

# Characteristics of hailstorms over the South-African highveld

H Havenga

 [orcid.org/0000-0002-9238-0295](https://orcid.org/0000-0002-9238-0295)

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Supervisor: Dr RP Burger

Co-supervisor: Prof SJ Piketh

Assistant supervisor: Dr CL Bruyere

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In memory of Twan Relou,  
1988 – 2017,  
a life too short.



## Abstract

Extreme hail has been among the most costly of natural disasters in South-Africa. Despite the havoc that hail is known to cause, we have limited knowledge about these spatially and temporally rare events and how they are linked from the small scale convective environment to larger scale synoptic circulation. This study attempts to characterize hail events across different atmospheric scales to analyze the trends and cycles of hail favouring conditions.

The Weather Research and Forecasting Model (WRF) was used to understand the meso- $\gamma$  scale,  $2\text{ km} \leq 20\text{ km}$ , environment by simulating 5 extreme hail events that occurred over the Gauteng province. In the simulations convective parameterization was omitted to simulate convection explicitly, a known improvement to high resolution modeling of severe weather. For each case the simulated thermodynamic and bulk shear ( $\Delta V$ ) profile for the major cities in Gauteng was represented at the time the most unstable parcel was simulated. Results indicate that within the simulated thermodynamic profiles CAPE was well represented spatially and temporally across the major cities, while the simulated Showalter index was also within thunderstorm thresholds. The bulk shear was highly variable in the 0 - 1km and 0 - 3km layer. The 0 - 6km shear showed the least variability within individual cases, however the 0 - 6km shear between case studies had a high variability compared to CAPE which was well-defined in all the cases.

Next the macro- $\beta$  scale synoptic environment,  $2000\text{ km} \leq 10,000\text{ km}$ , was examined by using a two-step cluster analysis consisting of a k-means and hierarchical cluster analysis. Due to CAPE being well-defined spatio-temporally it was selected as the only convective scale feature for the analysis. Mean sea-level pressure and geopotential at 500 hPa was selected as variables to represent the surface and upper-air at a synoptic scale. The cluster analysis was successful at characterizing synoptic types associated with hail, replicating the annual distribution and patterns of the South-African hail season with reasonable accuracy. Synoptic circulation associated with hail events are accompanied with a surface trough, a ridging anti-cyclone along the east coast and well distributed CAPE over South-Africa.

The study concludes by analyzing the trends and cycles of hail related indicators as identified in the meso- $\gamma$  and macro- $\beta$  scale. Historical media, weather reports and radiosonde data from the integrated global radiosonde archive (IGRA) was reevaluated in the context of this chapter. Media records indicate a well observed annual variation in reports of hail; peaking in October, November and December while an overall increase in media reports was observed in the last century. The analysis of the seasonal variation for the selected variables from the (IGRA) indicate an increase in atmospheric conditions favouring convective storms during the summer months while an overall increased trend towards a convective favouring atmosphere is observed over the last 40 years. The last analysis examined the relationship between the Southern Oscillation Index (SOI) and hail related synoptic conditions which indicated no synoptic patterns had a statistically significant relationship with the SOI.

**Keywords:** *hail, weather, climate, highveld, wrf, convective storms*



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# List of Abbreviations

**AMSR-E** Advanced Microwave Scanning Radiometer for Earth Observing System. 14

**AUSD** Australian Dollar. 3

**B.C** Before Christ. 1

**BEWMEX** Bethlehem Weather Modification Experiment. 1

**CAPE** Convective Available Potential Energy. 6–8, 10, 11, 50, 52, 54–61, 63–69, 71, 74–76, 78, 79, 81–84, 87–89

**CIN** Convective Inhibition. 7, 8, 10, 50, 51, 54, 56, 58–61, 63–67, 71, 74–76, 78, 79, 87

**CPM** Convection Permitting Model. 19–21, 26, 38, 50, 51, 65, 87, 88

**CSIR** Council for Scientific and Industrial Research. 1

**CT** Cross Totals. 8, 76

**EL** Equilibrium Level. 7, 8, 10, 75

**ENSO** El Niño-Southern Oscillation. 2, 12, 14, 15, 29, 49, 71, 84–86, 88, 89

**FOA** Food and Agriculture Organization. 43

**GCM** Global Circulation Models. 19, 21

**HCA** Hierarchical Cluster Analysis. 28, 47, 48, 66, 67, 87

**HDF** Hail Day Frequency. 12–15, 71–73, 84, 86

**IAS** Institute for Advanced Study. 18

**IGRA** Integrated Radiosonde Archive. 10, 11, 29–32, 49, 71, 74–76, 79, 81, 86, 88, 89

**ITCZ** Inter-Tropical Convergence Zone. 11, 12, 52, 82

**KI** K-Index. 75, 77–80, 88

**LBLRTM** Line-by-Line Radiative Transfer Model. 41

**LCL** Lifting Condensation Level. 7, 8, 10, 75

**LFC** Level of Free Convection. 7, 8, 10, 57

**LI** Lifted Index. 7, 8, 11, 71, 75, 78–82, 88

**LSM** Land Surface Model. 22, 24, 25, 43

**MCC** Mesoscale convective complex. 66

**McICA** Monte Carlo Independent Column Approximation. 41

**MM5** Mesoscale Meteorological Model Version 5. 19

**MMM** mesoscale meteorological model. 19

**MSLP** Mean sea level pressure. 51, 65, 67, 87

**MUCAPE** Most Unstable Convective Available Potential Energy. 6, 51

**NCAR** National Center for Atmospheric Research. IX, 19, 30

**NOAA** National Oceanic and Atmospheric Administration. 31

**NWP** Numerical Weather Prediction. 2, 5, 6, 11, 18, 19, 21, 25, 29, 30, 50–52, 64, 87, 89

**PBL** planetary Boundary Layer. 20, 22–26, 45, 46

**PCA** Principle Component Analysis. 27, 66

**PCACA** Principal Component Analysis Cluster Analysis Scheme. 47, 66, 67, 88

**RCM** Regional Climate Model. 19, 21

**RDA** Research Data Archive. IX, 30

**RRTM** Rapid Radiative Transfer Model. 40, 41

**RRTMG** Rapid Radiative Transfer Model Global. 38, 41, 42

**SAWS** South-African Weather Service. 1, 32, 51, 75

**SBL** Stable Boundry Layer. 47

**SI** Showalter Index. 8, 11, 50–52, 55, 57, 59, 61, 71, 74, 75, 77–82, 87, 88

**SICZ** South Indian Convergence Zone. 12, 52, 68, 69, 82

**SOI** Southern Oscillation Index. 1, 12, 14, 15, 28, 31, 49, 71, 82, 84–86, 89

**SOMs** Self Organizing Maps. 27, 66, 88

**SRH** Storm Relative Helicity. 51

**SST** Sea Surface Temperature. 14

**SWEAT** Severe Weather Thread Index. 8

**TT** Totals Totals. 8, 11, 71, 76, 78, 79, 81, 82, 86

**TTT** Tropical Temperate Trough. 12, 82, 88

**USA** United States of America. 2–4, 6, 26

**USD** United States Dollar. 2–4

**USGS** United States Geological Survey. 34, 43

**UWYO** University of Wyoming. 10, 30, 32, 76

**VT** Vertical Totals. 8, 9, 76

**WPS** WRF Preprocessing System. 34

**WRC** Water Research Commission. 1

**WRF** The Weather Research and Forecasting Model. II, IV, IX, 2, 19, 20, 22–26, 28–30, 32–35, 38, 40, 41, 43, 47, 50, 51, 57, 64–66, 87–89

**WWII** World War II. 26

**YSU** Yonsei University Scheme. 45, 46

**ZAR** South-African Rand. 4, 5, 52, 57

# Preface

The Highveld and its major cities is the economic hub of Africa. The region has been at the pinnacle of development in South-Africa and Africa ever since the discovery of minerals in the region, but it's location makes its inhabitants the unfortunate victims of devastating thunder and hailstorms over the summer months. The physical and economic impact of such events is tremendous and serves as motivation to understand and characterize hail storms over Gauteng. These impacts (current and historically) of severe weather, have been of particular interest during the research conducted and was considered as an extra chapter but was instead added as a research note in the appendix, the reader is encouraged to also read Neumann (1975, 1977, 1978, 1993); Neumann and Dettwiller (1990); Neumann and Flohn (1987, 1988); Neumann and Lindgrén (1979) fascinating work on the impact of severe weather on the course of history.

The aim of the study was to use high-resolution numerical simulations and synoptic classification techniques to better understand hailstorms over the Highveld; more specifically the highly industrialized Gauteng province. The study approaches this question by characterising hail events on different scales in the atmosphere as defined by Orlanski (1975) and using this information to analyze the trends and cycles of hail favoring environments over the study area. The specific objectives of the study are to;

1. identify meso- $\gamma$  scale indicators associated with severe hailstorms,
2. characterize the relationship between meso- $\gamma$  indicators and macro- $\beta$  scale patterns associated with severe hailstorms by the use of clustering methods
3. and to finally examine severe hailstorm's trends and cycles by analyzing historical records, radiosonde data and the identified meso- $\gamma$  indicators and macro- $\beta$  patterns.

The literature review provides a brief overview of the background and history related to this study. First the impact of severe weather and hailstorms is examined as it affects our lives and economics, this also provides some justification towards the importance of the study from a socio-economic stance. The literature review then analyzes some concepts related to the aims and objectives of the study. Central to the problem of understanding hail events and convective events is the problem of scale (Prein, 2013). This is reviewed in the literature study to provide perspective on how hail events fit into this multidimensional spatio-temporal aspect. The review continues with a background of South-Africa's weather patterns hail events over the region by examining the current body of knowledge on the spatial and temporal distribution of the phenomena. A background is given on the classification techniques related to this study. An overview of Numerical Weather Prediction (NWP) as a tool to understand convective scale events is investigated, followed by a background of synoptic classification techniques to understand larger scale events.

WRF was used to simulate selected cases on a convective scale, the output was used to gather information on the spatial and temporal distribution of several key *indicators* related to convective events and hailstorms on the small scale. Next, an objective clustering method was applied on historical reanalysis data with the identified indicators to understand the relationship between the large scale synoptic circulation and the small scale events associated with hailstorms. The results indicate that the cluster analysis was able to represent characteristic synoptic patterns and the occurrence thereof on an annual basis, with the inclusion of convective scale indicators. Using this information and other key datasets such as historical radiosonde data from the Integrated Radiosonde Archive (IGRA) and weather records the trends and cycles of hailstorms and hail favoring conditions over Gauteng is analyzed. The section concludes by investigating the relationship between the El Niño-Southern Oscillation (ENSO) and the cycles of synoptic patterns related to hailstorms.

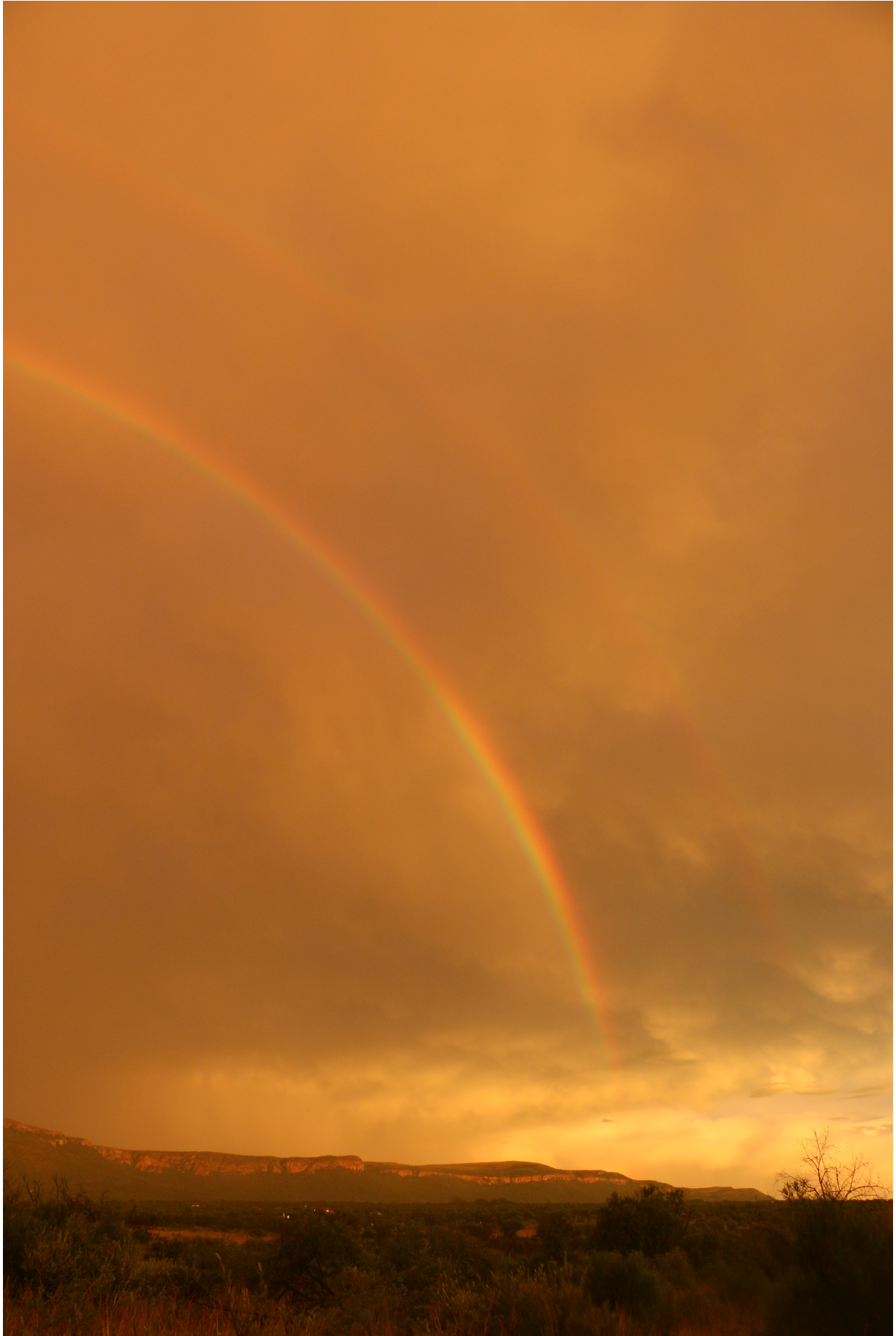
I am, without a doubt, privileged to be here. Life takes so many turns that I cannot help but think of all the privileges I've had until now. Privileged to be born to a supportive family, privileged to have gone to a good school and university and privileged that I grew up in a healthy environment. So many talented young people in South-Africa and around the world don't have these benefits. I might have worked hard along the way leading up to this moment, but I firmly believe that with all things equal, I am not exceptional nor special in any way.

It goes without saying that this privilege was afforded to me by various people who motivated me and supported me, they deserve a special shout-out. The first and foremost thank you goes to my parents Don and Hetta, my sister Donett and Dr. Lukas. Never have I not been supported in any of my endeavors, be it driving for days after some track meeting or supporting me through 7 (it could be more, I've lost count) years of studying. No amount of thank you will ever be enough. Secondly, Roelof Burger, who has been the key driver of my post graduate studies to date. Roelof has become much more than a supervisor but also a role model, his openness and willingness to assist students deserves a special note. Prof Stuart Piketh has been invaluable in this study, his financial support and the opportunities he's given to me and the other post graduate students have been tremendous, I wish I could say this a million times over Prof, and I know you don't always hear it enough, but from the bottom of my heart, thank you! Then, Dr. Cindy Bruyere and Dr. Andreas Prein, Cindy was the co supervisor of this study and provided access to the infrastructure necessary to perform the computationally expensive work. Thank you Cindy for the exposure to the world's foremost atmospheric research institute, the National Center for Atmospheric Research (NCAR) and access to the Yellowstone supercomputer. Your Skype sessions formed a key part in conceptualizing this study and your input and knowledge on WRF and South-African weather was key in my efforts to understand the model. Andreas Prein, also at NCAR, was one of the most friendly and open scientists I've ever met, Andreas provided me with the opportunity to present a poster at the GENWEX conference in Boulder and help me setup the COST733class software to perform the synoptic classification. I hope that I can one day be half the scientist the above mentioned people are. Once again thank you for kindness, patience and willingness to share your knowledge.

On a last note, the learning experience I got during the course of this study made this *fun*. Effort was made to only use open source software in the entirety of this study, I learned basic Fortran, Python, R, GRADS and NCL but the most fun of all was learning to use GNU/Linux as a daily operating system and writing my document in L<sup>A</sup>T<sub>E</sub>X. I doubt I'll ever look back. I have to say thanks to Dr. Cindy for access to Yellowstone Supercomputer located in Wyoming, the computer was later upgraded to Cheyenne, a massive 5 petaflops system. All data was obtained through the NCAR's Research data archive (RDA). Cluster analysis were done by using the COST733class software developed by Philipp et al. (2014). WRF was used to perform model runs on selected severe hailstorms over Gauteng. I had this conversation with Roelof throughout my studies, but I think my biggest hurdle in finishing my masters was the *coolness* of, well, everything! I would get so caught up in whatever I was busy with and end up spending days on the most trivial things, be it WRF, python or L<sup>A</sup>T<sub>E</sub>X – I have to admit that I spend a weekend (3 full days) reading up on fonts but thinking back I absolutely loved it (it's Garamond, if you wondered). I hope the reader can appreciate the wonder of the atmosphere and its complexity that, in my mind, we'll never be able to fully grasp. Writing this dissertation has been a truly wonderful journey and if you're ever in hailstorm, I hope you'll think of me!

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

Henno Havenga  
7 May 2018



*Look up, marvel at the ephemeral beauty, and live with your head in the clouds*

- The Manifesto of the Cloud Appreciation Society

Photo: Henno Havenga

X

# Chapter 1

## Introduction and literature review

*African thunderstorm, your soldiers march through the air*  
*The African rain will fall and wash away all my tears*  
*African falling rain*  
*African falling rain, will you bless my life?*  
*Oh will you bless my life?*  
Johnny Clegg, African Sky Blue, 1981

Understanding the atmosphere has been an endeavor of man since the ancient Greeks. In 340B.C, Aristotle wrote the first known meteorological text, *Meteorological*, speculating on the processes of various meteorological phenomena (Frisinger, 1972). This was to be the start of future endeavors that would shape our understanding of the earth's climate and weather systems. Centuries later the concept of anthropogenic climate change was formed by Arrhenius (1896) as he speculated that an increase in carbon dioxide may lead to an increase in the average temperature. He later stated that *the advances of industry might noticeably increase the atmospheric concentration of carbon dioxide in the course of a few centuries* (Arrhenius, 1908). Years later Arrhenius (1896, 1908) theories would be proven correct; the IPCC (2007, 2014) found greenhouse emissions as a possible driver of increased global temperature and severe weather events (Botzen et al., 2010; Kapsch et al., 2012). These severe events and more specifically severe hailstorms form the basis of the study. Hailstorms which are by nature rare seem to have increased in frequency (Changnon, 2009; Hermida et al., 2015; Li et al., 2016; Wuebbles et al., 2014). The implications of such an increase could be dire for humans in regions prone to such events. It is known that severe hail events have a devastating socio-economic impact on a region and numerous hail storms have resulted in unprecedented loss throughout history, from the origins French revolution to the complete destruction of agricultural regions, damage to property and automobiles and in extreme of cases the loss of human lives. South-Africa has not been spared from these severe hail events. Recent storms over the Gauteng province, the economic hub of Africa, has been among the costliest of natural disasters the country experienced until now. Extreme hail is a phenomenon that can cause havoc and yet we understand little about this spatially and temporally rare event and how they are linked from the small scale convective environment to larger scale synoptic circulation.

Recent severe hailstorms over South-Africa has renewed interest in hail studies to build upon past research. During the 1960s to 1980s three major hail research programs existed in South-Africa. These programs were funded by both state and/or private organizations at the time (Kelbe, 1984; Olivier, 1989). The first program funded by the Council for Scientific and Industrial Research (CSIR) was a network of hail-pads set-up in Gauteng with around 800 volunteers in a 2800km<sup>2</sup> area (Carte, 1967; Held, 1974). The presence of the hail-pad network assisted in various hail related research publications during this era (Carte, 1967, 1979; Carte and Held, 1978; Held, 1974; Held and Carte, 1979; Schulze, 1965). Other programs included a weather modification program established by the South-African Weather Service (SAWS), Sentraoes Insurance Co. and the Water research commission (WRC) in the 1970s. The program known as Bethlehem weather modification experiment (BEWMEX) originally studied hail suppression but subsequently shifted its focus to rainfall research (Erasmus, 1980). Finally, the Program for the Augmentation of Atmospheric Water Supply (Mather, 1977) in Nelspruit Mpumalanga was a privately funded hail suppression program established in the 1970s, but it also switched objectives towards rainfall studies later on. The research of Mather (1977) was such a breakthrough at the time that a subsequent review published later by Summers (1978) noted that the work was an important step in hail suppression research as it was the first to directly seed the supercooled portion of clouds. Mather (1977) also introduced the concept of a *severity ratio* in his work; this is defined as the area damaged to 100% divided by the area hit by hail (Summers, 1978). The last major investigation of hail was by Olivier (1990) in her PhD thesis where she examined the spatial-temporal and atmospheric characteristics of hail events on maize production across the Highveld. Later research by Olivier and Van Rensburg (1995) investigated the links between Southern Oscillation Index (SOI) and hail events. Understanding the physical and dynamical properties of hail events is crucial for South-Africans, climate change

predictions estimate that there may be an increase in extreme convective events that could result in increases of heavy rainfall, flooding and possibly severe hailstorms while a temperature increase of 4°C is projected for Gauteng and the northern parts of the country (Engelbrecht et al., 2013; Piketh et al., 2014). These studies show we need to place emphasizes on forming a better understanding of the environmental conditions associated with severe events, partly is addressed in the sections following here.

### **The outline of the current study**

The study aims to build on existing research by characterizing hailstorms across different atmospheric scales over the Highveld with the aim to answer the main research question; **What are the trends and cycles of hailstorms over the Highveld?**

The dissertation is divided into 6 major chapters, each addressing the main question related to this study in different ways. First the background and introduction examines the impacts of severe weather events and also severe hailstorms with the aim of providing the reader with an overview of the devastation that these events can have on our daily lives. The chapter moves on to briefly discuss the climatology of South-Africa and which systems impact our daily weather followed by a brief hail climatology of South-Africa and Gauteng. The section continues by providing a background of literature relating to *the problem of scale*. First a review of numerical weather prediction (NWP) is provided as related to micro- and meso scale events in the atmosphere. This is followed by an overview of macroscale classification techniques used to understand the larger scale synoptic circulation. Chapter 2 deals with the data and methods related to this study; briefly discussing the WRF model and cluster analysis setup. In chapter 3 we examine the data and results obtained through the numerical simulations and then using these results to drive the cluster analysis. Chapter 4 reviews the results of the synoptic classification and evaluates the link of the derived clusters with hail events. The seasonal variation of each pattern is investigated and also the occurrence between the events and past hailstorms investigated. The last chapter attempts to understand how the links identified have changed in time and if there is an observed increase towards environments favoring hail producing storms. Several relationships are investigated as part of this: first an examination of media reports of severe hailstorms is conducted relating to the spatio-temporal distribution of these storms. The next part examines the trends of several thermodynamic variables over a period of more than 40 years to examine the prevalence of convective favouring conditions and finally the cycles of synoptic conditions associated with hail events and the relationship to El Niño-Southern Oscillation (ENSO) is investigated.

### **A brief overview of the economic and social impacts related to severe weather events**

Anthropogenic climate change has become a mainstream topic worldwide. The Intergovernmental Panel on Climate Change (IPCC) has stated in its reports this is mainly due to human activities related to the burning of fossil fuels around the world (IPCC, 2007, 2014; Kruger and Sekele, 2013). The effect of this on the occurrence of hail events has been documented. Changnon (2009) noted there is an increase in severe hailstorms over the United States of America (USA) since the 1950s while Rosenzweig et al. (2002) estimated that the annual loss due to severe weather is likely to increase by USD3 billion per year. This increase in losses related to hail events can be attributed to an atmosphere increasingly favorable for convective environments and subsequently hailstorms. Brooks (2013); Sanchez et al. (2017) predicts that environments suitable for severe storms may increase in the future in regions already prone to convective events. Observational data over South-Africa has already indicated an increase in extreme heat days (Kruger and Sekele, 2013), a decrease in extreme cold days (New et al., 2006) and an increase in extreme precipitation events and convective events (Roy and Rouault, 2013).

The impacts of a changing climate could be far-reaching: impacting insurance, agriculture, health and water availability. The most vulnerable part of the population – those who live in rural areas and low income settlements, suffer economic hardship, lack government support and quality infrastructure – are the people who will



be affected by this possible increase in severe events. The Intergovernmental Panel on Climate Change describes vulnerability as:

*... the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change* IPCC (2007).

The World Health Organization (WHO) (Hales et al., 2003) reports that deaths related to extreme events in the 1980s and 1990s numbered around 1.2 million. There is also a relationship between meteorological events and diseases. After heavy rainfall events an abundance of surface water could lead to an increase in infectious diseases such as malaria, yellow fever and dengue (all carried by mosquitoes). Other vectors such as rodents and ticks also thrive in certain climatological conditions, carrying more infectious diseases (Hales et al., 2003).

Severe weather and natural disasters also have serious economic implications. According to Okuyama and Sahin (2009) damages from 1960 to 2007 as a result of natural disasters amount to USD742 billion while meteorological and climatological events make up 36% (USD271 billion) of these damages. Understanding severe events can be helpful to minimize the possible damages and losses that can occur, this is however difficult for some countries faced with other economic and social issues (Doswell, 2003). Damage related to extreme events that occurs in countries with diverse, high to middle-income economies tend to have a major higher order economic impact compared to countries with a simple economic structure, however, these *poor* countries tend to struggle with the aftermath of extreme damage while economically stronger countries can endure and successfully recover from such events (Noy, 2009; Okuyama, 2008). Jahn (2015) classifies the economic impact due to severe weather into; direct or indirect, non-market, time-horizon and positive impacts, and direct losses by sector and time.

*Direct losses* refers to direct impact an event has e.g. the physical destruction of property, whilst *indirect losses* refers the losses of a third party affected by the direct losses. *Non-market effect* refers to any commodities damaged in the event of a storm, but the monetary value of such losses is hard to assess. Jahn (2015) uses the example of an attraction being damaged (e.g. religious statue), although the monetary value can be quantified the symbolic value of the original work is not assessable. *Time horizon and positive impacts* focuses on the spatio-temporal impacts. With the advent of an extreme event damage cost starts to accumulate and when the event ceases it can either yield economic gains or losses for two reasons: (1) the stimulus effect; where there is additional demand for a resource and (2) the productivity effect; when damaged goods are replaced by new goods (Jahn, 2015). Noy and Vu (2010) found that natural disasters has a short term positive growth effect in developed regions but not in remote regions. Jahn (2015) emphasises that when there is no economic stimulus following a disaster a region can fall into a poverty trap or cycle of long-term negative growth. Finally, *direct losses by sector and time* examines the influence of an event on specific sectors contributing to the economy; these can be short term and/or long term effects on critical sectors. While some events may have a positive effect for some sectors other events may lead to a loss in another sector. It is clear that if a country can identify the possible impacts on crucial sectors and plan mitigation methods for when such events may occur, economic and social resilience can be improved.

## **The economic implications of severe hailstorms around the world**

The economic loss due to hailstorms can be extensive especially when these storms occur over densely populated urban areas. Hail damage in the past has dominated the percentage of total insurance pay-outs within a specific area and year; Munich, Germany 1984 (55%), Denver, USA 1990 (50%) and Sydney, Australia 1990 (43%) are examples of such costly events (Hohl et al., 2002). Severe hail storms have also set some records related to insurance payouts; a hailstorm in Sydney Australia caused damages of over AUD 1.6 billion in damages, exceeding the cost of any previous natural catastrophe in the country (Gero et al., 2006). In the USA a 2001 hailstorm lasted 8 hours, covered over 550km and caused over USD 1.5 billion in damages in the states of Illinois and Missouri (Changnon and Kunkel, 2006). A 2006 storm in the United States' Mid-Western region broke the record for the costliest hailstorm to date when the event caused over USD 1.8 billion in damages to property. This was also

the costliest catastrophe in the USA for 2006 (Changnon, 2009). Two separate hailstorms on two different continents resulted in another costly day for insurers in 2013 – in Europe a hailstorm amounted damages of EUR 2.8 billion (Punge and Kunz, 2016) and in South-Africa damages amounted to over ZAR 1.6 billion in the country's costliest insurance payout to date.

The effects of hailstorms are also felt in other sectors. Agriculture is heavily impacted by hail events and according to Punge and Kunz (2016) measuring the agricultural impact of hail is a difficult task as data over agricultural land is generally recorded during the growing season and events outside this frame go unrecorded. In Europe most losses due to hailstorms on agricultural production occurs in Spain, followed by France and Italy (Sánchez et al., 2003). Insurance companies pay an estimated EUR100 million to crop losses in Spain's hail prone areas annually. In the Lleida valley located in Spain farmers pay an average of EUR15 million towards hail damage insurance (Aran et al., 2011; Sánchez et al., 2003). In Cyprus a total of EUR22.7 million was paid out by insurance companies to cover the damage on agricultural sectors from 1996-2006 or 28.4% of the total compensation paid in this period nationwide (Nicolaidis et al., 2009). Changnon Jr (1972) estimated the total crop loss due to hail in the USA at USD284 million (an estimated USD1.6 billion in 2016) and about 1% of total crop production. Argentina's Mendoza province records 10% losses to agriculture from hailstorms (Rosenfeld et al., 2006). The impacts of hail on agricultural regions not only carries an economic cost to farmers, but it also affects the food security of a country and the socio-economic circumstances of communities dependent on the agricultural sector.

## **The impacts of severe hailstorms on the South-African economy**

The history of hailstorms over South-Africa has been well documented in Caelum (1991); the first recorded hailstorm in South-Africa was in 1692 off the Cape Town coast. Since then South-Africans have documented frequent severe hail events across the country. Hailstorms over the Gauteng Province have been documented as early as 1928 when a storm over Johannesburg caused ZAR1 million in damages – a substantial amount at the time. In 1936 *hailstones the size of coconuts* killed 10 people and an unknown amount of livestock in Northern Gauteng (Grobler, 2003; Perry, 1995). On 17 November 1949 a storm so severe occurred over Pretoria it apparently damaged every building within the city and resulted in the National Building Research Institute Council For Scientific and Industrial Research publishing a report on the hail resistance of South-Africa roofing material (Caelum, 1991; Rigby and Steyn, 1952). Another hailstorm in the region on 1 November 1985 was ranked as one of the worlds top 10 most destructive hailstorms at the time, while a storm in 1992 resulted in the death of 14 people in East-Griekwaland (Perry, 1995).

The costliest day for insurers in South-Africa occurred on 28 November 2013 when a massive hailstorm over the Gauteng area caused over ZAR1.6 billion in damages. More than a hundred houses were damaged in the suburbs Dobsonville, Bramfischerville, Emdeni and Soweto; trees in the suburbs of Florida and Roodepoort and Vereeniging were destroyed by the storm (Makhubu et al., 2013). Power-lines across the province were damaged resulting in electricity shortages (Rahlaga, 2013). The storm was preceded by other severe convective events on the 11 and 18 November that resulted in hail and flood damage. The combination of these events and the damage caused led to renowned interest in hail research, especially over the Highveld where these storms caused extreme damage. In 2014 the Insurance Institute of South-Africa shed light on the ZAR1.6 billion in losses experienced by the public and insurers during these 2013 hail events.

South-Africa's agricultural regions aren't spared from these severe events. Early research by Theron et al. (1973) on the impact of hailstorms on agriculture in estimated the hail events to amount to a 2.1% loss in agriculture production. Olivier and van Rensburg (1992) estimated the annual loss could be as high as 9% of the total production. Caelum (1991) has various details about storms impacting agriculture. In 1914 over 500 sheep were killed in a storm over Harding in KwaZulu-Natal and a storm in 1946 killed 42 sheep and damaged crops over a large part of the Free-State. On New Years Eve of 1959 one of the most devastating storms hit the farming sector, in addition to crops being destroyed, several thousand animals including sheep, poultry and game were killed. On 29 December 1997 a severe hail storm over the Free-State caused ZAR15 million in damages to crops in the Reitz area (De Coning et al., 2000). The impact of hail may not always be direct as observed in 1986 where a hail

event in the Cape province resulted in pine plantation becoming infected with *Sphaeropsis sapinea*, a blight disease, causing an estimated loss of 55% of total potential production or an estimated ZAR2.5 million (Zwolinski et al., 1990). The effects of severe events on agriculture is also far reaching as these industries are large employers and in many cases the only economic stimulus in a region.

The review on the economic impacts of severe events and more specifically hail storms indicate how important it is to understand these events. The economic impacts can be far-reaching as documented by Jahn (2015). This also has societal impacts mostly felt by the poor and in countries that may not be able to economically *absorb* and recover from severe events. The effect may be even larger if the increases of *extremes* as observed by (Kruger and Sekele, 2013; New et al., 2006; Roy and Rouault, 2013) is continuing. It is important to note the uncertainties related to our understanding of these events and their impacts and this is discussed in more detail in the following sections.

## Scales in the atmosphere

Scale in the atmosphere can be defined as the spatio-temporal characteristics of weather and climate phenomena and their interlinked relationship. Hermida et al. (2015); Wuebbles et al. (2014) notes there is a limited understanding of extreme events like hail, ice storms, tornadoes and strong winds – events rare in their spatial and temporal extent (Carte and Held, 1978). This poses problems when trying to analyze the events on any scale, however, because extreme damage can occur in a short period, often without any warning a better understanding of these events is a necessity.

Defining the spatio-temporal variation (scale) of different atmospheric phenomena was first addressed by Orlanski (1975). He defined the atmosphere into three major divisions, microscale ( $20\text{m} \leq 20\text{m}$ ) < mesoscale ( $2\text{km} \leq 2000\text{km}$ ) < macroscale ( $2000\text{km} +$ ), subdivided in  $\gamma$ ,  $\beta$  and  $\alpha$  scales respectively. Because the atmosphere is dynamic each scale also has a temporal element linked to it; microscale phenomena are typically in the order of  $\leq 1$  hour, mesoscale phenomena  $1 \text{ hour} \leq 1 \text{ week}$  and finally macroscale phenomena  $\geq 1 \text{ week}$ . According to Dyson (2013) mesoscale systems may produce extreme rainfall over South-Africa. Thunderstorms are associated with these mesoscale systems and occur within the meso- $\gamma$  range. These mesoscale systems are linked to larger scale circulation patterns ranging from the upper meso- $\alpha$  to the macro- $\beta$  scale range also known as synoptic circulation (Pielke et al., 1992). Similar scales exist in atmospheric modelling which is further discussed in page 19.

**Table 1.1:** Scales in the atmosphere after Orlanski (1975)

| Macro -                        |                                             | Meso -                                    |                                        |                                       | Micro -                               |                                      |                           |
|--------------------------------|---------------------------------------------|-------------------------------------------|----------------------------------------|---------------------------------------|---------------------------------------|--------------------------------------|---------------------------|
| $\alpha, \geq 10,000\text{km}$ | $\beta, 2000\text{km} \leq 10,000\text{km}$ | $\alpha, 200\text{km} \leq 2000\text{km}$ | $\beta, 20\text{km} \leq 200\text{km}$ | $\gamma, 2\text{km} \leq 20\text{km}$ | $\alpha, 2\text{km} \leq 200\text{m}$ | $\beta, 200\text{m} \leq 20\text{m}$ | $\gamma, \leq 20\text{m}$ |
| General circulation            | Synoptic cyclones                           | Fronts                                    | Mountain winds                         | Thunderstorm                          | Tornadoes                             | Plumes                               | Turbulence                |
| $\geq 1 \text{ week}$          |                                             | $1 \text{ week} \leq 1 \text{ hour}$      |                                        |                                       | $1 \text{ hour} \leq 1 \text{ sec}$   |                                      |                           |

In each of the mentioned scales there are characteristic features that influence surface weather. To understand the links between the meso- $\gamma$  scale features and surface weather meteorologists around the world launch radiosondes into the atmosphere on a daily basis to gather atmospheric data. The upper-air soundings allow meteorologists to form an idea of the current state of the atmosphere in a limited spatial and temporal area. Not only can products such as tephigram, skew-t and hodographs be created from these soundings, describing the vertical state of the atmosphere, it also forms a crucial part in the collection of data used to initiate NWP models. Unfortunately upper-air soundings only give scientists an idea of the atmospheric properties within the meso- $\gamma$  and meso- $\beta$  scale. NWP offers an alternative method to understand the dynamic properties of the atmosphere over a larger spatial and temporal extent, however, this requires powerful computer resources especially to resolve convection. Attempts to understand larger circulation (macro- $\beta$  scale) has similar limitations and although simulating convection is less challenging on a synoptic scale with the use of parametrization schemes, it tends to increase uncertainty. To overcome this, models that have a lower resolution can help us to form a general understanding

of the circulation of the atmosphere while methods such as synoptic clustering can also add value to understanding the atmosphere with less computer resources than that needed for high-resolution NWP, but these models give us limited detail on local scale events. Clustering is a known and often used method that is computationally more efficient to understand large atmospheric circulation patterns (Cahynová and Huth, 2014; García-Ortega et al., 2011; Huth et al., 2008; Sheridan and Lee, 2011). This study attempts to use these two methods to link the small and large scale systems with each other and examine the relationship when extreme events are observed.

## The structure of thunderstorms, thermodynamic derived indicators and wind shear

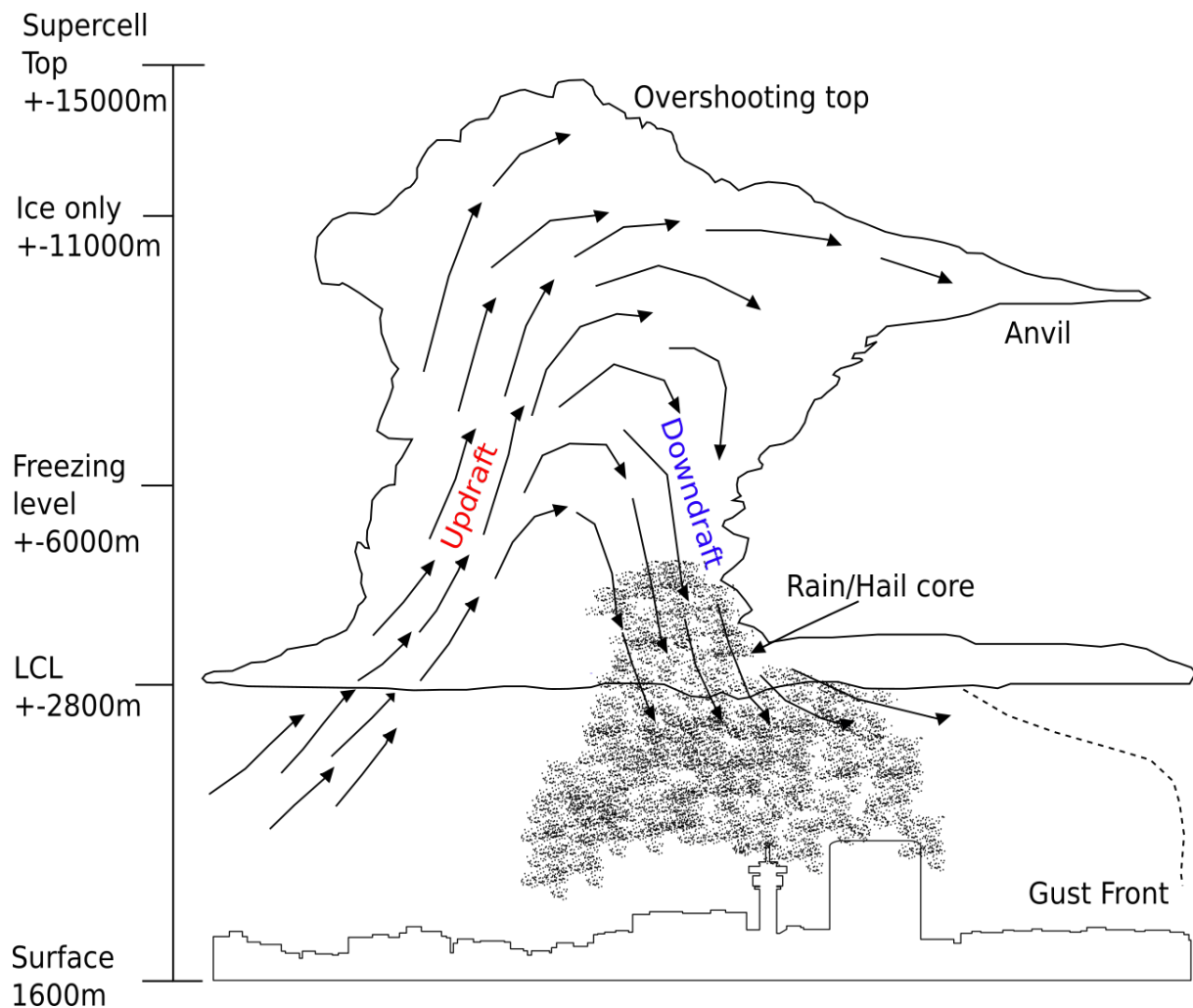
Thunderstorms, defined as;

*a high frequency mesoscale system associated with vigorous convection, giant towering and thundery cumulonimbus cloud, strong wind in the form of squall, lightning flashes, and heavy rain, sometimes accompanied with hail* (Halder et al., 2015),

are small scale features that can invoke havoc on a region. A severe thunderstorm can produce heavy rain, hail, severe winds, tornadoes (a rare occurrence in South-Africa) and damaging lightning. Because these events are short-lived and develop rapidly it poses a challenge for atmospheric scientists to understand the complex processes within these storms. The smallest of these are isolated single cell thunderstorms followed by multicell storms. The most notable of thunderstorms is the supercell storm often extending over 30km and reaching heights of over 15km (Rae, 2014). In all three thunderstorm types hail, rain and lightning can occur and these storms are sustained by updrafts; warm, moist air that feeds the system. As this warm moist air rises latent heat is released and the air parcel's buoyancy increases and along with sustained updrafts lifts saturated air high into the troposphere and lower stratosphere and in the process reaching freezing levels where ice particles and supercooled droplets start forming. The particles continue to grow in size until the particle's weight exceeds the strength of the updraft when finally down bursts of hail and heavy rainfall occur. Figure 1.1 provides a simple illustration of the thunderstorm structure. Our understanding is further improved by the use of thermodynamic profiles of severe events to understand the critical lifting process that impacts a parcel of air as it is transported in the atmosphere.

The thermodynamics of convection play an important part in understanding severe storm formation. Through the use thermodynamic diagrams scientists have been able to represent processes in the atmosphere related to various atmospheric conditions including severe events such as hailstorms. Research related to sounding derived severe storm climatologies is relatively abundant for Europe (see Berthet et al. (2013); Groenemeijer and Van Delden (2007); Mohr and Kunz (2013); Sánchez et al. (2003, 2009)) and North-America (see Allen et al. (2015); Doswell III and Schultz (2006); Dupilka and Reuter (2006); Rasmussen and Blanchard (1998)). Over South-Africa Blamey et al. (2016); Dyson (2013); Dyson et al. (2015); Rae (2014) research is the related to the topic of thermodynamic characteristics of weather events. Dyson et al. (2015) focused on the examining sounding derived parameters from 1977 to 2015 to assess storm environments and found that most severe convective indices that were recorded during summer months were Convective Available Potential Energy (CAPE) and wind shear, furthermore these indices were comparable to that of severe events observed in the USA. Rae (2014) had a similar finding, showing that most unstable convective available potential energy (MUCAPE) values are the highest during summer and also noting the sudden increase in observed MUCAPE from September to October. Blamey et al. (2016) analysis of convective indices over South-Africa supports these findings, they show that a marked increase in CAPE is observed over the spring and summer months.

To record these thermodynamic indicators mentioned meteorological agencies typically launch weather balloons known as soundings at certain points to gather atmospheric data. In South-Africa this occurs at Cape-Town and Irene on a daily basis while other sites have irregular the frequency of launches. Thermodynamic indicators



**Figure 1.1:** Understanding conditions leading up to hailstorms are important due to the devastation of these events. Cumulus and cumulonimbus clouds are generally associated with hail formation and form in an unstable (warm) atmosphere with adequate freezing levels. The turbulent air currents in clouds force water particles in the clouds to move upwards to freezing levels and as soon as the water freezes the nucleus of the hailstone is formed. When the terminal velocity of hailstones is larger than that of the updrafts hailstones fall to the surface. If the hailstones are not heavy enough it may be carried upwards again and grow in size until the hailstones can no longer be held up by updrafts and fall to the ground. In a supercell warm air can carry unstable air parcels as high as 20km (Foote, 1984; Heymsfield et al., 1980). Note that the figure is not to scale and for illustration only. (Illustration by Henno Havenga. Johannesburg silhouette is a derivative work (tracing copy). Original image credit: Johannesburg Skyline photo by Chris7cn licensed under CC BY 4.0)

derived from these soundings are used to evaluate the thermodynamic structure of the atmosphere and the possibility of severe weather occurrence. Johns and Doswell III (1992); Sánchez et al. (2009) mentions three *ingredients* that indicate an environment ideal for storm formation; this includes a moist deep layer in the low/mid troposphere, instability and a triggering mechanism which can be deduced from sounding observations and the derived indicators. The basic movement of a parcel of air in a warm unstable environment can be summed up as follows: as a parcel is lifted through a colder region of stable air it becomes saturated and reaches the lifting condensation level (LCL) where clouds typically form. In a warm unstable environment the parcel continues lifting to its level of free convection (LFC). To achieve this the parcel requires a certain amount of energy to *break* through the stable atmosphere known as convective inhibition (CIN). If a parcel is warm it will continue to rise to the equilibrium level (EL) where it has the same density to that of the surrounding environment. When this occurs a parcel is said to be positively buoyant and this is represented by the function CAPE. Figure 1.3 shows a simple indication of how the thermodynamic properties of a rising parcel. Meteorologists use soundings to evaluate these *ingredients* and this has led to the formation of severe storm indices such as CAPE, lifted Index (LI),

severe weather thread index (SWEAT), vertical totals (VT), totals totals (TT) and various other derived indices. Also, measured from the soundings is vertical and horizontal wind shear. The low and upper level vertical shear is important in the storm formation, however it is known that strong wind shear can also lead to its demise. Figure 1.2 indicates how a hodograph is used to plot and analyze the motion and wind shear in the atmosphere. A couple of the above mentioned indices stand out and these are briefly discussed here in further detail (De Coning and Adam, 2000; Dyson et al., 2015; Grieser, 2012; Groenemeijer and Van Delden, 2007; Kaltenböck et al., 2009; Litta et al., 2012; Sánchez et al., 2009; Tippett et al., 2015).

CAPE is a derivative of thermodynamic sounding is formulated as,

$$CAPE = \int_{p_n}^{p_f} (a_p - a_e) dp, \quad (1.1)$$

CAPE is a theoretical measure of instability of the buoyancy of an air parcel with an increase in height as it is heated adiabatically (through the LCL, LFC until it reaches its EL). If this buoyancy is positive an environment conducive to storm formation can be expected (Groenemeijer and Van Delden, 2007; Sánchez et al., 2009). CAPE is expressed as  $\frac{J}{kg}$  and values  $\geq 1000$  indicates instability, although storms have been recorded in lower values. The importance of CAPE has been emphasized by Groenemeijer and Van Delden (2007); Kaltenböck et al. (2009); Sánchez et al. (2009) where a strong relationship was found between CAPE, thunderstorms and hail.  $\int_{p_n}^{p_f}$  represents the parcel rising from the pressure at the level of free convection (LFC -  $p_f$ ), the pressure at the equilibrium level (EL -  $p_n$ ),  $a_p$  the volume of a parcel moving upwards moist-adiabatically from the LFC and  $a_e$  environment specific volume of the profile (AMS, 2016). CIN is known as negative CAPE and is a measure of the energy that a parcel has overcome to rise above the cold/stable inversion layer into the atmosphere and become positively buoyant. CIN is written as;

$$CIN = \int_{\text{source level}}^{LFC} B_T dz = \int_{\text{source level}}^{EL} \frac{T'_v}{T_v} dz \quad (1.2)$$

The Showalter index (SI) is a widely used severe storm evaluation index. The original SI was perhaps the first major thunderstorm indicator derived from soundings (Doswell III and Schultz, 2006; Showalter, 1953). The SI is defined as the temperature difference of an air parcel lifted from 850hPa dry-adiabatically to its LCL and then wet adiabatically to 500hPa (see Figure 1.3. This can be written as,

$$SI = PT_{850} - PT_{P_{500}} \quad (1.3)$$

where  $PT_{P_{500}}$  is the parcel temperature at 500hPa when lifted dry-adiabatically from 850hPa to the LCL and then wet adiabatically to 500mb. Positive SI values ( $\geq 0$ ) indicate a stable atmosphere and negative values ( $< 0$ ) an unstable atmosphere. Tyson and Preston-Whyte (2000) notes that a value of  $-3^\circ\text{C}$  is *defining* conditions for cumulus formation. Similar to the SI is the LI (Galway, 1956) calculating the temperature difference of a parcel as it is lifted dry-adiabatically to the LCL and then wet-adiabatically to 500hPa. An important difference is that the LI is calculated between the surface ( $z = 0$ ) and 500hPa.

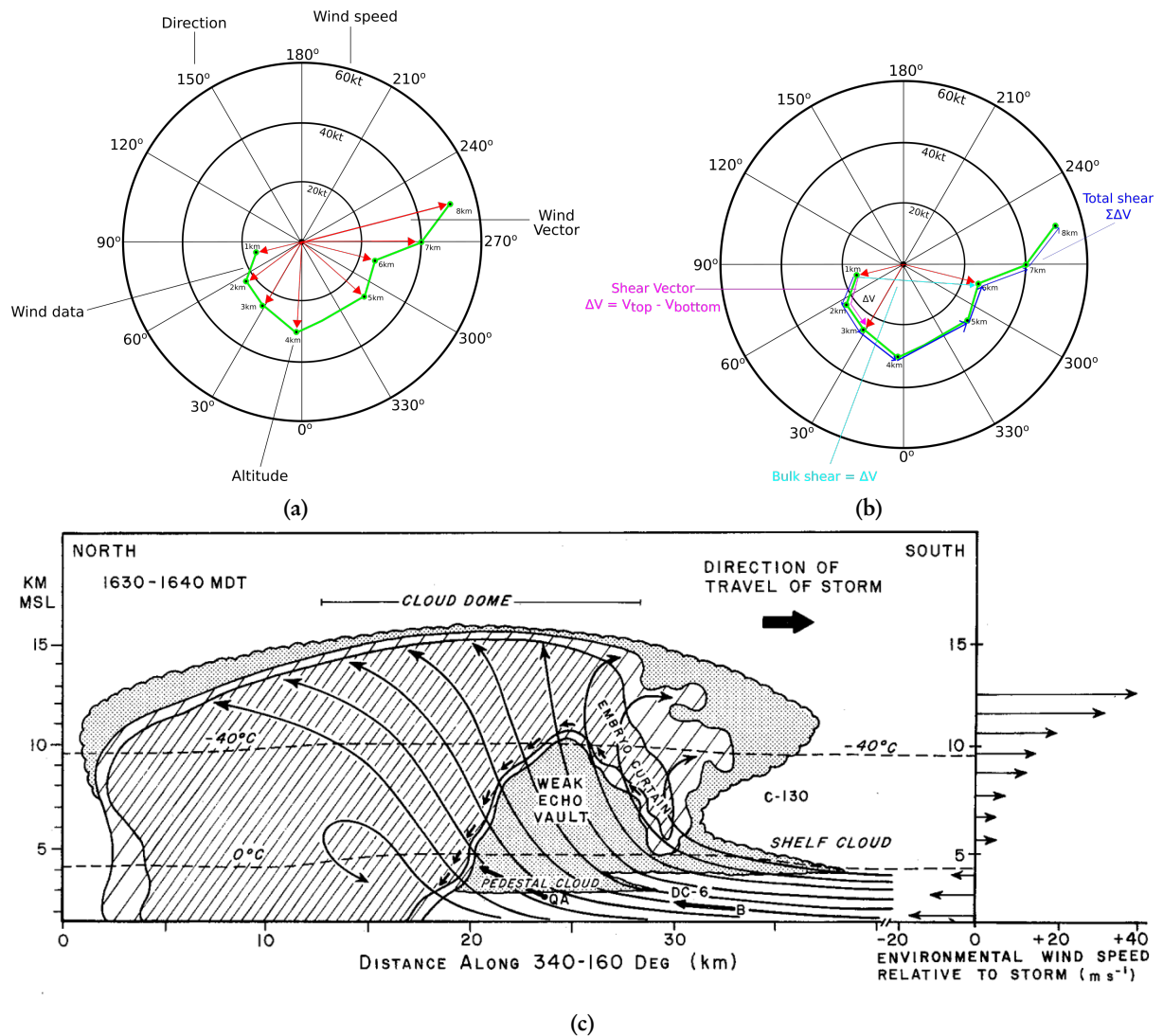
Two other important indicators are derived from temperature and humidity. First the TT index; the TT is formulated by combining the VT and cross totals (CT). The VT is defined as temperature difference between 850hPa and 500hPa while the CT is the difference between the 850hPa dew-point temperature ( $T_{d,850}$ ) and 500hPa temperature ( $2T_{500}$ ). The TT can thus be written as Grieser (2012); Miller (1972),

$$TT = VT + CT = T_{850} + T_{d,850} - 2T_{500}, \quad (1.4)$$

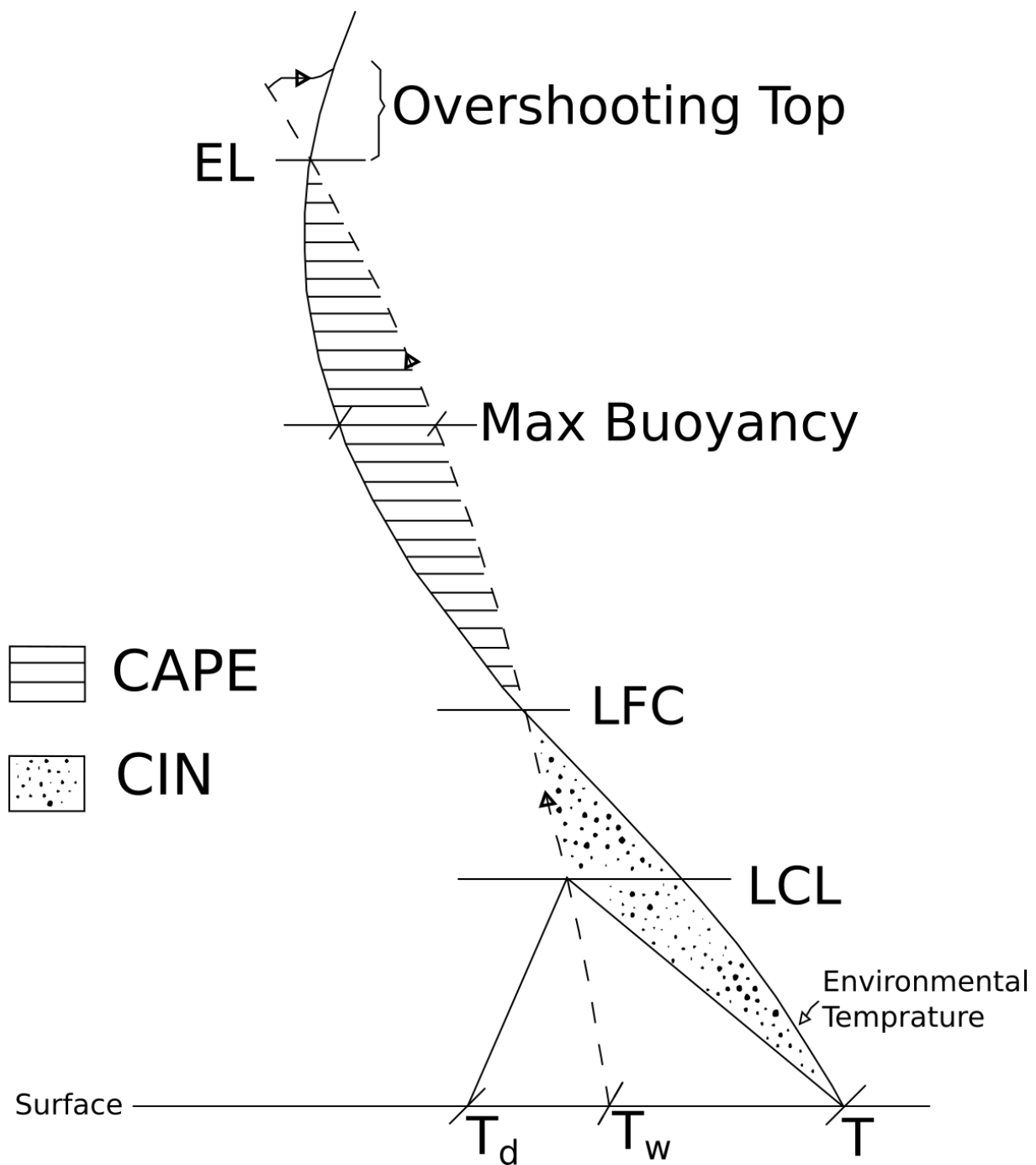
when TT values are  $\geq 44\text{K}$  the environment has conditions that could result in thunderstorm formation. The

K-Index is similar to the VT but includes temperature and dew-point temperature at 700hPa but was developed to assess the possibility of heavy rainfall and not hail.

