Hail nowcasting over the South African Highveld

N Ayob

Orcid.org 0000-0001-9616-6395

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Supervisor: Dr RP Burger

Co-supervisor: Prof SJ Piketh

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DEDICATION

I dedicate this dissertation to my dearest father, Ahmed and mother, Lailah and siblings Aquil and Nadia who have shown me unconditional love and support throughout my study. Mom and dad you are my inspiration to achieve greatness, without you I would not be where I am today.

I love you.

PREFACE

This full dissertation is in accordance with the General rules and guidelines of the North-West University (NWU). This dissertation was conducted between January 2016 and November 2018 and comprises data that has not been previously published or submitted to any tertiary institution. The layout and reference style is done according to the requirements provided in the Guideline for Post-graduate students.

Part of this dissertation has been presented in the following publication. The paper addresses the third objective of this dissertation: to assess the perceived benefits of hail nowcasts.

Ayob, N., Burger, R.P. & Piketh. S.J. 2018. Perceived benefits of hail nowcasts over the Gauteng Highveld. In: *Journal of Neutral Atmosphere*. ISBN: 978-0-620-80825-5, Durban, South Africa, 20-21 September 2018.

This paper was presented at the South African Society for Atmospheric Sciences held in Ballito (Durban), South Africa, 20-21 September 2018. This paper was peer-reviewed and published in the conference proceedings (**ISBN: 978-0-620-80825-5**).

Dissertation outline

Chapter 1 gives an overview of this study and provides background information regarding the motivation for this study, comprised of the main objectives of this research.

Chapter 2 presents a comprehensive overview of the literature regarding hailstorms. The frequency of these events will be discussed briefly as well as damages that resulted from hailstorms. Hail forecasting and nowcasting will be explained in detail with the associated algorithms that are used to predict this type of meteorological event. The perception and benefits of hail nowcasts will be well discussed.

Chapter 3 provides a thumbnail overview of the data and methodology to be employed, per objective. Each method is discussed in detail of its contribution towards the study.

Chapter 4 serves to provide information and discussion regarding current nowcasting procedures of SAWS and the nowcasting algorithms employed by SAWS.

Chapter 5 provides information and discussion of hail nowcasts in minimising damage as well as the benefits to end-users.

Chapter 6 is the final chapter of this dissertation and merge the results in the form of a summary of significant findings. It also discusses the limitations and the unique contributions to the broader area of knowledge

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ABSTRACT

Hailstorm is one of the main meteorological phenomena that signify sources of damage to vehicles, property, infrastructure and agriculture over the Highveld. This event poses a strain to societies and is one of the costliest insured natural hazards in South Africa. This dissertation aim is to evaluate the current state of a hail nowcasting system that provides early hail warning to end-users over the Gauteng Highveld. The objectives of this dissertation are three folded: First, to review the current nowcasting procedures of the South African Weather Service (SAWS). Secondly, to evaluate the objective nowcasting algorithm used by SAWS and thirdly, to assess the perceived benefits of hail nowcasts.

Radar data was obtained from SAWS in Pretoria, Irene for the period November 2013-February 2015 using the S-band weather radar. The Thunderstorm Identification Tracking Analysis Nowcasting (TITAN) algorithm was programmed to run for 3 years. During this time period, 6 hail cases were reported. The nowcast products of TITAN were used to nowcast hailstorms for periods of 0-2h and verification of nowcasts was undertaken. Media and hail reports were used to subjectively identify hail events and results were correlated to the verification scores on a storm to storm basis; identifying how well the algorithm performed. Lastly, open-ended interviews were undertaken with individuals residing within the Gauteng Highveld. The aim of the interview was to explore the perceived benefits of nowcasts and what would be a successful nowcast to enhance or maximise those benefits.

It was found that SAWS do not forecast hailstorms or tornadoes, however, severe thunderstorms are forecasted. The criteria used in issuing warnings for severe thunderstorms was found to be similar to that of National Severe Storms Laboratory (NSSL). The forecast process was similar to the ones for the Meteorology Office UK and the Indian Meteorology Department (IMD). When forecasting severe thunderstorms, the main tools that were used were weather models and radiosonde observations for identifying storms. Along with instability, wind shear was the biggest role player when it came to identifying hail events. TITAN was used with its default settings and was not customised to identify big damaging events. The algorithm indicated a heavy overestimation of hail events. The hit rate performed extremely well and had a POD score of 0.85. The FAR was exceedingly high and had a score of 0.93. TITAN performed poorly in terms of the Critical Success Index (CSI) and scored 0.05 which showed no skill of the forecasts. The verification scores indicated a poor performance with low CSI and high FA scores, although some events are warned during these occurrences. TITAN displayed a low Heidke Skill Score (HSS) with a forecast skill of 0.01 which indicated no skill due to the great amount of FA. It was found that South African radars have severe limitations and algorithms cannot be used alone, specialists are needed to interpret these products. The weather service needs better and customised algorithms for radars using TITAN. Nowcasts can help individuals in ensuring the safety of their loved ones. Interestingly, it was found that hail nowcasts could help city officials in making sure the drainage systems are well organised thus reducing floods caused by severe storms. Nowcasting could make a difference at the weather service, where there is currently a gap in this space.

Keywords: Hail, Nowcasting, Highveld, SAWS, Radar, TITAN and Verification scores

”If you want to see the sunshine, you have to weather the storm”.

- Frank Lane

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ABBREVIATIONS

CAPE	Convective Available Potential Energy
CAPPI	Constant Altitude Plan Position Indicator
CII	Combined Instability Index
CRED	Centre for Research on the Epidemiology of Disasters
CSI	Critical Success Index
dBZ	RADAR reflectivity (unit of)
ECMWF	European Centre for Medium-Range Weather Forecasts
FAR	False Alarm Rate
FOKR	Foote Kraus Index
GII	Global Instability Indices
HDF	Hail Day Frequency
IPCC	Intergovernmental Panel on Climate Change
IMD	Indian Meteorology Department
LI	Lifted Index
MDV	Meteorological Data Volume
NCEP	National Centre for Environmental Prediction
NMS	National Meteorological Service
NSSL	National Severe Storms Laboratory
NWP	Numerical Weather Prediction
POSH	Probability of Severe Hail
POH	Probability of Hail
POD	Probability of Detection
RADAR	Radio Detection and Ranging
RII	Regional Instability Indices
SAWS	South African Weather Service
SCIT	Storm Cell and Identification Tracking
SHI	Severe Hail Index

SSS	Storm Structure Severity
TITAN	Thunderstorm Identification, Tracking, Analysis and Nowcasting algorithm
TTI	Total Totals Index
VIL	Vertical Integrated Liquid
VOL	Volume
WER	Weak Echo Region
WMO	World Meteorological Organisation
WRF	Weather Research and Forecasting Model
ZMAX	Maximum Reflectivity

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CHAPTER 1

INTRODUCTION

1 Background

Severe hailstorms are meteorological phenomena that signifies one of the main sources of loss and damage to property, vehicles, agriculture and infrastructure over the Highveld. This event constantly poses a significant strain on societies and is by far one of the costliest insured natural hazards in South Africa. The extent and frequency of hail appear to be increasing globally (Tobin & Montz, 1997; Loster, 1999; Jackson, 2000; Pyle, 2007). The socio-economic costs of severe hail events can be excessive, including lost lives, injuries and substantial damage to infrastructure and property (Doswell, 2001; Botzen *et al*., 2010; do Amarante et al., 2011; Fernandes et al., 2012; Bosco et al., 2015). The following map illustrates regions with the most persistent severe thunderstorm potential as shown in Figure 1-1. Areas with the highest incidence of favourable significant severe thunderstorm conditions are the central United States and equatorial Africa. Regions with the least incidence of severe thunderstorms are near southern Brazil, northern Argentina and the Himalayas. Areas surrounded by a thick black line have a 5% or larger probability of favourable environments for severe thunderstorms the area of South Africa included in the >5% per year area, is only the south-eastern part basically from Lesotho south-eastwards and somewhat outside the area of interest. Over the Eastern Highveld according to the map, there is about a 1% and a greater chance for severe thunderstorms per year.

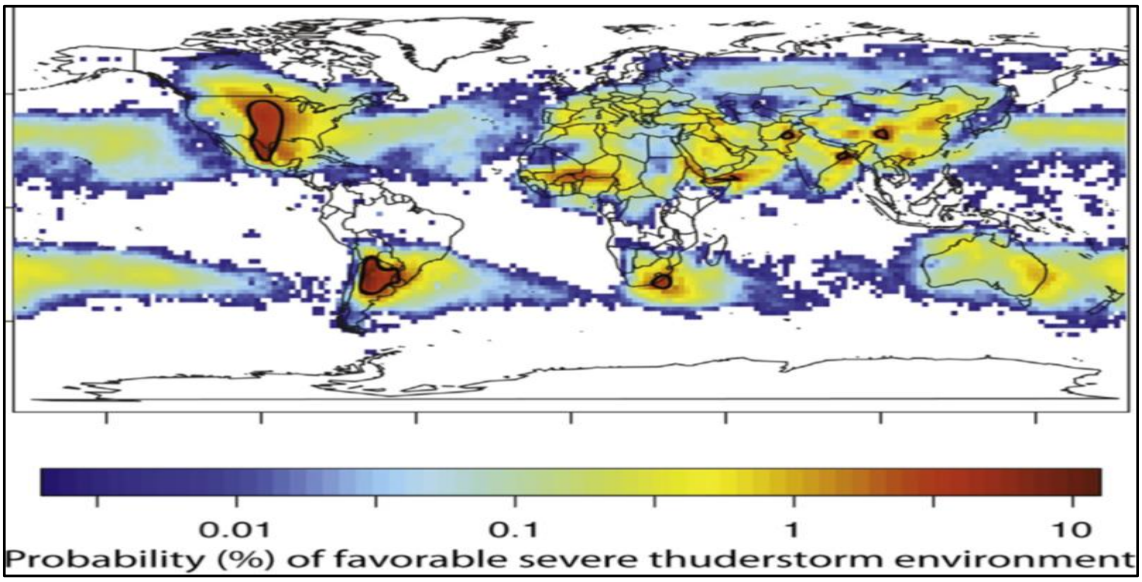

Figure 1-1: The yearly probability (%) of environments favourable for severe thunderstorms calculated from global reanalysis data over the years 1948-2008. (Source: Brooks, 2003).

Severe thunderstorms occur during summer and are accompanied by strong winds, heavy rainfall, lightning and large hail (Bosco *et al*., 2015). Thunderstorms bearing hail of substantial amounts may damage crops, buildings and vehicles (Kunz & Puskeiler, 2010). Hail is frequent during December-February and occurs over the warmer countries of the globe in areas where rainfall is expected during summer. Figure 1-2 illustrates the global distribution of hail incidence (number of events per day) during summer seasons in December, January and February. The South African Highveld has a sub-tropical climate and experiences summer rainfall and a considerable number of hail events (Carte, 1977*a*). Therefore, severe hail can be classified as a natural hazard being of importance for risk management and essential to the various insurance industries in South Africa.

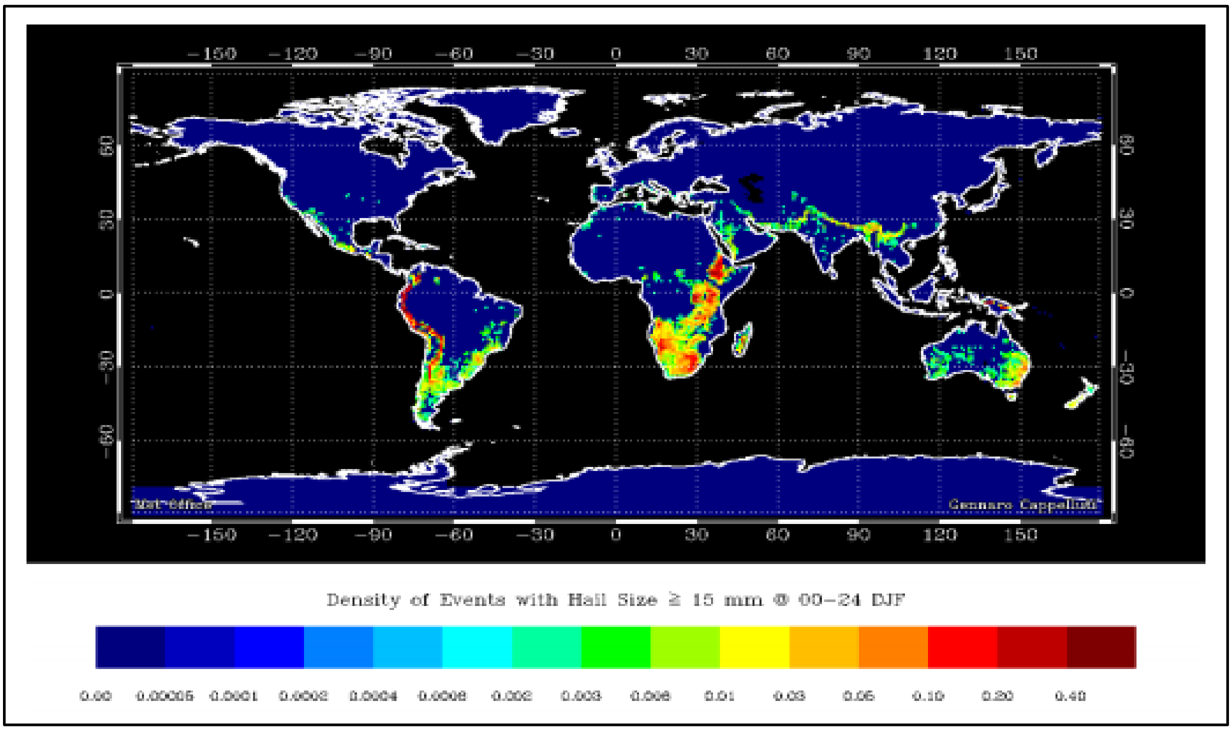

Figure 1-2: The Global distribution of hail events (number of events per day) during the summer season in December, January and February (Source: The Insurance Institute of South Africa, 2014).

Severe hailstorms may pose a threat to economic activities, mainly to insurance industries as a result of economic loss from insurance claims and agriculture (Garcia-Ortega *et al.,* 2001; Pflaum 1980). Hailstorms in the United States causes approximately $1.2 billion in damage to agricultural crops and property per year (Basara *et al.,* 2007). During the past 50 years, there had been substantial growth in damage produced by hailstorms and a sudden increase in economic costs worldwide (Changnon *et al.,* 2009). In the last 20 years, destructive hail events were studied in several countries (Changnon, 1999; Visser & Van Heerden, 2000; Schuster *et al*., 2006; Kunz & Puskeiler, 2010). Due to the destruction and amount of damages that can occur from a single hail event, there had been several studies conducted on hail events over different parts of the world as illustrated in Table 1-1.

Table 1-1: The geographical distribution of severe hail events in different countries during summer, spring and winter (Source: Martins, 2017).

Region	Country	Season	Authors
North America	United States	Spring/summer	Lemons, 1943; Kelly et al., 1985; Kerschner, 2011; Cintineo et al., 2012; Allen et al., 2015
	Canada		Paul, 1980; Admirat et al., 1985; Etkin and Brun, 1999
Europe	Finland		Tuovinen et al., 2009; Saltikoff et al., 2010; Tuovinen et al., 2015
	Great Britain		Webb et al., 2001; Webb et al., 2009
	Germany		Gudd, 2003; Deepen, 2006; Suwała, 2013
	Switzerland		Admirat et al., 1985
	Czech Republic		Brázdil et al., 2016
	Castilha-La Mancha - Spain		González Martin, 2010
	Lleida - Spain		Aran et al., 2011
	Ebro Valley - Spain		Garcia-Ortega et al., 2011
	Valencia - Spain		Cantos, 1994; Cantos et al., 1998
	France		Dessens, 1986; Fraile et al., 2003; Berthet et al., 2011; Merino et al., 2014b
	Northern Italy		Morgan, 1973; Giaiotti et al., 2003; Manzato, 2012
	Continental Croatia		Počakal et al., 2009
	Romania		Apostol and Machidon, 2009; Lungu et al., 2010
	Serbia		Ćurić and Janc, 2015
	Moldavia		Apostol and Machidon, 2011
	Bulgaria		Simeonov, 1996
	Macedonia		Dimitrievski, 1983
	Northern and Central Greece		Dalezios and Spanos, 1995; Sioutas et al., 2009
	Turkey		Kahraman et al., 2011; Kahraman et al., 2016
Oceania	Australia		McMaster, 2001; Schuster et al., 2005
Africa	Transvaal - South Africa		Admirat et al., 1985
Asia	Northern and Northwestern China		Zhang et al., 2008
	Southern China	Winter/spring	Xie et al., 2010
	India		Frisby and Sansom, 1967; Nizamuddin, 1993
	Myanmar and Easthern Pakistan		Frisby and Sansom, 1967
	Iran		Farajzadeh and Mostafapoor, 2012; Banafsheh et al., 2016
South America	Northeastern Argentina*		Mezher et al., 2012
	Paraguay		Frisby and Sansom, 1967
	Tropical Brazil		Frisby and Sansom, 1967
	Southern Brazil		Berlato et al., 2000; Marcelino et al., 2004; Iliine et al., 2010

Early warning can reduce the loss of life and potential economic costs (Ostby, 1992). The significance of hail nowcasts to warn the public of this weather event, therefore, becomes critical (de Coning & Poolman, 2011).

Predicting hailstorms had been a challenging task for weather forecasters because it is presented on small temporal and spatial scales (Roberts et al., 2012). During the last few years, this problematic challenge has been tackled in the scientific literature from many points of views (Collier, 1989; Doviak et al., 1993). From predicted conditions, key characteristics associated with hailstorms are identified which can also provide valuable inputs for nowcasting. The development of different algorithms was one of the first methods that utilise meteorological radar data that allows tracking and nowcasting of hailstorms (Joe et al., 2004; López & Sánchez, 2009). There have been recent developments in forecasting weather for periods of 6 hours too few days ahead.

Nowcasting is on the forefront in meteorology as it is the closest link the public has to forecasts due to the frequency of severe weather such as hailstorms (Behen, 2016). The fundamental aim of providing warnings ahead of hail events is to empower communities and individuals to respond to the event, to decrease the risk of death, property loss and damage. Nowcasting is composed of a full description of current weather conditions together with forecasts attained by extrapolation or nowcast models for a short period of 0 to 2 hours in advance (Brooks & Doswell, 1996; Smith, 1999; Ebert et al., 2005). Within this time, severe thunderstorms are forecasted with reasonable accuracy. A forecaster using advanced satellite, radiosonde observations and radar data can make a short division of small-scale features such as individual storms present in a small area with an accurate prediction for a few hours (White et al., 2009 & Haiden et al., 2011). Thus, it serves as a powerful tool in advising the public of dangerous high-impact weather such as tornadoes, hailstorms, thunderstorms, lightning, damaging winds and flash floods. The public is interested in how fast warnings and predictions of severe weather are released. Hence, it is important that research within this sector continues as it can aid in improving public perception of hail nowcasts.

Several factors drive societal views on severe weather events such as experiences with extreme weather (the intensity as well as the frequency of past events), social demographics and their confidence in forecasts (Zhang et al., 2007). If the individual detects weather forecasts as a false alarm or unreliable, they will not take precautionary actions unless the forecast is correct. Hayden (2007) adds that the correct perception of a weather event will decrease the vulnerability of an individual, while a wrong perception of weather events may reinforce vulnerability. The manner in which forecasts are presented to the public may have an influence on their perception of hail events. Silver and Conrad (2010) mentioned that precise and available warnings do not always influence the importance of the situation to the public. For example, when a severe hailstorm hit Bloemfontein on the 22 October 2016, most people were unable to handle a storm of its size. Regardless of hail warnings made by SAWS.

Literature published on societal perceptions of severe weather events is focused on cyclones and tornadoes (Anderson-Berry, 2003 & Zhang et al., 2007; Schmidlin et al., 2009 & Sherman-Morris, 2010). There are not many studies publishes both internationally and in South Africa on an individual's perception of hailstorms. However, noteworthy exceptions include Lazo et al. (2009).

1.1 The motivation for this study

Severe weather events may have disastrous impacts on society. Nearly 90% of all disasters over the past 10 years have been caused by meteorological related hazards, i.e. severe thunderstorms, floods and tropical cyclones (Buranszi & Horvath, 2014). Extreme weather events which include hail has been ranked by the World Economic Forum, (2017) as the event that has the highest impact and the most likely outcome of all economic risks in the world as shown in Figure 1-3. Hence, hailstorms were chosen to be the hazard of interest in this dissertation since they are the most prominent severe weather-related hazard in South Africa (Caelum, 2010; CRED, 2014).

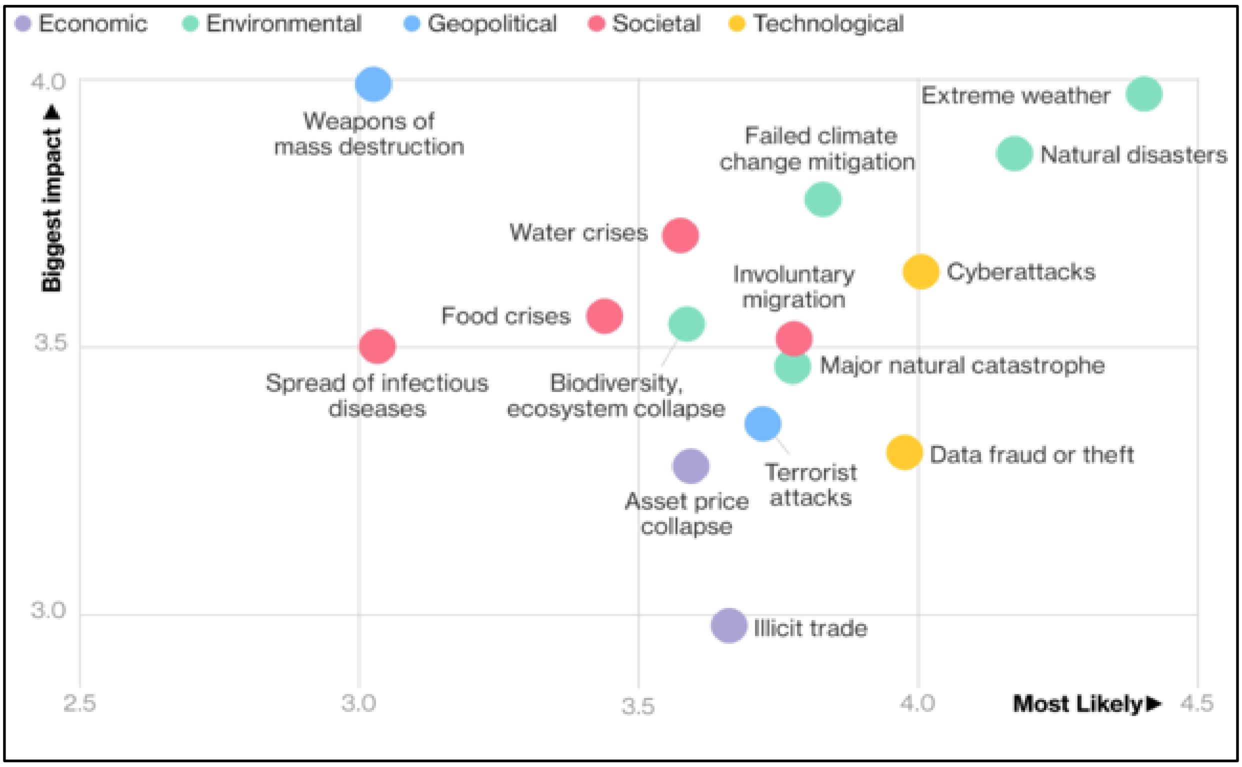

Figure 1-3: The probability of likelihood and impacts of economic risks in the world. The global risk landscape 2017 (Source: World Economic Forum Global Risks Perception Survey 2017).

The South African Highveld is home to recurrent occurrences of thunderstorms during the summer season (Tyson, 1986; Goliger et al., 1997; de Coning & Adam, 2000; Gill, 2008; Gijben, 2012). Most of these thunderstorms are austere in nature and are related to severe hail, damaging winds, floods as well as lightning (Carte & Basson, 1970; Carte & Held, 1972; Held, 1973). Gijben (2012) stated, "During 2007-2011 there has been approximately 28,778 paid insurance claims with an average of 6261 claims per year over the Highveld region". Amongst others, Pyle (2006) studied the socio-economic impacts of severe thunderstorms in the Eastern Cape province of South Africa and found that the majority of storms are associated with severe hail. From the aforementioned, severe hailstorms are related to mass destruction and have a significant impact on the economy (de Coning & Adam, 2000; de Coning et al., 2000b).

A catastrophic hailstorm in the Gauteng province that occurred on the 28 November 2013 caused an insured loss of over R1.4 billion, hence, making it one of the most damaging weather event in the South African insurance history (Visser, 2014). This was an example of a classical long-lived hailstorm that started in Pretoria and travelled to Johannesburg which resulted in hail damages, especially in Randburg, where tennis ball sized hail destroyed vehicles and properties. Consequently, on the same day, thunderstorms across the Gauteng Province were associated with damaging winds and hail (Burger & Powell, 2013). Therefore, to minimise damages as mentioned above, accurate predictions of hailstorms are important in a disaster risk mitigation perspective (Bunkers *et al*., 2006*b*). Hail occurs on a short time scale and has disastrous impacts on the public. Thus, there is a pressing need for effective forecasting, nowcasting and communication system.

Similarly, there has been very little research done on hail nowcasting in the last 15 years over the South African Highveld. As a result, this is an exploratory study focusing on forecasting and nowcasting hailstorms and lastly the perceived benefits of hail nowcasts to end-users.

1.2 Aim and objectives

The main aim of this dissertation is to evaluate the current state of a hail nowcasting system that provides early hail warning to end-users over the Gauteng Highveld. Thus, to achieve this aim, three primary objectives are followed in this study namely:

1) Review the current hail forecasting and nowcasting procedures of the South African Weather Service (SAWS)

2) Evaluate the objective algorithm used by SAWS to nowcast hailstorms; and

3) Assess the individual's perceived benefits of hail nowcasts.

1.3 Study design

To meet the study objectives, scientific principles governing data collection, analysis and the presentation of results were employed. The method used to meet the first objective required the use of interviews. Hence, an appropriate sampling method was used to represent the population. A well-structured interview was undertaken and comprised of open-ended questions. The interview was conducted in person to selected persons who were experts in nowcasting and forecasting on weather operations from SAWS. The second objective was to evaluate the objective algorithm used by SAWS. This was done by using radar data. The Thunderstorm Identification Tracking Analysis Nowcasting (TITAN) algorithm was programmed to run for 3 years. The nowcast products of TITAN were used to nowcast hailstorms for periods of 0-2h and verification of nowcasts was undertaken. Media and hail reports were used to subjectively identify hail events and results were correlated to the verification scores on a storm to storm basis; identifying how well the algorithm performed. The third objective was to assess the individual's perceived benefits of hail nowcasts. This was done by conducting interviews and the most applicable sampling technique was found to be the non-probability sampling method. Open-ended interviews were undertaken with individuals residing within the Gauteng Highveld. The aim of the interview was to explore the perceived benefits of nowcasts and what would be a successful nowcast to enhance or maximise those benefits. Details of the scientific principles governing data collection and methods of analysis are documented in Chapter 3.

CHAPTER 2

LITERATURE REVIEW

This section begins with a comprehensive overview of hailstorms. The formation and frequency of these events will be discussed briefly. Including, the damages that resulted from hailstorms. Hail forecasting and nowcasting are explained in detail with the associated algorithm which is used to predict this type of meteorological event. Lastly, the socio-economic benefits and the need for hail nowcasts will be well documented.

2 Severe thunderstorms

The purpose of this section is to present a brief breakdown regarding the different types of thunderstorms. The National Severe Storms Laboratory (NSSL, 2014) in the United States of America (USA) defines a severe storm as being the manifestation of a thunderstorm, associated by one or more of the subsequent weather phenomena (Johns & Doswell, 1992*a*; Rae, 2015):

- Large hail, greater than 18 millimetres (mm) diameter.
- Strong, destructive winds with measured gusts reaching or greater than 26 $m.s^{-1}$
- Any tornado, irrespective of intensity thereof.

In South Africa, SAWS follow the same criteria as NSSL; however, with two additional criteria namely; "significant urban flooding" and "large amounts of small hail" (SAWS, 2013; Rae, 2015). Thunderstorms are a mesoscale system as shown in Figure 2-1 with a spatial scale of 2 meters (m) to 100 kilometres (km) and a temporal scale of less than an hour (Bal *et al.,* 2014). Severe thunderstorms are associated with convection which requires three important ingredients. These ingredients are categorised as the following:

a. Sufficient atmospheric moisture.
b. Atmospheric instability to allow a substantial positive buoyancy and last, a lifting parcel so the moist layer can reach free convection moving upwards.
c. Cold fronts create unstable thermodynamic structures and the lift is provided by mesoscale features (Bal et al., 2014).

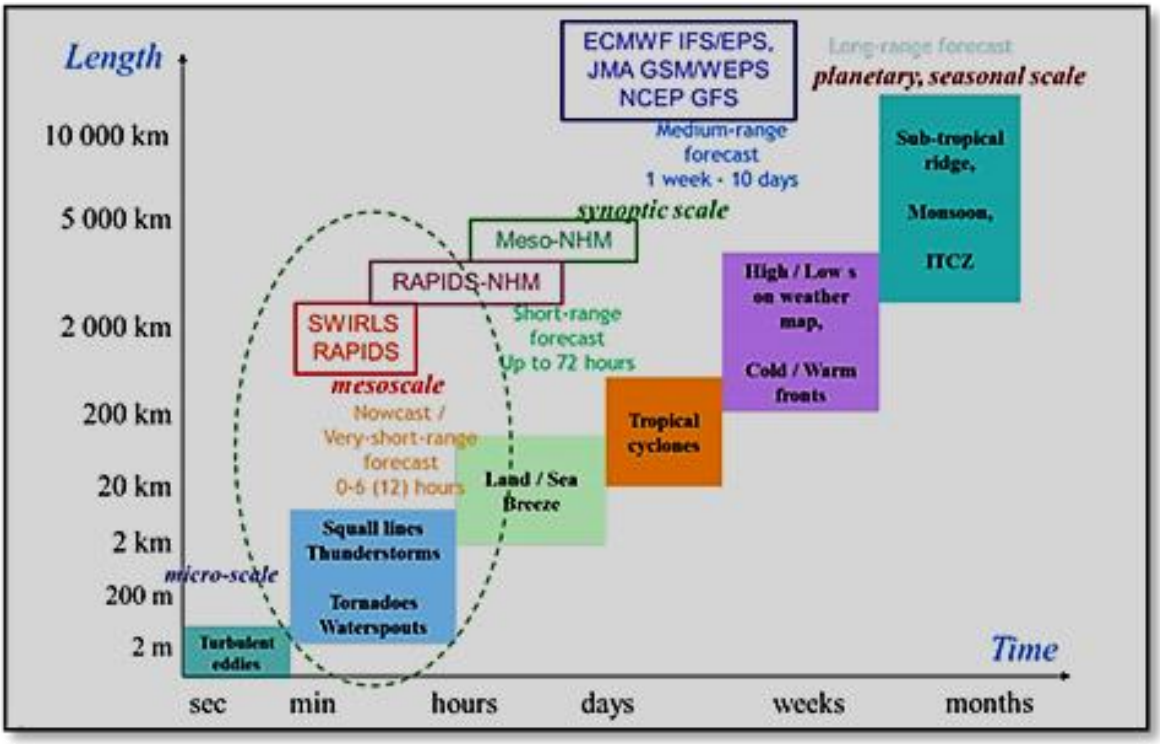

Figure 2-1: Various scales on nowcasting, short range and large range forecasting (Source: WMO, 2016).

Categorising thunderstorms according to the phases of development are the most typical encountered way in the literature (Whyte, 2000). Thunderstorms are arranged into three distinct types based on their associated climatological or physical features, for example, single-cell, multi-cell and super-cell (Whyte, 2000). These can appear as a scattered line or cluster storms. Wind shear, instability and upper winds can determine what type of thunderstorm may occur over an area.

The three primary types of thunderstorms are represented in Figure 2-2. Single-cells are like ordinary storms, however, the updrafts are short <30 minutes which forms a single pulse. Radar echoes in these storms are higher than 6-9 km than a normal thunderstorm. When the thunderstorm is in the mature stage, the area of the highest radar reflectivities 50Dbz maintain stability with descending and strong downbursts. Multi-cells are an organised pattern of cells at different phases of development with new cells continuously evolving. As the storm moves, new cells become mature as older cells move to the dissipation stage on the opposite storm flank. Echo regions begin to occur below a weak echo region (WER). Single cells have a lifetime of 30 minutes, however, the whole storm may last over hours. Multi-cell thunderstorms can manifest to weak tornadoes. These storm environments have moderate wind shears. Most thunderstorms that occur on the Highveld are of this type (Pyle, 2007).

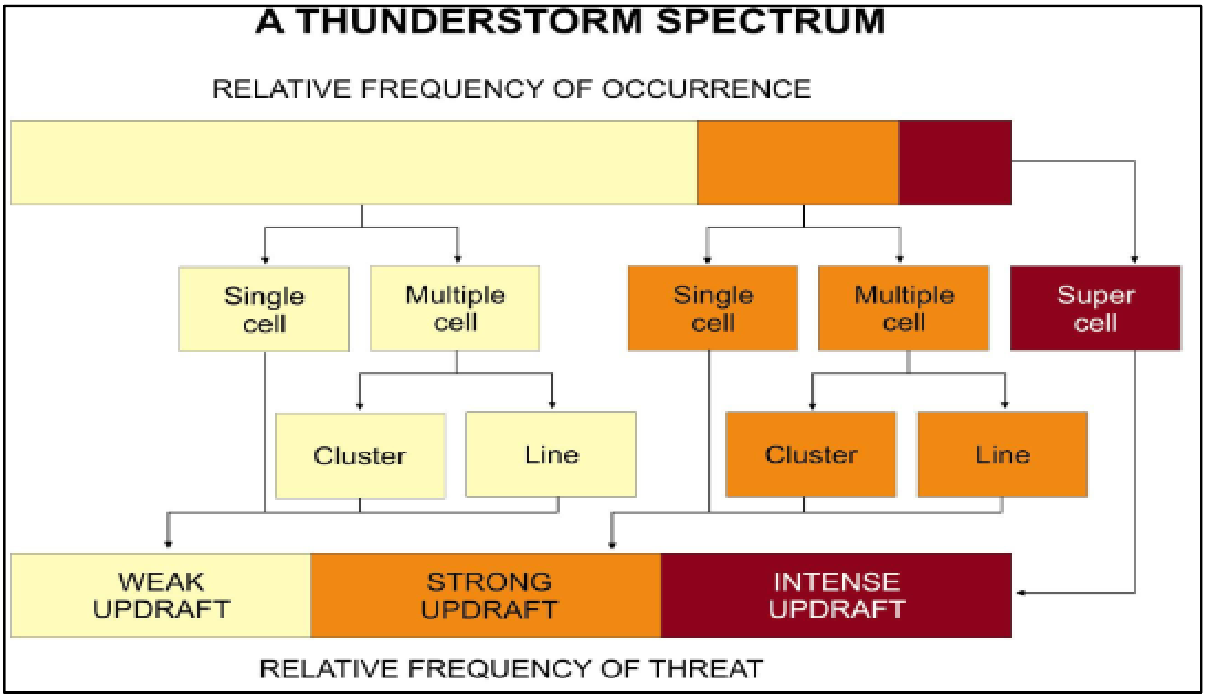

Figure 2-2: Different types of thunderstorms with their relative frequency of threat (Source: Pyle, 2007).

Supercells are rare and can develop from multi-cells. They are powerful and destructive of all types. Geer (1996; 221) explains a supercell as:

"Persistent, single, intense updraft (usually rotating) and downdraft co-existing in a thunderstorm in a quasi-steady state rather than in the more usual state of an assemblage of convective cells, each of which has a relatively short life; often produces severe weather including hail and tornadoes".

These thunderstorms are known for their large and intense updrafts that coexist during several hours. Mature supercells show a region of WER which persists near the centre of the updraft. As they strengthen, it becomes bounded (BWER) which gives rise to a hook like characteristics that appear on radar images. As a result, it produces severe lightning, damaging hailstorms, surface wind squalls, downbursts and tornadoes (Brandes et al., 1997; Bal et al., 2014). These thunderstorms are difficult and challenging to predict due to their quick occurrence.

Moreover, all thunderstorms, non-tornadic and tornadic, non-severe and severe, produce hail, strong winds, flash flooding and lightning of varying extent, duration and intensity. However, this dissertation is concerned with severe thunderstorms that are associated with hail (hailstorms). Hence, emphasis will be placed on how severe hailstorms can be nowcasted in advance to avoid potential losses.

2.1 Hailstorms

Hailstorms have an effect on individuals, the economy, society and the environment. The severity of this meteorological event varies upon several factors including the duration, timing and location of the event. Hail is a form of precipitation of ice (hailstones) and has a diameter of 5 mm either falling separately or agglomerated into irregular lumps (World Meteorological Organisation, 1956; Liu & Shou, 2011). Furthermore, hailstorms are formed by atmospheric instability, strong updrafts and organised low-pressure systems of vertical development, which is produced by tall cumulonimbus convective clouds (Robert, 2009). They are preceded by severe lightning and thunder, typically with a substantial amount of rainfall, strong winds and is short-lived (Liu & Shou, 2011; Blamey & Reason, 2012). Roberts et al. (2012:25) mentioned that “hailstorms result from atmospheric instability and makes up an overturning of air layers to achieve a more stable density stratification”. A strong updraft is a unique characteristic in a hailstorm during the initial phases. Strong downdrafts in a row of precipitation results in its dissipating stage (Pyle, 2006; Nicolaides, 2009).

Humid air rises within cumulus clouds, condensation and the growth of water droplets form clouds. Updrafts carry hail into the upper ice regions of the cloud, which fall into the super-cooled layer below with a temperature of less than 0°C (Whyte, 2000; Alexander, 2003). Figure 2-3 illustrates the storms descent and arrival at the ground after 4 minutes (T4). Its deposition forms a path of hail labelled as a hail streak, ending after 14 minutes (T14). Frozen droplets accumulate into ice crystals until they fall as hail. The size of the hailstones results from the severity and size of the storm (Adego, 2009; Kunz, 2009). Pflaum (1980) explained that hailstones are formed from super-cooled droplets which interact with cloud condensation nuclei (CCN) or through collecting other ice pellets or hailstones and it will fall through the warmer part of the cloud. A layer is formed around the hailstone through accretion. They are lifted by a strong updraft and it passes through various levels of moisture content and falls down. This process is continued until a hailstone structure is formed (Pflaum 1980; Nelson 1983; Brimelow et al., 2002; Knight & Knight, 2003). The physics of hail formation is discussed further in Mason, (1971); English, (1973); Rogers, (1979).

