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Synoptic circulation patterns and atmospheric variables associated with significant snowfall over South Africa in winter

by

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Declaration

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

-------------------------------------- 30 April 2013

SIGNATURE DATE

Dissertation summary

Synoptic circulation patterns and atmospheric variables associated with significant snowfall over South Africa in winter.

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South Africa is located in the sub tropics with an elevated plateau which is located approximately 1500 m above mean sea level (a.m.s.l). Every year, snow occurs on the mountains of Lesotho, but on occasions this snow descends to lower elevations which impacts on the livelihood of people. Severe weather originating from extra-tropical weather systems has been well documented in South Africa and yet very little research has been done to predict significant snowfall from these weather systems. The main aim of this research is to identify those weather systems responsible for snow and to understand the processes causing snow to form when these systems occur.

A comprehensive database of significant snowfall events is supplied from 1981 to 2011. The database is subjectively classified into characteristic synoptic patterns. The snow cases are then objectively classified using self-organising maps (SOMs) to obtain synoptic configurations most typically associated with significant snowfall over South Africa.

Case studies which aim to explain the synoptic conditions, formation mechanisms as well as critical surface temperature and relative humidity during snowfall events are described. This is done by analysing each case study with respect to synoptic circulations, surface observations, atmospheric soundings, satellite imagery as well as atmospheric thickness.

Conclusions are drawn and critical threshold values of atmospheric thickness, surface temperature and humidity are identified when snowfall occurs.

A methodical snow forecasting decision tree is devised. It takes the synoptic classification of circulation patterns during significant snowfall, atmospheric thickness, height of the freezing

level, surface temperature, and relative humidity into account. This process is explained by case studies.

It is recommended that results from this dissertation are made available to weather forecasters in South Africa and that the results are implemented in the operational forecasting environment. Further case study investigations are suggested, taking the mesoscale processes effects into account.

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List of abbreviations

- a.m.s.l: above mean sea level
- a.g.l: above ground level
- AOH: Atlantic Ocean High
- AWS: Automatic weather station
- b.g.l: below ground level
- COLs: Cut-off lows
- EUMETSAT: European Organization for the Exploitation of Meteorological Satellites
- gpm: geopotential metre
- GRaDS: Grid analysis and Display System
- IOH: Indian Ocean High
- KZN: KwaZulu-Natal
- METARs: Meteorological Aerodrome Reports
- MSG: Meteosat Second Generation
- MSLP: Mean Sea Level Pressure
- NCEP: National Centers for Environmental Prediction
- NWP: Numerical Weather Prediction
- ORTIA: OR Tambo International Airport
- RGB: Red-Green-Blue colour combinations
- RH: relative humidity
- SAWB: South African Weather Bureau
- SAWS: South African Weather Service
- SEVIRI: Spinning Enhanced Visible and Infrared Imager
- SOMs: Self-organising maps
- SPECIs: Special Meteorological Aerodrome reports
- SUMO: Software for the Utilisation of Meteosat in Outlook Activities
- SYNOPS: Synoptic weather reports
- UTC: Coordinated Universal Time

Chapter 1: Introduction

1.1 Background

Snowfall sparks a particular interest in South Africa, especially when it descends from the mountain peaks to lower elevations. For this reason these snowfall events are well publicised by the media, especially during the past 10 years. The rarity of these events causes enthusiasts to drive great distances to see the snow on the ground. South Africa enjoys a temperate climate and as a result, snow is not a frequent occurrence in winter. However when it does happen, it is often unforeseen. Weather forecasters in South Africa acknowledge that they are not very familiar with snowfall since it does not occur frequently and which means they are not necessarily equipped to provide sufficient information to the public (Gambrell, 2012). On 7 August 2012, snow fell in the cities of Johannesburg and Pretoria in Gauteng. No snow had been forecast. The revised forecast issued that morning also did not anticipate the snow. Likewise, when snow occurred in Johannesburg on 27 June 2007, no snowfall was forecast. Forecasters seem to anticipate the threat of very cold conditions during these snowfall events but they underestimate the severity of the cold. They usually predict snow and very cold conditions over sparsely populated mountainous regions.

This may be due to insufficient knowledge regarding synoptic circulation types associated with significant snowfall over South Africa. There is a limited understanding of the upper air conditions under which it forms and the surface conditions that allow snow to reach the ground.

Significant snowfall events in this research were defined when there was snowfall on the ground in areas with an altitude of less than 2000 m a.m.s.l. Snowfall in South Africa normally occurs in the sparsely populated mountainous regions but during significant events it reaches the more populated lower elevated regions. The average height of the interior of South Africa is at 1500 m a.m.s.l (850 hPa level) and as a result, significant snowfall can affect the livelihood and daily activities of people.

When ice crystals in cold clouds grow to such an extent that they become heavy, they will start to fall. Ice crystals that fall through a warmer layer in the atmosphere will melt but if temperatures are cold enough they will fall to the ground as snow (Van Heerden and Hurry, 1995). Snowfall can occur when temperatures at the surface are warmer than 2 °C (Lankford, 2001). When the air is very dry, the surface temperature can be as high as 10 °C during snowfall and the snow can fall as far as 300 m below the freezing level before melting. This can happen because as the snowflake falls through dry air, it starts to evaporate and releases latent heat, which cools the flake even further (Lankford, 2001).

Distinction is made between snow and other types of frozen precipitation such as snow pellets, soft hail and graupel which are mostly associated with cumuliform clouds in polar regions. They occur when ice crystals fall through supercooled droplets on their way to the ground where the surface temperatures are close to freezing. Ice pellets and sleet are normally associated with freezing rain where pieces of ice in frozen raindrops, or refrozen snowflakes fall to the ground.

1.2 Study area

The topography of South Africa starts to rise from about 200-300 km from the coast. This rise forms part of the eastern escarpment which increases to a plateau height of 1500 m above mean sea level (a.m.s.l).

This escarpment with a north-south alignment extends from the eastern part of Limpopo, Mpumalanga, the KwaZulu-Natal (KZN) Drakensberg through Lesotho to the north-eastern part of the Eastern Cape. In this region of the escarpment, the change in height from east to west is sudden as can be seen in Fig. 1.1. This sudden rise in altitude is indicated by the change from light brown to dark brown with the height of the escarpment reaching a height above 2000 m a.m.s.l. Over the western part of the Eastern Cape, the escarpment changes its orientation from west to east and consists of several mountain ranges that do not exceed 1000 m a.m.s.l. These mountains parallel to the coast are called the Roggeveld, Nuweveld, Sneeuberg, Bamboes and Stormberg ranges. Over the south-western part of the Western Cape, the alignment of the escarpment changes again to north-south (Taljaard, 1994d).

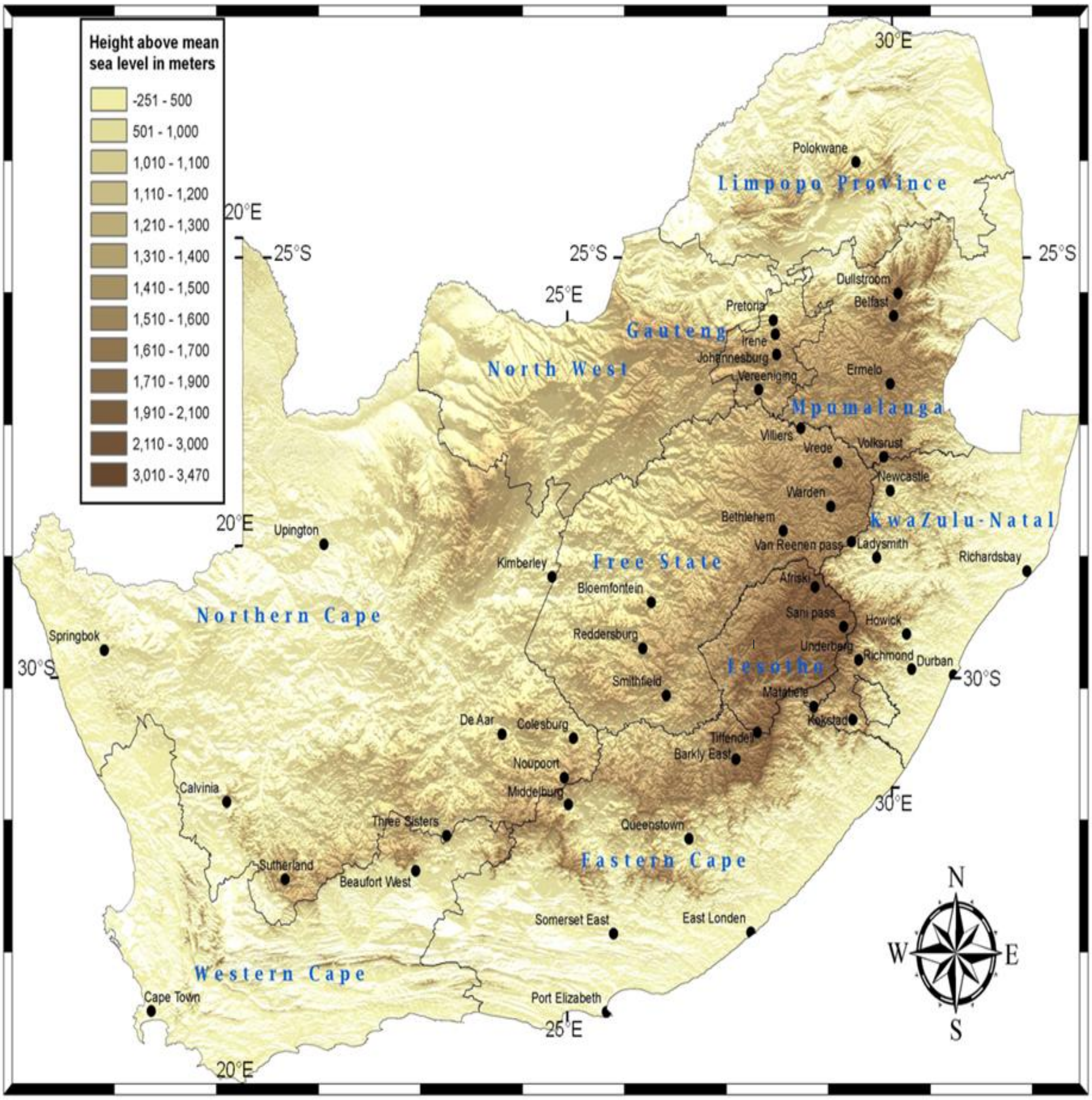


Figure 1.1: Topographical and location map of South Africa. Areas shaded in dark brown represent elevations higher than the 2000 m contour.

1.3 The impact of snowfall

Snowfall events can have significant negative consequences. For example, it has a substantial impact on power usage, air and road transportation as well as public safety. The impact of snowfall on South Africa was felt during 2011 and 2012 when four significant events occurred and there was widespread disruption to infrastructure. A short discussion of some noteworthy snowfall events impacting South Africa is provided here in order to illustrate the negative effect that it can have.

On 7 August 2012 heavy snow occurred over many parts of the country with lighter falls as far north as Pretoria. KZN and the eastern Free State received heavy snowfall on 6 and 7 August 2012, closing major routes such as the N3 national road (Pretoria News, 2012).

Figure 1.2: Snow flurry at Erasmus Rand, Pretoria east, South African Weather Service on 7 August 2012 at 1321 UTC – Picture taken by Jannie Stander

Before 7 August 2012, it had been 44 years since the last significant snowfall in Pretoria. This happened on 12 June 1968 when the snow extended as far north as Waverley in Pretoria.

In September 2008 several roads in KZN and the Eastern Cape had to be closed due to heavy snowfalls. The N2, which is a national road between Harding and Kokstad, had to be closed as well as the roads between Underberg and Bulwer. Several motor vehicle accidents occurred and there were a number of power outages in the affected areas (Beeld, 2008).

In June 2007 very cold conditions caused many power failures in KZN. This included parts of Kokstad, KZN midlands, Nottingham Road, Underberg and Mooi River. Several roads also had to be closed to traffic (Daily News, 2007). On 22 July 2002 snowstorms caused loss of life in KZN, 22 in total, loss of livestock and destroyed infrastructure (Muirhead, 2002). Many areas in the Eastern Cape that were affected by the snow had to be declared disaster areas (allAfrica, 2002).

In July 1996, 17 people died and 44 were missing in the worst snowstorms since 1964 (Beeld, 1996c). On Saturday 6 July 1996 the first snow started falling over southern KZN and continued until 9 July 1996. Many roads were blocked. Several people were trapped in the snow and millions of Rands' damage had been caused by the snow. It was described as one of the biggest snowfalls in living memory (Pretorius, 1996). All cars that passed through Bethlehem were prevented from passing to KZN until 9 July 1996. The Coca-Cola warehouse roof caved in causing R3 million in damage (de Waal, 1996). There were widespread communication- and power cuts in KZN and the Free State (Pretoria News, 1996).

To support disaster risk management, the South African Weather Service (SAWS) issues warnings when snow and very cold conditions (temperatures below 10 °C) are expected. These warnings are issued as snow may lead to the closure of roads and mountain passes and negatively effect the public at large (SAWS, 2010).

Snowfall also has an impact on aviation. On 27 June 2007, flights from Johannesburg International airport were delayed by 3 hours in the morning due to snow on the wings of aircraft. Due to the rarity of snow at the airport, systems to deal with it were not in place (Beeld, 2007). Snow that forms in an atmosphere that has a high liquid water content (wet snow) can cause structural icing on an aircraft and could also potentially effect the aerodynamic properties, performance and weight of the aircraft (WMO, 2007b). At temperatures below 0 °C, supercooled water droplets and ice crystals can be found (Pruppacher and Klett, 2010). The icing on the aircraft is caused by the presence of supercooled water between 0 °C and -10 °C (Glickman, 2000). The supercooled water droplets can imply the occurrence of mixed to clear icing which is a hazard to the aviation industry (Lankford, 2001). Furthermore, snowfall events seriously reduce horizontal visibility at an airport making it difficult or even impossible for aircraft to land without the correct instrumentation (WMO, 2007b).

However, snow also has some positive effects on the economy of South Africa. One of the positive aspects is that tourists are drawn to snow covered regions. This boosts the local tourism industry and economy in those areas, because many people congregate in the Drakensberg mountain resorts in the winter. Snow that falls over the Drakensberg mountains can last for weeks and the melting of this snow has an impact on the total water budget of the area, although the exact amount is not known (Nel, 2005). The positive effect of this snowmelt is that it enhances ground water levels. An example of such is the Table Mountain group aquifer system (Wu and Xu, 2005) where ground water reserves are replenished.

South Africa heavily relies on the water from the Katse dam in Lesotho to sustain the economy and accordingly the melting snow, especially in Lesotho is beneficial to water reserves during the normally dry winter season.

Industries such as the Tiffendell Ski Resort in the Eastern Cape and Afriski Ski Mountain Resort in Lesotho rely on winter snow to remain economically viable. Tiffendell Ski Resort is situated on the slopes of Ben MacDhui, 3001 m a.m.s.l (Muirhead, 2002). This topographically high area in excess of 1500 m a.m.s.l can be seen in section 1.2, Fig. 1.1.

1.4 Atmospheric conditions associated with snow formation

Snow can be defined as “precipitation consisting of white or translucent ice crystals, in complex branch hexagonal form and agglomerated into snowflakes” (Glickman, 2000). In conditions where the air is very moist and temperatures are close to freezing (0 °C), large snowflakes form, while more powdery snow forms in dry air. The most common form of snowflake is the dendrite crystal and depends on the temperature and relative humidity (RH) in the air (Ahrens, 2007). Several studies have been conducted which associate the formation of snowfall with atmospheric conditions.

1.4.1 Synoptic circulation patterns

Kocin and Uccellini (2004) studied the upper atmospheric and surface synoptic flows associated with snowfall along the east coast of the USA. They found that steep upper troughs amplifying into a closed 500 hPa vortex and associated with upper level jet streaks were common role players when snowfall occurs. Cuviello (2007) did a study on precipitation type forecasting in the Piedmont region of North Carolina in the USA. Weather systems that were important in the production of snow were systems which provided sufficient cold air advection, such as extra tropical cyclones (cold fronts) and cold anticyclones. In 87% of the significant snowfall events, surface anticyclones were responsible for the cold air advection.

Esteban et al. (2004) looked at typical synoptic patterns related to heavy snowfall in Andorra in the Pyrenees. They found that circulation patterns which advect moisture from the Mediterranean and cold air from the northern latitudes lead to favourable conditions for snow formation. Typical upper air configurations included troughs and cut off lows (COLs) that were responsible for creating the vertical uplift through the atmosphere.

According to Jones (2003) cold outbreaks which are linked to heavy snowfall events over Tasmania in Australia were due to cold fronts and large amplitude troughs at 500 hPa either ahead or behind the cold frontal air mass, however, no formal classification of the systems were done. Budin (1985) found that high snowfall over the Australian highlands was related to dominant westerly flow with the subtropical jet being strong. Orographic lift over the eastern mountain ranges played an important role in the snowfall.

In South Africa, snowfall at higher elevations have been researched by Mulder and Grab (2009) who did a study regarding the synoptic weather systems influencing snowfall over the Lesotho Drakensberg (see section 1.2, Fig. 1.1). They found that the two main synoptic systems accounting for snowfall over the Drakensberg were COLs and cold fronts. De Villiers (2001) did a surface synoptic discussion of snowfall events at Tiffendell Ski Resort during 2001 which is highly elevated (>2000 m). He found that the snow on 5 May 2001 was caused by marked low level cold air advection and an associated COL. For other events (24-25 June 2001 and 28-30 of June 2001), snow occurred at the resort due to an upper air trough system without any pronounced surface cold on shore flow. As a result, he stressed the role of the upper air circulation on the formation of mid-level clouds and snow. “Heyer (the resort manager)” ,cited in De Villiers (2001), commented that the resort received snow when the surface temperatures were between 1 °C and 4 °C but when temperatures were -3 °C and lower, less snow occurs. De Villiers (2001) suggested that further research should be conducted into the upper air characteristics associated with snow over South Africa.

Authors such as Taljaard (1982a; 1995a) and Tyson and Preston-Whyte (2000) discussed in some detail the synoptic circulation patterns over South Africa. Synoptic scale weather systems and patterns that have a significant effect on the weather of South Africa are known as surface ridging anticyclones, cold fronts and upper COLs. Tyson and Preston-Whyte (2000) discussed the importance of westerly wind disturbances associated with the surface ridging anticyclones as major winter weather systems over South Africa. Taljaard (1982a) showed during a 30 year study from 1952-1981, how 75% of South Africa’s heavy precipitation producing systems can be attributed to westerly wind troughs and the COL, while other systems such as Tropical temperate troughs and tropical lows accounted for 25% of the events and were mainly summer based. COLs are particularly more frequent during the late winter and early spring. Taljaard (1996) classified the winter rain-producing systems over South Africa as being cold front troughs, low pressure systems close to land, COLs and long waves in winter. Cold fronts associated with the cold core westerly disturbances at 500 to 300 hPa are primarily responsible for large changes in surface temperature as a result of the cold air advection. It is especially during the winter season that these circumpolar vortices migrate northwards (Tyson and Preston-Whyte, 2000). Within cyclones air rises when there is instability. Cold (denser) air moves northward dislodging warmer (less dense) air and forcing it to move southward. A narrow belt of snow forms at the cold front in the cold air (Spiridonov and Curic, 2010).

Another factor that may affect the strength and movement of pre-existing cyclones and anticyclones at the surface is the presence of an upper air jet stream.

During the period 1981-2011, the most common levels in the atmosphere that were looked at for this dissertation were 850 hPa, 700 hPa, 500 hPa, 300 hPa and 200 hPa to obtain a three dimensional view of each synoptic situation. For snowfall to occur, it is important to identify the appropriate synoptic weather system associated with their occurrence. This will greatly enhance the understanding of weather systems which cause significant snowfall over South Africa. It may also aid weather forecasters in anticipating these events. The aim of this research is to identify which weather systems are associated with snowfall over South Africa.

Snow does not only depend on the synoptic weather patterns, but also on the physical processes during the occurrence of snow (Lackmann, 2011).

1.4.2 The cloud microphysics of snow and identification of precipitation type

Temperature and humidity are two important factors that play a role in the growth of snow crystals within the atmosphere (Pruppacher and Klett, 2010). Steep upper air troughs or COLs combined with low level moisture are important snow producers. Bergeron, one of the pioneers in the investigation of precipitation mechanisms (1950, cited in Jiusto and Weickmann, 1973:1148) explained that there are two types of clouds associated with the formation of snow. They are known as releaser and spender clouds. Upper air troughs and lows such as COLs produce mid- and high- level clouds such as Altostratus and Cirrostratus which are effective in producing ice crystals (Jiusto and Weickmann, 1973). In cold clouds where temperatures are below 0 °C, water vapour occurs together with ice crystals and supercooled water droplets. Since the water droplets are so small, it requires very cold temperatures to make them freeze and they have to join together and become large enough to form a small ice nucleus that can then serve as a growth point for ice crystals. At -10 °C there are less than two ice crystals for every million supercooled droplets (Ahrens, 2007). Between temperatures of -10 °C and -20 °C clouds consist of a combination of supercooled droplets and ice crystals (AMS, 1996). This is illustrated in Fig. 1.3 A to C where small supercooled water droplets co-exist with ice crystals in cold clouds.

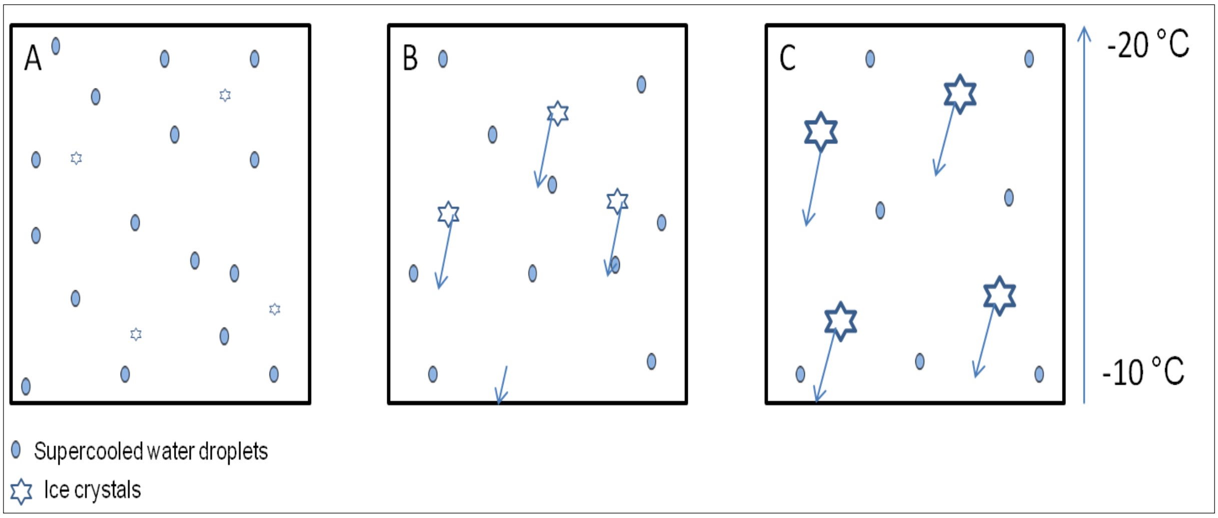


Figure 1.3: Bergeron-Findeison cold cloud process where supercooled water droplets are in co-existence with ice crystals between -10 °C and -20 °C in a cold super saturated cloud (adapted from AMS, 1996)

It can be seen from Fig. 1.3 A, that supercooled droplets are at first far more prevalent than ice crystals within a cold cloud. Supercooled droplets have vapour pressures larger than that of ice. As a result, ice crystals will grow at the expense of the evaporating water droplets when both water vapor and supercooled water is present (Fig. 1.3 B) (Pruppacher and Klett, 2010). The greatest difference in vapour pressure between the tiny water droplets and the ice crystal occurs close to -15 °C, causing water droplets to move from the water to the ice surface causing the ice crystal to grow quickly at the expense of the surrounding water droplets (Fig. 1.3 C) (Ahrens, 2007). The growing ice crystals in Fig. 1.3 C grow even larger as they fall and collide with supercooled droplets and later cannot be sustained in the atmosphere and fall to the ground as snow. In clouds where temperatures are warmer than -10 °C, supercooled droplets are in abundance, while the ice content of clouds increases at temperatures colder than -10 °C so that at -20 °C, 90% of the cloud consists out of ice (Ahrens, 2007).

1.4.2.1 Methods of ice crystal growth

These ice crystals may grow due to deposition, riming and aggregation within cold clouds (Pruppacher and Klett, 2010).

When water freezes onto ice it is called accretion (riming) and when they collide and stick together to form a snowflake it is called aggregation (clumping) (Ahrens, 2007). Accretion occurs when ice particles fall through supercooled droplets and this is more prevalent in the lower cloud levels (Baumgardt, 1999). Riming is the process whereby snow crystals grow when supercooled water droplets collide with ice particles and freeze on contact, or ice crystals may collide with each other to aggregate and form snowflakes (Pruppacher and Klett, 2010). The efficiency of the aggregation process is most when the air is saturated in the vertical, as this would contain a wide range of different ice crystals. Typically below 700 hPa and at temperatures warmer than -10 °C when there is an abundance of supercooled water, this provides the adhesive properties necessary for this aggregation process to become more efficient (NOAA, 2013; Baumgardt, 1999). When ice crystals aggregate, they form snowflakes. The best chance of having snowflakes form by aggregation is when the ambient air temperature is near 0 °C in the area of their formation. The more the ice crystals that are available for seeding into the low level orographic or stratiform cloud in the vicinity of 0 °C, the better the chances of producing flakes with a larger diametre.

Ice crystals may also grow by the seeder feeder mechanism. This typically occurs when ice bearing clouds with cloud tops of -15 °C (seeder clouds) move over warmer clouds with cloud tops of -6 °C (feeder clouds) that contain supercooled water droplets. When the ice particles are large enough, they fall through the supercooled droplets and grow, but the separation between the seeder and feeder cloud should not be more than 1500 m (Baumgardt, 1999). The clouds that contain the ice crystals are the releaser clouds while clouds such as low level stratus and Nimbostratus clouds are the spender clouds that contain large amounts of precipitable water. Releaser clouds contain prism ice crystals at -37 °C (Jiusto and Weickmann, 1973). In the absence of a spender cloud there is little chance of these ice crystals riming and forming snowflakes. If lower clouds such as Stratocumulus are present, these crystals can grow by droplet riming and ice crystal aggregation as they fall through the lower layers (Jiusto and Weickmann, 1973). The presence of low level spender clouds increases the precipitation efficiency. In cases where seeder clouds are absent and only spender clouds are observed, they are normally winter Cumulus clouds that may cause light snow. However, when thick convective spender clouds are present, heavy snowfall may occur (Jiusto and Weickmann, 1973).

Deposition is probably one of the biggest and important processes pertaining with regard to ice crystal growth (Baumgardt, 1999). This is the process whereby snow crystals grow by diffusion of water vapour in an environment where the air is saturated with ice crystals (Pruppacher and Klett, 2010). This is essentially when water vapour changes phase to the ice form and the ice grows quickly when the air is saturated (RH = 100%). This normally occurs in the mid- to upper atmospheric levels (Baumgardt, 1999).

It has been shown by Pruppacher and Klett (2010), that the largest concentration of snow crystals are found in the region of the mid-levels of the atmosphere where temperatures are around -16 °C as indicated in Fig. 1.4.

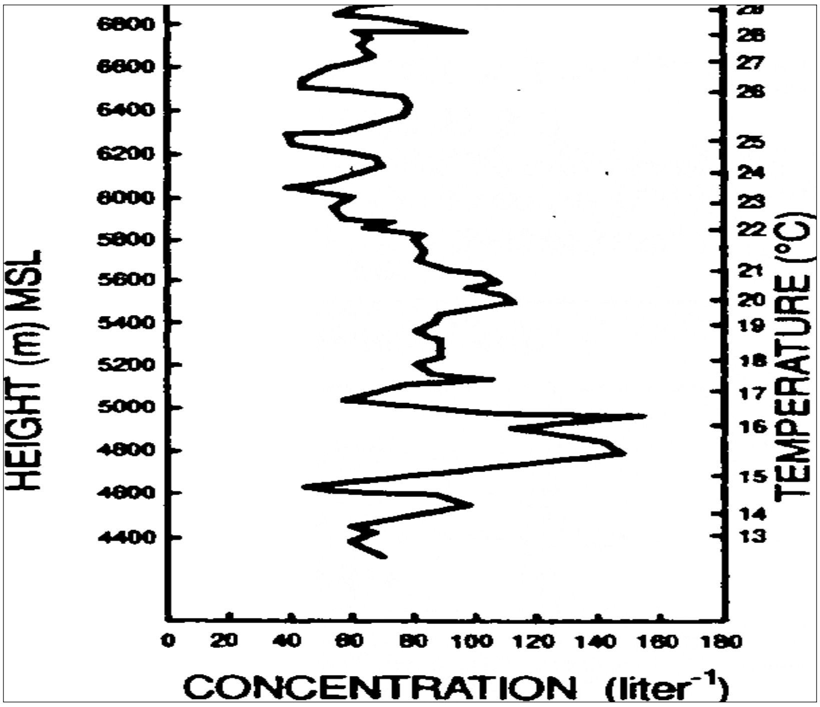


Figure 1.4: Snow crystal concentrations as a function of height in wintertime snow storms over N. Colorado in the USA (adapted from Pruppacher and Klett, 2010)

At 500 hPa and around -16 °C the growth rate of ice crystals are at a maximum (Pruppacher and Klett, 2010).This is illustrated in Fig. 1.5 where dendrite crystals that have the snowflake structure are most likely to grow (Ahrens, 2007). The deposition process occurs at temperatures between -12 °C and -16 °C and is typically found in winter between the layers of 700 to 500 hPa where the air is saturated and vertical motion is maximized (NOAA, 2013). Taljaard (1985a) found that during the COL occurrence of 18 to 23 August 1979 over South Africa, 500 hPa temperatures at Cape Town and Durban ranged between -12 °C and -20 °C. On September 1981 when heavy snow fell over the eastern interior of South Africa and Johannesburg, the temperatures at 500 hPa at Durban were between -17 °C and -19 °C.

Consequently, such temperatures that are conducive to the growth of dendrite ice crystals typically occur with mid- and upper level synoptic weather systems such as COLs. Wetzel and Martin (2001) suggested that these temperatures can best be determined by the use atmospheric soundings and satellite-derived cloud top temperatures. These methods will be demonstrated in Chapter 5.

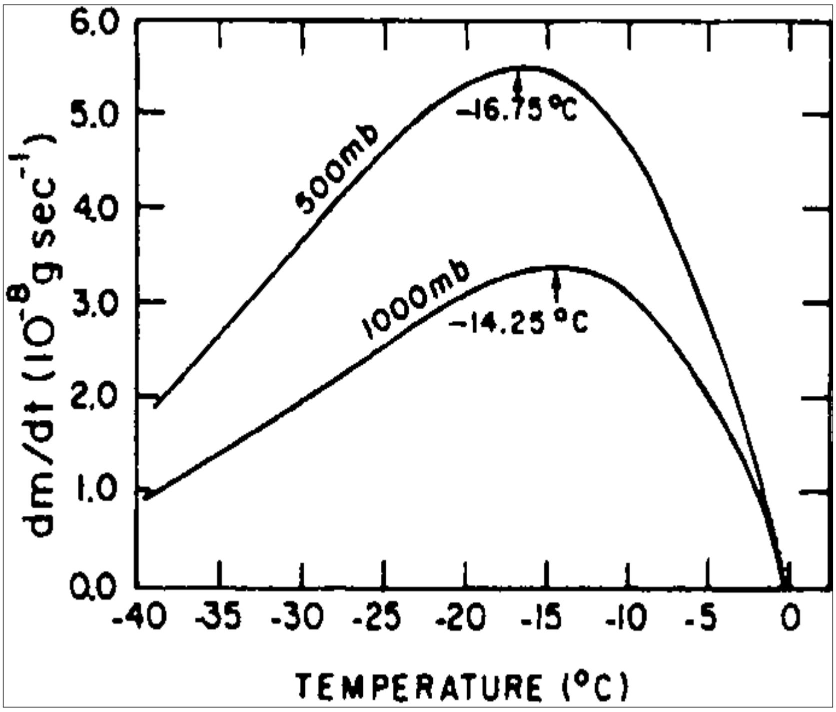


Figure 1.5: Diffusion mass growth rate of an ice crystal in a water saturated environment (Pruppacher and Klett, 2010)

Depending on the temperatures at which ice crystals grow, various shapes and ice crystal sizes can be found. Fig. 1.6 illustrates the structure of dendrite crystals which occur between -12 °C and -16 °C. These dendrite ice crystals have open spaces between the crystals, which effectively causes water vapour to condense on them and grow by deposition (NOAA, 2013).

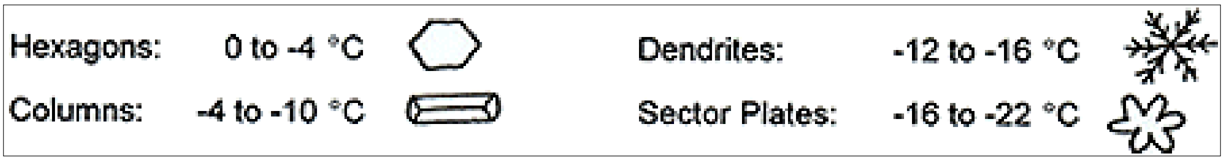


Figure 1.6: Different ice crystal types (adapted from NOAA, 2013)

According to Baumgardt (1999), the -10 °C temperature threshold should be considered the lowest temperature in the ice cloud. When the cloud top temperature is -10 °C, there is a

60% chance that the cloud contains ice. The cloud top temperature range of -12 °C to -15 °C, would indicate a high likelihood of ice (between 70% and 90%). At around -20 °C, ice is guaranteed in the cloud.

1.4.2.2 Freezing level (melting level) and factors that affect the air temperature in the vertical.

The freezing or melting level is the height in the atmosphere a.g.l where the 0 °C isotherm occurs. More than one of such a layer can occur in the atmosphere due to the presence of warmer layers in the atmosphere (Glickman, 2000). These warmer layers normally manifest as inversions (temperature increase with height). The air temperature in the vertical is critical in determining precipitation type, due to the presence of warmer layers in the atmosphere. According to Hobbs et al. (1974b, cited in Pruppacher and Klett, 1978:44) and Rodgers (1974b, cited in Pruppacher and Klett, 1978:44) snow is most likely to reach the earth's surface when the freezing or melting level is close to the ground.

Lamb (1954) found that both the height of the freezing level a.g.l and the air temperature near the surface of the earth is critical in determining whether snow or liquid precipitation will develop. Snow can fall all the way to the ground when the air temperature throughout the vertical is at or below freezing (0 °C) and there is moisture. Beckman (1987) indicated that when forecasting snow, the 850 hPa level (1500 m a.m.s.l) temperature should be considered.

Snow that falls from the mid-levels of the atmosphere can still reach the ground when the temperature in the atmospheric layer between the ground and the freezing level is greater than 0 °C. Normally snowflakes will begin to melt as they reach this warmer temperature layer, which occurs below the freezing level. However, this diabatic process of melting consumes sensible heat which has a cooling effect on the temperature in the vertical which becomes nearly isothermal near the freezing level allowing some flakes to make it to the ground (Cuviello, 2007). The melting also causes evaporative cooling which cools the air immediately around the snow flake. This cooling delays the melting process. As such, a snowflake can fall several hundred metres and the surface temperature can be as high as 5 °C (Pruppacher and Klett, 2010). As snow melts on its way to the ground, the melting leads to a release of latent heat which cools the surrounding air to the freezing point. In the presence of heavy rain, the temperature in the vertical may cool sufficiently for the precipitation to change into snow even if temperatures are above freezing on the ground (Lackmann, 2011).

Another process that can affect the air temperature in the vertical of the atmosphere is adiabatic cooling. This occurs through the rising of air parcels which adiabatically cools the atmosphere. The warming effect through the release of latent heat through condensation is negligible (Cuviello, 2007). This cooling typically occurs with large-scale ascent in COLs.

The other factor that can affect air temperature in the vertical and lead to atmospheric conditions conducive to snowfall is the horizontal advection of temperature by synoptic scale weather systems. Cold air advection occurs to the rear of cold fronts due to the advection of cold polar air from the Atlantic Ocean High (AOH) pressure systems and lowers the height of the freezing level and reduces atmospheric thickness (Lackmann, 2011).

1.4.2.3 Partial atmospheric thickness

A method used to determine precipitation type is known as the partial thickness method. The atmospheric thickness is determined by the height difference between two layers in the atmosphere. The 1000-700 hPa layer thickness is fundamental in determining the lower thermodynamic structure of the atmosphere and can aid in explaining snowfall (Keeter and Cline, 1991).

During studies done by Cantin and Bachand (1993, cited in Bourgouin, 2000), the 1000-850 hPa and the 850-700 hPa thickness were deemed useful in helping to distinguish between different precipitation types. One of the measures to determine if snow will occur is to investigate the geopotential thickness between specified pressure levels. The 1000-500 hPa thickness is often used and is compared to the height of the freezing level above the ground to distinguish between frozen and liquid precipitation. Lamb (1954) found that for stations in the United Kingdom which are close to sea level (1000 hPa), the transition from rain to snow occurred when the 1000-500 hPa thickness were about 5310 m and the 1000-700 hPa thickness were 2788 m. The 1000-500 hPa thickness synoptic patterns as well as the geopotential heights at 1000 hPa and 500 hPa and the temperature at 500 hPa were examined during heavy snowfall events over the western USA by Younkin (1968). Heavy snowfall occurred mainly when the 1000-500 hPa thickness values were between 5340 m and 5460 m and most snowfall occurred when temperatures at 500 hPa were between -20 °C and -30 °C. In some cases, snow also developed when the 500 hPa temperatures were between -15 °C and -20 °C. In Tasmania, mean thickness values of the 1000-500 hPa layer were used to determine how cold the lower portion of the atmosphere was (Jones, 2003). Jones (2003) also considered the temperatures at 850 hPa and 500 hPa and the height of the freezing level to forecast snow. Cold outbreaks with snow in Tasmania were associated with a mean freezing level height of 950 m a.g.l and 1000-500 hPa thickness of 5320 m.

To determine whether snow will reach the ground or not, one has to consider the thickness of thinner slices (700-500 hPa) in the atmosphere (partial thickness). Wagner (1957) found that there was good correlation between the 1000-700 hPa thickness and the 700-500 hPa partial thickness during snowfall events. Koolwine (1975) and Heppner (1992) found that the 1000-850 hPa, 850-700 hPa and 700-500 hPa atmospheric thickness can definitely assist in the identification of liquid as opposed to frozen precipitation. The partial thickness layer below the freezing level is important in determining the amount of cold air available to support the frozen precipitation. Cold air close to the surface is available through low level horizontal cold air advection. There are cases where the rate of cold air advection in the upper air (unstable cases) exceeds that of the lower layers and if this happens, the snow could melt into raindrops (Heppner, 1992).

It is therefore useful to consider the thickness at pressure levels close to the ground. In New York, which is located at sea level, the 1000-500 hPa thickness were found to be 5440 m during snowfall. When the atmosphere was unstable at sea level, cases were observed where rain occurred with geopotential thickness below 5440 m. Heppner (1992) concluded that in those unstable cases where the rate of cold air advection is larger aloft than at the surface, the 850-700 hPa layer could help in identifying frozen precipitation. This is because there is less cold air advection in the low layers and obtaining a critical thickness for snow to remain frozen becomes essential. This is especially true if the thickness of the 850-700 hPa layer is more than the 1550 m threshold. When this happened, snowflakes could melt through this warm layer and reach the surface as rain. A 850-700 hPa thickness of less than 1540 m implied that, somewhere in the layer, the temperature was below freezing and this was good for snow (Keeter and Cline, 1991).

The RH from the surface up to the 500 hPa level is standard output in Numerical Weather Prediction (NWP). It provides good guidance to indicate cold enhanced clouds producing snow in satellite imagery and is related to the movement of the upper level COL or vorticity centre.

When station altitudes are significantly higher than sea level, the pressure levels used to calculate the thickness should be adjusted. For instance, the interior of South Africa is an elevated plateau with a height close to 1500 m a.m.s.l (see section 1.2, Fig. 1.1) with surface pressures close to the 850 hPa level (Taljaard, 1995a). Using 850 hPa as the surface pressure level in the calculation of the thickness would be appropriate. Adapting the surface level in the calculation of thickness is common practice in elevated areas such as the Rocky Mountains (Lackmann, 2011). Heppner (1992) used a critical 850-700 hPa thickness value of 1550 m to forecast snow in Pennsylvania in the USA which has an altitude of 347 m a.m.s.l. Stranz and Taljaard (1965) investigated the 700-500 hPa thickness to identify snow over Bloemfontein and Johannesburg in June 1964. They found critical thickness values of between 2520 to 2560 m. In the forecasting offices in South Africa, a thickness value of less than 1570 m for the 850-700 hPa layer is used to forecast snow.

1.5 Aim of the study

The aim of this dissertation is to investigate synoptic circulation patterns and atmospheric variables associated with significant snowfall over South Africa in winter. In order to achieve this aim, the following objectives are addressed.

Objective 1
Identify significant snowfall cases over South Africa for the period 1981 to 2011.

Objective 2
Identify surface and upper air synoptic scale weather systems associated with significant snowfall subjectively, in order to identify atmospheric variables that play an important role in the occurrence of significant snowfall.

Objective 3
Create an objective climatology of surface and upper air synoptic scale weather patterns as well as 850 hPa temperatures for significant snowfall using self-organising maps (SOMs).

Objective 4
Conduct several case studies to create a better understanding of the local atmospheric variables conducive to snowfall over the interior of South Africa. Special attention is given to the partial thickness method, critical freezing level heights and surface temperatures and RH during snowfall.

Objective 5
Provide a snow forecasting decision tree to forecast significant snowfall over the interior of South Africa.

Significant snowfall events in this research were defined when there was snowfall on the ground in areas with an altitude of less than 2000 m a.m.s.l. Snowfall in South Africa normally occurs in the sparsely populated mountainous regions but during significant events it reaches the more populated lower elevated regions. The average height of the interior of South Africa is at 1500 m a.m.s.l (850 hPa level) and as a result, significant snowfall can affect the livelihood and daily activities of people.

1.6 Outline of this document

The objectives described in Section 1.5 were achieved throughout the seven chapters of this dissertation.

Chapter 2 deals with the winter synoptic scale circulations that effect South Africa and their importance in the occurrence of snowfall is discussed. Atmospheric variables that are important in the forecasting of snowfall are discussed and they are related to the synoptic pressure patterns.

The data and methodology used within this dissertation is described in Chapter 3. The method of identifying the significant snowfall case studies is described (Objective 1) along with the various data sets applied. Methods that are used to subjectively classify synoptic patterns along with the objective classification methodology using the SOMs software (Objective 2 and 3) are discussed.

Results of the subjective synoptic classification, along with the objective classification using the SOMs software, is described and presented in Chapter 4. The different synoptic patterns associated with snowfall obtained from Chapter 4 are then analysed through case studies in Chapter 5. These cases provide an in depth synoptic analysis of the vertical distribution of temperature and moisture throughout the atmosphere during significant snowfall. Guidance is provided to weather forecasters in order to better anticipate these types of severe weather events.

Chapter 6 provides a snow forecasting decision tree that can be used by weather forecasters to anticipate these severe weather events. Chapter 7 concludes the dissertation with a summary and discussion of results. Suggested further research into this topic is discussed.

Chapter 2: Winter synoptic circulation

In this chapter, winter surface and upper air synoptic circulation systems which contribute to the formation of significant snowfall over South Africa are discussed. The surface and upper air weather systems are discussed separately, but as surface and upper air systems interact to produce snowfall, they are discussed together in some instances. Temperature is a very important atmospheric variable that has an effect on the occurrence of snowfall, consequently, the effect that topography and winter synoptic circulation systems have on temperature is discussed. Temperature is also used within objective classification of synoptic weather systems in Chapter 4.2.

2.1 Surface synoptic pressure patterns

Synoptic scale weather systems are defined as having a horizontal scale of hundreds to thousands of kilometres with time scales of days to weeks (Tyson and Preston-Whyte, 2000). Synoptic scale circulation systems include surface and upper air troughs and ridges as well as high pressure and low pressure systems (Lankford, 2001). In South Africa in winter, high pressure systems and cold frontal troughs dominate the circulation pattern at the surface while, in the upper air, westerly upper ridges and troughs occur frequently (Taljaard, 1995b). The important surface synoptic circulation patterns over South Africa are illustrated in Fig. 2.1. West of South Africa, the AOH dominates with the Indian Ocean High (IOH) east of South Africa. These surface highs are separated by westerly waves or frontal troughs. A coastal low very often precedes the passage of a frontal trough.

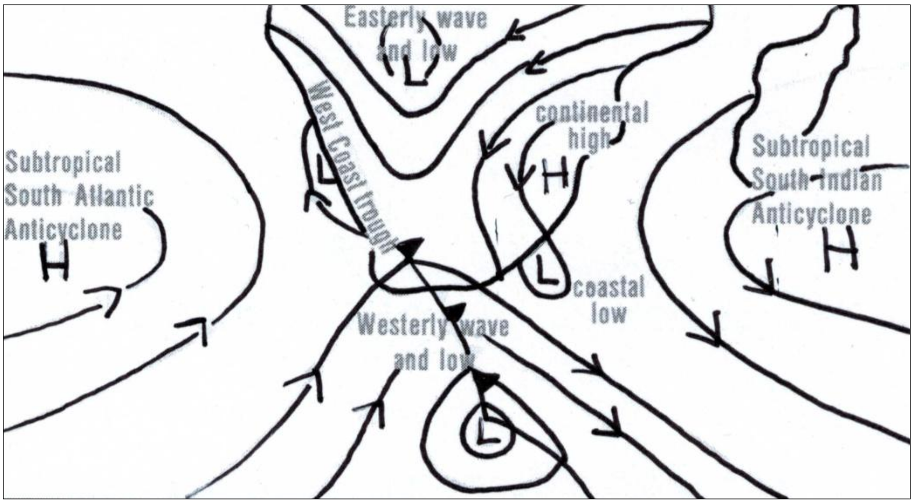


Figure 2.1: Important surface circulation patterns over South Africa (adapted from Tyson and Preston-Whyte, 2000)

The main surface synoptic circulation systems that play a role in significant snowfall in winter over South Africa are the subtropical AOH and IOH and westerly waves better known as cold fronts (Tyson and Preston-Whyte, 2000). Synoptic circulation type classification is done in order to understand how the surface and upper air pressure patterns interact with each other in order to modify the stability of the atmosphere, cause uplift and produce rainfall (Tyson and Preston-Whyte, 2000). Taljaard (1995a) did a classification of the main surface and upper air circulation patterns that contribute to the weather of South Africa and the results are summarised in Fig. 2.2. The five main circulation types were identified as anticyclones (highs), cyclones (lows), trough, ridges and zonal flow. He also classified synoptic systems (Fig. 2.2) as cold or warm and whether they occurred in summer or winter.

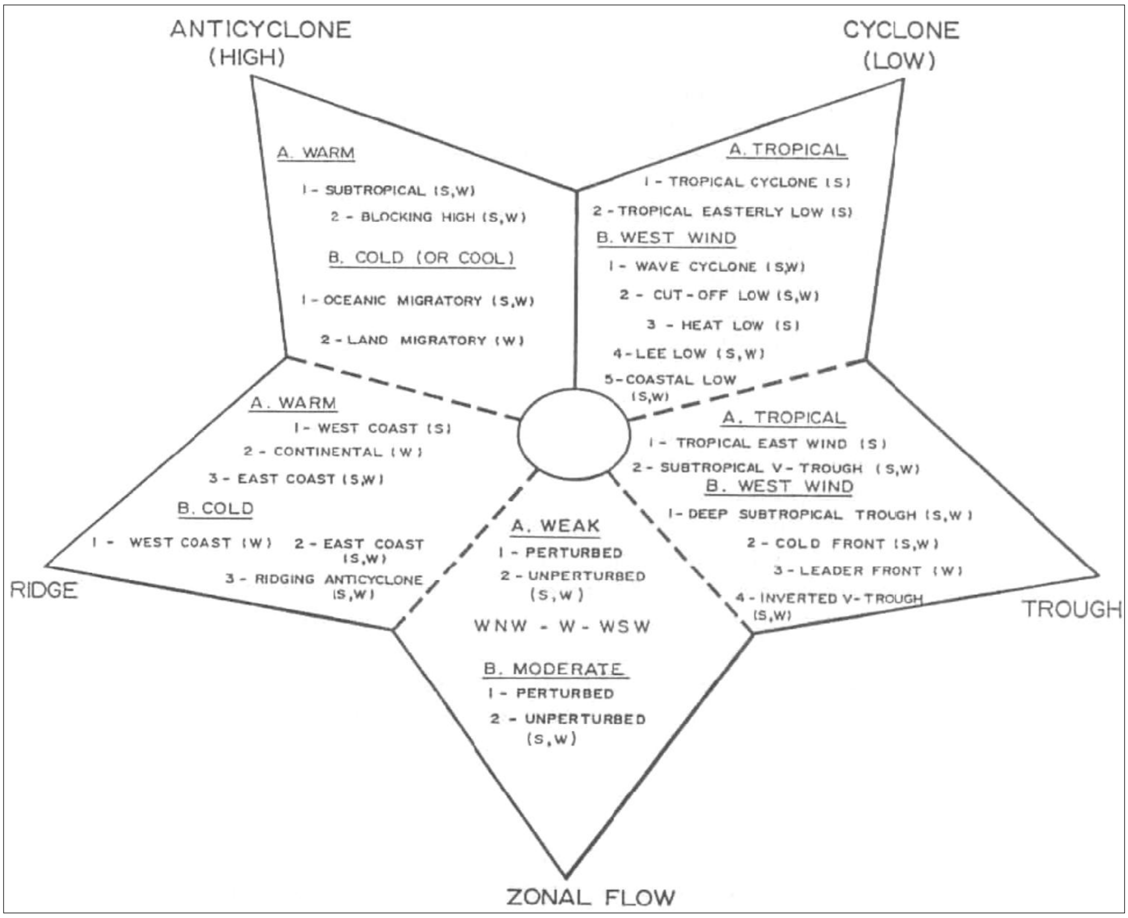


Figure 2.2: The five main surface circulations, warm or cold cored, their location to the land and whether they are weak or moderate in summer or winter (adapted from Taljaard, 1995a)

The cold winter surface and upper air circulation types will be discussed in more detail in the following sections of this chapter and emphasis is placed on how they contribute to the formation of snowfall.