Another product derived from the upper air sounding and that has been shown to have particular value in the formation of severe storms is wind shear. Wind shear is a measure of the directional variations in the wind vector. The vertical wind shear is a function of the speed (vertical speed shear) and directional (vertical directional shear) changes of wind with an increase in height when a parcel of air is lifted, this is represented on a hodograph (see Figure 1.2). The vertical wind shear is calculated as a magnitude of the vector difference between two pressure levels ( $\Delta V = V_{top} - V_{bottom}$ ) while horizontal wind shear refers to the lateral change of wind direction at a given altitude (Barry and Chorley, 2009). Common products derived from the hodograph are bulk shear represented as  $\Delta V$  and mean shear represented as  $\sum \Delta V$ . The bulk shear is used to evaluate the 0 - 6km levels while the directional wind shear represents the storm rotation and subsequent lifting of air parcels. Overly strong wind shear can prevent the evolution of cumulonimbus clouds by dispersing heat and moisture in the upper atmosphere, referred to as shearing. In the Southern Hemisphere wind shear associated with convective events typically have counterclockwise rotation also known as backing (Doswell III, 1991).



**Figure 1.2:** The diagram indicates how hodographs are used to estimate storm motion, vorticity, direction and shear values. The hodograph represent wind shear which is an important feature in storm formation and sustaining convective events. Diagram a and b indicates the hodograph from an event simulated in this study adapted from NWS (2014). The backing, or counterclockwise rotation, seen in storms in the Southern-Hemisphere is visible in this example. The wind fields are represented as vectors from which bulk shear, total shear and mean shear can be calculated. Diagram c from Browning and Foote (1976) illustrates how this wind environment is related to storm motion and the flow of winds within a convective event.

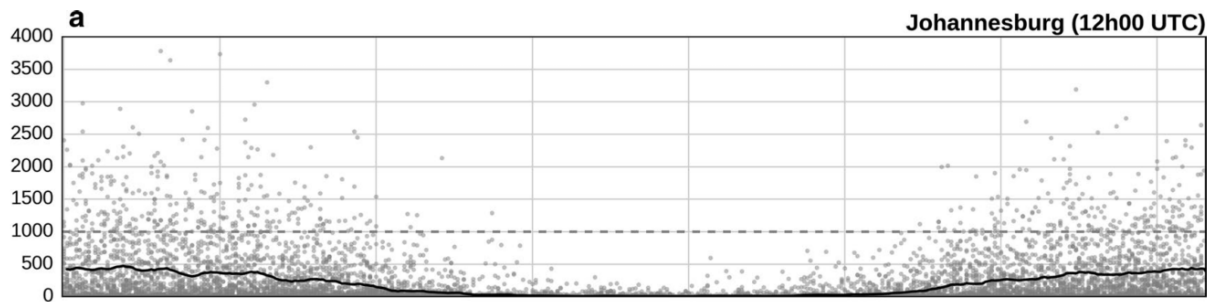


**Figure 1.3:** A simplified thermodynamic structure of a typical thunderstorm adapted from Cairo (2011) illustrates some key concepts that influence thunderstorm formation; as a parcel of air rises it reaches the LCL where saturation occurs, the parcel is then lifted wet adiabatically and in a warm atmosphere the parcel continues to rise to the LFC. Between the LCL and LFC is a region of stable atmosphere, to break through this cold/stable region requires a certain amount of energy known as CIN. Once the parcel breaks through this cold region it can continue to rise until it reaches the EL. If it is positively buoyant CAPE can be used as a measure of instability.

Two major data sources exist where radiosonde data can be accessed, the University of Wyoming (UWYO) database is a well-known resource containing real-time radiosonde data from across the world, the database allows for easy plotting of raw upper-air sounding data in the form of hodographs, thephigrams, skew-t or even the rarely used stuev diagram. A issue regarding the UWYO data is the lack of thorough quality control before release. A manual quality control procedure has to be undertaken before data is used. The other source is the Integrated radiosonde archive (IGRA) which contains historical radiosonde data for weather stations around the world. The IGRA data undergoes a quality control procedure before released (Durre et al., 2006, 2008). Dyson



(2013) however cautions about the use of the IGRA dataset as errors related to dew-point calculations have been noted. Over South-Africa two major investigations examined the thermodynamic connection to severe events. Dyson (2013)'s study into the climatology of severe rainfall events and the more recent study by Blamey et al. (2016) showed that thermodynamic variables have a characterized seasonal trend and association with severe weather occurrences. Figure 1.4 after Blamey et al. (2016) illustrates the seasonal distribution of CAPE over South-Africa's central interior. In the summer months CAPE is especially high and a similar distribution was noted by Dyson (2013) for indicators of adverse weather, such as the SI, LI and TT.



**Figure 1.4:** *The annual distribution of CAPE over Johannesburg after Blamey et al. (2016) again demonstrates the well defined seasonal distribution of this variable associated with convective storms.*

Although the use of severe weather indicators from radiosondes is valuable, they are prone to errors in instrumentation and/or calibration. According to Doswell III and Schultz (2006); Markowski et al. (2003) the combination of various indicators should be used as an assistance to meteorologist and as the sole predictor for storm possibility, as these measurements are limited in space and time. Using other tools such as NWP can allow us to better understand the thermodynamic properties of events with less space-time limitations. Our understanding of the links between observed thermodynamics and surface weather could improve by examining the synoptic circulation patterns in the order of  $\geq 2000\text{km}$ . These large scale circulation patterns are seasonally well organized over South-Africa and brings about characteristic weather over all parts of the country discussed in the next section.

## Synoptic weather of South-Africa

South-Africa's location in the middle latitudes ( $22^{\circ}$ – $35^{\circ}\text{S}$  and  $15^{\circ}$ – $35^{\circ}\text{E}$ ) and the surrounding Indian and Atlantic ocean has a profound impact on circulation patterns occurring over the country. The country is characterized by a dominantly semi-arid climate (Dyson et al., 2015; Engelbrecht et al., 2013), while the Highveld falls into the Cwb climate region (warm temperate, winter dry and warm summer), Cwa (warm temperate, winter dry and hot summer) and Bsh (arid, summer dry and hot arid) regions according to the Köppen-Geiger Climate Classification System (see table 1.2 (Kottek et al., 2006)). The Highveld receives between 600mm - 700mm rainfall per year during the summer mostly from convective thunderstorms (Dyson, 2009; Fatti and Vogel, 2011). The weather and climate is dominated by a prevailing anticyclonic circulation at 850hPa over the subcontinent that brings about strong subsidence over the interior (Piketh et al., 1999). Several other circulation patterns that influence the weather and climate have a strong seasonal variation with characteristic weather types prevalent during the summer and winter months (see Figure 1.5). Due to the prevailing continental anti-cyclone the Highveld is generally in a state of fine and dry weather (Roy and Rouault, 2013; Tyson and Preston-Whyte, 2000) in winter months and during summer the systems gives way to the tropical easterly systems from the Inter-tropical convergence zone (ITCZ) which extents down to central South Africa from late spring (October) until December, also known as easterly wave circulation. During this change of season the upper freezing levels are cold enough for ice process to produce large hail while a warming surface provides convective energy for air to lift.

This continental anticyclone and the tropical easterly disturbances follow a clear seasonal cycle (Figure 1.5, bottom right). Summer weather is characterized by the presence of the South-Atlantic High and the South-Indian

**Table 1.2:** *The Köppen-Geiger Climate Classification System after Kottek et al. (2006) indicates that the Highveld region falls within an area of Cwb and Cwa.*

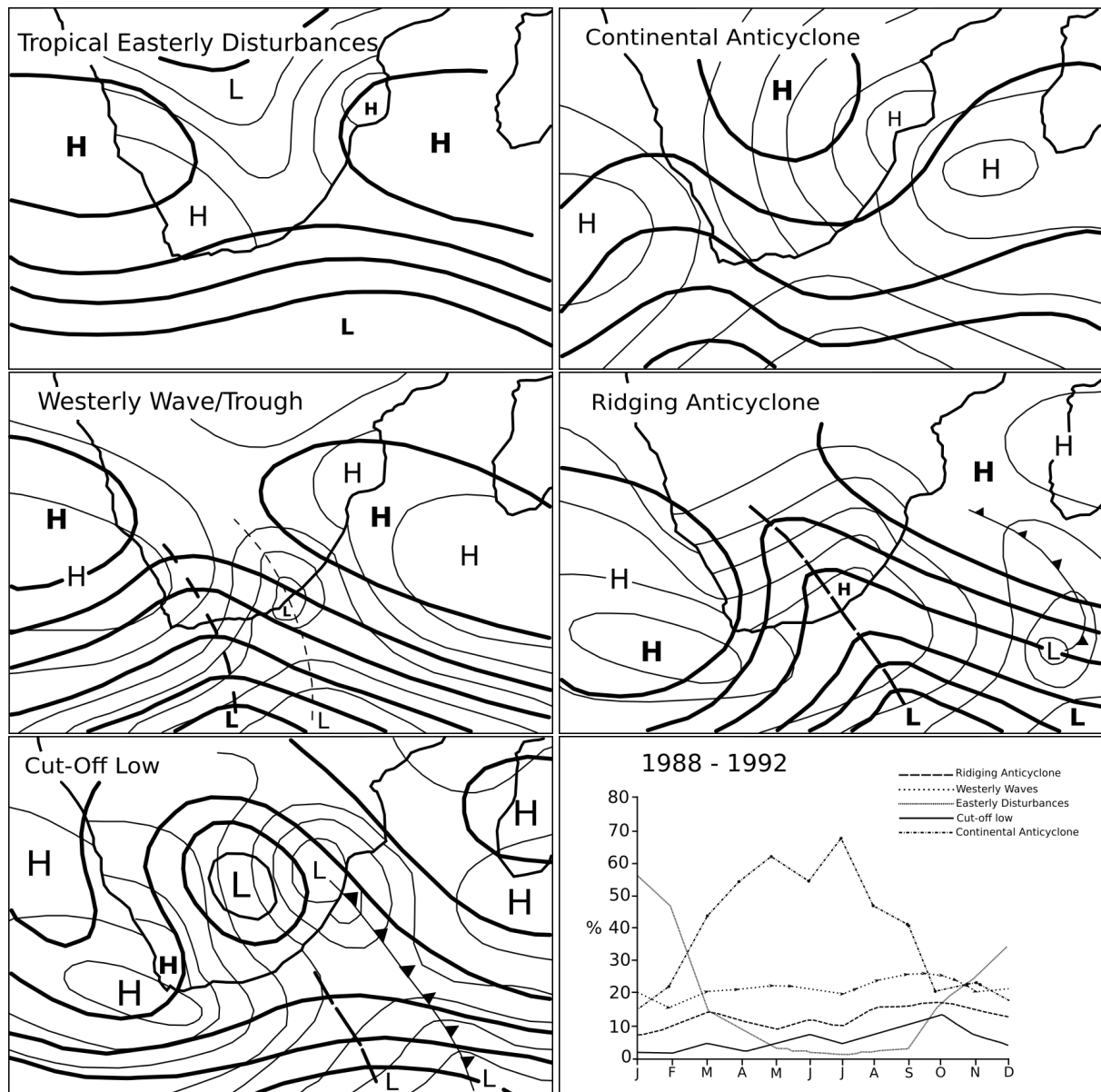
| First Letter        | Second Letter  | Third Letter   |
|---------------------|----------------|----------------|
| A: Tropical         | f: Fully humid | h: Hot arid    |
| B: Dry              | m: Monsoon     | k: Cold Arid   |
| C: Mild temperature | s: Dry summer  | a: Hot summer  |
| D: Snow             | w: Dry winter  | b: Warm summer |
| E: Polar            | W: Desert      | c: Cool summer |
|                     | S: Steppe      | d: Cold summer |
|                     | T: Tundra      |                |
|                     | F: Frost       |                |

High surrounding mainland and a shallow heat low over the interior of the country. The ITCZ shifts to approximately 17°S during this time, resulting in highly convective weather over parts of the country (Dyson and Van Heerden, 2002)(Figure 1.5, top left). The movement of the ITCZ is a source of deep convection that is associated wide-spread, heavy, convective rainfall in the Highveld region. This displacement of the ITCZ associated with the Tropical Temperate Trough (TTT) also forms the South Indian Convergence Zone (SICZ) (Blamey and Reason, 2013; De Coning et al., 1998; Dyson, 2009, 2015; Hart et al., 2010). Hail over the Highveld is not purely tropical as these systems are too warm for ice formation even at high levels. Dyson (2009, 2015) makes it clear that with the changing season in October and November the freezing levels are still adequate for hail formation while convection is strong enough for parcel to lift unstably and form convective clouds. With the advent of winter these systems dissipate or move towards the equator and a prevailing high pressure system sets in over the interior of the country leading to fine and dry weather (Figure 1.5, top right), a synoptic system dominated by subsiding air (Engelbrecht et al., 2013; Roy and Rouault, 2013; Tyson and Preston-Whyte, 2000). Other synoptic systems which occur with less frequency include the westerly waves (Figure 1.5, middle left), the ridging anticyclone (Figure 1.5, middle right) and cut-off lows (Figure 1.5, bottom left), this is also illustrated in the time series analysis (Figure 1.5, bottom right). Dyson (2013); Tyson and Preston-Whyte (2000) identified westerly trough, cold fronts, southward extending tropical low or V-shaped trough, the cut-off low, tropical cyclones, ridging high and blocking high or long wave ridge as the important systems that influence summer rainfall in South-Africa. these systems do have considerable impact on weather over parts of the country. Dyson (2013, 2015); Tyson and Preston-Whyte (2000) states that these systems have been linked to rainfall over Gauteng. Although they are less dominant than the continental anticyclone and easterly wave in their intensity of appearance (Tyson, 1986; Tyson and Preston-Whyte, 2000).

The synoptic conditions related to hail storms is also considerably impacted by the upper-air circulation. In the 500hPa level the westerly wave has an impact on the dominant wind fields and provides the influx of cold air in the upper levels. This mass of cold air allows for parcels of air to freeze and form hail and ice, whereas a purely tropical system would be too warm for the formation of hail events as ice processes will likely not occur. The system further plays a major role in the movement of systems across the country (Dyson, 2015). Furthermore, the eastern escarpment, its abrupt rise and the ENSO/SOI, which drives the El Nino and La Nina phenomena, are other known factors impacting the country's climate and weather (Hastenrath et al., 1995; Preston-Whyte and Tyson, 1973).

## Hailstorms over South-Africa

Often lasting only a few minutes and invoking havoc on a region, the high spatial and temporal variability of hailstorms presents challenges for scientist studying these events (Carte and Held, 1978; Sanderson et al., 2015). Part of this variability can be attributed to seasonality, topography, urban effects and altitude (Tyson and Preston-Whyte, 2000). To study hail at a specific region the term hail day frequency (HDF) was defined referring to the probability of a hail event to occur on a certain area within a year. In South-Africa this is at its highest between the latitudes of -25°N – -28°S, with HDF lowering towards the tropics and the Antarctic. Coincidentally the two



**Figure 1.5:** The dominant circulation patterns of South-Africa adapted from Tyson (1986). The lower right graph shows the distinct cycle between the tropical easterlies (summer) and the continental anticyclone (winter) patterns. With the advent of summer the tropical easterlies reach South-Africa. This is associated with the easterly wave and low that brings warm moist air from the tropics to over the country and results in an increase of convective activity. The continental anticyclone is dominant during the winter when the Highveld weather is characterized by fine and dry weather. The coastal low impact on Highveld weather is less profound; these systems however effect the coastal regions of South-Africa. The westerly wave brings cold, rainy weather to the Southern Cape during winter (Tyson, 1986; Tyson and Preston-Whyte, 2000).

biggest cities at these latitudes are Johannesburg (-26°S) and Pretoria (-25°S) (Le Roux and Olivier, 1996; Schulze, 1965). Johannesburg and Pretoria also have the highest number of reported severe hailstorms in the country. Between 1911-2012 Johannesburg and Pretoria had far more reports of severe hail events than any other city in the country (Caelum, 1991). Cecil and Blankenship (2012) makes an important note of an area's population density on the bias of hail reports; larger cities or metropolitan areas such as Johannesburg and Pretoria have a higher likelihood of hail actually being reported. The altitude and urban extent may also influence the HDF. Locations at higher altitudes seemingly have a higher HDF even when these locations are in relative close proximity to each other, this was observed by Held and Carte (1979) who noted that the HDF is greater in Witwatersrand than the lower-lying Pretoria. It was observed that urban areas have a higher HDF than the neighboring rural areas, possibly as a result of changes in the cloud microphysics (Held and Carte, 1979). Figure 1.8 provides

a well represented indication of the annual hail frequency. Isolated areas within central South-Africa and the Eastern Cape also have a high HDF but due to Gauteng's high population density and urban extent these storms cause more damage in the region. Although the damage in smaller towns and to farmers may be proportionally higher, media attention towards areas with an important social economic stance such as Johannesburg gives it a high reporting priority.

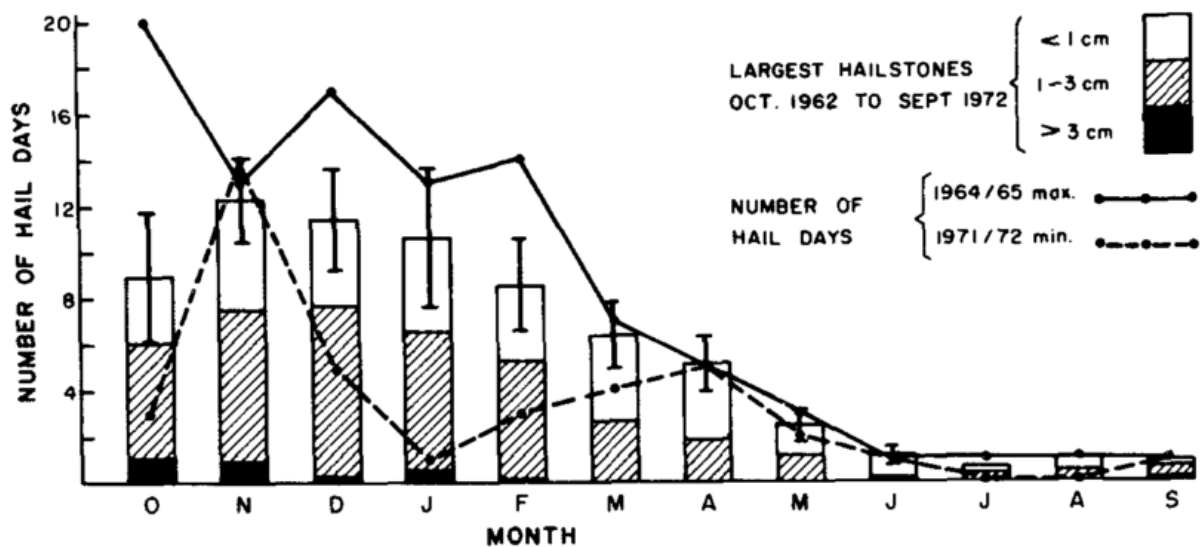
Over the Highveld, hailstorms usually peak from October to December when most severe thunderstorms are also observed. The largest hailstones usually occur in October, November and January according to Carte and Held (1978). According to Cecil and Blankenship (2012); Smith et al. (1998) hail is observed on 38% of storm days during a typical six-month hail season in the Highveld area. The average number of hail producing storm cells can exceed 7 on a hail day over Gauteng. The average time of a hail event over the Witwatersrand area around is 7.3 minutes while very few storms lasted over 30 minutes (Mader et al., 1986; Tyson, 1986; Tyson and Preston-Whyte, 2000). Although their occurrence gradually subsides with the advent of winter and the movement of the continental high pressure system over the interior of the country, storms are still observed as late as March and early April (see Figure 1.6 (Carte and Held, 1978; Olivier and van Rensburg, 1992)). Held and Carte (1979) looked at different synoptic situations giving rise to a variety of hailstorms during 1975 within the Johannesburg area and found that the conditions for hail days were not much different from days with normal thunderstorm activity usually characterized by a trough or low pressure system over central South-Africa. (Olivier, 1989) also noted that low pressure/cyclonic conditions are favored during hail producing storms up to 500mb. Held and Carte (1979) notes that high-pressure systems from the south-west following a cold front can result in even more severe hailstorms than normal thunderstorm producing conditions. According to Olivier (1989) line storms along squall lines are linked with severe hail damage, but accounts for less hail fall than scattered and isolated thunderstorms over the Highveld.

There is an important relationship between the occurrence of thunderstorms and hail events - Lesotho and the surrounding Drakensburg mountains experience the highest HDF and thunderstorm events, both exceeding 100 days per year Tyson and Preston-Whyte (2000). These results are supported by Cecil and Blankenship (2012) research into the worldwide distribution of hail by use of the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) estimated a higher number of events during the South-African hail season around Lesotho while decreasing towards the Highveld (see Figure 1.10). Cecil and Blankenship (2012) observations also supports that of Carte and Held (1978); Held and Carte (1979); Olivier and van Rensburg (1992); Schulze (1965) whose findings show that South-Africa's hailstorms occur in October, November and December, when convective activity is at its highest over the Highveld. It has to be noted that remote sensing data such as the AMSR-E is prone to errors, according to Li et al. (2016) data derived from satellites have a coarse temporal and spatial resolution leading to some distortion in the representation of hail distribution. Instances of hail in the Western Cape region are also observed in the Mountainous areas around in the region, however, these events are not typically of a convective nature such as Highveld events (Tyson and Preston-Whyte, 2000). Schulze (1965); Tyson and Preston-Whyte (2000) found a similar spatial distribution as that of Le Roux and Olivier (1996) where there is a high concentration of events observed over central South-Africa (see Figure 1.7).

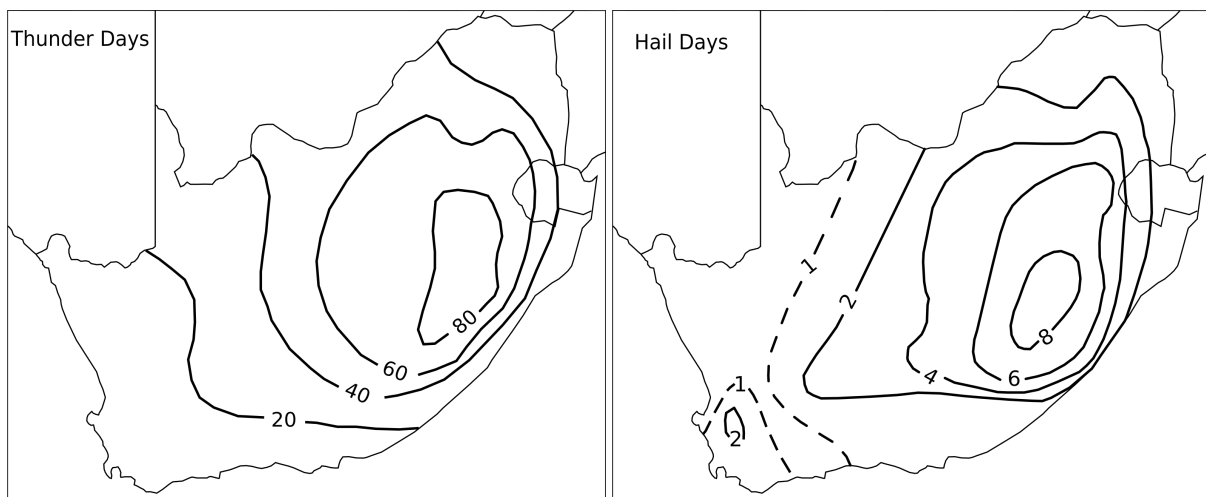
### **ENSO and convective events**

ENSO is mainly driven by changes in sea surface temperature (SST) and directly affects Southern-Africa's weather, this is notably observed in changes above and below the mean in rainfall. ENSO has two characteristic phases; first a high phase associated with above averaged rainfall and then a low phase where abnormally dry conditions prevail. The phases are calculated by measuring the difference in pressure between Darwin and Thaiti (Blamey and Reason, 2013; Driver and Reason, 2017; Jury, 2015; Reason and Mulenga, 1999; Tyson and Preston-Whyte, 2000). Research papers related to the relationship between ENSO and severe convective/hail events over South-Africa included work by Blamey et al. (2016); Olivier (1990); Olivier and Van Rensburg (1995). Olivier and Van Rensburg (1995) investigated the links between the HDF in the Pretoria – Witwatersrand area and SOI. The

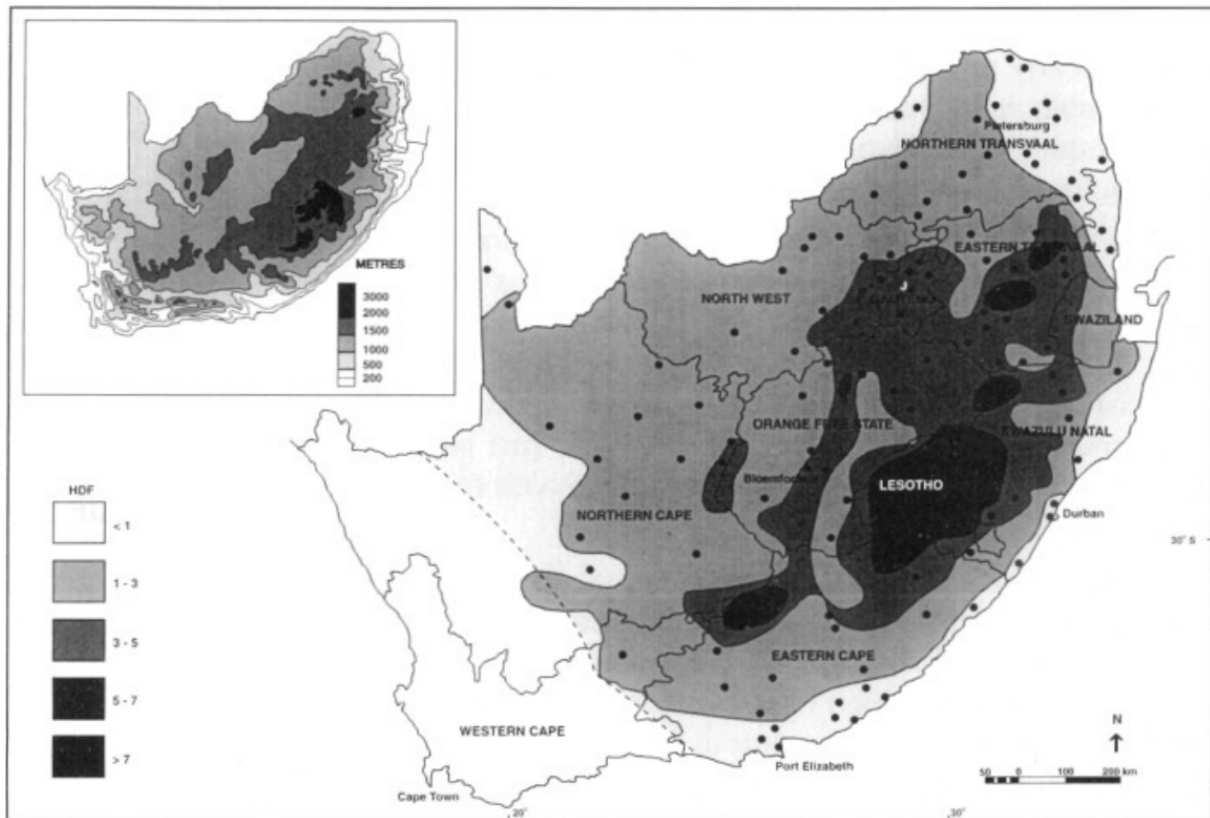
study revealed a slight relationship between the variables; a high HDF was more evident during the ENSO low phase and vice versa (see Figure 1.9). There was however several *event peaks* out of phases which Olivier and Van Rensburg (1995) attributed to several possible factors; (1) there is no statistical relationship between the variables, (2) non-linear negative relationship between the variables or (3) a lack of quality in the datasets. A more recent examination by Blamey et al. (2016) also found no statistically significant correlation between ENSO and environments associated with convective events. However, the study only investigated the relationship between a limited set of variables and further research can possibly provide insight into the correlation between ENSO and environments suitable for severe storm development. Both studies have several uncertainties, however, Olivier and Van Rensburg (1995) study indicates that a further examination between the occurrence of hail events and ENSO/SOI warrants further research.



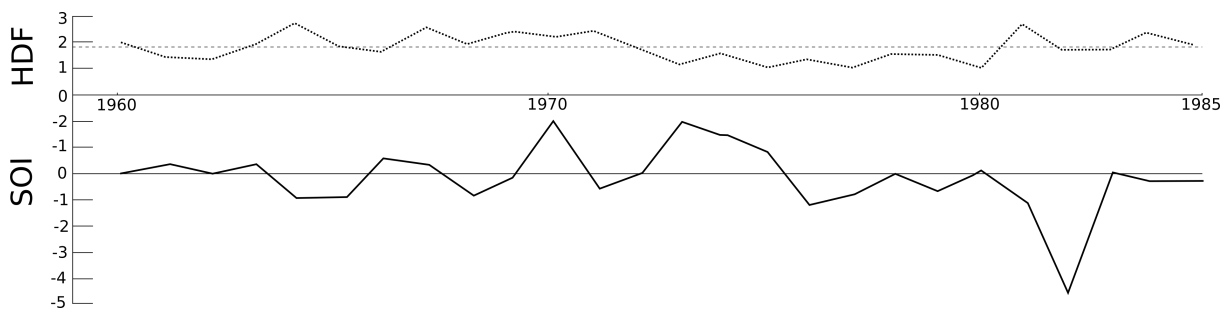
**Figure 1.6:** The HDF monthly distribution over the Highveld after Carte and Held (1978) shows the peak occurrence of hail in spring and summer months, while the largest hailstones ( $\geq 3$  cm) are generally observed October, November and January.



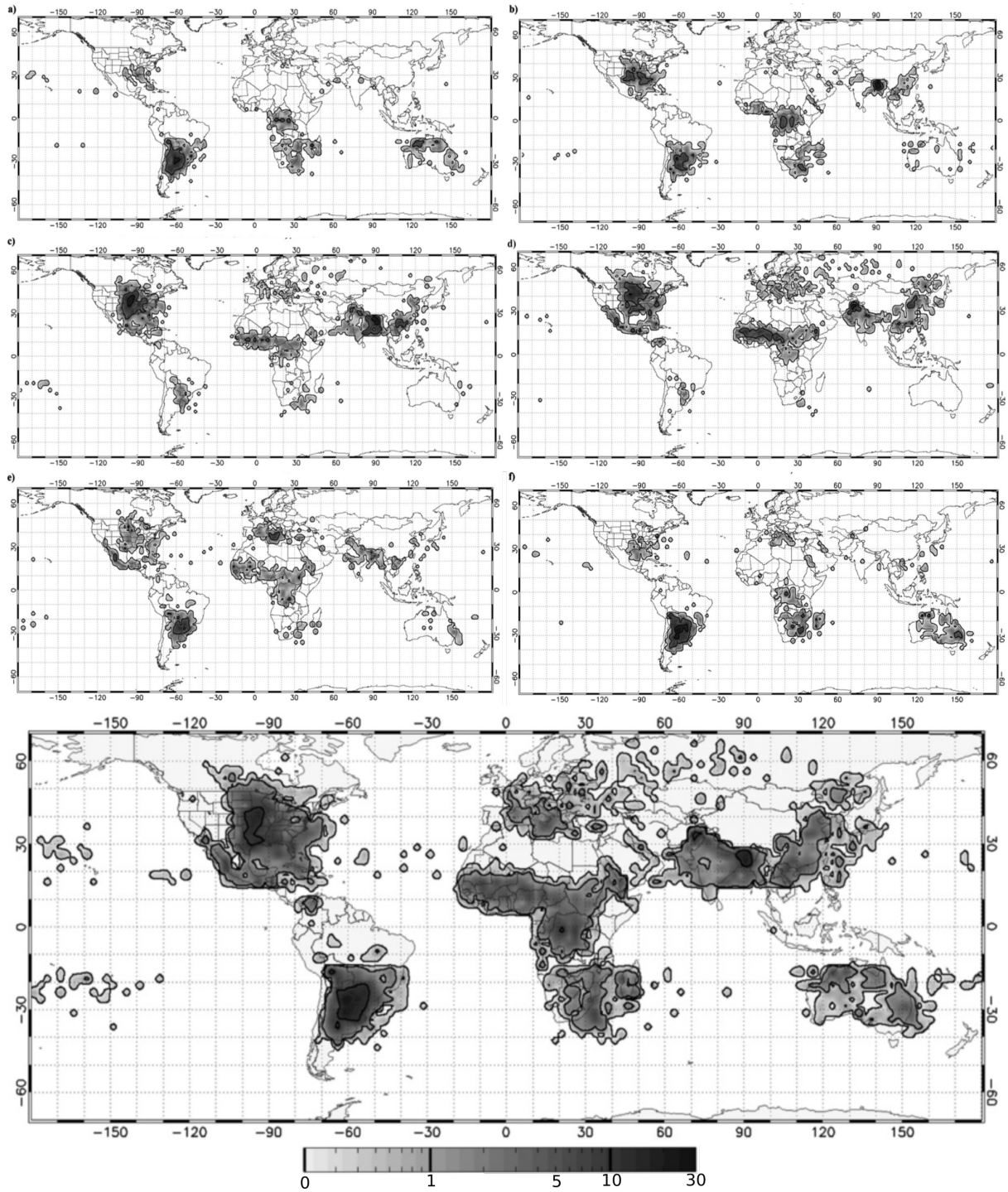
**Figure 1.7:** HDF and thunderstorm relationship adapted from Schulze (1965); Tyson and Preston-Whyte (2000). The relationship between hail and thunderstorms is prominent, both events are associated with a convective favouring atmosphere and occur under the same circumstances.



**Figure 1.8:** The HDF map from Le Roux and Olivier (1996) indicates the spatial distribution of hail over South-Africa. Data was recorded from rainfall stations around the country and shows that there is a high occurrence of hail over the interior of South-Africa. The highest HDF is around the mountainous region of Lesotho, but the area has a low population density and storms typically result in less economic damage compared with the industrial Highveld.



**Figure 1.9:** The relationship between SOI and haildays from 1960 to 1985 adapted from Olivier and Van Rensburg (1995). The Figure shows that there is a relationship between ENSO/SOI and HDF over the Pretoria – Witwatersrand area, a low ENSO phase is associated with a higher HDF and vice versa over the area.



**Figure 1.10:** Time series distribution of hail around the world from ARMS-E remote sensing observations after (Cecil and Blankenship, 2012). The Figures are ordered monthly; a - January/February, b - March/April, c - May/June, d - July/August, e - September/October, f - November/December. The Bottom Figure indicates the yearly average distribution. A high occurrence of hail is visible across central South-Africa and over the mountainous region of Lesotho, especially during November, December, January and February, this supports the spatial and temporal distributions observed by Le Roux and Olivier (1996); Schulze (1965); Tyson and Preston-Whyte (2000). Gauteng is economically important to South-Africa, as such the area is densely populated and hail events often result in extreme damage over the region. Locations in the tropics, South and Western Africa receive similar amounts of hail events, while other areas in the mid-latitudes in the Northern and Southern Hemisphere also exhibit a high HDF.





**Figure 1.11:** The highly convective Cumulonimbus cloud is the source of localized flooding and hail around many parts of the globe, including the Highveld. In this photo we can see a pileus cloud forming over the cumulonimbus cloud, the pileus cloud is often associated with the strong updrafts observed during convective events (Rosenfeld et al., 2006). Photo: Henno Havenga.

## Applying NWP to predict meso- $\gamma$ scale features

Although the idea behind NWP was already conceptualized in 1904 by Vilhelm Bjerknes the lack of computational technology at the time limited development. Lewis Fry Richardson later theorized the workflow necessary for a NWP system and developed a horizontal grid system similar to modern systems in use today (Kimura, 2002). Richardson envisioned *forecast factory* where 64,000 people acting as calculators would form a NWP system (Charlton-Perez and Dacre, 2011). Luckily Richardson didn't have to find 64,000 people because in 1946 the Electronic Computer Project was put into place by John Von Neumann at the Institute for Advanced Study (IAS) and by 1958 the first operational model, a single level barotropic model was brought into service (Shuman, 1989). The following year (1959) Japan introduced its own NWP infrastructure (Kimura, 2002) and these early advances set the tone for further development of NWP infrastructure. South-Africa followed suit not long after. The first NWP was in development in the 1960s and operational by 1970 (Schulze, 2007; Triegaardt, 1962, 1965). More recently Engelbrecht et al. (2007) developed South-Africa's first non-hydrostatic model.

In the simplest of functions the prediction of weather can be represented by the equation

$$\frac{\partial X}{\partial t} = F(X) \quad (1.5)$$

where  $\partial X$  represents the change of a given variable at a specific point in space,  $\partial t$  the change in time and  $F(X)$  the cumulative effect of processes that change the value of  $X$ . From this basic equation we can calculate meteorological variables change in time by including the variable's initial condition and calculating the force acting upon the variable over a given time period, this is written as:

$$X^{forecast} = X^{initial} + F(X)\partial t \quad (1.6)$$



NWP differs between the resolution the atmosphere is modeled on. Generally Global circulation models (GCM) resolve large scale circulation patterns very well, historically global models lacked vertical approximation and needed parameterizations schemes to resolve fine scale features. Today numerical models are based on the primitive equations describing the state and changes in the atmosphere by using equations for conservation of motion, energy, mass and moisture (Tyson and Preston-Whyte, 2000). The non-hydrostatic approach to weather and climate modelling is a relatively new and evolved with the advancement of computational resources. Non-hydrostatic equations allow NWP models to simulate mesoscale phenomena such as convection with better accuracy at high resolutions and retain a complete representation of the Coriolis force (Saito et al., 2007). Throughout the development of NWP models the resolution of models have consistently increased as computing power and efficiency has increased, Regional Climate Model (RCM) allowed scientist to simulate regional scale events. RCM have been improved upon and in recent years as models have become able to simulate events at convective scale (Prein et al., 2013). South-Africa recently introduced its own high High-Performance Cluster (HPC) in Cape Town powerful enough to run high resolution Convection Permitting Model (CPM). Community models are further improving access to advanced weather models capable of simulating events at high-resolutions and allowing researchers to implement their own run time operations and modifications. WRF is the one such model that has shown success with high resolution simulations and the model is implemented in this study to simulate case studies of extreme hail events.

## **The Weather Research and Forecasting Model**

WRF was developed as a community model by NCAR for the simulation and forecasting of regional weather (Bukovsky and Karoly, 2009). The model was created to improve the previously used Mesoscale Meteorological Model Version 5 (MM5) and the Eta-NWP model. The model is a non-hydrostatic, fully compressible and terrain following sigma coordinate model. WRF can be used for idealized simulations, parameterization research, data assimilation, forecasting, real-time numerical weather prediction, hurricane research, air-quality modelling, ocean-atmosphere coupling and regional climate research (Skamarock et al., 2008).

Using WRF to simulate severe storms has produced positive results in previous studies. Kumar et al. (2008) applied WRF to simulate a severe rainfall event in Mumbai 2005 which led to large economic and human losses for the region. The operational models used couldn't provide an accurate forecast at the time and contributed to the loss suffered. WRF was able to reproduce the storm and identify factors contributing to the development of the storm. Berthet et al. (2013) applied WRF to examine the climatology of hail in the South-West of France and was able to successfully examine conditions leading up to hailstorms in the region through WRF Berthet et al. (2013) found simultaneous low-level, mid-level and high-level forcing and the presence of low pressure systems over Portugal and/or Ireland contributes to severe hail for the area. WRF research over South-Africa has been more focused on rainfall, much like other meteorological research over South-Africa (Olivier and van Rensburg, 1992). Work by Cr  tat et al. (2012); Maisha (2014); Nikulin et al. (2012); Ratna et al. (2014); Ratnam et al. (2013) mainly focused on assessing the ability of WRF to simulate precipitation over the sub-continent. The work of Ratna et al. (2014) provides valuable insight into the way convective parameterizations are resolved over South-Africa. Because cumulus parameterizations are major source of error in models this is useful to understand the uncertainties associated with particular schemes.

WRF has several other advantages; the model has the ability to run at high resolutions, provided adequate computing resources. This allows the model resolve weather features at various scales. Various parameterization schemes are also available to users, and users have the advantage of using accessing WRF source code and applying their own configurations as necessary.

### **WRF as a convective permitting model**

Traditionally three major scales existed in atmospheric modelling; (1) global, (2) regional and (3) mesoscale models (Figure 1.12). These scales are also simulated by models bearing a similar name; GCM, RCM and mesoscale

meteorological model (MMM) respectively. Further improvement in computer resources led to the development of CPM where deep convection within the atmosphere is modeled explicitly without convective parameterization schemes. The method is applied on scales  $\leq 4\text{km}$  – the lower meso- $\gamma$  and the upper micro- $\alpha$  as described by (Orlanski, 1975). According to Weisman et al. (1997) parametrizing convection is a must when model resolutions exceed  $20\text{km}$ . Prein et al. (2013); Segele et al. (2013) states that at resolutions between  $8\text{km}$  -  $12\text{km}$  convection is still reasonably well simulated by parameterization schemes, but under  $4\text{km}$  resolutions deep convection parameterization schemes has been shown to account for large errors within models (Prein et al., 2015; Segele et al., 2013; Trapero et al., 2013). Convective permitting models are useful to accurately simulate storms that result in hail (Cao, 2008). CPM is as of yet an unexplored field in South-African research on severe weather (Blamey and Reason, 2013; Eckardt et al., 2013; Halder et al., 2015).

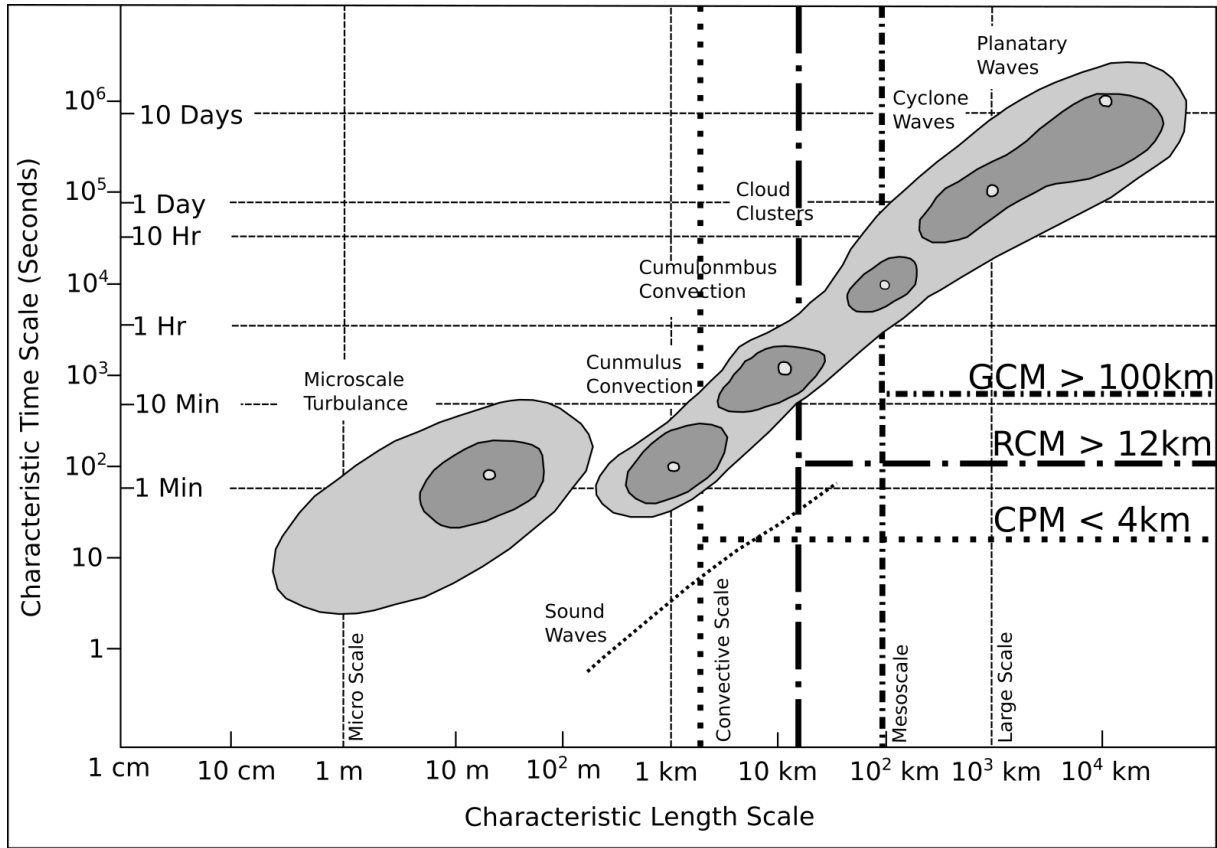
According to Prein et al. (2015) four types of CPM models currently exist, each with its own approach and application to different scales in the atmosphere. The first approach, which is used in this study, is known as the limited area modelling where a specific area is selected for the simulation, this area is usually consists of a larger parent domain over a smaller nested domain e.g. a province covering a smaller municipality. This allows the model to downscale input data from the parent to the nested domain. This approach is particularly useful for simulations of severe weather events (Prein et al., 2015). The second approach is a global CPM approach where integration or downscaling from the convective to global scale occurs (Prein et al., 2015). This requires massive computational resources to run such as model, however, (Prein et al., 2015) predicts that this may well change within the next decade with the rapid increase in computational power. The third approach also attempts to incorporate CPM into a global circulation model, but instead utilizes *superparameterizations*, the computational cost of this approach still exceeds more traditional GCM's but according to Prein et al. (2015) it is  $10^6$  less computationally expensive than the second approach. Similar to the limited area modelling approach, the forth CPM technique utilizes stretched-grid domains. This allows for an area with a higher grid-spacing to be nested within the model, the larger area is usually lower in resolution which increases computational efficiency.

CPM simulations have seen limited use in Africa and South-Africa. From a South-African perspective this could be due to the lack of computer resources before the recent introduction of the Center for High-Performance Computing in Cape-Town. Prein et al. (2015) mentions two CPM studies over Africa, one over Kilimanjaro (Mölg and Kaser, 2011) and the other over West African (Lauwaet et al., 2010). Mölg and Kaser (2011) downscaled his model run from  $39\text{km}$  to a convective scale of  $813\text{m}$  over the Kilimanjaro region. Although Mölg and Kaser (2011) focused on glacier-atmosphere interactions, the success of his high resolution study is encouraging for other areas of atmospheric research. Over South-Africa Engelbrecht et al. (2007) introduced the Non-hydrostatic Sigma Model (NSM) using convective parameterization schemes at resolutions where convection can be partially resolved. Convective scale assessments on severe storms over South-Africa is clearly a field with potential for research development to better understand severe weather events.

### **The role and interactions of parameterization schemes**

Due to the complexity of the atmosphere the direct simulations of physical processes are difficult. Simplifications of these processes are made in order to make models computationally effective especially when these processes occur on a sub-grid scale known as parametrization (Stensrud, 2009; Tyson and Preston-Whyte, 2000). WRF has a database of several schemes ranging from simple, computationally inexpensive schemes to complicated, resource expensive schemes. Processes resolved by parameterization schemes in WRF include microphysics, short and long wave radiation, convective processes, Planetary boundary layer (PBL) and land surface processes.