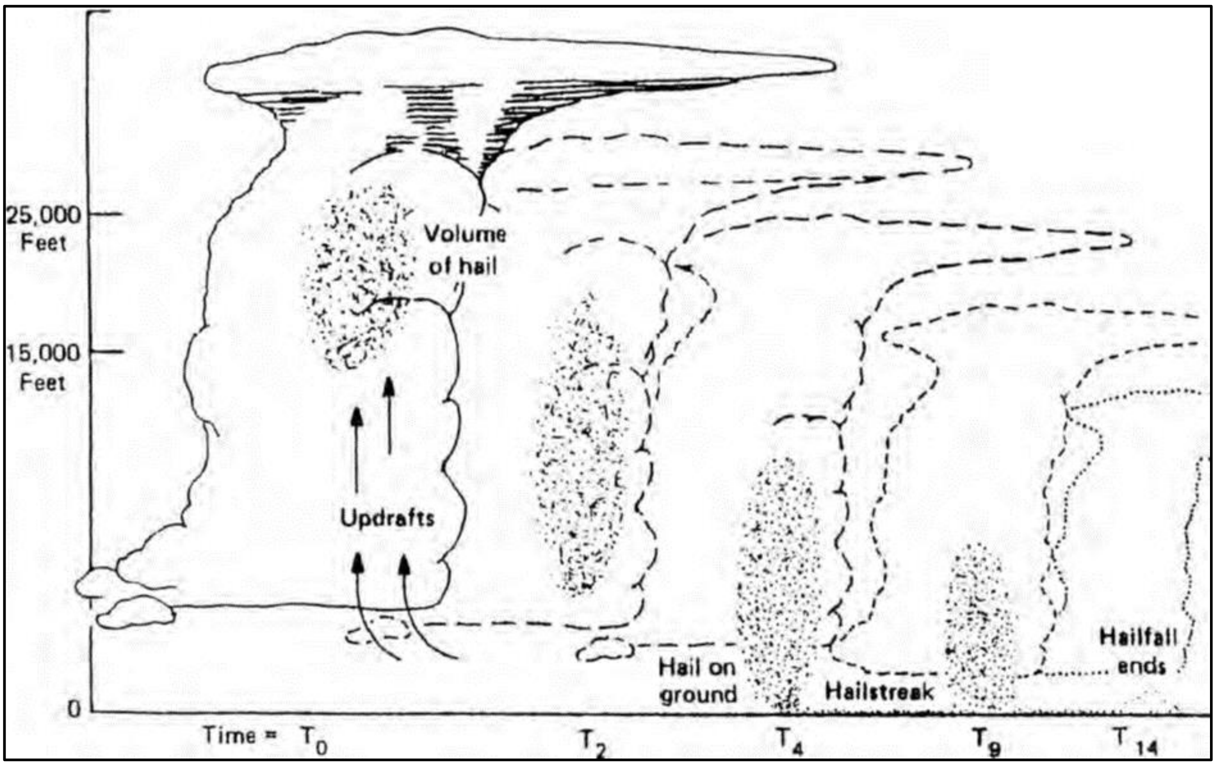

Figure 2-3: A sequence illustrating the development of hail inside a thunderstorm. (Source: Changnon, 2009).

2.1.1 Hailstorms over the Highveld

Hailstorms are seen to be one of the most damaging weather occurrences in the mid-latitudes (Olivier, 1988; Olivier, 1990). Hailstorms formed in summer may reach large diameters (Ludlam, 1980). These storms have a spatial extent of a few kilometres and may last an hour (Pawar & Kamra, 2004). The South African Highveld is susceptible to severe hailstorms, resulting in damages reported to be millions of rands annually (CAELUM, 2004). Furthermore, Admirat *et al.* (1985) stated that South Africa has a higher frequency of hail days per annum when compared to Canada and Switzerland. Le Roux and Olivier (1996) mentioned it is important to classify areas where the occurrence of hail is frequent. The frequency of hail intensifies as one moves inland and the Highveld experiences more hail than areas at a lower altitude (Carte, 1977*b*).

Scattered hailstorms are frequent over the Highveld, however, line storms are more austere, hence, leading to significant damage and flooding (Carte & Held, 1978). Line storms over the Highveld are not related to passaging cold fronts (Held & Van den Berg, 1977). Cold fronts may be related to severe hail conditions (Tucker, 1971; Estie, 1978; Held & Carte, 1979; Garstang *et al.,* 1985). During summer, cold fronts over the interior of South Africa remain allied with low-level convergence and mesoscale wind (Olivier, 1990). Olivier (1990) found that the occurrence of severe hail events over the Lowveld is closely related to westerly waves, which are subjected by the latitudinal position of the Indian Ocean Anticyclone. Throughout winter, westerly waves are limited to the Escarpment and Lowveld by a precipitous barrier along the southeast. During the early summer and spring months, there are changes in the daily heating cycle which influence variations in atmospheric stability. Thus, convection over the Escarpment and Highveld is initiated (Kelbe *et al*. 1983). Olivier (1990) further added that the majority of hail events occur during mid-late summer. During this season, circulation controls over the interior are temperate and tropical which are accompanied by easterly waves. Hence, easterly waves are the focal driver of general rains over the interior (Jackson, 1951; Olivier, 1990). The mechanisms responsible for hail generation in squall line storms are well documented in (Carte & Held, 1972; Held, 1973; Held, 1985; Carte & Mader, 1977; Held & van den Berg, 1977; Mader *et al*., 1986; Tyson, 1986).

Previous studies conducted on spatial patterns of hail yielded complex curvy connections between hail day frequency (HDF) in South Africa with two variables, namely altitude and latitude (Olivier, 1988; Olivier, 1990). HDF increases with latitude and altitude. Differences in altitude account for most of the temporal and spatial differences in hail occurrences. Pretoria and Johannesburg have the highest number of reported hailstorms than any other cities in South Africa (Caelum, 1991). Areas at higher elevations have a higher HDF than lower altitudes, possibly due to changes in cloud microphysics (Held & Carte, 1979). Hailstorms peak from early summer and the biggest hailstone sizes occur during mid-late summer (Carte & Held, 1978). Cecil and Blankendship (2012) found that 38% of thunderstorms are associated with heavy hail over the Highveld. The frequency is approximately five days of hail per year over the Highveld, with hailstones larger than 3 cm in diameter (golf ball size). During the peak months of November and December, hail is estimated every second day (Carte, 1977*b*). Figure 2-4 depicts a well-represented indication of areas vulnerable to hailstorms. The Eastern Cape and areas within the interior of the country experience a high HDF. However, due to the high population density in Gauteng, hailstorms are seen to cause more damage in the province than the Eastern Cape. There is an estimate of 3-5 hail events per year over the Highveld.

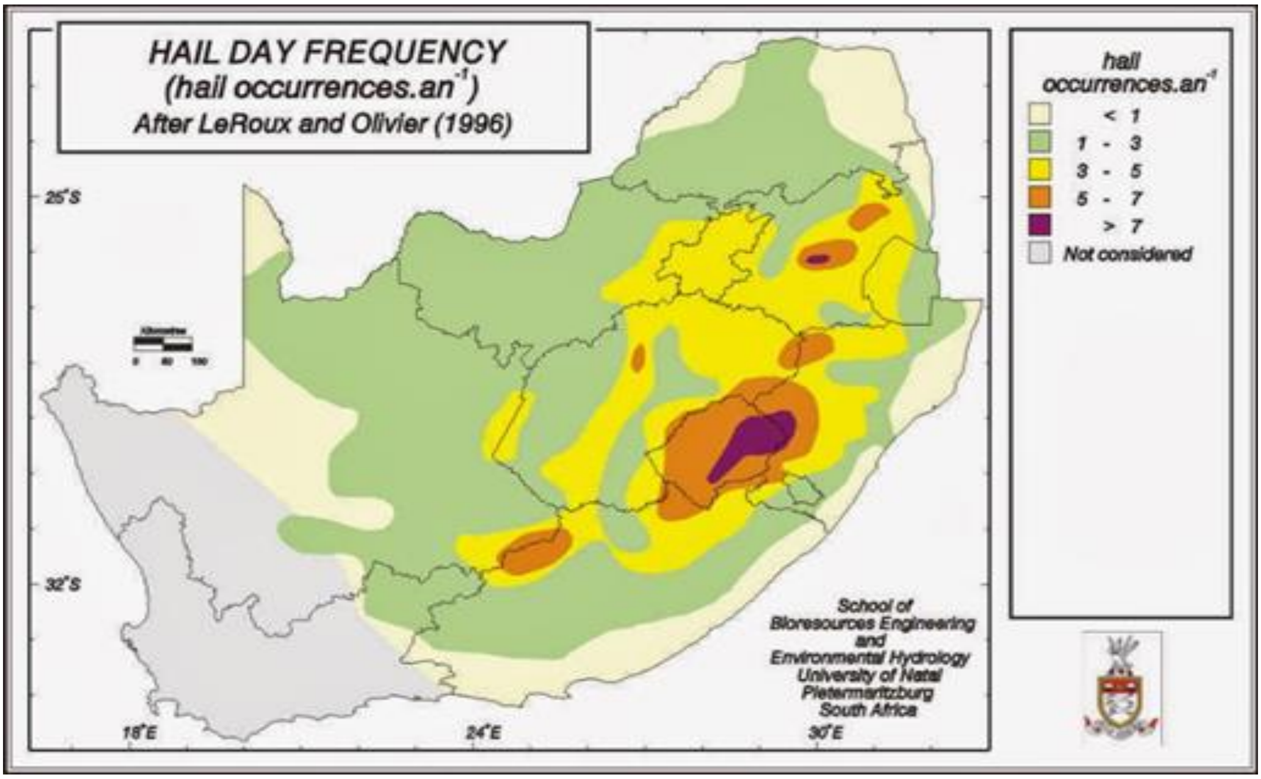

Figure 2-4: Areas prone to hail in South Africa. (Source: Schulze, 2007).

With the movement of the continental high pressure over the interior during late autumn and early winter, hailstorms are still observed in April and May. Hailstorms peak during late spring and early-mid summer, whereas the largest hailstones observed in October, November and January as depicted in Figure 2-5 (Carte & Held, 1978; Olivier & van Rensburg, 1992).

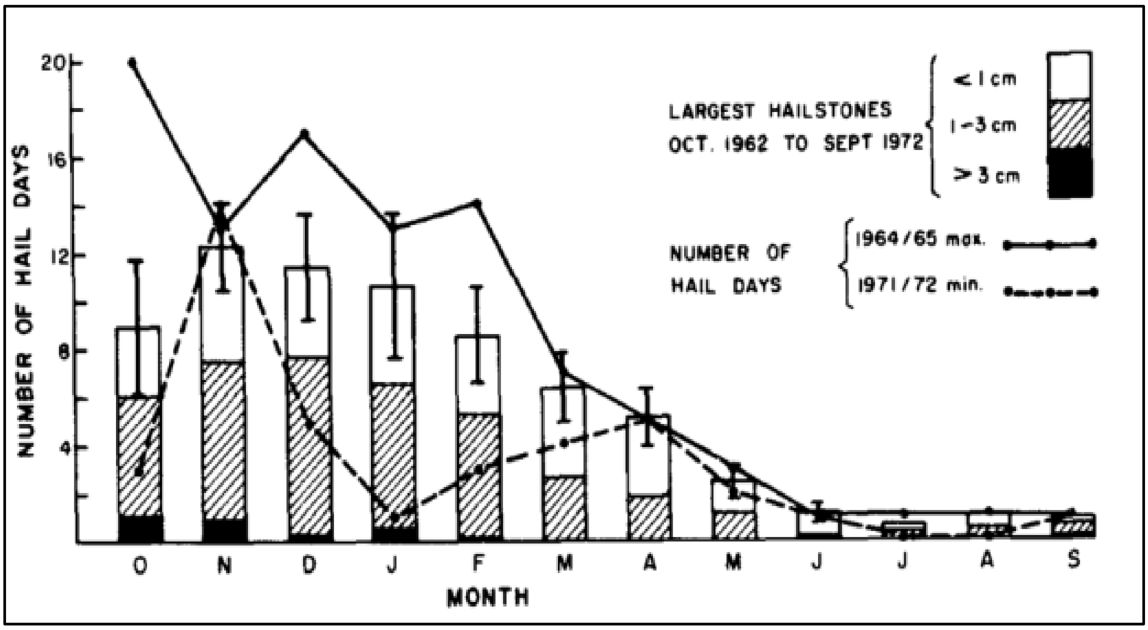

Figure 2-5: The monthly hail day frequency distribution over the Highveld. (Source: Carte & Held, 1978).

2.1.2 Hail damage and losses

The South African Highveld is a region vulnerable to recurring occurrences of thunderstorms (Gill, 2008) which are severe in nature (Goliger *et al.,* 1997; de Coning & Adam, 2000; Goliger & Retief, 2007). A severe hailstorm is a class of thunderstorms which are intense and short-lived (Browning, 1962; 1964; Bunkers *et al*., 2006*a*; 2006*b*) and may develop into a super-cell thunderstorm (Houze, 1993*a*; 1993*b*; Burgess & Lemon, 1990; Glickman, 2000).

Severe hailstorms are documented as dangerous and catastrophic meteorological events, which may result in extensive damage to agriculture, property, infrastructure, including the loss of life (Pyle, 2006; Nicolaides, 2009). Hail occurs frequently over the Highveld (Pyle, 2007). Admirat *et al*. (1985) found that South Africa has a higher percentage of hail days than Canada and Switzerland. The yearly cost of hail losses has been valued to millions of Rands (Gill, 2008). Hail losses are determined by characteristics that contain the number and size of hailstones which is dropped and the speed during hail fall (Zipser, 2006). Morrison (1997) concluded that the bulk of the damage to property occurs when hailstone diameters are 20 mm or greater. Theron *et al.* (1973) found that hail resulted in a 2.1% loss in agriculture production. Similarly, in 1997 a hailstorm caused 15 million rands in damages to crops over the Reitz area (de Coning *et al.,* 2000). The economic impacts specify the importance of understanding these events. The impacts of hail on the economy are well documented in (Jahn, 2015). Hailstorms also have an impact on the public whereby the poor are affected the most.

On the 28th of November 2013, a powerful hailstorm which struck the Gauteng province caused over ZAR1.4 billion in damages. This resulted in damages to houses and vehicles (Makhubu *et al.,* 2013). More recently, a hail event occurred on the 9 January 2016, wherein a powerful hailstorm struck a suburb of Johannesburg (Krugersdorp). Figure 2-6 illustrates a satellite image showing the intensity of the storm (Coetzer, 2016; Norris, 2016). Large hail caused severe damages which uprooted trees that fell on vehicles as shown in Figure 2.7-2.10.

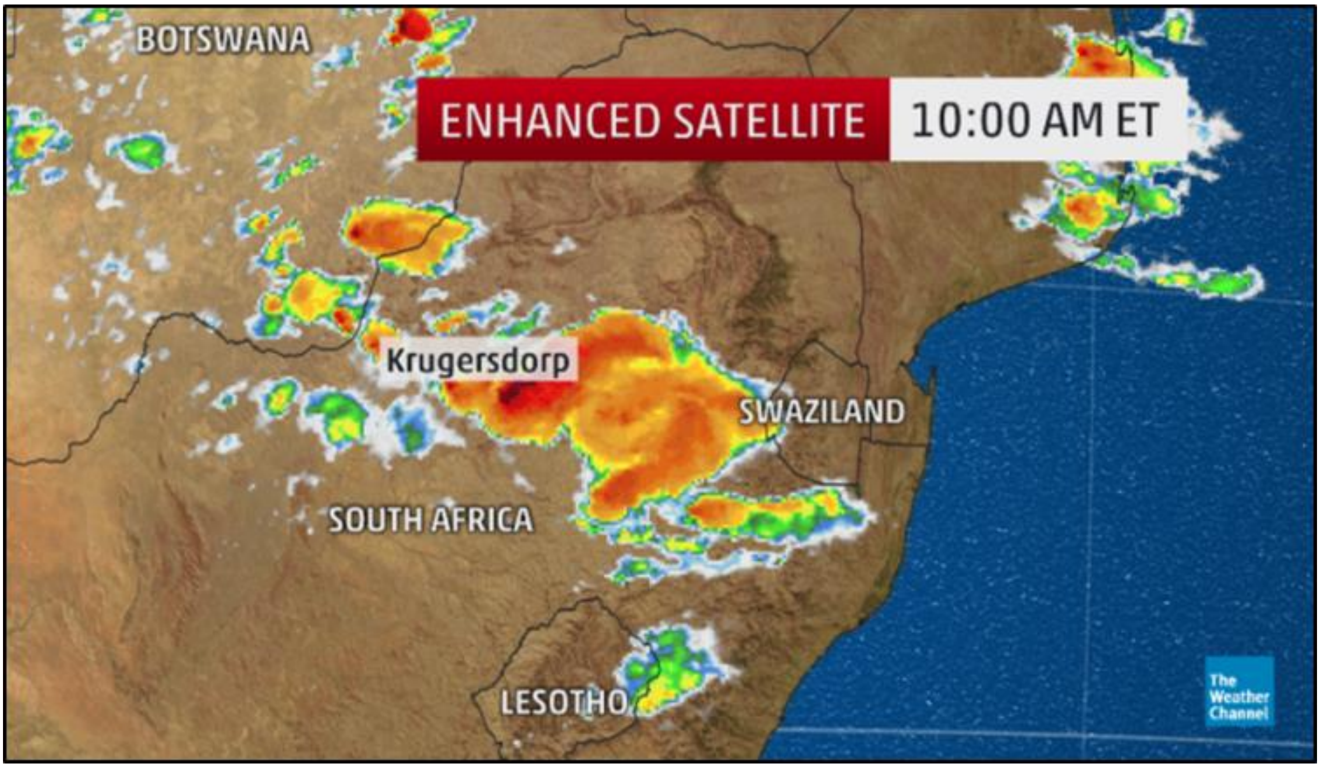

Figure 2-6: False colour infrared image from a Meteosat satellite. During 17:00 SAST severe hailstorms broke out over the Gauteng Highveld (Source: Coetzer and Norris, 2016).

Figure 2-7: Golf ball sized hailstones that precipitated over the Gauteng Province.

Figure 2-8: Illustrates a collapsed roof on vehicles prior to the hail event.

Figure 2-9: Floods that occurred in certain areas of Johannesburg.

Figure 2-10: Uncovered vehicle has been damaged.

2.2 Hail forecasting: An overview

Lopez *et al.* (2005) mentioned that hailstorms are difficult to forecast because hail falls in a small area during a severe thunderstorm and the duration is short. However, by understanding factors that affect hail development and the microphysics, forecasting models can, to an extent determine the probability of a hailstorm. Donovon and Jungbluth (2007) added that the forecast should be guided by the potential impact of the hail event. When stipulated thresholds are exceeded weather services around the world provide advisory products to end-users (Lean *et al*., 2008). Advanced warnings in hail forecasts will undoubtedly prevent some economic losses (Garcia-Ortega *et al.,* 2001).

Hail forecasting is carried out through different statistical and dynamical models which are used to predict daily weather, such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and Global Forecast System (GFS) among others. Numerical models can predict where hail will occur as well as the size that will precipitate with marginal success (Kaltenböcka *et al.,* 2009; Brimelow & Reuter 2009). Satellite images are used to indicate cloud top temperatures of thunderstorms to illustrate where severe hailstorms are located (Heinselman & Ryzhkov 2006). Forecasts are composed of primitive equation models such as NWP models. The extrapolative ability of the models is restricted by numeral factors consisting of the accuracy and the coverage of regular weather observations. Grid lengths and model formulations allow the appropriate dynamical and physical processes to be modelled. Warnings from numerical weather prediction (NWP) models can be distributed a few days prior to a potential weather event such as severe hailstorms or strong winds (de Coning *et al.*, 2015). General weather services, for example, the South African Weather Service (SAWS) has an obligation to advise the general public regarding anticipating precarious weather events. Figure 2-11 illustrates that the forecast skill is excellent during a short period of time whereas, the seasonal to sub-seasonal (S2S) and the seasonal models forecast weather and climate fairly well.

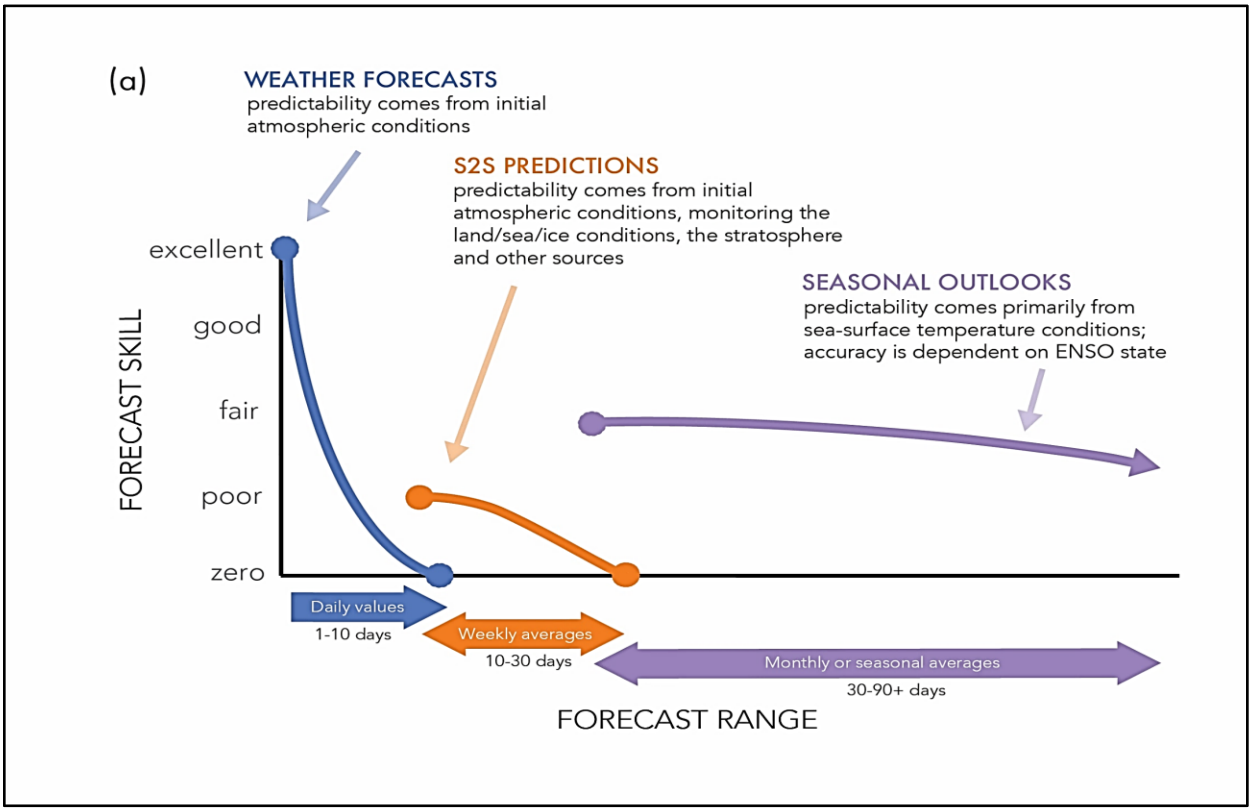

Figure 2-11: Qualitative estimate of forecast skill based on three types of forecast ranges (Source: Gawthrop, 2015).

Extrapolation of weather by radars and satellites are seen to be ideal when doing short-term forecasts such as nowcasting. Browning (1980) highlighted the comparative advantages of extrapolation weather and NWP model forecasts. Figure 2-12 indicates that the latter had a higher forecast quality up to 6 hours in advance. NWP cannot be used alone, radar and satellite observations are needed. Due to the limitations these tools have, specialists within the field are needed to interpret forecasts.

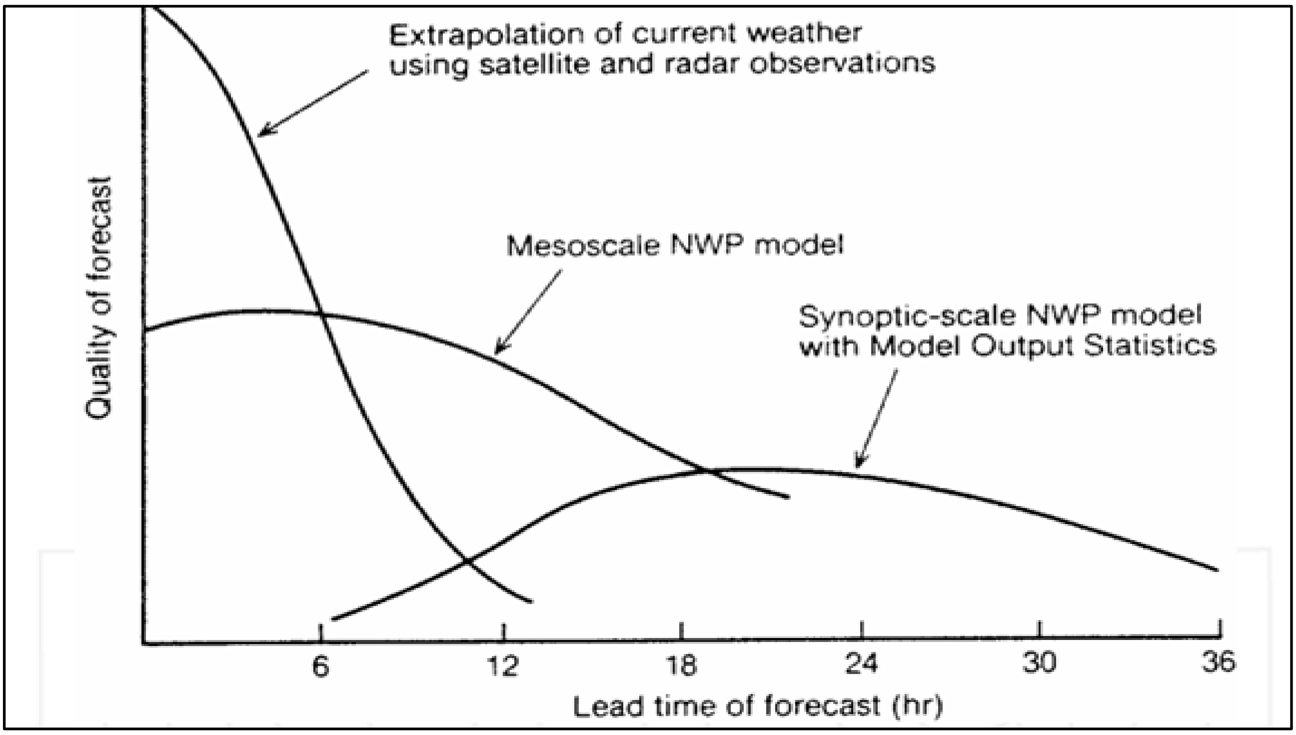

Figure 2-12: A graphic diagram after conceptualising the link between quality of forecast and the forecast lead time (Source: Browning, 1980).

Early warnings issued by SAWS provides weather information about expected weather based on radar and numerical weather prediction products, with limited descriptive information concerning impacts associated with these risks. There is no detailed information on how severe weather hazards will affect a specific community. This is typical to severe weather warnings issued by most weather services, and those in developing countries. It is expected of users to make their interpretation of how they will be affected by the expected severe weather hazard (WMO, 2012). This may be challenging because individuals may interpret forecasts incorrectly, hence, weather services need to communicate warnings effectively. There are various developments and improvements of forecasting systems of the weather-related risks (Georgakakos, 2005; Theis *et al*. 2005; Toth *et al*., 2007; Collier, 2007; Lean *et al*., 2008; Hey *et al*., 2009; de Coning & Poolman, 2011; Georgakakos, 2011; Warner, 2011; Landman *et al*., 2012).

2.2.1 Radar technology in forecasting

Hail has been a great concern for many years due to the substantial damage it causes to buildings, vehicles, property and agriculture (Plumandon, 1901; Changnon, 1978). During the 1950s, studies were undertaken to examine the presence of hail in severe thunderstorms by means of weather radars (Donaldson, 1961). Most of these studies investigated the relation regarding different radar parameters such as maximum reflectivity, strong echoes, the height of the contours and the vertical integrated liquid and the presence of hail (Wilk, 1961, Mather et al., 1976; Waldvogel et al., 1979; Amburn & Wolf, 1997). Radar hail detection algorithms are useful for examining the frequency of hailstorms over larger areas and in countries where long observations do not exist, such as Switzerland (Basara et al., 2007; Cintineo et al, 2012). Most weather services around the world employ radar methods to estimate the probability of hail. (Sánchez et al., 2013). The commonly used hail identification techniques are presented in Sánchez et al. (2013) and Kunz & Kugel (2015).

Weather radars are instruments which provide fast updates and volumetric exposure of present weather using remote sensing techniques (Fujita, 1990). Radars provide vital observations of the atmosphere with a high resolution so that small-scale features depict spatial variations (Toomay, 1989 & Wilson, 1990). Radars are operational tools that provide data to examine severe hail on an adequate spatial and temporal resolution that facilitate forewarnings of severe weather (Baumgart *et al*., 2008 & Schumacher *et al.,* 2010). They are used due to the three-dimensional (3D) view at approximately five-minute intervals at a spatial resolution of less than 1 km. Given the latest satellite, radar and other observational data, a forecaster will make an improved examination of the small-scale features present and will make an accurate prediction for the next few hours (Yadav *et al*., 2012). These forecasts improve storm warnings and support activities such as recreation, construction, aviation systems and traffic.

Attempts to identify and quantify hail has been ongoing for several years. Forecasters use radars for the identification of hail and had numerous successes (Donovan & Jungbluth, 2007). The radar itself does not delineate between snow and hail. However, different algorithms are used for different atmospheric conditions (Kennedy *et al*., 2001; Donovan & Jungbluth, 2007; Depue *et al*., 2007; Bal *et al*., 2014). The weather radar database plots the predictable movement of significant storms over the next hour and provides details regarding the storm such as hail and rotation. Figure 2-13 represents a microwave pulse, which is directed out from the radar transmitter. The pulse scans hail or raindrops and a part of its energy are returned to the weather radar (Kumjian 2013; Bal *et al*., 2014).

During the 1990s, new NWS radars were used to identify hail aloft. However, in most cases it was unsuccessful (Edwards & Thompson, 1998). Conventional radars (including the SAWS radars before the polarimetric upgrade) transmit horizontally polarised waves, which gave one measurement of the dimension of the cloud such as hail or rain. This radar makes it challenging to identify different precipitations (Heinselman & Ryzhkov 2006).

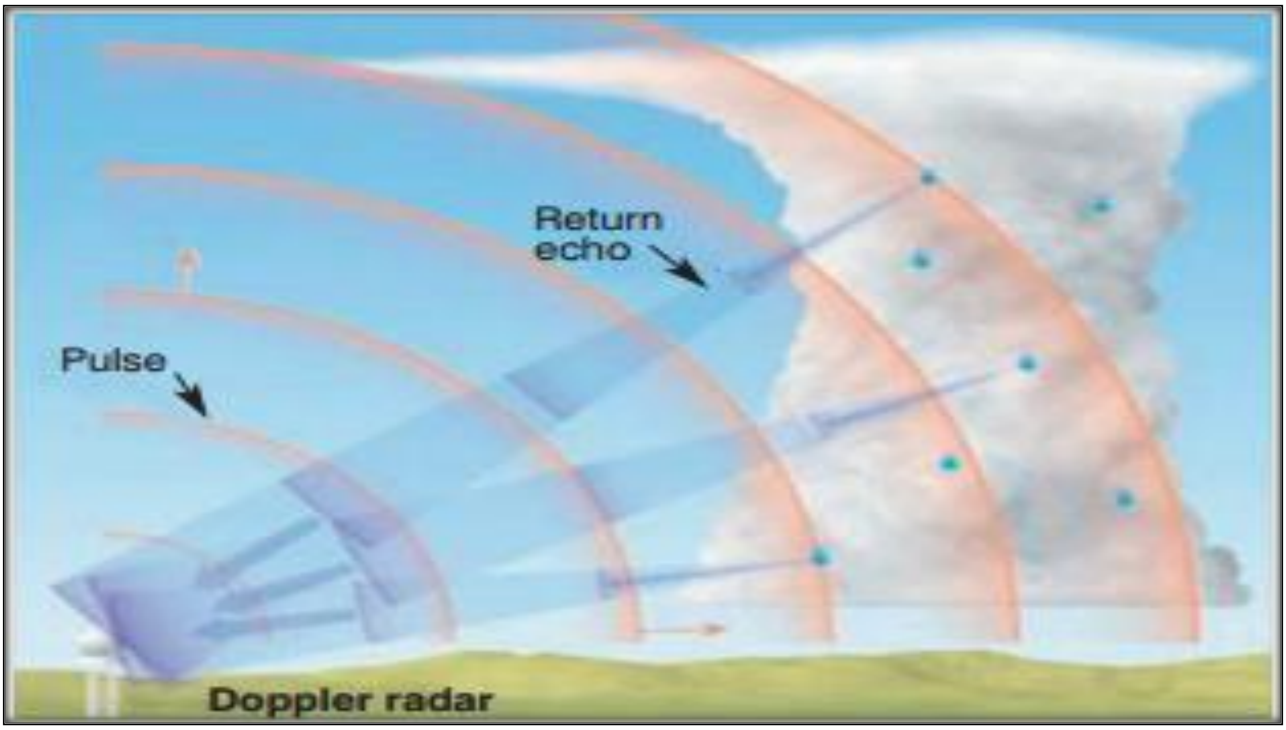

Figure 2-13: A microwave pulse sent out from the radar transmitter (Source: Bal *et al*., 2014).

Dual polarised radars have progressed significantly. These radars are effective in weather services. Polarised radars have illustrated substantial possibility towards research of remote sensing on hydrometeor classification, rainfall microphysics and the study of precipitation (Chandrasekar *et al.,* 2010). Dual polarised radars use two different wavelengths because the radar sends both vertical and horizontal polarised waves as shown in Figure 2-14. As these fields bounce off a moving object and are received, a computer program separates information about the vertical and horizontal dimension of the particles such as hail. Dual polarised radars offer a better possibility compared to single-wavelength radars for detecting hail and distinguishing it from rainfall (Bal *et al.,* 2014).

The dual polarised measurements have illustrated to be more precise in estimates as opposed to conventional radars (Li & Mesikalski, 2012). As mentioned above, these radars are the best for identifying and detecting hail in advance. United States, Australia and Europe where hail is prominent use dual polarised measurements, however, this radar is rarely been used in South Africa. In contrast, South Africa uses 16 single wavelength radars which can be upgraded to dual polarised radars. There is only 1 dual polarised radar in Bethlehem, however, it is not been utilised.

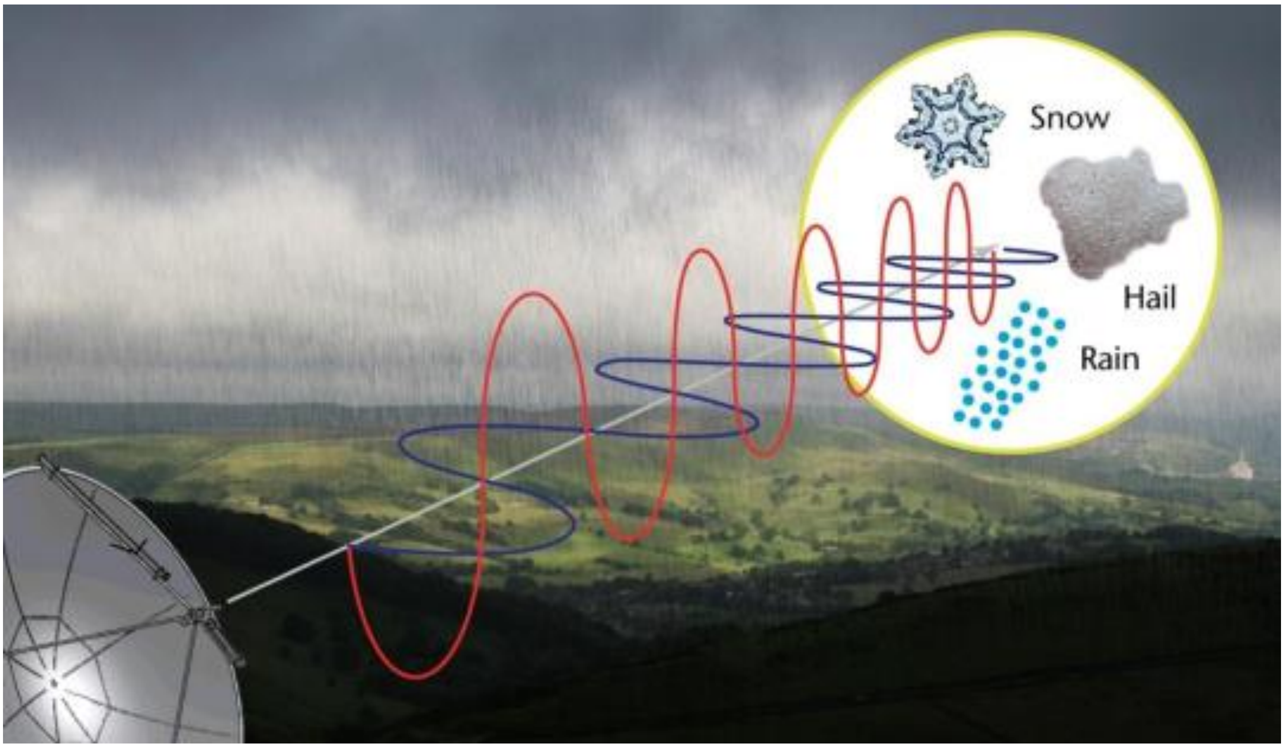

Figure 2-14: Schematic representation of a dual polarised radar measurement. The blue annotated line indicates the horizontal electromagnetic wave and the red line depicts the vertical scan (Source: Met office 2016).

Radar algorithms were one of the first methods that used meteorological radar data that tracked and nowcasted hailstorms (Joe *et al*. 2004; López & Sánchez, 2009). Radar algorithms are used to identify hail events (Kessler & Wilson, 1971; Johnson *et al*., 1998; Dance & Potts, 2002; Joe *et al*., 2004; Lakshmanan & Smith, 2009*a*; Lakshmanan *et al*., 2009*b*). The ability of detection relies on the type of the radar (Marshall & Ballantyne, 1975; Brown *et al*. 2000; Lakshmanan *et al*., 2006; Heinselman *et al*., 2008; McLaughlin *et al*., 2009).