Topographically most of the interior plateau of South Africa is situated at 1500 m a.m.s.l (see Section 1.2, Fig. 1.1). Consequently the height of the 850 hPa pressure surface is generally used to represent the surface level over the interior of South Africa (Tyson and Preston-Whyte, 2000). The same approach is followed in this dissertation.

2.1.1 Subtropical anticyclones

2.1.1.1 Climate

There are two distinctive oceanic high pressure systems surrounding South Africa, namely the AOH and the IOH. These form part of a nearly continuous band of high pressure circling the globe in the vicinity of 30° latitude and is known as the subtropical high pressure belt. The subtropical high pressure belt around South Africa is located approximately 5° further north in winter than in summer (Taljaard, 1995a; Tyson and Preston-Whyte, 2000). The high pressure systems normally occur in the lower atmosphere between the surface and 700 hPa (Taljaard, 1995a). In winter at the 850 hPa pressure level over the interior of South Africa, the synoptic circulation is frequently dominated by a high pressure system along 23° S (Taljaard, 1995b). At the surface, they are associated with a divergent wind flow with temperature inversions. Anticyclones are generally associated with stable weather conditions (sinking air) and have a diametre of a few thousand kilometres (Van Heerden and Hurry, 1995). The AOH and IOH generally move eastwards with a small northward component on the east coast of South Africa and a southward movement possible on the south-west coast of South Africa.

2.1.1.2 Ridging high pressure systems and snow

The subtropical high pressure belts play an important role in the weather and climate of South Africa especially when they ridge along the coast (Tyson and Preston-Whyte, 2000). When an area of surface high pressure intrudes along its west-east axis into an area of lower pressure, it is said to ridge (Van Heerden and Hurry, 1995). During winter over South Africa several synoptic configurations of the surface AOH in association with surface cold fronts are possible (Taljaard, 1995a). Depending on their configuration, snow or no snow can occur.

On occasions the eastwards ridging AOH will extend south of the country and develop a new cell of high pressure over the Indian Ocean (the IOH). This discussion is limited to these weather systems as they are known to cause precipitation over South Africa. Fig. 2.3 indicates the different synoptic patterns involving an AOH following to the rear of the surface cold front which are typically not associated with significant snowfall. Fig. 2.3 A indicates a typical situation when a cold front approaches South Africa. Fig. 2.3 B indicates the AOH ridging behind the surface cold front producing precipitation along the southern and south-eastern coastal belts with the cold air limited to this region. In Fig. 2.3 C, the AOH does not move over the entire South Africa into the Indian Ocean, instead the existing AOH ridges overland and remains in its position west of the country with a new high developing over and to the east of the country (IOH) (Fig. 2.3 D). The importance of this with respect to significant snowfall is that the cold air is unable to penetrate far northwards into the country. This is due to the fact that the high recedes back to the west instead of moving south of the country and producing horizontal cold air advection. The synoptic patterns indicated in Fig. 2.3 B and C normally produces precipitation along the south-west, southern and south-eastern coastal areas of South Africa.

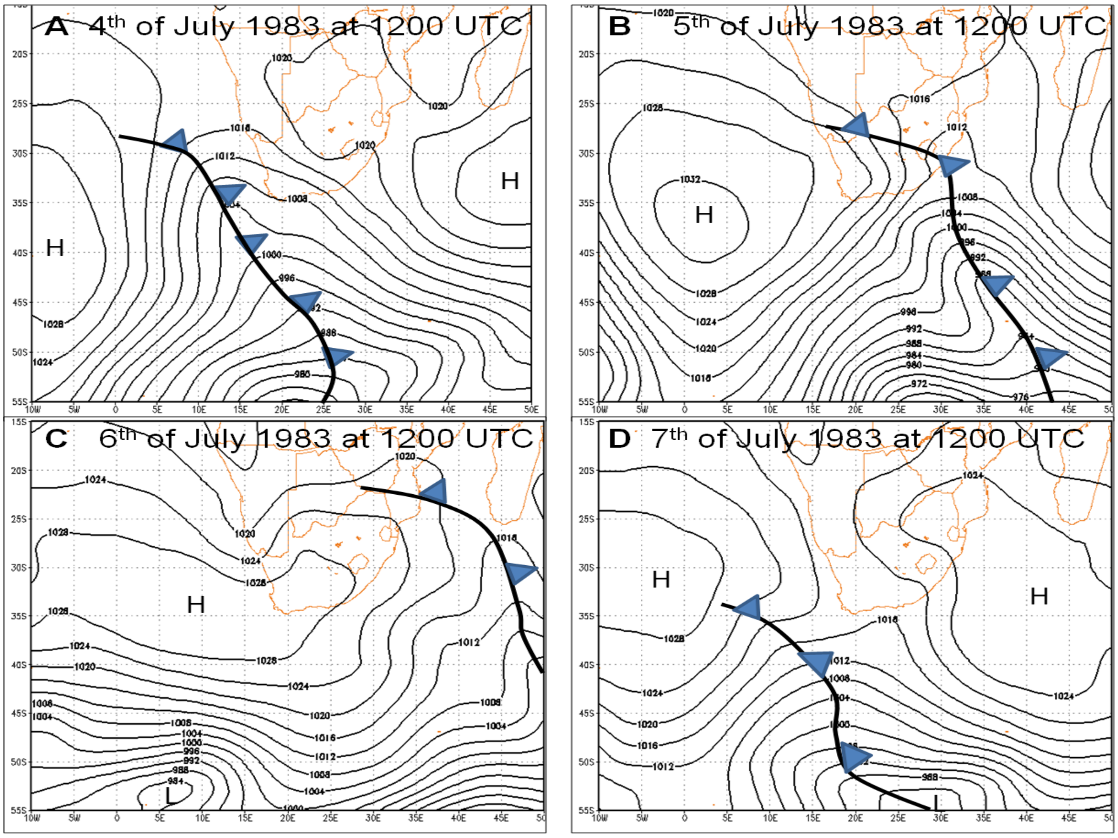


Figure 2.3: Mean sea level pressure map in hPa indicating the different synoptic patterns involving an AOH following to the rear of the surface cold front which are typically not associated with significant snowfall (adapted from Taljaard, 1995a with NCEP reanalysis data).

A less frequent situation is indicated in Fig. 2.4 where the cold front is followed by a strong AOH at 35° S tracking along the southern coastal belt (Fig. 2.4 A and B) of South Africa and ending up in the Indian Ocean as an IOH (Fig. 2.4 C and D).

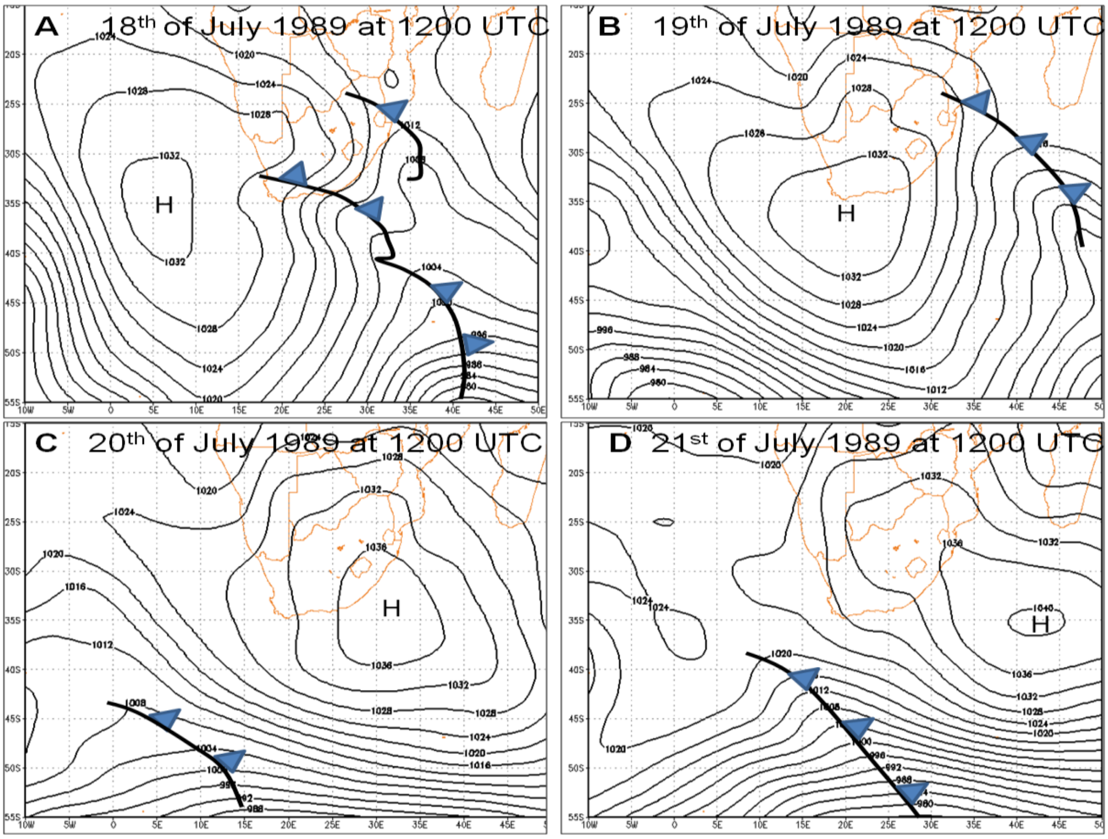


Figure 2.4: Mean sea level pressure map in hPa of a cold front crossing South Africa followed by an intense high at 35° S (adapted from Taljaard, 1995a with NCEP reanalysis data)

This synoptic sequence in Fig. 2.4 is especially important with respect to significant snowfall as cold air can penetrate far northwards behind the cold front (compare to Fig. 2.3). Fig. 2.4 A is representative of the left hook pattern that indicates that the flow comes from the left around the surface low to the south-east of the country (Van Heerden and Hurry, 1995).

On the odd occasion a slow eastwards moving AOH will follow the cold front at latitude 40° S across to the Indian Ocean as illustrated in Fig. 2.5. This type of circulation is extremely effective in producing significant snowfall over the interior of South Africa. Furthermore, this type of surface circulation is associated with the formation of a COL in the upper air which is imperative in the occurrence of significant snowfall over South Africa (Taljaard, 1985a). Fig. 2.5 A, B, C and D is indicative of a strong eastwards moving AOH following the surface cold front which has a cyclonic circulation, and is referred to as the right hook (Van Heerden and Hurry, 1995).

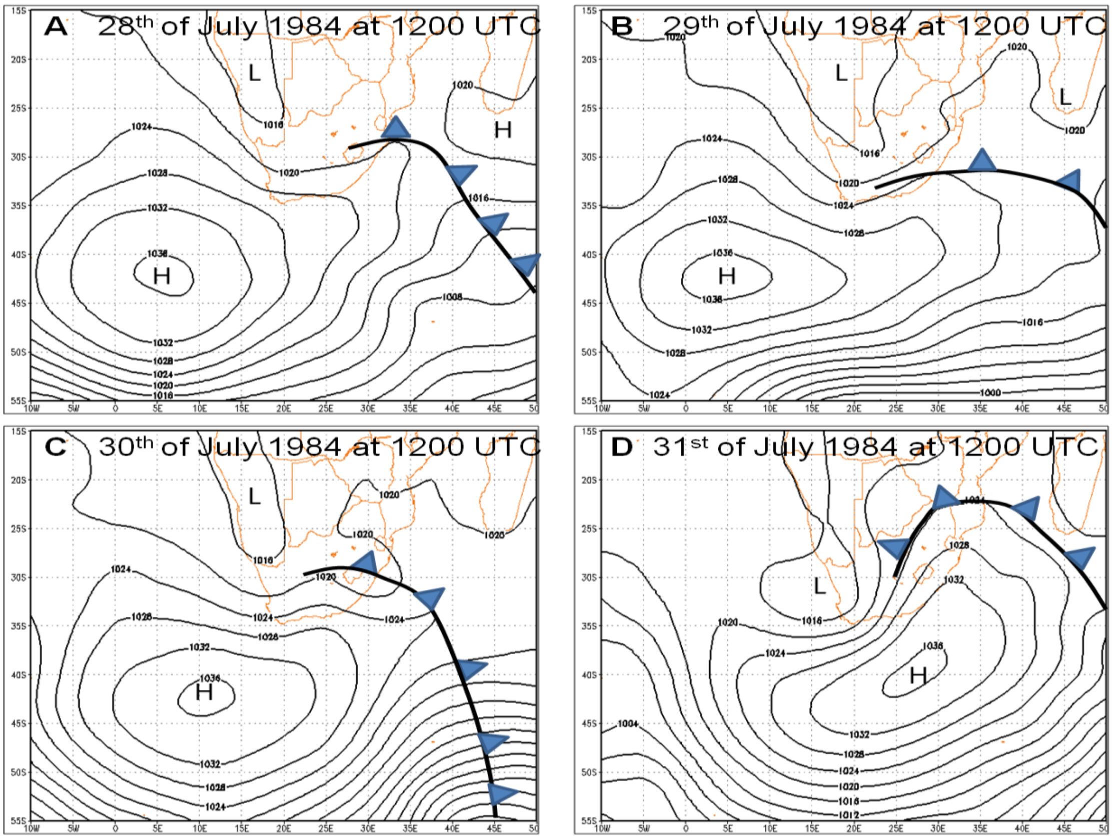


Figure 2.5: Mean sea level pressure map in hPa of a cold front crossing South Africa followed by an intense high south of 40° S (adapted from Taljaard, 1995a with NCEP reanalysis data)

The weather system that normally produces an influx of low level moist air over the eastern escarpment and Highveld of South Africa is referred to as the right hook as the moist air flow comes in from the right over the Ocean (Fig. 2.6). Air that moves over warmer bodies of water (Fig. 2.6 right hook) will acquire higher moisture content as it moves over the continents (Van Heerden and Hurry, 1995).

In the region surrounding South Africa, the position of the ridging AOH south of the country in the presence of large surface pressure gradients play an important role in forcing large amounts of cold air and moisture in over the country behind well-developed frontal systems. This is one of the quintessential factors necessary to create favourable synoptic conditions for significant snowfall over South Africa.

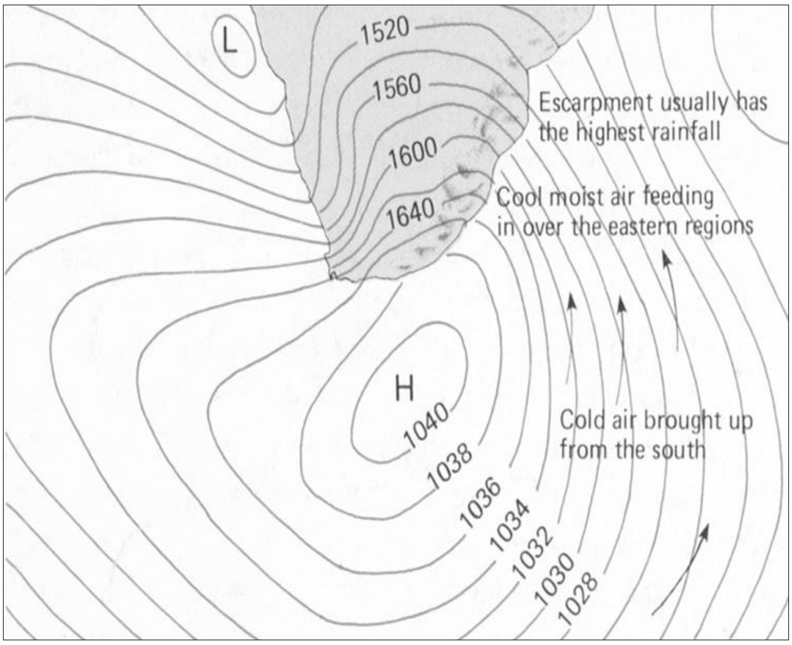


Figure 2.6: Mean sea level pressure map in hPa (ocean) and 850 hPa geopotential height in metres (land) indicating the right hook over South Africa (adapted from Van Heerden and Hurry, 1995).

Depending on the configuration of the upper air weather systems over the eastern interior in conjunction with the right hook of Fig. 2.6, such as an upper COL or pointed trough, heavy rain or snow can result due to the enhanced uplift and condensation (Van Heerden and Hurry, 1995). The infrequent pattern involving the right hook combining with an upper COL over the eastern interior of South Africa is one of the patterns associated with significant snowfall and is described in Chapters 4 and 5 in more detail.

The effect surface anticyclones have on South Africa's weather is accentuated when the surface anticyclone advects moist air over the country in the presence of an upper air westerly trough causing upward motion and upper wind divergence (Fig. 2.7). East of the pointed upper air trough and ahead of the surface ridging anticyclone, convergence occurs in the lower layers of the atmosphere as depicted in Fig. 2.7. This is especially prevalent along the south-eastern and eastern escarpment areas of South Africa (see Section 1.2, Fig. 1.1). In the upper air (above 500 hPa), wind divergence occurs in the presence of an upper level jet stream ahead of the advancing upper air trough with surface convergence taking place in the vicinity of the cold frontal boundary.

When these systems are baroclinic as in Fig. 2.7, large amounts of rising motion takes place between the surface and 500 hPa levels, resulting in the cloud and weather necessary to cause precipitation. To the west of the upper air trough, convergence occurs at the 500 hPa level with associated wind divergence above the surface high, causing descending motion and settled weather. Significant rainfall can then occur due to the combined effect and relation of the surface and upper air weather systems to each other. The ridging surface high pressure system is mostly responsible for advecting significant amounts of moisture along the southern and eastern coastal belts of South Africa, resulting in summer rainfall (Tyson and Preston-Whyte, 2000). This pattern, however, also transpires during the winter months when significant snowfall occurs as considerable amounts of cold air and moisture are advected over the country to the rear of the passage of the cold front. An example of this process is described in detail in the case studies of Chapter 5.

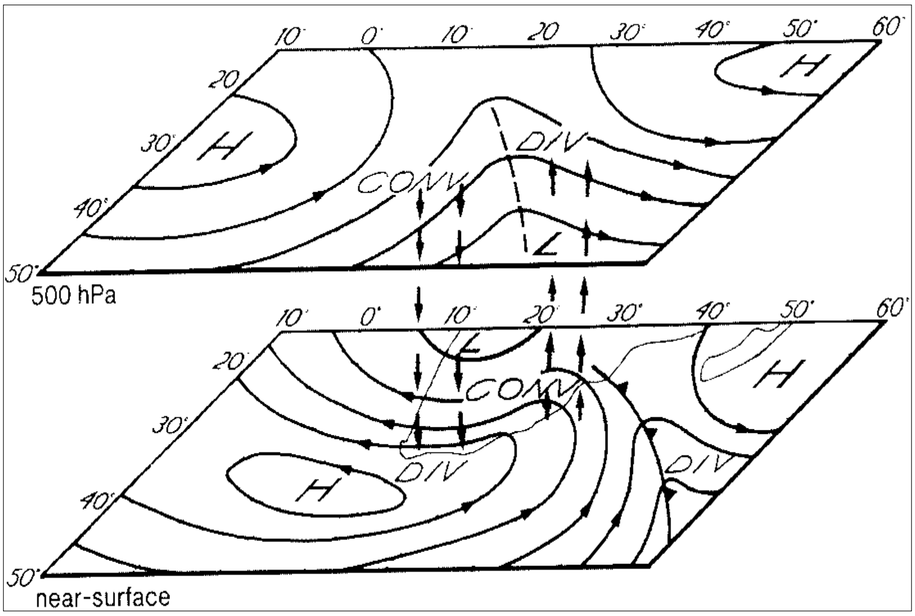


Figure 2.7: Near surface and 500 hPa circulations associated with a ridging surface anticyclone (adapted from Tyson and Preston-Whyte, 2000)

Taljaard (1972) found that there was a clear trend for the strongest anticyclones with an atmospheric pressure in excess of 1035 hPa to occur to the south of the subtropical ridge which is located at 32° S. These strong anticyclones with pressures in excess of 1035 hPa occurred most frequently along 38° S. It is these strong surface anticyclones situated around 38° S that are of particular importance to the occurrence of significant snowfall over South Africa. During the winter of 1957 when 500 to 1000% of the normal winter rainfall occurred over South Africa's plateau, moderate to strong anticyclones moved 5-10° pole ward of their normal winter tracks with a large number of COLs and strong upper troughs (Taljaard, 1972). Taljaard (1985a) found that, when strong surface high pressure systems move eastwards south of the country close to 38° S, they are associated with an upper COL.

In the USA, anticyclones play an important role in snowfall events as they are similarly responsible for sourcing and maintaining the very cold temperatures needed at the surface for snowfall to take place. In the USA, the air is normally sourced from north (Canada). This low level flow also assists in the thermal advection of cold polar air into surface cyclones which helps maintain the structure of these systems (Kocin and Uccellini, 2004). Similarly, in South Africa the northward advection of cold air by the surface anticyclones cause very cold temperatures over the interior allowing snowfall to reach the ground. Cold air damming occurs when cold polar air in the lower layers is guided southward between the Appalachian Mountains and the Atlantic coast in the USA (Kocin and Uccellini, 2004). This cold polar air is supplied by the surface anticyclone situated to the north of the USA. Similarly, the north-eastern part of the Eastern Cape and the southern part of KZN is situated in the channel between the highly elevated Drakensberg range and the warm Indian Ocean (see Section 1.2, Fig. 1.1). When a strong surface anticyclone is situated to the south of the country, colder air is advected from the south-east perpendicular to this mountain range as in the right hook case (Fig. 2.7). As a result, it becomes a favoured area of thermal advection, convergence and orographic lift, enhancing heavy snowfall in that area (Van Heerden and Hurry, 1995). As this study is confined to synoptic scale features, mesoscale effects such as topography will not be discussed in further detail.

2.1.2 Surface cold fronts

2.1.2.1 Climate

Cold fronts over the subtropical region of South Africa (25 to 40° S) are more frequent and well defined in winter as in summer. As a result, they exhibit a strong seasonality in their occurrence (Taljaard, 1972). Warm fronts generally occur to the south of 35° S latitude causing the sub tropics to be effected only by cold fronts which can be of the same intensity as those occurring in the mid-latitudes (Taljaard et al., 1961). These strong cold fronts when they occur contribute to significant snowfall over South Africa by providing the necessary cold temperatures.

Cold air outbreaks in subtropical regions cause great discomfort due to very cold temperatures and efforts have been made to identify the source and synoptic conditions under which they occur. Air causing cold outbreaks with a drop in temperature of 5-10 °C over South Africa comes from latitudes 40-55° S (Taljaard, 1972). Cold fronts are the most dominant during the winter months when they occur with a frequency of one to two systems per week within a distance of 800 km from the coast. These cold fronts are normally interrupted and followed with lower level anticyclones (AOH and IOH) as discussed in detail in Section 2.1.1. When these cold fronts are intense and close to the coast, they can produce severe weather (Taljaard, 1995a). They generally have a life cycle of three to four days (Taljaard, 1994d). Significant snowfall cases in South Africa also last a few days and are linked to the passage of these systems.

Low pressure systems situated between 30° S to 60° S latitude are normally associated with cold fronts. Cyclones in the mid-latitudes are associated with unstable conditions and rising air motion. They are therefore associated with cloud formation and precipitation (Van Heerden and Hurry, 1995). Most frontal low pressure systems occur well to the south of 40° S, with a smaller number to the north with very few north of 30° S (Taljaard, 1972; 1995a). In the winter, fronts can move as far north as the latitude of 15 to 20° S (Taljaard et al., 1961). Progression of cold fronts into latitudes of 15 to 20° S is possible if there is a COL or pointed upper air trough present over South Africa (Fig. 2.8) (Taljaard, 1995b). In the discussion of the synoptic classification of weather systems associated with significant snowfall in Chapter 4, these patterns are found to be associated with significant snowfall.

On occasion, surface lows can develop between 25° S and 35° S. When this happens, they can be manifestations of upper air COLs (Fig. 2.8) or strong pointed upper air troughs (Taljaard, 1995a).

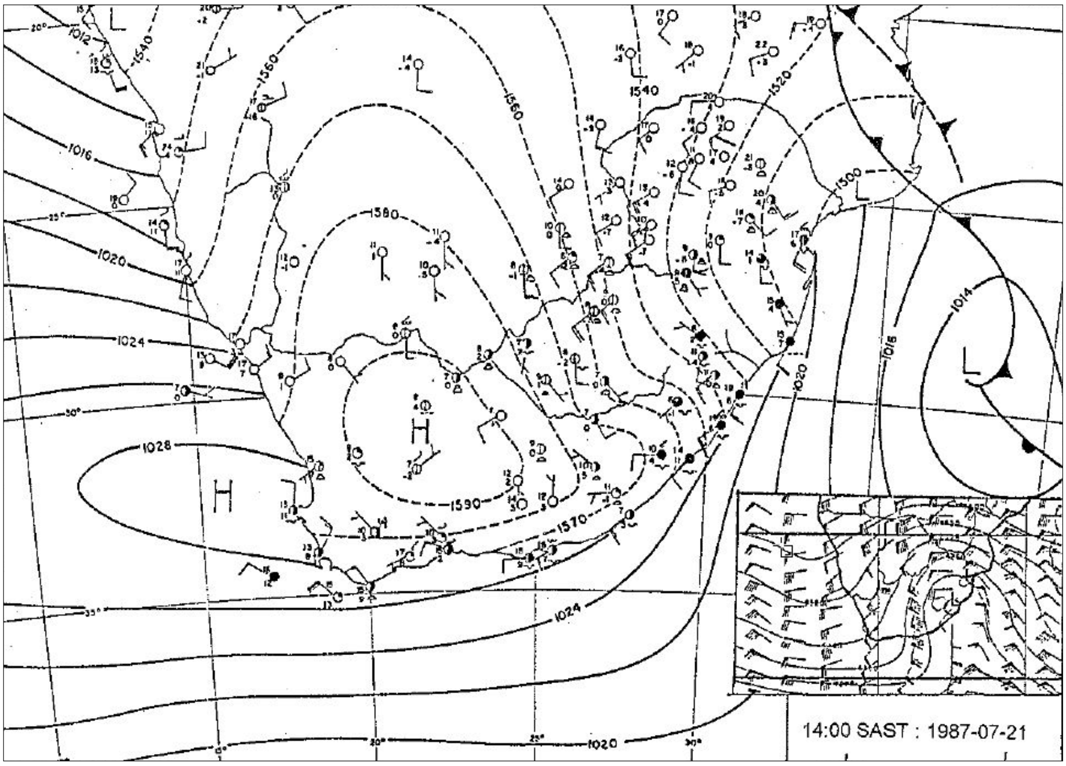


Figure 2.8: Mean sea level pressure map in hPa (solid lines) indicating surface frontal low east of South Africa associated with a 300 hPa COL (window). The front is followed at 850 hPa by a surface anticyclone (dotted lines overland) (adapted from Taljaard, 1995a)

2.1.2.2 Movement of cold fronts over South Africa.

All cold fronts exhibit a general eastwards movement due to their location within the westerly wind belt. Cold fronts normally approach South Africa at a longitude of 5°-10° from the west and south-west and have a north-west to south-east orientation (Taljaard, 1995a; 1995b). While the cold front is approaching, there is a general fall in three-hourly pressure values of 1-2 hPa along the south-western coastal regions. There is also a 10-25 knots north-westerly wind ahead of the cold front over the interior of South Africa (Taljaard, 1972; 1995b). The north-westerly winds ahead of the cold front are generally associated with clear and stable conditions (Tyson and Preston-Whyte, 2000). A coastal low pressure normally precedes the cold front (Taljaard, 1972; 1995b,). Cold fronts are very often associated with a pre-frontal boundary where temperature changes can be as much as 5-10 °C. Taljaard (1972; 1995a) refers to this type of front as a leader front when cooler, moister maritime air from the Atlantic Ocean associated with the north-westerly flow causes stratus clouds and drizzle to infiltrate the warmer, drier continental air (Taljaard, 1995a). Due to the orientation of the topography in the south-western part of the Western Cape, this north-westerly flow undergoes orographic ascent leading to prefrontal precipitation over this region in the form of drizzle or light rain (see Section 1.2, Fig. 1.1).

When a cold front passes over the South African coast, the winds turn anticyclonically and surface pressure rises. When the cold front is approaching, the winds are north-westerly but turn westerly to south-westerly and rain occurs but precipitation turns to showers due to the advancing cold air.

Due to the effect of the continent cold fronts tend to exhibit a northerly movement over the interior plateau. The speed of northward progression is not consistent and is dependent on the characteristics of the front such as the strength of the pressure gradient force driving it across South Africa. The magnitude of the pressure gradient force is determined by the strength of the ridging anticyclone and the depth of the low pressure associated with the cold front east of the country (see example provided in Chapter 3.2.2, Fig.3.5). The stronger the high pressure system and the deeper the low pressure system the further north the front and cold air is able to penetrate the country. The cold front slows down and dissipates once this pressure gradient has dissipated or the gradient is reversed to that of a flow from the equator (Taljaard, 1995a).

2.1.2.3 Identification of cold fronts using surface and upper air data

A front is a boundary between different air masses, especially with regard to temperature gradient in the horizontal and usually coincides with a strong vertical wind shear in the presence of an upper level jet stream (Glickman, 2000). Taljaard (1961; 1972; 1994b) described a cold front to be **"**a narrow sloping layer, with a vertical extent of at least 3 km, across which the temperature changes sharply in the horizontal direction by an average of at least 3 °C in subtropical regions (25° S to 35° S) and 4-5 °C in middle latitude and polar regions (35° S to 70° S)**"** The change in temperature should also be sudden in a short space of time and not gradual. Taljaard (1972) refers to cold fronts associated with strong upper troughs in winter as discontinuities in air masses which coincide with a wind change from north/north-westerly to westerly and a dramatic drop in temperature and rise in dew point temperature south of the interior plateau.

Surface cold fronts are associated with a westerly trough in the upper air (Taljaard, 1995a; Schultz, 2005). The cold fronts cause pronounced changes in temperature, wind direction and gustiness at the surface (Taljaard, 1985a; Tyson and Preston-Whyte, 2000). Certain characteristic features are associated with the passage of frontal systems. The cold fronts are located within a trough of low pressure at the surface, where they have their strongest intensity. This coincides with a horizontal wind shift and change in horizontal temperature and or moisture. They are characterised by strong vertical wind shear, rising motion, cloud formation and precipitation (Glickman, 2000).

The horizontal distribution of air temperature and pressure through a cold front is shown in Fig. 2.9.

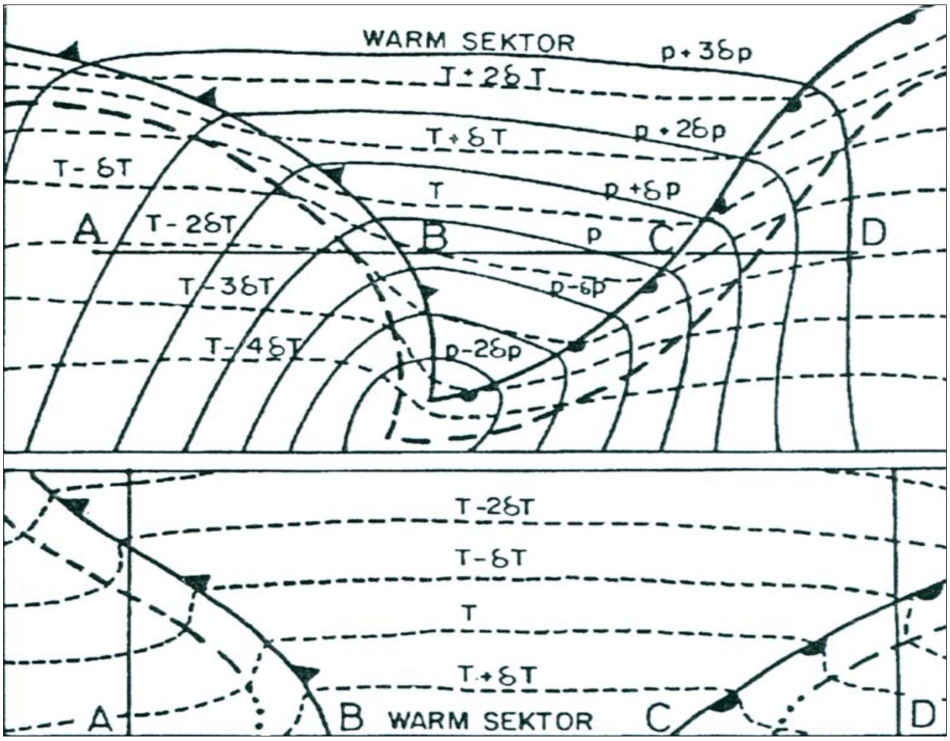


Figure 2.9: Typical pressure and temperature distribution through a cold front at points A, B, C, D. Temperature is indicated by dotted black lines and pressure by solid black lines (adapted from Taljaard et al., 1961; Taljaard, 1994c)

The surface isobars (solid black lines) indicate the south-westerly flow behind a cold front and the north-westerly flow ahead with the cold front located in the axis of maximum cyclonic curvature (trough). The isotherms (dotted black lines) indicate that warmer air occurs ahead of the cold front in the warm sector with colder air to the rear of the cold front.

According to Taljaard (1995a) cold fronts can be detected by considering the temperature contrast at the surface and the wet bulb potential temperatures behind the cold front. Taljaard (1994c) indicated that stronger cold fronts can have a vertical depth that extends up to the tropopause and the transition zone at the surface can be 30 –100 km wide. On occasions, a surface low at 850 hPa can form on a cold front over the central plateau and this normally occurs once or twice in July. This is referred to as a wave on a cold front. This typically occurs when there is a COL present in the upper air. However, to identify cold fronts, not only surface conditions should be analyzed as indicated in Fig. 2.9. Changes in temperature, moisture and wet bulb potential temperature in the vertical need to be considered on Aerological diagrams (Taljaard, 1994c).

Taljaard et al. (1961) indicated that the use of atmospheric thickness calculations close to the surface can also aid in frontal analysis as it addresses the analysis of the air mass as well as the horizontal frontal and contour analysis. The amount of warming or cooling within the three-dimensional structure of the atmosphere and the related stability of the atmosphere is most adequately addressed by the use of tephigrams (Tyson and Preston-Whyte, 2000). Where aerological diagrams (tephigrams) are available at regular intervals, the temperature, humidity and wind can be compared in two succeeding ascents to perform frontal analysis. This analysis may provide evidence whether the changes in temperature and humidity are due to vertical motion, advection or a change in air mass. They were also used to analyse the extent of the moisture and cold air distribution within the vertical. Fig. 2.10 indicates a typical example of the change in air mass that occurs with a passage of a cold frontal system through a weather station.

Between 2 and 3 May 1957, a cold front passed through Cape Town. The vertical temperature and moisture distribution on 2 May 1957 is indicated by the dotted line and 3 May 1957 by the solid lines. During the passage of the cold front, a dramatic decrease in the vertical distribution of temperature and dew point occurred. Surface temperature and dew point temperature dropped, while the winds changed from north-westerly to south-westerly at the surface behind the cold front. It is important to note that the cooling occurred in the vertical throughout the troposphere and not just at the surface. In this dissertation, the use of tephigrams with regard to the identification of the passage of the cold front has been extensively used in Chapter 5 during the case study analysis.

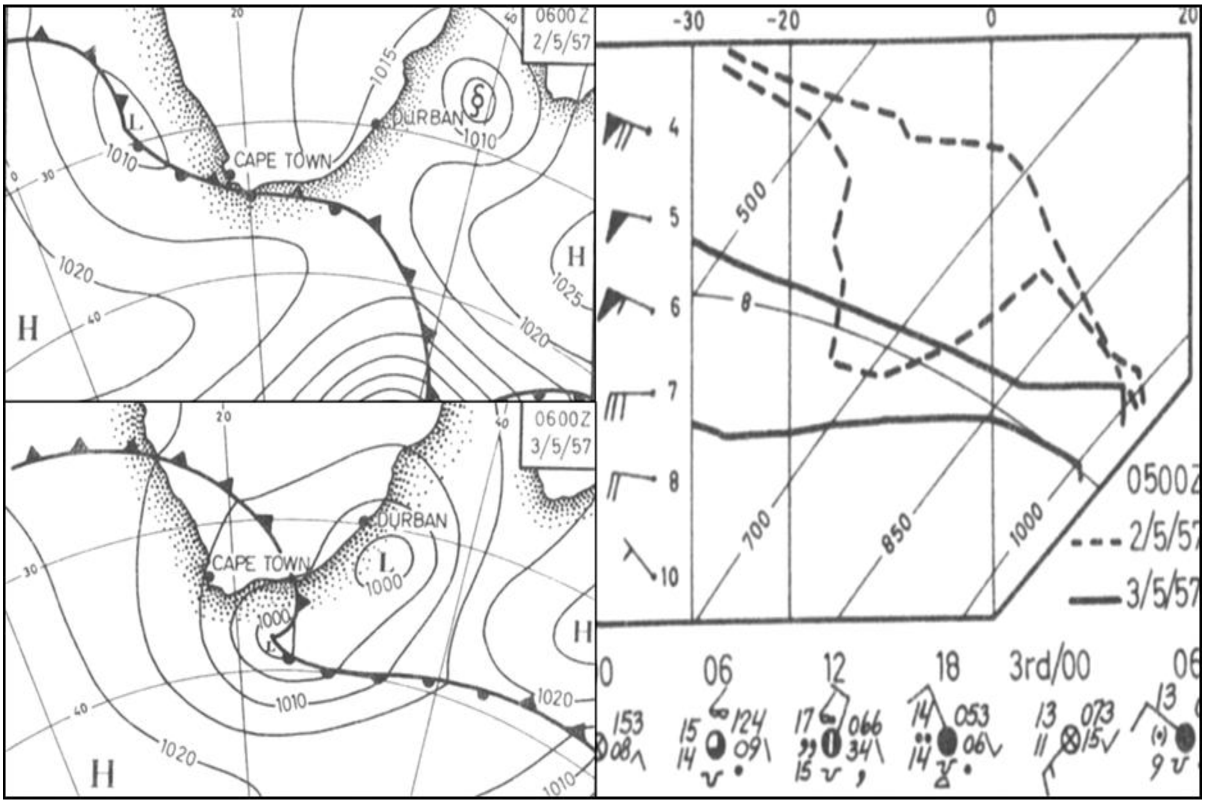


Figure 2.10: Change in air mass (temperature and dew point) that occurs with the passage of a cold front through a weather station (adapted from Taljaard et al., 1961)

2.2 Upper westerly waves and cut-off lows

Cold lows, “Kaltluft tropfen” and “kona storms” are typical names given to COLs and play a very important role in the rainfall of the subtropics between 20° S and 40° S (Stranz and Taljaard, 1965). A COL is a cold cored low pressure system between the atmospheric levels of 500 hPa and 300 hPa and is a very important synoptic scale weather system in South Africa (Taljaard, 1985a). According to Taljaard (1982b), COLs are described as cold pools of cyclonic circulations which intensify with height and are displaced towards the equator from pointed, westerly troughs. The coldness of the cold pool is increased by vertical motion on its inside and subsidence on the outside. Taljaard (1972) defined a COL as a low that had been displaced towards the equator out of the basic westerly current in such a way that it is trapped by an anticyclone on its poleward side. In the rest of the world, the most notable areas of occurrence are Europe, China, Siberia, the North Pacific, north-east USA and the north-east Atlantic (Nieto et al., 2005). Wright (1989) referred to the same COLs in the Australian region as **“**Cold lows**”.** They are associated with either cyclonic surface or anticyclonic curvatures that are related with 500 hPa or higher cyclonic circulation patterns.

2.2.1 Climate

During a 30 year study, which was conducted by Singleton and Reason (2007) for the period 1973 to 2002, COL systems were most frequent during the months of March, April, May and June with the least amount occurring in December and January. These systems do not occur many times in winter (July) but when they do they contribute significant amounts of precipitation to the summer rainfall regions and cause major flooding over the south-eastern coastal regions (Taljaard, 1995a). In South Africa, COLs develop more or less twice in July and significantly affect the weather over the regions where it passes (Taljaard, 1995a). According to Taljaard (1996), COLs are most frequent during the transition seasons (March/April) and (September/October). They very often develop over the interior, are slow moving and exit South Africa over the eastern and southern coastal belts. When they are located over the country they have a general north-easterly movement (Favre et al., 2012). They are associated with showers in winter on their eastern flanks. When they exit the country or move close the coast, they are normally associated with a strong surface onshore flow of moisture to the rear of the system. COLs result in significant rainfall as well as many cold spells in winter. They play a major role in producing winter rainfall in summer rainfall areas.

The cold core within the upper COL is most noticeable in the upper troposphere decreasing down towards the surface of the earth where the presence of a surface high pressure system is possible. Sometimes a weak cyclonic circulation at the surface can be initiated during the final phase of cut-off during the formation of a COL. The COL is associated with moderate to heavy rainfall and is one of the important weather systems for southern Europe and Northern Africa lasting seldom longer than 2-3 days (Nieto et al., 2005).

When cold fronts occur, their circulation is very often manifested in the upper air westerly waves or troughs, although the surface and upper air patterns can differ dramatically in some situations. The baroclinic upper air trough associated with the passage of the surface cold front normally lags by about 6° of longitude to the west of the surface system (Taljaard, 1995a). The upper westerly troughs are baroclinic, which means that they are displaced westwards with height causing upper wind divergence east of the trough line with subsequent rising motion above the surface cyclone (Tyson and Preston-Whyte, 2000). This was indicated in Fig. 2.7.

2.2.2 Synoptic configurations involving upper air troughs and COLs.

Taljaard (1995a) characterized the most frequent upper circulation patterns that occur over South Africa in winter into three different types of upper air westerly troughs, namely pointed, moderate and broad troughs. This is dependent on the rate of change in the cyclonic curvature at the trough axis. Cold frontal troughs are located approximately 5-10° of longitude to the east of the upper air systems (400-800 km) which indicates a deepening in the cold air westwards and upwards of the initial cold front. Fig. 2.11 indicates a pointed trough at two positions over South Africa. The first is, over the central interior (Fig. 2.11 A) and the second is seen to be exiting the east coast of South Africa (Fig. 2.11 B). The trough axis is indicated on each of the images which pin points the inflection point of maximum cyclonic curvature. Weather occurs to the east of this trough axis.

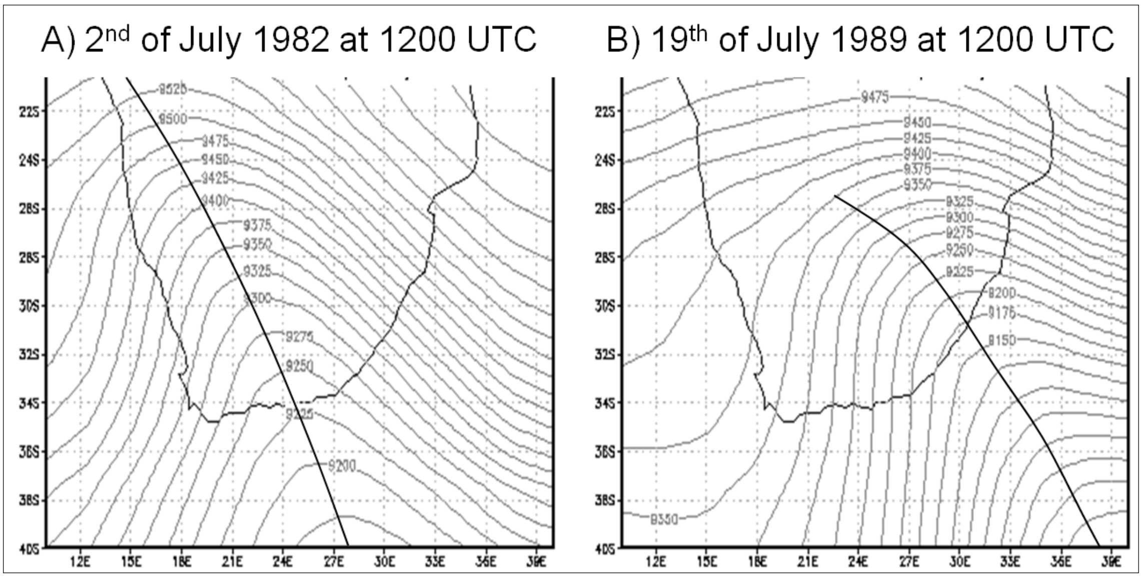


Figure 2.11: A) Pointed trough axis at 300 hPa over the central interior of South Africa and B) over the eastern interior of South Africa (adapted from Taljaard (1995a) using NCEP reanalysis data)

The Fig. 2.12 indicates a moderate trough which is slightly weaker than a pointed trough due to less cyclonic curvature, but similarly located at various positions over South Africa. In the first position (Fig. 2.12 A), the trough is approaching South Africa and in the second position (Fig. 2.12 B) it is passing over the eastern interior.

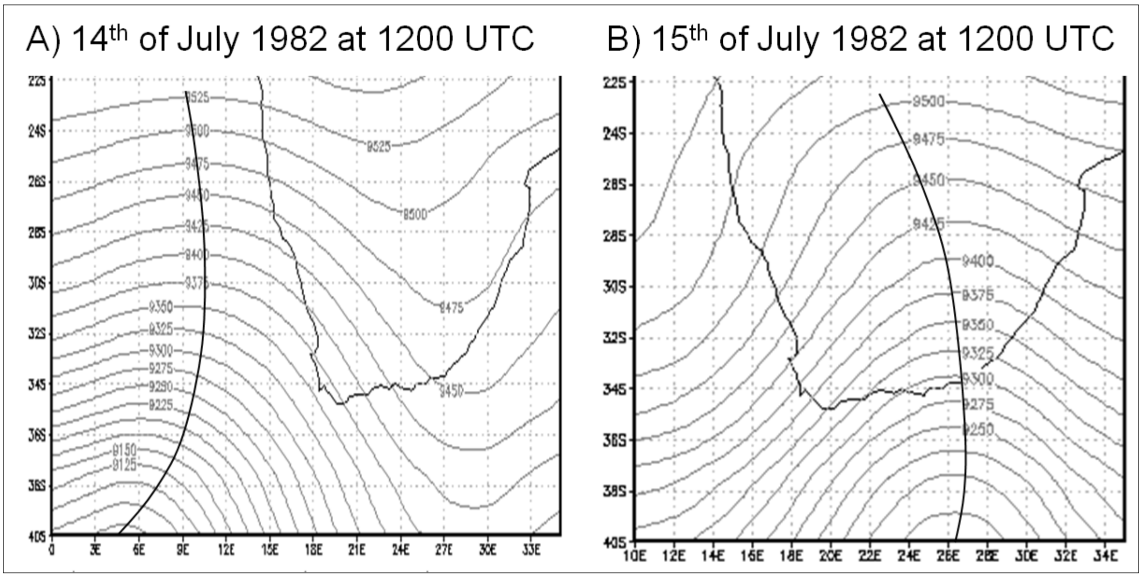


Figure 2.12: Moderate trough axis A) west of South Africa and B) over the eastern part of South Africa (adapted from Taljaard (1995a) using NCEP reanalysis data)

Fig. 2.13 (A and B) indicates an example of a broad trough at various positions across South Africa. The trough axis becomes less defined, making it difficult to pin point.

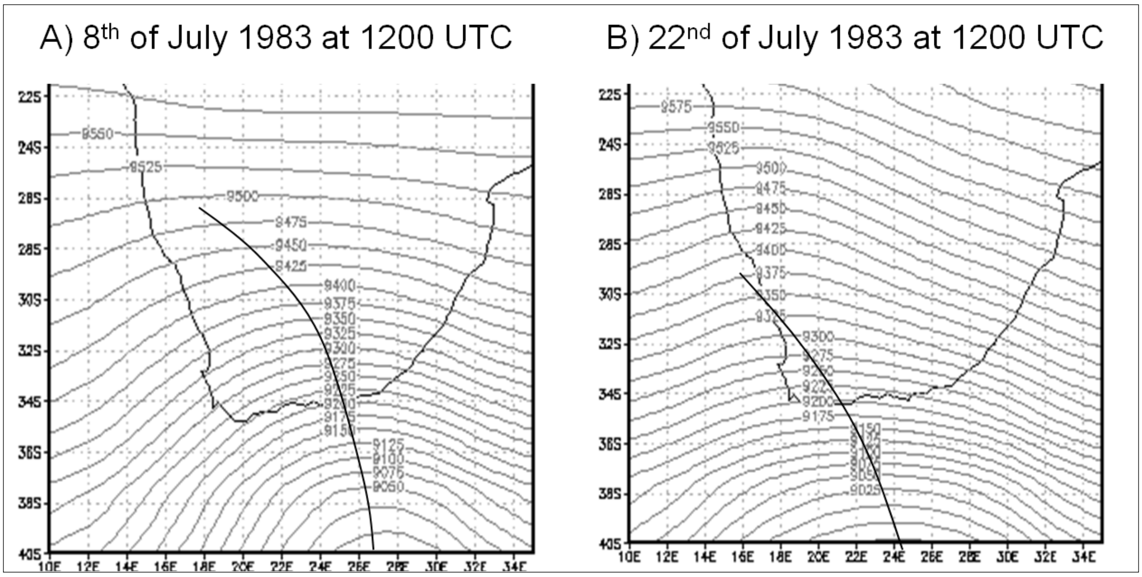


Figure 2.13: Broad/weak trough axis A) over the central interior of South Africa and B) over the south-western interior of South Africa (adapted from Taljaard (1995a) using NCEP reanalysis data)

Fig. 2.14 indicates COLs at various positions over South Africa. Fig. 2.14 A indicates a COL on the west coast of South Africa, Fig. 2.14 B indicates a COL over the central interior and Fig. 2.14 C indicates a COL east of South Africa.