The parameterization of hail requires some special considerations; parameterization schemes must be able to distinguish between hail, snow, freezing rain and other ice species. Progress has been made with the development of CPM models and models are able to represent the different hydrometeor species better, however, convective events remain hard to simulate. According to Sanderson et al. (2015) parameterization schemes usually over- or underestimate hail during severe storms as convective parameterizations are not able to distinguished hydrometeors at this scale accurately. Improvement is observed when omitting convective schemes and allowing models

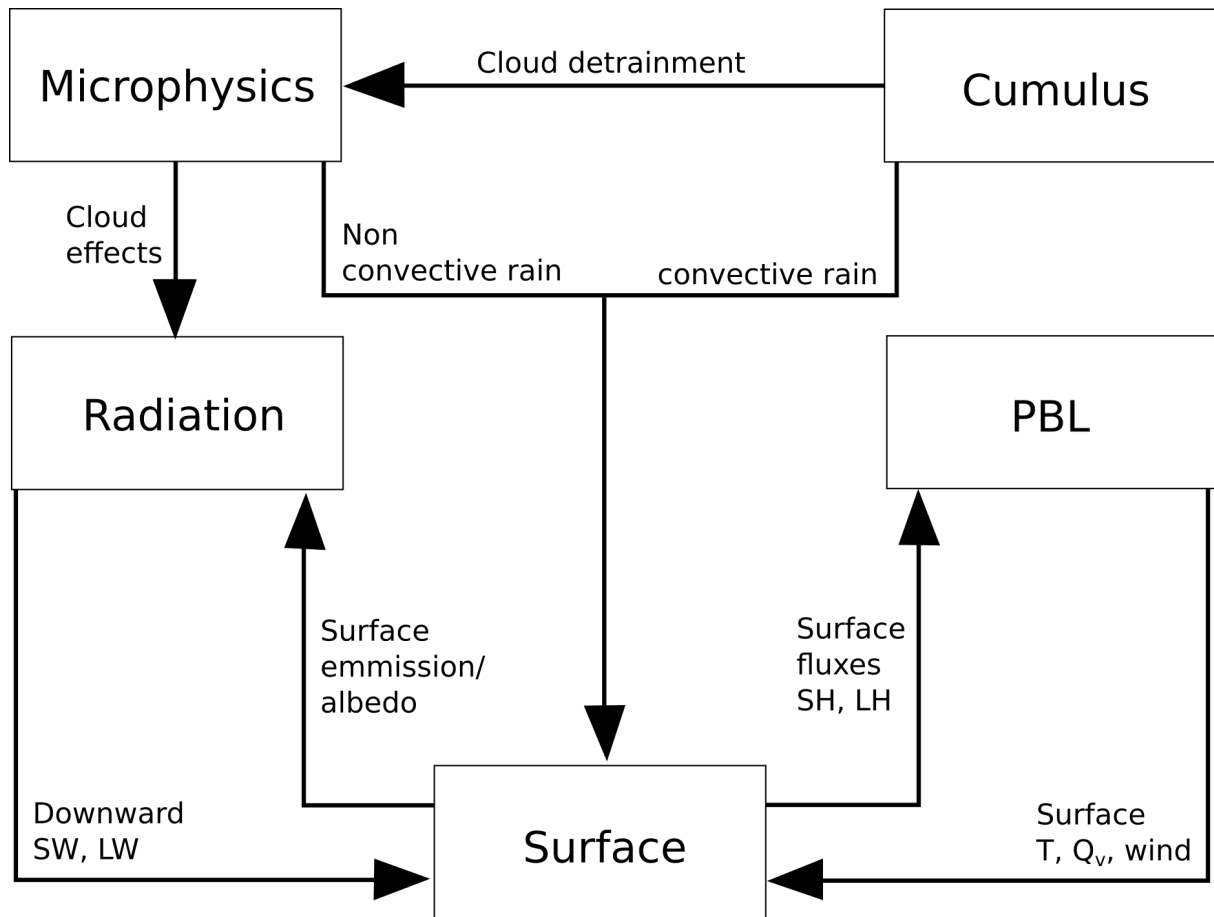


**Figure 1.12:** Adapted from Prein et al. (2013), the Figure shows the spatial and temporal scales within atmospheric modelling: GCM ( $>100\text{km}$ ), RCM ( $>12\text{km}$ ) and CPM ( $<4\text{km}$ ). Parameterizations play an important role in numerical models. When a feature occurs on a sub-gridscale within the model it is necessary to parametrize the feature to accurately represent it. With the improvement in computer resources the resolution that can be achieved with NWP has increased. Convective permitting models are the most recent of these, when modelling at scales of less  $<4\text{km}$  CPM is advantageous to model convection explicitly. The inserts in the Figure indicate processes that typically occurs within a certain atmospheric scale, microscale turbulence, cumulus convection, cumulonimbus convection, cyclone waves and planetary waves

to explicitly simulate storms. Parameterizations interactions are an important consideration during model setup as the processes resolved are interlinked, see (Figure 1.13). A brief description of the important parameterizations and their basic functions follows in this section. The full physics of the schemes selected for this study is discussed in the data and methods section.

### Microphysics parametrization in WRF

Microphysics parameterization allow models to solve processes related to the evolution of particles such as ice, rain, snow, graupel and also the aerosols impact on cloud formation. This plays an important role in the representation of short lived events such as convective storms, but the complicated nature of such events and the underlying processes account for a major source of uncertainty within models (Halder et al., 2015; Lee and Hong, 2005; Stensrud, 2009). Differentiating between hail and other ice species is based on assumptions on air temperature, freezing levels, cloud levels and droplet size. Generally water vapor is allowed to change form following an auto-conversion table and depending on the temperature the water vapor can either condensate, freeze, sublimate or ice and water particles can coexist within a cloud. Depending on the vertical profile and position in a cloud various of these forms exists and consistently change form. Assumptions are then made on how these particles interact individually and with each other in different conditions. The microphysics scheme must be able to solve Bergeon process, coalescence-collision and the phase change from liquid to ice and back to liquid again as the particle moves (Stensrud, 2009; Thompson et al., 2008; Wobrock et al., 2003). A full explanation of the physics for the scheme used in the study is described in the data and methods section.



**Figure 1.13:** WRF has a database of several parameterizations available to users. The most important of these are the microphysics, radiation, cumulus, land-surface and planetary boundary layer (PBL) schemes. The parameterizations simplify processes within WRF that occurs on a sub-gridscale and are not explicitly modeled, but these parameterizations account for uncertainties within WRF and other numerical models. The ability to explicitly model convection has improved models but there are still various other processes that occur on a sub-gridscale that requires parametrizing (Dudhia, 2014).

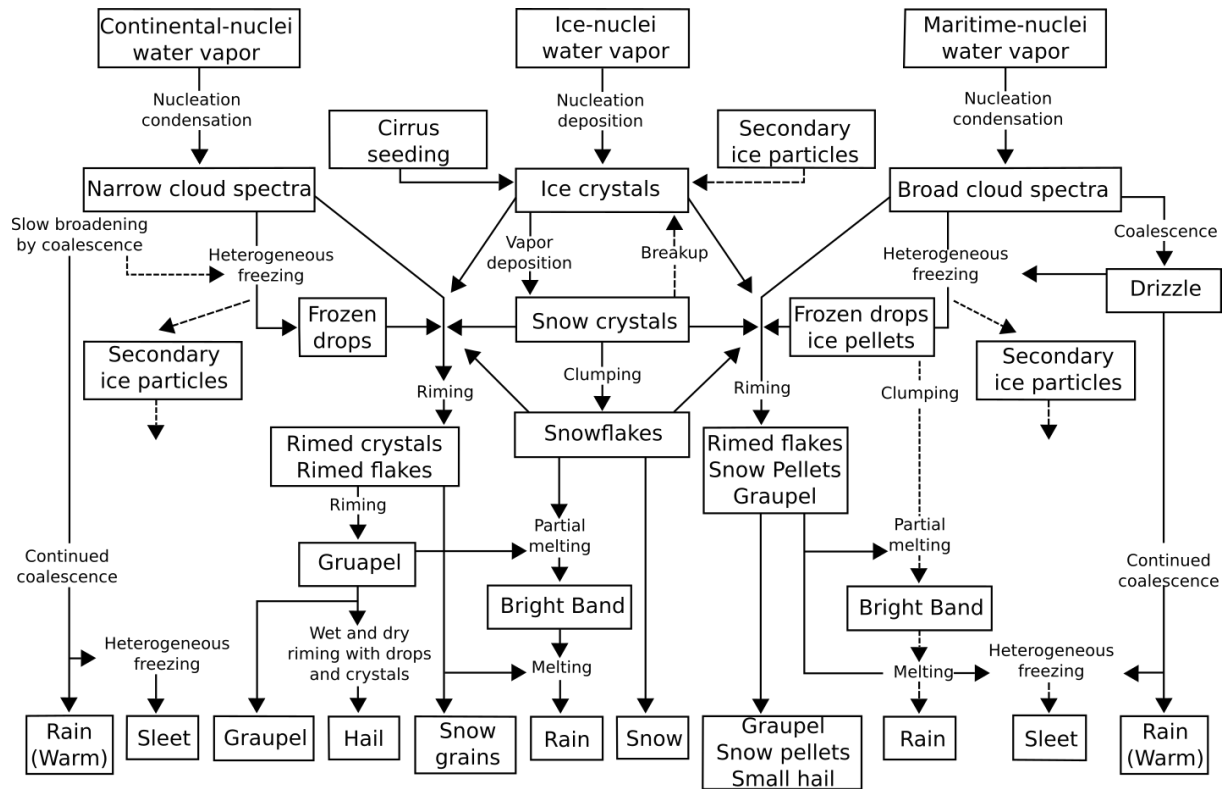
WRF has a total of 17 Microphysics schemes included available to the user, depending on the computational resources and processes the user is interested in simulating. Microphysical processes interact with the other physics in the model, changes in altitude, radiation, temperature and topography all have an effect on cloud forming processes (Skamarock et al., 2008). Figure 1.14 (Dudhia, 2014) indicates various physical processes that the microphysics schemes have to resolve within models.

#### Short and long wave radiation parametrization in WRF

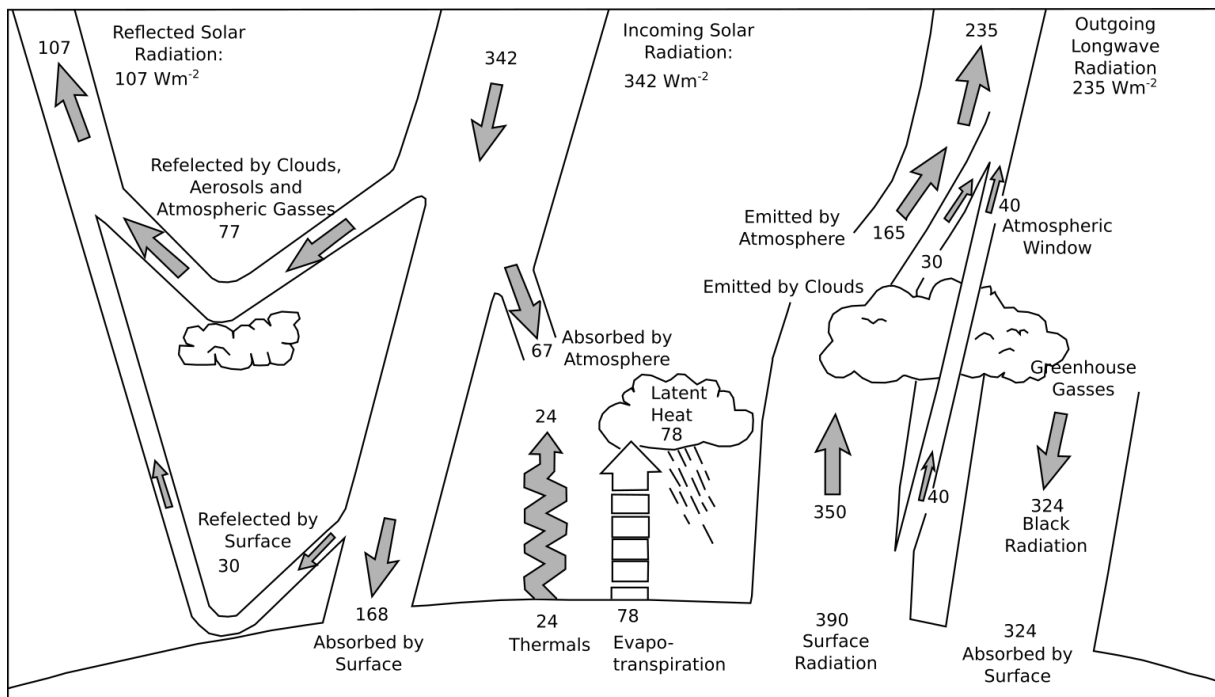
According to Stensrud (2009) radiation is the main driver of atmospheric circulation patterns around the world. Along with microphysics parameterizations radiation schemes are computationally more expansive than other parametrizations (Thompson et al., 2016). WRF allows the user to select between incoming shortwave and outgoing long wave radiation schemes, and has 8 and 6 schemes available to users respectively. The radiation schemes have to incorporate functions for absorption and scattering by different particles and aerosols present in the atmosphere. The radiation scheme also interacts with clouds, vegetation, snow and soil parameters to define albedo, absorption and scattering. This in return impacts surface heating and the evolution of PBL, crucial to cloud formation and surface atmosphere interactions (Gero et al., 2006), see Figure 1.15.

#### Land surface model

Land Surface Model (LSM) allows numerical models to include surface energy, water budget, vegetation, green fraction, soil, sub soil properties and their interaction with atmospheric processes in simulations. These processes



**Figure 1.14:** A representation of the microphysical processes parameterized in the WRF model after Dudhia (2014), are important to represent different particles, their formation and interaction with each other in the atmosphere. Particles are never in a fixed form and as such microphysics schemes have to be able to represent this form change often multiple times over.

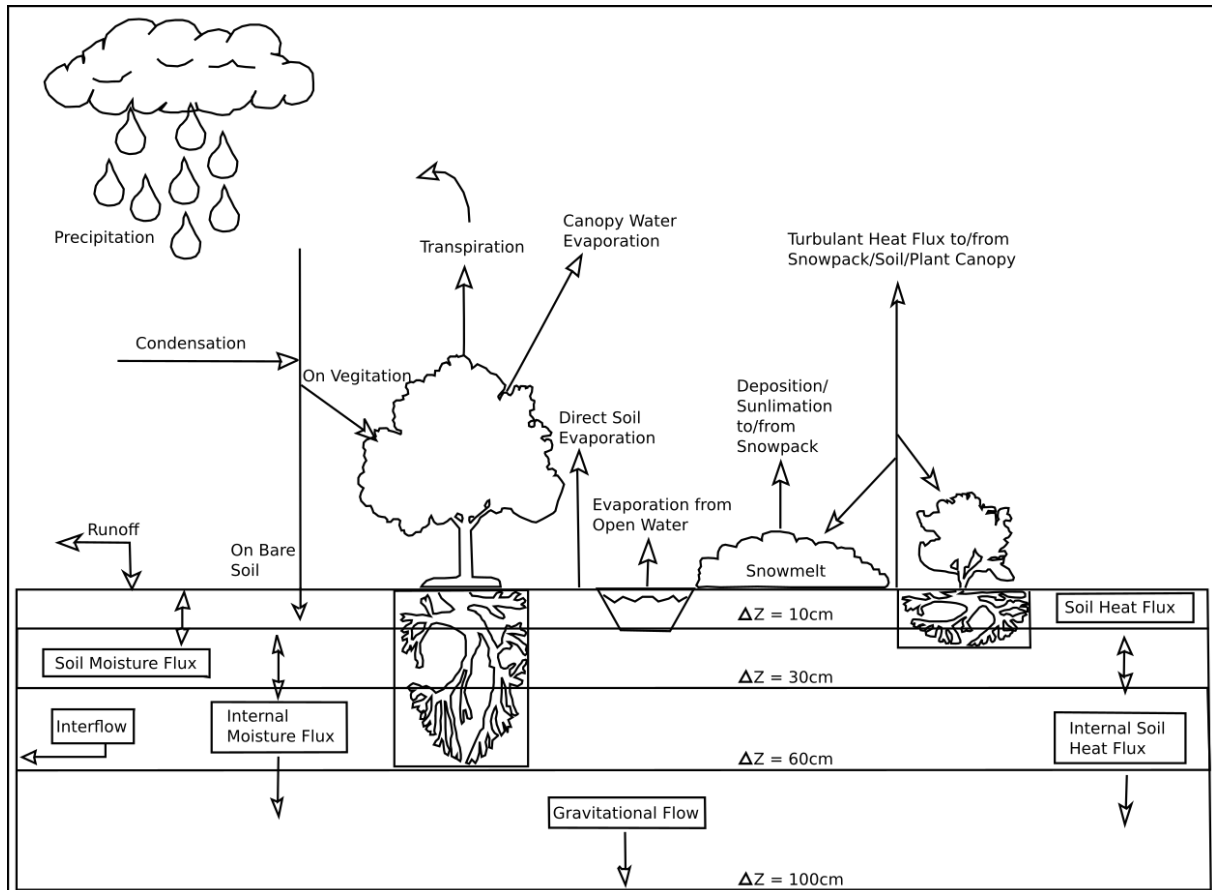


**Figure 1.15:** The earth's energy budget adapted from IPCC (2007) indicates the processes resolved within the Radiation scheme. Incoming and outgoing radiations as well as their interaction with the land surface scheme and clouds, especially cumulus clouds, plays a crucial part in the formation of the PBL's diurnal variation and convective storms.

influence radiation, evaporation, transpiration, surface temperature and albedo properties and play an vital role in general circulation as well as mesoscale and regional models (Chen and Dudhia, 2001a). Land-surface processes

are crucial to the evolution of the PBL and the diurnal heating and cooling and topography of the earth surface are factors that impact the PBL, discussed in the following paragraph section (Burger, 2016).

In WRF the LSM allows for inputs from radiation, the microphysics and convective schemes (see Figure 1.16 ). Land surface processes play a major role in the realistic simulation of the PBL; heat and moisture fluxes over land provides the lower boundary conditions for the vertical transport within the PBL. WRF has 7 LSM options for users, ranging from simple schemes with only soil characteristics to advanced schemes providing hydrological, soil and vegetation output (Skamarock et al., 2008). WRF also provides an urban canopy model to represent urban processes such as street canyons, building radiation and reflection and heat equations from roofs, walls and road surfaces (Skamarock et al., 2008).



**Figure 1.16:** Schematic representation of processes represented in LSM, adapted from Chen et al. (2010). LSM process play an important role in the formation of the PBL due to diurnal surface heating and cooling and has to account for surface properties including variations in heating, cooling, absorption and albedo from different vegetations types and soils.

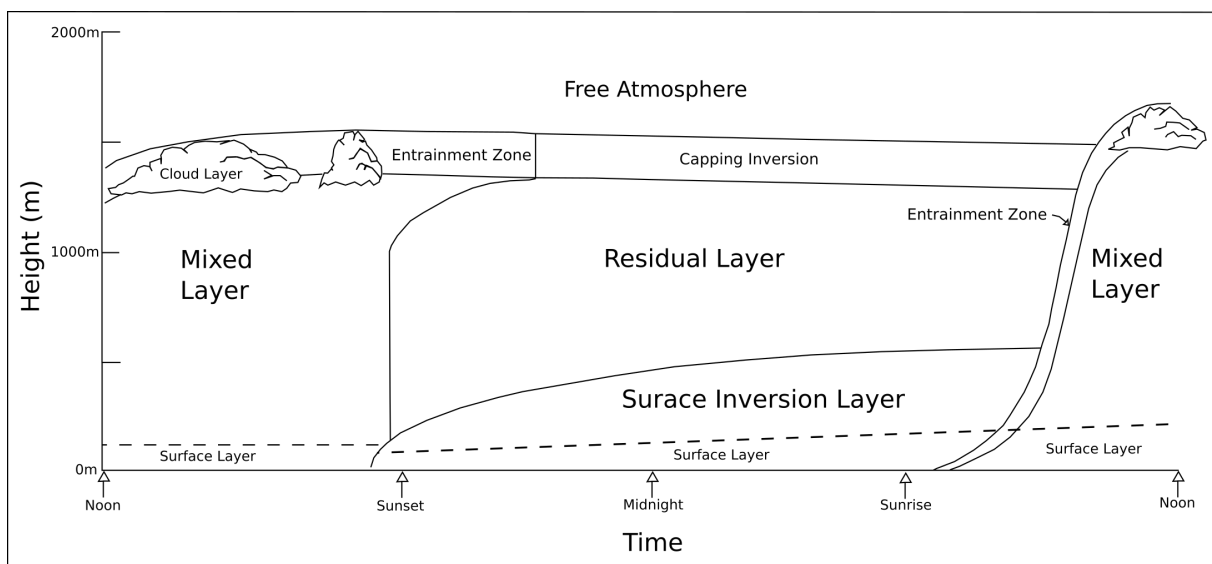
### Planetary boundary layer parametrization in WRF

The PBL represents the first part of the troposphere in contact with the surface. In this layer convection, momentum, heat and moisture transport occurs from the land-surface to the atmosphere on various spatial and temporal timescales. Due to this spatio-temporal variation the PBL could be several kilometers deep to a few meters shallow depending on topography, albedo and moisture availability while interactions between the surface and the PBL occurs on a timescale of  $\leq 1$  hour (Burger, 2016; Cohen et al., 2015; Stensrud, 2009). The PBL plays an important role in initial formation of convection and subsequent thunderstorms from which hail usually occurs (Madala et al., 2014; Stull, 2012).

PBL schemes parameterizes the vertical diffusion and vertical sub-grid scale fluxes due to eddy transports. The PBL derives surface fluxes from the LSM and determines the flux profiles within the mixed layer and the stable

layer providing temperature and moisture tendencies within a vertical column (Skamarock et al., 2008). Because the PBL's temporal scale and interactions with the LSM and other parameterizations is  $\leq 1$  hour the diurnal cycle plays an integral part of the PBL's evolution as illustrated in Figure 1.17. The PBL goes through various stable and unstable phases as the day passes, the layer is in a stable condition during evenings and as the surface begins to warm up after sunrise when heat and moisture fluxes start to impact the structure of the PBL and some instability occurs. As the day goes on this energy increases which increases the PBL height, this occurs within the mixed layer. Above this layer the temperature inversion usually occurs; a increase in potential temperature with a increase in height (Burger, 2016; Stensrud, 2009).

The PBL is more stable over South-Africa during winter when there is a prevailing anticyclone over the subcontinent. Simulating the processes of the PBL requires parametrization within NWP models, as many microscale phenomenons occur within this layer. According to Burger (2016) some processes are modeled explicitly but small scale phenomenons such as turbulence is approximated within parametrization schemes instead. WRF has 13 PBL parametrization schemes allowing the user to select between local and non-local schemes. Non-local schemes require more computer resources but have been shown to represent deep PBL circulation with more accuracy than local schemes.



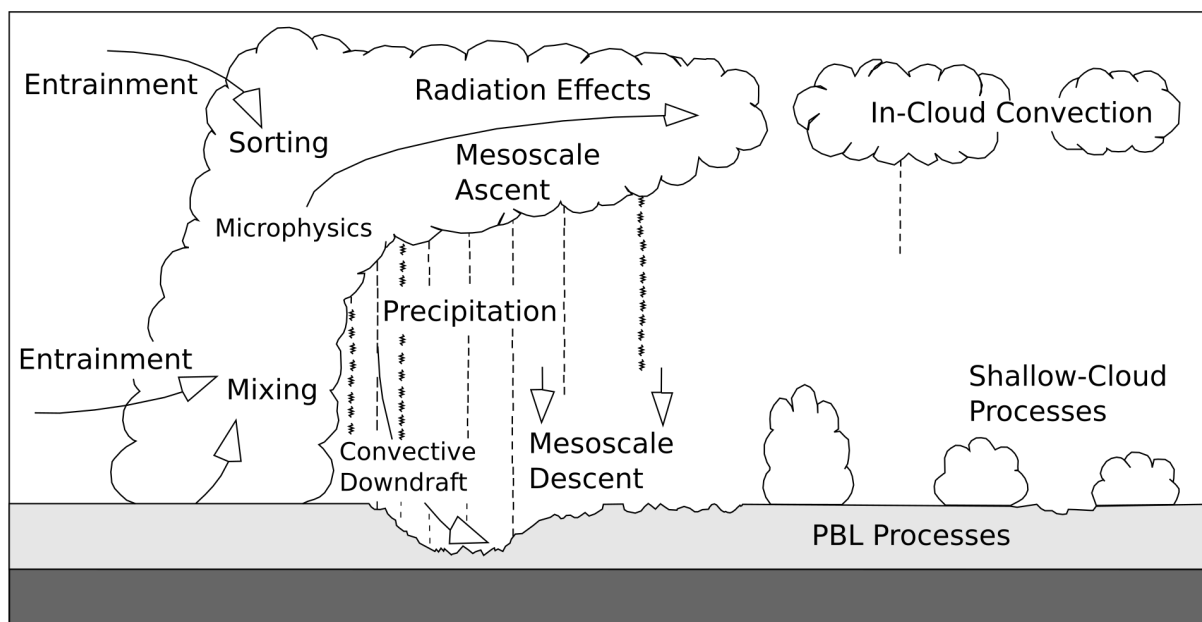
**Figure 1.17:** Simplification of the diurnal evolution of the PBL structure, adapted from (Stull, 2012). The PBL represents the first part of the troposphere. This means the PBL is in interaction with land-surface processes, which in return effects heating, cooling and fluxes within the layers. The PBL's temporal scale is in the order of  $< 1$  hour and the interactions with the land-surface means the PBL plays an important role in convective formations.

### Cumulus/convective parameterization in WRF

Cumulus/Convective parameterizations is used to represent convection at a scale where it could not be resolved explicitly within models due to the computational cost and time constraints (Engelbrecht et al., 2007; Skamarock et al., 2008), however, interactions between the cumulus scheme and other physical processes in the atmosphere results in large uncertainties within NWP models. The importance of the cumulus/convective processes in the atmosphere and for accurate modelling is emphasized by Arakawa (2004) as he states that clouds are perhaps the most important forcing in our atmosphere. The accurate parametrization of clouds and convection is crucial to describe various climate system interactions. This means that the use of parametrization schemes with known uncertainties and limitations is unavoidable in many cases especially when simulating at scales  $\geq 4$ km. Figure 1.18 (Arakawa, 2004) illustrates the different characteristics that have to be accounted for in cumulus parameterizations, this includes and is not limited to PBL and microphysical processes such as lower level moisture convergence, turbulence mixing, heat exchange and radiative properties of clouds (Cr  tat et al., 2012; Fadnavis

et al., 2014; Skamarock et al., 2008). According to Arakawa (2004) shallow clouds can be seen as part of convection processes, this means that PBL and cumulus schemes must be unified accordingly to achieve greater results but this is also the source of uncertainties within models (Arakawa, 2004). According to Dedekind et al. (2013); Nikulin et al. (2012) convective parameterization is not able to reproduce several key aspects related to rainfall over South-Africa accurately.

As mentioned a relatively new field of study is the use of CPM to simulate events on a resolution of  $\leq 4\text{km}$  (see Figure 1.12), allowing for convective processes to be explicitly resolved by models. This removes some of the uncertainties related to the parameterization of convection (Prein et al., 2015). No study related to South-Africa has assessed cumulus parameterizations' relation to severe storms and subsequently no convection permitting studies have been done on hailstorms either. WRF includes 13 cumulus parameterization options for users to choose from. The combination of parameterizations play a major role in the representation of convection. Cr  tat et al. (2012) stresses that the choice of particular scheme can be counterbalanced by another for instance the combination of different cumulus and PBL schemes.



**Figure 1.18:** A simplified adaption of convective processes from Arakawa (2004) is shown in the above diagram. Parametrizing convection is a major source of uncertainty within models because these features are usually sub grid scale and have to rely on parameterizations but it is possible to omit the parameterization in what is known as CPM. The benefit of CPM is that convection is modeled explicitly leading to greater results but this means the resolution of models have to be set to  $\leq 4\text{km}$  which makes models computationally expensive.

## An overview of macro- $\beta$ classification techniques

Weather and climate is dependent on large scale atmospheric circulation patterns known as synoptic circulation. To understand synoptic circulation patterns the field of synoptic climatology was developed in the early 1940's. Initially the term synoptic climatology was coined by the USA military air-force during World War II (WWII) and Court (1957) explains that the original definition was developed as a way to *conveniently* index the historical weather types of a region. This classification was related to the air-flow, the pressure field, air-mass and map patterns associated with a specific region. Barry (1980); Yarnal (1993) build upon this definition later on, both emphasized that synoptic climatology is an attempt to link large scale circulation patterns with the local weather experienced in a region. A clear definition of the spatio-temporal scale of synoptic patterns was first defined by Orlanski (1975) as falling within the macro- $\beta$  circulation range (see Table 1.1). The link between synoptic circulation and local/regional weather has since become an important field of study for forecasters and atmospheric



researchers. This led to the development of synoptic classification techniques<sup>1</sup> to study synoptic scale circulation associated with surface weather (Cahynová and Huth, 2014; Demuzere et al., 2011; García-Ortega et al., 2011; Jiang et al., 2012). Clustering can be defined as *grouping of entities so they share common features within each group* (Huth et al., 2008; Sheridan and Lee, 2011). A distinction must be made between weather classification, air mass classification and synoptic classification. Weather classification refers to a method using only near surface variables from a single or a few sites. Air mass classification uses various data sets from different levels in the troposphere and the surface. Synoptic classification, as used in this study, deals with circulation patterns over large areas on one or two levels in the atmosphere (Huth et al., 2008). It is also a useful tool for weather forecasting purposes and climate model validation (Philipp et al., 2014). The history of atmospheric circulation classification is well documented in a report by Huth et al. (2008).

Various procedures exist to perform the synoptic classification. Huth et al. (2008) divides these into three basic groups, namely subjective (manual), mixed (hybrid) and objective (automated, computer assisted). Although Huth et al. (2008) uses the term *computer assisted* the author notes the term is not adequate as a number of subjective decisions have to be made when an objective cluster analysis is compiled (Huth et al., 2008; Sheridan and Lee, 2011). To apply a clustering method effectively other research uses a two-step procedure. First a Principle Component Analysis (PCA) is applied to data with the aim to reduce the data dimensions. This is generally followed by a second clustering method to group the data into a final number of clusters. Careful considerations have to be taken into account when performing a cluster analysis as the over fitting of data might result in unrealistic clusters created and to avoid this a limited number of variables is usually selected (see Table 1.3), the uncertainty is further reduced by applying the two-step procedure to increase the accuracy of the cluster groups (Fraley and Raftery, 1998; Jolliffe and Philipp, 2010).

Due to the high variability of hailstorms there has been limited research on synoptic weather classifications of hail days. Attempts to understand specific synoptic links resulting in hailstorms over the Highveld has been made by Held and Carte (1979); Olivier and van Rensburg (1992). Over South-Africa Self Organizing Maps (SOMs) and objective synoptic typing have been used to understand rainfall (Dyson, 2009, 2013; Dyson et al., 2015) and fog (Van Schalkwyk and Dyson, 2013). Recent research by Aran et al. (2011); García-Ortega et al. (2011); Hermida et al. (2015) examined atmospheric circulation patterns associated with hail days in Spain. Synoptic classification can be used to examine the trends of synoptic scale circulation patterns as in the case of Kapsch et al. (2012) who examined the occurrence of hailstorms over Germany and also possible future trends. Table 1.3 details the indicators used for examination of atmospheric patterns associated with hail in literature. As mentioned earlier the amount of variables used in a cluster analysis can create a situation where unrealistic clusters are formed. All the reviewed cluster analysis for hailstorms used between 2 and 3 variables (Aran et al., 2011; García-Ortega et al., 2011; Kapsch et al., 2012; Li et al., 2016).

Recently the Cost733class software package was created to compare, visualize and evaluate weather and circulation type classifications (Philipp et al., 2014). The software was developed for the *Harmonisation and Applications of Weather Types Classifications for European Regions* (Beck and Philipp, 2010; Demuzere et al., 2011). Schiemann et al. (2010) evaluated the software to resolve heavy rainfall events in the Swiss Alps and Cost733class automatic classifications yielded superior results compared to manual classifications, however, limited research on the application of Cost733class on hail exists presently. In a study by Li et al. (2016) Cost733class was used to examine atmospheric circulation patterns associated with hail days over China. Cost733class application dominates Europe with limited research in other regions, see (Li et al., 2016; Prein et al., 2016) for Cost733class related studies outside of Europe. The objective selection of certain variables described in literature as relevant to hail formation can greatly influence the output of the results. Synoptic classifications is a simplification of complex reality and no classification method should be considered an absolute truth (Huth et al., 2008; Jacobbeit, 2010).

<sup>1</sup> Also known as weather typing and/or synoptic typing

**Table 1.3:** *Clustering setup as applied in previous research by Aran et al. (2011); García-Ortega et al. (2011); Kapsch et al. (2012); Li et al. (2016).*

| Aran et al. (2011)           | García-Ortega et al. (2011)                         | Kapsch et al. (2012)                                                                                               | Li et al. (2016)        |
|------------------------------|-----------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|-------------------------|
| Mean Sea Level Pressure      | Geopotential Height at 500mb & Temperature at 500mb | Mean flow at 700hpa - calculated from wind direction                                                               | Mean Sea Level Pressure |
| Geopotential Height at 500mb | Geopotential Height at 850mb& Temperature 850mb     | Cyclonality in middle troposphere - calculated from the geostrophic vorticity in the pressure vertical coordinates | Geopotential height     |
| Temperature at 500mb         | Relative Humidity at 850mb                          | Humidity Index - calculated from precipitable water at 1000 and 500hpa                                             | -                       |

## Aims and objectives

This study aims to characterize hail events that occur over the industrialized Highveld and the Gauteng province of South-Africa by examining hail occurrence from the small local scale environment and linking this to the larger scale synoptic circulation. The data is used, along with media reports to evaluate the trends and cycles of hail events and the links to the SOI. To achieve this the following is investigated as part of the study;

1. the identification of meso- $\gamma$  scale indicators associated with severe hailstorms,
2. a characterization of the relationship between meso- $\gamma$  indicators and macro- $\beta$  scale patterns associated with severe hailstorms
3. and finally examination of severe hailstorms trends and cycles by analyzing historical records and the identified meso- $\gamma$  and macro- $\beta$  indicators and patterns respectively. The link between the macro- $\beta$  scale circulation patterns and the SOI is also investigated.

## Study design

Assessing the characteristics of the meso- $\gamma$  scale was conducted by selecting 5 extreme events that occurred over Gauteng, all the cases where associated with large hail while some events caused wide spread damage. To understand the storm environment upper-air soundings from the storm day was analyzed and once a picture of the atmospheric environment was formed WRF was initiated to simulate the selected cases. The model data is further evaluated and known links with severe storms, their evolution and occurrences across the cases are detailed. Within the scope of this study only certain indicators was selected to characterize the convective environment associated with hailstorms. Two model outputs where used; first the thermodynamic profile for the most unstable parcel as well as the corresponding hodograph and secondly the spatial representation for selected indicators at 12:00UTC. The 12:00UTC time step was selected as convective events occur after this time Merino et al. (2013). Next the macro- $\beta$  scale patterns associated with severe events is characterized<sup>2</sup>. In this study the Cost733class classification software (Demuzere et al., 2011) was used to perform a two-step clustering procedure; first a Hierarchical cluster analysis (HCA) is applied to the selected variables chosen followed by a K-means cluster analysis to group unclassified variables and determine the final position of variables within meaningful clusters (discussed in the following section). In the last objective the question, *what are the trends and cycles of hailstorms across the Gauteng and its major cities*, is answered by evaluating the links identified in the meso- $\gamma$  scale and how these

<sup>2</sup>NOTE:Macro- $\beta$  scale is also known as synoptic scale, these terms may be used interchangeably.

patterns have changed over time. The macro- $\beta$  scale synoptic patterns is examined to assess hail related synoptic pattern's change over time. Media and historical hail data is also revisited and analyzed to examine the extend of hail in a South-African and socio-economic context. The study concludes by investigating the link between synoptic patterns associated with hail events and ENSO.

## Limitations of the current study

Several uncertainties have to be mentioned as related to the current study. In objective one WRF was used to simulate several severe events that occurred over the Gauteng province with the goal to better understand the convective nature of these events. The selection of five events is a small sample size and not representative of all hail and convective events. In the context of this study it does provide an overview of the storm day environment, but the reality is that atmospheric and convective events occur under a variety of conditions and not all can be represented here. The next limitation is the subjective setup of the NWP model. WRF has a vast amount of parameterizations schemes and run time options and while the setup was based on previous research related to convection it was however beyond the scope of this study to evaluate the complete set of possible parameters that one can use in such a setup.

In objective two a clustering method was used to analyze the synoptic scale circulation patterns which required the selection of a clustering method and certain variables to drive the cluster analysis, all with some subjectivity. The results from the first objective was used to make an informed decision on the variable selection and reanalysis data was used as the data source. A variety of other variables could be used to drive the analysis and to gain a different perspective on the synoptic relationship between events. Media reports are used to evaluate hail occurrence within the different synoptic conditions, the data is used with the knowledge that a lot events go unrecorded in the media, it does however give an indication of these extreme event's occurrences.

The last objective relied on several data sources. Media reports where used to evaluate the occurrence of hail events with the knowledge that a large amount of events go unreported. To evaluate the trends and cycles of thermodynamic indicators data from the IGRA was used and although the IGRA does undergo a quality control procedure some uncertainties is associated with the dataset, this is noted in more detail in chapter 3.

# Chapter 2

## Data and methods

In this section the data sources and tools used to characterize hail events is discussed in more detail. The study area is clearly defined as the Gauteng province that lies on the South-African Highveld. The setup of the NWP model (WRF) and the input data to initialize the model is detailed as the selected method to analyze the meso- $\gamma$  scale environment. This is followed by a discussion of the synoptic classification clustering method related to the macro- $\beta$  scale environment. The chapter ends with a discussion on the analysis of the trends associated with hail events over Gauteng through the use of media reports and a Theil-Sen trend analysis on data from the IGRA dataset on indicators related to convective storms.

### The Gauteng province of South-Africa

The study area is located in the South-African interior plateau known as the Highveld. At a mean altitude of 1500 m - 1700 m above sea level and covering an area of 30 000 km<sup>2</sup> (Freiman and Piketh, 2003), the Highveld extends across several provinces in South-Africa; the Free-State, Gauteng and Mpumalanga. The region is the location of some of Africa's most industrialised areas and accounts for 75% of South-Africa's industrial activities. Around 70% of the Highveld is covered by grasslands and utilized for agriculture (Collett et al., 2010; Scheifinger and Held, 1997).

The Gauteng Province (hereafter Gauteng) is the main area of interest in the study. Gauteng is divided into three metropolitan municipalities (City of Tshwane, City of Johannesburg and the City of Ekurhuleni) and two district municipalities (West Rand and Sedibeng) which is further divided into eight local municipalities. The region forms an integral part of the South-African economy accounting for around 34% of South-Africa's gross domestic product (GDP) and with a population of over 12 million people Gauteng is the most densely populated province in the country and home to 20% of the country's population (Dyson, 2009). Johannesburg is known for its gold deposits<sup>1</sup> and the Witwatersrand ("White Water Ridge") region is a well known mining region in South-Africa as gold has been extracted in this area for over two hundred years. Figure 2.1 indicates the area of interest in this study.

Due to the nature and scale of atmospheric circulation patterns the results of this study will cover the whole Gauteng, most of the Highveld and a large part of South-Africa not in the Highveld region. It must be emphasized that Gauteng and its major cities is the main area of interest in this study. Care has been taken to minimize confusion when using the terms Highveld and Gauteng. A clear distinction will be drawn between the regions when mentioning specific impacts related to severe weather events.

### Observational data and model configuration

ERA-Interim reanalysis data is used as the meteorological dataset to drive the numerical simulations and the cluster analysis. The reanalysis data was obtained from the NCAR RDA. ERA-Interim data offers multiple variables at high spatial and temporal resolution (0.75°x 0.75°). Some key limitations in the dataset include overestimation of precipitation over the oceans and positive temperature biases in the arctic where the data does not capture low level inversions. According to Gensini et al. (2014) peer reviewed papers with the word 'reanalysis' have been used in 3140 studies from 2010 to 2014 indicating the popularity of reanalysis datasets in research. In the study 5 extreme cases were simulated and to represent the storm day thermodynamic profile from the UWYO upper-air sounding database was used<sup>2</sup>. This data was further used to evaluate the model simulations conducted. According to Dyson (2013) caution should be practised when using data directly for the dataset, however, the data is

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<sup>1</sup>Johannesburg has been given many nicknames by South-Africans; Jozi, Jo'burg and Egoli - the city of gold (also the name of a now defunct television show playing off in the city)

<sup>2</sup>Clarification: to represent the individual cases examined the UWYO data was used, but for the long term trend analysis of the thermodynamic state the IGRA data was used



**Figure 2.1:** The study area - Gauteng province located in South-Africa as indicated in the insert map is the main area of interest for this study.

assumed to be complete and accurately representative of the storm environment. Insurance and media reports provided information about the spatial extent of the hail damage across the province and also the economic damage caused across different sectors. Media reports and data from the IGRA provided historical upper-sounding data from 1975 onwards and this allowed the analysis of thermodynamic indicators associated with convection to be assessed for trends by the use of the Thiel-Sen slope analysis. The last dataset used was the SOI index from National Oceanic and Atmospheric Administration (NOAA) climate monitoring datasets NOAA (2017). SOI is a function of the sea level pressure differences between Tahiti and Darwin and formulated as,

$$SOI = \frac{(\text{Standardized Tahiti} - \text{Standardized Darwin})}{\text{Monthly Standard Deviation}}, \quad (2.1)$$

where the standardized index (Tahiti and Darwin) is,

$$\text{Standardized index} = \frac{(\text{Actual SLP} - \text{Mean SLP})}{\text{Standard Deviation}}, \quad (2.2)$$

and the Monthly Standard Deviation (MSD) as,

$$MSD = \sqrt{\sum (\text{Standardized Tahiti} - \text{Standardized Darwin})^2 / N}. \quad (2.3)$$

## The identification of meso- $\gamma$ scale indicators

Five extreme hail events that occurred between 2011 and 2013 over Gauteng were used as case studies to examine the spatio-temporal characteristics of meso- $\gamma$  scale storm environments through numerical simulations by WRF. All the storms damaged property and some even resulted in the loss of life. The severest of these, case one, was the most expensive natural catastrophe over South-Africa to date. The storms selected fall within the range of the ERA-Interim data (1979 - 2014) and also the radiosonde data from the IGRA. A description of each storm is summarized below and a more detailed discussion follows in chapter 4.

By simulating these extreme event a holistic analysis of meso- $\gamma$  scale indicators and the relationship to hailstorms can be formed. Due to the popularity of thermodynamic diagrams for operational use the simulations were all represented as thermodynamic profiles and compared to the storm day thermodynamic observation from the UWYO database. The shear environment was also analyzed and compared to the storm day shear. In the simulations 6 major cities in Gauteng were selected to analyze the thermodynamic properties across the province namely Irene, Johannesburg, Pretoria, Krugersdorp, Vereeniging and Benoni.

The cases chosen are briefly summarized below:

### Case one: 2013/11/28 - Greater Gauteng

The storm caused an estimated damage of over R1.6 billion, the storm was described as *one of the most catastrophic events experienced in South Africa to date* (Barry, 2014). Parts of the Tshwane Metro Area had been declared a disaster area with more than R100 million allocated to support families in the affected area (Eliseev, 2013).

### Case two: 2013/11/11 - Benoni

In Benoni on 11 November 2013 hailstones size ranged from 10mm to 32mm (golf ball sized) was observed with various reports of damage to property. In Mamelodi township some shacks were destroyed and people dislocated. Some suburbs in Pretoria and Johannesburg were also affected (ENCNA, 2013).

### Case three: 2012/11/09 - East Rand

The hailstorm followed a severe storm that occurred two days before in Polokwane, Limpopo that resulted in over ZAR3 million damages and a storm the previous day in Benoni. The storm accounted for over ZAR6 million in damage claims (COVER, 2013)

### Case four: 2012/11/08 - Benoni

The hailstorm resulted in several injuries and one death after a tree that was hit by lightning fell on a person, destruction of property also occurred and emergency services were put on standby after the storm (TimesLive, 2013)

### Case five 2011/10/19 - Krugersdorp

Although no notable damage was recorded, hailstones the size of small eggs were observed. The storm occurred over Krugersdorp in Gauteng (SAWDIS, 2013).

For each case upper-air sounding data is used to analyze the observed storm day environment, the data was recorded at the Irene weather observing site (68263) where the SAWS launches weather balloons daily. The raw data was gathered from the University of Wyoming upper-air sounding database for analysis of the observed atmospheric conditions. To represent the wind shear of the selected case studies hodographs were plotted to represent the shear. The simulations were represented in the same manner to allow for easy comparison. The thermodynamic profile selected from the simulations was at the moment the most unstable parcel was simulated.

After this analysis on the unstable parcel simulated the spatial extent of the identified indicators the WRF output for 12:00 UTC is visualized over Gauteng. 12:00 UTC was selected due to the nature of convective events usually occurring later in the afternoon and to allow for the constant representation across the case studies.

## The Weather Research and Forecasting Model setup

An brief introduction to WRF was covered in the previous chapter. WRF has several products available, the model can produce upper air soundings and also simulate radar reflectivity, both popular forecasting tools for used around the world. The following section will cover the model setup as related to this study.

WRF uses a terrain following hydrostatic pressure vertical coordinate ( $\eta$ ) defined as:

$$\eta = \frac{(\rho_b - \rho_{bt})}{\mu}, \quad (2.4)$$

where

$$\mu = \rho_{bs} = \rho_{bt}. \quad (2.5)$$

where  $\rho_b$  represents the hydrostatic component of pressure (Skamarock et al., 2008),  $\rho_{bs}$  the hydrostatic surface values and  $\rho_{bt}$  the hydrostatic values at the boundary top. WRF's governing equations are based on the flux-form Euler equations (Skamarock et al., 2008):

$$\partial_t U + (\nabla \cdot \mathbf{V}u) - \partial_x(\rho\phi_\eta) + \partial_\eta(\rho\phi_x) = F_U, \quad (2.6)$$

$$\partial_t V + (\nabla \cdot \mathbf{V}v) - \partial_y(\rho\phi_\eta) + \partial_\eta(\rho\phi_y) = F_V, \quad (2.7)$$

$$\partial_t W + (\nabla \cdot \mathbf{V}w) - g(\partial_\eta \rho - \mu) = F_W, \quad (2.8)$$

$$\partial_t \Theta + (\nabla \cdot \mathbf{V}\theta) = F_\Theta, \quad (2.9)$$

$$\partial_t \mu + (\nabla \cdot \mathbf{V}) = 0, \quad (2.10)$$

$$\partial_t \phi + \mu^{-1}[(\mathbf{V} \cdot \nabla \phi) - gW] = 0, \quad (2.11)$$

$$\partial_\mu \phi = -\alpha\mu, \quad (2.12)$$

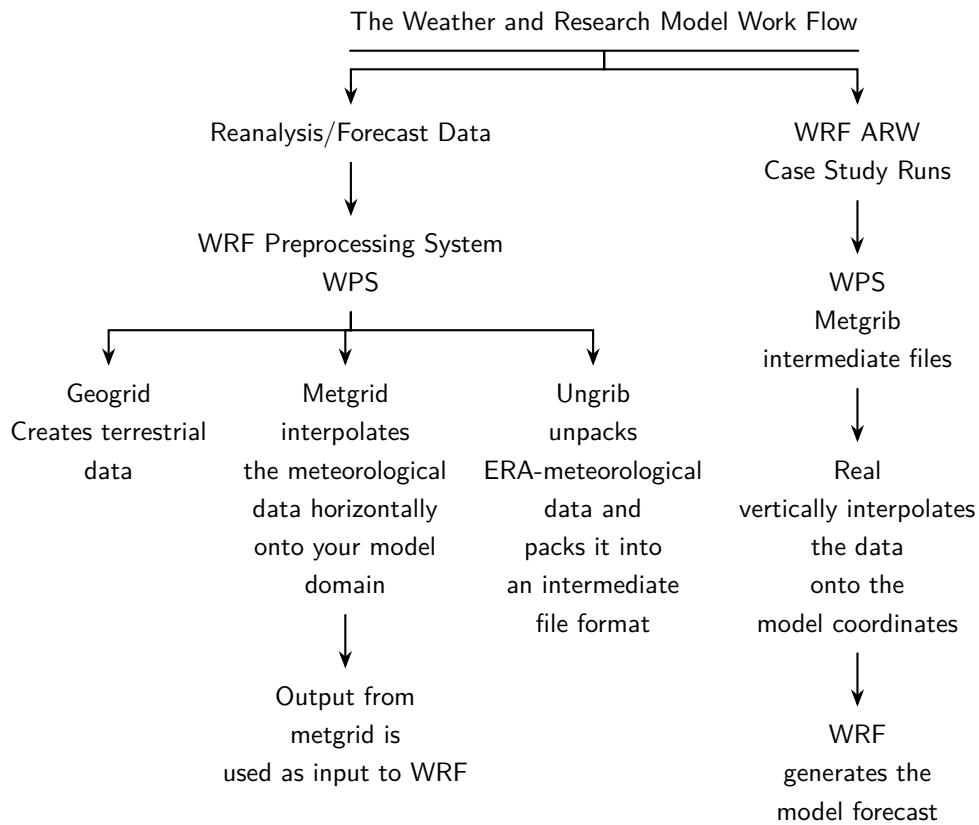
$$\rho = \rho_0(R_d\Theta/\rho_0\alpha)^\gamma. \quad (2.13)$$

Equation 2.6 and 2.7 are the horizontal momentum equations, 2.8 the vertical momentum equation, 2.9 the conservation of potential temperature, 2.9 the conservation of dry air, 2.11 geopotential, 2.12 the equation of inverse density and 2.13 the equation of state. Equation 2.11 is the only non-conservative equation in governing equations.  $\mathbf{V}$ , is the three dimensional coupled vector velocities,  $F$  forcing term for  $U$ ,  $V$ ,  $W$  and  $\Theta$ ,  $\rho$  pressure and  $\rho_0$  sea-level reference pressure,  $\alpha$  the inverse density of dry air,  $\mu$  pressure difference between the surface

and model top,  $\phi$  geopotential,  $\Theta$  coupled potential temperature,  $g$  acceleration as a function of gravity,  $\eta$  terrain following hydrostatic-pressure vertical coordinate,  $R_d$  the gas constant for dry air,  $\gamma$  heat capacity for dry air at a constant pressure (as a ratio),  $U$ , the coupled horizontal component of velocity in the x-direction,  $V$  the coupled horizontal component of velocity in the y-direction,  $W$  the coupled vertical component of velocity,  $u$  the horizontal component of velocity in the x-direction,  $v$  the horizontal component of velocity in the y-direction and  $w$  the vertical component of velocity (Skamarock et al., 2008). The variables are further redefined to include perturbation variables, map projections, parametrized physics and Coriolis terms that are subsequently solved by the WRF model (Skamarock et al., 2008)

### The WRF setup to simulate the selected case studies

As mentioned before ERA-Interim data was used to initiate the WRF runs while the geographical data used in for all the case studies was United States Geological Survey (USGS) data with a resolution of  $30^\circ \times 30^\circ$ . WRF has two main components; first the WRF preprocessing system (WPS) which reads reanalysis and land-use data to create intermediate data files readable in WRF. The WRF workflow is detailed in figure 2.2



**Figure 2.2:** *WRF Workflow*

For the simulations in this study WRF was setup with three domains (Figure 2.3); one parent domain with an horizontal grid-spacing of 12km and a nested domain with a horizontal grid-spacing of 4km and a final domain with a horizontal grid spacing of 1.3km. The center point was Johannesburg Central ( $28.047^\circ \text{E}$ ,  $-26.204^\circ \text{S}$ ). For each case the model was initialized at 12:00 the day before the storm-day and ran for a total of 48 hours (eg 12:00, 27 November 12:00, 29 November) allowing for adequate model spin up. The parametrization schemes were chosen on their ability to simulate ice processes in the mid-latitudes.

The USGS dataset used to represent the land-use and topography contains 24 land-use category descriptions based on climatological averages and soil data from the United Nations Food and Agriculture Organization



# WRF Domains

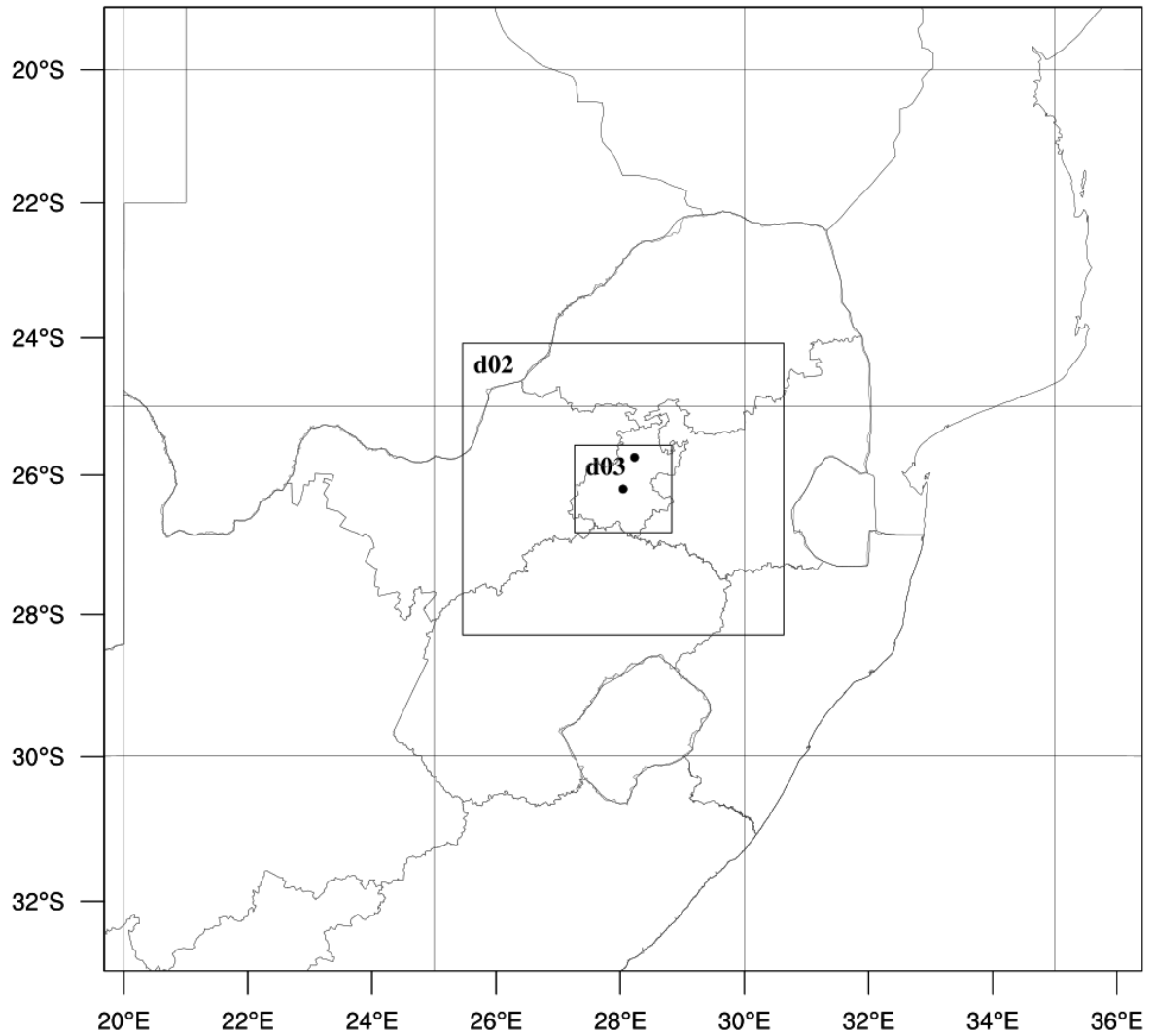


Figure 2.3: WRF Domains

(Crétat et al., 2012) and is freely available for WRF users. Figure 2.4 indicates the 24 land use index and Figure 2.5 the topography generated as used in the model for the selected case studies.

