales of rainfall intensity require

high-resolution, accurate microphysics measurements of clouds. Instruments like weather radars and rain gauges have been used in the past for rainfall studies. However, these conventional methods have their limitations and consequently specialized instruments such as the Parsivel disdrometer have started playing a bigger role due to its ability to measure microphysical processes within clouds (Krajewski & Smith, 2002; Nikolopoulos et al., 2008; Tokay et al., 2010). High-resolution data and quality observation are needed to do accurate investigations into rainfall dynamics, cloud dynamics, microphysical processes within clouds and synoptic types associated with high-intensity rainfall events (Nikolopoulos et al., 2008). Parsivel disdrometers, weather radars and tipping-bucket rain gauges all measure rainfall but at different scales and they measure different aspects of rainfall. The disdrometer measures the size and velocity of each particle of rain that moves through the sampling area at a 10-second resolution. Tipping-bucket rain gauges measure the volume of rainfall at a 0.2 mm resolution. Weather radars measure the reflectivity of particles at a large spatial scale (200km).

The high variability of rainfall intensity in the Mooi River catchment, the upgraded, “state of the art” weather radar network operated by SAWS and a large number of tipping-bucket rain gauges in South Africa warrant the undertaking of further investigations in this study. The SAWS upgraded the entire weather radar network of South Africa in 2005 for roughly \$20 million. Understanding the variability of rainfall can help to improve weather radar data by exploring different rainfall estimate algorithms. Using these radars to their maximum potential is consequently very important. Finally, measuring rain rates accurately across South Africa is not possible because of the use of siphons in the tipping-bucket rain gauges. In this study a newly-developed algorithm has been used to eliminate the errors created by the siphon to measure these rainfall rates accurately.

1.6 Literature Review

“Changes in many extreme weather and climate events have been observed since about 1950. Some of these changes have been linked to human influences, including a decrease in cold temperature extremes, an increase in warm temperature extremes, an increase in extreme high sea levels and an increase in the number of heavy precipitation events in a number of regions.” (IPCC, 2014).”

1.6.1 Spatial and Temporal Variability of Rainfall

Southern Africa is a region characterized by rainfall which is highly variable both inter-annually and inter-seasonally (Tyson *et al.*, 1975; Janowiak, 1988; Walker, 1990; Lindesay & Jury, 1991; Matarira & Jury, 1992; Levey & Jury, 1996; Mason & Jury, 1997; Reason & Mulenga, 1999; Landman *et al.*, 2001; Cook *et al.*, 2004; Reason *et al.*, 2005; Rouault, 2014). Changes in

rainfall have also been seen over long periods. A number of studies have been conducted that discuss the different factors influencing the rainfall variability over South Africa. El Niño Southern Oscillation (ENSO) is a phenomenon caused by variations in the sea surface temperature (SST) of the Pacific Ocean that affects most of the tropics and subtropics and can cause changes in rainfall over southern Africa (Jin et al., 2008). Climate change, both natural and anthropogenic, is also proving to be one of the main causes for the observed rainfall variations (IPCC, 2014). The intensification of different rain-producing synoptic types also has an effect on rainfall (Walker, 1990; Matarira & Jury, 1992; Reason et al., 2005).

Observed droughts in South Africa have awakened new concerns regarding the impact of climate change in the country (Dube & Jury, 2000; Kephe et al., 2015). In South Africa the Gauteng Province¹ is the region that is the most vulnerable to changes in rainfall intensity (Piketh et al., 2014). Researchers believe that South Africa is either drying up or undergoing large-scale cyclic rainfall variation (Tyson et al., 1975). This is problematic for the agriculture sector as it depends heavily on more evenly distributed rainfall distributions (Tyson et al., 1975). Food security in the country is consequently under threat (Reason et al., 2005).

El Nino and La Nina are phenomena that may contribute to changes in rainfall patterns over South Africa (Reason et al., 2005; Rouault, 2014). El Nino is normally associated with droughts and occurs because of the higher temperature (warming) of the sea surface temperature (SST) in the Pacific Ocean. This normally results in droughts especially over southern Africa. La Nina is associated with the cooling of the SST and most of the time causes above average rainfall years in countries south of the equator. El Nino years are therefore associated with lower rainfall and La Nina years with higher rainfall (Jin et al., 2008).

On average the rainfall observed during La Nina years are 20%-25% more than in El Nino years (Rouault, 2014). However, exceptions to the norm have been observed where variations do occur in the results of these phenomena² (Reason et al., 2005; Rouault, 2014). For farmers, knowing when El Nino and La Nina years are expected is crucial. Late October and the start of November is very important in maize production and therefore variations in rainfall in this critical period of germination can have a large negative impact on production (Dube & Jury, 2000; Reason et al., 2005).

Changes in synoptic types in South Africa impact hugely on the variability of rainfall over the country (Taljaard, 1986; Walker, 1990). Rain-producing synoptic weather patterns are explained

¹Part of the Highveld of South Africa

² El Nino = Dry year, La Nina = Wet year

in Chapter 1.6.9. Dominant rain-producing systems change from time to time in intensity and composition. This can cause widespread variability in the amount and intensity of rainfall (Reason et al., 2005). The dominant synoptic weather systems that can cause this variability in the northern parts of South Africa is mostly the movement of warm, moist air from the tropics that rises orographically and forms tropical low-pressure systems (Engelbrecht et al., 2013). These systems are called easterly low-pressure systems and cause a large number of isolated convective systems over the Highveld. The South Indian anti-cyclone also produces rainfall when it moves closer to the coast of South Africa and brings moist air from the warm Indian Ocean³ inland and creates favourable conditions for rainfall (Lindesay & Jury, 1991; Tyson & Preston-Whyte, 2000; Dyson & van Heerden, 2001; Reason et al., 2005; Tadross et al., 2005).

Climate change - anthropogenic and natural - is one of the main reasons for the observed high levels of variability in rainfall intensity (IPCC, 2014). The frequency of events with high rain rates has increased drastically over the last few decades and it is predicted that this will keep on rising (Mason & Joubert, 1997; Mason et al., 1999; Piketh et al., 2014). The opposite is also true that, for some places in South Africa, droughts have become more evident (Dube & Jury, 2000; Rouault & Richard, 2003). Continued emissions of greenhouse gasses may cause these events with high rain rates to increase and the occurrence of droughts may also occur more often (IPCC, 2014).

South Africa, a country stricken by poverty, is extremely vulnerable to changes in the rainfall intensity (Reason et al., 2005). Most researchers suggest that the level of variability in both the frequency of events with high rain rates and droughts is increasing. Agriculture and rural communities will be affected the most (Taljaard, 1986; Walker, 1990; Mason & Joubert, 1997; Mason & Jury, 1997; Mason et al., 1999; Dube & Jury, 2000; Rouault & Richard, 2003; Engelbrecht et al., 2013; Piketh et al., 2014). Locally, global plans should be drawn up to counter this effect and to ultimately mitigate the effects of climate change (IPCC, 2014; Piketh et al., 2014).

1.6.2 Importance of rain rates globally and locally

The changing character of rainfall globally is a cause of concern (IPCC, 2014). Various parts of the world are experiencing significant increases in the amount of days per year with heavy rain events associated with high rain rates (Easterling et al., 2000). Studies have shown that this increase in rain rates is, especially in the United States of America, receiving more media coverage. People are becoming more and more concerned about changing rain rates and the

³Caused by the warm Mozambique sea current

increase in the frequency of events with high rain rates. This increase in media coverage was however not found in the rest of the world (Ungar, 1999). Over the last decade societies have become more susceptible and vulnerable to extreme weather due to the increase in population and built-up areas. This makes the impact of events with high rain rates far worst (Kunkel et al., 1999). Globally there are not many countries that have data records that go back far enough for changes in rainfall intensity to be observed. A total of 15 out of a possible 22 countries have seen increases in rain rates and seven has observed decreases in rain rates (Easterling et al., 2000) (Figure 1-3).

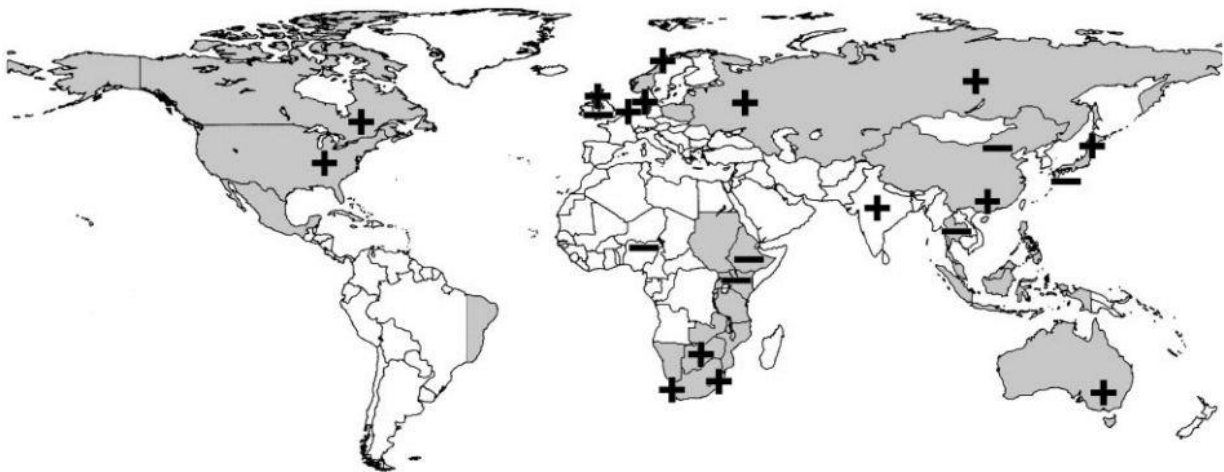


Figure 1-3: Countries in grey has large enough data sets so that trends in rain rates can be observed. These periods are all from 1950 until 2000. The plus and the minus signs indicate areas where significant changes have been observed (Easterling et al., 2000).

Several studies have shown that in South Africa rainfall intensities are changing (Groisman et al., 2004; Kruger, 2006; Groisman et al., 2009; Lennard et al., 2013) (Figure 1-4). The country has seen large increases in heavy precipitation (Easterling et al., 2000). Some other studies that investigated trends in rain rates include those of Mason *et al.* (1999), Hulme *et al.* (2001), Fauchereau *et al.* (2003) and New *et al.* (2006). All of these found that the character of rainfall in South Africa is changing.

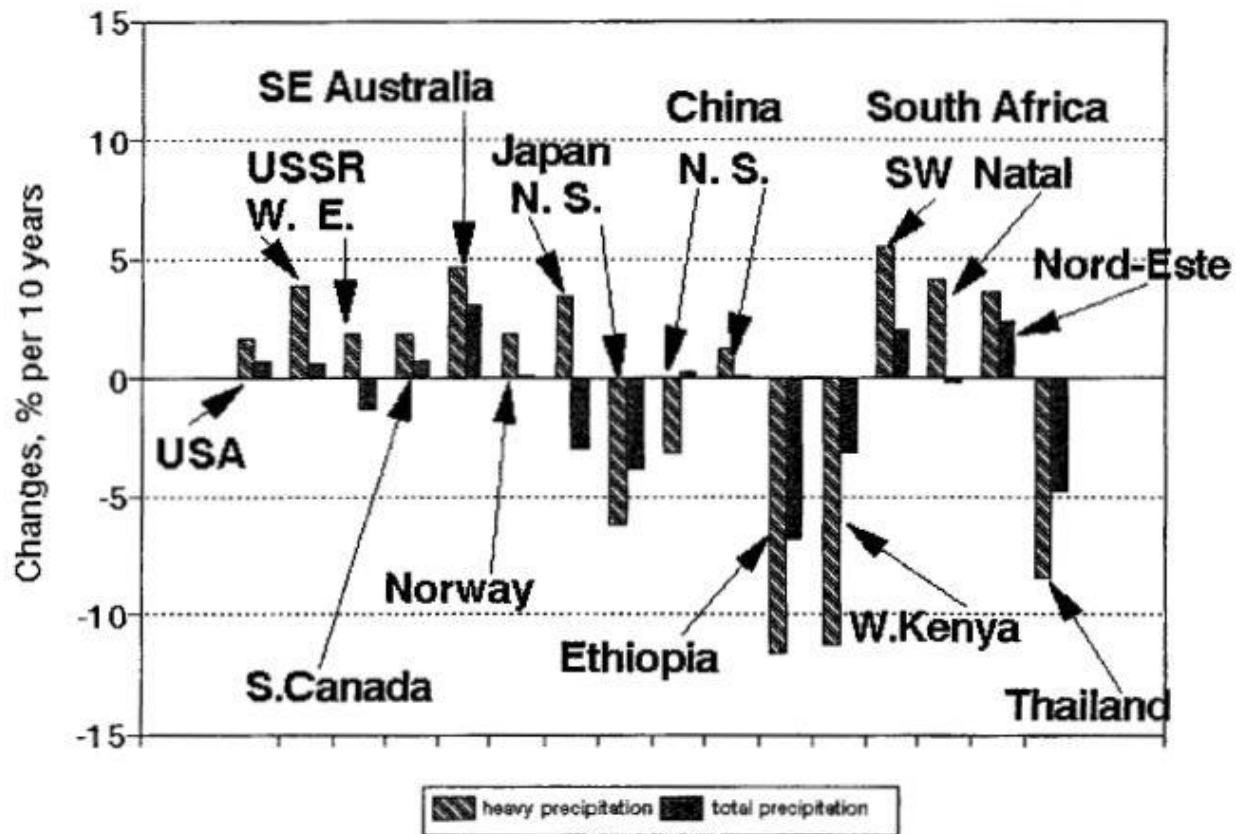


Figure 1-4: Changes observed in precipitation over the world including South Africa. The solid bars represent total precipitation and the line bar is changes in heavy precipitation over the last ten years (Easterling et al., 2000). It is clear that South Africa have seen increases in heavy precipitation the past ten years.

1.6.3 Measurements of rainfall using ground-based instruments

Prediction of rainfall is a term used to improve preparation for future events. To predict is thus reliant on the observation and measurement of rainfall. Rain gauges, disdrometers and radars are all instruments that measure rainfall at different scales and also measures different aspects of rainfall. Disdrometers measure the diameter and velocity of every particle with a very small sampling area on the ground at a high resolution (10s). Rain gauges measure a volume of rain at a resolution, depending on the type of rain gauge, of either 0.2mm or 0.4mm. The weather radar can measure rainfall at a large spatial extent within a radius of up to 300km. These instruments measure the reflectivity of rainfall (Tapiador et al., 2012). Combining the data and exploring linkages between these instruments can improve the accuracy and reliability of rainfall measurements.

1.6.4 Measuring rainfall by using optical rain gauges

Rainfall is highly variable over space and time and consequently the need for improved measuring methods is increasing (Tyson *et al.*, 1975; Janowiak, 1988; Walker, 1990; Lindesay & Jury, 1991; Matarira & Jury, 1992; Levey & Jury, 1996; Mason & Jury, 1997; Reason & Mulenga, 1999; Landman *et al.*, 2001; Cook *et al.*, 2004; Reason *et al.*, 2005; Rouault, 2014). Scientists have been very interested in measuring the size and velocity of particles (Löffler-Mang & Jurg, 2000). Disdrometers are instruments that have this ability. There are three types of disdrometers.

Impact disdrometers use the impact of each particle that makes contact with the sampling areas and converts it into an electrical pulse or acoustic signal of which the size can be correlated to the size of the particle (Lewis, 2012). This way of measuring rainfall is relatively old compared to new optical disdrometers. The correlation between optical disdrometers and impact disdrometers is relatively good with the impact disdrometer often showing a slightly lower reading (Tokay *et al.*, 2001). One of the disadvantages of this technique is the difficulty when it comes to evaluating the measurements. One of the main reasons for this is the fact that, as a particle makes contact with the measuring pad, droplets will break up and smaller droplets of the same particle will be measured (Löffler-Mang & Jurg, 2000).

Another type of disdrometer that is also used often is a two-dimensional video disdrometer. It uses two orthogonal sheets of white light separated vertically by a short distance. Particles passing through the light cast a shadow on the photodetectors that measure the size and the velocity of the particle (Krajewski *et al.*, 2006).

1.6.4.1 Parsivel disdrometer principle of operation

New, innovative instruments have been developed through technological advances to measure rainfall more accurately. The Parsivel disdrometer is an optical rain gauge that uses cutting-edge laser technology to measure each particle's size and velocity as it moves through the laser beam (Löffler-Mang & Jurg, 2000)(Figure 1-5).



Figure 1-5: The Parsivel disdrometer consists of two housing units that contain the receiver and transmitter. The sampling area is between these two units (Löffler-Mang & Jurg, 2000).

It consists of two housing units that hold the receiver and the transmitter (Figure 1-6). It has a height of 340mm, width of 100mm and length of 520mm (Löffler-Mang & Jurg, 2000). With a sampling area of 54cm² it can measure particles up to 25mm in diameter and velocities between 0.2 and 20m/s (Battaglia et al., 2010; Jaffrain & Berne, 2010; Tokay et al., 2010). This is, however, not the true sampling area as some additional aspects should be taken into account. The first two classes of sizes (0.062 and 0.187 mm) have a very low signal-to-noise ratio. These particles are normally drops that are only partially detected by the laser beam and are considered as insignificant.

Therefore the effective sampling area can be estimated as a function of drop diameter:

$$S_{eff}(D_i) = L \times \left(W - \frac{D_i}{2} \right), \quad (1)$$

where S_{eff} is the effective sampling area, D_i represents the centre of the i th diameter class, L is the length (180mm) of the laser beam and W the width (30mm) (Löffler-Mang & Jurg, 2000; Battaglia et al., 2010; Jaffrain & Berne, 2010).

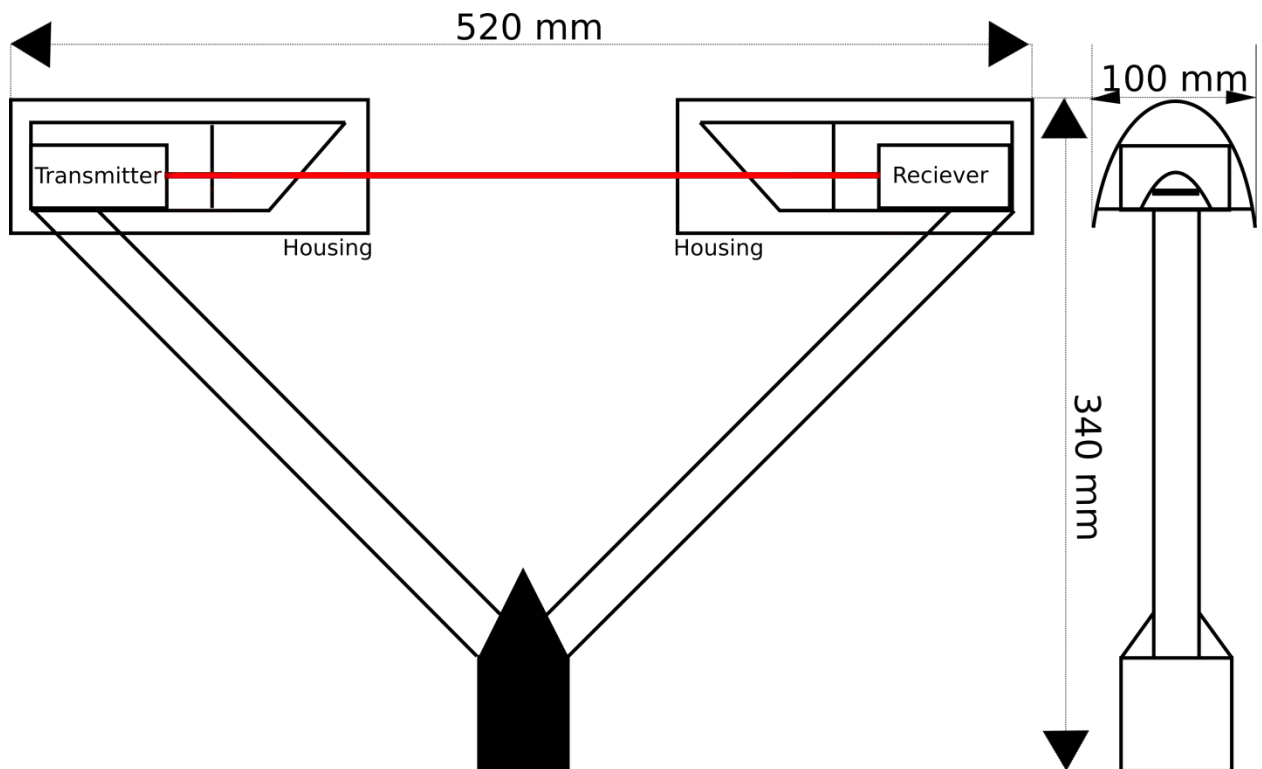


Figure 1-6: The Parsivel disdrometer has a height of 340mm, length of 520mm and width of 100mm (Löffler-Mang & Jürg, 2000).

The particles are then categorised into 1024 classes of size and velocity and is displayed on a 32×32 matrix (Jaffarin et al., 2001). The measuring principle is based on the attenuation of the laser beam as the particle passes through the beam (Jaffarin et al., 2001). Attenuation can be seen as the loss in power due to blockage that, in this instance, may be caused by the rain particle (Figure 1-7). These disdrometers are the most widely-used today because of their ability to measure each particle accurately. This new way of measuring rainfall is said to be the most accurate of all ground-based measuring methods (Tokay et al., 2001). The Parsivel disdrometer, manufactured by OTT in Germany is the most used optical disdrometer.

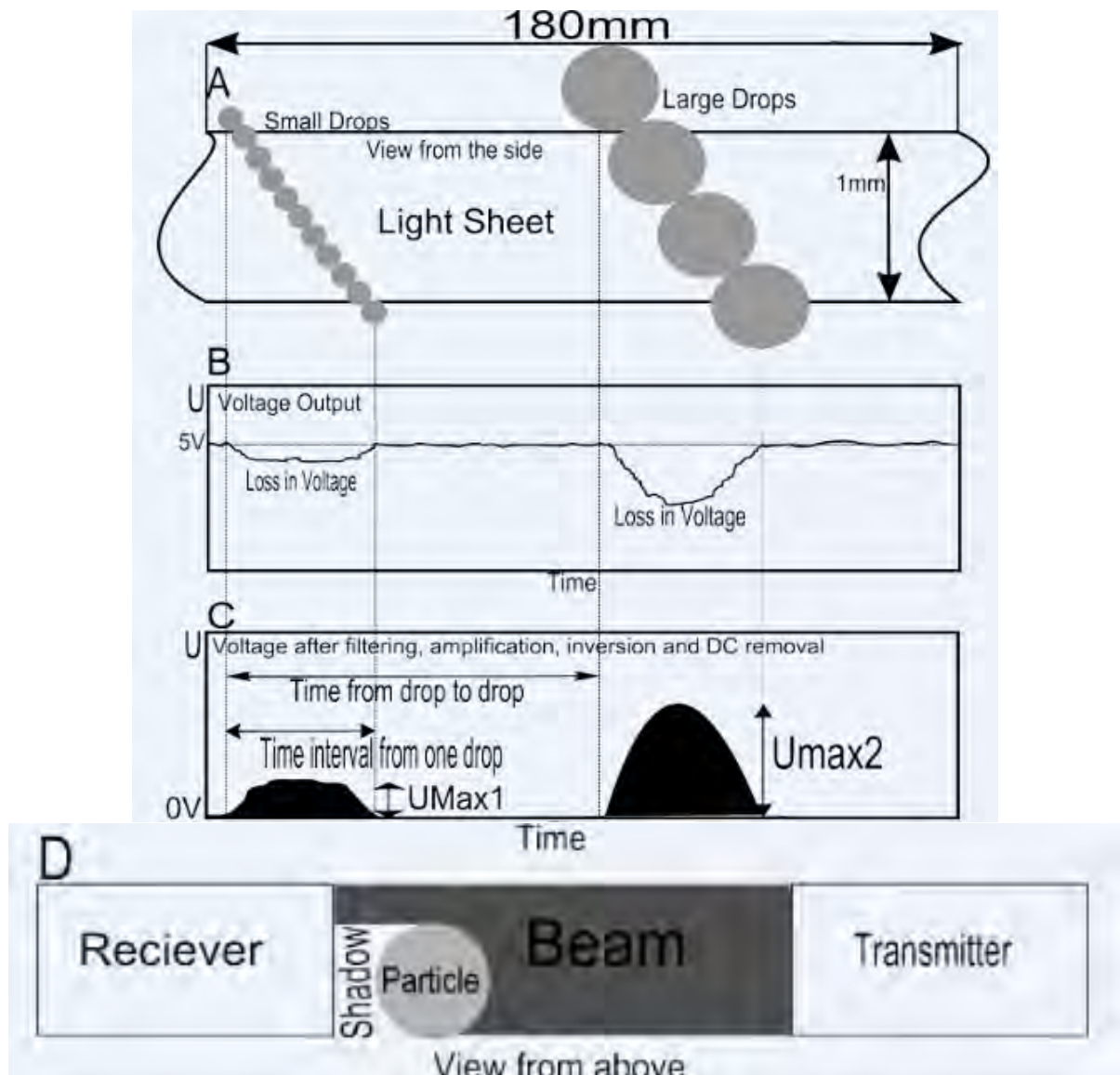


Figure 1-7: The process of measuring rainfall by the disdrometer is based on attenuation from the particle that moves through a laser beam. The sequence of events is described from figure A to C. Figure D is an image of the disdrometer measuring a particle from above (Löffler-Mang & Jurg, 2000).

To study the microphysical processes within clouds it is important that data be measured at a very high resolution. The disdrometer has the ability to measure the size and velocity of each particle that moves through the laser beams. This is a direct measurement of the DSD. It also can measure the reflectivity (Z) and rain rate (R) on the ground simultaneously. These new

algorithms can improve rainfall estimates and can also help in the validation of climate models (Chapter 5.3) (Ulbrich & Miller, 2001).

When the data of all these disdrometers are compared, a constant underestimation is observed by the impact and two-dimensional video disdrometer. Compared to tipping-bucket rain gauge data, the optical disdrometer, specifically the Parsivel disdrometer, showed the best correlation (Tokay et al., 2001).

1.6.5 Single and dual-polarised weather radars

Remote sensing estimates of rainfall are exceedingly important when studying the variability of rainfall intensity. Such estimation involves the process of measuring an object from a distance without being in contact with it (Campbell, 1996:105).

Weather radar is crucial instrument when measuring rainfall because of the ability to measure large areas with a small infrastructure footprint. The most important components include the transmitter, antenna, receiver and the display (Rinehart, 1997:3)(Figure 1-8). The transmitter sends out a high-frequency signal which returns and is picked up by the antenna that listens for an echo made by a particle. This is then detected by the receiver which in turn gets amplified and displayed.

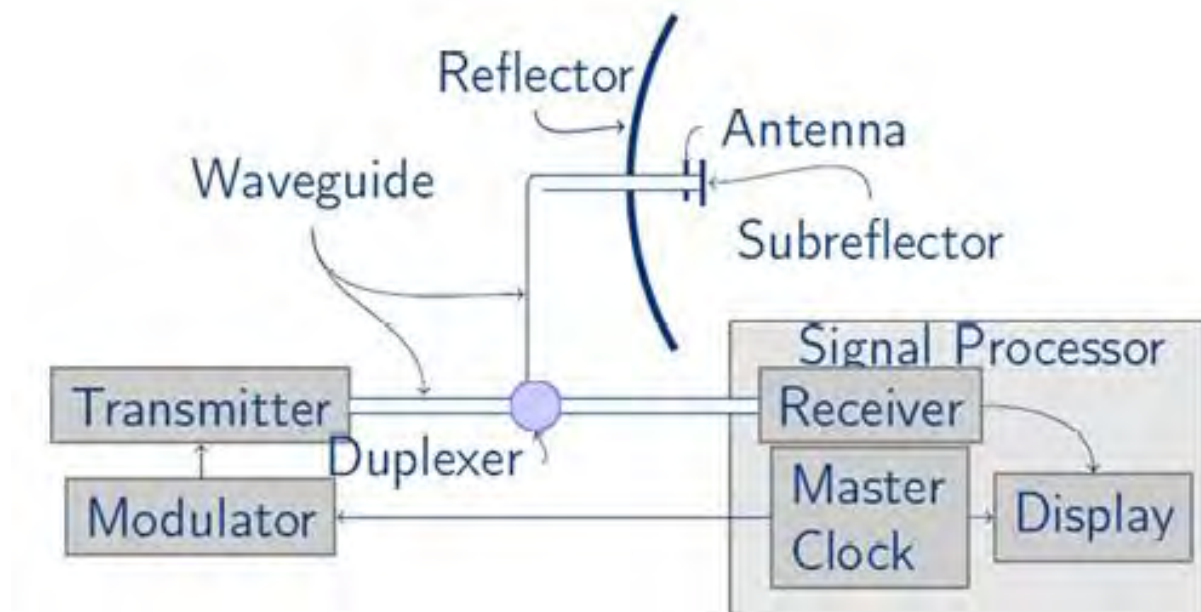


Figure 1-8: The schematic of a weather radar. The main components shown in this image is the receiver, transmitter and antenna (Rinehart, 1997:16).

1.6.5.1 Weather radar principle of operation

Weather radars are vital in the measurement of rainfall due to their ability to measure rainfall from large distances with a minimal infrastructural footprint. Radars work by sending out powerful electromagnetic waves into the atmosphere (Figure 1-9). The returning echo made by drops is measured by the receiver and this returned power is calculated using Eq. (2) (Vivekanandan et al., 1999). This equation describes the relationship between the power received, the properties of the radar as well as the properties of the target and the distance between the target measured and radar:

$$\overline{P_r} = C \frac{|K|^2}{r^2} Z \quad (2)$$

where $\overline{P_r}$ (Watts) is the mean of the power that is returned from the raindrops at a certain range r (km), the radar constant is C , $|K|^2$ is the coefficient of the dielectric of water (the ability of water to store electrical energy) (~ 0.93) and Z is simply the returning power which is directly related to a physical quantity called reflectivity (dbz) measured in mm^6/m^3 (Uijlenhoet, 2001; Krajewski & Smith, 2002). All the properties of the radar is contained in the radar constant C and all the properties of raindrops in $|K|^2$ and Z .

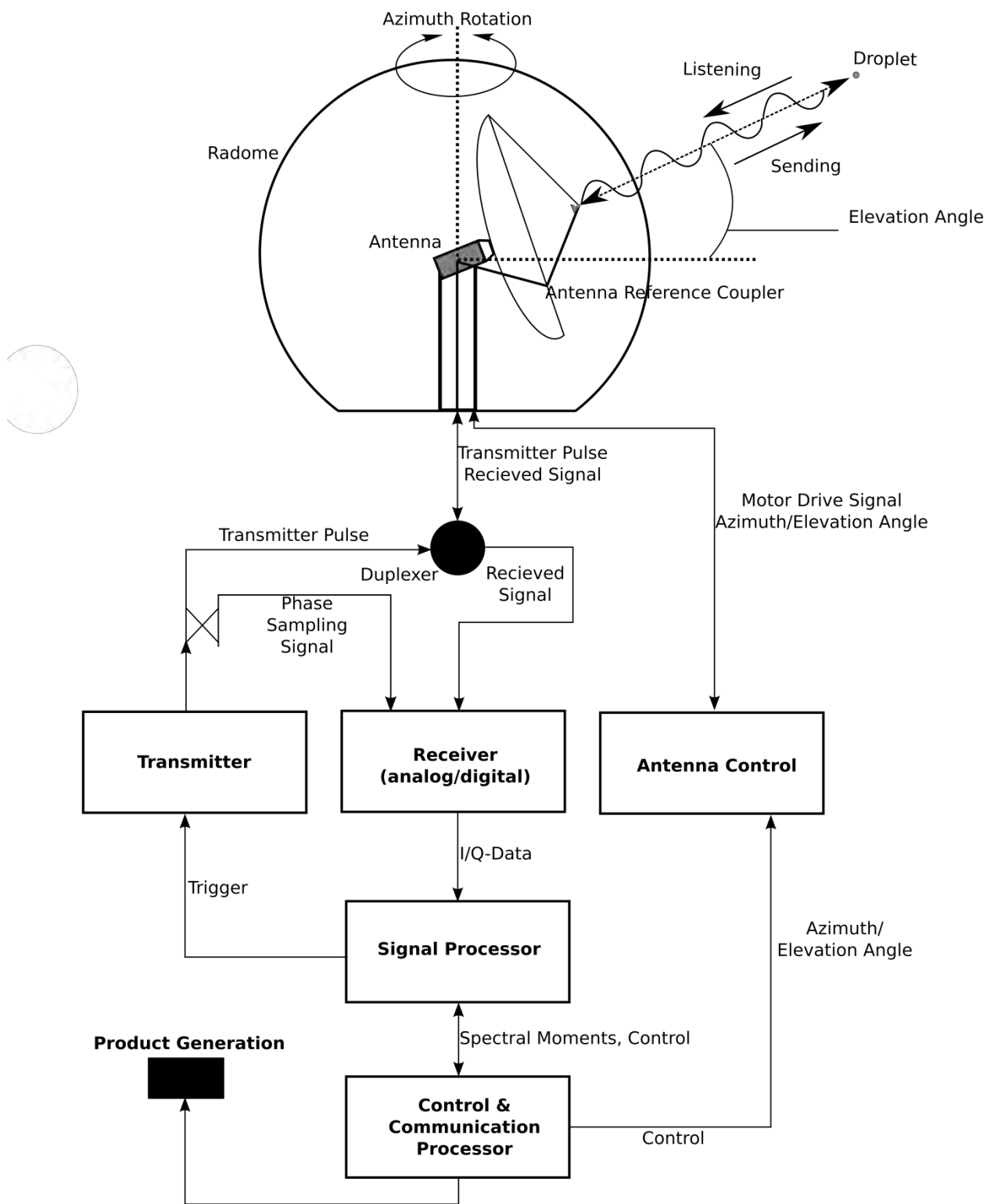


Figure 1-9: The principle of weather radar operation (Rinehart, 1997:23; Meischner, 2004:100).

1.6.5.2 Errors associated with the estimating rainfall using weather radars

There are also a number of errors associated with weather radar measurements. At large distances radars tend to underestimate events because the beam of the lowest constant altitude plan position indicator (Cappi) increases in height above sea level as the distance from the radar increases (Ulbrich & Miller, 2001)(Figure1-10). Some other errors and limitations associated with the use of radars include ground and sea clutter, mountains, shallow rain, attenuation, partial beam blocking, the bright band etc. (Doviak & Zrinic, 1993:38; Rinehart, 1997:13; Scarchilli et al., 1993)(Figure1-10).

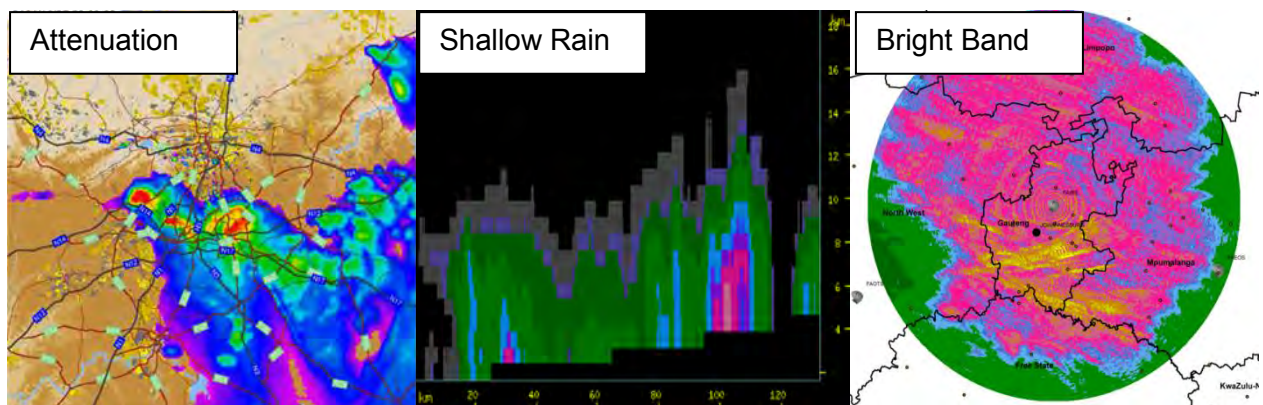


Figure1-10: Errors associated with radar data. The errors shown in this figures are attenuation, shallow rain and the bright band. This is especially problematic in C-band weather radars (Doviak & Zrinic, 1993:112).

1.6.5.3 Single Polarised Weather Radars

Single polarised radars are the most widely used weather radar today. The concept of measuring rainfall in only one horizontal plane has been well known to climatologists for decades (Figure 1-11). It involves the process of measuring rainfall in only the horizontal plane (Doviak & Zrinic, 1993:10). The variables measured by these radars include (Dufton & Collier, 2015):

1. DBZ

This is the power returned (reflectivity) from the raindrop measured in mm^6/m^3 .

2. DBuZ

Uncorrected horizontal reflectivity returned to the radar.

Conventional Radar

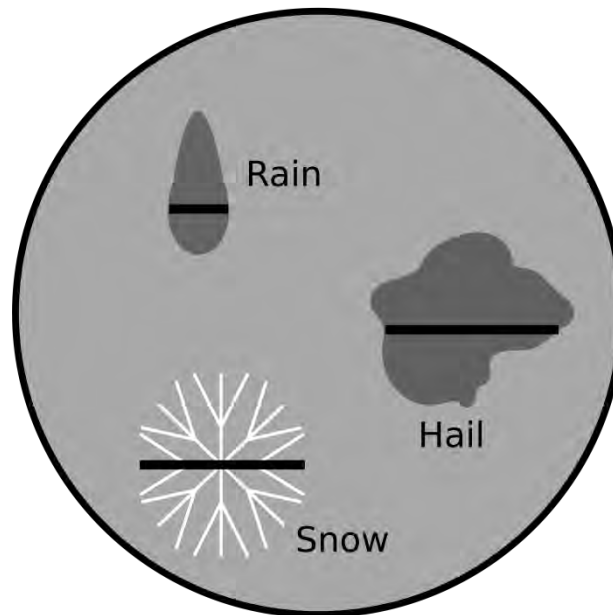


Figure 1-11: Conventional radars only send magnetic waves into the atmosphere in a horizontal plane. The black line through the particles represents the plane the radar measures in (Batten, 1973:14).

1.6.5.4 Dual-polarised Weather Radars

Technological advances have developed new ways to measure rainfall using weather radars. Dual polarisation is becoming a standard for new radar rainfall estimates (Paulitsch et al., 2009). These dual-polarised radars have the ability to transmit polarised electromagnetic pulses in the horizontal and vertical plane and measure both these returning powers simultaneously (Figure 1-12). Some advantages using dual-polarised radars include improving radar rainfall estimates, identifying different types of rain⁴, identifying different types of events and improving early warning systems (ANON, 2014). Unlike conventional single polarised radars these radars provide additional variables (Goddard *et al.*, 1982; Guili *et al.*, 1991; Hubbert *et al.*, 1992; Doviak & Zrinic, 1993:142; Vivekanandan *et al.*, 1999; Bringi *et al.*, 2002; Bringi *et al.*, 2003; Uijlenhoet *et al.*, 2003; Meischner, 2004; Paulitsch *et al.*, 2009; Snyder *et al.*, 2010):

⁴Rain, Hail, Snow, Graupel etc.

1. Differential reflectivity Z_{DR}

This is the ratio of the power returning in the vertical and the horizontal plane. This variable provides information about the size of the raindrop which is very important when studying the DSD.

2. Correlation coefficient ρ_{HV}

The correlation coefficient is the correlation between the horizontal and vertical power returns.

3. Differential phase shift ϕ_{DP}

The differential phase shift is the shift in time between the returning vertical and horizontal pulse.

4. Specific differential phase K_{DP}

This is the range derivative of the differential phase.

5. Linear depolarisation ratio LDR

LDR is the ratio of the cross-polar to the co-polar return of power from the horizontal and vertical planes.

The use of dual polarisation technology has a number of advantages. As opposed to single parameter radars that tend to underestimate deep convective rain, dual-polarised radar retrieval of the DSD in these convective storms is far more accurate. These radars, however, also have limitations. Accuracy decreases as the size of the particles decreases. This is especially evident in stratiform rain (Bringi et al., 2009).

Dual-Polarised Radar

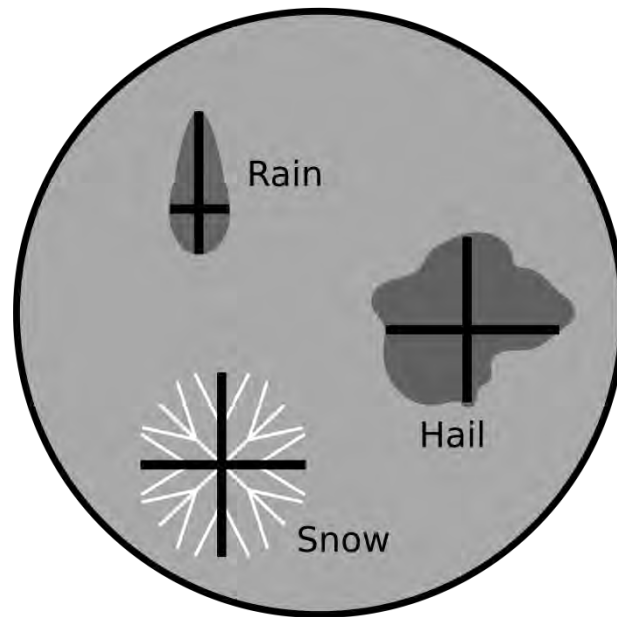


Figure 1-12: Dual polarised radars have the ability to send magnetic waves into the atmosphere horizontally and vertically (Batten, 1973:14).

1.6.6 The industry standard Tipping-bucket rain gauges

Tipping-bucket rain gauges (TBR) are some of the most primitive instruments still used today for rainfall measurements. They remain very popular and are widely used by scientist and weather services around the world because of their relatively cheap operating costs, simplicity, ruggedness, mechanical operation and user-friendliness (Maksimović et al., 1991; Sieck et al., 2007; Wang et al., 2008; Strangeways, 2010). Because the low maintenance and purchase costs these instruments are often deployed in a large network of TBR's and if within the coverage area of a weather radar it will help in the calibration thereof by comparing the ground truth measured TBR data to that measured by the radar (Lanza & Stagi, 2002).

There are some advantages when using TBR; the most important one is the fact that it is relatively cheap. This makes it possible to deploy this instrument in dense networks to study rainfall on the spatial scale. Other advantages include that it can be installed in remote areas, it can connect to a number of different monitoring or recording devices and it is not prone to any electrical errors as it is an instrument that is based mostly on mechanical principles (Maksimović et al., 1991; Humphrey et al., 1997).

Identifying disadvantages can help in responding proactively to ensure information is reliable and accurate. Tipping-bucket rain gauges are prone to a number of errors. One of the most significant is the overestimation of events with high rain rates (Humphrey et al., 1997; Li et al., 2010). The fast flow of water into the buckets can cause the system to tip before the buckets are full (Marsalek, 1981). Newer models of TBR are developed with a siphon that controls the flow of water from the catchment into the bucket, as explained in Chapter 1.6.6.2. Evaporation also plays a big part in the uncertainties associated with TBR data. Water left over in the buckets from previous events ($<0.2\text{mm}$ after the last tip of the event) evaporate and cause underestimation of events (Fankhauser, 1998). Strong winds can also cause false tips that may result in overestimation. Therefore it is very important that rain gauges must be tied down to prevent movement of the gauge in strong winds. Another problem with TBR is the start and end time, the first and last tip, of events. Depending on the type of TBR, let's presume the buckets have a resolution of 0.2mm , the first tip of an event may only occur after the buckets are filled with 0.2mm of water. The data will then show the event started later than in reality. This is the same for the end of the event. Once the last tip of an event has occurred, it does not necessarily mean that the rain has stopped. Water may still accumulate in the buckets if the rainfall is less than 0.2mm after the last tip. The data may then show that the event had ended earlier than in reality. The first tip of the next event may then tip more rapidly as there is water left over from the previous events (Humphrey et al., 1997; Molini et al., 2005; Wang et al., 2008).

1.6.6.1 Tipping-bucket rain gauge principle of operation

The TBR consist mainly of a catchment area and collecting buckets. These newer model gauges are also equipped with a siphon which is also a very important part and will be explained in Chapter 1.6.6.2. These gauges work by collecting rainwater in the catchment area and feeding it into the buckets. Once one of the buckets is full of water, the bucket mechanism tips and the magnet in the centre of the bucket triggers an electrical pulse that is then picked up by the reed switch and subsequently recorded as a tip. Another bucket replaces the bucket and the process is repeated (Molini et al., 2005; Li et al., 2010; Strangeways, 2010; Tapiador et al., 2012)(Figure 1-13).

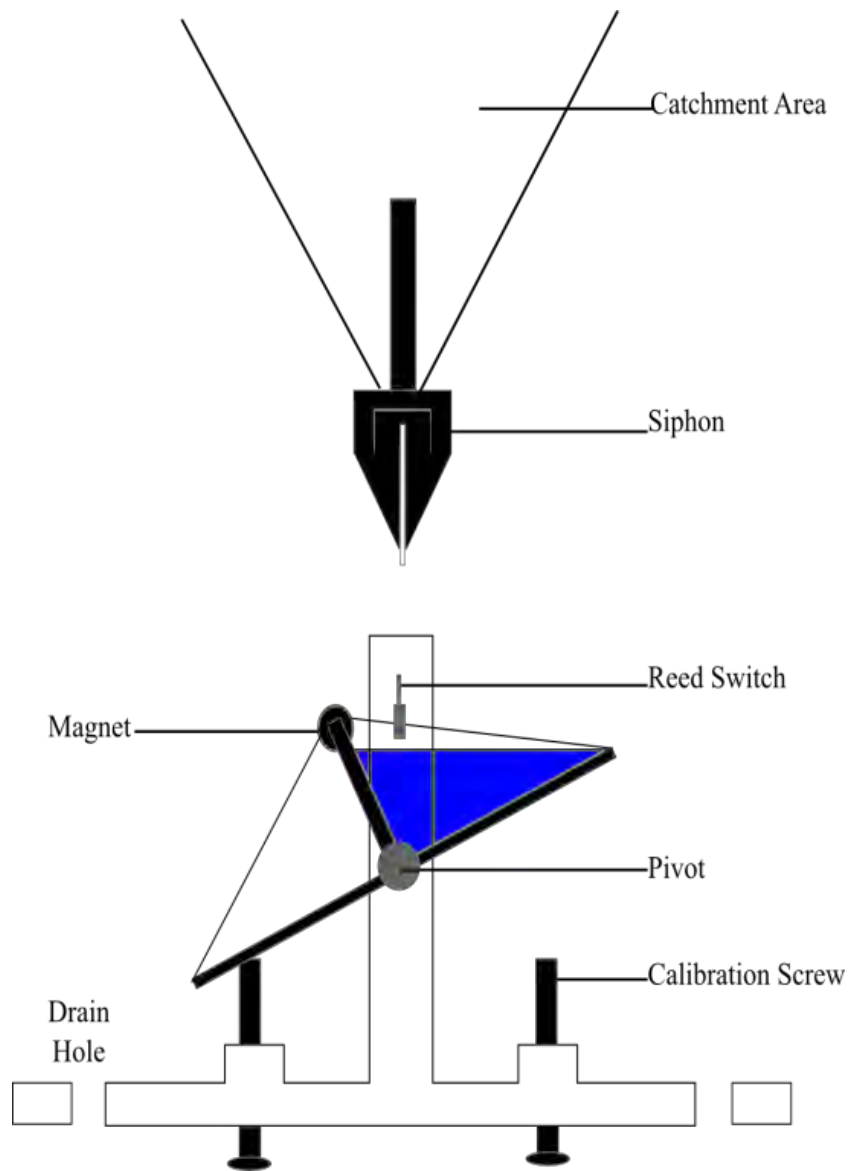


Figure 1-13: The industry standard siphon tipping-bucket rain gauge. The main components include the siphon and buckets. Droplets are collected in the catchment area which is funnelled to the siphon. The siphon regulates the flow of water and only when it is full (0.4mm) it disposes of the water into the buckets which then tips. The number of tips is then recorded through the reed switch which counts every time the magnet passes (Wang et al., 2008).

1.6.6.2 The Siphon

As mentioned in section 1.6.6 TBRs are prone to a number of errors. One of the biggest is the overestimation of events with high rain rates. The siphon is a feature of newer model TBRs that regulates the flow of water into the buckets at a constant speed (Overgaard et al., 1998).

Siphons work by collecting water and only disposing a predetermined amount into the buckets. As water fills within the catchment, it also fills the suction area. When the water level reaches the inlet, all the water is disposed of which consequently causes a sucking effect because of the pressure build up by the stem cap in the suction area (Figure 1-14). This allows the TBR to provide consistent results during events with high and low rain rates. Non syphoned TBR models are only calibrated at one specific rainfall intensity. The accuracy of siphon TBR is as follows (Lysaght, 2009):

- $\pm 2\%$ at 25-300mm/hr
- $\pm 3\%$ at 300-500mm/hr

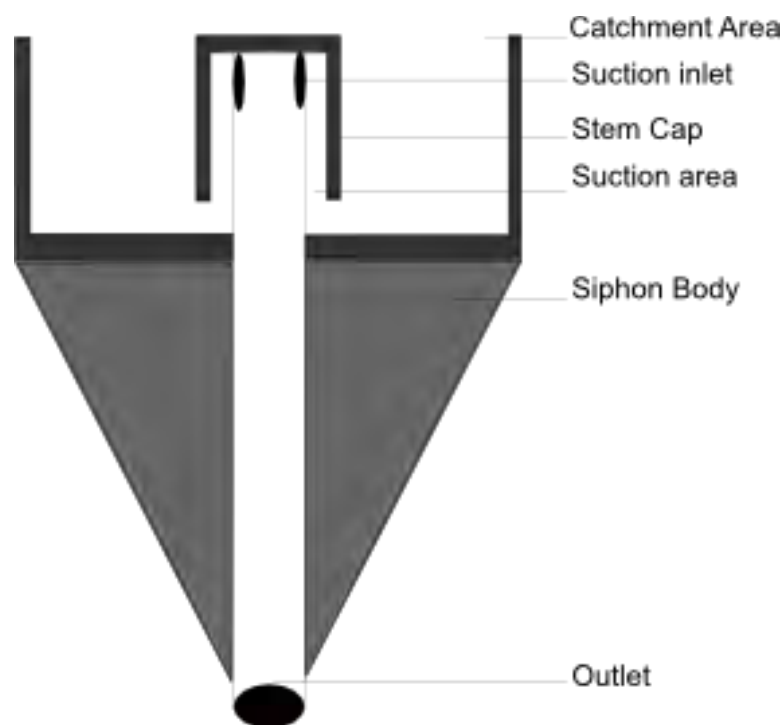


Figure 1-14: The siphon used by newer models of tipping-bucket rain gauges (Li et al., 2010).

1.6.7 Measuring rain rates using the conventional Tipping-bucket rain gauges

Tipping-bucket rain gauges are normally used in large networks covering big areas because they are relatively cheap (Maksimović et al., 1991; Wang et al., 2008; Strangeways, 2010). They can consequently provide invaluable data on the spatial variability of rainfall amount in a region. Instruments, like disdrometers, measuring rain rates are far more expensive and not economically viable to be distributed in a network. The challenge for climatologists therefore is to measure rain rates using TBR while mitigating the problems involved in using the instruments as discussed in Chapter 1.6.6.2.

Because of the large uncertainties in rain rate data measured by TBR's a number of different studies have been conducted to develop new algorithms to minimize these uncertainties. One of these methods is called the cubic spline algorithm (Wang et al., 2008). It works by adding up the number of raw tips within an event to cumulative tip numbers at each tip minute. A tip minute is defined as the time at which a tip takes place. Cumulative rainfall is then calculated by multiplying the cumulative tips with the size of the TBR. A number of different interpolation methods can then be used to determine rain rate, like linear interpolation shown in Eq. (3)

$$R(x_{i+1} + x_i) = \Delta v / (x_{i+1} + x_i), \quad (3)$$

where the rain rate between two tips is $R(x_{i+1} + x_i)$, consecutive tip minutes, x , and i the different tips (1, 2, 3....., n) where n is the number of tips in an event and Δv being the bucket size. Linear interpolation can however cause some problems because it does not consider zero values. Another interpolation method is the cubic spline shown in Eq. (4)

$$f_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + d_i \quad (4)$$

that is essentially a function of $f(x) = f_i(x)(x_i \leq x < x_{i+1}, i = 1, 2, \dots, n - 1)$ where x_i is the same as in Eq. (3). The coefficients a_i , b_i , c_i and d_i can be determined through a symmetric linear tridiagonal system (Wang et al., 2008).

It is important to note that all these methods are done with TBR's without a siphon. This data is therefore prone to over- estimation of events with high rain rates as the bucket tips before it is full of water (Humphrey et al., 1997; Li et al., 2010). Measuring rain rates using a siphon TBR that counteracts these errors by regulating the flow of water into the buckets poses its own unique challenges. Exploring better methods and algorithms to measure rain rates using siphon TBR's is therefore very important.

1.6.8 Microphysical Processes in Rainfall

All the air in the atmosphere contains water in some form or quantity. Precipitation occurs in the form of liquid and in some extreme cases hail would be observed in the form of a solid. Warm air has the capacity to store more moist air than cold air. Therefore the climate at the equator normally experiences far more rainfall than any other latitudes.

Moisture in the atmosphere is extremely important and plays a crucial role in the existence of all life forms on earth. Rain is a mechanism that provides valuable water to sustain life. For precipitation to occur, a number of different processes need to take place. This is a very balanced and complex system. Small changes in the process, or the absence of any of the changes, can suppress the occurrence of rainfall and can have devastating effects (Tyson & Preston-Whyte, 2000:24; Xie et al., 2010; Perlman, 2015).

The two most important mechanisms needed for rainfall is upliftment and moist air. The rising moist air cools adiabatically to form water droplets at the condensation level. These water droplets grow to a size at which updrafts cannot keep it aloft and falls to the ground in the form of rain (Tyson & Preston-Whyte, 2000:27; Lawrence, 2005).

Evaporation of water is a result of the heating from the sun. Moist air can develop from water bodies on the ground or the heating of the ocean transported inland by synoptic types like the South Indian anticyclone and the South Atlantic anticyclone which is situated east and west of the country respectively. Moist air can also be brought inland from the equator which is caused by the warm climate creating favourable conditions for evaporation and moist air. Evaporation also causes heat to be absorbed from the atmosphere, known as latent heat which cools down the air (Penman, 1947; Tyson & Preston-Whyte, 2000:25).

Moist air in the form of gas needs upliftment to cool down and to form water particles. Low-pressure systems can be defined as raising air with divergence in the upper air and convergence on the ground. These systems will cause moist air to rise, cool down and form water droplets. Air can also rise orographically which means that air rises according to the topography of the earth's surface. This normally occurs from coastal regions inland as the landscape becomes higher above sea level. Normally mountain ranges act as barriers as the rain normally cools down and rains before the mountain ridge (Tyson & Preston-Whyte, 2000:33). Another method of air rising is simply the sun heating air molecules on the ground. Warm air is less dense than colder air and therefore would start to rise. As it warms up, the capacity to hold moist air would also increase.

In the atmosphere, temperature changes with height. These can be changes to a warmer or a colder temperature depending on how high above sea level the air moves. For the purposes of rainfall we assume that rain forms within the troposphere. In this region of the atmosphere the temperature will decrease with increased height which is known as the adiabatic lapse rate. Cooling air reduces its ability to store water vapor which triggers the formation of water droplets. The temperature lapse rate in the atmosphere is a drop of 1°C for every 100m increase in height. In other levels in the atmosphere, like the stratosphere and thermosphere, the temperature increases as height increases. The same temperature drop as observed in the troposphere is applicable in the mesosphere (Tyson & Preston-Whyte, 2000:28).

Rain occurs in the form of liquid. The process of the development of rain starts off with air in a gaseous state. The base of clouds is normally uniform for a region. This is just above the condensation level. The condensation level is the level at which moist air has cooled down sufficiently to change into a liquid and form clouds (Korolev & Mazin, 2003). This does not necessarily mean that rain would occur in the early part of the water droplet development as these particles are very light and are kept suspended in the air by updrafts (Tyson & Preston-Whyte, 2000:29).

Water grows around a nucleus and forms a water particle. These nuclei are normally created from a number of different sources. Particulate matter suspended in the air is emitted from pollution sources like power stations etc. Dust particles, salt from the ocean and exhaust gasses can also serve as a nucleus (Ferron & Soderholm, 1990). The nucleation process plays a crucial role in the development of particles (Hamill et al., 1997). Without this integral part of the rainfall process, precipitation will not be observed (Tyson & Preston-Whyte, 2000:29).