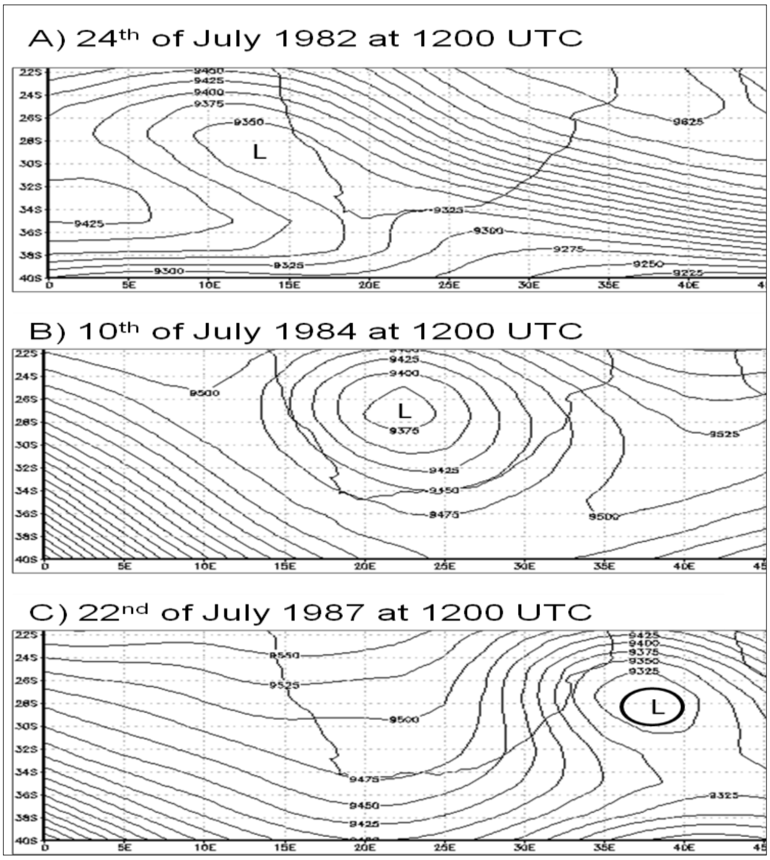


Figure 2.14: Cut off lows at various positions relative to South Africa at 300 hPa (adapted from Taljaard (1995a) using NCEP reanalysis data)

2.2.3 Cut off lows and their influence on precipitation

Taljaard (1982a) noted that COLs played a significant role in the precipitation, very cold conditions and snow that occurred in winter with them. COLs are known to occur between 20° and 40° latitude over Argentina, Uruguay, South Africa, Australia and New-Zealand. An important ingredient in the development of COLs is the surface ridging high pressure system south-west and south of the country leading to strong cold air advection from the south and south-east over the escarpment areas of the Cape to KZN (Taljaard, 1982a).

Fig. 2.15 shows typical areas that can expect precipitation (dotted) when a well developed COL moves over the eastern interior and combines with a ridging AOH south-west of the country near 40° S. During this particular case on 28 August 1970, heavy snow occurred in Queenstown due to low level moisture and temperature advection at pressures higher than 700 hPa being fed in from the south in conjunction with an upper COL located to the north at 500 hPa. This is also an example of the right hook synoptic circulation pattern referred to by Van Heerden and Hurry (1995).

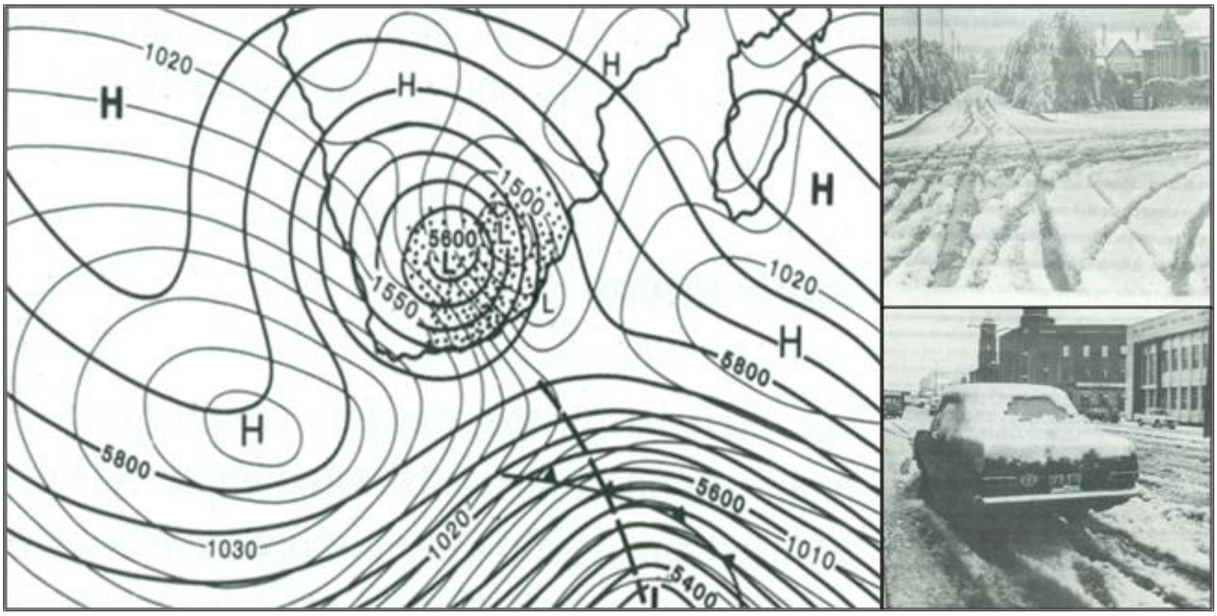


Figure 2.15: Typical 500 hPa cut off low circulation represented by thick black lines, mean sea level pressure and 850 hPa overland circulation, thin lines. Dotted areas are receiving precipitation (After Hayward and van den Berg, 1970) cited in Tyson and Preston-Whyte, 2000)). Photos of snow at Queenstown on 28 August 1970 by Mr. Kallaway cited in (Hayward and van den Berg, 1970)

When a ridging surface high pressure system is associated with an upper COL it often leads to widespread precipitation over the country, since the surface anticyclone promotes a strong pressure gradient leading to a strong influx of surface moisture over the country that enhances precipitation especially due to mesoscale orographic forcing over the eastern escarpment areas (Tyson and Preston-Whyte, 2000). Not only does it provide a strong influx of moisture, but also a strong influx of cold air, which is important in causing significant snowfall over South Africa. Taljaard (1985b) found that a surface eastward-moving high south of the country was a common factor in the formation of all COLs and that the high could weaken between Gough Island and South Africa, and in many instances even intensify.

Between 6 and 9 July 1996, significant snowfall occurred over KZN in particular. The KZN province was ill prepared to deal with heavy snow that normally occurs in the mountains. It was the heaviest snow in 40 years. With regard to this particular case, Prof Robert Preston-Whyte stated that these events normally occur in September. He also stated that the weather resulted from a COL pressure system that occurred 2-3 times a year and normally passed south of the country. “The fact that that system arrived in the colder season means that it was associated with more snow and ice instead of rain” (Daily News, 1996). The weather event of 24-26 July 1983 is an example of a significant snow case associated with a COL, but is also a rare case of heavy rain over the southern and eastern part of the Eastern Cape

Province (Taljaard, 1995a). The case of 16-20 June 1964 is an example of a COL that caused heavy snow to fall for three days on the high ground of the Orange Free State and Natal, now known as the Free State and KZN. It also caused snow over the old Transvaal, now known as Gauteng and Mpumalanga and South West Africa, now known as Namibia (Stranz and Taljaard, 1965; Taljaard, 1985a). Communication, rail and air traffic was disrupted. Bloemfontein was worst hit and isolated for more than a day. About 0.6 m of snow fell over most of the Free State (Gouws and van der Wateren, 1964). This event was noted as one of the most pronounced and long enduring snowstorms over South Africa. The severity and long duration of the cold was also attributed to the fact that the cloud cover over the three to four days resulted in the outgoing solar radiation being more than the incoming radiation below the cloud layers. Heavy rain was caused on the eastern flanks of the COL where there was an influx of warmer, south-easterly air over the cold land resulting in orographic lift. Over the higher ground, heavy snow fell in the same air mass (Stranz and Taljaard, 1965).

According to Taljaard (1985a), during the development of a COL the cold anticyclone should be located south of its mean position around 35° S to 45° S and the pressure should be higher than normal in the region of 1025 to 1035 hPa. The authors (Gouws and Anderssen, 1965) noted that snowfalls over the Eastern Cape normally occur with an active cold frontal trough, followed by a cold anticyclone. In most of these cases, these are associated with an upper air COL and surface trough. The position of the COL was also important. When the COL was over the western interior of the Eastern Cape, it caused more maritime air to penetrate the Eastern Cape and KZN with heavier snowfalls over the eastern interior. Snowfall was mostly light when the upper COL was situated off the country and precipitation mostly orographic in nature.

2.3 Jet streams

Jet streams can be defined as **"**thin, fast moving currents of air that occur at the top of the tropopause on the equatorward side of frontal discontinuities with cold air to the south**"** (Tyson and Preston-Whyte, 2000). In the USA, upper level jet streaks are common role players in all snowstorms. Above the surface anticyclone that provides the cold air advection for snow, the confluence region of the upper jet stream is found. In the diffluent exit region of the jet, surface cyclones normally develop (Kocin and Uccellini, 2004).

Fig. 2.16 indicates the typical areas where wind divergence and convergence can be expected within the upper level jet stream. The right exit side of the jet is normally associated with upper air wind divergence which is the diffluent area of the trough which initiates surface convergence and the possible development of a surface low pressure system. The right entrance side of the jet is an area of confluence and is normally associated with convergence with low level wind divergence occurring above the AOH pressure system (Tyson and Preston-Whyte, 2000). The opposite occurs at the right exit region.

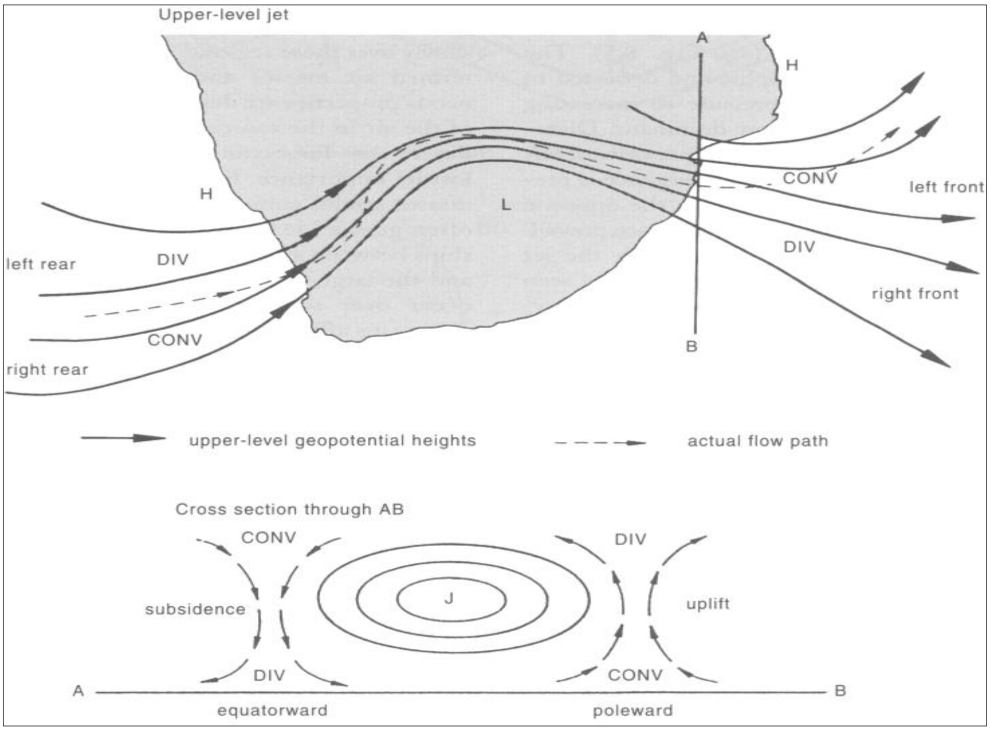


Figure 2.16: Areas of wind divergence and convergence associated with an upper jet stream (adapted from Tyson and Preston-Whyte, 2000)

2.4 Temperature and its effect on snowfall

Temperature is one of the principal determinant variables that contribute to the occurrence of snowfall. Temperature is the main driving force that affects the energy within the atmosphere and without energy, no work can be done in order to drive the weather (Lankford, 2001). South Africa is normally associated with a temperate climate and is situated in the sub tropics (Taljaard, 1972). Thus, it is important to identify large cold air incursions from the mid-latitudes and variables that effect the temperature distribution across South Africa. These will be discussed separately in the following sections.

2.4.1 Influence of topography on surface temperature

South Africa's topography is such that it rises steeply from the coastal regions to an elevated central plateau that is roughly situated at the 850 hPa pressure level which is 1500 m a.m.s.l (see Section 1.2, Fig. 1.1). The height of a station above sea level and the distance it is located from the ocean has an impact of the temperature that station will acquire (Taljaard, 1994d). According to Van Heerden and Hurry (1995) the fact that temperature decreases with height implies that higher elevated stations are colder than lower elevated stations at the same latitude. For example, a highly elevated station far from the ocean will naturally be colder than a highly elevated station close to the ocean. South Africa's elevated plateau makes it ideal to further lower temperatures over its interior. For this reason, most of the significant snowfall events occur over the southern, south-eastern and eastern interior regions which are higher elevated (see Section 1.2, Fig. 1.1). Closer to the coast, precipitation is enhanced due to its closer proximity to the coast where moisture levels are increased. The 850 hPa temperature has been used as a surface predictor in the objective synoptic classification of Chapter 4.2.

2.4.2 Synoptic induced temperature changes

Temperature decreases can also be caused by changes in air masses when air associated with very cold temperatures are advected from the polar regions towards the equator causing a decrease in temperature over the surface over which it is moving (Van Heerden and Hurry, 1995). Air that moves slowly over a specific region will tend to acquire the properties of that surface over a long time. This gives rise to air masses which are dependent on the airflow. These air masses can be propagated into different regions causing significant changes in the temperature fields. For this reason, slow moving high pressure systems are much more effective in establishing cold air masses. In winter, a south-westerly to southerly flow from the polar region causes negative changes in temperatures due to the cold air being advected over the country. A northerly airstream over the country (from the equator) tends to have a warming effect as it moves southward (Tyson and Preston-Whyte, 2000).

Air mass changes typically occur when mid-latitude cold fronts penetrate into the sub tropics over South Africa, followed by strong surface anticyclones which help to advect cold polar air northwards over South Africa. In the atmosphere, heat can be transported horizontally by advection. The coldest temperatures are produced by southerly cold air advection behind cold fronts (Tyson and Preston-Whyte, 2000; Schultz, 2005). This cold air advection is forced by a surface high pressure system (AOH/IOH) behind a cold front. This is one of the most important factors contributing to cold temperatures in the lower part of the atmosphere and, together, with the cold cored upper westerly trough systems (COLs) form the bases of the investigation into snow within this dissertation.

When mean sea level pressure (MSLP) and 500 hPa geopotential heights are displayed in the objective classification of synoptic weather systems in Chapter 4.2, one can determine the amount of cold air or warm air advection within the 1000-500 hPa layer (Lackmann, 2011). Where MSLP isobars cross 500 hPa geopotential heights at right angles, maximum values of advection occur and if the circulation or wind flow is from a colder area such as the polar regions, it is then referred to as cold air advection. The effect of temperature advection on the development of the upper air trough system is discussed in detail in Section 3.2.4. Suffice to say that cold air advection will cause a decrease in atmospheric thickness.

Chapter 3: Data and methodology

This dissertation makes use of various data types. These data sources will be discussed together with the software used to manipulate and display them. Media reports, South African Weather Bureau (SAWB) newsletters, observed weather data and climate station data are used to identify the significant snow cases in Appendix A. The vertical distribution of temperature and moisture in the atmosphere was obtained from atmospheric soundings using tephigrams. Meteosat Second Generation (MSG) satellite imagery was used to picture the cloud structure of weather systems and the cloud top temperatures within these systems. The Grid Analysis and Display System (GrADS) is used to visualise the National Center for Environmental Prediction (NCEP) reanalysis 2 data in order to subjectively analyse the identified significant cases into different synoptic patterns (See Chapter 4.1). Self-organising maps (SOMs) which are used in an objective analysis of synoptic snow circulation types are discussed in Chapter 4.2. Lastly, derived atmospheric variables that are important in describing the formation of snowfall, together with surface variables that are important in determining whether snow will melt upon reaching the ground, are discussed.

3.1 Data and software used

3.1.1 South African Weather Service media reports

The SAWS newspaper archive of weather related events was used in order to establish and validate significant snowfall events for the period 1981 to 2011. The SAWS newspaper archive is a collection of regional newspaper articles across South Africa, which contains reports on significant weather events from 1906 until now. As these snowfall events are infrequent, they are highly publicised and often contain information regarding snowfall location, intensity and the effect on local communities. Photographs, when available, were also used to validate the significance and location of the events. The snow cases are included in Appendix B and their regional distribution is given in Appendix A.

3.1.2 South African Weather Bureau newsletters

Weather forecasters from regional weather forecasting offices across South Africa, reported on noteworthy weather related events in the monthly SAWB newsletters. These newsletters were published from 1949 to 1998. This information was used to substantiate the media reports which identified snow (Section 3.1.1) and provide additional detail to the selected cases in Appendix A and B.

3.1.3 Observation data

Three sets of surface observation data were used. Firstly, data from synoptic weather stations (SYNOPs) (3 hourly), data from Automatic Weather Stations (AWS) (every 5 minutes) and lastly, data from Meteorological Aerodrome Reports (METARs) (hourly) or Special Meteorological Aerodrome Reports (SPECIs). The differences and similarities in these data are outlined below. Upper air ascent data was used to observe the vertical distribution of temperature and moisture throughout the atmosphere.

Where weather observations were available, these were scrutinised to determine whether snowfall occurred. Here, weather observations refer to weather stations where a trained weather observer reported the snowfall event within a synoptic weather code. The synoptic weather codes used to identify snowfall events are given in Table 3.1.

Table 3.1: Synoptic weather codes for land stations; source (WMO, 1995)

66	Rain, freezing, slight
67	Rain, freezing, moderate or heavy (dense)
68	Rain or drizzle and snow, slight
69	Rain or drizzle and snow, moderate or heavy
70	Intermittent fall of snowflakes Slight at time of
71	Continuous fall of snowflakes observation
72	Intermittent fall of snowflakes Moderate at time of
73	Continuous fall of snowflakes observation
74	Intermittent fall of snowflakes Heavy at time of
75	Continuous fall of snowflakes observation

Synoptic weather reports (SYNOPs) from automatic weather stations contain information on wind direction and speed, temperature, dew point temperature, atmospheric pressure at station level and rainfall in the past 24 hours. When a weather observer is present, total cloud cover, amount of low cloud, cloud type, visibility, present weather and past weather is reported as well. This data are necessary to correctly place and identify synoptic scale weather systems on synoptic maps and provide information about local conditions at the time of the snowfall. This data are used in the case study descriptions of Chapter 5. The SAWS SYNOP Plot program version 5.0 (6 September 2010) was used to visualise the synoptic data for the case studies in Chapter 5. A limitation of this study is the lack of weather observations from the remote areas of South Africa where automatic stations are present.

When SYNOPs were not available, AWS data were used to identify possible snowfall events. This data provides detailed information regarding surface temperature, relative humidity, station pressure, rainfall- and surface wind direction, and speed. Where temperatures were close to zero and rainfall was reported, these stations were flagged, as snowfall was possibly occurring. Surface temperatures from the climate database of the SAWS were used to authenticate the significant snowfall cases of Appendix A. Synoptic weather stations were inspected when they had surface temperatures <= 4 °C.

METARs detailing wind speed and direction, visibility, present weather, cloud amount, cloud base height, surface temperature and dew point temperature were used where necessary. When weather deteriorated and warranted the issue of SPECIs, this data was also used. A SPECI contains the same information as a METAR.

Table 3.2: Codes used in Meteorological Aerodrome and Special Meteorological Aerodrome reports; source (WMO, 2007a)

-SN	Light snow
+SN	Heavy snow
DZ	Drizzle
-RA	Light rain
+RA	Heavy rain

The upper air observation data of SAWS obtained from balloon soundings was used to investigate the vertical distribution of temperature and moisture. This data is generally available twice daily (0000 UTC and 1200 UTC) at Cape Town, Port Elizabeth, Durban, Springbok, Upington, De Aar, Bloemfontein, Bethlehem and Irene. This data is necessary to determine the vertical distribution of temperature and moisture in the atmosphere and to identify precipitation, cloud type and the stability of the atmosphere. The atmospheric soundings comprise data of temperature, dew point temperature and wind direction and speed at different pressure levels. At SAWS this data is plotted on a tephigram as indicated on the right of Fig. 3.1. A tephigram is an aerological diagram where, the environmental temperature is represented by a solid line and the dew point temperature by a dotted line. Fig.3.1 indicates the various lines that are found on a tephigram, comprising isotherms, dry adiabats, isobars, saturation mixing ratio and saturated adiabats.

Tephigrams are used to identify the passage of cold fronts and upper COLs which cause changes in air mass (see Section 2.1.2.3). The SAWS Tephigram Plot program version 2.1 (23 September 2003) was used to visualise the upper air data for the case studies of Chapter 5 and 6.

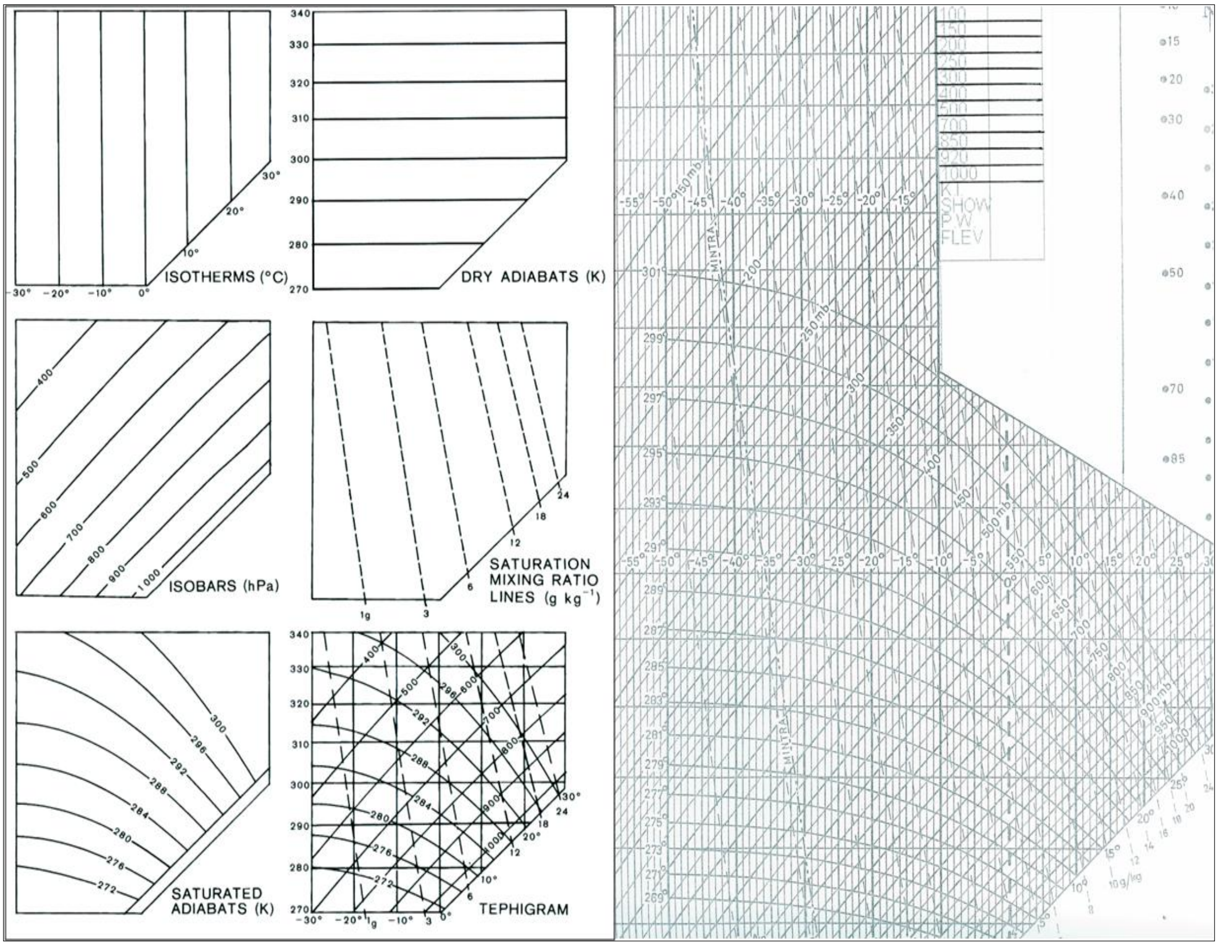


Figure 3.1: Isotherms, dry adiabats, isobars, saturation mixing ratio (dew point) lines and saturated (wet) adiabats on tephigrams (adapted from Tyson and Preston-Whyte, 2000)

3.1.4 NCEP reanalysis data

NCEP data was used in three ways in this dissertation. Firstly, it was used in the subjective classification of synoptic scale weather systems and secondly, for the objective classification of weather systems and lastly for the case studies of Chapter 5 and 6.

This data has a 2.5° horizontal grid resolution (210 km) (Kalnay et al., 1996). This is sufficient to identify synoptic scale weather systems which are investigated in this dissertation. Data is available at six hourly intervals (0600 UTC, 1200 UTC, 1800 UTC and 0000 UTC). The NCEP reanalysis 2 data set was used to do the subjective as well as objective identification of weather systems associated with significant snow. In the subjective identification of synoptic weather systems (Chapter 4.1), the mean sea level pressure data and the 500 hPa geopotential height were used to identify characteristic synoptic patterns associated with significant snowfall events. In the objective classification (Chapter 4.2), the 850 hPa temperature data were added as a third atmospheric variable. The atmospheric variables used in Chapter 5 and 6 were sea level pressure as well as temperature, geopotential heights, meridionial and zonal wind components, RH and vertical motion on several pressure levels (NCEP, 2011). The GrADS software was used to visualise the NCEP reanalysis 2 data.

3.1.5 Satellite data

The Software for the Utilisation of Meteosat in Outlook Activities (SUMO) version 3.0 was used to visualise satellite data at the appropriate geographical locations (Chapter 5 and 6). Meteosat Second Generation (MSG) imagery obtained from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) of the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) were used. Red-Green-Blue color combinations (RGBs) are a visualisation technique used within MSG data (Eumetsat, 2012).

The Day Natural Colours RGB (Eumetsat, 2012) uses channel 3 (near infrared 1.6 µm channel on the red beam), channel 2 (visual 0.8µm channel on the green beam) and channel 1 (visual 0.6 µm channel on the blue beam). The Day Natural Colours RGB was used as a verification tool to identify snow cover on the ground. It is also helpful in discriminating between water and ice clouds. Water clouds will appear grey while ice clouds will be bright cyan. A bright cyan color that does not move in a satellite animation is also indicative of ice or snow on the ground (Eumetsat, 2012).

The Day Microphysical RGB makes use of channel 2 (Visual 0.8µm channel on the red beam), channel 4 (Infrared 3.9µm channel on the green beam) and channel 9 (Infrared 10.8 µm channel on the blue beam). This RGB is of practical use in determining the different cloud properties such as droplet size, presence of ice and supercooled water droplets within clouds. These ice clouds will appear in a pink to red color on the image (Eumetsat, 2012).

The Airmass RGB utilises channel differences. On the red beam (channel 5 (WV 6.2 µm) – channel 6 (WV7.3 µm)), on the green beam (channel 8 (Infrared IR9.7) – channel 9 (IR10.8)) and on the blue beam (channel 5 (WV6.2 µm)) inverted. This RGB is useful to determine synoptic weather systems (cold fronts and COLs) and some of the properties of the air mass associated with it. For instance, a warm air mass can be identified by a green color in the image while a cold air mass appears blue (Eumetsat, 2012). Furthermore, channel 9 (IR10.8 µm) is valuable in obtaining cloud top temperatures (Eumetsat, 2012).

Images from the Moderate Resolution Imaging Spectroradiometre (MODIS), Terra and Aqua polar orbiting satellite (from 2004 to 2011) were used to discriminate snowfall on the ground (NASA Earth Data, 2012). This data is necessary to assist in determining the geographic areas where snowfall occurred. Visible satellite imagery is particularly useful in determining snow covered mountain regions which show up as dendritic patterns on cloud free images. This is because snow has a high albedo (Bader et al., 1995).

3.2 Methodology

The identification of significant snowfall cases are dealt with by discussing both the subjective and objective classification methods.

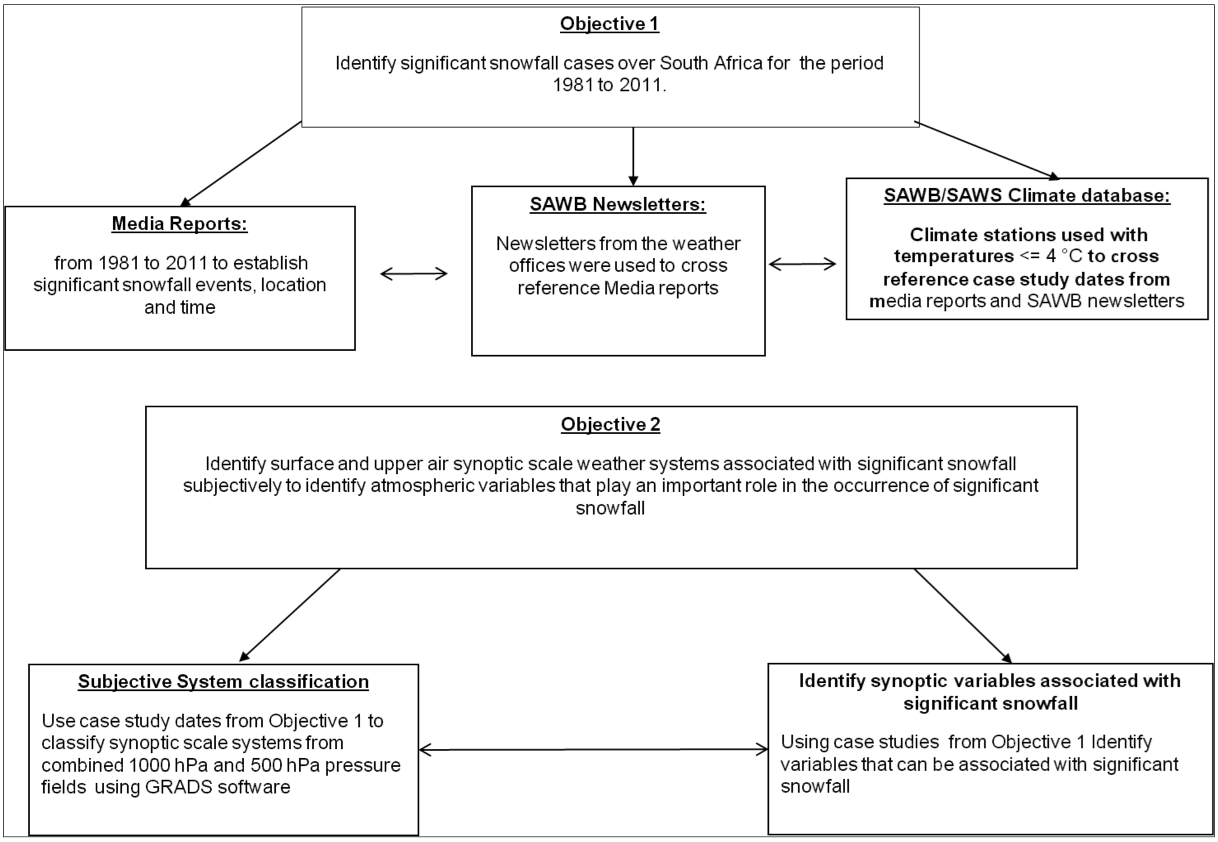


Figure 3.2: A schematic is provided which indicates the method used to ensure Objective 1 and 2 were achieved during this dissertation

These methodologies are summarised in Fig. 3.2 and Fig. 3.6 which provide a schematic of how the objectives defined in Section 1.5, were achieved throughout this dissertation.

3.2.1 Identification of significant snow case dates

As part of Objective 1 (Fig. 3.2), 60 significant cases were identified for the period 1981 to 2011. These 60 cases comprised 148 days (some cases spanned over several days) and considering the 6 hourly time steps in a day in the NCEP data, there were 426 time steps identified for analysis. Snow did not necessarily occur on all four time steps on each of the snow days. These 426 times steps are henceforth referred to as snow events.

Fig. 3.3 provides a schematic of the steps that were followed in defining significant snowfall cases and creating an archive of significant snowfall events over South Africa (See Appendix A and B). Dates in media reports were first scrutinised to determine when significant snowfalls reached altitudes below 2000 m a.m.s.l and when mountain passes were closed and the livelihood of people were disrupted. Severe cold outbreaks are noted by the longevity of the cold event across several regions of the country. The large-scale effect of these outbreaks is testimony to the synoptic scale weather systems that produce them. In step 2 (Fig. 3.3), the case study dates were cross referenced with SAWB newsletters from the various regional weather offices across the country. In order to ensure that these were real snow events, climate data reports (AWS) were further scrutinised (step 3 in Fig. 3.3) by verifying that surface temperatures were sufficiently cold (surface temperatures<= 4 °C). It will be shown in Chapter 6 that snowfall can occur in temperatures higher than 4 °C and this temperature threshold serves only as a confirmation of snow. These were further correlated with satellite imagery where available. Lastly, Appendix A and B were created as a significant snow case archive.

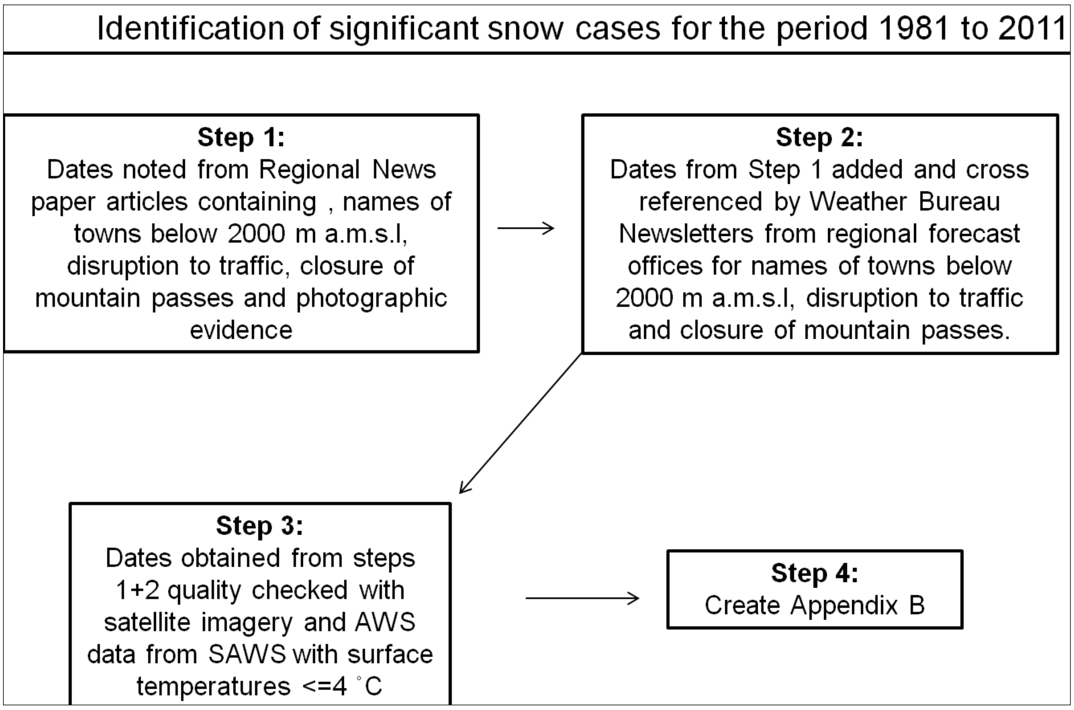


Figure 3.3: A schematic diagram of the methodology used to identify significant snowfall cases for the period 1981 to 2011

3.2.2 Subjective synoptic classification

The subjective analysis was done to achieve Objective 2 (Fig. 3.2). This was done to ascertain which atmospheric variables would best describe significant snowfall. The result of this subjective classification is shown in Chapter 4.1. The method used to achieve Objective 2 is explained in Fig. 3.4.

In step 1 (Fig. 3.4), the atmospheric variables (geopotential heights and temperature) were analysed for each of the atmospheric pressure levels in order to establish which combinations of variables would be most suitable for the objective classification. At step two (Fig. 3.4), it was decided to use the combined MSLP and 500 hPa geopotential height circulation patterns, as the dominant weather systems responsible for snowfall were captured by these two pressure levels. For each of the case studies, the regional effects of snowfall were identified by listing the towns affected by snowfall (see Appendix A). To simplify the subjective synoptic classification of multiple atmospheric variable patterns over many time steps, it was decided to approach this problem in the following way. In step 4 (Fig. 3.4), one representative synoptic circulation pattern was identified for each case and tabulated together with the snowfall areas in Appendix A. The way in which this circulation pattern was chosen was done as follows. Each significant snow case study normally spans a few days (two to three) with its eastwards progression across South Africa. The most intense synoptic circulation pattern in the MSLP field as well as the 500 hPa geopotential heights was chosen over the two to three day period to represent the severe weather snowfall event. This chosen pattern is sufficient for the subjective classification. This was used in step 5 to create Appendix A.

It is important to discriminate between the AOH and the IOH in the synoptic classification as it affects the source of air mass advected across the country. This has an impact on the atmospheric temperature and moisture distribution below 700 hPa. In this subjective classification, the movement of the AOH past 24° E latitude was deemed a transition from the AOH to the IOH and consequently named as such in the subjective classification of Chapter 4.1.

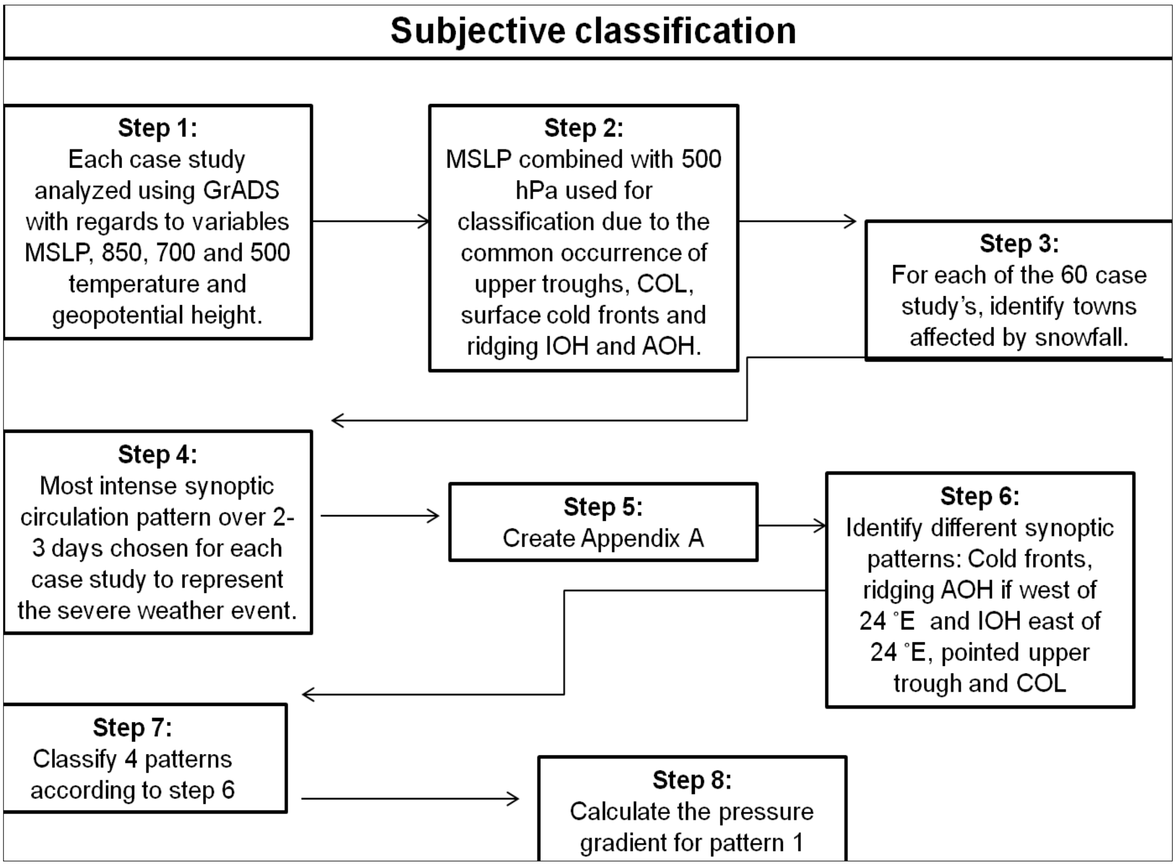


Figure 3.4: A schematic of methodology used for subjective synoptic classification of weather systems in Chapter 4.1

The COL or pointed upper air trough was present in all of the identified patterns and was used as part of the classification as it affected the atmospheric temperature and moisture distribution between 700 hPa and 500 hPa.

Four distinctly different synoptic patterns were identified in step 7. For pattern 1 (the AOH), the pressure gradient was calculated between the AOH west of the country and the frontal low to the south-east of the country (step 8 in Fig. 3.4). Fig. 3.5 is an example of how the surface pressure gradient between the surface AOH and frontal low was calculated .This was used within the synoptic classification of pattern 1 in Chapter 4.1.

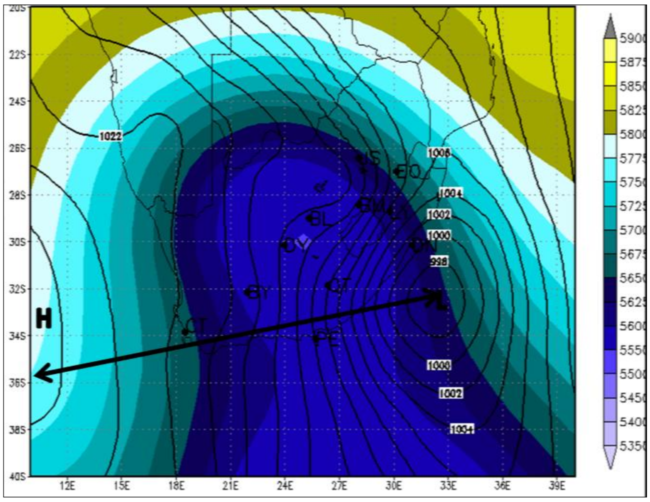


Figure 3.5: An example of the surface pressure gradient calculation between the AOH and frontal low for 10 September 2002 (1026 hPa – 998 hPa = 28 hPa)

This pressure gradient is important to establish the amount of temperature advection from the AOH behind the cold front (Van Heerden and Hurry, 1995; Taljaard, 1995a).

3.2.3 Objective synoptic classification

According to (Taljaard, 1985a), classification of weather systems can be a complex exercise due to the considerable amount of variations present in different weather systems.

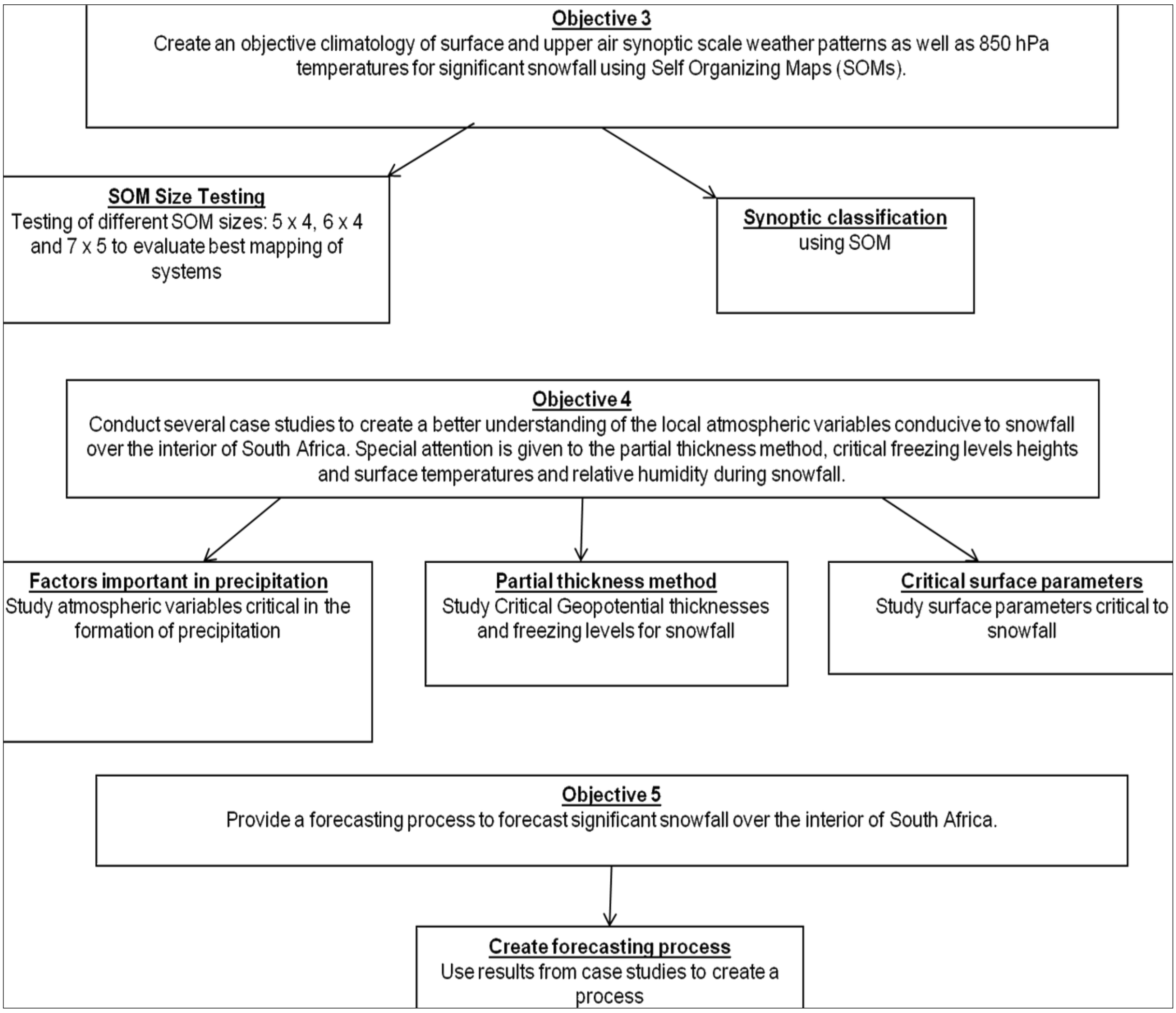


Figure 3.6: A schematic which indicates the method used to ensure Objective 3, 4 and 5 were achieved during this dissertation

It is however very important to determine frequencies of systems and their similar history and effect on weather in particular regions. The objective classification made use of SOMs as a data reduction technique to associate atmospheric variables to their synoptic pattern in order to achieve Objective 3 in Fig. 3.6.

3.2.3.1 Self organizing maps method

The SOMs method will be discussed first and then the application of this method in this dissertation will be explained.

The algorithm used in this dissertation was acquired through the SOM_PAK software package (Kohonen et al., 1995). The SOMs software (Kohonen, 2001) was used to visualise the multi dimensional atmospheric data sets in the objective synoptic classification in Chapter

4.2. It is used to visualise a high dimensional data space in a two-dimensional array of nodes.

Kohonen (2001) was the first to explain the use of the SOMs method. Since then, this technique has been used in a number of scientific applications where the SOM trains the input vectors and places them into characteristic nodes within the SOM space (Hewitson and Crane, 2002). The SOM identified characteristic nodes in the data space in such a way that the original observed data set can be connected with the individual nodes, maintaining the integrity of the observed data set. Within the atmospheric sciences, these nodes are directly interpretable in terms of weather patterns and can be explained easily in terms of their effects on weather (Tennant, 2004; Liu and Weisberg, 2011). As a result, the SOMs method is sufficient to use for its intended purpose within this dissertation. Hewitson and Crane (2002) used SOMs to create a synoptic climatology using atmospheric data, more specifically, sea level pressure over the north-eastern USA. A random set of input vectors produce a first set of nodes that are trained by the SOM algorithm. These nodes now become the input to a second round of training which optimises the results in the sense that the training input vectors are now defined and are not random. The SOMs method is able to take a high dimensional data space such as atmospheric data sets (four dimensions) and map it into a two-dimensional node space where similar nodes are placed next to each other and different nodes apart from each other (Tennant, 2004).

An example of other applications where SOMs were used was that to indicate the changes in circulation patterns before and after 1979 due to the advent of satellite data (Tennant, 2004). Another is the mapping of fire weather conditions to typical synoptic conditions associated with that phenomenon in the south west USA (Crimmins, 2006).

In this dissertation, SOMs were used in the following way. The reanalysis 2 data from NCEP were used as the input data to train the SOM (Kalnay et al., 1996). In the period 1981 to 2011, 426 events were identified which were used as the input vectors to train the SOM (see Chapter 4). The grid from 20- 40° S and 10- 40° E was chosen. This domain was chosen to sufficiently map weather systems on the synoptic scale over South Africa, yet include enough of the Atlantic and Indian Oceans where cold fronts, AOH and IOH migrate from west to east. The objective classification was done for the months of May to October from 1981-2011. Data prior to 1981 was not included because of the improved quality of NCEP data due to the advent of drifting buoy data in the southern oceans, upper air data from St. Helena and satellite data after 1978 (Taljaard, 1985a). Tennant (2004) alluded to the fact that, due to the shortage of observational data south of 50° S before 1979 analysis of the atmosphere should only be done after 1979 due to the introduction of satellite data.