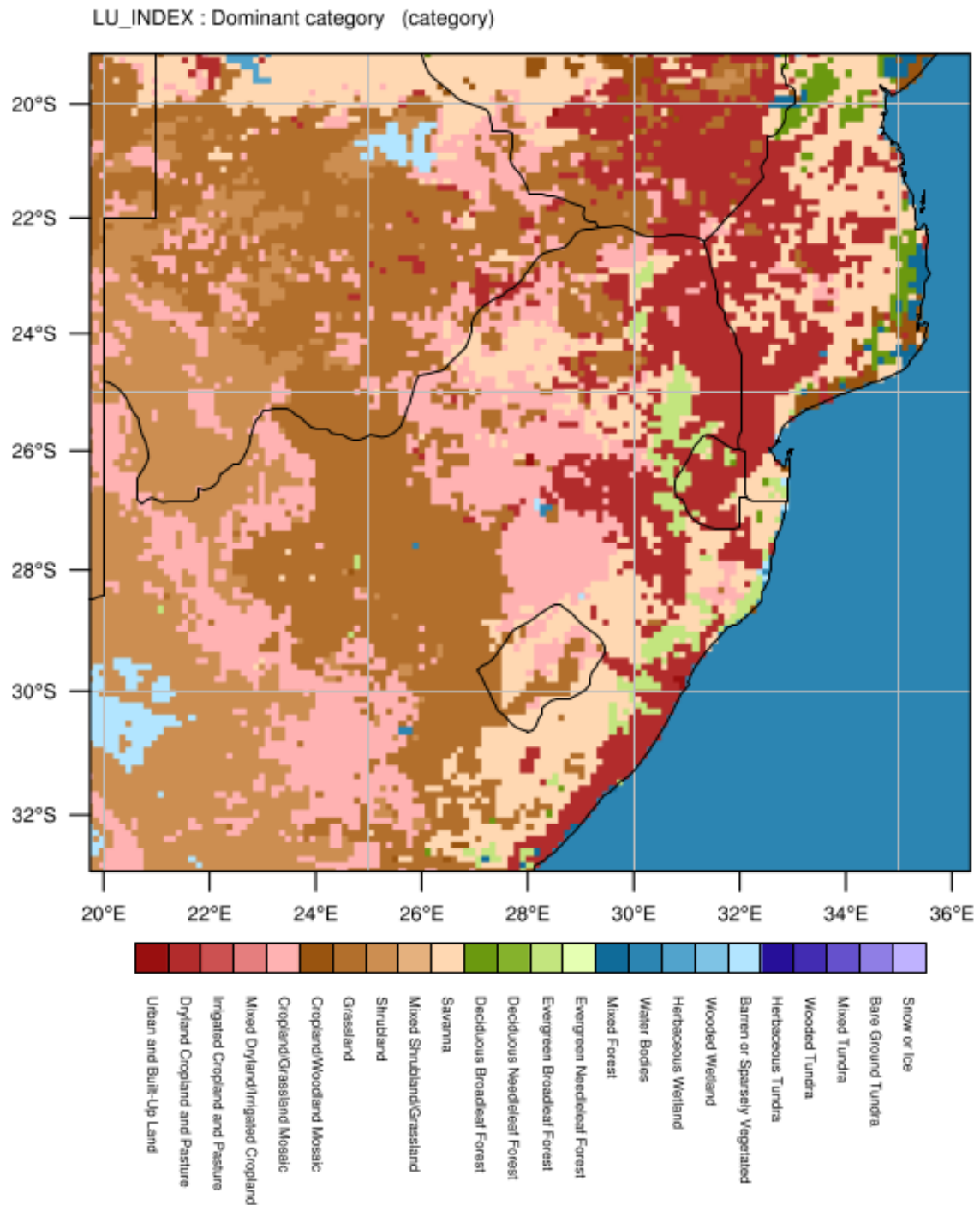


Figure 2.4: Land use index from the USGS input data used in the WRF model run

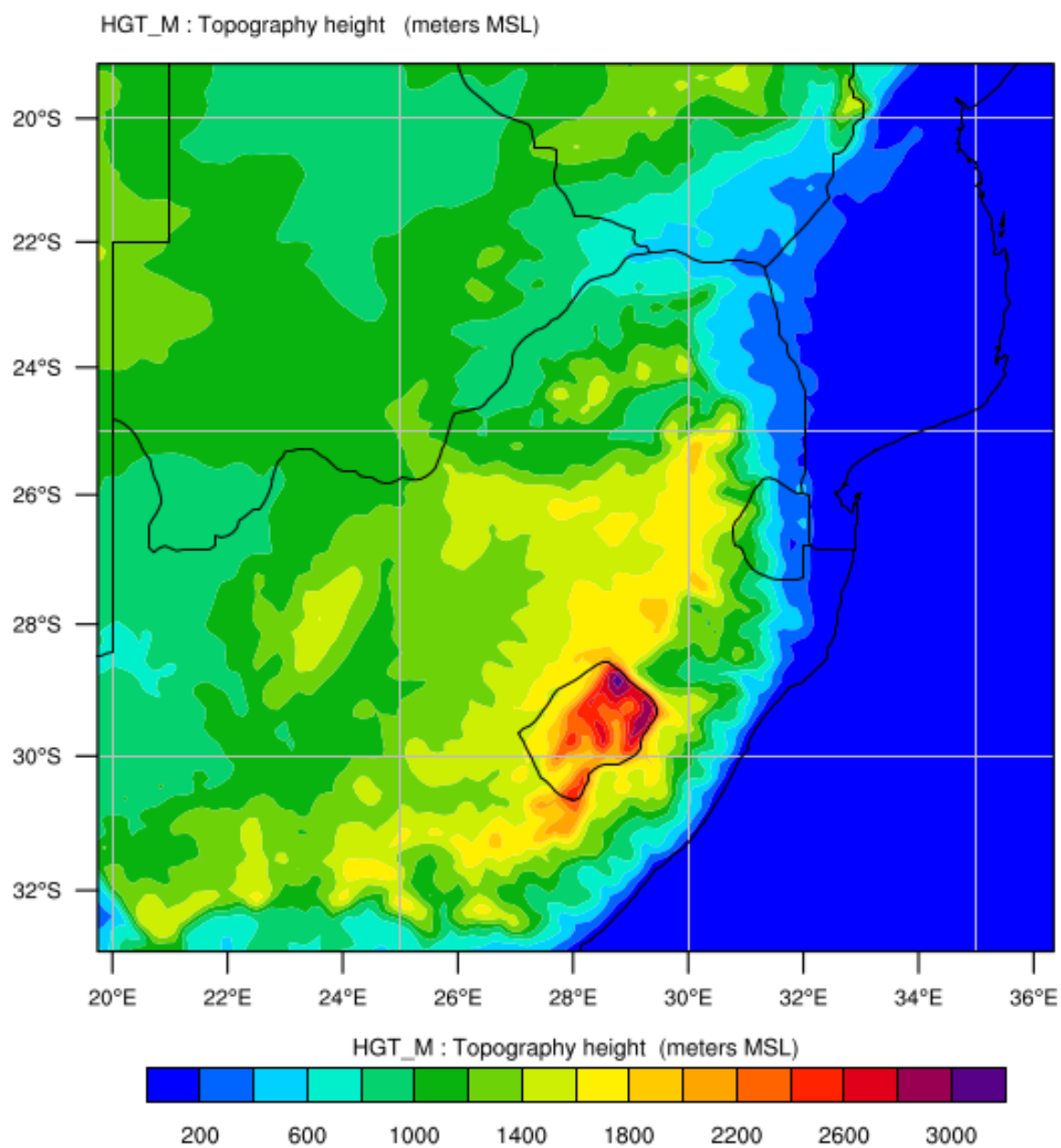


Figure 2.5: WRF topography from the USGS input data used in the WRF model run

## A description of parametrization schemes used

WRF was set up as a CPM to resolve convective processes explicitly. Cumulus parameterization schemes were turned off for the 4km and 1.3km domain. Feedback from the nest to the parent domain was allowed in the model meaning the simulation from the nested domain is computed into the outer domains. WRF offers a variety of physics options to drive the processes in the model, these range from simple computationally inexpensive schemes to more sophisticated, computationally expensive schemes. Schemes used in the simulation are outlined below and summarized in Table 2.1.

**Table 2.1:** *WRF Configuration*

| Numerics & Dynamics    | Configuration                          |
|------------------------|----------------------------------------|
| Resolution             | 12km, 4km, 1.3km                       |
| Integration time step  | 20 seconds                             |
| Map projection         | Mercator                               |
| Geographical Data      | USGS                                   |
| Center Point           | 28,047°S -26.206°E                     |
| Run Time               | 48h                                    |
| Microphysics Scheme    | New Thompson, <i>et al</i>             |
| Longwave Radiation     | RRTMG Scheme                           |
| Shortwave Radiation    | Dudhia Scheme                          |
| Land Surface Model     | Noah Land Surface Model                |
| Cumulus Parametization | 12km - Tiedtke Scheme, 4km/1.3km - CPM |
| PBL Scheme             | Yonsei University Scheme               |

## The microphysics scheme

The New Thompson, *et al* (Thompson et al., 2008) scheme drives the microphysical processes in the WRF run. Thompson's microphysical scheme calculates mixing ratios of five hydrometeor (liquid and ice) species namely; cloud water, rain, cloud ice, snow, and graupel (hail) (Thompson et al., 2008).

Thompson's scheme assumes all hydrometeors, apart from snow, conform to a single gamma distribution,

$$N(D) = \frac{N_t}{\Gamma(\mu + 1)} \lambda^{\mu+1} D^\mu e^{-\lambda D}, \quad (2.14)$$

where  $N_t$  is the total number of particles,  $D$  the particle diameter,  $\lambda$  the distribution slope and  $\mu$  the shape parameter<sup>3</sup>. A Marshall-Palmer distribution<sup>4</sup> is followed when  $\mu = 0$ . The shape parameter for cloud-ice representation ( $\mu_i$ ) needs to be preset at a value between 0 and 2.

The mass ( $m$ ) and velocity ( $v$ ) relation is a function of the hydrometeor diameter. Mass relation is calculated as

$$m(D) = aD^b, \quad (2.15)$$

and the velocity ( $v$ ) relation as:

$$v(D) = \left( \frac{\rho_0}{\rho} \right)^{1/2} \alpha D^\beta e^{-fD}, \quad (2.16)$$

<sup>3</sup> $c, i, r, s$ , and  $g$  represents cloud water, cloud ice, rain, snow and graupel species shape parameters subsequently

<sup>4</sup>Exponential distribution

where  $\rho_0$  reference air density (1.185),  $\rho$  moist air density.  $a, \alpha, \beta, f$  are calculated from the mass and terminal velocity constants for the Hydrometeor species, as detailed in Thompson et al. (2008). Initially cloud water in the parameterization scheme starts at  $N_c = 100 \text{ cm}^{-3}$  (number concentration of cloud water droplets) – a good representation of air in the planetary boundary layer. Although this number can be user defined, the default is used. Because Thompson et al. (2008) implements a new Gamma distribution, a shape parameter for cloud water ( $\mu_c$ ) is calculated:

$$\mu_c = \min\left(15, \frac{10_9}{N_c} + 2\right) \quad (2.17)$$

Thompson's scheme differentiates between warm rain<sup>5</sup> and rain formed from melted ice. First Thompson rearranges the gamma distribution as

$$N(D) = N_0 D^\mu e^{-\lambda D}, \quad (2.18)$$

where  $\mu = 0$  and  $N_0$  is the intercept-parameter and the physical  $y$  intercept of the exponential distribution, however, the parameter has no physical interpretation when  $\mu > 0$ , as is the case with cloud ice particles when  $\mu_i > 0$ .  $N_0$  is calculated as,

$$N_{0,r} = \left(\frac{N_1 - N_2}{2}\right) \tanh\left[\frac{4(q_{ro} - q_r)}{q_{ro}}\right] + \frac{N_1 + N_2}{2} \quad (2.19)$$

The upper intercept limit is  $n_1 = 9 \times 10^9 \text{ m}^{-4}$ , the lower intercept limit  $N_2 = 2 \times 10^6 \text{ m}^{-4}$  and the transition between the limits is calculated as  $1 \times 10^{-4} \text{ kg kg}^{-1}$ .

The intercept parameter attempts to replicate the transition from *drizzle* to larger raindrops while the presence of melted snow and graupel is considered. The top and bottom of melted level is determined and replicates the fall of ice through the melting layer and its transformation to rain.

Warm rain formed from collisioncoalescence will have a large intercept parameter to replicate the presence of large amounts of small drops and also the low terminal velocity. To mimic the presence of both warm rain and rain formed through melting Thompson's scheme applies a large median volume diameter to particles that linearly increases from the top of the melting layer to the size equivalent of melted ice at the bottom of the layer.

The auto conversion of cloud water to rain per unit of time is similar to that of Berry and Reinhardt (1974a,b,c,d) with the exception of the gamma distribution followed, Thompson's follows equation 2.14 and Berry and Reinhardt (1974a,b,c,d) follows a Golovin distribution. Thompson et al. (2008) calculates the auto-conversion as:

$$\frac{dr_r}{dt} = \frac{0.027 \rho q_c \left(\frac{1}{16} \times 10^{20} D_b^3 D_f - 0.4\right)}{\frac{3.72}{\rho q_c} \left(\frac{1}{2} \times 10^6 D_b - 7.5\right)^{-1}}, \quad (2.20)$$

where  $D_b$  and  $D_f$  is derived from (Berry and Reinhardt, 1974a,b,c,d) as;

$$D_f = \left(\frac{6 \rho q_c}{\pi \rho_w N_c}\right)^{1/3}, \quad (2.21)$$

$$D_g = \frac{\left[\frac{\Gamma(\mu_c + 7)}{\Gamma(\mu_c + 4)}\right]^{1/3}}{\lambda_c}, \quad (2.22)$$

---

<sup>5</sup>forms by collisioncoalescence

$$D_b = (D_f^3 D_g^3 - D_f^6)^{1/6}. \quad (2.23)$$

Graupel is captured by reducing the  $N_0$  parameter from the traditional  $10^6 m^{-4}$  to increase fall speed and mixing ratio. The relationship between the mixing ratio  $q_g$  and  $N_{0,g}$  is calculated by:

$$N_{0,g} = \max \left[ 10^4, \min \left( \frac{200}{q_g}, 5 \times 10^6 \right) \right] \quad (2.24)$$

A density constant of  $400 kg m^{-3}$  is used to represent both snow and hail, (Thompson et al., 2008) notes that there is minimal change in results when the density is increased by a factor of two. Thompson uses Heymsfield and Kajikawa (1987) to calculate the terminal velocity. Graupel subsequently has a low mixing ratio but the terminal velocity is twice that of snow. Ice nucleation in Thompson's scheme does not occur until the water vapor mixing ratio  $> 25\%$  supersaturation and  $T < 250K$ . The number of crystals nucleated is determined by the Cooper (1986) curve. Thompson calculates the probability ( $P$ ) of water drops freezing with volume ( $vol$ ) at specific air temperatures ( $T$ ), where  $T_0 = 273.15 K$  represents the melting temperature as,

$$P = 1 - \exp\{-120 \times vol \times 5.2 \times 10^{-4} \times [\exp(T - T_0) - 1]\}. \quad (2.25)$$

This results in larger raindrops forming graupel and smaller cloud droplets forming cloud ice. When  $T < -38^\circ C$  homogeneous freezing of cloud water occurs. The scheme is also able to represent the sublimation of snow and graupel when  $T > 0^\circ C$ . To represent collision-collection (where  $x$  species grow by collection of  $y$  species) in WRF the scheme the model performs calculations at every time step after Verlinde et al. (1990),

$$\frac{dr_y}{dt} = \frac{\pi}{4} \int \int E_{xy} m(D_x) (D_x + D_y)^2 \times [v(D_x) = v(D_y)] N(D_x) N(D_y) dD_x dD_y, \quad (2.26)$$

where  $E_{xy}$  represents collision-collection efficiency. Thompson simplifies (Verlinde et al., 1990) equation to represent rain, snow and graupel,

$$\frac{dr_y}{dt} = \frac{\pi}{4} E_{xy} q_x \rho \int D_y^2 v(D_y) N(D_y) dD_y \quad (2.27)$$

Thompson applies substitution by approximation where  $D_y \gg D_x$  and  $v(D_y) \gg v(D_x)$  to get

$$\frac{dr_y}{dt} = \frac{\pi}{4} E_{xy} q_x \rho \int D_y^2 \left( \frac{\rho_0}{\rho} \right)^{1/2} \alpha D_y^\beta e^{-fD} N_{0,y} D_y^\mu e^{-\lambda D_y} dD_y \quad (2.28)$$

which is integrated by Thompson in

$$\frac{dr_y}{dt} = \frac{\pi}{4} E_{xy} r_x \left( \frac{\rho_0}{\rho} \right)^{1/2} \alpha_y N_{0,y} \frac{\Gamma(\mu_y + \beta_y + 3)}{(\lambda + f_y)^{(\mu_y + \beta_y + 3)}}. \quad (2.29)$$

Thompson's scheme makes the assumption that collision-collection of droplets with a mass  $>$  snow will form hail and mass  $<$  snow simply grows as snow mass while the total rain decreases. Melting of ice particles in Thompson scheme starts occurring at levels where  $T > 0^\circ C$ , the scheme assumes the shape of the specie and integrates it into the melting process. The Thompson scheme is able to be integrated into the subsequent long and shortwave radiations schemes at each time step. The gamma distribution is used in the Rapid Radiative Transfer Model (RRTM) scheme to calculate the radiative effective diameter.

## The long wave radiation scheme

The sun and the radiation processes resulting from it is the main driver of the earth's weather and climate (Spellman, 2012). Long wave radiation is emitted from the earth back into the atmosphere and space and influences the climate and weather in various ways. The outgoing radiation is also impacted by the emittance of greenhouse gases into the atmosphere, which results in the trapping of heat (Yu et al., 2014). The Rapid Radiative Transfer Model Global (RRTM) scheme is applied to simulate long wave radiation processes and the interactions with cloudy and clear skies, cloud upward and downward fluxes as well as radiation interaction with aerosols in the atmosphere (optional in WRF).

The RRTMG scheme is derived from RRTM scheme and was developed to improve on the computational efficiency while keeping maximum accuracy of the RRTM scheme. Radiation schemes can account for up to 50% of computational time in modeling. In WRF RRTMG scheme uses an correlated k-method, k-distribution and lookup tables to increase efficiency (Iacono et al., 2008).

RRTMG uses Monte Carlo Independent Column Approximation (McICA) to represent cloud inhomogeneity, cloud water content variability and cloud overlap. The scheme represents 16 long-wave bands from 10 - 3250  $cm^{-1}$  while the absorption coefficients is derived through a k-distribution, this distribution is derived from the line-by-line radiative transfer model (LBLRTM). Water vapor, carbon dioxide, ozone, methane, nitrous oxide, oxygen, nitrogen and halocarbons (CFC-11, CFC-12, CFC-22, and CCL4) are represented as molecular absorbers in the scheme (Clough et al., 2005; Dudhia, 2014; Iacono et al., 2008).

Using correlated k-method, k-distribution and lookup table allows for accelerated calculations of atmospheric processes associated with radiation. Within the RRTMG lookup tables derived from the LBLRTM model, wavelength, radiative effective radius of water droplets and ice crystals, asymmetry parameters of hydrometeor, single scattering albedo and cloud optical depth is calculated (Thompson et al., 2016).

Water droplet and ice crystal size in the RRTMG assumes a radius of 2.5 to 60  $\mu m$  and 2 to 140  $\mu m$  respectively (Fu et al., 1998; Hu and Stamnes, 1993; Thompson et al., 2016). To account for this limitation, WRF (version 3.5 and up) allows for explicit coupling of hydrometeor diameters from the Thompson's microphysics scheme to the RRTMG scheme, allowing the RRTMG scheme to assume the droplet/ice size calculated in the microphysics to be accounted for (Thompson et al., 2016).

According to Thompson et al. (2016) the radiative effective diameter ( $D_e$ ) of water droplets is a ratio of the droplets size distribution from the third ( $M_3$ ) to second ( $M_2$ ) moments as determined by Slingo (1989),

$$D_e = \frac{M_3}{M_2} = \frac{\int_0^\infty D^3 N(D) dD}{\int_0^\infty D^2 N(D) dD} \quad (2.30)$$

where  $d$  is the rearranged gamma distribution from the microphysics scheme (equation 2.18). The size distribution is then integrated into equation 2.30 to produce the final radiative effective radius ( $r_e$ ) as,

$$r_e = \frac{1}{2} \times \frac{3 + \mu}{\lambda}. \quad (2.31)$$

As mentioned cloud ice follows a Marshall-Palmer distribution when  $\mu = 0$ . Changes calculated within the microphysics scheme such as the concentration of cloud water can lead to changes in the size distribution within the RRTMG scheme. Previous validations of the RRTMG longwave scheme have shown an clear sky long wave accuracy of 1.0  $W m^{-2}$  for the net flux at any altitude. A cooling rate error in the troposphere and lower stratosphere of 0.1  $K day^{-1}$  and 0.3  $K day^{-1}$  in the upper stratosphere (Clough et al., 2005).

## The shortwave radiation scheme

The Dudhia scheme (Dudhia, 1989) is a widely used shortwave radiation scheme carried over into WRF from the MM5 model and is also known as the MM5 shortwave scheme. The scheme has proved efficient and reliable and

has been used in various studies (Ruiz-Arias et al., 2013). The scheme is relatively simple and as such has a simple downward integration of solar flux, considers water vapor absorption, cloud albedo and clean air scattering and assumes a consistent scattering of 10% in the atmosphere (Dudhia, 1989, 2014; Ruiz-Arias et al., 2013; Zhang et al., 2012). It's *simplicity* is also a possible cause for uncertainty as it lacks the accuracy and ability to resolve some radiation processes directly and incorporate aerosol effects compared to schemes such as RRTMG SW scheme (Dudhia, 2014; Skamarock et al., 2008).

In Dudhia (1989) the importance of the shortwave flux relies on the downward beam and the angle of the solar zenith. The scheme also allows for albedo and absorption, clean air, scattering and water vapor absorption interactions with clouds to be represented as;

$$S_d(z) = \mu S_0 - \int_z^{top} (dS_{cs} + dS_{ca} + dS_s + dS_a), \quad (2.32)$$

where  $\mu$  is  $\cos\theta$  of the solar zenith angle and  $S_0$  the solar constant (Dudhia, 1989).

Cloud albedo and absorption is calculated from tabulated functions of  $\mu$  and the vertically integrated liquid water path ( $\ln(w/\mu)$ ). To determine  $w$  the cloud optical thickness  $Tn$  must be determined after (Stephens, 1978a,b),

$$TN \approx \frac{3}{2} W / r_e \quad (2.33)$$

$W$ , the total liquid water path and  $r_e$  radius in micrometers.  $W$  is calculated as

$$W = \int_0^{\Delta\xi} w dz \quad (2.34)$$

Assuming the cloud and precipitation is vertically uniform (as in the Dudhia scheme) we can derive  $W$  as,

$$W = w \Delta z \quad (2.35)$$

When a cloud is above height  $z$  the effect of the cloud is calculated as a percentage of the downward solar flux absorbed or reflected. To estimate the subsequent value of  $\Delta z$  a new percentage is calculated for the height  $z - \Delta z$  and applied to  $\mu S_0 - \Delta S$ , where  $\Delta S$  is clean air. This allows for the clean-air effect above height  $z$  to be removed.

Clean-air water vapor absorption is calculated as an function of the water vapor path followed along the solar zenith angle. Dudhia (1989) uses the clear sky absorption described by Lacis and Hansen (1974). A scaling approximation is used to account for altitude and temperature's effect on the absorption along a non-homogeneous path,

$$y^{eff} = y \left( \frac{P}{P_0} \right)^n \left( \frac{T_0}{T} \right)^{\frac{1}{2}} \quad (2.36)$$

The true water vapor amount is replaced by a scaled amount at a given pressure and temperature. As Lacis and Hansen (1974) notes that using this scaling may not be theoretically useful but it could provide benefit where no pressure and temperature correction was applied previously.

Dudia scheme assumes clean air scattering as uniform and proportional to the earths atmosphere mass path length and related to the zenith angel with a consistent 10% scattering (Dudhia, 1989). The heating rate for the atmosphere is calculated as

$$R_T = R_T(\text{longwave}) + \frac{1}{p C_p} \frac{\partial}{\partial Z} S_{abs} \quad (2.37)$$



$S_{abs}$  is derived from the absorption function  $S_d$  (equation 2.32). Although the Dudhia scheme is widely used some drawbacks are the exclusion of various scattering and absorption processes such as Rayleigh scattering, stratospheric ozone and aerosol absorption (Cr  tat et al., 2016)

### The land surface model

The LSM in WRF allows the model to deal with land surface processes such as diurnal variations in temperature and moisture and the relationship with vegetation, evaporation, ground cover and soil characteristics. LSM plays important role in the accuracy of the planetary boundary layer structure Chen and Dudhia (2001a). The LSM can be regarded as a one dimensional column where grid points within do not interact with each other.

In the this study the Noah LSM is in used. The Noah LSM has 4 soil layer variables with an thickness of 10, 30, 60 and 100cm from the top down; moisture, water and ice and water. It also provides canopy moisture and snow cover prediction. Three soil layers are represented in non-forest areas while the 4th soil layer is included in where forest areas are represented. Vegetation data is determined from the USGS database and soil types from the Food and Agriculture Organization (FOA) database (Chen and Dudhia, 2001a,b; Skamarock et al., 2008; Yin et al., 2016).

Several aspects have to be accounted for the LSM; the radiation budget (surface energy equation), evaporation and their interaction. The Noah LSM formulates the radiation budget/surface energy balance equation as (Chen and Dudhia, 2001a; Chen et al., 2010; Yin et al., 2016),

$$R_{net} = (1 - \alpha)S \downarrow + \varepsilon(L \downarrow - \sigma T_{surf}^4) \text{ and } R_{net} = H + LE + g_0, \quad (2.38)$$

where  $R_{net}$  is the total radiation.  $S \downarrow$  incoming solar radiation and  $L \downarrow$  outgoing long-wave radiation. The surface temperature is represented by  $T_{surf}$ .  $\sigma$  represents the Stefan-Boltzmann constant<sup>6</sup> (Stensrud, 2009; Tyson and Preston-Whyte, 2000).  $\alpha$  represents albedo and  $\varepsilon$  ground surface emissivity (Yin et al., 2016). The second part of the equation refers to the energy budget equation where  $H$  is the turbulent sensible heat flux,  $LE$  the turbulent latent heat flux and  $G_0$  the soil surface heat flux as (Yin et al., 2016).

The Noah LSM calculates sensible heat flux through the bulk surface equation (Chen et al., 2010),

$$H = -\rho c_p C_b \mu (\theta_{air} - \theta_{sfc}), \quad (2.39)$$

where  $\rho$  = air density,  $c_p$  specific heat capacity of air at a constant pressure,  $C_b$  surface exchange coefficient for heat,  $\mu$  wind speed,  $\theta_{air}$  adiabatically adjusted air temperature for the height above the surface and  $\theta_{sfc}$  the corresponding variable at the surface.  $C_b$  is a function of the atmospheric stability and is obtained from the MoninObukhov similarity theory (Chen et al., 2010).

The surface soil heat flux  $G_0$  is formulated as a function of the soil thermal conductivity  $k_T$  which is dependent on the soil water content  $\Theta$  and the soil type.  $T_1$  is the soil temperature in the top layer and  $h_1$  is equal to half of the depth of  $T_1$

$$G_0 = k_T(\Theta_1) \frac{T_{sfc} - T_1}{h_1} \quad (2.40)$$

To calculate evaporation  $E$  direct evaporation from the top soil layer  $E_{dir}$ , evaporation intercepted by the canopy layer  $E_c$  and transpiration through the canopy and roots  $E_t$  has to be calculated. Evaporation  $E$  is represented as (Chen et al., 2010; Yin et al., 2016);

$$E = E_{dir} + E_c + E_t \quad (2.41)$$

---

<sup>6</sup>describes the power radiated from a black body as a as function of temperature

where  $E_{dir}$  (direct evaporation from the top soil layer);

$$E_{dir} = (1 - f_g) \frac{\Theta_1 - \Theta_w}{\Theta_{ref} - \Theta_w} E_p, \quad (2.42)$$

$E_c$  (evaporation intercepted by the canopy layer);

$$E_c = f_g \left( \frac{W_c}{W_{c,max}} \right)^{0.5} E_p \text{ and } \frac{\partial W_c}{\partial t} = f_g P - S_p - E_c, \quad (2.43)$$

and  $E_t$  (transpiration through the canopy and roots);

$$E_t = f_g E_p \left( 1 - \left( \frac{W_c}{W_{c,max}} \right)^{0.5} \right) \frac{1 + \frac{RH_s}{R_r}}{1 + R_c C_b + \frac{RH_s}{R_r}}, \quad (2.44)$$

where  $E_p$  potential evaporation,  $\Theta$  soil moisture content,  $\Theta_{ref}$  field capacity and  $\Theta_w$  wilting point,  $W_c$  intercept canopy water content,  $W_{c,max}$  maximum intercepted canopy water capacity,  $P$  input total precipitation,  $S_p$  ground reaching precipitation when  $W_c > W_{c,max}$ ,  $C_b$  and  $R_c$  surface exchange coefficient for heat and moisture, canopy resistance, respectively.  $RH_s$  is a function of the saturation specific humidity curve,  $R_r$  is a function of the surface air temperature and pressure and  $f_g$  represents green vegetation fraction as a function of the total evaporation between bare soil evaporation and canopy transpiration (Yin et al., 2016).

### Cumulus parameterization

The cumulus parameterization scheme plays an important role in calculating various sub-grid scale convective processes such as convective precipitation, the release of latent heat and also the redistribution of heat, moisture and momentum in the vertical column (Kain and Fritsch, 1990; Zhang et al., 2011). The cumulus parameterization is only implemented in 12km parent domain as cumulus processes cease to be subgrid scale at resolutions lower than 8km (Prein et al., 2015).

The Tiedtke cumulus scheme was developed by Tiedtke (1989) and assumes convection is dependent on the moisture supply from large scale flow convergence and boundary layer turbulence (Tiedtke, 1989). According to Stensrud (2009) Tiedtke can thus be seen as a moisture control scheme. Tiedtke also includes shallow convection within the scheme with the assumption that detraining of shallow clouds occurs at the level of natural buoyancy and the model level above it.

Entrainment<sup>7</sup> is assumed to occur by turbulence exchange of mass through cloud edges ( $E_u^{(1)}$ ) and organized inflow from large scale convergence ( $E_u^{(2)}$ ) while detrainment<sup>8</sup> is assumed to occur through turbulent exchange ( $D_u^{(1)}$ ) and organized outflow at the cloud top ( $D_u^{(2)}$ ) (Olivie et al., 2004; Tiedtke, 1989). This can be written as;

$$E_u = E_u^{(1)} + E_u^{(2)} \text{ and } D_u = D_u^{(1)} + D_u^{(2)} \quad (2.45)$$

after (Stensrud, 2009; Tiedtke, 1989) where,

$$E_u^{(1)} = \epsilon_u^1 M_u \text{ and } D_u^{(1)} = \delta_u M_u \quad (2.46)$$

and the fractional entrainment and detrainment rates are dependent on the cloud radii

$$\epsilon_u = \frac{0.2}{R_u} \text{ and } \delta_u = \frac{0.2}{R_u}. \quad (2.47)$$

<sup>7</sup>Entrainment: incorporation of surrounding air by a rising thermal

<sup>8</sup>Detrainment: loss of mass from a rising thermal (Tyson and Preston-Whyte, 2000)

The fractional entrainment/detrainment values is set at  $1 \times 10^{-4} m^{-1}$  for penetrative and mid-level convection in the presence of large scale flow and  $3 \times 10^{-4} m^{-1}$  for shallow convection in suppressed conditions (Tiedtke, 1989). For larger scale convergence  $E_u^{(2)}$  the updraft entrainment rate is defined as,

$$E_u^{(2)} = -\frac{\bar{\rho}}{\bar{q}} \left( \vec{\nabla} \cdot \nabla \bar{q} + \bar{w} \frac{\partial \bar{q}}{\partial z} \right) \quad (2.48)$$

where the entrainment rate is directly proportional to the large scale moisture convergence (Stensrud, 2009). The updraft mass flux at the cloud base has to be calculated to define the downward mass flux as,

$$(M_d)_{LFS} = \gamma (M_u)_{base} \quad (2.49)$$

where

$$\gamma = -0.2 \quad (2.50)$$

When the updraft mass flux is set the downdraft mass flux at the levels of free sinking is defined to be 20% of updraft mass flux at the cloud base (Stensrud, 2009; Tiedtke, 1989).

Downdraft entrainment and detrainments is assumed to begin at the level of free sinking. The assumption is made that downdrafts are associated with convective precipitation from the updrafts and originate from cloud air influenced by the injection of environmental air. Entrainment and detrainment rates are set to  $\epsilon_d = \delta_d = 2 \times 10^{-4} m^{-1}$  using the same parameterization as the updrafts.

Tiedtke (1989) applies a moisture convergence hypothesis stating that convective activity is linked to the deep layer of conditional instability and large scale moisture convergence. These conditions entrains air through the cloud abase and sides and is proportional to the supply of moisture and detrain cloud air at higher levels. The moisture balance of clouds is assumed to be a function of large scale, turbulent and convective transport, this balance is written as,

$$[M_u(q_u - \bar{q} + M_d(q_d - \bar{q})]_{cb} = - \int_0^{cb} \left( \vec{\nabla} \cdot \nabla \bar{q} + \bar{w} \frac{\partial \bar{q}}{\partial z} + \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} (\bar{\rho} \overline{w'q'}_{PBL}) \right) \bar{\rho} dz, \quad (2.51)$$

where  $cb$  indicates the cloud base height. It is possible for the Tiedtke scheme to determine the updraft cloud mass flux with the subsequent downdraft mass flux at the cloud base and then calculate the updraft mass flux at the cloud base needed to match large scale moisture convergence in the subcloud layer, while shallow clouds detrains at the level of natural buoyancy and the model level above it (Stensrud, 2009; Tiedtke, 1989). Convection by moisture convergence accounts for some uncertainty as the idea is not well supported in literature (Stensrud, 2009). Tiedtke (1989) states that the hypothesis is accurate for areas where boundary layer moisture content changes little over time.

### The planetary boundary Layer Scheme

The parameterization of the PBL plays an important role in the representation of unresolved fluxes such as heat, moisture and momentum as well as the vertical distribution of these fluxes. The Yonsei University Scheme (YSU) is a popular non-local PBL scheme characterized by an explicit entrainment layer and a parabolic K-profile in unstable conditions (Banks et al., 2016; Hu et al., 2010). The non-local K-means scheme applies the vertical diffusion coefficient,  $K$ , to a fixed profile over the depth of the PBL. The top of the PBL is determined by setting the bulk Richardson number to zero so the effective height is determined from the buoyancy profile where the PBL top is defined at the maximum entrainment layer (Hong and Kim, 2008; Hong et al., 2006; Skamarock et al., 2008).

The YSU scheme along with other non-local schemes uses results obtained from large eddy simulations in its formation (Hong et al., 2006; Stensrud, 2009). The scheme expresses momentum diffusivity for prognostic variables ( $u, v, \theta, q$ ) (Stensrud, 2009) as,

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z} \left[ K_c \left( \frac{\partial C}{\partial z} - \gamma_c \right) - (\overline{w'c'})_b \left( \frac{z}{h} \right)^3 \right] \quad (2.52)$$

where  $K_c$  is the eddy coefficient and  $\gamma_c$  is a correction to the local gradient that incorporates the role of large-scale eddies, this correction is only applied to potential temperature and humidity equations (Stensrud, 2009).  $(\overline{w'c'})_b$  is the flux at the inversion layer and  $\left(\frac{z}{h}\right)_3$  includes the asymptotic entrainment at the inversion layer.

The momentum diffusivity equations as defined by (Troen and Mahrt, 1986) is formulated as

$$K_{zm} = kw_s z \left( 1 - \frac{z}{h} \right)^2, \quad (2.53)$$

where 2 is the profile shape parameter,  $k$  the von Karman constant, ( $=0.4$ ),  $z$  and  $h$  the height of the surface and PBL respectively and  $w_s$  the mixed layer velocity scale.  $w_s$  is defined as,

$$w_s = (u_*^3 + \phi_m k w_{*b}^3 z / h)^{1/3} \quad (2.54)$$

at the velocity  $z = 0.5h$ , where  $u_*$  is the surface friction velocity,  $\phi_m$  the wind profile function evaluated from the top of the surface layer and  $w_{*b}$  the convective velocity scale for moist air defined as (Hong et al., 2006; Stensrud, 2009),

$$w_{*b} = \left[ (g / \theta_{va}) (\overline{w'\theta'_v})_0 h \right]^{1/3} \quad (2.55)$$

The correction for the counter gradient for  $\theta$  and momentum is written as,

$$\gamma_c = b \frac{(\overline{w'c'})_s f c}{w_{s0} h}. \quad (2.56)$$

Earlier Troen and Mahrt (1986), used a constant of 7.8 to represent the proportionality constant  $b$  but Hong et al. (2006) uses the exponent of  $-\frac{1}{3}$  to ensure the free convection limit.  $(\overline{w'c'})$  represents the surface flux for  $\theta, u$  and  $v$ . Compatibility between the top of the surface layer and the bottom of the PBL is achieved by using identical profile functions for both layers. For unstable and neutral conditions this can be written as,

$$\phi_m = \left( 1 - 16 \frac{0.1h}{L} \right)^{-1/4} \quad (2.57)$$

for  $u$  and  $v$ , and

$$\phi_t = \left( 1 - 16 \frac{0.1h}{L} \right)^{-1/2}, \quad (2.58)$$

for  $\theta$  and  $q$ . While stable regimes profile functions are defined as

$$\phi_m = \phi_t = \left( 1 + 5 \frac{0.1h}{L} \right) \quad (2.59)$$

where  $L$  is the Monin-Obukov length, typically between -50 and 0 in unstable conditions,  $\phi_m$  and  $\phi_t$  represents momentum and mass variables respectively. To close off the scheme the boundary layer height is determined

from the surface by (Hong et al., 2006; Stensrud, 2009) as,

$$h = Ri b_{cr} \frac{\theta |U(h)|^2}{g[\theta_v(h) - \theta_s]} \quad (2.60)$$

where  $Ri b_{cr}$  is the bulk Richardson number,  $U(h)$  the horizontal wind speed at  $h$ ,  $\theta_{va}$  the virtual potential temperature at the lowest model level,  $\theta_v(h)$  the virtual potential temperature at  $h$  and  $\theta_s$  the surface temperature.  $Ri b_{cr}$  originally defined as zero over land by Hong et al. (2006), after research indicated that a value 0 was linked to some uncertainty in the mixing of the Stable Boundary Layer (SBL). A revision by Hong and Kim (2008) changes to a constant  $rib_{cr}$  value of 0.25 over land to allow for enhanced mixing in the SBL.

Near surface temperature,  $\theta_s$ , is defined as,

$$\theta_s = \theta_{va} + \theta_T \left[ = b \frac{(\overline{w'\theta'_v})_0}{w_s} \right], \quad (2.61)$$

where  $\theta_T$  is the virtual temperature excess near the surface. The mixed surface velocity scale,  $w_s$ , is defined as a function of surface velocity scale,  $u_*$ , and the wind profile function,  $\phi_m$ , evaluated at the top of the surface layer and can be written as,

$$w_s = u_* \phi_m^{-1}. \quad (2.62)$$

$\overline{(w'\theta'_v)}_0$  represents the virtual surface heat flux and  $b$  the proportionality factor set to 7.8.

Hong et al. (2006); Stensrud (2009) indicates that the boundary layer height,  $h$ , is first computed without considering the  $\theta_T$ . The calculated value of  $h$  is then used to determine all the other values and then  $\theta_t$ .  $h$  is then recalculated with the incorporation of  $\theta_T$  until a stable value for  $h$  is found. Using  $\theta_T$  and  $w_s$ ,  $h$  is enhanced and used in the calculation of the bulk stability between the surface and the  $z$  levels above it, this can be defined as

$$Ri b(z) = \frac{g[\theta_v(z) - \theta_s]z}{\theta_{va} U(z)^2} \quad (2.63)$$

Hong et al. (2006) uses this to represent entrainment effects by additional mixing between  $h$  and the bottom of the inversion layer. The computer bulk Richardson number at the level  $z$  is compared with  $rib_{cr}$ ,  $h$  is determined by linear interpolation between two model adjacent levels (Hong et al., 2006).

## A cluster analysis on macro- $\beta$ scale circulation patterns

The goal of the cluster analysis is to examine the possible link between severe hailstorms meso- $\gamma$  scale environment and the larger scale macro- $\beta$  circulation patterns. The selection of meteorological variables identified in chapter 3 related to hail events on the small scale is used to drive the cluster analysis. After the prominent variables were identified from the WRF run data was extracted for a 35 year period (1979 - 2014) from the ERA-Interim reanalysis data to be used in the cluster analysis run. Similar studies have identified and implemented the same variables for synoptic classification of hailstorms over parts of Europe (Aran et al., 2011).

The cluster analysis was performed using the Cost733class software (Philipp et al., 2014). The method used was the principal component analysis cluster analysis scheme (PCACA) within the software package. The PCACA scheme requires a user defined number of clusters. In this case 12 clusters was selected for the study as Tyson and Preston-Whyte (2000) identified 10 dominant synoptic patterns over South-Africa that result in characteristic weather types. Figure 2.6 indicates the work flow of the Cost733class synoptic analysis tool.

The PCACA method within Cost733class applies two cluster analysis types on the selected ERA-Interim indicators. First an HCA is applied to determine the initial amount of clusters. In Cost733class the HCA is an

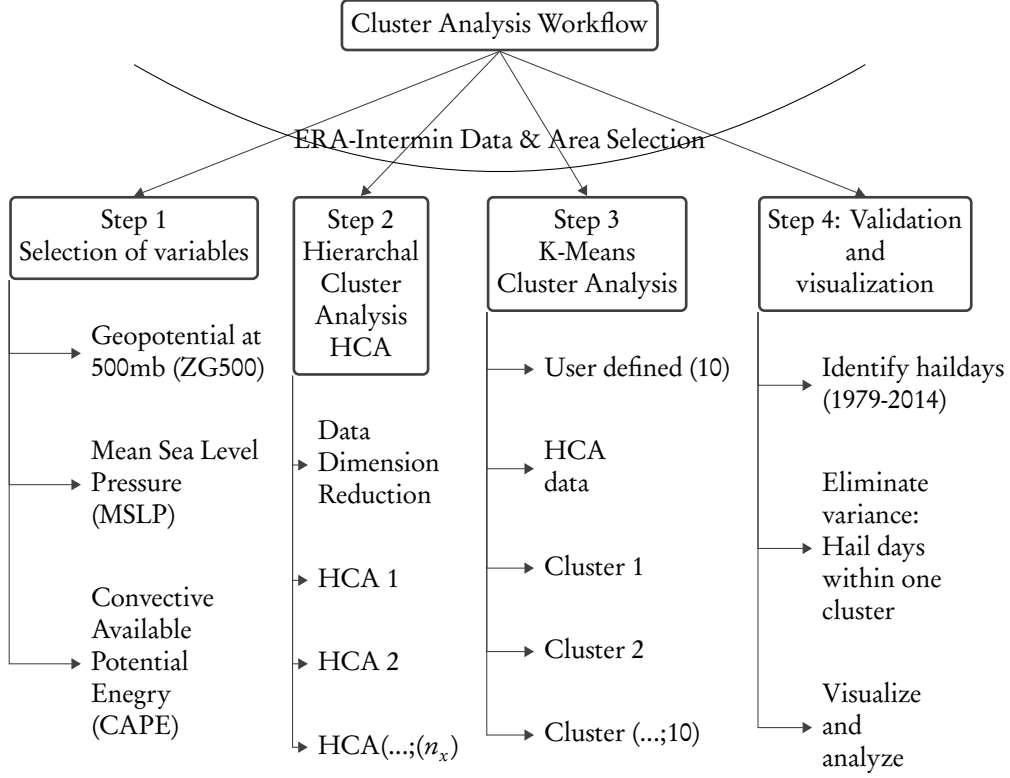


Figure 2.6: COST733class workflow

agglomerative<sup>9</sup> clustering method known as Ward's Minimum Variance Method (hereafter Ward's method) for dividing data. Each observation is treated as a single cluster and two nearest clusters on each hierarchical level is merged and Ward's method does not operate on a distance matrix as opposed to other HCA methods. The method begins with  $n$  single member groups then finds data points that are closest in their  $K$ -dimensional space and combines them to form a new group ( $n - 1$ ) this process is repeated until a reasonable number of clusters is reached.

$$\mathcal{W} = \sum_{g=1}^G \sum_{i=1}^{n_g} \|x_i - \bar{x}_g\| = \sum_{g=1}^G \sum_{i=1}^{n_g} \sum_{k=1}^K (x_{i,k} - \bar{x}_{g,k})^2 \quad (2.64)$$

In Equation 2.64,  $g$  (groups or clusters) are calculated by dividing the initial number clusters, in this case individual days, into smaller clusters of similar values.  $g$  is calculated based on the values of the  $K$  dimension of  $x$ -variable until  $n$  number of clusters is reached.  $n$  is calculated based on the distance between values in the clusters, minimum within cluster variance and maximum between cluster variance. This process reduces the data into a more reasonable number of clusters for processing.

The HCA is followed by an k-means cluster analysis which classifies the initial clusters obtained from the HCA into the final clusters. A HCA doesn't allow for the repositioning of points within clusters that may have been grouped wrongly. It is thus beneficial to apply a *non-hierarchical* cluster analysis after HCA. In Cost733class the k-means cluster analysis lets the user select a set amount of clusters into which data is grouped. Smith et al. (1998); Tyson and Preston-Whyte (2000) indicated 10 characteristic synoptic patterns over South-Africa, however, these were based on surface and upper level pressure data. With the addition of the highly variable meso- $\gamma$  variable twelve clusters were chosen. The position of the synoptic type is defined by a cluster average centroid which averages the selected indicators and places them within a cluster of similar averages. The euclidean distance is used for between cluster distance measurement (Prein et al., 2016). Both methods may result in misclassification of

<sup>9</sup>as opposed to *divisive* clustering

variables and by using the two methods in succession we reduce some uncertainty. Once the analysis is performed around 13,000 days are classified into the 12 clusters specified.

## Determining the trends, cycles and variability of hail related indicators

Due to hailstorm's extreme spatial and temporal variability it poses a problem for researchers when attempting to accurately analyze trends. Several attempts have however been made to overcome this and to some degree of success. Although other studies focus on precipitation trends the methods used in them can still be useful towards hail studies. Cao (2008); Hermida et al. (2015) applied the Mann-Kendall (Kendall and Gibbons, 1955) test to analyze probable patterns related to hail events. Similarly Mohr and Kunz (2013) also applied the Mann-Kendall test on the selected convective parameters and an criteria was setup to assess hail insurance claims and their relationship with convective parameters recorded on specific days. Hermida et al. (2015) in comparison made use of the following hail variables: hail days per year, annual hail frequency and annual hail intensity to examine the trends of hail events over France.

The final objective relies on the indicators identified in objective one as relevant to hail formation. These findings are used to analyze the trends and cycles of haildays over South-Africa. The analysis is supplemented with IGRA radiosonde data. The trends of these indicators along with insurance and media reports are analyzed. The HDF frequency maps of Le Roux and Olivier (1996); Schulze (1965) is reevaluated by using Bureau (1986) datasets, reports from Caelum (1991), media outlets and insurance companies. Data from the IGRA is used to calculate the trends of the indicators shown to be relevant to hail formation as identified in objective one and two. The IGRA dataset undergoes a quality control procedure before being made available to the public and is available for the time period of the study (Durre et al., 2006, 2008; Seidel et al., 2010).

An regression analysis is performed by using the Thiel-Sen slope analysis on the IGRA data for the time period. This allows for the analysis of seasonality and long term trends in the data. The Thiel-Sen determines the trend slope of  $n$ -pairs of data as;

$$T_i = \frac{x_j - x_i}{j - i} \quad (2.65)$$

where  $x_j$  and  $x_i$  represents time at  $j$  and  $i$  (Khan et al., 2015). The Thiel-Sen has the advantage of being 'robust' (Dennison et al., 2014; Sen, 1968; Theil, 1992) to outliers as it is based on the median slope, this is a advantage when using a radiosonde dataset where outlier values are frequent.

In the last analysis a Pearson Correlation Coefficient test is applied to examine the relationship between ENSO/SOI and the occurrence of synoptic patterns identified in the cluster analysis. Pearson's Correlation Coefficient can be written as,

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{(n-1)S_x S_y}, \quad (2.66)$$

where  $n$  is the length of the data frame,  $\bar{x}$  the mean value for the first variable,  $\bar{y}$  the mean value for the second variable and  $S_x$  and  $S_y$  the standard deviation of the first second variable respectively. Pearson's correlation coefficient indicates the relationship between variables with values between -1 and +1, where values  $\leq -0.1$  indicates a negative relationship and values  $\geq 0.1$  a positive relationship.

# Chapter 3

## Meso- $\gamma$ scale indicators of severe hailstorms

According to Orlanski (1975) classification of atmospheric scales the meso- $\gamma$  scale refers to features within the atmosphere that occur between  $2\text{km} \lesssim 20\text{km}$  including convective events and thunderstorms associated with hail events. The concept of scale is important in an atmospheric context as there is a direct interaction between the scales and various phenomena we encounter and this interaction is not well understood especially as related to hail processes. This chapter attempts to understand the meso- $\gamma$  scale environment of hailstorms through the use of NWP models to resolve some selected cases that resulted in extreme hail damage over Gauteng from 2011 to 2013. Each case was run with the WRF model and the simulations were initiated with Era-Interim data. Each simulation started at 12:00 UTC a day before and ended 12:00 the day after the storm occurred, this allowed for adequate model *spin-up*. Three domains were used in the simulation but only the inner 1.3km domain is represented hereafter. The setup of the model is detailed in Table 2.1. The model was setup as a CPM to resolve convection explicitly as this has been shown to improve simulation accuracy (Prein et al., 2013). In the study the thermodynamic profile from the simulations was used to evaluate the storm environment, the popularity of these types of diagrams in operational use is well-known. By examining the meso- $\gamma$  scale thermodynamic environment an analysis of the spatio-temporal variation of the related thermodynamic links across the Gauteng province is possible. If there is a well represented spatial and temporal link between the cases the results can then be used to drive the cluster analysis in the following chapter and examine how these variables are represented over the large macro- $\beta$  scale. Note that figures referring to the skew-t and hodograph simulations are found in the appendix.

### The selection of indicators for the meso- $\gamma$ scale analysis

The energy related to a parcel of air as it moves in the atmosphere plays an important role in the type of weather we experience. Convective storms are especially impacted by the amount of energy available in the atmosphere because a warmer environment where air can rise abruptly and hold more moisture has a higher likelihood of events such as hail and extreme rainfall occurring. For the evaluation of the thermodynamic state of the atmosphere a variety of diagrams have been developed of which the most common is the skew-t and tephigram which are used in a variety of operational centers across the world. They also play an important part in research where scientists examine the state of the atmosphere. From the thermodynamic diagrams various instability indices have been developed. These indices are derived from a combination of temperature, pressure and lifting characteristics measured in the atmosphere. Some of these variables have shown to be exceptionally valuable in understating instability in the atmosphere (De Coning and Adam, 2000; Grieser, 2012; Litta et al., 2012; Thompson et al., 2007; Tippet et al., 2015).

There is a large amount of analysis types that could be done on the thermodynamics of the atmosphere but within the scope of this study only three indicators are evaluated from the model simulations, this includes CAPE, CIN, SI and shear. These variables are briefly discussed below, their thresholds related to convective events and instability are also described. It has to be noted that the thermodynamic profile has limitations related to the location of the soundings, factors like altitude and topography have an influence on the values and other errors related to instrumentation is a common occurrence Dyson (2013). The values described below are however generic values for the evaluation of instability in the atmosphere and not specific to the Higheveld.

CAPE and CIN are two opposing thermodynamic variables that have a major impact on the triggering of convection. CIN is also known as negative CAPE and refers to the energy required by a lifting parcel to *break* through the stable layer of the atmosphere and trigger thunderstorm formation. Once a parcel breaks through the stable layer it can rise through the atmosphere and if the parcel is positively buoyant CAPE can be calculated. Table 3.1 indicates CAPE and CIN values and the associated convection type.