Rainfall occurs once the weight of the particle exceeds the force of the updraft, keeping the particles suspended in the air. Particles collide with one another that may cause droplets to grow. Other particles will also grow as the water in the atmosphere will condense directly to an existing droplet. Once the weight of the particle is heavy enough, rain may be observed (Tyson & Preston-Whyte, 2000:30) (Figure 1-15).

The process of the development of rainfall is an on-going circular process that is very finely balanced. Rainfall will not be observed if one of these processes is not present. Precipitation is also very susceptible to small-scale changes within the DSD that lead to far bigger changes in the day to day weather.

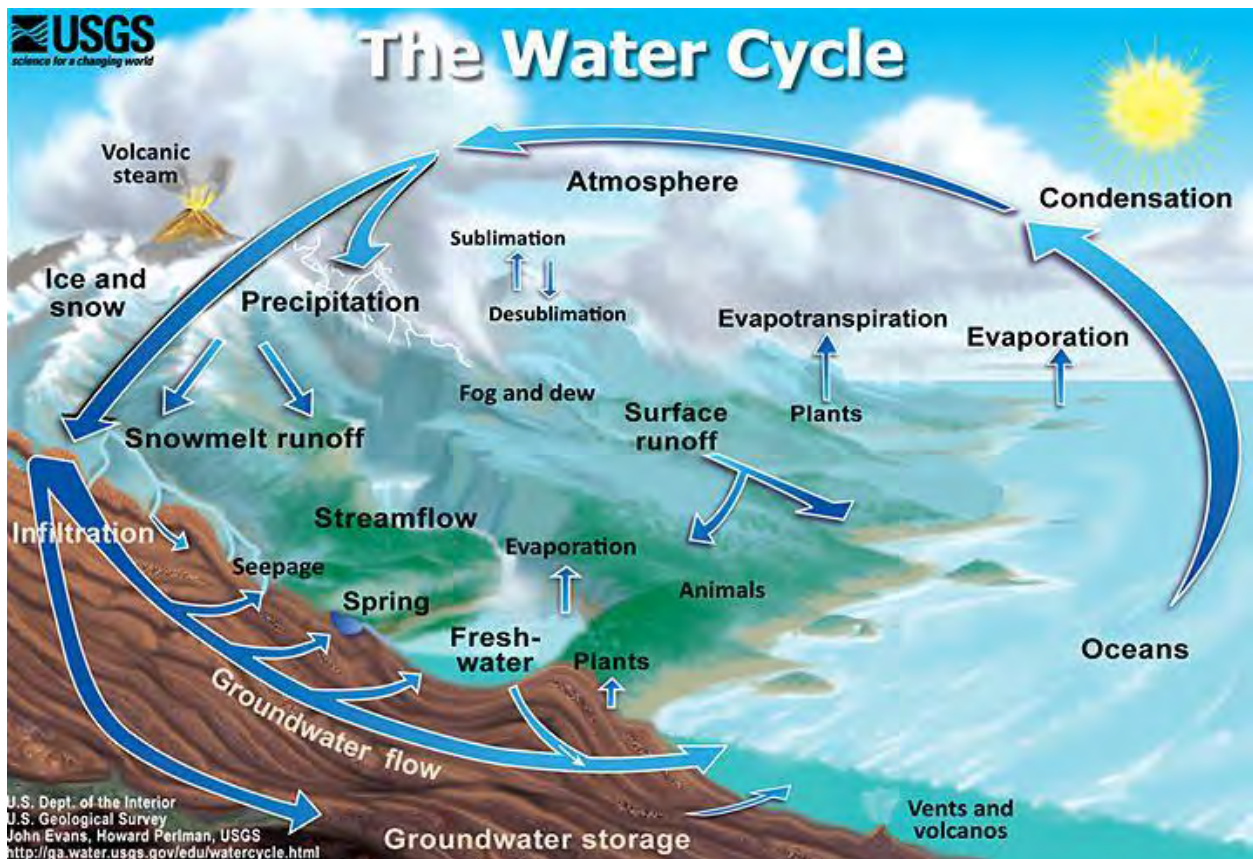


Figure 1-15: The two most important conditions needed for rainfall is upliftment and moist air. Moist air generally originates from warm oceans but can also form from water bodies on land. Upliftment can develop from a low-pressure system with convergence on the ground and divergence in the upper air or it can raise orographically (Perlman, 2015).

1.6.9 Dominant rainfall producing synoptic types over the Northern Highveld of South Africa

Synoptic types derived from the pressure differences in the air are good indicators of the weather for a specific day. It is especially important to predict rainfall. Two very important aspects are needed for rain-producing clouds. Firstly, there needs to be upliftment for the air to cool down and condensate. This can either be from convergence on the ground caused by a low-pressure system or from air rising orographically because of the topography of the earth's surface. Vertical motion is a key factor in the development of clouds. Without vertical movement there would be no weather. Secondly, air needs to be moist to be able to condensate and form rain (Tyson & Preston-Whyte, 2000:98,114).

The South African climate and weather are mainly influenced by the mean circulation of the atmosphere over southern Africa and by disturbances of these circulations (Tyson & Preston-Whyte, 2000:98,114). Rainfall in South Africa occurs mostly in the summer. Most of the rain occurs in the eastern parts of South Africa because of the humid climate and the warm Mozambican sea current that warms the ocean on the coast. The Western part of the country receives the lowest amount of rainfall annually because of a cold ocean caused by the cold Benguelan sea current that consequently hampers evaporation.

Although certain patterns of atmospheric pressure, wind and precipitation constantly change, there are a number of aspects in the South African weather circulation patterns that stay the same (Van Heerden & Hurry, 1992:15). South Africa has eight dominant synoptic conditions which dictate the day-to-day weather. This includes the continental high, coastal low, ridging high-pressure system, easterly wave and easterly low, westerly wave and cut-off low, cold front, southerly meridional flow and west coast trough. However only six of these synoptic conditions impacts the weather of the southern parts of South Africa (Tyson & Preston-Whyte, 2000:184) (Figure1-16). The easterly movement of warm, moist air from the tropics creates ideal conditions for the development of clouds and rain. Most floods that occur on the Highveld of South Africa normally occur because of an easterly low-pressure system (Tyson, 1986:174; Dyson & van Heerden, 2001; Dyson & van Heerden, 2002; Dyson et al., 2012; Engelbrecht et al., 2013). Tropical cyclones have also been observed moving in from Madagascar.

Figure 1-16A is an example of an easterly wave that normally produces clouds and, in some instances, rain for the biggest parts of the country. This movement of air from the equator may also occur with a strong low-pressure system developing over the country. These synoptic conditions create favourable conditions for rain as the moist air from the east gets caught up in the strong up- and downdrafts caused by the low-pressure system. Easterly lows (Figure1-16B) are mostly responsible for heavy rainfall events on the Highveld of South Africa whereas westerly low-pressure (cut-off lows) systems produce severe events mostly on the southern coast of South Africa but does also account for some rain in the North of the country. The development of isolated convective events on the Highveld of South Africa is as a result of these synoptic conditions. These events normally occur between December and February and are very rarely observed between April and October (Van Heerden & Hurry, 1992:21; Crimp & Mason, 1998; Tyson & Preston-Whyte, 2000:19).

The movement of air from the cold Atlantic Ocean is associated with cold conditions over most parts of the country, especially over the Cape and the southern coast. Known as a westerly wave, this system develops because of the westerly movement of air (Figure1-16C). Westerly

waves are favourable for cloud development over the southern parts of the country but it usually doesn't lead to rain. As mentioned earlier, the rain that is responsible for high amounts and rain rates is normally associated with a cut-off low (Figure1-16D). This deep, isolated low-pressure system over the country forms when it becomes isolated from the main low-pressure system far south of the country. Strong convergence on the surface and divergence in the upper air cause heavy rainfall for the entire country when a cut-off low is present (Van Heerden & Hurry, 1992:8; Tyson & Preston-Whyte, 2000:191).

The South Atlantic and South Indian high-pressure systems south-west and south-east of the country plays a big role in the dynamics of the weather of South Africa. The South Atlantic anti-cyclones are mainly responsible for transporting cold air from a cold ocean to the country whereas the South-Indian anti-cyclone will bring warm, moist air from a warm ocean to the country which will usually rise orographically, then condensate and form clouds and eventually rain will be observed. Normally this rain will deplete on the other side of the Drakensberg Mountains. However, the South Atlantic anticyclone often ridges far over the continent, bringing cold air to the country as it moves over the cold ocean that may cause strong onshore winds on the southern coast and cold weather over most parts of the country (Figure1-16E). In some cases the path of the high pressure system will move so far east that warm moist air from the warm Indian Ocean will be brought to the eastern coast of South Africa which may then cause rain in the eastern parts of the country (Figure1-16F) (Van Heerden & Hurry, 1992:6; Crimp & Mason, 1998; Tyson & Preston-Whyte, 2000:200).

Cold fronts always move from west to east over the country. The temperature is normally very low behind these cold fronts with a cloud band also present because of the undercutting effect that may cause the air to rise. These systems originate from the cold Atlantic Ocean near the South Pole and brings with extremely cold temperatures (Van Heerden & Hurry, 1992:1; Crimp & Mason, 1998; Tyson & Preston-Whyte, 2000:191).

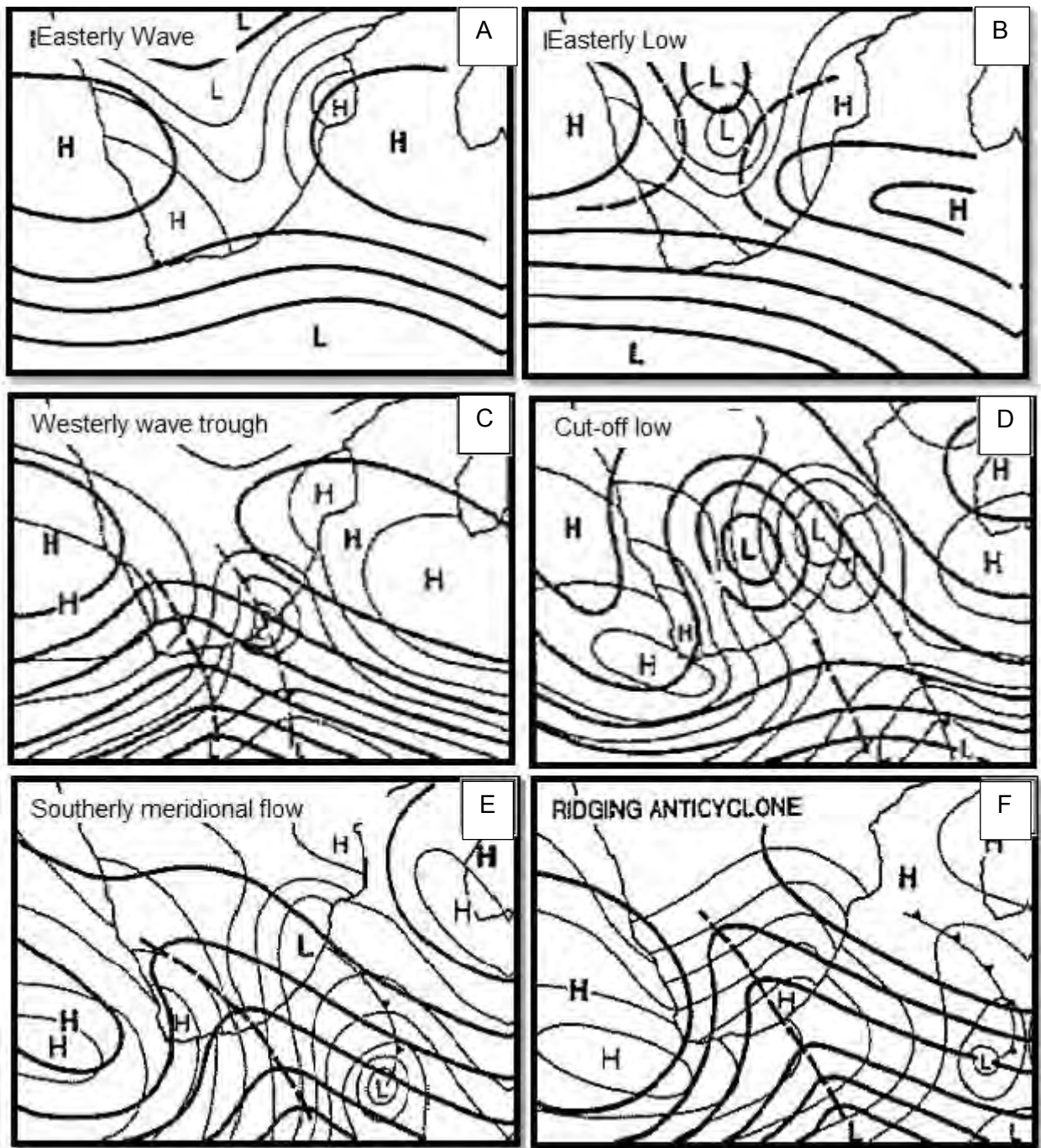


Figure1-16: Dominant South African weather patterns (Tyson & Preston-Whyte, 2000:216). A) Easterly Wave. B) Easterly low. C) Westerly wave trough. D) Cut-off low. E) Southerly meridional flow. F) Ridging Anticyclone.

Events with high rain rates that may cause flooding occur from time to time over South Africa (Dyson et al., 2012). These events are called cut-off lows and normally form from the westerly movement of cold air coming from the South Pole combined with a strong low-pressure system over the country (Van Heerden & Hurry, 1981:15; Crimp & Mason, 1998; Mason et al., 1999; Singleton & Reason, 2007; Lennard et al., 2013). As this low-pressure system becomes isolated from the main system it forms a cut-off low often accompanied by ridging anti-cyclone (Preston-Whyte & Tyson, 1988:227; Van Heerden & Hurry, 1992; Tyson & Preston-Whyte, 2000:196; Engelbrecht et al., 2013; Lennard et al., 2013). Cut-off lows account for the majority of flood-producing rains. These weather systems are very important because they are capable of stratosphere-troposphere exchange and are associated with deep moist convection which may lead to heavy rainfalls (Singleton & Reason, 2007). One of the most devastating floods in the history of South Africa, the Laingsburg floods, resulted from a cut-off low over South Africa (Tyson & Preston-Whyte, 2000:196). Cut-off lows are baroclinic systems that are very unstable with strong convergence at the surface (Figure1-17). The synoptic condition presented in Figure1-17 resulted in heavy rains across the country. Port Elizabeth, Grahamstown and East London all experienced rainfall of over 100mm (Van Heerden & Hurry, 1992:62)

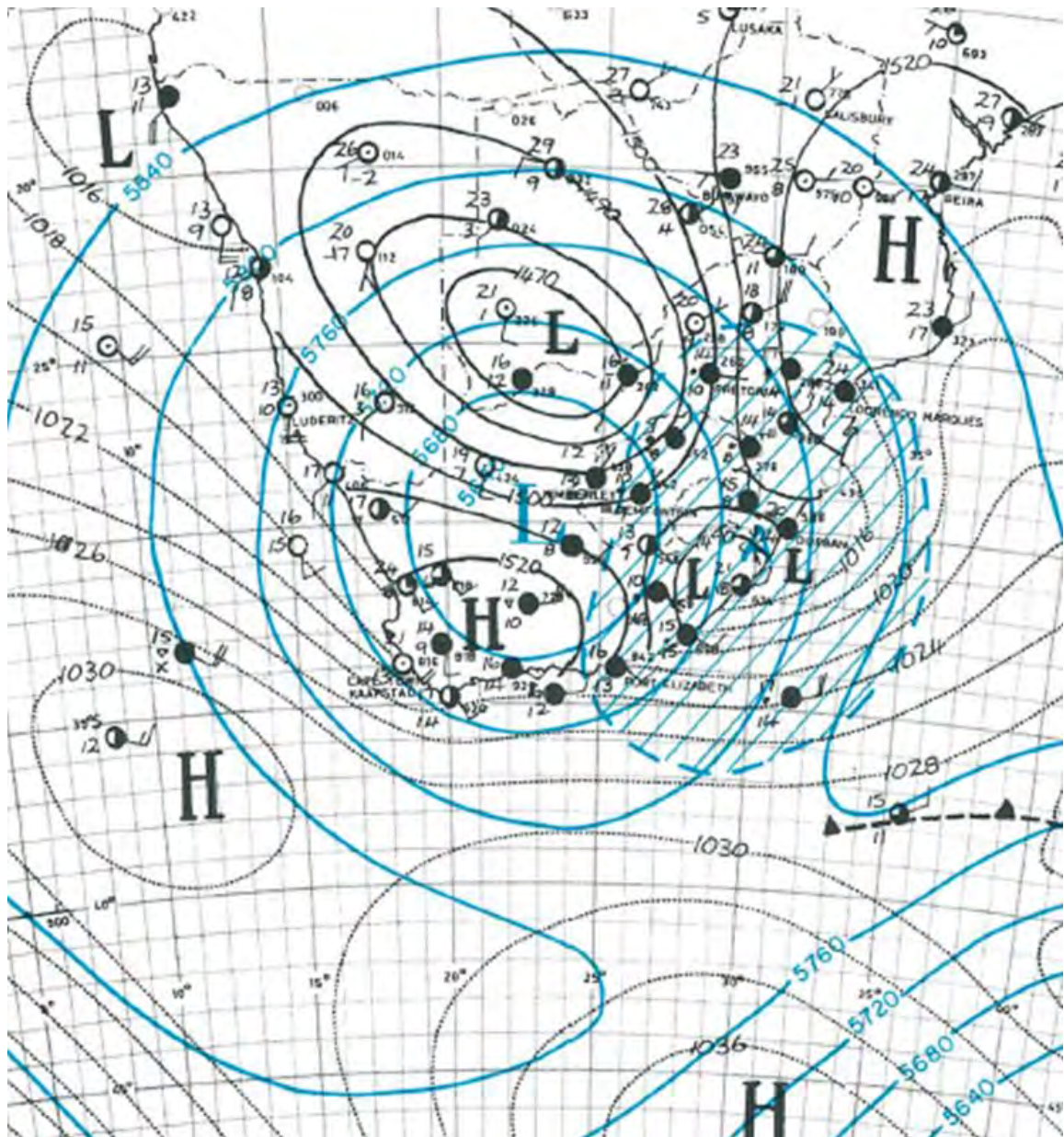


Figure1-17: Cut-off Low over South Africa (Van Heerden & Hurry, 1992:62). The blue lines represent the isobars in the upper air and the black line the isobars at the surface.

Synoptic conditions do not always occur in well-defined single synoptic type examples. Often the situation is a combination of a few complex synoptic conditions which are normally responsible for large-scale rain across the country (Todd et al., 2004). Figure 1-18A shows a cut-off low with a ridging anticyclone over the country. Both these systems are known for their cold weather and rain. Large-scale rain can be expected over the country. Most of the rain observed in South Africa is a result of the interaction between westerly and easterly conditions. The combination of these two conditions often creates the well-known tropical-temperate trough

which creates cloud bands across South Africa resulting in rainfall over most parts of the country. Easterly systems can also combine with a ridging South Indian anti- cyclone. These conditions will again be favourable for rainfall across northeasterly parts of the country (Tyson & Preston-Whyte, 2000:212).

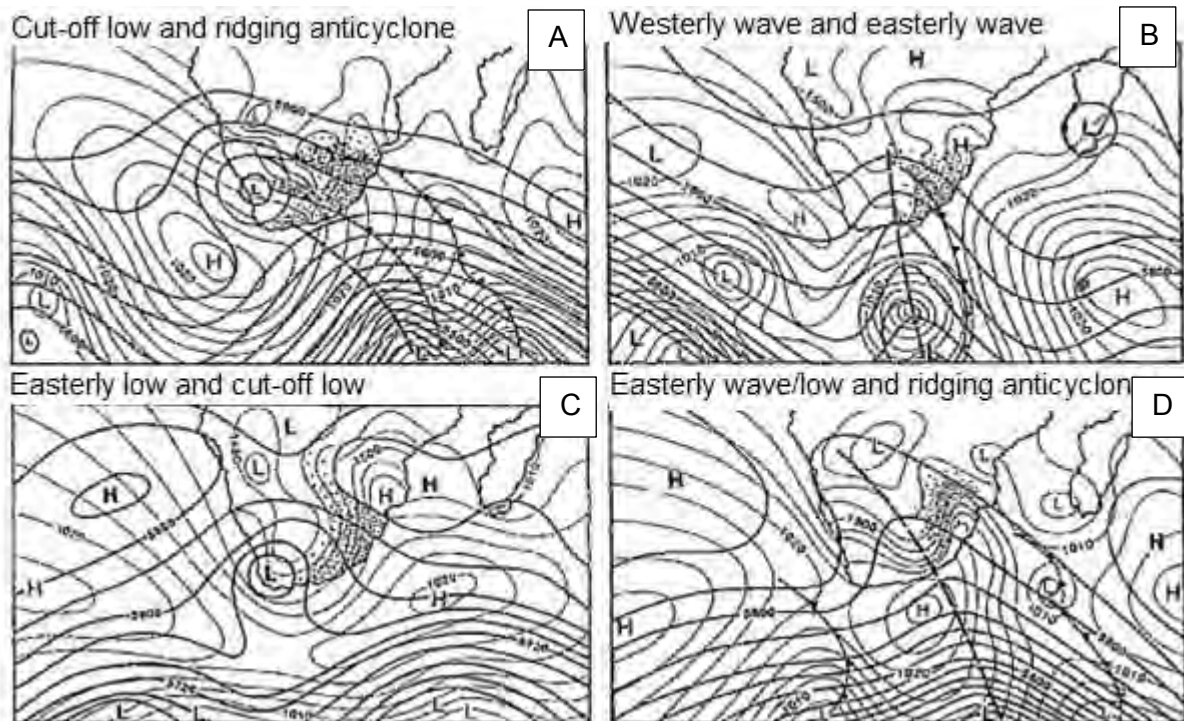


Figure 1-18: Synoptic conditions over South Africa producing large scale rainfall. These conditions often occurred in complex systems consisting in conjunction with two or more basic synoptic patterns. It includes cut-off low and ridging anticyclone, westerly wave and easterly wave, easterly low and cut-off low and the easterly wave/low and ridging anticyclone (Tyson & Preston-Whyte, 2000:212).

The tropical-temperate trough (TTT) is considered to be the synoptic condition that is responsible for the highest amount of rain in the Northern parts of South Africa, resulting in 35% of the mean annual rainfall of South Africa (Crimp & Mason, 1998; Todd et al., 2004; Ratna et al., 2013). These systems are most evident in the summer months with a peak in occurrences between January and May (Tyson & Preston-Whyte, 2000:213). The TTT develops when a westerly disturbance interacts with those in the tropical east that is easily identifiable on a satellite image (Todd & Washington, 1999; Tyson & Preston-Whyte, 2000:213; Ratna et al., 2013). Cloud bands are evident across the country with rain observed east of the cloud bands (Figure 1-19) (Todd & Washington, 1999; Tyson & Preston-Whyte, 2000:213). It is widely

considered that the TTT is one of the main reasons for the intra-annual variability of rainfall in South Africa according to its frequency of occurrence, intensity and position (Todd & Washington, 1999; Todd et al., 2004; Ratna et al., 2013).

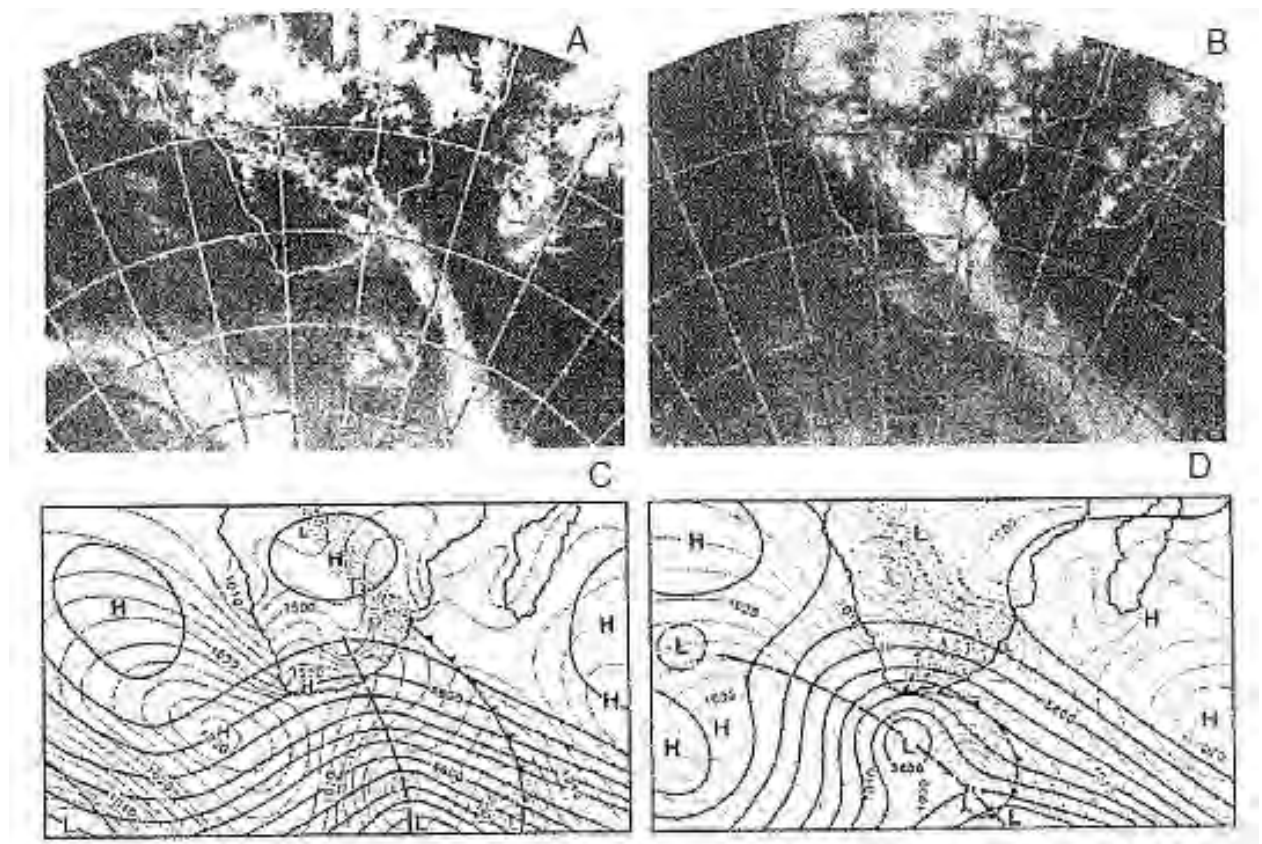


Figure 1-19: Tropical- temperate trough shown as a satellite image (A, B). These systems occur when an easterly wave and westerly wave interacts or the interaction between the easterly low and the westerly low (Tyson & Preston-Whyte, 2000:213).

1.6.10 Different storm structures associated with convective and stratiform rainfall

The two basic forms of precipitation are convective and stratiform (Houghton, 1968; Batten, 1973:68; Steiner & Houze Jr, 1997; Biggerstaff & Listemaa, 2000). Analysing different clouds associated with these types of precipitation is very important. To do this it is crucial to know which fraction of rain is stratiform and which is convective (Simpson et al., 1988; Steiner & Houze Jr, 1997). This enhances the understanding of clouds' microphysical processes, the development of clouds as well as the thermodynamics and dissipation of clouds (Cui et al., 2007).

Stratiform and convective events differ in characteristics and structure. One of these is the difference in rain rates. Rain rates above 20mm/h are normally classified as convective precipitation and below 20mm/h stratiform (Atlas et al., 2000). Convective events are also characterized by their high rain rate, short, strong horizontal reflectivity gradients and large vertical velocity duration. These events are normally much localised and have strong up-and-down drafts. In contrast, stratiform events have lower rain rates, weak horizontal reflectivity gradients, a bright band near the melting layer, weak vertical velocity, they have a longer duration and they are widely distributed (Houghton, 1968; Atlas et al., 2000; Uijlenhoet et al., 2003; Cui et al., 2007).

A number of different studies have been conducted to stratify clouds in convective and stratiform regimes (Churchill & Houze Jr, 1984; Toa & Simpson, 1989; Sui et al., 1994; Xu, 1995; Steiner & Smith, 1998; Atlas et al., 2000; Sempere-Torres et al., 2000; Lang et al., 2003; Cui et al., 2007). In most cases convective and stratiform rainfall is classified by assuming that convective rainfall has peak rain rates twice as high as surrounding rainfall rates (Churchill & Houze Jr, 1984). Another partitioning method includes adding ice and cloud-water exceedances of updraft threshold values (Churchill & Houze Jr, 1984). Points will be identified as convective only if all these criteria are met (Toa & Simpson, 1989). Other criteria such as fall speed of particles (Lang et al., 2003) and vertical motion (Xu, 1995) are also used for stratifying events.

Drop size distribution (DSD) is a term used to describe the spectrum of different drops within a water mass such as clouds (Smith, 1993; Sauvageot & Lacaux, 1995; Jaffrain & Berne, 2010). It forms the core part of rainfall and is highly variable over space and time. Changes in the DSD can have a big effect on the day-to-day weather of a region. To study the drop size distribution high-resolution rainfall data is needed. This data will give climatologists the ability to study small-scale changes, microphysical processes within clouds, synoptic conditions, cloud dynamics and the nucleation process.

The drop size distribution is measured by the amount of particles within the body of water and the diameter of the particles. It can be characterized by the diameter, shape, concentration and distribution of the particles (Bringi et al., 2003). All of these aspects will influence the reflectivity and the rain rate of a specific event. Therefore the reflectivity and rain rate are products related to each other and associated with the drop size distribution (Steiner & Houze Jr, 1997; Atlas et al., 1999; Uijlenhoet, 2001; Uijlenhoet et al., 2003; Atlas & Ulbrich, 2006). Reflectivity (Z) is normally measured in the atmosphere by instruments like weather radars and rain rate on the surface using ground-based instruments.

One of the greatest challenges for climatologists is the conversion of the reflectivity measured aloft to rain rate on the ground (Atlas et al., 1999; Uijlenhoet, 2001; Uijlenhoet et al., 2003). There is a difference between the rain rate measured by a ground-based instrument and a radar as the beam of the radar is well above the ground (Steiner & Houze Jr, 1997). Determining the variability of the DSD involves how the relationship between the reflectivity and the rain rate changes. This is known as the Z-R relation of the form:

$$Z = AR^b \quad (5)$$

where Z represents the reflectivity, R represents the rain rate and A and b are coefficients that may vary from one location to another and between seasons (Twomey, 1953; Fujiwara, 1965; Carbone & Nelson, 1978; Steiner & Houze Jr, 1997; Ulbrich & Atlas, 1998; Ulbrich & Miller, 2001; Krajewski & Smith, 2002; Uijlenhoet et al., 2003). Reflectivity (Z) and rain rate (R) are physically related (Steiner & Houze Jr, 1997). Z-R relations are highly variable in time and space and can change between different regions, climates and storms⁵ (Twomey, 1953; Fujiwara, 1965; Batten, 1973:202; Carbone & Nelson, 1978; Ulbrich, 1983; Steiner & Houze Jr, 1997; Ulbrich & Atlas, 1998; Atlas et al., 1999; Bringi et al., 2003).

As mentioned before, the Z-R relation is highly variable between different events and regions. A theoretical equation was consequently developed that was aimed at providing a Z-R relation that may be more accurate for the most number of events and regions. This equation

$$Z = 200R^{1.6} \quad (6)$$

is used by weather services around the world for radar rainfall estimates for all types of events (Marshall & Palmer, 1948). Fixed Z-R relations can however cause large-scale uncertainties within radar products derived because the DSD is highly variable spatially, temporally and between storms (Uijlenhoet et al., 2003). Using the same equation for all storms measured will cause inaccurate and unreliable estimates of rainfall (Carbone & Nelson, 1978; Smith, 1993).

To measure rainfall as accurately as possible, it is important to consider stratiform and convective events separately (Atlas et al., 1999; Uijlenhoet et al., 2003). Convective storms have the tendency to have lower A values, Eq. (5), than stratiform events that tend to have higher A values (Uijlenhoet et al., 2003; Atlas & Ulbrich, 2006). It is therefore very important that these differences should be considered when the strategies used to measure stratiform and

⁵Convective and stratiform precipitation

convective events are implemented (Fujiwara, 1965; Atlas & Ulbrich, 2006). The right algorithm must be used for the right event and climate (Atlas et al., 1999).

1.6.11 The general characteristics of rainfall on the Highveld of South Africa

The climate of South Africa is incredibly diverse. The Koppen-Geiger climate classification system is a tool which is used to classify different climatic regions across the world (Rubel & Kottek, 2010; Peel et al., 2007). According to this system, South Africa is classified into seven different climatic regions. The west coast of South Africa is classified as a dry arid region which does not receive much rain throughout the year. This is mostly because of the cold Benguela sea current on the west coast which suppresses evaporation and is also true for the entire western parts of the country-for example the Kalahari and western-Karoo regions. The Western parts of South Africa experienced steppe-like rainfall and classified as warm-temperate. The warm Mozambique sea current on the east coast of the country creates favourable conditions for evaporation and therefore the eastern regions observed the most rain in South Africa. Northern parts of South Africa are classified as arid with steppe-like climate. This area also experiences very hot summers. Central South Africa is classified as warm and temperate with warm summers and dry winters. The Southcentral parts of the country receive steppe-like rainfall and is classified as arid (Rubel & Kottek, 2010).

The Highveld of South Africa is a summer rainfall area with a mean annual precipitation of between 400 and 800mm (Schulze, 1997:32). The rainfall on the Highveld is quite significant when one considers the relatively small areas that have rainfall higher than 800mm (Figure 1-20).

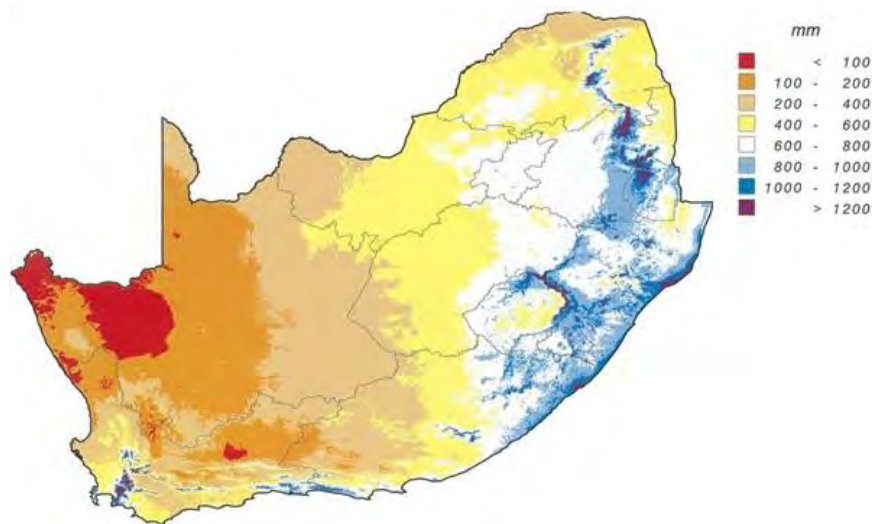


Figure 1-20: South African Mean Annual Precipitation (Schulze, 1997:32).

The coefficient of variation of annual precipitation on the Highveld is between 25%-30%. This indicates the level of fluctuations to which rainfall can vary (Schulze, 1997:36). This justifies the effort of exploring the spatial and temporal variability of rainfall intensity (Figure 1-21).

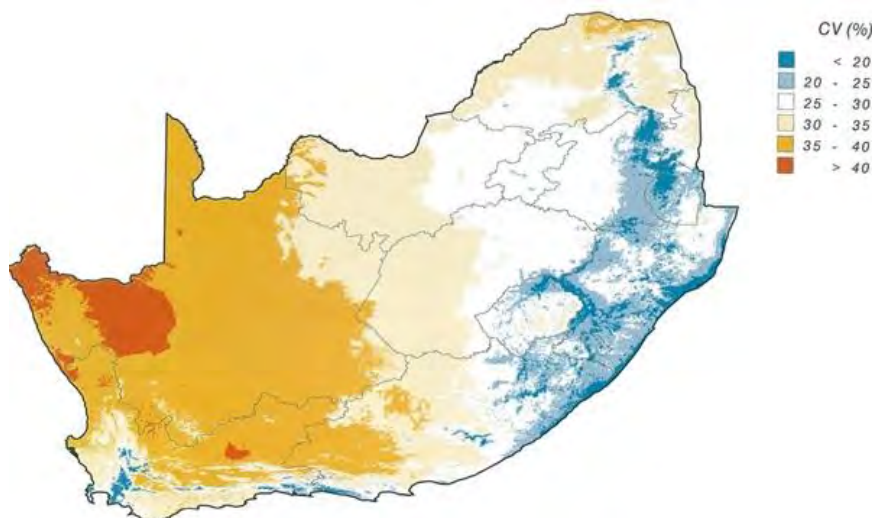


Figure 1-21: South African Coefficient of Rainfall Variation (Schulze, 1997:36).

The concentration of rainfall over the Highveld of South Africa is between 60%-65% where 0% means that rainfall is distributed evenly throughout the entire year and 100% of the rainfall can occur only for a small portion of the year whether this is a lot of rain or not (Schulze, 1997:38). Rainfall on the Highveld where the Mooi River catchment is situated is therefore not distributed

evenly throughout the year. The slight lean towards unevenly distributed rainfall can be explained by considering the fact that the Highveld receives rainfall for the largest part of summer (Figure 1-22).

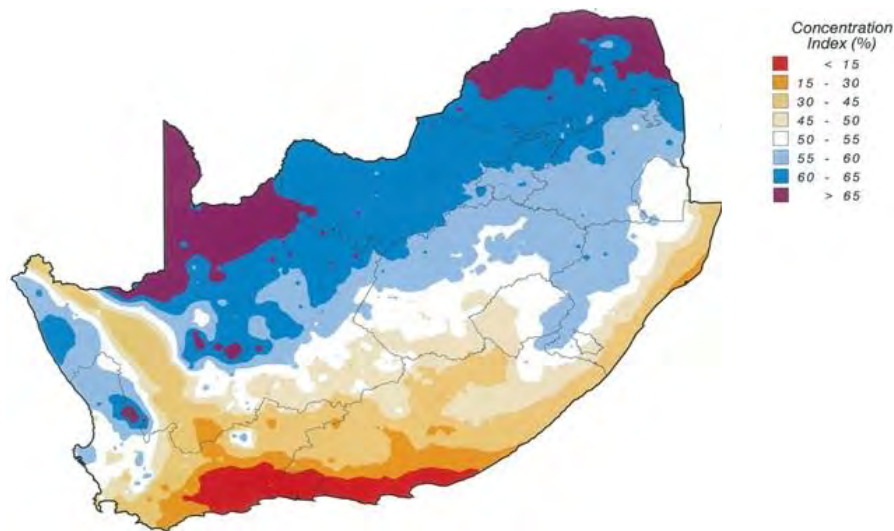


Figure 1-22: South African Rainfall Concentration (Schulze, 1997:38).

Most of the rain occurs mid-summer between January and April (Figure 1-23) (Schulze, 1997:40). The constant occurrence of a continental high-pressure system over the Highveld of South Africa in the winter creates conditions that are not suited for rainfall. In the summer months, the easterly movement of warm, moist air from the tropics creates favourable rainfall conditions (Figure 1-23).

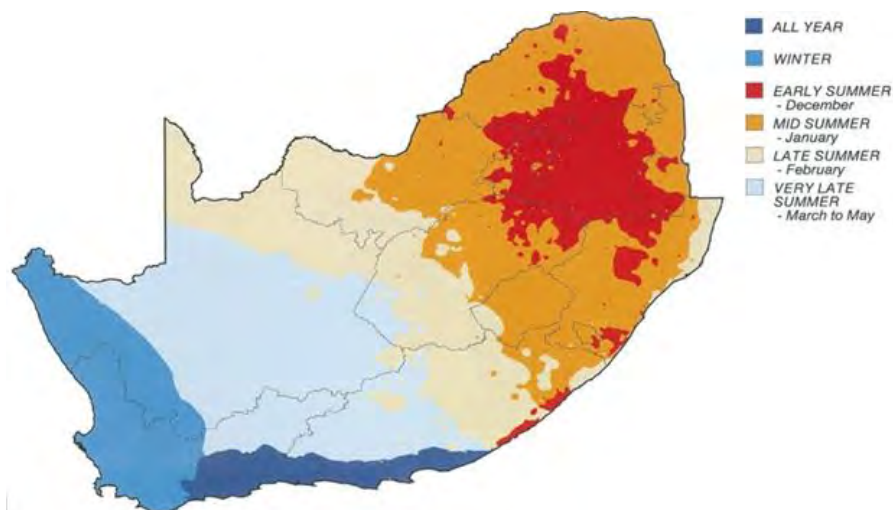


Figure 1-23: South African Rainfall Seasonality (Schulze, 1997:40).

CHAPTER 2 DATA AND METHODS

In this dissertation the spatial and temporal variability of rainfall in the Mooi River catchment situated in the Highveld region of South Africa will be characterised and discussed. Understanding the character of rainfall in the Mooi River catchment can help in improving the accuracy and reliability of rainfall measurement for the entire Highveld region which includes Gauteng, parts of the Freestate and parts of the North West. The Highveld is extremely important for the well-being of the country. A developing country is highly susceptible to anthropogenically induced climate change as many residents live in extremely vulnerable conditions and natural disasters such as flash floods can have devastating effects on their day-to-day lives (Mason & Joubert, 1997).

The Highveld of South Africa is important for a number of different reasons. It is extremely important that an area with such a vast amount of dolomite like the North West Province and the Mooi River catchment be thoroughly investigated on what the impact of a changing rainfall pattern will have on infrastructure. Dolomite is a type of sedimentary rock which under excessive exposure to water can become extremely brittle. These areas often will form sinkholes which can have devastating effects on infrastructure (Figure 2-1B). Agriculture is a very important part of the economy of South Africa, especially for food security. This sector is highly dependent on rainfall. The need for improved rainfall measurements has never been greater as historical climatic trends have shown that the character of the rain is changing. Agricultural activities in the Mooi River catchment are predominantly grain production. This includes corn and wheat crops. Other farming activities include cattle, sheep and substance agriculture (Figure 2-1C). The Gauteng Province has the largest amount of citizens, namely 12 272 263, accounting for 23% of the entire country's population (Statssa, 2011). The population density in the urban areas of Johannesburg and Pretoria can reach 1942 people per square kilometre (Figure 2-1D). Natural disasters like flash floods can cause large scale damage to these areas with high densities. A better understanding of rainfall in the Mooi River catchment can be extrapolated and improve rainfall prediction on the entire Highveld region as the Irene radar covers the entire Gauteng region and parts of the North West, Limpopo and Freestate provinces.

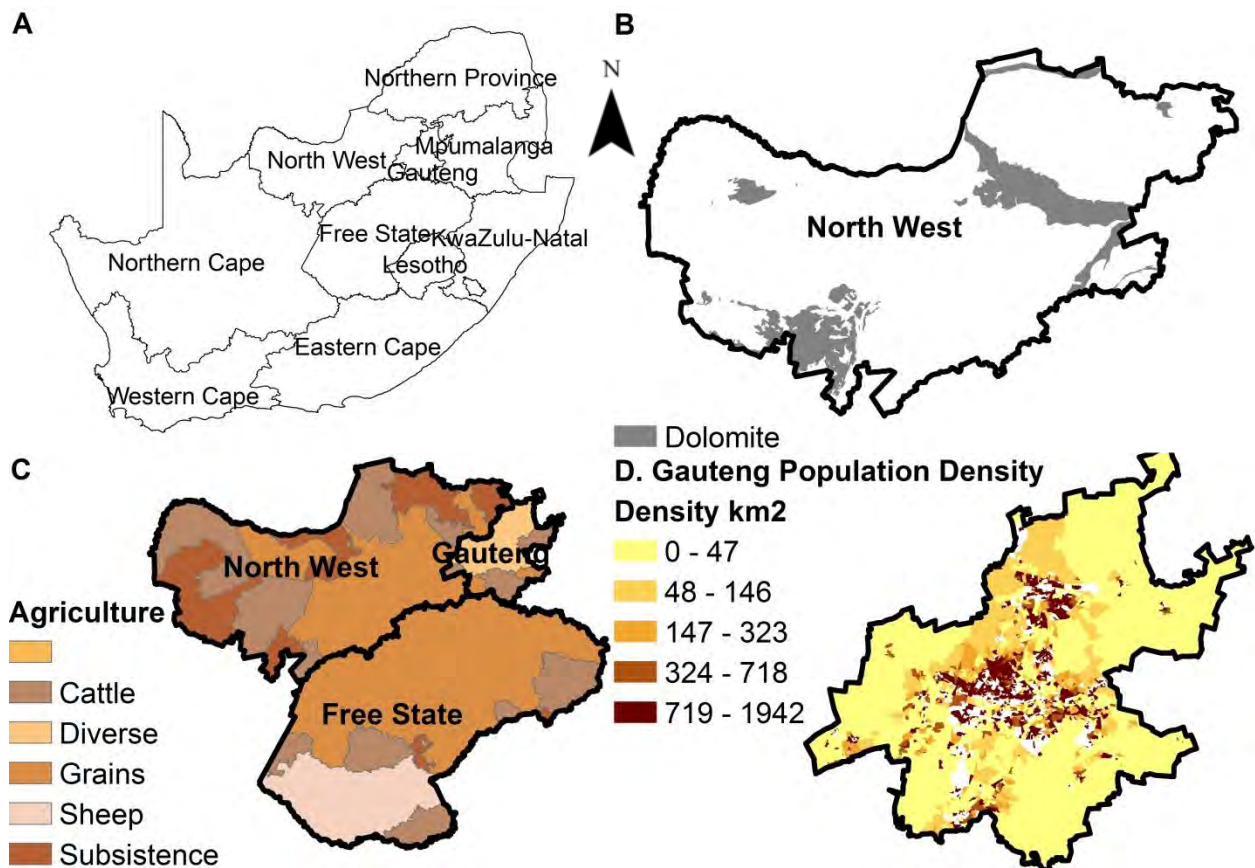


Figure 2-1: The study includes the Gauteng, North West and Freestate provinces which all play a significant role in the South African Economy. A) South Africa. B) Dolomitic areas in the North West. C) Agricultural Activities in the Gauteng, North West and Freestate provinces. D) The population density of Gauteng.

The economic hub of the country, Gauteng, is also in this area. Johannesburg has a large number of citizens living in poverty-stricken, high-density townships. These people are usually extremely susceptible to changes in rainfall which can cause drought or floods. The Gauteng province has a large number of informal settlements. This type of settlement is the most in Gauteng, compared to the rest of the country, and therefore an improved understanding of the character of rainfall intensity would be beneficial (Figure 2-2).

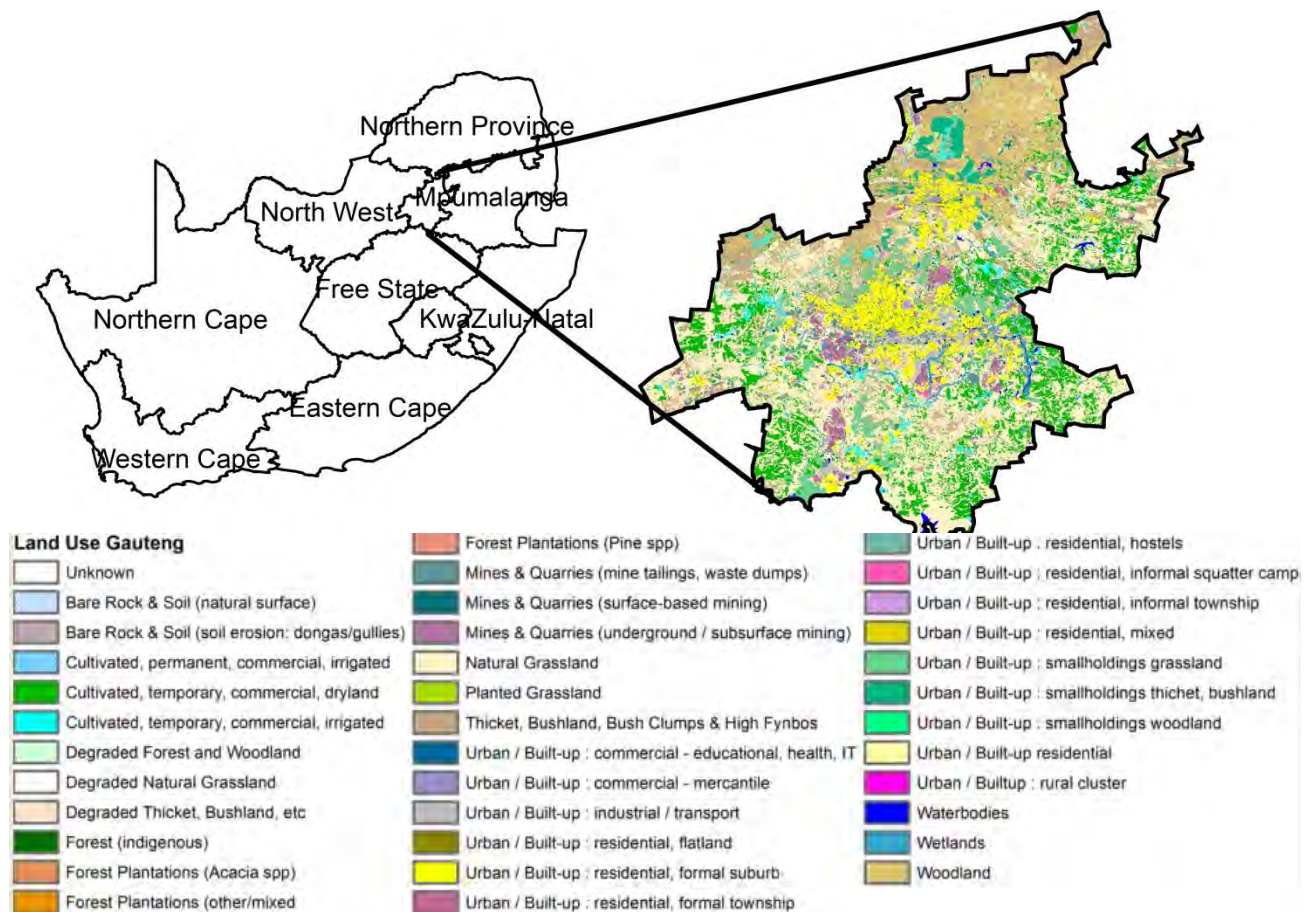


Figure 2-2: Land use in the Gauteng Province of South Africa. The majority of land uses in the region are built-up urban areas. It is for this reason that understanding the character of rainfall in the region is so important. These areas increase the risk of flash floods because hard surfaces do not absorb water as good as natural areas.

Cape Town, Port Elizabeth and Durban are all considered as metropolitan areas. However, the three largest metropolitan areas are in the Gauteng region. These metro's include the East Rand, Johannesburg and Pretoria (Figure 2-3).

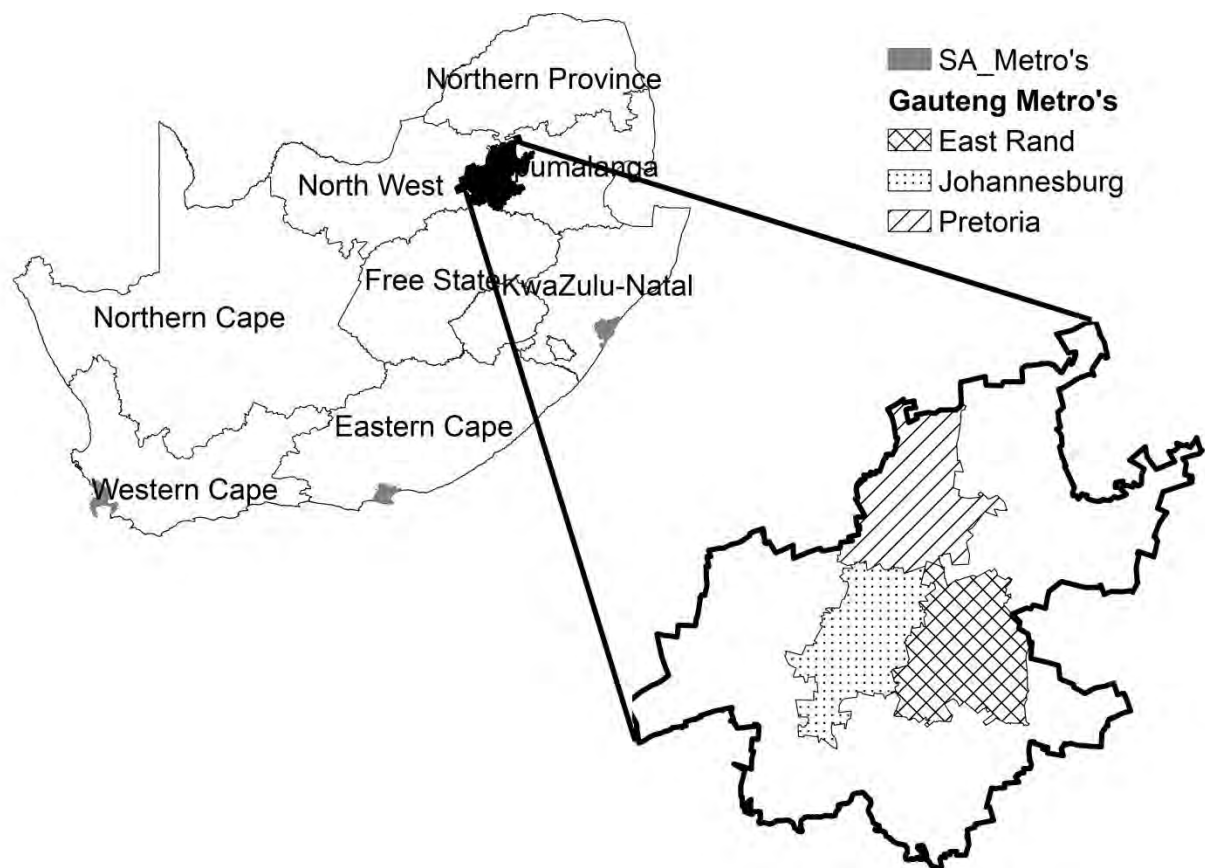


Figure 2-3: Metro's of South Africa. These areas have a higher population density than smaller municipality regions. They are also normally very important economic areas for the country. The Highveld region contains three of the main metros in South Africa namely the East Rand, Johannesburg and Pretoria metros

Built-up areas also make urban areas very susceptible to floods. Natural areas like grasslands counter water built-up by absorbing water. Areas with hard surfaces like cement in urban areas cannot absorb water which can cause flooding. Drainage systems must be in place to direct water to reservoirs or areas where this water can be absorbed. A large area of the Gauteng province has a low infiltration capacity due to a large number of tar and concrete surfaces compared to the rest of the country (Figure 2-4).

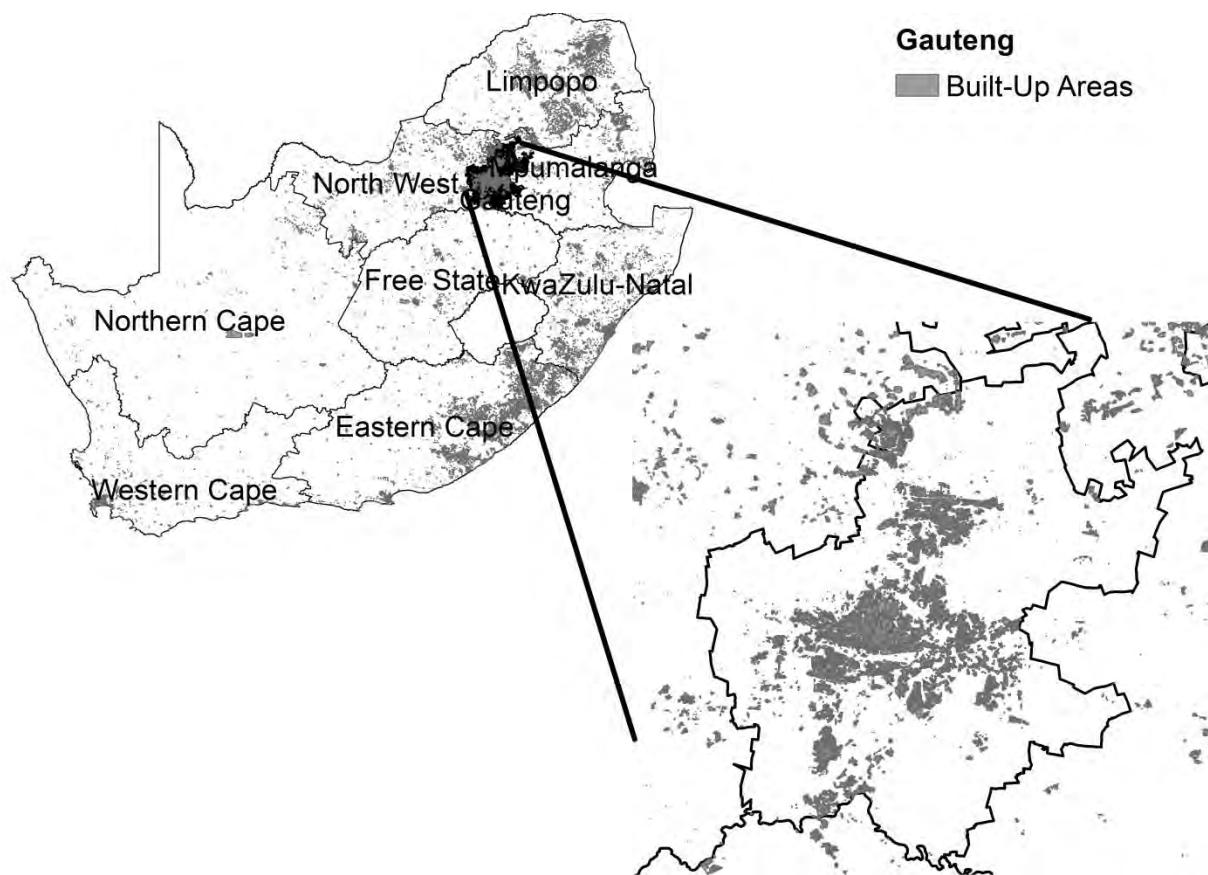


Figure 2-4: Built-up areas in South Africa. These regions have large populations and is very susceptible to flooding.