These different radar algorithms help warn end-users of approaching hailstorms. In countries where weather radars are well maintained and accessible, radar data form a vital role in nowcasting systems. Well-calibrated weather radars provide a considerable amount of information to weather services (de Coning *et al.,* 2015). Burger and Powell (2013) studied the 28 November 2013 hailstorm that struck the Gauteng province using the S-band weather radar. The size of hail was estimated to be ~8cm, which resulted in damage to the roofs of households in various areas over the Gauteng Province. Figure 2-15 exemplifies a cross section of the hailstorm that hit the province through the application of the Thunderstorm Identification Tracking Analysis Nowcasting (TITAN) algorithm. The grey shaded area represents the intensity of the storm with a cloud base of 15km and a height of 10km. On the top right of the image, the array of colours illustrates the maximum reflectivity of each storm, whereby it indicates the severity and intensity of the storm. With grey being severe and dark green less severe and associated with light rainfall.

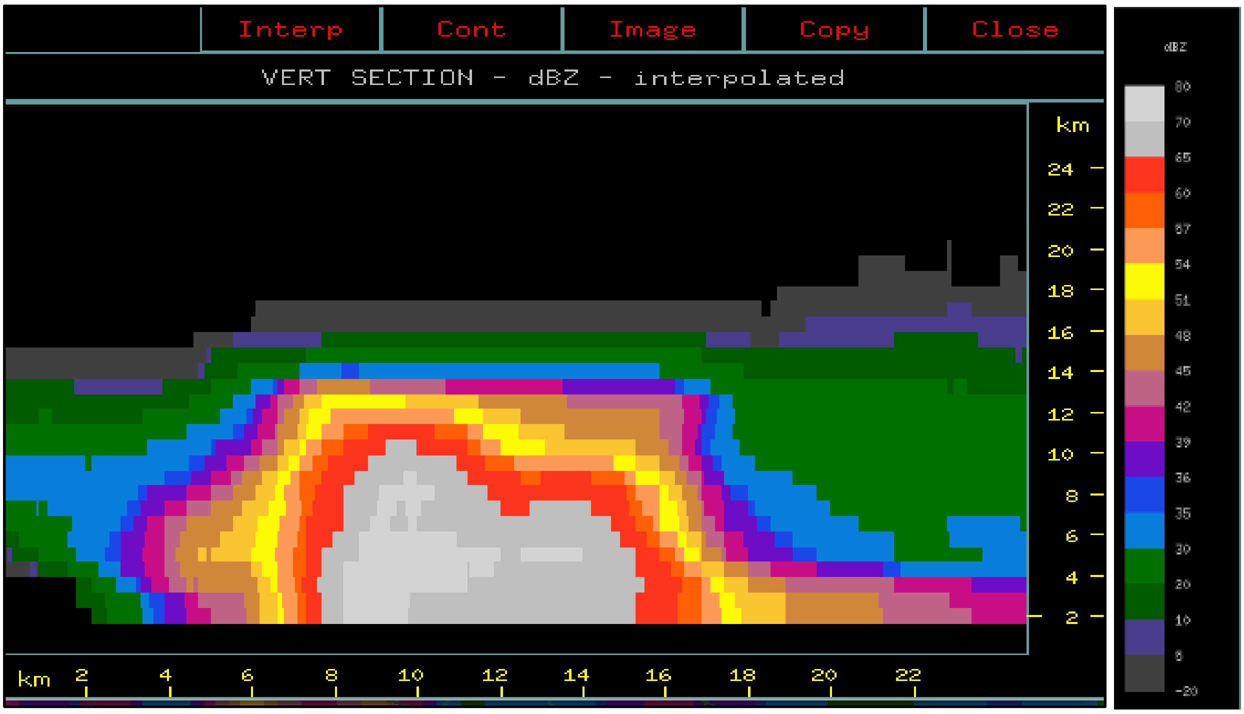

Figure 2-15: Cross section of one of the hailstorms that occurred on the 28th November 2013 using the TITAN algorithm.

2.3 Hail nowcasting

Weather forecasting plays an integral role in early warning systems within crisis management. In the last few years, there have been improvements in the evolution of severe weather prediction such as the improvement of forecasts and early warning. The main component of the weather prediction system is nowcasting. This weather forecast and analysis for the next few hours have improved greatly.

Nowcasting was initially defined by (Browning, 1981) as “the description of the current state of the weather in detail and the prediction of changes that can be expected on a timescale of a few hours” as shown in Table 2-1. Within this time, it is possible to forecast individual storms with reasonable accuracy. Figure 2-16 illustrates forecast skill against lead time. Theoretically, forecast skill is high closer to when the event occurs. Nowcasts performs just as well, however, at a shorter lead time. Nowcasts are issued by nowcasters (forecasters) who are well trained.

Nowcasting depends on fast updated observations on an integrated system that can be operated by the forecaster (Brooks & Doswell, 1996; Smith, 1999; Ebert *et al.,* 2005) it can also be done on any weather event, however, the emphasis in this dissertation will be on severe hailstorms.

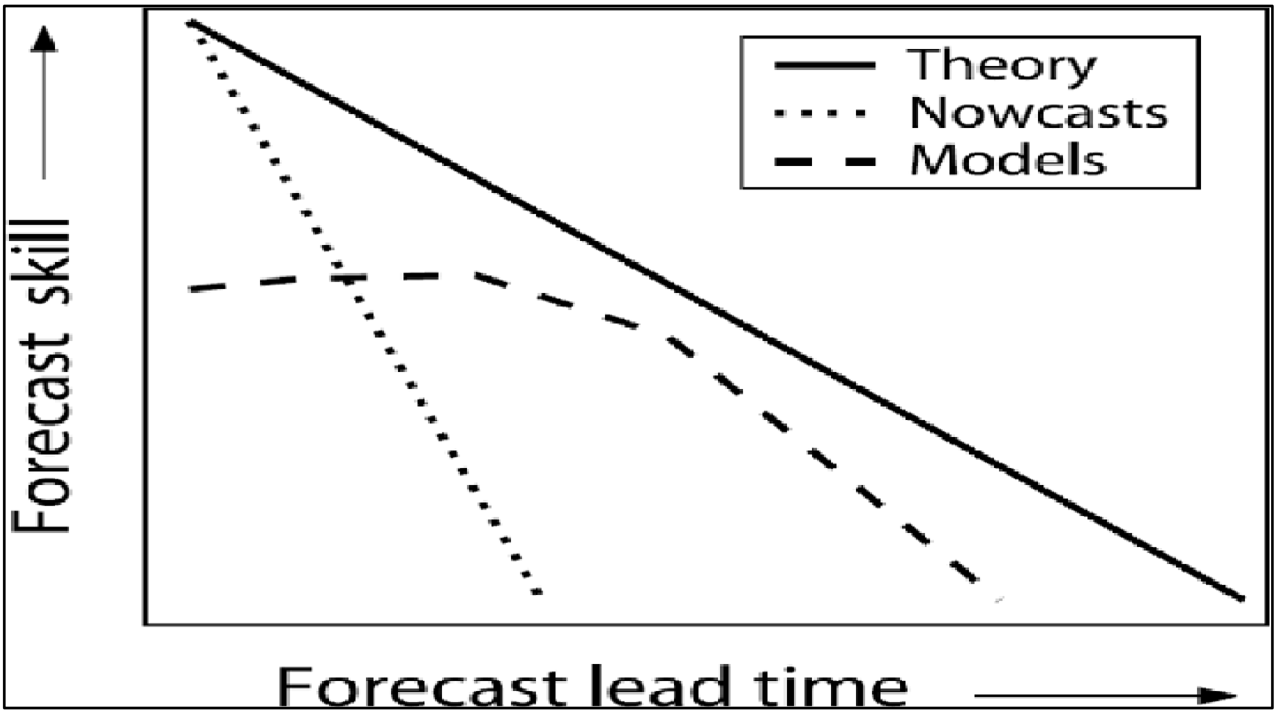

Figure 2-16: Schematic illustration of the loss of forecast skill as forecast lead time increases (Source: Lin et al., 2005).

Nowcasting hail can lead to substantial improvement in warnings and is of great practical importance. Hail nowcasts are done over temporal and spatial time scales in order for action to be taken to prevent damages to property, vehicles and losses of life. Therefore, the term "nowcasting" highlights the time and the specificity of a severe weather forecast (Browning 1982; Wilson 2004). The latest weather radars provide favourable measurement in range and resolution for nowcasting. Radar-derived products such as the Vertically Integrated Liquid (VIL) and reflectivity are useful for nowcasting hailstorms (Greene and Clark 1972; Smalley *et al.,* 2003). The South African Weather Service (SAWS) radar in Bethlehem provides high resolution dual polarised radar and measurements to facilitate observation and study severe events.

Table 2-1: Definition of meteorological forecasting ranges with their descriptions.

Types of forecast	**Description**
Nowcasting	A forecast with a lead time of less than 24 hours
Short range	Forecasts with a lead time of 1 to 3 days
Medium range	Forecasts with a lead time of 4 to 10
Long range	Forecasts of a lead time more than 10 days. This is usually known as seasonal forecasts.

2.3.1 Nowcasting observations

Nowcasting is based on extrapolating observations. During the early 1950s, severe thunderstorm nowcasts were based on extrapolating radar images (WMO, 2017). There are many ways in extrapolating for example thunderstorm nowcasts are built on the extrapolation of maps from lightning sensors, thunderstorm intensity is based on extrapolation of satellite images, nowcasts of winds, precipitation or temperature are based on dense networks of surface stations (Bailey et al., 2009). Nowcasting relies on observations that need to be quality controlled, assimilated by high-resolution models, evaluated by comparing the early frames of a forecast and analysis, action taken if there is a mismatch between the observations and the model input and lastly to verify the forecasts (Haiden *et al*., 2011; WMO, 2017). Although upper-air observations are important, only remote sensing can sufficiently provide high-resolution spatial coverage. Nowcasting techniques are developed in countries where radars used are robust. In developing countries, there is a lack of radars for nowcasting severe weather events. In these remote areas, "low cost" nowcasting systems are created using lightning and satellite data combined with NWP (WMO, 2017).

The integrated system comprises of observations from sensors and instruments which includes (satellites, lightning networks, radars and radiosondes). During periods of severe weather, the forecaster monitors the latest updated observations via integrated displays. NWP analysis from nowcasting systems is viewed on the same display (James *et al*. 2015). Hail nowcasts are radar-based observations that depend on accurate and new data to indicate initial storm conditions. The temporal and spatial resolution of nowcasts is finer than most NWP in capturing extreme values in hail events (Brooks & Doswell, 1996). Weather radars are the primary observation system for issuing warnings of severe weather events (Fabry, 2015; WMO, 2017). Radars have a distinct advantage over other observing systems because it directly observes precipitation in three dimensions (3D) over a large area with an update time of 5 minutes. At radar ranges of less than 60 kilometres, resolution of precipitation is less than 1 kilometre. This becomes possible to:

a) Estimate the amount of rain
b) Observe the structure of a severe thunderstorm and
c) Obtain the movement of thunderstorms which is the core to nowcasting

Hence, radar is a powerful tool in advising the public of extreme high-impact weather such as hailstorms. Extrapolating echoes is the backbone of nowcasting because radar data is comprehensive and identifies the shape, size, speed, intensity and direction of hailstorms (Wilson, 1998). Continuous monitoring of current severe weather is important for assessing the potential in nowcasting severe weather (Browning, 1980 & Wilson *et al.,* 1998). Severe weather also depends on the forecasters' knowledge and experience in the field, the conceptual models of weather processes, the dominant weather systems and triggers that lead to severe weather.

2.3.2 Hail warnings and watches

The fundamental aim of providing warnings ahead of hail events is to empower communities and individuals to respond appropriately to the event, to minimise the risk of death, property loss and damage (WMO, 2017). Nowcasts are fixed on providing accurate watches and warnings. These terms are based on the Glossary of Meteorology (Glickman, 2000). A watch is issued when the chance of the event has increased but the timing is uncertain. The aim of a watch is to provide individuals with enough lead time to take precautionary measures. Warnings are issued when the risk of the event is occurring. Warnings are issued for conditions posing a threat to individuals.

The South African Weather Service (SAWS) issue warnings when the public is threatened by severe weather events. These warnings are issued by forecasters to inform the general public of a high probability of severe weather, for example, a hailstorm. Improvements in warnings over the previous years in the United States have reduced fatalities from extreme weather events (Riberger *et al.,* 2014). Hail warnings and watches represent an essential form of communication wherein SAWS forecasters inform the public for the potential or imminence of hail development. However, this is effective if the public receive, to adhere and understand the information (Lindell and Perry 2012; Riberger *et al.,* 2014). People do not engage in precautionary measures to protect themselves from hailstorms if they do not receive and understand warnings issued by forecasters.

Nowcasting is a potential solution for predicting hailstorms. There has been less research on nowcasting hail; however, tornadoes are well nowcasted. Tornadoes have had a negative impact on people, especially in the United States. Previous studies Price, 2008; Dance, 2012 and Mass, 2011 have shown that if there is a good nowcast. If it is communicated well it will have a re-mediated impact on tornadoes. Roberts and Wilson (1989) conducted a study in the United States and found nowcasting successes for tornadoes, has saved lives and reduced vehicle and property damage. Hence, nowcasting hail may benefit the public, save money and even lives.

2.4 Radar-based nowcasting algorithms

Radar-based algorithms identify objects in the current radar scan and track the motion by identifying the same object in successive scans (WMO, 2017). This is known as cell tracking and is ideal for detecting and tracking severe thunderstorms (Dixon & Weiner, 1993). NWP models are customised to meet the requirements of nowcasting. Integrating data into a high-resolution model is the first priority. To evaluate the objective nowcasting algorithm in this study, different nowcasting algorithms will be discussed. Algorithms assign storm cells and track characteristics over a period and provide important information to weather forecasters in evaluating the storm growth, intensity and decay (Wilson *et al*., 1998).

During the 1950s radar-object based tracking of thunderstorms were studied in the United States to date. Battan (1952) found that the storm tops were "longer-lived" (> 20 min) cells and are more frequent than the shorter-lived (≈10 min) ones. Browning (1964) defined the super-cell storm as one of the "Most organised, severe, and longest-lived form of isolated, deep moist convection". In 1966, Wilson examined the relation of thunderstorm size and intensity (Wilson, 1966). In addition, during the 1970s, the development of surface observation and remote sensing techniques allowed to update the definitions of supercells (Wilhelmson & Klemp, 1978; Lemon & Doswell, 1979). The most widely accepted theory about super-cell associated with hail was by Klemp, (1987). Henry (1993) and MacKeen *et al*. (1999) analysed the relationship between storm longevity and reflectivity derived storm characteristics. Furthermore, during the last hundred years, radar object based algorithms were introduced for tracking thunderstorms (Lakshmanan & Smith, 2010). Dixon & Weiner (1993) developed the TITAN technique, while Morel *et al*. (1997) used a process of the extent of overlaps. Johnson *et al*. (1998) applied estimated centroid locations and Han *et al*. (2009) combined TITAN and the overlap methods.

The National Research Council (1995) found extrapolation-based nowcasts of 30 minutes have led to improvement in warnings. Radar-based nowcasting methods are categorised into four categories: object, area-based, probabilistic and statistical approaches. However, in this study, the object-based method will be used. This method identifies areas of high radar reflectivity's to track the shape, size and features across successive observations. An example of the current object-based method is TITAN (Dixon & Wiener 1993), where combinatorial optimisation techniques identify cell splits and mergers are used to track reflectivity objects.

Storm tracking procedures are the main constituent of nowcasting. The challenge on how to identify thunderstorms has earned vast attention from the research entity. Various methods in relating thunderstorm cells across time have been mentioned in previous studies. For example: using predicTable centroid location (Johnson *et al*., 1998), minimising a global cost function (Dixon & Wiener 1993), using extent of overlap (Morel *et al*., 1997), acquisitive optimisation of position inaccuracy and longevity (Lakshmanan *et al*., *2009b*) as well as examining the overlap. It is essential to assess these methods to decide which method can provide the best skill.

2.4.1 An overview of nowcasting techniques

Nowcasting methods depend on the efficient filtering of high-resolution data sets composed through satellites and weather operational radars. Hence, the development of nowcasting is perceived as a division of meteorology that has been closely bound up with recent improvements in telecommunications, digital computing and remote sensing. Nowcasting techniques are applied to forecasting of small-scale weather systems such as thunderstorms that cause damaging winds, hail, lightning and flash floods. This is a powerful tool in warning the public of severe hail events (Schumacher *et al*., 2010).

Ligda (1953) was the first to propose extrapolating radar echoes for the nowcasting of precipitation. In addition, Hilst and Russo (1960) described the initial demonstration for the use of scientific extrapolation to radar echoes. Noel and Fleischer (1960) were amongst the first to examine the probability of precipitation echoes. Additional studies were conducted by Russo & Bowne, 1962; Kessler & Russo, 1963. There were two significant findings from these past studies. The first finding was that small characteristics are short-lived than big storm characteristics. Secondly, in addition to the first, large-scale characteristics are long-lived (minutes to hours). These findings are found to be reliable with preliminary studies into the multiscaling properties of the atmosphere (Lorenz, 1973).

Algorithms were set up on the tracking of radar echoes and progressed with field-based pattern matching methods. These algorithms were designed to nowcast storms in America. Wilk and Gray (1970); Zittel (1976) were the first to define echo centroid trackers. The extrapolation trajectories were detected using a certain least square fit through continuous centroids. Blackmer *et al*. (1973) expressed grouping methods to solve challenges and complexities in cases that relate to the splitting and merging of echoes. Alterations to those methods were advanced and applied in operative tools throughout decades. Noteworthy examples are the Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN) system and the Storm Cell Identification and Tracking (SCIT) algorithm (Dixon & Wiener, 1993; Witt & Johnson, 1993).

Nowcasting algorithms are progressive in regions where hailstorms are a significant threat or hazard. Cell-based procedures are used to forecast the region of hailstorms in advance, therefore assigning characteristics of the events to that area. For example, a severe convective thunderstorm could be predicted which are associated with large hail. Therefore, warnings will be distributed. The fundamentals of cell tracking are to:

1. Formulate a set of algorithms that will be utilised to recognise the restrictions of a feature (for example small-scale thunderstorms) in either two or three dimensions;

2. Examine existing data to categorise features and allocate characteristics to them (large hail, heavy rainfall, damaging wind, etc.)

3. Relate the features to current tracks and approximate the advection velocity;

4. Forecast the area of objects in advance.

Algorithms describe an object as a small region of increased reflectivity (Crane, 1979) or connecting points that exceed the radar reflectivity, 40 or 45 dBz threshold as proposed by (Dixon & Weiner, 1993; Han *et al*., 2009). Describing the object in 3D allows one to calculate the height and volume of the cell. This adds value when conveying the basics of weather events and to the tracking and identification of thunderstorm cells. All objective-based algorithms must deal with challenges such as mergers, splits and terminations. In addition, this is frequently the point of distinction amongst numerous methods.

2.4.2 Hail nowcasting algorithm: TITAN

Hail nowcasting and identification using radar data are central features in predicting the strength and location of hailstorms. Numerous nowcasting methods using radar data has been advanced over previous years. These methods are categorised into two folded groups namely: centroid tracking (Austin & Bellon 1982; Rosenfeld 1987; Dixon & Wiener, 1993; Johnson *et al*., 1998) and cross-correlation tracking (Tuttle & Foote, 1990; Li *et al*., 1995). Wilson et al. (1998; 2004) gave an exceptional review of these algorithms; however, in this study, the centroid tracking method will be given more attention.

The centroid-type algorithm identifies single storm cells contained by a volumetric radar scan and is correlated with storms by predicting the thunderstorm position based on the storm centroid. This algorithm has several advantages, however, the main advantage is that it tracks confined storm cells and can provide time-based data of storms (Johnson *et al*., 1998). A classic centroid algorithm is TITAN as shown in Table 2-2, TITAN has been applied in different nowcasting systems all over the world, especially in Asia, South Africa and in Australia (Dixon & Wiener, 1993). The TITAN algorithm defines a thunderstorm cell as a contiguous area that displays reflectivity above a certain threshold. TITAN uses only one threshold to detect storm cells (Dixon, 1994). Furthermore, these storms tracked across successive radar scans using a combination optimisation method followed by a supplementary geometric method to handle splits and mergers. Lastly, this algorithm uses the centre of a recognised thunderstorm to make nowcasts on storm movement (Dixon & Wiener, 1993). Throughout the previous years, there were few changes made to this algorithm. In essence, this algorithm is a software for integrating data from vast types of radars and secondary data from surface observations, lightning sensors, numerical models as well as satellites.

The latest radar algorithmhms to detect hailstorms are not currently being utilised in South Africa. The algorithms that are used are not customised for South African conditions, which could be problematic because it could have an effect on the False Alarm Rate (FAR).

Table 2-2: List of nowcasting systems and their associated algorithms. Source: WMO, 2017.

Type of system	*Acronym (name)*	*Main reference*
Cell tracker	TITAN (Thunderstorm Identification Tracking Analysis and Nowcasting)	Dixon and Wiener (1993)
	SCIT (storm cell identification and tracking)	Johnson et al. (1998)
	TRT (thunderstorm radar tracking) algorithm	Hering et al. (2004)
	FAST (fuzzy logic algorithm for storm tracking)	Jung and Lee (2015)
Area tracker	CO-TREC (continuous tracking radar echoes by correlation)	Li et al. (1995); Reinhart and Garvey (1978)
	MAPLE (McGill algorithm for precipitation nowcasting by lagrangian extrapolation)	Germann and Zawadzki (2002)
	Optical flow in the GANDOLF (Generating Advanced Nowcasts for Deployment in Operational Land-based Flood Forecasts) system	Bowler et al. (2004)
	CASA (Collaborative Adaptive Sensing of the Atmosphere radar network)	Ruzanski et al. (2011)
Multiple observation system	ANC (Auto-Nowcast) system	Mueller et al. (2003)
	SWIRLS (Short-range Warnings of Intense Rainstorms in Localized Systems)	Li and Lai (2004)
	NowCastMix – Autowarn (nowcast mix – automatic warning)	James et al. (2015); Reichert (2009)
	CAN-Now (Canadian Airport Nowcasting) system	Bailey et al. (2009)
	INCA (Integrated Nowcasting through Comprehensive Analysis)	Haiden et al. (2011)
Probabilistic approach	STEPS (Short-term Ensemble Prediction System)	Bowler et al. (2006)

2.5 Nowcasting process

Nowcasting is a complete description of the current weather to the next few hours ahead with detail over a period (Sun *et al*., 2014). Previously, nowcasting was considered as a brief description with a forecast resulting through the extrapolation in time with a resolution of few kilometres (Wilson *et al*. 2010). Recurrent updates of present weather conditions are essential, especially during the occurrence of hailstorms (Wilson *et al*., 2010 & Sun *et al*., 2014). Figure 2-17 represents the core process of nowcasting severe weather (Gray, 2012). The nowcast process frequently examines ground-based data (rain gauge measurements, pressure, temperature and humidity) to identify approaching weather such as changes in local conditions, sea breezes or cold fronts (Wilson *et al.,* 1998). Radar, satellite-visible infrared imagery and lightning data if available, are used to track the movement of severe convective events, including hailstorms approaching the area (Conway, 1996).

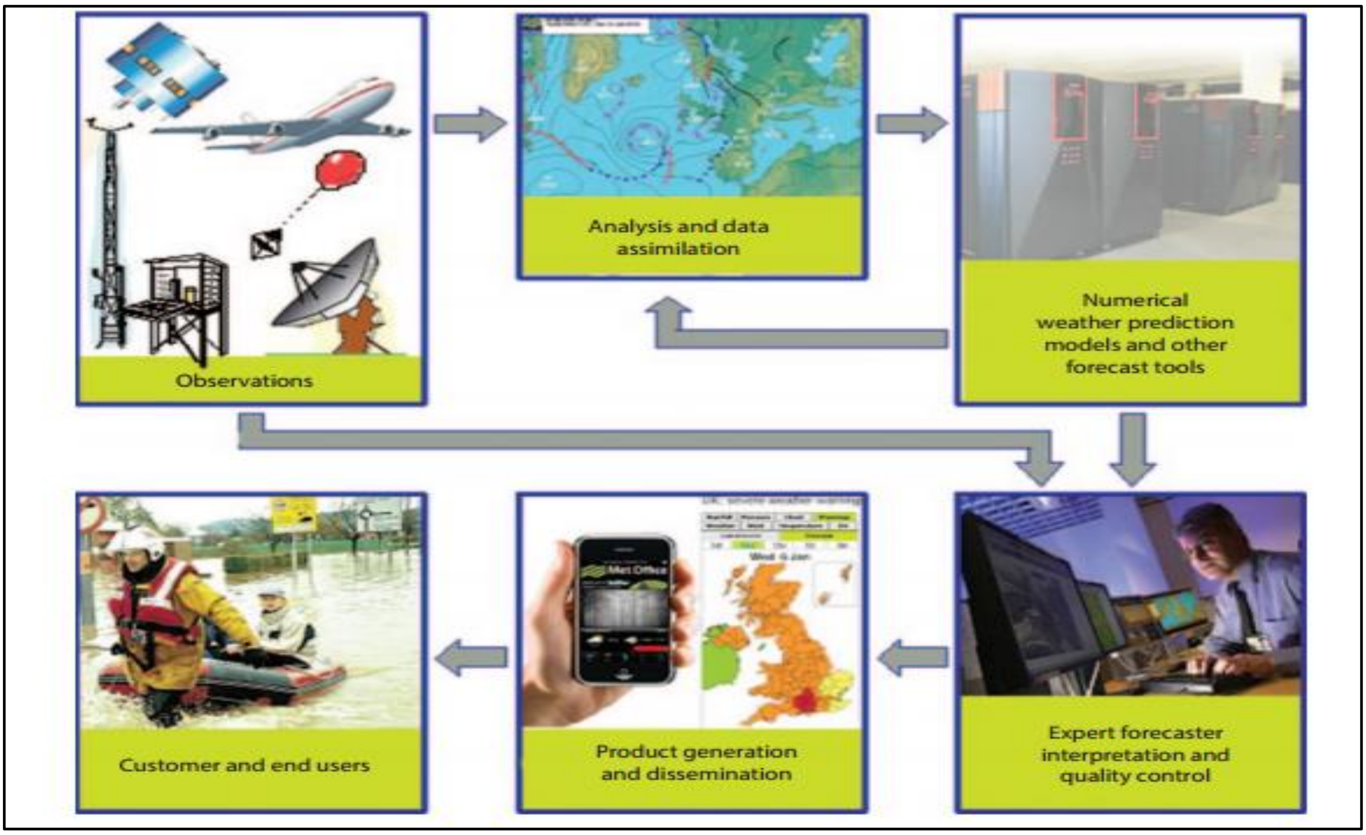

Figure 2-17: The basic nowcasting process that is commonly used (Source: Gray, 2012).

2.5.1 Convective Weather Outlook

The forecaster examines weather maps, NWP model analysis and available real-time observations to examine if there is a possibility of hail as well as to provide a convective outlook for the day (Wilson & Roberts 2006). The ability of NWP models to correctly forecast severe weather on spatial (~1-km horizontal) and temporal (0-2 hours) scales are limited. However, these NWP forecast errors are because of the lack of operational observations required to present a comprehensive depiction of the environment when they are initialised (Benjamin *et al*., 2004; Stensrud *et al*., 2009). NWP models at horizontal resolutions less than 12 km show development in signifying hail intensities and structure (Done *et al*., 2004). However, as the resolution increase, objective verification scores are lessened due to temporal and spatial inaccuracies in the hail forecast (Mass *et al*., 2002). Integrating satellite, radar and other datasets into NWP models aids in the improvement of nowcasts (Benjamin *et al*., 2004; Done *et al*., 2004; Sun 2005; Weygandt *et* *al*., 2008; Stensrud *et al*., 2009). Sun *et al*. (2014) have shown that integrating radar data into progressive numerical models improves the forecasts for 2-3 hours. Therefore, forecasters use these models and tools in examining the convective outlook for the day.

2.5.2 Conceptual models and climatology

The forecaster uses climatological information by integrating patterns in different observational datasets to develop a hypothetical estimate of what is happening in the atmosphere and what is predicted for the next 0-2 h. Conceptual models are developed and applied by forecasters to represent detailed synoptic or mesoscale characteristics. Previous studies have found that storms originated near noon due to solar heating along the boundary layer convective rolls or the slopes of small hills. Some of these storms precipitate and produce cold pools with spherical gust fronts alongside the cold pool. In the afternoon, gust fronts collide, hence, causing massive storms to form. Nowcasters need to develop similar conceptual models for their area.

Knowledgeable forecasters are needed in nowcasting severe weather for example hailstorms. This is achieved through forecast experience and is facilitated by the background of climatological frequency and location of hail events as drawn from statistical processing of data (Lima & Wilson, 2008). Forecaster skills are necessary for nowcasting it includes knowledge of weather and weather patterns, better personal meso-analysis skills for fast detection of meteorological systems and the quality of real-time observations.

2.5.3 Stability Analyses

Forecasters evaluate the possibility of convective weather by using recent radiosonde thermodynamic features. These indices are used for hail forecasting which is required to be validated for the specific area for critical values. Amongst several indices, the K-Index, Lifted Index, and Total-Total Index is used in forecasting convection as an unstable atmosphere. The Wet Bulb Zero Height gives a good indication of surface gusts and hail.

Stability is vital in the nowcast process since it helps the forecaster to predict weather that may occur later during the day. Current techniques for evaluating the instability of the atmosphere using both satellite-derived stability indices integrated with NWP forecasts of environmental stability seems promising in providing 6-9 h lead times for the convective potential of the atmosphere as well as areas with a probability for severe convection (Koenig & de Coning, 2009; de Coning *et al*., 2011). The satellite-retrieval method for deriving the Global Instability Index (GII) products is currently calculated during pre-convective conditions.

With the high frequency, 15-min MSG update cycle, changes in atmospheric stability can be continuously monitored. This is a distinct advantage over using NWP model forecasts (Koenig & de Coning, 2009). Examples of the GII products available to forecasters from EUMETSAT are shown in Figure 2-18. SAWS usually integrate a regional version called the Regional Instability Indices (RII) with a mesoscale model, and factors for orographic lift, to produce a likelihood for convection in the form of a new Combined Instability Index (CII) (de Coning *et al*. 2011).

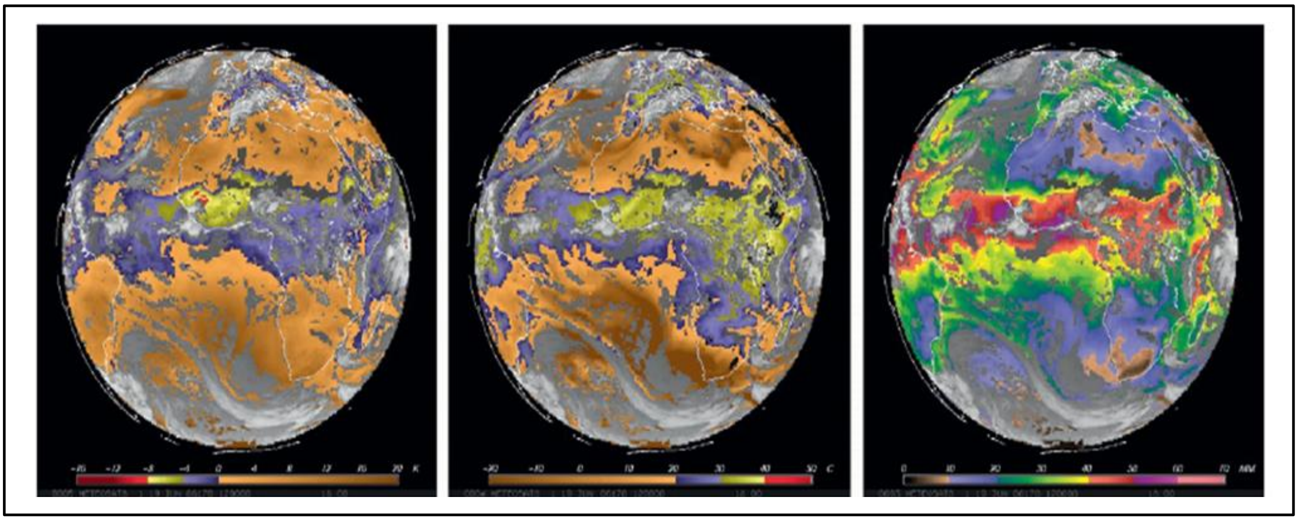

Figure 2-18: Examples of the EUMETSAT GII products derived from the MSG satellite for Africa on the 19 June 2006. Indices are shown in panels are lifted index (left), K index (centre) and total perceptible water (right) (Source: Koenig and de Coning, 2009).

2.5.4 Storm type

Weather forecasters decide if there is fair CAPE to support the potential for convective weather. If the values are significant for their region, the forecaster must determine if there is a possibility for severe weather and what type of severe weather might occur, for example, hailstorms. The vertical shear indicates the type of storm that can occur. Vertical wind shear takes the form of unidirectional speed or may have characteristics of speed and directional shear, which tend to support single cell, multi-cell super-cell type storms. Grounded on past studies from North American storms, Figure 2-19 is an example of what a classic shear profile may look like for West Africa and the type of storm that would occur (Chisolm & Renick, 1972).

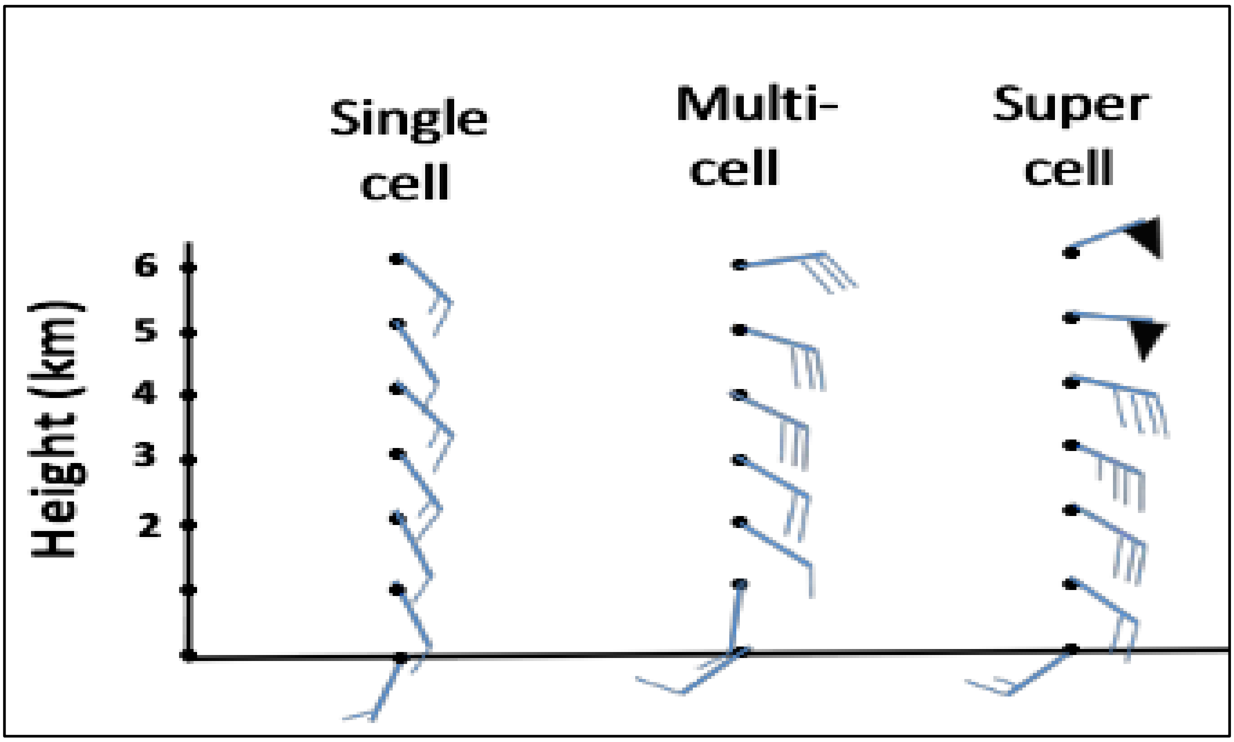

Figure 2-19: Proposed sample vertical wind shear profiles for single, multi and supercell storms for West Africa (Source: Roberts, 2012).

Additionally vertical wind shear and the buoyant energy of the atmospheric environment also contributes to storm type and severity. The bulk Richardson number is a warning of the seriousness of the storm as well as the ratio of stability to the shear in the atmosphere.

2.5.5 Extrapolation of Existing Storms

Nowcasting, the region where hailstorms occur has been based on extrapolation of current satellite, lightning and radar observations. Satellites and radar have been most suited for use in nowcasts because they provide large spatial coverage of the weather at high temporal and spatial resolutions. Figure 2-20 is an example of automated storm detection and extrapolation techniques applied to radar data, respectively. Shown are 30min (orange polygons) and 60min (red polygons) storm extrapolations and the storm motion vectors on 3rd of July 2008.

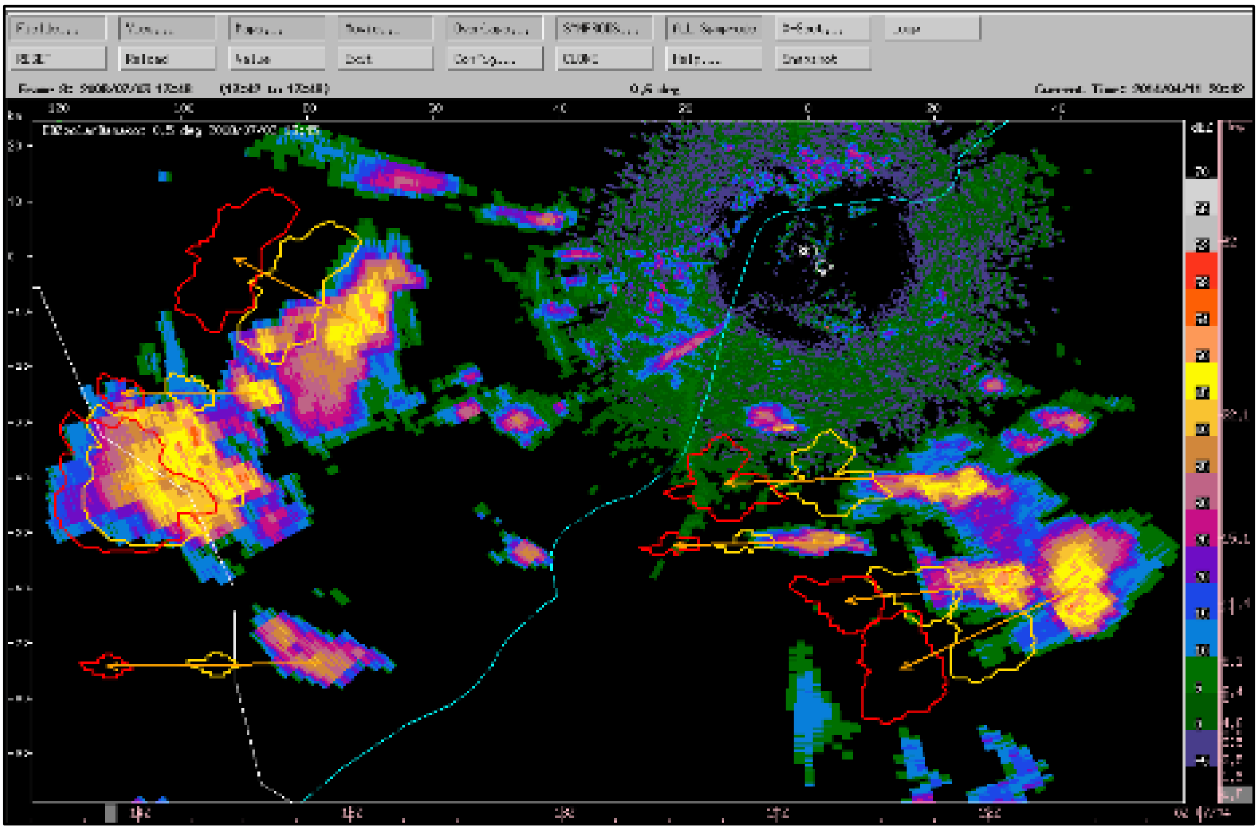

Figure 2-20: Example of automated storm extrapolations run on radar data in Mali, using the TITAN algorithm (Source: Roberts, 2012).