**Table 3.1:** *CAPE and CIN values associated with convective events (Grieser, 2012)*

| CAPE (J/kg)          |                           | CIN (J/kg)               |                                    |
|----------------------|---------------------------|--------------------------|------------------------------------|
| Weak instability     | 0 - 1000                  | $\leq -15$               | Minor convection (early formation) |
| Moderate instability | $\geq 1000$ & $\leq 2500$ | $\geq -15$ & $\leq -50$  | Possible singlecell storms         |
| Strong instability   | $\geq 2500$ & $\leq 4000$ | $\geq -50$ & $\leq -200$ | Possible multicell storms          |
| Extreme instability  | $\geq 4000$               | $\geq -200$              | No convection (stability to high)  |

The simulated thermodynamic diagrams also contain SI values. The SI is also representative of instability in the atmosphere as a function of the temperature difference of an air parcel lifted from 850hPa dry-adiabatically to its LCL and then wet adiabatically to 500hPa. Values associated with severe convective activities are summarized in Table 3.2 (Showalter, 1953).

**Table 3.2:** *SI-Index values associated with convective events (Showalter, 1953)*

| Showalter Index                                   |           |
|---------------------------------------------------|-----------|
| Weak instability & little to no rain              | $\geq 0$  |
| Moderate instability & thunderstorm activity      | 0 to -3   |
| Strong instability & severe thunderstorm activity | $\leq -3$ |

Winds are an important driver of severe weather events and wind characteristics regarding the rotation (storm relative helicity (SRH)) and the storm depth have been well documented in literature (Davies-Jones, 1984; Thompson et al., 2007). The bulk shear, as represented in this study, provides an indicator of the storm depth and calculated as the  $\Delta V$  where  $V$  is the wind vector difference between two levels, e.g 0 - 1km, 0 - 3km or 0 - 6km.

The above mentioned indicators all represent the storm environment on a much smaller meso- $\gamma$  scale as defined by Orlanski (1975). The indicators are simulated using the WRF as a CPM and the spatio-temporal variations of these indicators are subsequently analyzed. Links between these small scale features are examined in the following chapter as part of a cluster analysis, that is if the variable shows a spatial distribution large enough to use in the macro- $\beta$  scale environment which spans 2000 - 10,000km covering the whole South-Africa.

## The meso- $\gamma$ scale storm environment for the selected cases

The thermodynamic structure of the atmosphere for each case study is represented here in the form of a skew-t and a hodograph from observational data. The sounding provides valuable real-time observational data for the forecasting and evaluation of severe storms but it is limited by space and time. Instrumentation and measurement errors are also common during soundings and in a lot of cases a second sounding is not conducted either at the time a fault is realized or later, however, in the selected cases the soundings were complete except for one case. With this in mind we represent the Irene observation as a framework from which to analyze the NWP output and its accuracy in representing the storm environment. Synoptic maps are used to briefly describe the circulation of the storm days after Tyson and Preston-Whyte (2000) classification of weather types of South-Africa. The synoptic weather maps were redrawn using ERA-Interim data for the selected storm days, in all cases the mean sea level pressure (MSLP) and Geopotential at 500 hPa is represented on the synoptic map similar to the daily synoptic maps released daily by the SAWS (2017). The five case studies selected are not indicative of all hail events during 2011 - 2013 but were selected due to the availability of media reports that showed above average damage occurring.

The NWP output is represented in two ways; first the most unstable parcel from the model output is identified and then represented as a skew-t and hodograph, this allows for a simple comparison with the Irene sounding, the thermodynamic diagram's popularity makes it an understandable method to visualize the atmosphere's structure at the moment of when the highest instability is simulated. The simulation output contains the calculated SI value that can be used to evaluate instability further. Next MUCAPE and CIN is represented on a map over Gauteng.

To allow for consistent representation across the 5 cases a method after Merino et al. (2013) is followed where only NWP output at 12UTC is visualized. He argued that convective events occur in the afternoon and using the output at 12UTC represented the state of the atmosphere before deep convection occurs.

### **Case 1, 2013/11/28**

Case study 1 was one of the costliest natural catastrophes that's occurred over South-Africa and resulted in over ZAR1.6 billion damage over a larger part of Gauteng (Barry, 2014; Eliseev, 2013). Figure 3.1 represents the observations taken at Irene on the storm day. High CAPE was recorded indicating an unstable atmosphere while the hodograph showed a backing movement of wind within the lower atmosphere. The CAPE values recorded exceeded 1700 J/kg and an inversion is visible at 650 hPa, however, the parcel is already positively buoyant beyond this point. The synoptic circulation on this day is characterized by a prominent surface trough/low pressure extending system over Southern-Africa allowing for an influx of moisture over a large part of South-Africa. Tyson and Preston-Whyte (2000) classification of weather types indicates that this circulation is associated with surface trough and ridging high over the Indian ocean that links with the ITCZ and the SICZ allowing for the transport of warm air from this region. On this day the system extended into the northerly and central parts of South-Africa. As mentioned the system is not purely tropical as ice processes will be hindered with such a warm atmosphere Dyson (2015). The skew-t shows a dominating wind in from a westerly direction, indicating that the storm had a movement from South West → North West. As stated by Tyson and Preston-Whyte (2000) there tends to be a common characteristic among thunderstorms across the various continents in the form of a cold upper air region and a warmer surface region. There is ridging anticyclone that allows for the movement of surface winds in an easterly direction as seen on the skew-t. We can assume that the westerly upper level wind is a cold dominating airmass which allows the warm air to rise more rapidly and dominates the movement of the storm, this is also supported by Vigaud et al. (2012)'s work indicating the presence of a mid-latitude westerly wave. The interaction of these two air masses impact the shear difference between the surface and upper levels. To the east of the system convergence would have taken place resulting in the subsequent hail events experienced (Tyson and Preston-Whyte, 2000).

### **The simulated thermodynamic and wind environment**

The NWP output (see Figure 1) shows similar instability as the Irene sounding. The simulated skew-t graphs indicated high CAPE across the province while the most unstable parcel was simulated over Pretoria with a CAPE value of 2045 J/kg. No inversion layer is observed in the simulations and this is expected as the most unstable parcel is assumed to have overcome the stable layer. The SI values simulated in for the case indicated massive instability in over all the cities. Benoni had a SI value of -5 while Irene, Johannesburg, Vereeniging and Pretoria had a value of -4 and Krugersdorp the lowest with a SI -2. There is a correlation between the observed and simulated winds, a dominant westerly wind is seen in both cases, possibly as a result of the mid-latitude westerly wave as described earlier. The simulated hodographs Figure 6 over Irene showed the same backing movement as the observation. Over Benoni and Johannesburg a similar rotation was observed. There was high variability in the direction bulk shear at the 0 - 1km level. Johannesburg and Irene did have a similar bulk shear at this level, compared to the other major cities. In the 0 - 6km level the bulk shear shows similarity between the different cities, the directional shear is between 50 ° and 90°. The bulk shear velocity is also similar between the majority of the cities, however, Vereeniging has a lower than average velocity in comparison.

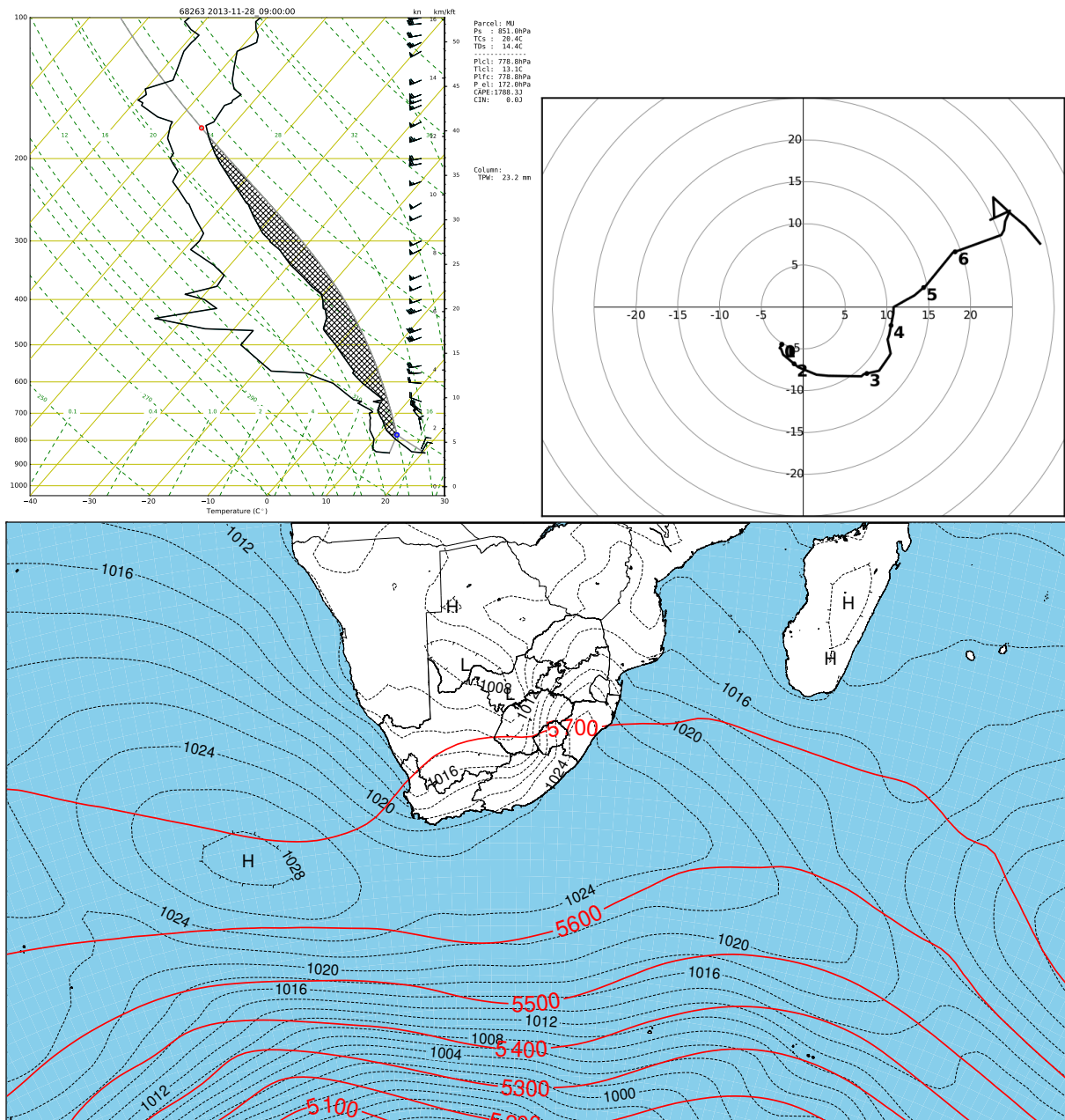
### **Spatio-temporal variations in the simulations**

The thermodynamic diagrams have a characteristic spatio-temporal pattern over Vereeniging. The unstable parcel was simulated at 13:50 UTC, from here it is assumed that the storm moved in a Northerly direction. Johannesburg, Krugersdorp and Benoni showed massive instability around the same time at 14:30 - 14:40. The storm then continued its path towards the Northern part of Gauteng by crossed over Irene at 15:20 UTC and the data shows

that the last unstable parcel was recorded at Pretoria 20 minutes later at 15:40 UCT. This could be explained by the easterly movement associated with summer circulation along with the ridging high-pressure along the east-coast.

An interesting observation can be seen at the simulated hodograph for Vereeniging (figure 6, f); typically a counterclockwise movement is associated with severe storms in the Southern-Hemisphere, this is however not the case, the hodograph shows a definite veering movement at the moment of the highest instability indicating that the wind field might have low temporal relationship with instability. The change in wind direction could also be very sudden and the specific graphs might not be indicative of the average direction across the province.

### Skew-T, hodograph and synoptic conditions on 28 November 2013



**Figure 3.1:** The sounding taken at Irene shows a very unstable atmosphere at the time of measurement. The maximum CAPE recorded during this sounding was 1788 J/kg. An inversion layer is visible at 650 hPa, the parcel is however already positively buoyant at this level. The EL is reached at  $\pm 180$  hPa,  $\pm 12.5$  km. The hodograph indicates backing and as the parcel was lifted an anticlockwise rotation occurs from the north-westerly  $\rightarrow$  south-easterly direction indicating rotation in the lower levels of the atmosphere. In both the observations and sounding a strong mid-latitude westerly wind is observed, this strengthens the trough and impacts the cloud microphysical processes as the cold mid and upper air-masses impact cold cloud processes

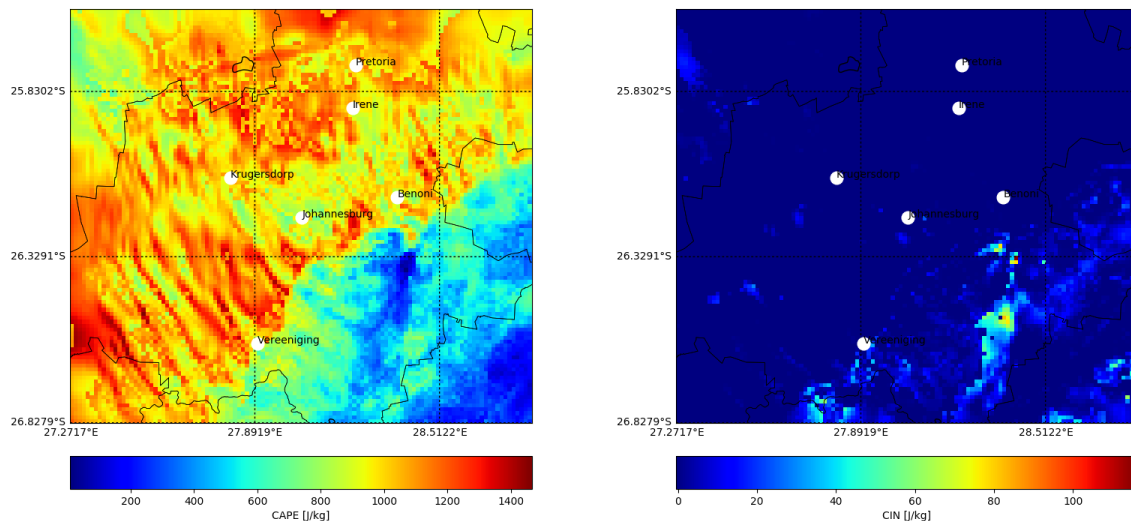
**Table 3.3: Case 1: Simulated wind shear analysis**

|               | Benoni        | Johannesburg | Irene         | Krugersdorp   | Pretoria      | Vereeniging  |
|---------------|---------------|--------------|---------------|---------------|---------------|--------------|
| 0 - 1km Shear | -177°, 0.9m/s | 150°, 1.2m/s | 150°, 0.9m/s  | -157°, 0.5m/s | -142°, 1.4m/s | -99°, 0.2m/s |
| 0 - 3km Shear | 111°, 7.9m/s  | 63°, 9.9m/s  | 140°, 11.2m/s | 175°, 7.1m/s  | 116°, 8.4m/s  | 136°, 7.1m/s |
| 0 - 6km Shear | 52°, 32.9m/s  | 51°, 23.9m/s | 63°, 24.6m/s  | 66°, 22.9m/s  | 86°, 28.2m/s  | 74°, 15.6m/s |

### The spatial distribution of CAPE and CIN

The relationship between CAPE and CIN is clearly visible here – CAPE is distributed across a large part of the province and in the south-east and where low CAPE is simulated CIN is observed. In these areas unstable air was likely prevented from rising above the stable layer, however temporary for a storm of this size. The lower levels of CAPE compared to the thermodynamic simulation is again expected, here only the 12UTC simulation is showed where the unstable parcel was deliberately selected previously

### Spatial distribution of CAPE and CIN



**Figure 3.2:** CAPE and CIN are represented spatially from the WRF simulation results at 12UTC. The figures represent the thermodynamic and dynamic state of the atmosphere before the storm occurred later in the afternoon. High CAPE values are observed over the whole Gauteng, indicating that the stable layer of the atmosphere was breached, triggering unstable lifting and convection.

### Case 2, 2013/11/11

Although not as costly as the storm 17 days later, the case study is in many ways noteworthy, exceptionally large hail was observed while the CAPE recorded exceeded the other cases. Media reported hail the size of golf balls over parts of Gauteng, people in the Township of Mamelodi were displaced and damage was recorded around Johannesburg and Pretoria (ENCNA, 2013). At Irene the sounding large instability was recorded, CAPE values exceeded 2610 J/kg, (Figure 3.3). The hodograph indicates the characteristic backing movement as the wind moves from a north-westerly direction and a rotation develops into a south-easterly directional flow, this rotation is particularly important in forming and sustaining the storm. As with case one a prominent ridging high pressure system and trough extending over Botswana and Central South-Africa associated with tropical disturbances is observed. We see the importance of warm air from the tropics, the warm Indian ocean as well as dominating westerly winds in the upper-air in the formation of convective storms observed on this day.

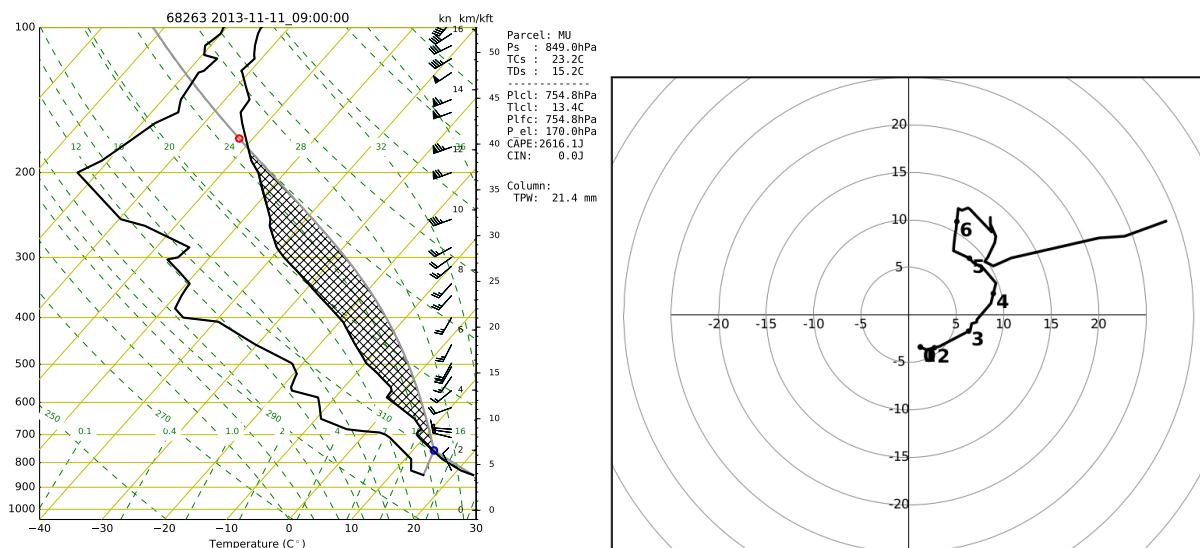
## The simulated thermodynamic and wind environment

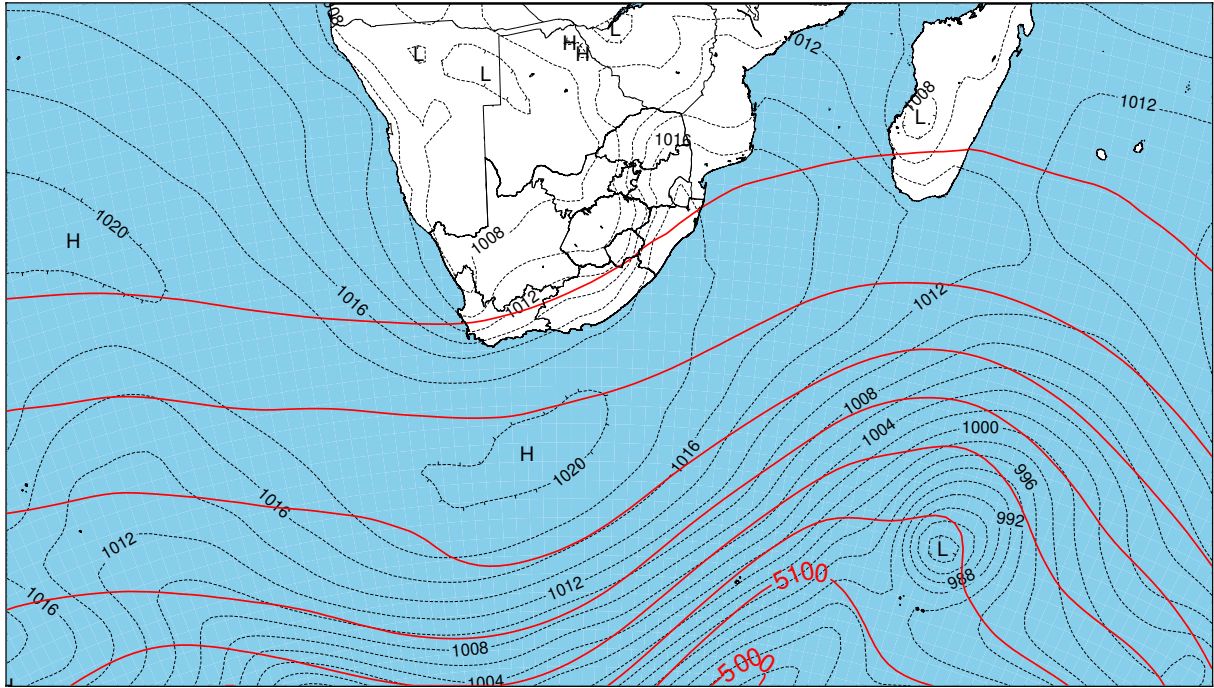
The simulated thermodynamic profile accurately indicated massive instability over Gauteng. All the cases had simulated CAPE values  $\geq 2000$  J/kg. The highest CAPE was simulated over Pretoria  $\geq 3100$  J/kg (Figure 2). The SI index for the event was also under threshold of -1, a good indicator of a severe convective event's probability. The hodographs show a similar pattern as the Irene observation (Figure 7). The 0 - 1km level values were all between 0.6m/s - 1m/s, however there was a large variation in the directional shear at this level. The 0 - 3km bulk showed high variability in both velocity and direction. The highest velocity simulated was 11.3 m/s over Johannesburg while all the other cities had values  $\pm 7$  m/s. The 0 - 6km level shows a more homogeneous bulk shear in both speed and direction. The overall backing movement in Case 2 is less pronounced than the simulations of the 28 November 2013 event (see (Table 3.4).

## Spatio-temporal variations in the simulations

Two distinct events seem to appear when looking at the simulated skew-t's; first in the early afternoon three highly unstable parcels are observed over Vereeniging (14UTC), Pretoria (14:40 UTC) and Irene (15:30 UTC) and at 16:40 UTC an unstable parcel is simulated to be over Benoni and then at 18:00 and 18:20 the most unstable parcels are recorded over Krugersdorp and Johannesburg respectively. It could be that multiple cells developed early and then later in the highly unstable environment. The hodographs indicate that similar wind conditions were observed across the province in the lower and upper levels of the atmosphere see (see Figure 7 and Table 3.4).

Skew-T, hodograph and synoptic conditions on 11 November 2013





**Figure 3.3:** The Irene sounding indicates a highly unstable atmosphere at the time of observation, CAPE values of over 2100 were recorded at. Although not as prominent as Case 1 rotation is still observed in lower levels of the atmosphere. The synoptic chart shows a surface trough and ridging high-pressure system extending over the mainland, transporting warmer air from the tropics over South-Africa. When this warm air rises and cools down as it reaches 500 hPa dominated by cold westerly airmass ice can form and lead to hail events.

**Table 3.4:** Case 2: Simulated wind shear analysis

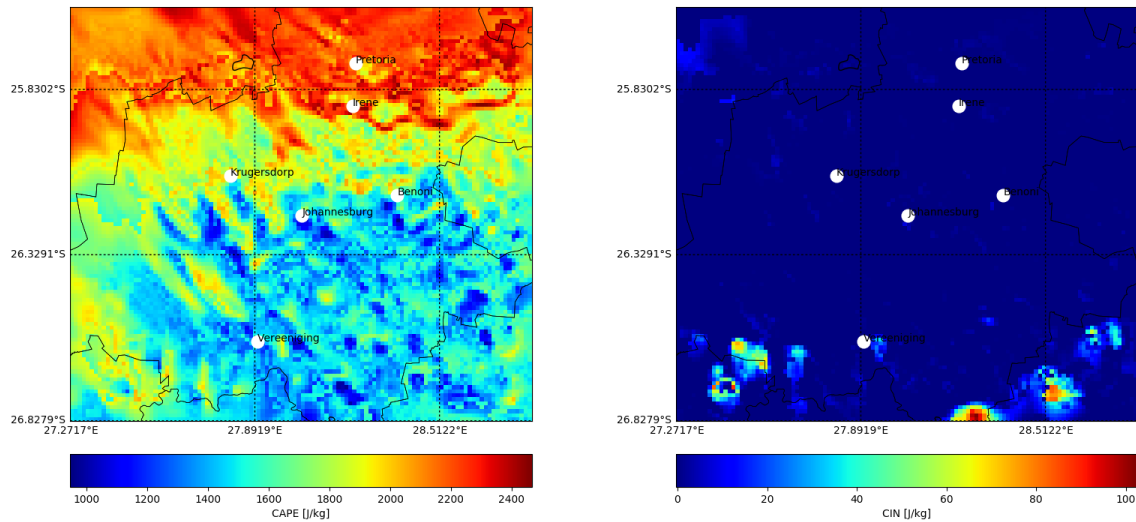
|               | Benoni       | Johannesburg  | Irene        | Krugersdorp  | Pretoria     | Vereeniging  |
|---------------|--------------|---------------|--------------|--------------|--------------|--------------|
| 0 - 1km Shear | 167°, 1.0m/s | -177°, 1.0m/s | 179°, 0.4m/s | 177°, 1.0m/s | 170°, 0.6m/s | 124°, 0.7m/s |
| 0 - 3km Shear | 59°, 7.4m/s  | 32°, 11.3m/s  | 44°, 7.7m/s  | 175°, 7.5m/s | 61°, 7.1m/s  | 14°, 6.9m/s  |
| 0 - 6km Shear | 33°, 14.9m/s | 37°, 15.6m/s  | 32°, 15.5m/s | 66°, 16.2m/s | 33°, 15.1m/s | 16°, 12.2m/s |

### The spatial distribution of CAPE and CIN

The 12:00UTC visualization showing CAPE and the CIN distribution across Gauteng indicate a highly unstable environment in the northern parts of Gauteng with values  $\geq 2000$  J/kg simulated. The southern parts of the province shows slightly less instability but values  $\geq 1000$  J/kg is present across the whole area. The CIN values are negligible as convection already resulted in the stable layer being breached across the province. Some areas of CIN in the south-eastern part of the province can be observed. These areas here also have a lower CAPE value then the rest of the area. Like case 1 an inverse correction is observed between the two thermodynamic indicators and CAPE has a large spatial extent.



## Spatial distribution of CAPE and CIN



**Figure 3.4:** The WRF simulations for the 11 November 2013 storm shows massive instability in the area, the overall CIN value is low indicating that the stable layer was already breached and that unstable lifting occurred. The 12UTC time frame only shows a limited picture of the overall variation across space and time during the day, but does indicate the importance of this derived indicator.

### Case 3, 2012/11/09

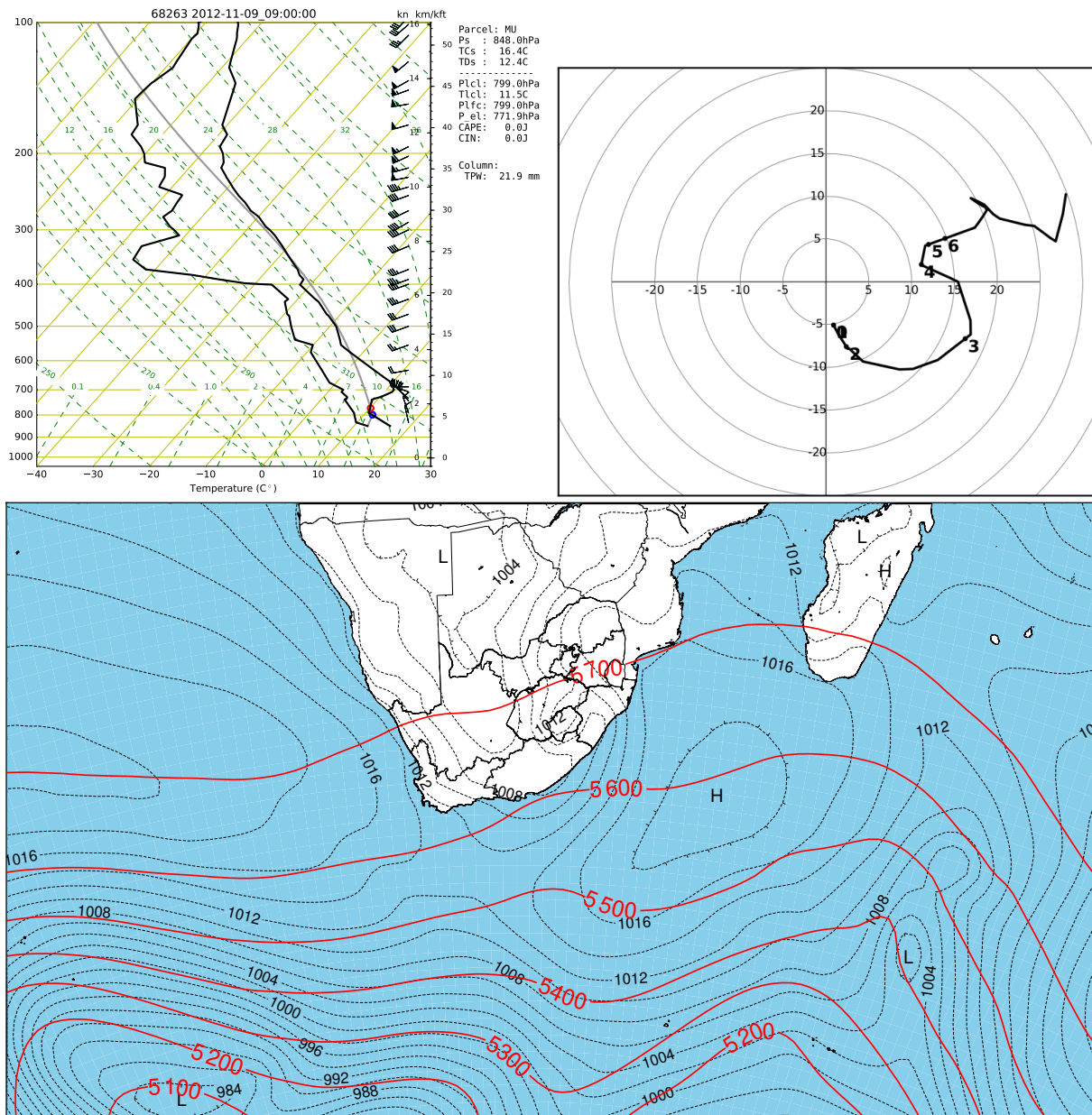
The 9 November 2012 storm was the second severe hail event experienced over Gauteng in two consecutive days and accumulated a damage cost of ZAR 6 million (COVER, 2013). The observed skew-t is shows a clear stable layer in the lower atmosphere (Figure 3.5), the stable layer is related to the temperature inversion that a lifting parcel has to overcome to lift to its LFC. The stable layer also results in low CAPE observed during the sounding, indicating that the stable layer is effectively blocking the parcel from rising unstably into the atmosphere. The hodograph shows a backing rotation from the north-west counterclockwise into a south-easterly direction. The synoptic map indices the presence of a surface trough over Botswana, while a strong low pressure system is observed over central South-Africa.

#### The simulated thermodynamic and wind environment

The WRF simulations of the thermodynamic (Figure 3) environment accurately show the stable layer. CAPE is still simulated, while not particularly high in comparison to the previous cases. Comparing the Irene sounding with the simulations it seems like the particular storm day was characterized by isolated storm cells in the south-east/central part of Gauteng. The SI index supports this as values associated with convective events is only observed over Irene and Pretoria and not all the cities. Clear rotation is visible in the hodographs over the areas with instability (Figure 8).

#### Spatio-temporal variations in the simulations

The simulations support the possibility that this was a storm conceiting of multiple single cells, a relatively common occurrence over the Highveld. The storm did not have the spatial extend of the previous cases and the temporal variations between the most unstable parcels indices that the events where short-lived and isolated.



**Figure 3.5:** The sounding did not indicate exceptionally high CAPE values, but an inversion can be seen at 700 hPa level. This inversion layer often prevents unstable air from rising into the atmosphere and forming storm cells. Again there is a prominent ridging high pressure system over the eastern seaboard while the westerly wave in the upper air is prominent, providing an favorable storm environment as the warm surface air can rise higher up into the atmosphere.

**Table 3.5:** Case 3: Simulated wind shear analysis

|               | Benoni       | Johannesburg | Irene         | Krugersdorp  | Pretoria     | Vereeniging  |
|---------------|--------------|--------------|---------------|--------------|--------------|--------------|
| 0 - 1km Shear | 164°, 0.5m/s | 161°, 0.8m/s | -171°, 0.5m/s | 166°, 0.7m/s | 167°, 0.5m/s | 178°, 0.5m/s |
| 0 - 3km Shear | 66°, 13.2m/s | 60°, 13.5m/s | 68°, 14.1m/s  | 62°, 15.0m/s | 81°, 14.5m/s | 72°, 13.3m/s |
| 0 - 6km Shear | 62°, 18.1m/s | 66°, 19.9m/s | 66°, 19.6m/s  | 65°, 19.5m/s | 66°, 19.7m/s | 61°, 19.9m/s |

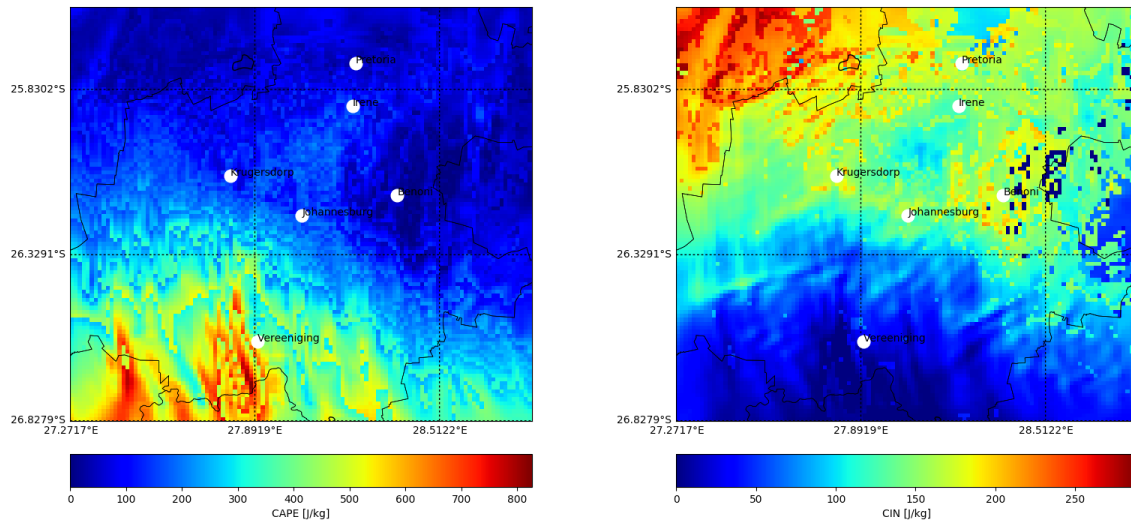
### The spatial distribution of CAPE, CIN and SHR

The 12:00 UTC indicates no extreme CAPE across the province apart from the Southern areas where values of  $\geq 500$  J/kg are simulated. The high CIN on the other hand is prominent over the northern parts where the



atmosphere seems to be in a relatively stable condition.

### Spatial distribution of CAPE and CIN



**Figure 3.6:** The WRF simulation for the 9 November 2013 hailstorm shows an inverse correlation between CIN and CAPE as expected, areas of low CIN indicates that the parcel has already risen above the stable layer and is now positively buoyant.

### Case 4, 2012/11/08

Case 4 was the first of two consecutive hail events over the Gauteng province along with the previous case. The storm caused the death of one person after a tree struck by lightning fell on a person (TimesLive, 2013). The observational data for this case is incomplete and subsequently not shown here, a sounding was launched but it seems that the radiosonde malfunctioned midway through the launch. The previous cases do however indicate that the simulations represented the actual storm environment reasonably well, as such the assumptions made of the storm day atmospheric environment will be made from the simulations. The synoptic map available for the day shows a similar pattern as the previous case studies. The surface trough extending over the mainland and wide spread rainfall over much of central South-Africa is observed.

### The simulated thermodynamic and wind environment

The simulations (Figure 4) of the event indicate a maximum CAPE value of 1952 J/kg over Pretoria while the other cities also had CAPE values  $\geq 1000$  J/kg, Benoni is the exception as the CAPE value was a mere 356 J/kg. A possible reason for this could be seen in Figure 3.8, where low recorded CIN could mean convection was triggered earlier over the specific area and no further convective events occurred. The SI for the various cases also support the notion that severe events could occur over the area, except for Benoni all the values were  $\leq -1$ . The hodographs again show a characteristic backing motion while a strong rotation can be observed in the lower 0 - 1km layer of the atmosphere (Figure 9).

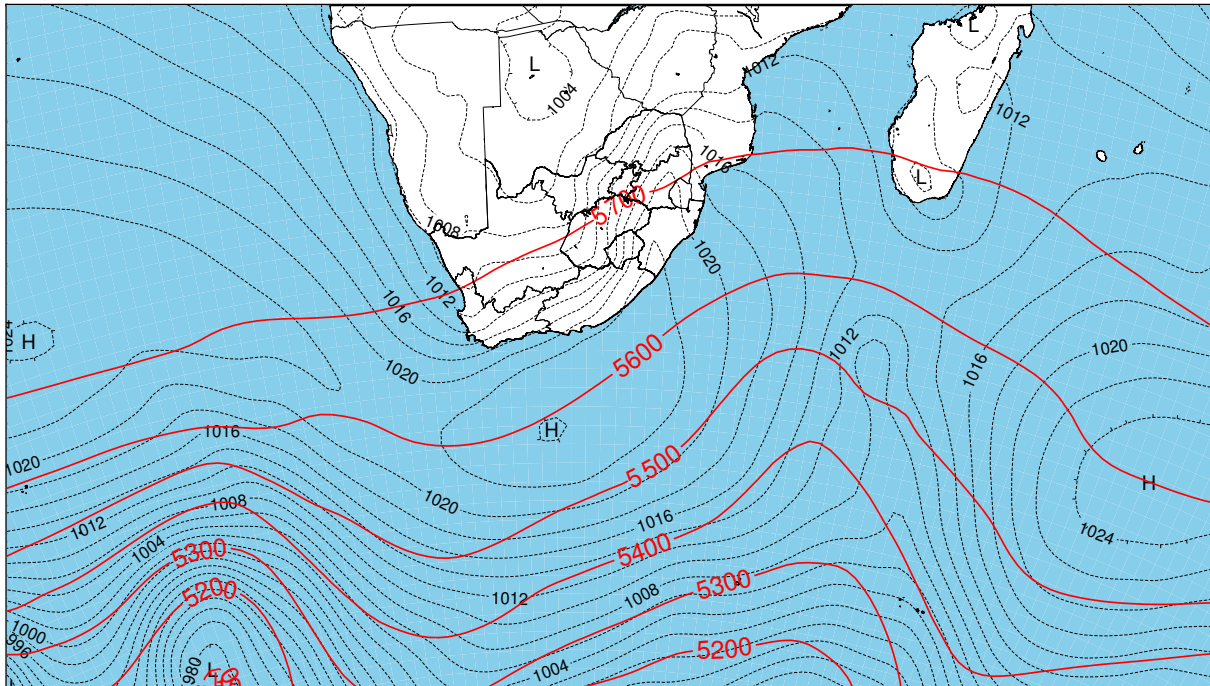
### Spatio-temporal variations in the simulations

The most unstable parcels were all simulated before 12 UTC, indicating that the storm occurred relatively early compared to the other events simulated. Like Case 1 the storm seems to be moving from a southerly direction north-wards, but the simulated Krugersdorp sounding could mean that the day was the result of isolated cells spread across the province. The hodographs (Figure 9) all show intense rotation in the 0 - 1km level and then backing occurs slightly above this level.

## The spatial distribution of CAPE and CIN

In Figure 3.8 CAPE values  $\geq 2000$  is observed in the simulated data, however, most of these fall in the North West province while Pretoria, Irene and Krugersdorp appear to be right on the edge of this highly unstable environment. The CIN values show an unusual pattern, high CIN values are recorded in close proximity with high CAPE in the Northern parts of the province. The CIN in the Southern part could be expected as low CIN and low CAPE mean that the atmosphere was in equilibrium at this stage, convection could have already occurred and the atmosphere ceased to be in an unstable state or the atmosphere was never in a state of instability over this area.

Synoptic chart of 08 November 2012

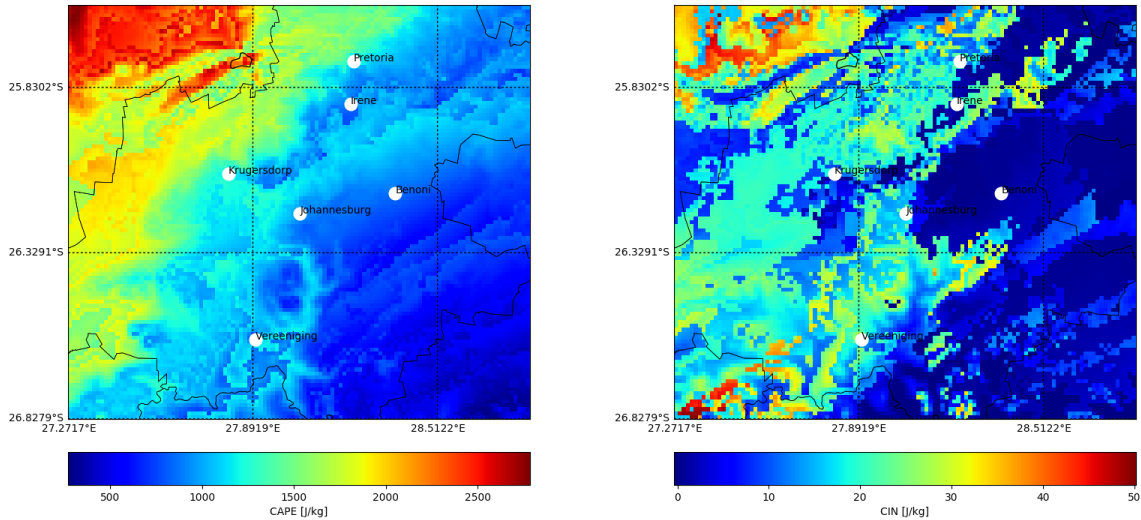


**Figure 3.7:** The 8 November 2012 hailstorm synoptic conditions shows the presence of a ridging high pressure over the east-coast. South low pressure system over Botswana a trough is present with strong pressure gradient. Geopotential at 500 hPa was well developed over the interior possibly providing a influx of cold air allowing for ice processes and the subsequent formation of hailstorms.

**Table 3.6:** Case 4: Simulated wind shear analysis

|               | Benoni        | Johannesburg  | Irene        | Krugersdorp   | Pretoria     | Vereeniging   |
|---------------|---------------|---------------|--------------|---------------|--------------|---------------|
| 0 - 1km Shear | -130°, 0.2m/s | -109°, 0.5m/s | 160°, 0.8m/s | -133°, 0.9m/s | -78°, 0.7m/s | -90°, 0.4m/s  |
| 0 - 3km Shear | 109°, 7.1m/s  | 131°, 11.0m/s | 133°, 6.4m/s | 149°, 7.6m/s  | 127°, 9.0m/s | 116°, 12.1m/s |
| 0 - 6km Shear | 68°, 26.3m/s  | 77°, 27.2m/s  | 75°, 28.8m/s | 72°, 26.5m/s  | 77°, 26.9m/s | 77°, 26.9m/s  |

## Spatial distribution of CAPE and CIN



**Figure 3.8:** The WRF simulations for 8 November 2012 shows an interesting relationship between CAPE and CIN, because high CAPE is generally associated with a weakened CIN, as the CAP is already breached, we see here areas of high CAPE and CIN occurring in the same proximity. There is however areas, in the North-West where is seems low CIN is present. This could be where the lifting parcel overcame the CIN triggering convection. Low CIN and CAPE in the south-east could indicate a that the storm over the area already occurred and the atmosphere is in a state of equilibrium, this could also explain the North-West's high CAPE and CIN values as the storm moved in that direction.

### Case 5, 2011/10/19

Case 5 is the only event examined in this study that did not occur in November, this does not mean the event is an exception as the South-African hail season is already in full force from October onwards (Olivier and van Rensburg, 1992). This event did not account for extreme damage, but from media reports hail the size of small eggs were observed (SAWDIS, 2013). No 09:00UTC sounding was available for the day, and the 00:00UTC was represented instead as it was the closest sounding to the storm event. The CIN value indicated a very stable atmosphere, but this is expected as the sounding was taken at nighttime when instability is at a minimum. The hodograph indicates rotation occurred in a counterclockwise direction. Although the stable layer is prominent some CAPE is observed. The synoptic pattern for this storm day shows two coastal low systems while a weak surface trough is present. This was the only case that occurred in October and could explain the dominant westerly wave presence in the upper-air, this is also observed in the skew-t where the dominant westerly winds in the high troposphere is visible, as with previous storms.

### The simulated thermodynamic and wind environment

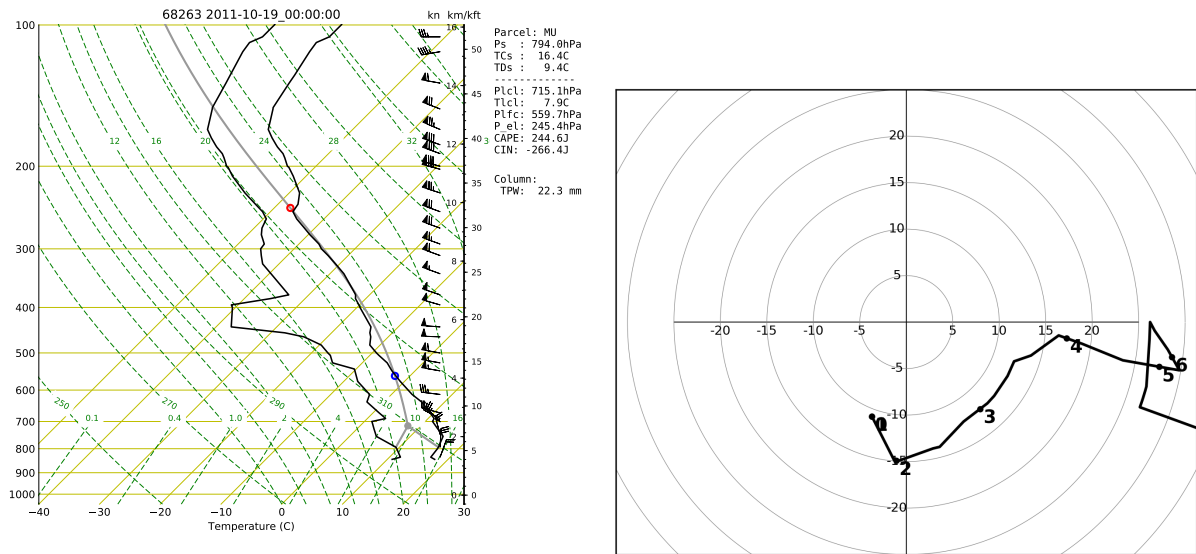
The simulated thermodynamic diagrams (see Figure 3) indicate that the atmosphere across Gauteng was highly unstable, the highest CAPE value was recorded at Irene being  $\geq 3000$  J/kg while Krugersdorp, where the egg size hail was observed, was also highly unstable at  $\geq 2700$  J/kg. Most of the convection occurs in the early afternoon within a 30 minutes time frame. The SI for each diagram further supports the highly unstable environment with  $SI \leq -2$  across all the cities. In the hodographs (Figure 9) no rotation is observed.

### Spatio-temporal variations in the simulations

From examining the storm's spatio-temporal extent it seems to be that the maximum instability was recorded within a similar time period (within  $\pm 30$  minutes) across all the selected cities, indicating that the whole area

was massively unstable and prone to extreme convective events. The egged sized hail was only reported over Krugersdorp, and this area also had the 2nd highest instability.

### Skew-T, hodograph and synoptic conditions on 19 October 2011



**Figure 3.9:** This was the only case examined to occur in October. The synoptic map indicate that dominant westerly wave present and along with the low pressure system over the interior created an favorable environment for storm formation. The thermodynamic profile was only available for the 00:00UTC sounding on this day and as can be expected CAPE and SI was not well defined here. Unfortunately no sounding data was present for this case and the synoptic chart is the only observational data available.

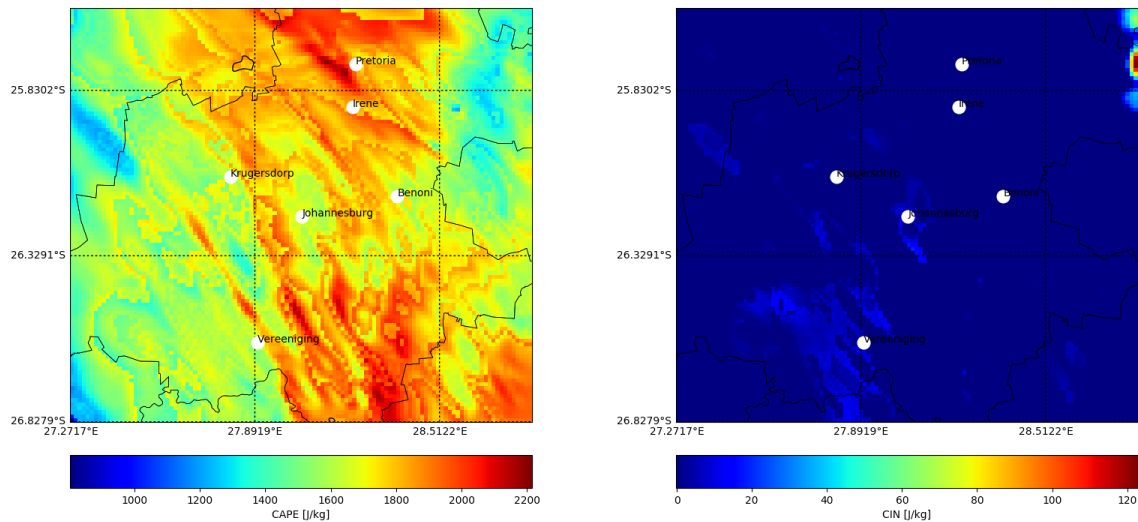
**Table 3.7: Case 5: Simulated wind shear analysis**

|               | Benoni        | Johannesburg  | Irene         | Krugersdorp   | Pretoria      | Vereeniging   |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 0 - 1km Shear | 145°, 0.7m/s  | 144°, 1.2m/s  | 130°, 1.1m/s  | 134°, 1.1m/s  | 121°, 1.3m/s  | 143°, 0.8m/s  |
| 0 - 3km Shear | 131°, 5.5m/s  | 139°, 9.9m/s  | 141°, 6.2m/s  | 125°, 6.6m/s  | 130°, 7.2m/s  | 145°, 5.5m/s  |
| 0 - 6km Shear | 114°, 23.2m/s | 111°, 19.1m/s | 111°, 15.4m/s | 111°, 19.7m/s | 112°, 15.9m/s | 116°, 21.0m/s |

### The spatial distribution of CAPE and CIN

Figure 3.8 indicates a highly unstable environment over all of Gauteng and the major cities. This is also the only case where the simulated thermodynamic diagrams and the hodographs were within  $\pm 20$  minutes of the spatial illustration. As expected, low CIN is simulated for this time as the CAPE indicates that the stable layer has been breached.

### Spatial distribution of CAPE and CIN



**Figure 3.10:** The 12:00 UTC WRF simulation for case 4 indicates the spatial distribution of CAPE, CIN. CAPE and CIN seem to show an inverse correlation. These two thermodynamic variables are well defined spatially.

## The meso- $\gamma$ scale environment

This section dealt with the identification of selected meso- $\gamma$  scale indicators associated with hailstorms over the Highveld. Five case studies were selected that occurred from 2011 to 2013. The goal of the simulations was to identify the spatial and temporal extent of the selected variables within the meso- $\gamma$  scale and the thermodynamic diagram was selected as an effective way to do so and the product's popularity for operational use. In each case the model output was examined and the most unstable parcel over the specific city/suburb was selected for analysis. For the same parcel a hodograph was then created to examine the wind shear associated with the case.

As mentioned, the selected case studies are by no means representative of all hailstorms that have occurred during the last couple of decades. The cases were selected based on the availability of data such as the thermodynamic profile, shear and media reports. The accuracy of the simulations in comparison to the observation is noteworthy. A few key deductions can however be made by comparing the two. The Irene soundings are not always representative of the storm environment as the spatial extent of the sounding is limited to this area and this can be seen where the model indicates an unstable atmosphere in cities relatively far away from Irene while the observation at the site indicates a more stable atmosphere.



## The wind environment of the selected case studies

The hodograph assists in the assessment the wind environment for the analysis of the storm data, the wind is represented as vectors between each level (e.g. 0 - 1km) and used to derive shear; an identification of dominant wind direction and speed between specific level. The hodographs in all the cases showed a similar pattern as the observed data, backing or counterclockwise rotation occurs. One exception is case 2 over Vereeniging where veering occurs and a clockwise rotation is observed.