Other advantages include helping water resource management with plans for the future. This is considered as one of the biggest challenges for municipalities (Piketh et al., 2014). It is imperative that future rainfall changes should be taken into consideration in the planning of new water resource infrastructure. This will keep the run-off from rain to a minimum and more water will end up in reservoirs. It will be uneconomical to develop infrastructure for increased rain rates while trends show that events with high rain rates will decrease. This is also true for the opposite. If trends show that the frequency of events with high rain rates are increasing and infrastructural development is done for a decrease in these events, precious water will be lost. Disaster management will also benefit from an improved understanding of the variability of rainfall intensity. Flash floods and landslides can cause large-scale damage. Identifying areas that are susceptible to disasters, such as flash floods, can be a proactive way of preventing settlements to develop in these areas. Early warning systems can be used by insurance companies to minimize damages caused by rainfall disasters.

Agricultural management is very important. Farmers are moving more towards precision farming. This involves knowing when it will rain, what the intensity of the rainfall will be and what the spatial variability of the rainfall is. Corn crops are very fragile and rainfall is needed at a specific time during germination and development of the seeds. Too little rainfall and the seed will not germinate. Too much rainfall and the seed will drown. Irrigation systems can be synchronized to assist in times of drought or be suppressed if rainfall is high. True precision farming is practised when these types of consideration are done. Assisting these farmers with high-resolution, accurate data can help in improving the food security of the country. All of these sectors can only benefit if we fully understand the spatial and temporal variability of rainfall.

2.1 Rainfall measuring instruments used

Different instruments were used to measure rainfall in this study. This includes rain gauges, disdrometers and weather radars. Using all of these instruments enabled the study of rain at different scales. Each instrument measures different aspects of rainfall. The calibration of these instruments was confirmed before they were used. These measurements were taken throughout the 2013/2014 rainfall season. Rainfall in this area usually peaks in February and March. It is also the times where tropical- temperature trough is often observed which account for the majority rainfall in the region.

In this dissertation a number of different instrument were used. This includes a Parsivel disdrometer, tipping bucket rain gauges and weather radars. All of these instrument measures different aspects of rainfall and at different time scales. The Parsivel disdrometer measures each particles size and velocity; rain gauges measures the volume and rainfall and weather radar the reflectivity of droplets.

2.1.1 Deployment of the Parsivel disdrometer

Technological advances have developed new, innovative instruments to measure rainfall more accurately. The North-West University (NWU) Parsivel disdrometer is an optical rain gauge that measures each particle's size and velocity as it moves through a laser beam. It consists of the disdrometer, input and output data ports, power supply, processor, display, UPS and power source (Figure 2-5).

Measurements were conducted just outside Potchefstroom; North West Province where the disdrometer, was in close proximity to a tipping-bucket rain gauge and under the coverage of 4 radars namely: the Irene, Ottosdal, Bethlehem and NWU LeKwena radar (Figure 2-6). The two

gauges were also placed in similar ways to eliminate inconsistencies in data for instance the height at which they were placed was exactly the same.

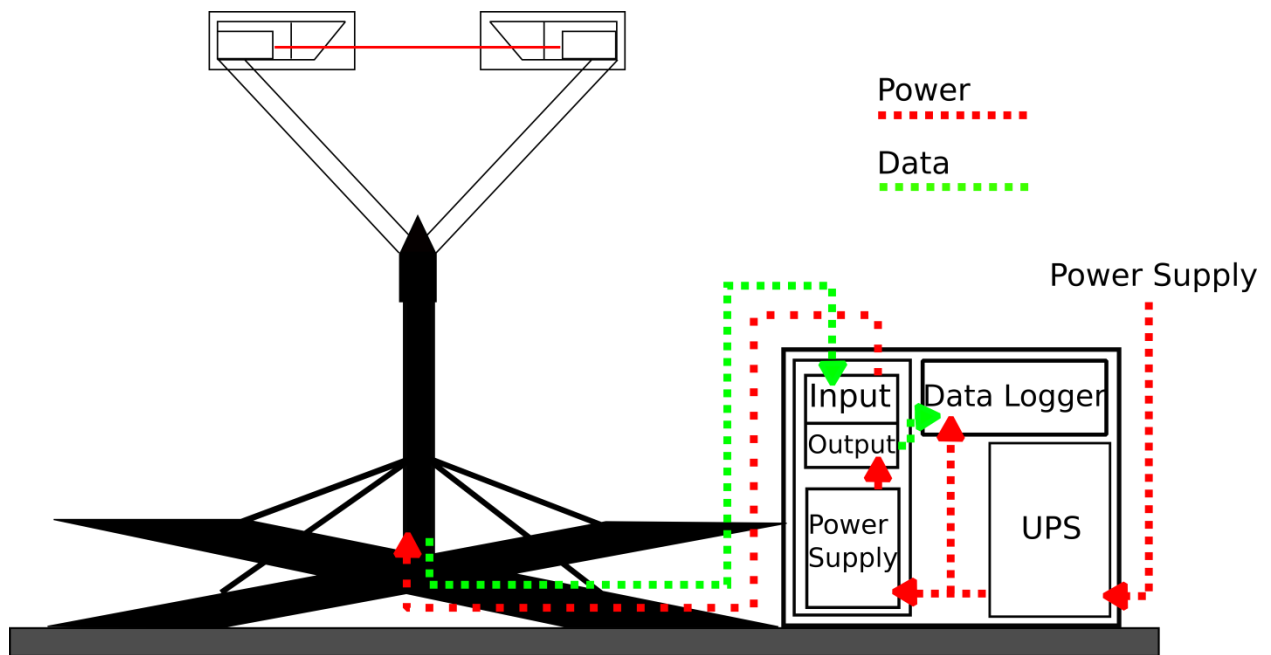


Figure 2-5: Parsivel disdrometer schematic. The green lines show the transfer of data and the red the electricity.



Figure 2-6: The Parsivel disdrometer deployed outside Potchefstroom, North West in close proximity to a tipping-bucket rain gauge.

The decision on the placing of the disdrometer was a long and tedious process. A 30° open horizon was ensured to eliminate any uncertainties in the data caused by obstructions. The security at the site was also considered and access to the instruments had to be easy. The disdrometer was also connected to a UPS to ensure a constant supply of electricity. Fences were erected around the instruments to eliminate tampering.

In close proximity to the Parsivel disdrometer was a tipping-bucket rain gauge which was part of the Mooi River Rain Gauge Network (Chapter 2.1.2) (Figure 2-6). This was done for a few reasons. Using this rain gauge as a ground-truth referencing instrument to compare different radar algorithms was one of the most important reasons to use it. This will be explained in Chapter 5.3. The calibration of instruments was also very important. Throughout this study the calibration of both instruments was confirmed by comparing the rainfall accumulation data. Figure 2-7 confirms this by showing a good correlation between the increments of rainfall for both the instruments. Small errors were expected because both these instruments measure rainfall at different scales and resolutions. They are also prone to different errors. Tipping-bucket rain gauges have the tendency to overestimate events with high rain rates. Challenges unique to the location outside Potchefstroom, North West Province were experienced. Monkeys created a few problems by tampering with the instruments. These errors were eliminated by comparing the data of the rain gauge and disdrometer to one another. Times where only one of the two instruments showed rain was considered as false and was removed from the data. Periods with low rain rates, however, normally showed on the disdrometer data and not the TBR data. This was also considered when false measurements were eliminated.

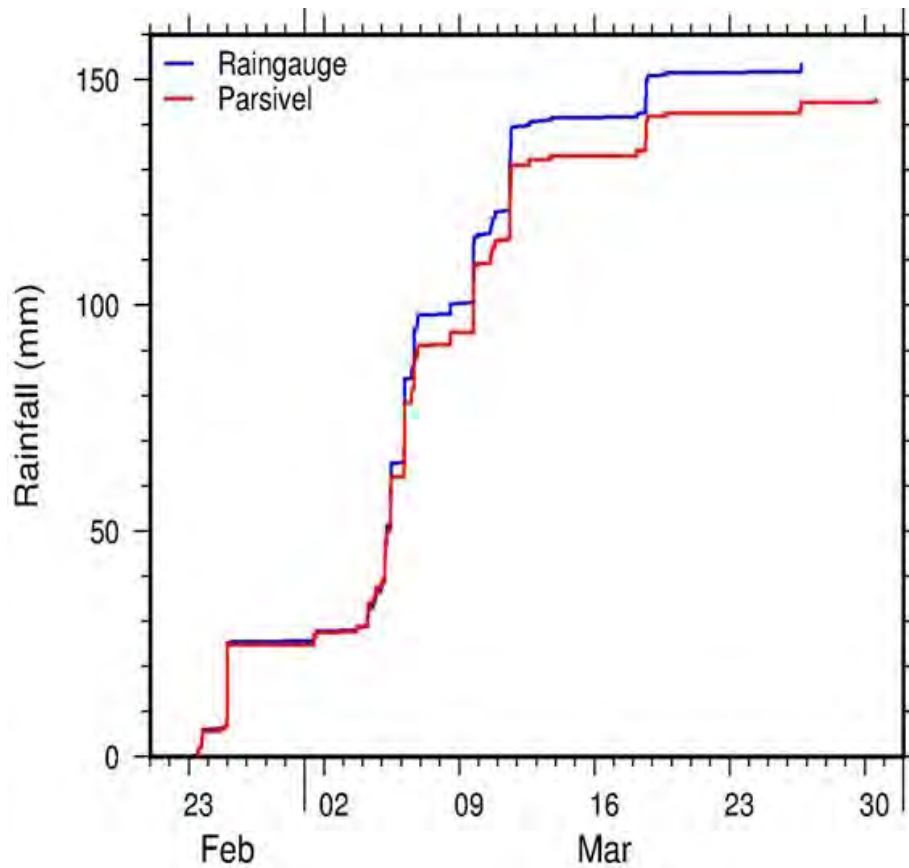


Figure 2-7: Parsivel disdrometer and tipping-bucket rain gauge rainfall accumulation comparison. This was done for calibration purposes. The blue line represents the rain gauge and the red the disdrometer. Measurements were taken between the 21st of February and the 31st of March 2014.

The disdrometer and tipping-bucket rain gauge were also in the coverage area of all three radars operated by SAWS, covering the Highveld and the Mooi River catchment namely the Irene, Ottosdal and Bethlehem weather radars (Figure 2-8). It is also in close proximity (12km) to the newly acquired NWU Lekwena weather radar operated by the North-West University.

The main weather radar used in this study is the Irene weather radar that is approximately 140km from the disdrometer site. This is an acceptable distance without compromising the accuracy and reliability of the data. Similar reasoning has been found in different radar rainfall estimate studies (Marshall & Palmer, 1948; Fabry et al., 1992; Chumchean et al., 2008). The first cappi of the Irene weather radar reaches the North-West University at a height of 3km above sea level (Figure 2-9A).

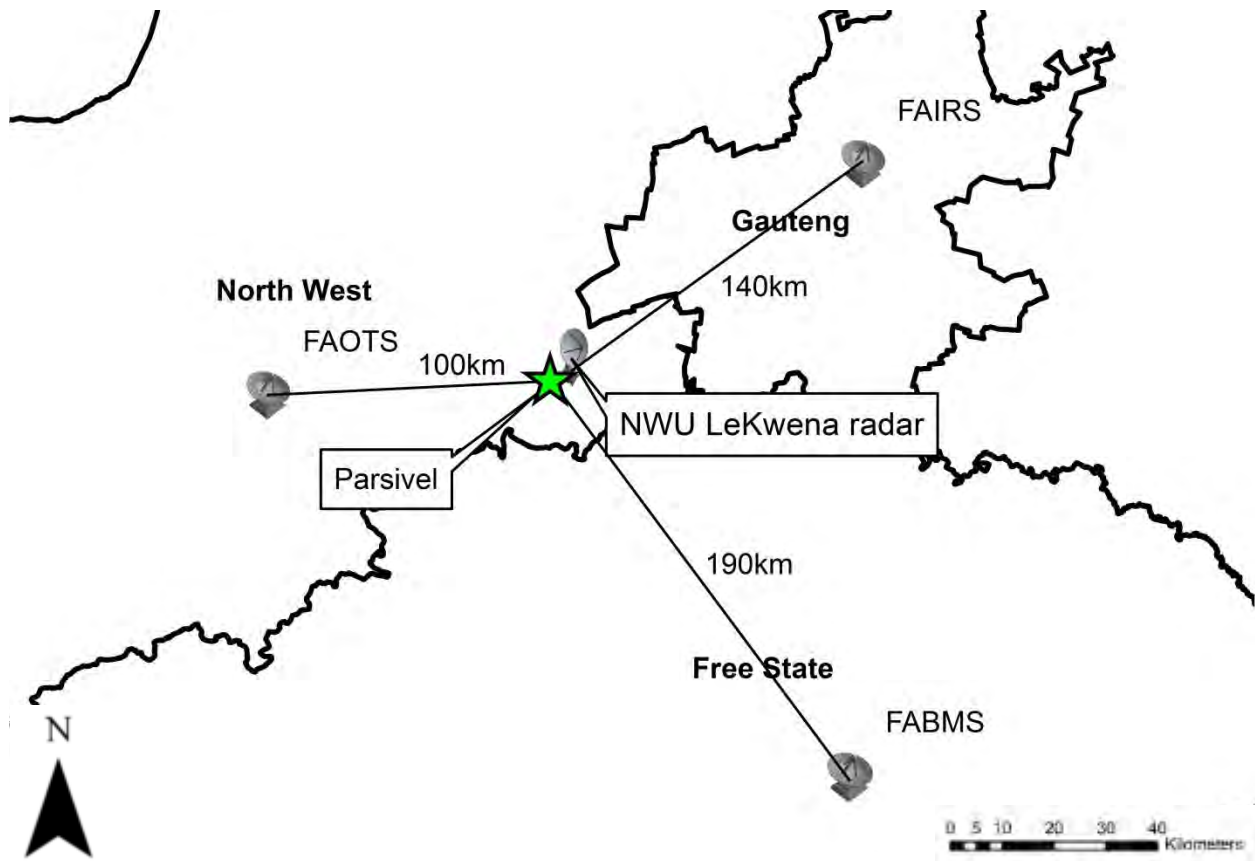


Figure 2-8: Radars covering the Highveld and the Parsivel disdrometer situated outside Potchefstroom. Radars include the Irene weather radar (FAIRS), Ottosdal weather radar (FAOTS) and the Bethlehem weather radar (FABMS). The distance between the radars and the disdrometer is also shown.

The distance between the disdrometer and the Ottosdal weather radar is 100km (Figure 2-8). At this distance the accuracy of weather radar data is at its optimum potential without any ground clutter interference, which is usually a problem at close distances. However, the Ottosdal weather radar has some unique challenges which will be explained in Chapter 5.1.2. The first cappi of this radar reaches the disdrometer outside Potchefstroom at 2km above sea level (Figure 2-9B).

The Bethlehem weather radar is 190km from the disdrometer (Figure 2-8). At this distance the beam of the first cappi reaches the disdrometer at 4km above sea level (Figure 2-9C). Low-lying clouds will therefore not be measured by the first beam and events will be underestimated.

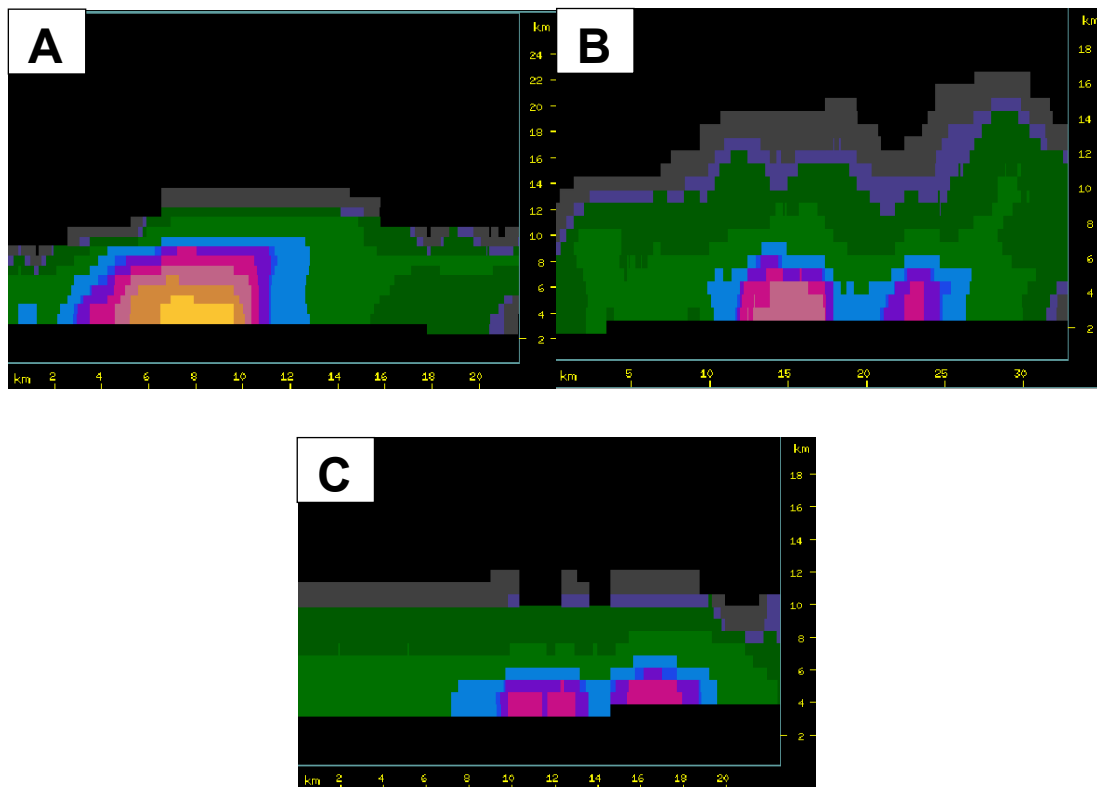


Figure 2-9: The height above sea level at which the first capping of the Irene weather radar (A), Ottosdal weather radar (B) and the Bethlehem weather radar (C) reaches the disdrometer.

2.1.2 The Mooi River Rain Gauge Network operated by the NWU

The Mooi River Rain Gauge Network consists of 15 TBR's over an area of 3294km² (Figure 2-10). These rain gauges are placed in a rain gauge network to the North of Potchefstroom. The Mooi River rain gauge network is considered as a high-density rain gauge network compared to other networks in the country. Other rain gauge networks are not as dense as the Mooi River rain gauge network. This area has been chosen due the proximity to the SAWS radars and the NWU Lekwena radar. The area includes agricultural land and built-up areas. In this study the rain gauges in the Mooi River network was used as reference instrument to measure the true rainfall and the spatial variability thereof on the ground. Newly-developed algorithms used for radar rainfall estimates were implemented and compared to TBR data.

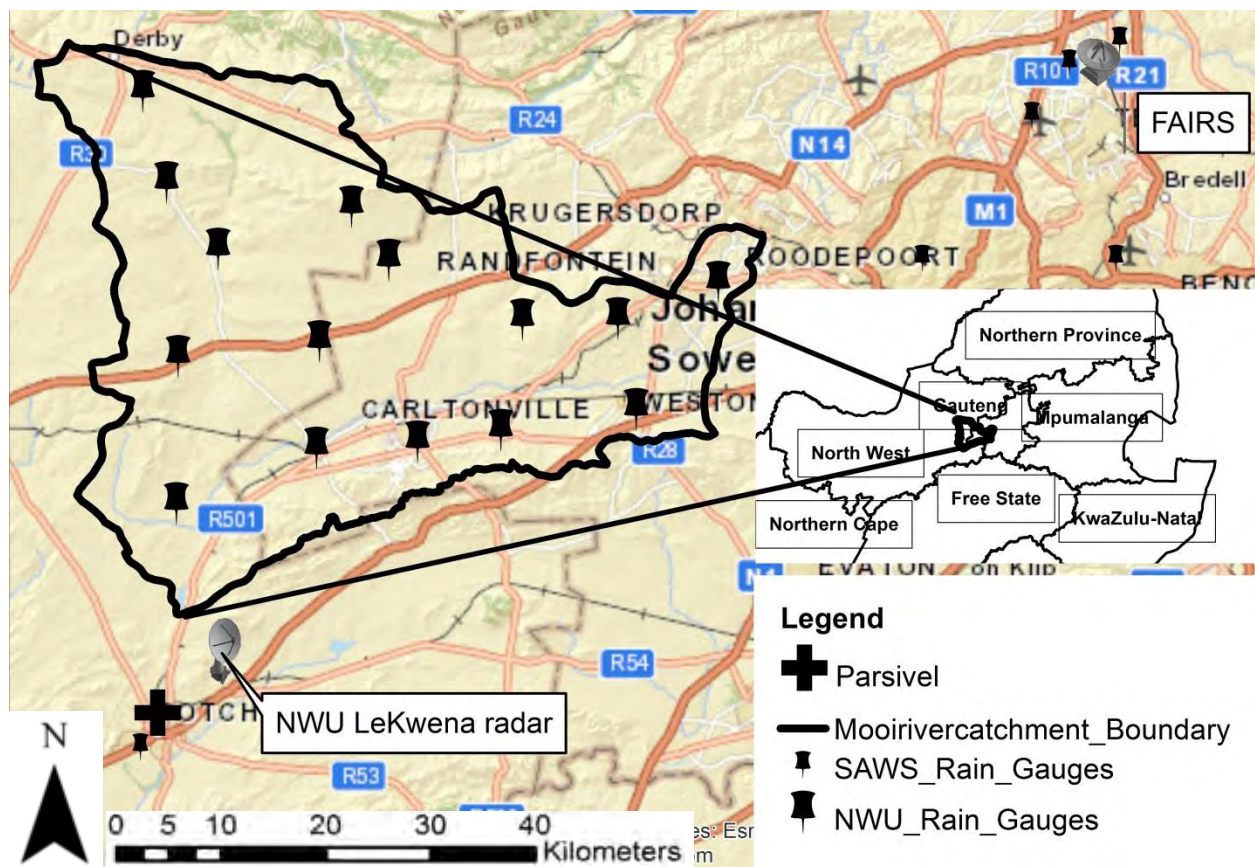


Figure 2-10: The Mooi River Rain Gauge Network operated by the North West University. The network consists of 15 siphon tipping-bucket rain gauges in the coverage area of the Irene and Ottosdal weather radars.

2.1.2.1 The NWU tipping-bucket rain gauge

The rain gauges used in the Mooi River Network are Model TB3 tipping-bucket rain gauges manufactured by hydrological services. It measures rainfall at a resolution of 0.2mm. These rain gauges are equipped with a siphon to minimize errors in especially events with high rain rates. The siphon used in this model has a capacity of 0.4mm. This means that the siphon will dispose the water into the bucket with every 0.4mm of rain observed. The siphon of the rain gauge was frequently cleaned. This is because debris like dust and soil can block the siphon and therefore data would be lost. The rain gauge also consists of a protective cover which helps in minimizing the effect of wind-induced errors (Figure 2-11).



Figure 2-11: The TB3 Siphon tipping-bucket rain gauges used in the Mooi River Rain Gauge Network.

Field calibration of these rain gauges was done on a constant basis. Calibration was done by using an RM Young calibrator fitted to the rain gauge with three different flow rates. The instrument is calibrated if a constant amount of tips is observed that correlates to the amount that must be observed under optimum calibration (79 tips) (Figure 2-12).



Figure 2-12: The RM Young calibrator used to ensure that the instruments are calibrated and accurate data is measured.

2.1.2.2 Custom developed data logger used in the operation of NWU tipping-bucket rain gauge

Each tip made by the rain gauge is stored on the data logger (Figure 2-13). The tip is stored by recording the time of the tip and is assigned one of the following identities namely: \$RD, \$ED and \$TD according to the type of stamp on the data loggers. A \$RD tip represents a test tip which is simulated by the user to see whether the system works. This simulated tip is made by pressing a button on the data logger which sends an electrical pulse and logs a tip. Tips caused by rainfall is assigned the symbol \$ED. It is also very important to know when the system is not working. This can be very confusing because when the system does not work, it may appear that it was a day with no rain. Therefore a simulated tip, identified as \$TD, is added every 12 hours. If the timestamp (\$TD) is not recorded on the data it means that the system is not working. The data logger also records other valuable information like the date and time of the tip, gauge ID, and rainfall volume and accumulation (Table 2-1).



Figure 2-13: The data logger used to store data measured by the rain gauge.

Table 2-1: The data logger used to store the data measured by the NWU tipping-bucket rain gauges stores the type of tip, gauge ID if multiple gauges are used in a network, the date of the tip, time of tip, the number of tips, rainfall volume and rainfall accumulation.

Rain Gauge Data Logger Raw Data						
Type	Gauge		Time	Number of tips	Rainfall Volume	Rainfall
	ID	Date				Accumulation (mm)
\$RD	6	3/14/2014	14:56:42	17	0.2	0.2
\$RD	6	3/14/2014	14:59:17	18	0.2	0.4
\$ED	6	3/14/2014	15:00:56	19	0.2	0.6
\$ED	6	3/14/2014	15:00:57	20	0.2	0.8
\$ED	6	3/14/2014	15:00:58	21	0.2	1
\$ED	6	3/14/2014	15:00:59	22	0.2	1.2
\$ED	6	3/14/2014	15:01:03	23	0.2	1.4
\$TD	6	3/15/2014	0:00:00	24	0.2	1.6

2.1.2.3 The design of the NWU tipping bucket rain gauge system

The NWU tipping-bucket rain gauges consist of the tipping-bucket rain gauge, siphon, solar panel, data logger, battery and solar regulator (Figure 2-14).



Figure 2-14: The NWU tipping-bucket rain gauge.

These rain gauges were built as cost-effectively as possible. The read switch is connected to the data logger in order to store data. The data logger is powered by the battery that gets charged through the solar regulator that receives its power from the solar panel (Figure 2-15).

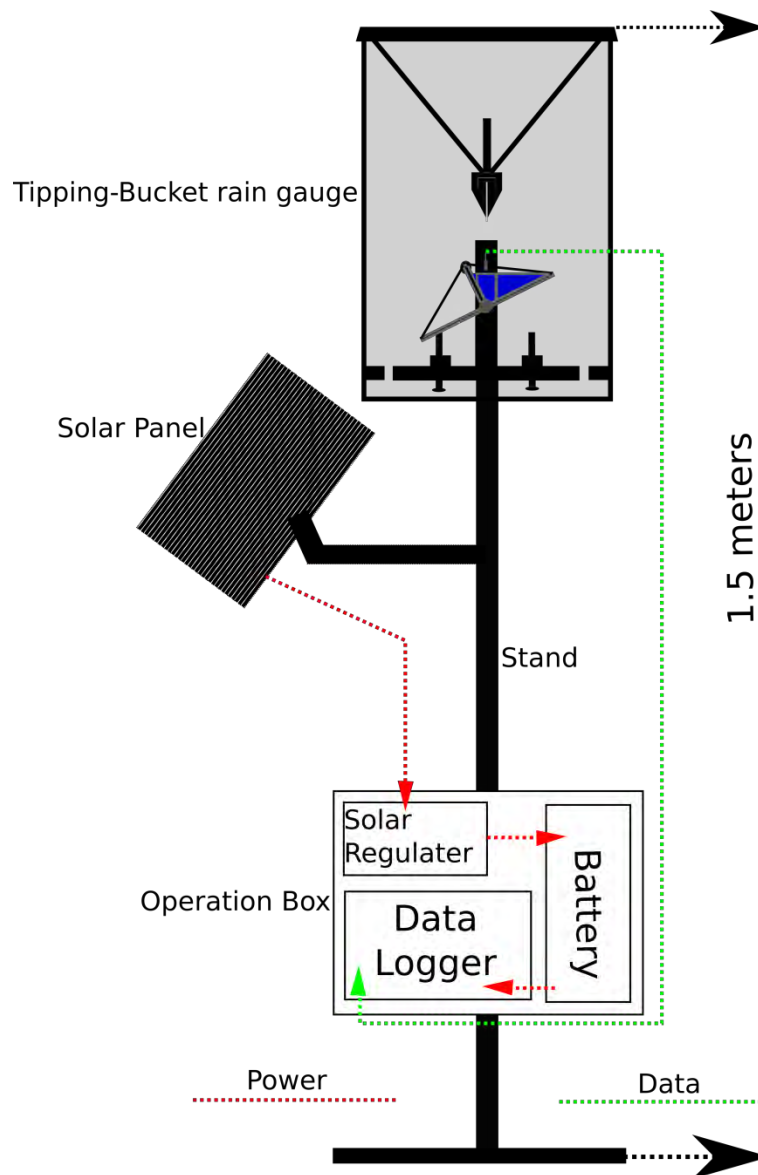


Figure 2-15: NWU Tipping-bucket rain gauge schematics. The green line shows the transfer of data and the red line power.

2.1.3 The SAWS tipping-bucket rain gauge and weather radar network

The South African Weather Service has an extensive network of weather radar which has been upgraded between 2009 and 2012. It includes nine single-polarised S-band radars, 1 dual-polarised S-band weather radar, two mobile dual-polarised X-band radars and 5 C-band radars upgraded from the old network which included 10 Enterprise C-band and 1 modified MRL-5 S-band radar (Terblanche et al., 1994)(Figure 2-16). Maintaining the network with limited funds presents unique challenges in a developing country.

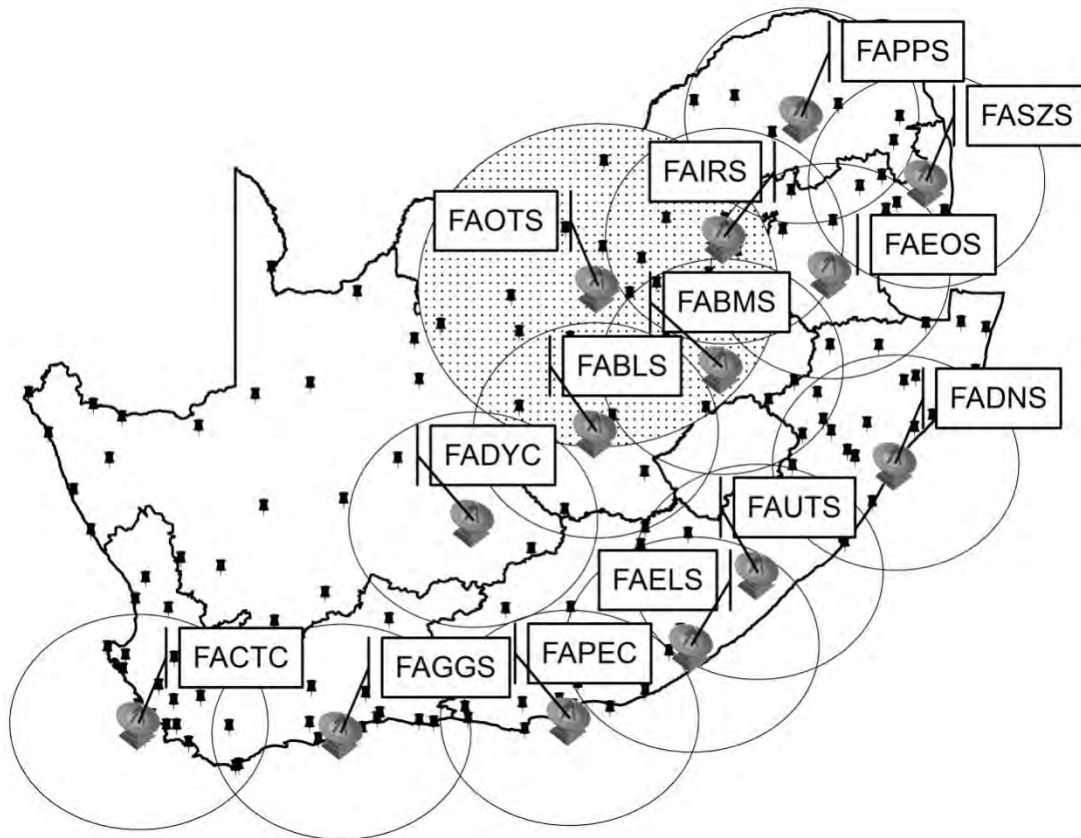


Figure 2-16: SAWS weather radar and rain gauge network. The Ottosdal weather radar coverage area is shown by the dotted coverage zone due to its different range at 300km compared to 200km of the other radars. Radars are named as follows: FACTC = Cape Town radar; FAGGS = George radar; FAPES = Port Elizabeth radar; FAELS = East London radar; FAUTS = Umtata radar, FADNS = Durban radar; FAEOS = Ermelo radar; FASZS = Skukuza radar, FAPPS = Polokwane radar; FAIRS = Irene radar; FAOTS = Ottosdal radar, FABMS = Bethlehem radar; FADYC = De Aar radar.

Three weather radars operated by SAWS and the NWU LeKwena weather radar were used in this study. SAWS weather radars that were used included the Irene (FAIRS), Ottosdal (FAOTS) and Bethlehem (FABMS) weather radars. These radars were chosen for a number of reasons.

The Irene weather radar situated in Irene, Gauteng, is considered one of the most accurate and reliable weather radars in the network. Being in close proximity to the SAWS technical office makes the access for maintenance work on the radar easier for technicians. This was the first new S-band Gematronik radar installed in the upgrade of the network. It was installed a few

meters to the southeast of the old C-band radar that was in operation until the end of March 2010.

The most noticeable difference between the old C-band and the S-band radar is the wavelength. The C-band has a wavelength of 5.3cm that makes it prone to errors like attenuation and RLAN interference. The S-band radar has a wavelength of 10.5cm that minimizes the effect of these errors. The Irene radar also has one of the most reliable data sets with 87% of data available for 2014 (Figure 2-18). This is a full set of data if one takes into consideration the fact that these radars are switched off during some days in the winter months because Gauteng is a summer rainfall region which also renders it a good time to do maintenance. Frequent visits were made to the Irene weather radar during this study (Figure 2-17).



Figure 2-17: The author made numerous visits to the Irene weather radar.

The Ottosdal weather radar is also an S-band Gematronik radar. This radar is situated in Ottosdal, North West. The radar is the only radar in the network where the range is set at 300km as opposed to the 200km of the other radars (Figure 2-16). This may create errors in the data as the accuracy of the data decreases with an increase of distance from the radar. The Ottosdal weather radar has an 18% data reliability. This low data reliability is not sufficient for scientific investigation (Figure 2-18).

The Bethlehem weather radar in the Free State is a state-of-the-art, S-band dual-polarised Gematronik weather radar. This is the only dual polarised weather radar in the country. There are, however, the following issues with the radar:

- Sensitivity of the receiver

Because the Bethlehem radar is constantly underestimating events it can be concluded that the sensitivity of the receiver is experiencing problems.

- The cooling of the system

Radar hardware produces a lot of heat. Cooling systems like air cons are therefore very important and when these systems fail the radar will shut down. In the context of the Bethlehem radar the cooling system very often fails.

- Data transfer

The transfer of data from the radar to SAWS head office relies on fast and reliable bandwidth. This in South Africa is often a problem.

- Hardware Problems

The maintenance of the radar hardware is problematic due to lack of expertise and financial problems.

- Electricity (Generator)

With the energy crises experienced in South Africa and the fluctuation in power supply generators are used to keep a constant supply. The unexpected shutdown of a radar due to electricity failure causes problems when the radar reboots.

- Location of the radar

The Bethlehem radar is situated 300km from the SAWS technical office. Bethlehem also does not have an airport for flights. Therefore deploying maintenance teams is a problem.

- Expertise in dual-polarised radars

Expertise in especially dual-polarised radars in South Africa remains a huge problem which also has an effect on the operation and maintenance of the radar.

This makes the data from the radar unsuitable for scientific investigation. The availability of data is also problematic at 39% (Figure 2-18).

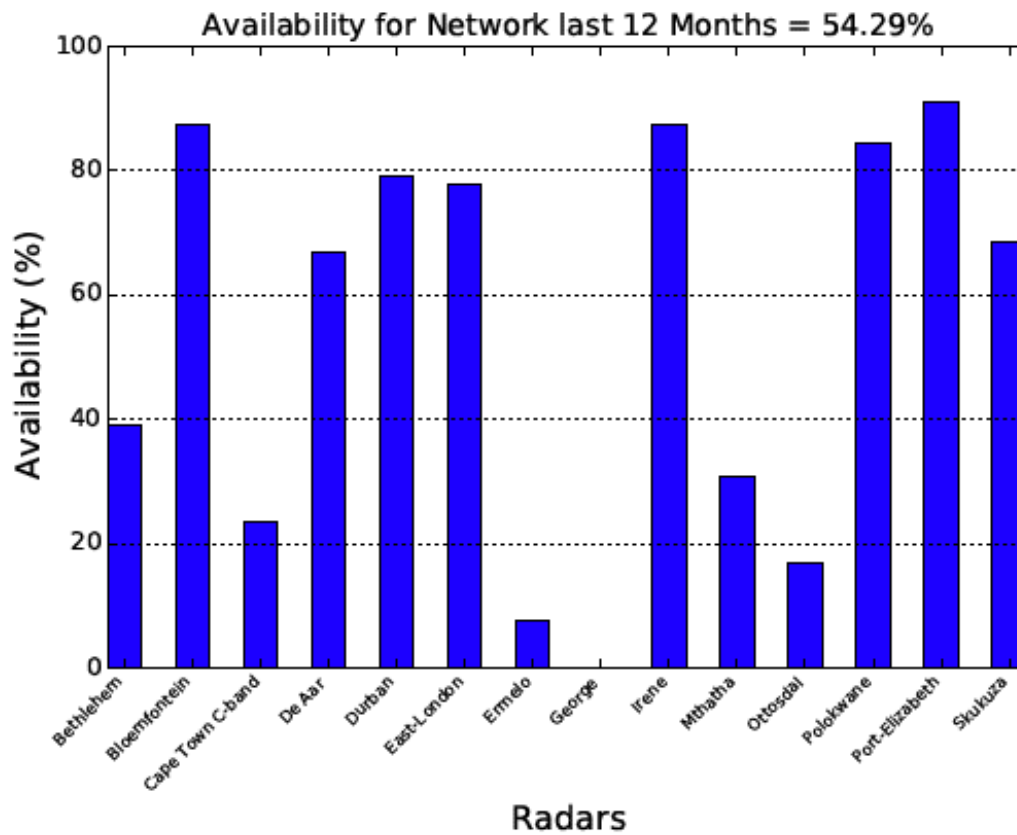


Figure 2-18: The availability of SAWS weather radar data between January and December 2014.

It was consequently decided that the majority of the investigations for this study would be done using the Irene weather radar. This included testing new radar rainfall algorithms, the stratifying of convective and stratiform regimes and investigating bias and calibration offsets. The performance of the Ottosdal and Bethlehem radar was, however, tested by comparing the reflectivity (Z) of both the radar and the Parsivel disdrometer to each other.

2.2 DATA

Weather radar data was obtained from the South African Weather Service. Parsivel disdrometer and rain gauge data were measured under the supervision of the author.

2.2.1 The Parsivel disdrometer

Measurements made by the Parsivel disdrometer were done between the 21st of February and the 31st of March 2014. This time period is very significant as this is when the area of the Mooi River catchment observes the highest amount of rainfall and convective events which mostly creates these inconsistencies in data and radar rainfall estimates. It is also the time when the majority of tropical- temperature trough Synoptic conditions such as the easterly wave and easterly low creates these favourable conditions for intense convective events and normally occurs between December and February. These events are rarely observed between April and October. Other periods of the year does not have that much rainfall as the area is predominantly a summer rainfall region and in the winter months mostly stratiform rain occurs. These rains normally do not result in damage or loss of life as they have much lower rain rates than convective events. Also, these events are far easier to measure accurately as they are more uniform in rain rate and evenly spread spatially. During this time 60 events were measured and 162mm of rain and a total of 24 rain days were observed. The disdrometer measured a maximum rain rate of 62mm/h and a reflectivity of 60dbz.

The Parsivel disdrometer measures each particle's size and velocity as it moves through the laser beam and it has the ability to measure reflectivity and rain rate on the ground simultaneously. This makes it the ideal instrument for radar comparison purposes. In this study disdrometer data was used for three main reasons. Firstly, measuring reflectivity on the ground is crucial for radar bias and calibration offset measurements as the radar measures reflectivity aloft. The correlation between measured radar and disdrometer reflectivity was calculated to evaluate the performance of the weather radars. Secondly, new unique Z-R relations, Eq. (5), were derived for individual storms because reflectivity and rain rate gets measured on the ground simultaneously (Figure 2-19). Lastly, this instrument also has the ability to measure rainfall at a high resolution (10s). By setting up a co-located disdrometer and rain gauge, these errors were corrected in the data. The rain gauge does not have the ability to accurately measure the start and end times of events as explained in Chapter 1.6.6. The disdrometer data was used to determine when events started.

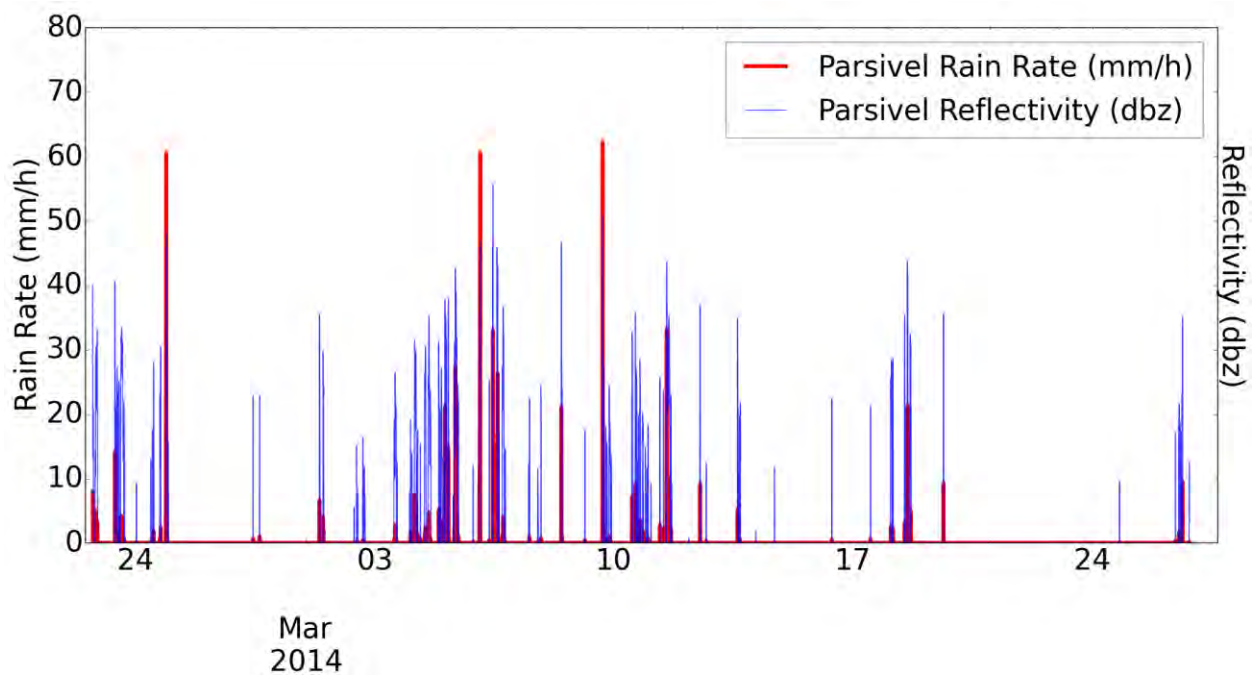


Figure 2-19: Reflectivity (Blue) and rain rate (red) measured by the Parsivel disdrometer between the 21st of February and the 31st of March 2015.

2.2.2 Irene, Ottosdal and Bethlehem weather radar data operated by the South African Weather Service.

Weather radar data was obtained from the South African weather service for the Irene, Ottosdal and the Bethlehem radars. Reflectivity data was in volume format (.vol) with a Cartesian projection. Variables for the single -polarised radars (Irene and Ottosdal) included DBZ and DBuZ. Dual-polarised radar data (Bethlehem) variables included ρ_{HV} , Z DR, ϕ_{DP} , K_{DP} and LDR. These variables were explained in Chapter 1.6.5.4. Volume data was converted, using TITAN (Thunderstorm Identification, Tracking, Analysis and Nowcasting), to Meteorological Data Volume (MDV) format. The data consists of 17 cappi levels and an 800×800 two-dimensional grid with a bin size of $500\text{m} \times 500\text{m}$ for the Irene and Bethlehem radar. Because the Ottosdal radar has a maximum range of 300km compared to the 200km of the other radars this increases the size and amount of bins. The Ottosdal radar consists of a 1200×1200 grid of bins which is $750\text{m} \times 750\text{m}$ in surface area.

The movement of storms posed a unique challenge when radar data was extracted. The radar completes a volume scan between four and six minutes. The movement of storms can cause data to be lost if it's not addressed. With a scan, if the event is at the pixel adjacent or above the disdrometer pixel the movement of the storm will pass this pixel before the next scan. This

creates inconsistencies in the data as this data will be lost. Using the 8 pixels around the Parsivel disdrometer will eliminate this error by averaging the maximum reflectivity observed for all 9 pixels (Figure 2-20).

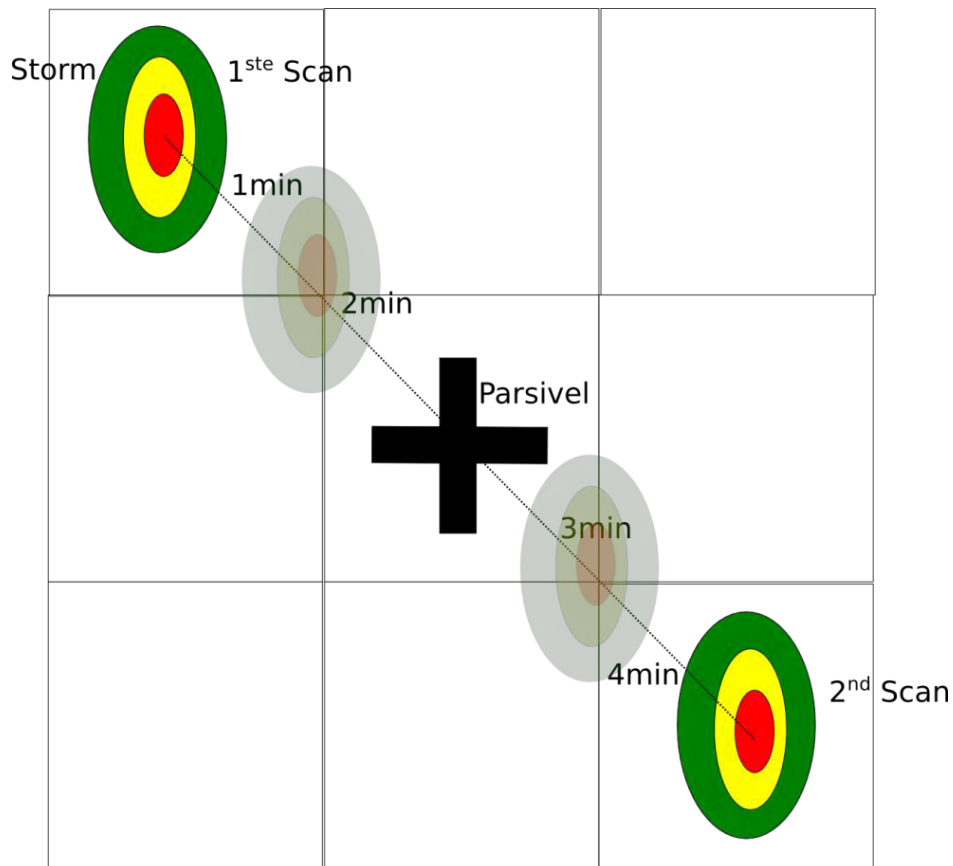


Figure 2-20: 9-pixel method used to extract radar data due to the movement of storms. This ensures that data does not get lost and that all storms that move over the pixel in question get measured.

The disdrometer pixel was identified by its coordinates ($S\ 26^{\circ}41'22.83''$; $E\ 27^{\circ}05'25.98''$) and by overlaying this with an 800×800 grid to determine the x and y number of the pixel (574; 177) (Table 2-2). The surrounding pixels were then easily identifiable.

Table 2-2: Pixel data extracted from radar data. The Parsivel disdrometer pixel was identified as x, 574, and y, 177. Surrounding pixels were 573;176, 573;177, 573;178, 574;176, 574;177, 574;178, 575;176, 575;177 and 575;178. The average of the reflectivity measurement for all pixels was also calculated.

Date_Time	573 176	573 177	573 178	574 176	574 177	574 178	575 176	575 177	575 178	Average Radar Pixel
2014/02/24 20:40	7	7	0	7	8	6	7	7	7	7
2014/02/24 20:45	13	12	6	13	13	8	11	13	12	11
2014/02/24 20:50	17	16	13	17	17	13	15	17	17	16
2014/02/24 20:55	19	19	18	19	20	20	18	20	22	19
2014/02/24 21:00	21	21	20	20	21	22	20	21	22	21
2014/02/24 21:05	23	24	25	23	24	26	23	24	26	24
2014/02/24 21:10	26	25	25	27	26	26	26	27	26	26
2014/02/24 21:15	29	27	26	28	28	27	27	28	27	28
2014/02/24 21:20	31	29	28	30	30	29	30	30	29	30
2014/02/24 21:25	35	33	34	36	33	32	37	35	32	34
2014/02/24 21:30	46	45	43	47	45	41	46	44	41	44
2014/02/24 21:35	46	47	46	47	47	45	44	46	45	46
2014/02/24 21:40	38	41	43	36	39	40	34	36	38	38
2014/02/24 21:45	32	34	37	29	32	35	30	31	33	33
2014/02/24 21:50	32	32	34	31	32	33	33	32	34	32
2014/02/24 21:55	36	35	33	37	37	35	38	37	37	36
2014/02/24 22:00	38	38	34	39	39	36	37	38	38	37
2014/02/24 22:05	28	29	33	28	29	31	26	30	31	29
2014/02/24 22:10	28	29	30	28	29	29	30	29	29	29
2014/02/24 22:15	17	19	22	11	17	19	18	17	18	17
2014/02/24 22:20	5	7	9	0	5	7	5	5	6	6

It was clear that there were problems with the Bethlehem radar data. Large periods of no rain were measured by the Bethlehem radar while both the Irene and Ottosdal radars and the Parsivel disdrometer measured rainfall. The radar data shown in Figure 2-21 was extracted and represent the bin that includes the disdrometer. This was done to compare and to evaluate the performance of the radars.

The conclusion was that the Bethlehem weather radar data was not adequate for scientific purposes and that the problems that were observed were hardware faults and not software faults.

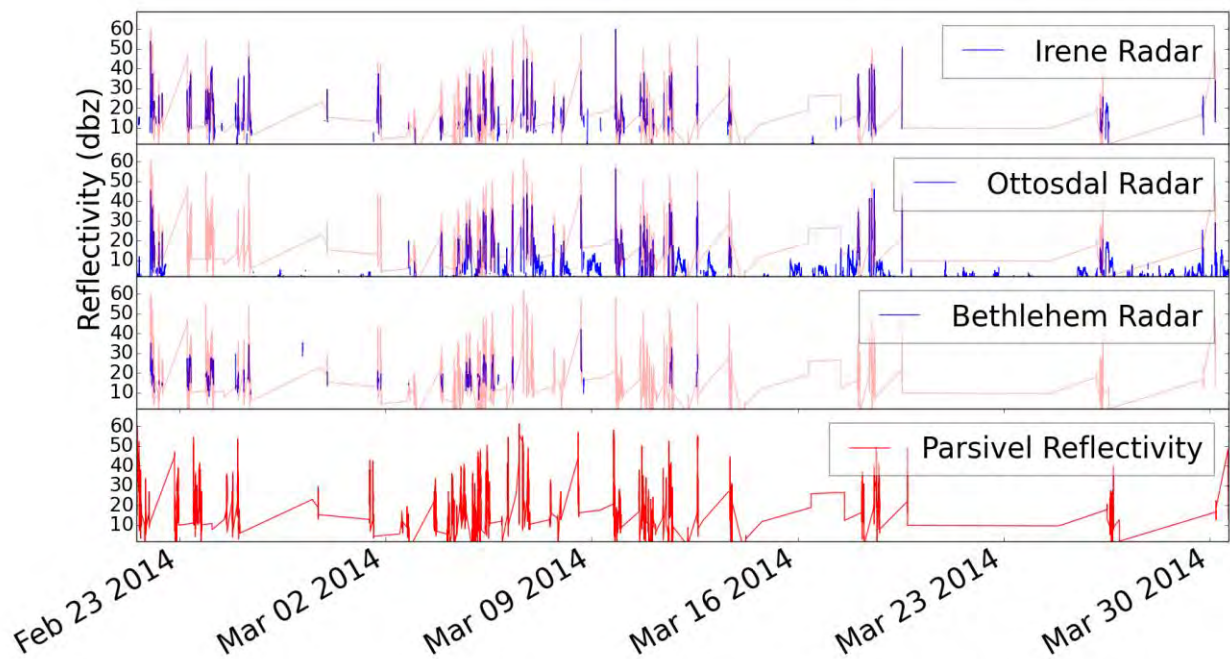


Figure 2-21: Reflectivity measurements made by the Irene weather radar, Ottosdal weather radar, Bethlehem weather radar and Parsivel disdrometer. The dbz values of the radars are shown in blue and that made by the disdrometer in red.

2.2.3 NWU tipping-bucket rain gauge data

Tipping-bucket rain gauges measure a point measurement of the volume of rainfall (Figure 2-22). The data is considered very reliable as the mechanical function of the TBR makes it prone to fewer errors. This data was firstly used to develop a new algorithm to measure rain rates with a siphon TBR data as this poses unique challenges. The newly-developed algorithm uses the timestamp measured by the TBR at which a tip occurs. The total rainfall measured by the rain gauge was also used to identify significant events. Secondly, the data used to test new

radar rainfall estimates' algorithms by comparing the rainfall accumulation measured by the radar to that measured on the ground by the TBR.

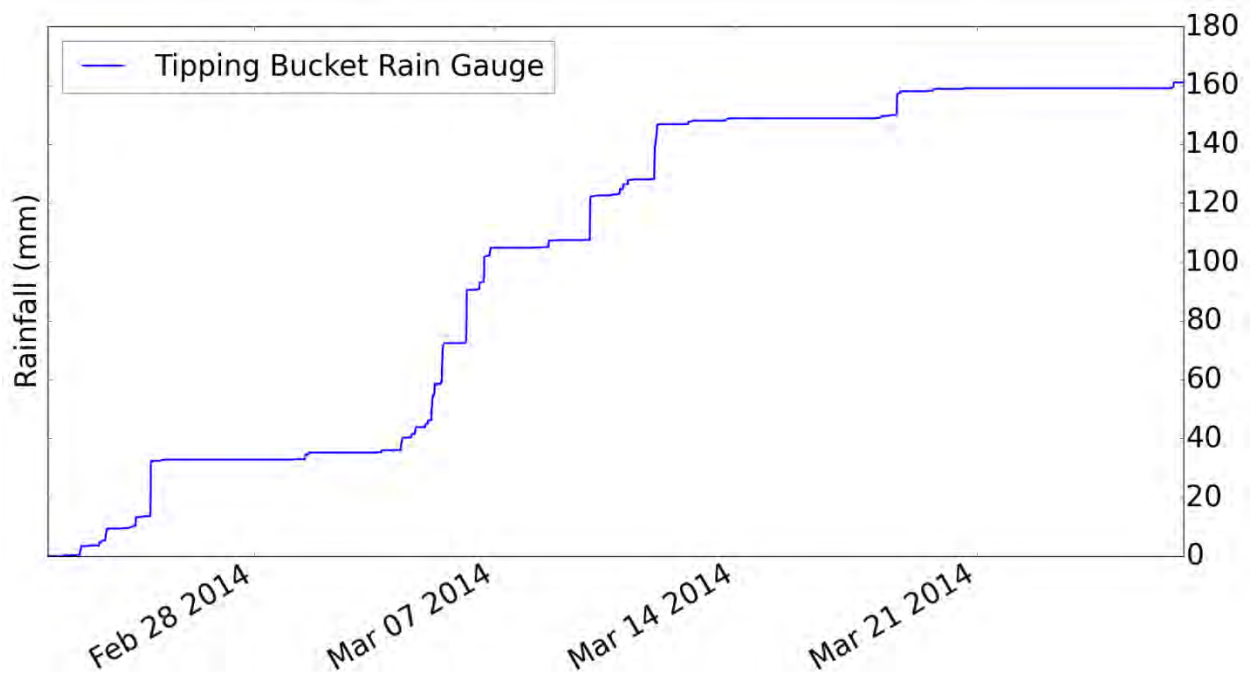


Figure 2-22: Rainfall accumulation measured by the TBR between February and March 2014.