It is imperative to note that the constant assessment of most extrapolation techniques are that storms do not alternate in intensity or size but maintain a steady state. Previous studies have shown that they link the forecast of hailstorms with storm size, evolution, and duration (Kessler & Russo 1963; Wilson, 1966). Multi and super-cell storm complexes are organised which merge or split during their lifetimes and have longer durations of >1 hour as portrayed in Figure 2-21. While small-scale single cell storms are shorter with mean duration of less than 25 minutes (Foote & Mohr 1979; Henry, 1993).

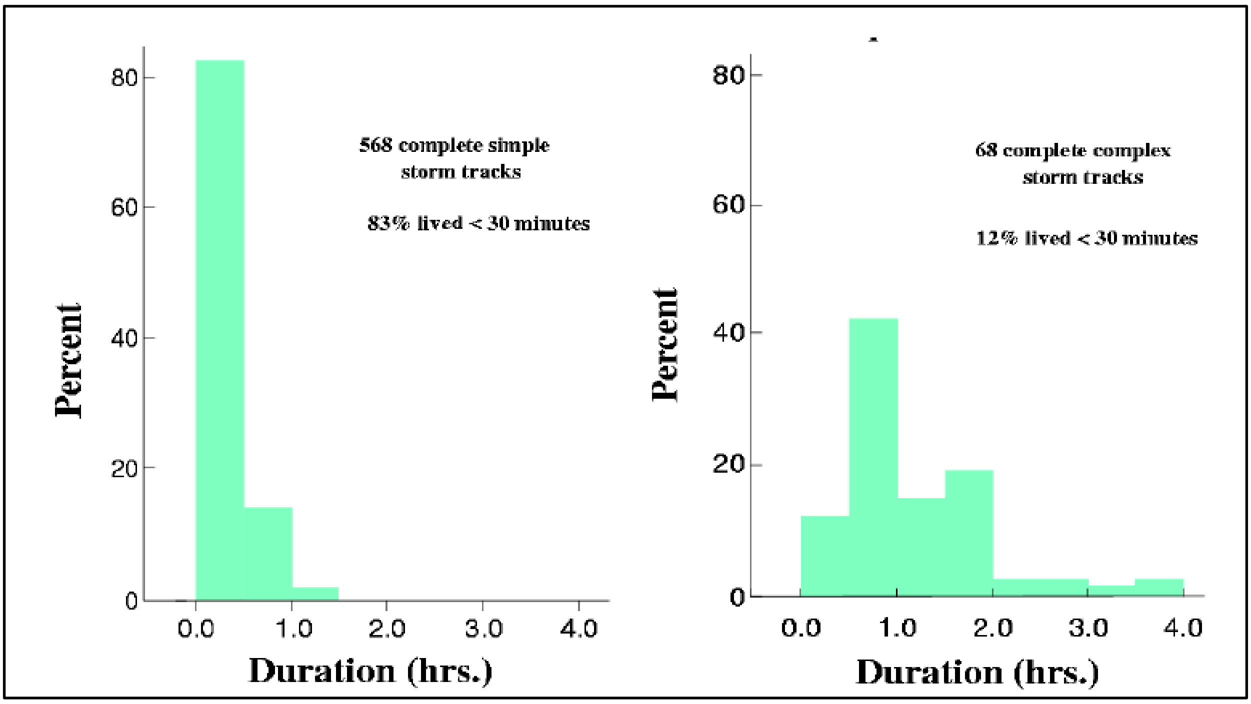

Figure 2-21: Histograms illustrating the lifetime of complex and simple storms observed in summer near Denver, Colorado (U.S.A), based on data from an automated cell tracking system called TITAN (Source: Roberts, 2012).

2.5.6 Deciding on the opportunity to issue warnings

When hail is expected in an area, warnings need to be issued as soon as possible (WMO, 2010). The decision to issue warnings will result from the assessment of specific forecast weather elements (temperature, wind speed, precipitation) with fixed thresholds. The decision to issue warnings are not only governed by the expected value of meteorological parameters but also on the expected impact (WMO, 2010). For example, forecasting hail during traffic hours may justify the issue of warnings even if the expected hail accumulation does not exceed the agreed threshold. It is not possible to develop rules to decide whether severe hail warnings should be issued.

2.5.7 Distributing the various products to end-users

The role of a forecaster is vital in providing end-users with detailed information regarding severe weather features as well as expected hazardous weather for the next few hours (Roberts & Wilson, 1989; Mass, 2003 & Mass, 2012). Mass (2012) found that forecasters will undergo a significant change in the upcoming years from long-term forecasts to nowcasting on a 0-6 h period. Rapid and efficient communications for nowcasts to end-users will be greatly improved using social media (Mass, 2012).

The distribution of weather products entails preparing a forecast for the users (e.g. civil protection, aviation and hydrological services). Products should meet the agreed requirements of end-users, and sometimes it might be appropriate to provide “raw” information such as satellite imagery or radar imagery (WMO, 2010). The workload needed to elaborate forecasts in tabular form, special bulletins, and pictures for the media or other clients depends on the degree of involvement of the Meteorological Centre in the preparation of customised products.

2.6 Platforms of severe hail warnings

It has been well documented in the literature that the majority of people obtain severe warnings from mass platforms such as the radio and television (Hammer & Schmidlin, 2002; Comstock & Mallonee, 2005; Sherman-Morris, 2005; Schmidlin *et al.,* 2009; Blanchard-Boehm & Cook, 2009). Television channels are a robust device that can be effective in hail warning distribution. For example, news channels can interrupt daily programmed televised programs to broadcast important warnings during times of severe weather. These forecasters can adjust their weather coverage to include illustrations of hailstorm intensity and images. Regular viewers of television bulletins may see amity amongst their weather forecaster and themselves; this perceived link is commonly referred to as a para-social relationship.

Furthermore, Sherman-Morris (2005) mentioned: “Viewers who develop a parasocial relationship are more likely to follow his or her protective action advice during occurrences of severe weather events”. Even though television, radio and sirens remain the most publicly retrieved methods of severe weather distribution, there is growing literature that mentions social networking platforms as a source of warnings, disaster reaction and recovery information. Social networks are mobile and web centred that allows users to create and share information, and view individuals content (Hyvärinen & Saltikoff, 2010). Twitter and Facebook (with more than 140 and 800 million users) are illustrations of common social networking sites. Social networks and media have numerous benefits over conventional media sources as an alternative communicative tool. First, different social media platforms may be updated constantly by many end-users during an austere weather event. These new updates may offer vital data, however, it may be unavailable to emergency management personnel and weather forecasters positioned in the outer part of the vulnerable area. Second, information circulates quickly on different social networking websites thus, reaching millions of users within a short period. Social networks such as Twitter is a flexible network that allows users to share trending content by the use of “hashtags”, which increases the availability of user-created contents

There are critiques using social networks, one critic is that it can become problematic in assessing the integrity and legitimacy of user-created content. (Jefferson, 2006; Hyvarinen & Saltikoff, 2010;

Kaplan & Haenlein, 2010). Gossip unintentional and intentional remains frequent on social media platforms. Therefore, the aforementioned may pose a stumbling block for users to distinguish among this content and more reliable information. This signifies a cause of helplessness for people who depend on social media when looking for weather information. As a trusted source to the public, SAWS need to provide efficient severe warnings through multiple social platforms.

2.6.1 Public perception of hail events

Previous studies were on societal perceptions of severe weather such as windstorms and tornadoes (Anderson-Berry, 2003; Zhang *et al*., 2007; Schmidlin *et al*., 2009; Sherman-Morris, 2010). However, there are not many studies published internationally and in South Africa are on individual's perception of hailstorms. Nevertheless, notable exceptions include Lazo *et al*. (2009).

The societal perception on hail events is driven by several factors such as previous experiences with severe weather (the intensity and frequency of past events), social demographics and lastly their confidence in forecasts (Zhang *et al*., 2007). If an individual perceives weather forecasts as a false alarm or unreliable, they do not take precautionary actions than if they consider the forecast to be trustworthy. Consequently, Hayden (2007) adds that correct perception of weather events will lower the vulnerability of an individual, while a wrong perception of weather events may cause people to be susceptible to these occurrences. The way in which the forecast is presented to the public may have an influence on their perception of hail events. Silver & Conrad (2010) mentioned that precise warnings do not always aid the public due to storm size or magnitude. For example, when a severe hailstorm struck the Gauteng province on the 28th of November 2013, regardless of warnings that were issued, individuals were left vulnerable due to the magnitude of the storm.

Past studies on the perception of natural risks have taken shape of close-ended questionnaires carried out to a random sample (Zhang *et al*., 2007; Schmidlin *et al*., 2009; Sherman-Morris, 2010). However, there has been less research using in-person interviews (e.g., Donner, 2007 & Burningham *et al*., 2008; Tekeli-Yeşil *et al*., 2010). There are four types of knowledge that may be grasped from social studies which include: attitudes, attributes, beliefs and behaviours. Attitudes and beliefs are subtle and attributes and behaviours are best suited for quantitative techniques (McGuirk & O'Neill, 2010). Attitudes and beliefs are generally accessed via qualitative methods which reassure individuals to speak about information beyond the surface level (Silver, 2012). From the above stated, in this study, interviews will be undertaken when assessing individuals perceptions on hailstorms and the benefits of hail nowcasts.

2.6.2 Social susceptibility and societal response to hailstorms

Individuals are socially vulnerable to hailstorms. Their vulnerability is determined by different factors such as; the timing of the storms, public reaction, socio-economic status and lastly their past experience with the event both within a broader social context or personal. These factors may have an effect on people's decision-making for the duration of hail events.

Socio-economic status may significantly influence an individual's vulnerability to hailstorms in several ways, either indirectly and directly. Individuals within low-income households are expected to be in "squatter camps". Low-income homes are extremely susceptible to the weakest storm winds and do not have any protective measures during these severe weather events (Sutter & Simmons, 2010). Previous studies have shown that people in low-income areas are 10 times vulnerable to encounter severe damages than those people in middle-income areas (Daley *et al*., 2006; Schmidlin *et al*., 2009). The economic status of a person or family may also influence technology in which they have frequent access to the internet. It has been well recognised that communication (e.g. television, radio, cell phones as well as computers with internet access) play a major part in the distribution of warning information before and the duration of severe thunderstorm events (Hammer & Schmidlin, 2002; Comstock & Mallonee, 2005; Sherman-Morris, 2010). Lastly, the economic status of an individual may influence the type and range of protective actions taken against severe hail events. For example, individuals within a higher income bracket can afford the latest technologies that would help in taking precautionary measures, such as cell phone weather applications, personal storm shelters and motor vehicles.

Hence, the aim of hail nowcasts is to issue accurate and timely information that can be used by end-users, particularly insurance companies. The duty and responsibility of SAWS are to create and disseminate several weather products such as daily forecasts and severe watches and warnings effectively. Meteorologists employ challenging monitoring infrastructure that comprises of radars, satellites as well as surface weather stations that can aid in creating weather products. Despite the considerable amount of research conducted on the different facets on weather meteorology which includes: verification, accuracy and implementation; there are fewer studies done on the public's perception on severe weather events (Doswell, 2003). There is an increase in literature that indicates how people react to extreme weather warnings (Wong & Yan, 2002; Silver & Conrad, 2010).

2.7 Socio-economic benefits of hail nowcasts

There are not many studies that have been done internationally or in South Africa that focus on the benefits of hail nowcasts on end-users. For example nowcasts are amongst the most general weather products delivered by weather services, however, there is less research done on how these nowcasts are being used by end-users. Notable studies include (Morss *et al.,* 2008; Lazo *et al.,* 2009; Demuth *et al.,* 2011) on the perceptions of weather forecasts/warnings. These previous studies observed how end-users in America attained and used weather products, for example, severe weather warnings. Conclusions from these studies signified that there is a substantial economic value of weather forecasts, and their essential role in the daily lives of several end-users (Lazo *et al.,* 2009).

Though these studies have a considerable contribution to the uses and understanding of weather products, most of these publications have been published from an American perception. When compared with South Africa, there is less research done. Nowcasting hail events fill a need to a selection of end-users (e.g., emergency services, agricultural community, recreational groups, transport and insurance industries and air quality agencies). The influence of hail on human livelihood is unquestionable (ISDR, 2005; Parry *et al*., 2008 & Pelling, 2011). Hail events that occur generally have a negative influence on society and on their livelihood. Since nowcasting systems often outperform numerical weather prediction during the first hours of a forecast (Freebairn, 2002). Nowcasts are seen to be of utmost importance in reducing hail impacts, supported by the Intergovernmental Panel on Climate Change (IPCC, 2012) early cautionary systems are usable when individuals can interpret and identify overall warnings into relevant local actions and impacts.

According to Mason, (1966); WMO, (1978) & Lamb, (1981), it is recognised that weather conditions may influence human and economic activities such as: retail trade and business (Hallanger, 1963; Roth, 1963; Maunder, 1966), construction (Russo, 1966; Greenburg, 1976; Prior & King, 1981), road and street departments (Suchman *et al*., 1981), agriculture (Vining *et al*., 1984; Brown *et al*., 1986; Mjelde *et al*., 1988) and aviation (World Meteorological Society, 1968). These past studies propose that decision-makers can develop economic value from nowcasts. Table 2-3 summarises the economic benefits described in previous publications relating to the value of climate information. Warnings need an adequate steadiness of decision-making that takes into account societal risk behaviour, climatology, socio-economic infrastructure, lead time and several other factors (Westefeld *et al*., 2006; Baumgart *et al*., 2008; Schmeits *et al*., 2008; Mercer *et al*. 2009). Nowcasting high impact weather (Wilson, 2004) such as severe thunderstorms associated with hail have significant economic and societal benefits. These benefits include the following:

a. Fewer injuries and fatalities.
b. The reduced property, vehicle, infrastructural and industrial damages.
c. Improved efficiency for the agriculture sector and insurance companies would save.

Table 2-3: Economic Value of Weather/Climate Predictions as Described in Certain Studies. (Source: Mjelde et al, 1989).

Study	Activity	(Units)	Attribute[b]	Design[c]	Unit
Brown et al. (1986)	Wheat Production	$ 10.08/ha/yr $196.62/ha/yr	Accuracy	Current, Perfect	Individual
Bergen and Murphy (1978)	Residential Housing and Wind Damage	$200,000/yr	Accuracy	Improved	Market
Byerlee and Anderson (1982)	Fodder	$312/farm/yr	Accuracy	Perfect	Individual
Greenberg (1976)	Agriculture Construction Boating Flood Control	$50-120 million/yr $50-130 million/yr $ 1 - 4 million/yr $ 4- 12 million/yr	Accuracy	Improved	Market
Hofing et al. (1987)	Seed Corn Production	2 to 5% of total production costs	Accuracy	Perfect	Individual
		1 to 3% of total production costs	Accuracy	50% Accurate	Individual
Katz et al. (1982)	Orchard	$270/ac/season $569/ac/season	Accuracy	Current, Perfect	Individual
Mjelde et al. (1988)	Corn Production	Results dependant on the attribute being valued.	Prior knowledge, Accuracy, and[1] lead time	Improved, Perfect	Individual
Mjelde and Cochran (1988)	Corn Production	$0.00-218/ha/yr	Prior Knowledge, risk aversion	Perfect	Individual
Sonka et al. (1987)	Corn Production	$21.20-45.99/ha/yr	Accuracy, Periods of the year	Perfect, Improved	Individual
Thompson (1972)	All Processes Totalled	$739 million	Accuracy	Perfect	Market
Vining et al. (1984)	Agriculture	$1420/farm/yr	Accuracy	Perfect	Individual
Wilks and Murphy (1986)	Corn/Wheat Production	$.004-.138/ha/yr	Accuracy	Current	Individual

Public and private activities and the economic sector, are affected by these destructive events. Hailstorms pose social and financial risks for individuals, businesses and industries insurance companies (Williamson *et al*. 2002). Hence, accurate hail nowcast may aid the economy and well-being by reducing damage to property, infrastructure, agriculture and loss of lives. Williamson *et al.* (2002) reported that nowcasts enhanced benefits for the following:

a) Improving natural hazard mitigation, response, and recover: Hail nowcasts may aid to extensively reduce the costs to the public. Better information encourages government, businesses as well as people to participate in loss-reduction activities which may decrease costs from unwanted loss reduction activities that arise from hailstorms.

b) Prevarication against uncertainty: Issuing nowcasts about the possibilities of hailstorms aid the development of specific markets that assist in alleviating the financial and economic consequences, such as insurance companies.

Economic sectors would benefit greatly from hail nowcast and forecasts; it will help individuals and families who base choices and decisions about their daily activities on the weather forecast. Table 2-4 below classifies some of the subdivisions that are mostly affected by meteorological events. Firms inside these subdivisions try to alleviate weather-related variations by avoiding their perils in futures markets, retaining meteorologists, and investing funds and time in weather prediction.

Table 2-4: Representative industries for which weather nowcasts have an important financial impact.

Major Industry	Examples of Specific Applications
Agriculture	• Crop management • Irrigation decisions • Prevention of weather-related diseases
Energy	• Planning purchases of gas and electric power • Managing responses in emergency situations • Managing capacity & resources
Aviation/Transportation	• Optimizing flight patterns • Reducing wait times on runways • Avoidance of sudden volcanic plumes
Tourism/Recreation	• Improving ski slope demand/production of artificial snow • Marine forecasts/warnings

It can be seen that end users (e.g. disaster managers or the public) find it problematic to interpret complex scientific information into practical understandable disaster-related information. Auld (2008) stated that "Research and development are needed to move from weather prediction to risk prediction that can identify general impacts, prioritise the most dangerous hazards, assess potential contributions from cumulative and sequential events to risks and determine thresholds linked to escalating risks for infrastructure, communities and disaster response."

The World Meteorological Organisation (WMO, 2012) supported the above mentioned and stated that "In the case of hazardous weather, nowcasts identifies areas and assets which are most vulnerable to the hazard and allows prioritisation of areas where services need to be deployed". Impact nowcasting is a mechanism to alter forecasts of weather variables into economic, social or environmental variables that support more focused decision making by users. For example, severe hail can lead to flash flooding. Instead of only forecasting severe hail, forecasts of which roads could be closed, or communities could be cut off due to hail would add immense value to better decision making by the general public (Neal *et al*., 2013). Hence, impact nowcasting is integrated between social sciences (social and economic impacts) and natural sciences (weather forecasting) to produce range societal information related to damages.

WMO (2012; 2017) further reported that impact nowcasting is a reasonably new and growing development in weather forecasting internationally. Limited national meteorological services made an effort into the growth of sophisticated impact forecasting systems. Various national meteorological services also follow this same route of providing high-level impact information with their warnings (WMO, 2012). WMO (2017) is strongly encouraging the development of impact nowcasting systems by national meteorological services, recognising that it is a new area for most services and that significant research is still required to optimally develop the methodology utilised.

2.8 Chapter summary

Hailstorms over the Gauteng Highveld have proven to be disastrous with huge impacts. These events are frequent and may pose several threats to the environment and the public. The impact and destruction of severe hail events served as a motivation to nowcast these hailstorms well in advance with a low false alarm rate. The main reason for nowcasting severe weather is to warn end-users to act against imminent thunderstorms or hailstorms. Therefore, there is an acknowledged need to offer better hailstorm warning forecasts to end-users. The procedures in nowcasting were explained in detail and it was found that most of the weather services follow rather similar procedures. Different nowcasting algorithms were described, TITAN was explained in depth since it is the algorithm that will be used in this study. Last, sources of severe hail warnings were explained. It was well documented in the literature that most end-users prefer mass sources in getting weather warnings. It was found that individuals can benefit from nowcasts either by being prepared and taking protective action or by saving lives or money. The majority of the studies has only been done in the US on tornadoes or hurricanes. Fewer studies have been conducted on thunderstorms in the US. Thus it can be seen that hail is a big problem however, less research has been done internationally and in South Africa on how hailstorms are forecasted, nowcasted or the public's perception to nowcasting hail events. This study is the first to be done in South Africa and it provides a building block to future studies like these in the future.

CHAPTER 3

DATA AND METHODOLOGY

The main aim was to evaluate the current state of a hail forecasting and nowcasting system to identify individual's perception of hailstorms over the Gauteng Highveld. This is an explorative study that provides contextual information regarding the numerous types of data that are instrumental in this dissertation. Second, the description of the study area with associated climatological and terrain features will be discussed. The role of each data type will be discussed, relative to the objectives of this dissertation. Lastly, for each objective, a method will be prescribed.

3 Study area

The Highveld is located primarily within the Gauteng, Free State, Mpumalanga and North West province Figure 3-1. The majority of rainfall occurs in summer commonly by thunderstorms (Held, 1973; Tyson, 1986; Kruger, 2007; Dyson, 2009). This region has an elevation of approximately 1300-1500 m above sea level. The Gauteng Highveld is notorious to one of the highest rates of thunderstorms in addition to lightning within Southern Africa (Gill, 2008). Additionally, Gijben (2012) states that "The Highveld and eastern escarpment region record on average between 10 and 15 lightning flashes per square km per annum." Common incidences of severe thunderstorms may consist of large hail, strong damaging winds as well as lightning and flash floods (SAWS, 2013).

3.1 The current nowcasting procedures of the South African Weather Service

With the data obtained from the interview, it can be used to discover the gaps of hail nowcasts to decide where research emphasis is needed. Without many hail days to study, forecasters are usually not prepared to recognise the danger of it. Furthermore, forecasters might not officially know the threat of this event, both internally and to the public. As a result without the understanding of the likelihood of hailstorms, catalogues for the gathering of these storm occurrences and verifying are unlikely to be generated. Results obtained may be utilised by weather services while forming severe hail warning and forecasting programmes.

To achieve this objective a set of sub-questions have been formulated namely:

1. How do SAWS forecast hail events
2. How does SAWS nowcast hail events
3. What are the challenges in forecasting and nowcasting hailstorms

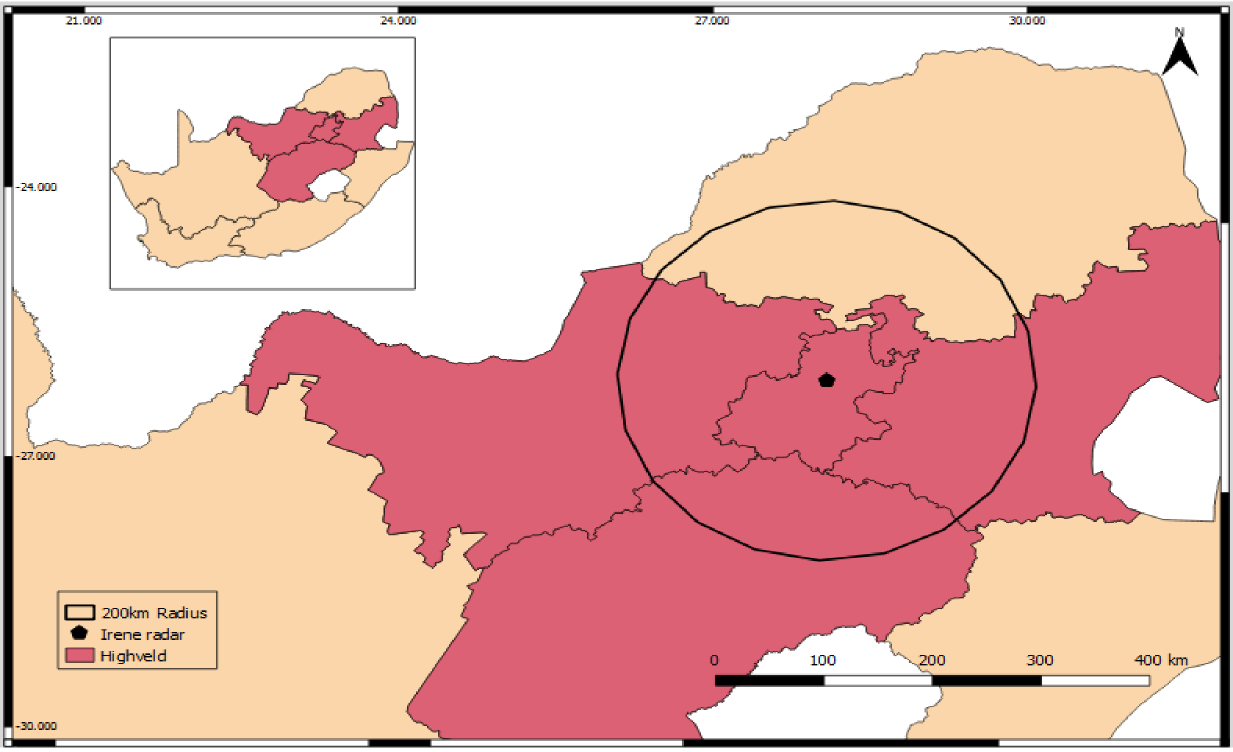

Figure 3-1: Study area and a 200km radius around the Irene Radar.

3.1.1 Interviews

Interviews are well-established tools in social science for getting statistics and information on the interviewee's standards of behaviour or attitudes, social characteristics, present and past experiences and their reasons for action regarding the subject under investigation (Bulmer, 2004). These tools are exceptional in providing meaningful information to disaster agencies in establishing risk management measures (Bird, 2009).

For this objective, a well-structured interview was undertaken and comprised of open-ended questions. The reason these questions were chosen was because of the spontaneity and freedom of answers and a chance to probe as well as the effectiveness of testing assumptions about concepts (Oppenheim, 1992). These type of questions have various advantages such as it allows space and time for spontaneous answers and are likely to invite interviewees to share their knowledge, understandings, experiences and their responses to social situations (McGuirk & O'Neill, 2005). It was assumed that a large selection of answers provided for one question can be challenging. Hence, open-ended questions may be probed in a way that guides interviewees into a fixed way without proposing responses (Payne, 1951)

This study was reviewed by the North West University (NWU) Ethics committee. The statistical services at the NWU were consulted in designing the interviews. This dissertation is based on a well-structured interview to SAWS in March 2017. The interview was conducted in person to selected persons who are experts in nowcasting and forecasting on weather operations from SAWS see *Annexure A* for the detailed interview questions. Additional questions were asked if clarity was needed. The interview addressed the following:

a. Hail forecasting
b. Hail nowcasting
c. Hail nowcasting process
d. Problems encountered in developing their warning operations
e. Hail warnings

3.1.2 Sample

Sampling techniques usually govern how representative the sample is of the population of study. In this dissertation, the most applicable sampling technique was found to be the non-probability sampling as shown in Table 3-2, the purposive technique was selected since this questionnaire targeted experts in the nowcasting and forecasting field (Sarantakos, 2005). The non-probability sampling method cannot make statistical generalisations, however, it is frequently used when individuals are based on a mutual characteristic (McGuirk & O'Neill, 2005; Patton, 1990). This technique is associated with qualitative research.

Table 3-1: A short summary of non-probability sampling methods (Source: Sarantakos, 2005).

Non-probability:	• Accidental	All people that the researcher accidentally meets during a certain period are considered for the investigation
	• Purposive	Participants who are thought to be relevant to the research are purposively chosen
	• Quota	A "quota" of participants to be chosen from a specific population group is predetermined
	• Snowball	The first participant recommends other people who meet the research criteria

3.1.3 Data analysis

The interview was transcribed and analysed using thematic analysis to note the answer patterns within the interview transcript. Information was analysed using techniques like those defined by McCormack, (2000), whereby the transcript is revised numerous times to select and find emerging patterns from various 'lenses' such as narration, language and context. The results were compared to other weather services and studies across the world. Lastly, comparisons and differences were concluded.

This section provided a constructive base, whereby the results of the current nowcasting procedures employed by SAWS will be linked to the results found in section 4.4. The following section 3.2 will focus on the nowcasting algorithms used by SAWS and the purpose of this was to see how well the nowcasting algorithm performed in identifying severe thunderstorms by doing a verification test as done in previous studies.

3.2 Nowcasting algorithm used by SAWS

The purpose of this section is to evaluate the TITAN algorithm. TITAN will be used in its default settings to see how well it performs in detecting severe thunderstorms (hail). This is similar to how the weather service uses the algorithm. There are many ways in optimising this algorithm for the South African climate that should significantly increase the accuracy of the algorithm. However, for this dissertation, optimisation techniques are out of the scope of this study.

3.2.1 Data

This methodology is similar to Banitz, (2001) and Ebert et al. (2002). Radar data was obtained from the South African Weather Service (SAWS) using the S-band (10 cm wavelength) Irene radar, located between Pretoria and Johannesburg (25.9119° S, 28.2107° E). The radar finishes a full volume scan, comprising of 12 altitude angles (between 0.5° and 30°), in 5 minutes, with a range of 200km. The MDV data is of the flat (Cartesian) projection type with a 1km x 1km horizontal resolution. A total of 17 CAPPI levels ranging from 3 km MSL to 19 km MSL at intervals of 1km, make up the vertical levels within the MDV dataset. The Linux operating system was used to access the data. In order to run the TITAN algorithm, the MDV files were converted to a Cartesian coordinate system. The data was passed to the TITAN algorithm, which identified a storm as a 3D contiguous region in which the radar reflectivity exceeds defined thresholds which in this study is >45 decibels (dBZ).

In order to use the radar data in this dissertation, the VOL files were converted into Meteorological Data Volume format. The TITAN algorithm has an application called "GemVolXml2Dsr" that allowed the unpacking of the VOL files as File Message Queue (FMQ) data. This data stored radar scans temporarily, which was then converted to MDV files. Another TITAN application called "Dsr2Vol" generated user specified MDV files. For this dissertation, the reflectivity file (dBz. vol) was used to create the MDV file. Raw data were interpolated to Cartesian coordinates with a 1 km grid cell size. TITAN tracked storms with its default settings. It worked best when thunderstorms had a good edge definition. TITAN stored its output in storm and track files, which provided data on motion, growth and decay of the storm. Last, tracks2ascii wrote ASCII data in a Comma Separated Values (CSV) format. This was suitable for transferring storm properties to plotting packages or spreadsheet for further analysis as shown in Figure 3-2.

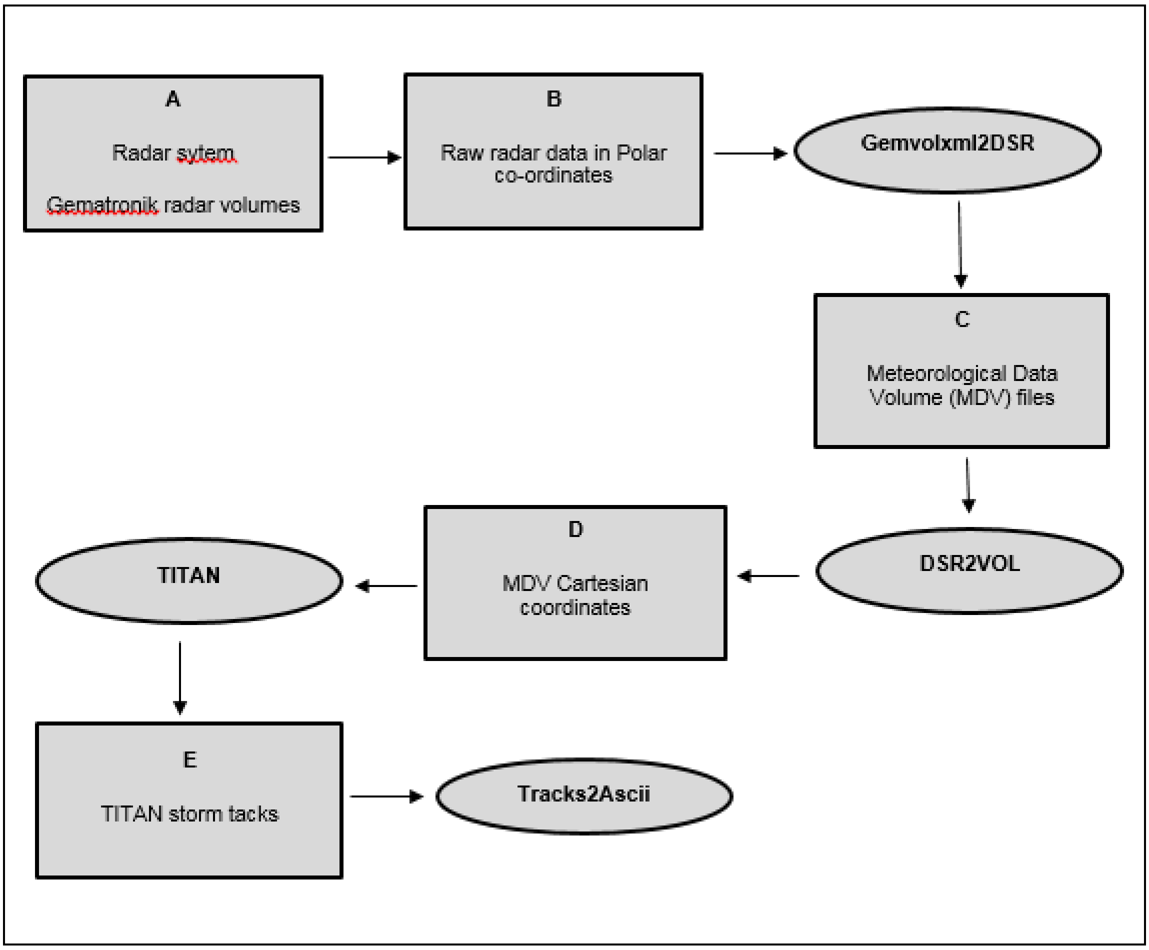

Figure 3-2: Conceptual diagram of the processes and conversions of radar data.

3.3 TITAN

Dixon and Weiner (1993) developed the Thunderstorm Identification, Tracking, Analysis and Nowcasting algorithm (TITAN) to track storms using volume-scan radar data. TITAN is widely used and well-known (Fox *et al.*, 2000). TITAN is programmed to track the whole area of reflectivity, considering a reflectivity threshold as a limiter of the tracked region as well as measuring distances between centroids as the method to obtain the tracking motion. TITAN remains a popular and reliable method of tracking storms (Goudenhoofdt & Delobbe, 2012). TITAN is a set of software structure that supports storm forecasting, tracking and does a variety of tasks such as: assimilating individual radars into a mosaic, removal of clutter and anomalous propagation and a bright band correction (Reyniers, 2008).

In this dissertation, radar volume data in polar coordinates were transformed into a 3D Cartesian grid size of 0.5km. Dixon and Weiner (1993) mentioned that “The TITAN algorithm describes a thunderstorm as a 3D region with reflectivity values exceeding a given threshold; however, the volume of the region must be bigger than a given threshold to be known as a valid hailstorm”. Therefore, TITAN matches storms through two continuous radar images using combinatorial optimisation. It detects a fixed storm swath that reduces a cost function, which is the sum of distance and volume weighted differences for each path. For example, the storm identification and tracking are shown in the TITAN algorithm that was programmed to run during November 2013-February 2015 where big and damaging hailstorms were reported.

The algorithm is constructed on various criteria’s influencing its performance. The grid size of the 3D interpolation grid was set to 0.5km. This is reliable with the radar resolution and provides adequate accuracy for thunderstorm detection as proposed in (Goudenhoofdt & Delobbe, 2013). The basic and most central parameter in this study was the Foote Krauss index (FOKR) which was used to detect a severe hail event. TITAN was used with its default settings as the weather service does. This permits easier tracking; however, growth and decay stages of the hailstorm may be missed. Undesired behaviours of the tracking algorithm contain dropped association which is broken down into various parts, the incongruity between an old cell and a new storm cell as well as permuted match between two storms close to each other. A performance examination of TITAN can be found in (Han *et al*., 2009) with recommendations for new developments.

3.3.1 Statistical Methods

Storm selection

The performance of TITAN depends on the distance to the radar. At smaller distances, hailstorms might not be detected because of the cone of silence however, at large distances, hail events with big upright development will be recognised. The volume increases at a greater distance for beam enlargement. In order to do an in-depth hail assessment, the structure of the hailstorm needs to be detected by radar. Thus, this study area was restricted to the two main cities of Gauteng namely: Johannesburg and Pretoria. A boundary was created around the built-up suburbs of these cities as illustrated in Figure 3-3. The boundary of 40 km is represented by the thick solid line around the suburbs of Johannesburg and Pretoria. The storms are illustrated by the points whereby, yellow shows the number of storms that occurred over the area. The reason for this was because most severe hail events occur around these areas and are frequently reported to different media platforms. Second, there might be remote areas that are affected by hail, however, it goes unreported. This criterion was utilised for the Eulerian approach which is grounded on the detected thunderstorms and the Lagrangian approach is built on the tracked storms. To be certain that the whole path of hailstorms was captured; tracks that existed before or after a missing file were not used. It is essential to know this spatial range discarded long-lived thunderstorms, usually mesoscale storms that travelled hundreds of kilometres.