In each case study the shear between 0 - 1km, 0 - 3km and 0 - 6km from the model output was detailed. The variations between the different levels and also within levels is prominent. In the 0 - 1km level there is a high variation in the rotation between the selected cities and their most unstable parcel simulated, this is expected as the level is highly variable and the represents a relatively small sample size. Compared with the upper levels the lower 0 - 1km shear values is easily influenced by surface heating and uneven topography. As the level from the surface increases the winds become more homogeneous and start to follow a dominant directional flow and speed, Figure 1.2 begins to illustrate these phenomena, as the dominant upper level winds can be seen to influence the storm updrafts, these updrafts could also account for the high variability in the 0 - 1km level. This change into a more homogeneous pattern can be observed in the 0 - 3km layer, however, noticeable variation in the direction and speed between the selected cities are observed. The 0 - 6km wind environment shows the most homogeneity between the cases, using this as an indicator of severe events would however not be representative of severe events, the daily dominant wind of an area could be represented instead of a wind *representing* the storm environment. There is however too much variation in the 0 - 1km and 0 - 3km levels to use this in the cluster analysis, the small scale nature of these features could result in unrealistic cluster formation.

## The spatial distribution of CAPE and CIN

In all the cases the high CAPE was observed, in case 2 CAPE values  $\geq 2500$  was simulated. Although the most unstable was subjectively selected the fact that all the cases had noticeably high CAPE values indicates the importance in identification of severe events, consequently, CIN could be inversely correlated to the storm environment as stated in various studies.

The CAPE and CIN figures shows the spatial distribution of this study to see of the selected meso- $\gamma$  scale is noticeable over a large part of Gauteng and if it can be effectively used in further analysis on larger scales. To represent a more objective and holistic analysis of the selected storm days only the 12:00 analysis was used after Merino et al. (2013) study that used a similar methodology and argued that convective storms occur after this time. CAPE will be used in the next chapter to analyze the macro- $\beta$  scale and to avoid over fitting of data CIN will be omitted as the variable's inverse correlation with CAPE.

## Some limitations of the simulated thermodynamic analysis

The uncertainties associated with this chapter relate with the use of NWP model to simulate the selected case studies. The use of WRF requires the user to subjectively select and set up the model. The set up gets even more complicated when the storms are small scale and convective in nature. In this case the time step selected for analysis of CAPE and CIN has to be taken into account as a major limitation of the study it is known that the storm environment for each case differs and further research into the temporal variations of storms. The storm environment could potentially become more *representative* closer to the actual event, as opposed to only using the 12:00 time step. The various parameterizations need to be carefully selected for the events simulated and special considerations need be acknowledged based on location, this includes latitude, topography and altitude. The combination of the parameterizations are also important as some schemes interact efficiently with each other and others not. The evaluation of the model setup and all the parameterization schemes was beyond the scope of this study.

The selection of variables was also subjective as the number indicators and variables that could be derived from simulations and thermodynamic profiles is enormous. Chapter 6 does however analyze the trends of other ther-

modynamic variables to form a better idea of these are changing over time. Bias within the input data and the selected parameterization schemes are also acknowledged for further investigation but was not focused on during the study.

## Linking the meso- $\gamma$ scale with the macro- $\beta$ scale

The chapter examines the storm environment of selected case studies, here WRF was applied as a CPM to form a holistic *picture* of the dynamic and thermodynamic state of the atmosphere during the selected hail events. Within the scope of this study the selected indicators seem to show a relationship; high CAPE values are shown to be well represented spatially while an inverse relationship with CIN is observed on all the days. The hodographs observations show the prevalence of backing, during hail events, but variation within and between the levels are prominent and cannot be ignored when considering the application in a cluster analysis of the macro- $\beta$  scale and the simulations further support this. The accuracy of the WRF simulations where also remarkable; a visual comparison to the Irene sounding shows the accuracy of CPM simulations. The variation of the wind direction and rotation have to be considered before moving on to the next section. Small variations that occur in wind could mean that data may show a unrealistic relationships in the data. Instead it was decided to use MSLP and geopotential at 500 hPa to represent the surface and upper levels instead as this data has shown good homogeneity and use in clustering (Prein et al., 2016).

# Chapter 4

## A macro- $\beta$ scale analysis of severe hailstorms

Chapter 3 investigated the meso- $\gamma$  environment of five severe hail events that occurred in the Gauteng province through an analysis of the simulated thermodynamic and shear profile of each storm as these are popular tools for operational centers to evaluate the state of the atmosphere and the potential weather. This chapter continues to build on the results by using a cluster analysis to examine the possible links between these small scale variables identified and the relationship to the larger macro- $\beta$  scale synoptic environment. To achieve this a cluster analysis is performed on selected atmospheric variables to find the link between the small scale environment and the synoptic circulation. The cluster analysis is driven by Cost733class classification software (Demuzere et al., 2011), in this study a PCACA clustering method comprising of a HCA and K-means cluster analysis is used. ERA-Interim data is used as the data source and the variables identified and used in the cluster analysis were extracted for the period 1979 - 2014.

The macro- $\beta$  scale as defined by Orlanski (1975) refers to circulation types on a spatial scale of 2,000km - 10,000km, this is commonly known as synoptic scale circulation. Understanding the links between large scale circulation and surface weather has been achieved through the use of cluster analysis techniques such as SOM or a PCA. All these methods aimed at defining circulation patterns into discrete groups of similar circulation types (Cahynová and Huth, 2014; Demuzere et al., 2011; García-Ortega et al., 2011; Huth et al., 2008; Jiang et al., 2012; Sheridan and Lee, 2011). In this study a two-step PCACA cluster analysis is performed using Cost733class software package developed by Demuzere et al. (2011). The workflow for the software package is detailed in the data and methods section (see Figure 2.6).

### Linking macro- $\beta$ scale circulation patterns with hail events

South-Africa's weather has been classified into discrete categories on various occasions by Blamey and Reason (2013); Dyson (2009, 2013); Dyson et al. (2015); Manhique et al. (2015); Taljaard (1986, 1981); Tyson and Preston-Whyte (2000). The common circulation patterns associated with the extreme convective events experienced during summer months has been noted to be a result of the localized- and mesoscale convective systems as well as Mesoscale convective complex systems (MCC) over the country. As noted by (Blamey and Reason, 2013) MCC can be long-lived ( $\pm 10$  hours) and cover a large spatial area ( $350,000 \text{ km}^2$ ) in some cases, while the convective systems associated with hailstorms are generally short-lived and localized and influenced by the convective tropical environment and cooler westerly waves over South-Africa in the lower latitudes (Blamey and Reason, 2013; Dyson, 2015; Hart et al., 2010). Blamey et al. (2016) recently examined the prevalence of environments ideal for the development of severe storms over South-Africa, the study showed the importance of CAPE over the subcontinent during summer months. The previous chapter also showed the presence of the ridging anticyclone and dominant westerly waves driving the storms, the skew-t observations and simulations showed the dominant west winds clearly.

In the previous chapter that dealt with the meso- $\gamma$  scale environment, five hail events over Gauteng were examined by analyzing the thermodynamic and shear environment. To achieve this WRF was used to simulate these events on a convective scale of 1.3km. In the thermodynamic environment CAPE and CIN was well represented spatially, the two variables also showed an inverse correlation with each other. Due to the correlation between the variables only CAPE was used in the cluster analysis to avoid over-fitting of data points. The simulations also allowed for the analysis of the shear environment by examining simulated hodographs. The analysis looked at the bulk shear ( $\Delta V$ ) of each case at three different, but commonly used levels; 0 - 1km, 0 - 3km and 0 - 6km. In the simulations high variability in the bulk shear of the 0 - 1km  $\Delta V$  is observed, both directionally and in the velocity within this level. Possible reasons for this high variability include the relatively low vertical extend, which means that changes are more prominently observed. The bulk shear on levels over 1km begin to show more homogeneity. This is already seen in the 0 - 3km level where a dominant rotation and a homogeneous



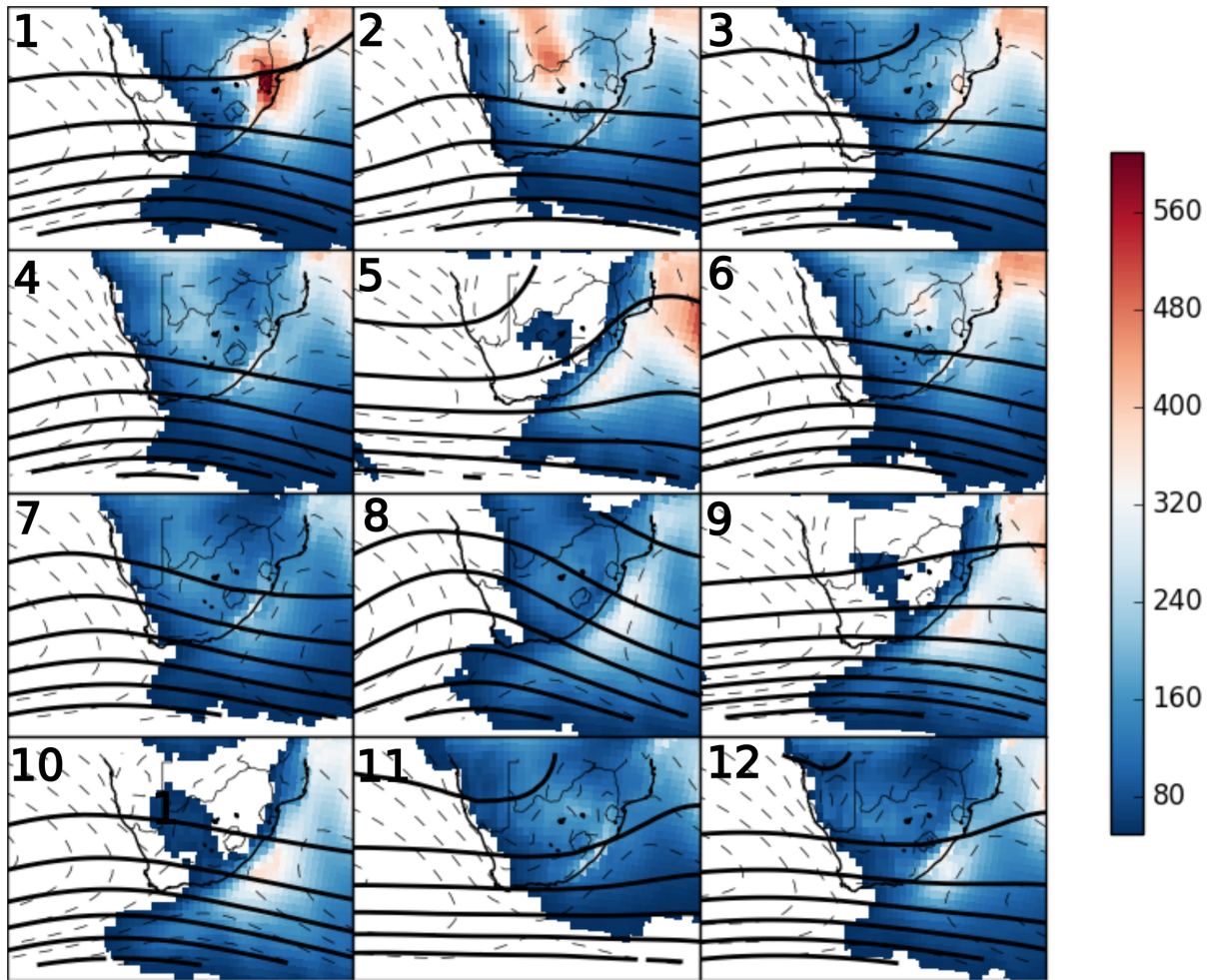
wind speed is observed, however the simulations indicate that in the 0 - 3km bulk shear the variability between the case studies is still too high to consider for the use in the cluster analysis. The 0 - 6km shear shows the most homogeneity in a space and time but this is expected as the dominant upper level winds start influencing the storm environment and motion considerably closer to the storm top, illustrated in Figure 1.2, d (Browning and Foote, 1976).

Careful consideration was taken for the selection of variables in the cluster analysis. CAPE was chosen as the variable shows a well-defined spatial distribution across the study area. CIN was not included due to the inverse correction with CAPE. The variability bulk shear of the lower levels 0 - 1km and the 0 - 3km meant that the variable is not spatially well-defined and could result in over-fitting of data in cluster analysis, resulting in unrealistic clusters. Although the 0 - 6km wind environment showed the most homogeneity, it was decided that the 0 - 6km environment can be better represented by using MSLP and geopotential at 500 hPa in a cluster analysis as demonstrated by other case studies (see Aran et al. (2011); García-Ortega et al. (2011); Hermida et al. (2015)). The over-fitting of data with any type of cluster analysis has to be taken into consideration to avoid findings unrealistic relationships that may not exist.

## Cluster analysis results

The cluster analysis required some subjective selections to be made; CAPE, MSLP and geopotential at 500 hPa was selected as the input variables to drive the clustering. Cost733class software was used to perform the cluster analysis by the use of a PCACA clustering method. For the first step of the PCACA an HCA analysis on the data is performed to reduce the data dimensions. This step is automatic and the number of clusters generated is independent of the user input. After the data has been reduced the next clustering method is performed namely a k-means analysis. The k-means analysis requires a number of clusters to be subjectively defined by the user in this study 12 clusters were defined taking into consideration Tyson and Preston-Whyte (2000) classified the weather observed in South-Africa into 10 characteristic types. The selection of 12 clusters allows for the extra dimension in the data, in this case CAPE to be accounted for. A last consideration was the resolution of the ERA-Interim data which is  $0.75^\circ \times 0.75^\circ$ , to accurately account for this and the nature of synoptic scale circulation the whole South-Africa is subsequently shown in the results. The synoptic patterns associated with each cluster is indicated in Figure 4.1. The synoptic patterns show that CAPE is observed in the eastern parts of the subcontinent. The influence of the warm Indian Ocean plays a major role in this observed instability as more convective heat and moisture is available over the Indian Ocean and a subsequently convective favoring atmosphere.

Figure 4.3a indicates the annual (seasonal) distribution of the synoptic patterns per cluster, this similar to observations as seen in Tyson and Preston-Whyte (2000). The frequency of hail events within the individual clusters can be observed in Figure 4.3b, these are events that were recorded in media outlets during and corresponding with the cluster analysis time frame. Clusters 3, 7 and 11 have the highest number of reported hail events occurrence. These clusters are all prominently observed during summer months as seen in Figure 4.3a. In the clusters the synoptic patterns associated with hail events are defined by the presence of a surface trough extending from the tropics towards central South-Africa (a known association to severe weather over South-Africa), while CAPE is well distributed across the whole South-Africa. Figure 4.2a indicates a synoptic composite map of the case studies examined in the previous chapter. This figure shows the observed distribution of CAPE during hail days which seems similar with the CAPE observed in the hail clusters as seen in figure 4.1. There are also similarities between the MSLP indicating a ridging high pressure system along the east coast. The geopotential height at 500hPa does however seem to be similar across the hail day clusters making it difficult to draw a comparison to the composite map. There is however a lower observed CAPE in the synoptic results compared to the local scale model simulations. A comparison between (Blamey et al., 2016) research and the composite map created from the case studies indicates how CAPE is concentrated similarly in this study. This distribution is similar also to cluster 2, showing high CAPE concentration over the North-West and Gauteng area with a peak value in November when these severe events are observed, this also highlights a possible limitation in the cluster analysis.



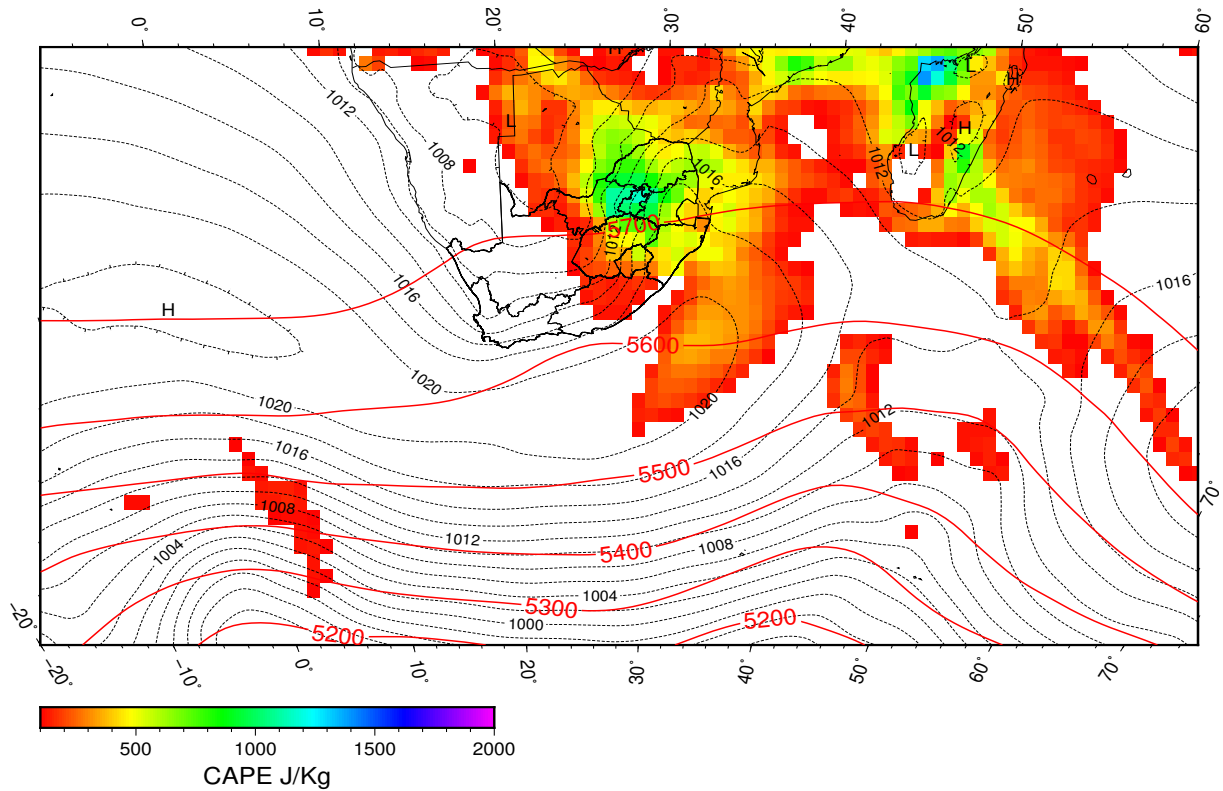
**Figure 4.1:** Characteristic synoptic types over South-Africa based on twelve clusters. Note that the clusters are not ordered according to months but as the raw output from the cluster analysis. The clusters accurately represent South-Africa's weather types based on previous research, characteristic summer and winter weather types is observed and this is supported in the following figure where we can see the temporal variation of the weather types is similar to that documented Tyson and Preston-Whyte (2000). Shaded values indicate CAPE, thick lines represent geopotential at 500hPa and the intermittent thin lines indicate MSLP.

Cluster 2 is shows the most similarity to the composite map, (Blamey et al., 2016) data and also shows a seasonal distribution peaking in October, November, December, however the cluster does not have such a high amount of hail reports.

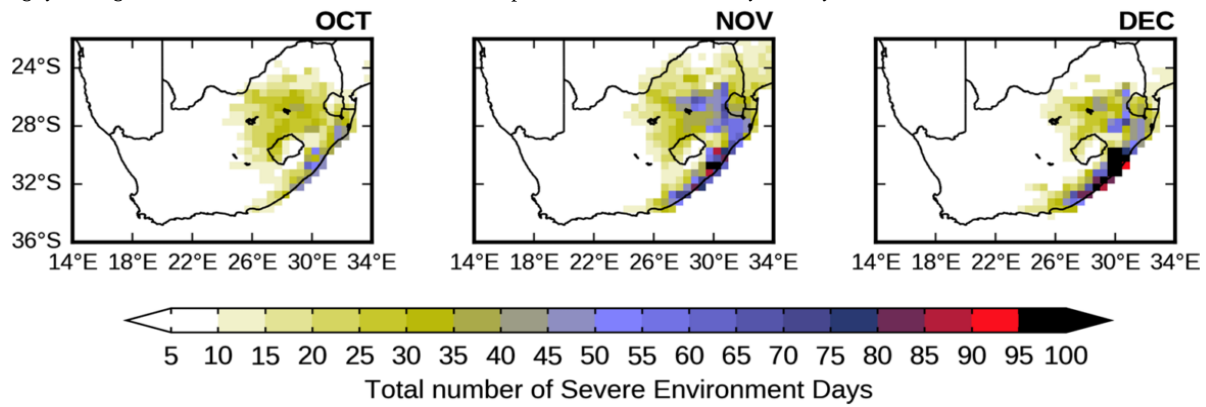
## The link between the meso- $\gamma$ scale and macro- $\beta$ circulation patterns

The cluster analysis was successful in representing synoptic conditions associated with hail events. Storm reports were used to validate the occurrence of hail events within clusters. Cluster 3, 7 and 11 had the highest prevalence of hail events. The three mentioned clusters show a characteristic seasonal variation, all observed during spring and summer months. Cluster 11, where hail events were observed in has the same peak occurrence in October/November as observed in previous studies and a similar distribution is observed in cluster 7. Cluster 3 has a less pronounced peak, but shows a definite summer distribution. Key features in these maps is the distribution of CAPE and also the very prominent featuring of the SICZ, linking the observable ridging high pressure system over the eastern coast.

The synoptic conditions of the hail related clusters share a similar surface trough extending from the tropics towards the mainland. Comparing the synoptic patterns with a composite map created from ERA-Interim data of chapter 4's case studies indicates the influence of the ridging high pressure system over the eastern part of the



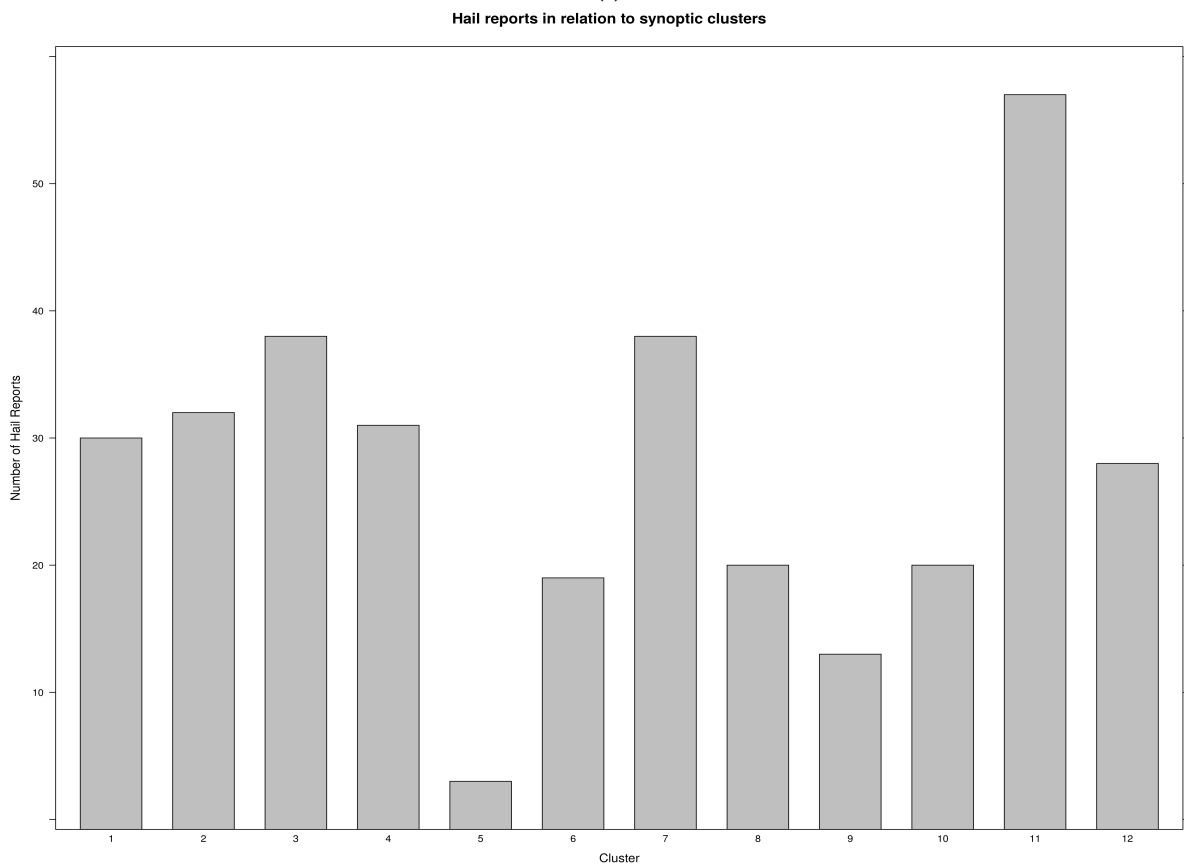
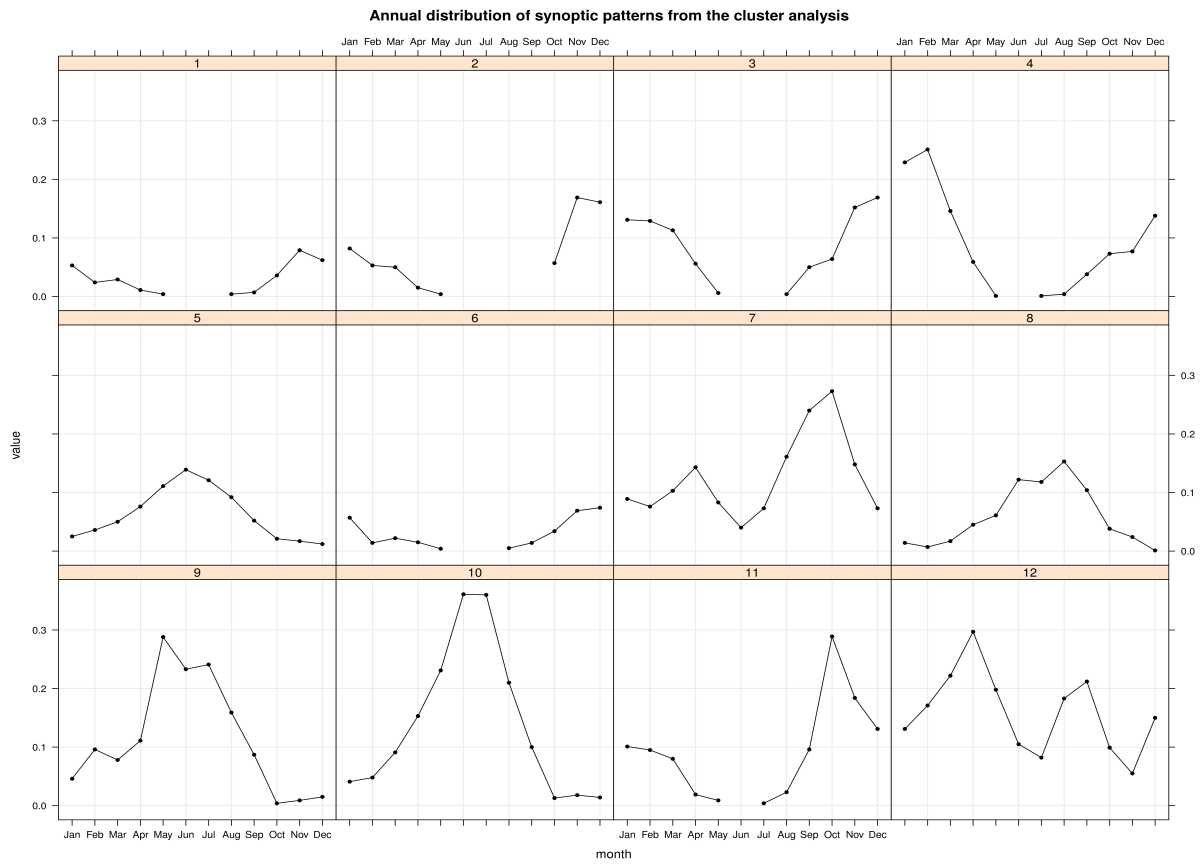
(a) The above composite map of the case studies examined in chapter 3 indicates the synoptic flow and associated CAPE values of these 5 extreme hail events. The map clearly indicates the ridging anticyclone, surface trough and 500 hPa geopotential heights impacting vorticity and impacting freezing levels. CAPE indicates a warm, unstable atmosphere during these events. The combination of high freezing levels and convective unstable, moist air provides ideal conditions for hail formation.



(b) The Spatio-temporal map of severe storm days by Blamey et al. (2016) shows a similar distribution of environments ideal for storm formation when compared to the composite map created from the case studies.

**Figure 4.2:** Comparing the composite map from the case studies (Figure a) with Blamey et al. (2016) (Figure b) map of the days with an environment suitable for severe events illustrates that October-November-December's CAPE distribution is correlated with an overall environment suited for storm formation. From 4.1 it can be seen that the SICZ and the ridging high-pressure and surface trough plays an important role in the hail formation.

coast while we can see a well developed westerly wave dominating the upper-air. This also impacts the movement of the storms and the cold airmass allows for the unstable, warm surface air to rise high into the troposphere and freezing levels (see Figure 4.2a). This has long been known as a cause for summer weather events. The clusters are also reasonably accurate in replicating Tyson and Preston-Whyte (2000) common weather types of South-Africa. With regard to convective environments associated with hail and thunderstorms there are similarities with Blamey et al. (2016) recent study of severe storm environments over South-Africa which shows a correlation between clusters, CAPE and the ridging high pressure system.



**Figure 4.3:** The annual distribution of synoptic patterns from the cluster analysis (a) and hail events reported per cluster across South-Africa (b) indicate a that cluster 3,7 and 11 have a majority of hail events in them.

# Chapter 5

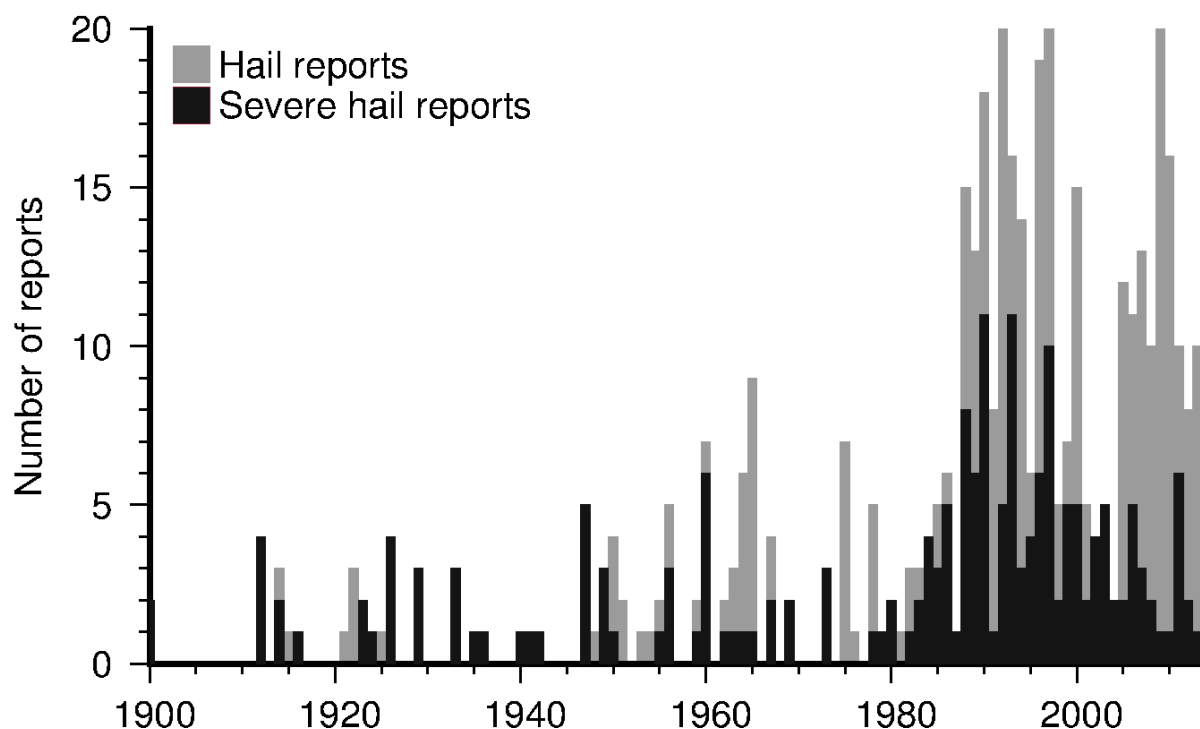
## Trends and cycles of hailstorms over the Highveld

The final chapter addresses the main research question posed in this study namely; What are the trends and cycles of hailstorms over the Highveld? The previous chapters examined the atmospheric environment characteristic of hailstorms and these findings are applied to analyze the long-term trends or possible links between hailstorms and ENSO. The chapter starts by examining media reports related to severe hail events over the last 100 years while media reports provide insight into the reporting frequency and trends of hail events over the Highveld and also South-Africa. The data also provides an alternative perspective into the spatial distribution of these events and based on these findings a new HDF map is created based on Le Roux and Olivier (1996); Schulze (1965) HDF original map. The second part of the chapter builds on the numerical simulations of the selected case studies which focussed on simulating the thermodynamic profile of the severe storm days. Here additional sounding derived indices are evaluated from the IGRA database, this includes CAPE, CIN, K-index, TT, LI and SI recorded at the Irene weather station. The seasonal and long term variation of the thermodynamic indicators are evaluated by the use of a Thiel-Sen slope analysis. The aim of this section is to evaluate the possibility of an atmosphere that may increasingly favour convective storms and concludes by correlating the cycles of the macro- $\beta$  scale synoptic patterns and the possible association with ENSO. The final analysis is conducted by using the SOI and the occurrence of specific clusters identified in chapter 4 to be related to hail events and a Pearson correlation test is used here to evaluate the link between the events.

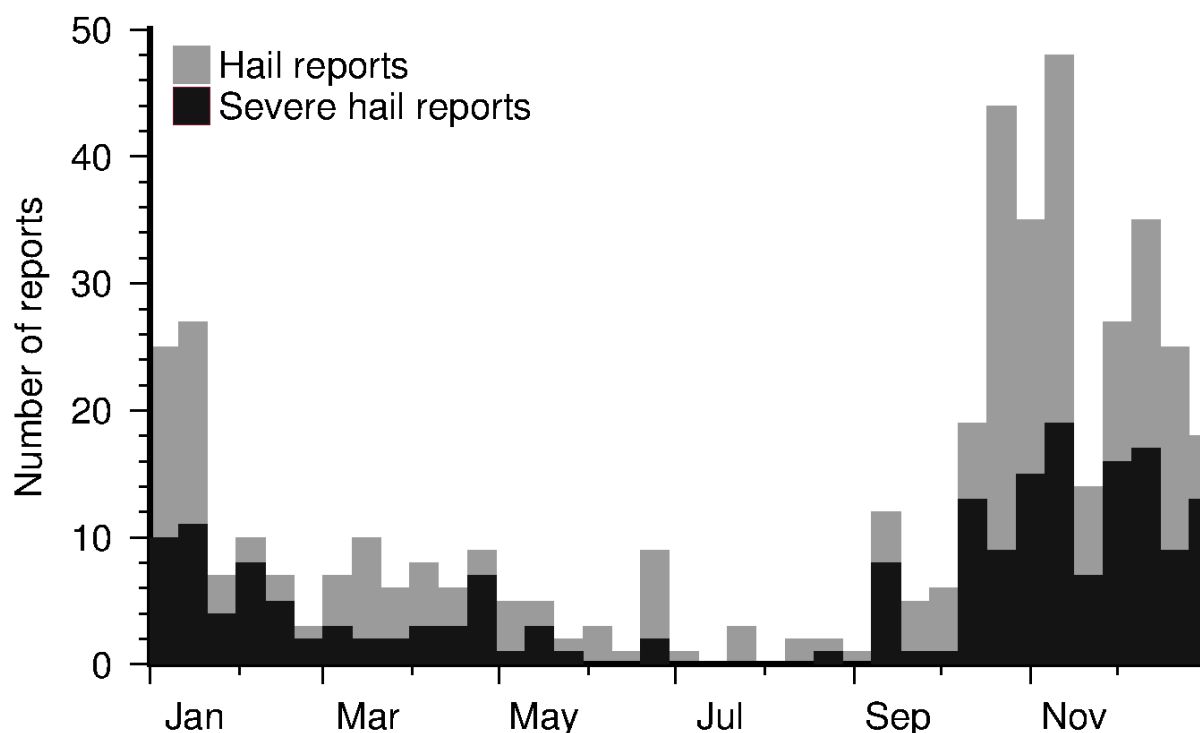
### Media coverage of hail events and a new hailday frequency map

This section uses media reports to analyse the spatio-temporal distribution of hail events over South-Africa and the Highveld. It is known that using media reports has some biases that need to be considered and this is discussed later on. These reports still provide a valuable source of data to assess the trends and the historical relevance of key hail events and go as far back as the 1600s when one of the first notable weather events in South-Africa's documented weather history was a hail event in 1692 (Caelum, 1991) affecting ships along the Cape province. Weather events have been relatively well documented in modern times due to their impact on society. In some areas where there is no official weather record and media reports serves as an alternative way to analyze data from events. However weather events reported is based on factors such as location and population density, for example De Coning and Adam (2000) noted how several tornadic events in 1998 and 1999 generated above average interest in tornadoes during the time period. The same could be said for other severe events; the media's interest in particular storms could have an influence on how it is reported and consequently perceived by the public. It should also be noted that the small spatial extent of severe events could mean that many events occur in unpopulated areas and go unreported. Punge and Kunz (2016) also supported this notion as he states there is a higher chance of storms being reported during the growing season in agricultural regions as the economic and social implications are highlighted in this period. With these uncertainties and biases in mind, in Figure 5.1 illustrates the reporting frequency for hail events over the last century. For an event to be classified as severe some loss of life (human or livestock) occurred and/or damage to property was emphasized in the report. Figure 5.1 clearly indicates an increase in reported hail events from the 1980s onwards. Several factors have to be considered; first the increase in reports could be correlated to the expansion of urban areas in a region, secondly some storms may go unreported if the areas effected did not suffer a noteworthy loss and the resources dedicated to reporting severe events also plays a role, such as other newsworthy events happening at a similar time. Figure 5.2 represents the annual distribution of hail reports over the whole South-Africa and as expected the majority of events fall within the Summer when convective events are common over a large part of South-Africa.

To represent the spatial distribution of the media reports seen in Figure 5.2 data points are plotted spatially over South-Africa in Figure 5.3. The Figure illustrates the high prevalence of hail reports in populated areas as would be expected. Densely populated places will have a higher chance of hail being reported compared to rural or unpopulated areas. Around the Drakensburg there is also high frequency of hail events but the area is rural



**Figure 5.1:** The diagram represents media reports on hail over the last 100 years. The data was obtained from Caelum (1991) while additional data was gathered from media reports in popular newspapers. This was used as sources to date Caelum (1991) reports. As can be seen the number of reports has steadily increased from 1900s, this could mainly be due to the fact that the extent of media coverage has increased and more news outlets are in existence. Another factor is the increase in weather monitoring sites, population density and industries affected by hail storms.

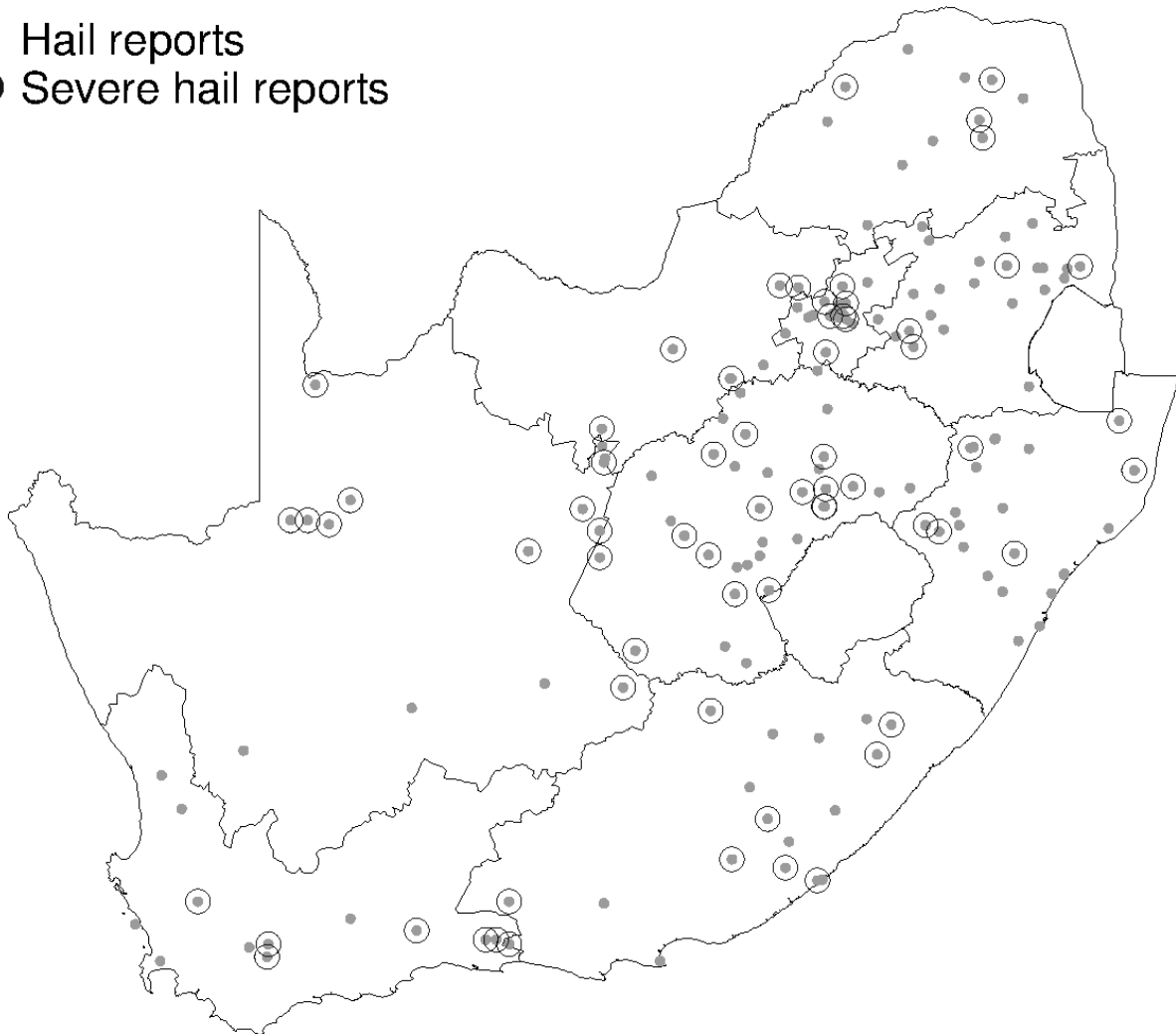


**Figure 5.2:** The annual distribution of hail media reports and is in general agreement with the annual distribution of hail over South-Africa. October and November have a proportionally higher reporting instances.

with some midsize towns so the high hail reports could be attributed to the agricultural sector prevalent around the Drakensberg. In Le Roux and Olivier (1996); Schulze (1965) HDF map it is clear that this area also has a

high HDF. Several reports over the Western Cape are visible and these events usually occur in the mountainous regions in the form of graupel (Tyson and Preston-Whyte, 2000).

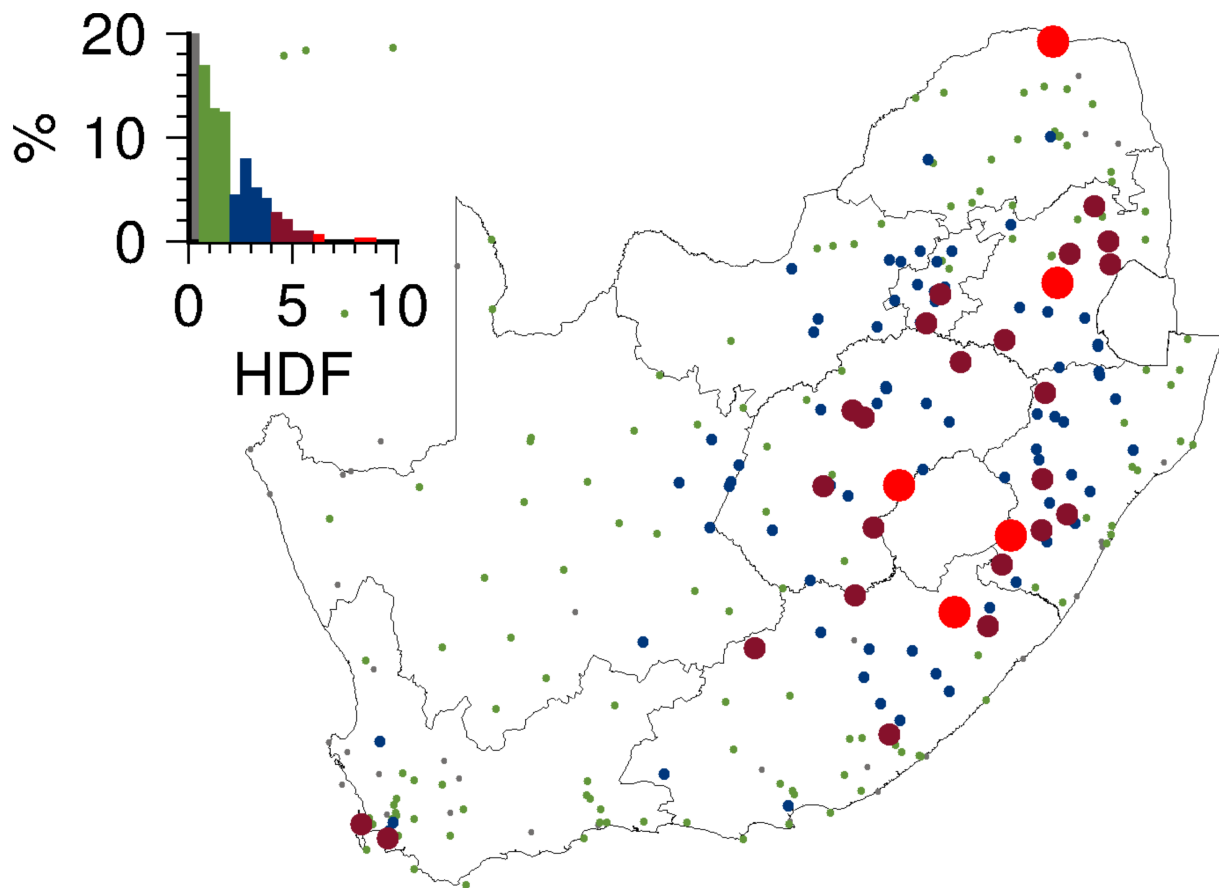
- Hail reports
- Severe hail reports



**Figure 5.3:** *The spatial distribution of severe hail events according to media reports correlates with the distribution of hail over South-Africa as described by Cecil and Blankenship (2012); Le Roux and Olivier (1996); Schulze (1965). The number of severe hail reports are higher over Gauteng mainly due to the area's high population and infrastructure density.*

An alternative HDF is illustrated in Figure 5.4 by the combination of media and historical weather data for South-Africa. The new HDF map shows a similar distribution of hail events to that of Cecil and Blankenship (2012); Le Roux and Olivier (1996); Schulze (1965). The map does not interpolate the data spatially but instead shows the HDF as reported at a specific site. Figure 5.4 illustrates that the Highveld area consisting of parts of Mpumalanga, Free-State, Gauteng and North-West shows a high density of hail events. Parts of the northern Eastern-Cape around Lesotho also have a high density of events compared with the southern parts of the province.

Some limitations of using the above dataset has already been mentioned. Arguments can be made that media reports are biased towards reporting storms that resulted in extreme damage or storms that can *sell*, as such many storms that are deemed insignificant from an economic or social perspective may never be heard of again in the media. However, the data indicates that the annual reports of hail is generally in agreement with the known seasonal distribution of severe weather and hail events occurring from early October to late February. Winter hail events could be disproportionally reported because of the rare nature of these events. Two interesting studies by Lobb et al. (2012) and Brown and Minty (2008) noted the impact of news reports and their frequency on the public's perception and charitable giving related to natural disasters and the papers found that the news agencies had considerable influence on the public's perception of events. It was found that events receiving more news



**Figure 5.4:** A new hail day frequency map created from Bureau (1986) data and Caelum (1991) reports. The HDF map is in agreement with that of Cecil and Blankenship (2012); Le Roux and Olivier (1996); Schulze (1965), a high HDF is observed around the Lesotho highlands. The Highveld region as a whole has a HDF between 2 - 4, while Johannesburg metropolitan area has a HDF between 4 - 6 per year. As noted by Tyson and Preston-Whyte (2000) the mountains around the Western Cape region receives hail, which is evident in the above Figure, but this is usually in the form of soft hail and ice rain.

coverage receive more relieve donations even if the loss of one event was greater than another. The biases in the media is well understood, however the data can be useful to understand the perception and impact of hail events in certain areas.

## The seasonal and long term trends of thermodynamic indices

Chapter 3 provided insight into the spatio-temporal extent of small scale thermodynamic variables associated with severe hailstorms. It is noted that these cases are not representative of all hailstorms over the Highveld or Gauteng but was used as sample to evaluate the thermodynamic properties of severe hailstorms on the small meso- $\gamma$  scale. The results show the prominence of some thermodynamic variables in the simulations of severe events. CAPE, CIN and SI values associated with severe events were within the threshold values associated with severe convective events in all the cases simulated. In the following section these thermodynamic variables are evaluated to examine seasonality and the long term trends. The IGRA dataset was used in this section to conduct the long term time series analysis. The IGRA (Durre et al., 2006) database contains radiosonde data from weather stations around the world, including data from the Irene station, here we used the 12UTC sounding as this would be representative of the atmosphere in the afternoon when convection usually occurs.

Radiosonde data is prone to failures and within the scope of this study the data underwent a minimum sanity check as the IGRA already undergoes a quality control procedure (Durre et al., 2006). Dyson (2013) advises against the use of the IGRA database as data for some periods is missing and erroneous dew point are could impact soundings on convective days. After an extra sanity check for missing or erroneous values the soundings



were used for analysis. Dyson (2013) emphasizes that thermodynamic variables and values associated convection may differ across geographic locations. The values discussed serve as baseline and is not specific to the Highveld. The indices derived from the data and the associated *values* related to severe weather events is briefly discussed below.

## CAPE and CIN

CAPE (see equation 1.1) is a well-known indicator associated with severe storms. The variable serves as an indication of a lifting parcels buoyancy. CAPE values  $\geq 1000$  J/kg are associated with a high possibility of severe weather events occurring. In the case studies from chapter 3 high CAPE was observed spatially and temporally. The simulations also indicated that CIN (see equation 1.2) has an inverse correlation with CAPE as discussed previously CIN refers to the negative energy a parcel has to overcome in order to break through the CAP and lift to its EL.

**Table 5.1:** *CAPE and CIN values associated with convective events (Grieser, 2012).*

| CAPE (J/kg)          |                           | CIN (J/kg)               |                                    |
|----------------------|---------------------------|--------------------------|------------------------------------|
| Weak instability     | 0 - 1000                  | $\leq -15$               | Minor convection (early formation) |
| Moderate instability | $\geq 1000$ & $\leq 2500$ | $\geq -15$ & $\leq -50$  | Possible singlecell storms         |
| Strong instability   | $\geq 2500$ & $\leq 4000$ | $\geq -50$ & $\leq -200$ | Possible multicell storms          |
| Extreme instability  | $\geq 4000$               | $\geq -200$              | No convection (stability to high)  |

## The Showalter and lifted index

The SI provides an indication of the instability in the atmosphere (Showalter, 1953) (see equation 1.3)<sup>1</sup>. Table 5.2 indicates the values of the indices and the associated convective event. Dyson (2013) found that the lowest average SI value occurs during December over the Highveld ( $-2^{\circ}\text{C}$ ). The LI (Galway, 1956) is similar to the above mentioned SI. According to Groenemeijer and Van Delden (2007) the LI shows considerable skill to forecast severe convective events associated with hail. The index represents a parcel as it is lifted from the surface to the LCL whereas SI calculates a parcel lifting from 850 hPa. Because of this similarity between SI and LI Table 5.2 similar thresholds exist.

**Table 5.2:** *SI-Index and LI values associated with convective events ( $^{\circ}\text{C}$ ) (Showalter, 1953).*

| Showalter Index                                   |           |
|---------------------------------------------------|-----------|
| Weak instability & little to no rain              | $\geq 0$  |
| Moderate instability & thunderstorm activity      | 0 to - 3  |
| Strong instability & severe thunderstorm activity | $\leq -3$ |

## The K-Index

The K-index (George, 1960) is another thermodynamic derived product used to evaluate instability in the atmosphere, but is more suited for rainfall evaluation. The ki-index is based on the vertical temperature gradient between 850hPa and 500hPa. Table 5.3 indicates the values of the indices and the associated level of instability. According to Dyson (2013) the K-Index (KI) over South-Africa is  $\geq 30^{\circ}\text{C}$  during the South-African thunderstorm season. January has the highest average KI at  $37^{\circ}\text{C}$  well above the threshold used to evaluate the possibility of thunderstorm occurrences. The KI may also be prone to erroneous values as dry air at 700 hPa could falsely indicate instability. Considering that the index is more suited for rainfall, in the scope of this section the index is still evaluated as it provides insight into the trend of instability examined.