2.2.4 Identifying events using rain rate, duration and reflectivity

Events were identified by a 15min gap between measurements (Table 2-3). These events were limited to those with a duration longer than 3 minutes. The reflectivity (Z) and rain rate (R) values were extracted from the disdrometer data. The maximum reflectivity and rain rates were used to identify significant events. The mean of Z and R was calculated by adding all Z and R values and dividing that by the number of data points (EventN). Variations in rainfall and reflectivity values from the mean Z and R values are also shown by the standard deviation of the two variables, DBZStd and RainStd respectively. This was calculated by subtracting the measured rainfall from the mean.

Table 2-3: Events measured by the Parsivel disdrometer (Continued on next page).

		Parsivel															
		Reflectivity (dbz)							Rain Rate (mm/h)								
	Start	End	DBZ25	DBZ50	DBZ75	DBZMax	DBZMean	DBZMin	DBZStd	Rain25	Rain50	Rain75	RainMean	RainMin	RainMax	RainStd	EventN
1	2014-02-21 14:58:40+02:00	16:59:20+02:00	16.1	26.3	34.8	52.5	25.8	3.3	11.3	0.4	1.8	6.8	5.7	0.1	60.3	9.2	417
2	2014-02-21 20:06:10+02:00	20:53:10+02:00	9.5	19.1	24.3	33.5	17.4	0.1	8.9	0.1	0.5	1.4	1.0	0.0	5.6	1.2	163
3	2014-02-21 23:26:50+02:00	23:40:40+02:00	14.0	18.7	21.8	26.9	18.0	8.6	5.1	0.2	0.4	0.5	0.4	0.1	1.2	0.3	53
4	2014-02-22 20:08:30+02:00	20:41:50+02:00	11.4	17.5	21.0	47.1	16.5	-1.0	7.8	0.2	0.5	0.9	0.7	0.0	13.1	1.5	114
5	2014-02-22 21:50:10+02:00	23:31:40+02:00	20.2	25.4	29.0	39.2	24.0	1.6	6.9	0.6	1.6	3.0	2.0	0.0	7.2	1.6	575
6	2014-02-23 11:41:20+02:00	11:57:40+02:00	19.9	24.3	44.7	54.5	30.5	10.0	13.8	0.5	1.2	12.8	7.3	0.1	61.7	11.7	65
7	2014-02-23 12:30:20+02:00	14:45:50+02:00	15.1	18.8	23.0	36.5	19.2	4.1	5.4	0.3	0.5	0.9	0.7	0.1	4.0	0.6	409
8	2014-02-23 15:47:10+02:00	18:26:20+02:00	18.8	25.3	30.1	41.6	24.3	0.8	7.2	0.5	1.1	2.2	1.5	0.0	6.2	1.3	833
9	2014-02-24 14:09:00+02:00	15:01:00+02:00	16.5	22.8	28.5	35.9	22.6	6.4	6.7	0.3	0.8	1.4	1.0	0.1	3.7	0.8	154
10	2014-02-24 19:18:20+02:00	19:57:50+02:00	15.1	18.3	23.7	36.6	19.6	3.9	6.8	0.3	0.4	0.9	0.8	0.1	5.6	0.9	224
11	2014-02-24 23:22:20+02:00	00:29:30+02:00	23.1	30.6	42.9	53.8	32.5	2.8	11.9	1.0	3.9	23.9	18.5	0.0	102.7	27.0	354
12	2014-02-27 17:14:10+02:00	17:18:10+02:00	16.5	22.9	25.0	29.5	21.6	13.1	5.1	0.3	0.9	1.2	0.8	0.2	2.6	0.6	20
13	2014-03-01 11:10:30+02:00	11:35:50+02:00	24.4	31.7	35.6	43.2	30.5	6.8	7.3	1.7	3.6	6.3	4.6	0.1	16.0	3.6	132
14	2014-03-01 13:48:30+02:00	14:20:30+02:00	15.4	23.1	26.1	42.4	21.6	3.5	7.8	0.4	1.4	2.1	1.8	0.0	14.4	2.1	188
15	2014-03-02 17:36:20+02:00	18:06:30+02:00	9.4	11.7	14.3	19.5	11.8	3.7	3.6	0.1	0.2	0.3	0.2	0.1	0.7	0.1	98
16	2014-03-02 18:39:40+02:00	19:44:40+02:00	6.8	10.5	12.3	15.9	9.5	-1.5	3.6	0.1	0.1	0.2	0.1	0.0	0.3	0.1	136
17	2014-03-03 15:38:50+02:00	17:55:30+02:00	14.1	18.2	22.2	33.6	17.9	4.7	5.4	0.3	0.5	0.9	0.7	0.1	3.9	0.7	627
18	2014-03-04 02:28:50+02:00	03:21:00+02:00	5.4	8.7	14.1	27.2	10.4	-1.1	6.6	0.1	0.1	0.4	0.5	0.0	4.8	0.9	118
19	2014-03-04 04:13:10+02:00	04:25:50+02:00	2.8	7.6	13.8	21.1	7.9	-2.2	6.7	0.1	0.2	0.4	0.3	0.0	1.6	0.4	72
20	2014-03-04 05:57:40+02:00	07:15:20+02:00	20.4	24.6	28.2	36.3	24.4	5.9	5.0	1.5	3.1	5.3	3.6	0.1	14.2	2.5	466
21	2014-03-04 07:50:00+02:00	08:23:30+02:00	6.4	12.7	15.8	22.6	11.2	-4.2	6.3	0.1	0.5	0.9	0.6	0.0	3.4	0.6	199
22	2014-03-04 10:02:40+02:00	10:11:30+02:00	10.9	14.5	16.8	20.1	13.6	4.7	4.3	0.2	0.5	0.7	0.5	0.1	1.0	0.3	39
23	2014-03-04 13:05:30+02:00	14:02:10+02:00	20.6	24.1	27.9	39.7	24.0	8.4	5.6	0.6	1.1	1.7	1.3	0.1	5.8	0.9	329
24	2014-03-04 15:33:30+02:00	17:29:20+02:00	19.8	23.2	28.9	41.0	24.3	8.1	6.4	0.6	1.0	2.1	1.5	0.1	9.5	1.4	508
25	2014-03-04 22:31:30+02:00	01:31:10+02:00	7.7	17.5	24.5	36.5	16.3	-4.7	9.6	0.1	0.5	1.7	1.1	0.0	9.6	1.4	642
26	2014-03-05 02:46:30+02:00	06:11:00+02:00	16.2	26.8	31.9	48.1	24.9	-4.3	10.5	0.5	2.3	5.9	5.3	0.0	50.5	8.5	717
27	2014-03-05 09:59:30+02:00	13:08:30+02:00	18.1	25.5	31.3	50.3	25.1	3.2	8.7	0.6	1.5	4.5	4.3	0.1	61.2	7.2	1009
28	2014-03-05 23:08:00+02:00	23:16:30+02:00	6.6	10.0	12.0	14.5	8.8	0.1	3.9	0.1	0.2	0.2	0.2	0.0	0.4	0.1	48
29	2014-03-06 03:26:40+02:00	04:21:10+02:00	27.9	35.2	42.0	54.5	34.8	4.5	9.7	2.9	10.1	25.0	19.0	0.1	129.7	24.2	312
30	2014-03-06 13:00:10+02:00	13:11:40+02:00	26.4	41.4	50.1	61.4	38.3	10.3	14.7	1.6	8.5	27.8	20.7	0.1	107.5	28.0	50

	Start	End	DBZ25	DBZ50	DBZ75	DBZMax	DBZMean	DBZMin	DBZStd	Rain25	Rain50	Rain75	RainMean	RainMin	RainMax	RainStd	EventN
31	2014-03-06 15:51:00+02:00	16:37:00+02:00	27.3	35.3	42.5	54.9	34.2	7.5	10.1	2.0	6.1	15.7	10.5	0.1	48.7	11.2	245
32	2014-03-06 19:37:10+02:00	20:56:20+02:00	26.1	31.0	34.4	49.1	30.0	7.8	6.2	1.1	2.2	3.3	2.4	0.1	11.3	1.7	386
33	2014-03-07 14:07:00+02:00	14:53:30+02:00	13.4	18.8	22.1	32.9	18.6	8.9	5.9	0.2	0.4	0.8	0.6	0.1	2.3	0.5	84
34	2014-03-07 20:25:10+02:00	20:51:50+02:00	5.8	7.8	10.5	15.0	8.1	0.2	3.5	0.1	0.1	0.2	0.1	0.0	0.3	0.1	42
35	2014-03-07 22:49:10+02:00	22:59:50+02:00	17.6	21.2	23.7	27.0	20.5	12.7	4.0	0.4	0.5	0.8	0.6	0.2	1.3	0.3	52
36	2014-03-08 13:00:10+02:00	13:43:40+02:00	22.3	27.8	36.6	56.9	30.0	14.2	9.7	0.6	1.6	5.2	5.1	0.2	58.0	8.9	187
37	2014-03-09 17:54:10+02:00	19:12:50+02:00	19.6	28.3	45.8	58.3	30.9	1.8	14.9	0.6	1.9	29.5	17.1	0.0	93.0	25.1	313
38	2014-03-09 20:10:20+02:00	21:21:30+02:00	10.8	13.4	15.0	19.0	12.6	-2.0	4.0	0.2	0.2	0.3	0.2	0.0	0.5	0.1	73
39	2014-03-09 22:37:30+02:00	00:17:10+02:00	13.8	17.0	19.6	28.4	16.9	6.1	4.3	0.2	0.3	0.5	0.4	0.1	1.7	0.3	306
40	2014-03-10 14:32:40+02:00	15:06:30+02:00	24.0	28.4	31.6	38.0	27.6	-0.3	5.3	1.4	3.4	5.2	3.7	0.0	13.5	2.6	202
41	2014-03-10 16:58:50+02:00	18:04:20+02:00	22.6	25.4	30.8	50.1	26.6	7.9	7.8	0.8	1.2	2.8	2.8	0.1	27.6	4.3	196
42	2014-03-10 20:09:20+02:00	20:40:50+02:00	23.4	26.0	28.6	34.1	25.0	-3.7	5.7	1.5	2.9	3.6	2.8	0.0	8.4	1.7	165
43	2014-03-10 22:05:40+02:00	22:38:30+02:00	11.8	15.1	21.2	28.0	16.1	1.3	5.7	0.2	0.4	1.6	1.0	0.0	5.1	1.1	82
44	2014-03-11 00:00:00+02:00	02:08:30+02:00	7.3	10.5	14.1	24.1	10.6	-1.3	5.3	0.1	0.2	0.3	0.2	0.0	1.5	0.2	194
45	2014-03-11 10:19:30+02:00	10:27:30+02:00	17.0	23.9	27.6	38.8	22.0	2.4	9.4	0.6	2.0	3.0	2.2	0.0	7.9	2.0	49
46	2014-03-11 12:55:40+02:00	12:58:50+02:00	19.2	24.3	30.6	33.9	23.7	9.5	7.7	0.8	1.4	3.8	2.3	0.1	6.3	1.9	20
47	2014-03-11 14:32:10+02:00	17:22:30+02:00	22.2	27.8	32.6	52.6	27.0	-5.4	10.0	1.3	3.0	6.1	6.2	0.0	78.8	9.8	939
48	2014-03-11 17:58:40+02:00	18:09:00+02:00	13.0	18.0	25.0	29.2	17.5	-1.9	8.8	0.3	0.9	2.3	1.4	0.0	4.9	1.4	62
49	2014-03-12 06:30:40+02:00	06:42:50+02:00	-1.9	-0.5	1.3	9.0	0.1	-5.1	3.4	0.0	0.0	0.0	0.1	0.0	0.2	0.1	41
50	2014-03-12 14:20:30+02:00	14:42:40+02:00	15.5	21.5	28.6	55.2	23.7	4.2	12.0	0.3	0.6	1.5	3.2	0.1	37.4	6.9	121
51	2014-03-13 16:42:40+02:00	18:45:00+02:00	10.4	15.2	20.4	44.7	16.4	0.6	8.3	0.2	0.3	0.7	0.8	0.0	10.9	1.4	428
52	2014-03-14 05:25:10+02:00	05:42:50+02:00	-3.2	-0.4	1.1	4.8	-1.0	-6.7	3.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	23
53	2014-03-18 04:16:40+02:00	06:10:00+02:00	17.4	22.6	26.9	37.1	22.1	0.2	6.6	0.4	0.7	1.3	1.1	0.0	6.1	1.0	361
54	2014-03-18 13:56:50+02:00	14:15:20+02:00	20.7	22.9	35.6	40.0	26.5	10.5	8.5	0.4	0.7	2.8	1.6	0.2	5.3	1.6	34
55	2014-03-18 15:52:20+02:00	16:32:40+02:00	28.1	37.0	42.3	49.5	33.4	0.6	12.1	1.6	8.2	15.9	10.9	0.0	43.1	10.5	217
56	2014-03-18 18:00:50+02:00	18:44:40+02:00	13.4	18.8	26.5	41.5	20.5	6.1	8.8	0.3	0.6	1.8	1.5	0.1	12.8	2.2	210
57	2014-03-19 17:22:00+02:00	17:29:40+02:00	25.0	33.9	40.9	49.0	32.7	9.8	10.4	0.8	3.7	10.4	6.6	0.2	23.3	6.8	45
58	2014-03-26 14:30:40+02:00	16:03:00+02:00	10.0	14.7	19.9	27.7	14.8	-0.5	6.4	0.2	0.4	1.1	0.8	0.0	5.0	0.9	328
59	2014-03-26 16:35:00+02:00	17:15:30+02:00	14.6	20.6	30.1	40.1	21.5	0.5	9.8	0.4	1.3	4.6	3.1	0.0	18.4	4.1	187
60	2014-03-30 14:47:10+02:00	15:04:40+02:00	31.1	33.1	36.6	48.3	32.4	13.0	7.2	1.8	2.9	6.1	4.0	0.2	15.1	3.5	34

Convective events are characterized by their high rain rates ($>20\text{mm/h}$) and short duration whereas stratiform events are much longer in duration with lower rain rates. A scatter plot to identify significant events was developed by comparing the rain rates of events to their duration (Figure 2-23). These events included both convective and stratiform. A total of 60 events were measured. The duration was determined by the amount of measured points made by the Parsivel disdrometer (RainN). Data points closer to the x-axis (lower rain rate) and further from the y-axis (longer duration) can be assumed to stratiform events. Points closer to the y-axis (short in duration) and further from the x-axis (higher rain rates) fit existing scientific descriptions of a convective event.

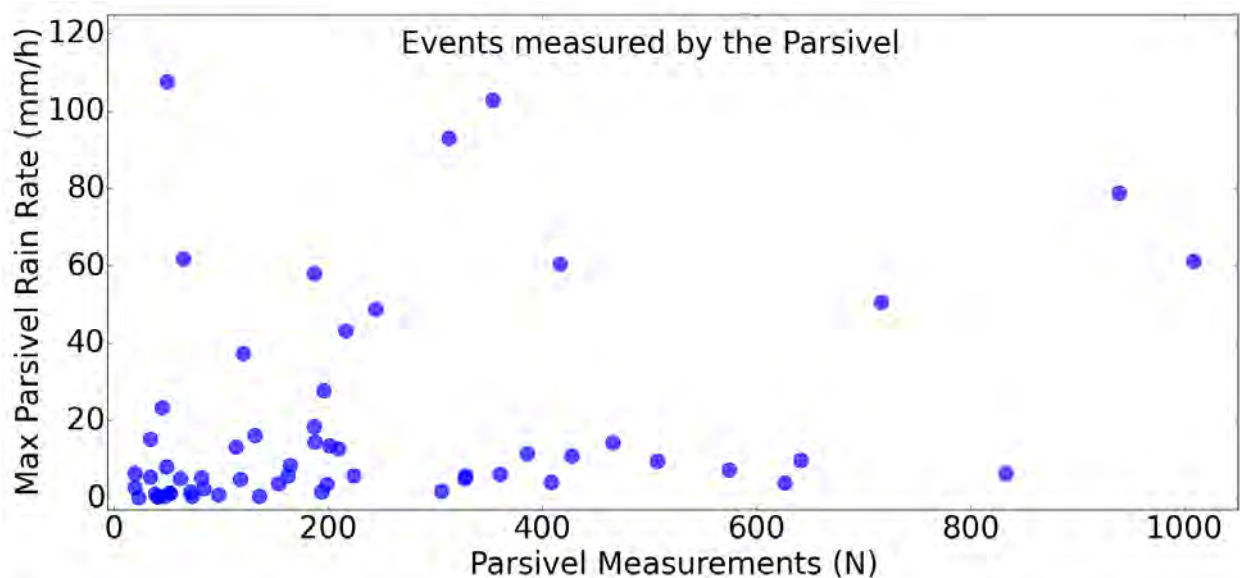


Figure 2-23: Events measured by the Parsivel disdrometer. These events were categorized by their maximum rain rate and their duration measured by the disdrometer.

2.2.5 Merged Parsivel disdrometer, radar and tipping-bucket rain gauge data

The instruments used in this study all measure rainfall at different scales and resolutions. The Parsivel disdrometer measures each particle's size and velocity at a 10s resolution, the radar measures the reflectivity at a 4min resolution and the TBR measures the volume of rainfall at a resolution of 0.2mm. Combining all this data from different instruments proved to be a challenge. Data was re-sampled at 5minute intervals for all the instruments and was merged (Table 2-4). Events were determined once again as re-sampling the data changed the number of events that were measured. The same method of event identification was used, as explained in Chapter 2.2.4. Once the data was merged the comparison of instruments was done.

Table 2-4: Parsivel disdrometer, Radar and TBR data merged.

				Radar		Tipping Bucket Rain Gauge	Parsivel		
							Max		
				Max Radar	Mean Radar	Total Gauge	Max Parsivel	Mean Parsivel	Mean Parsivel
				Reflectivity	Reflectivity	Rainfall	Reflectivity	Reflectivity	Rain Rate
				y (dbz)	(dbz)	(mm)	y (dbz)	y (dbz)	(mm/h)
Start	End								
1	2014/02/22 18:00	06:45		29.0	19.0	0.7	40.0	16.1	8.0
2	2014/02/22 19:45	21:35		37.1	26.5	2.8	33.0	21.1	5.0
3	2014/02/23 10:25	12:50		28.3	18.2	1.1	27.3	15.1	1.8
4	2014/02/23 13:40	16:30		40.5	28.1	3.3	33.4	20.9	4.2
5	2014/02/24 12:00	13:05		34.0	19.0	0.4	28.0	12.5	1.8
6	2014/02/24 17:10	18:00		35.9	29.3	0.4	30.4	15.8	2.5
7	2014/02/24 21:15	22:30		45.6	33.4	14.8	48.0	26.0	60.6
8	2014/03/01 09:05	09:40		30.6	24.0	1.2	35.5	21.3	6.6
9	2014/03/01 11:40	12:25		25.4	13.0	0.7	29.8	15.4	4.0
10	2014/03/02 15:30	17:45		12.5	12.5	0.2	16.4	5.2	0.4
11	2014/03/03 13:30	16:00		14.9	10.5	1.2	26.5	13.8	2.7
12	2014/03/04 00:20	01:25				0.2	19.1	5.6	1.6
13	2014/03/04 03:50	05:20		12.6	8.8	3.9	31.4	21.1	7.7
14	2014/03/04 05:45	06:25				0.2	17.5	8.3	1.4
15	2014/03/04 11:00	12:05		30.7	17.4	0.9	30.4	20.0	2.4
16	2014/03/04 13:25	15:30		37.2	22.5	2.1	35.1	20.9	4.7
17	2014/03/04 20:25	23:35		16.6	10.8	1.9	31.3	10.5	5.2
18	2014/03/05 00:40	04:15		37.2	24.5	10.0	37.9	14.3	21.2
19	2014/03/05 07:50	11:10		38.5	21.8	11.3	42.6	22.2	27.5
20	2014/03/06 01:20	02:25		34.4	27.4	13.0	47.0	27.8	60.6
21	2014/03/06 13:45	14:40		43.3	24.0	5.8	45.8	27.4	26.4
22	2014/03/06 17:30	19:00		43.0	34.6	2.4	36.6	25.0	4.0
23	2014/03/07 12:00	12:55		25.9	18.4	0.1	22.4	7.0	1.0
24	2014/03/07 18:20	18:55		19.3	18.0	0.0	11.6	3.5	0.2
25	2014/03/08 10:55	11:45		36.2	24.1	2.3	46.8	23.6	21.1
26	2014/03/09 15:45	17:15		59.6	32.0	12.7	50.7	21.9	62.3
27	2014/03/09 18:05	19:25		14.3	8.2	0.1	18.0	4.9	0.4
28	2014/03/09 20:30	22:20		26.1	18.7	0.4	24.3	11.4	1.0
29	2014/03/10 12:25	13:10		33.1	24.6	1.5	32.7	21.0	7.2
30	2014/03/10 14:50	16:05		36.1	21.3	1.5	35.9	17.1	9.0
31	2014/03/10 16:30	17:15		14.2	10.9	0.1	19.7	6.7	0.4
32	2014/03/10 18:00	18:45		23.8	18.1	0.9	28.5	16.3	3.5
33	2014/03/10 20:00	20:40				0.3	20.2	9.7	1.8
34	2014/03/10 21:55	00:10		17.3	9.0	0.2	18.3	5.1	0.7
35	2014/03/11 12:25	15:25		36.0	23.6	14.8	43.6	23.1	33.2
36	2014/03/11 15:50	16:40		11.3	7.6	0.3	22.9	5.7	2.2
37	2014/03/12 12:15	12:45		40.4	26.2	0.7	36.9	16.5	9.3
38	2014/03/13 14:35	16:50		29.4	17.2	1.2	34.9	13.1	5.2
39	2014/03/18 02:10	04:15		37.0	23.6	1.2	28.5	13.4	2.6
40	2014/03/18 11:50	12:20		39.9	28.7	0.3	35.4	17.2	3.1
41	2014/03/18 13:45	14:35		41.5	28.4	4.9	43.7	25.6	21.4
42	2014/03/18 15:55	16:45		35.3	25.6	0.8	32.4	16.5	5.0
43	2014/03/26 12:25	14:05		18.0	9.2	0.7	21.5	9.8	1.7
44	2014/03/26 14:30	15:20		25.1	18.6	1.2	35.0	14.2	9.6

2.3 Methods

The following methods were used in this dissertation to achieve all the research goals as stipulated in Chapter 1.3.

2.3.1 Characterizing the variability of rainfall intensity in the Mooi River catchment

Rainfall is highly variable over space and time. The variability of rainfall intensity was characterized mainly by using data measured by the Parsivel disdrometer. Events were identified by a 15min gap between measurements. The rain rates of each event were estimated to explore the temporal variability of rain rates in the catchment. Small-scale changes in the microphysical process were observed and measured.

2.3.1.1 The spatial variability of rainfall in the Mooi River catchment

The Mooi River rain-gauge network was used to study the spatial variability of rainfall. The difference in measurements between these gauges showed that rainfall in the catchment is highly variable in space. Both the total rainfall and the rainfall intensity were used. All gauges were in operation between the 15th of November 2015 and June 2016. These gauges were maintained by regular visits to clean up gauges, collect data and ensure no blockage of the gauge is present. This ensured that the data was accurate and reliable

The total rainfall accumulation was measured by taking the amount of tips measured and multiplying this by 0.2mm as this is the size of the buckets used in the rain-gauges deployed in the catchment. All these totals were compared to each other to study the spatial variability in the catchment.

The rainfall intensity was derived by the inter-tip times between tips. By calculating the time it takes for a next tip to occur the rainfall intensity could be investigated. The lower the intertip time the higher the rain rate and the greater the difference in time between two consecutive tips the lower the rain rate.

2.3.1.2 Measuring rain rates in the Mooi River catchment

Events were identified by a 15min gap between measurements. These events were then characterized by their rain rates, duration and reflectivity. The rain rates were measured by the Parsivel disdrometer to understand the variations in rain rates.

Convective events were identified by their high rain rates and short duration. These events are normally very localized in the Mooi River catchment and fast moving. Therefore the sudden

spike in rain rate and a gradual decrease after the peak in the data is a characteristic of a convective event.

Stratiform rain rates were identified as events with low rain rates and long in duration. These events are more evenly distributed in the catchment with more uniform rainfall unlike convective events. A gradual time series profile of rain rates is indication of stratiform precipitation.

2.3.1.3 Calculating the A and b coefficient used in the Z-R relation of events

The Parsivel disdrometer was used to measure the rain rate and the reflectivity on the ground simultaneously. The A and b coefficient of the Z-R relation (Eq.(5)) were calculated using these measurements. It is important to note that this was done without re-sampling the data or merging the data with other instruments.

Reflectivity is measured in dbz. To determine the A and b coefficient the reflectivity (Z) measured for the entire event needs to be converted to a logarithmic reflectivity (z) value by using the following equation:

$$\log_{10} Z = z, \quad (7)$$

where Z is the reflectivity measured and z the logarithmic reflectivity. The same needs to be done to the rain rate. Rain rate (R) measured on the ground by the disdrometer needs to be converted to logarithmic rain rate (r). The following equation was used:

$$\log_{10} R = r, \quad (8)$$

where R is the rain rate measured and r the logarithmic rain rate. Once the z and r values are known these are compared to each other on a linear scale. The point at which the linear line crosses the y-axis will be the A coefficient and the slope of the line will be the b coefficient.

2.3.1.4 Identifying convective and stratiform events using Titan

Irene weather radar data was used and events were separated in their convective and stratiform regimes by using Stratiform Filter, a program in TITAN. Stratiform Filter uses threshold values to distinguish whether an event is convective or stratiform. If a value of a bin is above 35dbz it is considered to be a convective event. Between 35dbz and 15dbz will be identified as stratiform precipitation. A bin that was below 15dbz was not taken into consideration because this is normally ground clutter or non-rain objects. The program also has the ability to identify potential convective events by considering the movement of the event and the proximity of bins to

convective events. Trailing rain of a convective event is also identified as part of the event. Events with a lower dbz value and in close proximity to events with high dbz values are likely to develop into a convective event and are therefore also identified.

The Stratiform Filter program created an MDV file with two fields. The first field displayed only the convective areas with dbz values above 35dbz (Figure 2-24C). The second displayed both convective and stratiform regimes. The program also assigned the number 1 to bins with values lower than 35dbz and 2 to values higher than 35dbz. This gave an image of possible areas with convective and stratiform precipitation (Figure 2-24B).

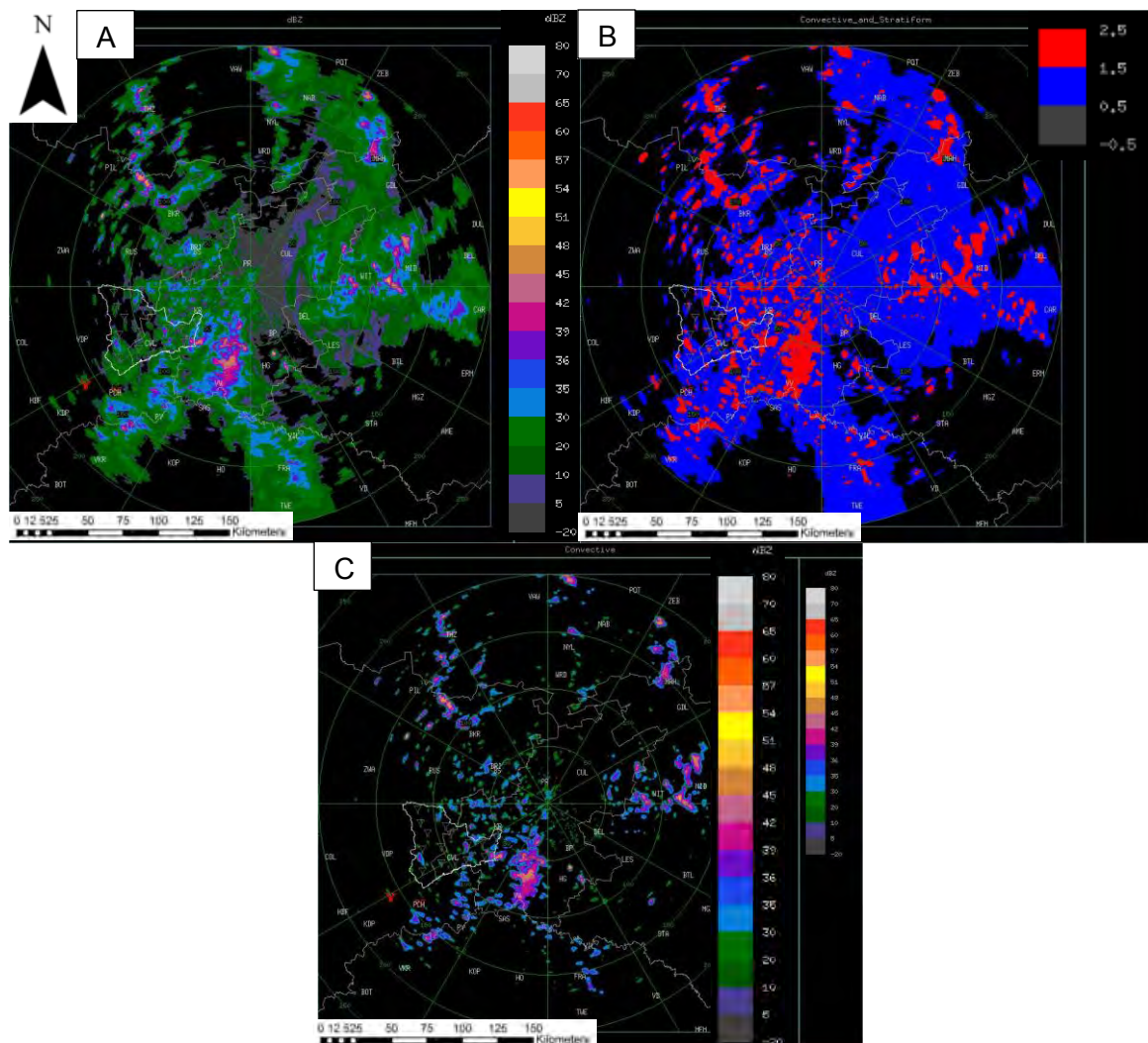


Figure 2-24: The process of stratifying regimes using Stratiform Filter. (A) Shows the rainfall not stratified. (B) shows the stratiform and convective precipitation and (C) shows only the convective event (dbz value above 35dbz).

2.3.2 Improving single-parameter weather radar rainfall estimates

The need for improved radar rainfall measurements has never been greater in Africa. The improvement will have to address a number of issues. One of the most important issues that are currently under discussion, is the Z-R relation. Around the world theoretical Z-R relations are used like the Marshall and Palmer (1948) relation to measure rain rates using radar data. This however can cause inconsistencies in data as Z-R relations are storm, location and climate specific. This means that when a Z-R relation is used that it must be based on the storm structure for that specific climate and not a theoretical relation that is widely used. The aim of improving radar rainfall estimates does not only include considering the Z-R relation but also investigating the performance of the radar to calculate the calibration offset measurement and whether to implement a bias measurement.

2.3.2.1 Identifying significant events

A large number of insignificant events were removed and the ten most significant events were used. These events were identified by their rain rate, reflectivity and duration measured by the disdrometer while the radar image generated in TITAN was also examined to determine whether the core of the event passed over the disdrometer. These ten events included five convective events and five stratiform events (Table 2-5). Convective events developed mostly because of an easterly low-pressure system over the northern parts of the country - a common occurrence in summer. The easterly low-pressure system can also be joined by a ridging anticyclone system to the east or the west of the country. Stratiform events can develop because of an easterly wave, easterly low or a ridging anticyclone.

Table 2-5: Significant events were chosen according to their maximum rain rate, maximum reflectivity and duration to include both convective and stratiform events.

			Max Parsivel Rain Rate (mm/h)	Max Parsivel Reflectivity (dbz)	Duration (min)
	Start	End			
1	2014/02/22 19:45	21:35	5.0	33.0	100
2	2014/02/23 10:25	12:50	1.8	27.3	135
3	2014/02/23 13:40	16:30	4.2	33.4	160
4	2014/02/24 21:15	22:30	60.6	48.0	65
5	2014/03/03 13:30	16:00	2.7	26.5	140
6	2014/03/04 20:25	23:35	5.2	31.3	180
7	2014/03/05 7:50	11:10	27.5	42.6	190
8	2014/03/06 1:20	02:25	60.6	47.0	55
9	2014/03/06 13:45	14:40	26.4	45.8	45
10	2014/03/09 15:45	17:15	62.3	50.7	80

2.3.2.2 Evaluating the performance of weather radars covering the Mooi River catchment

The performance of weather radars which covers the Highveld and Mooi River catchment was evaluated by comparing the radars data to the best performing radar. The best performing radar was determined by comparing reflectivity measurements aloft by the radar to the reflectivity measurements measured by the disdrometer on the ground (Figure 2-25). In this way also the calibration offset and the correlation between these two data sets can be determined. Calibration offsets and bias measurements need to be considered for improved radar rainfall estimates. Calibration offset was determined by:

$$Z_{CO} = Z_D - Z_R, \quad (9)$$

where Z_{CO} is the calibration offset, Z_D the reflectivity measured by the disdrometer and Z_R the reflectivity measured by the radar. This shows whether the radar over- or underestimates rainfall. This was done for all three radars under the coverage area of the disdrometer which includes the Irene, Ottosdal and Bethlehem weather radars (Figure 2-16).

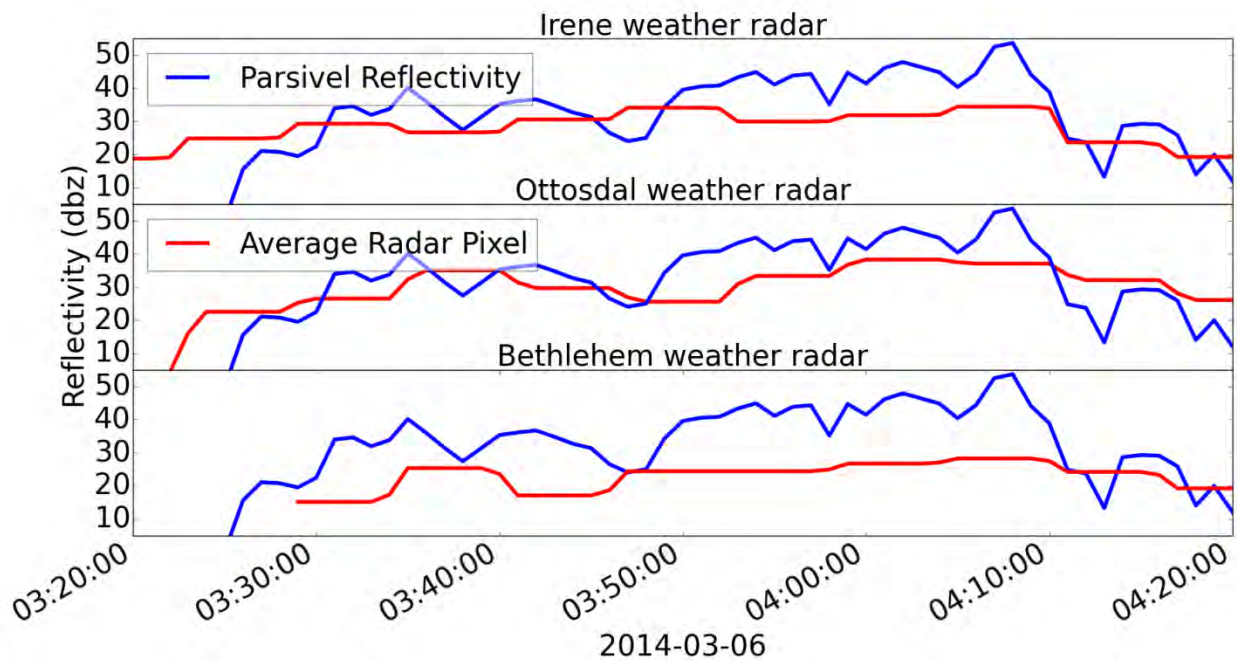


Figure 2-25: The reflectivity (Z) measurements of radars operated by SAWS covering the Mooi River catchment compared to the Parsivel disdrometer reflectivity measurement.

2.3.2.3 Convective versus stratiform

The same method used in Chapter 2.3.1.4 to identify convective and stratiform regimes was used in this section. Disdrometer data taken during convective and stratiform events was extracted at and the Z-R relation for that time period was determined.

2.3.2.4 Measuring new Z-R relations

The disdrometer has the ability to measure custom Z-R relation on the ground for individual storms. A new unique Z-R relation was derived for each storm by measuring the rain rate and the reflectivity on the ground simultaneously, then comparing these variables to each other and subsequently creating a linear line through the measurements. The same method used in Chapter 2.3.1.4 was applied to measure the custom Z-R relation of events using the merged data set.

2.3.2.5 Improved radar rainfall estimates

An attempt was made to improve radar rainfall estimates through using the custom Z-R relation and also the calibration offset for specific storms, by calculating using Eq. 7. Merged data was used. The Parsivel disdrometer was used to measure a custom Z-R relation and to determine

the calibration offset of the radar. Once the calibration offset had been measured, a bias measurement was implemented. The TBR was used as a reference instrument on the ground. Total rainfall could not be compared to the disdrometer as this is the instrument that measures the changes. The total rainfall measured by the TBR was compared to the total rainfall measured by the radar. Four totals were calculated. Firstly the total radar rainfall was measured using only the theoretical Z-R relation⁶ (Eq. (6)). Secondly, the Marshall and Palmer relation were used with the calibration offset also taken into consideration. This was done by:

$$Z_R \pm Z_{CO} = 200R^{1.6}, \quad (10)$$

where Z_R is the reflectivity measured by the radar, Z_{CO} calculated using Eq. (9), R the rain rate which we want to calculate and A and b coefficients (200 and 1.6) are unique to the Marshall and Palmer relation. Thirdly the total radar rainfall was measured by using the custom Z-R relation (using Eq. (10) and (11)) measured by the disdrometer using Eq. (10). Lastly the total rainfall was calculated by using the custom Z-R relation and the calibration offset measurement between the radar and the disdrometer. All the radar rainfall totals were compared to the total measured by the TBR. The TBR total was calculated by:

$$H_{TBR} = T_n \times 0.2, \quad (11)$$

where T_n is the amount of tips made by the TBR and 0.2 is the size of the TB3 rain gauges' buckets.

2.3.3 New algorithm for deriving rain rates using a siphon tipping-bucket rain gauge

Siphon tipping-bucket rain gauges pose unique challenges when measuring rain rates. Therefore a new algorithm was developed in this study to derive the rain rate from the rain gauge data measured using a siphon.

Tipping-bucket rain gauges do not have the ability to measure the start of an event accurately. Therefore the rain rate of the first 0.2mm is unknown. Figure 2-26 shows that the time it takes the first 0.2mm of rainfall to rain varies. In most cases the first 0.2mm of rain has a rain rate of between 0.5 and 5 mm/h. Parsivel disdrometer data was used to calculate the median time it takes for the first 0.2mm of rainfall to rain per event. The time was calculated at 8.3minutes which in turn equals 1.45mm/h for the first 0.2mm of rainfall.

⁶ Marshall and Palmer, $A=200$; $b=1.6$

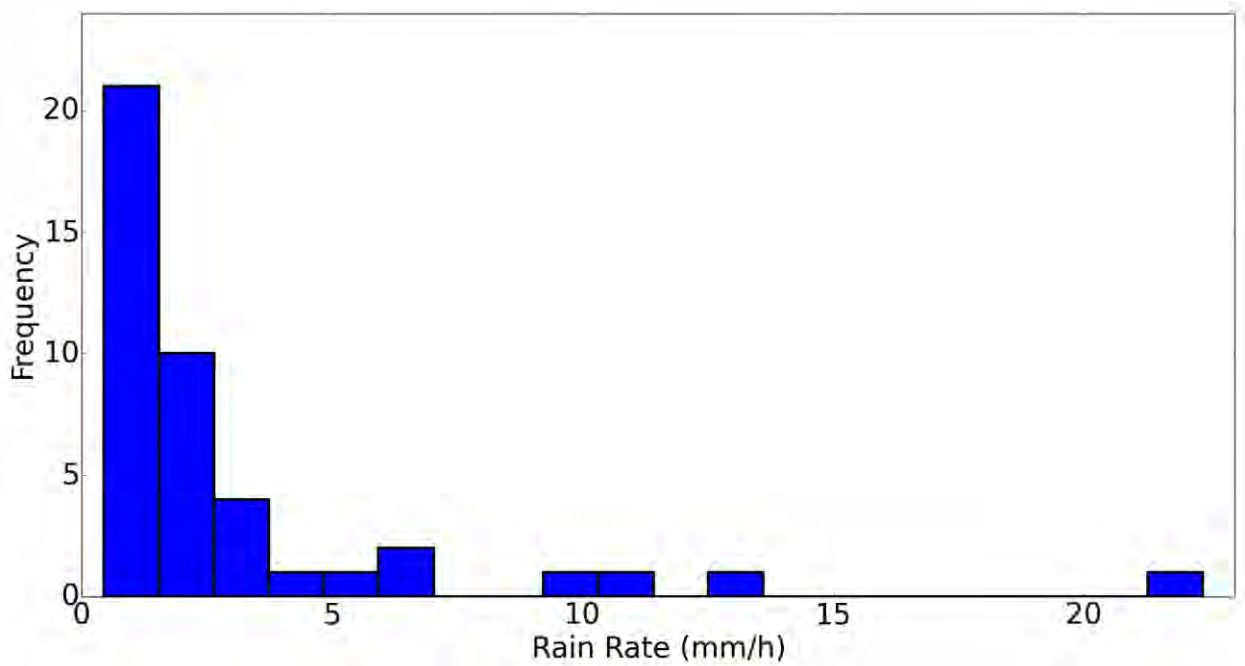


Figure 2-26: The frequency of rain rates for the first 0.2mm of rain observed per event. The figure show for the most cases the first 0.2mm of rain in an event has a rain rate below 5mm/h.

Double tips also cause problems in calculating rain rates. The new algorithm identifies the second tip of the double tip by:

$$t_1 - t_2 \geq 0.4s, \quad (12)$$

where $t_1 - t_2$ represents two consecutive tips. Research has shown that tips where the time difference is shorter than 4 seconds must be considered as false or in this case double tips (Upton & Rahimi, 2003). These extra tips are therefore deleted but the volume of water measured is still considered. The algorithm calculates the difference between the times of two consecutive tips and if the difference is equal or smaller than 4s this is identified as a double tip and t_2 is deleted from the data. This extra volume of water that was deleted, because of the second being a double tip, was then added to t_1 .

As mentioned in Chapter 2.1.2.2 the data logger used by the rain gauges saves tips in three categories. To calculate rain rates only the ED tip is used and the algorithm does not include any other tip. The algorithm therefore also periodically calculates the total rainfall, Eq. (11), to ensure that valid tips are not deleted by mistake.

2.3.3.1 Degree of error in rain rate data measured by a siphon tipping bucket rain gauge

The magnitude of error was calculated for rain rate data measured by the TBR. This was done to determine the performance of the new algorithm at high and low rain rates. The difference between the TBR rain rate and the disdrometer rain rate was calculated using the following formula:

$$TBR_{Err} = TBR_{RR} - Pars_{RR}, \quad (13)$$

where TBR_{Err} is the error in a specific TBR rain rate measurement, TBR_{RR} is the rain rate measurement of the tipping-bucket rain gauge and $Pars_{RR}$ is the rain rate measured by the Parsivel disdrometer. This process was done at a 1min, 2min, 5min, 15min, 30min and 60min time scale.

The correlation between TBR and Parsivel disdrometer rain rate data was further examined by exploring the autocorrelation of both the data sets. Autocorrelation is the correlation of data points after the data point in question. This was done by comparing a tip ($n_1, n_2, n_3, n \dots$) to all the tips which is 60 minutes (time lag) after the initial tip.

CHAPTER 3 THE SPATIAL AND TEMPORAL VARIABILITY OF RAINFALL INTENSITY IN THE MOOI RIVER CATCHMENT

Rainfall intensity varies in time and space. The DSD is a direct representation of the microphysical properties of rain. Changes in rainfall intensity is a consequence of the changes in the DSD and understanding these changes may consequently help with improved rainfall measurement data, predictions and the validation of different types of measurements like satellite and radar and may contribute to improving the accuracy of climate models.

3.1 The temporal variability of the rain rate in the Mooi River catchment measured by the Parsivel disdrometer

South Africa is a developing country that is extremely susceptible to natural disasters like flash floods. Most of the rain in the Mooi River catchment originates from the easterly movement of air from the tropics. Cases of intense tropical cyclones have also been observed, especially to the northeast of the country. One of the most well-known cases was Demoina which originated over Madagascar making landfall in Mozambique and part of Northern Kwa-Zulu Natal. These cyclones do not ridge far inland and are therefore not a threat to the Highveld. When these tropical cyclones move over the Limpopo River basin, it can cause heavy rain over the North Easterly parts of South Africa. However, most of the rain in the catchment originates from the same area.

The rainfall measured in the Mooi River catchment is mostly in the form of convective or stratiform precipitation. It is important that these events must not be considered in isolation but in their entirety when characterizing the rain rate of the area. The variation of rain rates can be explored in this manner (Figure 3-1). A large number of convective and stratiform events were measured. In this chapter the rain rates of events, and the event as a whole, will be characterized by their rain rate, maximum rain rate, mean rain rate, Z-R relation and the duration of events.

It is important to note that the rainfall of January, February and March 2014 (JFM 2014) observed rainfall which was very much above normal. The position of the tropical lows/waves over Botswana created very favourable conditions for widespread and at times heavy rain. Other summers may be drier, specifically because of the absence of a tropical system over Botswana. These conditions were also observed during JFM 2000.

During the measurement campaign where the disdrometer was used most synoptic charts showed that severe rainfall events with high rain rates occurred because of an easterly low. Notably, the three events with the highest rain rates were easterly lows with a far ridging South-Indian anti-cyclone over the country. This easterly low created a large number of isolated convective events over the catchment. Events measured on the 24th of February and two measured on the morning and evening of the 6th of March showed rainfall intensities of up to 120mm/h (Figure 3-1). A number of events with high rain rates were measured. The event on the 24th lasted for 20 minutes and the events on the 6th lasted 17 and 7 minutes respectively. The duration of these events are normally very short. This is an indication of how localised these events are. Rain is only observed for these events in those periods where little or no rain is observed before the spike in rain rate. Trailing rain has also been observed in most cases of convective events. This shows that rainfall occurs on a logarithmic scale with high rain rates at first and a gradual decrease as the storm moves on. The rain rate can vary within 1km between 10mm/h-120mm/h and back to 0mm/h. This can also be seen clearly on radar data which will be explained in Chapter 5. A number of convective events were also measured. The same types of characteristics were observed here. It is important to note that events were identified with a 15min gap between measurements. Therefore, as in the case of the events of 5th of March 2014, a cluster of convective events was measured. Between these events no rain was observed while a sudden spike in rain rate was measured. Spatially and over time, rain rates, especially those of convective events, are highly variable in the Mooi River catchment.

Stratiform events were also measured. Synoptic charts indicated that the most of the stratiform precipitation develop because of an easterly wave being the dominant synoptic condition over the country. Warm moist air is brought inland from the east originating in the warm climate close to the equator. The difference is that the easterly wave does not have a low-pressure system over the country. This hampers the development of clouds as there is no divergence on the ground and consequently no upliftment of the moist air. Rainfall is more evenly distributed because the air rises orographically according to the topography of the surface. From the coast inland there is a uniform rise in topography. This can be seen by the longer duration of these events (Figure 3-1). Stratiform precipitation also has very low rain rates with a spike seldom seen in data. Therefore, in contrast to convective events, stratiform events in the catchment are much more evenly distributed and do not vary to such a large extent. This is also evident in Figure 3-2.

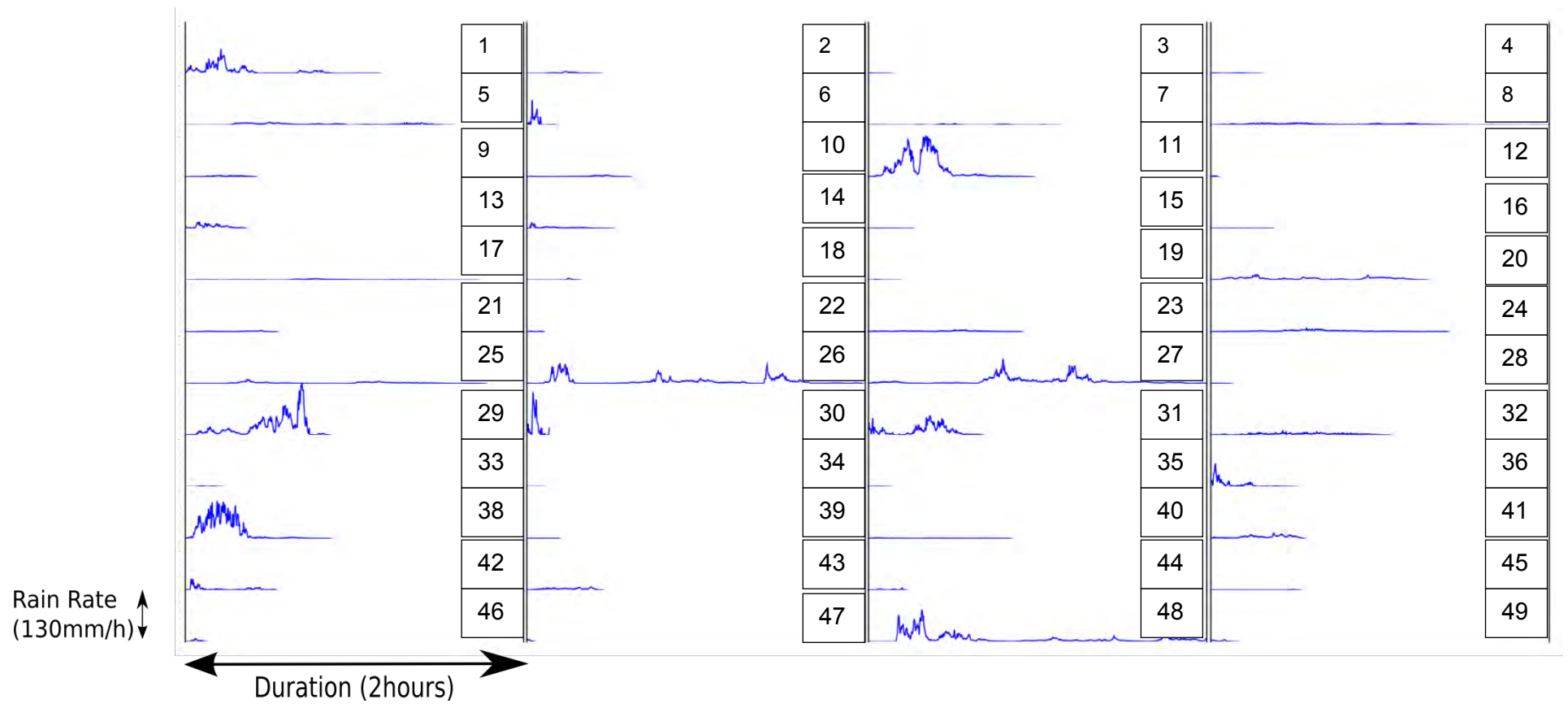


Figure 3-1: Rain rates of all the events measured by the Parsivel disdrometer on the y-axis and their respective duration on the x-axis.

Rainfall intensities higher than 20mm/h are considered to be convective events and below 20mm/h are considered stratiform events. The assumption made in this study agrees with what is measured by the Parsivel disdrometer as is evident in Figure 3-2. Stratiform events are more uniform in their rain rates. Within the Mooi River catchment the differences between the maximum rain rates of stratiform events are very low. The sudden drop in frequency higher than 20mm/h is an indication of the clear separation between convective and stratiform events. The frequency of events between 0.5mm/h and 20mm/h are higher because stratiform events in the catchment are uniform in their rain rates. Events with rain rates higher than 20mm/h are more variable. This indicates that these events are convective precipitation because of their short duration and high rain rate. The maximum rain rate for convective events varies between 20mm/h and 130mm/h and the frequency of these events are lower. Figure 3-2 shows the variability of rain rates in convective events and the more uniform rain rates of stratiform events in the Mooi River catchment.

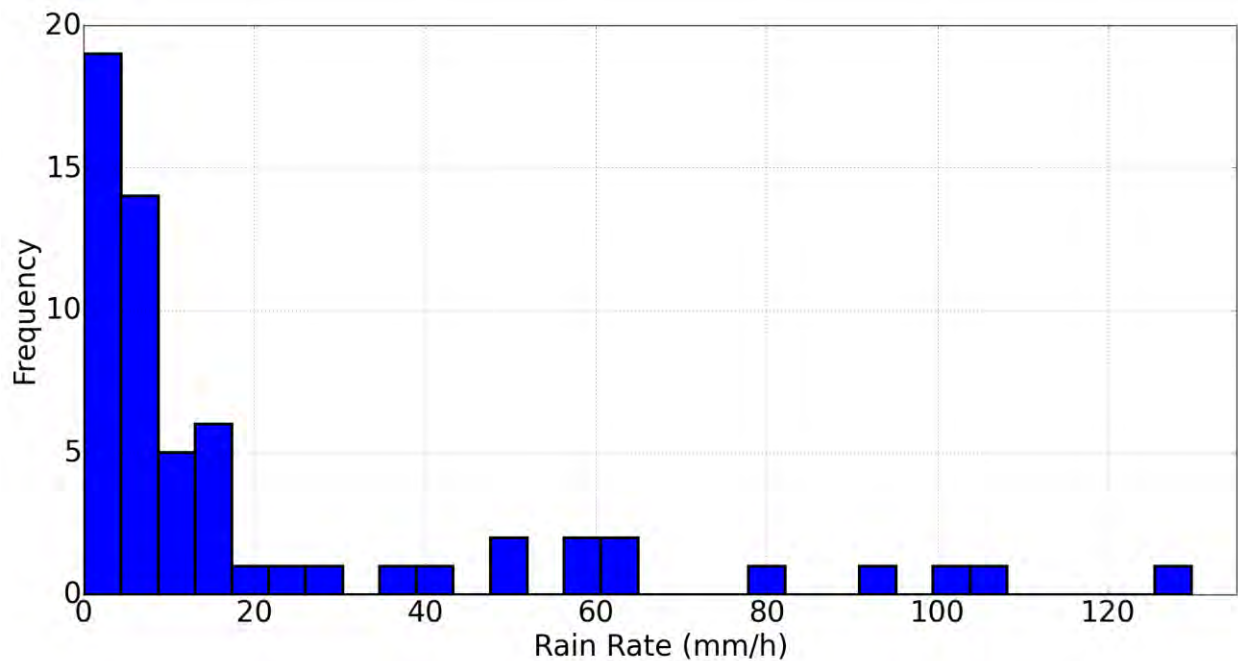


Figure 3-2: Probability Density function of the maximum rain rate of events measured by the Parsivel disdrometer on the Highveld.

The standard deviation from the mean also shows that variation in rainfall intensity does exist from the mean rain rate. This deviation is mostly between 1 and 5mm/h from the average which is not that significant with a spike in deviation of 10, 25 and 27mm/h. The significance of the deviation can be more accurate if more data is used over a longer period. This will improve the accuracy of the norm and therefore the deviation will be more significant. Taking this into account and considering that rain rates were only measured for 39 days using the disdrometer a prediction can be made that the longer the rain rate data for the catchment specifically, the higher the standard deviation (Figure 3-3).