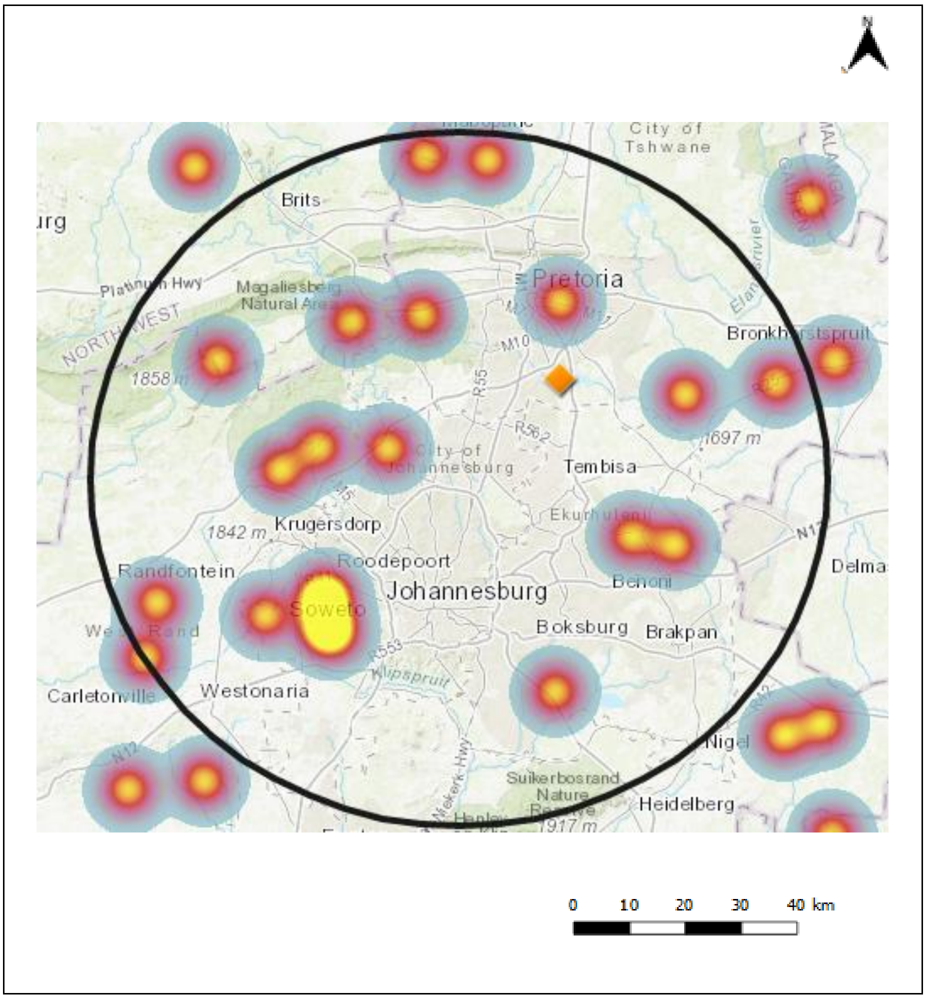

Figure 3-3: Map of Gauteng that illustrates hail events passing over the major built-up suburbs surrounding the two main cities of the Province.

Storm properties

The algorithm was utilised in the ARCHIVE mode and the characteristics of tracks formed the base for the analysis. The TITAN algorithm has processed 3 years of volumetric radar data. For each detected hailstorm, diverse properties are computed by TITAN such as morphological characteristics (precipitation area, volume as well as cloud tops) and physical properties precipitation rate resulting from reflectivity values. A record of the total mesh points that make up the detected thunderstorm was challenging due to the massive quantity of data. A 2-dimension depiction of the area attained from the 3-dimensional volume forecast on the surface was utilised as an adequate substitute. Motion characteristics for example; the direction and speed result from consecutive tracked locations of the thunderstorm. The program named “Tracks2Ascii” extracted the data for the storm tracks for the specified time period.

TITAN has combined algorithms that detects possible severe thunderstorm “signatures”, for example, the hail metrics, to form the POH founded on (Waldvogel *et al*., 1979). It means that hail occurs after 45dBZ reflectivity is present at 5.5 km or greater above the freezing level. The Foote-Krauss index (FOKR) is also associated to hail events, and it was formed by (Foote *et al*., 2005). This index was primarily applied to severe hail events in Argentina. It was further utilised for the SSS (Storm Structure Severity) index, formed by (Visser, 2001) for hail events over the Highveld.

In order to identify severe hail events from the statistics that were generated from TITAN the following hail metrics were used:

- **FOKR index.**

The FOKR index consists of four categories:

I. “Potentially hail dangerous, newly developing cumulus congests, with first radar echo above the -8 degree level;
II. Hail dangerous convective cells at a later stage, having a possibility of growing into hailstorms;
III. Hailstorms;
IV. Intense and severe hailstorms”.

In this dissertation, all the storms that were associated with category “4” were considered.

- **Hail Waldvogel probability**

  The POH values do not include hail size, it is only a measure of hail. POH was calculated by the height distance between maximum height which is 45dBZ and where the freezing level occurs. Height less than 1.64 km has a POH value of 0% and a height greater than 5.5 km has a POH value of 100% as shown in Figure 3-4. The success of this algorithm was confirmed by previous studies illustrating that it provides fair results for single polarisation radars (Holleman, 2001; Delobbe & Holleman, 2006; Skripniková & Rezácová, 2014). In addition, this algorithm has been applied by different weather services (Holleman, 2001; Šálek et al., 2004; Betschart & Hering, 2012). In this study, a POH score between 0.8 and 1 will be considered.

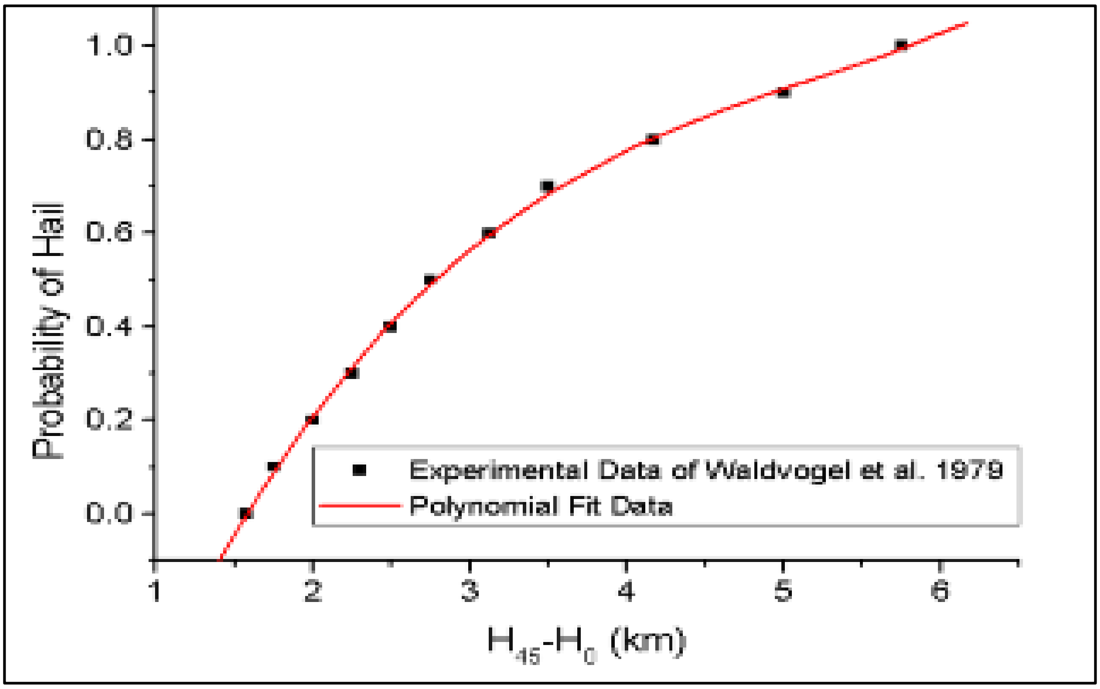

Figure 3-4: POH at the surface to the height of the 45dBz above the freezing level (Source: Foote et al., 2005).

- **Hail mass aloft**

  Hail mass aloft performs well by actual reflectivities. The volume of Z>45 dBZ was used in this study. The units of the volume are suggested that the metric is the total estimated hail mass (tons) aloft. Hail mass aloft was calculated using the following:

$$\mathbf{G_A} = \int_{\substack{Z>45 \\ H>H_2}} \boldsymbol{M\,dV}$$

  Where "M (g m^{-3}) is a function of reflectivity at each range gate (see below) and the integration is done over the TITAN cell for reflectivity >45 dBZ at heights >2 km above the 0C level".

3.3.2 Media reports

Hail reports are important in order to verify nowcasting algorithms (Sokol *et al*., 2014; Allen *et al*., 2015; Mohr *et al*., 2015; Sokol *et al*., 2016). Media and hail reports were used to subjectively identify hail events and results were correlated to the verification scores on a storm to storm basis; identifying how well the algorithm performed. Media reports were used because weather radars are not always operational. The radar that was used in this study is not dual polarised hence, it is difficult to identify hail. Unlike radar data, media reports such as online newspapers are not fixed to a specific location. A number of hail reports were counted using these non-conventional sources. However, this study only focused on extreme hail events with damages that were reported. The two datasets allowed for a robust analysis over the Gauteng Highveld. Media reports were considered only if the time/date and province were given. The limitations of using media reports are mentioned in Chapter 6. Hail reports of severe hail damages were retrieved by online newspaper sources in South Africa. These sources have been used for the verification of hail events. Amongst others, the two sources which supplied the hail damage reports were:

a) News24

b) ENCA

In the media reports, time and date were shown. The method in which the areas of the hail damage were indicated and governed by the source of the reports: it was given as longitude and latitude coordinates. This information will be used in the verification procedure in identifying hail events. During November 2013-February 2015, 6 cases in total have been reported by these news channels. These cases are illustrated below in Table 3-2.

Table 3-2: Hail events over the South African Highveld during November 2013-October 2015.

Hail events over the Gauteng Highveld between 2013 and 2015		
Date	**Location**	**Weather**
11 November 2013	Ekurhuleni	Hail (golf ball size)
28-29 November	Johannesburg, Pretoria and Witwatersrand	Hail (golf ball size)
4 December 2013	Pretoria	Hail
14 December 2013	Pretoria	Hail
20 September 2014	Johannesburg and Roodepoort	Hail
17 October 2014	Centurion, Johannesburg, Ekurhuleni and Randburg	Heavy hail

3.3.3 Verification methods and scores

The TITAN algorithm employed in this dissertation is validated against media reports by categorical verification. This is widely used in meteorology (Saltikoff et al., 2010; Skripniková & Rezácová, 2014; Kunz & Kugel, 2015). A 3 x 3 contingency Table for was used to calculate the probability of detection (POD), critical success rate (CSI), false alarm rate (FAR) and the heidke skill score (HSS) (Wilks, 2006).

A detailed evaluation of the TITAN algorithm skill needs unbiased validation when compared to detected severe weather. This verification is an imperative constituent of the weather service. There are numerous reasons for undertaking nowcast verification. The confirmation gives algorithm developers certain statistics around the skill of their algorithms to forecast hail events that occurred using several analytical and statistical methods (Brown *et al.,* 2001; Nurmi *et al.,* 2001; Banitz, 2001; Ebert, 2004; WMO, 2017). Forecasters usually use the verification results to spot estimated errors in hail nowcasts as well as to study in which classic weather circumstances the assumed algorithm is unreliable or reliable. Constant nowcast certification allows the systems to be checked, and upgrades to be assessed. The WMO, (2017) defines the following:

a. "**Hit** as an occurrence of at least one observation of severe weather conditions, as defined by the thresholds anywhere in the forecast area, any time during the forecast valid time"
b. "**False alarm** is recorded when severe weather is forecast, but there is no severe weather observed anywhere for which the forecast is valid during the valid period".
c. "**Missed event** is recorded when severe weather is reported outside the area and/or the time period for which the warning is valid, or whenever severe weather is reported and no warning is issued. Only one missed event is recorded on each day, for each region where severe weather has occurred that is not covered by a warning".
d. "**Correct negative** is recorded for each day and each fixed forecast region for which no warning is issued and no severe weather is reported".

In the verification process, the results of the verification data were categorised using a 3 x 3 contingency Table. Hail detected which was confirmed by the verification data were categorised as a hit (**H**), if there was no report that confirmed hail, it was seen to be a false alarm (**F**), hail reports or observations which were not identified by the algorithm were perceived to be a miss (**M**), and an event that was not forecasted or observed was a non-event (**N**). These four categories are illustrated in Table 3-3.

Table 3-3: 3 x 3 Contingency Table used to verify hail and non-hail as adopted by the World Meteorological Organisation (WMO, 2014).

Event forecast	Event observed		
	Yes	No	Marginal total
Yes	Hit	False alarm	Fc Yes
No	Miss	Correct non-event	Fc No
Marginal total	Obs Yes	Obs No	Sum total

Event forecast	Event observed		
	Yes	No	Marginal total
Yes	a	b	a + b
No	c	d	c + d
Marginal total	a + c	b + d	a + b + c + d = n

The nowcast products from the algorithm were used to forecast hailstorms for the period of 0-2 hours and verification of nowcasts was undertaken. The TITAN algorithm has a mathematical component in which the verification of the thunderstorm forecasting and tracking is calculated. The nowcasting results were assessed using the performance guides, such as the:

a. Critical Success Index (CSI)
b. The probability of detection (POD)
c. False alarm rate (FAR).

These indices were defined by the WMO (2014) as:

$$PoD = HR = \frac{A}{A+C}$$

"PoD has a range of 0 to 1, by 1 being a perfect forecast. HR can be improved by over-forecasting the occurrence of hail.

$$FAR = \frac{A}{A+B}$$

FAR has a range of 0 to 1 with 0 indicating a perfect score. It can be improved by under forecasting “rare event”.

$$CSI = \frac{A}{A+B+C}$$

CSI is used as a standard verification measure and has a range of 0 to 1, by 1 being an ideal score. The POD, FAR and CSI were used to exemplify the behaviour on certain hail detection algorithms. Additional comprehensive explanation on the performance of these can be found in the literature (Doswell *et al*. 1990; Kok, 2000; WMO, 2014, 2017).

$$The\ Heidke\ skill\ score\ (HSS) = \frac{(a+d)-\frac{(a+b)(a+c)+(c+d)(b+d)}{T}}{T-\frac{(a+b)(a+c)+(c+d)(b+d)}{T}}$$

Where *T* is the sample size. When all forecasts are correct value of 1 is assigned and 0 when the number correct is equal to the expected number correct”.

The next section 3.4 will focus on the perceived benefits of hail nowcasts and the purpose of this was to see how hail forecasts and nowcasts impacted end-users and the maximum benefits they received from nowcasts. This section will build on the results from chapter 4 and will address the challenges experienced by SAWS in nowcasting hailstorms. Building this end-to-end comprehension will aid in guiding investment decisions as well as product development for SAWS for example; numerical modelling, what nowcast products to offer and when to make it available given limited resources.

3.4 The perceived benefits of hail nowcasts

Nowcasts remain one of the most common weather products distributed by weather services around the world, nevertheless, there are not enough studies on how these nowcasts are being utilised by end-users. Understanding how people perceive hail nowcasts shows a sign of efficiency in communication processes and information delivery. An individual’s use of information may aid forecasters to develop improved nowcasts to fit the end-user’s needs. The perceived value and benefits of nowcasts provide an insight into the significance of this study.

To achieve this objective a set of sub-questions have been formulated namely:

1. How do individuals perceive general weather especially hail and does SAWS influence the perceived reliability of that information?

2. By what means are hail warnings linked and communicated to the public?

3. What was the estimated financial loss to their property and vehicles?

4. What typical time scales do end-users need as an early warning?

5. How do end-users perceive false alarms?

6. Can end-users benefit from hail nowcasts?

3.4.1 Methods of data collection

The most applicable sample technique was found to be an appropriate non-probability sampling method for this study. Exponential Non-Discriminative Snowball Sampling (Abubakar *et al.,* 2016) was chosen due to its explorative, qualitative and descriptive nature. The Snowball sampling method was used because interviewees could identify additional individuals who were in similar circumstances as themselves and might educate other people about the benefits and advantages of this study and reassure them of confidentiality. Four potential subjects in the population sample were identified who resided in different suburbs within the Gauteng province. Thereafter, those potential subjects were asked to recruit other people or to encourage people to come in for a short interview. They were made aware that they did not have to provide other names. This was repeated until the necessary sample size was found.

3.4.2 Interviews

To conduct interviews the most applicable sampling technique was found to be the non-probability sampling method. Snowball sampling was chosen because this objective is mainly qualitative, descriptive and explorative. Therefore, the snowball technique was found to be practical as suggested by (Blanken & Adriaans, 1992). Furthermore, this sampling method is frequently utilised to conduct various qualitative research by means of interviews as well as for creating inferences about people who have been challenging to count from other methods (Atkinson & Flint, 2001).

In pragmatic social science studies, structured interviews remain one of the most used interviews for eliciting information directly from several respondents. A state-of-the-art method for developing and testing interview questions was used (Presser *et al.,* 2004). The interview was formed to examine numerous themes associated with this research objective, such as demographics, overall weather knowledge, hail warning communication and lastly the benefits of hail nowcast information. Even though people’s attitudinal relationships with hail nowcasts are complex that no structured interview can fully access them, results were compared with previous literature to illustrate how and why they may differ.

Interviews conducted in this study was in a form of structured interviews which was led by a script and it was suitable for spontaneity and flexibility of probes (Dunn, 2010). These interviews started on the 1st of October 2017 and were completed on the 5th of December 2017. In this period a sum of 30 people was interviewed from different suburbs in Gauteng. The sample size in this dissertation was reliable with numerous past studies on severe weather perception and response which used interviews in their approach (Moore *et al*., 2004; Donner, 2007; Silver, 2012). The interviews were less than 25 minutes to over 40 minutes, with the majority of the interviews lasting 35 minutes. It was conducted at a location and time which was accessible and convenient for the interviewees as well as the student researcher. In addition, most interviews took place at their home or shopping malls and coffee shops.

Numerous questions that were in the interviews were from past studies which investigated the perceptions on tornadoes as well as individual responses in the United States for example (Lazo & Chestnut, 2002; Donner, 2007; Schmidlin *et al*., 2009; Lazo *et al*., 2009; Sherman-Morris, 2010). The interview questions were ordered into four segments:

3.4.2.1 Demographics

The purpose of this section was to understand the interviewee's socio-demographic profile. The core aim of these set of questions was to collect statistics on characteristics, for example, their gender, age, income group, education background and residential suburb etc. which are known to influence risk propensity, decision making as well as social vulnerability. These set of questions were used with the purpose of linking responses amid other interviewees.

3.4.2.2 Weather knowledge

This segment was intended to get an insight into how people perceived general weather and hail warnings. Considering where, when and how frequent different end-users obtain nowcasts is fundamental to understand the best possible way to supply them with such information. Therefore, individuals were asked how frequent and where they attained weather information. One aspect of how people use nowcasts was assessed namely: for what activities or decisions nowcasts are used. The findings will bring valuable insight into why and how participants use hail nowcasts.

The questions in this section were to:

1. Explore how the participants gained weather information and where they retrieved this set of information as well as what encourages them to check the weather on a daily basis.

2. Understand if people perceive weather nowcasts and warnings, for example; interviewees were asked to briefly describe what is the difference between hail warning and a hail watch in their own words.

3. Identify damages caused by hailstorms

Lastly, individuals were asked to explain the most efficient and effective way/s for SAWS to notify them about severe hail events for example (text messages, radio or television broadcasts or through different social media platforms).

3.4.2.3 Hail warning communication process

One of the key thrusts of this objective was to understand how interviewees gained, understood as well as distributed essential information before a hail warning.

This section was intended to:

1. Obtain an understanding of how interviewees attained and used weather and hail warnings.

2. Determine what role the communication of hail warnings played in the short-term recovery process.

3.4.2.4 Perceived benefits of hail nowcasts

Building this end-to-end comprehension from general weather knowledge through to the perceived socio-economic benefits will aid in guiding investment decisions as well as product development for SAWS for example; what nowcast warnings or products to give and when to provide it with insufficient resources. For example, understanding how end-users obtain, perceive, use, and value hail nowcast information shapes a groundwork for determining related concerns associated with hazardous weather. The responsibility of the weather service is to increase the societal benefits resulting from hail nowcasts.

The main objective of this dissertation was to understand how individuals perceive benefits of hail nowcasts prior to a hailstorm event. Interviewees were asked to define what role nowcasts played in the long and short-term recovery process as well as to what typical time scales they need as an early warning. They were further asked if they valued hail nowcasts. Hail nowcasts are of utmost importance since people’s activities are affected by severe hail events. Hence these nowcasts are valuable. Refer to *Annexure B* for the type of questions that were asked during the interview.

3.5 Analysis

Interviews were transcribed and analysed by means of thematic analysis to note answers and identify emerging patterns within the interview transcriptions. The information was examined by making use of techniques like those defined by McCormack (2000), where transcriptions are revised numerous times to identify patterns from distinctive 'lenses' such as: (context, narration and language). The results were formatted for analysis in LibreOffice Calc. LibreOffice Calc was used to determine percentage frequencies and averages as well as to log relationships among variables through participant groups using cross-tabulation.

CHAPTER 4

FINDINGS AND DISCUSSION: NOWCASTING HAILSTORMS

This section will begin with an overview of hail forecasting and the process of forecasting these storms. Second, a detailed examination of the procedures of hail nowcasting and lastly the challenges encountered when forecasting hail events. The purpose of the detailed analysis was to identify the shortcomings of hail nowcasts and to emphasise where research is needed. Without many hail days to study, forecasters are not prepared to recognise the risk. Decision makers may use this result when developing severe hail forecasting/nowcasting or warning programs. The section following will discuss the results of the interview script under the original titles (e.g., hail forecasting; hail nowcasting; hail warnings and the biggest challenges in forecasting and nowcasting hailstorms).

4 Forecasting

4.1 Hail forecasting

Hailstorms may impact individuals, the economy, society as well as the environment. The severity of this meteorological event varies upon several factors including the duration, timing and location of the event (Lean *et al.*, 2008). Donovon and Jungbluth (2007) mentioned that the forecast should be guided by the potential impact of the hail event. SAWS provide weather forecasts to specific sectors such as aviation and the public as required by the government.

Experts (Chief forecaster), (senior forecaster) and (nowcaster and severe weather) in the leading field of forecasting from the South African Weather Service were interviewed and were asked if SAWS forecasted hailstorms. Interestingly, it was found that SAWS do not forecast hailstorms or tornadoes, however, they forecast severe thunderstorms. Thunderstorms are based on certain ingredients that are required when forecasting severe thunderstorms. Nevertheless, any thunderstorm could have a potential for hail, however, there is a chance that large hail is not associated with the storm. There are days when the weather service forecast thunderstorms accurately with a potential of hail and there are days when they are not accurate in forecasting thunderstorms well in advance.

From the interviews and observations, it was evident that the criteria used by SAWS for issuing alerts for severe thunderstorms similar to that of National Severe Storms Laboratory (NSSL). The criteria are as follows:

- Strong damaging winds with wind gusts over 50 knots
- Large hail which would be larger than 19mm or large amounts of small hail
- Significant rainfall, heavy rainfall within a short period of time which may cause localised flooding

Rauhala and Schultz (2009) conducted a study on tornado warnings and severe thunderstorms in Europe. Questionnaires were sent to 39 European National Hydrological and Meteorological Services (NHMSs). The questionnaire addressed severe storm warning processes, warning methods and lastly the shortcomings encountered by NHMSs in emerging their warnings. Interestingly, 85% of the European NHMSs criteria used to forecast severe thunderstorms were like SAWS such as damaging winds, large hail or heavy rainfall. These weather projections were used to disseminate warnings in 70% of the European weather services (Rauhala & Schultz, 2009). Rauhala and Scholtz (2009) further found that out of the 26 countries that completed the questionnaire, only 58% of the countries used to hail as a criterion in severe thunderstorm warnings.

The forecasters at SAWS use NWP modelling to check if temperature, wind flow patterns and atmospheric conditions may lead to the development of severe thunderstorms. Similarly, the Indian Meteorology Department (IMD) forecast and observes the atmosphere for indicators of severe thunderstorm development (IMD, 2012). The forecaster uses synoptic charts as a guide to delineate areas of possible thunderstorm development (Met Office, 2009; Goyal, 2017).

Severe thunderstorms are forecasted using radars, synoptic charts and weather models which are verified with satellite imagery. The Met Office UK employs the same tools as SAWS when observing weather (Met Office, 2009). Forecasters depend on reports of thunderstorm development and their movement. These reports are observed by weather stations, radar and satellite imagery are used to aid the forecaster to track weather systems that could produce thunderstorms (Goyal, 2017). 46% of the countries used weather reports from observation stations and satellite images as the base for thunderstorm warnings. In contrast, Bulgaria is the only weather service that relied solely on NWP models during its warning decision making (Rauhala & Schultz, 2009).

Wind shear is generally used for forecasting severe thunderstorms. Past studies have shown that thunderstorms rely on the wind shear (e.g., Chisholm, 1972; Marwitz, 1972*a*, Marwitz, 1972*b*;

Fankhauser *et al*., 1977). Stronger wind shears are accompanied by the development of austere thunderstorms which can have large hail (Doswell & Burgess, 1993; Moller, 2001). Severe thunderstorms are more likely to occur when there is an increase in vertical wind shear (Markowski & Richardson, 2006; Glickman, 2000). SAWS stated that wind shear is one of the main criterions because often forecasters found that wind shear and high instabilities are needed to forecast hailstorms. Wind shear is the biggest role player in identifying hail events. In addition, Pilorz et al. (2016) found that shear is common during squall lines which may include bow echoes, hence resulting in strong damaging winds. The change in the extent and direction of wind shear is more favourable for hail in a given super-cell (Smith *et al.,* 2012). A recent study showed that the impact of wind shear on hail growth in severe thunderstorms may aid in improving forecasts (Dennis & Kumjian, 2017).

It was found that the forecaster depends on the ingredients in forecasting thunderstorms; if the wind shear is not ideal, then they look at speed sheering and directional sheering. The senior forecaster at SAWS mentioned that the forecasters try to be specific in issuing warnings or watches but usually it is a general warning. Weather models are essential and imperative because it guides the forecaster. However, there is a challenge when working with models. There had been few cases whereby SAWS have not issued out a warning because weather models were not accurate. The senior forecaster further reported that weather observations to verify weather models are vital. SAWS use a set of weather products to communicate forecasts of severe thunderstorms 1 day in advance and are constantly improving the forecast until the event has ended.

Severe thunderstorm warnings are issued for areas where conditions are favourable for thunderstorms such as atmospheric instability and moisture, a lifting mechanism and wind shear. Rauhala and Schultz (2009) found that the majority of the countries disseminate severe thunderstorm warnings based on the radar severe storm features.

4.1.1 The typical time to forecast severe thunderstorms

Severe thunderstorms are forecasted within two days however, it relies on weather systems such as classic weather systems, upper trough coming through or surface high ridging into the east. Those systems will alert forecasters to be on a lookout for two-three days. Thus, in issuing alerts for severe thunderstorms it is usually a day before with a watch and if it is approaching, then it is preceded with a warning. In addition, most European countries that completed the questionnaire mentioned that the most appropriate time was seen to be 24-48 hours in advance (Rauhala & Schultz, 2009). Contrastingly, some weather services in Europe send out warnings within 6 hours or a shorter lead-time, followed by 3 hours. This can be due to different warning philosophies that are used in South Africa and Europe (Rauhala & Schultz, 2009).

SAWS were asked if forecasting severe thunderstorms vary in season. In South Africa thunderstorms are more likely to develop in early spring through late summer (Goliger *et al*., 1997; de Coning & Adam, 2000; Gill, 2008; Gijben, 2012). However, in 2016 during mid-winter in July, there were severe thunderstorms for two days on the 25th and 26th July 2016. It must be noted that any time of the year, there can be a possibility for severe thunderstorms. Hence, a forecaster needs to be prepared for the occurrence of severe thunderstorms. For example, when doing a forecast, the forecaster will pick up on strong upper air winds compared to the surface. Therefore, wind shear aids the forecaster to make a forecast. It also depends on the different seasons. It was evident that years 2014-2015 was dry followed by several heat waves in the last summer season. Thus, every time heat waves broke, very often severe thunderstorms developed with potential hail and strong winds. Olivier, (1990) found a similar correlation between hail and particularly dry seasons. Hence, it depends on the season and how the season also progresses.

4.1.2 Verifying forecasts

Verification has three key goals firstly to assess the forecast accuracy; second, to compare different forecast methods and third, to provide feedback to improve accuracy (Lack *et al*. 2010). Forecasters try to find innovative ways to predict weather and find techniques to determine methods for different situations. The chief forecaster at SAWS mentioned although they have not quite worked on the verification, the forecaster's capture information from social media reports or from wherever they can find the information while on shift. This information includes the size of the hail, damaging hail and location of the hailstorm. Once this information is received, verification becomes easy by comparing to see if there was an alert issued out or if it was a severe thunderstorm containing large hail or not. In contrast, Rauhala & Schultz (2009) found that only 6 of 22 countries in Europe use media reports. A reason for this is that European countries are developed and have skilled individuals to verify their forecasts. While in South Africa, the weather service relies on media reports. Rauhala and Schultz (2009) found 17 out of 22 countries verified their forecasts operationally and ground-based reports are not used in the verification due to the lack of spotter networks; 2 of the countries verify their forecasts after major events e.g. (hailstorms). In addition, 79% of the countries make use of surface weather observations in their verification process. The majority of the countries use radar or lightning data in their verifications.

The weather service uses the two-by-two contingency Table analysis to verify forecasts. SAWS try to be specific as possible when warnings are issued. For example, if severe thunderstorms are forecasted it can be seen what the effect will be such as: is it large hail, is it large amounts of small hail, is there no hail or it is damaging winds etc. However, the main problem in verifying forecasts is that not every incident is being reported.

The nowcaster from SAWS mentioned that often an alert will be issued however, there will be no report if it occurred or not. For example, on the 26th of July 2015, there were two tornadoes one in Thembisa and another in Delmas. The tornado that happened in Thembisa was reported. However, the one that went over Delmas was not heard of. It was only reported the following week. Sometimes there could be a delay in reports or there are no reports on any severe event. For example, a farmer somewhere in the middle of the Free State will not mention he had hail damage to crops.

4.2 Nowcasting hailstorms over the Highveld

Nowcasting comprises of a full description of current weather together with forecasts attained from extrapolation or nowcast models for 0 to 2 hours (Brooks & Doswell, 1996; Smith, 1999; Ebert *et al*., 2005). Within this time, it is possible to forecast individual storms with reasonable accuracy. SAWS does some sort of nowcasting, however, to an extent. Few hazards (gale force winds, flooding etc.) in South Africa can be predicted in advance. However, with severe thunderstorms it is a bit more complex, it has to be done on a nowcasting basis. It is challenging in being confident by sending out warnings before the thunderstorm approaches. Therefore, for a nowcaster is needed to specifically nowcast severe thunderstorms. For example, due to the considerable number of hail events in the United States, weather services in the US have nowcasters to nowcast these storms in advance.

4.2.1 Nowcasting algorithms for severe thunderstorms

The algorithms used by SAWS are not customised to South African conditions; it is used with default settings which can be challenging because it may impact the False Alarm Rate (FAR). The main tool that is used is the weather radar and the algorithm which does thunderstorm tracking, hail mass aloft etc. Another tool used in nowcasting is satellite imagery from Meteosat Geostationary imagery which shows overshooting cloud tops or vigorous updraft. Due to South Africa being a large country, only a subset of the country is covered under the radar. Hence satellite imagery is vital in viewing thunderstorm characteristics such as cold U-shaped anvil cloud. The Met Office UK uses similar tools in nowcasting severe events such as hailstorms (Met Office, 2009). Similarly, Ray and Bhan (2015) reported that the IMD uses the latest radar data and satellite imagery in nowcasting. SAWS do not only depend on algorithms because doing automatic analysis can be problematic thus, but they also conduct analysis on radar data and super-cell signatures (overshooting cloud tops, bow echoes etc.). The thunderstorm tracking algorithm tracks and identifies potential storms such as the movement and direction of the storms. The forecaster identifies features in the thunderstorm, for example, echo regions. The forecaster also looks at the severe storm criteria before issuing out a warning. However, it is challenging to do it automatically using algorithms.

4.2.2 Current nowcasting procedures employed by SAWS

The main procedure is by viewing observations because the weather service does not have a nowcasting model, thus, they rely on and use observations. Figure 4-1 summarises the current nowcasting procedures.

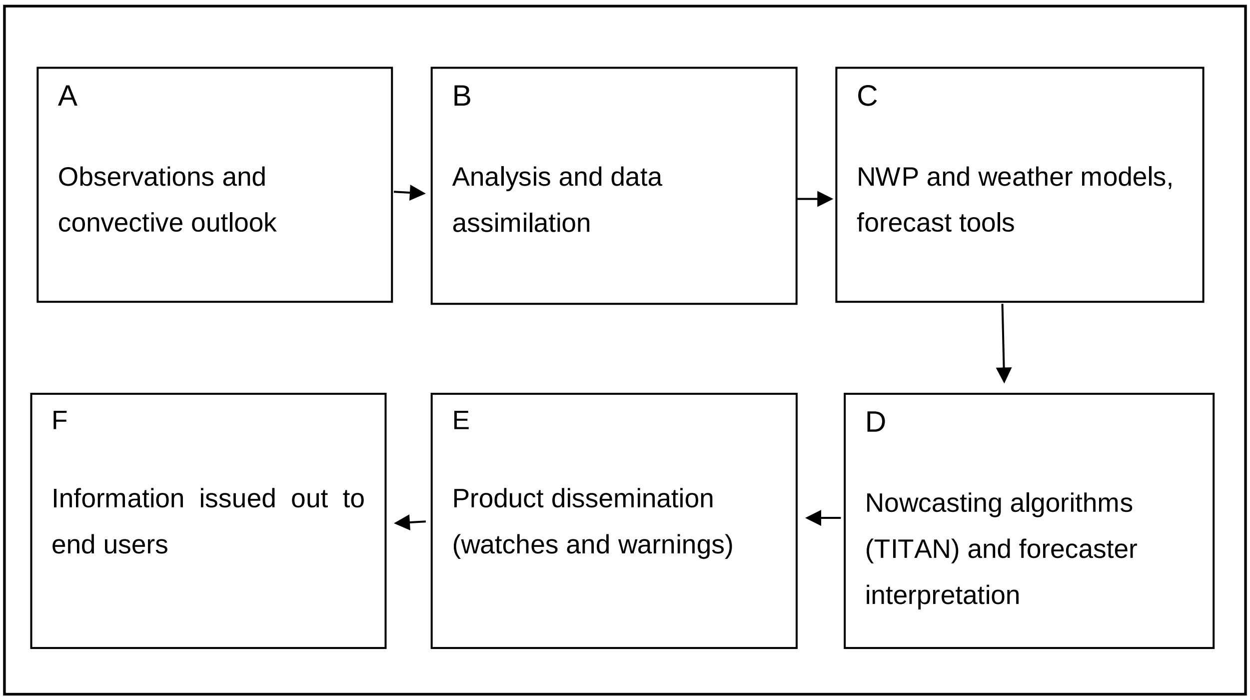

Figure 4-1: Brief overview of the current nowcasting procedures employed by SAWS.

a) The first procedure is the convective outlook for the day. Thunderstorms often develop during the afternoons hence, upper air soundings for the afternoon can assist the forecaster.

b) It aids the forecaster to see how the condition of the environment, for example, if the environment is favourable for severe thunderstorms or not. If thunderstorms are developing, it can be seen on satellite. The nowcasting process by SAWS is similar to the IMD. IMD (2012) forecasters analyse the predominant synoptic condition and examine environmental conditions that are likely for the development.

c) Once the forecaster knows the environment he/she can expect certain things to occur either on radar or satellite hence, the forecaster can make better nowcasts on what will happen in advance. For example, from weather models the forecaster can see which areas are most favourable in expecting thunderstorms and which areas are not; is it a big thunderstorm or not or will it dissipate before developing in other areas (Met Office, 2009).

d) As soon as the forecaster examines the environmental soundings for the day, he/she will decide is the Convective Available Potential Energy (CAPE) value is adequate for the potential of severe thunderstorms. The wind shear can also assist the forecaster in deciding if it is a single-cell, multi-cell or super-cell thunderstorms. According to the Met Office (2009) & IMD (2012), the forecaster examines thermodynamic features. Various indices are used for thunderstorm forecasting. The thermodynamic indices amongst others are CAPE, Lifted Index (LI) and Total Totals Index (TTI) and their threshold values are available to forecasters to highlight the area of occurrence of severe weather. As soon as the environment is favourable for thunderstorms over an area, the forecaster targets the expected time of occurrence utilising the latest radar data and satellite imagery. Surface map observations are also used, whereby synoptic maps are drawn that comes in every three hours which aids the forecaster. The forecaster analyses the synoptic charts every three hours. The surface data usually assist forecasters to identify where the dry line is and which areas are more favourable for severe thunderstorms etc. Therefore, observation is one of the first things that is done when nowcasting.

e) The forecasters verify these observations by using weather models (ECMWF; WRF; NCEP and ASIS). For example, the forecaster may view the midnight ascent, however, the environment was not ideal and sometimes there are midday ascents which are favourable for thunderstorms. The environment changes over the next hours. Hence, forecasters verify observations using weather models. The different models that are used by the forecaster are compared to each other to see which model performs well, thus, it will aid the forecaster in being confident about his/her forecast. Forecasters examine NWP products which are used to predict atmospheric conditions. It must be noted that these NWP models do not forecast severe thunderstorms. Different weather models track the movement of thunderstorms (Kuldeep *et al*., 2008). The chief forecaster at SAWS reported that forecasters evaluate and compare the models mentally and not on a screen. By comparing the models, the forecaster builds confidence with a model. There are certain weather systems that certain models do not accurately predict. For example, Thaele (2017) mentioned that she usually uses the Unified model when there are upper troughs, and it does well with that. Hence, she begins to establish which models do better with which weather systems and that gives the forecaster more confidence.

f) The forecaster extrapolates thunderstorms by using the nowcasting algorithm, for example, TITAN to view the potential thunderstorm characteristics such as cloud base and height, the speed of the thunderstorm, maximum reflectivity etc. However, the algorithm used by SAWS is not customised to South African conditions; it is used with default settings which can be challenging because it may impact the FAR.

g) Lastly, the forecaster will decide to issue out watches and warnings as shown in Figure 4-2. The forecaster’s decision depends on the forecast weather elements with thresholds for each of the element. The decision to issue out warnings is also governed by the expected impact that the storm might have such as large hail, damaging winds and heavy rainfall (flooding).

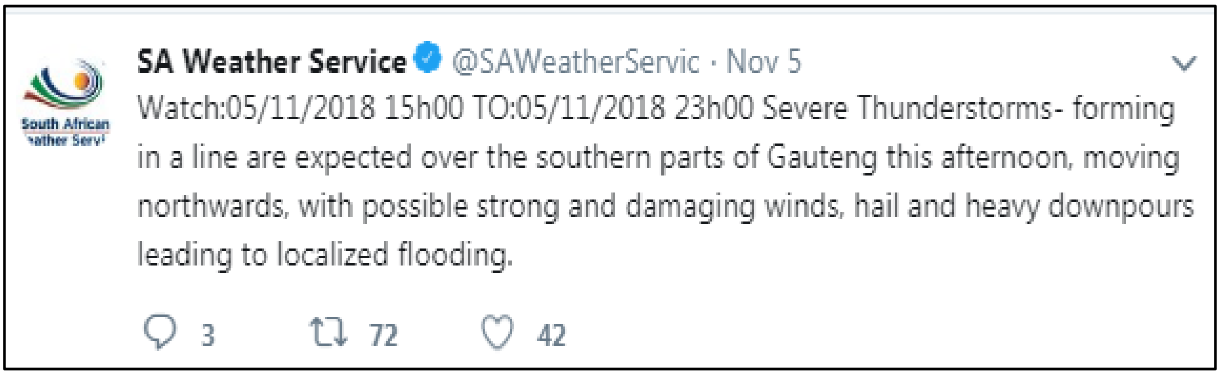

Figure 4-2: A tweet from the weather service warning people of severe thunderstorms with possible strong damaging winds and hail (Source: South African Weather Service, 2018).