<sup>1</sup> According to Tyson and Preston-Whyte (2000) the SI has been configured for use over South-Africa by the SAWS, this method is however not used and the IGRA derived SI is used in its original form

**Table 5.3:** *K-Index values associated with convective events ( $^{\circ}\text{C}$ ) (George, 1960)*

|                      | K-Index   |
|----------------------|-----------|
| Weak instability     | $\leq 20$ |
| Moderate instability | 20 - 30   |
| Strong instability   | $\geq 30$ |

### The total totals index

The TT, is a sum of the VT and CT (see equation 1.4). Along with providing a measure of instability the indicator can also provide an estimate of storm strength (Miller, 1972). Table 5.4 shows the TT values and the associated convection in the atmosphere. Dyson (2013) found that the TT values are the highest in December. The variation between the TT values in October, November, December and January differs minimally. In De Coning and Adam (2000) study of the 15 November 1998 and 18 January 1999 tornadic events only TT met the threshold for the indication of a possible severe event on both occasions.

**Table 5.4:** *Total Totals Values ( $^{\circ}\text{C}$ ) associated with convective events (Miller, 1972)*

|                                      | Total Totals Values |
|--------------------------------------|---------------------|
| Weak instability & little to no rain | $\leq 40$           |
| Possible thunderstorm activity       | 40 to 50            |
| Severe thunderstorm activity         | $\geq 50$           |

### Seasonal trends of thermodynamic indicators

The IGRA dataset for the Irene weather station was used to analyze the trends of thermodynamic indicators for a period of 45 years. Each indicator was analyzed for seasonal and long term trends. The section is similar to Dyson (2013) analysis of heavy rainfall events using sounding derived indicators. The exception is that Dyson (2013) used radiosonde data from the UWYO database while the IGRA database is used in this study. A Theil-sen slope analysis is used to determine the trends of the selected parameters along with the 95% confidence interval of the slopes. In the analysis seasons are defined as summer (December, January & February), autumn (March, April & May), winter (June, July & August) and spring (September, October & November).

Figure 5.5 shows a clear indication of the seasonal variation observed in CAPE. Spring and summer months are associated with the highest average CAPE values and summer averages slightly over  $1000 \text{ J/kg}$ . This is ideal for the formation of convective storms. The high values are expected as the circulation over South-Africa during summer is associated warm tropical circulation which is highly unstable and increases the amount of buoyant energy in the atmosphere. There is also a significant upward trend in the buoyant energy available in the atmosphere over the last 40+ years, particularly in the spring and summer months. The Thiel-Sen slope analysis indicates a significant trend of 0.59 and 0.46 for the spring and summer months respectively. No significant trend is observed in the autumn and winter months and CAPE values seem to be relatively stable. These observations support Dyson (2013) findings that CAPE values peak in December and January. The positive seasonal trend that is observed in the CAPE values indicate that the atmosphere is becoming increasingly favorable for the formation of severe events associated with convection.

The inverse correlation between CIN and CAPE has been discussed previously in chapter 2. In Figure 5.6 we see that the seasonal trend is less pronounced than that of CAPE. The lowest values of CIN is observed during the summer months from November to February with only a marginal difference between the seasons. The fine balance between CIN and CAPE is emphasized again and if the CIN is too low severe storms will not appear and only cumulus clouds will form while high CIN can completely prevent storm formation. According to Grieser (2012) values of  $-15 \leq -200$  is favorable for convective activity. The values remain stable throughout the year and no significant difference is observed between the seasons.

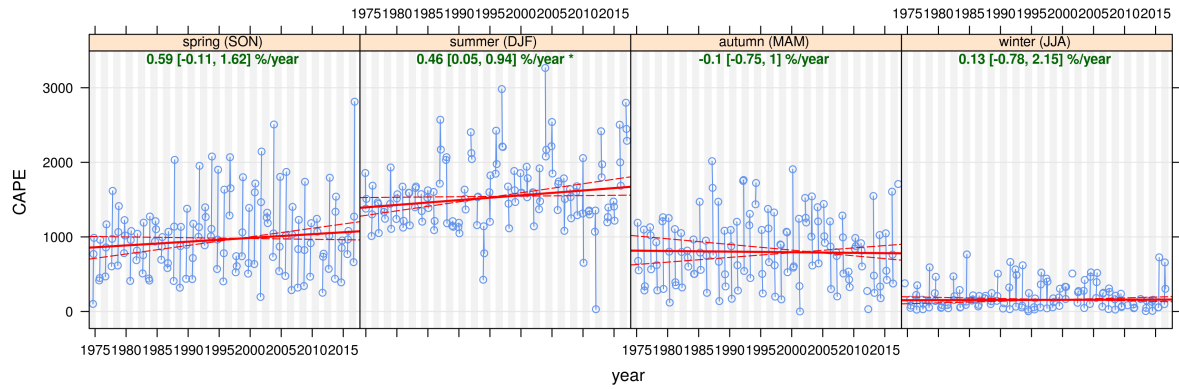


Figure 5.5: The seasonal distribution of CAPE

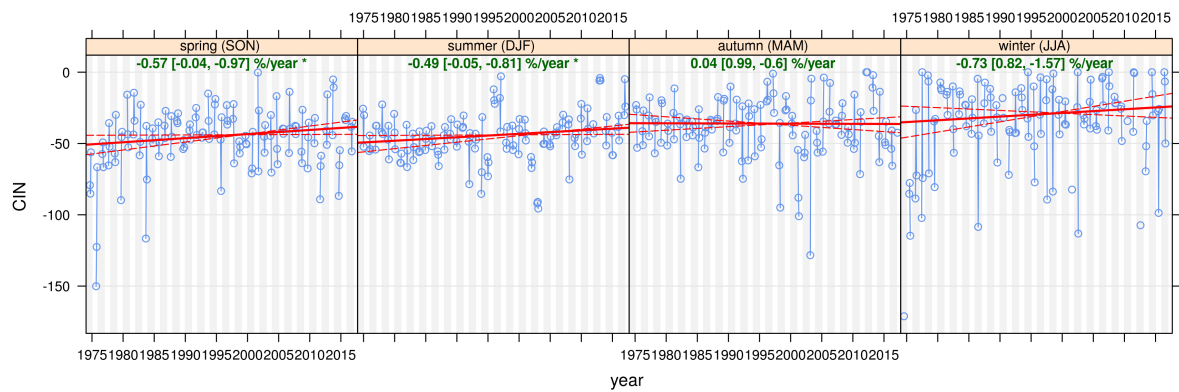


Figure 5.6: The seasonal distribution of CIN

The KI based on the vertical temperature gradient between 850hPa and 500hPa has a well-defined seasonal variation (see Figure 5.7). The highest KI values are observed in the summer months and there is also an observed positive trend in this value indicating an increasingly convective favoring atmosphere during summer months. A positive trend is also observed during spring months, although not that significant. Autumn and winter months show no significant positive trend but it is observed that the winter months show a trend towards a more stable atmosphere with a slight decreasing trend. This is similar to that observed by Dyson (2013).

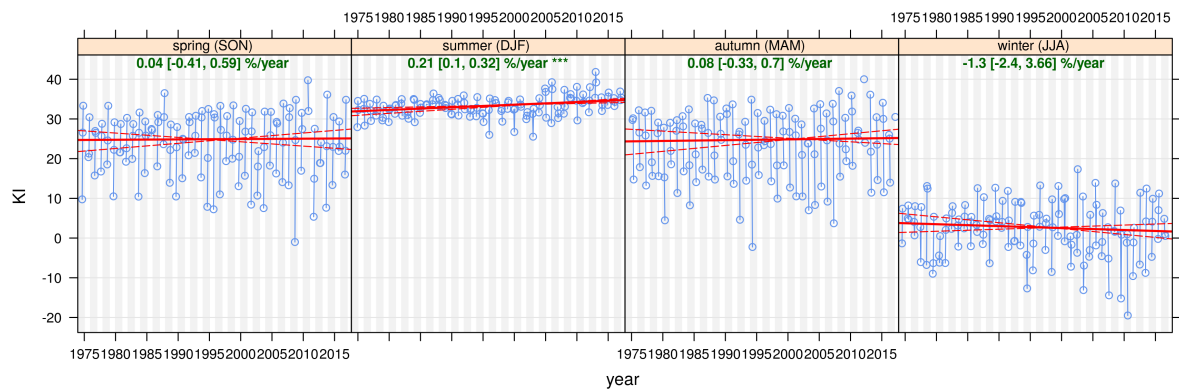


Figure 5.7: The seasonal distribution of the K-Index

The SI was well represented in each of the case studies simulated in chapter 3. In Figure 5.8 the SI shows a well-

defined seasonal variation. The summer months have an average of  $-3^{\circ}\text{C}$  indicating an unstable atmosphere favoring convection but this is only observed in the summer months. In autumn, winter and spring all SI values are slightly positive (stable atmosphere). The SI values also show no significant trend towards a convective favoring atmosphere in any of the seasons. The LI, Figure 5.9, shows a similar seasonal variation to the SI, however there is a significant trend seen in summer, spring and autumn months towards a more unstable atmosphere. Winter LI values show no significant positive trend indicating that the atmosphere remains in a relatively stable state.

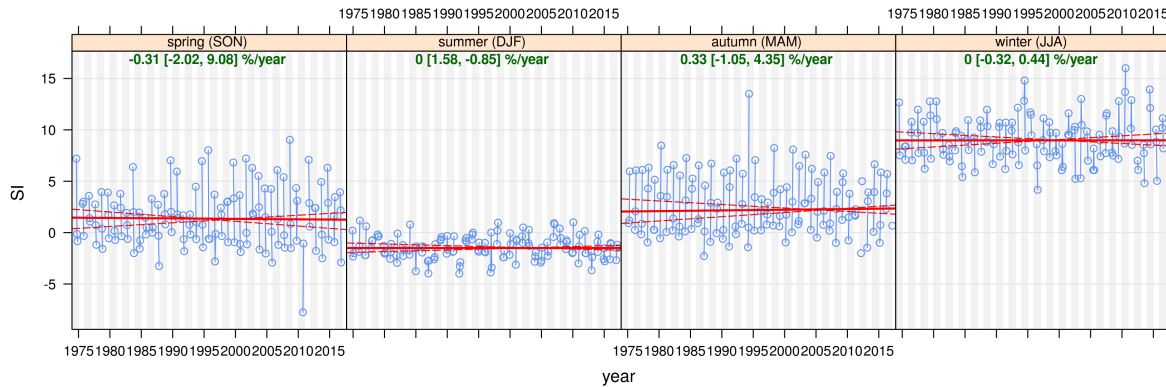


Figure 5.8: The seasonal distribution of the Showalter index

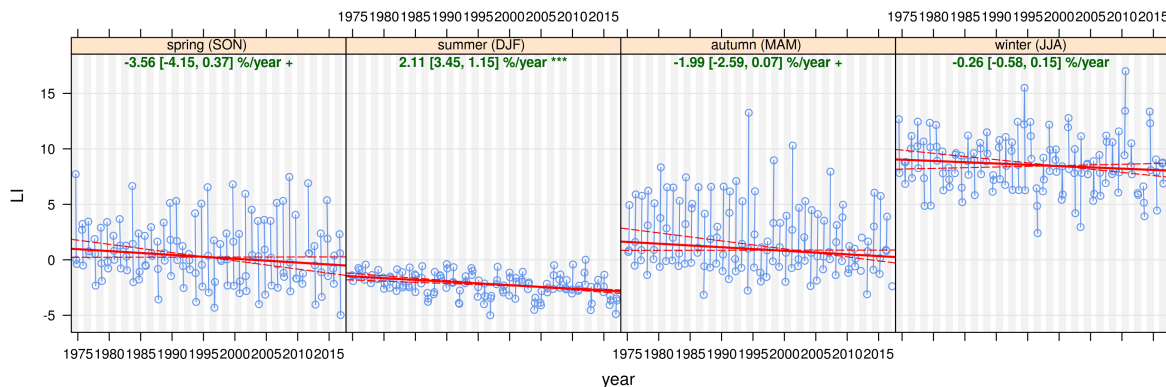
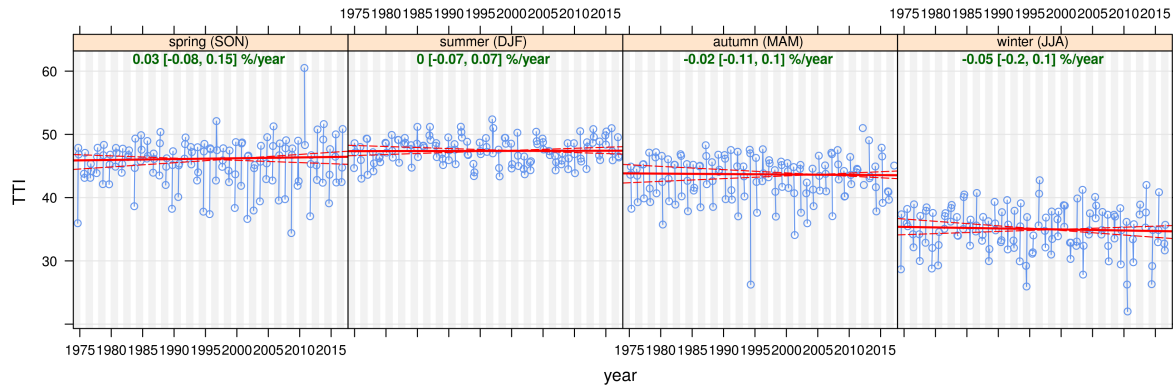


Figure 5.9: The seasonal distribution of the Lifted index

The TT values observed at the Irene weather station show a clear seasonal variation, similar to the indicators already discussed. The TT value is useful in that it provides a measure of possible storm intensity as well as instability (Grieser, 2012). In Figure 5.10 no significant trend is observed in the TT values. The seasonal variation between spring and summer is minimal while the winter conditions are stable as expected. According to Dyson (2013) summer highs are in the order of  $\pm 53^{\circ}\text{C}$ , however Figure 5.10 indicates marginally lower values compared to work by Dyson (2013).

In this section the seasonal trends and variations of selected sounding derived variables were evaluated. The Thiel-sen slope analysis was used to evaluate the seasonal trends of the selected indicators from 1975 to 2016. The Thiel-Sen analysis is robust and depends on the median slope of the data this means that outliers influence the data less. Furthermore, only the 12:00 UTC sounding was extracted from the dataset as convective storms occur within the early to later afternoon. Six thermodynamic variables were analyzed namely CAPE, CIN, KI, SI, LI and TT. Three indicators showed a significant trend towards a convective a favoring atmosphere, this was CAPE, KI and LI. CAPE was also used in the previous two chapters, first as a variable to evaluate the meso- $\gamma$  scale environment associated with severe weather events and then as a variable to drive the cluster analysis. A



**Figure 5.10:** *The seasonal distribution of the total totals index trends*

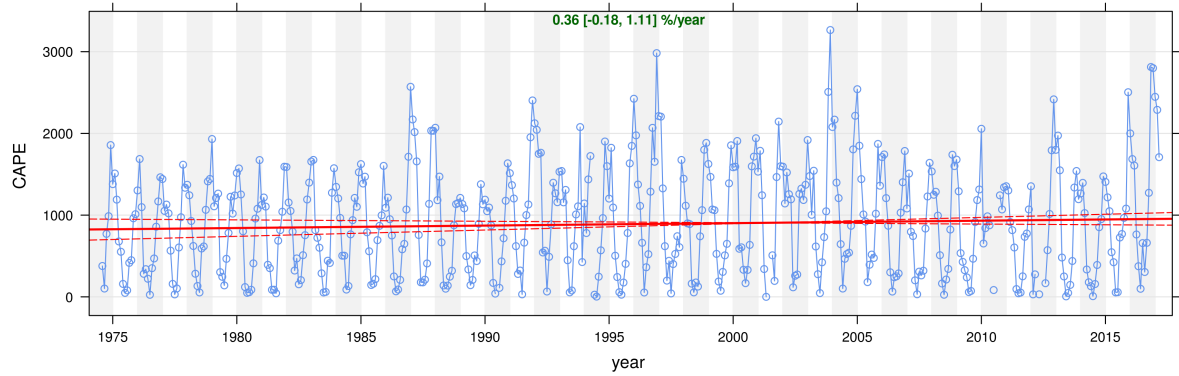
significant increase in CAPE is observed during spring and summer months while winter and autumn remain stable. The KI only showed a positive trend during summer months for convective favoring atmosphere while LI indicated that spring, summer and autumn had a significant trend towards a more unstable atmosphere. CIN also showed a significant positive trend, however, the indicator is difficult to evaluate as there is a balance between the stable layer represented by CIN and buoyancy represented by CAPE. If CIN values are too low ( $\leq -15$ ) only minor convection will occur and storms could form too early for powerful storms to occur. High CIN,  $\geq -200$  could prevent lifting and convection might not occur either. If CIN is evaluated along with the increasing CAPE observed during spring and summer, it could be that the positive CIN trend observed shows an atmosphere where lifting is increasingly favoured. The SI and TT show no significant trend in the seasonal analysis.

## Long term thermodynamic trends of thermodynamic indicators

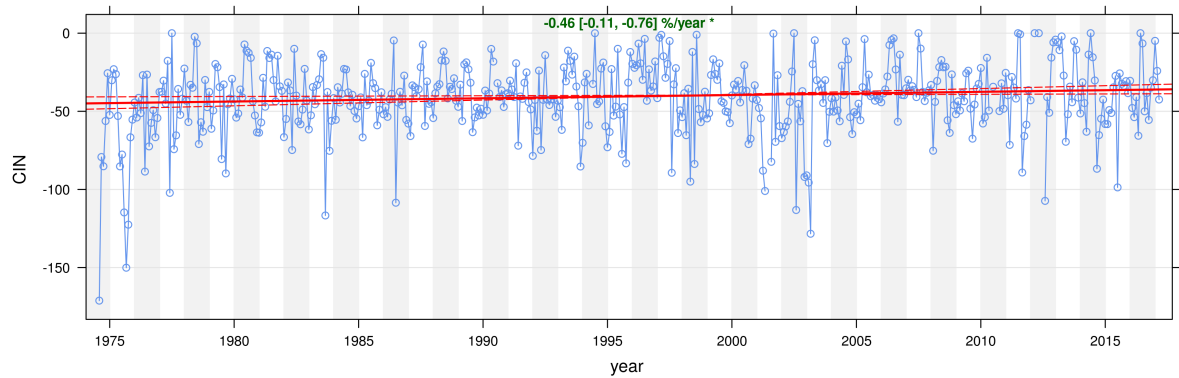
Over South-Africa scientists have stated that climate change could result in an increase in extreme events associated with heavy rainfall, flooding and possibly more severe hailstorms. The  $4^{\circ}\text{C}$  increase projected would have a strong effect on convective nature of the atmosphere (Engelbrecht et al., 2013; Piketh et al., 2014). More heat allows the atmosphere to hold more moisture and also increases the amount of convective energy. In the following section the long term trend of CAPE, CIN, KI, SI, LI and TT is evaluated from the IGRA dataset. As with the seasonal analysis a Thiel-Sen slope analysis is used as the method is robust and insensitive to outliers. Only the 12:00 UTC was used in the analysis as convection is likely to occur in the afternoon and later afternoon.

Figure 5.11 indicates that CAPE has increased significantly over the last three decades (0.36). The increased CAPE supports the climate change predictions of (Engelbrecht et al., 2013; Piketh et al., 2014) as the variable is a function of the energy in the atmosphere which effects the convection type and intensity. When the seasonal analysis is considered we can observe the increase in CAPE in the spring and summer months while winter and autumn remain stable. This is expected as CAPE is a function of heat and moisture, with a warming atmosphere both these variables can be expected to increase, the freezing levels also play an important role in ice formation, if more heat and moisture is lifted into the atmosphere and freezing levels allow for ice formation we can expect an increase in hail events. The long term trends from the IGRA dataset indicate that CIN is significantly decreasing (-0.46) (Figure 5.12). The decreasing CIN value is still within the thunderstorm threshold as described by Grieser (2012). However, the CIN value should be evaluated concurrently to CAPE. The increasing CAPE value along with the observed CIN value could indicate that the conditions for thunderstorm formation is becoming more favorable and the CIN is not increasing to a level where convection is completely halted neither do we observe low CIN where convection is triggered too early.

The SI showed accuracy in the simulations discussed in chapter 2, in all five case studies the SI was simulated within thunderstorm thresholds. Figure 5.13 indicates that the low value of the SI shows a slightly decreasing trend over the last three decades. This decreasing SI supports the CAPE observations that an increasingly unstable

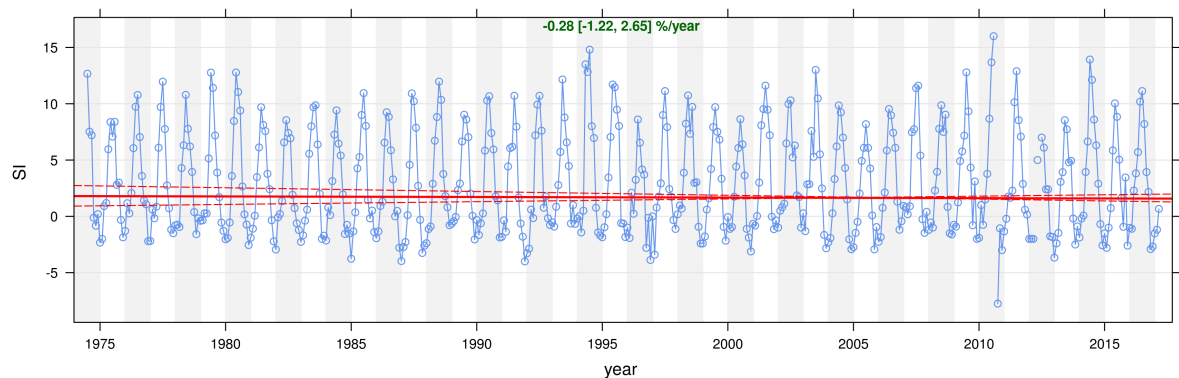


**Figure 5.11:** *The long term trend of CAPE based on the IGRA dataset and a Thiel-Sen slope analysis*



**Figure 5.12:** *The long term trend of CIN based on the IGRA dataset and a Thiel-Sen slope analysis*

atmosphere is ever more present over Gauteng. However, the trend is marginal and by referring back to the seasonal variation of the SI index this can also be seen. The slight decreasing value is however important to observe and when the rare spatio-temporal nature of severe events is taken into account this trend is significant. The LI is similar to the SI but a stronger trend towards convective favoring atmosphere is observed with a Thiel-Sen slope of -2.61 (Figure 5.14).

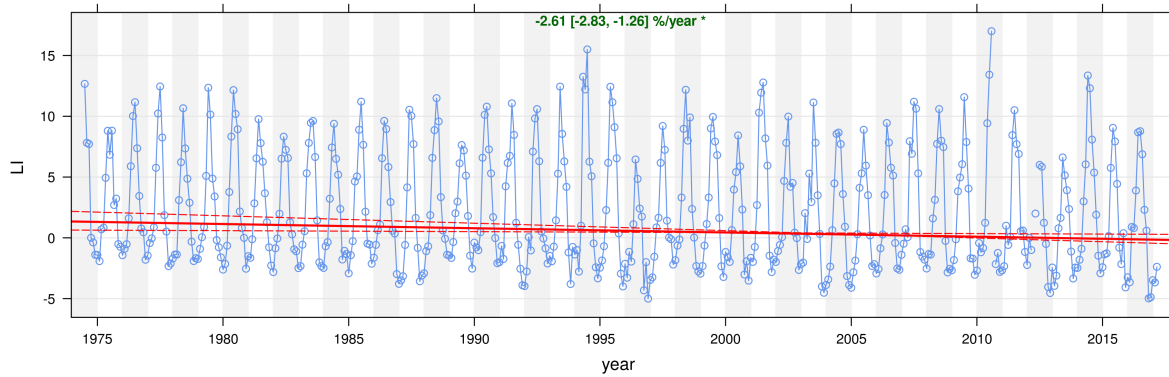


**Figure 5.13:** *The long term trend of SI based on the IGRA dataset and a Thiel-Sen slope analysis*

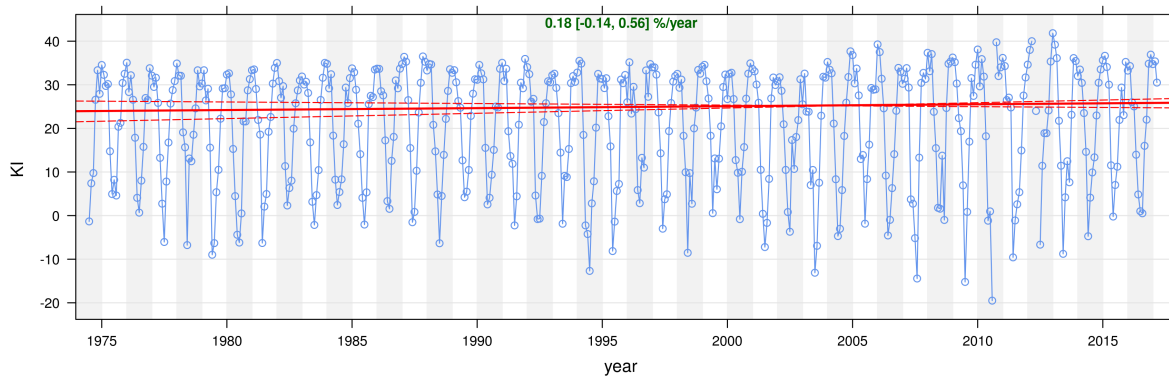
The KI (Figure 5.15) also indicates a marginal increase towards a slightly more convective favoring atmosphere, the Thiel-Sen slope analysis indicates a positive trend over the last three decades. The seasonal analysis of the KI



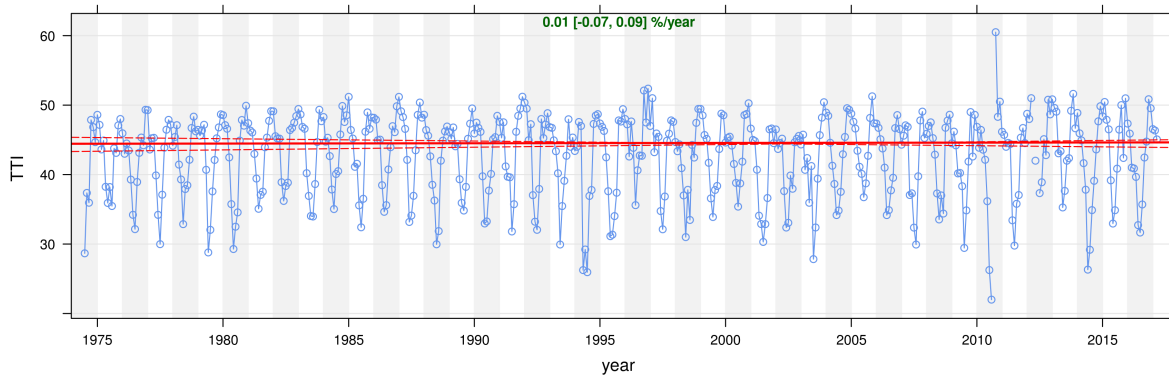
shows that this increase is observed in spring and summer, similar to CAPE, SI and LI variables.



**Figure 5.14:** *The long term trend of LI based on the IGRA dataset and a Thiel-Sen slope analysis*



**Figure 5.15:** *The long term trend of KI based on the IGRA dataset and a Thiel-Sen slope analysis*



**Figure 5.16:** *The long term trend of TT based on the IGRA dataset and a Thiel-Sen slope analysis*

The TT does not show the same significant trend towards a convective favoring atmosphere. The seasonal analysis of the TT shows supports this and although a slight increase in the seasonal analysis is observed, it is insignificant. The long term analysis indicates a 0.01 increase which is also not significant.

The section investigated the long term trends of thermodynamic indicators associated with severe events usually occurring along with convective storms. Each of the selected variables are popular derivatives of sounding data used to evaluate the possibly of severe storm occurrences. Data was gathered from the IGRA database and starting

in 1975 until early 2017. The long term trend analysis indicated that the atmosphere is increasingly becoming favorable for convective storms. CAPE shows a significant increase with a Thiel-Sen value of 0.36. The next three variables analyzed all showed the same trend towards a marginally more unstable atmosphere. The SI and LI again indicated a trend towards a convective favoring environment. This increase is mainly observed in the spring and summer months. The TT did not indicate a significant increase or decrease and this was also observed in the seasonal observations.

## **The trends and cycles of synoptic patterns associated with hail events**

In the previous section the trends of specific thermodynamic indicators were evaluated for a 40-year time span and the results indicated that the atmosphere is becoming more favorable for the development of convective storms especially in the summer months. Moving on towards the larger scale synoptic circulation. The following section investigates the trends and cycles of the macro- $\beta$  scale environment. Data from chapter 4 is used in this analysis and here it was observed that hail events occur within synoptic patterns that are prominent in spring and summer months characterised by a low pressure system over the interior of South-Africa and a well-defined area of CAPE over a large part of the country and the SICZ. As in the previous trend analysis a Thiel-Sen slope analysis is used to evaluate the long term occurrence of hail related synoptic environments while the next analysis investigates the correlation between the synoptic environments and the SOI.

### **Long term trends of synoptic patterns associated with hail**

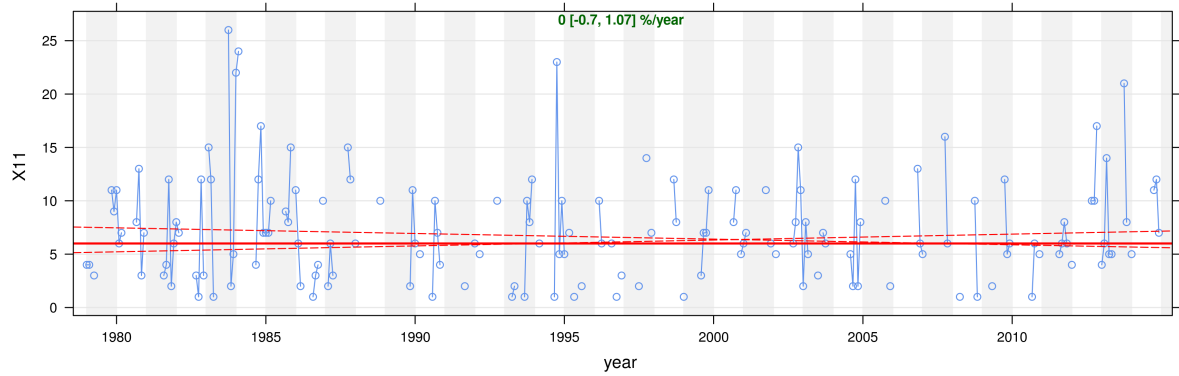
In chapter 4 an analysis of the macro- $\beta$  scale circulation patterns associated with hail events was conducted; three patterns showed a high frequency of occurrence during the hail season and also a high number of reported events namely cluster 11, 7 and 3 (see Figure 4.3b). The following analysis used the data from the above mentioned results and each cluster's monthly occurrence was counted for the 40-year time period and a Thiel-Sen slope analysis was applied. The analysis was only conducted on cluster 11, 7 and 3 respectively as these clusters were prominent during the known hail season and also had more reported events occurring in them. The analysis is conducted in a descending order from cluster 11.

Severe hail events seen in media reports occurred within cluster 11 while the annual distribution of the cluster also falls within the *traditional* November, December, January and February hail season (see Figure 4.3b, 4.3a). The circulation in this cluster is similar to the easterly wave described by Tyson and Preston-Whyte (2000). The circulation was characterised with a ridging high pressure system along the east coast and a surface trough or TTT over the central and northern-western parts of the country. The TTT transports warm, moist air from the ITCZ and in October and November the upper levels are cold enough for ice formation and subsequent hail to occur before the circulation becomes predominately tropical, which in turn is not conducive to an hail favoring environment. This leads to hail events seen during this time of the year over the Highveld. CAPE observed in this cluster is evenly distributed across the country, it appears as if no exceptionally high CAPE is associated with the clusters but due to the local small scale nature of severe events this can be expected. In Figure 5.17 the long term trend and occurrence of cluster 11 is examined. The results yielded no statistically significant indication of an increase of days related to this circulation over the 35-year period.

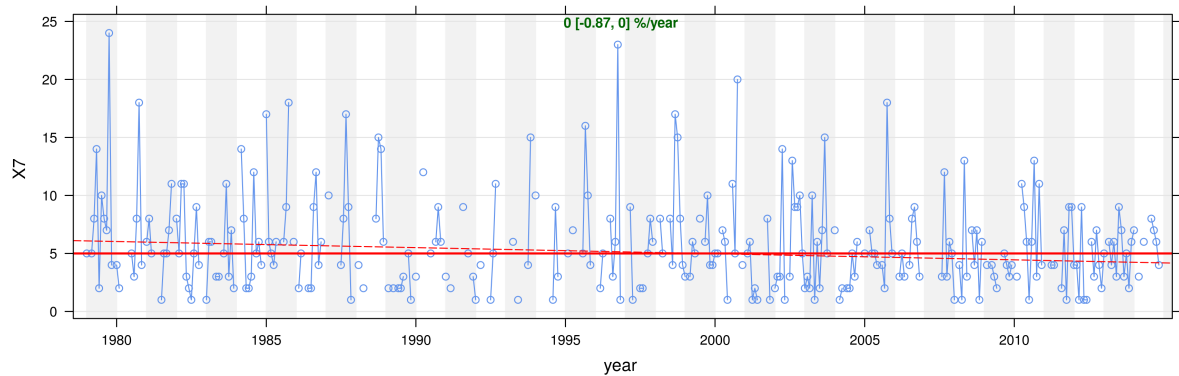
Similar to cluster 11, cluster 7 is characterised by a ridging high pressure system and the TTT extending over the central, north-western interior, the 500hPa winds is also well defined over South-Africa dominating the movement of air over the country and also associated with cold upper air allowing for rising parcels to reach the freezing levels. Cluster 7 annual cycles shows a more evenly distributed pattern with some occurrences in autumn and winter months but the characteristic peaks are still observed during the hail season. The counted cluster occurrence per month and the subsequent Thiel-sen analysis again indicated no significant trend towards more hail favouring days occurring over the time period (see (Figure 5.18).

In cluster 3 a pattern emerges which is only observed during the spring/summer months associated with hail events (see Figure 4.3a). Absent from cluster 3 is the prominent TTT extending over the interior of the country

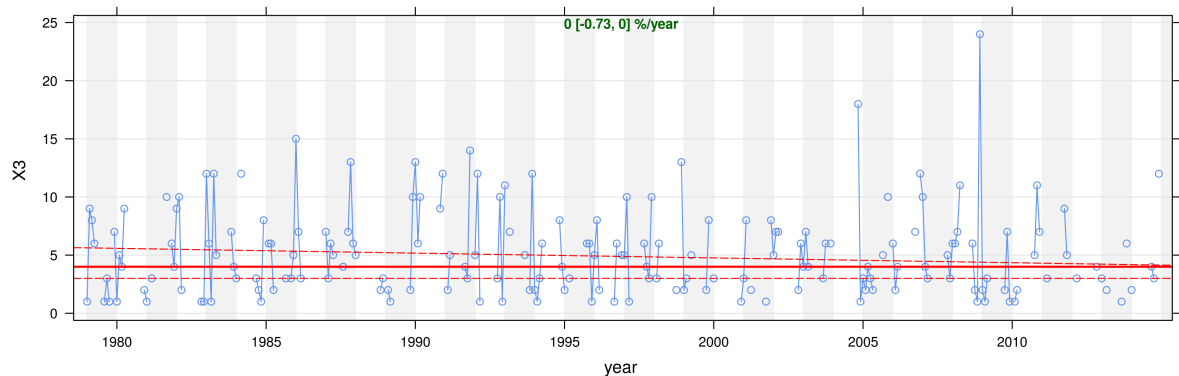




**Figure 5.17:** Cluster 11 had the highest number of related hail media reports. The cluster showed a characteristic summer peak that is generally associated with hail events as seen in previous literature, however, the Thiel-sen analysis did not indicate any increase in days associated with this pattern being observed over South-Africa.



**Figure 5.18:** The Thiel-Sen analysis of days associated with cluster 7's synoptic pattern associated with hail events did not show an increase in prevalence over the last 35 years



**Figure 5.19:** The long term trend of cluster 3 hail related synoptic pattern showed no significant increase in days associated with this type of large scale circulation

along with the ridging high along the east coast. The 500hPa The cluster is characterised by high CAPE over the eastern seaboard. The resulting synoptic pattern is similar to an easterly low as described by Tyson and Preston-Whyte (2000) where the Indian ocean high extends over the eastern coast and rainfall originates from the northerly direction. The synoptic pattern is characteristic of summer months, showing the highest occurrence in November - January. As seen in Figure 5.19 the Thiel-sen analysis again showed no significant trend towards

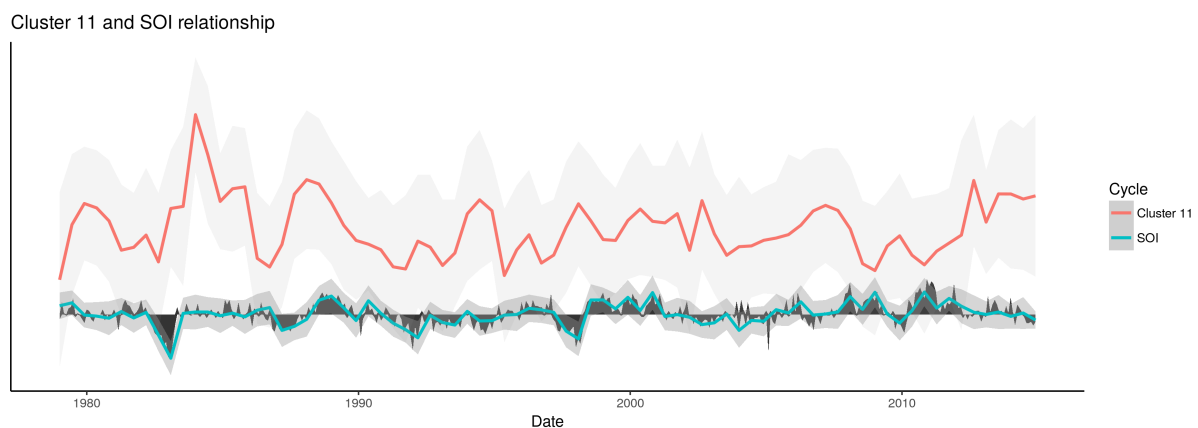
an increase in the observed pattern.

The Thiel-sen was used in the section to evaluate the trends of hail related synoptic days and because of the convective nature of hail events the results also have a correlation to severe thunderstorms and rainfall days. In chapter 4 three characteristic clusters indicative of synoptic days related to hail events stood out. These clusters were counted as the occurred per month over a time period. The results indicate that none of the three hail related clusters showed a significant increase in frequency. The spatio-temporal nature of convection impacts the analysis of these events on a synoptic scale. The goal is to use these characteristics and form a holistic idea of the dominant circulation patterns associated with these events, results found here are in agreement with observations related to the synoptic patterns of South-Africa by Dyson (2013); Taljaard (1986, 1981); Tyson and Preston-Whyte (2000).

## The relationship between hail related synoptic patterns and the SOI

Three studies examined the relationship between hail/convective events and ENSO/SOI over South-Africa, see Blamey et al. (2016); Olivier (1990); Olivier and Van Rensburg (1995). Olivier and Van Rensburg (1995) explicitly examined the links between the occurrence of hail events over the Pretoria – Witwatersrand area and SOI – the authors found a relationship between the occurrence of hail events and SOI, where a low SOI was associated with an above average HDF (see Figure 1.9). Recent investigation by Blamey et al. (2016) looked at potential days favoring severe events based on CAPE and 0 - 6km bulk shear showed no relationship to ENSO. In this section the correlation between SOI and hail events is investigated by examining the occurrence of synoptic patterns identified in chapter 4.

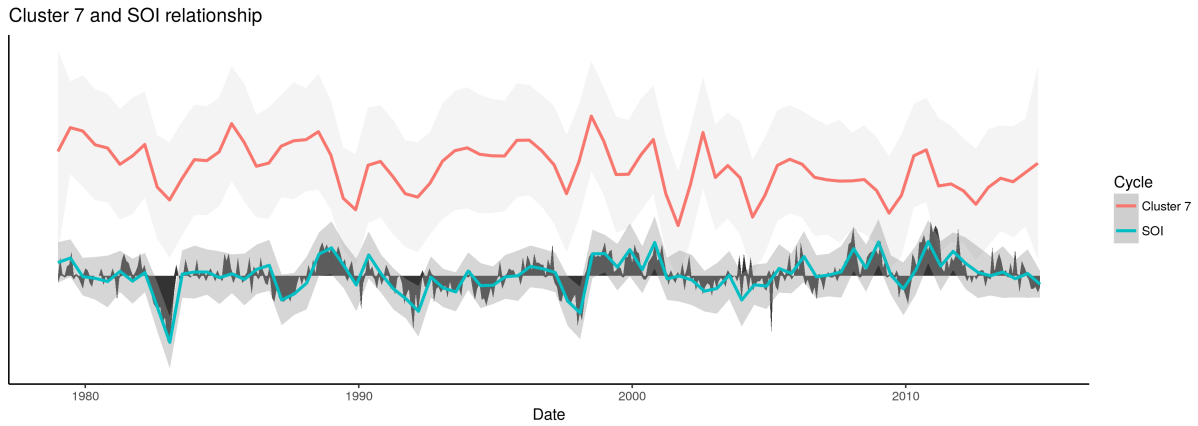
In this section a Pearson correlation is performed on the datasets to accurately examine the relation between SOI and the occurrence of synoptic patterns associated with hail/convective events. The cluster data is represented as a monthly count of cluster occurrence and SOI was used unedited as derived from NOAA (2017). The analysis on the clusters is performed in a descending order similar to the previous section. Chapter 4's results indicated that cluster 11 had the highest frequency of severe hail events in media reports. This cluster also has a circulation with a peak occurrence during the South-African hail season in agreement with findings by Taljaard (1986, 1981); Tyson and Preston-Whyte (2000) on the dominant circulation patterns over South-Africa during this period. Figure 5.20 illustrates the relationship between the occurrence of cluster 11 and the SOI index between 1979 to 2014. A Pearson Correlation test between the variables (cluster occurrence and SOI) indicates a Pearson Coefficient value of  $r = -0.7747304$  which effectively means that there is no statistical relationship between the occurrence of cluster 11 and the ENSO/SOI phenomena.



**Figure 5.20:** The relationship between the SOI and hail related synoptic patterns of cluster 11. The results indicate a Pearson Coefficient of  $r = -0.077447304$ , effectively meaning that there is no statistical relationship between the events.

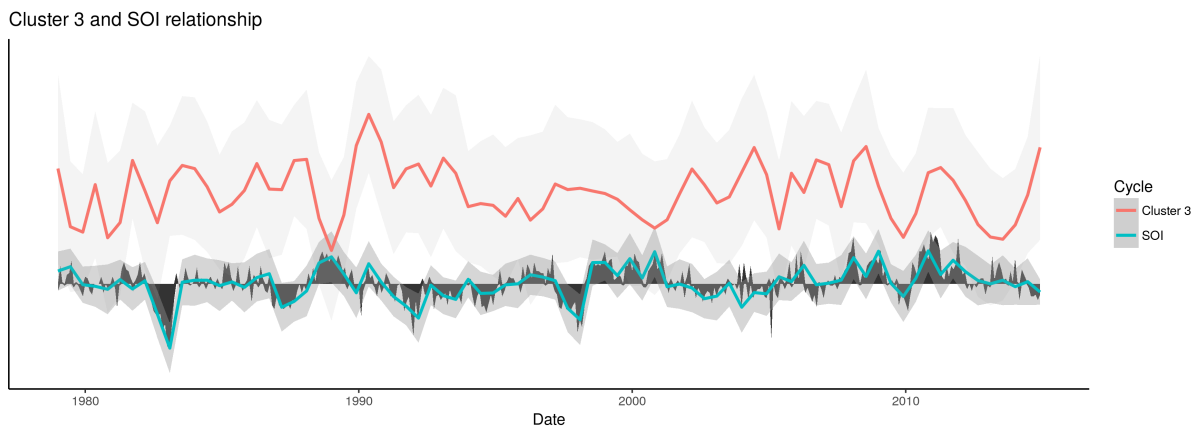
Cluster 7 and cluster 3 had an equal frequency of media reports related to the occurrence of severe hail events within these clusters. Similar to cluster 11 the two above mentioned clusters had an annual distribution correlat-

ing with the South-African hail season. Figure 5.21 shows the relationship between the occurrence of cluster 7 and the SOI and a correlation can be observed between the high and low phases of SOI and cluster 7. It appears that a low (high) SOI phase is accompanied by a low (high) occurrence of the synoptic pattern associated with the cluster. The Pearson Coefficient of  $r = 0.1041593$  indicates a slight relationship between the occurrence of cluster 7 and SOI.



**Figure 5.21:** The relationship between the SOI and hail related synoptic patterns of cluster 7 indicated a Pearson Coefficient of  $r = 0.1041593$ . Cluster 7 is thus the highest correlated to the SOI compared to cluster 11 and 3.

The final Pearson analysis on cluster 3 indicated no statistically significant relationship between SOI and the occurrence of the synoptic patterns. The relationship is illustrated in Figure 5.22 with a correlation value of  $r = -0.383774$ .



**Figure 5.22:** The relationship between the SOI and hail related synoptic patterns seen in cluster 3 indicates no relationship between SOI and the specific pattern, the analysis indicates a value of  $r = -0.383774$ .

In the final section of this chapter a Pearson Coefficient was applied to analyze the relationship between cluster occurrence and the SOI and the main aim of this was to examine the possible correlation between the high and low phase of the ENSO/SOI phenomena and circulation patterns associated with hail events. In chapter 4 three clusters had a majority of hail events occurring in them and these clusters were chosen for further analysis. The three clusters had a similar annual distribution that correlated with the South-African hail season. The Pearson Coefficient indicated no relationship between cluster 11 and 3 with the SOI, both were negatively correlated ( $r = -0.077447304$  and  $r = -0.383774$  respectively). Cluster 7 did however show a slightly positive correlation ( $r = 0.1041593$ ) with the SOI.

## A discussion on the temporal variation of hail indicators

In this section severe hailstorms were investigated by using data sources that included media reports and radiosonde data. In the first part the media reports were analyzed from the Caelum (1991) and by investigating media reports from regional and local media outlets. The media reports were examined for long term and seasonal distribution. The long term distribution indicated that there is an increase in hail reports as seen in print media (Figure 5.1). Figure 5.2 indicates the annual distribution of hail reports as seen in the media. The reporting distribution follows the same pattern as the annual hail frequency observed where events are frequently reported in the spring and summer months. It should be noted that there are various factors affecting this. The increase in the population of Gauteng and the subsequent increase in print media outlets made it possible to report more storms. The population distribution also impacts the reporting of hailstorms and as populated cities expand there is a higher chance of incidence reports. Following this a temporal analysis of hail reports was conducted. A map representing the spatial distribution of media reports were created representing South-Africa (Figure 5.3) indicating a high concentration of reports in the Gauteng area. Based on the media reports a HDF map (Figure 5.4) was constructed similar to that of Le Roux and Olivier (1996); Schulze (1965). The map indicates a high HDF over the Drakensberg region and Gauteng, as observed in previous studies mentioned.

Data from IGRA show a clear seasonal trend between the selected thermodynamic indicators. In all cases the thermodynamic variables associated with convection is prominent during November, December and January. Apart from the TT index, all the sounding derived variables indicated a trend towards conditions favoring convective environment. The effects of severe events will especially be felt by those in impoverished areas where infrastructure and emergency services are least prepared to handle events such as severe hailstorms and flash flooding, associated with convective weather, which according to predictions could become a more frequent occurrence. Next the long term trends of hail related synoptic circulation was investigated by using a Thiel-sen analysis. The results indicated that there was no significant increase in the occurrence of synoptic patterns associated with hail events. Reasons that the trend is not observed in the synoptic clusters is mostly a problem of scale; the large scale nature of synoptic circulation that might not accurately capture small scale features including convective parameters, so the synoptic trends might have a lot more *noise* distorting the fine local scale trend. Historical radiosonde data is a better method to evaluate the trends of small scale convective features.

The final investigation examined the relationship between the synoptic patterns of the three hail related clusters (11, 7 and 3) and ENSO/SOI using the Pearson Correlation Coefficient. Cluster 11 and 3 had a negative relationship ( $r = -0.077447304$  and  $r = -0.383774$  respectively) with SOI indicating no relationship between the variables. Cluster 7 did however show a slightly positive correlation ( $r = 0.1041593$ ) with the SOI and this is also visible in Figure 5.21 where a correlation can be observed between the high and low phases of SOI and cluster 7; a low (high) SOI phase is accompanied by a low (high) occurrence of the synoptic pattern associated with cluster 7. However, the statistical relationship is weak and not conclusive of a well-defined cycle between cluster 7 and ENSO/SOI.

# Chapter 6

## Summary and conclusions

The study aims to assess the trends and cycles of hail over the South-African Highveld by attempting to characterize hail events across atmospheric scales. First the convective, meso- $\gamma$  scale, was characterized by using a NWP model to simulate the thermodynamic properties of several severe events. These findings were then used to perform a cluster analysis of the large scale, macro- $\beta$  circulation patterns, with the inclusion of a thermodynamic indicator, to assess the associated large scale circulation associated with hailstorms. The study concluded with an analysis of associated trends and cycles based on the findings in the aforementioned chapters and the by incorporating media and radiosonde datasets into the analysis. The findings are discussed below as set out in the aims and objectives:

### 1. The identification of meso- $\gamma$ scale indicators associated with hail events:

By using the NWP model, WRF, five case studies of extreme hailstorms that occurred over Gauteng were simulated at a resolution of 1.3km. Convective parameterization was omitted from the model setup to simulate convection explicitly. The thermodynamic profile for several of the major cities in Gauteng along with the bulk shear for the following levels 0 – 1km, 0 – 3km and 0 – 6km, were represented for the most unstable parcel in the simulations. In the WRF output CAPE was well-defined spatially across all the major cities and this was supported by the spatial analysis of the variable at 12:00UTC for each case, as expected CIN was inversely correlated with CAPE in all cases. The bulk shear ( $\Delta V$ ) showed high variability in the 0 – 1km and 0 – 3km levels. The 0 – 6km bulk shear showed homogeneity within cases, however no correlation was observed between the bulk shear of the respective cases. Homogeneity within the 0 – 6km layer can be attributed to dominating mid/upper level winds within the storm environment. The limitations and uncertainties with NWP models is well noted and a key point has to be made that the selection parameterizations schemes needs to be further evaluated, but was not within the scope of this study. A comparison of the WRF thermodynamic plot with the Irene sounding does however demonstrate that WRF shows considerable skill as a CPM.

*Summary:*

- CAPE is spatially well-defined in the meso- $\gamma$  scale during storm simulations,
- the SI was accurately simulated within thunderstorms thresholds in all the cases,
- bulk shear showed high variability in the lower levels 0 - 1km and 0 - 3km of the atmosphere,
- 0 - 6km bulk shear showed homogeneity within individual storms, but there was no correlation between the 0 - 6km bulk shear of the case studies.
- WRF shows potential as a CPM model and further investigation is required to assess the effective set up related to the field of convective permitting modelling over South-Africa.
- A key limitation was the selection of parameterization schemes which should be subjected to further study in future work.

### 2. Linking the meso- $\gamma$ scale links to larger macro- $\beta$ scale circulation patterns:

In the meso- $\gamma$  scale environment CAPE was the best defined indicator spatially and selected as a variable in the cluster analysis. To represent the surface and upper air environment normalised MSLP and geopotential at 500 hPa was also incorporated. A two-step cluster analysis was performed on the selected variables; first a HCA was performed to reduce the data dimension followed by a k-means cluster analysis. In the k-means analysis the data was grouped into a user defined number of clusters, in this case  $n = 12$ . The results indicated three characteristic synoptic patterns associated with hail events, usually accompanied by a surface trough extending inland and a

ridging high-pressure system along the east coast. We also saw that CAPE was well defined over the South-Africa mainland.

*Summary:*

- The small spatial scale of hail and convective events results in difficulty to associate these events with a specific synoptic circulation patterns,
- CAPE is observed year round along the east coast and this is due to the influence of the Indian Ocean which creates a warmer atmosphere, although this does not mean that severe events occur along with the higher CAPE.
- The PCACA cluster analysis was able to reproduce seasonal synoptic patterns similar to that of Tyson and Preston-Whyte (2000),
- a majority of hail events occurred in three well defined clusters where a ridging high was observed over the east coast and a TTT which extended over North-West and Gauteng was visible,
- the wester wave dominated the movement of the storm across South-Africa while also providing cold upper air mass for freezing to occur.
- In these *hail* clusters CAPE was distributed across a large part of South-Africa.

### **3. Analyzing the trends and cycles of hail related circulation patterns and indicators:**

The sounding derived indicators show a trend towards an increasingly unstable atmosphere over the Highveld. CAPE shows a statistically significant trend and this is supported by other instability indices (SI, LI and the KI). An increase in highly convective events associated with hail, flash floods and lightning could be expected with this increasingly warm and unstable. The analysis of the synoptic days associated with hail events indicated no statistically significant increase in hail favoring synoptic days, this could be due to the local nature of such events not adequately represented in synoptic scale analysis.

*Summary:*

- There has been an increase in the amount of hail related media reports over the last century, however, this is expected due to an increase in media outlets and higher population density.
- South-African hail reports are highly concentrated in the Gauteng province.
- From the IGRA data a trend towards a warmer and more unstable atmosphere is observed. Key variables such as CAPE, SI, LI, KI indicate an increasingly convective favorable atmosphere over the last 35 years,
- the increasingly unstable atmosphere is mainly associated with spring and summer months, while autumn and winter remain relatively unchanged over the period, however,
- there is no statistically significant increase in synoptic days favoring hail or convective events and
- the correlation between ENSO and hail related synoptic days is weak and not conclusive.