The first step in the SOM routine is to apply user defined settings to the SOM algorithm. Firstly, prior to the running of the SOM, the following settings were applied. During this study, the rectangular topology was chosen and the SOM size was set to 6x4. The neighborhood function type was set to bubble, the length of training (rlen) was set to 1 000 000 iterations during both sets of training. The learning rate parameter (alpha) was set to 0.04 during both sets of training while the radius was set to 3 during the first training and 2 during the second training phase.

The SOM was trained using three atmospheric variables, namely mean sea level pressure, 500 hPa geopotential heights and 850 hPa pressure level temperatures. Since temperature is a key variable in snow formation and important in identifying significant gradients in temperature associated with surface cold fronts, it was decided to include this as a third variable in the objective classification of synoptic weather systems. These three variables used to train the SOM were standardised with respect to the average and standard deviation prior to running the SOM.

It was decided to use a 24 node SOM (6x4) in this dissertation. The SOM size was set to 6x4 (Fig. 3.6) and the SOM was run for the 426 snow events on which snow occurred for the period 1981 to 2011 to create 24 different nodes. Different SOM sizes were experimented with (Fig. 3.6). SOMs with a different number of nodes (5x4, 6x4 and 7x5) were created and the results were compared. The 5x4 SOM results provided generalised patterns of the AOH, IOH, cold fronts and COLs but did not pick up subtle patterns such as the surface frontal low pressures that developed in association with COLs over the Indian Ocean to the east of KZN. This pattern was one of the important patterns that were identified within the subjective classification and the 5x4 node SOM was therefore not used. The 7x5 SOM provided more detail than the 5x4 SOM in as far as the frontal low on the east coast of KZN was also picked up. More detailed differences were apparent in the 7x5 SOM but the detail did not contribute to a better understanding of the synoptic circulation associated with snow. It was therefore decided to use the 6x4 SOM as it sufficiently mapped the major systems that were identified during the subjective analysis.

Lastly the results are visualised using the GrADS software.

3.2.4 Atmospheric variables

Factors important in the formation of precipitation and precipitation type are discussed along with the surface variables critical to the melting of snowfall. Atmospheric variables such as wind divergence or convergence and vertical velocity are used to identify areas favorable for precipitation. Values of atmospheric thickness, which is affected by cold air advection, are used to determine precipitation type. These variables are described here.

3.2.4.1 Atmospheric thickness

The difference in the geopotential height between two pressure levels in the atmosphere is referred to as the geopotential thickness of that layer and is expressed in geopotential metres. Geopotential thickness between two atmospheric layers in the atmosphere is measured in geopotential metre (gpm) which will be referred to as metre (m) from now on. The thickness of any atmospheric layer is directly proportional to the mean temperature of that layer (Tyson and Preston-Whyte, 2000).

This relationship is given by:

$$\Delta z = \frac{RT}{g}(lnp1 - lnp2)$$

where

R	gas constant for dry air	287 J kg^{-1}
T	temperature in K	
g	gravitational acceleration 9.8 ms^{-2}	

Several studies have been done where the height of the 1000 hPa pressure level defines the lower level reference point of atmospheric thickness calculations (Lamb, 1954; Wagner, 1957; Younkin, 1968; Koolwine, 1975; Heppner, 1992; Bourgouin, 2000; Jones, 2003). However, adapting the surface level or reference point in the calculation of thickness is common practice in elevated areas such as the Rocky Mountains (Lackmann, 2011). In this dissertation, the 850 hPa geopotential height was used as the lower boundary of an atmospheric thickness layer as 1000 hPa is below ground level for the interior plateau of South Africa which is close to 1500 m a.g.l or 850 hPa (see Section 1.2, Fig. 1.1). This was done in accordance with work done by (Taljaard, 1995a; Tyson and Preston-Whyte, 2000). Atmospheric thickness is used as a discriminator for precipitation type and will be discussed in the case studies of Chapter 5 and 6.

a. Partial atmospheric thickness

The atmospheric thickness of the 850-500 hPa layer is used in conjunction with the partial atmospheric thickness of two layers within this layer namely the 850-700 hPa and 700-500 hPa partial atmospheric thickness. The importance of partial atmospheric thickness in the determination of precipitation type was discussed in Section 1.4.2.3 and is used to ensure that no warm layers exist within a column of air. The atmospheric thickness in the 850-500 hPa layer where the average layer temperature is 0 °C (273 K) is 4242 m and 1552 m in the 850-700 hPa layer. This provides an idea of which values of atmospheric thickness are necessary to provide a cold enough atmosphere for snowfall to reach the ground.

3.2.4.2 Cold air advection

Cold air advection often occurs when a strong surface high pressure system follows a surface cold front. Cold air advection has also been shown to be fundamental in the lowering of upper tropospheric geopotential heights which may result in the formation of COLs (Fig. 3.7) (Lackmann, 2011). The strength of the horizontal wind depends on the horizontal pressure gradient and the stronger the wind, the more cold air can be advected (Van Heerden and Hurry, 1995).

Cold air advection is defined as:

$$\overline{v}.\overline{\nabla}T$$

$\bar{v}$ is the horizontal wind

$\overline{\nabla}$T is the gradient of the temperature

Fig. 3.7 a) and b) indicate the effects that maximum warm and cold air advection has on the 1000-500 hPa atmospheric thickness layer (respectively).

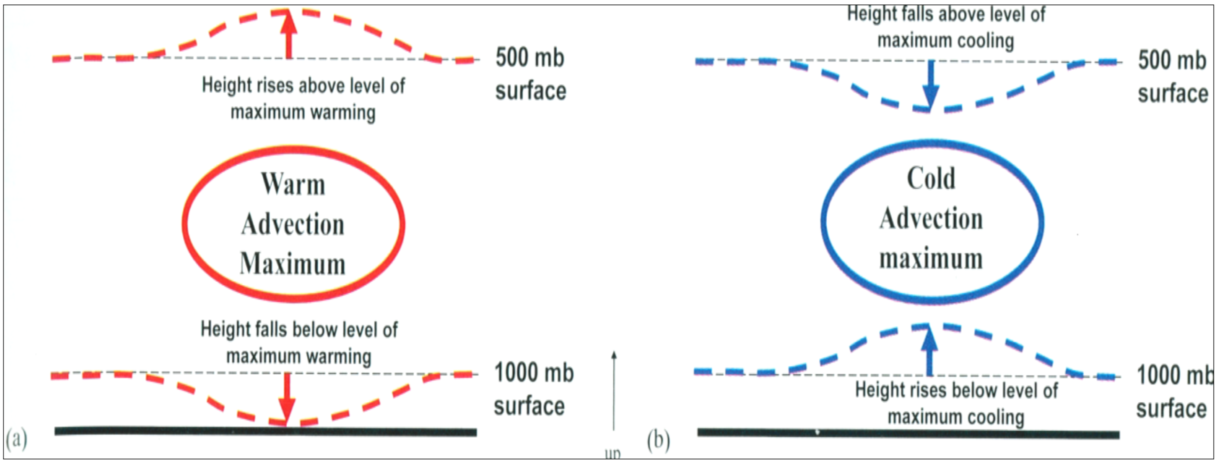


Figure 3.7: Geopotential height changes between two atmospheric layers (1000-500 hPa) due to warm (a) or cold air advection (b) (adapted from Lackmann, 2011)

When the surface flow is perpendicular to the 500 hPa flow, maximum temperature advection occurs. If the surface flow has a cold source then maximum cold air advection is said to occur. This causes a decrease in the thickness of a layer (right in Fig. 3.7). When warm air is added to a layer, it increases the geopotential thickness of that layer with time.

Triegaardt et al. (1989a) noted the importance of the upper diffluent trough causing upper wind divergence in a case study investigating snowfall with extreme cold temperatures over South Africa between 16 and 19 July 1989. The upper trough intensity was maintained by the cold air advection from the strong surface high pressure system between 30° and 40° S. This diffluent flow resulted in a surface low pressure system developing, which intensified the existing pressure gradient and therefore increasing the cold air advection over the country. They concluded that a strong baroclinic high west of the country and a deep trough east of the land (as in Fig. 3.5) causes pronounced cold air advection over the northern parts of South Africa and Namibia. The surface pressure gradient is used in Chapter 4.1 during the subjective analysis of weather systems impacting on significant snowfall.

Triegaardt (1988) and Triegaardt et al. (1989a) analysed the snowstorm of 9 and 10 July 1988 as well as on 16-19 July 1989 with specific reference to cold air advection. The sea level circulation and the 500 hPa geopotential heights were considered during this analysis as well as the horizontal thermal advection field. The surface cold air advections lead to the development of the 500 hPa trough. When the ridging high is situated in a favourable position thermal advection of cold air around the anticyclone will partly contribute to the intensification of the 500 hPa trough. During the 16-19 July 1989 event, a fairly strong high of 1036 hPa was located south of the country. This type of upper air trough development into a

COL is also called the anticyclonic disruption (Sutcliffe, 1953). This type of circulation was also present during 9-10 July 1988 snow storm in Natal, now referred to as KZN (Triegaardt et al., 1989b). On the particular date, an upper diffluent trough with an intense surface anticyclone to the west of the upper trough was present over South Africa. Significant cold air advections were visible on satellite imagery to the rear of the cold front and the cloud deck. This was due to the strong surface onshore flow from the surface high pressure system contributed to the heavy snowfall over the KZN midlands.

3.2.4.3 Wind divergence and vertical velocity

According to Taljaard (1985a), when considering COL development and associated precipitation, one should consider horizontal divergence (hereafter wind divergence), vorticity, and vertical motion at various levels in the atmosphere. Rainfall intensity, provided adequate moisture is available, is associated with the extent of the low level convergence, vertical motion and upper air wind divergence. The most probable area for rainfall is located 300 to 1 000 km east of the upper low where upper air motion is greatest (Fig. 3.8). Pointed troughs bear similar characteristics to COLs. They produce low level convergence, vertical motion between 700 and 400 hPa and upper wind divergence on their eastern flanks. Diffluent contours east of the system at 500 hPa are good for rainfall, since it enhances wind divergence. A V-shaped trough or surface low at 850 hPa, 300 to 1000 km east of the 500 hPa low is good for surface convergence and rain, especially if the southward moving air is warm and moist (Fig. 3.8). A COL that lies vertical on top of the surface low throughout each atmospheric level is labelled barotropic and a sign of a decaying weather system.

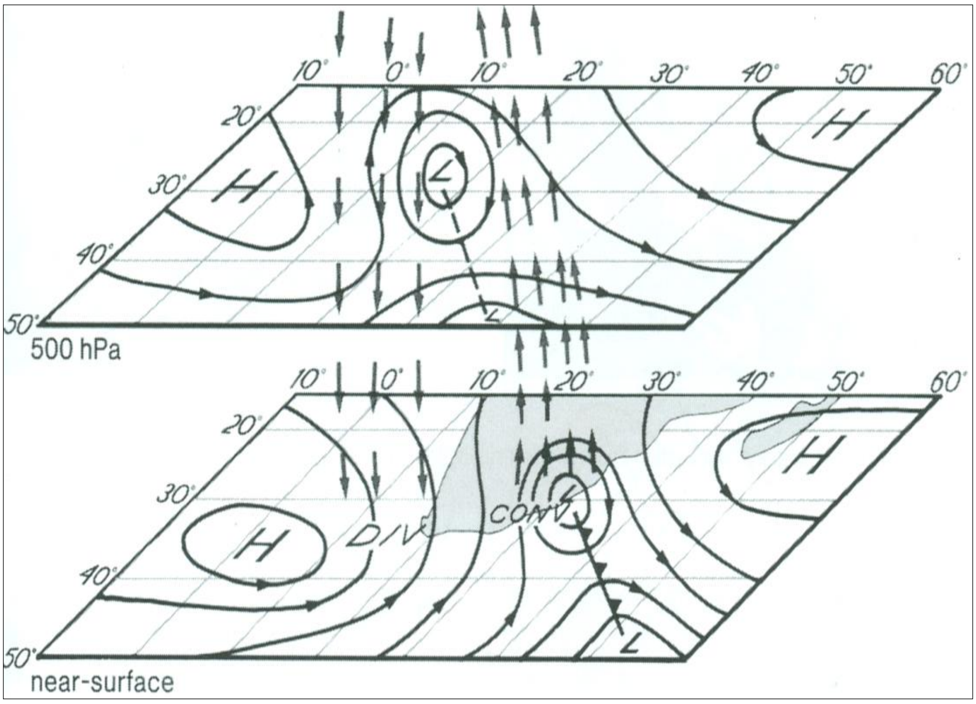


Figure 3.8: Near surface and 500 hPa circulations associated with a cut off low. The figure indicates typical areas of wind divergence (DIV), convergence (CONV) and vertical motions (arrows) (adapted from Tyson and Preston-Whyte, 2000)

When considering the atmosphere in the vertical, Dines compensation makes provision that those areas of surface wind convergence are compensated by areas of upper wind divergence (Petterssen, 1956). Fig. 3.9 indicates how upward vertical motion results when upper level divergence is superimposed on surface convergence. The opposite occurs when upper air convergence is overlaid with surface divergence.

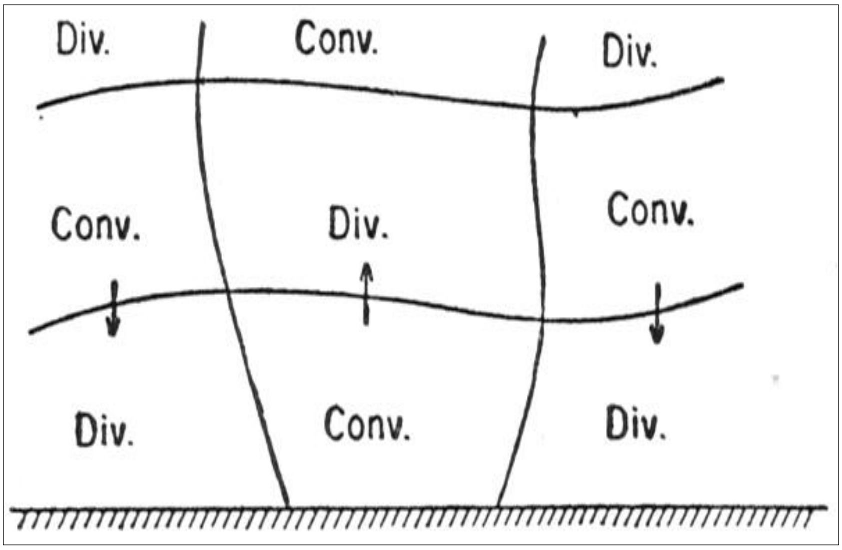


Figure 3.9: Illustration of Dines compensation (adapted from Pettersson, 1956)

The areas that are associated with wind divergence and convergence are indicated in Fig. 3.10 for an upper air trough on its own (A) and a developing cyclone (B). The situation in Fig. 3.10 A occurs when a surface cyclone is not present at sea level, then no surface convergence occurs although upper air divergence takes place due to the upper trough. The situation indicated in Fig. 3.10 B occurs when snowfall occurs over South Africa when surface and upper air systems interact, causing surface convergence and upper air divergence. Due to a presence of a developing surface anticyclone, surface convergence occurs in the presence of upper air divergence.

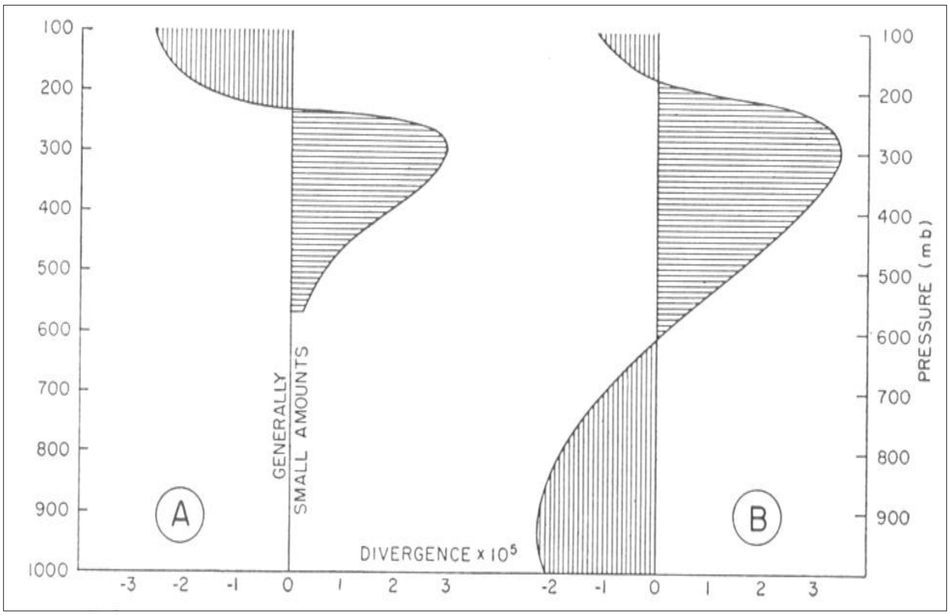


Figure 3.10: Distribution of surface convergence (negative values) and upper wind divergence (positive values) associated with an upper air trough without a surface cyclone (A) and with a developing cyclone (B) (adapted from Pettersson, 1956)

The direction of surface wind flow is important in determining horizontal wind divergence and convergence. Horizontal wind divergence (Fig. 3.11 A) of air takes place at the surface due to air subsiding from aloft, which can change the surface air pressure as winds spread out uniformly from the centre. The opposite happens due to horizontal directional convergence (Fig. 3.11 B) when air flows to a central point resulting in vertical motion.

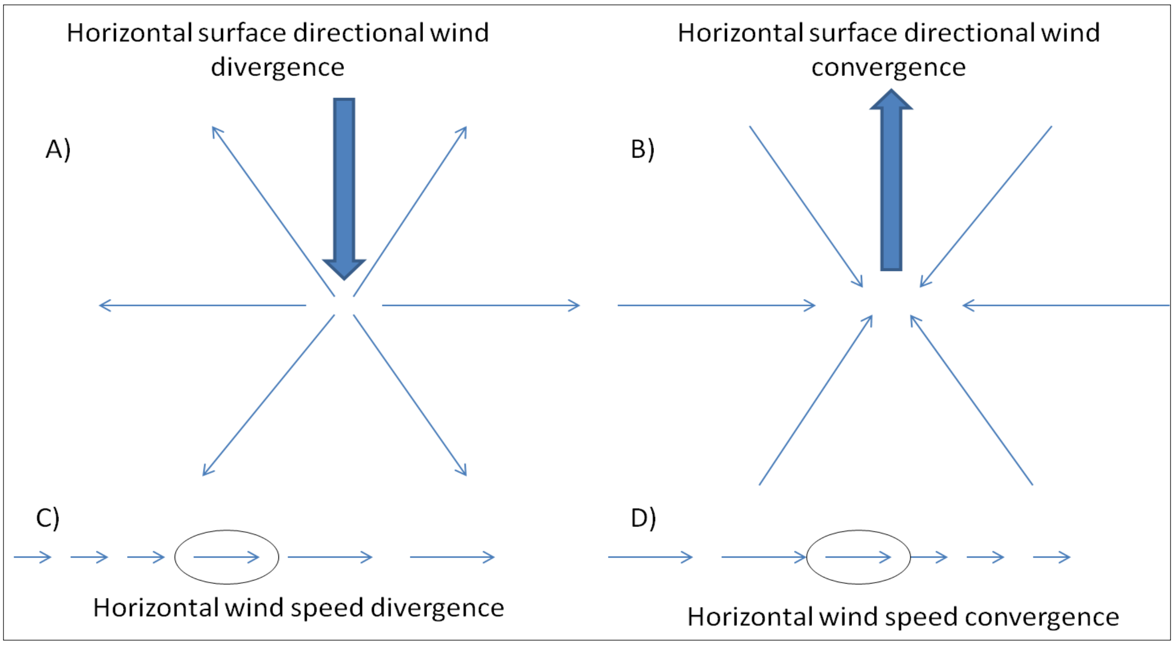


Figure 3.11: Horizontal surface directional wind divergence (A), horizontal surface directional wind convergence (B), horizontal wind speed divergence (C) and horizontal wind speed convergence (D) (adapted from AMS, 1996)

Horizontal wind speed divergence is indicated in the encircled area in Fig. 3.11 C where the wind speed gradually accelerates and pulls away, while horizontal wind speed convergence occurs when the wind speed decelerates and piles up at the encircled area in Fig. 3.11 D.

In isobaric co-ordinates, the continuity equation can be written as

$$\bar{v}.\bar{\nabla}v + \frac{\partial\omega}{\partial p} = 0 \quad \text{(Holton, 1992)}$$

where

$\bar{v}.\bar{\nabla}v$ is the horizontal wind divergence.

$\frac{\partial\omega}{\partial p}$ is the change of omega with pressure.

$\omega = \frac{dp}{dt}$

The continuity equation is based on the conservation of mass and indicates the relationship between horizontal divergence and vertical motion. When there are changes in horizontal wind divergence it results in vertical motion (Lackmann, 2011).

The change of omega with pressure is related to the sign of the wind divergence term (positive sign is divergence and negative sign is convergence). In air columns with mean positive wind, divergence omega will increase with pressure (or decrease with height). Divergence would then imply that the vertical motion increases with height.

3.2.4.4 Surface variables used in anticipating snowfall.

A critical factor in determining whether snowflakes will reach the ground as snow or melt on their way down, is the surface air temperature and relative humidity (RH).

1. **Surface temperature and relative humidity.**

When the surface temperature is above freezing (T >= 0 °C) and the surface RH is below 100% (or the wet bulb temperature is at 0 °C or below), then snow can reach the ground (Ahrens, 2007). Matsuo and Sasyo (1981) indicated that snowfall can reach the ground in surface air temperatures below 2.5 °C. Above this temperature, rainfall usually occurred. They further explained that snowfall can also occur at temperatures greater than 2.5 °C. They indicated that a non-melting layer below the freezing level could be attributed to the effect that RH has on the subsaturated air had on the melting snowflake apart from the obvious effects of temperature. When surface RH was below 60%, snow could occur at surface temperatures of 4-6 °C. Similarly, Pruppacher and Klett (2010) indicated that snowfall could also occur at surface temperatures of 4-6 °C. A case study example of this is given in Chapter 6. Temperatures at which snowfalls occurred over the east coast of the USA showed a large variation with some of the warmer storms having positive temperatures close to 0 °C and in one particular case even 10 °C prior to a Washington storm (Kocin and Uccellini, 2004).

In situations when it is snowing, the lapse rate below the freezing level follows a near wet adiabatic lapse rate. As a consequence the use of surface RH is adequate, since those values below the freezing level will not vary by much with those at the surface. In cases where the air is saturated close to the ground; the temperature, dew point temperature and wet bulb temperature are the same. In dry surface conditions, evaporative cooling occurs towards the wet bulb temperature (Ahrens, 2007). At Nikko station in Japan, which is located at an altitude of 1292 m a.m.s.l, the critical surface relative humidity was given by the following formula: $RHcri = -6.2T+91$ (Matsuo and Sasyo,1981).

RH can be defined as

$$RH = 100\,\frac{x}{xs} \text{ (Tyson and Preston-Whyte, 2000)}$$

where

x is the humidity mixing ratio and

x_s is the saturated humidity mixing ratio

This is the relation between the total humidity that the atmosphere contains to the amount it would need, to become saturated at a given temperature. It is normally expressed as a percentage. A greater percentage may indicate the presence of clouds (Van Heerden and Hurry, 1995). In this dissertation, a RH of 60% and above is used when analysing the tephigram to indicate the presence of clouds. This means that if the temperature and dew point differs by 6 °C or less then the RH is >= 60%.

A critical surface RH was determined at which all precipitation would be snow. At higher surface RH in excess of 60%, snow occurs at lower temperatures. This is because in the area of high surface RH, the water vapour density is higher than that of the snowflake and condensation of water takes place onto the snowflake. This release of latent heat melts the snowflake. At low surface RH the water vapour density is less than the snowflake and sublimation of water vapour occurs from the snowflake cooling the flake and the subsequent ambient air temperature in that location.

A relationship between surface temperature and critical surface RH can be calculated when melting occurs. The melting temperature can be calculated using the snow probability calculator of Shaviv (2006). The following important facts regarding the relationship between surface air temperature and surface RH are indicated in Fig. 3.12.

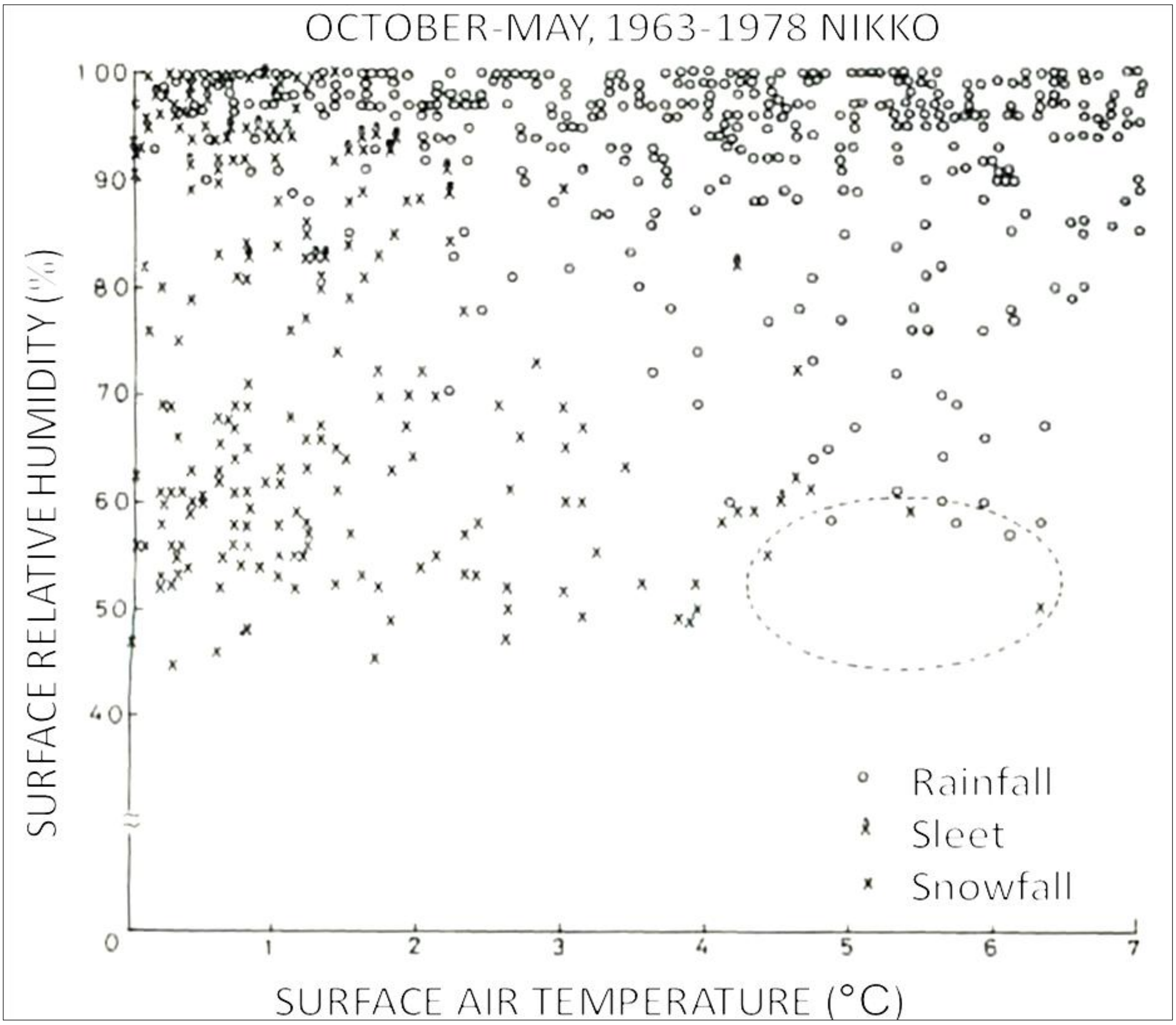


Figure 3.12: October to May, 16 year surface observations of snowfall (1963-1978) with reference to surface temperature and RH for Nikko station, Japan (adapted from Matsuo and Sasyo, 1981)

When surface RH is close to 100%, snow has been observed in temperatures below 1 °C and close to zero. The higher the surface RH, the higher the probability of rainfall above 1 °C. As surface RH decreases below 100%, it becomes possible to encounter snowfall at higher surface temperatures. When surface temperatures were below 2.5 °C and surface RH below 90%, snowfalls were frequent as opposed to temperature above 2.5 °C and surface RH above 90%. Exceptional cases of snowfall above surface temperatures of 3 °C occurred when the air was drier and the surface RH was less than 75%. Snowfall at temperatures from 4-6 °C only occurred when surface RH was close to and below 60%.

2. Freezing level (melting level height) above ground level conducive to snowfall

The most accurate way of obtaining freezing level data is by observing the vertical distribution of temperature in the atmosphere with the use of radiosonde data or tephigrams. The height where the temperature is 0 °C, is the freezing or melting level height (see Section 3.1.3). This is normally referred to as the height of the freezing level a.g.l.

Even if the remainder of the vertical distribution of temperature is below 0 °C and conducive to snowfall, snowflakes will melt in their passage into sub saturated (dry) air when temperatures are greater than 0 °C below the height of the freezing level. Snow starts to melt once it falls through the freezing level (melting level, see Section 1.4.2.2) at 0 °C. For this reason, the freezing level is referred to as the melting level as this is the level where falling snowflakes start to melt on their way down from the higher atmosphere. The melting of the snowflakes will not happen instantaneously when the snowflakes pass the melting level. It will depend on the rate of latent heat dissipation which is dependent on the environmental conditions through which it passes.

Figure 3.13 indicates the distance which snow can fall in temperatures above freezing below the height of the freezing or melting level.

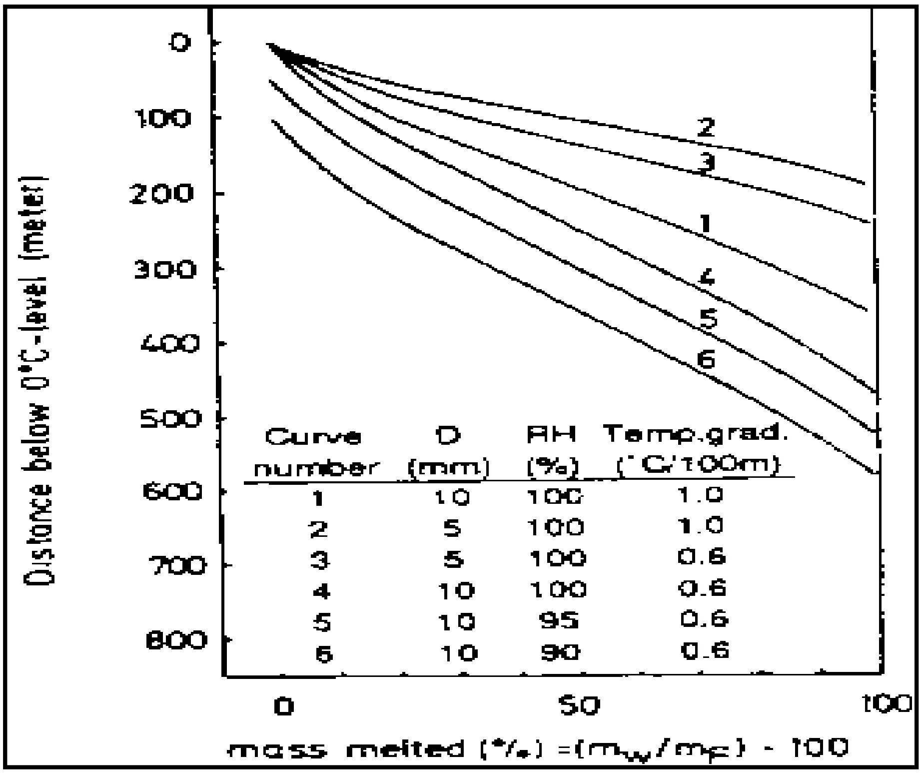


Figure 3.13: Melting distance below height of the freezing level given different RH, diametres and temperature gradient (adapted from Pruppacher and Klett, 2010)

The snowflake can fall several hundreds of metres below the freezing level before melting completely when the environmental temperature is 5 °C (Pruppacher and Klett, 2010).

When surface RH is 90% and lower, the vertical distribution of temperature follows a wet adiabatic lapse rate, then snowflakes can fall approximately 600 m in above freezing temperatures below the height of the freezing level before melting. As the RH amount increases, this distance that a snowflake can fall before melting becomes less. At a surface RH of 100% and a dry adiabatic lapse rate it can only fall approximately 150 m but when the vertical distribution of temperature follows a wet adiabatic lapse rate it can fall approximately 250 m.

McNulty (1988) found that, when the freezing level was below ground level, there was a 100% probability of snow. When the height of the freezing level was approximately 100 m a.g.l (12 hPa), there was a 90% probability of snow. As the height of the freezing level a.g.l increases to 200 m, the probability of snowfall decreases to 70% and when the height further increases to 300 m, the probability decreases to 50%. The average height of the freezing level needs to be about 400 m a.g.l before snow melts into rain.

3.2.5 Identification of ice crystals in clouds

Wetzel and Martin (2001) suggested that temperatures conducive to the formation of ice crystals can be best determined by the use of atmospheric soundings and satellite derived cloud top temperatures. This method will be used to identify ice bearing clouds, by referring to tephigrams and MSG satellite imagery. The Day Microphysical RGB is of practical use in determining the different cloud properties such as droplet size, presence of ice and supercooled water droplets within clouds (Eumetsat, 2012). Furthermore, the use of satellite images to identify ice clouds is particularly useful in the absence of upper air atmospheric assents. Baumgardt (1999) used temperatures ranges of between -10 °C and -20 °C to identify the presence of ice crystals within cloud. The same method will be employed within this dissertation (see Section 1.4.2).

Chapter 4: Synoptic system classification

When considering synoptic scale weather systems, it is important to focus on the atmospheric variables associated with these weather systems and how they change with time. In this chapter the 60 significant snow cases are analyzed subjectively in order to understand what variables will be important to investigate and to establish what significant weather patterns exist within the various combinations of atmospheric variables. This is explained in Chapter 4.1 where 5 characteristic patterns are identified subjectively (pattern 1 to 5). Once the optimum combinations of variables were found, namely MSLP, 500 hPa geopotential heights and 850 hPa temperature, these were then objectively scrutinized using SOMs. This is described in Chapter 4.2 where dominant nodes or synoptic patterns that contribute to snowfall for each month (May to October) are discussed.

The frequency of the 60 significant snow cases per month (Appendix A) for the period 1981 to 2011 are graphically depicted in Fig. 4.1. The frequency of significant snowfall cases represents a strong seasonality. The highest frequency occurs in the month of July, with a small increase from the onset of winter (May) and a gradual decrease during spring. The difference between May and September is noticeable. According to Taljaard (1996) COLs are most frequent during the transition seasons (March/April) and (September/October). Although Favre et al. (2012) indicated a higher occurrence of COLs in May than September. it is of interest to note that twice as many snow cases occur in September versus that of May. This is most likely due to the effects of other surface weather systems which play a role in snowfall such as the ridging high pressure system behind cold fronts.

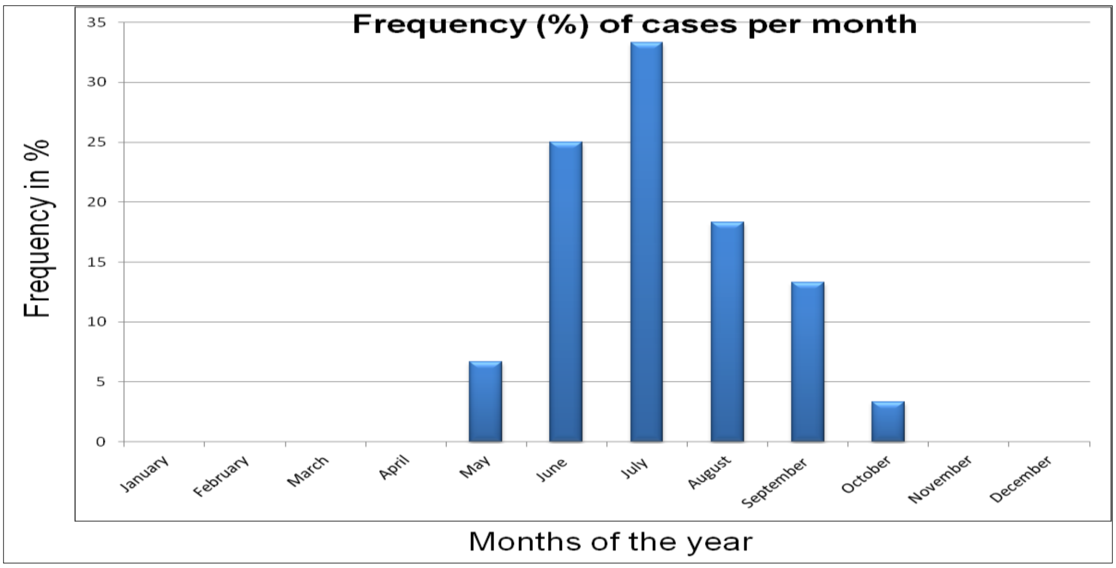


Figure 4.1: Frequency per month of the 60 significant snow cases for the period 1981-2011

4.1 Subjective synoptic classification related to the occurrence of significant snowfall

This section describes how without the aid of computers a subjective synoptic classification related to the significant occurrence of snowfall for the period 1981 to 2011 can be created. During the subjective analysis of 60 case studies for the period 1981 to 2011, characteristic synoptic patterns were observed associated with the occurrence of significant snowfall. The complete list of case studies used for the subjective classification can be found in Appendix A. Key synoptic circulation patterns were found to be important during the occurrence of significant snowfall.

The ridging surface AOH, IOH and cold fronts were the dominant surface related synoptic systems during snowfall along with upper air pointed troughs and COLs. The surface and upper air circulation systems were working in unison during the snowfall events. Consequently the subjective classification had to consider the complex combination of surface and upper air atmospheric patterns over different time periods as opposed to viewing surface and upper air systems separately at a specific time. The subjective classification lead to 5 distinctive patterns, which will now be discussed briefly in terms of their importance and inclusion.

4.1.1 Synoptic pattern 1

Pattern 1 includes the AOH as a key synoptic system. The ridging AOH is a shallow weather system not extending further than 700 hPa or 3000 m a.m.s.l (Taljaard, 1995a). It develops west of the country and is responsible for advecting cold, moist air to the rear of the cold front, northwards over the country in the lower layers. The temperature and RH close to the surface of the earth is critical in determining whether snow will reach the ground or not (see Section 3.2.4). The stronger the surface pressure gradient between the AOH west of the country and the low pressure associated with the cold front to the east, the stronger the thrust of cold air northwards over the country (see Section 3.2.2). The position of the AOH with regards to latitude is critical because if the high pressure system is located between the latitudes of 35° S and 40° S it can lead to the formation of an upper COL (Taljaard, 1985a). The surface wind flow associated with this system is normally south-westerly to southerly but can change to south-easterly depending on the position of the high and mostly effect's the south-western, southern and south-eastern parts of the country.

Pattern 1 encompasses 62% of all the significant snow cases and is indicated in Table 4.1. In all the cases of Table 4.1 there was a substantial surface pressure gradient involved causing a significant amount of horizontal cold temperature and moisture advection.

Table 4.1: Subjective synoptic classification for pattern 1 and surface pressure gradient for the period 1981-2011

Pattern 1(37 cases) Pointed trough/COL, cold front with associated surface low south or east of the country. AOH (1024-1036 hPa) between 30°-40° S. Average pressure gradient 21 hPa	**Surface pressure gradient in hPa**
7-8 July 1981	**25**
28-29 August 1981	**26**
1-3 July 1982	**20**
13-14 June 1984	**20**
11-12 July 1985	**24**
20-21 July 1987	**24**
28 May 1988	**12**
9-11 July 1988	**24**
17-18 July 1989	**20**
19-20 August 1990	**16**
29-30 August 1990	**20**
15 October 1990	**22**
18-19 October 1990	**26**
7-8 June 1991	**12**
26-27 July 1991	**22**
8-10 August 1992	**18**
11-12 June 1993	**20**
21-22 September 1993	**24**
28-29 June 1994	**24**
25-26 July 1994	**16**
20-21 August 1994	**22**
15-17 June 1995	**16**
17-18 July 1995	**24**
27-29 May 1997	**10**
14-15 July 2000	**30**
20-23 July 2001	**18**
12-14 September 2001	**22**
14-15 June 2002	**12**
16-20 July 2002	**12**
9-11 September 2002	**30**
19-20 August 2003	**28**
13-14 July 2004	**20**
6-7 September 2004	**18**
21-22 May 2007	**36**
26-27 June 2007	**14**
10-11 July 2010	**18**
25-27 July 2011	**22**

Since snowfall is dependent on the temperature and the RH of the air close to the surface (see Section 3.2.4), it is important to determine what role the surface pressure gradient plays in creating a vertical distribution of temperature and moisture, cold and moist enough close to the ground for snowfall to occur. Of the 37 cases subjectively classified under pattern 1, the lowest surface pressure gradient was 10 hPa and the highest 36 hPa. The average surface pressure gradient was 21 hPa and is an example of a subjective predictive tool that can be used to anticipate whether surface temperature and RH will be good for snowfall to occur.

The cold front associated with the upper air pointed trough or COL is essential as a weather producing system and features in all the different subjective pattern classifications. The cold front is an air mass boundary and is thus efficient in producing the cold air necessary to be advected over the country by the AOH or IOH. This moist, cool maritime airflow is normally from a south-westerly to southerly direction across the country. The position of the surface cold front implies a baroclinic upper air pointed trough or COL a few 100 km to the west above the baroclinic surface anticyclone (AOH or IOH). According to Taljaard (1985a) this surface and upper air configuration is important in the development of an upper COL system when a deep surface high forms to the south of the country isolating a cold pool over the interior of the country in the form of a COL.

4.1.2 Synoptic pattern 2

The IOH system is important in classifying synoptic pattern 2 which accounted for 22% of the cases (Table 4.2). The ridging AOH changes into the IOH once it moves round to the east of the country passing 24° E latitude (See Section 3.2.2). The purpose of the IOH is the same as that of the AOH but cold air and moisture is advected in the lower layers from a southerly to south-easterly wind flow over the south-eastern and eastern parts of the country instead of the south-western and southern parts (pattern 1). Due to the position of the IOH, the passage of the airflow over the warm Agulhas current lends itself to the advection of a warmer, moister air mass than in the case of the AOH. The stronger the surface pressure gradient between the IOH and the advancing surface cold front cyclone, the stronger the horizontal moisture and temperature advection will be. Similarly to the AOH, the maximum advection of moisture and cold air is obtained when a strong surface IOH of at least 1030 hPa to 1040 hPa is located between the latitudes of 35° S to 40° S.

4.1.3 Synoptic patterns 3, 4 and 5

In pattern 3 (5% of cases) (Table 4.2), the surface temperature and moisture advection is caused by a prominent frontal low pressure system which is located close to the south-east coast of South Africa. The limiting effect that the AOH and IOH have is noticeable in these cases, although the COL is present. Pattern 4 (8% of cases) (Table 4.2) has the sole presence of the upper COL as the defining circulation pattern indicative of the importance of this system in snowfall. Pattern 5 (3% of cases) (Table 4.2) did not fit with any of the other patterns. This pattern will not be considered further in this study due to the small number of occurrences.

Table 4.2: Subjective synoptic classification of patterns 2, 3, 4 and 5 for the period 1981-2011

Pattern 2 (13 cases) Pointed trough/COL, cold front followed by ridging IOH 1028-1036 hPa) between 36°-40° S)	**Pattern 3 (3 cases)** Pointed trough/COL, cold front with surface low over the south-eastern Cape coast.	**Pattern 4 (4 cases)** COL	**Pattern 5 (2 cases)** Other
10-11 September 1981	24-26 July 1983	25-26 June 1987	14-15 July 1987
7-8 August 1983	27-28 June 1988	15-16 August 1987	16-18 July 1996
24-25 June 1985	1-3 Aug 2006	10-12 June 1997	
17-18 June 1987		29-30 June 1997	
25-26 August 1987		8 June 2011	
27-28 September 1987			
6-10 July 1996			
18-19 September 2000			
27-29 July 2004			
23-25 May 2006			
20-21 September 2008			
9-10 June 2009			
15-16 August 2011			

4.2 Objective synoptic classification related to the occurrence of significant snowfall

This section describes the results obtained in the objective synoptic classification of significant snowfall events for the period 1981-2011, May to October.

A preliminary subjective investigation into the 60 snowfall cases (see Section 4.1 and Appendix A) confirmed that the variables used to train the SOM would help to identify the character of synoptic systems responsible for snow over South Africa. Although the detail of the classification increased with increasing SOM sizes, the 24 node SOM (6x4) sufficiently mapped the major systems as identified within the subjective classification and was used in this dissertation (see Section 3.2.3).

4.2.1 Characteristic synoptic scale weather patterns related to snowfall

The 6x4 SOM depicted in Fig. 4.2 indicates 24 characteristic synoptic weather patterns that were present within the original data set and are associated with significant snowfall over South Africa for the period 1981-2011. The original data set which served as input for the SOM where the 60 significant snowfall cases identified in the subjective analysis of Appendix A for the period 1981-2011 (see Section 3.2.3). The main snow-producing weather systems identified in Chapter 2, can be seen within the SOM of Fig. 4.2, namely the ridging AOH/IOH behind cold fronts along with pointed upper air troughs and COLs.

Instead of including one synoptic pattern representative of a few days as in the subjective classification, six-hourly patterns were included in the objective classification as part of the original dataset. A three-variable SOM was chosen that relates the MSLP, 500 hPa geopotential heights and 850 hPa temperature patterns within one characteristic node or pattern.

Nodes that appear adjacent to each other within the SOM space (Fig. 4.2) are similar to each other with subtle variations, for example node 1 and 2 has a similar synoptic pattern (see Fig. 4.2). Nodes that appear on the opposite side of the SOM space differ completely from each other, as is the case of node 1 and node 24 (see Fig. 4.2). Although 24 synoptic patterns occur in Fig. 4.2, there are two distinct synoptic patterns, located on the left and right side of the SOM.

Over the left half (12 nodes) of the SOM (Fig. 4.2) very deep 500 hPa pointed troughs or COLs (dark blue shading) arise that are associated with intense surface cold fronts (strong 850 hPa temperature gradient in yellow) which are associated with surface frontal lows south-east of the country followed by the AOH (black isobars) with south-westerly to southerly flow producing the cold air and moisture advection. The 850 hPa temperatures (yellow) indicates the major thermal gradient across the central interior pinpointing the surface frontal position.

Over the right half (12 nodes) of the SOM (Fig. 4.2) weaker COLs (light blue shading) are found at 500 hPa with a ridging IOH at 40° S to the south of the country producing south to south-easterly flow over the Indian Ocean. The result of this airflow over the warmer Indian Ocean is that the 850 hPa temperatures are warmer with less defined frontal boundaries.

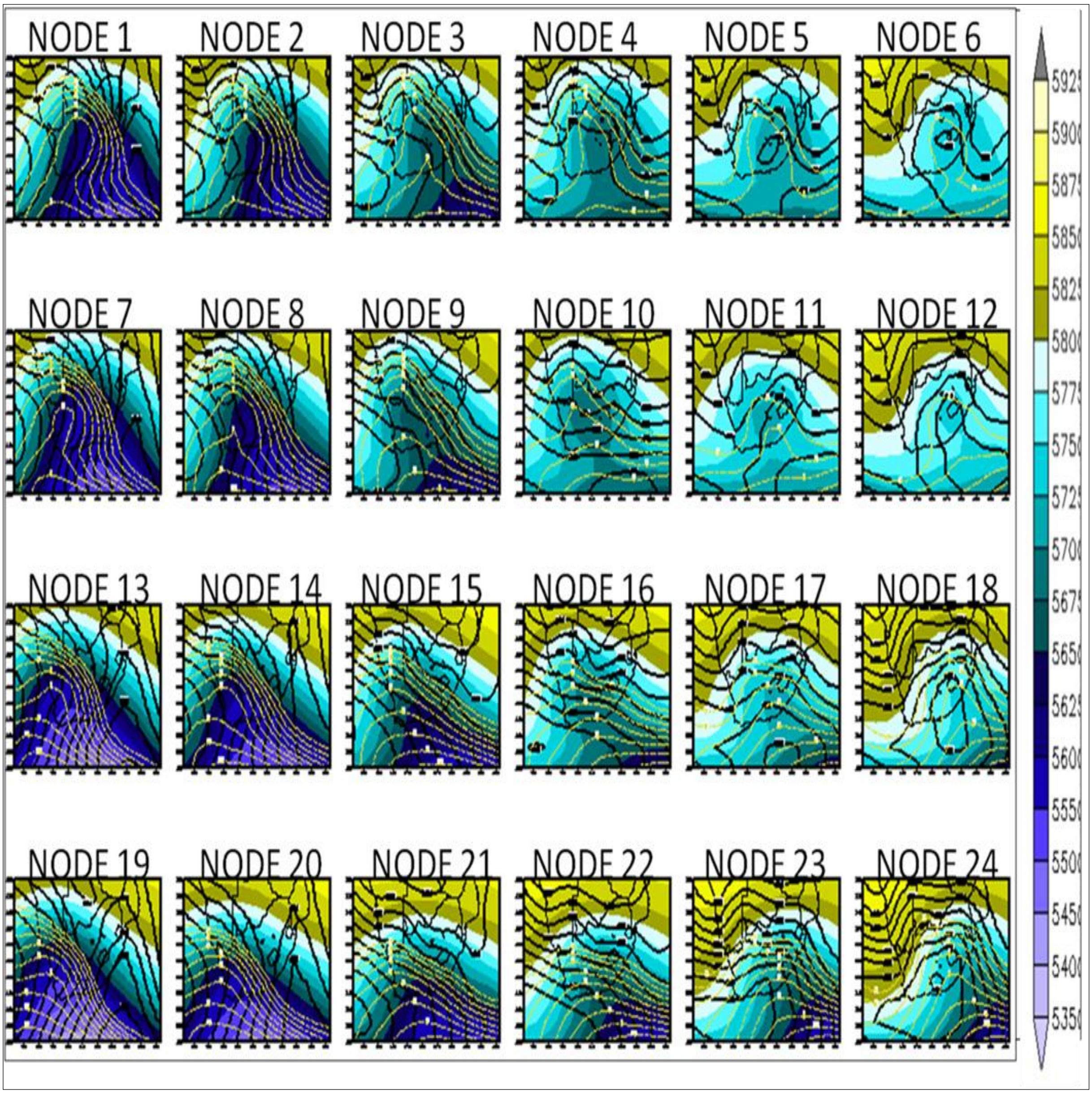


Figure 4.2: Twenty-four node self-organising map indicating characteristic mean sea level pressure in hPa (black solid), 500 hPa geopotential heights in metres (shaded) and 850 hPa temperatures =< 6 °C (yellow) synoptic patterns associated with significant snowfall over South Africa for the period 1981-2011

When one is mapping data from a higher dimensional space to a two-dimensional space, the integrity and structure of the data needs to be kept. Where node points (Fig. 4.3) are closer together, it exhibits a denser data space (Tennant et al., 2002). The Sammon map in Fig. 4.3 indicates a high-quality two-dimensional mapping of the higher dimensional data set, because each node point is located equidistant from each other.