4.2.3 Hail warnings

Severe thunderstorm watches and warnings are sent out before imminent severe weather occurs through television, text messages or radio stations. Forecasts are issued to warn the public of potential localised thunderstorms with associated hail. Poolman (2006) highlighted that one of the main shortcoming SAWS experienced was the adequate issuing of warnings to remote areas. Nevertheless, it is stressed, that an operative severe thunderstorm warning system relies on a well-organised functioning of all the different steps of warning and forecast from data gathering to the comprehension and interpretation of warnings. Figure 4-3 illustrates observations from satellite, radar and NWP which are sent to the National Forecasting Centre where weather products are created. Forecasts are divided into two types namely: Long and short-range forecasts/nowcasts/warnings. The warnings are disseminated to end users, for example, Disaster Management Structures.

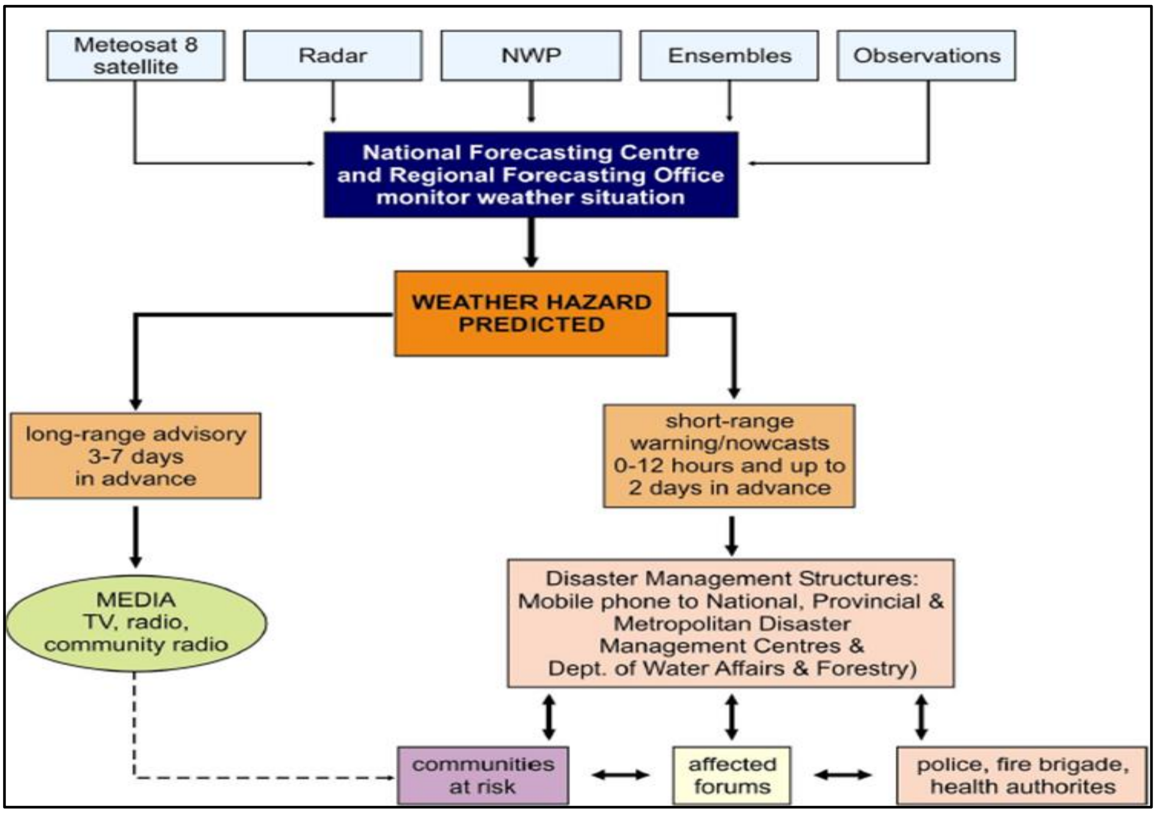

Figure 4-3: Early warning monitoring and dissemination process employed by SAWS with other role players (Source: Poolman, 2006).

SAWS stated that they issue warnings for severe thunderstorms, localised flooding, heavy hail, strong winds, high fire danger and high tidal waves. It was found that warnings are sent out to the aviation sector, major end-users and the public to take precautionary measures. The weather service was asked if they include instructions for the public to take. Previously they did not have instructions in their warning messages. However, recently, the weather service has been active and interacting with the public on social networking sites such as Facebook and Twitter where warning messages are communicated with the precautions one can take. The majority of the warnings are based on radar characteristics and satellite imagery. Rauhala and Schultz (2009) found some countries disseminated, severe storm warnings based on the radar severe storm features. 46% of the countries used weather reports from observation stations and satellite images as the base for thunderstorm warnings. The senior forecaster from SAWS gave an example of a sample warning message as follow:

"Severe thunderstorms with possible hail, heavy rainfall and strong wind gusts are observed and forecast over parts of the East Rand (Gauteng). If outdoors seek shelter immediately but do not seek shelter under telephone lines, trees. Avoid near metal objects such as; fences or power lines. Do not take a shower during a severe thunderstorm and disconnect electrical appliances".

4.2.4 False alarms

The severe weather network in South Africa is undeveloped and most of the time one depend on reports of such events from the media or members of the public (Banitz, 2001). If any report is accessible, the storm is seen as severe. Severe thunderstorms with hail or wind damage that are not predicted may lead to a low FAR. SAWS reported that it can be challenging because they do not want to ‘cry wolf’ and there is no severe thunderstorm. Therefore, it depends on the forecaster and the experience when issuing alerts. For example, the maximum reflectivity might be 60 DBz which is a high potential for hail however no warning was issued. This can be seen from a cross-section of the storm. Hence, some forecasters might miss this and issue out warnings which are false alarms. The prediction of thunderstorms depend on radar data, however, predictions can only be made once the storm has developed such as echo shape, storm movement or high reflectivity. Better radar coverage can lead to improved forecasts and less FA (Banitz, 2001).

4.3 The biggest challenges in forecasting/nowcasting severe thunderstorms

Weather services throughout the world are confronted with challenges and problems from general challenges within the workplace or issues with forecasting. Similarly, the SAWS face challenges, the main shortcoming they experience is that there are no individuals who are specialists in their field for example, in severe weather. The chief forecaster assists where he can, however, if a severe event were to happen over the weekend and the forecaster is not around it becomes a loophole for the weather service. The senior forecaster from SAWS further mentioned:

“It would be great to have a specialist in severe weather and nowcasting purposes monitoring the situation”.

There is space for nowcasting at the weather service however, there is a lack of skilled individuals who can communicate nowcasts in real time. Nowcasting can make a difference at the weather service but that space is not being filled. Without a specialist in the severe weather sector, it remains a constraint to the weather service. The nowcaster from SAWS reported that it is expensive to implement specialists in the severe weather section. Hence, it remains a stumbling block. Rauhala and Schultz (2009) found that weather services in European countries experience challenges such as the need for extra forecasting tools. The majority of these countries has a lack of forecasting knowledge. The lack of forecaster experience with severe thunderstorms and forecast training are potential problems that countries mentioned (Rauhala & Schultz, 2009).

The second challenge is the automotive system. At the time this study was conducted, the senior forecaster from SAWS mentioned the weather service do not do anything automotive it is all forecaster texting which can be difficult. The chief forecaster mentioned that these risks are so-called human factors. Whereby the forecaster is overloaded with so many things that he/she may confuse what they are doing. Hence, the weather service would like to automate however, they need a specific forecaster eye to train to identify those types of storms and is difficult to automate. Another challenge is that the weather service might not have issued any warning due to lack of data. In Contrast, if the forecaster knew from experience that it was a day for severe thunderstorms then with the use of satellites, it would be easier to send out warnings. Banitz (2001) mentioned that with real-time data, the forecaster will have improved knowledge of the situation, hence, it will enable to predict accurately. More data may be valuable to the assessment of statistics and fewer events will be "missed" (Banitz, 2001).

Rauhala and Schultz, (2009) found that few European countries which had a lack of full radar coverage had a limitation in severe thunderstorm warnings. Few countries suggested the need to increase the number of forecasters to aid in attaining better thunderstorm forecasts and warnings. Radars are becoming more costly to maintain, for example, the senior forecaster from SAWS mentioned that the severe hailstorm that occurred on the 20 October 2016 in Bloemfontein, the radar was down nevertheless, it showed up well on the satellite imagery. However, it was impossible to differentiate the hail sizes because the radar was switched off. Last, the SAWS face funding issues throughout their organisation which puts a strain on them such as: unable to maintain their radars or using specialists in different fields.

There have been recent developments on how SAWS communicate forecasts and warnings. SAWS has two interactive social media platforms (Twitter and Facebook) and recently launched a weather application which can be downloaded onto smartphones. From the results in the current nowcasting procedures used by SAWS, the next section builds on this objective. The nowcasting algorithm that is used by the weather service is tested to see the accurateness of the algorithm and it is expected that TITAN will yield positive results (less FA).

4.4 Nowcasting algorithm

In this section, the verification scores will be discussed. The TITAN algorithm will be evaluated using the contingency table statistics as discussed in chapter 3. Lastly, three different case examples will be presented and discussed with reference to the hail metrics.

4.4.1 Thunderstorm Identification Tracking Analysis and Nowcasting (TITAN)

The TITAN algorithm that was programmed to run during November 2013-February 2015 where big and damaging hailstorms were reported. From the available radar data, TITAN detected a total of 28491 storm tracks. Based on the hail metrics criteria set out, the algorithm detected a total of hailstorms 83 storms, 5 of those hail events occurred and were reported, 1 event was missed by the radar as shown in Figure 4-4. The reason for this was because the radar been switched off due to maintenance or another reason might be because the radar was not operational. 78 of the storms were detected by the radar, however, it was not reported on any media platform as illustrated in Table 4-1.

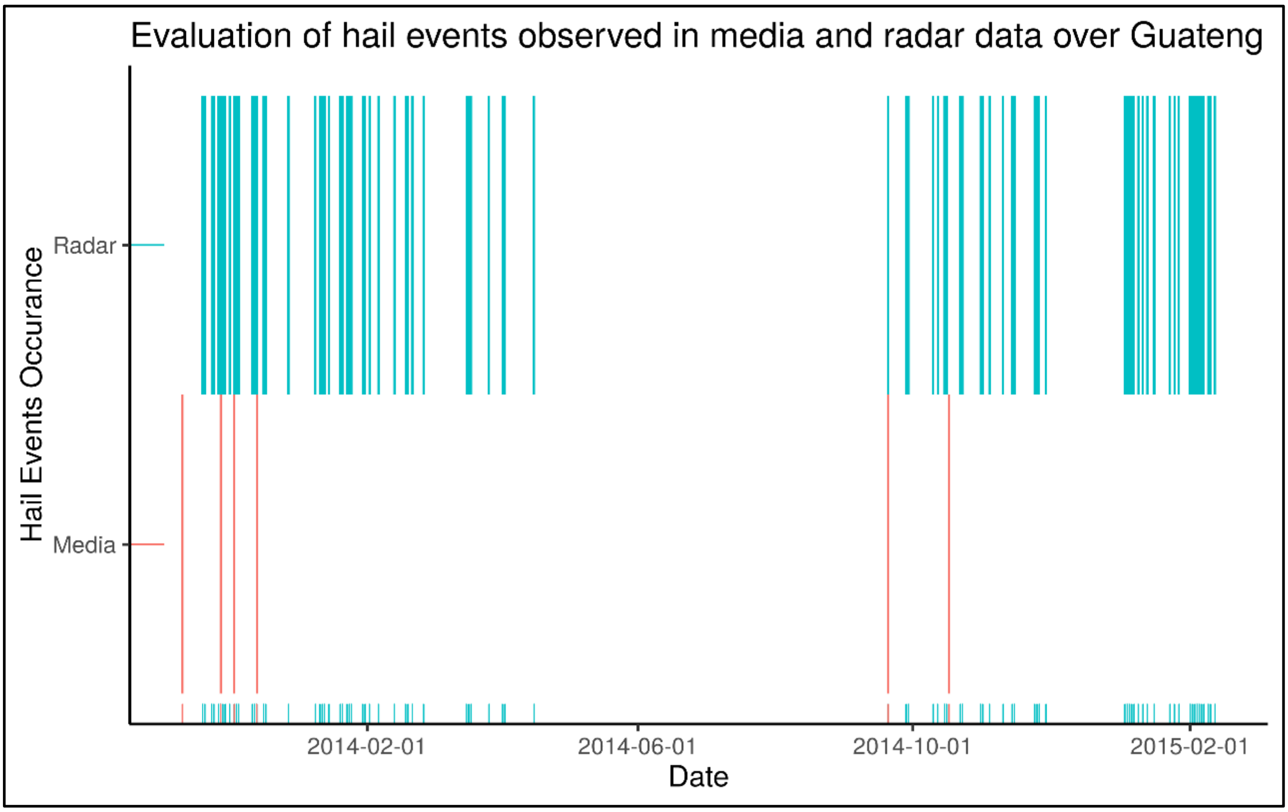

Figure 4-4: Hail events observed from the available radar data which is annotated by the blue lines and hail media reports were used to verify these observations (red lines).

Table 4-1: Number of hail events over the Highveld between 2013 and 2015

Hail events over the Gauteng Highveld between 2013 and 2015		
Date	**Location**	**Weather**
11 November 2013	Ekurhuleni	Hail (golf ball size)
28-29 November	Johannesburg, Pretoria and Witwatersrand	Hail (golf ball size)
4 December 2013	Pretoria	Hail
14 December 2013	Pretoria	Hail
20 September 2014	Johannesburg and Roodepoort	Hail
17 October 2014	Centurion, Johannesburg, Ekurhuleni and Randburg	Heavy hail

Due to 1 of the hail event being missed by the radar, it was excluded from the hail reports. It can clearly be seen that 2013 has been a year with the most hail events to date with a total of 4 storms over the Highveld Table 4-1. The most destructive hailstorm occurred on the 28 November 2013 with damages over ZAR1.4 billion for that day. Figure 4-5 is an example of how the TITAN algorithm detects current severe thunderstorms and forecasts the movement of storms in advance. The current storms are annotated by the cyan line around the storm and the forecasted storms are illustrated by the red line. On the top right of the image, the array of colours illustrates the maximum reflectivity of each storm, whereby it indicates the severity and intensity of the storm. With grey being severe and dark green less severe and associated with light rainfall.

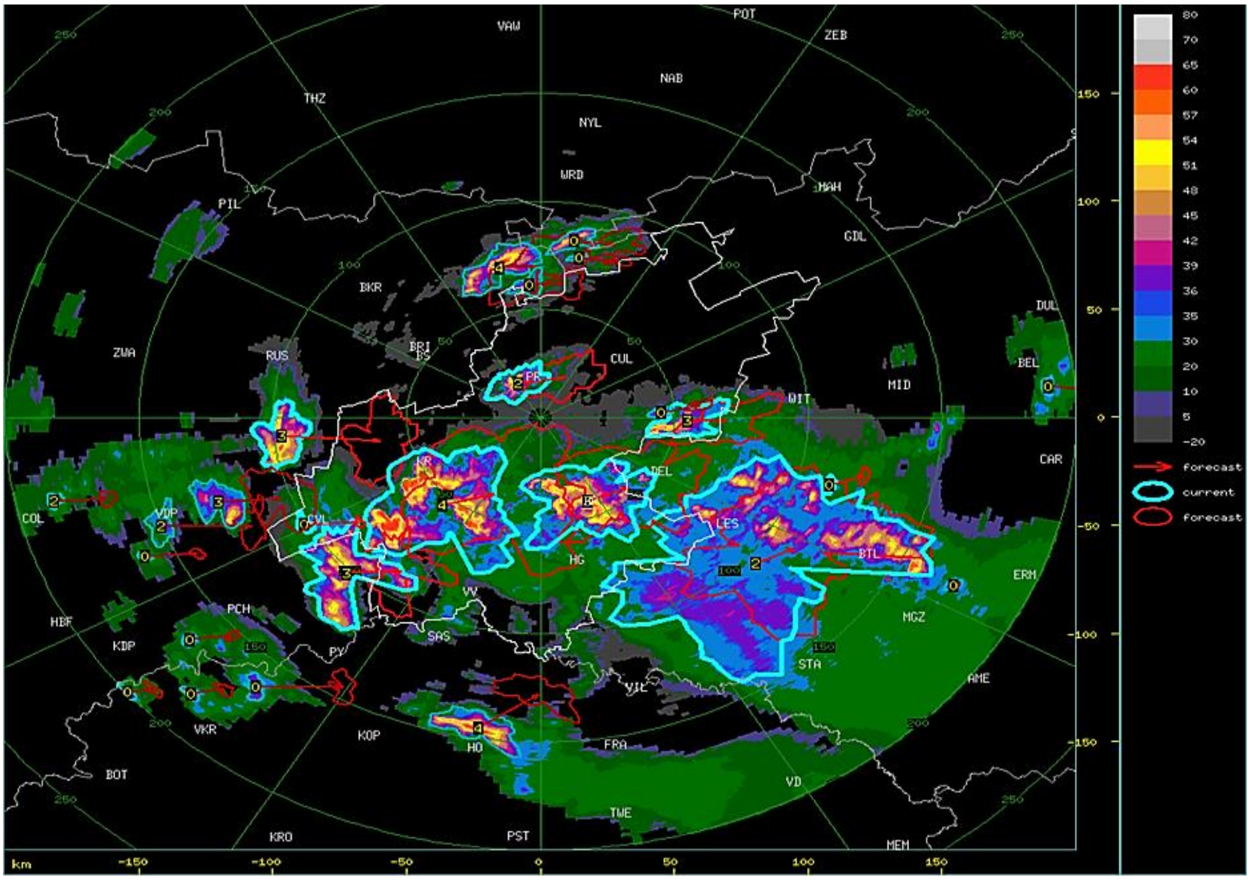

Figure 4-5: This is a 400 x 400 equal-area Transverse Mercator projection from the Irene S-band radar 25.91° S, 28.21°E.

4.4.2 Verification scores

A preliminary verification on TITAN with media reports data will be presented. Based on the TITAN algorithm presented in the previous sections, different statistics of forecasted hail events were calculated. The contingency Table illustrates hail events that were observed versus events that were forecasted. 6 storms were observed from 84 hail events that were forecasted and 78 of them were false alarms. 1 of the event was observed however, it was not forecasted. This could be that the radar was not operational at the time. 231 of the events were not observed nor forecasted (Table 4-2).

Table 4-2: The contingency Table illustrates hail events that were observed versus events that were forecasted.

Hail forecasted	**Hail observed**		
	Yes	**No**	**Marginal Total**
Yes	5	78	84
No	1	231	232
Marginal Total	6	309	**316**

The prediction of hailstorms relies mostly on radar information and can only be made once the event has started to develop. Hence, radar characteristics such as echo shape, storm movement high reflectivity can be recognised by radar images. The reports of extreme hail events depend on the media and individuals who can call the weather service to notify them. If there are available reports, then it is seen as a severe event. These severe hailstorms are not anticipated well and typically have a high FAR (Banitz, 2001). Interestingly, TITAN performed extremely well in detecting hail events, a possible reason for this, is that it detects hail of all sizes. Hence, small hail that is not damaging was also detected. Nevertheless, there was a positive observation in the POD, it performed well and had a POD score of 0.85. In contrast, the FAR was exceedingly high and has a score of 0.93, thus, supporting the heavy overestimation of forecasts. This is because there were not many hail events that occurred as well as the availability of radar data. This parameter is difficult to predict in terms of time and space.

Therefore, one needs to be careful when using POD and FAR under these circumstances as a low frequency of occurrence can be misleading. Nisi et al. (2016) found similar results for different algorithms, a high POD of 0.84 and a FAR of 0.70. The relatively high FAR indicated the algorithms tend to overpredict severe hailstorms. Skripniková and Rezácová (2014) and Kunz and Kugel (2015) validated hail algorithms against loss data from insurance companies employing different skill scores from categorical verification. They reported that radar hail methods provided a reasonably high POD and a high FAR. Nevertheless, it is acknowledged that evaluation for FAR is complicated due to if no damages were recorded or reported for an area, it does not specify that there was no hail. The cause for any inconsistencies could be that insured losses are managed by numerous factors which include land use, insurance coverage (number of insured objects), the vulnerability of personal assets (property or vehicles) and the insurance practice.

Radars detect hail at higher altitudes, therefore, the melting processes can have an effect on the results. However, it must be noted that hailstones are proportionate to the square of the area and the volume is proportionate to the cubic, thus, melting may impact small hailstones (pea size) (Mahoney et al., 2012). Previously, it was perceived that over warning decreases the general public's readiness to respond to severe weather warnings (Barnes & Gruntfest, 2006). Breznitz (1984) conducted experiments to study an individual's reactions to recurrent FAs and found that FAs reduced participant's readiness to respond. However, in contrast, studies have shown that individuals may have a high acceptance of FAs. This will be discussed well in detail in chapter 5.

TITAN performed poor in terms of the CSI and had a score of 0.05 and showed no skill. The verification scores indicated a poor performance with low CSI and high FA scores, although some events are warned during these occurrences. Lastly, TITAN displayed a low HSS skill of 0.01 which indicated no skill due to the great amount of FA as depicted in Figure 4-6. If warnings are issued for every hailstorm which may contain small hail that is not damaging, the POD will be high but FAR will also be exceedingly high. However, if warnings are only issued for big, strong and damaging hail events, then there will be few FA. Hence, it was concluded that skilled and trained professionals (nowcasters) are required to interpret nowcasts before it is issued to end-users, however, this remains a challenge to the weather service as found above in section 4.3.

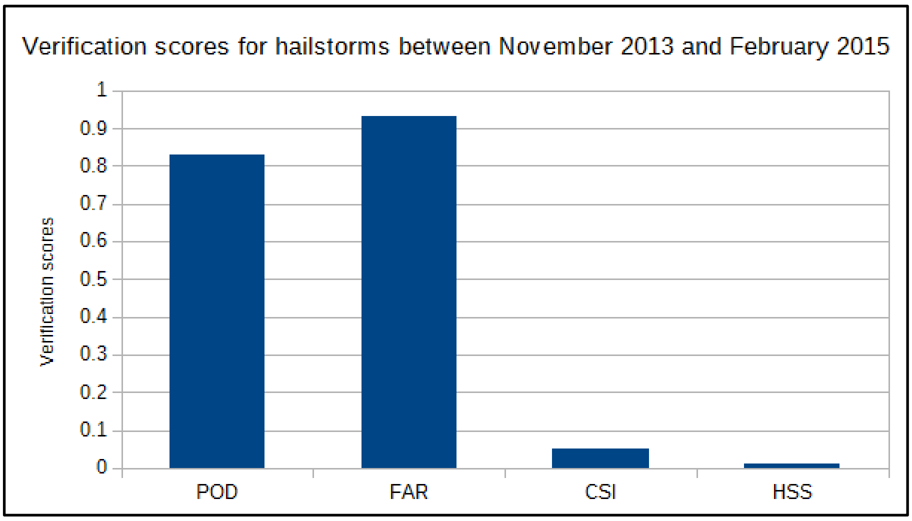

Figure 4-6: Verification scores for hail events that were observed and reported between November 2013 to February 2015.

4.4.3 Hail metrics and case examples

These case examples are presented with hail metrics such as the FOKR index, HMA, POH and VIL. The first case example is what a classic severe hail event looks like when using the TITAN algorithm with this event has been reported in media reports. The second case example is when the algorithm forecasted a storm and it was not reported which is known to be a false alarm. The third case example is when a hail event was reported however, the radar was not operational during the time. The purpose of this section was to show the reader different cases using radar data.

4.4.3.1 28th of November 2013

A disastrous hailstorm in the Gauteng province that occurred on the 28th of November 2013 caused an insured loss of over R1.4 billion, hence, making it one of the most destructive weather event in the South African insurance history (Visser, 2014). This was an example of a classical long-lived hailstorm that started in Pretoria and travelled to Johannesburg which resulted in a widespread of great hail damage, especially in Randburg, where tennis ball sized hail destroyed vehicles and properties as shown in Figure 4-7. On the same day, thunderstorms across the Gauteng Province were associated with damaging winds and hail (Burger & Powell, 2013). Figure 4-8 illustrates a vertical cross-section of the day using the TITAN algorithm. The hook echo is a classic radar characteristic found in super-cell thunderstorms and severe hailstorms. It can be seen in the lower area of the storm as precipitation flows into a mesocyclone creating a curved hook-like feature. This echo is produced by large hail. On the top right of the image, the array of colours illustrates the maximum reflectivity of each storm, whereby it indicates the severity and intensity of the storm. With grey being severe and dark green less severe and associated with light rainfall

Figure 4-7: This event travelled across major cities and suburbs in Gauteng. Bottom left illustrates hail sizes of tennis balls that hit the province. Bottom right shows damages to a motor vehicle.

The hail metrics of this storm were as follows:

a. **FOKR** index had a category 4 which indicated severe big hail could be expected

b. **POH** had a score of 1 which illustrated hail

c. The **hail mass aloft** (HMA) had the highest hail energy for the storm which was 122k/tons, the higher the value of HMA it indicated the intensity of the storm.

d. **VIL** is known to be an excellent indicator of hail. Results showed that there was a strong correlation between VIL and the occurrence of hail over the Highveld with 25.5km/m^2. In hail events VIL values are usually higher.

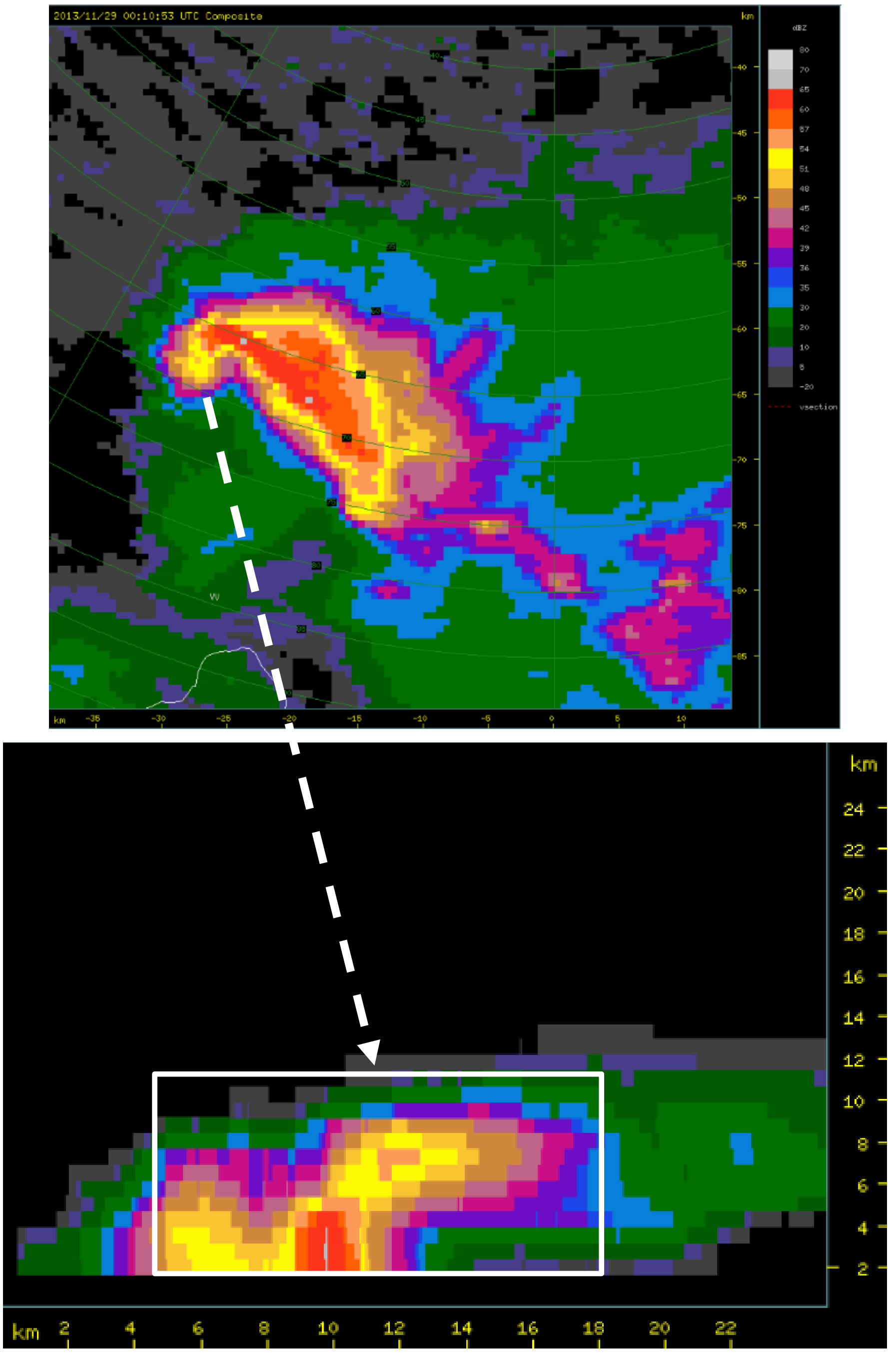

Figure 4-8: This is a 400 x 400 equal area Transverse Mercator projection from the Irene S-band radar 25.91° S, 28.21° E.

4.4.3.2 30th of November 2013

Two days after the severe hailstorm that pelted over Johannesburg and Pretoria, TITAN detected another storm across the East Rand and in Pretoria. High values of 68 dBz can be observed from the radar reflectivity in Figure 4-9. Figure 4-9 further illustrates a radar image that shows a hail event across the East Rand and in Pretoria. The dBz values are presented on the top right of the image. Whereby it indicates the severity and intensity of the storm. With grey being severe and dark green less severe and associated with light rainfall. However, there was no media report on this event, a possible reason could be that the event was not severe and damaging to be reported. A second reason could be that the algorithm overestimates severe thunderstorms by over forecasting these events.

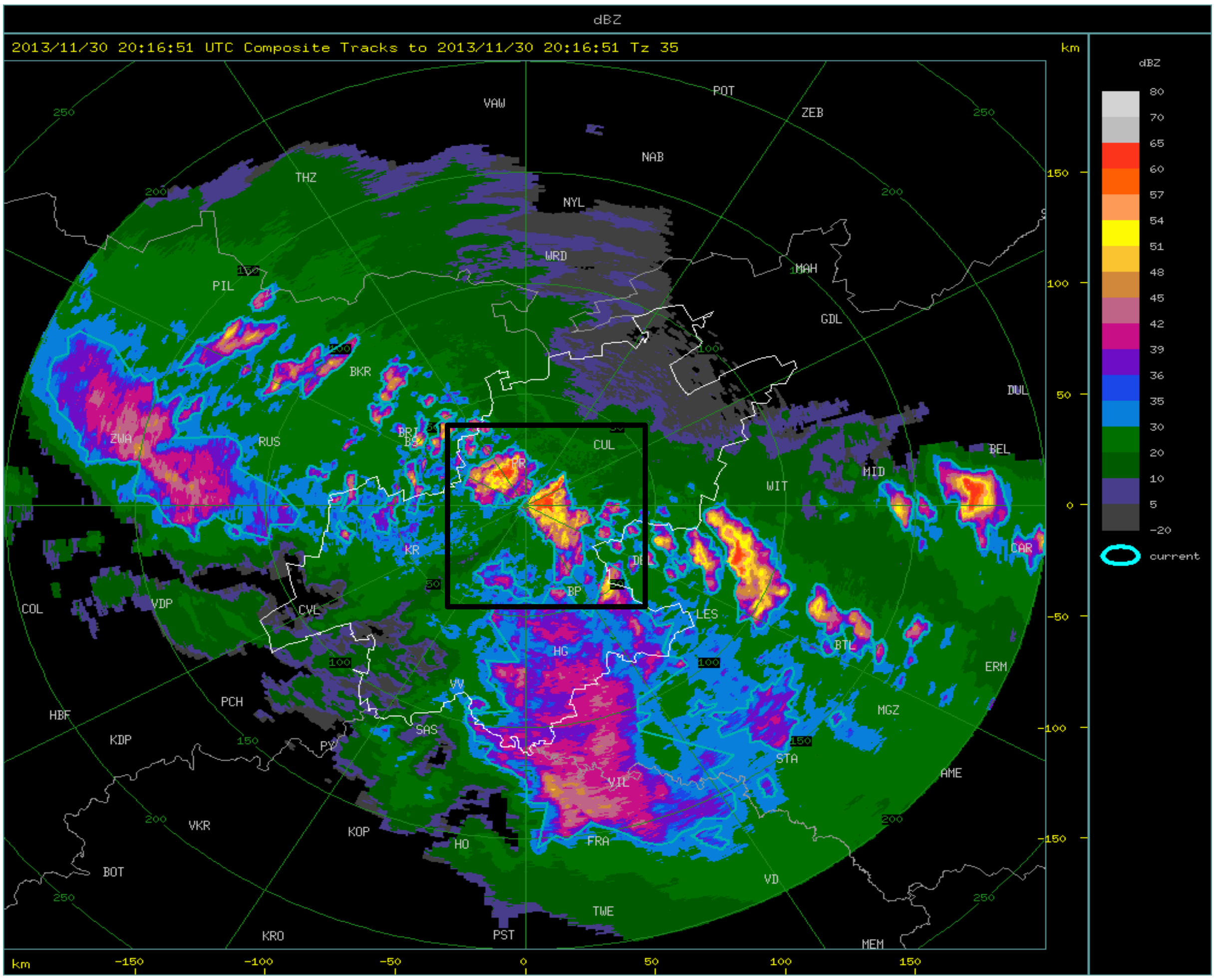

Figure 4-9: This is a 400 x 400 equal-area Transverse Mercator projection from the Irene S-band radar 25.91° S, 28.21° E.

4.4.3.3 20th of September 2014

Hailstorms are common in the city of gold, Johannesburg, however, it still takes people by surprise due to their unpredictable incidences. Hail precipitated over certain suburbs of Johannesburg during the evening on the 20th of September 2014. This hail event was reported to have caught people by surprise, leaving a path of damaged gardens and motor vehicles Figure 4-10. This storm was not as destructive as the one on the 28th of November 2013. It was reported due to the huge amount of hail that looked like snow covering their lawn. Individuals reported this event on different social networking platforms such as Twitter Figure 4-9. Figure 4-9 further depicts a tweet was tweeted about the storm that took the public by surprise. The bottom left illustrates the damages caused by this event leaving motor vehicles and gardens damaged. The bottom right shows the amount of hail that occurred covering lawn like snow. The radar did not detect this event. The reason for this could be the radar been switched off due to maintenances. This type of event was observed and not forecasted is known to be a miss.

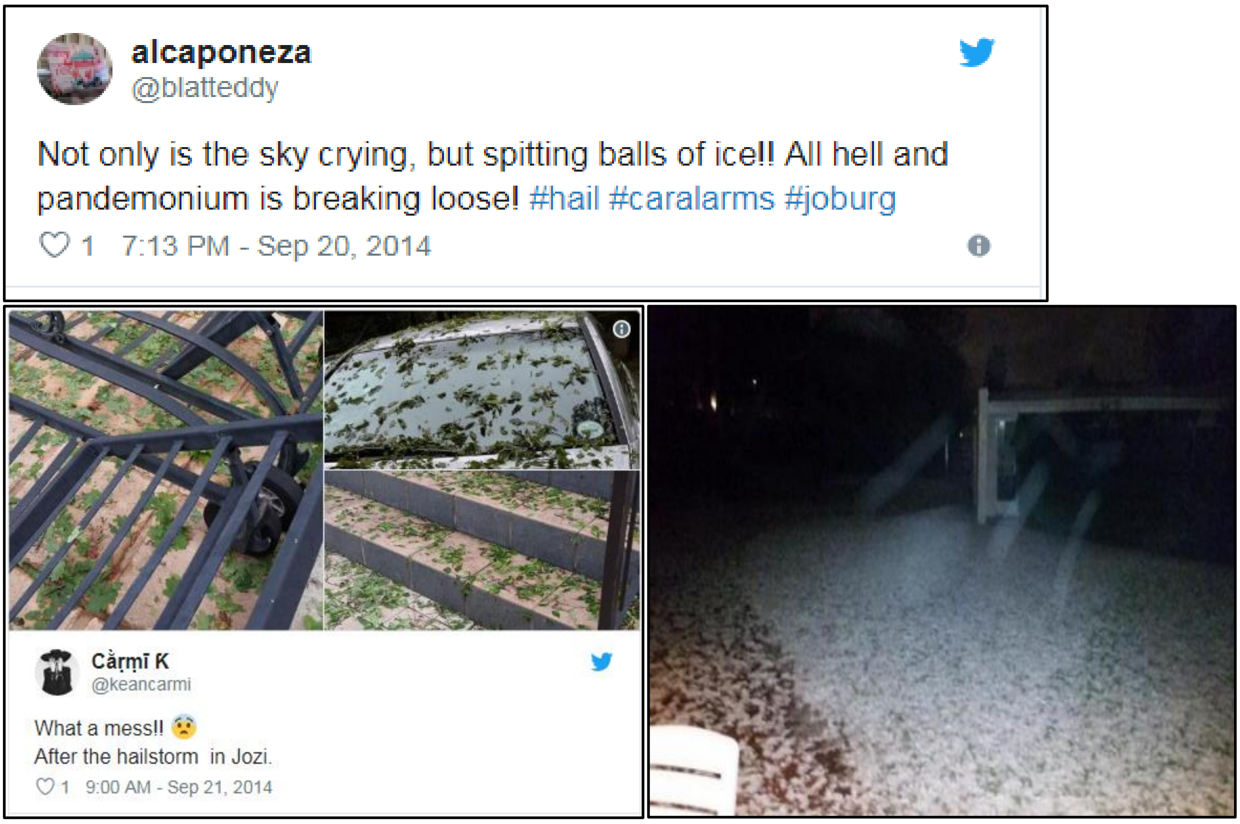

Figure 4-10: Aftermath of the hailstorm that pelted the suburbs of Johannesburg on the 20 September 2014.