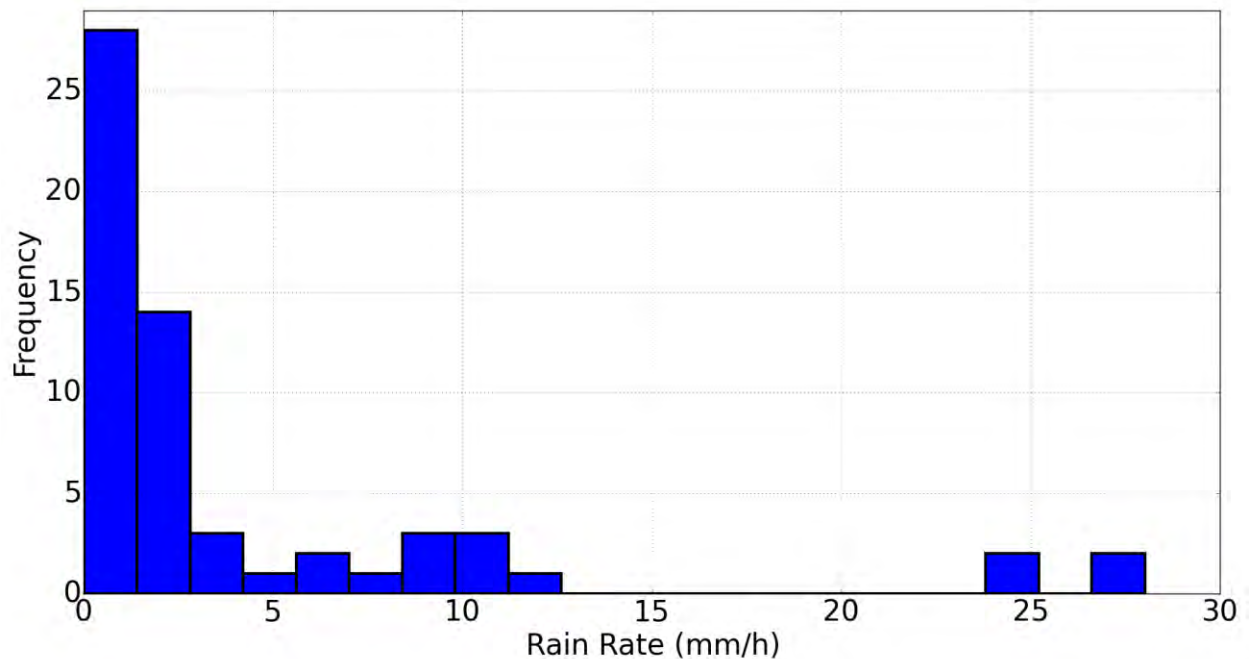


Figure 3-3: Probability Density function of the standard deviation of the rain rate from the mean of events measured by the disdrometer on the Highveld.

3.2 The spatial variability of rainfall in the Mooi River catchment

The rainfall in the Mooi River catchment also varies spatially. Using the Mooi River rain-gauge network the variability of rainfall from one area to another was investigated (Figure 3-4). Convective rain is especially in the summer months the dominant rainfall system over the Highveld of South Africa. One of the main characteristics of this systems is they are much localized in appearance. This means that spatially they vary significantly. These rain-gauges are placed in such a way so that spatial changes can be observed. In the next few paragraphs these changes were investigated and to what extent the rain varies on a spatial context.

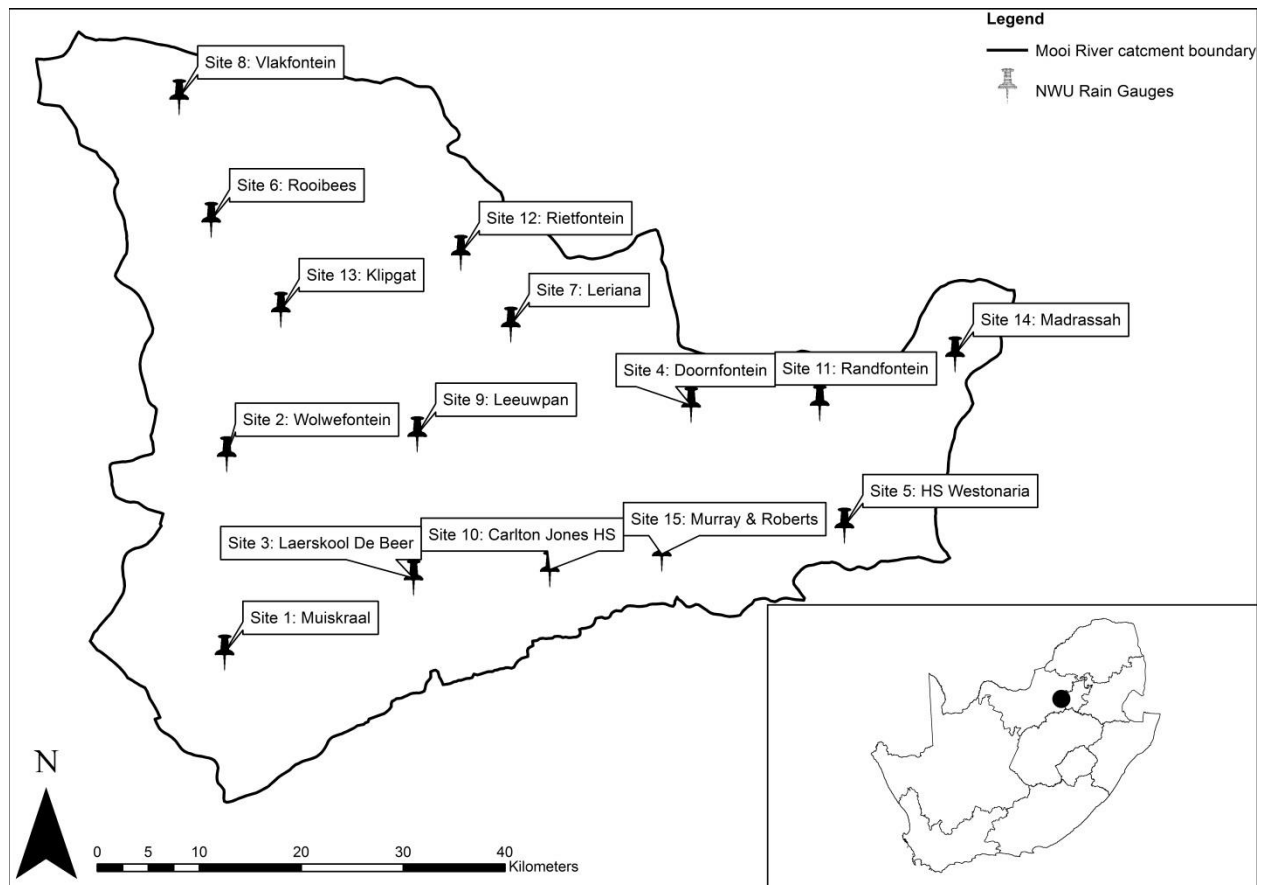


Figure 3-4: The Mooi River Rain-Gauge Network situated North-East of Potchefstroom. This network consist of 15 gauges which is considered a highly dense network in the South African context were such a dense network does not exist.

Spatial variability can play a huge part in agriculture and food security. Especially in a developing country like South Africa this is very important. Modern day farming techniques consider rainfall as one of the most important aspects of crop planning. Not just the rainfall amount but also the rainfall intensity.

Between November 2015 and June 2016, high volumes of rainfall have been observed in the Mooi River catchment. Gauges like Wolwefontein and Leeuwpans measured over 500mm of rainfall were De Beer Primary school only measured 145mm (Table 3-1). It is also evident that some gauges with a good correlation between rainfall amounts are not close to each other. Therefore it cannot be said that the rainfall is uniform throughout the catchment. Understanding this spatial difference is very important especially in agriculture for crop planning. This means that strategies must differ for different parts of crop production areas as precipitation changes within meters from one point to another.

Table 3-1: The total amount of rainfall measured by each of the rain gauges between November 2015 and June 2016.

Total Rainfall Mooi River Rain Gauge Network (November 2015 - June 2016)	
Gauge Name	Rainfall (mm)
Site 01 Muiskraal	401.025
Site 02 Wolwefontein	539.2271
Site 03 De Beer Primary School	145.6224
Site 04 Doornfontein	711.0523
Site 05 Westonaria High School	441.0284
Site 06 Rooibees	488.4092
Site 07 Leriana	326.2267
Site 08 Vlakfontein	363.4154
Site 09 Leeuwpan	539.0286
Site 10 Carlton Jones High School	361.034
Site 11 Randfontein	331.0255
Site 12 Rietfontein	442.0223
Site 13 Klipgat	486.8338
Site 14 Madrassah	449.7989
Site 15 Murrey & Roberts	474.0231

Figure 3-5 shows to what extent rainfall amount can differ. Between site 6 (Rooibees) and site 8 (Vlakfontein) for instance there is a significant difference in the rainfall amount. These gauges are only 12km from each other (Table 3-2). For a period of only two months, this is a big difference of 119mm of rain. This once again strengthens the findings in the previous section that rainfall in the catchment is predominantly convective. It shows that the rainfall is very localized and can change in very short periods.

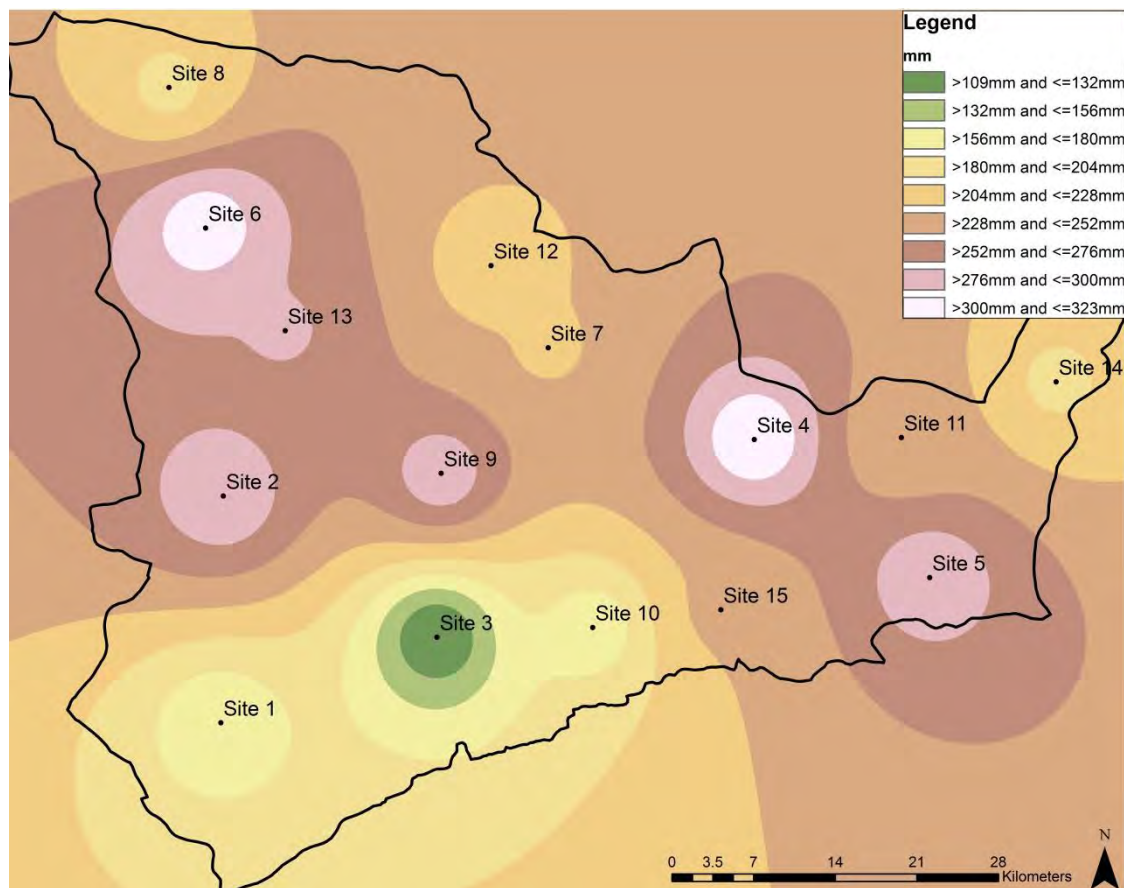


Figure 3-5: The amount of rainfall each rain gauge has measured between the 15th of November 2015 and the 15th of January 2016. The reason why this time frame has been chosen is that no gauges were faulty during this period. This shows that on this scale rainfall differs.

Table 3-2 shows the distance between the rain-gauges which includes the distance of a gauge compared to all other gauges in the network. The distance between these rain-gauges is on average 32km apart. Analysing the data showed that in some cases that there was a significant difference in the total rainfall. This complicates the process of measuring rainfall on the Highveld using weather radar data because currently SAWS uses a generic Z-R relation. The unpredictable nature of the convective events calls for an effort investigating the character of the rainfall.

Table 3-2: Distances between the rain-gauges in the Mooi River Catchment area (Continue on next page).

Mooi River Rain-Gauge Network (Distances)														
Distance			Distance			Distance			Distance			Distance		
Site	Site	(km)	Site	Site	(km)	Site	Site	(km)	Site	Site	(km)	Site	Site	(km)
1	3	18	4	11	11	8	3	51	11	14	13	15	5	16
1	10	30	4	7	18	8	10	57	11	13	48	15	2	40
1	15	40	4	14	24	8	15	62	11	12	35	15	9	24
1	5	56	4	13	37	8	5	72	11	6	57	15	4	15
1	2	19	4	12	25	8	2	35	11	8	64	15	11	20
1	9	27	4	6	46	8	9	39	12	1	44	15	7	26
1	4	48	4	8	54	8	4	54	12	3	32	15	14	32
1	11	58	5	1	56	8	11	64	12	10	32	15	13	41
1	7	41	5	3	38	8	7	37	12	15	34	15	12	34
1	14	71	5	10	26	8	14	73	12	5	43	15	6	51
1	13	34	5	15	16	8	13	23	12	2	29	15	8	62
1	12	44	5	2	55	8	12	29	12	9	18			
1	6	42	5	9	39	8	6	12	12	4	25			
1	8	54	5	4	18	9	1	27	12	11	35			
2	1	19	5	11	12	9	3	14	12	7	8			
2	3	20	5	7	35	9	10	18	12	14	45			
2	10	31	5	14	19	9	15	24	12	13	17			
2	15	40	5	13	54	9	5	39	12	6	22			
2	5	55	5	12	43	9	2	17	12	8	29			
2	9	17	5	6	63	9	4	24	13	1	34			
2	4	41	5	8	72	9	11	36	13	3	29			
2	11	52	6	1	42	9	7	14	13	10	35			
2	7	28	6	3	39	9	14	48	13	15	41			
2	14	65	6	10	45	9	13	17	13	5	54			
2	13	15	6	15	51	9	12	18	13	2	15			
2	12	29	6	5	63	9	6	28	13	9	17			
2	6	23	6	2	23	9	8	39	13	4	37			
2	8	35	6	9	28	10	1	30	13	11	48			
3	1	18	6	4	46	10	3	12	13	7	20			
3	10	12	6	11	57	10	15	10	13	14	60			
3	15	22	6	7	28	10	5	26	13	12	17			
3	5	38	6	14	67	10	2	31	13	6	11			
3	2	20	6	13	11	10	9	18	13	8	23			
3	9	14	6	12	22	10	4	20	14	1	71			
3	4	30	6	8	12	10	11	29	14	3	52			
3	11	40	7	1	41	10	7	24	14	10	41			
3	7	26	7	3	26	10	14	41	14	15	32			
3	14	52	7	10	24	10	13	35	14	5	19			

Site	Site	Distance (km)	Site	Site	Distance (km)	Site	Site	Distance (km)	Site	Site	Distance (km)
3	13	29	7	15	26	10	12	32	14	2	65
3	12	32	7	5	35	10	6	45	14	9	48
3	6	39	7	2	28	10	8	57	14	4	24
3	8	51	7	9	14	11	1	58	14	11	13
4	1	48	7	4	18	11	3	40	14	7	39
4	3	30	7	11	28	11	10	29	14	13	60
4	10	20	7	14	39	11	15	20	14	12	45
4	15	15	7	13	20	11	5	12	14	6	67
4	5	18	7	12	8	11	2	52	14	8	73
4	2	41	7	6	28	11	9	36	15	1	40
4	9	24	7	8	37	11	4	11	15	3	22
4	11	11	8	1	54	11	7	28	15	10	10

The increments of rainfall amount do coincide to a certain extent between some gauges in the network (Figure 3-6). However, it differs in the intensity. This emphasises the fact that there must be a shift in research from rainfall amount to rainfall intensity. Some rain gauges have shown in some instances a correlation in rainfall amount while other gauges are measuring no rain at a time when all the gauges around it are showing rain data. It is also clearly visible that the rainfall measured is a result of a sequence of different storms and not because of an individual block of rain. This can be seen in the sporadic increments and jump in rainfall throughout the entire period which is a unique characteristic of convective rainfall. Stratiform rainfall will show a more evenly distributed rainfall field. All the rain gauges in the entire network would most probably measure rain and the increment would coincide in amount and intensity. Figure 3-7 shows this in more detail.

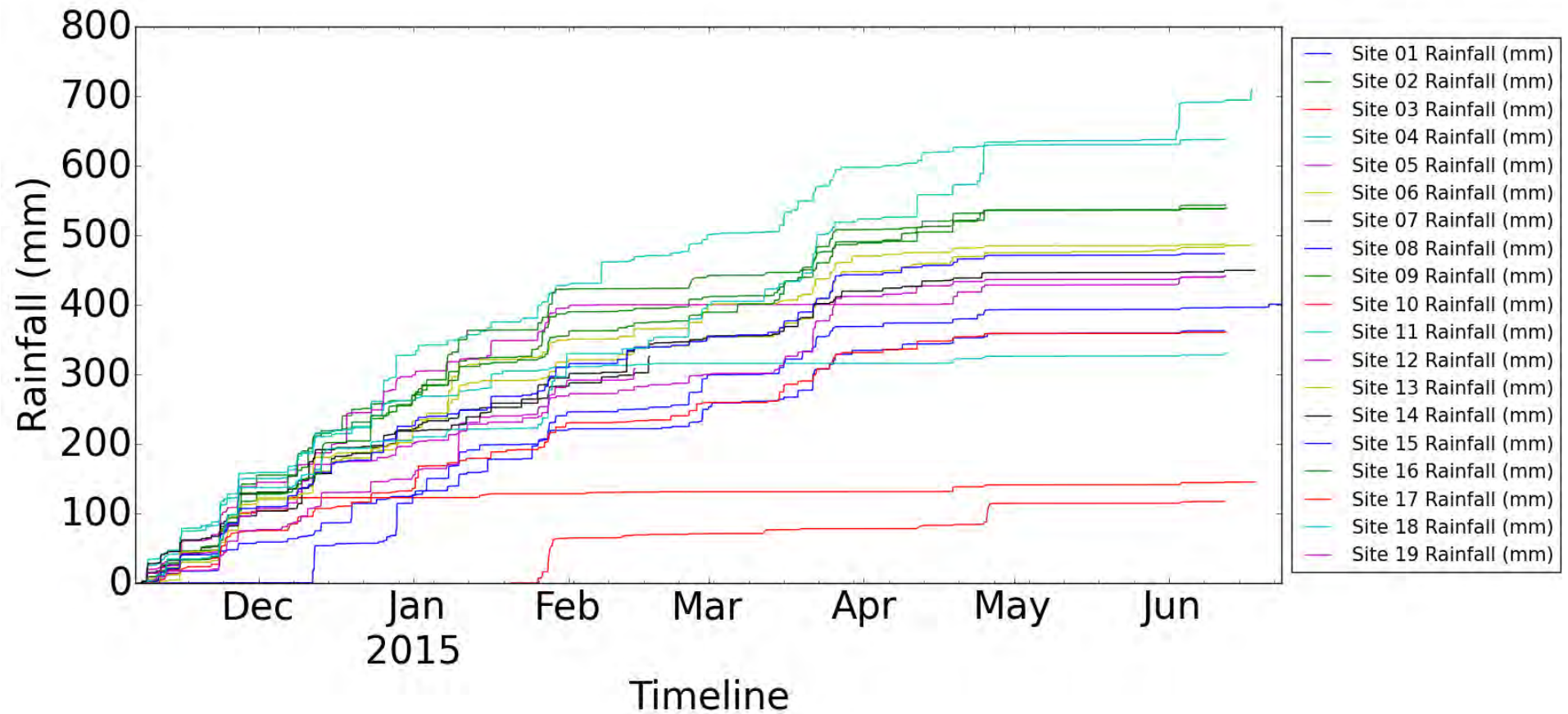


Figure 3-6: This figure shows the total rainfall for all the gauges in the Mooi River catchment area between November 2015 and June 2016. It is noticeable that in some cases the increments of rainfall do coincide. However these increments differ in magnitude. This means that rainfall is not that variable over space however rain rate is.

Considering the scale on the y-axis of each rain-gauge the Doornfontein gauge showed the most rainfall between November 2015 and June 2016 (Figure 3-7). This gauge measured a total of 711mm of rain. Throughout the entire period it observed rainfall and in February a convective event was measured which was not measured by the other gauges in the catchment. This made this rain gauge distinguishable in its high amount of rainfall measured compared to the other gauges in the catchment. Another such event was measured at the end of May which no other gauges have measured. It is important to note that the Randfontein gauge is situated 11km to the east of this gauge. Randfontein did not measure both these events with the intensity measured by the Doornfontein gauge.

The Randfontein gauge measured the majority of its rainfall within the first three months of operation (Figure 3-7). From the end of February to the end of June very little rain was measured by this gauge compared to the gauge in Madrasah which measured close to 150mm of rain for this period and the Randfontein gauge measuring just 25mm of rain. These gauges are within a distance of 13km of each other.

A large number of convective events has been observed at the end of April throughout the catchment (Figure 3-7). However these convective events differed in the amount of rainfall. The Rietfontein gauge measured over 150 mm of rain between the 18th of April and the start of May 2015. Klipgat also showed this jump in amount however it measured about 95mm of rain, 55mm less than Rietfontein which is only situated 17km to the south-west. To the north-west of the Rietfontein gauge the Rooibees gauge measured these convective events at only 50mm of rainfall. This rainfall developed because of an easterly low-pressure system over the central and Northern parts of the country. This brings a large amount of moist air into the country from the equator. This warm air gets uplifted by a low-pressure system which is highly favourable conditions for intense convective events. It is very important to note that this high amount of rain was not caused by a single convective event but rather scattered isolated convective events.

The Welverdiend gauge situated at the De Beer Primary School showed a unique increase in rainfall amount compared to all the other (Figure 3-7). Most of the rainfall measured occurred between November 2015 and the start of January 2016. The gauge measured a total of 125mm of rain within these first months and after that only 25mm was measured. This is much different to the rain gauges to the east and west of the Welverdiend gauge. To the east the Carltonville gauge situated at Carlton Jones High School a total of 150mm of rain was measured and to the west the Muiskraal gauge also measured 150mm of rain. The distance these gauges are from the Welverdiend gauge is 12km and 18km respectively.

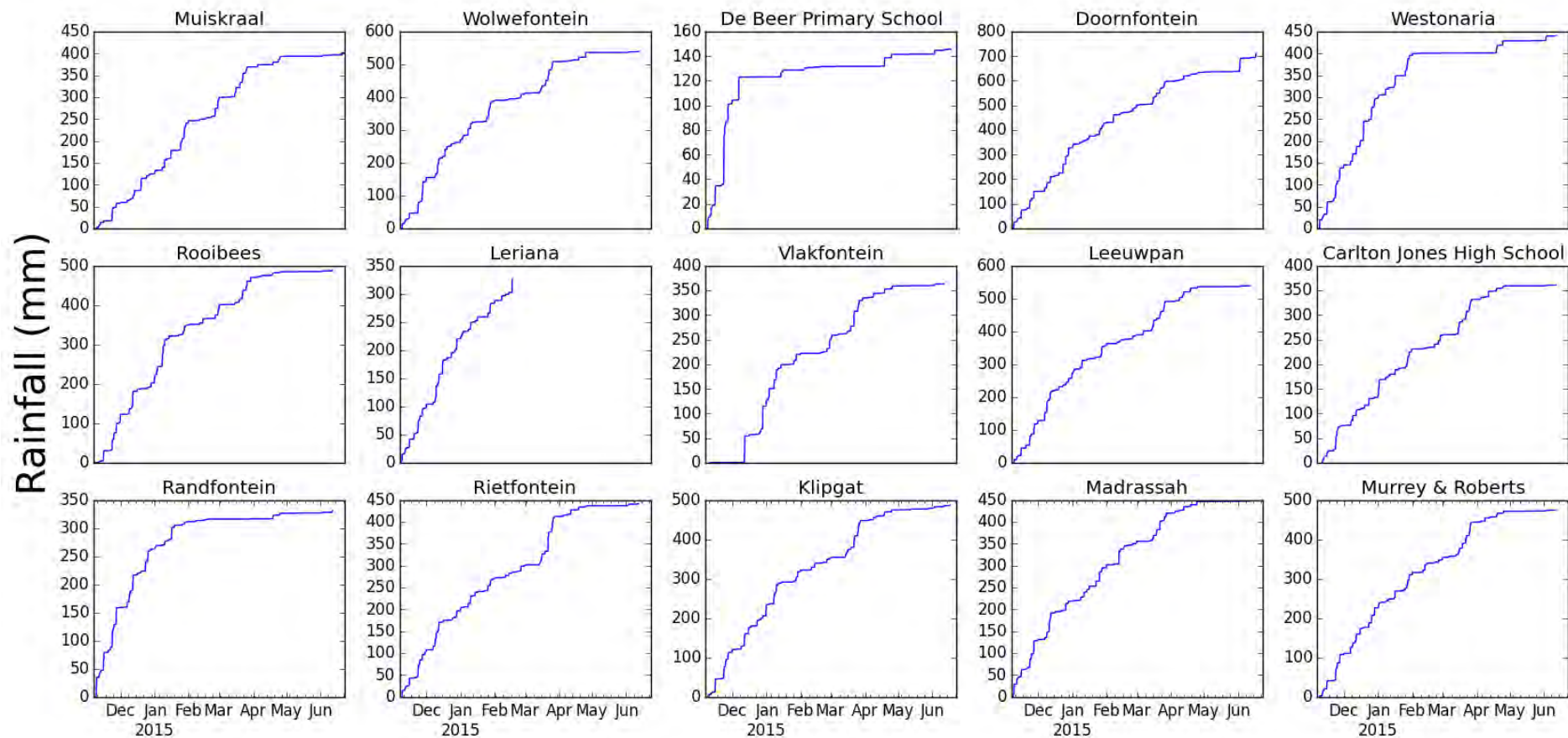


Figure 3-7: The total rainfall of each rain gauge differs in some cases significantly. Doornfontein measured a total of 711mm of rain were Randfontein only measure 331mm. This was measured between November 2015 and June 2016. These rain gauges are situated very close to each other.

As already mentioned there is a desperate need for a shift in rainfall research from the amount of rainfall to the intensity. The rain rate over the Mooi River catchment is highly variable between gauges (Figure 3-8). This is evident of the unpredictable nature of convective events in the catchment and that unique strategies specifically developed for this area must be used to measure rainfall. Using generic methods would create large inconsistencies in data.

Figure 3-8 shows the inter-tip times between tips. This is a reflection of the rain intensity of an event. The smaller the rain rate the higher the inter-tip time and vice versa. The Wolwefontein gauge measured the highest rain rates in the catchment. The majority of the inter-tip times measured was between 1 and 3 seconds. Wolwefontein is situated close to the Klipgat and Leeuwpan gauges. These gauges show different measurements in the intensity of events. Klipgat also measured some high rain rates however not as high as the Wolwefontein gauge. This shows that there is a high variability in rainfall intensity as the distance between Wolwefontein and Klipgat is only 15km.

The Doornfontein gauge also measured very high rain rates. The majority of inter-tip times measured was also between 1 and 3 seconds. Lower rain rates were also measured however this is not that frequent. The frequency of inter-tip times longer than 3 seconds is far less than rain rates between 1 and 3 seconds.

Some gauges in the catchment did not measure such a high number of higher rain rates. The Carltonville gauge measured rain rates with inter-tip times between 1 and 7 seconds. This is the same situation observed at the Welverdiend gauge.

It is clear that according to the inter-tip times measured by the gauges in the Mooi River catchment that the majority events are localized and highly variable convective events. The differences in the number of incidents with inter-tip times lower than 3 seconds are much higher than the number of incidents with inter-tip times greater than 3 seconds. This shows that the spatial variability of convective events is firstly highly variable and secondly these type of events are the majority observed. Stratiform events are far less measured and those that were measured are much more uniform over a large area.

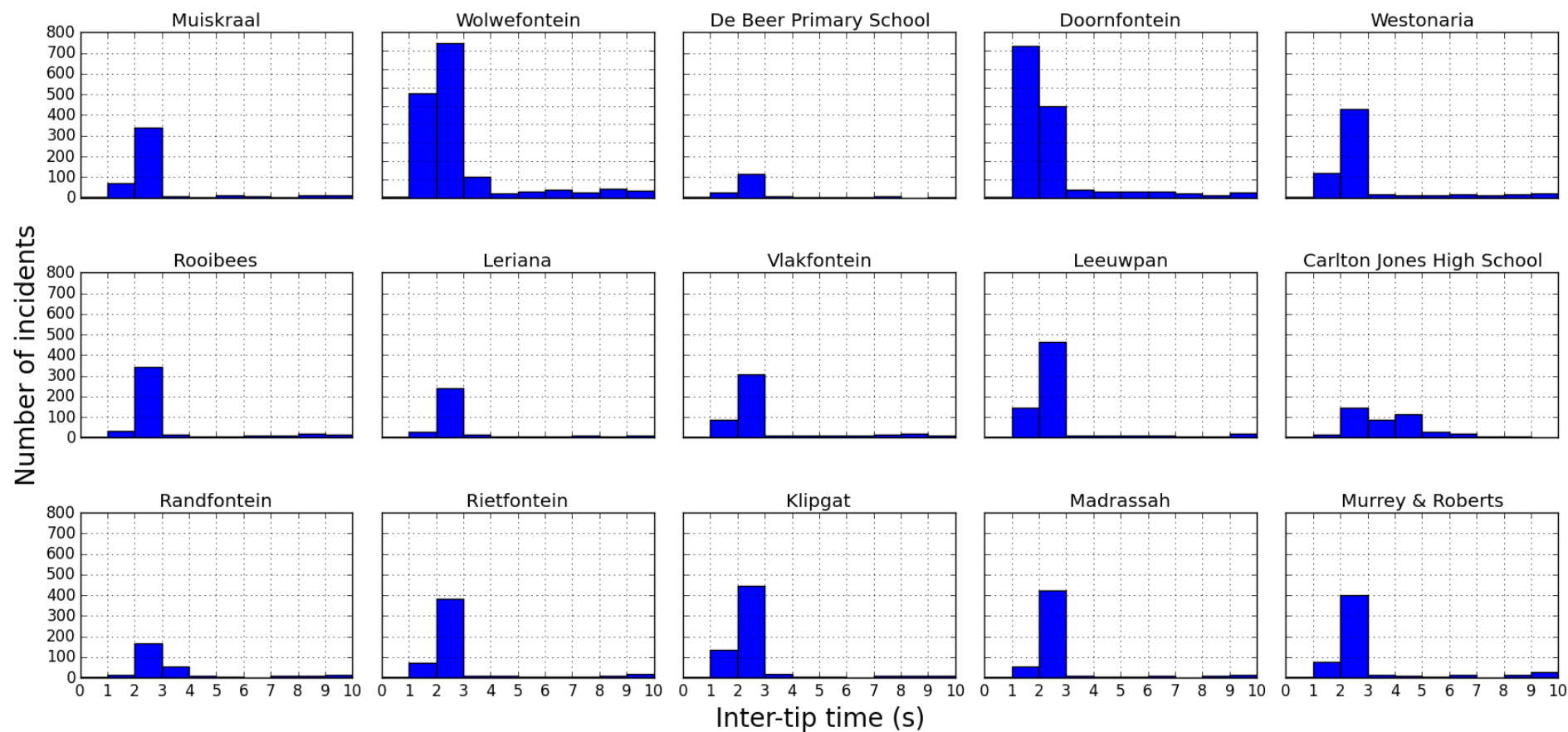


Figure 3-8: Inter-tip times are the time between two consecutive tips. Using this the rain rate can be derived. The shorter the inter-tip time the higher the rain rate and the longer the lower the rain rate. This figure shows the amount of which a certain inter-tip time occurs at all the 15 rain gauges in the network. This shows that rainfall varies spatially in the Mooi River catchment

3.3 Variability of the Reflectivity vs. rain rate relationships in the Mooi River catchment

Reflectivity and rain rate are two very important variables in the field of radar rainfall estimation. The Z-R relation is, however, also a good indicator of the variability of rainfall as it is very sensitive to small changes in the microstructure of storms and differs between events. The A coefficient used in the Z-R relation (Eq. (5)) is a good indicator of the variance in rainfall as it is prone to change significantly with small changes in the DSD. The A coefficient of events measured by the disdrometer varies between events. Stratiform events tend to have higher A values than convective events. There are, however, exceptions to the rule as can be seen in Figure 3-9. An event was measured with a high rain rate (64mm/h) and an A coefficient of 208. This is however not that a significant deviation to the norm. Events with lower rain rates are considered as stratiform rain and events with higher rain rates are convective. These convective events seem to consistently have smaller A coefficient values without exceptions. Events with rain rates higher than 20mm/h are convective events and all these events have A values of less than 180. The A values measured in this study varies between a maximum of 270 and a minimum of 35. This is a considerable difference and once again shows the variability of rain rates especially in convective events (Figure 3-9). As already mentioned, convective events normally have an A coefficient lower than 200. Stratiform events normally have A coefficients higher than 200 (Uijlenhoet, 2001). This is clearly visible in Figure 3-9. What is clearer is that firstly, convective events are more observed than stratiform events, convective events are highly variable and that stratiform events are not that variable as can be seen by the cluster of events measured with an A coefficient higher than 200.

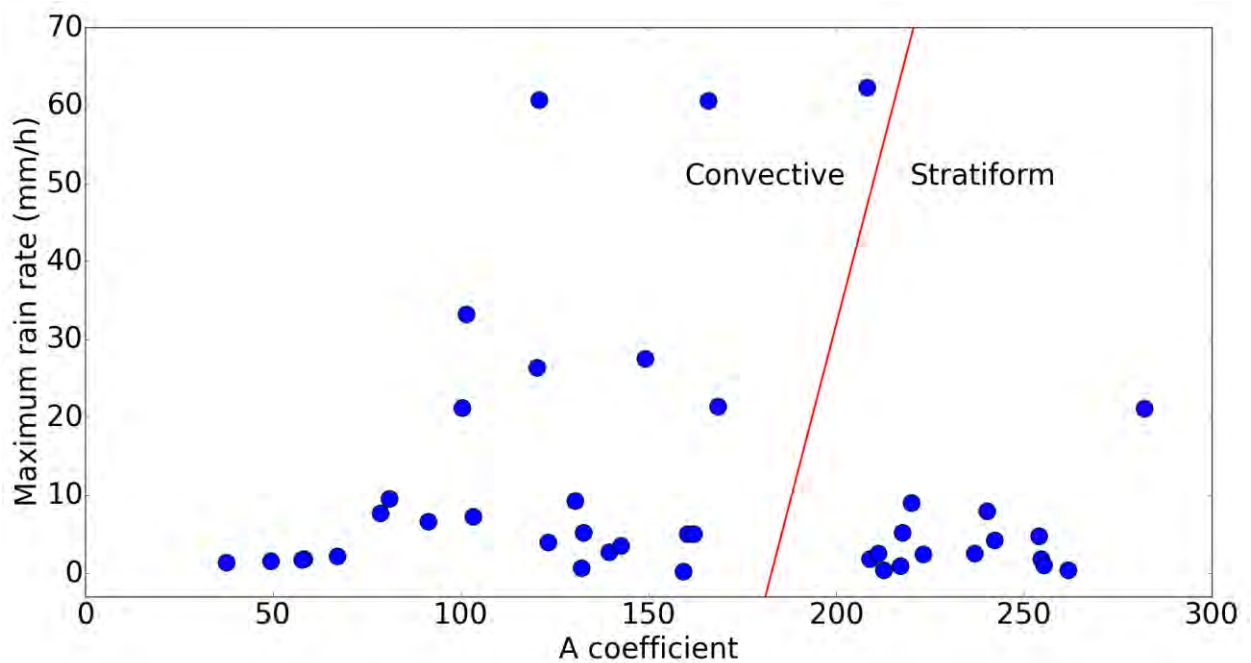


Figure 3-9: Maximum Parsivel disdrometer rain rate versus the A coefficient per event measured by the disdrometer between the 21st of February and 31st of March 2014 in the Mooi River catchment area is shown. A clear distinction can be seen between the highly variable convective events and the more uniform stratiform events.

The b coefficient is not that susceptible to changes in DSD as the A coefficient. Figure 3-10 shows that it is very difficult to see any pattern in the b coefficient. Events with high rain rates have b coefficients of 1.4 and a cluster of events with lower rain rates has a b coefficient of 1.6. Considering the previous results of the character of rainfall in the catchment it is difficult to observe the same pattern. It seems as though significant events⁷ tend to have b coefficients between 1.4 and 1.6 (Figure 3-11).

⁷ Significant in their rain rate or duration

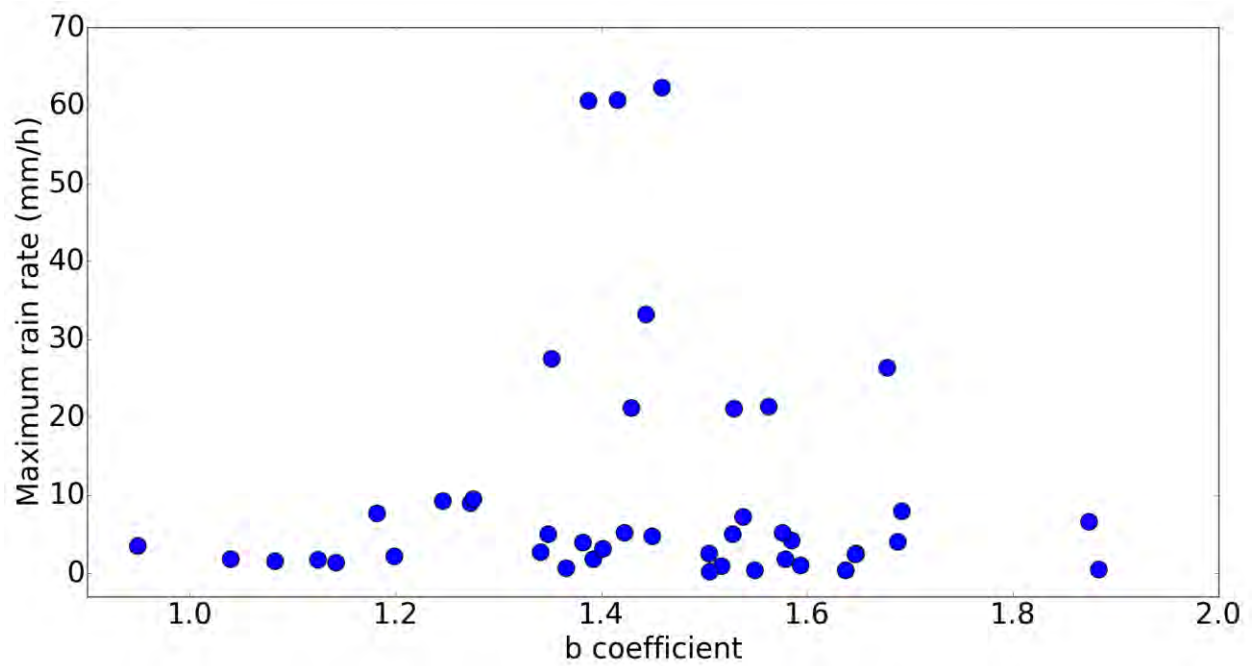


Figure 3-10: Maximum disdrometer rain rate versus the b coefficient per event measured by the Parsivel disdrometer.

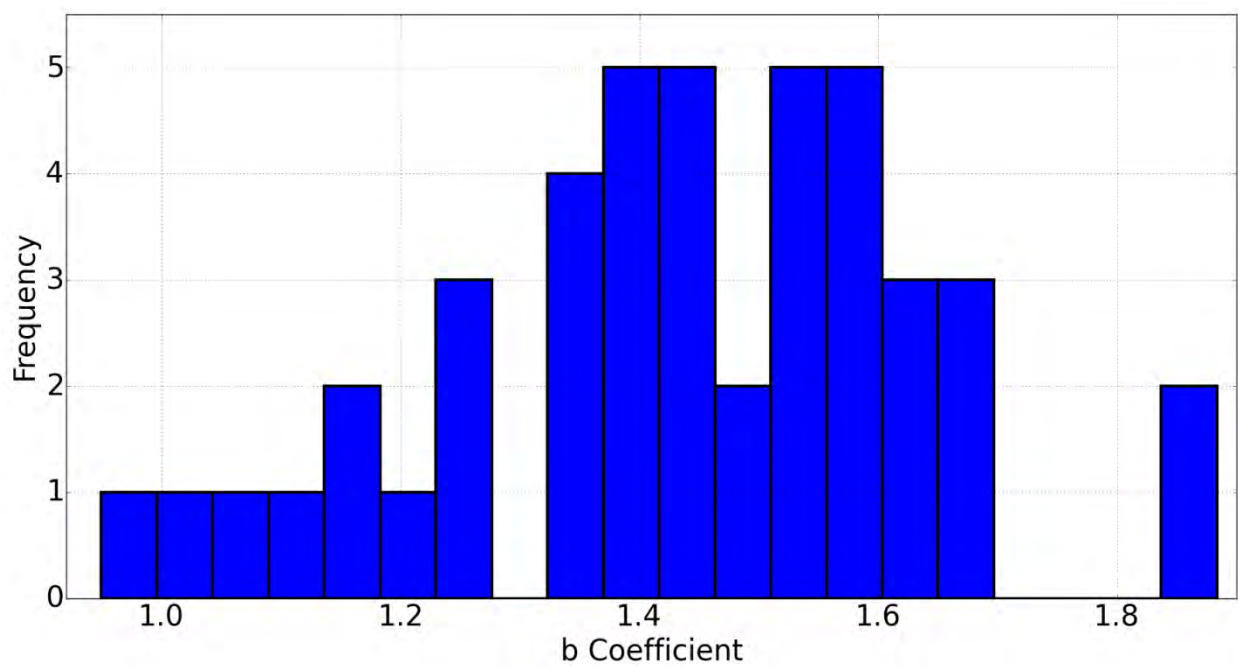


Figure 3-11: The frequency of different b coefficients measured per event. It is clear that the frequency of a b coefficient between 1.35 and 1.45 and then again between 1.55 and 1.6 is high.

The disdrometer was used to measure each event's Z-R relation. Measuring the Z-R relation means deriving the A and b coefficient as explained in Chapter 2.3.1.3. The A and b values were derived comparing the rain rate and reflectivity measurement made by the radar as shown in Table 3-3. The events were identified by a 15-minute gap between measurements. The start and end times of events were used to specify which data would be used for which events. The maximum rain rate per event was represented as "RainMax", the A coefficient as "Parsivel A" and the b coefficient "Parsivel b".

Table 3-3: A and b coefficient of the Z-R relation measured by the Parsivel disdrometer without the merged data. (Continue on next page).

Parsivel						
	Start	End	RainMax	DBZMax	Parsivel A	Parsivel b
1	2014-02-21 14:58:40+02:00	16:59:20	60.3	52.5	187	1.5
2	2014-02-21 20:06:10+02:00	20:53:10	5.6	33.5	175	1.4
3	2014-02-21 23:26:50+02:00	23:40:40	1.2	26.9	462	1.9
4	2014-02-22 20:08:30+02:00	20:41:50	13.1	47.1	203	1.6
5	2014-02-22 21:50:10+02:00	23:31:40	7.2	39.2	183	1.4
6	2014-02-23 11:41:20+02:00	11:57:40	61.7	54.5	353	1.8
7	2014-02-23 12:30:20+02:00	14:45:50	4.0	36.5	225	1.4
8	2014-02-23 15:47:10+02:00	18:26:20	6.2	41.6	269	1.6
9	2014-02-24 14:09:00+02:00	15:01:00	3.7	35.9	324	1.7
10	2014-02-24 19:18:20+02:00	19:57:50	5.6	36.6	271	1.6
11	2014-02-24 23:22:20+02:00	0:29:30	102.7	53.8	183	1.5
12	2014-02-27 17:14:10+02:00	17:18:10	2.6	29.5	270	1.5
13	2014-03-01 11:10:30+02:00	11:35:50	16.0	43.2	184	1.6
14	2014-03-01 13:48:30+02:00	14:20:30	14.4	42.4	146	1.5
15	2014-03-02 17:36:20+02:00	18:06:30	0.7	19.5	178	1.5
16	2014-03-02 18:39:40+02:00	19:44:40	0.3	15.9	178	1.5
17	2014-03-03 15:38:50+02:00	17:55:30	3.9	33.6	152	1.3
18	2014-03-04 02:28:50+02:00	3:21:00	4.8	27.2	69	1.2
19	2014-03-04 04:13:10+02:00	4:25:50	1.6	21.1	70	1.3
20	2014-03-04 05:57:40+02:00	7:15:20	14.2	36.3	78	1.3
21	2014-03-04 07:50:00+02:00	8:23:30	3.4	22.6	44	1.1
22	2014-03-04 10:02:40+02:00	10:11:30	1.0	20.1	69	1.2
23	2014-03-04 13:05:30+02:00	14:02:10	5.8	39.7	259	1.7
24	2014-03-04 15:33:30+02:00	17:29:20	9.5	41.0	256	1.6
25	2014-03-04 22:31:30+02:00	1:31:10	9.6	36.5	141	1.4
26	2014-03-05 02:46:30+02:00	6:11:00	50.5	48.1	126	1.5
27	2014-03-05 09:59:30+02:00	13:08:30	61.2	50.3	160	1.4
28	2014-03-05 23:08:00+02:00	23:16:30	0.4	14.5	112	1.4
29	2014-03-06 03:26:40+02:00	4:21:10	129.7	54.5	155	1.4
30	2014-03-06 13:00:10+02:00	13:11:40	107.5	61.4	313	1.7

	Start	End	RainMax	DBZMax	Parsivel A	Parsivel b
31	2014-03-06 15:51:00+02:00	16:37:00	48.7	54.9	200	1.6
32	2014-03-06 19:37:10+02:00	20:56:20	11.3	49.1	360	1.7
33	2014-03-07 14:07:00+02:00	14:53:30	2.3	32.9	298	1.7
34	2014-03-07 20:25:10+02:00	20:51:50	0.3	15.0	142	1.4
35	2014-03-07 22:49:10+02:00	22:59:50	1.3	27.0	342	1.7
36	2014-03-08 13:00:10+02:00	13:43:40	58.0	56.9	319	1.7
37	2014-03-09 17:54:10+02:00	19:12:50	93.0	58.3	225	1.6
38	2014-03-09 20:10:20+02:00	21:21:30	0.5	19.0	224	1.6
39	2014-03-09 22:37:30+02:00	0:17:10	1.7	28.4	269	1.6
40	2014-03-10 14:32:40+02:00	15:06:30	13.5	38.0	147	1.4
41	2014-03-10 16:58:50+02:00	18:04:20	27.6	50.1	254	1.6
42	2014-03-10 20:09:20+02:00	20:40:50	8.4	34.1	151	1.1
43	2014-03-10 22:05:40+02:00	22:38:30	5.1	28.0	86	1.1
44	2014-03-11 00:00:00+02:00	2:08:30	1.5	24.1	148	1.4
45	2014-03-11 10:19:30+02:00	10:27:30	7.9	38.8	127	1.5
46	2014-03-11 12:55:40+02:00	12:58:50	6.3	33.9	135	1.5
47	2014-03-11 14:32:10+02:00	17:22:30	78.8	52.6	122	1.5
48	2014-03-11 17:58:40+02:00	18:09:00	4.9	29.2	93	1.4
49	2014-03-12 06:30:40+02:00	6:42:50	0.2	9.0	33	1.1
50	2014-03-12 14:20:30+02:00	14:42:40	37.4	55.2	330	1.8
51	2014-03-13 16:42:40+02:00	18:45:00	10.9	44.7	237	1.6
52	2014-03-14 05:25:10+02:00	5:42:50	0.1	4.8	55	1.2
53	2014-03-18 04:16:40+02:00	6:10:00	6.1	37.1	276	1.5
54	2014-03-18 13:56:50+02:00	14:15:20	5.3	40.0	502	1.9
55	2014-03-18 15:52:20+02:00	16:32:40	43.1	49.5	210	1.6
56	2014-03-18 18:00:50+02:00	18:44:40	12.8	41.5	207	1.6
57	2014-03-19 17:22:00+02:00	17:29:40	23.3	49.0	335	1.6
58	2014-03-26 14:30:40+02:00	16:03:00	5.0	27.7	85	1.2
59	2014-03-26 16:35:00+02:00	17:15:30	18.4	40.1	106	1.4
60	2014-03-30 14:47:10+02:00	15:04:40	15.1	48.3	403	1.5

Figure 3-15 shows all the different Z-R relations of the different events that are derived directly from the rain rate and the reflectivity measurement made by the Parsivel disdrometer. The A and the b coefficients are compared to one another and the size of the point is determined by the intensity of the rain rate. An empirical analysis was performed to determine the variability of the Z-R relation between events by using the Parsivel reflectivity (Z_D) and Parsivel rain rate measured outside Potchefstroom, North West. Figure 3-15 shows that, although there is large-scale variability in the Z-R relations, there seems to be a well-defined relationship between A and b. The question remains whether these A and b coefficients can be used to identify stratiform and convective storms and if these coefficients are different between events. Sufficient evidence has thus far been presented that convective events have lower A coefficient than that of the Marshall and Palmer relation.

Stratiform events are harder to identify according to their Z-R relation because of the longer duration of the event. The longer the duration of an event, the bigger the chance that different rainfall types can mix and that the A value will not respond according to the preliminary results of identification.

The most significant event measured according to its duration with the highest A value has a Z-R relation of:

$$Z = 360R^{1.6}. \quad (14)$$

This was measured on the 6th of March 2014 at 19:37:10 (Table 3-3) (Figure 3-15). The event had a maximum rain rate of 11.3mm/h and a duration of 1h19m. This has all the characteristics of a typical stratiform event: long in duration, low rain rates and a high A coefficient. The radar image of that day showed that widely distributed stratiform precipitation occurred to the northwest of the Irene radar coverage area and confirmed the finding (Figure 3-12).

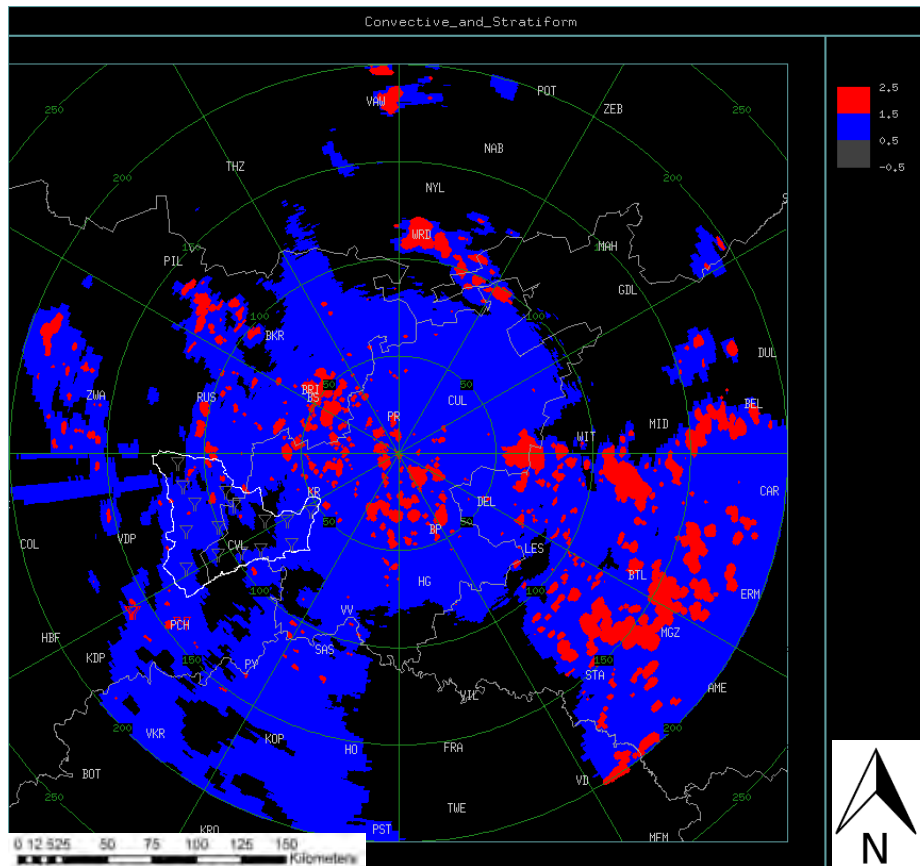


Figure 3-12: Irene radar image of stratiform events to the southwest of the coverage area were the disdrometer is situated. Blue areas represent stratiform precipitation and red convective.

There are however some exceptions to the rule that can create uncertainties in the data. The event measured on the 10th of March 2014 at 19:00 had a Z-R relation of:

$$Z = 245R^{1.6} \quad (15)$$

with a maximum rain rate of 27.6mm/h and it lasted for over an hour. A few variables contradict each other when considering the characteristics of this event. A high A coefficient and a long duration are good indicators of a stratiform event. However, a higher rain rate spoils the result. This is because of a mixture of event types that creates a problem when predominantly stratiform precipitation is observed. Convective and stratiform precipitation can exist in one event because of the long duration and uniformly distributed rain that can be observed between spikes in rain rates as can be seen in Figure 3-1 (p.85) number 26 and 27. The radar image also showed that widespread stratiform rain was prevalent southwest of the Irene weather radar where the disdrometer was located (Figure 3-13).

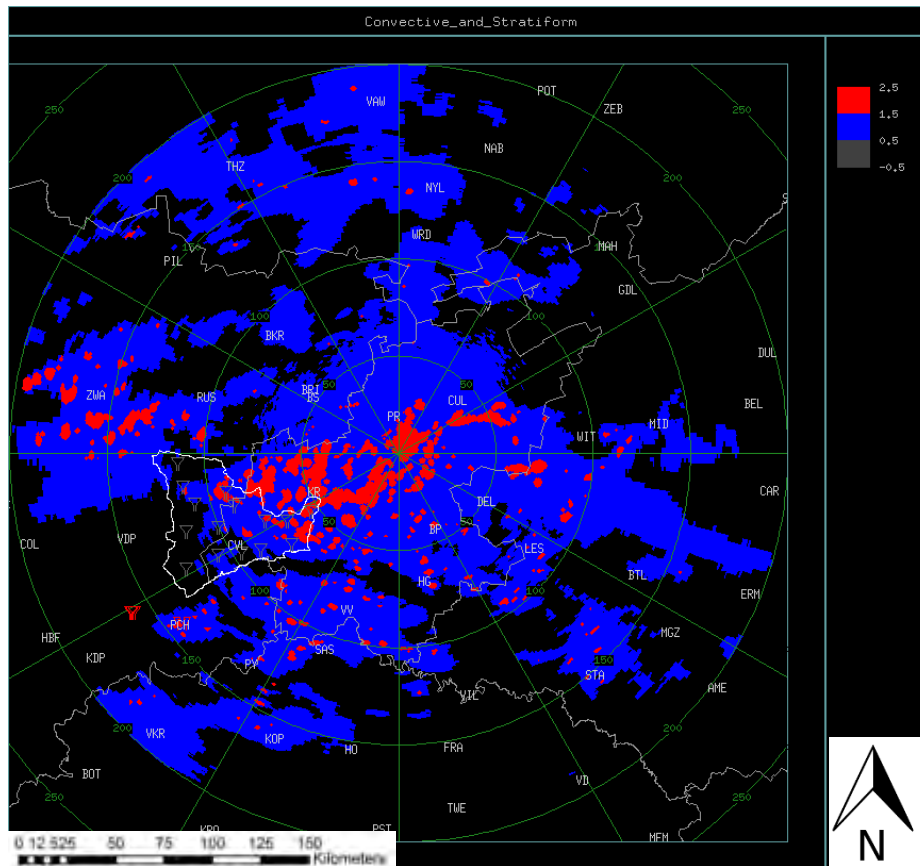


Figure 3-13: Irene radar image of stratiform events to the southwest of the coverage area where the disdrometer is situated with some isolated convective cells. Blue areas represent stratiform precipitation and red convective.