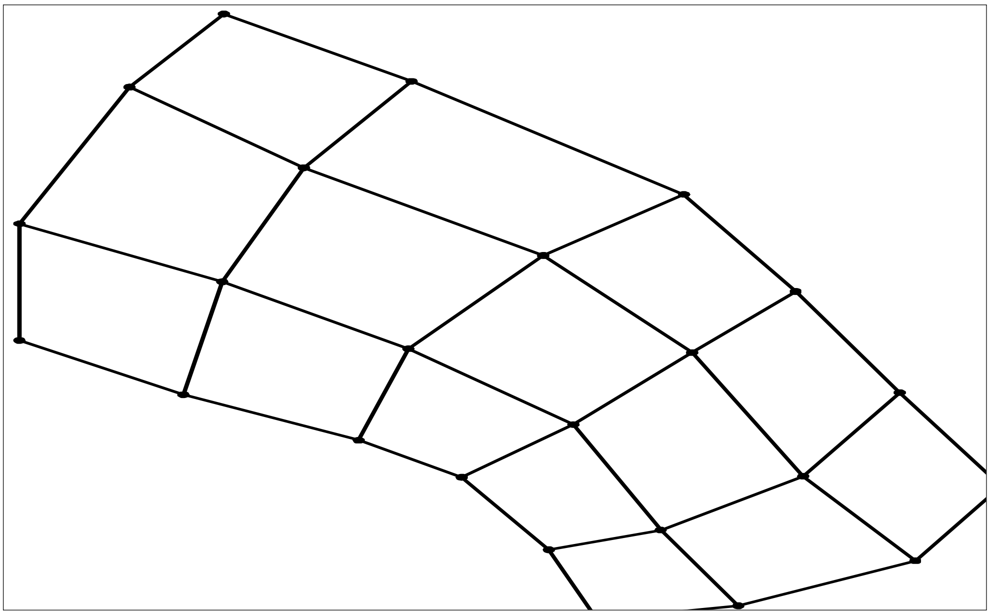


Figure 4.3: Sammon map of 6x4 self-organising map indicating the two-dimensional relationships between the 24 nodes

4.2.2 Frequency of all snowfall occurrences from 1981-2011

Each of the 24 squares in the 6x4 SOM in Fig. 4.4 represents a particular node pattern which is comparable to the nodes of Fig. 4.2. In other words, each of the nodes (squares) in Fig. 4.4 corresponds to the same position and sequence as the nodes in Fig. 4.2. The colour shading in the right hand bar of Fig. 4.4 is representative of the frequency of occurrence of that particular node in the entire SOM dataset (426 snowfall events) for the period 1981-2011. Of the 426 events that occurred for the period 1981-2011 more than 6% were mapped to node 6 and node 19. This corresponds to 27 events for node 6 and node 19 respectively (Fig. 4.4). Node 6 and node 19 appear on opposite sides of the SOM indicating that they are characteristically different from each other, yet they occur with a similar frequency within the entire SOM period. The synoptic features defining node 6 and node 19 will be discussed briefly.

Node 6 represents a weaker COL (light blue shading of 5720 m) over the interior of KZN associated with a baroclinic surface frontal low to the east of the KZN coast (Fig. 4.2). This is similar to Taljaard (1995a) that indicated the association of the upper COL with the surface frontal low (see Fig. 2.8, Section 2.1.2.1). The IOH that is situated to the south-east of the country combines with the surface frontal low east of KZN to create a strong surface pressure gradient. This pressure gradient increases the horizontal advection by the wind of cooler and moister air into KZN, the north-eastern part of the Eastern Cape, the eastern Free

State and Mpumalanga. This cooler, moister air is reflected by the 850 hPa temperatures in the SOM being slightly warmer due to the passage of the air over the warm Agulhas current. Node 6 is more representative of the left hook sequence described by Van Heerden and Hurry (1995) where the flow comes from the left around the surface low pressure system (see Fig. 2.4 A, Section 2.1.1.2).

Node 19 in Fig. 4.2 represents a different synoptic circulation to that of node 6. Very deep (colder) pointed upper air troughs or COLs pass over the Western Cape, indicated by the dark blue shaded colours of 5550 m (note that this is considerable lower than the 5720 m of node 6). The AOH near 35° S ridges strongly to the south-west of the country, setting up a very intense frontal boundary (strong 850 hPa temperature gradient in yellow) over the south-western part of South Africa associated with a surface frontal low south-east of the country. Node 19 is more representative of the right hook sequence described by Van Heerden and Hurry (1995) where the flow comes from the right.

All other nodes within the SOM occur with a frequency of between 2 and 5%. All patterns depict either COLs or pointed troughs associated with ridging AOH or IOH pressure systems behind strong cold fronts.

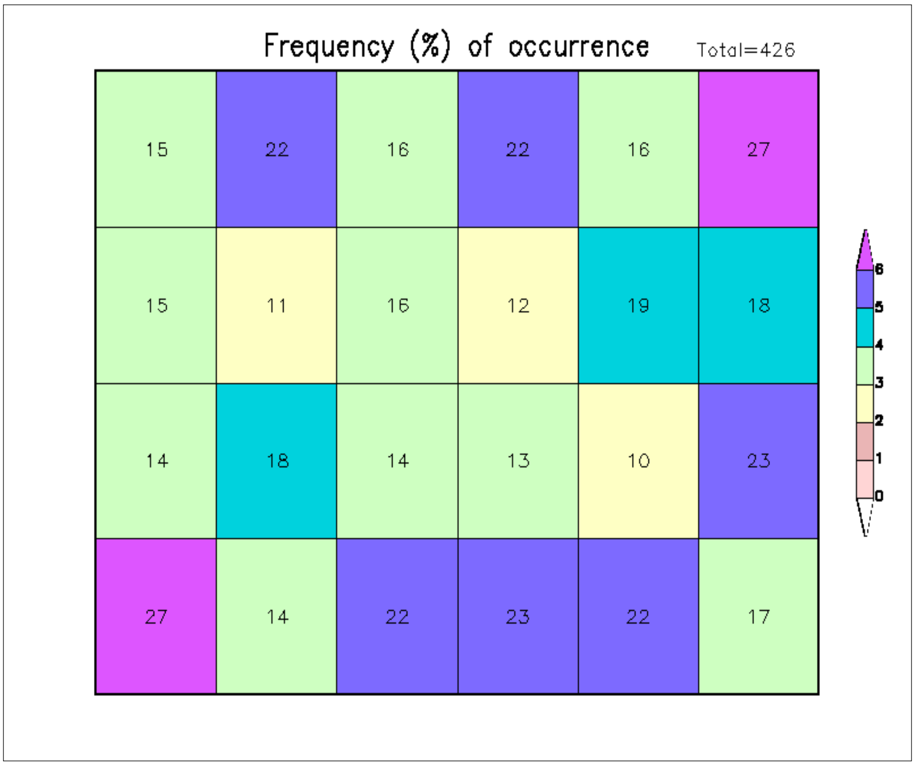


Figure 4.4: The frequency (%) of occurrence of snow in 60 significant cases (426 events) (shaded colours) for the period 1981-2011 with respect to each of the 24 nodes (the number of events is plotted in each square or node)

4.2.3 Frequency per node per month (May to October)

No significant snowfall events occurred during the month of April. As a consequence, the period from May to October will be discussed in the following section. To ascertain the distribution of the frequency per node for each particular month, the number of events per node was divided by the total number of events for that month to establish whether certain nodes were more prevalent during a particular month. This percentage value was then plotted for each particular node on each of the 24 node squares. For example node 1 occurred five times in May and there were 27 events in May, providing a frequency of 19% for node 1. This would provide evidence of the frequency of occurrence of node 1 in the month of May. The same approach is followed for the other months.

The colour bar shading on the right of Fig. 4.5 was calculated for each of the 24 nodes by taking the number of events for each respective node in May and dividing it by the total number of events that occurred for each respective node for all the months (May to October) under consideration. For example, node 1 has a percentage of 29% (dark brown) which was calculated by taking the five events of node 1 during the month of May and dividing it by 17 (the total amount of events added up for all the node 1s for the period May to October). This would provide evidence that, when snow occurred in the month of May, it occurred in node 1 with a frequency of 29% of the time. The same approach is followed for the other months to obtain the nodes that were dominant during those particular months.

Each respective month will now be discussed separately in detail for those nodes that had the highest frequencies in both their occurrence within a particular month and the nodes that are characteristic for snowfall in a particular month.

4.2.3.1 Frequency for each node in the month of May for the period 1981-2011

During the month of May, for the period 1981- 2011, there were 27 snowfall events in total. Of the 27 events that occurred, the nodes with the highest frequency of occurrence in May and nodes that are characteristic in May will now be discussed.

1. Nodes with the highest frequency in May

The highest frequency of occurrence is split between two areas within the SOM space. On the left side of the SOM, the highest frequencies were associated with nodes 1 and 2. They were node 1 with 19% and node 2 with 15% (Fig. 4.5).

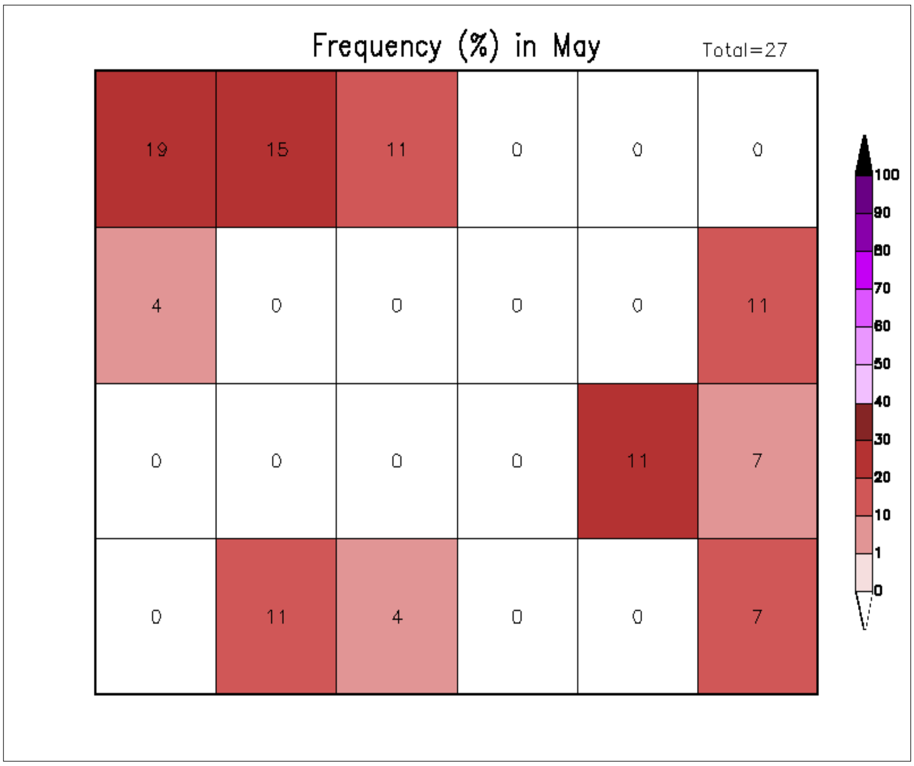


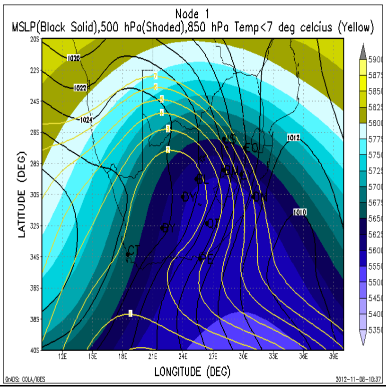
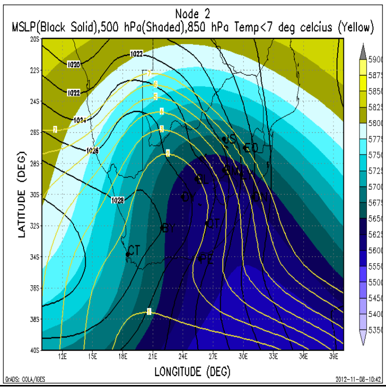
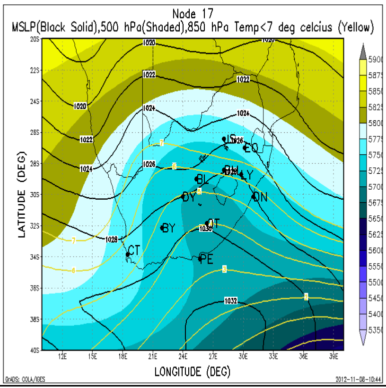
Figure 4.5: Frequency (%) of snowfall occurrence per node for the month of May and nodes characteristic of snowfall during the month of May (shaded) for the period 1981-2011

These two nodes are situated next to each other in the SOM space. As a result, they are characteristically very similar e.g. pointed upper trough/COL, strong surface cold front extending into low south-east of the country with strong ridging AOH of 1030 hPa at 35° S. In light of this, they can be depicted as one pattern and their frequency can be added together to obtain 34% as depicted in Table 4.3. Node 17 occurs on the opposite (right) hand side of the SOM space and was less frequent (11%). This node indicates a weaker pointed upper air trough/COL with the 1032 hPa IOH south of the country at 38° S, resulting in a weaker surface frontal boundary.

2. Nodes characteristic for snowfall in May for the period 1981-2011

When snow occurred in the month of May and node 1, 2 and 17 transpired; it was with a frequency of 20 to 30 % (brown shade in Fig. 4.5) of the time in May making these nodes characteristic for snowfall during the month of May (Table 4.3).

Table 4.3: Frequency (%) of occurrence for nodes 1, 2 and 17 characteristic for snowfall during the month of May for the period 1981 to 2011

Nodes dominant in May		Number of snowfall events associated with each node: Total 27 events for May
Node 1 	Node 2 	Node 1: 5 events = 19% Node 2: 4 events = 15% Total Frequency = 9 events (19% + 15%) = 34%
Node 17 		Node 17: 3 events = 11%

4.2.3.2 Frequency for each node in the month of June for the period 1981-2011

During the month of June, there were 95 snowfall events in total making this the month with the second highest occurrences of snow. Of the 95 events that occurred during the month of June, the nodes with the highest frequency of occurrence and nodes that are characteristic in June will now be discussed.

1. Nodes with the highest frequency in June

The highest frequency of occurrence was in the top right hand side of the SOM (Fig. 4.6). In this part of the SOM, the IOH is dominant south-east of the country in the presence of an upper COL over KZN with an associated surface low to the east of KZN. Node 6 had the highest frequency with 19% while node 5 has a frequency of 8%. These two nodes appear next to each other and are characteristically similar in their synoptic patterns (see Fig. 4.2).

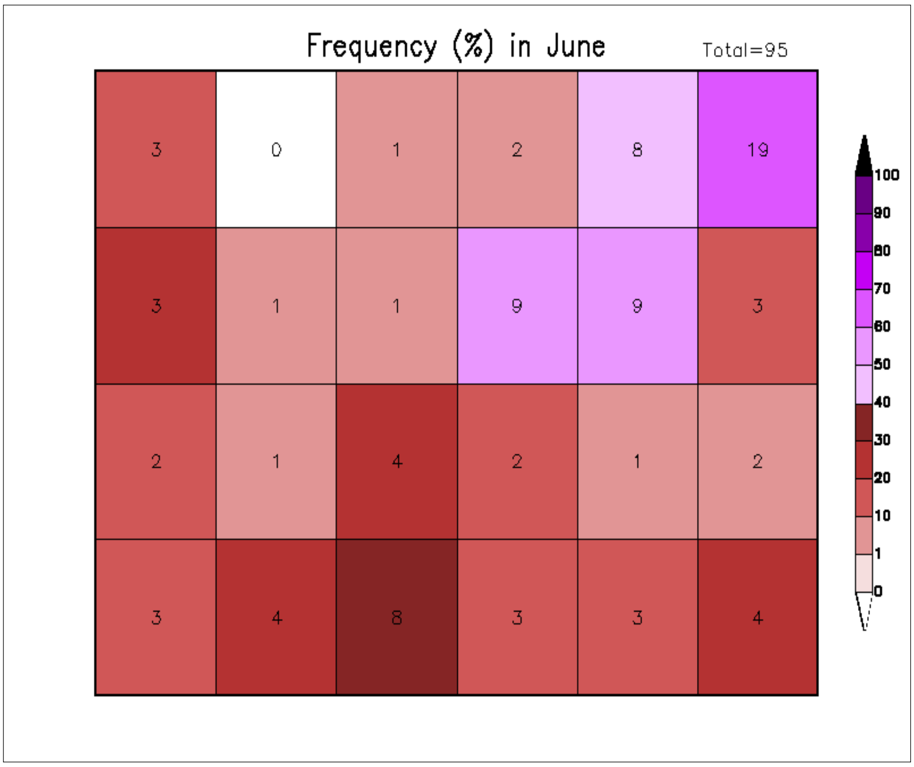


Figure 4.6: Same as Figure 4.5 but for the month of June

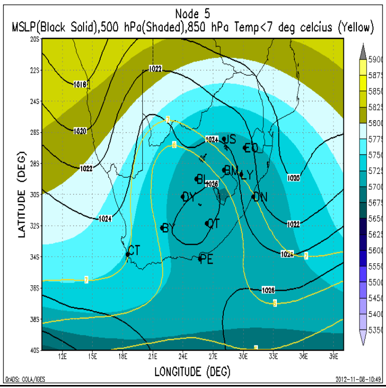
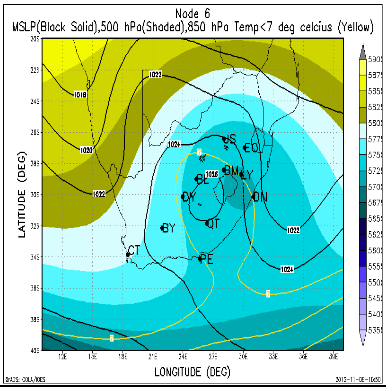
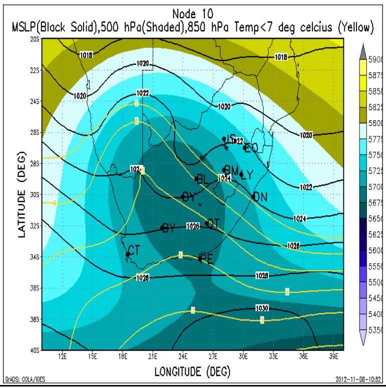
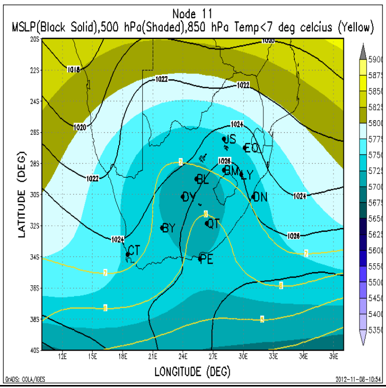
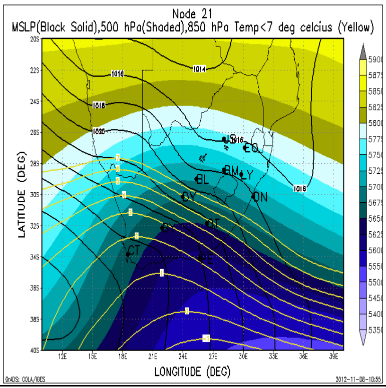
As a result, the frequency of these two patterns can be added together to obtain 27% (Table 4.4). This pattern is indicative of a weak COL over KZN, with an associated surface frontal low east of the KZN coast and the IOH of 1026 hPa south-east of the country at 38° S. Nodes 10 and 11 are also found on the right side of the SOM. They took place with a frequency of 9% and are also situated next to each other (see Fig. 4.6). These two nodes depict a COL over the Northern Cape near De Aar with the 1029 hPa IOH south-east of Port Elizabeth at around 37° S as indicated in Table 4.4.

Node 21 took place 8% of the time and is located on the left side of the SOM. It represents a deep pointed trough/COL over the southern interior of the Western and Eastern Cape with the 1030 hPa AOH ridging strongly along the southern coastal belt. This is more typical of the right hook case of Van Heerden and Hurry (1995), where the AOH is south-west of Cape Town at 37° S. Nodes 5, 6, and 11 in Table 4.4 are typical of the left hook as the circulation comes from the left around the surface low east of KZN.

2. Nodes that are characteristic for snowfall in June for the period 1981-2011

When snow occurred in the month of June, and node 6 occurred (Table 4.4), it was with a frequency of between 60% and 70%, making this node dominant in the month of June. When it snowed and node 10 and 11 occurred (Table 4.4) it was with a frequency of 50 to 60% of the time making these two nodes quite characteristic in June as well. Once again, these nodes are clumped together in the top right hand side of the SOM (Fig. 4.6), indicating a similarity in the patterns that they represent. When it snowed and node 21 occurred, it was with a frequency of 40 to 50% of the time.

Table 4.4: Same as Table 4.3 but for June for nodes 5, 6, 10, 11 and 21

Nodes dominant in June		**Number of snowfall events associated with each node: Total 95 events for June**
Node 5 	Node 6 	Node 5: 8 events = 8% Node 6: 18 events = 19% Total frequency = 26 events (8% + 19%) = 27%
Node 10 	Node 11 	Node 10: 9 events = 9% Node 11: 9 events = 9% Total frequency = 18 events (9% + 9%) = 18%
Node 21 		Node 21: 8 events = 8%

4.2.3.3 Frequency for each node in the month of July for the period 1981-2011

July had the most occurrences of snow and there were 168 snow events in total. Of the 168 events that occurred during the month of July, the nodes with the highest frequency of occurrence and nodes that are characteristic in July will now be discussed.

1. **Nodes with the highest frequency in July**

In contrast with the month of June, the highest frequency of occurrence of nodes is clustered together on the left hand side of the SOM. On this side of the SOM, the AOH is more dominant as a surface synoptic circulation system. The highest frequency occurred with node 4 with 11% (Fig. 4.7) which involves an IOH and a surface low east of KZN with a weaker frontal boundary similar to that of June.

Node 2 (7%) and 3 (8%) indicated a pointed upper trough or COL over the Eastern Cape with the AOH ridging behind a strong cold front in the case of node two and a weaker cold front the case of node 3 where the upper trough is also weaker.

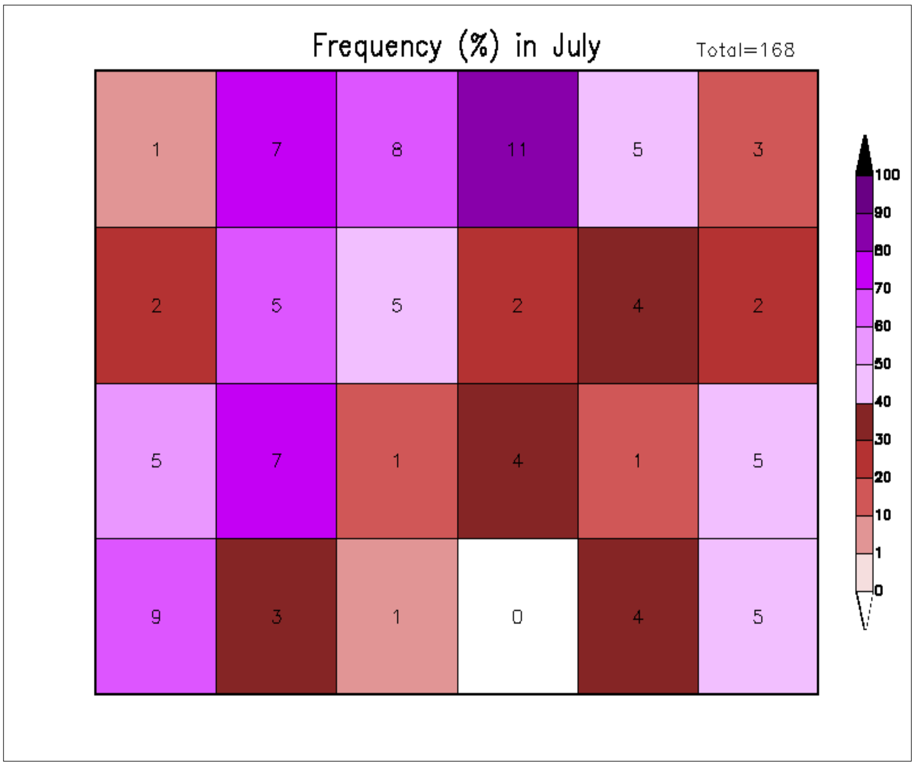


Figure 4.7: Same as Figure 4.5 but for July for the period 1981-2011

Node 19 (9%) and 14 (7%) are closely related to each other on the left hand side of the SOM. Their synoptic patterns are similar, indicating a deep upper air trough or COL with a sharp surface frontal boundary over the country into a frontal low south-east of the country. The 1030 hPa AOH is located south-west of the country at 35° S.

2. Nodes that are characteristic for snowfall in July for the period 1981-2011

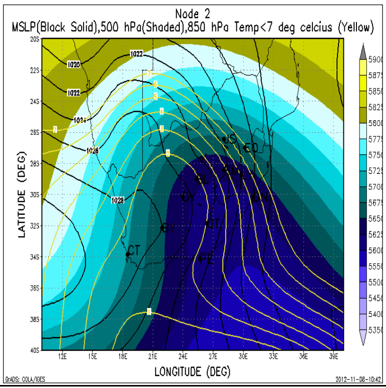
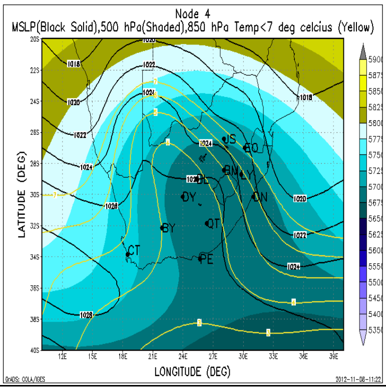
When it snowed in July and node 4 occurred, it was with a frequency of more than 80% of the time while node 2 had a frequency of 70 to 80% of the time making these nodes characteristic for the month of July (Fig. 4.7). In node 2, the upper trough is forming a COL over the Eastern Cape while the 1030 hPa AOH located at 35° S ridges strongly along the south and south-east coast forming a pronounced cold frontal boundary over the north-eastern Free State.

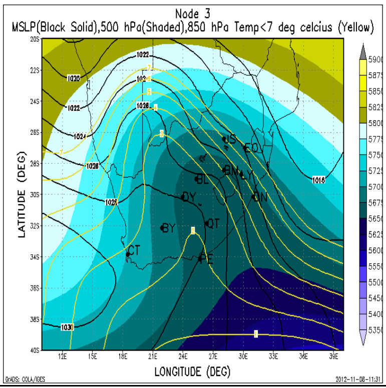
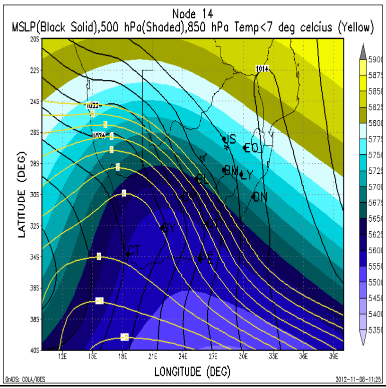
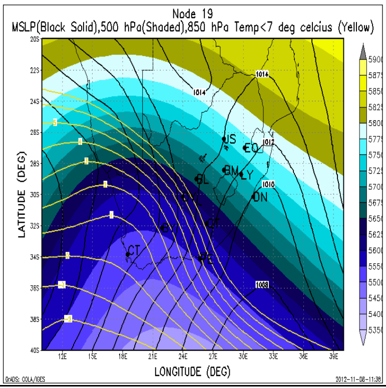
When node 14 transpired, it was with a frequency of 70 to 80% while node 19 was 60 to 70% of the time (Fig. 4.7). In node 14 (Table 4.5), a strong AOH is located at 38° S which produces a strong onshore flow over the south-western interior in the presence of a deepening pointed upper air trough or COL and a strong 850 hPa frontal boundary over the Northern and Eastern Cape.

When it snowed in July and node 3 arose, it was with the frequency of 60 to 70% making this node characteristic too (Fig. 4.7).

In July, the AOH dominates with more intense frontal boundaries and upper air troughs as compared to June.

Table 4.5: Same as Table 4.3 but for July for nodes 2, 4, 3, 14 and 19

<table>
<tr><td colspan="2">Nodes dominant in July</td><td>Number of snowfall events associated with each node: Total 168 events for July</td></tr>
<tr><td>Node 2

</td><td>Node 4

</td><td>Node 4: 18 events = 11%

Node 2: 12 events = 7%</td></tr>
<tr><td>Node 3

</td><td></td><td>Node 3: 14 events = 8%</td></tr>
<tr><td>Node 14

</td><td>Node 19

</td><td>Node 14:12 events = 7%

Node 19: 15 events = 9%

Total frequency =27 events (7% + 9%) = 16%</td></tr>
</table>

4.2.3.4 Frequency for each node in the month of August for the period 1981-2011

During the month of August, there were 72 events in total which makes August the third highest month for snowfall to occur (Fig. 4.8). Of the 72 events that occurred, the nodes with the highest frequency of occurrence and nodes that are characteristic in August will now be discussed.

1. **Nodes with the highest frequency in August**

The highest frequency mapping was node 22 with 12% and node 23 with 10%. These nodes appear in the bottom right hand side of the SOM and are similar (Fig. 4.8). These nodes indicate a strong 1031 hPa AOH south of Cape Town at 38° S which is in the process of transforming into the IOH as it moves further eastwards. Consequently, there is plenty advection of moisture and cooler air into the Eastern Cape in the presence of a pointed trough/COL with a strong frontal boundary over the southern interior. Node 7 and 9 occurred with a frequency of 7% and these two nodes occur in the top left side of the SOM (Fig. 4.8). Since they occur on opposite sides of the SOM, they are therefore characteristically different from each other.

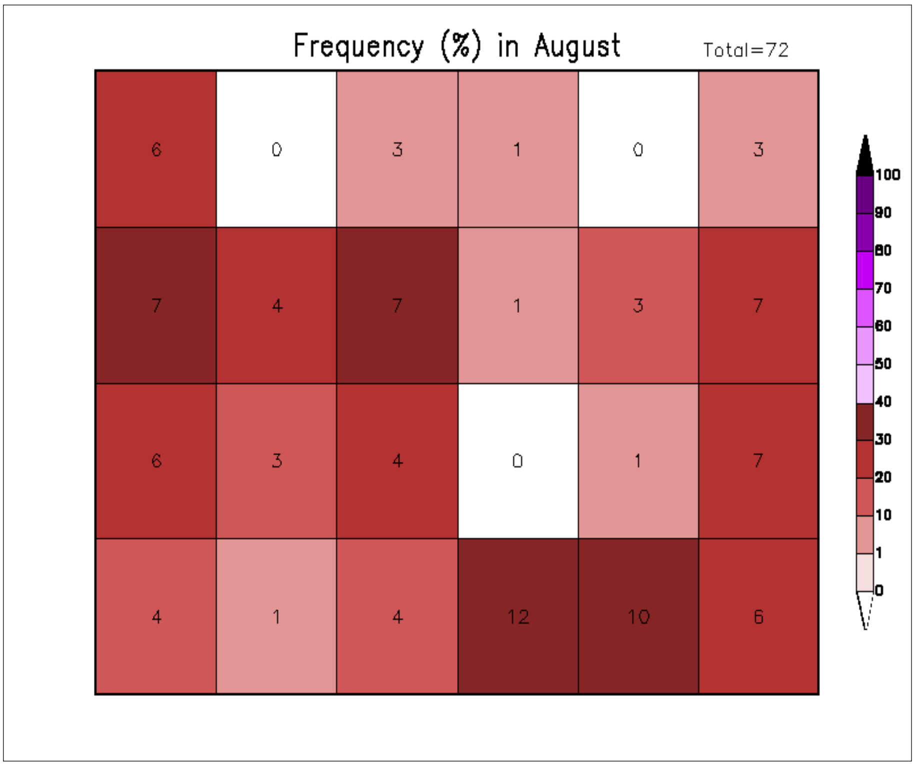


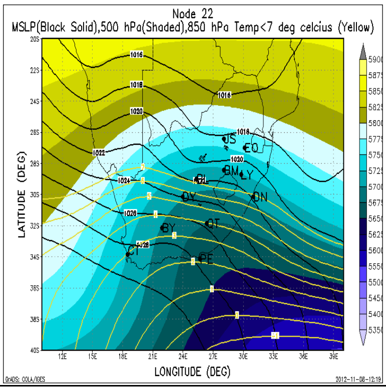
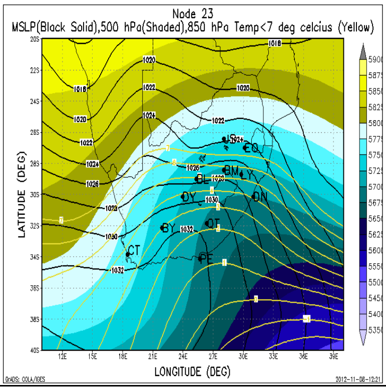
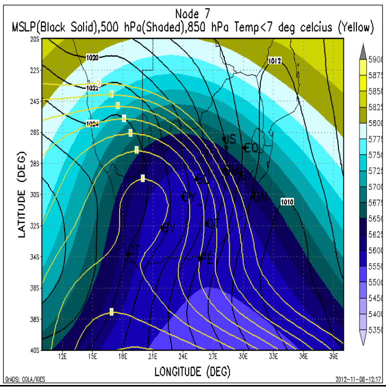
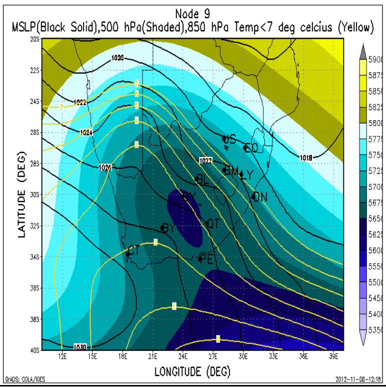
Figure 4.8: Same as Figure 4.7 but for the month of August for the period 1981-2011

2. **Nodes that are characteristic for snowfall in August for the period 1981-2011**

When it snowed in the month of August and nodes 22, 23, 7 and 9 occurred, it was with a frequency of 30 to 40% of the time in August making these characteristic nodes for the month of August. In these nodes the AOH dominates.

Node 7 is an example of a deep pointed trough or COL over the Eastern Cape associated with a deep surface frontal low to the south-east of Port Elizabeth, with the 1028 hPa AOH to the west of Cape Town at 34° S. The resultant pressure gradient of cold air advection ensures a well defined 850 hPa frontal boundary over the Free State. In the case of node 9, the surface AOH is located south-west of Cape Town at 37° S ensuring a strong influx of moisture and cooler air into the interior of the Eastern Cape and KZN resulting in an 850 hPa frontal boundary over the south-eastern interior. This occurs in association with an upper pointed trough developing over the Eastern Cape.

Table 4.6: Same as Table 4.3 but for August for the period 1981 to 2011

Nodes dominant in August		**Number of snowfall events associated with each node: Total 72 events for August**
Node 22 	Node 23 	Node 22: 9 events = 12% Node 23: 7 events = 10% Total frequency =16 events (12% + 10%) = 22%
Node 7 	Node 9 	Node 7: 5 events = 7% Node 9: 5 events = 7%

4.2.3.5 Frequency for each node in the month of September for the period 1981-2011

During the month of September, there were 56 events in total making it the fourth highest month in terms of the occurrence of snowfall (Fig. 4.9). Of the 56 events that occurred, the nodes with the highest frequency of occurrence and nodes that are characteristic in September will now be discussed.

1. Nodes with the highest frequency in September

Node 15 (9%), node 21 (9%) and node 22 (16%) are located in the same SOM space and have similar synoptic configurations. Node 16 and 17 are also similar and occurred with a frequency of 16% and 9% respectively during the month of September. They are situated in the same SOM space (bottom right, see Fig. 4.9), indicating that they are associated with similar synoptic patterns within the original data set.

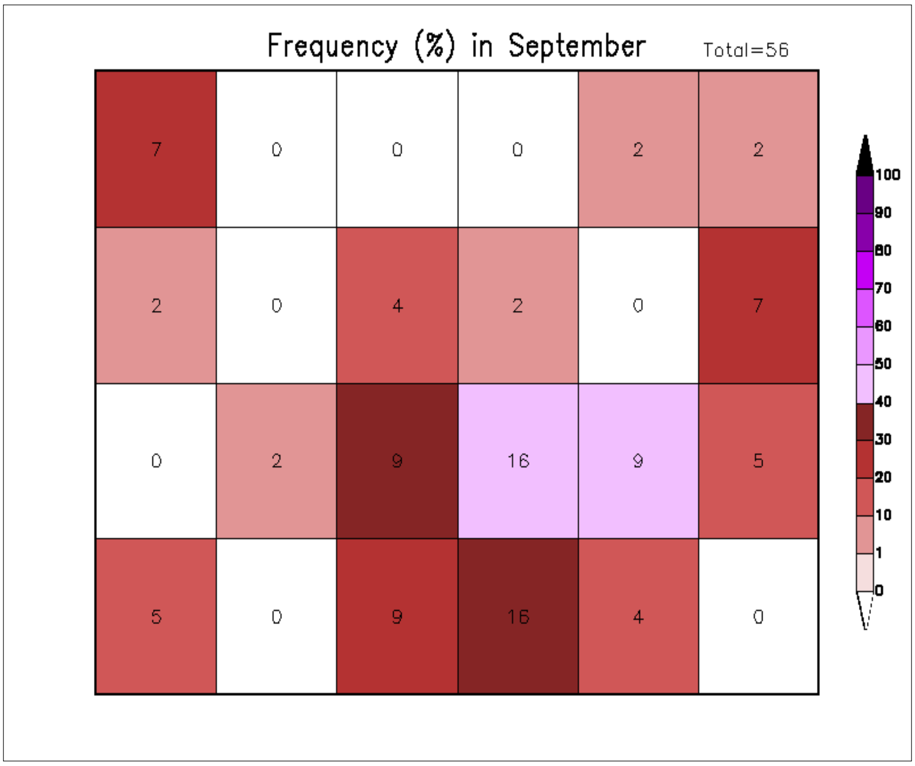
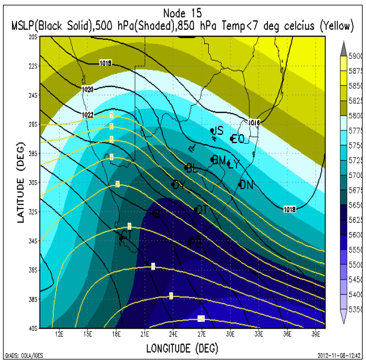
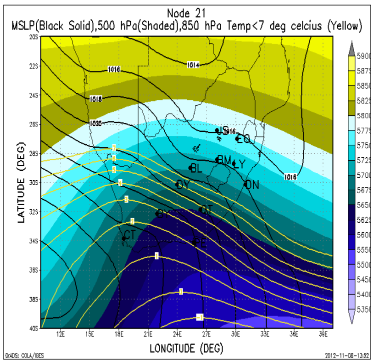


Figure 4.9: Same as Figure 4.8 but for the month of September for the period 1981-2011

Nodes 15, 21 and 22 are similar and indicate the 1030 hPa AOH at 38° S ridging eastwards causing a strong influx of colder moist air over the southern and south-eastern interior with the passage of the surface cold front. A deep pointed upper trough/COL that moves over the Eastern Cape (Table 4.7) is present.

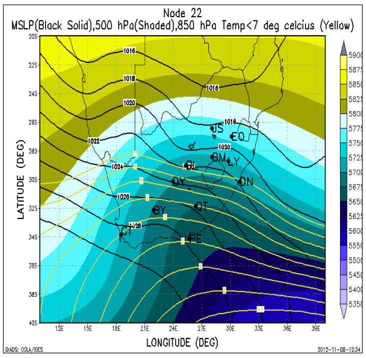
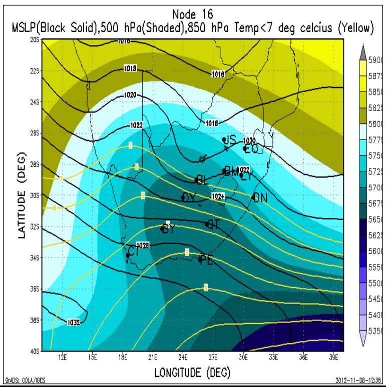
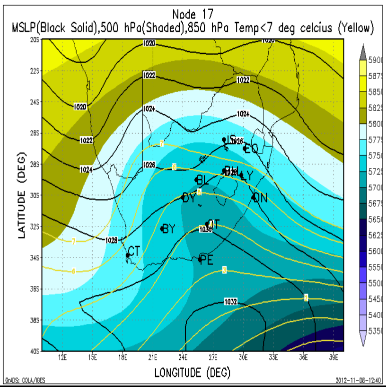
Node 16 and 17 are characterised by the ridging of the 1032 hPa AOH at 38° S and the development of a COL over the south-eastern interior as cold air advection reaches a maximum below the 500 hPa trough as surface isobars cross the 500 hPa geopotential heights at right angles. Node 17 is starting to become the IOH (Table 4.7).

Table 4.7: Same as Table 4.3, but for node 15, 16, 17, 21 and 22 which are dominant during the month of September

<table>
<tr><th colspan="2">Nodes dominant in September</th><th>Number of snowfall events associated with each node: Total 56 events for September</th></tr>
<tr><td>Node 15
</td><td>Node 21
</td><td rowspan="2">Node 15: 5 events = 9%

Node 21: 5 events = 9%

Node 22: 9 events = 16%

(Node15 + node 21 + node 22) = 36%</td></tr>
<tr><td>Node 22
</td><td></td></tr>
<tr><td>Node 16
</td><td>Node 17
</td><td>Node 16: 9 events = 16%

Node 17: 5 events = 9%

(Node16+Node17) = 25%</td></tr>
</table>

2. **Nodes that are characteristic for snowfall in September for the period 1981-2011**

When it snowed during the month of September and node 16 and node 17 occurred, it was with a frequency of 40 to 50 % of the time in September making these characteristic nodes for that month. Likewise when it snowed in September and node 15 and 22 occurred, 30 to 40 % of the time these nodes occurred making them characteristic of snowfall in September.

Consequently during September month the nodes in the middle of the SOM are more frequent where the AOH is situated more to the south of Cape Town.

4.2.3.6 Frequency for each node in the month of October for the period 1981-2011

During the month of October, there were eight events in total (Fig. 4.10) and snow in this month is very infrequent. Of the eight events that occurred, the nodes with the highest frequency of occurrence and nodes that are characteristic in October will now be discussed.

1. **Nodes with the highest frequency in October**

Node 20 occurred 25% of the time while node 21 and node 22 occurred 38% of the time. Nodes 21 and 22 were also dominant during the month of September.

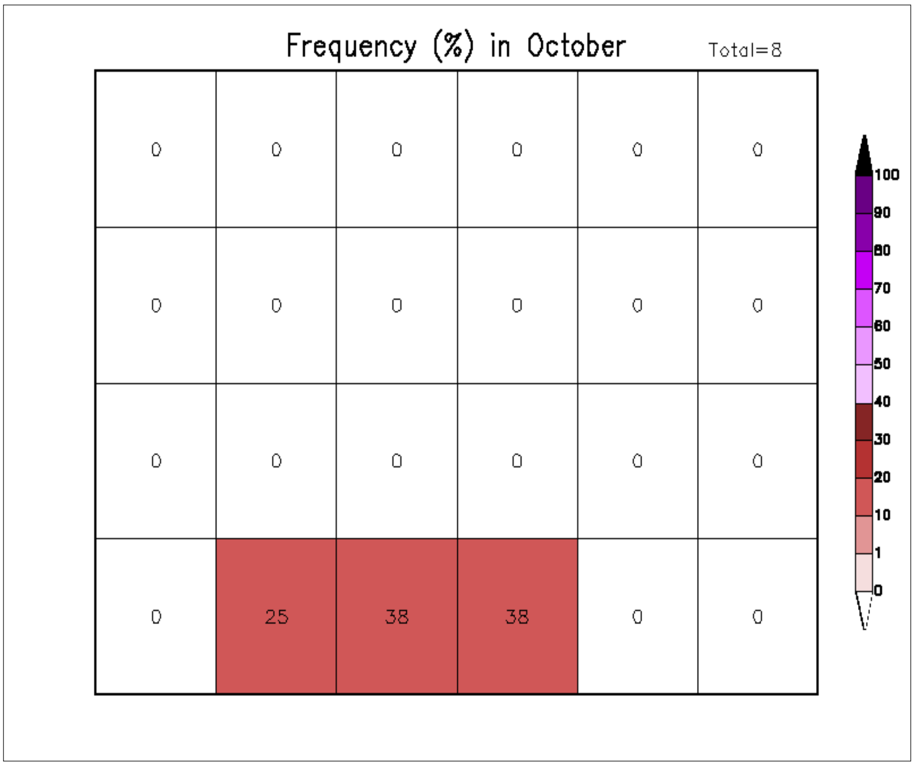


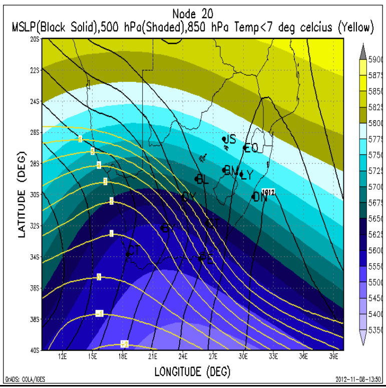
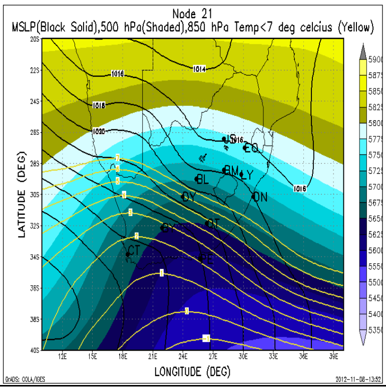
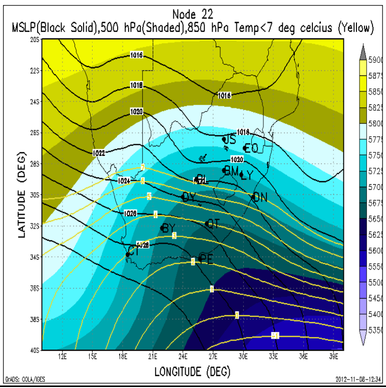
Figure 4.10: Same as Figure 4.8 but for the month of October for the period 1981-2011

2. Nodes that are characteristic for snowfall in October for the period 1981 to 2011

The eight times that it did snow in October, nodes 20, 21 and 22 were responsible for the snow with a frequency of between 10 to 20% making these characteristic nodes causing snow in October.

Nodes 20 and 21 lie in the same area of the SOM adjacent to each other and consequently exhibit very similar synoptic patterns. These two nodes indicate the cold front moving over the south-western interior extending into a low south-east of the country.

Table 4.8: Same as Table 4.3, but for node 20, 21 and 22 which are dominant during the month of October

Nodes dominant in October		Number of snowfall events associated with each node: Total 8 events for October
Node 20 	Node 21 	Node 20: 2 events = 25% Node 21: 3 events = 38% (Node 20 + node 21) = 63%
Node 22 		Node 22: 3 events = 38%

The AOH of 1028 hPa at 36° S is ridging strongly behind the cold front while a deep pointed upper air trough/COL lies west of the surface cold front over the southern interior indicative of the baroclinicity of the system. In node 22, the upper air trough sharpens in response to the surface cold air advection as the surface AOH of 1030 hPa at 39° S moves further eastwards over the Eastern Cape.

4.3 Subjective versus objective classification

In the subjective classification, the most intense synoptic pattern had to be chosen for each case study period and used within the subjective classification. The problem with this type of subjective approach is that only one pattern can be chosen as representative of a three day period over which the snowfall occurred. As such, it does not take into account the variation of the pattern with time. However, it is essential because it allows for a starting point into the investigation aimed at identifying synoptic weather systems conducive to significant snowfall and acts as a first guess for the objective approach.

During the subjective analysis, most of the significant snow cases (Appendix A) were found to be COLs. However, in the objective analysis, some of the detail of the depth of these upper air systems is lost. In many instances, the sharp upper air trough could also be interpreted as an upper COL within SOMs. Care must be taken in the generalisation that occurs when using the SOM. The classifications produced similar results.