TITAN used with the default settings can detect hail events as shown in the different case studies, however, there is a huge number of FA. In contrast to this, participants that took part in this study (chapter 5) were asked if they preferred to be over warned with some forecasts being FA or under warned with accurate warnings. The majority of the respondents reported that they preferred to be over warned despite the FA. This was due to most of the respondents being heavily impacted by hail than those who were not. However, it must be noted that FA can become monotonous, thus, not many people will comply with forecasts. This will be further discussed in **Chapter 5.**

4.5 Chapter summary

It is evident that SAWS nowcast severe thunderstorms which are associated with hail, however, only to an extent. This is due to the lack of specialists who are experts in their field. Another reason SAWS do not nowcast hailstorms is because some insurance industries do it using their "raw" nowcast products. However, for SAWS to nowcast storms, they need motivation or a reason to carry this out to end-users because it is costly. Chapter 5 builds upon this challenge and motivates why they (end-users) need nowcasts. The main tool that is used is by SAWS is the weather radar and an algorithm which does thunderstorm tracking (TITAN). In South Africa, there are 16 single wavelength radars which can be upgraded to dual polarised radars. There is only 1 dual polarised radar in Bethlehem, however, it is not been utilised. Similar to the Met Office in the UK, SAWS also utilise satellite imagery in identifying thunderstorms because only a subset of South Africa is covered by radar. SAWS do not have a nowcasting model compared to other countries such as the US, forecasters rely on observations and algorithms in nowcasting severe thunderstorms.

The current nowcasting procedures employed by the weather service was similar to the American, Asian and European countries. SAWS do not forecast hailstorms or tornadoes; however severe thunderstorms are forecasted. The criteria used in issuing warnings for severe thunderstorms was found to be like that of National Severe Storms Laboratory (NSSL). Previous studies found that other countries used a similar criterion in issuing warnings as SAWS. Wind shear is one of the main criterions. Wind shear was the biggest role player in identifying hail events as mentioned by SAWS. Severe thunderstorms are usually forecasted within two days, however, it relies on weather systems. Contrastingly, some weather services in Europe issued warnings with 6 hours or short lead-time, followed by 3 hours. One deduction was made for this was due to different warning philosophies that are used in South Africa and Europe. SAWS verified their forecasts using media reports and a two by two contingency Table. However, the main problem in verifying forecasts is that not every incident was reported.

SAWS are posed by challenges, the main shortcoming they experienced was lack of individuals who are specialists in their field for example, in severe weather. Without a specialist in the severe weather sector, it remains a constraint to the weather service. There is space for nowcasting at SAWS, however trained individuals who can communicate nowcasts in real time are required.

Furthermore, it must be noted that it is not simple to automate severe thunderstorms and it can be challenging to forecasters.

Previous studies have shown that European countries face challenges as well such as a need for extra forecasting tools. Furthermore, the lack of full radar coverage was a limitation in severe thunderstorm warnings. Last, SAWS face funding issues throughout their organisation which puts a strain on them for example, they are unable to maintain their radars or using specialists in different fields.

A good qualitative agreement is evident particularly the feasibility to adopt the TITAN algorithm for detecting and forecasting hail events observed by long-range radars such as the S-band radar which was employed in this study.

It must be noted that this study evaluated this nowcasting algorithm as the weather services currently use it. The TITAN algorithm indicated a heavy overestimation of hail events. TITAN can nowcast and detect hailstorms, the hit rate was extremely good and the FAR was poor due to the parameters not been tuned and sometimes there were very subtle differences between severe hail and storms with small hail. The second reason is that TITAN was used with default settings and was not customised to identify big damaging events. Therefore, it is very difficult for an automatic algorithm to differentiate between the two. The weather service needs better and customised algorithms for radars using TITAN. South African radars have limitations and algorithms cannot be used alone, specialists are needed to interpret these products. The WMO (2017) supported this and reported that forecasters need to be trained to interpret nowcast products and show end-users how these nowcasts can be applied.

CHAPTER 5

FINDINGS AND DISCUSSION: PERCEIVED BENEFITS OF HAIL NOWCASTS OVER THE GAUTENG HIGHVELD

This chapter will begin with a concise outline of the demographic profile of the interviewees, as well as a detailed assessment of the two interviewees. The purpose of the comprehensive examination was to demonstrate the diversity of hailstorm experiences described between the interviewees. The results will be shown under the original titles which were in the script e.g. (general weather knowledge; social media usage; socio-demographic and the perceived benefits of hail nowcasts). Lastly, this chapter will conclude with a short summary summarising key findings. In full compliance with the North West University Research Ethics guidelines for research concerning participants, results will be shown and explained confidentially. Therefore, no personally classifying information will be given. All the transcribed citations will include an alias and age of the interviewee.

5 Socio-demographics

The sample consisted of 18 males and 12 females which are a slightly unbalanced gender proportion than found by Silver (2015). The inconsistency may partly be described by the wish of some interviewees to be questioned with their significant other. Figure 5-1 illustrates the different age groups of the interviewees ranging from 30 to >55 years old. 30% of the interviewees were categorised in the 40-45-year group whereas, 20% were 45-50 years old. In terms of educational status, most of the individuals were found to be educated whereby, 43% of participants had a bachelor’s degree and 27% of them had an honours degree. The minority had a diploma as depicted in Figure 5-2. This could mainly be because of the smaller sample size and the focus group was people who fell under the middle-income bracket. Silver and Conrad (2010) found that out of 130 individuals, 40% had a post-secondary diploma, 27% had some sort of education, 16% had completed grade 12, and only 8% had graduate degrees.

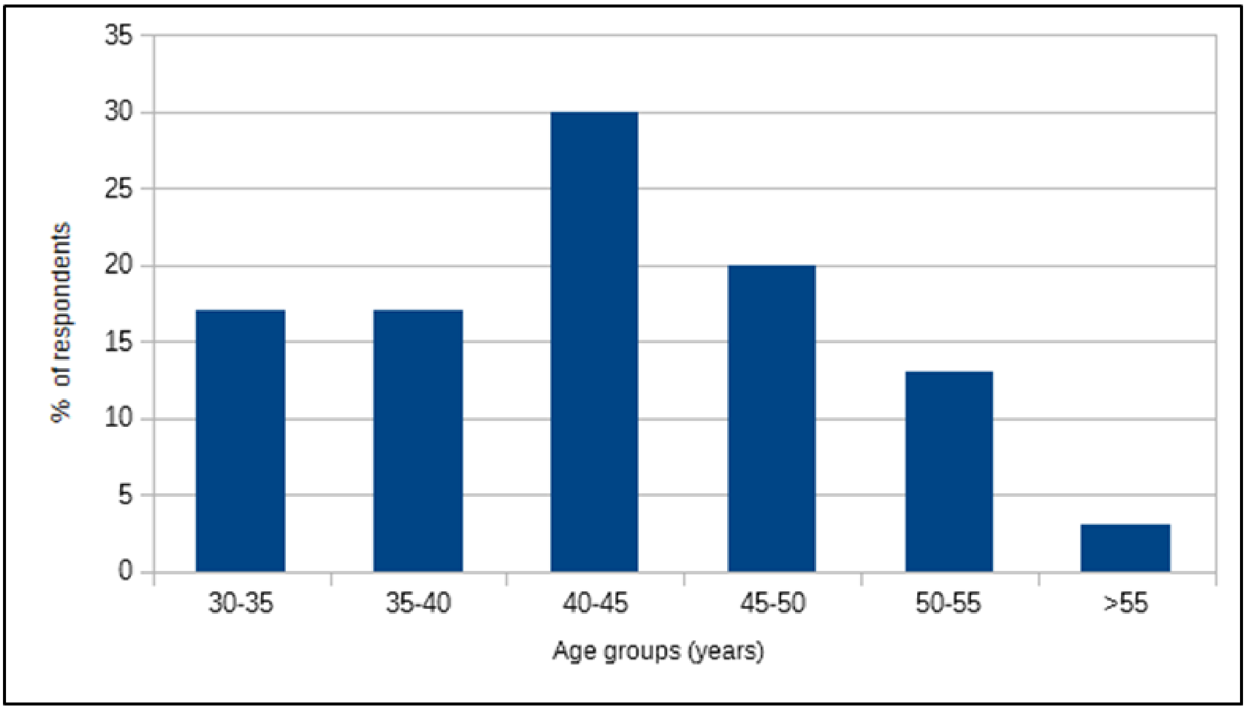

Figure 5-1: Responses to the question: ‘How old they were’.

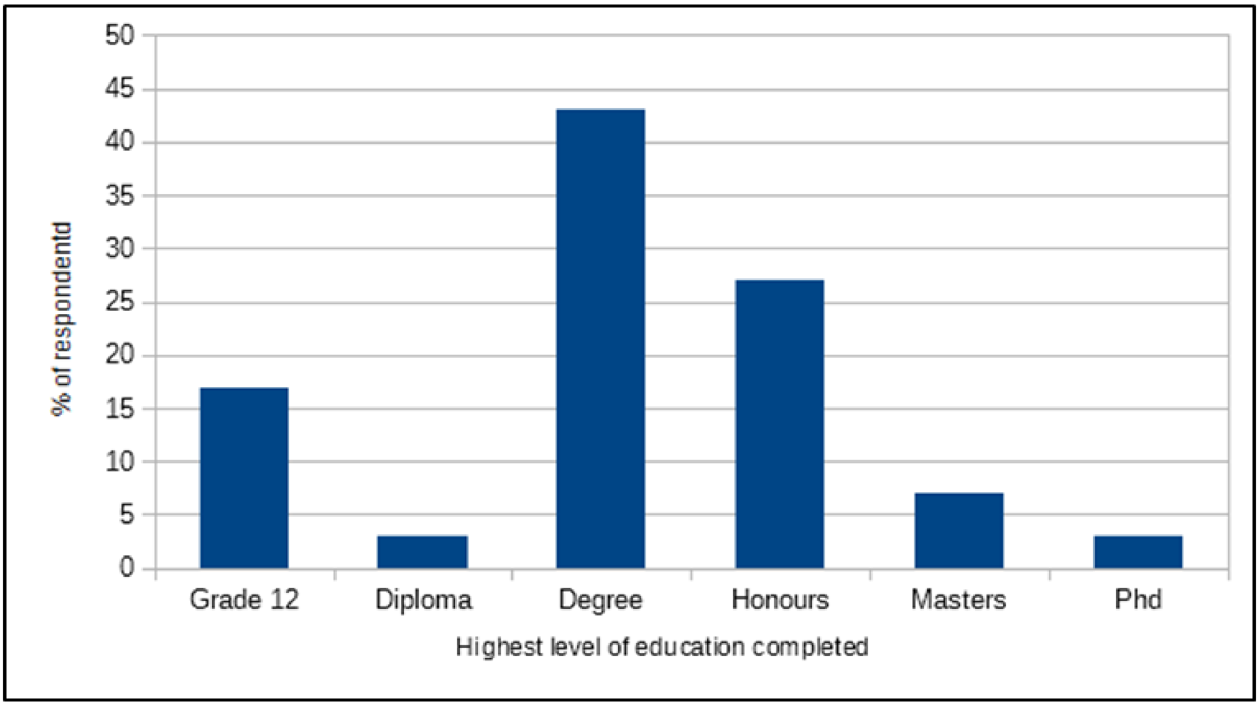

Figure 5-2: Responses to the question: ‘What is their highest level of education they completed’?

The residences of the participants were rather well diverse and included suburbs such as Soweto; Johannesburg; Roodepoort; Sandton; Randburg; Midrand; Kempton Park; Benoni; Rosebank; Krugersdorp; Randfontein and Boksburg. From the individuals that were interviewed some mentioned to have lived in the Gauteng province for more than five years, whereas, other participants have lived in the province for most of their lives. The monthly household income for the individuals ranged from <R10000 to >R30000 with an average amount of R15000. 44% of the interviewees earned a monthly income between R15000-R20000 followed by R20000-R25000 per month as shown in Figure 5-3. Contrastingly, Silver (2015) found that the annual income for respondents ranged from less than $20 000 to more than $150 000 with an average income of $70 000. When converted to the South African Rand, the monthly income for the participants living in Canada ranged from <R17600 to >R132700 with an average salary of R61600. This may be due to Canada being a developed country with a low unemployment rate. Another reason could be that the Canadian dollar is strong compared to the South African Rand. As expected, the racial composition was dominated by African (47%) followed by White participants (30%). The minority racial groups were Coloureds (17%) and Indians (6%).

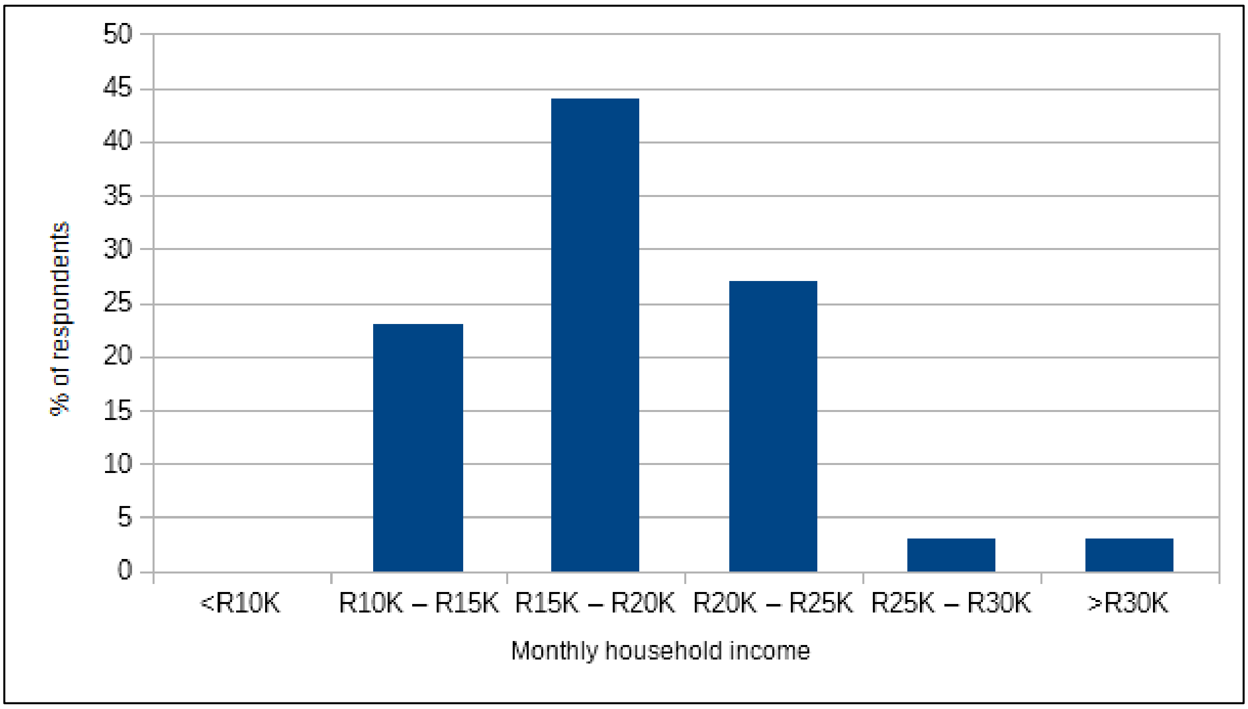

Figure 5-3: Responses to the question: ‘What is their total monthly income’.

The comparison of socio-demographics between this study and the South African Census can be found in (Table 5-1).

Table 5-1: Socio-demographics of the interview sample (n =30) in comparison to the census (Statistics South Africa, 2016).

Demographic characteristics	Present dissertation (2018)	Census South Africa (2016)
Gender	Male	Female
Age (years)	40-45	21.7
Education	University degree	Secondary education
Total household income (R)	15000-20000	8400
Race	African	African

The South African Census 2016 was compared to the demographic results in this dissertation. It must be known, that due to small sample size, attention must be taken when generalising the results from this study to the census. The socio-demographic characteristics are by far different to the census; these contrasts may be explained by the following:

Due to most of the participants that were referred by interviewees hence, the reason for more males being interviewed. Second, the interviewees that were interviewed were mainly from the working class either part or full time thus, being from the age group of 40-45 years old. Due to being from the working-class majority of the participants reported being in possession of a bachelor's degree earning more than R15000 a month which is far more than the average income in South Africa. Stats SA (2016) reported that 72, 6% of South African households get their total income from work hence; the typical household income is R100 246 per annum. Finally, unsurprisingly the dominant race was African in this dissertation which constitutes the majority in the South African census 2016.

5.1.1 Participant profiles

To understand the diverse range of hail perceptions as well as experiences stated between the interviewees, two of the respondents were selected for a detailed analysis. These interviewees were selected since they are an illustrative of the sample size, both in their perceptions of hail as well as their socio-demographic characteristics.

Participant A

Participant A is a college graduate and is 45-years-old who has resided in Krugersdorp since she was a toddler. Participant A describes herself as not really being concerned about the weather, she would only look at weather forecasts if there was a purpose (e.g. special occasions or functions). She had very limited knowledge of the different forecasts published by SAWS. After being hit twice by hail she became concerned on these chaotic hail events. Participant A had incurred severe damages to her vehicles as well to her house. She described the experience as "bad and scary" and thought that her roof was going to collapse due to the amount of hail that hit the roof.

The estimated loss to her personal assets summed up to +/- R15000. Since the horrible experience, she has become more aware of these types of severe storms. She preferred receiving hail nowcasts 3 hours in advance, so she has time to take precautionary steps such as securing her vehicles and the safety of her children. Participant A further mentioned that receiving hail nowcasts will help her to save money as well as aid her in preparing for the storm and most importantly keeping her children safe. Upon being asked if she would pay a fee to receive hail nowcasts from SAWS her reply was as follows:

"Yes, because you know sometimes the cell phone app says there is heavy rain but on some social networks they just say rain. So, it's very hard to decide upon. Also, the fee should be reasonable (laughs) because we are working people with family".

Participant B

Participant B is a 50-year-old man who has worked and lived in Midrand for more than five years. In his personal life, he does not have a habit of checking the weather; however, he passively attains weather forecasts from different sources such as the radio or television. He was not really interested in hailstorms until a few years back when he had experienced the most brutal storm that he had ever seen. Upon being asked if he had experienced any damages, his reply was as follows:

"I got stranded in the flood on my way home and my second car was blasted by these big balls of ice. My cars windscreen was broken as well as the back window. The car was left with minor dents here and there with paint being slightly removed. When going home my car was drenched in water because of the flood".

The estimated loss to his personal assets summed up to +/- R10000. He has become concerned about hailstorms as it can cost a lot. He preferred receiving hail nowcasts approximately 2 hours in advance, so preparations are taken, and it will give him time to warn others who were not fully aware. Additionally, he adds that receiving hail nowcasts will help him to prepare for the predicted storm, hence, he will be able to avoid traffic and possible floods. Thus, to him, these nowcasts have a vital role in the sense that it can save lives and money. Upon being asked if he would pay a fee to receive hail nowcasts from SAWS his reply was as follows:

"Oh yes, if means my family will be safe from this storm then it is worth it. Oh, and damages will be minimized".

5.1.2 Comparison of the two profiles

Participant A and B was a representative of the perceptions and experiences frequently mentioned by the interviewees. They obtained weather forecasts, however, they had no concern for severe storms such as hail. They both experienced severe hailstorms and tried to take some sort of action without knowing that SAWS has issued out a warning. They both had incurred losses to their vehicles or their property. Participant A opted in receiving hail nowcasts at least 3 hours before the storm, whereas Participant B preferred 2 hours. Their reasons for needing hail nowcasts were quite similar as they both mentioned it would help them save money as well as to take precautionary steps.

5.2 Thematic analysis

5.2.1 General weather knowledge

Interviewees were asked how often they checked weather forecasts as depicted in Figure 5-4. 67% of the respondents checked forecasts and identified themselves as 'weather enthusiasts'. People check the weather for different reasons, these reasons will be discussed in the following section. Nonetheless, 33% of the interviewees mentioned that they sometimes or never check weather forecasts. Silver and Conrad (2010) found that 58% of the individuals reported that they checked weather forecasts, while 14% mentioned that once in a while they checked the forecast. A similar finding was found by Silver (2015) whereby the majority of interviewees found themselves to be weather smart.

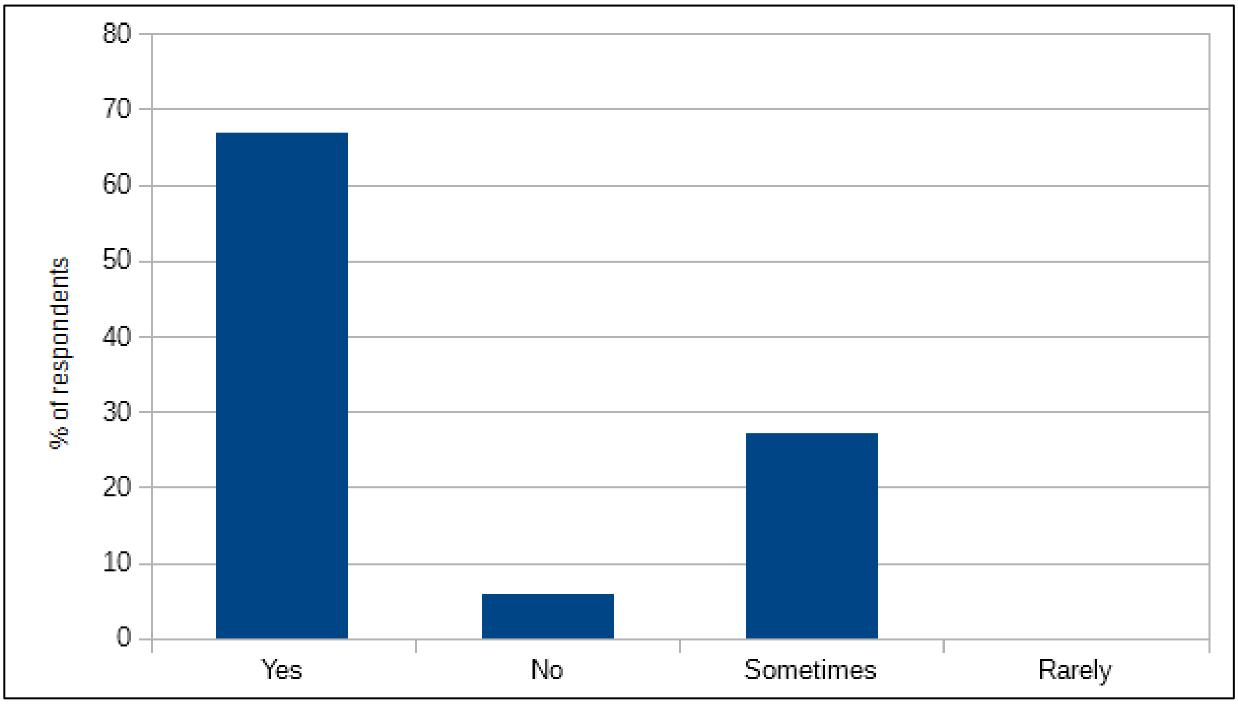

Figure 5-4: Interviewees were asked how often they checked weather forecasts.

Furthermore, 75% of the interviewees reported they receive general weather forecasts in the mornings. This is consistent with the results reported in the following section, which shows several participants use forecasts for deciding on what to wear or daily activities. Lazo et al. (2009) found similar findings in which more than 70% of the individual's accessed forecasts in the mornings. A common reason is that people used forecasts for planning their daily activities. 10% of the interviewees mentioned that they obtained forecasts during evenings, so they could plan for the next day for example; deciding what to wear or for special occasions such as weddings, funerals or outdoor events.

Interestingly, Lazo et al. (2009) further found that 91% of participants indicated they received forecasts from 19:00 pm to midnight. This might be due to a bigger population sample that was interviewed compared to a small sample of 30 individuals.

A previous study that was undertaken on the public perception of weather forecasts in the US found, 72% of the participants looked at the weather (Lazo *et al*., 2009). The respondents checked forecasts more often than interviewees in this dissertation. The difference between the study done by (Lazo *et al*. 2009) and this dissertation is that Lazo (2009) studied individual perceptions of general weather forecasts whereas this study focused on the perception of hailstorm forecasts. Additionally, another reason for the difference may be of the way the interviews were conducted. Lazo et al. (2009) have done online interviews with a target group, whereas in this study in-person interviews were conducted. Nevertheless, a past study has shown that the public has a habit of checking the weather more frequently if a severe storm has been forecasted such as a tornado (Zhang *et al*., 2007). For example, when the weather service issues warnings for a chance of hail in the morning, it would benefit end-users so they can receive hail nowcasts of a predicted hailstorm and take the necessary precautionary measures and are well prepared.

These are consistent with the results obtained by Silver & Conrad, 2010. Lazo et al. (2009) mentioned more than 70% of their respondent's attained forecasts from the television and radio as common sources. Furthermore, they also found that newspapers and internet web pages were the least common sources in receiving warnings. Interestingly, Sliver and Conrad (2010) reported that 98% of the Canadian respondents obtained weather forecasts from media sources such as Television Weather Network, local news, radio and Environment Canada. Another study conducted by Sliver (2015) also found that the average weather consumers tend to check their radio or television station to receive weather forecasts. From the above findings, it can clearly be seen that television is a dominant source in which people receive weather forecasts.

Most of the participants checked weather forecasts for pragmatic reasons (e.g., deciding on what to wear, social activities or doing laundry). Figure 5-5 depicts that 53% of the interviewees only checked the weather due to dressing for the next day, 22% mentioned they used weather forecasts for general activities such as sports or hikes. 18% added that they obtained forecasts for special occasions or functions, doing laundry or washing their vehicles. Lastly, only 4% mentioned that they checked forecasts to see how the day will be. Lazo et al. (2009) found similar findings whereby the majority of the respondents checked weather forecasts for dressing and general activities.

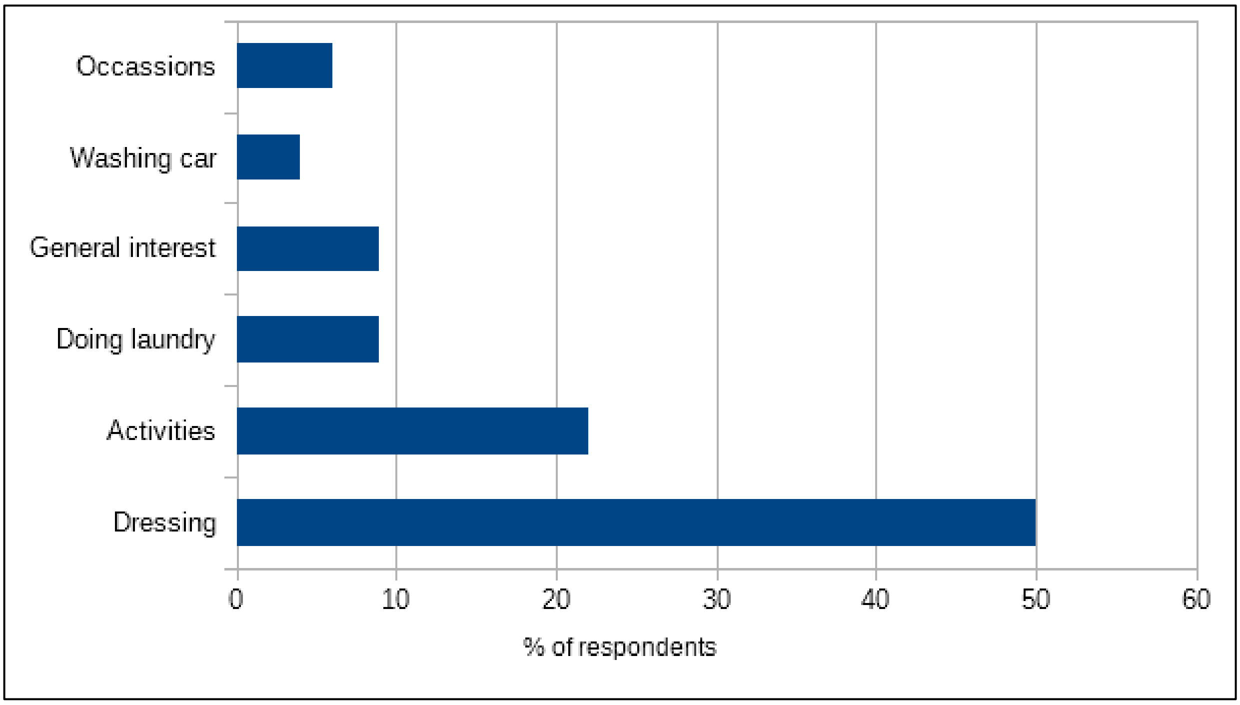

Figure 5-5: Interviewees were asked why they check the weather forecast.

Damages caused by hailstorms

Out of the 30 interviews that took place, 83% of the interviewees mentioned they had experienced mild to severe damages to either their homes or vehicles. Whereas 17% reported not to have had any sort of damage. The majority of the participants have explained that their cars took most of the beating from hail events for example; cars had been dented, windows had been broken or cracked and to extreme cases, their cars were stuck in a flood on their way home. Some reported damages to their property whereby their ceilings were completely destroyed by water or windows been shattered and broken. Most of the interviewees described their experiences has 'chaotic, horrifying, scary or dreadful'. Participant C (47 years old) explained that:

"Because of the clogged drains water started to seep under the doors and a portion of the living room was soaked with water. The pool over flowed, tree branches were inside the pool and the leisure area was no longer for relaxing it was really damaged. The electric equipment's in the leisure area was destroyed. My vehicles also got damaged through the big balls of ice. Windows were broken, I was fortunate the other vehicle was in the garage. I'm scared as it's that time of the year again where we can expect such violent storms".

The majority of the respondents mentioned that they incurred damages of R10 000-R15 000, followed by 26% who had damages between R15 000-R20 000 Figure 5-6. 16% of the interviewees reported that they incurred damage costs of R0 to R5000 followed by 13% who had no losses.

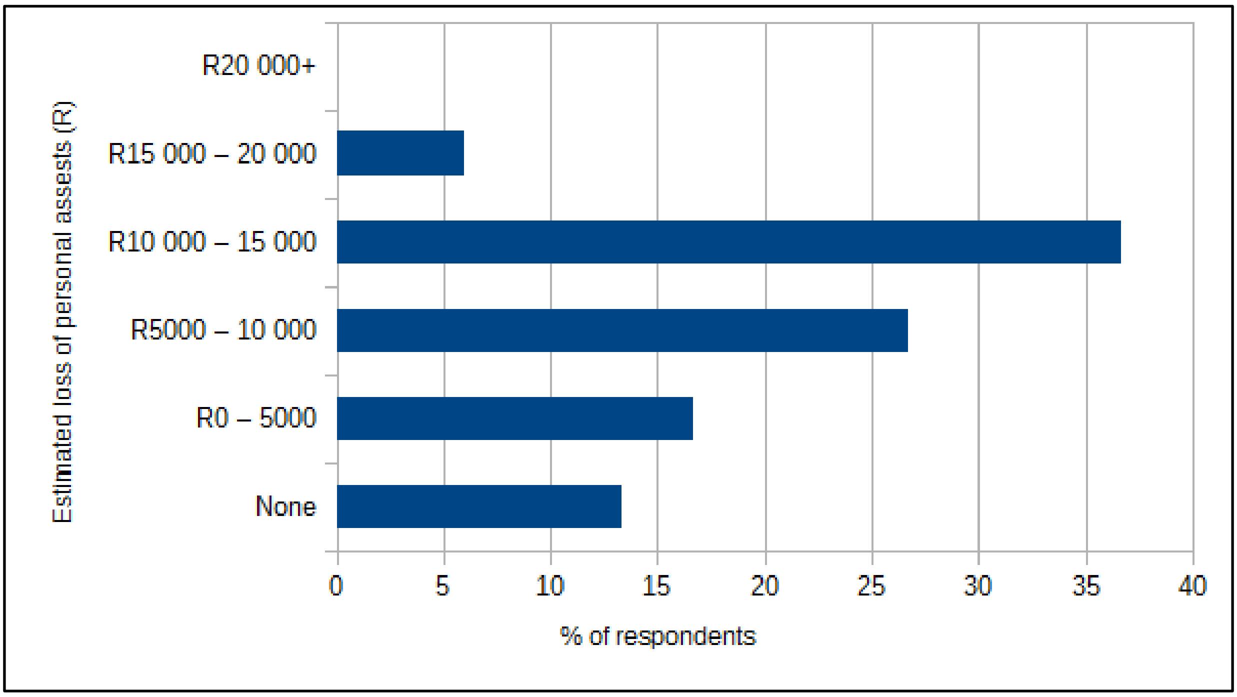

Figure 5-6: Interviewees were asked what their estimated loss of personal assets was.

Few interviewees had an over-all understanding between a hail warning and a hail watch. Most of the participants stated that a hail watch was not that serious than a hail warning, and a warning was more serious and severe. Participant C (35 years old) mentioned the following:

"Uhmmm, I think a hail watch is just to pay attention and be on a lookout or aware that there might be some hail or pass by. And a warning is deader on like severe for example hail is predicted so be careful".

The minority of the interviewees were able to explain both terms. Furthermore, several participants did not know that SAWS issue potential hail warnings. In addition, most of the interviewees mentioned that they are somewhat acquainted with severe weather patterns that are associated with hail, especially on the Highveld.

"You know I always knew we would get a storm on a hot summer's day, and then suddenly around 3 pm you get to see dark clouds build up. Then I knew we might get hail or just a heavy storm (Participant D, 45 years old").

Best way/s to warn people about hailstorms

This section serves as a motivation for the weather service to offer a variety of communication platforms to end-users. The interviewees were asked how they obtain weather forecasts as shown in Figure 5-7. Most of the participants obtained weather forecasts from television channels 38%, followed by cellphone weather applications such as Accuweather. 23% used radio stations in attaining weather forecasts whereas, 8% used the internet to access forecasts. Lastly, 2% of the interviewees reported that they get forecasts from their friends or family.

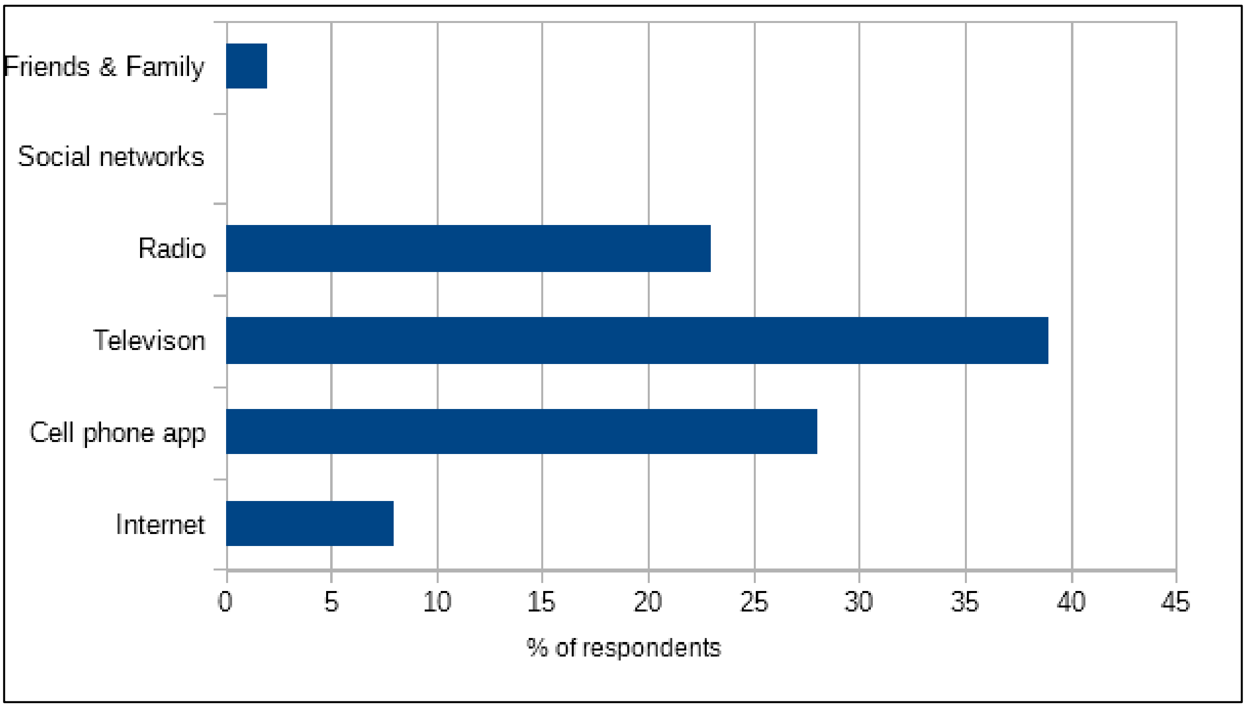

Figure 5-7: The interviewees were asked how they obtain weather forecasts

The interviewees were asked which ways were the best for SAWS to warn them about severe hail events (Figure 5-8). Although they had various and different suggestions (e.g., television, radio, social networks such as Facebook or Twitter, SAWS website or through SMS), 42% of the respondents said that an SMS will be the most preferred way of communication. Whereas 34% explained that they prefer social networks, 14% reported through media platforms such as television or radio. Similarly, Silver (2015) found that most people agreed to receive a text message in relaying weather information. As participant E (50 years old) mentioned that:

“Phew, I haven’t thought about it. But I think the best way is to send an SMS. Because not all of us might have internet access at that time. So, SMS will be a good way”.

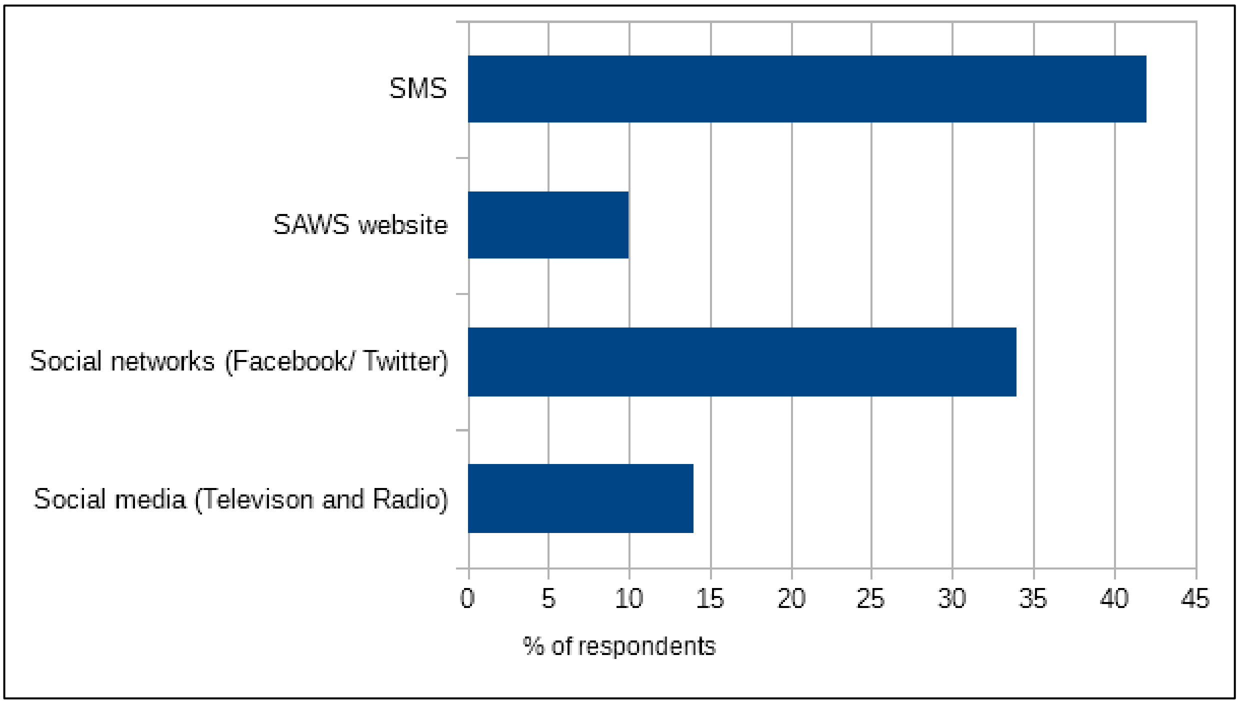

Figure 5-8: The interviewees were asked which the best ways for SAWS are to warn them about severe hail events.