## **Conclusion**

The study is unique for various reasons, for the first time WRF was run over the Highveld at a CPM resolution with accurate representations of convective processes, the results show the potential to use the model for research and operation purposes. The use of the Cost733class software was also a unique first in this study and aims to be a compliment to already well developed SOM's research for synoptic types. The last part of the study used the

IGRA database and SOI to evaluate the characteristic trends and cycles of hail events by comparing the results from the previous chapters with these datasets.

Through the use of NWP and objective clustering techniques provides a useful tool to understand the characteristics of hailstorms across different atmospheric scales. In the small meso- $\gamma$  scale environment CAPE was a well-defined variable. The synoptic patterns found in the cluster analysis were not different from previous studies by Dyson (2013); Tyson and Preston-Whyte (2000) which found extreme summer convective events related to a surface trough extending and ridging high pressure, as observed here. The main investigation in this study was to examine the trends and cycles of hailstorms over the Highveld. Data indicates that an environment suitable for convective weather events is becoming more prevalent. This is supported by the increasingly trend of several thermodynamic indicators, observed during the spring and summer months. However, the actual increase in synoptic circulation patterns associated with these events show no statistically meaningful trend, we can assume that the local nature of convective events make them hard to detect on a synoptic scale. This is also evident in the analysis of the links between hail related synoptic patterns and ENSO and there is no statistically significant correlation between these two events, possibly because of the inability to capture small scale events on the large scales as mentioned earlier.

The study supports the current body of knowledge related to severe hailstorms and the occurrence over South-Africa and the Highveld. Key limitations of the current study was related to the evaluation of all possible parameterization schemes within the NWP section, the subjective selection of clusters and the use of media reports as an evaluation tool. With the improvement of computer resources this study could serve as a baseline for future work using WRF over South-Africa to better understand extreme events.

# Chapter 7

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# Appendix A: Simulated Skew-T

## Simulated SkewTs across major cities of Gauteng on 28 November 2013

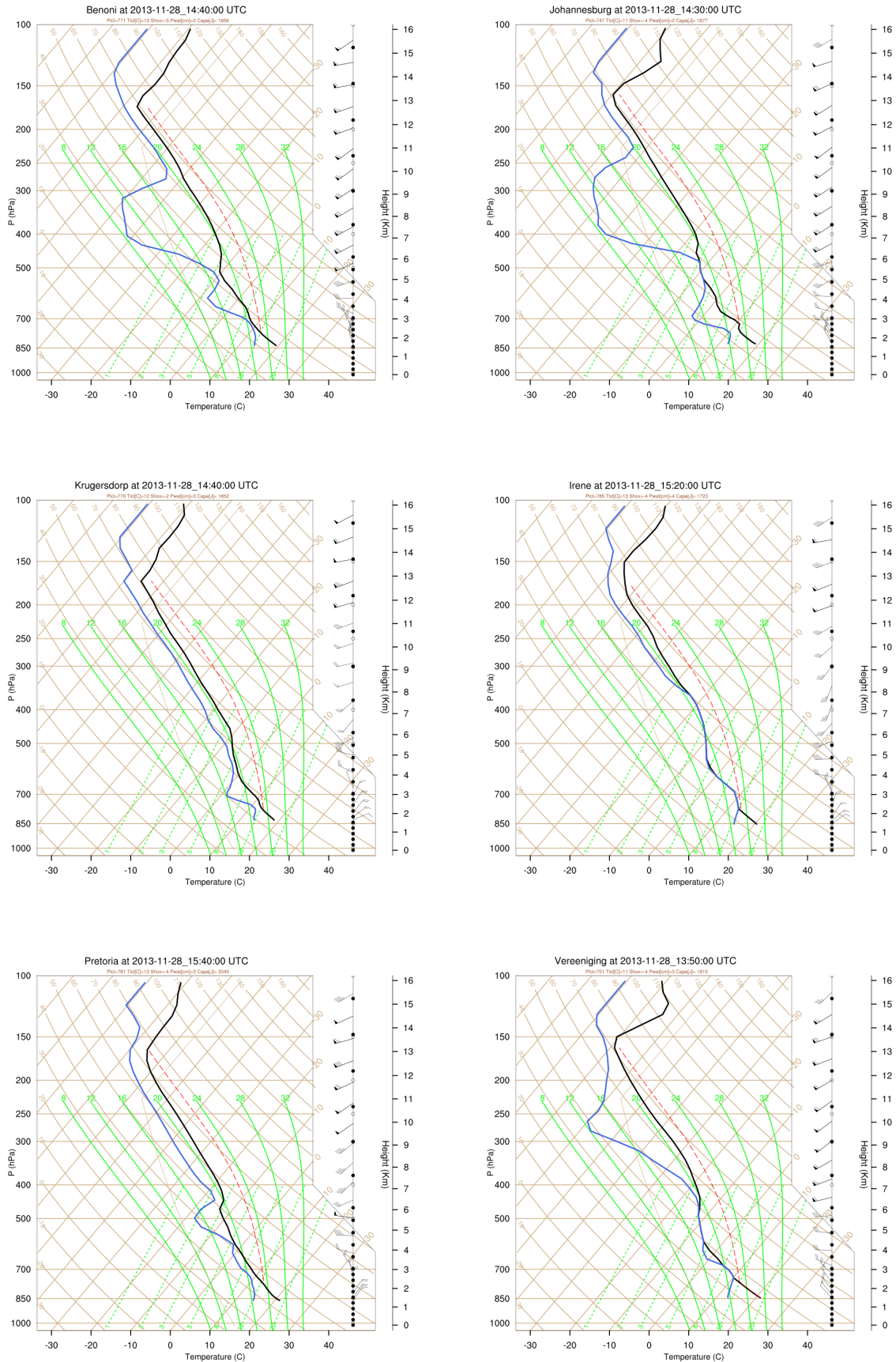
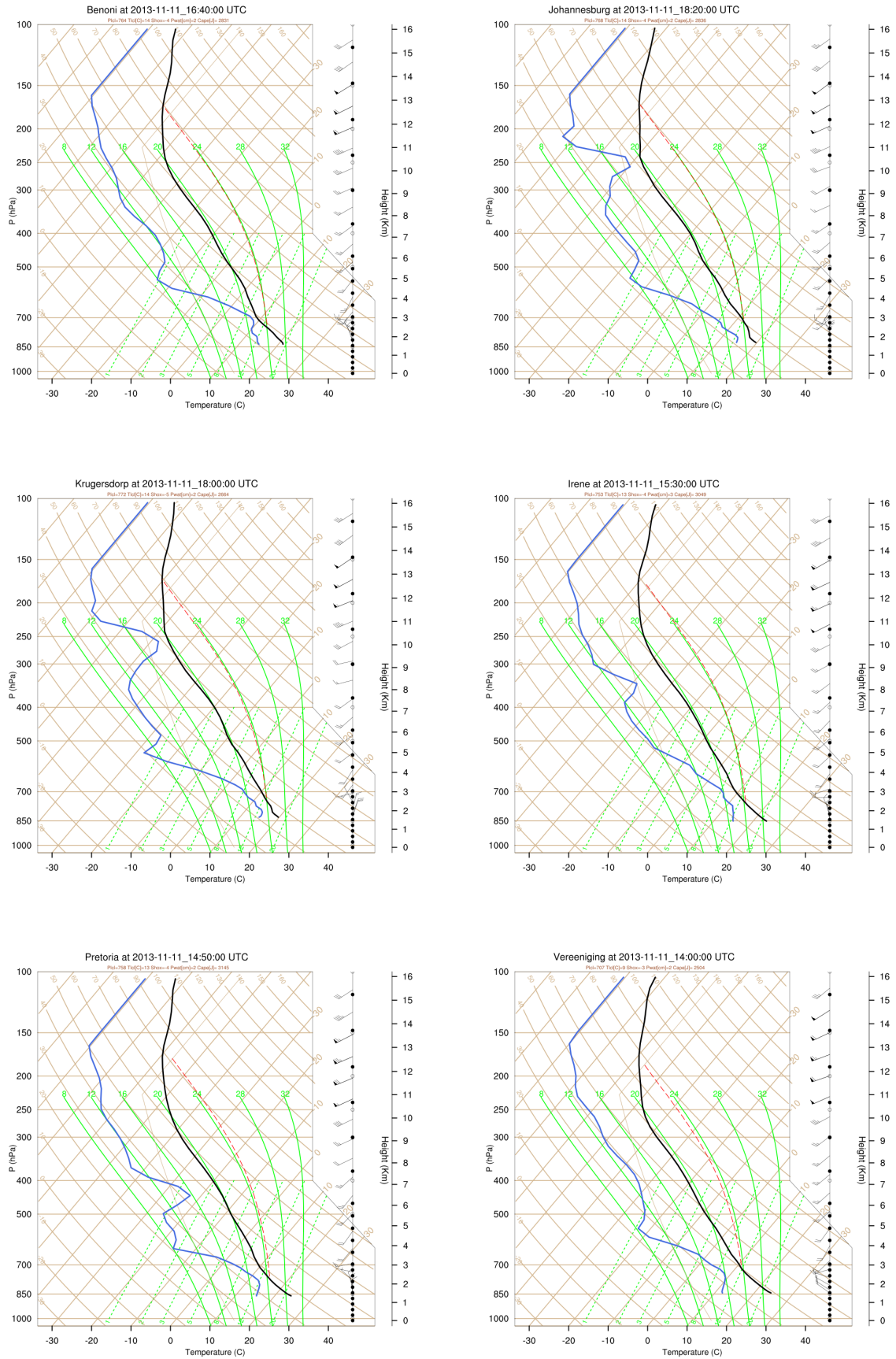


Figure 1: Most unstable parcels for major cities in Gauteng on 28 November 2013 as simulated by WRF.

## Simulated SkewTs across major cities of Gauteng on 11 November 2013



**Figure 2:** Most unstable parcels for major cities in Gauteng on 11 November 2013 as simulated by WRF.

## Simulated SkewTs across major cities of Gauteng on 9 November 2012

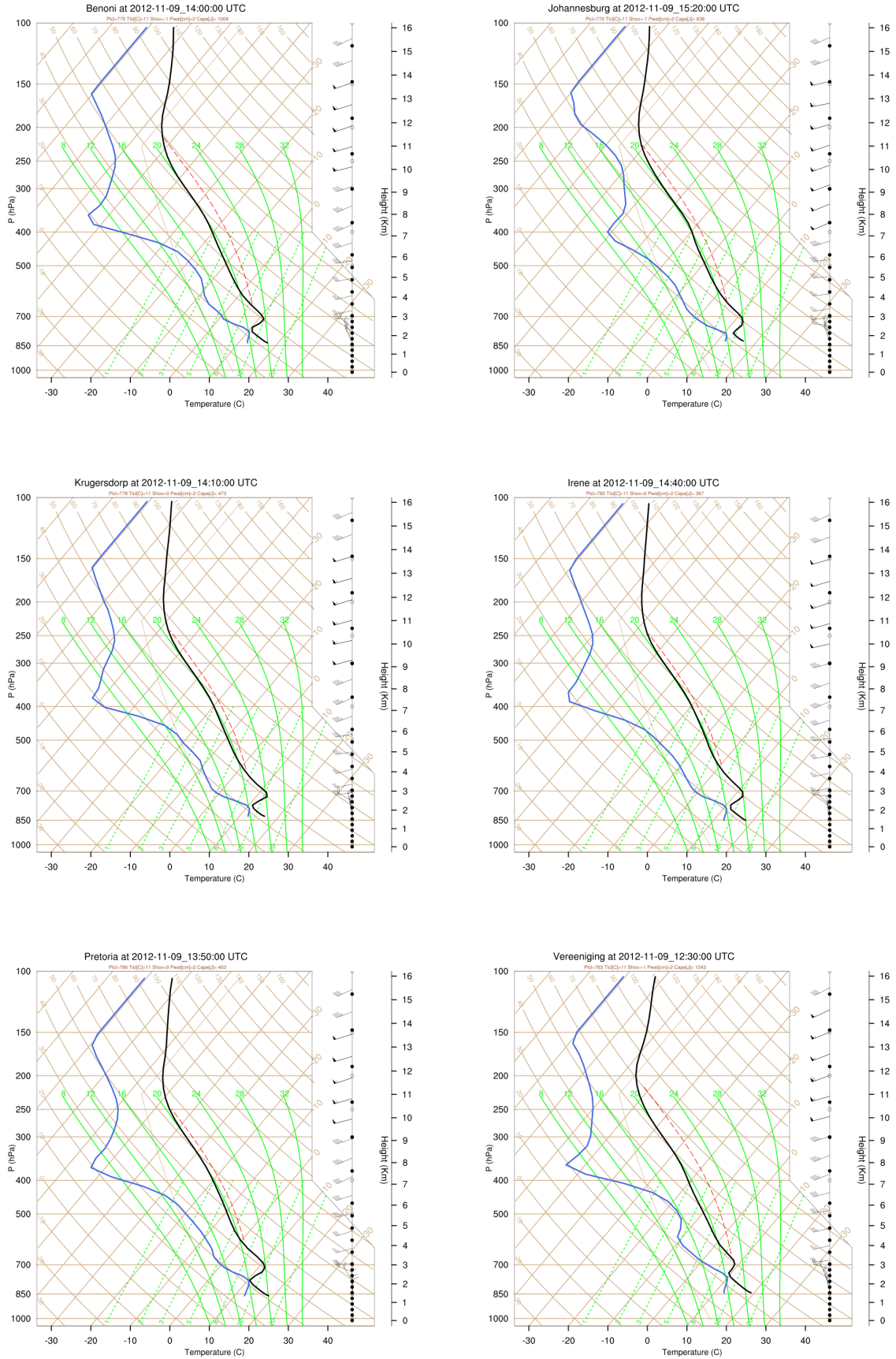
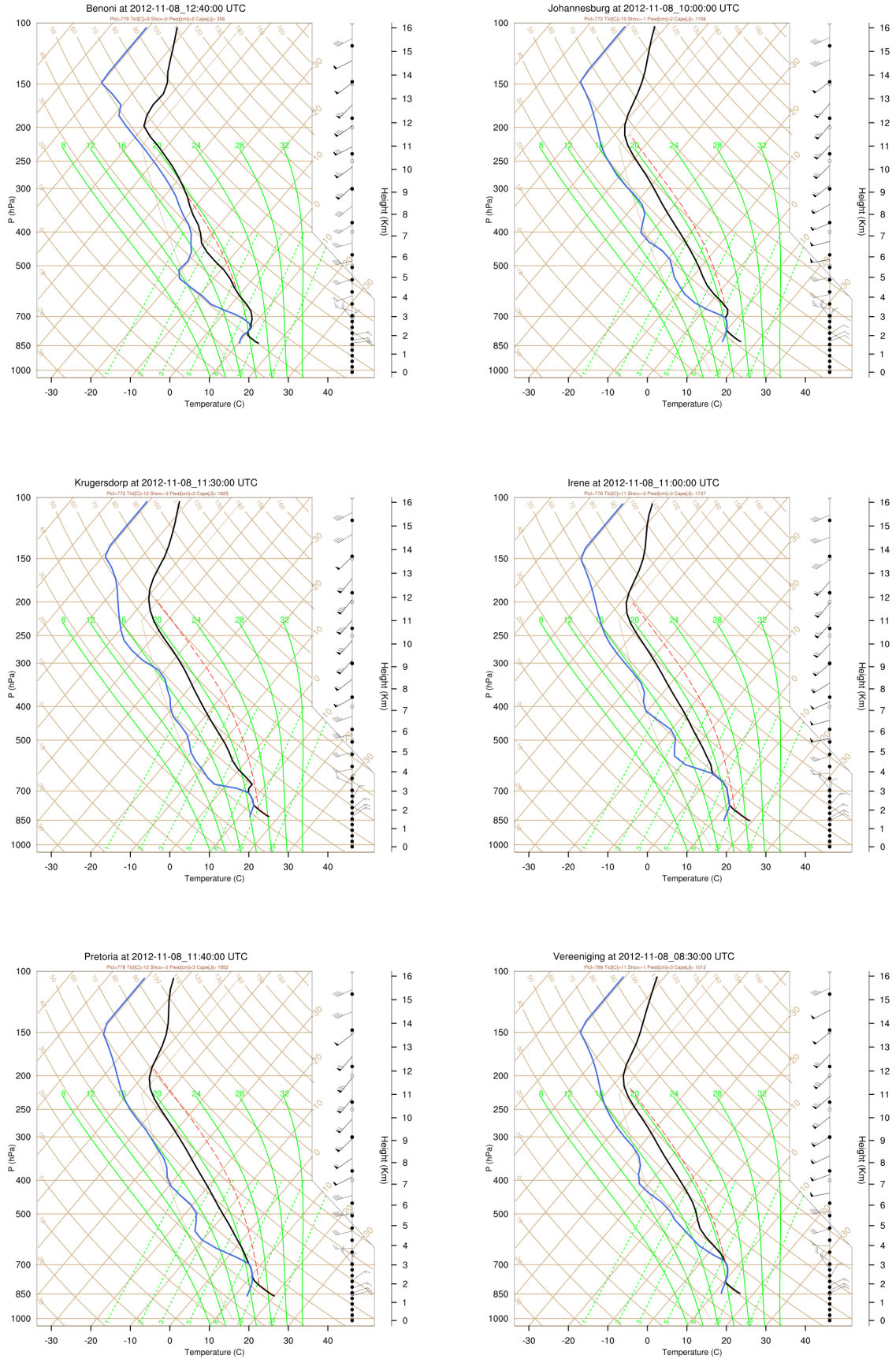


Figure 3: Most unstable parcel for major cities in Gauteng on 9 November 2012 as simulated by WRF

## Simulated SkewTs across major cities of Gauteng on 8 November 2012



**Figure 4:** Most unstable parcel for major cities in Gauteng on 8 November 2012 as simulated by WRF.



## Simulated SkewTs across major cities of Gauteng on 19 October 2011

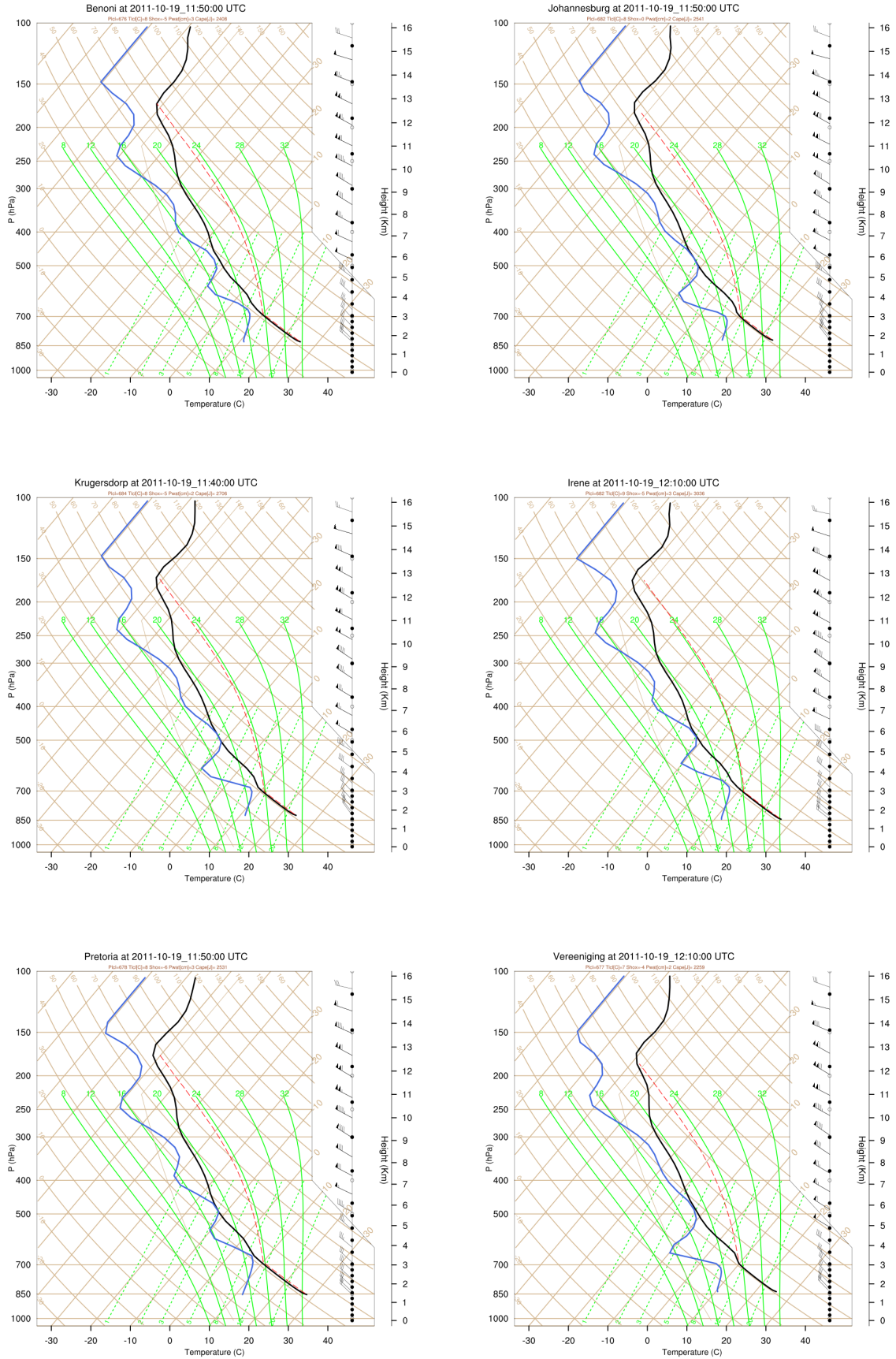
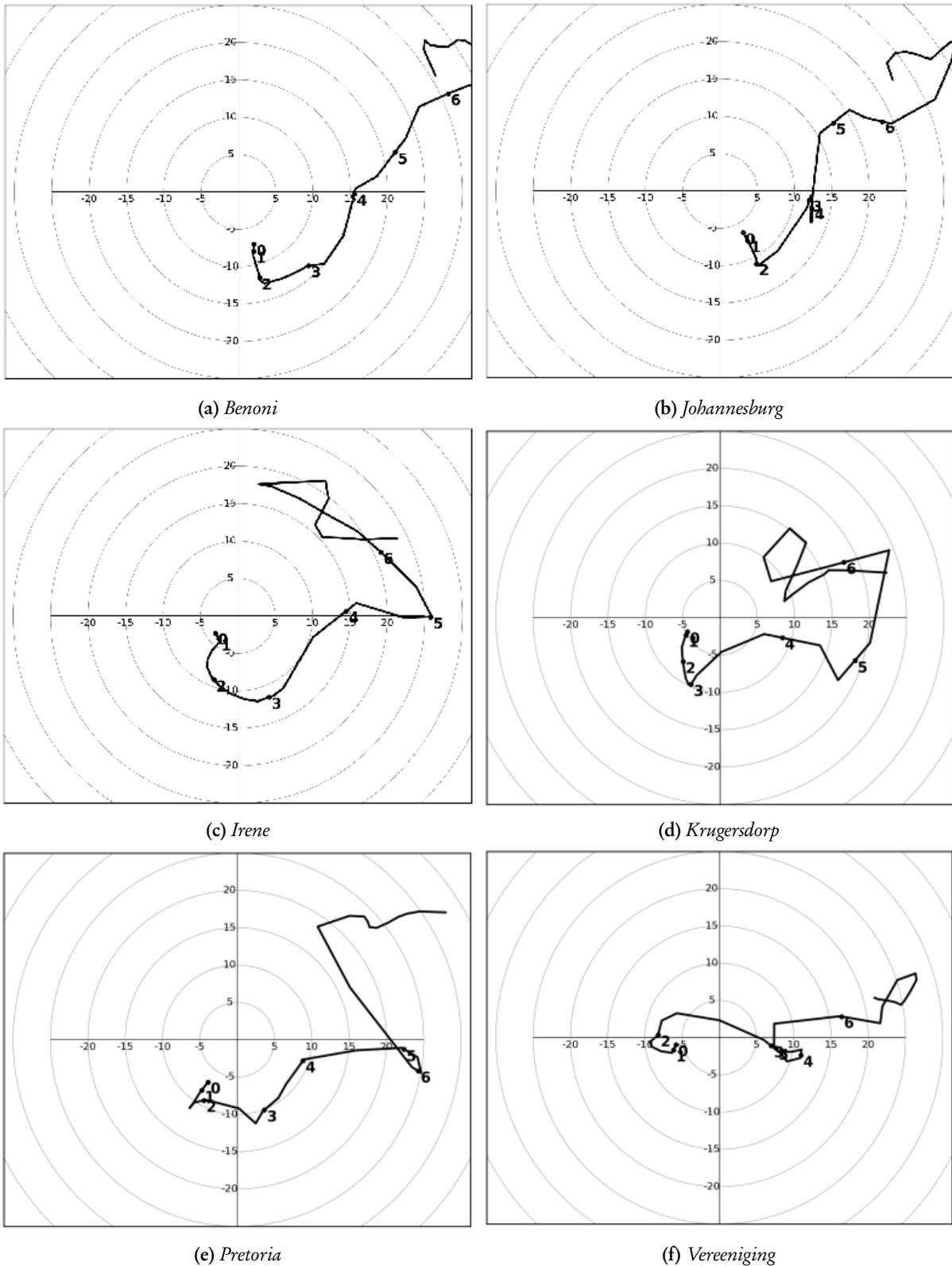


Figure 5: Most unstable parcel for major cities in Gauteng on 19 October 2011 as simulated by WRF.



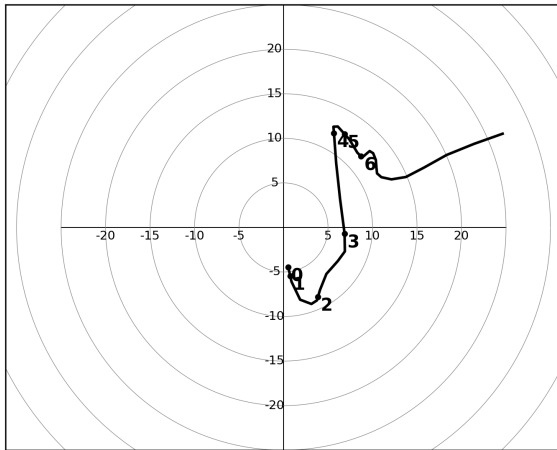
## Appendix B: Simulated Hodographs

Simulated hodographs across Gauteng's major cities on 28 November 2013

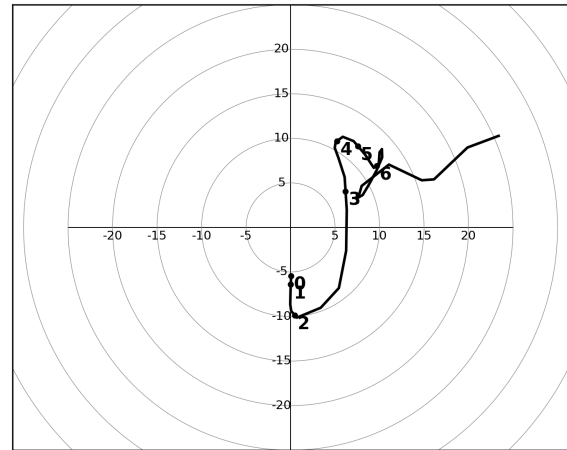


**Figure 6:** The above diagram represents hodographs for the most unstable parcels simulated over the major cities in Gauteng on 28 November 2013. Vereeniging stands out in this simulation; instead of the expected counterclockwise rotation (backing) the parcel veers in the lower levels. Rotation is the other hodograph is however as expected and strong backing is observed over all the other major cities.

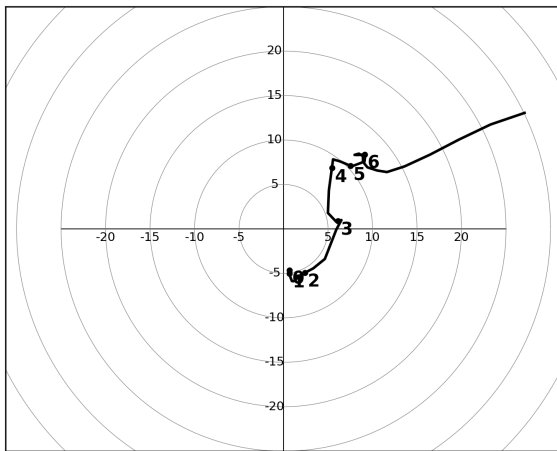
# Simulated hodographs across Gauteng's major cities on 11 November 2013



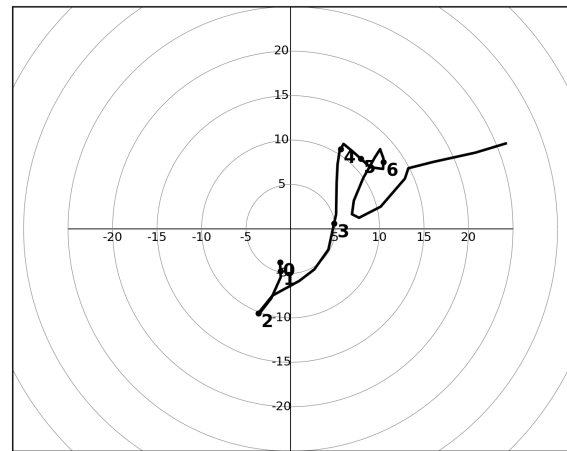
(a) Benoni



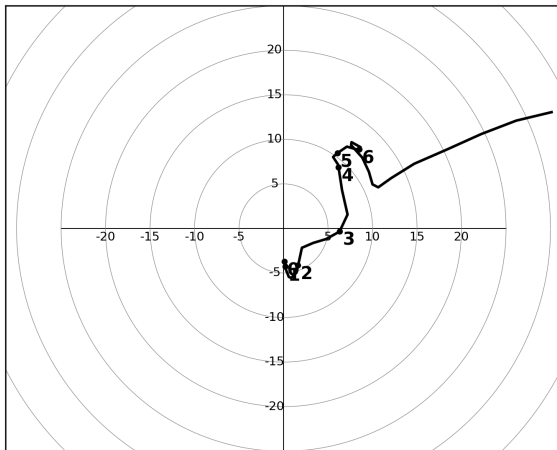
(b) Johannesburg



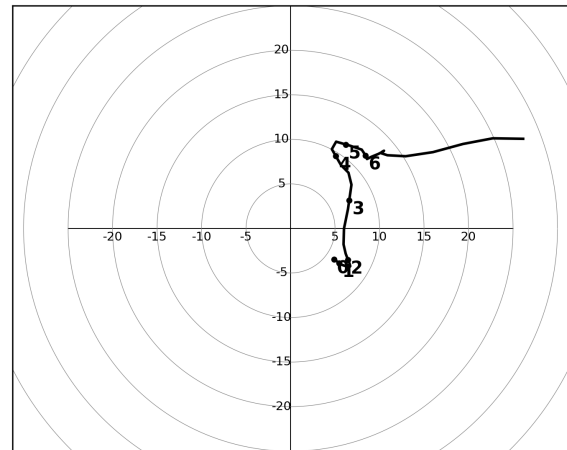
(c) Irene



(d) Krugersdorp



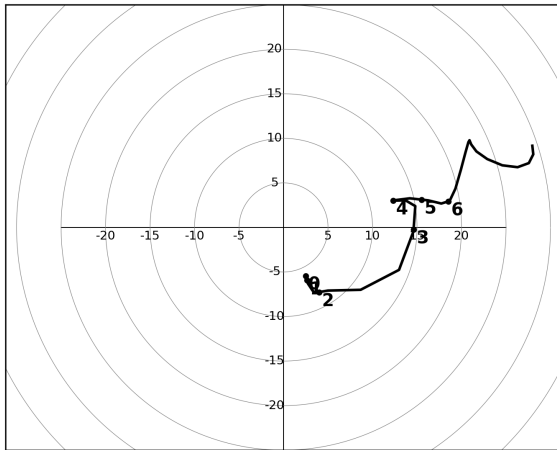
(e) Pretoria



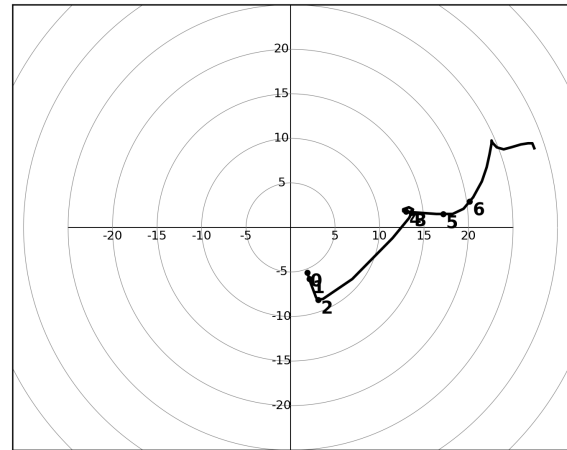
(f) Vereeniging

**Figure 7:** The above diagram shows the hodographs for the most unstable parcel simulated over the major cities in Gauteng on 11 November 2013. Backing is observed over Benoni, Johannesburg and Irene, while the other cities show strong directional and speed shear in the lower levels. All the hodographs show a similar directional shear in the upper levels indicating that the movement of air becomes more homogeneous across a large area higher in the atmosphere.

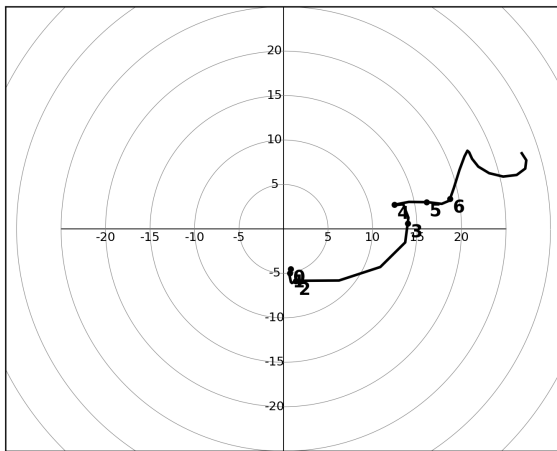
# Simulated hodographs across Gauteng's major cities on 9 November 2013



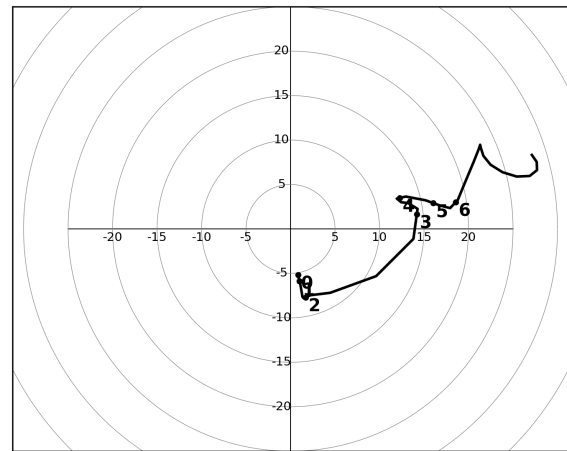
(a) Benoni



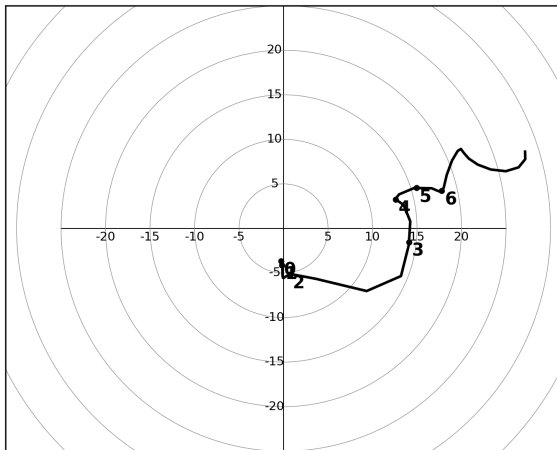
(b) Johannesburg



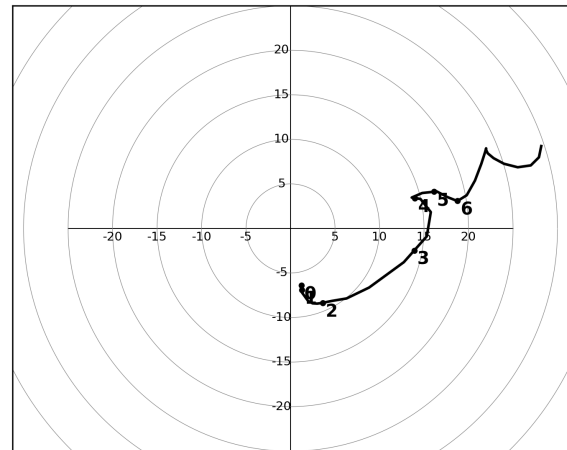
(c) Irene



(d) Krugersdorp



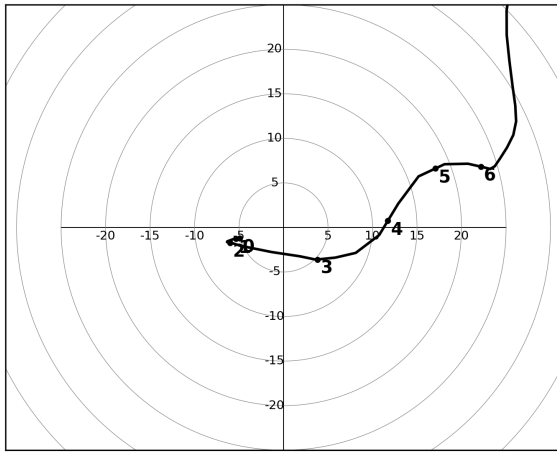
(e) Pretoria



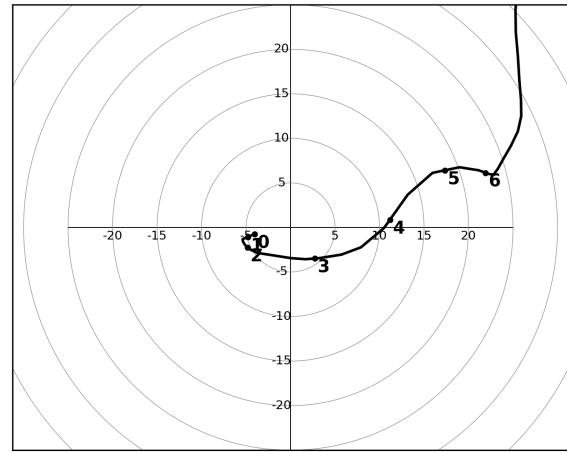
(f) Vereeniging

**Figure 8:** The hodographs for each of the most unstable parcels represented previously show backing across all the major cities and strong rotation in the lower levels of the atmosphere.

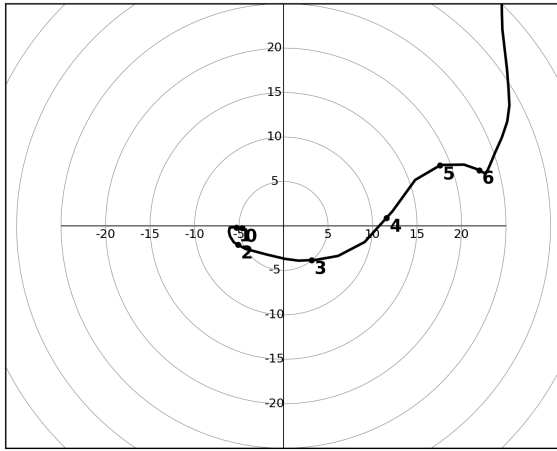
# Simulated hodographs across Gauteng's major cities on 8 November 2013



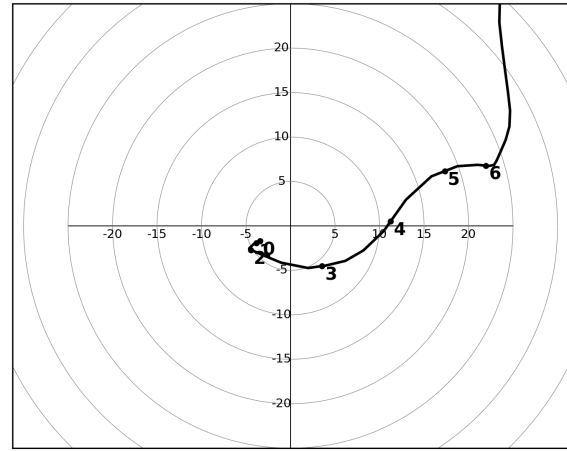
(a) Benoni



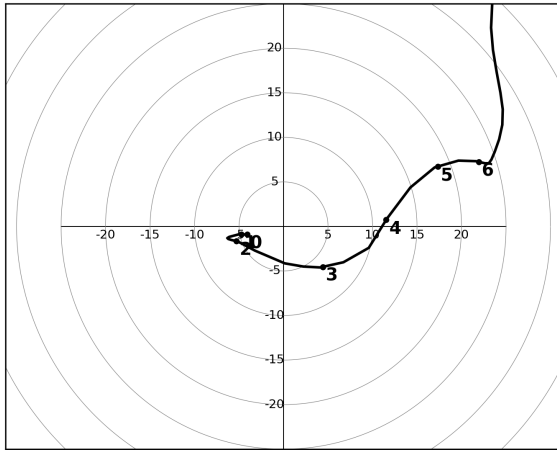
(b) Johannesburg



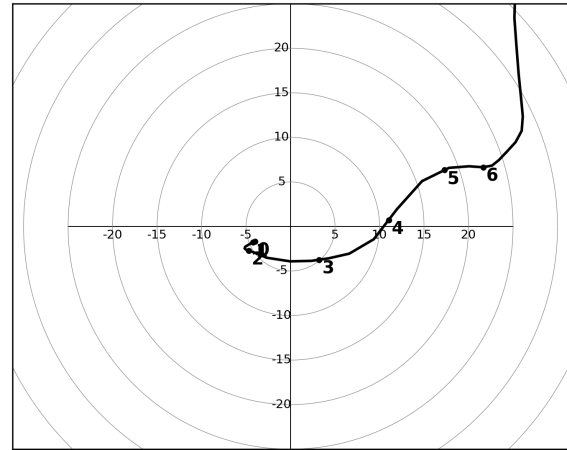
(c) Irene



(d) Krugersdorp



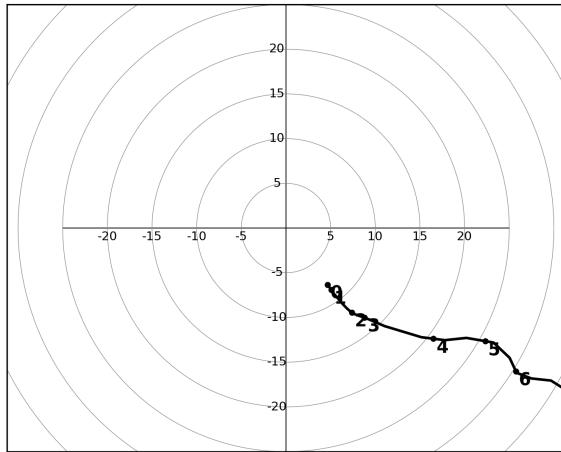
(e) Pretoria



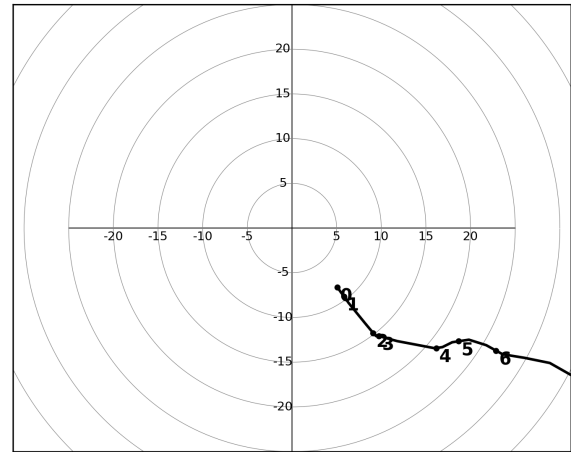
(f) Vereeniging

**Figure 9:** The hodographs simulated correlates to the most unstable parcel on the previous page. Subtle backing is observed over each of the cities while strong rotation is observed in first 1km of all the hodographs.

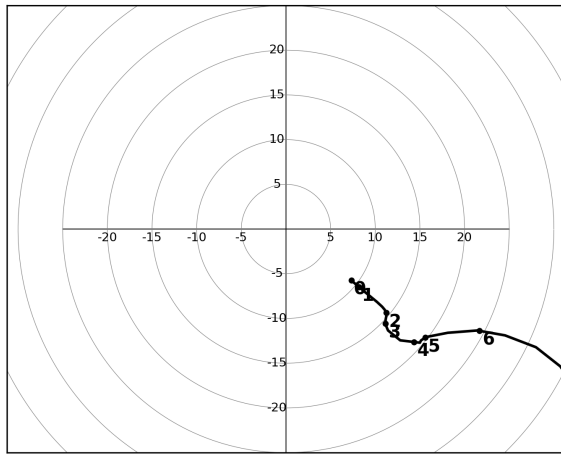
# Simulated hodographs across Gauteng's major cities 19 October 2011



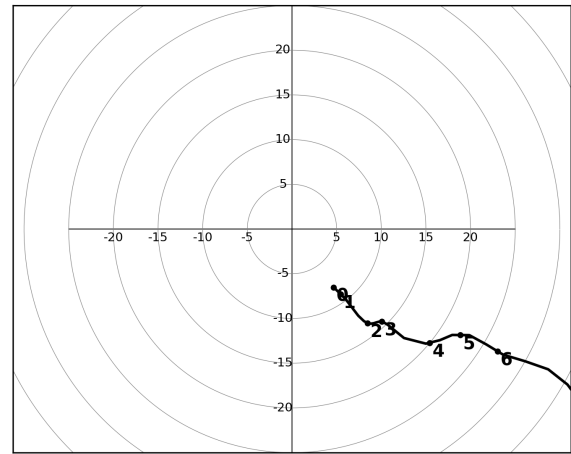
(a) Benoni



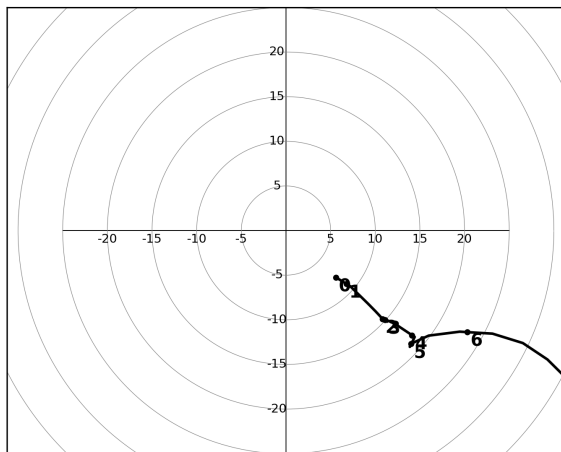
(b) Johannesburg



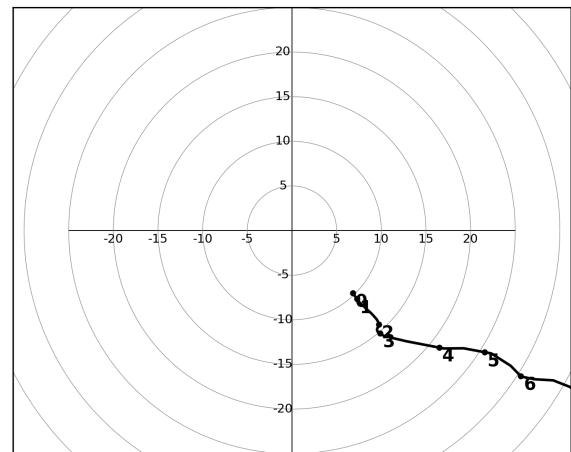
(c) Irene



(d) Krugersdorp



(e) Pretoria



(f) Vereeniging

**Figure 10:** The hodographs illustrated coincide with the most unstable parcel represented in the skew-t diagrams for each city. While less pronounced, backing is observed from a north-westerly to south-easterly direction over Johannesburg indicating rotation in the storms, there is however little backing simulated over the other cities across the area.

## Appendix C: Interesting notes on selected severe events

Severe weather has a profound socio-economic impact, everyone of us, in one way or another, have felt the destructive powers of events like tornadoes, hail, floods and drought. History is riddled with examples of these extreme events, some of these cases dramatically influenced the course of history in many countries around the world. The series of articles titled *Great Historical Events That Were Significantly Affected By the Weather* (Neumann, *et al.*), brings to light these events and their impact as briefly discussed here.

As early as 480B.C an invading Persian naval fleet was defeated by Greeks after an sea breeze resulted in bad sailing conditions for the invaders and a subsequent naval victory for the Greeks (Neumann, 1975). The weather not only saved the Greeks but prevented Khubilai Khan, 13th century Mongol ruler, from invading Japan in the early 1200's. Not once, but twice the Mongols, not known for their naval powers, were deterred by storms at seas, resulting casualties numbering well over 10000 men. It is believed atleast one of the weather events leading to this failed invasion was a typhoon near the coast of Japan, and became known as the *Kamikaze* or divine wind in Japanese society, a phrase still used to this day (Neumann, 1975). In other instances the severe weather played in favor of the invader, during the middle 1600's the Swedish engaged into a conflict with Denmark. Without any navy the Swedes where unable to cross to the island of Zealand, where Copenhagen is situated, but a severe winter in 1657-1658 made it possible for the Swedish army to walk over the frozen water mass between them and Zealand and forced the Danish into a peace agreement. That winter was so severe, personal records from the time notes how even rivers in Italy were completely frozen over and able to support heavy carts (Neumann, 1978).

Some weather events brought suffering to places. In the late 1690's Finland, Estonia and to a lesser degree Norway, Sweden and Northern Russia was hit by a succession of cold and long winters, above average rainfall over the summer months and some uncharacteristically severe hailstorms, this led to one of the worst famines in Europe, only surpassed by the *black death* (Neumann and Lindgrén, 1979). In France, the weather played a major part in the start of the French revolution. 1788 - 1789 was characterized by a variety of severe events; a drought in 1788 led to a low harvest and a subsequent famine in the country, in July 1788 a severe hailstorm caused additional damage in other areas. A British ambassador in France at the time notated that he observed hailstones over 16 inches (40 cm) in diameter, the storm also killed two men. The ambassador further describes the storm in detail noting several villages where completely destroyed and crops in the path of the hail where completely exterminated. France's peril did not stop there, these events where followed by unsparing winter. All these events led to an increase in the price of bread and flour, the staple food of the masses. On 14 July 1789 *Bastille day*, bread prices peaked and contributed to the destabilization of public order in France (Carte, 1979; Neumann, 1977; Neumann and Dettwiller, 1990).

Weather plays a major role in the outcome of conflicts around the world, the famous Battle of Waterloo was another such event. From 15 - 18 June 1815 Napoleon's army battled the Anglo-Dutch and Prussian army in Belgium, the first weather impact on this battle was heavy rainfall on 16 June resulting in non-operational muskets. This was followed by an violent thunderstorm and heavy showers, the soil was so muddy and sloppy Napoleon could not move any of his forces. The opposing Anglo-Dutch and Prussian army had time to retreat to Waterloo, Belgium. This meant they opposing force were in a better position and battle state than the French (Neumann, 1993). This however was not Napoleon's first weather related military disaster, after invading Russia in 1812, an early and severe winter rendered the unprepared French army, initially over 600,000 strong, powerless to the cold - a fate Hitler would also suffer.

In both of the world wars, weather forecasts started to play an ever increasing role. During World War One (WWI) the Germans started using deadly gas as a weapon of war and there was a urgency for forecasts to determine wind direction and speed. Meteorological officers also played an role in understanding the climate over the western front in attempt to predict to sort of conditions expected during battle days (Library and Archive, 2016). Several key battles in Word War Two (WWII) was influenced by the weather events, of these the severe Russian

winter of 1941-42 helped change the course of Russia's fate during Operation Barbarossa. Although not mentioned in Neumann's work, D-Day was also heavily influenced by the weather, a storm over the English channel delayed the landing initially, so much so German meteorologist believed the seas would be unstable until middle June, but upon advice from his meteorologist, Gen. Eisenhower launched his invasion on June 6 1944, in various popular media this was labeled "*The most important weather forecast of all time*". The German meteorologist Franz Baur and Russian meteorologist prepared long range weather forecasts for their respective armies throughout the war, Baur and his Russian counterparts expected the winter of 1941 to be mild, but the conditions turned out to much harsher than expected. Equipment malfunctioned and soldiers suffered to frostbite on many occasions. The German advance was also delayed by an *schlamm periode* in German or *rasputiza* in Russian, a mud period, in Russia during October and November which they did not account for. The Russians on the other hand also mis-predicted the severe winter, but due to the offensive nature of its fighting, tank designs and the immobilization of troops from Siberia, it was able to launch a successful counter operation against the German Forces. Realizing he was in the same predicament Napoleon was in, in 1812, Hitler refused to let those around him to talk about the French invasion of Russia and exclaimed; '*These damned meteorologists, also they are talking about Napoleon*'. This is an interesting remark by Hitler, although its truth is hard to validate, as Neumann and Flohn (1987) states the source of this quote is unknown (Neumann and Flohn, 1987, 1988). Another meteorological curiosity that has been the topic of many discussions is the cause of the 1937 Hindenburg disaster Potter (2007), although there remains much speculation about the cause of the historical event, some scientist speculate that static electricity from clouds charged the Hindenburg that had an hydrogen leak and ignited the famous fire Ho (2013).

The events above had a notable impact on history and possibly how we live today. This is fascinating, we can only wonder how such an uncontrollable force has impacted our present day existence.