In the subjective classification, two characteristic different patterns appeared. Patterns 1 and 2 were dominant but they had two major differences between them in the sense that in pattern 1, the AOH dominates and in pattern 2 the IOH is prevalent. This also turned out to be the distinguishing factor between the two patterns.

In the objective analysis using SOMs, two dominant patterns emerged on each side of the SOM which were similar to pattern 1 and 2 of the subjective classification. On the left side of the SOM, the AOH was dominant with deeper upper troughs/COLs and stronger frontal boundaries. On the top right side of the SOM, the IOH was dominant with weaker COLs/upper pointed troughs and weaker frontal boundaries. The weaker frontal boundaries could be accounted for, taking into consideration the flow of warmer air over the Indian Ocean when compared with the colder air over the Atlantic Ocean leading to more intense boundaries.

Both classifications were able to separate the AOH and IOH pressure systems and pick up the upper COLs. By combining mean sea level pressure, 500 hPa geopotential heights and 850 hPa temperatures in a SOM, detailed patterns associated with significant snowfall appear. The right side of the SOM was dominant in June and the left side was dominant in July.

Chapter 5: Case studies

In this chapter, four case studies of significant snowfall across South Africa will be discussed. These cases were specifically chosen due to their intensity and the fact that they represent snowfall over different regions of South Africa. They are also representative of the different node patterns found in the objective synoptic classification of snow using SOMs as discussed within Chapter 4.2.

In each of the case studies, the purpose was to establish the characteristics of the pre determined variables (Chapter 2 and 3) when snowfall occurs and to identify critical values for operational weather forecasting in South Africa. For each case study, a short background description is provided. A synoptic overview of the case which focuses on the time periods and regions when and where snowfall occurred is obtained.

In each case study, similar aspects will be discussed in order to understand factors that contributed to the snowfall. In some cases, it was worthwhile to investigate why snowfall did not occur in order to understand conditions that are favourable for snowfall.

The large-scale synoptic circulation is emphasised. It provides the moisture and cold temperatures necessary to form snowfall and is the basis for forecasting precipitation. The vertical temperature distribution and moisture content of the atmosphere is described with the use of tephigrams and satellite imagery in order to discuss the favourable conditions for the formation of ice crystals. Key features pertaining to snow are identified within the tephigrams. This includes the freezing level (melting level), the passage of cold fronts and vertical wind shear in the presence of surface AOH/IOH, cold fronts and upper COLs. Partial thickness, surface temperature and surface RH is discussed as it accentuates how important these variables are in snowfall. Lastly, the SOM node synoptic classification of Chapter 4.2 is related to the synoptic circulation pattern of each case study. This is done by using the synoptic circulations at various time steps in order to show that the classification was representative of the true synoptic situation within each case study.

5.1 Case study 1: 25 and 26 July 2011

5.1.1 Introduction

On 23 July 2011 at 1200 UTC (Fig. 5.1 A) a weak cold front passed to the south of the country causing no air mass change over Cape Town and maintaining settled weather conditions due to the surface south-easterly wind flow. A surface trough was present over the western interior extending southwards into a surface low over the Western Cape interior.

By 24 July 2011 at 1200 UTC (Fig. 5.1 B) the surface AOH of 1036 hPa continued to ridge eastwards at 40° S with pronounced southerly to south-easterly winds to the south of the country causing significant horizontal cold air advection. Consequently, a surface cold front formed over the south-western part of the Northern Cape and western part of the Eastern Cape. This is typical of the start of the right hook described in Chapter 2.1.1.2 by Van Heerden and Hurry (1995). The consequence was the formation of an upper COL. This type of surface circulation was also found to be instrumental in the formation of a COL by Taljaard (1985b). The pointed upper air trough at 500 hPa that was situated over Cape Town at 1200 UTC deepened into a COL over the south-western part of the Northern Cape by 1800 UTC. The cold air advection cooled the vertical atmospheric column in the lowest 3000 m (1000 hPa to 700 hPa). When the ridging high is situated in a favourable position, thermal advection of cold air around the anticyclone will partly contribute to the intensification of the 500 hPa trough (Triegaardt, 1988; Triegaardt et al., 1989a). The surface low in the Beaufort West region was developing in association with the deepening pointed trough at 500 hPa. This caused snowfall overnight in the Karoo and the Eastern Cape and for the first time in 75 years in the town of Somerset-East in the western part of the Eastern Cape.

In the Eastern Cape, several towns, schools and businesses were snowed in on 25 July 2011. Train services on the main routes from Gauteng to the Eastern Cape and KZN had to be cancelled (Pretoria News, 2011a). The cold front continued to develop on 25 July 2011 at 1200 UTC (Fig. 5.1 C) with a pronounced surface frontal low over the Free State in association with the upper COL. The main road between Beaufort West and Richmond was closed as well as the alternative route via Victoria West until 1300 UTC on 25 July 2011. The N1 national road from Johannesburg to Cape Town was closed between Colesburg and Three Sisters. The N9 national route from Bloemfontein to Port Elizabeth also had to be closed between Colesburg and Middleburg (van Rooyen et al., 2011). It was reportedly the worst snowfall in 30 years in the region (Cape Times, 2011). Later in the day, the surface

AOH moved further eastwards south of the country with a substantial influx of colder, moist air over the south-eastern interior behind the cold front. The movement of the surface frontal low over the Free State was in union with the movement of the upper COL. Snow fell at Bedford, Barkly East, Tarkastad and Hogsback by the afternoon of 25 July 2011 (Marais and Spoormaker, 2011). Snow fell on the night of 25 July 2011 over the Eastern Cape, KZN, southern and eastern Free State, Lesotho and the Highveld of Mpumalanga. It snowed in Harrismith, Newcastle and Ermelo where up to 0.05 m of snow fell (van Rooyen et al., 2011). This was due to the eastwards progression of the upper COL and surface ridging of the AOH behind the cold front. Many roads were closed in the Eastern Cape, Free State and KZN due to the heavy snowfall that left many people stranded in their cars and homes (Pretoria News, 2011a).

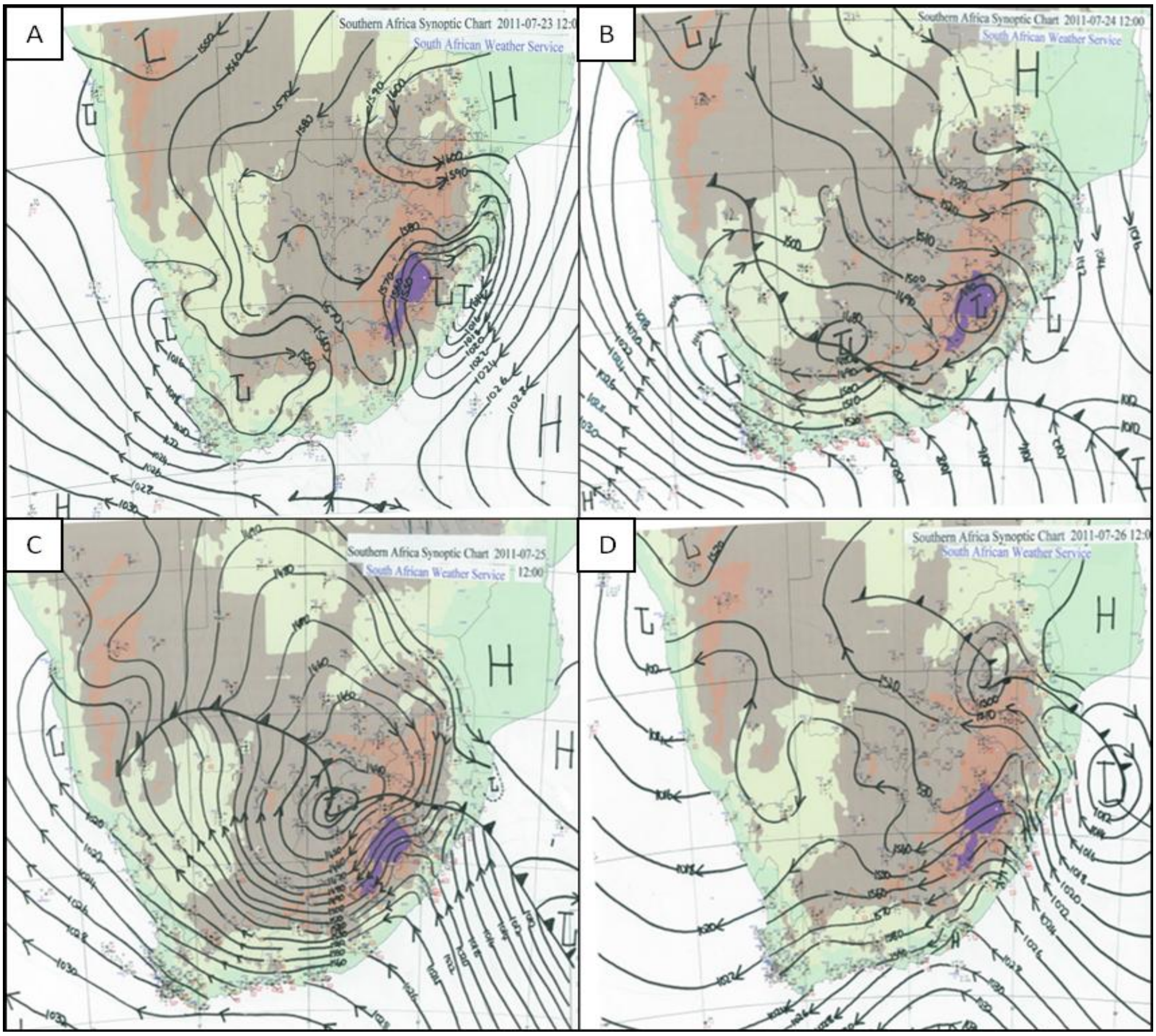


Figure 5.1: Surface synoptic analysis depicting mean sea level pressure (every 2 hPa) and 850 hPa geopotential height contours (every 10 m) for 23, 24, 25 and 26 July 2011 at 1200 UTC

On 26 July 2011 at 1200 UTC (Fig. 5.1 D), the upper COL and associated surface cold front was located east of the KZN coast, enhancing the influx of colder moist air to the south of the surface frontal low, increasing snowfall over KZN. It is important to note in this case that the strong influx of cold air was caused by the strong pressure gradient between the surface high and frontal low pressure east of the country. The effect of this strong pressure gradient on cold air advection was described in Chapter 3.2.4 (Lackmann, 2011).

The Day Natural Colours RGB (Fig. 5.2) reveal the extent of the snowfall visible, the day after on the 27 July 2011 at 0715 UTC. The deep cyan colour indicates snow on the ground with the more greyish colours representing low level water cloud (see Section 3.1.5). In many towns, the snow had already melted, but large extents of the southern, south-eastern and eastern high ground were still covered in snow (see Section 1.2, Fig 1.1).

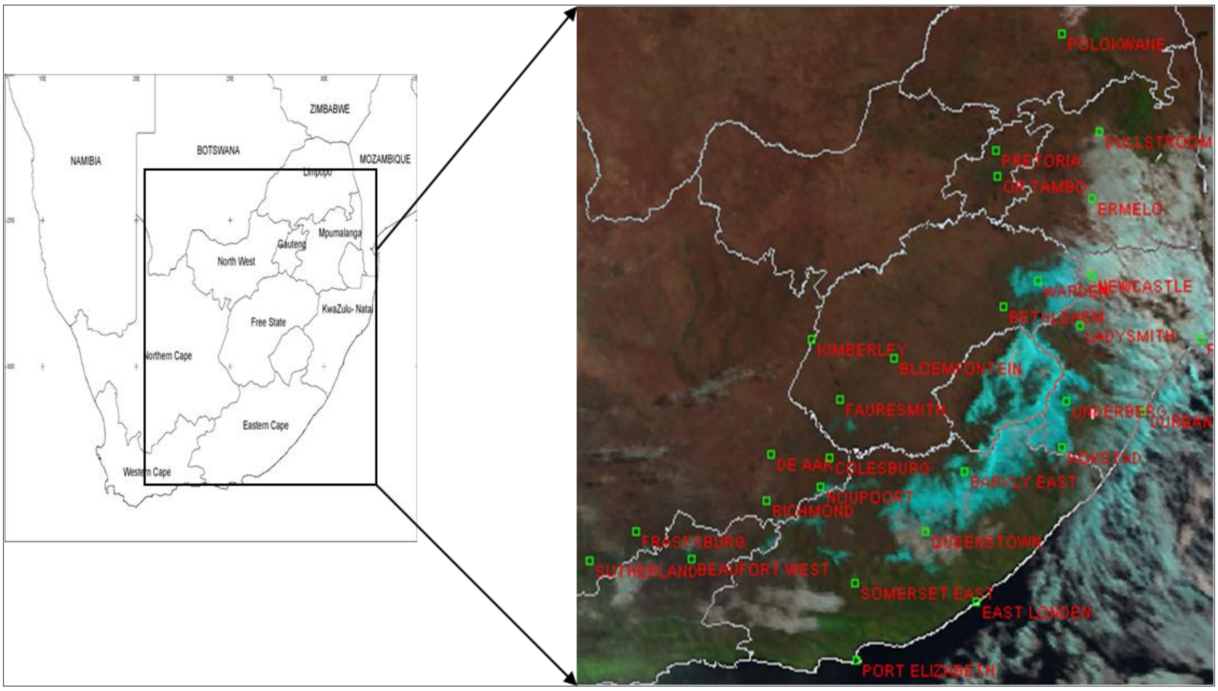


Figure 5.2: MSG satellite, Day Natural Colours RGB for 27 July 2011 at 0715 UTC; the deep cyan colour indicates snow on the ground in the area of interest © (2012) Eumetsat (location names are indicated in red)

5.1.2 Atmospheric conditions during snowfall

Significant snowfall occurred over the north eastern parts of the Western Cape, southern parts of the Northern Cape, Eastern Cape, KZN, eastern Free State and the south-eastern Mpumalanga Highveld. In the discussion of each time period, the importance of the large-scale synoptic circulation is emphasised as it provides the moisture and cold temperatures to form snowfall. It is important to provide examples of sound forecasting principles with regard to anticipating precipitation. The atmospheric ascents illustrate how the vertical temperature and moisture distribution of the atmosphere provide the necessary conditions which aid in the formation of snow. Partial thickness, surface temperature and RH is discussed as it accentuates how important these variables are in snowfall. Lastly, the SOM node synoptic classification of Chapter 4.2 is related to the case study synoptic circulation in order to show that the synoptic mapping was a good representation of the true synoptic situation in this case study.

As snowfall occurred from 25 July 2011 at 0000 UTC to 26 July 2011 at 0000 UTC, these time periods will be discussed separately by considering the three-dimensionality of the atmosphere over time.

5.1.2.1 25 July 2011 at 0000 UTC

The eastern part of the Western Cape and the western part of the Eastern Cape were affected by snow on 25 July 2011 at 0000 UTC when the COL was developing and will henceforth be discussed. Beaufort West surface synoptic weather data will be used to indicate the occurrence of snowfall in surface temperatures < 1 °C and in 100% surface RH. Snowfall at Queenstown in the Eastern Cape is an example of snowfall over the Eastern Cape region and demonstrates snowfall which was heavier and longer lasting in the presence of a COL. It indicates how the tephigram of Port Elizabeth which was representative of the vertical distribution of temperature and moisture over Queenstown at the time; can be used in conjunction with surface synoptic data to explain the occurrence of snowfall. Satellite imagery is used to indicate cloud top temperatures favourable for the growth of ice crystals over Queenstown and Beaufort West. It also demonstrates how a tephigram can be used in conjunction with satellite imagery to diagnose atmospheric conditions conducive to snowfall. At Beaufort West similar cloud top temperatures were observed compared to Queenstown (-10 °C and -20 °C). On the other hand, the boundary layer conditions at Queenstown were much colder with lower surface RH resulting in heavier snow. At Beaufort West it will be shown that due to the favourable atmospheric factors, snowfall could occur for a short period in the presence of a pointed upper air trough.

a. Synoptic circulation

In the first town of interest, Beaufort West, the snowfall started overnight on 24 July and continued into the early morning hours of 25 July 2011. On the 25 July, at 0000 UTC, a deep pointed upper air trough was starting to intensify into a COL over the Western Cape (Fig. 5.3 A). At the surface the AOH was positioned at 40° S and 15° E and was starting to ridge along the southern coastal belt of South Africa (Fig. 5.3 A). This is typical of the right hook (Van Heerden and Hurry, 1995). The 850 hPa south-easterly flow around the eastern periphery of the AOH south of the country served three purposes. It was instrumental in producing enhanced low level cold air advection over the southern interior of South Africa. This resulted in temperatures below 6 °C especially in the Beaufort West and Queenstown regions (Fig. 5.3 B). It resulted in the intensification of the surface temperature gradient and the consequent strengthening of the surface cold front over the south-western interior. This cold air was partially responsible for the formation of the COL by decreasing the geopotential heights in the 850-500 hPa layer (see Section 3.2.4.1 which indicates the effect cold air has on decreasing geopotential thickness).

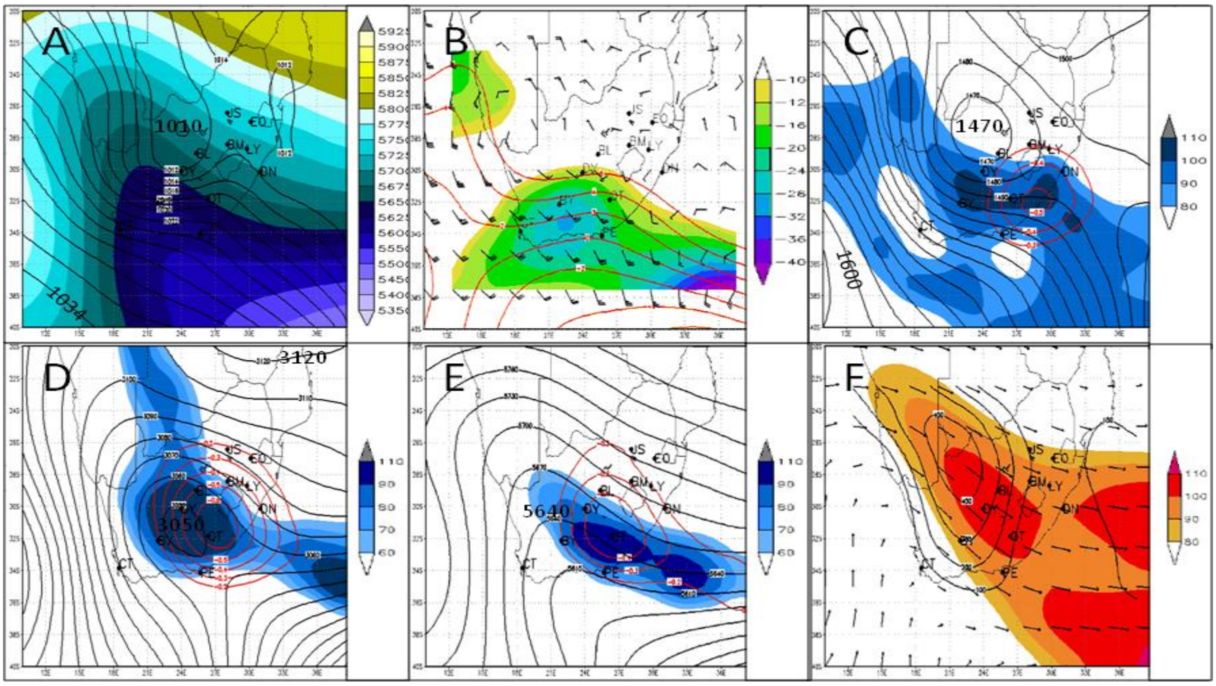


Figure 5.3: 25 July 2011 at 0000 UTC A): mean sea level pressure in hPa solid black, 500 hPa geopotential heights shaded in metres; B): 850 hPa temperature < 6 °C in red, 850 hPa cold air temperature advection*10e^{6} in °C s^{-1} shaded, 850 hPa wind barbs in knots; C): 850 hPa relative humidity shaded, 850 hPa negative omega in Pa s^{-1} red, 850 hPa geopotential heights in metres solid black; D): 700 hPa relative humidity shaded, 700 hPa negative omega in Pa s^{-1} red, 700 hPa geopotential heights in metres solid black; E): 500 hPa relative humidity shaded, 500 hPa negative omega in Pa s^{-1} red, 500 hPa geopotential heights in metres solid black; F): 300 hPa jet stream > 80 knots shaded, 300 hPa wind divergence solid black (s^{-1})

The 850 hPa south-easterly flow was also responsible for the advection of low level moisture into South Africa with RH values in excess of 80% over this region (Fig. 5.3 C). The 850 hPa frontal low over the central interior (Fig. 5.3 C), that developed in association with the upper COL (Fig. 5.3 D), was responsible for surface convergence over the escarpment areas of the Eastern Cape and the south-eastern Northern Cape. This contributed to the resulting vertical motion over those areas (Fig. 5.3 C) (see Section 3.2.4.3), which explains the effect surface convergence has on vertical motion).

Surface convergence occurred where the warmer north to north-easterly flow around the eastern edge of the 850 hPa frontal low over the central interior met with the relatively colder south-easterly flow around the eastern periphery of the AOH (Fig. 5.3 C). The south-easterly flow from the AOH was perpendicular to the escarpment (see Section 1.2, Fig. 1.1) in this area, resulting in a focused region of thermal advection, convergence and additional orographic uplift. See Section 2.1.1.2 where Van Heerden and Hurry (1995) indicated that, in the right hook, the south-eastern and eastern escarpment becomes an enhanced, focused region of thermal advection, convergence and orographic lift which promotes heavy snowfall in that area. Kocin and Uccellini (2004) indicated similar ideas.

At 700 hPa, a closed low was situated over the south-eastern interior of the Northern Cape with RH values > 80% over parts of the Western Cape, the Eastern Cape and the southern part of the Northern Cape (Fig. 5.3 D). On the eastern flank of this low, maximum values of vertical motion occurred (Fig. 5.3 D). At 500 hPa a band of mid-level moisture with RH values > 60% was situated east of the pointed trough (Fig. 5.3 E). The importance of this mid-level moisture around -15 °C was that it was responsible for a favourable atmospheric environment in which ice crystals could grow through deposition (see Section 1.4.2). East of the pointed trough, negative values (uplift) of vertical motion occurred (Fig. 5.3 E). A jet stream of over 100 knots with associated upper wind divergence was present over the central interior (Fig. 5.3 F) (see Section 2.3 which indicates the favoured areas for wind divergence). Consequently the atmospheric conditions over parts of the Western and Eastern Cape were favourable for precipitation.

b. Surface observations

The surface temperature dropped gradually during the evening of 24 July 2011 between 1640 UTC and 2200 UTC at Beaufort West (Fig. 5.4). The cold front over Beaufort West was intensifying with horizontal cold air advection to the rear of the cold front assisting in the gradual decrease of surface temperature (Fig. 5.1 B). At around 2300 UTC on 24 July, the surface temperature decreased rapidly to less than 1 °C after which it began to snow. Fig. 5.4 indicates that intermittent rain was recorded during the evening of 24 July, which contributed to the further cooling of surface temperature. At the same time, the surface RH was at its lowest between 94 and 96%. The effect of RH on the melting temperature of snowflakes is explained in Chapter 3.2.4.4. This causes snowflakes to reach the ground as indicated by the stars in Fig. 5.4. At the time of the snowfall, the melting temperature was 0.3 °C.

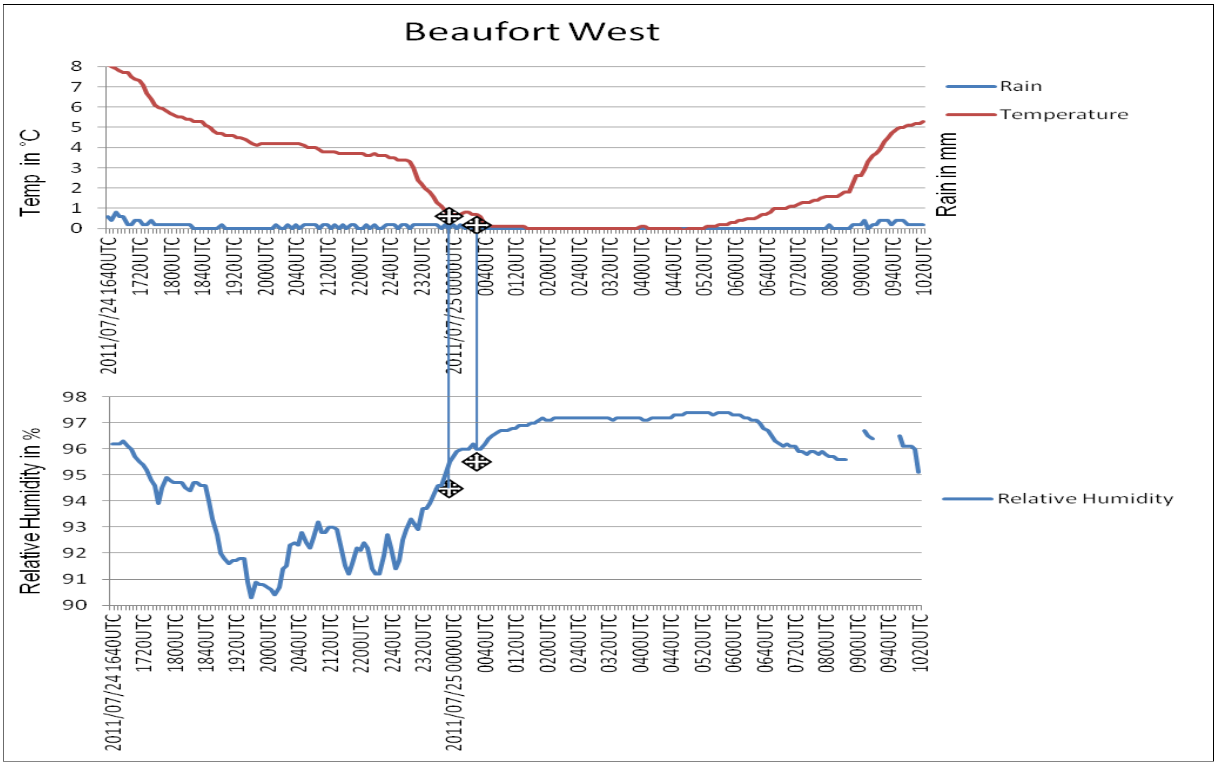


Figure 5.4: Temperature (°C), rain (mm) and relative humidity (%) at South African Weather Service, Beaufort West weather station on 24 and 25 July 2011; the stars in the figure indicate confirmed observations of snowfall; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

At Queenstown (Fig. 5.5), the snow was heavier than Beaufort West and lasted most of the day. As a consequence, it is discussed.

Surface temperatures were lower at Queenstown (close to zero) than Beaufort West. Throughout the snowfall, the surface RH was in the low 90s. The snow started to fall at around 0100 UTC on 25 July 2011 (Fig. 5.5). The temperatures remained close to zero until 1500 UTC while the surface RH fluctuated around the 91% mark. Due to the favourable surface conditions (temperature and RH), the availability of ice crystals in the cloud and a cold vertical distribution of temperature devoid of warmer layers snowfall occurred. Wetzel and Martin (2001) suggested that temperatures conducive to ice crystal growth can be best determined by the use atmospheric soundings and satellite derived cloud top temperatures (also see Section 3.2.5).

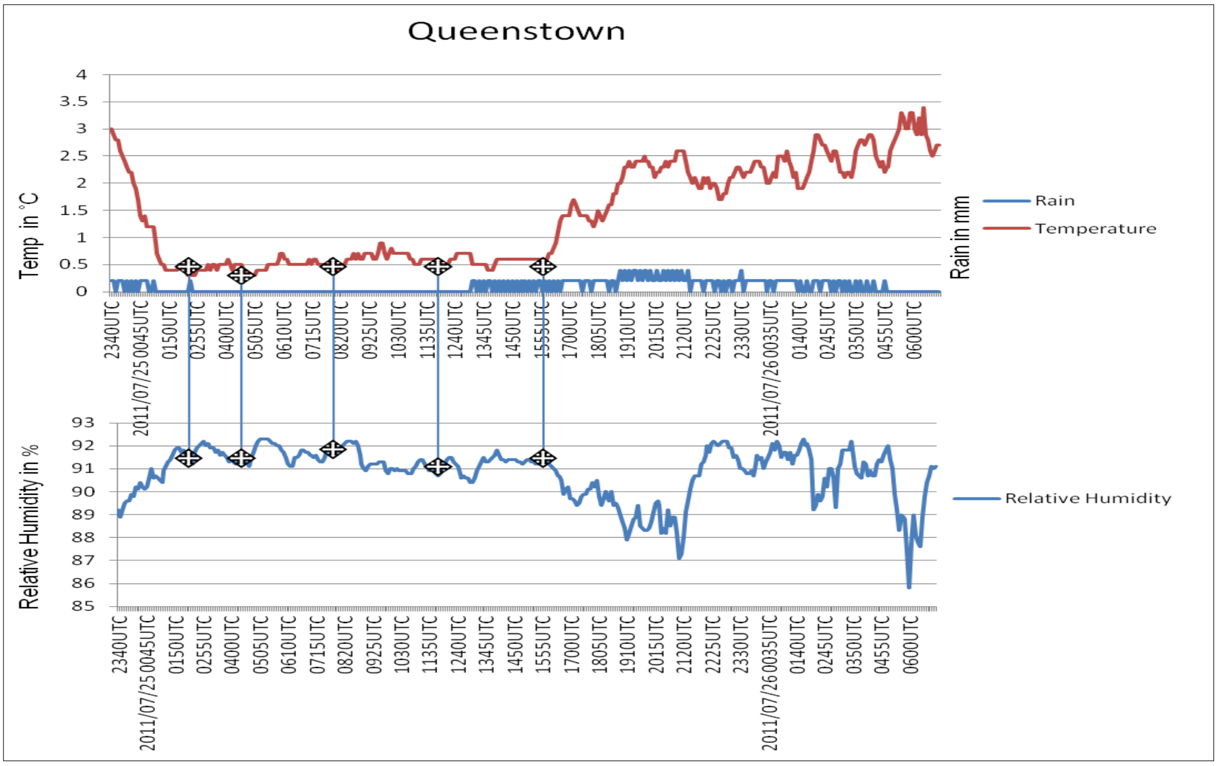


Figure 5.5: Same as Figure 5.4, but for South African Weather Service Queenstown weather station on 25 and 26 July 2011; the stars in the figure indicate confirmed observations of snowfall; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

c. Satellite imagery and upper air observations

The Airmass RGB in Fig. 5.6 A indicates the cloud band associated with the developing COL over the Northern Cape. The presence of moisture (white cloud) can be seen on Fig. 5.6 A on 25 July 2011 at 0000 UTC to the east, south and west of the upper COL, indicative of the cyclonic motion around the upper low. At Beaufort West (Fig. 5.6 B), during the snowfall, cloud tops extended from -10 °C down to -30 °C pinpointing clouds containing ice crystals. Similar cloud top temperatures could be seen at Queenstown around the time when snowfall started (Fig. 5.6 B).

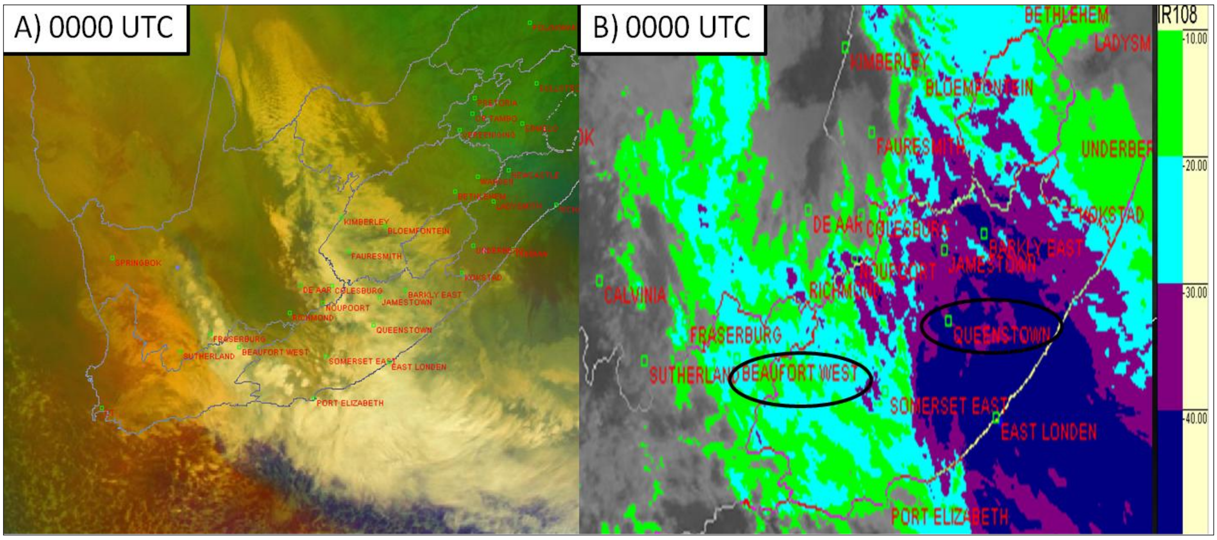


Figure 5.6: MSG satellite Airmass RGB (A): on 25 July 2011 at 0000 UTC; (B): false colour IR 10.8 image on 25 July 2011 at 0000 UTC indicating cloud top temperatures at Beaufort West and Queenstown © (2012) Eumetsat

Fig. 5.7 depicts the passage of the cold front between 24 July at 0000 UTC (green lines and barbs) and 25 July at 0000 UTC (blue lines and barbs) at Port Elizabeth. (Compare to Fig. 5.1 B depicting the passing of the front through Port Elizabeth at 1200 UTC on the 24th) This ascent was chosen to discuss here as of all available ascents it is most representative of the atmosphere during the snowfall event. The temperatures cooled significantly below 500 hPa with the cold frontal passage as indicated by the light blue shading (Fig. 5.7). The vertical distribution of temperature cooled between the green ascent (height of freezing or melting level 3658 m a.m.s.l) and blue ascent (height of freezing level 1524 m a.m.s.l) below the 450 hPa pressure level (shaded region). This depth is greater than three kilometres, which was defined by Taljaard (1972; 1994c) to be indicative of the passage of a cold front on an upper air sounding (see Section 2.1.2.3). The freezing level (melting level) descended to the height of the 850 hPa (1500 m a.m.s.l) atmospheric pressure level on 25 July at 0000 UTC. The vertical distribution of temperature throughout the atmosphere shows an absence of warm layers (T > 0 °C), resulting in very favourable conditions for snow formation. The deep layer of cold air advection is evident in Fig. 5.7 not only by the significant decrease in temperatures but also in the south-easterly winds present up to 700 hPa (circled in Fig. 5.7). These were responsible for the source of the horizontal cold air and moisture advection. Above this level, the winds were north-westerly ahead of the approaching COL and the windshear was indicative of the baroclinicity of the atmosphere over the Eastern Cape.

On 25 July 2011 at 0000 UTC (Fig. 5.7 blue lines), the vertical distribution of moisture was saturated throughout the atmosphere containing a wide variety of ice crystals. The atmosphere was moist within the region of -10 °C and -20 °C just below 500 hPa indicative of the presence of dendritic ice crystals. These optimally grow through deposition, which is maximised at the temperature of -15 °C (see Section 1.4.2). The vertical distribution of moisture was also saturated between 0 °C to -10 °C assisting in the further growth of ice crystals through aggregation and riming as they fell through the layer of supercooled droplets to form snowflakes (see Section 1.4.2).

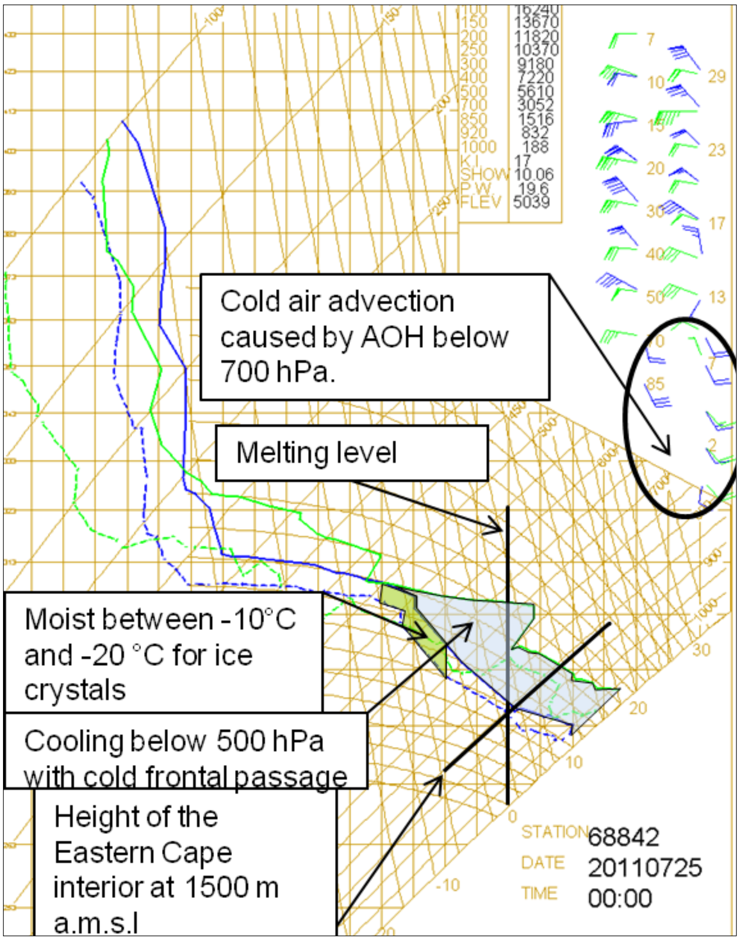


Figure 5.7: South African Weather Service tephigram for Port Elizabeth for 24 July 2011 at 0000 UTC (green lines and barbs) and 25 July 2011 at 0000 UTC (blue lines and barbs) (the solid lines are temperatures and the dotted lines are dew point temperatures)

d. Partial atmospheric thickness

The atmospheric thickness will be dealt with in the following manner (also see Section 3.2.4). The thickness of the 850-500 hPa layer will be dealt with first and consequently the partial thickness of two layers within this layer namely the 850-700 hPa and 700-500 hPa partial thickness will be discussed. The importance of partial thickness in the determination of precipitation type was discussed in Chapter 1.4.2.3.

On 25 July 2011 at 0000 UTC, when the snowfall started in the Beaufort West region the 850-500 hPa thickness dropped to below 4150 m (Fig. 5.8 A), the 850-700 hPa partial thickness to below 1560 m (Fig. 5.8 B) and the 700-500 hPa partial thickness to below 2580 m (Fig. 5.9 C). At this time there was considerable low level cold air temperature advection (see Section 3.2.4.2). The noteworthy factor for snowfall occurring here was the absence of warmer layers throughout the atmosphere and the fact that the lowest layer (850-700 hPa) was cold enough. This enabled snowflakes to reach the ground in temperatures above freezing. When warmer layers exist, it can cause the snowflakes to melt on their way down to the ground, especially when temperature inversions are present. The atmospheric thickness at Queenstown at 1200 UTC, when snowfall was still occurring, will be discussed at 1200 UTC (see Section 5.1.2.2).

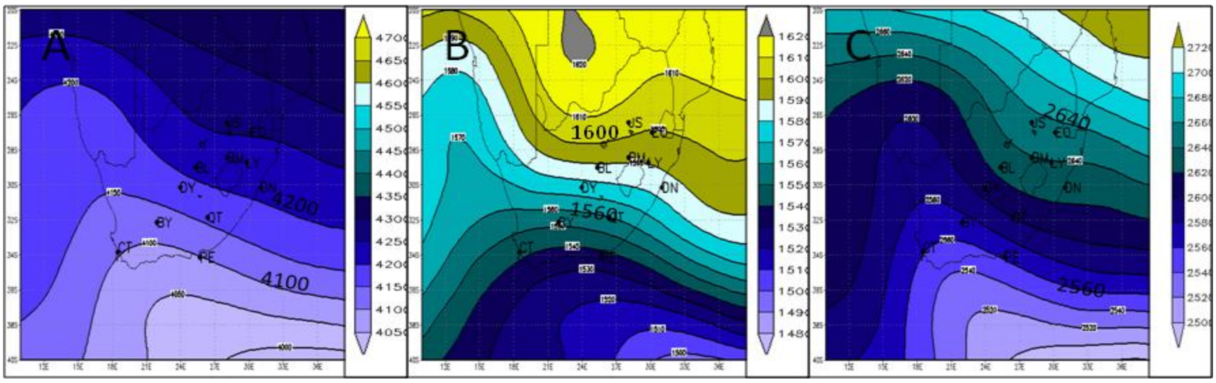


Figure 5.8: A): 850-500 hPa atmospheric thickness in metre; B): 850-700 hPa partial atmospheric thickness in metre; and C): 700-500 hPa partial atmospheric thickness in metre for 25 July 2011 at 0000 UTC

5.1.2.2 25 July 2011 at 1200 UTC

During this time period, the snowfall started to progress further eastwards into the rest of the Eastern Cape while starting to affect the southern part of the Northern Cape. The large-scale synoptic circulation is emphasised as the upper air trough had now developed into a COL which resulted in heavy snow over the Eastern Cape. The town of De Aar is referred to in this discussion to elaborate on why snowfall did not occur despite very low atmospheric thickness in the town, but occurred in the surrounding area. At De Aar, the tephigram is used to demonstrate how the lack of ice crystals in the vicinity of -15 °C together with surface temperatures above 2 °C in the presence of high surface RH can limit the fall of snow even when partial thickness are very low. Satellite imagery is discussed to outline the use of RGBs in the identification of cloud microphysical properties and location of synoptic weather systems such as COLs. The tephigram at Durban is representative of the KZN interior and is used to explain why snow did not occur at 1200 UTC despite the fact that the air in the atmosphere was saturated with ice crystals available for ice crystal growth through deposition and aggregation. The warm surface conditions causing snow to melt are highlighted.

a. Synoptic circulation

On 25 July 2011 at 1200 UTC, the pointed upper trough had developed into a COL at 500 hPa (5600 m) and was situated over the central interior (Fig. 5.9 A and E). The surface AOH strengthened and moved eastwards (Fig. 5.9 A). Cold air advection continued in the south-east (Fig. 5.9 B), contributing to the further deepening of the COL (Fig. 5.9 A, D and E) (see Section 3.2.4.2 for the effect of cold air advection on lowering geopotential heights). The surface frontal low at 850 hPa moved slightly northwards but with the same depth as at 0000 UTC. Warmer air from the north-east converged with the colder air from the Indian Ocean over the interior of the Eastern Cape causing vertical motion in a similar area (Fig. 5.9 C) (see Section 3.2.4 on the effect surface convergence has on vertical motion).

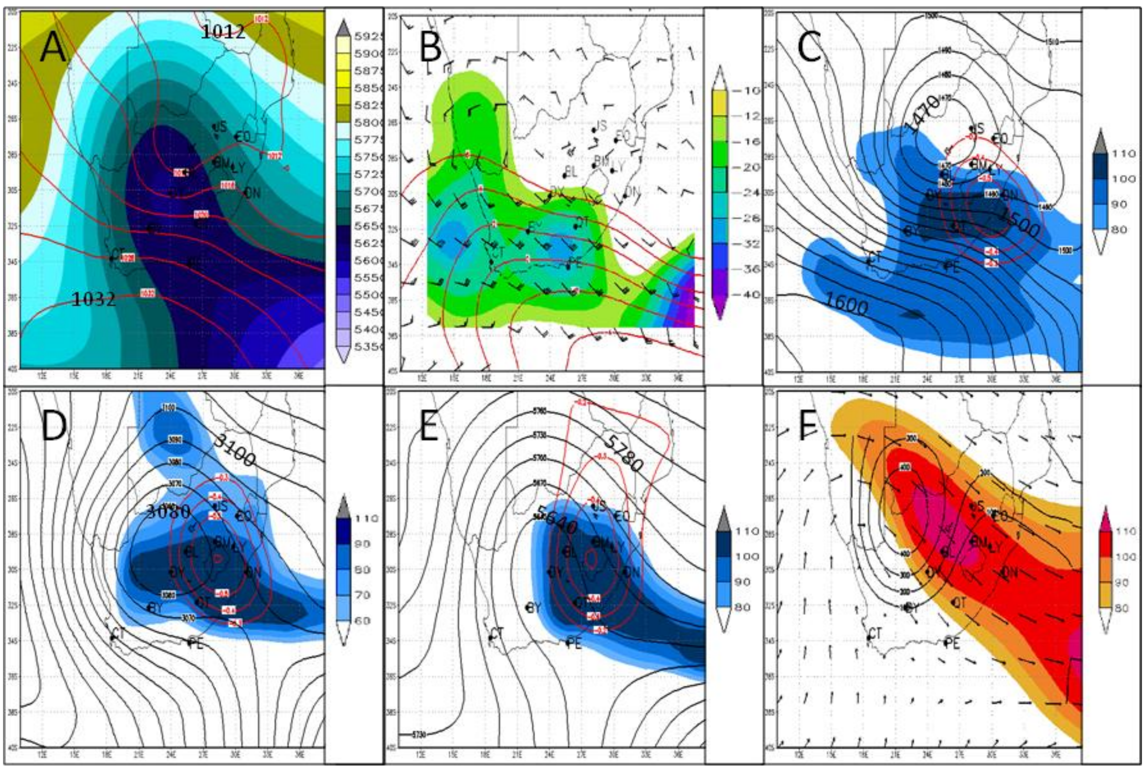


Figure 5.9: Same as Figure 5.3, but mean sea level pressure in red: A) for 25 July at 1200 UTC

The sustained low level onshore south-easterly flow below 700 hPa over the warm Indian Ocean was causing 850-700 hPa RH values > 80% (Fig. 5.9 C and D). The 700 hPa low moved slightly north-eastwards to the Free State with RH values > 90% and upward motion to the east (Fig. 5.9 D). The 500 hPa baroclinic low was located south-west of the 700 hPa low indicating a developing COL. RH values were > 90% over the south-eastern interior at 500 hPa. (Fig. 5.9 E).The upper jet with wind speeds in excess of 100 knots had moved slightly north-eastwards from 0000 UTC with upper air wind divergence over the area where snowfall was occurring (Fig. 5.9 F).

b. Surface and upper air observations

On 24 July 2011 between 1200 and 1300 UTC, the surface cold front passed over De Aar (Fig. 5.10) when the surface winds changed rapidly from a warm dry north-westerly ahead of the cold front to a colder, moister southerly to south-easterly wind behind the cold front.

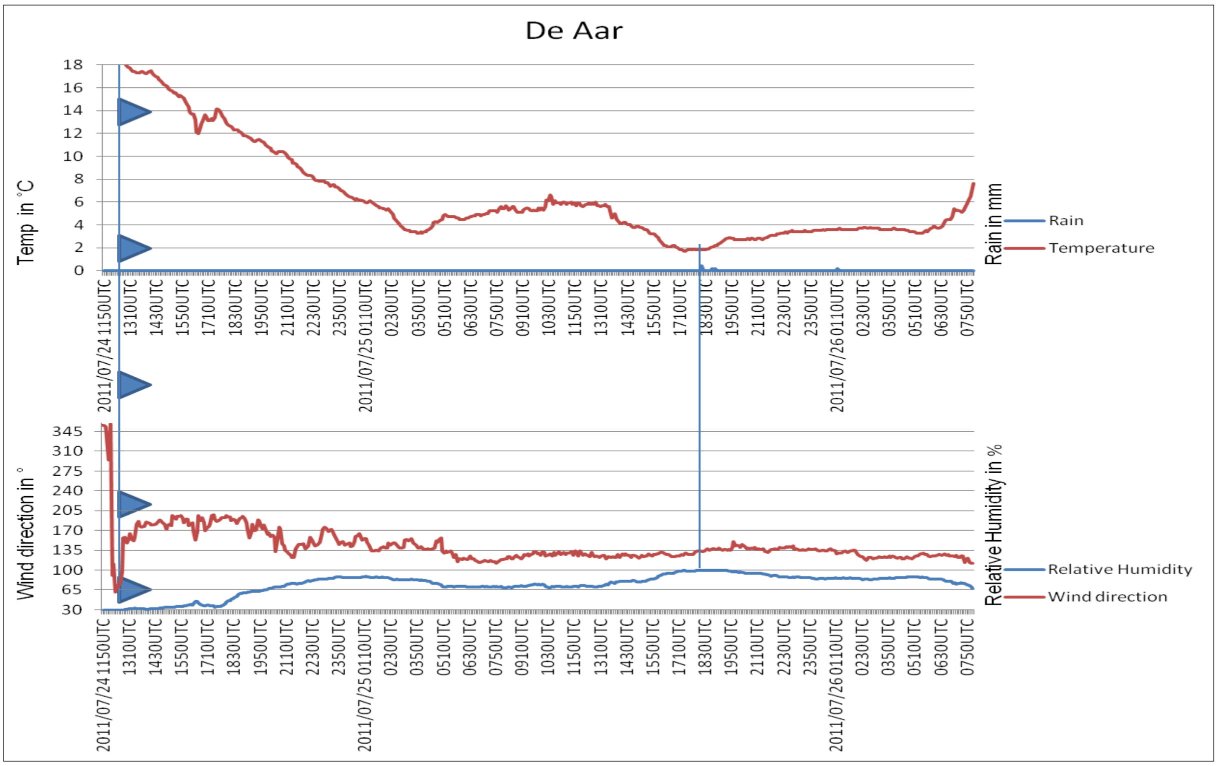


Figure 5.10: Temperature (°C), rain (mm), relative humidity (%) and wind direction (°) at South African Weather Service De Aar weather station for 24-26 July 2011; the triangles indicate the time of the passage of the surface cold front and the time when snowfall occurred in the vicinity of the station (vertical blue line) (the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated)

The change in wind direction from south-westerly to south-easterly occurred rapidly due to the significant pressure rise caused by the ridging of the surface high pressure system behind the cold front. This is important to note as the winds behind a cold front will usually be south-westerly in the absence of a significant pressure rise from a surface ridging AOH (see Section 2.1.2 which indicates the changes in surface variables with the passage of a cold front). At the same time, the surface RH started to increase due to the onshore southerly influx of moisture caused by the ridging AOH. At 1800 UTC (Fig. 5.10), the surface temperature at De Aar had dipped to 2 °C and the RH was close to saturation due to the continued influx of cold, moist air in the 850-700 hPa layer indicated in Fig. 5.9 A and B. Light traces of precipitation were recorded at De Aar (Fig. 5.10), where it snowed lightly in the vicinity but not in the town itself (vertical blue line).