The level of certainty is far higher when it comes to the fact that if the A coefficient is lower this event can be defined as a convective event (Figure 3-15). This can be because of the high variability of rain rates and because events occur more isolated. Therefore events cannot be classified as mixed precipitation which creates this higher correlation. Most convective events in the Mooi River catchment start very suddenly with a peak in rain rate and a gradual decrease (Figure 3-1 85p). Very seldom rain is observed for periods before and after events. These events are normally also very short in duration with high rain rates. A significant convective event was measured on the 24th of February 2014 with a maximum rain rate of 102.7mm/h and a Z-R relation of:

$$Z = 183R^{1.5}, \quad (16)$$

that indicates intense convective events. The lower A value, 183, of these events also shows that this is a convective event. This was also confirmed by the Irene weather radar (Figure 3-14).

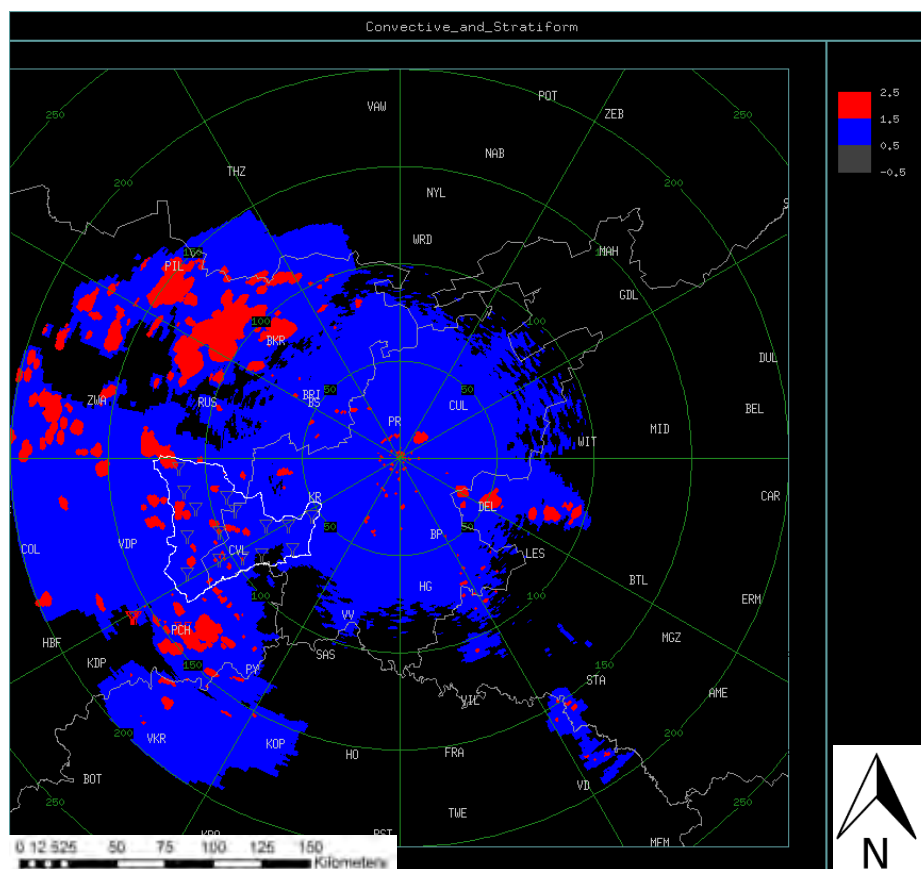


Figure 3-14: Irene radar image of convective events to the south-west of the coverage area were the disdrometer is situated with some isolated convective cells. Blue areas represent stratiform precipitation and red convective.

There is a clear relation between the A and b coefficients when compared to each other (Figure 3-15). These variables are directly proportionate to each other. Significant events according to their rain rates had mostly A coefficients between 100 and 300 with more events with A values in the first quartile. This indicates that more convective events were measured than stratiform (Figure 3-15).

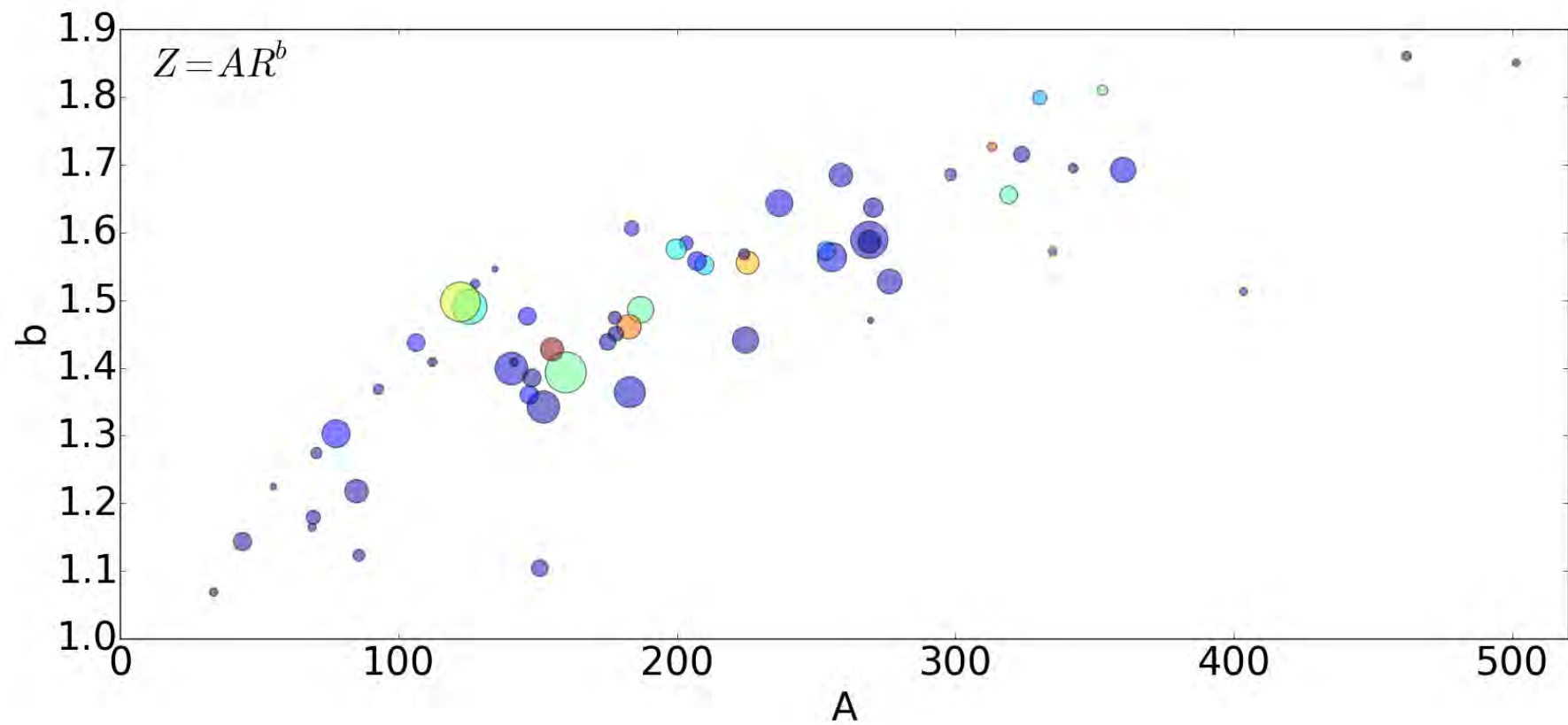


Figure 3-15: The Z-R relation of each event measured by the reflectivity and rain rate values measured by the disdrometer. On the x-axis the a coefficient and on the y-axis the b coefficient of the Z-R relation. The Z-R relation for each event was further characterized by the size of the point. The larger the circle, the larger the rain rate.

3.4 Identifying and characterizing the variability of convective and stratiform events in the Mooi River catchment using the Parsivel disdrometer

Convective and stratiform events are very frequent in the Mooi River catchment. A number of different variables were explored using the disdrometer data that could give clarity on the occurrence of these types of events in the catchment.

The A coefficient is a good indicator of the variability of the rain rate and type of events as already mentioned in the previous section. The higher the rain rates, the lower the A values. This is also the case when identifying convective events. Higher A coefficients are good indicators of convective events. Figure 3-16 shows the frequency of different A coefficients measured by the Parsivel disdrometer. It is clear that events with low A coefficients are in the 1st quartile. This shows the high frequency of convective events within the catchment.

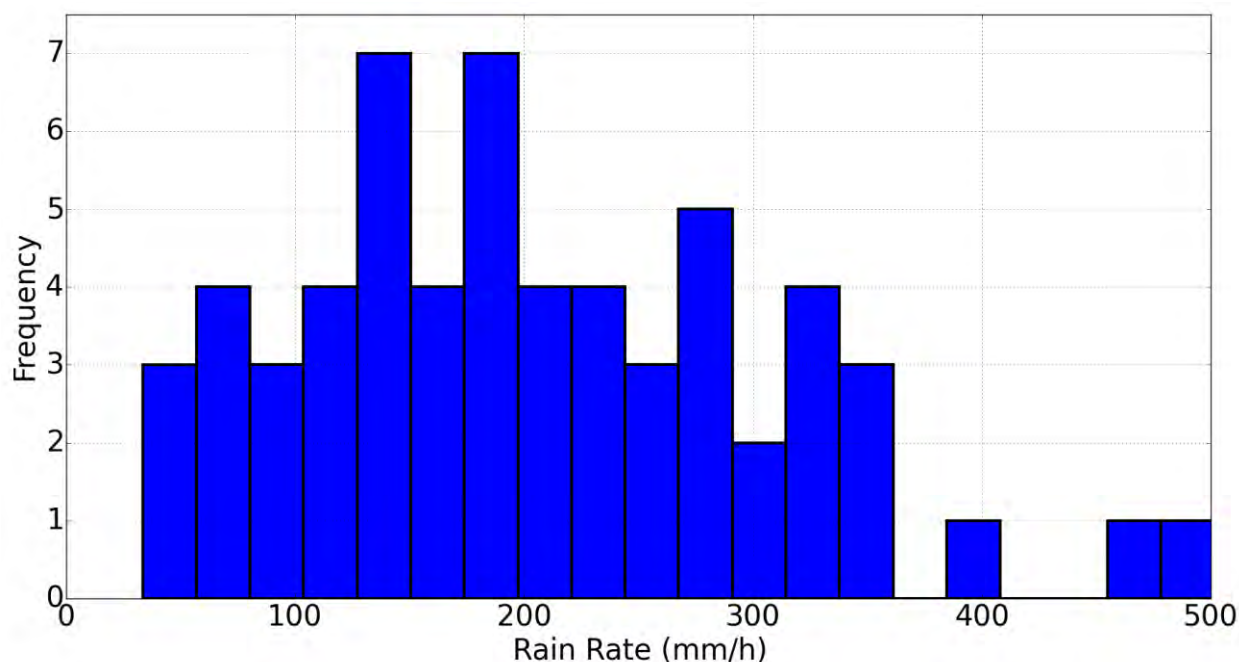


Figure 3-16: Probability density function of the A coefficient of events measured by the Parsivel disdrometer.

Convective and stratiform events also differ distinctly in their duration and can be identified using this variable. Because stratiform events are widely distributed these events are more likely to have a longer duration than convective events that are very isolated in their appearance. Figure 3-17 shows the frequency of events with different durations measured by the amount of

measurements made by the disdrometer⁸. The highest frequency is events with short durations. This is further proof of the dominance of convective events within the catchment. Events with lower rain rates have a lower frequency.

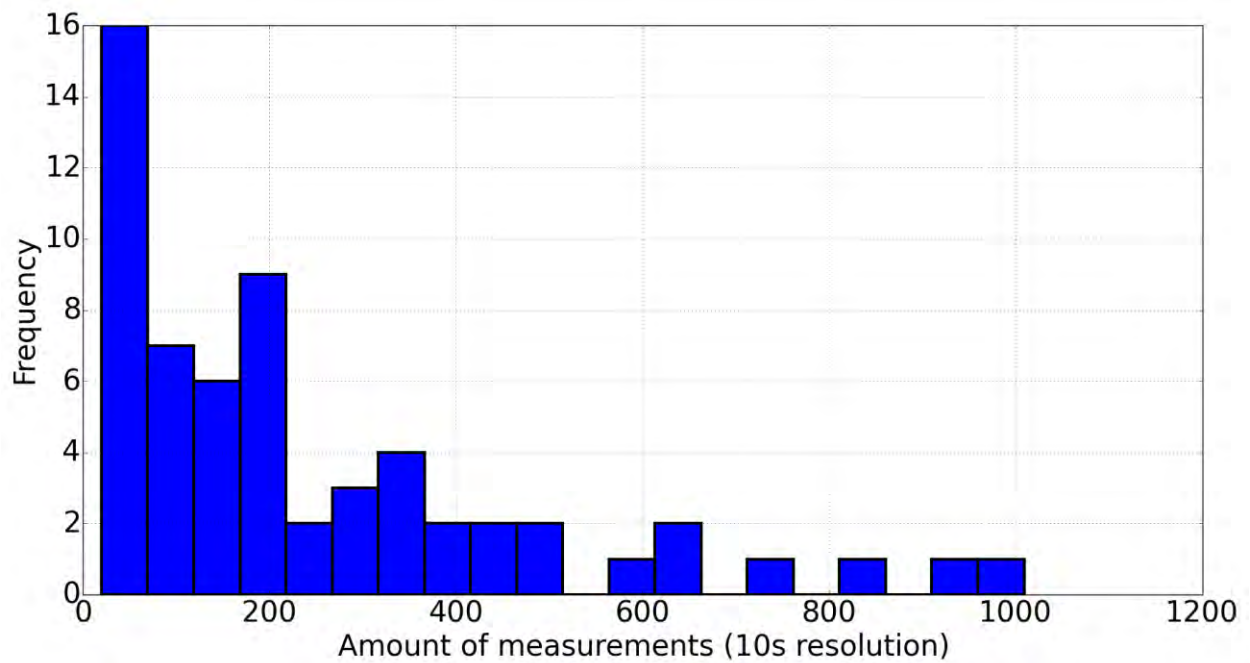


Figure 3-17: Probability density function of the duration of events measured by the disdrometer on the Highveld.

⁸ 200N=30minutes

CHAPTER 4 ESTIMATING RAIN RATES USING A SIPHON TIPPING-BUCKET RAIN GAUGE

Tipping-bucket rain gauges are the most widely used rainfall measuring instruments today. As the industry standard, these rain gauges are extremely rugged and user-friendly because of their mechanical function. Instruments like this are prone to a number of different errors, one of those being the overestimation of events with high rain rates. Therefore new models are developed with a device called a siphon which controls the flow of water into the bucket to eliminate this error.

4.1 Challenges measuring rain rates from a Siphon tipping-bucket rain gauge

Measuring rain rates with a tipping-bucket rain gauge poses unique challenges. Conventional methods include calculating the inter-tip times of two consecutive tips. The smaller the difference the higher the rain rate and vice versa. This way of measuring rain rates is done using some of the first TBR. Newer models are developed with a siphon that regulates the flow of water into the buckets. Two major problems must be dealt with before rain rates can be measured using a siphon TBR.

Firstly, the start and end times of events cannot be accurately calculated. An actual start of an event will normally be well before the first tip measured by the siphon TBR. This is the same at the end of an event. The actual end time would be well past the last tip. For example, an event was measured on the 6th of March 2014. The TBR measured the start and end of the event as 16:22:35 and 16:55:09 respectively. The actual start and end time of the events measured by the Parsivel disdrometer was 15:38:00 and 17:55:00. When using conventional methods, the rain rate can only be measured once 0.2mm of rain has already been observed. This will cause the event to be underestimated as the rain rate of the first 0.2mm will not be measured. A Parsivel disdrometer was used to solve this problem by measuring the median time it takes for the first 0.2mm to rain. This was calculated at 8.3minutes which result in a rain rate of 1.45mm/h added before every first tip. Secondly, double tips create inconsistencies in TBR rain rate data. The siphon has a capacity of 0.4mm. Double tips occur when water is still left behind in the bucket from a previous tip. When the siphon dumps the entire 0.4mm of water into a bucket which already has, for example, 1.5mm in it, two tips in quick concession will be measured. The difference in time between these double tips is below 0.4 seconds. This will cause the rain rate for that time to be overestimated. The algorithm developed in this study corrects this issue by identifying the second tip of the double tip (time difference smaller than 4seconds), deleting the

second tip from the data set and assigning the 0.2mm of water from the deleted tip to the first tip that will then measure a total of 0.4mm.

Tipping-bucket rain gauges are inexpensive instruments. This makes it the ideal instrument to be placed in a network of rain gauges over a large area. Having the ability to measure rain rates accurately will allow us to measure the spatial variability of very high rain rates in the Mooi River catchment.

4.2 Estimation of rain rates using a siphon tipping-bucket rain gauge

All the rain rate measurements made by the TBR was compared to the disdrometer rain rate measurements for validation purposes. The Parsivel disdrometer is assumed to have the most accurate measurement of rain rate due to its high resolution and the ability to measure each drop that moves through the laser beam. Data was measured between February and March 2014.

The majority of rain rates measured by the TBR using the new algorithm were between 0.5 and 10mm/h. This agreed with the disdrometer which also measured the majority of rainfall in this range. The TBR also measured higher rain rates. The frequency of rain rates above 30mm/h and the variability of rain rates measured by the TBR are more than that of the disdrometer. This means that the TBR measured a higher variability above 30 mm/h (Figure 4-1).

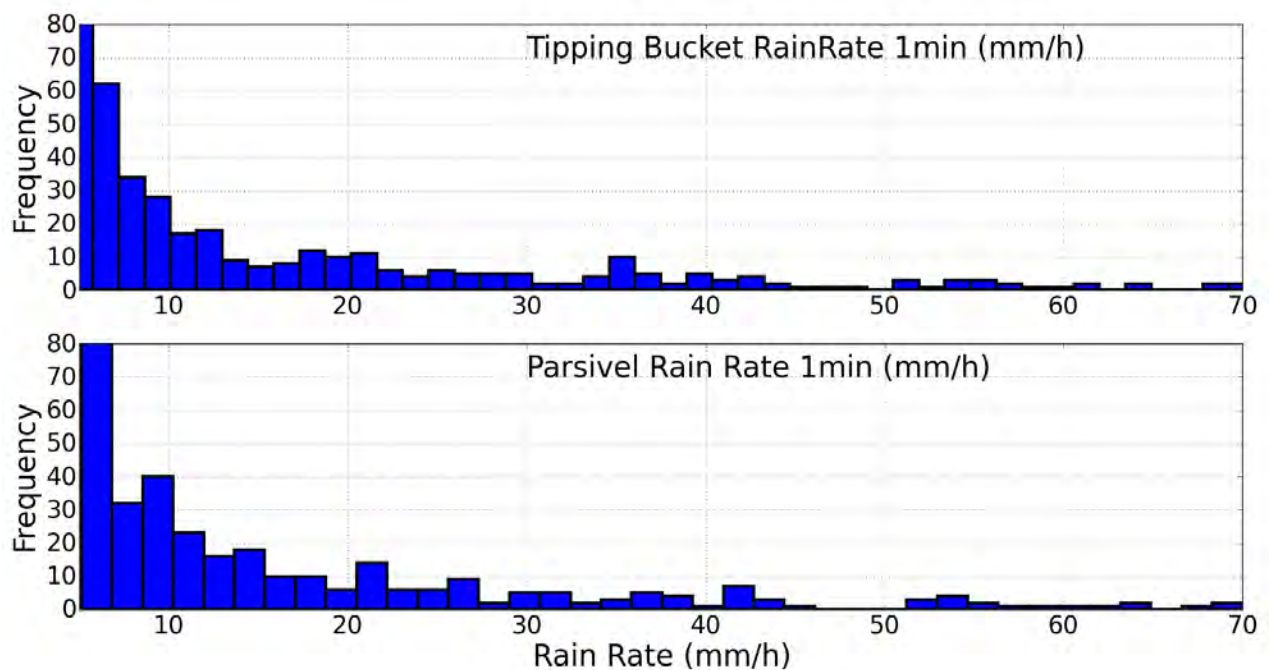


Figure 4-1: Probability density function of the rain rates measured by the TBR and Parsivel disdrometer.

Figure 4-4 shows the series of times at which rain rates are measured by the disdrometer and the TBR. The tipping-bucket rain gauge recorded total rainfall of 161mm and the disdrometer 180mm. The cumulative rainfall between the Parsivel disdrometer and the TBR were very close (Figure 2-7). In general, the rain rates also compared fairly well to each other. Rain rates were measured for the entire data set and re-sampled to 1min, 2min, 5min, 7min, 10min, 15min, 30min and 60min (Table 4-1). This was done to evaluate the performance of the algorithm at different time scales.

The scatter plots of TBR versus disdrometer rain rates are shown in Figure 4-2 at the different time scales. The correlation of the rain rates at a 1min time scale is 65%. It is expected that the correlation would be at the lowest at these lower time scales because of the increase in data points and the high variability of rainfall in the catchment. At lower rain rates the TBR tends to slightly over- estimate the rain rate. This is most likely because of the rain rate used for the first 0.2mm of rain before the first tip. It is important to remember that the majority of rain observed in the catchment is in the form of convective precipitation. This includes high rain rates that normally start off with a sudden increase in rain rate and a gradual decrease after the peak. This can be seen clearly in the measurement of rain rates using the disdrometer (Figure 3-1). Therefore, assigning the first 0.2mm of rain for a convective event as 1.45mm/h would be closer to reality for events with high rain rates. This is why low rain rates are often overestimated. The decision was made rather to overestimate lower rain rates than underestimate high rain rates that would have been the case if the rain rate for the first 0.2mm of rain was calculated for stratiform events.

The correlation between measurements improves as the time scale increases. A maximum correlation is reached on a time scale of 15min of 93%. After 15 min there is a slight decrease in correlation because of the methods used in the algorithm to eliminate errors caused by the siphon, re-sampling effects and the performance of the TBR at higher and lower rain rates. The reason for the decrease in correlation can also be because of data availability. Data was only measured by the disdrometer between February and March 2014. As time scales increase the amount of data points decrease (Table 4-1). Therefore, the longer the timescale, the less the amount of data points that may have an impact on the correlation. However, this problem is not expected and will be further investigated in Chapter 4.3.

At higher rain rates the TBR underestimates the rain rate. This can be because of the resampling of data. This problem has also been observed in previous studies (Wang *et al.*, 2008).

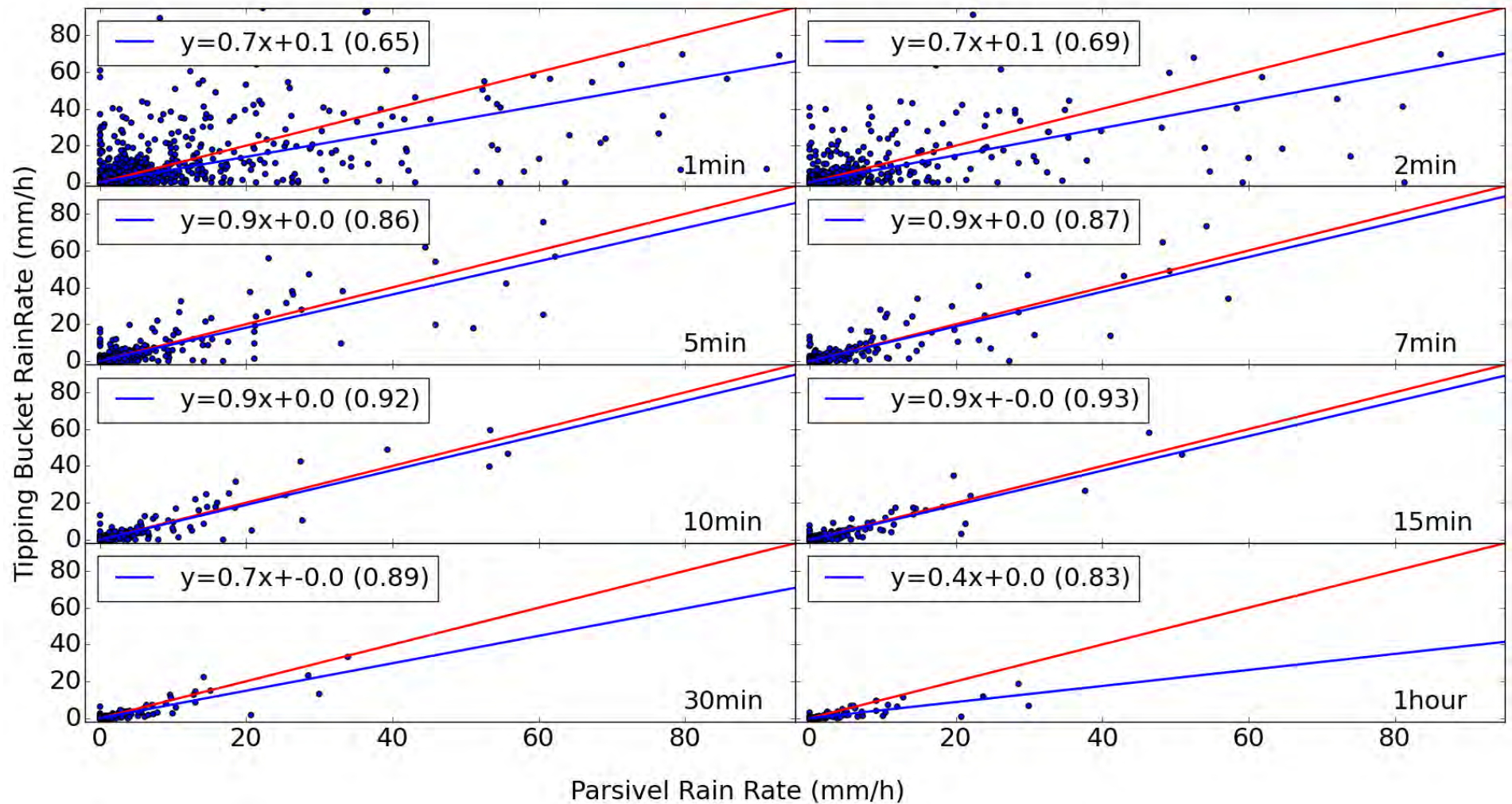


Figure 4-2: Rain rates measured by a siphon tipping-bucket rain gauge compared to the rain rates measured by the disdrometer re-sampled to 1min, 2min, 5min, 7min, 10min, 15min and 30min. Linear regression line indicates the correlation between measurements.

Rain rates measured by the TBR varied between 0.1 and 100mm/h. Both convective and stratiform events were represented in the dataset. The frequency of higher rain rates measured by the TBR was slightly correlated to that measured by the disdrometer. This is, however, not a significant difference and Figure 4-3 shows that rain rates measured by both instruments are relatively the same. This is another indication that the algorithm developed performs well compared to the disdrometer.

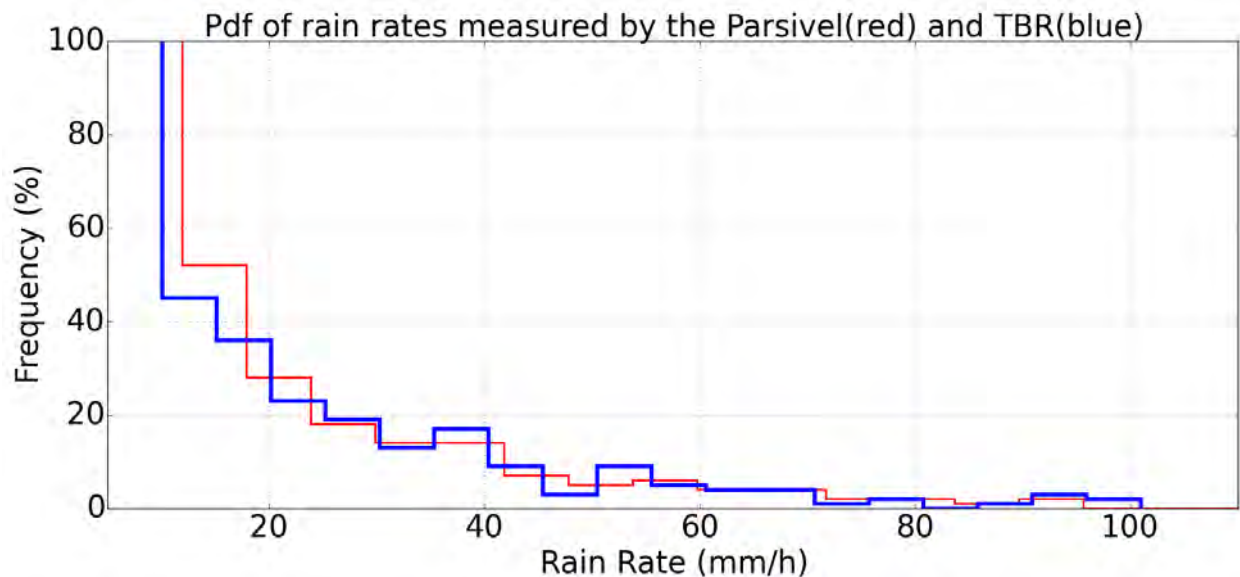


Figure 4-3: Probability density function of the rain rates measured by the TBR and the Parsivel disdrometer.

4.3 Errors in Tipping-bucket rain rate estimation

A preview of the rain rates measured by the Parsivel disdrometer compared to measurements measured by the TBR reveals that there is a lag in measurements from the Parsivel's early measurement by the TBR (Figure 4-2). The first problem that normally creates this issue is when the spatial variability of rain rates is extremely high. This is a very likely problem, especially in the Mooi River catchment, where the variability of rainfall spatially and temporally is very high. However, considering the dynamics of the study as explained in Chapter 1.6.11 this cannot be the problem. The disdrometer and the rain gauge are placed in close proximity which confirms that this can't be because of the variability of rain. Problems like this can also however be a consequence of using two different data-logging techniques, each with their own clocks. An offset in the time between the two instruments can be the reason for this lag. This problem was eliminated as frequent calibration of both the clocks was done to reduce time drifting that is

an issue with TBR. A possible problem can be the 1.4mm/h of rain rate added before each tip. This caused the start time of events to differ at events with high rain rates and events with low rain rates. Rain rates between 10 and 30mm/h did however not suffer from this problem as the median was used to calculate the rain rate of the first 0.2mm of rain. Events with high rain rates often showed that the disdrometer lagged in measurements. The reason for this is that events with high rain rates⁹ in the catchment are highly variable over space and therefore peak rain rates are often observed at the start of an event with a gradual decrease towards the end. Stratiform events with lower rain rates will face the same problem with an opposite outcome with the TBR measurements that will start measuring events later than the disdrometer. This problem will not be as significant as the error mentioned in Chapter 4.1. It is at the median rain rate of events where the lags in time of instruments will not be a problem.

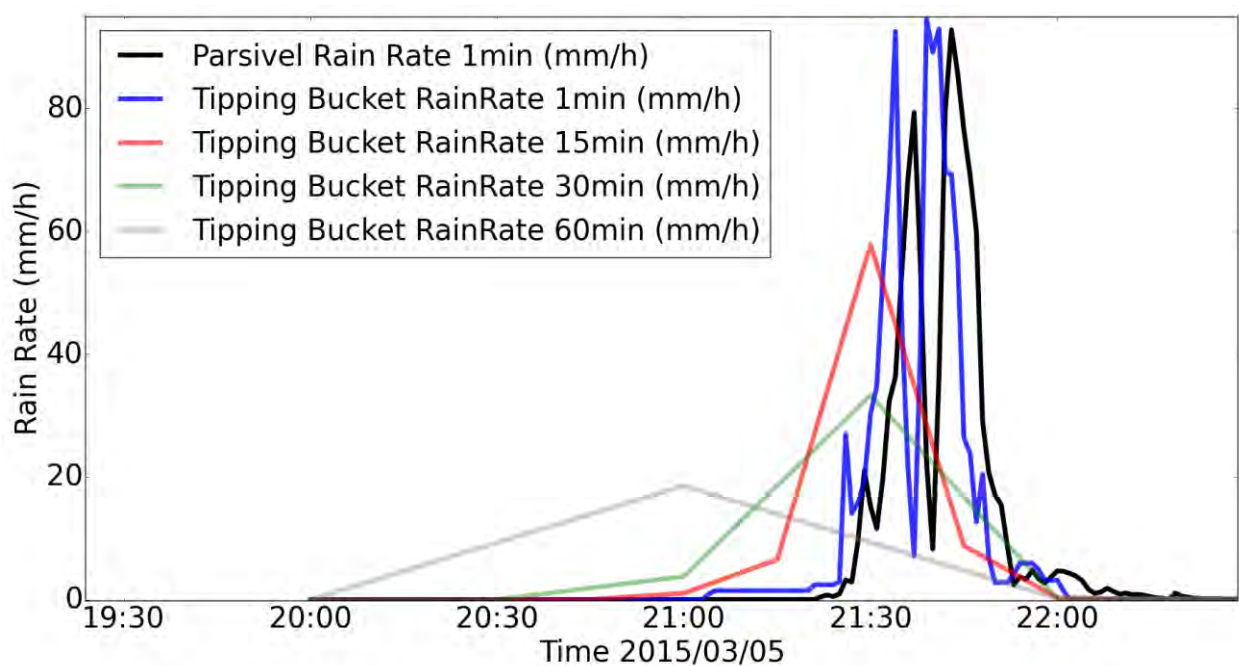


Figure 4-4: Rain rates measured by the TBR using the newly-developed algorithm and the rain rate measured by the Parsivel disdrometer for an event measured on the 5th of March 2014. Data were resampled to 1min, 2min, 5min, 7min, 10min, 15min, 30min and 60min.

The correlation between the TBR and the disdrometer was calculated by comparing measurements to each other. Data was re-sampled to 1min, 2min, 5min, 7min, 15min, 30min and 60 min (Table 4-1). It is very important that this process must be fully understood. Re-

⁹Convective events

sampling data cause the amount of tips to differ compared to the time of actual tips. This will have an impact on the correlation between disdrometer and TBR rain rate measurements.

The assumption in any type of measurement will always be that as the time scale increases the correlation will also increase. This was not the case when the siphon TBR was used for rain rate measurement. A peak in correlation was observed at 15 min with a slow decrease toward 1 hour. This is because of two reasons. Firstly, for convective events with high rain rates a large number of tips are measured with a small inter-tip time at a 1min time scale. As the time scale increases, the number of tips and rain rates decrease. The rain rates are then split up into more evenly distributed rain rates over a period of time. This can be seen in Table 4-1. An event was measured on the 5th of March 2014. This event had high rain rates of up to 40 mm/h and lasted for just over an hour which is often seen in the catchment. A sufficient amount of data points is available at a time scale of between 1 and 15min. Rain rates will therefore be averaged out at a timescale of 15min and set into four tips. This is enough data to show good correlation. At a time scale of 60min this becomes problematic as some data is re-sampled in 1 or 2 tips which show no variability. This is the same at a time scale of 30min that not enough data points are available to measure a good correlation. Rain rates are averaged over a period and thus convective storms with short duration, in some occasions shorter than 30min, will not be well represented. Events with longer durations will, however, show better correlation at bigger time scale because more data points are available.

Table 4-1: Rain Rates measured by the Parsivel disdrometer and tipping-bucket rain gauge re-sampled to 1min, 2min, 5min, 10min, 15min, 30min, 1hr for an event measured on the 5th of March 2014 (Continue on next page).

Date	1min		2min		5min		7min		10min		15min		30min		1hr	
	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)	Parsivel Rain Rate (mm/h)	Tipping Bucket RainRate (mm/h)
2014/03/05 07:50	0.0	1.3	0.0	1.3	0.0	1.4			0.9	1.4						
2014/03/05 07:51	0.0	1.4														
2014/03/05 07:52	0.0	1.4	0.0	1.4												
2014/03/05 07:53	0.0	1.4														
2014/03/05 07:54	0.0	1.4	0.0	1.4												
2014/03/05 07:55	0.0	1.4			0.9	1.4										
2014/03/05 07:56	0.0	1.4	0.0	1.4			1.0	1.4								
2014/03/05 07:57	0.0	1.4														
2014/03/05 07:58	0.0	1.4	0.9	1.4												
2014/03/05 07:59	0.9	1.4														
2014/03/05 08:00	0.8	1.4	0.9	1.4	1.6	1.4			2.5	1.2	2.6	0.9	1.6	0.8	5.7	6.6
2014/03/05 08:01	1.0	1.4														
2014/03/05 08:02	1.2	1.4	1.8	1.4												
2014/03/05 08:03	2.4	1.4					2.9	1.0								
2014/03/05 08:04	1.8	1.4	2.2	1.4												
2014/03/05 08:05	2.7	1.4			3.2	0.9										
2014/03/05 08:06	3.5	1.2	3.5	0.9												
2014/03/05 08:07	3.5	0.5														
2014/03/05 08:08	3.0	0.5	3.1	0.5												
2014/03/05 08:09	3.2	0.5														
2014/03/05 08:10	4.4	0.5	4.1	0.5	2.9	0.5	2.3	0.5	1.8	0.5						
2014/03/05 08:11	3.9	0.5														
2014/03/05 08:12	3.0	0.5	2.4	0.5												
2014/03/05 08:13	1.8	0.5														
2014/03/05 08:14	1.3	0.5	1.1	0.5												
2014/03/05 08:15	0.9	0.5			0.7	0.5					0.7	0.7				
2014/03/05 08:16	0.6	0.5	0.6	0.5												
2014/03/05 08:17	0.6	0.5					0.4	0.5								
2014/03/05 08:18	0.7	0.5	0.6	0.5												
2014/03/05 08:19	0.6	0.5														
2014/03/05 08:20	0.4	0.5	0.3	0.5	0.3	0.5			0.8	0.7						
2014/03/05 08:21	0.2	0.5														
2014/03/05 08:22	0.1	0.5	0.1	0.5												
2014/03/05 08:23	0.2	0.5														
2014/03/05 08:24	0.7	0.5	0.9	0.5			1.1	1.1								
2014/03/05 08:25	1.1	0.5			1.2	0.9										
2014/03/05 08:26	1.2	0.5	1.3	0.5												
2014/03/05 08:27	1.4	0.5														
2014/03/05 08:28	1.2	0.7	1.1	1.5												
2014/03/05 08:29	1.1	2.3														
2014/03/05 08:30	0.9	2.3	1.1	2.3	1.2	2.3			0.9	2.8	3.2	9.2	9.6	12.5		
2014/03/05 08:31	1.3	2.3					1.1	2.3								

	1min		2min		5min		7min		10min		15min		30min		1hr	
Date	Tipping Bucket RainRate (mm/h)		Tipping Bucket RainRate (mm/h)		Tipping Bucket RainRate (mm/h)		Tipping Bucket RainRate (mm/h)		Tipping Bucket RainRate (mm/h)		Tipping Bucket RainRate (mm/h)		Tipping Bucket RainRate (mm/h)		Tipping Bucket RainRate (mm/h)	
	Parsivel Rain Rate (mm/h)		Parsivel Rain Rate (mm/h)		Parsivel Rain Rate (mm/h)		Parsivel Rain Rate (mm/h)		Parsivel Rain Rate (mm/h)		Parsivel Rain Rate (mm/h)		Parsivel Rain Rate (mm/h)		Parsivel Rain Rate (mm/h)	
2014/03/05 08:32	1.5	2.3	1.4	2.3												
2014/03/05 08:33	1.3	2.3														
2014/03/05 08:34	1.2	2.3	1.2	2.3												
2014/03/05 08:35	1.2	2.3			0.7	3.3										
2014/03/05 08:36	0.8	2.3	0.7	2.3												
2014/03/05 08:37	0.5	2.3														
2014/03/05 08:38	0.4	2.3	0.4	4.8			5.7	17.1								
2014/03/05 08:39	0.3	7.3														
2014/03/05 08:40	1.3	13.1	2.9	16.0	7.8	22.0			17.7	25.0						
2014/03/05 08:41	4.5	18.8														
2014/03/05 08:42	9.5	21.2	9.6	23.8												
2014/03/05 08:43	9.8	26.3														
2014/03/05 08:44	14.1	30.3	14.0	42.8												
2014/03/05 08:45	14.0	55.4			27.5	28.1	24.0	24.7			15.9	15.7				
2014/03/05 08:46	26.2	36.0	24.0	30.7												
2014/03/05 08:47	21.7	25.5														
2014/03/05 08:48	34.4	13.1	37.9	11.8												
2014/03/05 08:49	41.3	10.5														
2014/03/05 08:50	20.4	11.6	15.0	16.1	12.7	12.0			10.0	9.6						
2014/03/05 08:51	9.6	20.7														
2014/03/05 08:52	9.3	7.8	10.1	8.7			9.1	7.9								
2014/03/05 08:53	10.9	9.6														
2014/03/05 08:54	13.3	10.6	11.1	9.6												
2014/03/05 08:55	8.9	8.7			7.4	7.1										
2014/03/05 08:56	8.2	5.3	7.4	5.5												
2014/03/05 08:57	6.7	5.6														
2014/03/05 08:58	6.1	7.9	6.5	7.9												
2014/03/05 08:59	6.9	7.9					5.4	7.8								
2014/03/05 09:00	7.1	7.6	5.7	5.9	5.2	7.4			6.2	12.5	11.8	17.1	9.7	11.2	6.0	6.5

The performance of siphon rain gauges is also problematic at lower rain rates. The new algorithm tends to overestimate low rain rates. This is because of the rain rate added before the first tip of an event. As the time scale increases, the rain rates are averaged over a period which lowers the measurements and counteracts this overestimation of low rain rates. At a 15min time scale the overestimation offset has been averaged and distributed over a period that the correlation is at its best. However, as the time scale increases, the number of data points decreases that will cause the TBR data to underestimate rain rates.

Errors in tipping-bucket rain gauges are uniform, predictable and easily identified. Calculating the error in TBR data by determining the difference between disdrometer rain rate data revealed the performance of the TBR at different rain rates. This was done at different time scales to determine the level of error.

The error scatter plots for the tipping-bucket rain gauge are shown in Figure 4-5. The number of tips for each time scale is also shown as n. The correlation between the TBR and the disdrometer rain rates increase until 15min where after a gradual decrease has been observed. At the 10-15min time scale the correlation is at its best. It is clear that the error in the TBR data is at its lowest at these time scales. The norm in error calculation is that the error is at its lowest at the highest time scale. This is not the case for the Mooi River catchment area and needs a closer look which will be explained in Figure 4-6. At a 1min time scale the error is the highest and has the most data points. The more data points, the higher the error. It is also very clear that in this figure there is a distinct straight line of high error at low rain rates. Normally this is an event with a rainfall accumulation of less than 0.2mm. The disdrometer would accurately measure the start of the events without having to wait for an amount of rain. The TBR however has to wait for 0.2mm of rain to record the first tip. At these low rain rates the disdrometer would record data where the TBR will not. The siphon also intensifies this problem as water will only be dumped into the buckets if 0.2mm of rain is observed.

Figure 4-5 shows that larger discrepancies exist at higher rain rates and lower time scales. This is most probably because of the variability of events with high rain rates in the catchment. As time scales increase the magnitude of error decreases because fewer data points are available.

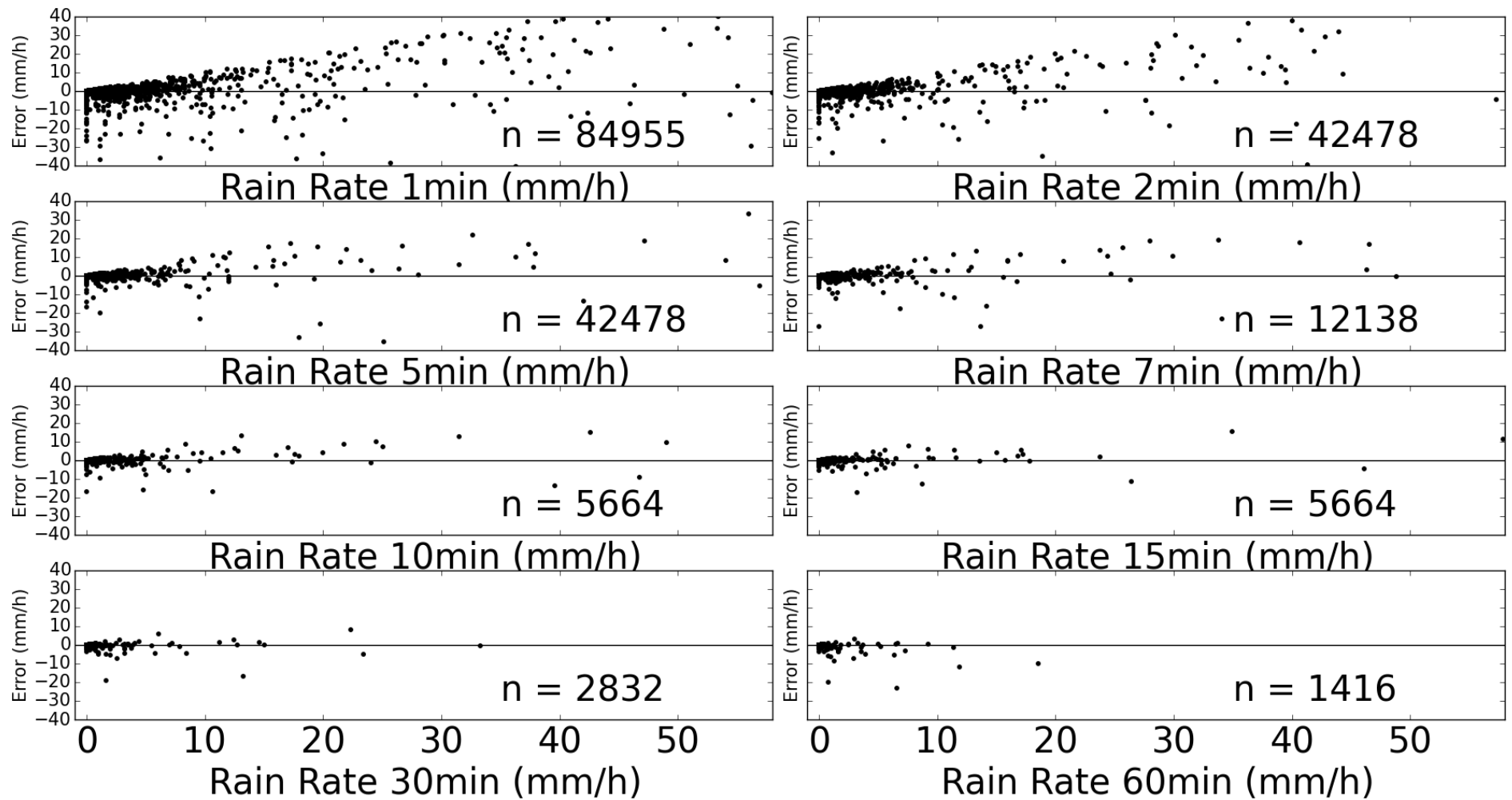


Figure 4-5: Errors in the TBR data were determined by calculating the error between the TBR data the disdrometer data. This was done at a time scale of 1min, 2min, 5min, 15min, 30min and 60min. The amount of tips for the specific time scale is presented as n.

In Figure 4-6 the result from the autocorrelation of the rain rate measured by the TBR and the disdrometer are presented at a 1min, 15min, 30min and 60min time scale. Autocorrelation shows the correlation of a time series with its past and future values. Problems in the correlation between these two instruments were identified.

It is clear from Figure 4-6 why there is a drop in correlation between the TBR rain rate and disdrometer rain rate at 30min. The problem is in the character of the rainfall of the region. Most events in the catchment measured by the both the TBR and the disdrometer has a duration of 15min according to these two data sets. This can be seen at a 1min time scale that a certain level of correlation is observed up until 15min. This correlates with the optimum correlation shown in Figure 4-2 which is at 15 minutes.

Understanding how a TBR works will also help to understand the drop in correlation. For a valid rain rate measurement with a TBR at least two data points needs to be measured. The reason for this is that the inter-tip time is used to determine the rain rate. Because the events in the region last mostly for 15 minutes, it means that when data is re-sampled to 15 minutes, there will still be a second tip to calculate the inter-tip time. The highest time scale at which two tips are observed from TBR data in the Mooi River catchment is 15 minutes.

This problem can clearly be seen when one looks closer at Figure 4-6. At a 1min time scale the second tip correlates well with the initial tip. At 15 minutes the second tip also shows a higher correlation than any other tip at any time lag. This is the highest time scale where the second tip still has a correlation which is better than all the other tips.

The problem, however, is at time scales greater than 15 minutes. The second tip at both the 30- and 60min time scales shows a correlation with the second tip which is the same, if not lower, than the initial tip. There is now correlation between the tips. This is because when the data is re-sampled to time scales bigger than 15 minutes, because of the time of events, there is only one tip in the data. As already mentioned, for tipping buckets to measure rain rates there needs to be two tips to calculate the inter-tip time. The Parsivel disdrometer Autocorrelation shows far better results. This is because the disdrometer measure the rain rate by calculating the velocity of the particle and not the time difference. Therefore one data point to measure rain rates using Parsivel disdrometer data is adequate.

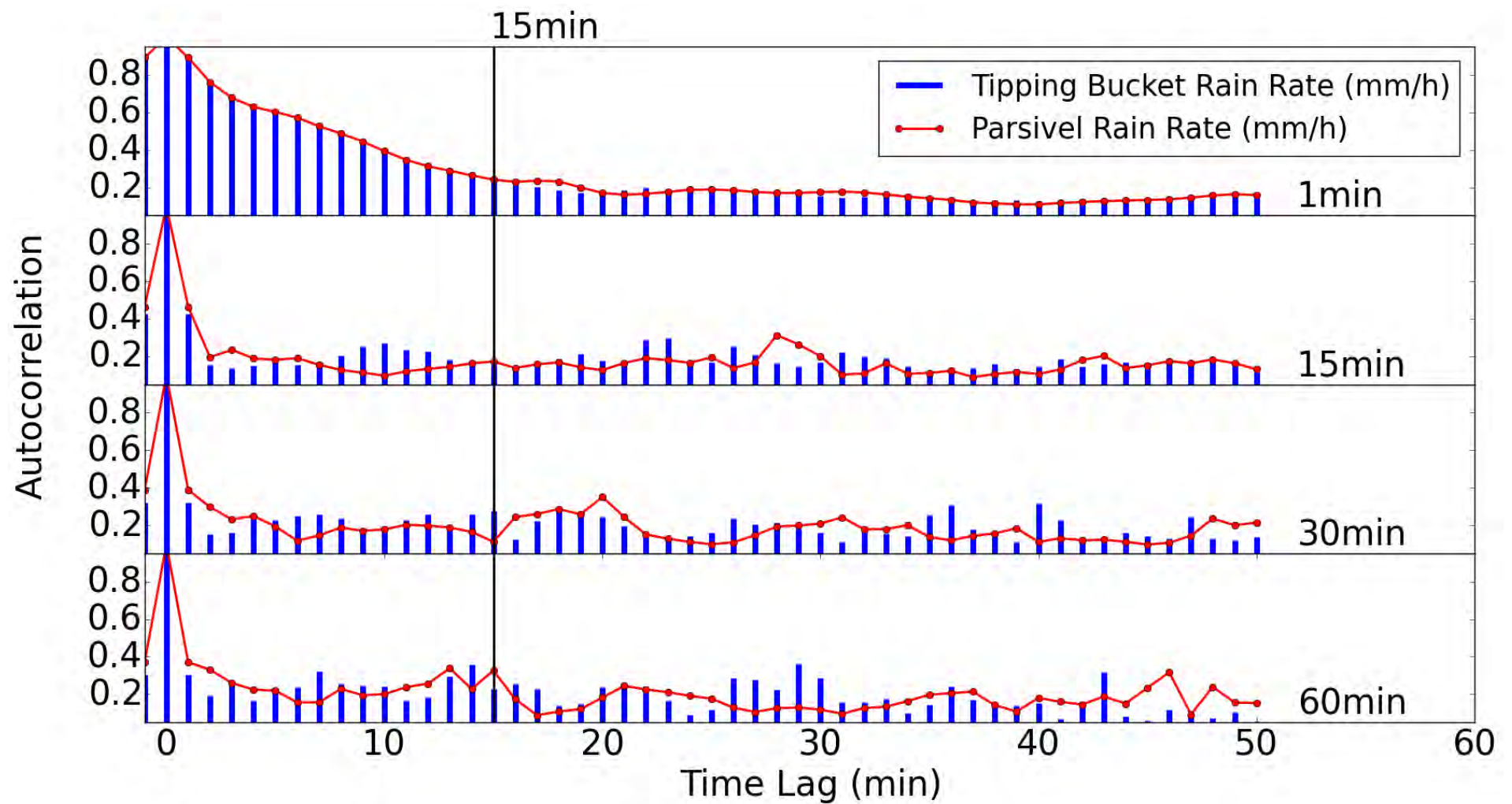


Figure 4-6: The autocorrelation for TBR and disdrometer data was calculated at different time scales to identify problems associated with correlation. Autocorrelation, lags 0 to 60min, based on 1min, 15min, 30min and 60min averaged rain rate observation was made by the Parsivel disdrometer (red dotted line) and the tipping-bucket rain gauge (blue bars).

Understanding rain rates and the variability thereof is extremely important when attempting to improve radar rainfall estimates. Tipping-bucket rain gauges are instruments that have the ability to measure the spatial and temporal variability of rain rates. However, challenges do arise when using a TBR equipped with a siphon. The siphon is used to counteract the overestimation of events with high rain rates.

When these TBR's with siphons are distributed over a large area in a rain gauge network this will be extremely helpful in the calibration of radars and the improvements of accuracy and reliability of data.

CHAPTER 5 IMPROVING SINGLE-PARAMETER WEATHER RADAR RAINFALL ESTIMATES

South Africa has a state-of-the-art network of weather radars across the country. The network was upgraded between 2009 and 2012 from C-band weather radars to S-band radar. The network includes nine single-polarised S-band radars, one dual-polarised S-band radar, two mobile dual-polarised X-band radars and 5 C-band radars. In a developing country like South Africa, the operation and maintenance of these radars is a challenge. Educating and training people to operate and maintain the radars is problematic. The accuracy and reliability of weather radar data is often not at its optimum potential. New and innovative measures need to be developed to improve the accuracy of radar rainfall estimates. This chapter is aimed at exploring new methods of estimating rainfall using weather radar data in the Mooi River catchment.

To improve radar rainfall estimates it is important to take a few factors into consideration. One of the first factors is the evaluation of the performance of the radar to identify problems in the data and to determine calibration offsets in the data. Events must also be investigated individually and not collectively. Therefore a new unique Z-R relation should be measured for each event and tested by comparing rainfall estimates to the most widely used Z-R relation, the Marshall and Palmer relation which is used by SAWS to estimate rainfall using radar data. Convective and stratiform events also differ completely in their storm structure. Using the same principle to measure both events can therefore cause inaccuracies in the data.

5.1 The performance of the weather radars, operated by the South Africa Weather Service, covering the Highveld and the Mooi River catchment

Radars in South Africa cover a large part of the country. In the Gauteng Province up to 4 radars cover certain areas. Large areas also exist where the coverage area of 2 or 3 radars intersect. There is no part of the province where merely one radar covers an area. The radars covering the Highveld include the Irene, Ottosdal, Bethlehem and Ermelo weather radars. The Gauteng province is extremely important for the well-being of the country because of its agricultural activities and large population (Figure 5-1). Therefore using the Mooi River catchment as a study area will help the entire region.

Another area that has a number of agricultural activities is the Free State where corn is predominantly harvested. This area plays a crucial role in the food security of the country. Precision farming is implemented by more and more farmers and it is consequently important to

have accurate data. The SAWS subsequently decided to locate their dual -polarised radar in Bethlehem. Here there are large areas where 2 or 3 radars intersect each other coverage area (Figure 5-1).

Other parts of the country are covered extensively by radars with the exception of the Northern Cape. This is justified when considering the Northern Cape receives very little rain and has the smallest population in the country. The coast is also covered sufficiently with areas where two coverage areas intersect especially at East London (Figure 5-1).