5.2.2 Hail warning communication process

Interviewees were asked if they were concerned about hailstorms and 87% mentioned that they were worried and concerned due to the amount of damage it can bring. 13% of them were not really concerned about hail events. Previous research has shown that individuals differ in their access to hail forecasts and warnings from various sources for different activities (Lazo & Chestnut 2002; Demuth *et al*., 2011). This could because some people have more access to forecasts than others. For example, an individual who has a cellphone is able to get constant hail warnings than an individual who relies on the television for providing him/her with information on approaching hailstorms. Out of the 30 interviews that were conducted 57% of the interviewees mentioned that they receive hail warnings, whereas 30% sometimes received warnings followed by 13% who never gets warnings. Furthermore, interviewees were asked how they receive warnings shown in Figure 5-9. 26% of the interviewees added that their insurance company sends out messages regarding hailstorms. 24% mentioned that they usually receive warnings on social networks such as Facebook through (weather groups and sometimes by the SAWS page).

The minority of the participants added they obtained warnings from media platforms such: television (news channel) or on the radio. The other interviewees said they get warnings from their colleagues at work or through their family and friends. Interestingly, 7% of the participants did not receive any form of warnings. Whereas, no one received warnings through SMS's or through the SAWS website. One significant finding was that some of the participants mentioned that they were not aware of the website operated SAWS.

Lead times

Firstly, idyllic prediction lead time is seen to vary amongst diverse people. Whereas, individuals might simply need minutes to look for a suitable shelter (Ewald & Guyer, 2002). However, previous studies suggest that longer lead times are not always interpreted into a minor risk as illustrated by death rates (Simmons & Sutter, 2008; Simmons & Sutter, 2009). A longer lead time might not be as effective due to the sense of preparedness as well as a skill which could end in a decrease of apparent risk (Doswell, 1999). This may cause people to be less driven to take proper precautionary actions.

Hail warning lead times were integrated into the interview. This segment answers the fourth research question: What is the ideal time in receiving hail warnings.

Interviewees were asked at which time intervals they would prefer to receive hail warnings as shown in Figure 5-10. 61% of the respondents reported that they would prefer at least between 0-2 hours in advance. Whereas, 23% mentioned they prefer 3-5 hours because they need time to prepare for the hailstorm. Additionally, these key findings are comparable to previous research such as (Ewald & Guyer, 2002). Simmons and Sutter (2008) similarly indicated “Longer lead times might not increase fatality statistics”. 10% of the interviewees reported that > 5hours would be ideal so they can alert others and take precautionary measures. Whilst 6% preferred >1day in receiving hail warnings. Interestingly, Simmons and Sutter (2008) found that as warnings in advance increases, morbidity drops in a linear manner.

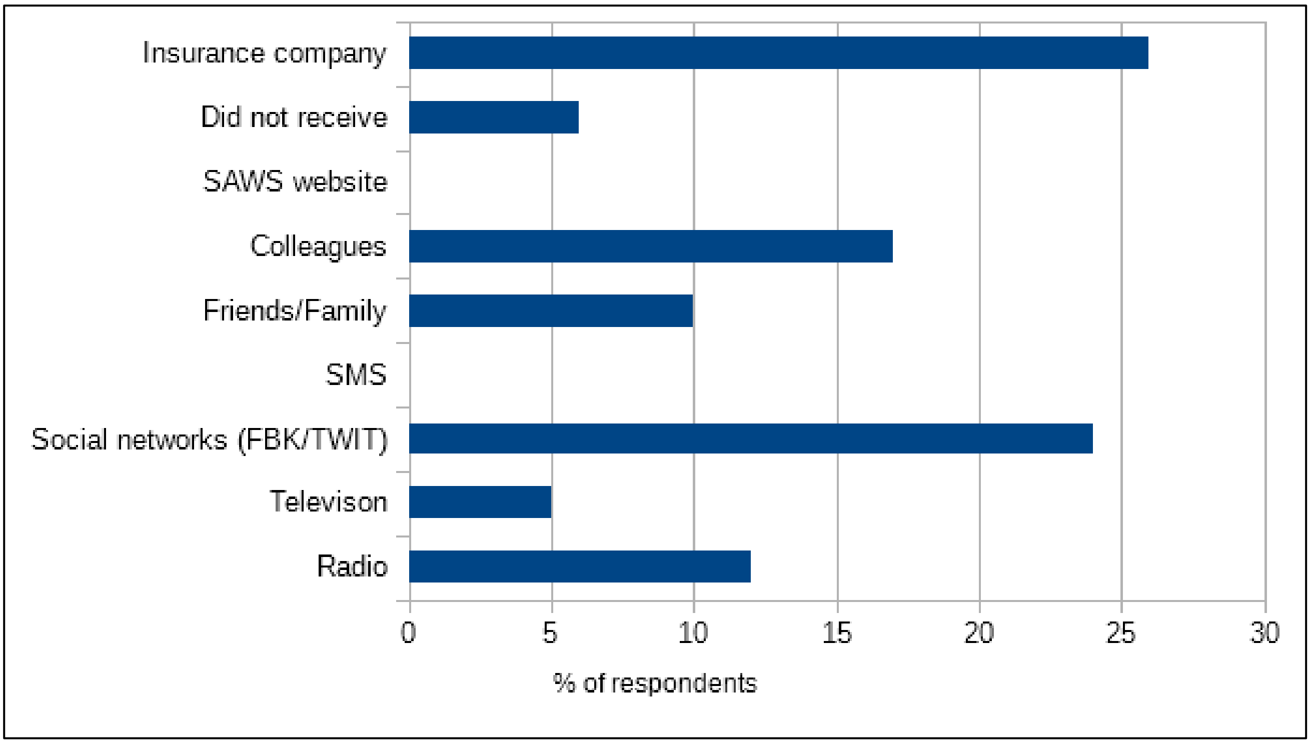

Figure 5-9: Interviewees were asked how they receive warnings.

Simmons and Sutter's (2008) study on tornado victims showed that lead times longer than 15 minutes did not reduce mortalities or damages that were associated with severe events without warnings. Interestingly, previous studies found a longer lead time in advance may decrease individual's confidence in severe warnings, particularly if the time is related with more uncertainty about the intensity of tornadoes (Doswell 1999; Ewald & Guyer, 2002). Individuals may associate a longer lead time with False Alarms (FA) because hailstorm event might not occur after the warning. Assumed that the FA is above 70% and the individual has little awareness with longer lead times, this is a practical response (Simmons & Sutter 2006). In addition, Hoekstra *et al*. (2011) supported this and reported that 85% of the individuals showed more certainty in forecasts with shorter lead times. Whereas, an individual's certainty decreases gradually with longer lead times. A possible reason might be due to the respondent's uncertainty in longer lead times and their understanding of forecasts may be less accurate. The majority of the participants explained that receiving hail nowcasts/warnings is important because it will help them in saving costs that resulted from damages.

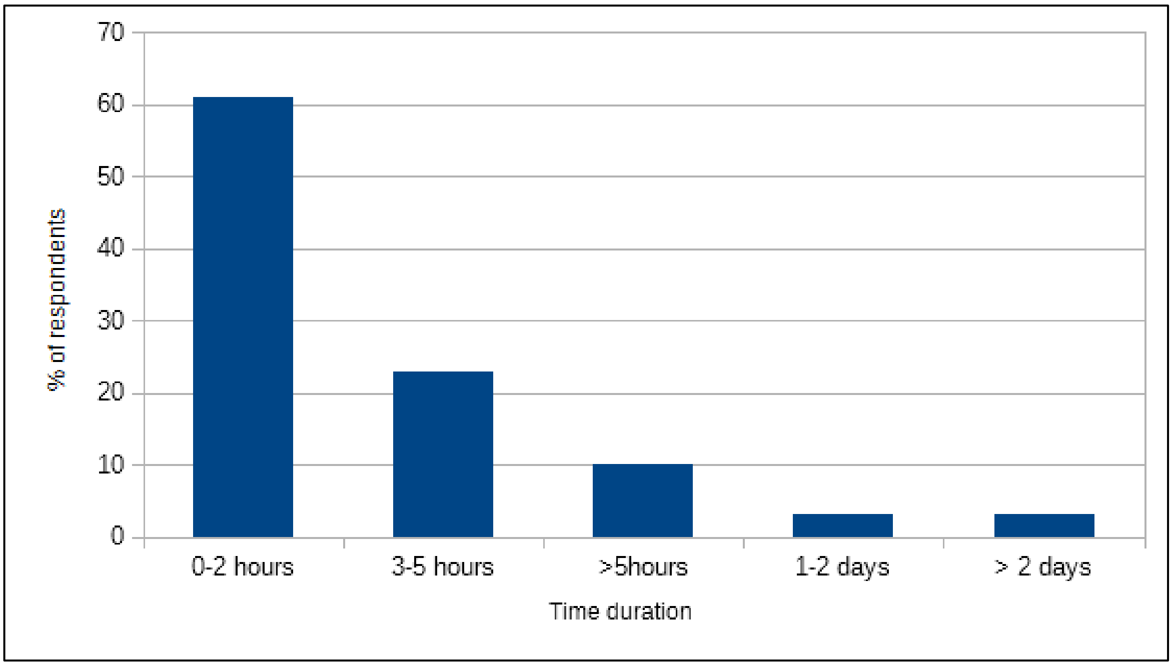

Figure 5-10: Interviewees were asked at which time intervals they would prefer to receive hail warnings

Age similarly was an imperative basis in hail lead times. Generally, the ideal time declined with age (50 years+) and differs from the results of (Hoekstra *et al*., 2011). A potential reason for this finding is that older people tend to be more susceptible to severe hail events; hence, they need more time to prepare. Interviewees who had experienced hailstorms mentioned lower lead times (0-2 hours in advance) compared to those who had no hail experience. Thus, participants who had hail experience may have the knowledge to evaluate how much time is needed for them to respond to hailstorms than those with no experience, hence they are well equipped when one hits again. Two of the interviewees mentioned the following:

"That's interesting because you see, I would like to receive hail warnings early like a day before but chances are high because of heavy winds within the next hour or so. So ideally it would be great to receive it like 1-2 days before (Participant F, 41 years old)".

"I would prefer if we could get the warnings 2hours or less in advanced so I still have time to take precautionary steps. Like my kids at school, make sure the pool is covered or my cars are parked under a sheltered spot (Participant G, 36 years old)".

False alarms

Previously, it was perceived that over warning decreases the general public's readiness to respond to severe weather warnings (Barnes & Gruntfest, 2006). Breznitz (1984) conducted experiments to study an individual's reactions to recurrent FAs and found that FAs reduced participant's readiness to respond. However, in contrast, studies have shown that individuals may have a high acceptance of FAs. Janis (1962) found that FAs may not reduce an individual's willingness to take precautionary measures in weather warnings and it can create a level of awareness if there is a reason for the warning. Janis (1962) further accentuated that the tendency to follow warnings is affected by an increase in the understanding of susceptibility to the severe weather event. These results were substantiated by Dow and Cutter (1998) in their study of behaviours of residents in North Carolina who had experienced a FA for a forecasted Hurricane. Dow and Cutter (1998) further found that the FA did not have an impact on the residents, instead, it helped the people to make changes in their future protective actions. These results were corroborated to the findings in this dissertation, whereby the majority of the respondents reported to be over warned with FAs than under warned with accurate warnings.

Interviewees were asked would they prefer to be over warned with false alarms or under warned but accurate hail forecasts as shown in Figure 5-11. Out of the 30 interviews that were conducted, 70% of the respondents reported that they would rather be over warned of hailstorms although it might be a FA. Whereas 30% of the interviewees added that they would rather be under warned of hail events, however, it should be accurate. Additionally, individuals who had a higher FAR held less trust in weather warnings, hence led to a rare chance of taking precautionary measures (Ripberger *et al*., 2015).

A laboratory study (LeClerc & Joslyn 2015) was conducted showing the "cry-wolf" effect is real in specific situations. It was found that low and high FAR led to sub-standard decision making, nonetheless, lowering the FAR somewhat did not significantly affect compliance. Most of the individuals in the interview mentioned that they would not mind the false alarms and be over warned because it will assist them in taking precautionary measures. Interestingly, Schultz *et al*. (2010) found most of their participants were not too worried about the "cry-wolf" effect. Over warned weather events such as heavy rainfall as well as hail were perceived to be close calls by the public. These occurrences may not necessarily increase the FAR but may aid as an educational learning experience (Barnes *et al*., 2007). Two of the interviewees mentioned the following:

"Hahaha from the experienced I had I would rather be over warned so if there is actually a hailstorm them I'm prepared and covered (Participant A, 45 years old)".

"You know I get tired of these false hailstorms because it eventually gets boring so I prefer to be under warned but then the forecasts must be accurate (Participant H, 38 years old)".

From the answer, Sarah had given it is evident that the false alarms do not particularly bother her because of the experience she had faced. Furthermore, Ryno mentioned that false alarms may be monotonous hence, he prefers to be under warned with accurate forecasts.

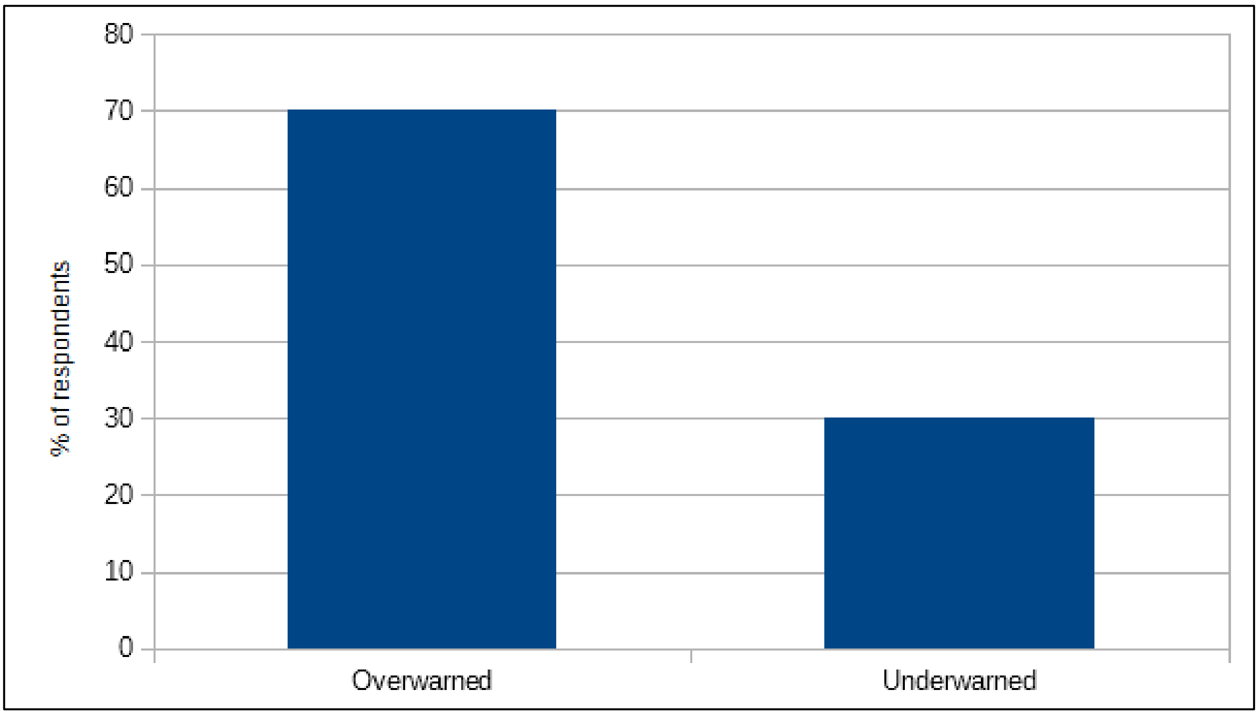

Figure 5-11 Interviewees were asked would they prefer to be over warned with false alarms or under warned but accurate hail forecasts.

5.2.3 Perceived benefits of hail nowcasts

It must be noted that this chapter was constructed on the challenges experienced by SAWS for example; not being able to nowcast hailstorms due to it being expensive, not enough specialists in the field and lack of motivation. Hence, the results of this chapter served as a motivation for the weather service to do nowcasting on a daily basis.

The majority of the interviewees expressed how hail warnings and nowcasts may aid them in the short-term recovery process. 80% of the interviewees explained they would save money and it would bring relief to them if they were prepared for hail events. They further explained they could protect their properties from hail damages as well as their vehicles by just receiving hail warnings on time. 60% of the respondents added that lives could be saved from these destructive storms and making their loved ones aware of hail events to prevent further losses and damages. Some interviewees agreed that by receiving warnings it will surely cut down the recovery process time. As Participant I (41 years old) mentioned:

“Well you know receiving hail warnings in time before a storm would help a lot especially from damages to my valuables and loss of money from these damages. Also after these storms, the cities especially are flooded, and we stuck in the flood or traffic so these warnings I think it will also help regarding flooding measures”.

Interviewees were further asked if they value hail nowcasts and 95% of them valued nowcasts. Reasons for valuing nowcasts varied from individual to individual. However, the majority of interviewees explained that by receiving hail nowcasts it will help them save and cut down on unnecessary costs such as a broken car window etc. 25% of the respondents added that it will aid in keeping their family and children safe from these disastrous storms. Most of the participants reported that by receiving nowcasts they will be able to prepare for example; parking their cars under covered parking or by alerting others who might not be aware. Hence, damages will be minimized and fewer lives will be lost compared to not receiving any hail nowcasts. Interestingly, few interviewees mentioned that it could help city officials in making sure the drainage systems are well organised thus reducing floods caused by severe storms. Participant J (48 years old) reported that:

“As I mentioned it will help me save a lot also to keep my kids safe as they are in school at times or at home. It will also help me to be prepared and I won’t have to worry about my car being damaged or home I mean it can really hit your pockets for nights if you are not warned or aware”.

Lastly, interviewees were asked if they were willing to pay a fee to receive hail nowcasts directly from SAWS as depicted in Figure 5-12. 30% of the respondents agreed to pay. Unsurprisingly, 43% also agreed to pay however, only if it was affordable. The majority of interviewees reported that they rather pay a small fee than suffer damages worth thousands. Furthermore, they also mentioned that by receiving nowcasts/forecasts from SAWS it will help them in trusting the source because they usually get confused when getting warnings from various sources with different information. 10% of the interviewees were not sure of receiving nowcasts from SAWS. Finally, 17% of the respondents did not agree into paying a fee because their insurance company does that. As participant A (45 years old) reported that:

“Yes, because you know sometimes the cellphone app says there is heavy rain but on some social networks, they just say rain. So it’s very hard to decide upon. Also, the fee should be reasonable (laughs) because we working people with family”.

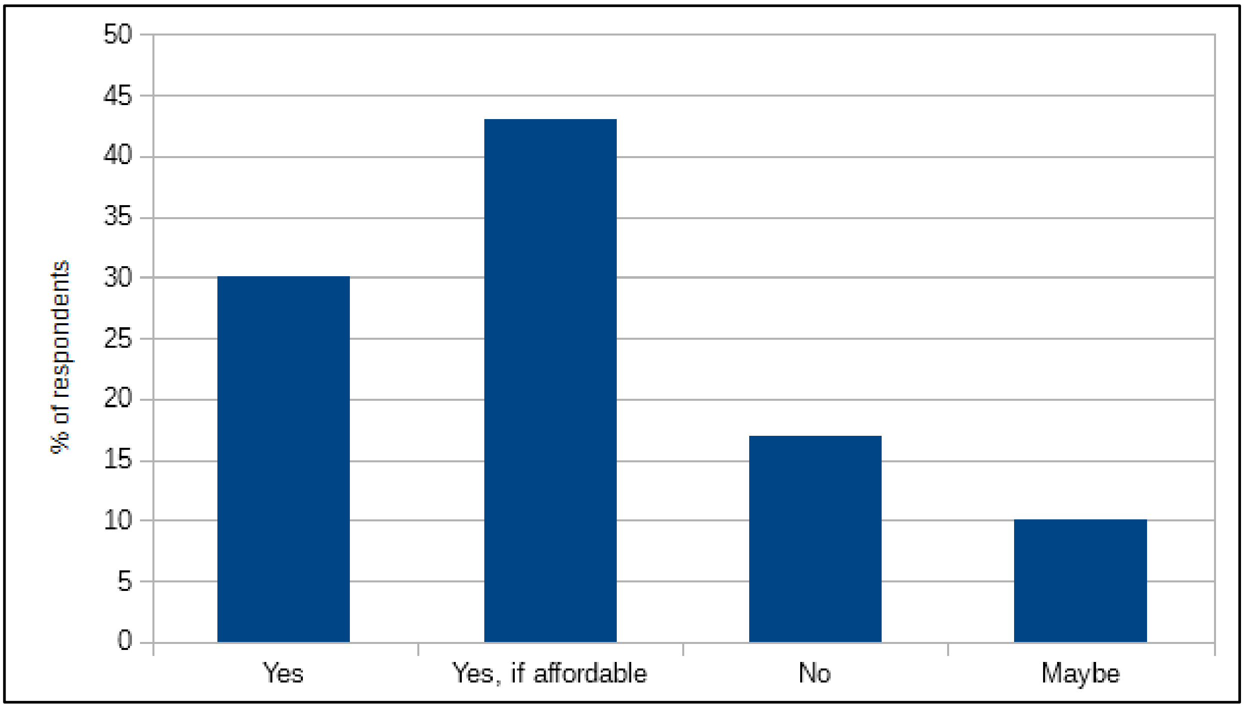

Figure 5-12: Interviewees were asked if they were willing to pay a fee to receive hail nowcasts directly from SAWS.

5.3 Chapter summary

The findings yielded valuable insight into why and how individuals used hail forecasts. As expected, the majority of the interviewees checked forecasts and identified themselves as 'weather enthusiasts'. This finding was reliable with the findings of previous studies. Most of the participants retrieved weather forecasts during the mornings and this was found to be consistent with the results below in which shows that several participants used forecasts for deciding on what to wear or for daily activities. Moreover, most of the respondents obtained weather forecasts from mass platforms such as television and radio. The majority of the participants checked weather forecasts for pragmatic reasons (e.g., deciding on what to wear). 83% of the interviewees mentioned they had experienced mild to severe damages to either their homes or vehicles. 42% of the respondents stated that an SMS would be the most preferred way of communication in sending out warnings followed by social networks.

The majority of the interviewees were concerned about hailstorms due to the amount of damage it can cause. Furthermore, more than half of the interviewees added that they receive hail warnings from an SMS their insurance sends out. Unsurprisingly, most of the participants preferred receiving hail warnings as soon as possible. These results were compared to other previous studies. Interestingly, out of the 30 interviews that were conducted, 70% of the respondents reported that they would rather be over warned of hailstorms although it might be a false alarm. This result was consistent with the study that was conducted by Ripberger *et al*., (2015).

80% of the interviewees explained they would save money and they would be relieved if they were prepared for hail events. It is evident that the majority of the interviewees valued hail warnings and their reasons for valuing warnings varied from individual to individual. The majority of the interviewees explained that hail nowcasts can help them in saving money and to cut on unnecessary costs such as damaged vehicles, properties etc. Nowcasts will also help them in ensuring the safety of their loved ones, interestingly, few interviewees mentioned that it could help city officials in making sure the drainage systems are well organised thus, reducing floods caused by severe storms. As expected, most of the interviewees agreed to pay a fee to receive hail nowcasts directly from SAWS, however, only if it was affordable. Lastly, 17% of the respondents did not agree into paying a fee because their insurance company does that.

It must be noted that this chapter was constructed on one of the challenges experienced by SAWS for example; not being able to nowcast hailstorms due to it being expensive, not enough specialists in the field and lack of motivation. Hence, the results of this chapter served as a motivation for the weather service to do nowcasting regularly.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This was an exploratory study that focused on forecasting hailstorms, nowcasting hailstorms, and individual's perception of how they dealt and understood hail and lastly the perceived benefits of hail nowcasts. Hailstorms were chosen to be the hazard in the focus of this dissertation since they are one of the most prominent severe weather-related hazards in South Africa. Severe hail events signified one of the main sources of destruction and damage to property, agriculture and infrastructure over the Highveld. Nowcasting hailstorms were seen to be a potential solution in predicting these events well in advance. End-users would significantly benefit from hail nowcasts. The main aim of this dissertation was to evaluate the current state of a hail nowcasting system that provides early hail warning to end-users over the Gauteng Highveld. This was achieved by three objectives; firstly, to review the nowcasting procedures employed by the South African Weather Service, secondly, to evaluate the objective nowcasting algorithm used by SAWS and thirdly, to assess the perceived benefits of hail nowcasts.

6 Conclusions

6.1 Forecasting and nowcasting procedures employed by the South African Weather Service

The main conclusions drawn from the forecasting and nowcasting procedures employed by SAWS are as follows:

1. SAWS do not forecast hailstorms, however, severe thunderstorms are forecasted. The reason for not forecasting hailstorms was because it is challenging to separate out what the impact of these events will be. Hence, it is difficult to issue hail forecasts on a forecasting basis.

2. The criteria used in issuing warnings for severe thunderstorms was found similar to that of the National Severe Storms Laboratory (NSSL).

3. As expected, the South African forecast process was similar to the Met Office UK and the IMD. In all these countries when forecasting severe thunderstorms, the main tools that were used were weather models and radiosondes observations for identifying storms and was confirmed with satellite imagery.

4. Wind shear was one of the main criterions. Along with instability, wind shear was the biggest role player when it came to identifying hail events as mentioned by SAWS.

5. It was evident that severe thunderstorms are usually forecasted within a day and if it is approaching then a warning is issued to the public.

6. It was found that SAWS verify their forecasts using media reports and a two-by-two contingency Table analysis of the warnings they issued out.

7. SAWS only nowcasts severe thunderstorms, though, to an extent due to lack of specialists who are experts in their field.

8. SAWS does not have an operational hail model to nowcast severe hailstorms compared to other countries such as the US.

9. Nowcasting hailstorms are complex and human intervention is needed by trained and skilled forecasters to nowcast severe hailstorms.

10. The main tool used by SAWS is the weather radar and the algorithm which does thunderstorm tracking is TITAN.

11. It is evident that radars are a valuable tool to observe hail therefore, radars need to be kept operational to increase the probability of detection of hailstorms.

12. The current nowcasting procedures that are employed by the weather service was similar to the American, Asian and European countries.

13. Weather services throughout the world are confronted with challenges and problems from general challenges within the workplace or issues with forecasting. The main shortcomings experienced by SAWS are as follows:

    a) SAWS do not deploy specialists that focus on hail nowcasting. This is due to the lack of skilled and trained individuals. Without a specialist in the severe weather sector, it remains a constraint to SAWS.

b) It was further found that it was costly to implement specialists in the severe weather section. Due to the lack of funds, SAWS cannot expand their resources and funds for nowcasting. Therefore, it remains a stumbling block in the weather service.

c) SAWS works on a cost recovery basis, hence, the weather service has to recover their costs.

d) In addition, for SAWS to allocate resources towards a specific problem there has to be a favourable cost benefit. Hence, the weather service has to identify whether there are methods of recovering costs through clients, for example, the aviation sector. The last objective of this study serves as a motivation for the weather service to implement nowcasting on a regular basis.

e) SAWS currently does not have automated texting for warnings. Presently all the texts are forecaster generated. This is a possible area of improvement in the process or issuing warning in a timeous manner.

6.2 Objective nowcasting algorithm used by SAWS

The main conclusions drawn from the nowcasting algorithms used by SAWS are as follows:

1. It must be noted that this study evaluated the TITAN algorithm as the weather service currently uses it with the default settings and it was not optimised.

2. Extreme hailstorms are sometimes handled well, however, they are not forecasted with great accuracy. The lack of operational radars for these events can contribute to problems within the verification system such as missed events due to the functioning of the radar.

3. The TITAN algorithm indicated a heavy overestimation of hail events. The hit rate performed well and the FAR was poor due to the parameters not been tuned and TITAN was used with default settings and not customised to identify big damaging events. The verification scores are as follows:

    a. There was a positive observation in the POD, it performed well and had a POD score of 0.85.

    b. The FAR was exceedingly high and had a score of 0.93.

c. TITAN performed poor in terms of the CSI and had a score of 0.05 and showed some sort of skill. The verification scores indicated a poor performance with low CSI and high FA scores, although some events were warned during these occurrences.

d. TITAN displayed a low HSS skill of 0.01 which indicated no skill due to the great amount of FA.

4. Among other purposes of verification, the main scientific purpose is to detect the areas where more research should be focused on. These areas are as follows:

    a. The verification of hail events aims to get a low FAR and a high POD. Additional information and technology are needed to enhance the skill of these events.

    b. The evaluation of these storms depends on remote sensings such as radars and satellites. When trained professionals were interviewed from SAWS they mentioned that radars are only available to a certain extent. Therefore, improvement in observations will benefit the nowcasters and make evaluation easier.

    c. It must be noted that SAWS have made improvements in their observation network such as the dual polarised radar that can detect hail, however, it is not running due to maintenance issues.

    d. Additional real-time data can aid the forecaster to forecast events with greater accuracy. This can be beneficial in evaluating statistics since few events will be "missed".

    e. Forecasters cannot rely on automatic algorithms therefore, the weather service needs better and customised algorithms for radars using TITAN. South African radars have limitations and algorithms cannot be used alone, specialists are needed to interpret these products.

6.3 Assess the perceived benefits of hail nowcasts

The main conclusions drawn from the perceived benefits are as follow:

1. **General weather knowledge**

    a) It is evident that most of the participants checked forecasts and identified themselves as ‘weather enthusiasts’.

    b) 75% of the interviewees reported they received general weather forecasts in the mornings. This is consistent with results reported in the next section, which shows that several participants used forecasts for deciding on what to wear or daily activities.

    c) Most of the respondents obtained weather forecasts from mass platforms (television and radio).

    d) As expected, interviewees checked weather forecasts for pragmatic reasons (e.g., deciding on what to wear).

    e) Lastly, 42% of the respondents stated that an SMS would be the most preferred way of communication.

2. **Hail warning communication process**

    a) As expected, the majority of the respondents were worried and concerned about severe hailstorms, due to the amount of damage it can bring.

    b) It is evident that most of the interviewees received hail warnings, whereas some of them hardly received any warning.

    c) The majority of the respondents mentioned that they receive warnings through their insurance company.

    d) As expected, interviewees reported that they would prefer to receive hail warnings as soon as possible.

    e) Surprisingly, 70% of the respondents reported that they would rather be over warned of hailstorms although it might be a false alarm.

3. **Perceived benefits of hail nowcasts**

a) 80% of the interviewees explained they would save money and they would be relieved if they were prepared for hail events.

b) It is evident that the majority of the interviewees valued hail warnings and their reasons for valuing warnings varied from individual to individual.

c) The majority of the interviewees explained that hail nowcasts can help them in saving money and to cut down on unnecessary costs such as damaged vehicles, properties etc. Nowcasts will also help them in ensuring the safety of their loved ones.

d) Few interviewees mentioned that it could help city officials in making sure the drainage systems are well organised thus reducing floods caused by severe storms.

e) As expected, most of the interviewees agreed to pay a fee in order to receive hail nowcasts directly from SAWS, however, only if it was affordable. This links to the finding found in objective 1, whereby the weather service needs to identify if there are ways of recovering costs through clients.

f) Lastly, 17% of the respondents did not agree into paying a fee because their insurance company does that.

6.4 Conclusion

Hailstorms are of great importance and signify one of the main sources of destruction and damage. Dual polarized radars can make direct measurements of hail and are best suited in identifying hailstorms. It was found that these radars were the best for identifying and detecting hailstorms in advance and are being used across the world. Dual polarized radars are extremely valuable for identifying hail. However, this type of radar is rarely being used in South Africa. The weather service has one dual polarised radar in Bethlehem, but it is not being utilised. It was found that South African radars have severe limitations and algorithms cannot be used alone, specialists are needed to interpret these products. The weather service needs better and customised algorithms for radars using TITAN. There have been recent developments in forecasting weather for periods of 6 hours to few days ahead. However, the ability to nowcast severe weather such as hailstorms, a few hours in advance remains unanswered. This study found that that hail nowcasting can result in the development of new programs which will integrate advances in different areas.

Nowcasts help individuals in ensuring the safety of their loved ones. Interestingly, it was found that hail nowcasts could help city officials in making sure the drainage systems are well organised thus reducing floods caused by severe storms. It is evident that there are significant benefits in receiving hail nowcasts. Nowcasting can make a difference at the weather service, however, that space is currently not being filled. Nevertheless, there have been recent developments on how SAWS communicate forecasts and warnings.

SAWS has two interactive social media platforms (Twitter and Facebook) and recently launched a weather application which can be downloaded onto smartphones. It is not certain that nowcasts can reduce the impact of hailstorms. However, previous studies on nowcasting tornadoes have proved to be a good technique in reducing the impacts of tornadoes on the public and businesses. Nevertheless, this is something to be studied. Nowcasting hailstorms were seen to be a potential solution in predicting these events well in advance and end-users would significantly benefit from hail nowcasts. Researching ways to implement a nowcasting system in South Africa will help end-users to take early precautionary measures and help people in saving from potential damages. This dissertation can be continued and can be a valuable asset to hail impact nowcasting. There is a pressing need for nowcasting, however, the scope and feasibility remains unanswered.

6.5 Study limitations

Prior to the **second objective**, a careful approach was adopted in obtaining hailstorm reports from an array of sources, however, some hail events might have been missed. Additionally, given the infrequent nature of recording in the past, not all hailstorms that have occurred might have been documented in this dissertation. Using media reports for these events is problematic because it is not an absolute measure. However, this study focuses on extreme hail events and it is very likely that all the events are being reported. In the **last objective**, in the 30 interviews that were conducted 5 were done over the telephone to accommodate the interviewees. The snowball, non-probability sampling technique might have biased the interview results. It was challenging to make inferences about the general populations based on the acquired sample. This sample represented a small part of the Highveld, in particular, the Gauteng Province. Future research may benefit from a larger sample size.

6.6 Unique contributions to the broader area of knowledge

There has been a lack of research that has been done in this field. This is one of the first study in the last 15 years to be done which studied the chain of forecasting hail, nowcasting hail and individual’s perceptions on hail nowcasts. This was an exploratory study on how we can improve our forecasting and nowcasting of hailstorms. The perceptions of tornadoes and warnings are well documented internationally, however, not many studies on hailstorms and hail nowcasts are recognised either internationally or in South Africa. The majority of previous studies has only been done in the US on tornadoes or hurricanes. Fewer studies have been conducted on thunderstorms in the US. Due to fewer studies conducted on hailstorms in South Africa, this was one of the first hail nowcast studies over the South African Highveld. The results yielded may serve as a reference for potential studies in broadening the knowledge concerning hail nowcasting over this region. This dissertation provides a building block to studies like these in the future.

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ANNEXURES

Annexure A: The current nowcasting procedures of the South African Weather Service

Interview script
Hail forecasting (Between 6 hours and 4 days)
Do SAWS specifically forecast hail events? If yes: ➢ Describe the process of forecasting possible hailstorms ➢ What types of data are used to forecast hail ➢ How does the data change with different forecasting lead times ➢ How does a forecasters role impact on hail forecasts ➢ Do you change the hail forecasting procedures with seasons ➢ How do you differentiate between possible hailstorms and other severe storms such as tornadoes ➢ What is the typical time period to forecast hail events What are the biggest challenges in forecasting hail events
If SAWS do not forecast hailstorms, do they forecast other severe storms? If yes: ➢ Why do SAWS not forecast hailstorms ➢ Which other severe storms are forecasted
If you do not forecast severe storms, please specify why?
Hail nowcasting (0 - 6 hours)
Does SAWS nowcast hail events? If yes: ➢ Describe the hail nowcasting procedures currently in use ➢ Which observation instruments are hail nowcasts based upon ➢ What types of data are used to nowcast hail events ➢ Which objective nowcasting algorithms are used to nowcast hail events

- How do you verify hail nowcasts What are the biggest challenges in nowcasting hail events
If SAWS do not nowcast hailstorms, do they nowcast other severe storms? If yes: Why does SAWS not nowcast hailstorms
If you do not nowcast severe storms, please specify why?
Hail warnings
Describe the typical warning process currently employed by SAWS?
On what information does SAWS base the warning?
Does SAWS verify hail warnings? If yes: *What observations are used in the verification procedure?*
Are the warnings different for other types of severe storms?
Who do SAWS issue out warnings too?
Does the warning message include instructions or guidance for the public to take cover? If so, please provide a sample message.

Annexure B: The perceived benefits of hail nowcasts

Demographics
A. How old are you? B. What is your highest level(s) of education completed? C. In which suburb do you currently reside in? D. How much total income (before taxes) do you earn?
General weather knowledge
A. Do you regularly check the weather? *If yes, how do you obtain weather forecasts?* B. What encourages you to check the weather? C. Briefly explain what the difference between a warning and a watch in your own words is D. Are you concerned about hailstorms? *If yes, why?* E. Have you experienced any damages? *If yes, what type of damages have you occurred?* F. What was the estimated loss of your personal assets? G. How much of your total assets are owned by the bank? H. Are you currently insured? I. Did/ Do you receive hail warnings? J. How did/do you receive these warnings? K. What time in advance would you prefer to receive a hail warning? L. Would you prefer to be over warned of an approaching hailstorm which could be false alarms or under warned but accurate?
Perceived benefits of hail warnings
A. What role hail warnings play in the short- and long-term recovery process? B. Do you value hail warnings? *If yes, why?* C. What are the best ways for SAWS to warn you about severe hail events? D. Are you willing to pay a fee to receive hail nowcasts directly from SAWS?