On 25 July 2011 at 1200 UTC (Fig. 5.11), the height of the freezing level (melting level) at De Aar in the south-eastern part of the Northern Cape was 513 m a.g.l reflecting that the cold front had already passed.

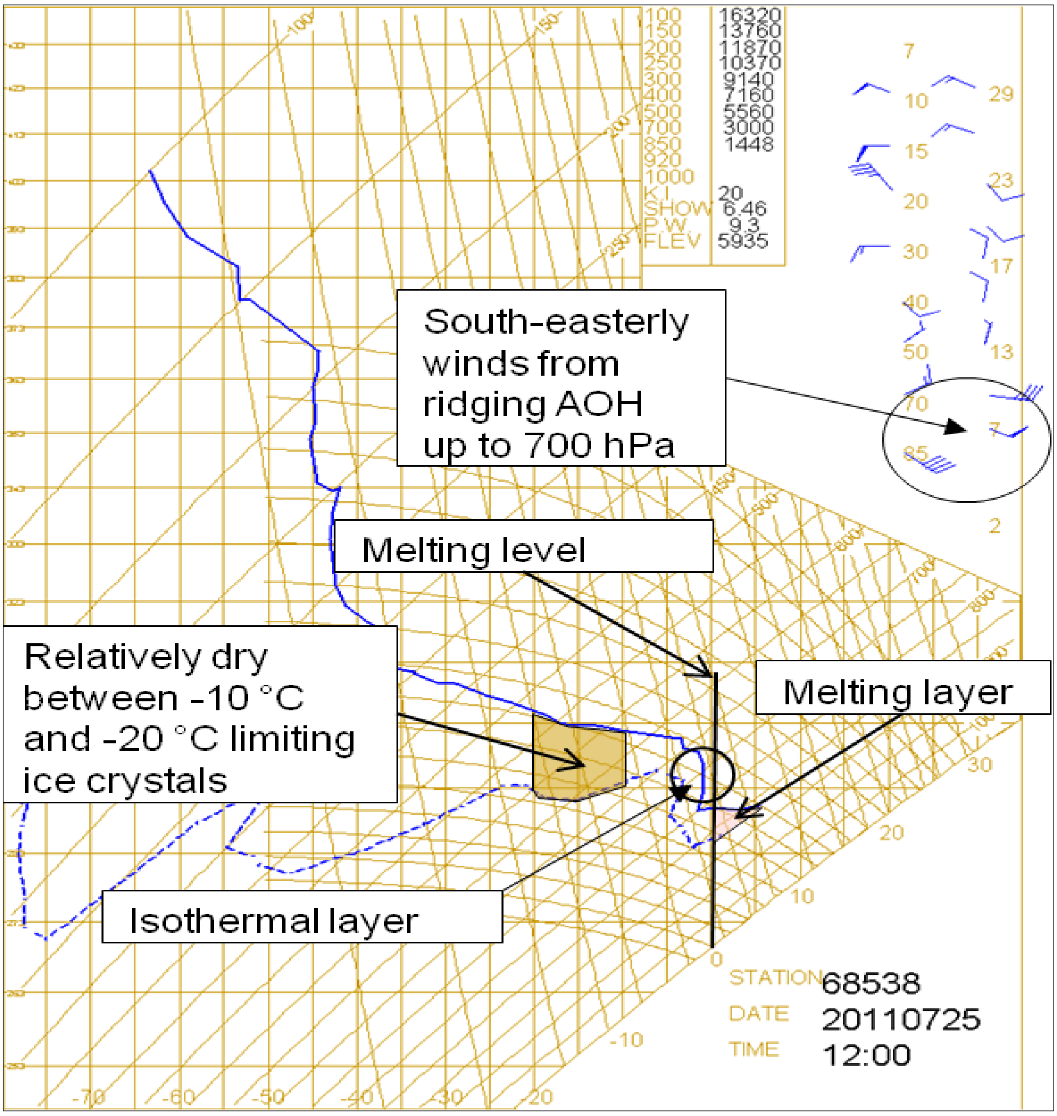


Figure 5.11: South African Weather Service tephigram for De Aar for 25 July 2011 at 1200 UTC (blue lines and barbs) (the solid lines are temperatures and the dotted lines dew point temperatures)

The height of the freezing level was too high above ground level for snowfall to reach the ground in the town (see Section 3.2.4). With a surface temperature close to 5.9 °C and surface RH of 72% at 1200 UTC on 25 July 2011, the melting temperature was close to 2 °C which meant that the temperature below 513 m a.g.l was a limiting factor for snow at this time. Another factor was the unavailability of ice crystals in the region of -15 °C as indicated by the relatively dry vertical distribution of moisture around 600 hPa in Fig. 5.11 (brown shading). The low level cold, moist south-easterly flow from the ridging AOH up to 1453 m a.g.l (700 hPa) was responsible (Fig. 5.11 encircled) for the moisture in the lower levels. The isothermal layer was indicative of the melting of the flakes close to 0 °C.

The cold front passed through Durban between 25 July 2011 at 0000 UTC (red lines and barbs) and 1200 UTC (blue lines and barbs) as indicated in Fig. 5.12. The entire vertical distribution of temperature cooled by more than 3 °C and the freezing level (melting level) height dropped from over 3300 m a.m.s.l to 2680 m a.m.s.l. The distance between the melting level and the ground was still too large for snowfall to occur over the lower elevated parts of KZN (1180 m a.m.s.l, see Section 3.2.4.4) with snowfall confined to the higher elevated Drakensberg Mountains (see topographical map in Chapter 1.2, Fig. 1.1) Colder moist air was being horizontally advected from the southerly to south-easterly flow of the ridging AOH up to a height of 3000 m a.m.s.l or 700 hPa (encircled area in Fig. 5.12). Above 700 hPa, the wind flow was north-westerly indicating the approaching COL in the 700-500 hPa layer (encircled area in Fig. 5.12). The atmospheric conditions around 500 hPa were conducive for the growth of ice crystals through deposition as indicated by the saturated air in the blue atmospheric ascent in the vicinity of -10 to -20 °C. The air in the atmosphere was also saturated from 500 hPa all the way down to the surface so that falling snowflakes could further grow by aggregation of supercooled water droplets between 0 °C and -10 °C. However, surface temperatures over the interior of KZN (850 hPa) were > 5 °C with surface RH close to 100% which was the limiting factor for snow to reach the ground at this time (see Section 3.2.4).

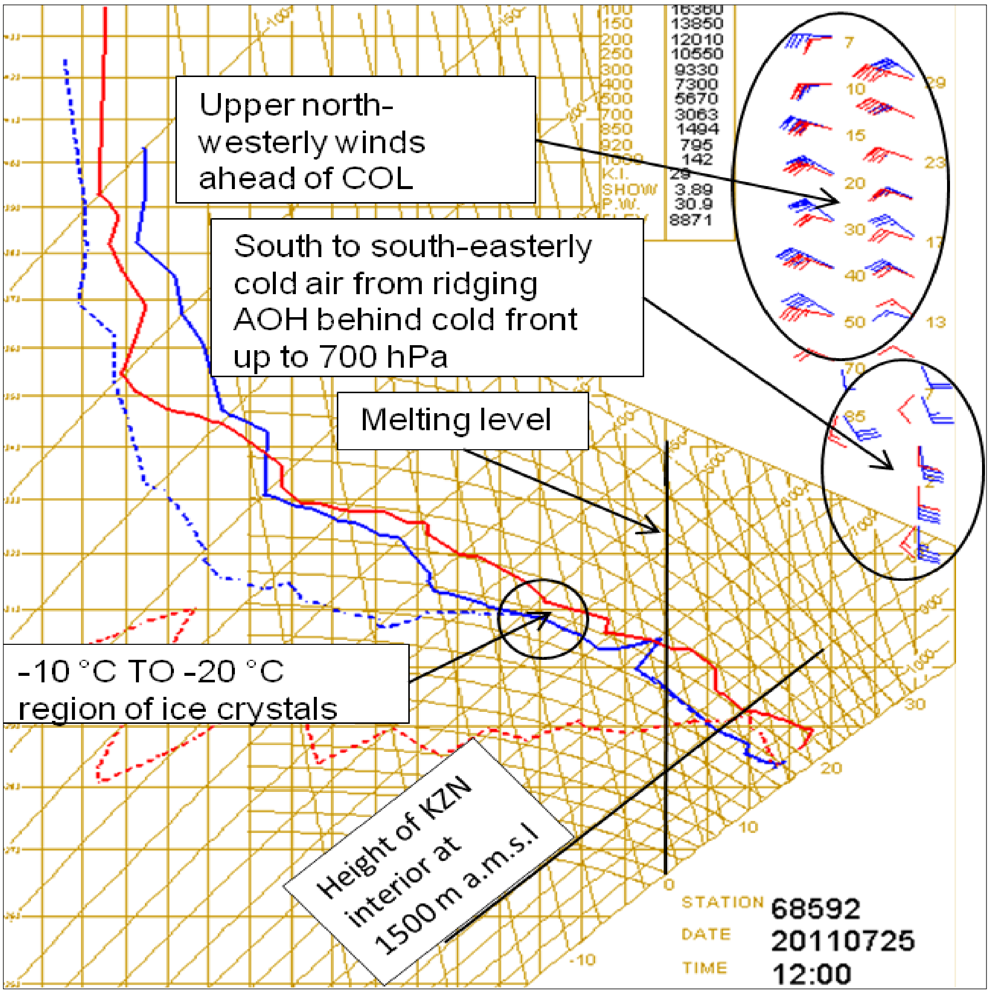


Figure 5.12: South African Weather Service tephigram for Durban on 25 July 2011 at 1200 UTC (blue lines and barbs) and 25 July 2011 at 0000 UTC (red lines and barbs) (the solid lines are temperatures and the dotted lines dew point temperatures)

c. Partial atmospheric thickness

At this particular time, snowfall was occurring over Queenstown. The 850-500 hPa atmospheric thickness fell below 4150 m over the Queenstown and De Aar region with atmospheric thickness as low as 4100 m over the southern interior of the Western and Eastern Cape (Fig. 5.13 A). The partial thickness between 850-700 hPa remained below 1560 m over the Queenstown region and 1570 m over the De Aar region (Fig. 5.13 B). This slight difference could also have contributed to snow not occurring at De Aar. In the 700-500 hPa partial thickness layer, values below 2580 m occurred over both towns (Fig. 5.13 C). Although thickness were very low at De Aar, snow did not occur there as the surface conditions were not conducive to snowfall. It is important to consider the entire vertical distribution of temperature and moisture when forecasting snow but especially the 850-700 hPa layer which is critical.

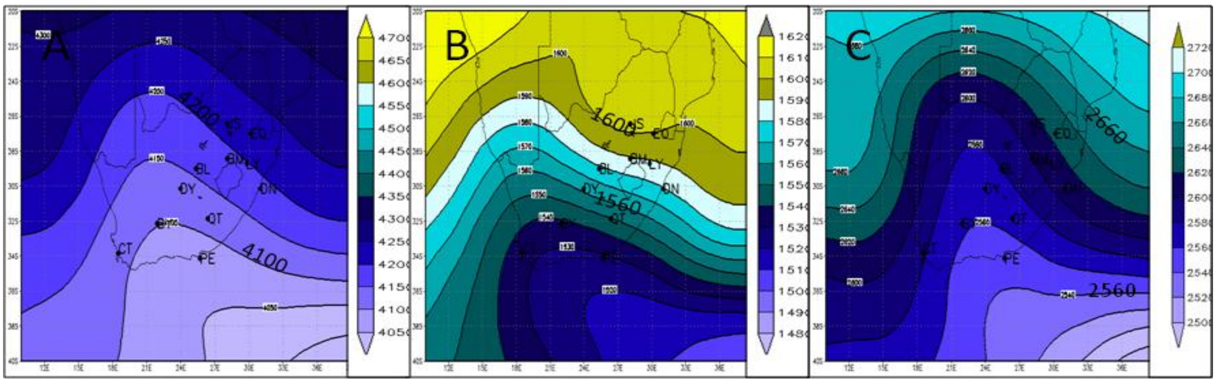


Figure 5.13: Same as Figure 5.8, but for 25 July 2011 at 1200 UTC

During the evening of 25 July 2011, the snowfall spread into the southern and eastern Free State as well as southern KZN.

d. Satellite imagery

The three RGBs that were most useful in the analysis of the snow were the Airmass RGB, Day Natural Colours RGB and the Day Microphysical RGB. The Airmass RGB indicates the cold air mass (bluish tinge) with low tropopause heights at the centre of the cold cored COL marked by an L in Fig. 5.14 A. The large amounts of dry descending stratospheric air are indicated in orange which represent areas of high potential vorticity which are associated with the southern extremities of the upper level jet stream (Fig. 5.14 A). The Day Natural Colours RGB (Fig. 5.14 B) shows the true colour image of the COL over the central interior with most of the cloud development indicated on the eastern and southern flank where cold, thick large ice clouds are denoted by the deep cyan colour (blue-green colour due to the dominance of channel 2 and 3).The whiter clouds are water cloud.

The false colour IR 10.8 channel (Fig. 5.14 C) indicates that the cloud top temperatures of these cold, thick ice clouds were between -10 °C and -40 °C. This is indicative of large amounts of ice crystals. When weather forecasters do not have aerological diagrams to their disposal as previously discussed, they can accurately obtain similar information by using this type of imagery (Fig. 5.14). This ice cloud is further confirmed by the Day Microphysical RGB (Fig. 5.14 D) which indicates cloud microphysical processes with cold Nimbostratus clouds with large ice particles indicated by the red colours of the deep precipitating cloud. The clouds on the western flanks of the COL, especially over the Northern Cape in the greenish, yellowish to light pink colour show layered clouds with small to large supercooled drops.

From the IR10.8 false colour image (Fig. 5.14 C) it can be seen that the temperatures of these cloud tops over the Northern Cape are between 0 °C and -10 °C. However, in this area there are also colder cloud tops between -10 °C and -30 °C (dark pink) indicating mixed phase clouds with snow in the air.

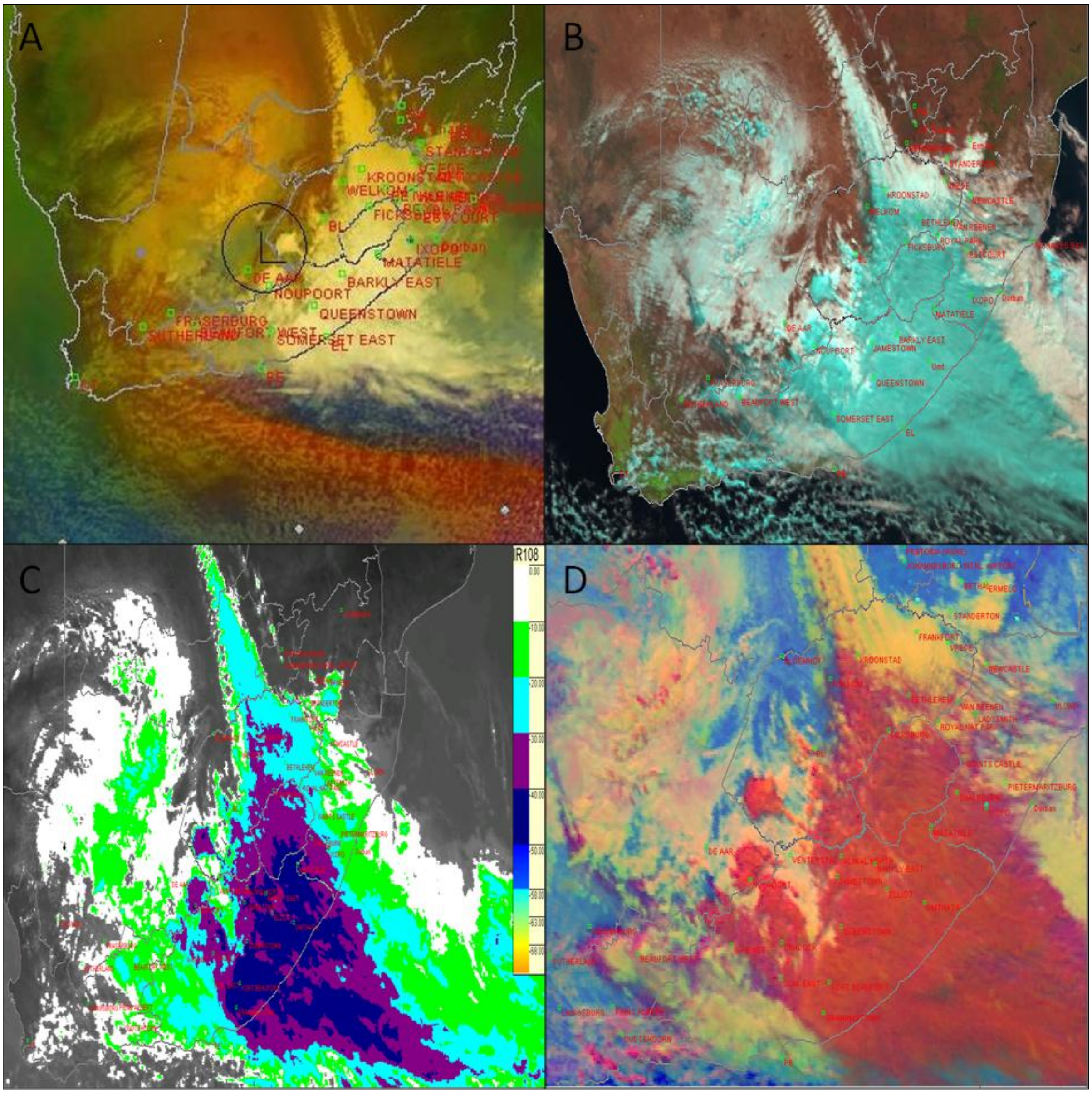


Figure 5.14: MSG satellite: A): Airmass RGB; B): Day Natural Colours RGB; C): false colour IR10.8; and D): Day Microphysical RGB on 25 July 2011 at 1200 UTC © (2012) Eumetsat

5.1.2.3 26 July 2011 at 0000 UTC

This time period will be discussed as the COL moved further eastwards with the intensification of the surface frontal low east of KZN. This frontal low played an important role in causing a renewed surge of moisture and cold air temperature advection due to the increased horizontal pressure gradient. The synoptic factors important in the occurrence of snowfall will be discussed. Snowfall in KZN is described by referring to the towns of Kokstad and Newcastle. The Durban tephigram will be referred to in order to explain the cooling that occurred throughout the atmosphere with the passage of the cold front leading to a drop in the freezing level height and causing upper level wind shear due to the approaching COL. The town of Kokstad will be shown to indicate how surface temperature can fall during the course of the morning due to the passage of a cold front when temperatures normally rise. Snowfall occurred most of the day with surface temperatures close to zero in the presence of high surface RH (saturated air). Newcastle indicates how snowfall can still occur when surface temperatures rise to 2 °C in the presence of high surface RH. This station also highlights the importance of local topographical conditions, especially with regard to where weather instrumentation is located as it might snow in surrounding higher elevated populated areas. Lastly, Bethlehem shows that snow can fall at surface temperatures of 1.5 °C with surface RH of 93%.

a. Synoptic circulation

The Free State, KZN and Mpumalanga Highveld regions were affected by snowfall during this time. The COL had slightly weakened to 5675 m and moved north-eastwards over the Free State while the surface AOH of 1032 hPa continued to progress eastwards at 40° S while transforming into the IOH (Fig. 5.15 A). The surface pressure gradient along the KZN coast increased due to the surface frontal low developing of the coast, east of Richards Bay in juxtaposition with the upper COL (Fig. 5.15 A). Consequently, the cold air and moisture advection into the Eastern Cape and southern KZN was maintained (Fig. 5.15 B). The 850 hPa frontal low moved further northwards and the surface convergence and resultant vertical motion (Fig. 5.15 C) was maximised over the eastern Free State, KZN and the southern Mpumalanga Highveld where snowfall occurred. To the east of the 700 hPa low located over the Northern Cape (Fig. 5.15 D), moisture and uplift was similar to that of the 500 hPa level (Fig. 5.15 E) and the 850 hPa level in Fig. 5.15 C. This made the Free State, KZN and Mpumalanga Highveld very favourable for precipitation. The upper jet had weakened slightly to 80 knots but was still orientated over the aforementioned regions assisting with upper wind divergence (Fig. 5.15 F).

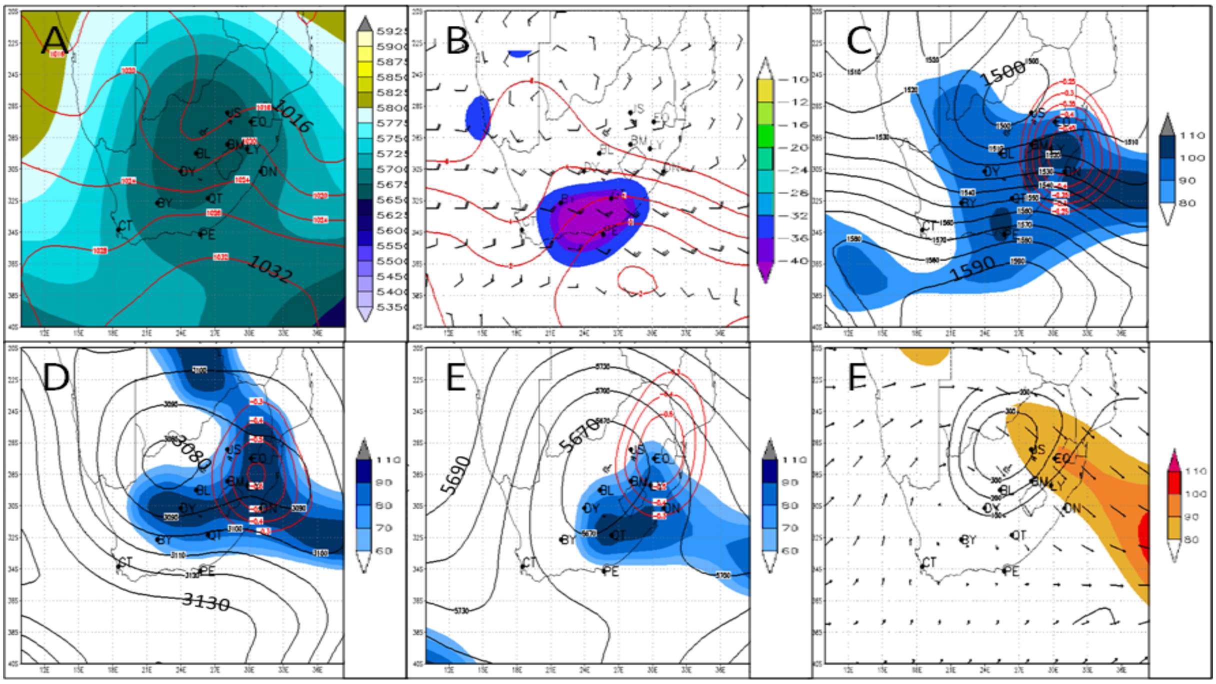


Figure 5.15: Same as Figure 5.3, but mean sea level pressure in red: A) for 26 July 2011 at 0000 UTC

b. Surface and upper air observations

The vertical distribution of temperature cooled throughout the atmosphere at Durban on 26 July 2011 at 0000 UTC (blue lines and barbs) from the previous 12 hours (red lines and barbs) as indicated in the shaded blue region in the tephigram (Fig. 5.16). The strength of the onshore south to south-easterly flow from the surface IOH had increased in depth to the lowest 4000 m of the atmosphere. The north-easterly to easterly flow at 5100 m a.m.s.l indicated in Fig. 5.16 (encircled area) was indicative of the cyclonic flow around the approaching mid-level COL located to the west. The vertical distribution of moisture was still indicating saturated conditions throughout the atmosphere while the freezing level height dropped to 2000 m a.m.s.l which is approximately 500 m a.g.l over the KZN interior making conditions more favourable for snowfall in lower lying regions (see Section 3.2.4.4). Between 25 and 26 July 2011, the vertical distribution of moisture (Fig. 5.16) remained saturated to beyond -40 °C which is typical of a mixed cloud phase of Bergeron–Findeison snow crystal growth.

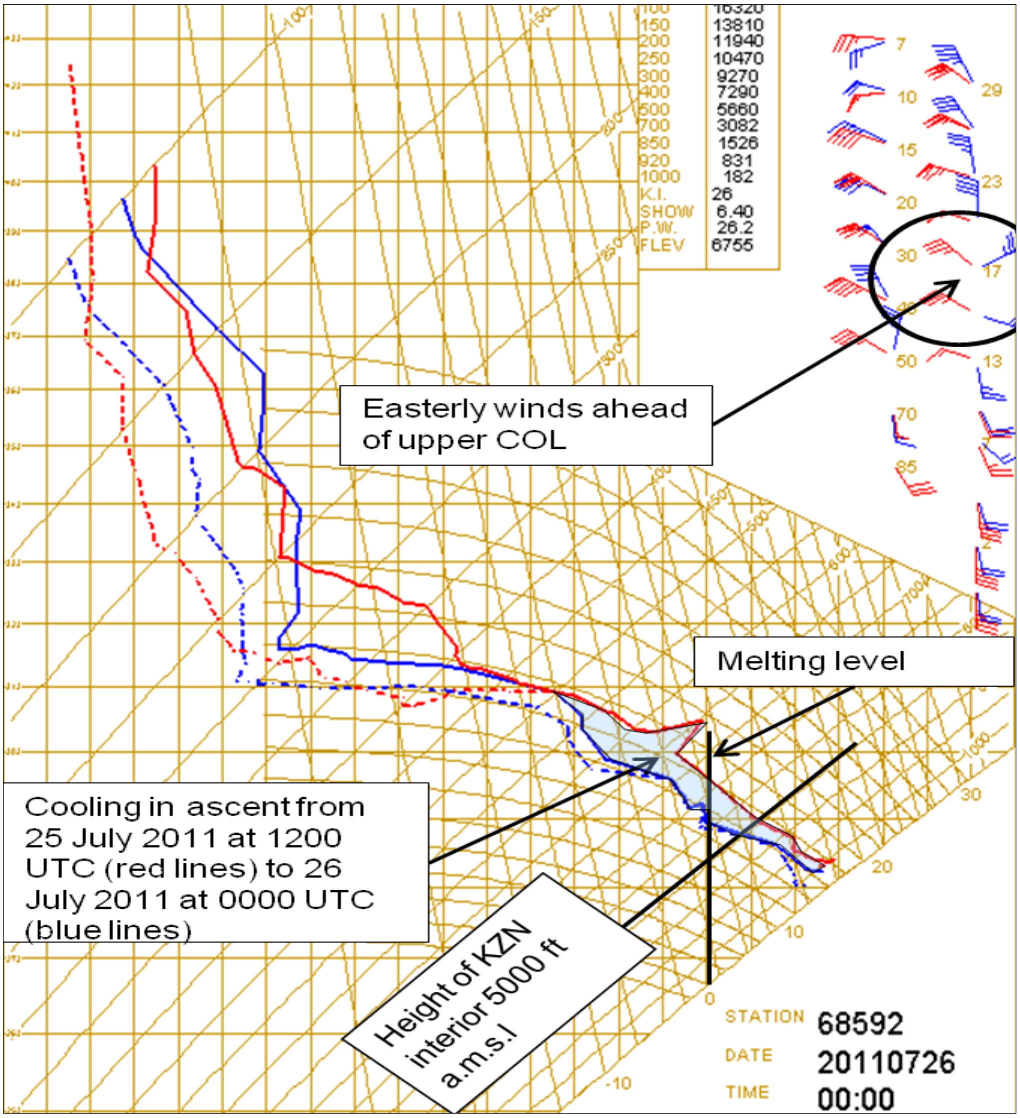


Figure 5.16: South African Weather Service tephigram for Durban on 26 July 2011 at 0000 UTC (blue lines and barbs) and 25 July 2011 at 1200 UTC (red lines and barbs) (the solid lines are temperatures and the dotted lines dew point temperatures)

The saturation in the vertical distribution of moisture was indicative of precipitation occurring at the time of the upper air ascent with plenty of ice crystals available for seeding the lower saturated levels for the formation of snowflakes (see Section 1.4.2). Consequently, the heavy snowfall started to extend from the Eastern Cape into southern KZN. Snow covered the south western high ground of Kokstad, Underberg and Matatiele (Moolla and Venktess, 2011). The R56 was closed between Kokstad and Matatiele, and the N2 national road between Durban and Port Elizabeth had to be closed at Brookes Nek in the Eastern Cape (Van Rooyen, 2011).

Fig. 5.17 indicates that the temperature dropped rapidly at Kokstad during the course of the morning of 25 July 2011, with snowfall already occurring at 0805 UTC. This continued on and off until the morning of 27 July 2011, when the surface temperature started to increase. At Kokstad, surface temperatures remained close to zero for the entire period with surface RH around the 98% mark which enables snowflakes to reach the ground without melting (see Section 3.2.4.4). Even when the surface temperature rose to 2 °C on the morning of 26 July 2011, snow was still probable due to surface RH in the upper 80s.

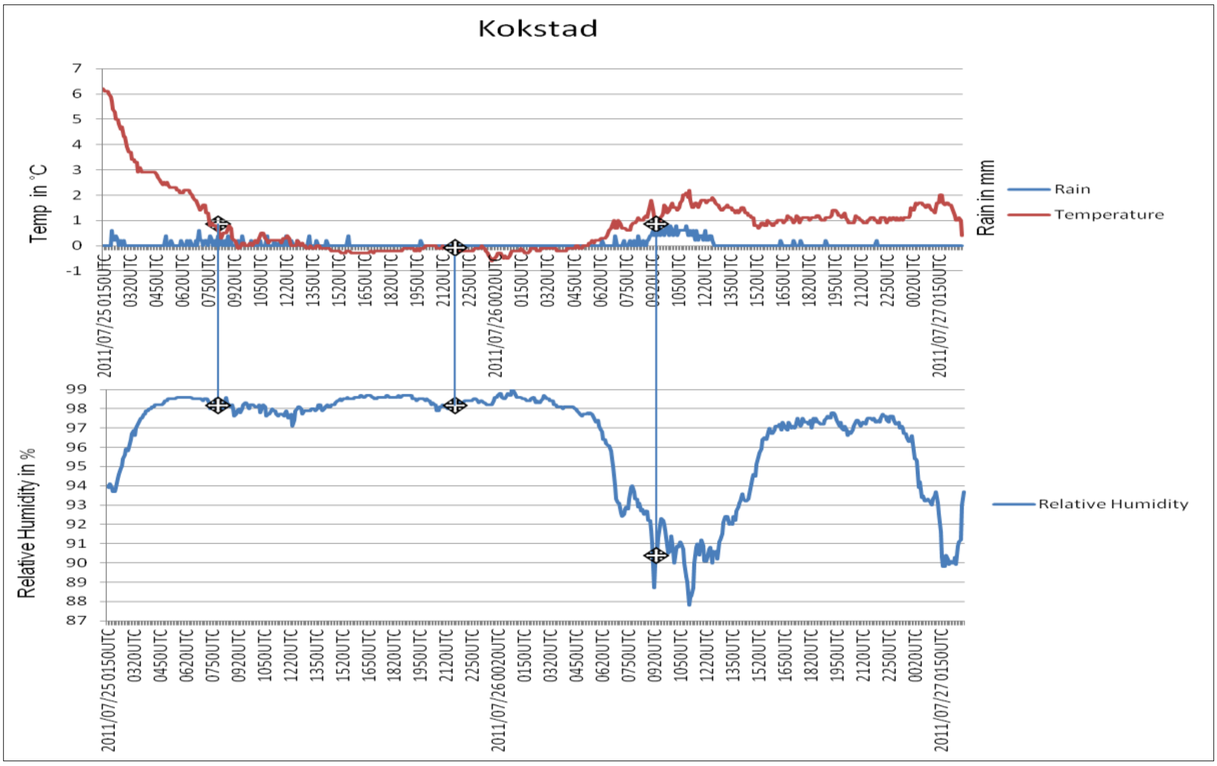


Figure 5.17: Same as Figure 5.4, but for South African Weather Service Kokstad weather station on 25, 26 and 27 July 2011; the stars in the figure indicate confirmed observations of snowfall; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

Newcastle in KZN was also snow bound (Moolla and Venktess, 2011; Pretoria News, 2011a). The temperature dropped dramatically during the late afternoon on 25 July 2011 (Fig. 5.18). Snowfall occurred during the early morning of 26 July 2011 when surface temperatures were around 2 °C and surface RH around 98%.

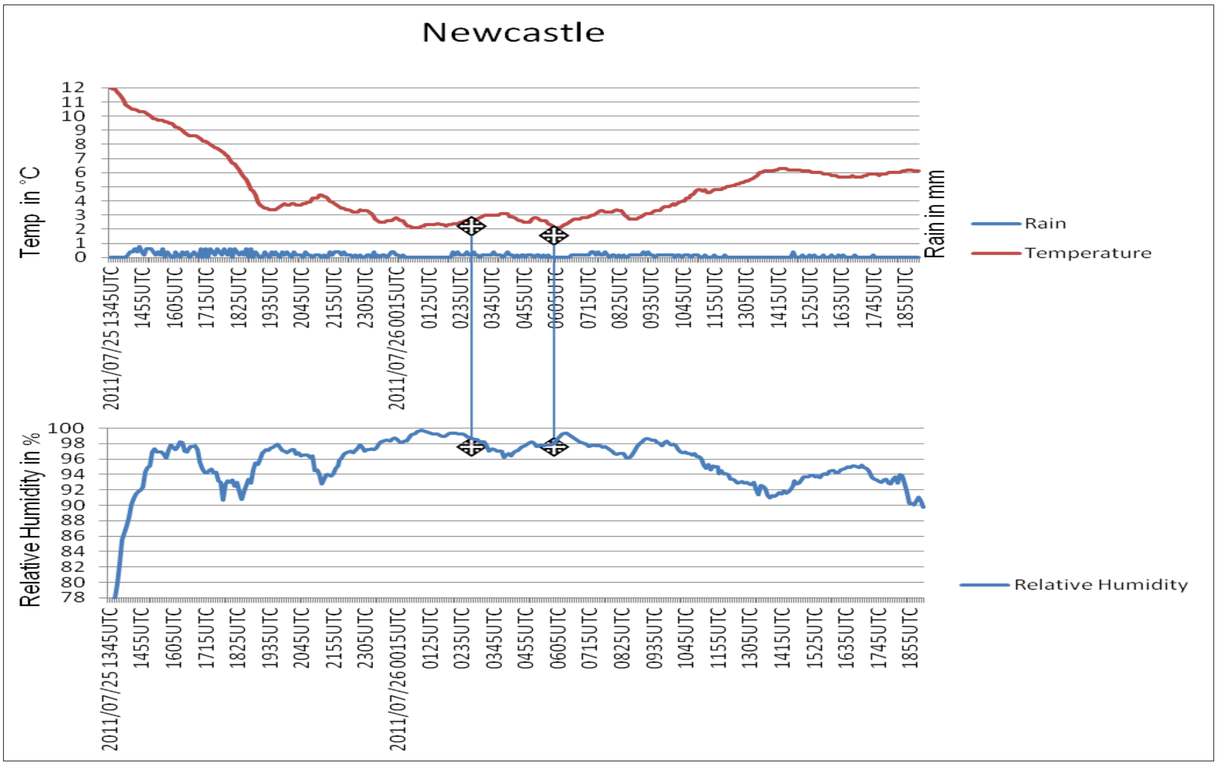


Figure 5.18: Same as Figure 5.4, but for South African Weather Service Newcastle weather station on 25 and 26 July 2011; the stars in the figure indicate confirmed observations of snowfall; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

Moreover, during the early morning of 26 July 2011, the snow also started in the eastern Free State. At Bloemfontein, the height of the freezing level dropped to 2370 m a.m.s.l, which is roughly 800 m a.g.l. Slight snowfalls were reported in the vicinity of the town but because the distance between the freezing level and the ground was large, no significant falls occurred (see Section 3.2.4.4).

The N3 national route between Johannesburg and Durban had to be closed near the Wilge Plaza on 26 July 2011 with 220 km of road rendered inaccessible. Many motorists were also trapped on Van Reenens pass and the N3 national route between Villiers and Howick was closed for the entire day. On the afternoon of 26 July 2011, cars and lorries stood still for more than 10 kilometres between the Tugela Plaza and Van Reenens pass with the alternative route of the R74 on the Oliviershoekpass also being closed (Van Rooyen et al., 2011).

Similar to Newcastle, the temperature at Bethlehem started to drop sharply during the afternoon of 25 July 2011 (Fig. 5.19) due to the passage of the cold front when precipitation was measured (blue traces). The precipitation was due to a thunderstorm with the approaching upper COL. During the night and early morning, there were no manned weather observations at Bethlehem but at 0200 UTC and on and off during the morning of 26 July 2011, snow occurred until 0700 UTC. Snow was reported in the 0400 UTC METAR when the surface temperature was 1.7 °C and surface RH 91.8% (see Fig. 5.19) It is however, possible that snowfall had started around midnight.

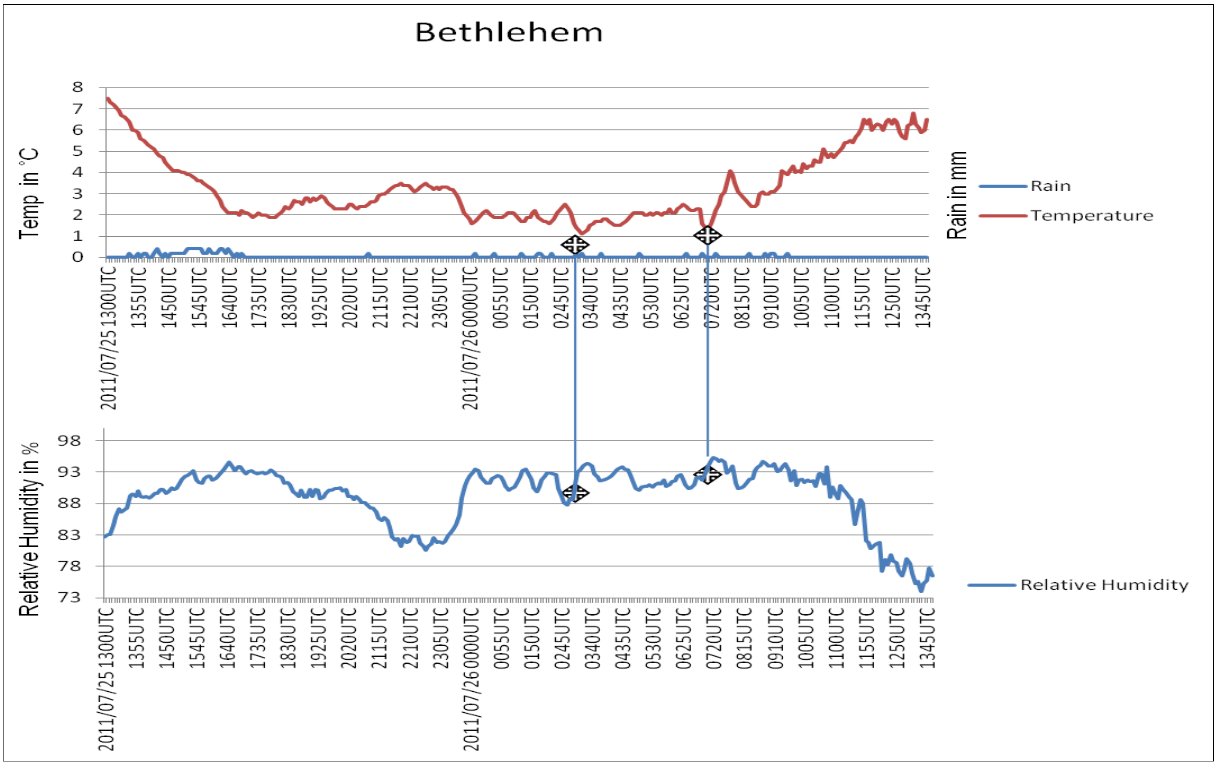


Figure 5.19: Same as Figure 5.4, but for South African Weather Service Bethlehem weather station on 25 and 26 July 2011

In Ermelo, the temperature dropped during the afternoon and evening of 25 July 2011 when precipitation started to occur. It was only in the early hours of 26 July 2011 that surface temperatures were low enough for snow to occur between 0300 UTC and 0400 UTC when the temperature was 0 °C and the surface RH 100%.

c. Partial atmospheric thickness

On 26 July 2011 at 0000 UTC, when snowfall spread to the eastern Free State, western KZN, KZN midlands and the southern Mpumalanga Highveld, the 850-500 hPa atmospheric thickness fell below 4170 m (Fig. 5.20 A), below 1580 m for the 850-700 hPa partial thickness layer (Fig. 5.20 B) and 2570 m for the 700-500 hPa partial thickness layer (Fig. 5.20 C). In Fig. 5.20 B, the cold cored IOH of 1540 m (low atmospheric thickness) can be identified south of Port Elizabeth. In Section 2.1, Fig. 2.2 (Taljaard, 1995a) referred to such cold cored systems in his classification of winter weather systems.

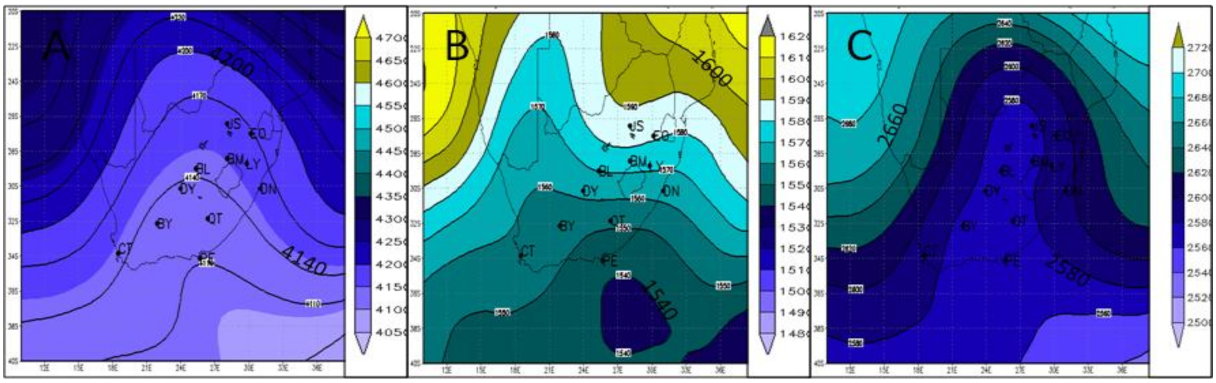


Figure 5.20: Same as Figure 5.8, but for 26 July 2011 at 0000 UTC

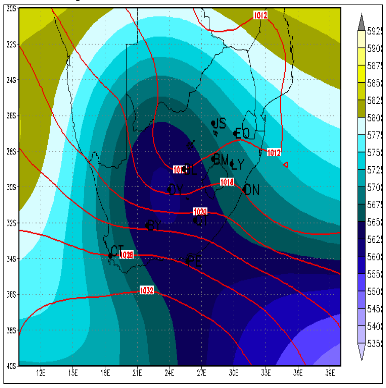
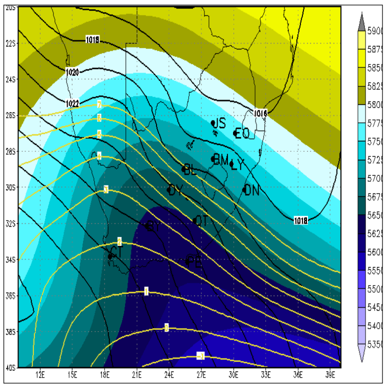
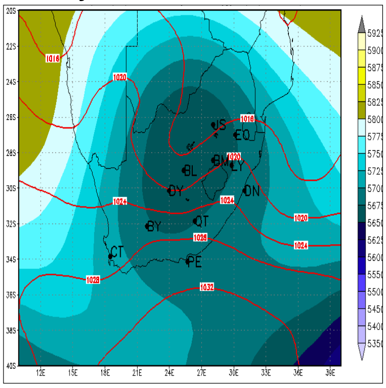
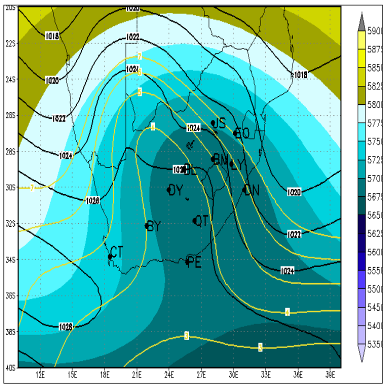
5.1.3 SOM node synoptic classification

The purpose of this discussion is to relate the synoptic classification of snowfall in Chapter 4.2 (Fig. 4.2) to the synoptic circulation patterns of 25 and 26 July 2011. This was done to indicate that the synoptic mapping made was indeed representative of the true synoptic circulation within this case study.

The synoptic circulation of 25 July 2011 at 1200 UTC (Fig. 5.9 A) was mapped to Node 15 as shown in Table 5.1. This node represents a COL over the Northern Cape region with the surface AOH located near 40° S ridging over the Eastern Cape. This circulation was referred to in Chapter 2.1.1.2 as the right hook by Van Heerden and Hurry (1995) which can result in heavy rain or snow over the south-eastern and eastern interior due to the enhanced uplift and condensation. It can be seen that node 15 captures the essential synoptic circulation although the extent and depth of the COL is underestimated.

Node 4 was one of the nodes with the highest frequency associated with snowfall during the month of July (see Section 4.2.3.3). The synoptic circulation on 26 July 2011 at 0000 UTC (Fig. 5.15 A) was associated with node 4 which is indicative of the COL over KZN with the associated frontal low to the east of Richards bay and the IOH south-east of the country producing an onshore flow into the KZN interior. The circulation patterns of node 4 shows a strong resemblance to the actual synoptic circulation.

Table 5.1 SOM node synoptic classifications for 25 and 26 July 2011

25 July 2011 at 1200 UTC	Node 15
	
26 July 2011 at 0000 UTC	Node 4
	

5.1.4 Summary

A COL and surface cold front developed over the interior of South Africa due to the cold air advection caused by the westward moving AOH south of the country near 40° S. This is unlike the normal winter circulation pattern when a surface cold front approaches the country from the west. The cold south-easterly flow caused by the AOH did not extend in the vertical deeper than 700 hPa or 3000 m a.m.s.l. Due to the quick pressure rise as the high moved eastwards, the surface winds behind the cold front changed rapidly from south-westerly to south-easterly, making this south-easterly surface winds the dominant wind direction during this snowfall event. The surface AOH contributed to the formation of snowfall in three ways.

Firstly, it cooled the lower atmospheric temperatures between (850-700 hPa), making surface conditions cold enough to allow the snowflakes falling from mid-levels to reach the ground. The 850-700 hPa layer is important, since the temperature in this layer is not close to freezing and contains warmer layers (T > 0 °C). Snowfall can then melt on its way down to the ground. The warmer layers below 700 hPa can contribute to snowflakes only reaching the 700 hPa or 3000 m a.m.s.l level such as the higher elevated mountain regions of the

Lesotho Drakensberg (see Section 1.2, Fig. 1.1). As such, the temperature and RH of this layer can affect snow falling on the mountain tops as opposed to lower elevated regions, which is the purpose of this study (see Section 3.2.5).

Secondly, it provided significant moisture and cooling to the lower part of the atmosphere below 700 hPa (850-700 hPa). The air in the atmosphere was always saturated below 700 hPa due to this effect. This layer of the atmosphere typically occurs between 0 °C and -10 °C where supercooled droplets occur, making conditions favourable for ice crystals to grow into snowflakes through aggregation and riming (see Section 1.4.2).

Thirdly, it provided the necessary cold air advection to strengthen and deepen the surface cold frontal boundary and develop the upper COL (see Section 3.2.4) over the country.

The Drakensberg Mountains caused orographic lift (see Section 1.2, Fig. 1.1). The IOH caused the south-easterly winds to be perpendicular to the north-easterly/south-westerly orientated mountain ranges. This south-easterly warmer air over the cold land, resulting in orographic lift, was also noted by Stranz and Taljaard (1965). Van Heerden and Hurry (1995) indicated that, in the right hook synoptic pattern, the south-eastern and eastern escarpment becomes an enhanced focused region of thermal advection, convergence and orographic lift enhancing heavy snowfall in that area (see Section 2.1.1). This was also found by (Kocin and Uccellini, 2004) who described the effects that topography has on cold air damming in the USA.

The COL was essential to the formation of snow in the following ways.

Firstly, it played an important role in generating a cold core in the 700-500 hPa atmospheric layer that assisted in the growth and sustainment of ice crystals in that layer through deposition. The associated mid-level moisture and vertical motion on its eastern and southern flanks enhanced ice crystal growth within the -10 °C to -20 °C range. In terms of the Bergeron process, this is important for the seeding of lower level clouds to produce snowflakes. This process that starts in the mid- and upper levels is the starting point for snowfall (see Section 1.4.2).

The upper jet stream was important as it is associated with the development of a COL system. In this particular case, there was a strong upper level jet stream associated with the upper COL (>100 knots). The right exit region of the jet was associated with wind divergence assisting with rising motion though the lower and mid-levels in order to compensate for the loss of air in the upper levels. Most of the snowfall occurred during 25 July 2011 and early on the 26th, when the upper jet was more than 100 knots in strength with the right exit region of upper air divergence located over the Eastern Cape. Kocin and Uccellini (2004) also found the jet stream to be a major contributor to snowfall in the USA.

Furthermore, it was important for providing vertical motion throughout the 700-500 hPa layer causing further diabatic cooling although this effect is minimal.