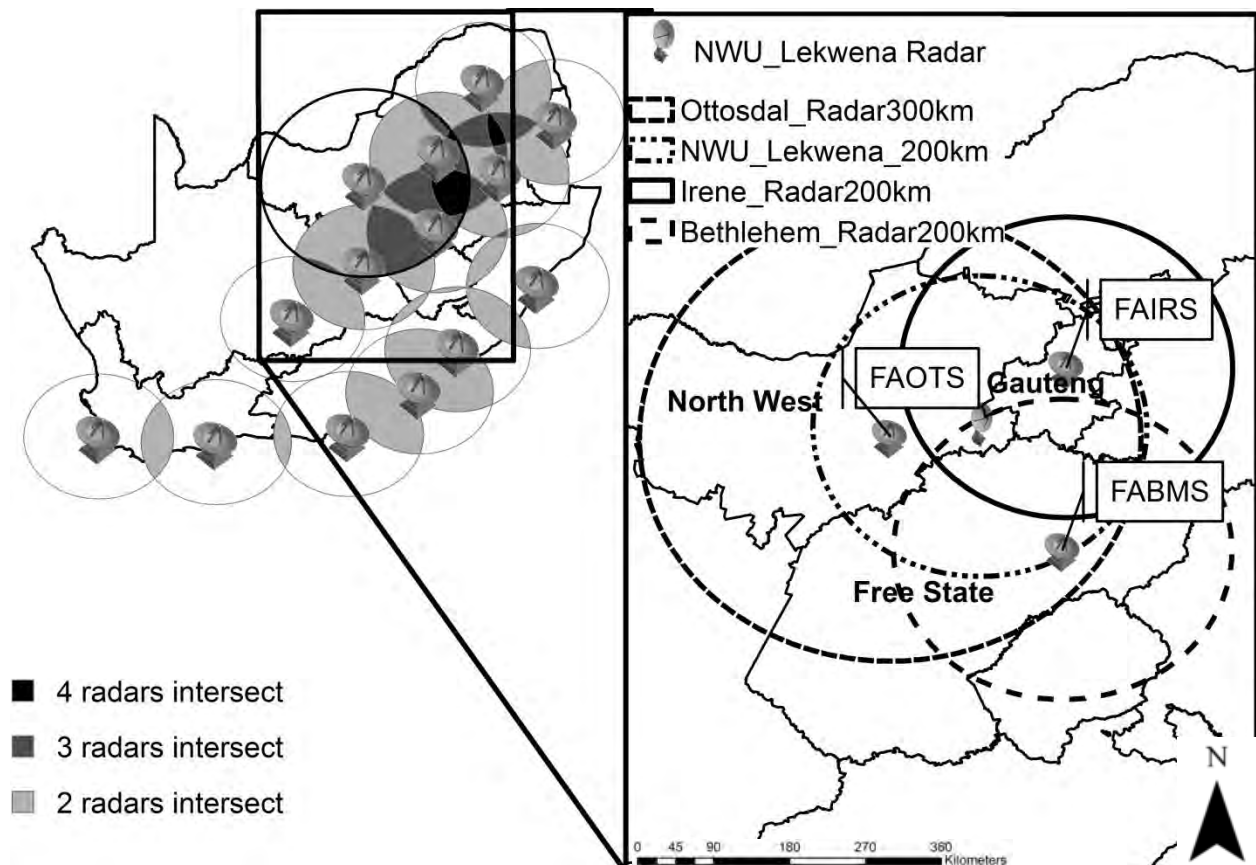


Figure 5-1: Intersection zone of the coverage areas of the radars in South Africa. The biggest area where four radars intersect include the Mooi River catchment.

Based on investigations, it is postulated that the Irene weather radar is the most accurate radar in the network and that hardware problems at the Bethlehem radar have caused data to be inaccurate and unreliable. The following chapter will test this assumption by comparing disdrometer Z values measured on the ground to those measured by the radar aloft. By creating a probability density function of the reflectivity values of all the radars covering each other, problems with the Bethlehem radar are already visible (Figure 5-2). More worrying is that the

correlation between all the weather radars mentioned are problematic as the three radars show different frequencies of reflectivity measurement for the pixel above the disdrometer. However, occurrences of the maximum reflectivities do correlate between the Irene and Ottosdal radar but the maximum reflectivity values differ. The Irene radar seems to be measuring higher reflectivity values than the Ottosdal weather radar. The Bethlehem radar shows no correlation and does not measure as high reflectivity measurements as the Irene and Ottosdal radars (Figure 5-2).

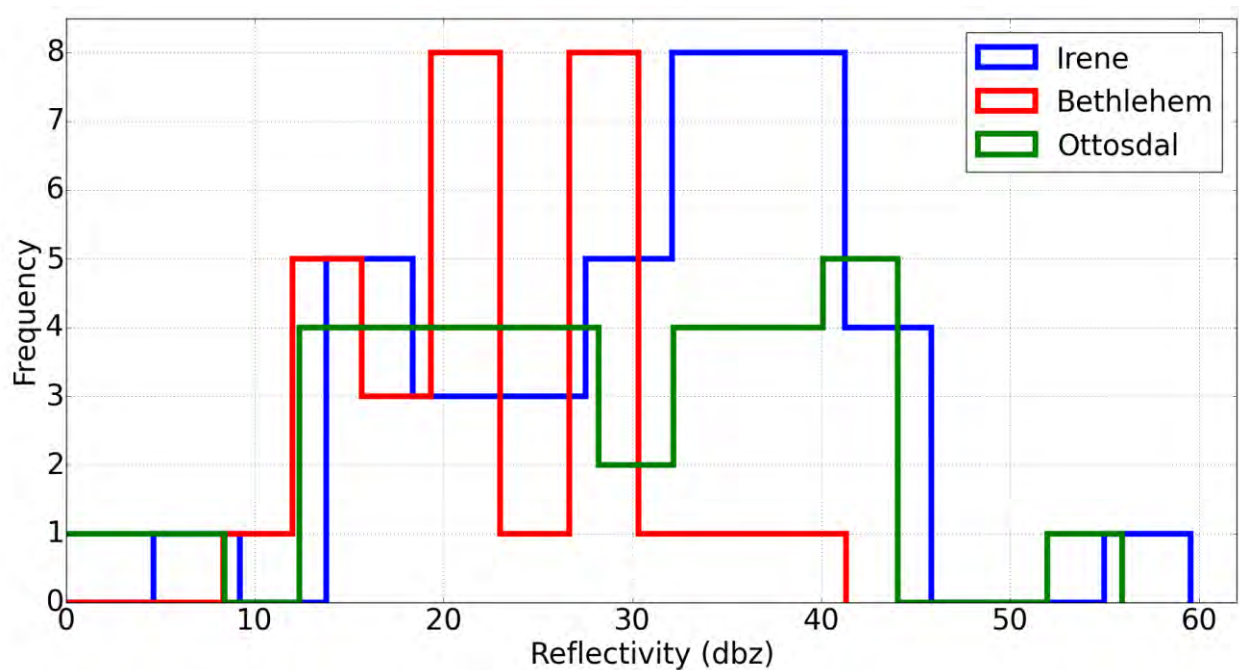


Figure 5-2: Probability density function of the Irene, Bethlehem and Ottosdal radars maximum reflectivity. The Bethlehem radar consistently measures dbz values below the Ottosdal and Irene radars.

5.1.1 The Irene S- band weather radar

The Irene weather radar is considered as one of the most accurate radars in the network. The radar covers the entire Gauteng and is in close proximity to the SAWS technical office. This means that technicians have quick and easy access if something goes wrong on the radar (Figure 5-3). Maintenance is also done on a constant basis and the results found in this section support this statement.

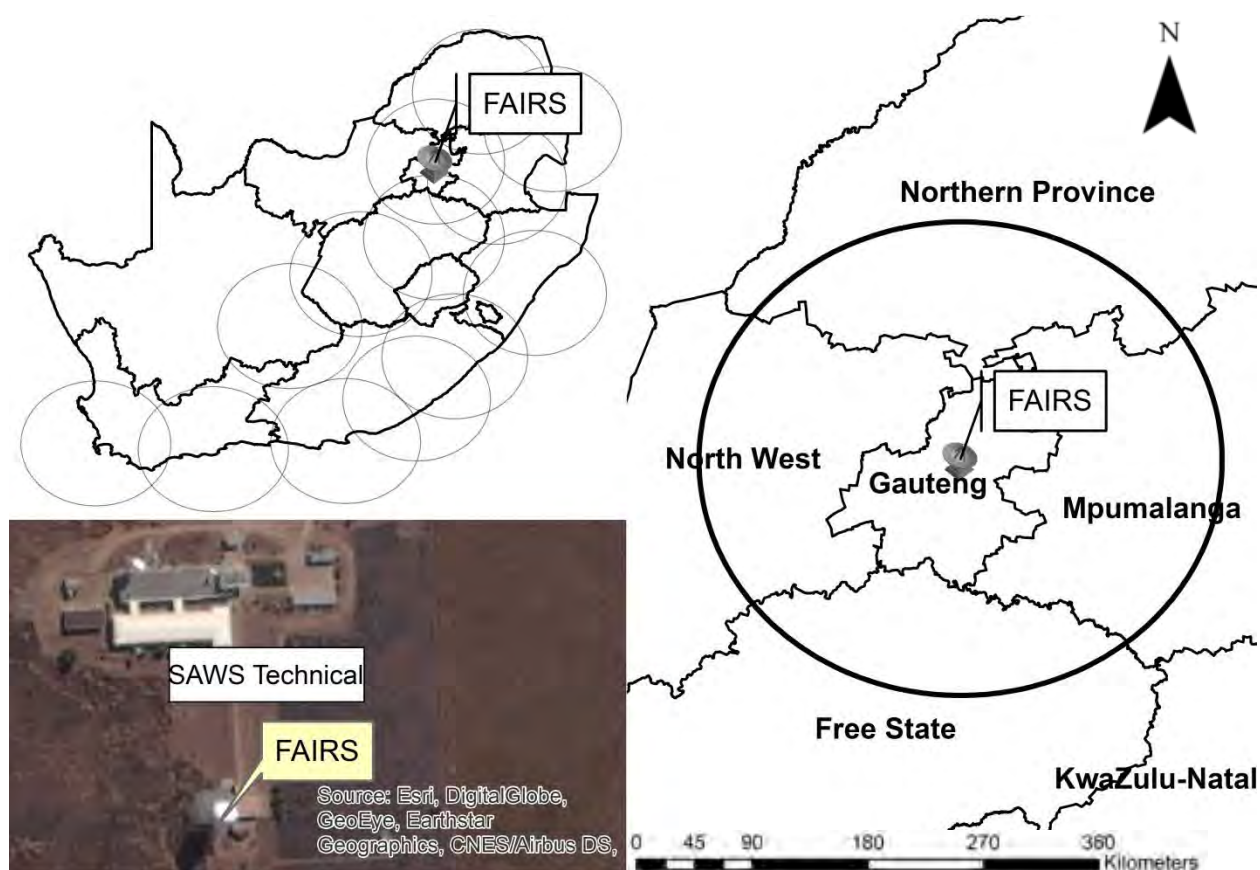


Figure 5-3: The Irene radar is situated in Irene and covers the entire Gauteng province as well as the neighbouring Limpopo (Northern Province), Mpumalanga, Freestate and North West provinces. This radar receives more attention in terms of maintenance from the technical staff of SAWS than the other radars in the network due to its close proximity to the technical offices.

The reflectivity that was measured the most during February and March 2014 was between 15 and 22dbz. These months are normally characterized by the frequent occurrence of synoptic conditions like the easterly low which brings moist air inland and creates clouds. Clouds with no rain are normally between 15 and 20dbz. Higher dbz values were also measured by the radar with a lower frequency (Figure 5-4).

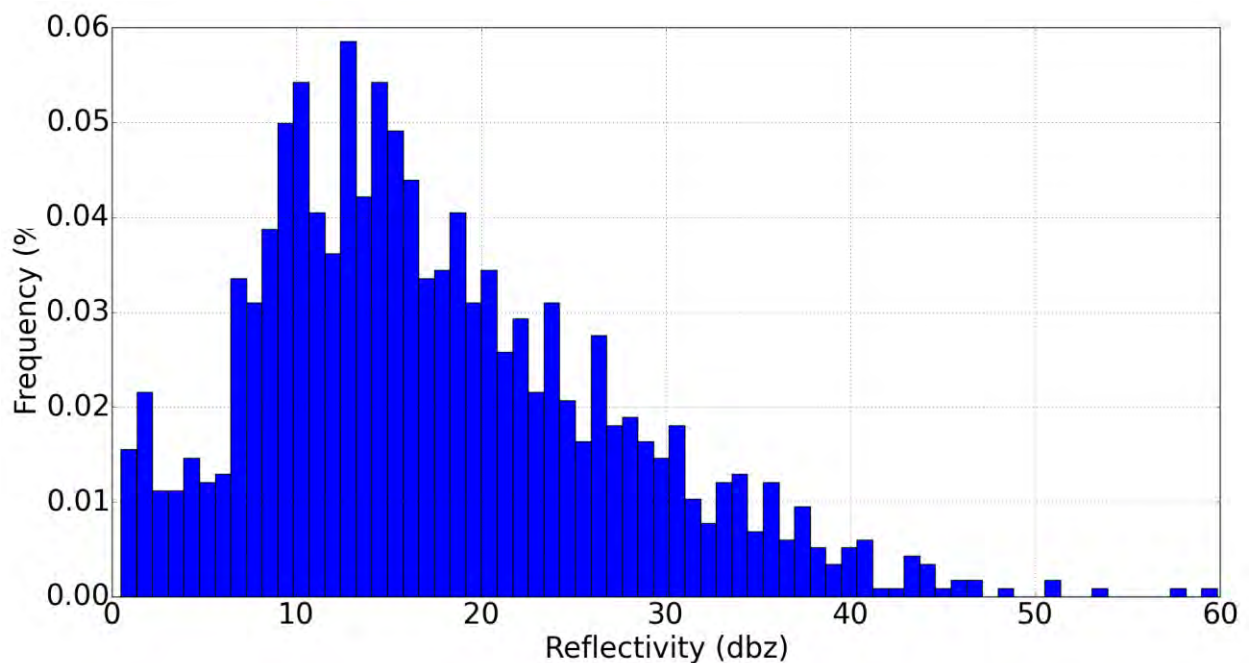


Figure 5-4: Probability density function of the maximum reflectivity measured by the Irene weather radar.

The performance of the radar can be tested by comparing radar reflectivity (Z_R) and disdrometer reflectivity (Z_D). The Parsivel disdrometer gives the ability to extend the measurement made aloft to the ground by calculating the calibration offset and correlation.

The Irene weather radar Z_R measurement had a correlation of 66% to Z_D . This is an acceptable correlation considering the distance of 140km from the radar to the disdrometer. This correlation can be improved by implementing a bias measurement when calculating the calibration offset. The Irene weather radar overestimates events on average with 12.8dbz. By implementing a bias measurement of -12.8dbz this problem can be resolved and the accuracy and reliability of data can be improved (Figure 5-5). The red line is a 1:1 line that shows where the data point would be if $Z_R = Z_D$. When previous results like Figure 2-25 are considered this is, however, not the case and an offset between these two values do exist. Events with a maximum reflectivity between 15 and 20 dbz tend to have a better correlation than higher and lower values. When one investigates the point of intersection of the red and blue lines- which is a linear regression between the Z_R and Z_D , it is clear that the Irene radar has the tendency to overestimate events lower than a maximum reflectivity of 17dbz and underestimate rainfall with maximum reflectivity values higher.

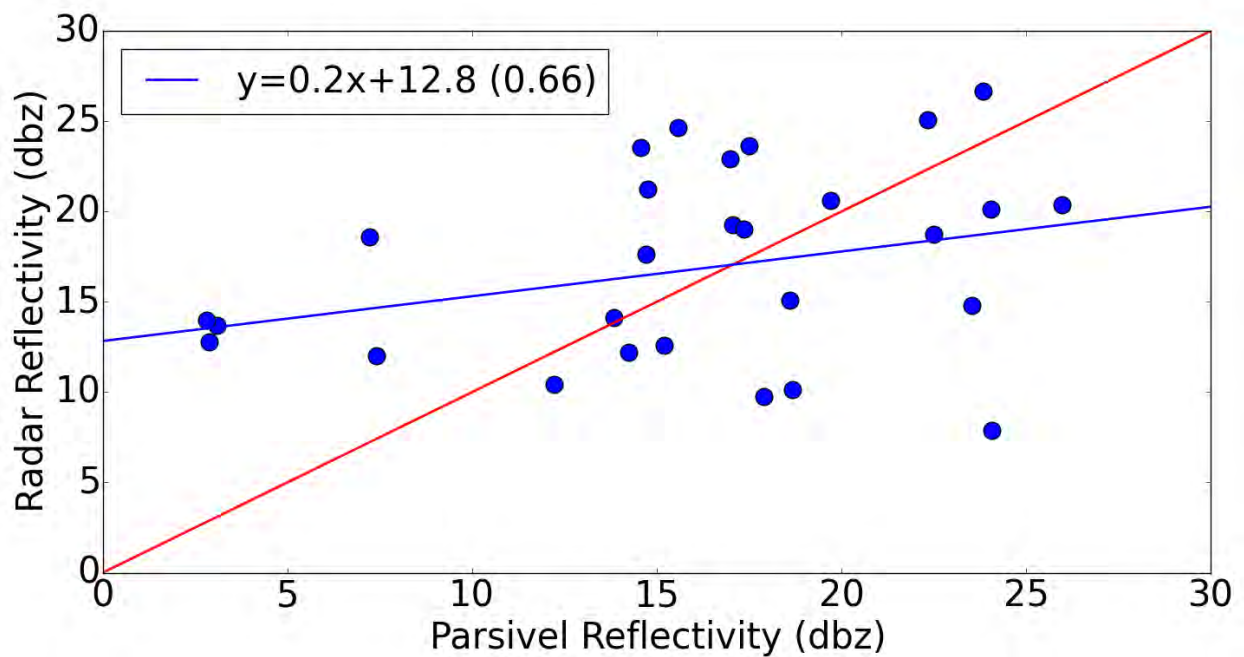


Figure 5-5: Correlation between the Parsivel disdrometer (x-axis) and Irene radar reflectivity measurements.

5.1.2 The Ottosdal S- band weather radar

The Ottosdal weather radar, situated in the North West Province near the town of Ottosdal is a unique radar (Figure 5-6). Most of the Northern Cape is not under the coverage area of a radar. This is because of the low amounts of rainfall observed in the area due to the cold Benguela sea current on the West coast of the country that hampers evaporation which is essential for rain-producing clouds. Therefore this radar coverage area is stretched to a 300km radius as opposed to the 200km of all the other radars in the network to cover the parts of the Northern Cape which receives some rain. Provinces that are also included under the coverage area is the Gauteng, Limpopo and Free state provinces. The radar also experience problems like missing data records and the accuracy of data.

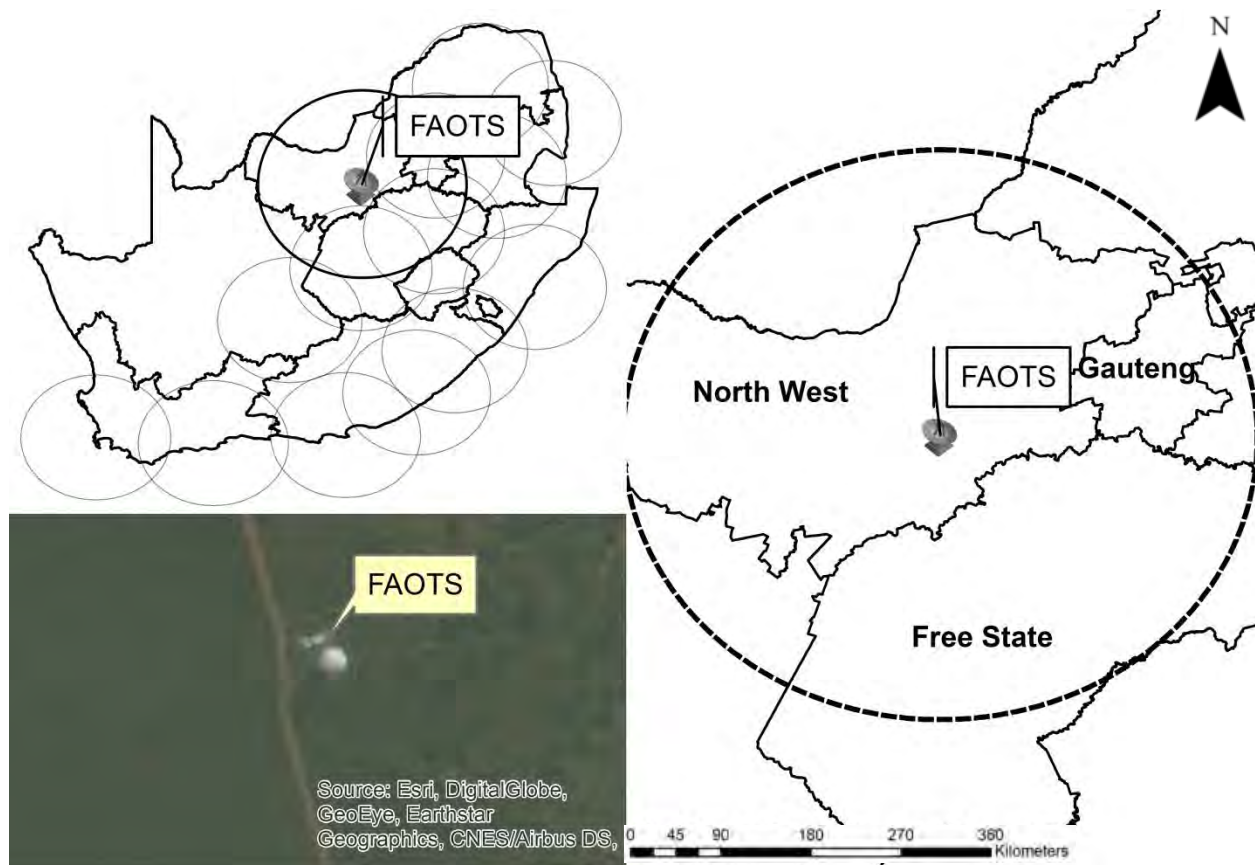


Figure 5-6: The Ottosdal weather radar is situated in the North West near the town of Ottosdal. This radar has a coverage area of 300km radius around the radar. This is to include areas of the Northern Cape Provinces which receives some rain during the year.

For most of the time the Ottosdal radar measures reflectivity values below 10dbz and less frequently values between 10 and 40 dbz (Figure 5-7). The accuracy of this radar may be affected because it measures rainfall within a radius of 300km whereas the other radars only measure within radiuses of 200km.

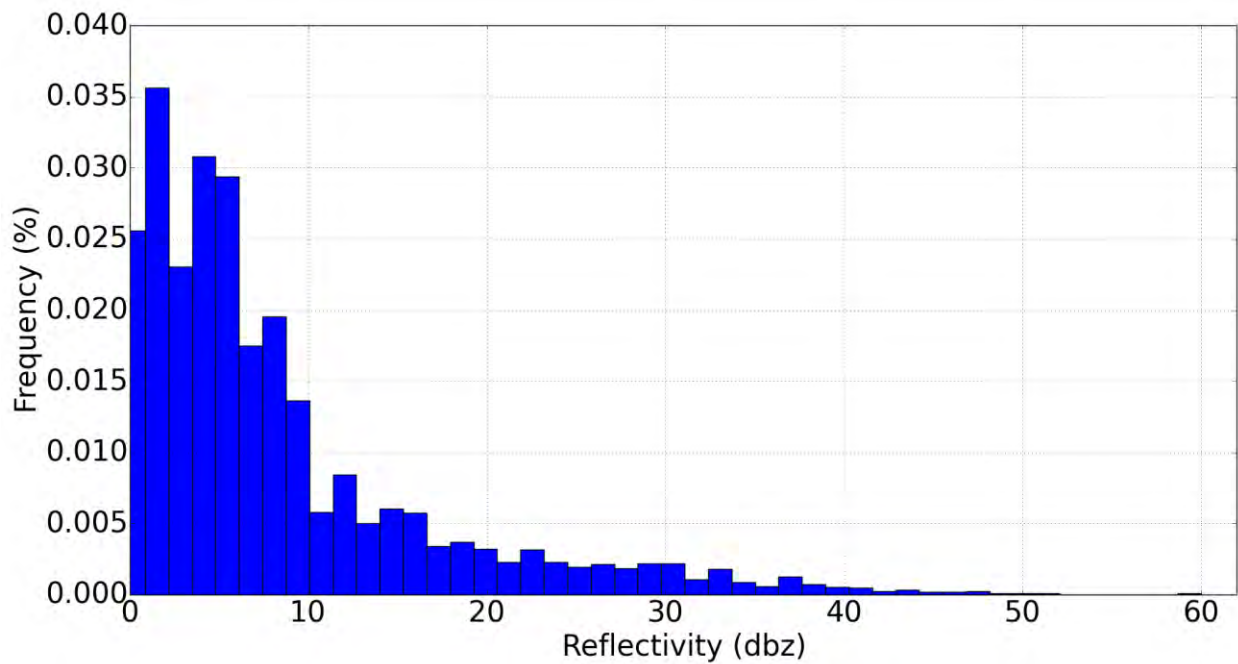


Figure 5-7: Probability density function of the maximum reflectivity measured by the Ottosdal weather radar.

The Ottosdal weather radar is approximately 100km from the disdrometer which is an acceptable distance for the accuracy of the data. However, Figure 5-8 shows that the correlation between Z_R and Z_D is only 42% -which is very low. No cluster of good correlation data points can be observed as measured by the Irene radar. Similar to the Irene radar the Ottosdal radar overestimates events with maximum rain rates lower than 17dbz and underestimates events with maximum rain rates higher than 17dbz. The weak performance of the Ottosdal radar may be attributed to the fact that it measures rainfall within a radius of 300km that could hamper data accuracy. This is because the size of the bins will increase which causes the resolution to decrease. Most scan strategies, like the Irene radar, has a maximum range of 200km which in turn has a bin size of 500m by 500m. The Ottosdal radar with a maximum range of 300km has a bin size of 750m by 750m.

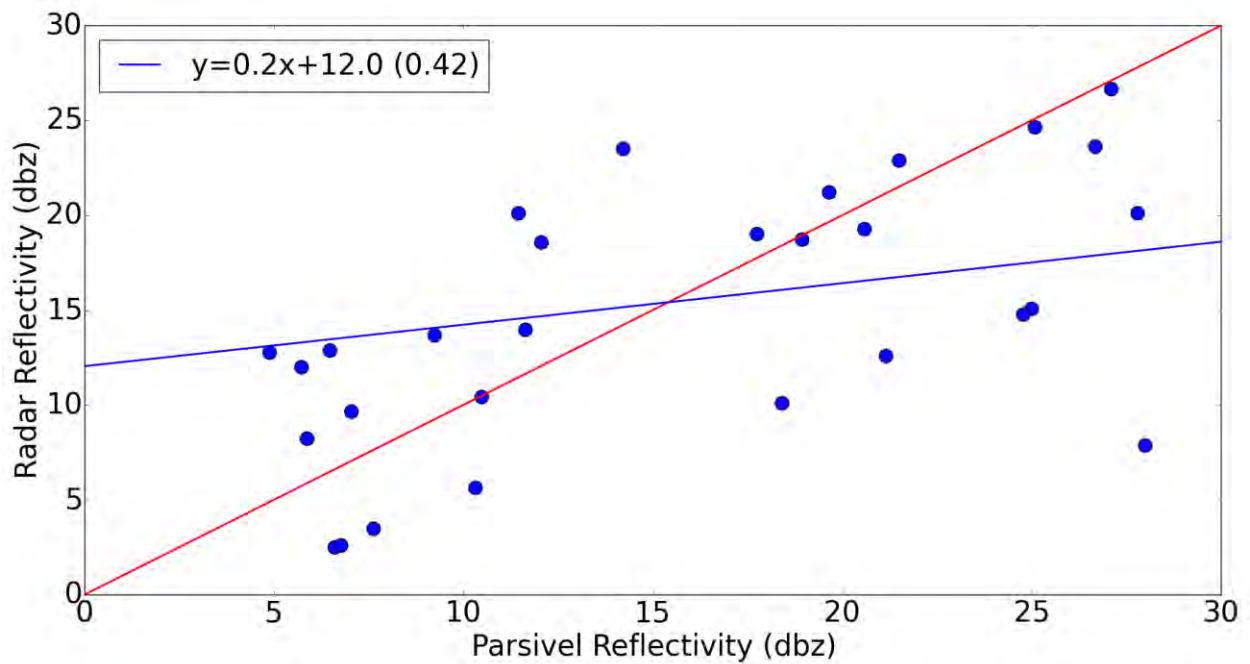


Figure 5-8: Correlation between the Parsivel disdrometer (x-axis) and Ottosdal radar reflectivity measurements.

5.1.3 The Bethlehem S- band dual-polarized weather radar

The best way to move towards improved radar rainfall estimates is by acquiring radars with dual-polarised capabilities. When SAWS upgraded the radar network it was decided that one of these radars will be installed at Bethlehem in the Freestate (Figure 5-9). At the time this was the hub for most of the atmospheric scientists working for SAWS and also a very important agricultural area. This is why the decision was made to place the radar at Bethlehem.

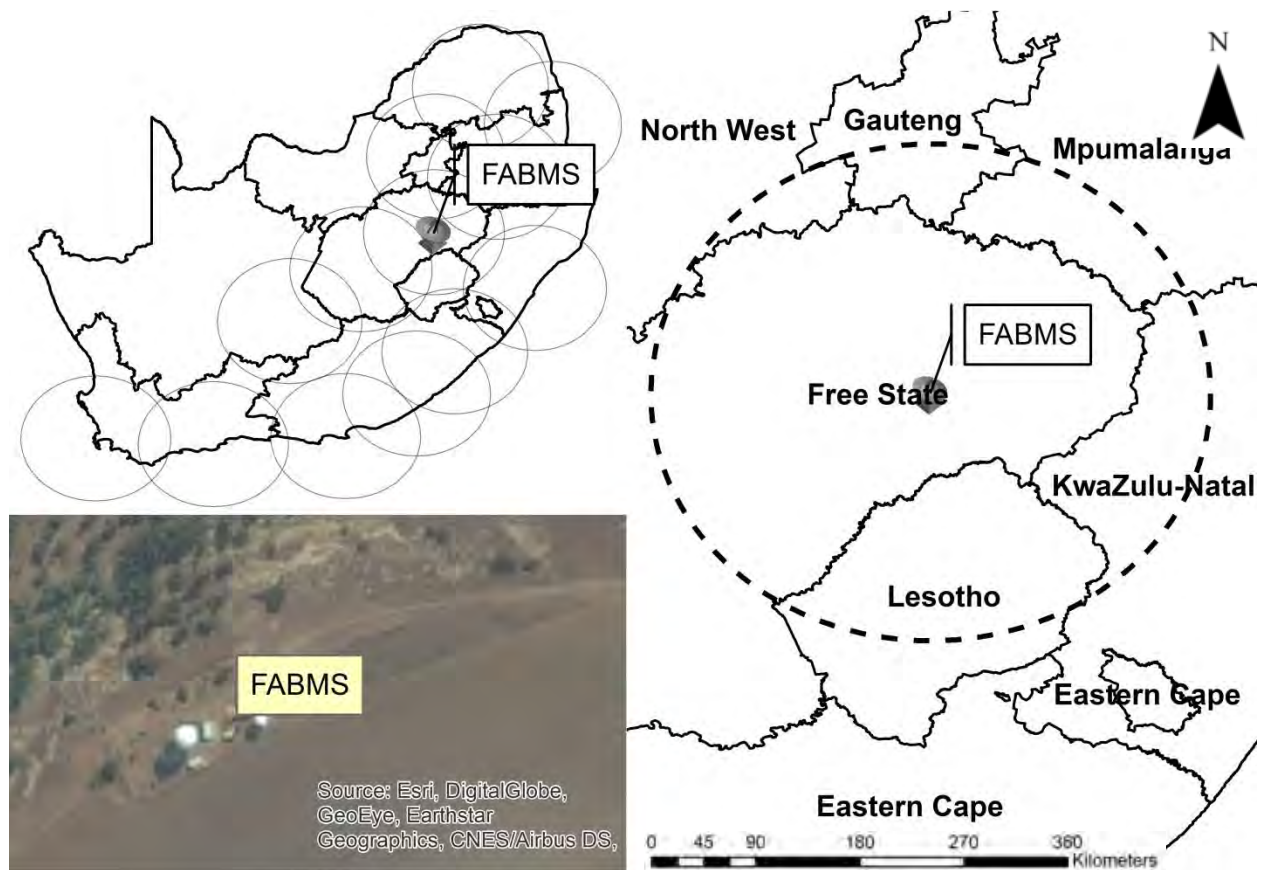


Figure 5-9: The only dual-polarised radar on the African continent is situated in Bethlehem, Freestate. This radar is operated by SAWS and the coverage area covers the majority of the Freestate province and a small part of the North West Province where the Parsivel disdrometer was situated.

The Bethlehem radar measures very low Z values most of the time with 19dbz being measured 49 times between February and March 2014 over the disdrometer (Figure 5-10). The radar also seems to measure more values that are higher than 20dbz than lower. This means that events with lower ground truth dbz values can be left out because the radar underestimates these measurements.

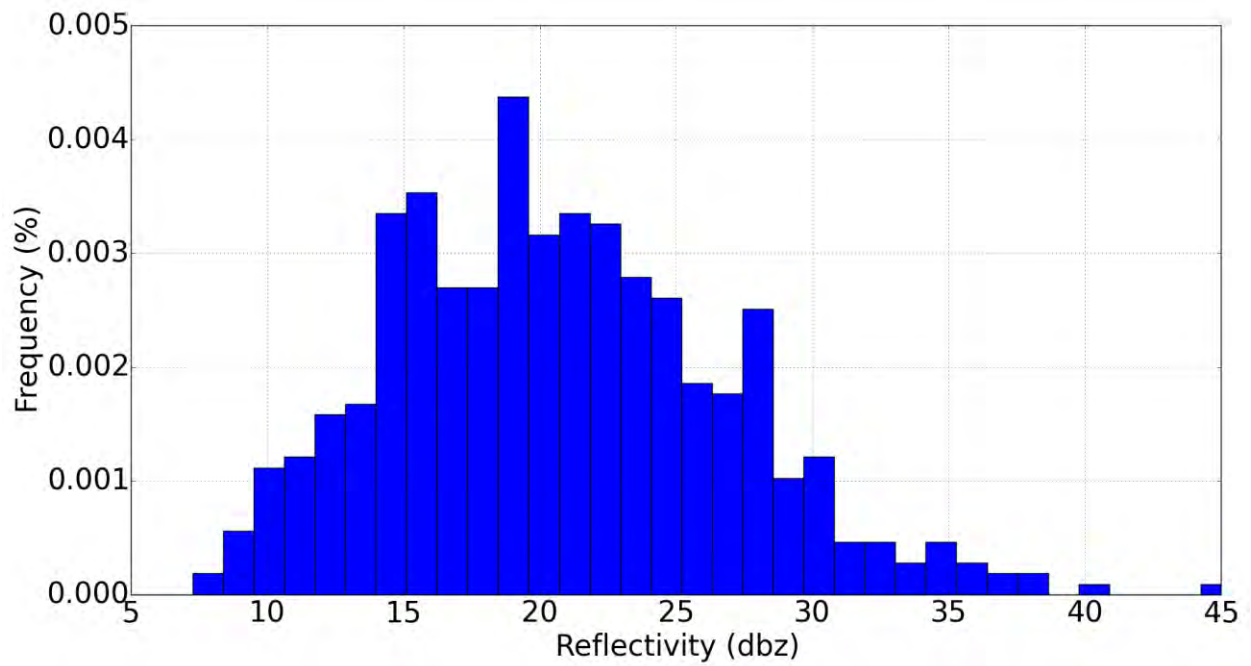


Figure 5-10: Probability density function of the maximum reflectivity measured by the Bethlehem weather radar.

The Irene radar measures more rain than the Bethlehem radar (Figure 5-11). The Bethlehem radar data has few Z values lower than 15dbz whereas the Irene radar has a higher number of low dbz values (Figure 5-11). The Bethlehem radar clearly underestimates precipitation. In Figure 5-11 it can be seen that the spike in Z_R of the Bethlehem radar correlates well with higher dbz values from the Irene radar. The Irene radar shows that a large number of Z values above 30dbz have been measured. According to the Bethlehem radar the frequency of these events are substantially less (Figure 5-11).

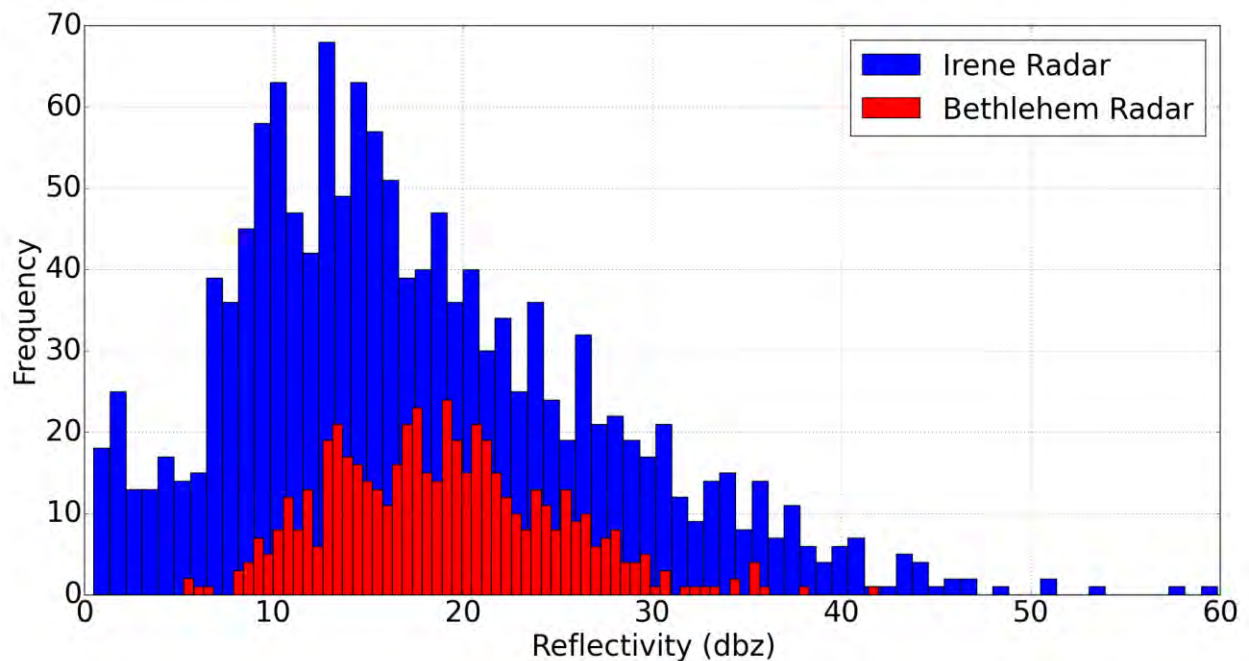


Figure 5-11: Probability density function of the maximum reflectivity measured by the Irene weather radar (blue) and Bethlehem radar (red).

The correlation between the Z_R from the Bethlehem radar and the Z_D of the Parsivel disdrometer are very weak. At 22% it is hard to justify the operation of this radar and the data can also not be used for scientific investigations. It is important to note that this is the only dual -polarised weather radar in Africa and that measurements made by this radar can produce ground-breaking discoveries. This is, however, not the case as data from the radar is plagued with errors and inaccuracies. The main issue with the Bethlehem radar is hardware faults such as, for example, the sensitivity of the receiver. The radar underestimates events with 14.1 dbz. This is very high and of great concern. Events do exist where the opposite is true and this complicates investigations even more.

The linear regression line of the reflectivity measurement made by the Bethlehem radar compared to the disdrometers reflectivity value also shows the magnitude of error within the data. The horizontal slope of the line shows that even with high Z values measured by the disdrometer the radar underestimates the events and measures rain rates on average at 14dbz. As already mentioned dbz values below 20dbz is normally considered as non-rain objects.

The error in the reflectivity measurement of the Bethlehem radar also fluctuates. This is a problem because a certain level of uncertainty would still exist even though a bias measurement has been implemented. For a bias measurement to improve the data the magnitude of error

needs to be fairly uniform. This is not the case in the Bethlehem radar. Figure 5-12 shows a good example of this. There are six events where the disdrometer measured a maximum reflectivity of 15dbz consistently. For all six of these cases the Bethlehem radar measures different dbz values ranging from 3dbz to 25 dbz.

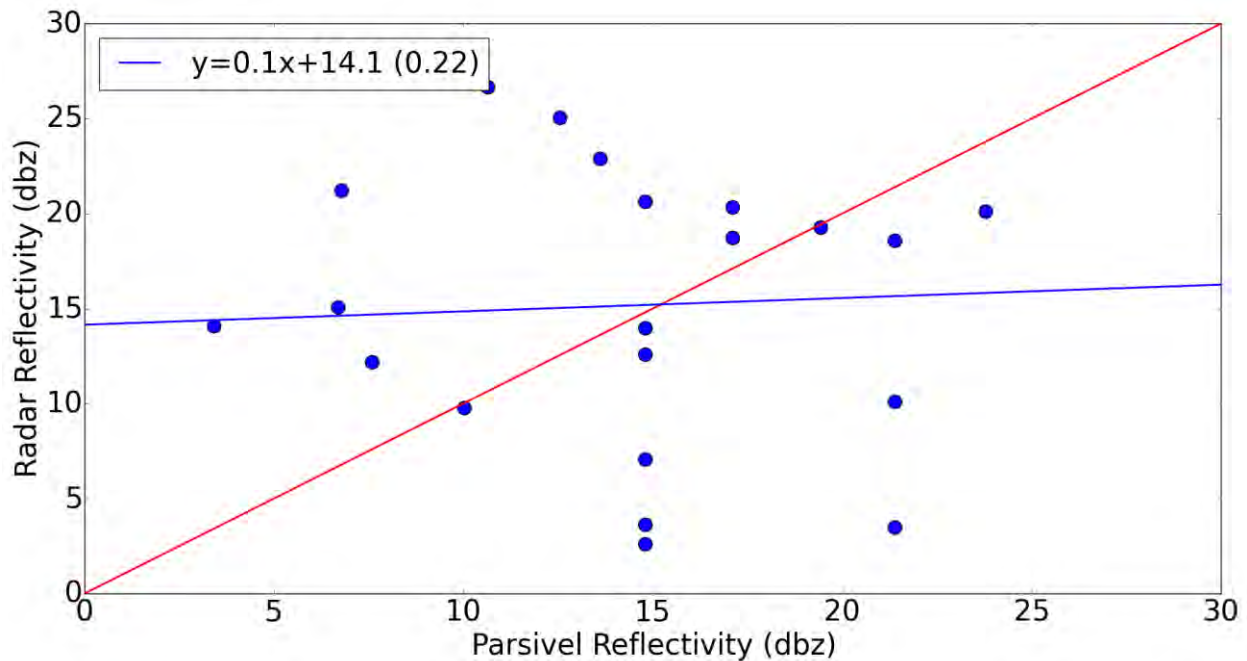


Figure 5-12: Correlation between the Parsivel disdrometer (x-axis) and Bethlehem radar reflectivity measurements.

A vertical line of data points in correlation graphs comparing radar Z and disdrometer Z means that the radar data is problematic. This is the case only in the Bethlehem radar (Figure 5-12) and not in the Ottosdal- (Figure 5-8) or Irene radar (Figure 5-5). This means that bias measurements can help in improving the accuracy of these radars.

The underestimation of events by the Bethlehem radar can also be seen on the image produced by TITAN. It is clear that the Bethlehem radar underestimates events north of the radar when it is compared to the Irene radar image measured on the 5th of March 2014.

Figure 5-13 shows a large convective event over Gauteng with the core of the event reaching a maximum reflectivity of 60dbz. According to the Irene radar this event can be considered as an event where hail may occur. These events are very important to identify - especially in early warning systems— in order to protect property against hail damage. More intense convective events are shown in Mpumalanga by the Irene radar. The Bethlehem weather radar, however,

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The investigation has so far shown that the Irene radar is the best-performing radar which covers the Mooi River catchment area. The radar has a reliable data record and when the ground measurements of Z measured by the Parsivel are compared to the radar reflectivity data, the accuracy is acceptable. The Ottosdal radar also shows data that is relatively accurate but there are inconsistencies with the correlation to ground measurements. The data record is also erratic. Various problems hamper the accuracy and reliability of the Bethlehem radar. The radar underestimates events to a large extent and the data record is below 40% which shows that hardware problems do also play a role in this inaccuracy (Figure 2-18). The Irene radar had shown the highest accuracy of data and was consequently more ideal for scientific investigation. It was therefore chosen to test new methods that could increase the accuracy of data on rainfall.

5.1.4 The variability of the Z-R relation within events in the Mooi River catchment

In the following section the A and b coefficients were measured by using the merged data (Table 5-1). The radars operated by SAWS use the well-known Marshall and Palmer Z-R relation, Eq. (6), to estimate radar rainfall. As shown in the previous chapter, rain rates are highly variable, especially in convective events as frequently observed over the Mooi River catchment. This variability justifies the effort of exploring whether the Marshall and Palmer relation adequately represent the climate of the Mooi River catchment which will impact the entire Highveld of South Africa. This section is aimed at analysing whether the Marshall and Palmer relation is a sufficient equation to use for the catchment and for calculating custom Z-R relations for convective and stratiform events.

Table 5-1: Z-R relation measured by the disdrometer. The A and b values given in this table are coefficients that form part of the Eq. (5) and the r is the correlation between these two values. These events were measured with the merged data.

		Parsivel							
		Max	Mean	Max	Mean				
		Parsivel	Parsivel	Parsivel	Parsivel				
		Rain Rate	Rain Rate	Reflectivity	Reflectivity	Parsivel	Parsivel	Parsivel	Duration
Start	End	(mm/h)	(mm/h)	(dbz)	(dbz)	A	b	r	(min)
1	2014/02/22 18:00 06:45	8.0	1.2	40.0	16.1	240.22	1.69	0.99	35
2	2014/02/22 19:45 21:35	5.0	1.7	33.0	21.1	160.42	1.35	0.96	100
3	2014/02/23 10:25 12:50	1.8	0.5	27.3	15.1	209.02	1.39	0.91	135
4	2014/02/23 13:40 16:30	4.2	1.2	33.4	20.9	242.14	1.58	1.00	160
5	2014/02/24 12:00 13:05	1.8	0.5	28.0	12.5	254.48	1.58	0.99	55
6	2014/02/24 17:10 18:00	2.5	0.6	30.4	15.8	236.83	1.65	0.99	40
7	2014/02/24 21:15 22:30	60.6	13.7	48.0	26.0	165.89	1.39	0.99	65
8	2014/03/01 09:05 09:40	6.6	2.8	35.5	21.3	91.43	1.87	0.99	25
9	2014/03/01 11:40 12:25	4.0	1.1	29.8	15.4	123.27	1.38	0.99	35
10	2014/03/02 15:30 17:45	0.4	0.1	16.4	5.2	212.59	1.55	0.98	125
11	2014/03/03 13:30 16:00	2.7	0.5	26.5	13.8	139.62	1.34	0.97	140
12	2014/03/04 00:20 01:25	1.6	0.2	19.1	5.6	49.52	1.08	0.98	55
13	2014/03/04 03:50 05:20	7.7	2.9	31.4	21.1	78.70	1.18	0.95	80
14	2014/03/04 05:45 06:25	1.4	0.5	17.5	8.3	37.72	1.14	1.00	30
15	2014/03/04 11:00 12:05	2.4	1.0	30.4	20.0	223.25	1.65	0.99	55
16	2014/03/04 13:25 15:30	4.7	1.1	35.1	20.9	253.93	1.45	0.98	115
17	2014/03/04 20:25 23:35	5.2	0.6	31.3	10.5	132.71	1.42	0.99	180
18	2014/03/05 00:40 04:15	21.2	2.9	37.9	14.3	100.46	1.43	0.98	205
19	2014/03/05 07:50 11:10	27.5	3.6	42.6	22.2	149.14	1.35	0.97	190
20	2014/03/06 01:20 02:25	60.6	14.2	47.0	27.8	120.95	1.42	0.99	55
21	2014/03/06 13:45 14:40	26.4	7.7	45.8	27.4	120.42	1.68	0.95	45
22	2014/03/06 17:30 19:00	4.0	1.8	36.6	25.0	311.15	1.69	0.99	80
23	2014/03/07 12:00 12:55	1.0	0.2	22.4	7.0	217.07	1.52	0.99	45
24	2014/03/07 18:20 18:55	0.2	0.1	11.6	3.5	159.34	1.51	1.00	25
25	2014/03/08 10:55 11:45	21.1	3.5	46.8	23.6	282.14	1.53	0.99	40
26	2014/03/09 15:45 17:15	62.3	9.5	50.7	21.9	208.29	1.46	0.98	80
27	2014/03/09 18:05 19:25	0.4	0.1	18.0	4.9	261.71	1.64	0.99	70
28	2014/03/09 20:30 22:20	1.0	0.3	24.3	11.4	255.31	1.59	0.99	100
29	2014/03/10 12:25 13:10	7.2	2.6	32.7	21.0	103.31	1.54	0.98	35
30	2014/03/10 14:50 16:05	9.0	1.4	35.9	17.1	220.09	1.27	0.96	65
31	2014/03/10 16:30 17:15	0.4	0.1	19.7	6.7	392.59	1.88	1.00	35
32	2014/03/10 18:00 18:45	3.5	1.6	28.5	16.3	142.69	0.95	0.88	35
33	2014/03/10 20:00 20:40	1.8	0.5	20.2	9.7	58.41	1.04	0.99	30
34	2014/03/10 21:55 00:10	0.7	0.1	18.3	5.1	132.12	1.37	0.97	125
35	2014/03/11 12:25 15:25	33.2	5.2	43.6	23.1	101.50	1.44	0.99	170
36	2014/03/11 15:50 16:40	2.2	0.4	22.9	5.7	67.26	1.20	0.95	40
37	2014/03/12 12:15 12:45	9.3	2.1	36.9	16.5	130.53	1.25	0.91	20
38	2014/03/13 14:35 16:50	5.2	0.6	34.9	13.1	217.66	1.58	0.98	125
39	2014/03/18 02:10 04:15	2.6	0.6	28.5	13.4	211.10	1.50	0.95	115
40	2014/03/18 11:50 12:20	3.1	0.8	35.4	17.2	440.07	1.40	0.97	20
41	2014/03/18 13:45 14:35	21.4	7.3	43.7	25.6	168.61	1.56	0.98	40
42	2014/03/18 15:55 16:45	5.0	1.1	32.4	16.5	162.05	1.53	0.98	40
43	2014/03/26 12:25 14:05	1.7	0.5	21.5	9.8	57.86	1.12	0.97	90
44	2014/03/26 14:30 15:20	9.6	1.8	35.0	14.2	80.95	1.28	0.98	40

The A coefficient of events in the catchment is in most cases well below 200 with a spike in occurrences between 50 and 60 (Figure 5-14). This is cause for concern as the Marshall and Palmer relation used by the SAWS to measure radar rainfall estimates has an A coefficient of 200. This means that, because these A values are per event, the use of the Marshall and Palmer for these events, may lead, in some cases, to rainfall being underestimated by a factor of 4. These low A values are also an indication that most of the rain that was measured were convective events.

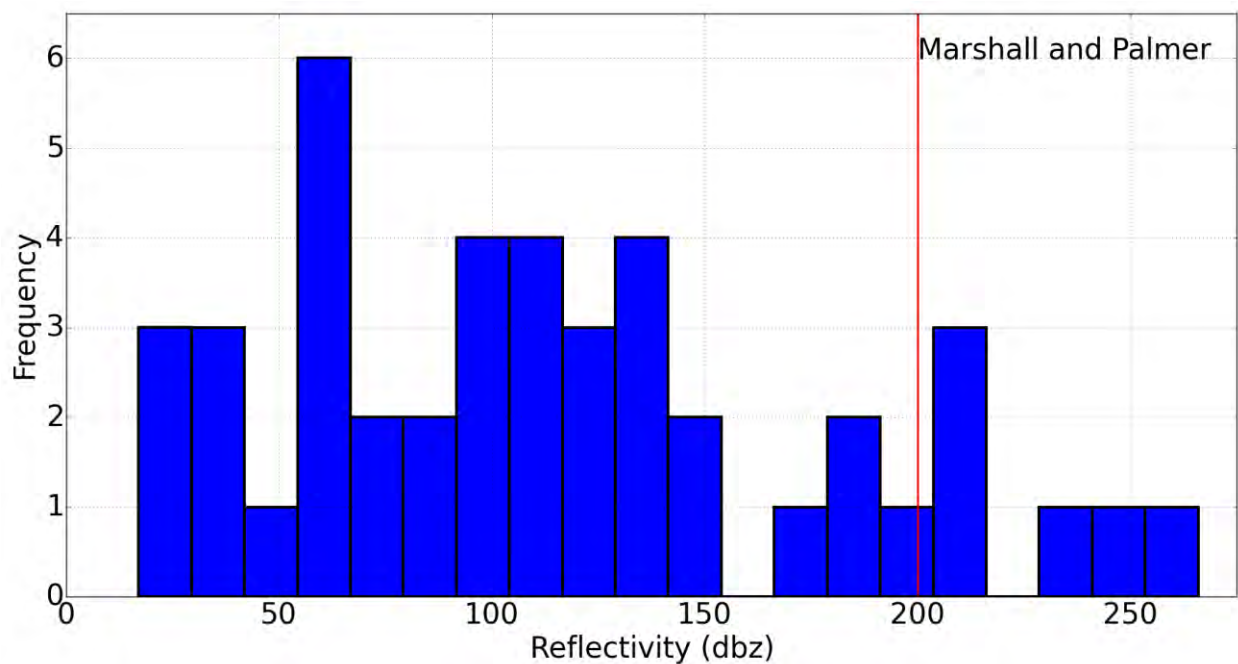


Figure 5-14: Probability density function of the A coefficient for the merged data.

All the results found in this section seem to prove that the Marshall and Palmer are not necessarily the best option to use for radar rainfall estimates in the Mooi River catchment. Results show that this relation may underestimate convective events. Stratiform events are better represented by the theoretical relation but data has shown that the majority of events in the Mooi River catchment are convective with only a few being stratiform. Adapting the Z-R relation to a more representative one will entail lowering the A value. In the next section the ideal Z-R relation for events will be discussed. It is also clear that the b coefficient must also be evaluated as to whether it adequately represents the rainfall of the region or not. Most Z-R relations fell far below both coefficients (Figure 5-15).

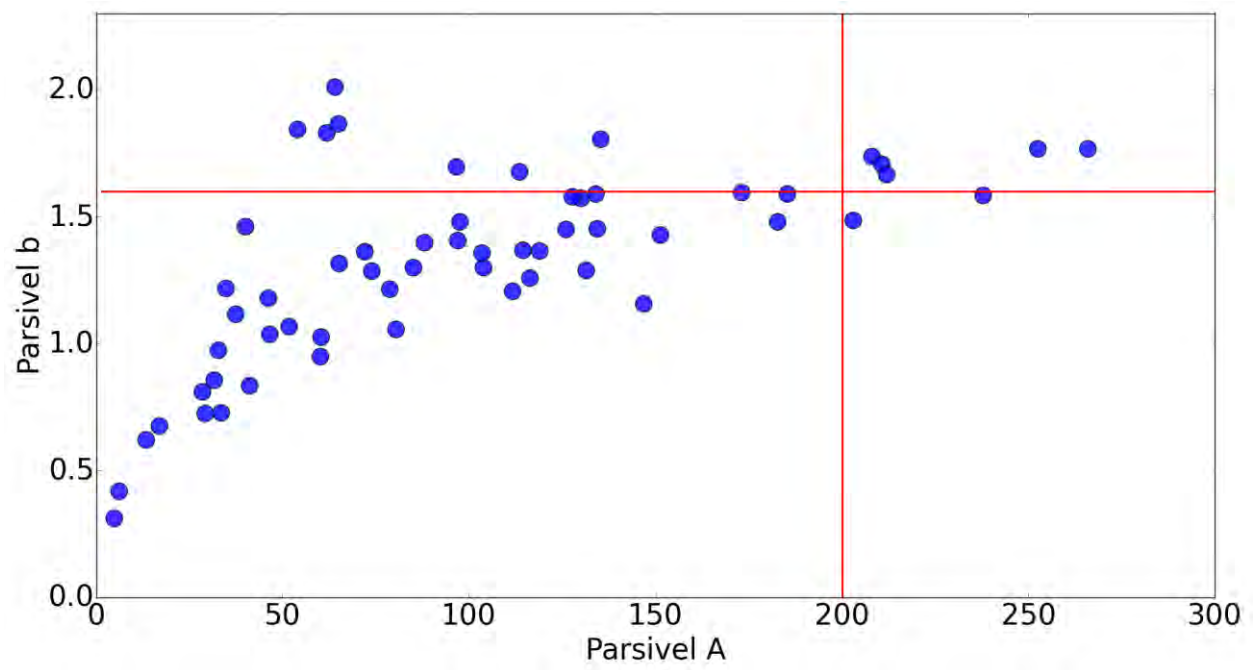


Figure 5-15: The A and b coefficient of events measured is plotted against each other. The red lines also show the Marshall and Palmer relation.

5.2 Stratifying storms into different rainfall regimes

Three types of precipitation will be explored in this section, namely: convective, stratiform and mixed precipitation. This section is aimed at characterising the Z-R relation for each of these storms measured in the Mooi River catchment and evaluating the performance of these Z-R relations using the Irene weather radar.

Reflectivity measurements made by the radar ranged between 1 and 64dbz. It is important to note that dbz values below 20dbz do not represent rainfall. This is because of ground clutter or non-rainfall objects like airplanes. The majority of dbz is highly variable with values between 20 and 64dbz (Figure 5-4). This correlates with previous results that showed that most events in the catchment are convective events with high rain rates.

Mixed precipitation includes both stratiform and convective events. The majority of the events in the catchment are convective (see Chapter 3). The Highveld's summer which includes the Mooi River catchment is known for intense, warm centered convective systems with a West east component in the direction of movement. Stratiform events also occur periodically and differ completely in structure from convective events. It can create uncertainties within the data when these events mix. A mixed precipitation Z-R relation was therefore developed that represents both these types of events. The Z-R relation for mixed precipitation:

$$Z = 179R^{1.5}, \quad (17)$$

developed by using the entire data set. This equation leaned towards a more convective equation because most of the rainfall was from convective precipitation (Figure 5-16). There is a positive correlation between this relation and the Marshall and Palmer. The Marshall and Palmer relation overestimate rain rates if the reflectivity is below 19dbz. Above this reflectivity the rain rate may be underestimated. This means that the majority of mixed events in the catchment may be underestimated because most of the reflectivity measurements are above 19dbz (Figure 5-16).

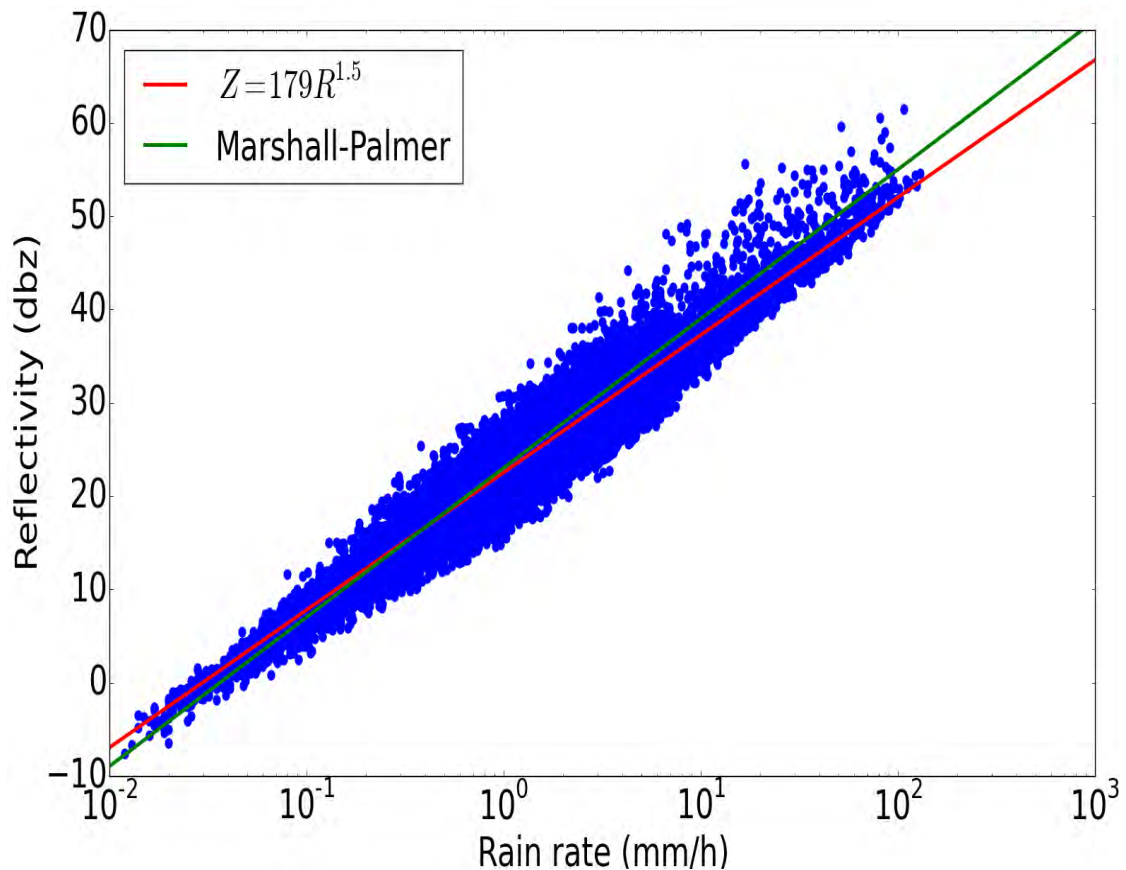


Figure 5-16: Z-R relation for mixed precipitation between the 21st of February and the 31st of March 2014.

The Irene radar image also supports this finding (Figure 5-17). A case study was used to test whether this Z-R relation does improve radar data or not. Mixed precipitation was identified by the rain rate, reflectivity and duration of an event. Exploring the temporal reflectivity of events and identifying spikes in dbz measurement with rain before or after the spikes showed which event could be identified as mixed precipitation. Mixed precipitation was measured on the 4th of February 2014. The synoptic chart of South Africa showed that, on this day, an easterly low-pressure system had developed over the northern parts of the country. The low pressure was located west of the catchment with some activity over the Highveld (Annexure A). Figure 5-17(Top left) shows the maximum reflectivity per bin for the entire Irene coverage area which means that all the convective events did not occur all at once. It is evident that both stratiform and convective precipitation was present on this day. This is supported by the image -top right - where events were stratified by using the stratiform filter algorithm in TITAN. Blue areas represent stratiform regions and red areas represent convective regions. Isolated convective events are shown with large areas also experiencing stratiform rain. Data measured by the

disdrometer showed that four events were measured on this day outside Potchefstroom. Three of these events had maximum rain rates of 5mm/h or lower and one had a rain rate of 21, 4mm/h. The duration of these events varied between 20 and 115minutes. By considering the maximum rain rate, duration, maximum reflectivity and the results from the stratiform filter algorithm, it was confirmed that the case study was ideal to test mixed precipitation Z-R relations.

Figure 5-16 showed that the correlation between the custom and Marshall and Palmer relations was not that significant and it is expected that small changes may be observed. The total rainfall measured by the rain gauge outside Potchefstroom for this day was 7.1mm. Using the Marshall and Palmer relation the radar measured 5.2mm. This is a difference of -1.9mm. Using Eq. (17) the radar measured a total rainfall of 6mm which is a difference of -1.1mm. This is an improvement in accuracy, but if calibration offsets between radar and disdrometer measurements are not considered, some uncertainties may still arise. Accounting for calibration offset will improve the accuracy even further. This will be explained in the next section. Small differences are evident for the entire catchment. Figure 5-17 shows the image of the total precipitation measured by the Marshall and Palmer. A slight decrease in total precipitation is shown in the figure on the bottom right using Eq. (17).

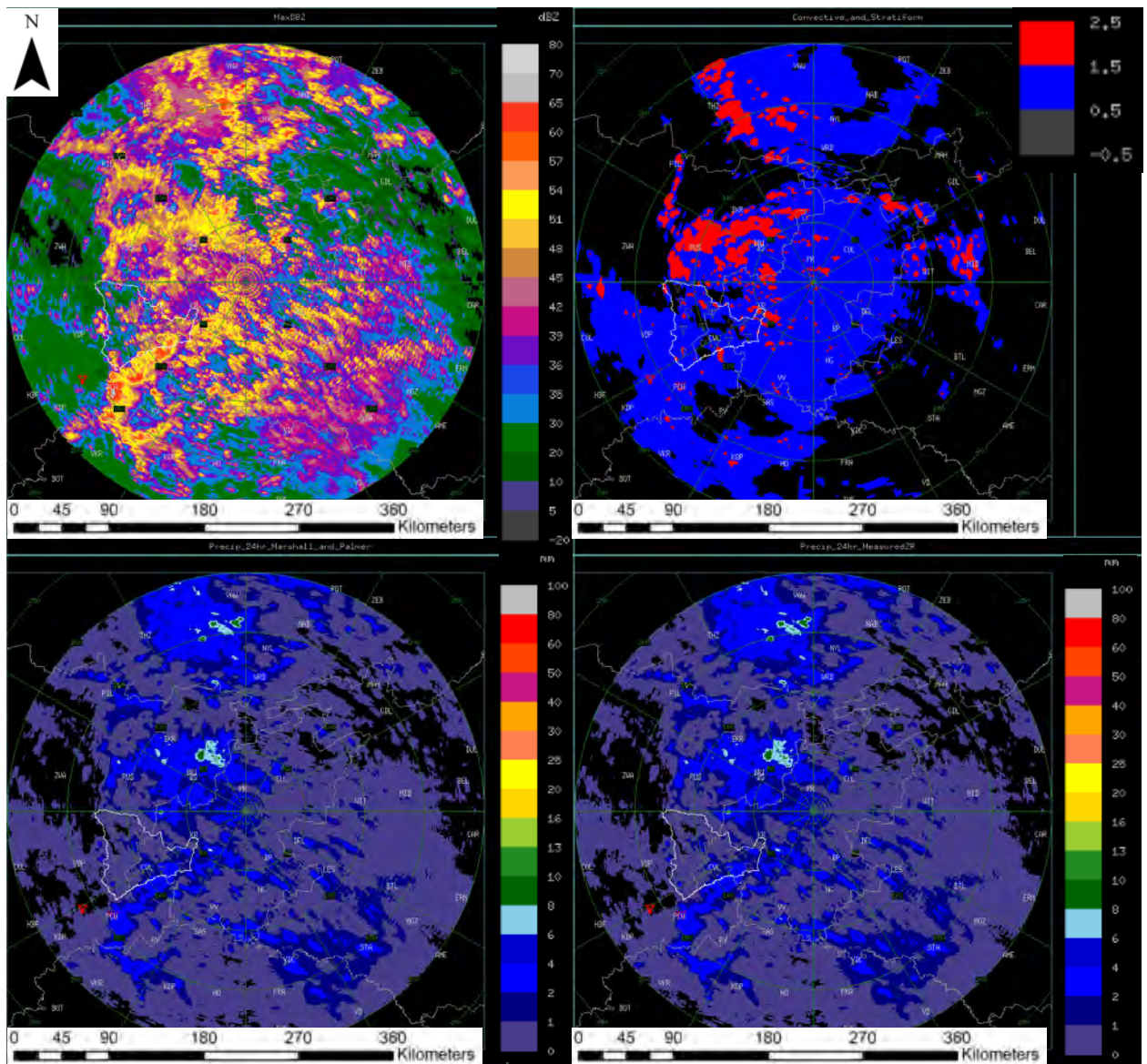


Figure 5-17: The measured custom Z-R relation was compared to the Marshall and Palmer to test whether the accuracy increases for mixed precipitation measured on the 4th of February 2014. Top left: The maximum reflectivity measurements for the entire day per bin. Top right: Stratiform and convective events stratified in their respective regimes. Bottom left: The total rainfall for the day measured using the Marshall and Palmer Z-R relation. Bottom right: The total rainfall for the day measured using the custom Z-R relation measured by the disdrometer.

Stratiform events are not that frequently observed over the Mooi River catchment. However some events were measured. Some of the main criteria to identify these storms as stratiform events is a long duration and low rain rates. Stratiform events were identified for the entire data set by their low rain rate and long duration. Previous results have shown that stratiform events are not that common over the catchment. The Z-R relation measured for these events were:

$$Z = 210R^{1.6}, \quad (18)$$

which correlated well with the Marshall and Palmer (Figure 5-18). Reflectivity values below 30dbz will be underestimated and above 30dbz will be overestimated compared to eq. (18). A large portion of reflectivity values was between 1 and 30 dbz which can create problems (Figure 5-4). However these uncertainties will be minimal.

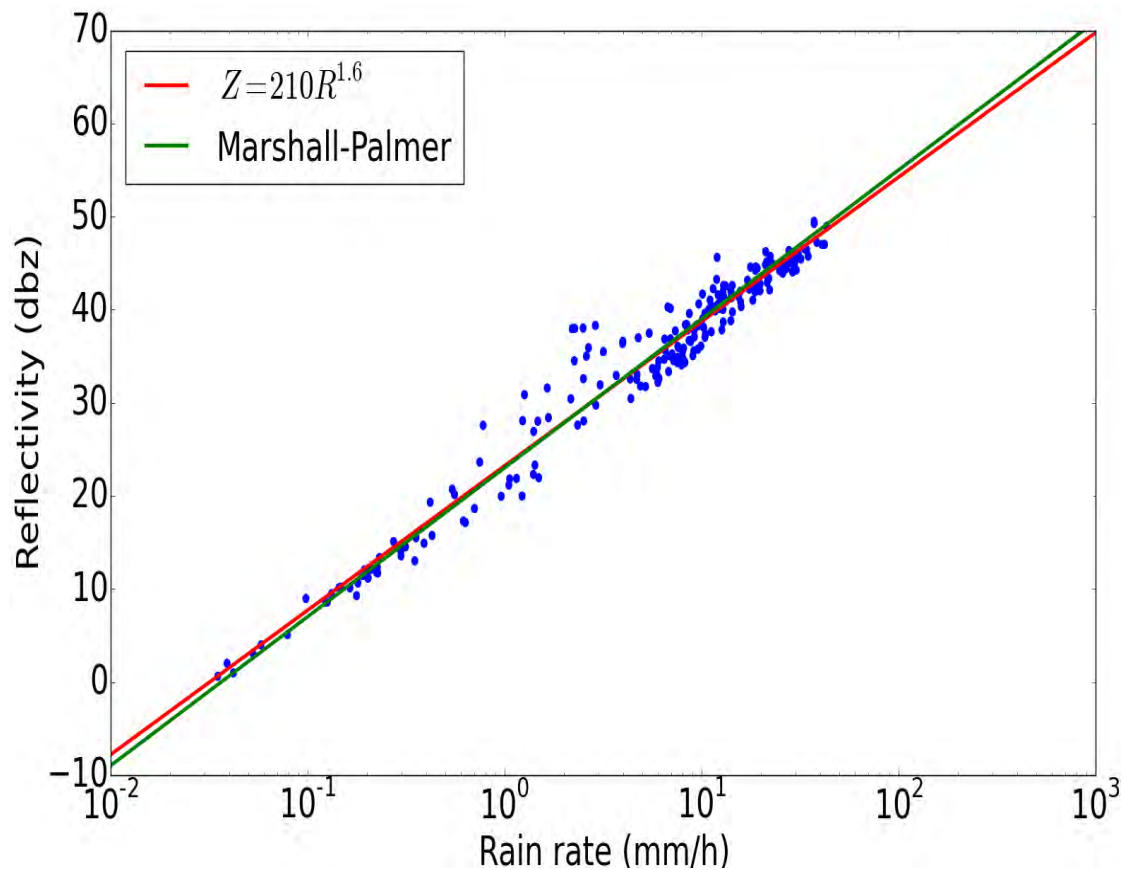


Figure 5-18: Z-R relation for stratiform events between the 21st of February and the 31st of March 2014.

Stratiform events were measured on the 18^h of February 2014 to test the performance of Eq. (18) compared to the Marshall and Palmer relation (Figure 5-19). These events were identified using TITAN's stratiform filter (top right), low maximum reflectivity's, low rain rates and long duration. Convective events for the entire day are much less when stratiform rain is dominant compared to the events observed in Figure 5-17. These convective activities are not observed as frequently as stratiform rain, especially to the southwest of the Irene radar coverage areas where the disdrometer is situated (Figure 5-19: Top left and right). An easterly low-pressure system was prevalent over the catchment which was responsible for the rainfall observed that day (Annexure B). The rain gauge measured a total of 2.6mm of rain for a stratiform event measured at 13:54:00 that had a duration of 130 minutes. Using the Marshall and Palmer relation the radar measured for this event a total of 5.4mm (Figure 5-19: Bottom left). Using eq. (18) the radar measured 5.3mm of rainfall that is only a slight decrease and was expected considering the good relation between the stratiform Z-R relation and the Marshall and Palmer. Calibration offset definitely plays a big role in this large offset. Referring back to Figure 5-5 (130) it is clear when one looks at both the linear lines that the Irene radar tends to overestimate events with low reflectivity values, especially below 20dbz. Stratiform events, having low dbz values will therefore be overestimated even though a different Z-R relation is used. It is thus clear that the Marshall and Palmer relation is an adequate Z-R relation to use for stratiform events within the Mooi River catchment. These radar rainfall estimates will have large uncertainties unless the performance of the radar is also considered.

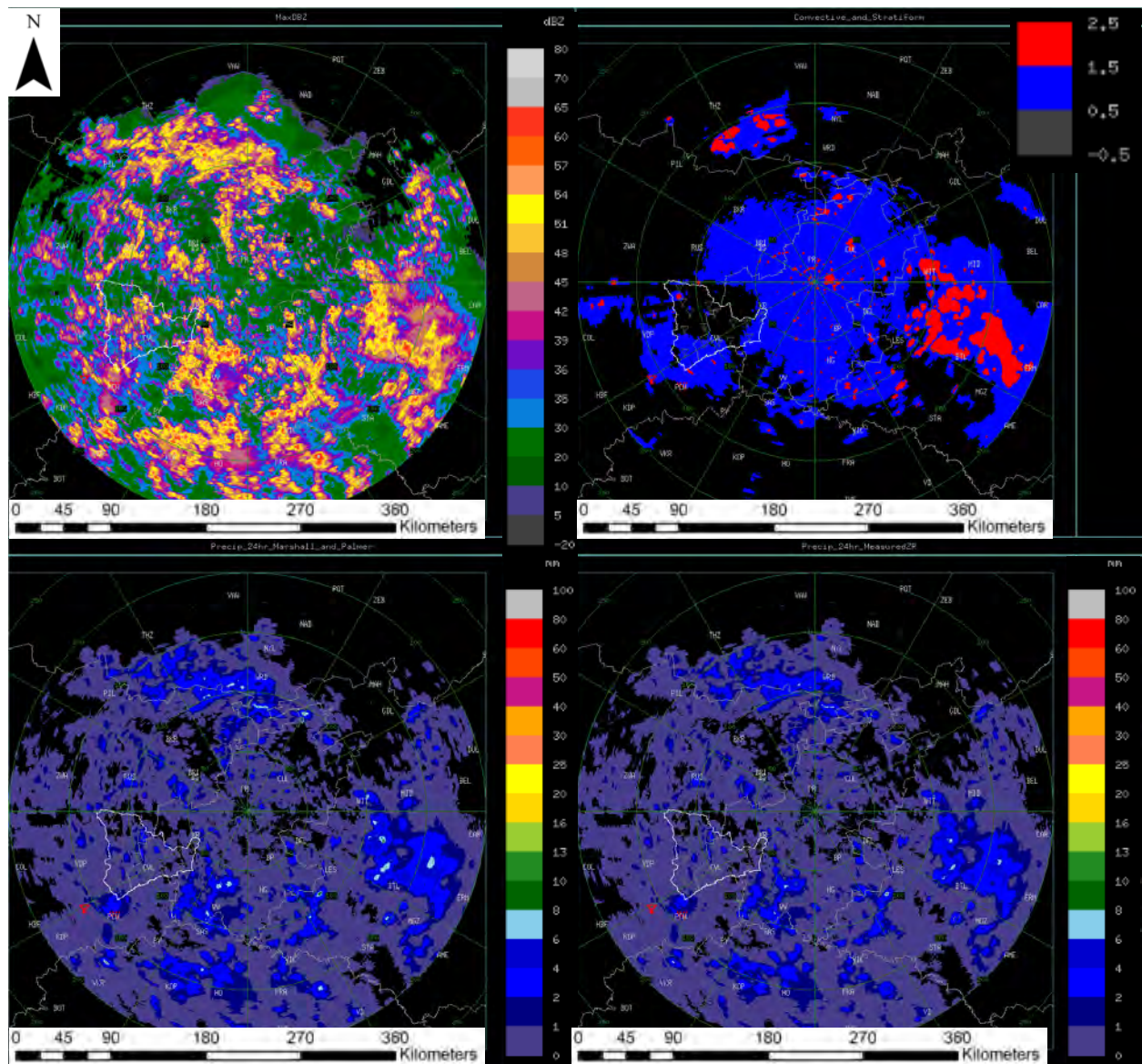


Figure 5-19: The measured custom Z-R relation compared to the Marshall and Palmer to test whether the accuracy increases for stratiform precipitation measured on the 18th of February 2014. Top left: The maximum reflectivity measurements for the entire day per bin. Top right: Stratiform and convective events stratified in their respective regimes. Bottom left: The total rainfall for the day measured using the Marshall and Palmer Z-R relation. Bottom right: The total rainfall for the day measured using the custom Z-R relation measured by the disdrometer.

It is however with convective events where the biggest problem lies. It is of particular importance to explore whether convective events are well represented by the Marshall and Palmer relation mainly because of 2 reasons:

1. Convective events are the predominant form of precipitation in the Mooi River catchment and on the Highveld of South Africa according to previous results found in this study.
2. These events are normally responsible for large-scale damages to property and infrastructure (Dyson, 2009; Lennard et al., 2013).

It is for these reasons that it is important to maximize the accuracy when measuring convective events. Convective events were identified by their high rain rates, high reflectivity and short duration. The new Z-R relation measured for convective events,

$$Z = 100R^{1.3}, \quad (19)$$

has an A (100) coefficient that is much more representative of the majority of coefficient for all the events measured with the disdrometer (Figure 3-16). It is expected that this relation will produce more accurate radar rainfall estimates than the Marshall and Palmer relation. Figure 5-20 shows that the Marshall and Palmer relation underestimate rain rates based on reflectivity's above 5dbz. This means that all convective events in the catchment will be overestimated as most reflectivity values measured is above 5dbz (Figure 5-4). The correlation between the eq. (19) and the Marshall and Palmer relation are significantly different.

Z-R relations for convective events will always have some level of uncertainty in the catchment. This is because of the high variability of rainfall intensity that is used to derive the Z-R relation. Using eq. (19) rain rate would be either over or underestimated but the degree of uncertainty for both these offsets would be the same.

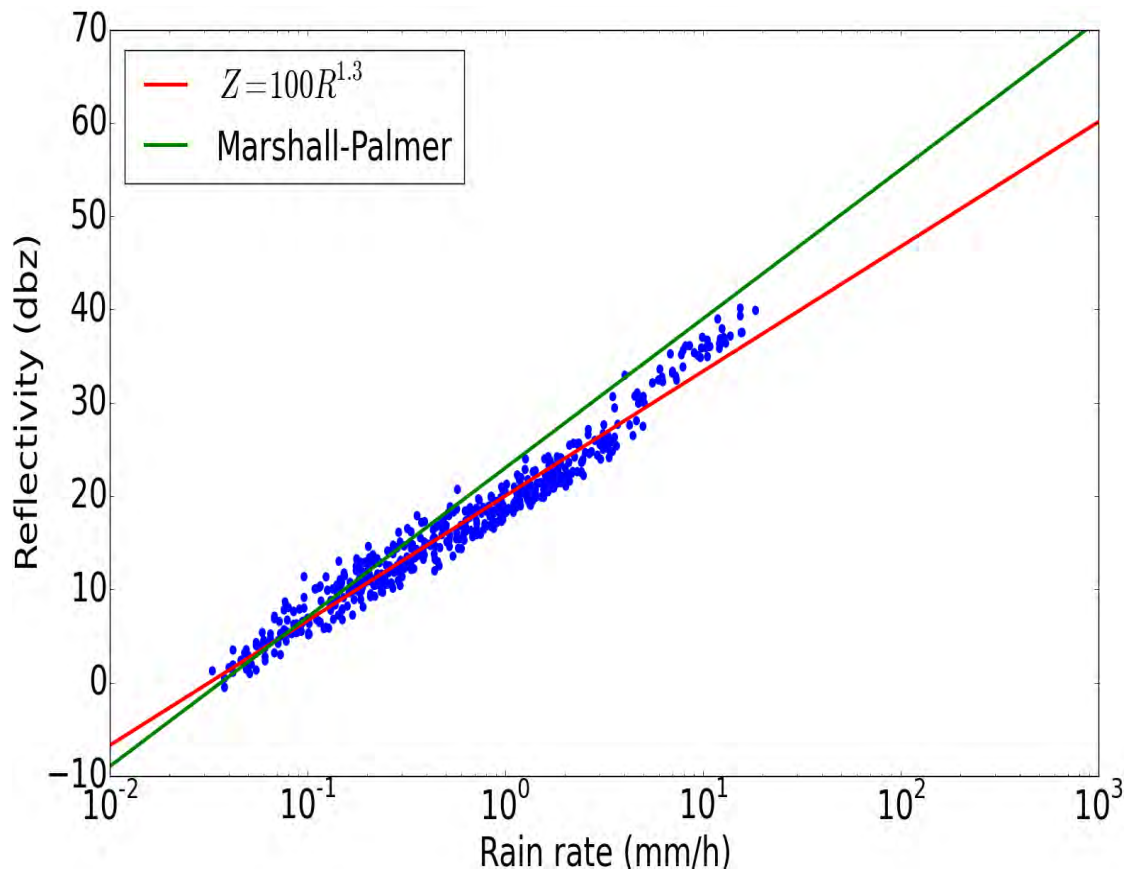


Figure 5-20: Z-R relation for convective events between the 21st of February and the 31st of March 2014.

Equation (19) showed much better correlation to the measurement made on the ground by the TBR. Intense convective events with high dbz values were measured on the 5th of March 2014 (Figure 5-21: Top left). An easterly low was once again present over the northern parts of South Africa that brought rain to most parts of the region (Annexure C). The region had a large number of isolated convective events with a maximum rain rate of 129.7mm/h and reflectivity of 54.5dbz measured by the disdrometer (Table 3-3; Figure 5-21: Top left). The TBR measured a total rainfall of 22.4mm. Using the Marshall and Palmer relation the radar measured a total rainfall of 18.4mm (Figure 5-21: Bottom left). This large scale overestimation was expected if the Marshall and Palmer were compared to the custom Z-R relation (Figure 5-20). Using eq. (19) the radar measured the total at 23.5mm that is a far better correlation (Figure 5-21: Bottom right). The slight overestimation is that the specific event had an A coefficient of 155 where the A coefficient for equation (19) was measured for all convective events in the catchment (Table 3-3). The lower the A coefficient, the higher the rain rate (Figure 3-9). As already mentioned

these measurements would never be exact. It is the degree of uncertainty that we can manipulate and a custom equation will keep these uncertainties to a minimum.

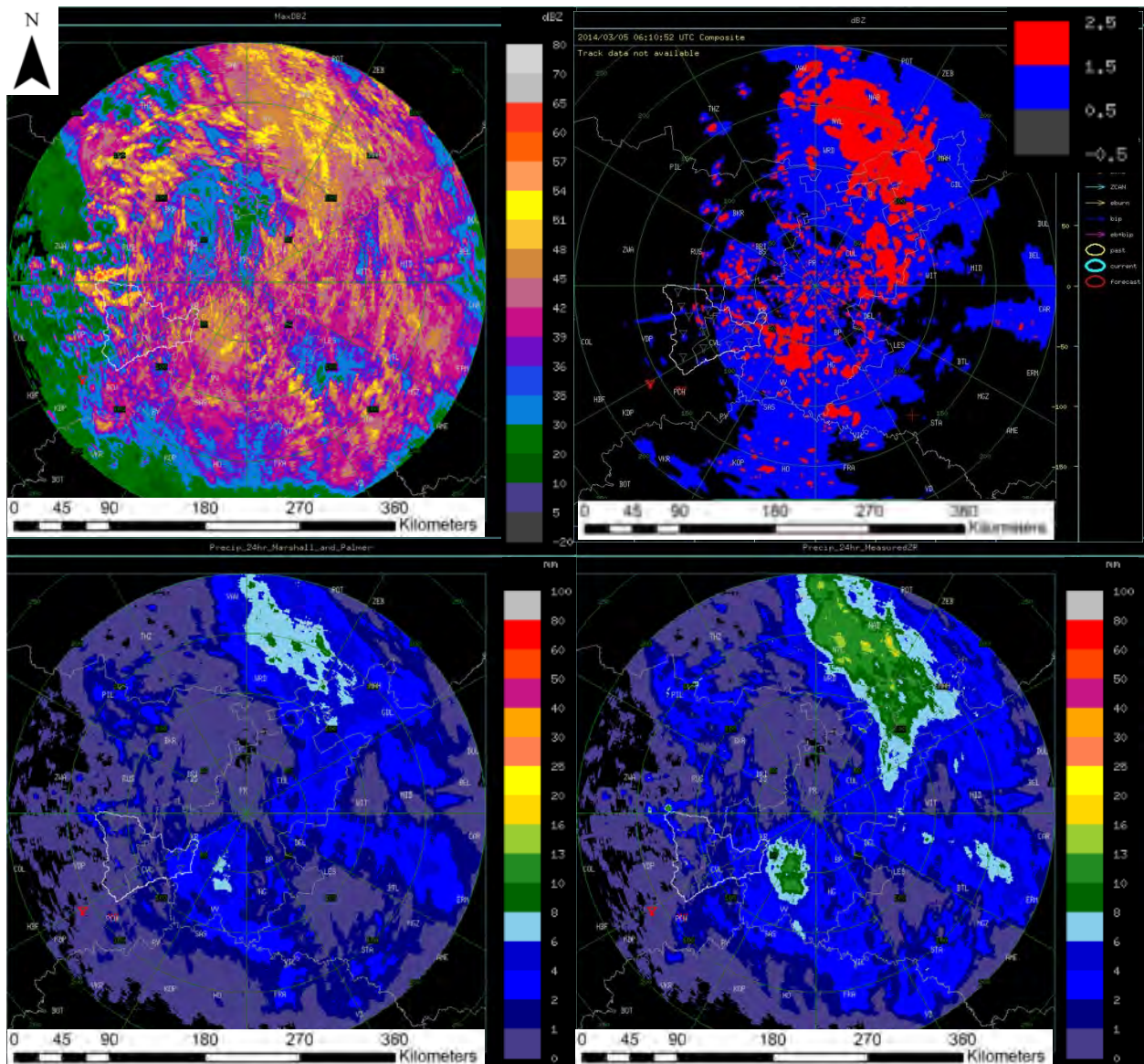


Figure 5-21: The measured custom Z-R relation compared to the Marshall and Palmer to test whether the accuracy increases for convective precipitation measured on the 5th of March 2014. Top left: The maximum reflectivity measurements for the entire day per bin. Top right: Stratiform and convective events stratified in their respective regimes. Bottom left: The total rainfall for the day measured using the Marshall and Palmer Z-R relation. Bottom right: The total rainfall for the day measured using the custom Z-R relation measured by the disdrometer.

The degree of improvement using the equation 16, 17 and 18 showed mixed results. Using equation 16 had a slight improvement although it was found that the Marshall and Palmer relation also showed good results for mixed precipitation. The A coefficient was unexpectedly high considering the large number of convective events in the catchment. However a distinction between the events measured with the longest duration¹⁰ and the portion of rain for which the most rain was measured must be made. Considering that the mixed Z-R relation was measured using the entire data set, the most data points that the disdrometer measured was for stratiform rain which had low rain rates and produced a small portion of the total rainfall. These events will have a big influence on the A coefficient and will result in a higher A coefficient than expected because of the longer duration of stratiform events. This caused the mixed Z-R relation to be much higher than the convective Z-R relation (Eq. (19)). The biggest portion of rainfall measured was from convective events with high rain rates but not that many data points (Figure 5-22). The Marshall and Palmer relation correlated well with equation (18). Radar rainfall estimates using both these equation showed very accurate results compared to ground-based measurements. The Marshall and Palmer are thus a valid equation to use when measuring stratiform rainfall (Figure 5-22). Convective events revealed significant results. It can be concluded that the Marshall and Palmer relation underestimates all convective events measured which produces the majority of rain in the Mooi River catchment. Equation (19) produced much better results and the correlation to ground-based measured data improved. It would therefore be recommended that the Marshall and Palmer relation must be re-evaluated and it must be considered that a new equation must be used (Figure 5-22).

¹⁰Most data points

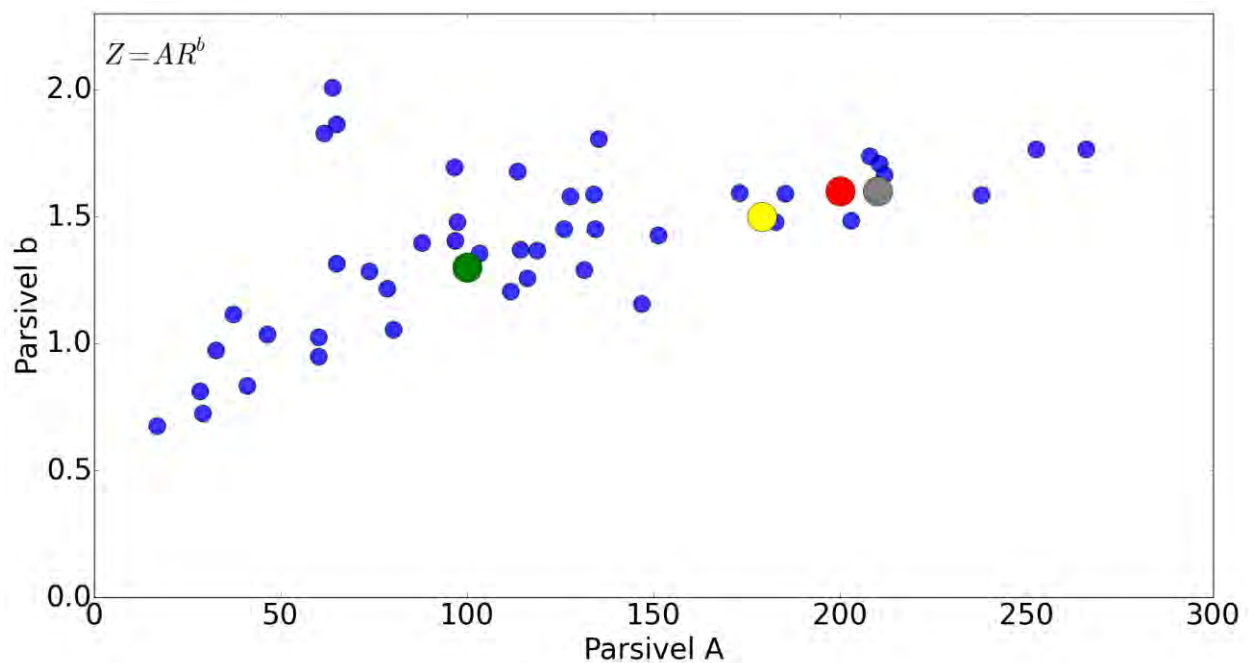


Figure 5-22: Different Z-R relations measured for all events. The red dot shows the Marshall and Palmer relation, grey dot the stratiform relation measured, the yellow dot is the Z-R relation for mixed precipitation and convective Z-R relation is presented by the green dot.

5.3 Improving Radar Rainfall Estimates

Improving single-parameter radar rainfall estimates involve the combination of a custom Z-R relation and also considering the calibration offset of the radar. These two interventions must not be looked at in isolation but in combination to improve radar rainfall estimates. The disdrometer and TBR were both used in combination to improve the Irene weather radar data. Tipping-bucket rain gauges were used as a reference instrument on the ground measuring the rainfall total and the disdrometer was used to measure radar calibration offset and to optimize a custom Z-R relation. This way of improving radar rainfall estimates is much the same as the methods used by Ulbrich & Miller, 2000. They found that only considering the variability in the A and b coefficient will not account for the substantial differences observed between radar rainfall accumulation and TBR total rainfall. Dramatic improvements in the radar rainfall estimates were found when a unique Z-R relation was combined with a bias measurement derived from the offset between ground measurements and those made aloft.

Data of all three instruments were merged and events were identified by a 15-minute gap between the start and end of an event (Table 5-1). Significant events were identified by the

maximum rain rate of an event and the duration (Table 2-5). This was done to include both convective and stratiform events (Figure 2-23). A total of 10 events were chosen with half being convective (4, 7, 8, 9, 10) and the other half stratiform (1, 2, 3, 5, 6) (Table 5-2).

An analysis was done in this section similar to the above-mentioned using disdrometer, TBR and weather radar data measured between February and March 2014. The aim is to compare radar rainfall estimates using different Z-R relations and radar calibration offset measurements to determine whether the correlation to ground-based TBR data can be improved. The temporal variability of the Z and R for the storms measured was fairly smooth which kept the uncertainty in the data to a minimum. It is clear that there was a calibration offset between the Irene radar and the disdrometer Z measurements on the ground (Figure 5-5). Very similar calibration offset measurements were found for all ten storms with the average offset being 4.11dbz (Δ). For all of the storms a tipping-bucket rain gauge was used to measure the total amount of rainfall on the ground. This was done to compare radar rainfall estimates calculated using different measuring techniques to ground truth measurements. These rainfall depths measured by the TBR was in good agreement to those measured by the disdrometer (Figure 2-7). It must be noted, as mentioned throughout the study, that it is very unlikely that significant errors would be found in disdrometer data. This makes the disdrometer the ideal instrument for calibration purposes.

Given the obvious offset between Z_R and Z_D , the variability of the Z-R relations was explored in several different ways. Firstly the total depth of rainfall measured by the radar was determined using the Marshall and Palmer relation (Eq. (5)), with an A coefficient of 200 and a b coefficient of 1.6. The total rainfall was then compared with TBR data for the same time and presented in Table 5-2 as total gauge measurement (mm). The difference between these two measurements is presented as ΔH_1 . It is apparent that the difference between these measurements without any calibration offset adjustment is in some cases out by a factor of 2 and bigger.

It can be concluded from the above that the Marshall and Palmer relation did not perform well and that the offset between the radar and the TBR remained high. It is therefore crucial that new Z-R relations must be explored. The second analysis that was done was measuring the rainfall depth by the radar using a Z-R relation that was measured using the disdrometer for the specific event ($A = \text{Parsivel } A$; $b = \text{Parsivel } b$). This was compared to the total rainfall depth measured by the TBR and the difference is shown as ΔH_2 in Table 5-2. It is still evident that large offsets remain a problem. This confirms the statement made in this study and by Ulbrich and Miller (2000) that improving radar rainfall estimates does not only include optimizing the Z-R relation.

In the third method, the total depth of rainfall was measured by the radar using the Marshall and Palmer relation (Eq. (5)) and taking the calibration offset into account. The difference between this measurement and the one made by the TBR was compared and shown as ΔH_3 (Table 5-2). This produced an improvement in correlation for 50% of the events measured but increased the offset for the others. It can therefore be concluded that the Marshall and Palmer relation did not perform well for the rain in the Mooi River catchment.

Lastly, using the new custom Z-R relation and the adjustment of the radar calibration offset the rainfall depth was measured. This was compared to the measurement made on the ground by the TBR and the difference was calculated and is shown in Table 5-2 as ΔH_4 .

The results yielded from this section are very similar to those found by Ulbrich and Miller (2000). Using the Marshall and Palmer relation the offsets compared to the measurements made by the TBR were in some cases out by a factor of 2 or more. This was even the case when the radar offset was implemented. Some of the errors were intensified when the calibration offset was applied. This proves that using the Marshall and Palmer relation will always create uncertainties within the data and that Eq. (5) does not result in accurate measurements. Using only the custom Z-R relation measured by the disdrometer some of the measurements showed results that correlated better with the TBR rainfall accumulation. When the new Z-R relation was applied with the correlation offset of the radar measurement all of the ten storms showed the best correlation to the TBR accumulation for all four methods (Table 5-2).

It can therefore be concluded from Table 5-2 that to improve radar rainfall estimates it is important that the variability of rainfall must firstly be understood. Differences in the storm structure of convective and stratiform events cause the composition of the DSD to be different. The Z-R relation is directly derived from the DSD and is therefore highly variable between different storms. These changes, if not taken into consideration, can cause errors within data. It is important to use a Z-R relation that represents the events in the Mooi River catchment. This will improve the correlation compared to ground-based instruments. This, however can't be the only intervention. The performance of radars can also cause problems. Calibration offset between the radar and the disdrometer must also be taken into consideration and reflectivity values must be adjusted to account for these discrepancies in data. Applying both these may yield more accurate results.

Table 5-2: Parameters derived from the disdrometer located outside Potchefstroom and the Irene weather radar in Irene, Gauteng for the dates and times indicated. Here the maximum rain rate and reflectivity measured by the disdrometer and the maximum radar reflectivity is indicated. The duration of each storm is also shown to include stratiform events. The calibration offset was calculated, $Z_D = Z_R$, and shown by Δ for the specific storm indicated. ΔH_1 =the difference between the total rainfall measured by the TBR(Total Gauge Rainfall) and the accumulation of rainfall measured by the radar using the Marshall and Palmer($A=200$, $b=1.6$); ΔH_2 = the difference between the total rainfall measured by the TBR(Total Gauge Rainfall) and the accumulation of rainfall measured by the radar using the new custom Z-R relation (A =Parsivel A, b =Parsivel b); ΔH_3 = the difference between the total rainfall measured by the TBR(Total Gauge Rainfall) and the accumulation of rainfall measured by the radar using the Marshall and Palmer($A=200$, $b=1.6$) with the calibration offset (Δ) taken into account ($Z_R \pm Z_D = Z_{CAL}$); ΔH_4 = the difference between the total rainfall measured by the TBR(Total Gauge Rainfall) and the accumulation of rainfall measured by the radar using the new custom Z-R relation (A =Parsivel A, b =Parsivel b) with the calibration offset (Δ) taken into account.

Parsivel-Radar-Rain Gauge																
	Start	End	Max	Max	Max	Max Radar	Duration	Parsivel A	Parsivel b	Total	Offset	ΔH1	ΔH2	ΔH3	ΔH4	
			Parsivel	Gauge	Parsivel					Gauge						
			Rain Rate (dbz)	Rain Rate (mm/h)	Reflectivity (dbz)	Reflectivity (dbz)	(min)			Rainfall (mm)						
1	2014/02/22 19:45		21:35	5.0	5.7	33.0	37.1	100	160.42	1.35	3.20	-5.4	1.1	3.0	-1.2	-0.7
2	2014/02/23 10:25		12:50	1.8	1.4	27.3	28.3	135	209.02	1.39	0.80	-3.2	0.8	0.7	0.2	0.3
3	2014/02/23 13:40		16:30	4.2	5.4	33.4	40.5	160	242.14	1.58	4.00	-7.2	7.6	6.4	-3.9	-0.3
4	2014/02/24 21:15		22:30	60.6	75.5	48.0	45.6	65	165.89	1.39	18.60	-0.4	-11.6	-5.7	-5.6	-2.0
5	2014/03/03 13:30		16:00	2.7	1.5	26.5	14.9	140	139.62	1.34	0.80	3.3	-0.4	-0.5	-0.8	-0.2
6	2014/03/04 20:25		23:35	5.2	5.2	31.3	16.6	180	132.71	1.42	2.20	-0.3	-1.7	-1.6	-1.7	-1.7
7	2014/03/05 7:50		11:10	27.5	28.1	42.6	38.5	190	149.14	1.35	13.80	0.4	-7.2	-3.0	-6.7	-2.2
8	2014/03/06 1:20		2:25	60.6	54.1	47.0	34.4	55	120.95	1.42	18.60	0.4	-15.9	-14.2	-15.7	-13.9
9	2014/03/06 13:45		14:40	26.4	36.3	45.8	43.3	45	120.42	1.68	8.60	3.4	-4.5	-3.7	-1.9	-0.7
10	2014/03/09 15:45		17:15	62.3	61.6	50.7	59.6	80	208.29	1.46	14.80	-10.1	25.0	46.6	-5.5	-2.4

SUMMARY AND CONCLUSION

The character of rainfall intensity in the Mooi River catchment

The character of rainfall in the Mooi River catchment is very unique and poses a number of challenges when measuring radar rainfall estimates. Convective events are events with very high rain rates and a short duration according to literature. This leads to the assumption that these events are in general highly variable as not a lot of rain is observed before or after the peak in rain rate. Stratiform events involve precipitation that is more evenly distributed over a large area, short in duration and has low rain rates. Events were identified by their rain rates, reflectivity, duration and by using an algorithm that stratifies events using a threshold dbz value.

A total of 50 events were measured that included both stratiform and convective events. Events with high rain rates in the Mooi River catchment are highly variable. The Z-R relation is directly derived from the DSD that is measured at a high resolution by a Parsivel disdrometer. It is used to convert reflectivity measurements made aloft to rain rates on the ground. This relation is extremely variable and differs between events due to different storm structures. The A coefficient of the Z-R relation tends to have lower values in convective events with high rain rates than stratiform events.

It has been found that the majority of events in the catchment with high rain rates have an A coefficient below 200. What this means is that the majority of events are convective. These events are highly variable and normally have an A coefficient of below 200. Stratiform events are more evenly distributed and has a lower variability. Large differences have been observed between stratiform and convective events. It is therefore extremely important that the same methods are not to be used for both events when events are measured using weather radars. These events need to be explored and measuring strategies for both events need to be developed separately.

Rain rates measured using a siphon tipping-bucket rain gauge

Improving radar rainfall estimates involve fully understanding the spatial and temporal variability of rainfall. The industry standard TBR is an instrument that is used throughout the world for the measurement of rainfall. Advantages include the relatively inexpensive cost of operation because of its mechanical function that makes it the ideal instrument to deploy in a network that will give the ability to investigate the spatial variability of rainfall. Because of errors like the overestimation of events with high rain rates newer models of TBR are developed with a siphon that regulates the flow of water into the buckets and therefore eliminates this error. Siphons,

however, pose their own unique challenges like being unable to measure the start and end of events accurately and double tips. The new algorithm developed during the studies showed good correlation between rain rates measured by TBR compared to the disdrometer rain rate measurements. Correlation increased with the time scales of 1min, 2min, 5min, 7min, 10min, 15min, 30min and 60 minutes. The correlations reached a maximum at 15 minutes and thereafter the correlation gradually decreased. Correlation decreased because of the performance of the TBR at lower rain rates.

It can therefore be concluded that this algorithm measured rain rates compared to the disdrometer with an acceptable correlation at different time scales. Understanding the limitation and the errors these rain gauges are prone to beforehand can help in identifying errors in data which is often the biggest challenges in rain rate estimation. Improving rain rate data can help in understanding the variability of rainfall that causes large uncertainties in radar data.

Improved single-parameter radar rainfall estimates

South Africa has a state-of-the-art weather radar network that was upgraded between 2009 and 2012 for millions of rand. These radars are often not used to their full potential. New innovative methods are needed to keep up with technological advances of radar rainfall estimates in developing countries.

Radars are instruments that can measure rainfall at a large spatial scale. This makes it ideal for research regarding precision farming and other agricultural practices. The catchment has a large agricultural sector that is highly dependent on rainfall. Three radars cover the Highveld and include the Irene, Ottosdal and Bethlehem radars. The performance of these radars is however problematic. The Ottosdal radar has a coverage area with a maximum radius of 300km. This increased distance compared to the 200km of other radars in the network hampers the reliability of data with a correlation of 42% in relation to the disdrometer measurement on the ground. The data record of this radar is the worst in the network with below 20% of data available for the 2014 rain season.

The Bethlehem radar is the only dual-polarised radar in the network. This radar has the capability of measuring rainfall very accurately because of the measurement in the horizontal and vertical plane. This radar, however, has a number of different hardware faults that makes the data unusable for scientific purposes. Compared to the Irene radar, that is considered the best performing radar in the network, the Bethlehem radar underestimates events to a large extent because of receiver sensitivity problems.

The Irene radar is the best performing radar in the network compared to the disdrometer dbz measurements on the ground. The reason for this is most probably the location of the radar. The radar is on the same premises as the technical offices of SAWS. Technicians are close at hand if a problem arises. Consequently, this radar was used to test new methods of measuring rain rates in the Mooi River catchment.

The South African Weather Service uses the Marshall and Palmer Z-R relation to convert reflectivity measurements aloft to rain rates on the ground. This method is used to measure both convective and stratiform events that, as already mentioned, will create uncertainties within data. Events have been stratified into convective and stratiform regimes. Reflectivity and rain rate measurements made by the disdrometer was compared to each other for the time convective and stratiform precipitation was identified and a new unique Z-R relation was derived. A mixed precipitation Z-R relation was also derived that included both types of precipitation. These were compared to the Marshall and Palmer relation to determine whether the Marshall and Palmer is a good generic relation to measure rainfall in the catchment or not. It has been found that the Marshall and Palmer relation perform well for stratiform and mixed precipitation with a slight overestimation for some stratiform events. Convective events, however, are underestimated to a large extent. The use of the Z-R relation to calculate this type of precipitation makes the rainfall measured more representative of what is measured on the ground. It is recommended that the more convective Z-R relation must be used for rainfall estimation in the Mooi River catchment and consequently the Highveld.

These interventions to improve radar rainfall estimates can, however, not be seen in isolation and do not, on their own, account for the large discrepancies observed between radar and ground-based measurements. Combining the performance of the radar in terms of whether a calibration offset exists and the optimization of a Z-R relation showed the best correlation and improved radar rainfall estimates. This idea is shared by Wang *et al.*(2008) that both these aspects need to be taken into consideration.

It can therefore be concluded that to improve radar rainfall estimates there are a number of different methods that can be implemented. The optimization of the Z-R relation, bias measurements, attenuation removal, ground clutter removal and bright band removal are all ways to improve radar rainfall estimates. The ultimate goal in South Africa, however, must be to improve radar measurements by moving towards dual-polarised capabilities which is used to its full potential.

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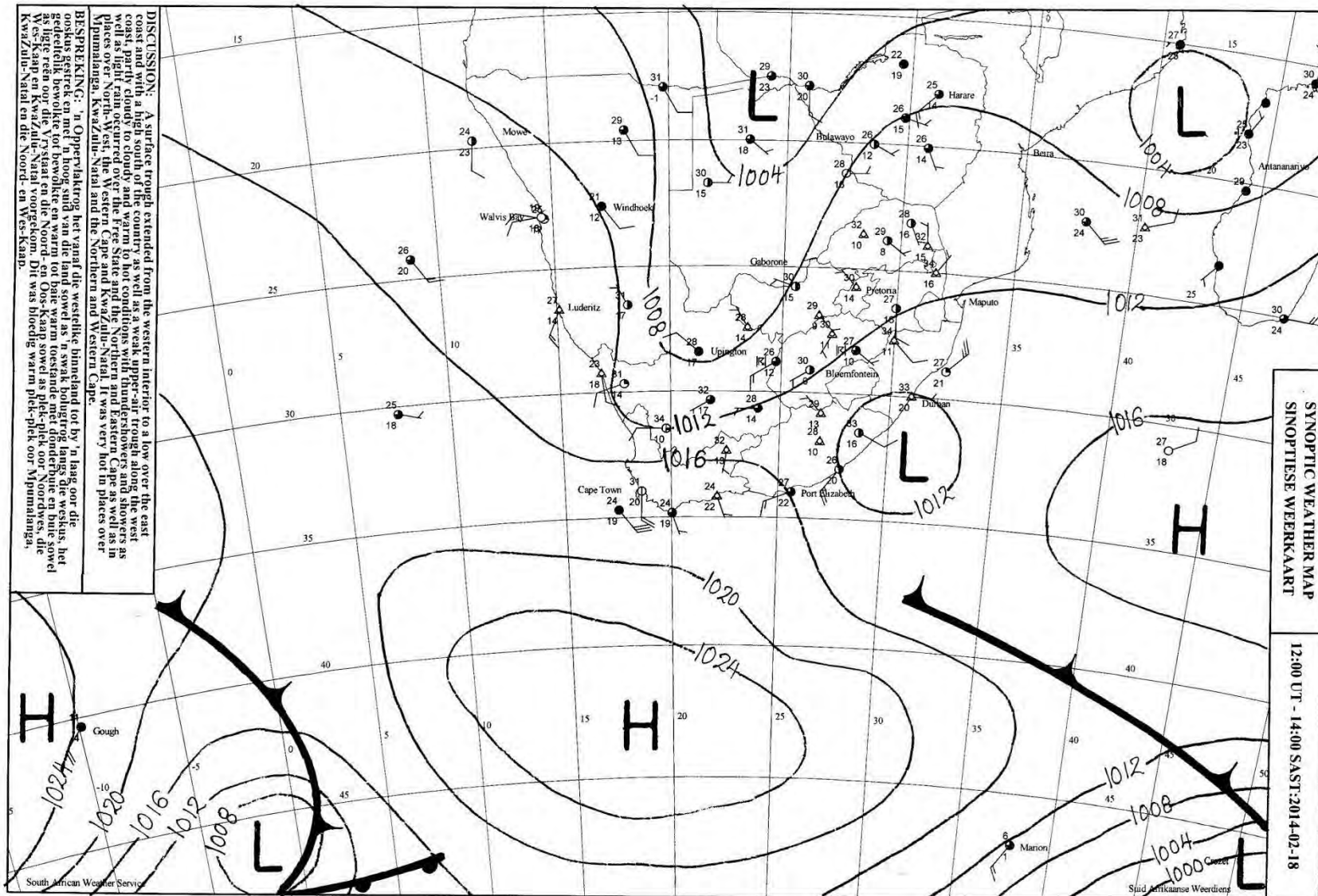
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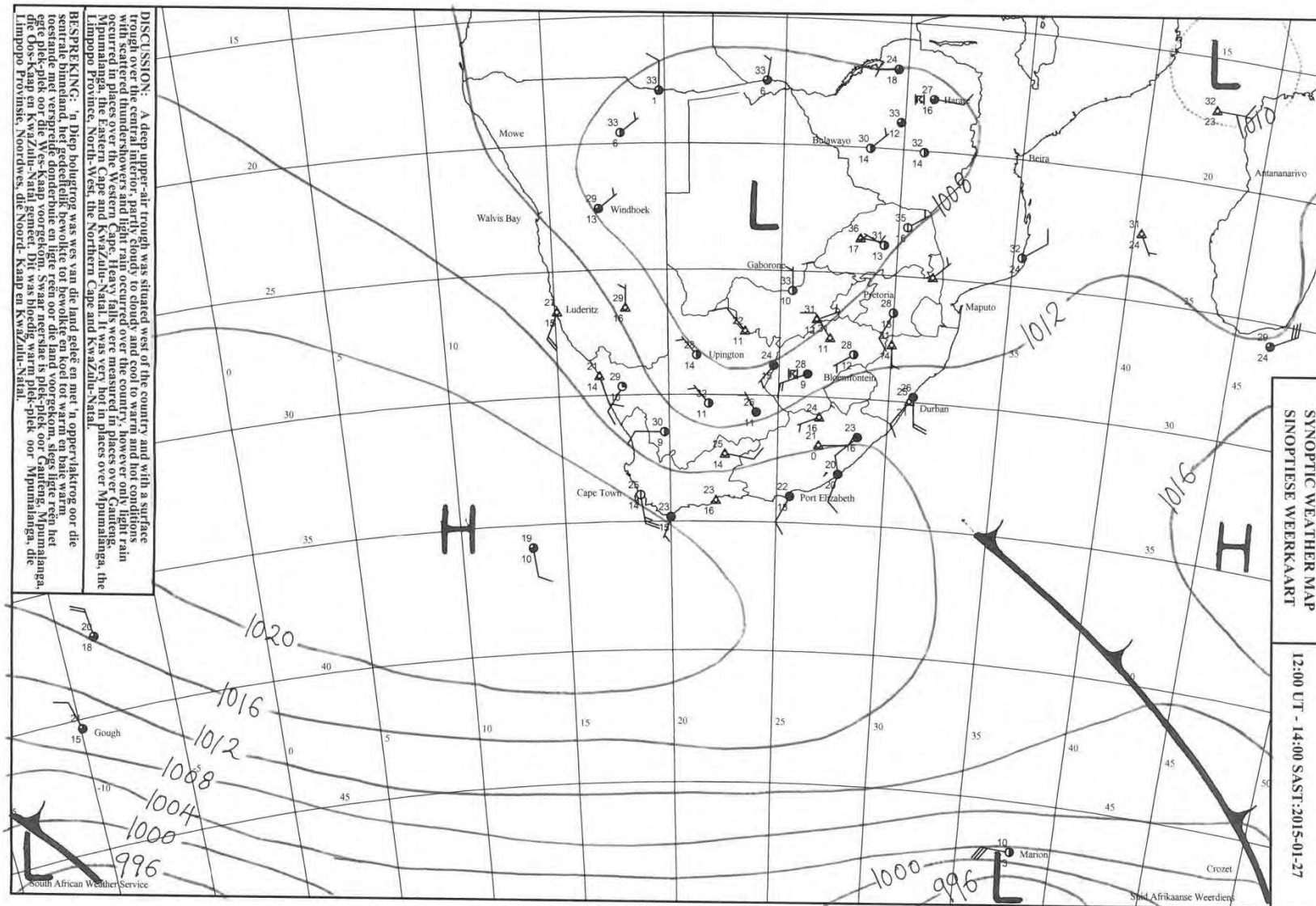
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Annexure A.



Annexure B.



Annexure C.