It is the combined effect of these two synoptic scale surface and upper air systems that provide an adequately cold and moist atmosphere from 1000 hPa to 500 hPa. When these two systems combine the vertical distribution of moisture and temperature is such that ice crystals can form, grow and develop into snowflakes and fall to reach the ground.

Atmospheric thickness were important when determining precipitation type (see Section 1.4.2). In this case study, the following atmospheric thickness values were obtained at different times and locations and are given in Table 5.2. These values were obtained from the NCEP reanalysis data. The height of the freezing levels were obtained from tephigrams representative of the air mass in that region.

Table 5.2: Atmospheric thickness (850-500 hPa, 700-500 hPa and 850-700 hPa) and freezing level height per region per synoptic station during snowfall on 25 and 26 July 2011

Region	Station elevation in metres a.m.s.l	Time in UTC	850-500 hPa thickness in m	700-500 hPa thickness in m	850-700 hPa thickness in m	Freezing level height in m a.m.s.l	Freezing level height in m a.g.l
North-eastern part of the Western Cape	Beaufort West (851)	25 July 2011 at 0000	4150	2580	1560	1525	448
Western part of the Eastern Cape	Queenstown (1076)	25 July 2011 at 0000	4150	2580	1560	1525	448
Central and Eastern Free State, Western KZN and Southern Mpumalanga		26 July 2011 at 0000	4170	2570	1580		
Free State	Bloemfontein (1395)	26 July 2011 at 1200				2372	977
KZN interior	Newcastle (1242)	26 July 2011 at 0000				2042	800
KZN interior		26 July 2011 at 1200	4160	2590	1570		

In this case study solid precipitation (snow) occurred with the following partial thickness indicated in Table 5.3 that were obtained from Table 5.2.

Table 5.3: Atmospheric thickness (850-500 hPa, 700-500 hPa and 850-700 hPa) during snowfall for the 25 and 26 July 2011

Thickness layer	850-500 hPa	700-500 hPa	850-700 hPa
Thickness values	4150 to 4160 m	2570 to 2590 m	1560 to 1580 m

Keeter and Cline (1991) indicated that the 850-700 hPa atmospheric thickness of less than 1540 m was good for snow. Heppner (1992) used a critical 850-700 hPa thickness value of 1550 m to forecast snow in Pennsylvania in the USA at an altitude of 347 m a.m.s.l. Stranz and Taljaard (1965) investigated the 700-500 hPa thickness to identify snow over Bloemfontein and Johannesburg in June 1964. They found critical thickness values of between 2520 to 2560 m. In the forecasting offices in South Africa, a thickness value of less than 1570 m for the 850-700 hPa layer is used to forecast snow.

When snowfall occurs in surface temperatures above freezing, the surface temperature and RH determine whether or not snowfall will reach the ground or not (see Section 3.2.4). Matsuo and Sasyo (1981) indicated that snowfall could occur in surface air temperatures below 2.5 °C which holds for the values obtained in Table 5.4. Matsuo and Sasyo (1981) showed that, when surface RH was close to 100%, snow was observed in temperatures between 0 and 1 °C. This seemed be the case in Ermelo. The surface conditions during snowfall are summarised in Table 5.4.

Matsuo and Sasyo (1981) stated that, as surface RH decreases below 100%, it becomes possible to encounter snowfall at higher surface temperatures. When surface temperatures were below 2.5 °C and surface RH below 90%, snowfalls were frequent. In this case study, when surface temperatures were below 2 °C, snow was likely to occur when surface RH was between 90% and 100%. This could be seen from Beaufort West, Queenstown, Matatiele, Bethlehem, Kokstad and Ermelo. When surface RH was close to 100%, the melting temperature was close to 0 °C.

Table 5.4: Surface temperature, surface relative humidity and melting temperature during snowfall per region per synoptic station during snowfall on the 25 and 26 of July 2011

Region	Station in metres a.m.s.l	Time in UTC	Surface temp in °C	Surface RH (%)	Melting temperature in °C
Western Cape	Beaufort West (851)	25 July 2011 at 0100	0.1	96.7	0.2
Eastern Cape	Queenstown (1076)	25 July 2011 at 0100.	0.2	90.6	0.6
Eastern Cape	Matatiele (1500)	25 July 2011 at 1200.	0.5	89	0.7
Free State	Bethlehem (1666)	26 July 2011 at 0400	1.7	91.8	0.5
KZN	Kokstad (1302)	26 July 2011 at 1100	1.7	90.7	0.6
KZN	Newcastle (1194)	26 July 2011 at 0100	2.1	99	0.1
Mpumalanga Highveld	Ermelo (1667)	26 July 2011 at 0300	0.4	100	0

When surface temperatures were close to 2 °C, a point in case being Newcastle where snow occurred at a surface temperature of 2.1 °C and a RH of 99%, careful consideration is needed. Snowfall most likely occurred in surrounding, slightly higher elevated areas of the town where temperatures would have been colder due to the topographic effects but with the same RH close to 100%. In the case of Bethlehem, light snow was reported when the temperature was 1.7 °C and the RH 91.8% at 0400 UTC on 26 July 2011, when the melting temperature was 0.5 °C. When temperatures are between 2 °C and 4 °C, the boundary layer conditions should be considered as well as whether snow might reach the ground or melt before it reaches the ground. This can be done by calculating the melting temperature.

5.2 Case study 2: 1 and 2 August 2006

5.2.1 Introduction

A weak cold front approached Cape Town on 30 July 2006 at 1200 UTC (Fig. 5.21 A). The following day, the cold front intensified over the south-western interior as the surface AOH started to advect cold air behind the front, intensifying the surface cold frontal boundary (Fig. 5.21 B). On 1 August 2006 at 1200 UTC (Fig. 5.21 C), the front strengthened further into several connected surface vortices in conjunction with an upper COL. The snowfall was 0.3 m deep in Sutherland on 1 August 2006 and was reported to be the worst since 1988. The Verlatenkloof Pass to the town of Sutherland had to be closed because of the snowfall. It had also snowed on the Matroosberg and was still snowing in Sutherland late on 1 August 2006 (Gosling, 2006).

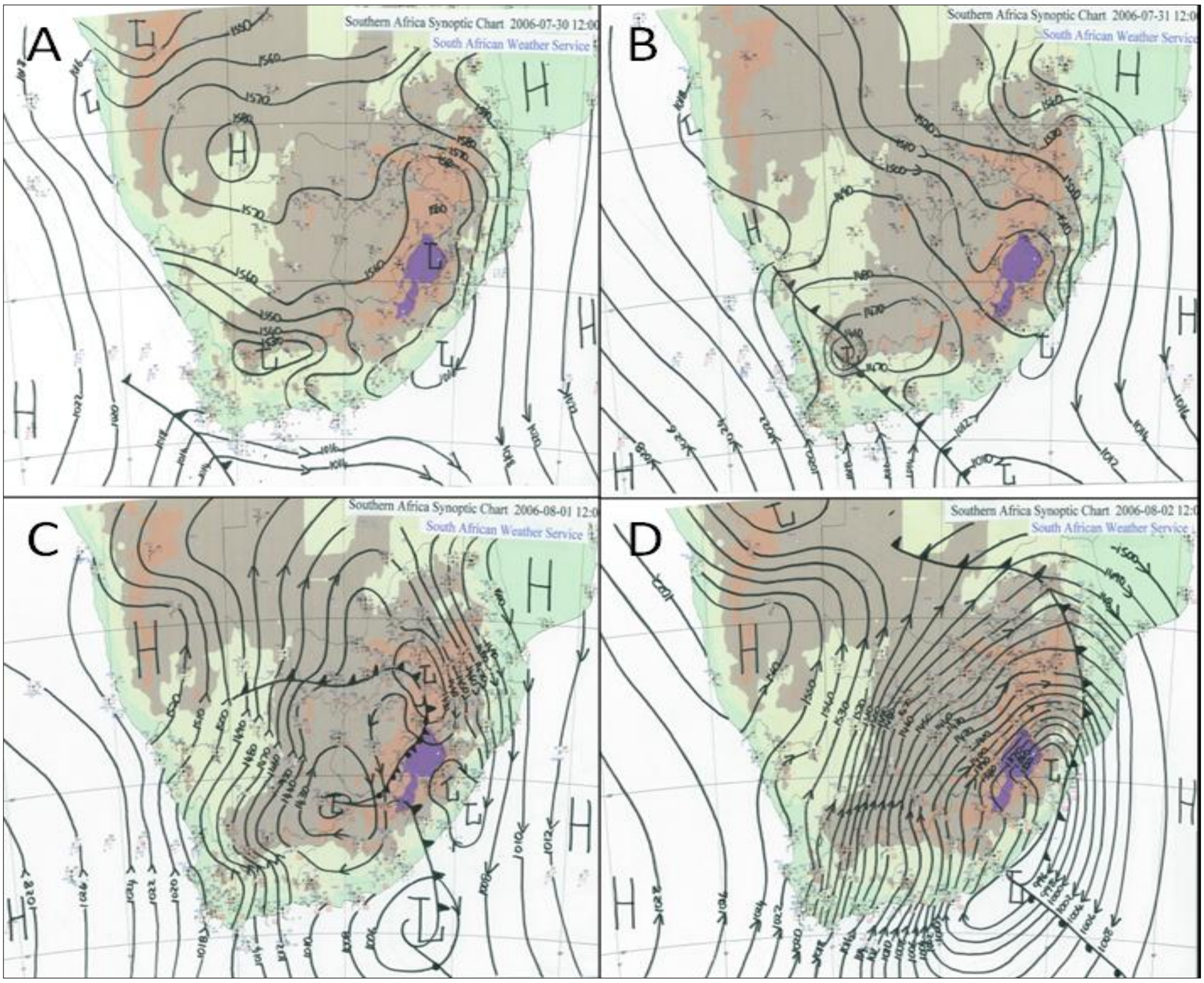


Figure 5.21: Surface synoptic analysis depicting mean sea level pressure (every 2 hPa) and 850 hPa geopotential height contours (every 10 m) for 30 and 31 July, and 1 and 2 August 2006 at 1200 UTC

The road between Willistown and Calvinia also had to be closed due to snowfall (Volksblad, 2006a). On 2 August 2006 at 1200 UTC, the cold front moved over Gauteng into the Limpopo province (Fig. 5.21 D). A deep frontal low was located on the south-east coast.

The first snow for more than a decade fell in Bloemfontein and surrounds. Clarens, Fouriesburg, Harrismith, Paul Roux, Senekal, Bethlehem, Kestell, Ladybrand and Ficksburg all received snow. Snow also fell in Philipstown in the Northern Cape on the morning of 2 August 2006. The N6 national route between Reddersburg and Smithfield also had to be closed in the early hours of the morning on 2 August 2006 where 150 cars were trapped. The snow started falling late on Tuesday night on 1 August 2006. The last car was pulled from a metre of snow on 2 August 2006 at 1000 UTC (Fourie, 2006). The road between Wepener and Paul Roux also had to be closed due to snowfall as well as the Lootsberg Pass into the Eastern Cape. Snow fell at De Aar and Hanover in the Northern Cape and Graaff- Reinet, Nieu Bethesda, Colesburg, Burgersdorp, Smithfield and Reddersburg (Volksblad, 2006b).

5.2.2 Atmospheric conditions during snowfall

The period from 1 August 2006 at 0000 UTC to 2 August at 1200 UTC will be discussed, as snowfall occurred over Sutherland in the south-western part of the Northern Cape, De Aar over the south-eastern part of the Northern Cape and the Free State (see Section 1.2, Fig. 1.1). The importance of the large-scale synoptic circulation is emphasised, as it provides the moisture and cold temperatures to form snowfall. It is also illustrated how the vertical temperature and moisture distribution of the atmosphere provide the conditions necessary for the formation of snowfall. Partial atmospheric thickness, surface temperature and RH is discussed as it accentuates how important these variables are in snowfall. Lastly, the SOM node synoptic classification of Chapter 4.2 is related to the synoptic circulation of this case study in order to indicate that the classification was representative of the true synoptic situation.

The surface cold front moved over Cape Town between 30 and 31 July 2006 (Fig. 5.21 A and B). On 30 July 2006 at 1200 UTC (Fig. 5.22) (red lines and barbs), the surface wind flow was still north-westerly (encircled) but changed to southerly on 31 July 2006 at 0000 UTC (blue lines and barbs) when the cold front Passed Cape Town, causing a considerable drop in temperature up to 300 hPa (shaded blue region in Fig. 5.22). The height of the freezing level dropped from 3100 m a.m.s.l to 2327 m a.m.s.l. On 31 July at 1200 UTC (figure not shown), the height of the freezing level dropped even further to 1710 m a.m.s.l as the south-easterly surface flow from the ridging high increased in speed and depth up to 700 hPa, causing an increase in cold air advection through the lowest layers of the atmosphere.

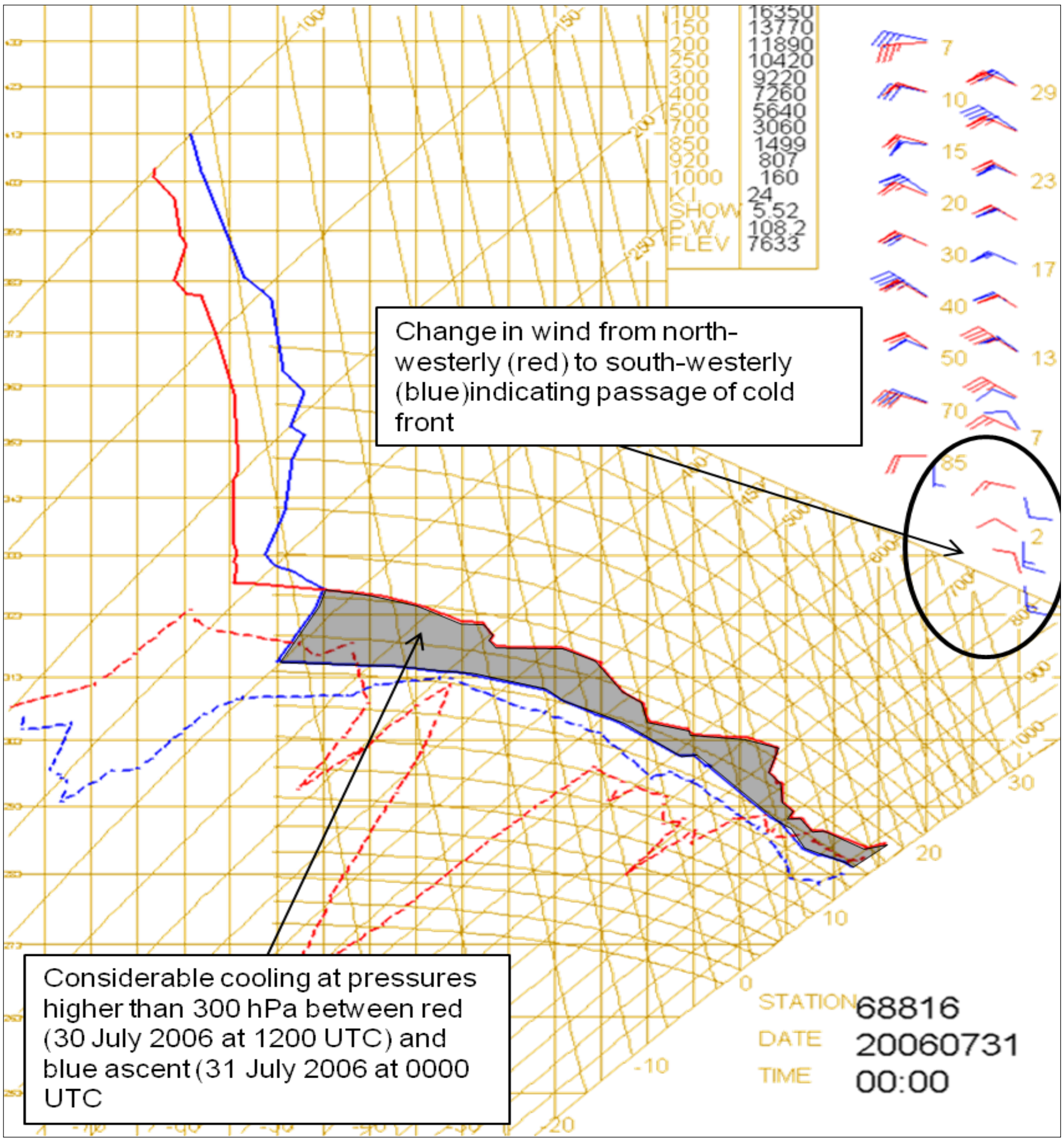


Figure 5.22: South African Weather Service tephigram for Cape Town for 31 July 2006 at 0000 UTC (blue lines and barbs) and 30 July 2006 at 1200 UTC (red lines and barbs) (the solid lines are temperatures and the dotted lines dew point temperatures)

5.2.2.1 1 August 2006 at 0000 UTC

This period will be discussed, since snowfall started over the south-western part of the Northern Cape as the COL was starting to develop. The passage of this COL impacted on snowfall over the remainder of the country the following day. The town of Springbok will be referred to in order to explain that despite the fact that the COL developed over the Springbok region, no snow was reported there because of the unavailability of ice cloud and warm surface conditions. The tephigram and satellite image of Springbok is referred to in order to illustrate the unavailability of ice cloud along with the warm surface synoptic conditions. This will be compared to the town of Sutherland, where snowfall started in the morning with favourable conditions throughout the atmosphere. The satellite image depicting cloud top temperatures is shown for Springbok, Calvinia and Sutherland in order to illustrate how it can be used with the tephigram to further validate the presence of ice cloud. Partial atmospheric thickness were similar between Springbok, Calvinia and Sutherland, yet no snow occurred at Springbok and Calvinia because of the aforementioned reasons.

a. Synoptic circulation

The surface cold front had progressed to the central interior of the country while the sharp upper trough developed into a COL south of the town of Springbok (Fig. 5.23 A and E). Surface temperatures fell below 6 °C behind the cold front over the south-western interior (Fig. 5.23 B).

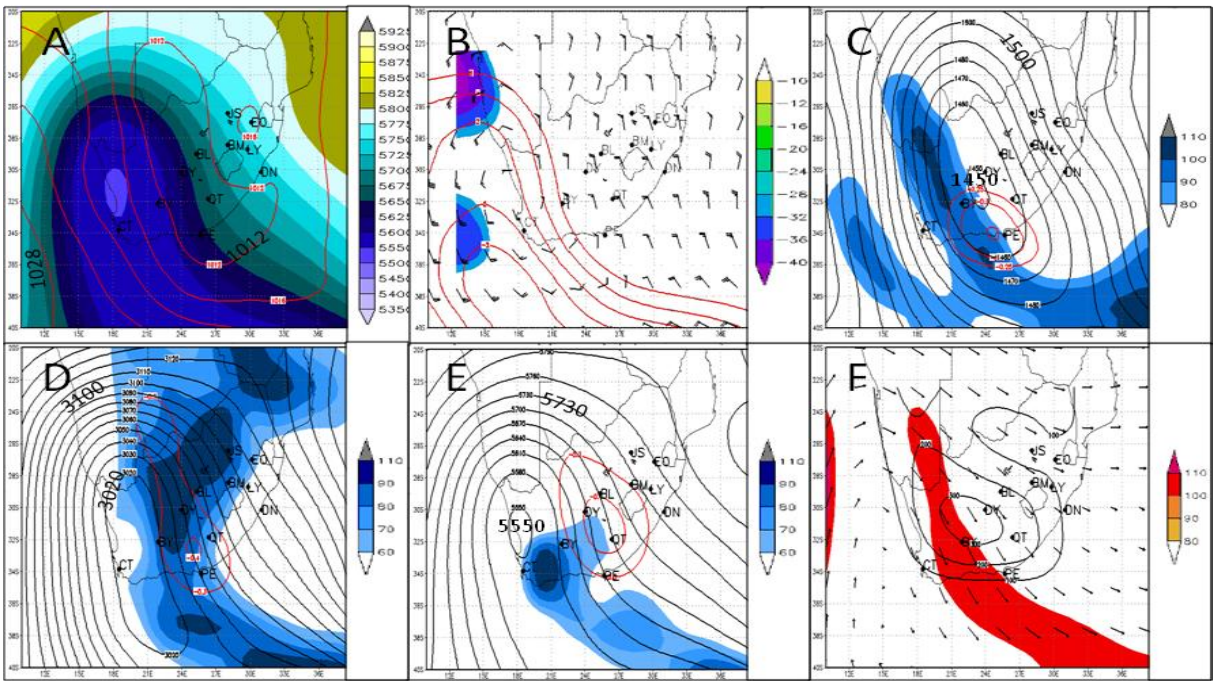


Figure 5.23: 1 August 2006 at 0000 UTC: A): mean sea level pressure in hPa red solid, 500 hPa geopotential heights shaded in metres; B): 850 hPa temperature < 6 °C in red, 850 hPa cold air temperature advection*10e^{6} in °C s^{-1} shaded, 850 hPa wind barbs in knots; C): 850 hPa relative humidity in % shaded, 850 hPa negative omega in Pa s^{-1} red, 850 hPa geopotential heights in metres solid black; D): 700 hPa relative humidity in % shaded, 700 hPa negative omega in Pa s^{-1} red, 700 hPa geopotential heights in metres solid black; E): 500 hPa relative humidity in % shaded, 500 hPa negative omega in Pa s^{-1} red, 500 hPa geopotential heights in metres solid black; F): 300 hPa jet stream > 80 knots shaded, 300 hPa wind divergence solid black (s^{-1})

At 850 hPa, a surface frontal low developed to the east of the upper COL over the southern part of the Eastern Cape. The cyclonic circulation in the vicinity of Port Elizabeth caused vertical motion and had an onshore component of wind flow perpendicular to the topography (see Section 1.2, Fig 1.1). Moisture (RH > 80%) and cold air was fed into the Western Cape to the west of the low (Fig. 5.23 C).

The upper low extended from 500 hPa down to the 700 hPa atmospheric level with the greatest depth of moisture over the Western Cape and south-western Northern Cape although moisture was also present on the eastern flanks of the COL at 700 hPa (Fig. 5.23 D and E). A jet stream of more than 80 knots was situated ahead of the COL over the Western Cape and the Sutherland region. This was also where upper air wind divergence was occurring in the right exit region of the jet (Fig. 5.23 F) (see Section 2.3).

b. Upper air observations and satellite imagery

During the day, it rained intermittently at Springbok from low level stratiform cloud, with the tephigram (Fig. 5.24) confirming the saturation in the lower atmosphere (at pressures higher than 750 hPa) within the stratiform cloud. The wind barbs throughout the atmosphere were south-westerly, indicative that the upper COL was located just to the east of Springbok. Conditions were dry at pressures lower than the 750 hPa level, especially in the region of -10 °C to -20 °C, indicative that no ice cloud was present or could grow via deposition and seed the saturated air within the lower cloud layer (see Section 1.4.2.1). As a result, no snow could further grow by accretion, aggregation and riming between 0 °C and -10 °C. The lack of moisture in the mid-levels at Springbok could be attributed to the position of the upper COL. This was one of the limiting factors for snowfall along with the fact that the height of the freezing (melting level) was located at 696 m a.g.l (Fig. 5.24) (see Section 3.2.4.4).

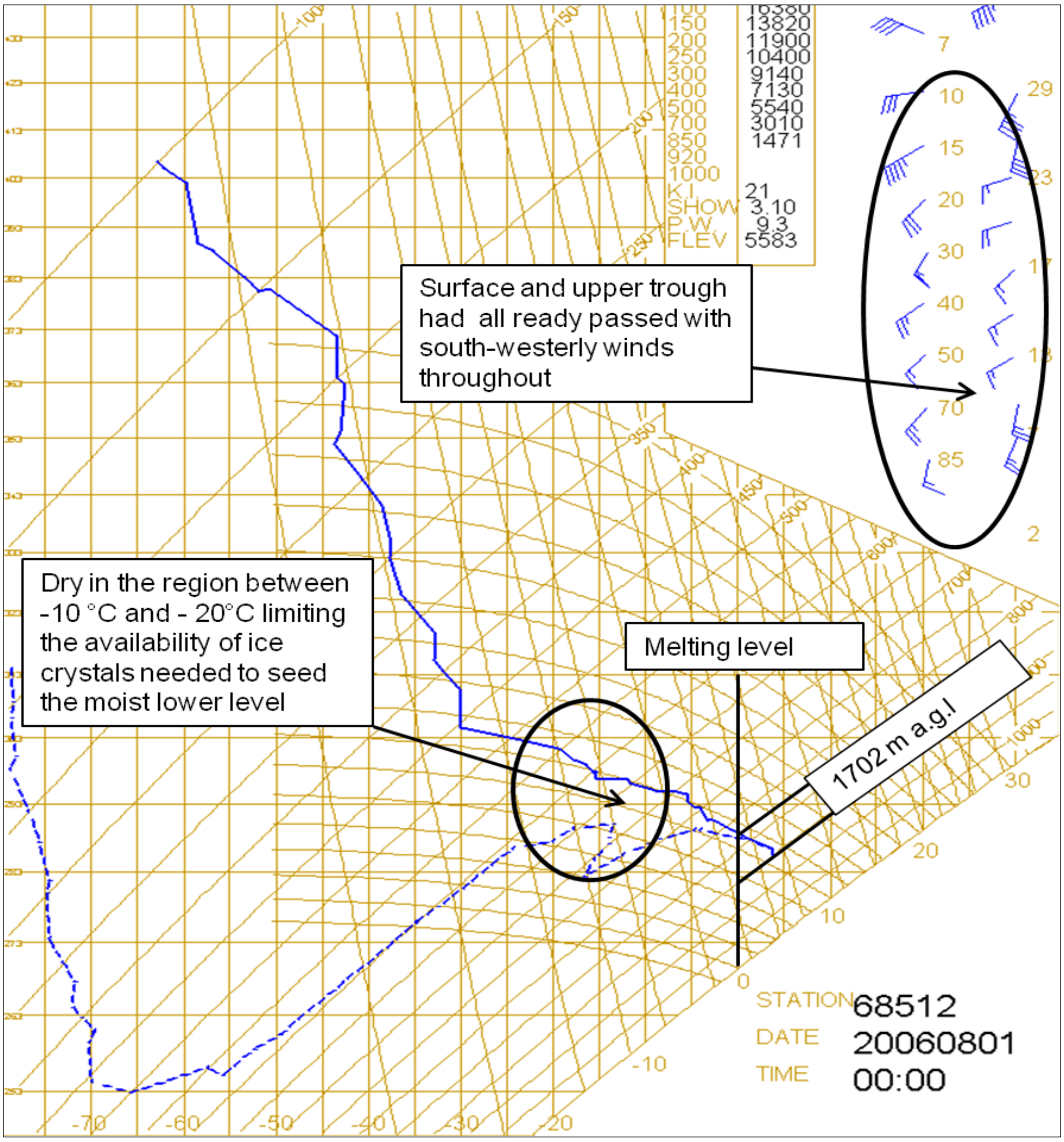


Figure 5.24: South African Weather Service tephigram for Springbok on 1 August 2006 at 0000 UTC (blue lines and barbs); the solid lines are temperatures and the dotted lines dew point temperatures

Fig. 5.25 further emphasises the non-existence of ice bearing clouds over the Springbok region at 0200 UTC (no clouds with cloud tops colder than -10 °C). This correlates well with the information contained within the tephigram which was indicating no moisture at temperatures colder than -10 °C (Fig. 5.24). At Calvinia where no snow occurred, there were few clouds (green patches) compared to Sutherland where overcast ice cloud was available (green and light blue). Subsequently, it started to snow in the early morning in Sutherland.

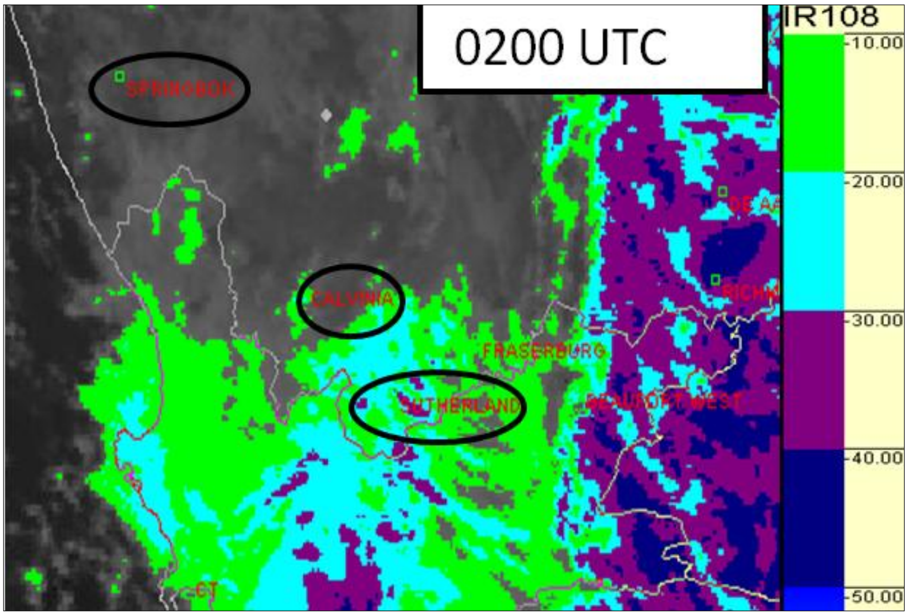


Figure 5.25: MSG satellite, false colour IR10.8 image for 1 August 2006 at 0200 UTC over Springbok, Calvinia and Sutherland © (2012) Eumetsat

c. Surface observations

Although the surface temperature remained < 4.5 °C during most of the day at Springbok (Fig. 5.26) surface conditions were moist with a RH of 100%. At around 0500 UTC, the surface temperature was at its lowest with 2.5 °C with a 100% RH. Had there been falling snowflakes, they would not have made it to the ground even with a low freezing level height of 696 m a.g.l (Fig. 5.24). The melting air temperature of the snowflake would have been 0 °C in this particular case, meaning that the temperature would have to drop to 0 °C before snow would be able to reach the ground (also see Section 3.2.4.4 highlighting the limitation of snowfall when RH is 100% and temperatures are above 2.5 °C). Due to these important aforementioned reasons, it did not snow at Springbok despite a favourable synoptic configuration which involved a COL.

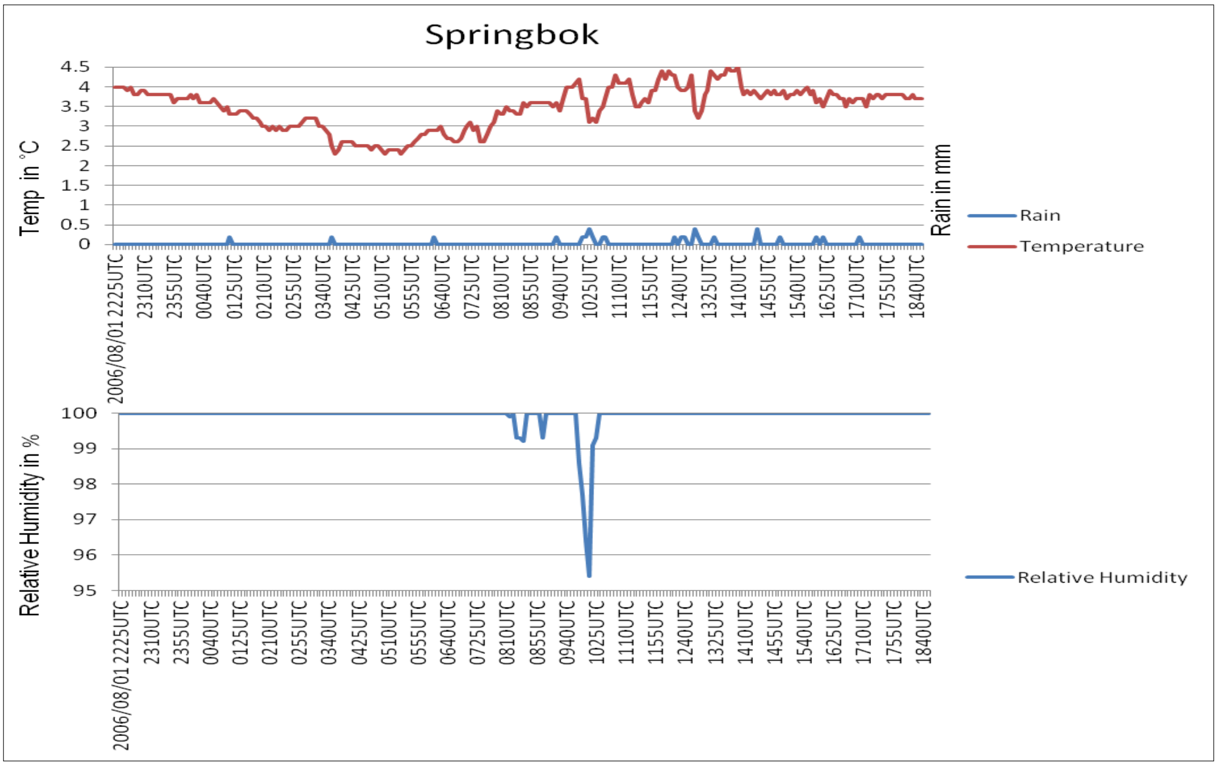


Figure 5.26: Temperature (°C), rain (mm) and relative humidity (%) at the South African Weather Service Springbok weather station on 1 August 2006; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

Similarly to Springbok, Calvinia surface temperatures dropped to 3 °C with surface RH close to 100% preventing snowfall (see Section 3.2.4.4).

Further east towards Sutherland, the situation was different. The vertical distribution of moisture at Cape Town was close to saturation throughout (figure not shown) and the freezing level height was at the 850 hPa level, which is the ground level at Sutherland. This tephigram was representative of the situation at Sutherland and consequently, at 0600 UTC heavy, continuous and intermittent snow was reported from Sutherland when the surface temperature was -0.9 °C, dew point -4 °C and surface RH 79%. In this particular case, the melting temperature of snowflakes would have been around 1.3 °C. Due to a snow producing synoptic pattern, the availability of ice cloud and favorable surface conditions, snowfall occurred.

d. Partial atmospheric thickness

At this time, it was snowing in the Sutherland region. The atmospheric thickness for the 850-500 hPa layer was below 4100 m over the Western Cape and south-western Northern Cape

(Fig. 5.27 A). For the 850-700 hPa layer, it was below 1550 m (Fig. 5.27 B) and below 2560 m for the 700-500 hPa layer (Fig. 5.27 C). Although atmospheric thickness at Springbok and Calvinia were just as low at Sutherland, snowfall did not occur at Springbok and Calvinia due to lack of ice bearing clouds and unfavourable surface conditions.

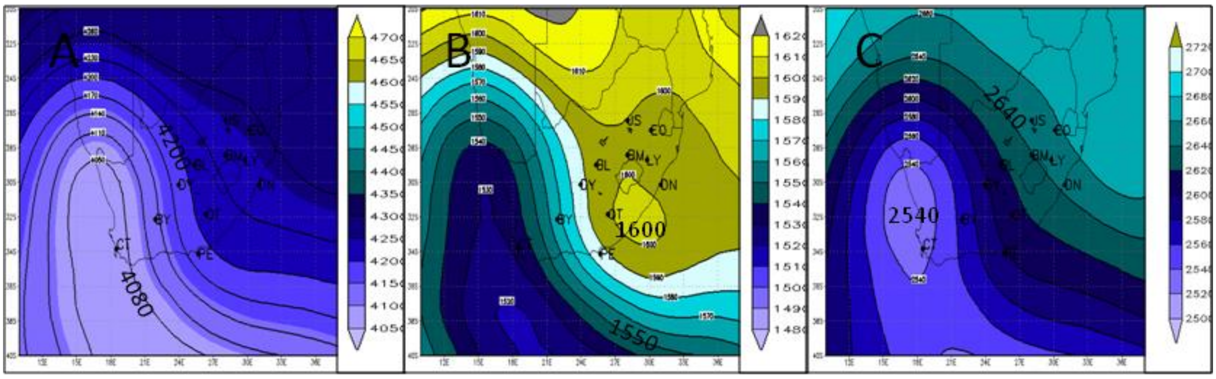


Figure 5.27: A): 850-500 hPa atmospheric thickness; B): 850-700 hPa partial atmospheric thickness; and C) 700-500 hPa partial atmospheric thickness for 1 August 2006 at 0000 UTC

5.2.2.2 1 August 2006 at 1200 UTC

This period will be discussed as snow was still falling at Sutherland. The upper COL continued to move further northwards to the north-western part of the Northern Cape. As the rest of the synoptic circulation was essentially the same as 0000 UTC, it will not be discussed further. The surface observations, satellite imagery and partial atmospheric thickness will be discussed with reference to Sutherland in order to explain the continued occurrence of snowfall there. The town of Springbok, where it did not snow, will be referred to in the satellite imagery in order to further indicate the lack of moisture despite favourable partial thickness values below the upper COL.

a. Surface observations and satellite imagery

Light, continuous and intermittent snow continued to fall at Sutherland at 1200 UTC when the surface temperature was -1.1 °C, surface dew point -4 °C and the surface RH 80%. Fig. 5.28 illustrates that the cloud top temperatures in Sutherland were still between -10 °C and -30 °C making the cloud microphysical conditions favourable for ice crystal growth, especially through deposition (Compare to Springbok where there were still no ice clouds available).

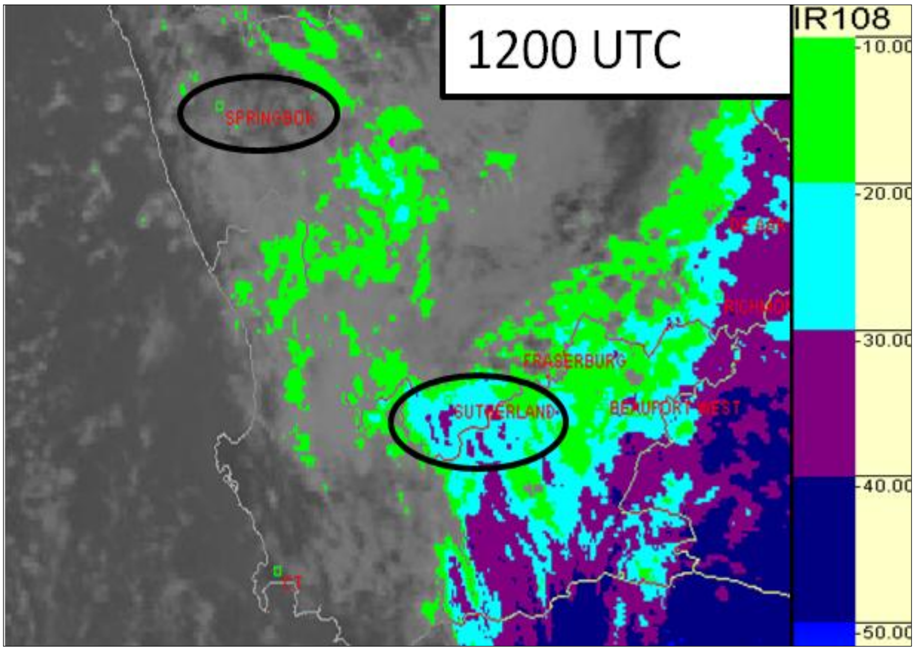


Figure 5.28: MSG satellite, false colour IR10.8 on 1 August 2006 at 1200 UTC over Springbok and Sutherland © (2012) Eumetsat

b. Partial atmospheric thickness

The 850-500 hPa atmospheric thickness in Sutherland was 4120 m (Fig. 5.29 A), for the 850-700 hPa layer it was 1550 m (Fig. 5.29 B) and for the 700-500 hPa layer it was 2560 m (Fig. 5.29 C). It is important to note that, over Springbok near the centre of the COL, atmospheric thickness were much lower than Sutherland. Despite this, no snow occurred at Springbok due to the lack of ice crystals and slightly warmer moist surface conditions.

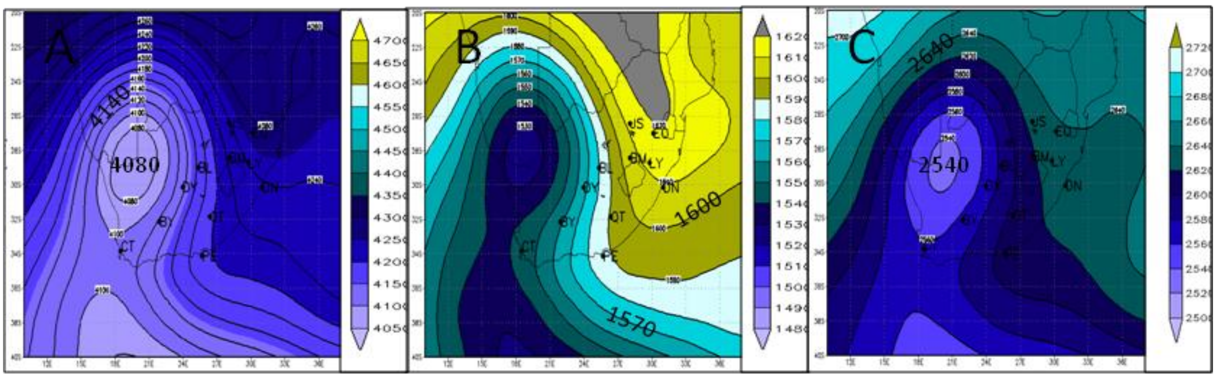


Figure 5.29: Same as Figure 5.27, but for 1 August 2006 at 1200 UTC

5.2.2.3 1 August 2006 at 1800 UTC

Snowfall at this particular time continued unabated at Sutherland. The COL moved slightly northwards to be situated over the northern part of the Northern Cape while a surface low was starting to form along the KZN coast. No new synoptic developments were taking place from the previous time step. Therefore, it will not be discussed further. The town of Sutherland will be referred to in terms of the surface synoptic observations and atmospheric thickness that were conducive to snowfall.

a. Surface observations and partial atmospheric thickness

Heavy, continuous and intermittent snow continued to fall at Sutherland at 1800 UTC when the surface temperature was 0.4 °C, surface dew point -0.4 °C and the surface RH 94%. In the Sutherland region, the 850-500 hPa atmospheric thickness was 4120 m (Fig. 5.30 A), for the 850-700 hPa layer it was 1550 m (Fig. 5.30 B) and for the 700-500 hPa layer it was 2560 m (Fig. 5.30 C). This is similar to the values that were obtained at 1200 UTC for Sutherland.

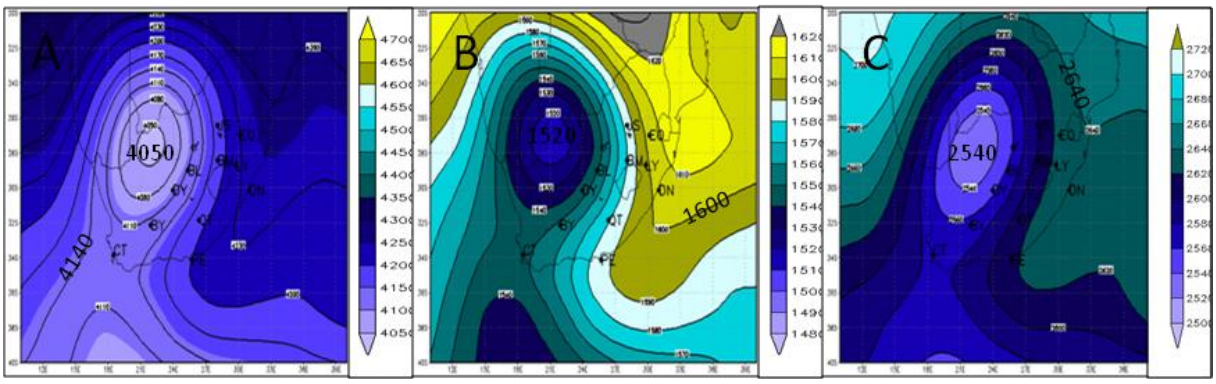


Figure 5.30: Same as Figure 5.27, but for 1 August 2006 at 1800 UTC

5.2.2.4 2 August 2006 at 0000 UTC

This period will be discussed, since snow fell in the Eastern Cape, south-eastern Northern Cape and southern Free State in towns such as Graaff-Reinet, Nieu Bethesda, Colesburg, Burgersdorp, Smithfield and Reddersburg (Volksblad, 2006b). Snow also fell at De Aar and Orania in the Northern Cape (Volksblad, 2006a). The synoptic pattern will be discussed as the upper COL had now moved over the Free State with horizontal cold air advection providing cold surface conditions over this area. The town of De Aar will be discussed by referring to the surface conditions and how snowfall occurred at temperatures below 1 °C when the air was saturated (RH = 100%). The De Aar tephigram is used to illustrate two different atmospheric ascents, one 10 hours after the snowfall and the other one two hours before the snowfall. This indicates the Passage of the cold front and upper COL. At both time periods, the height of the freezing levels were similar, close to the ground, however the boundary layer conditions below the height of the freezing level were different, highlighting the significant importance of considering these boundary layer conditions when forecasting snow. Satellite imagery is included to show the relevance of cloud containing ice and locating the position of the upper COL. Surface temperature and RH at Johannesburg is shown in order to indicate favourable surface conditions for snow. However, no snow occurred and cloud top temperatures are used to indicate the lack of ice clouds at the time despite the presence of the upper COL to the south. The tephigram at Irene is further used to substantiate this.

a. Synoptic circulation

On 2 August 2006 at 0000 UTC, the upper COL changed its northwards path and started to track eastwards. The COL was situated over the eastern part of the Northern Cape and the Free State (Fig. 5.31 A). Very cold temperatures below 6 °C were occurring over the Western, Northern and Eastern Cape, including the Free State and Gauteng (Fig. 5.31 B). Large amounts of cold air advection were occurring over the eastern part of the Northern Cape, Free State and the Eastern Cape (Fig. 5.31 B). High 850 hPa RH values > 80% were occurring in the onshore southerly flow to the rear of the frontal low which was located over the south-eastern interior extending as far north as Johannesburg (Fig. 5.31 C). The 700 hPa low was located just to the east of De Aar, with most of the high RH values occurring on the southern edge of the low (Fig. 5.31 D). The 500 hPa low was located slightly north of the 700 hPa low over the Bloemfontein region, with most of the high RH values on the southern, south-eastern and eastern flanks of the low with uplift situated to the east and north-east of Bloemfontein (Fig. 5.31 E). The upper north-westerly jet had slightly weakened and was located between Bethlehem and Johannesburg (Fig. 5.31 F).

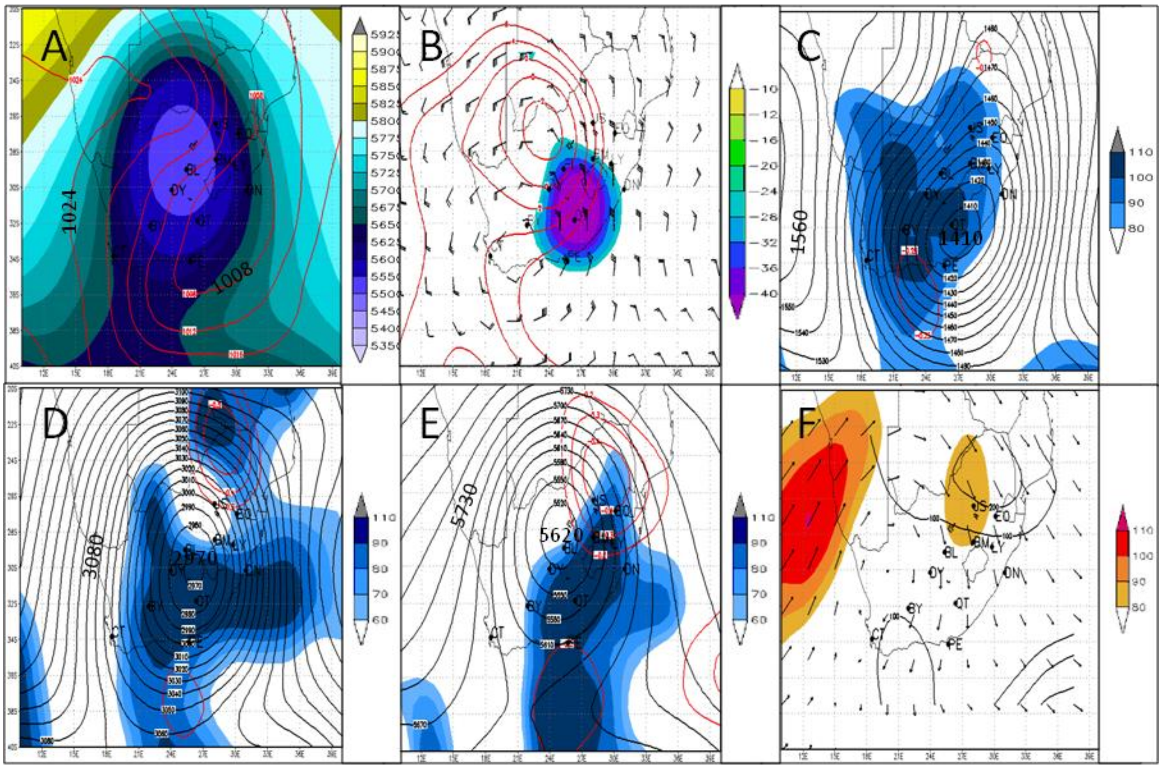


Figure 5.31: Same as Figure 5.23, but for 2 August 2006 at 0000 UTC

b. Surface observations

At 0200 UTC on 2 August 2006, light, continuous and intermittent snow was reported at De Aar (Fig. 5.32). Between 0000 UTC and 0200 UTC, it was raining lightly with five to seven eighths of mid-level cloud reported at 3000 m a.g.l. During this specific time, the surface temperature was slightly above 2 °C and the surface RH close to 100%, resulting in the melting temperature of snow being 0 °C. Consequently, light rain was occurring at this time (Fig. 5.32) and most likely had an influence on the further cooling of the lower atmosphere close to the ground before the start of the snow. When it snowed, the mid-level ice cloud was overcast, while the surface temperature dropped suddenly to 0.4 °C. The surface RH remained close to 100%. It continued to snow until it changed to light rain at 0255 UTC when the temperature increased rapidly to above 2 °C. Surface moisture remained saturated. It continued to rain lightly between 0300 UTC and 0600 UTC, while the surface temperature continued to rise gradually.

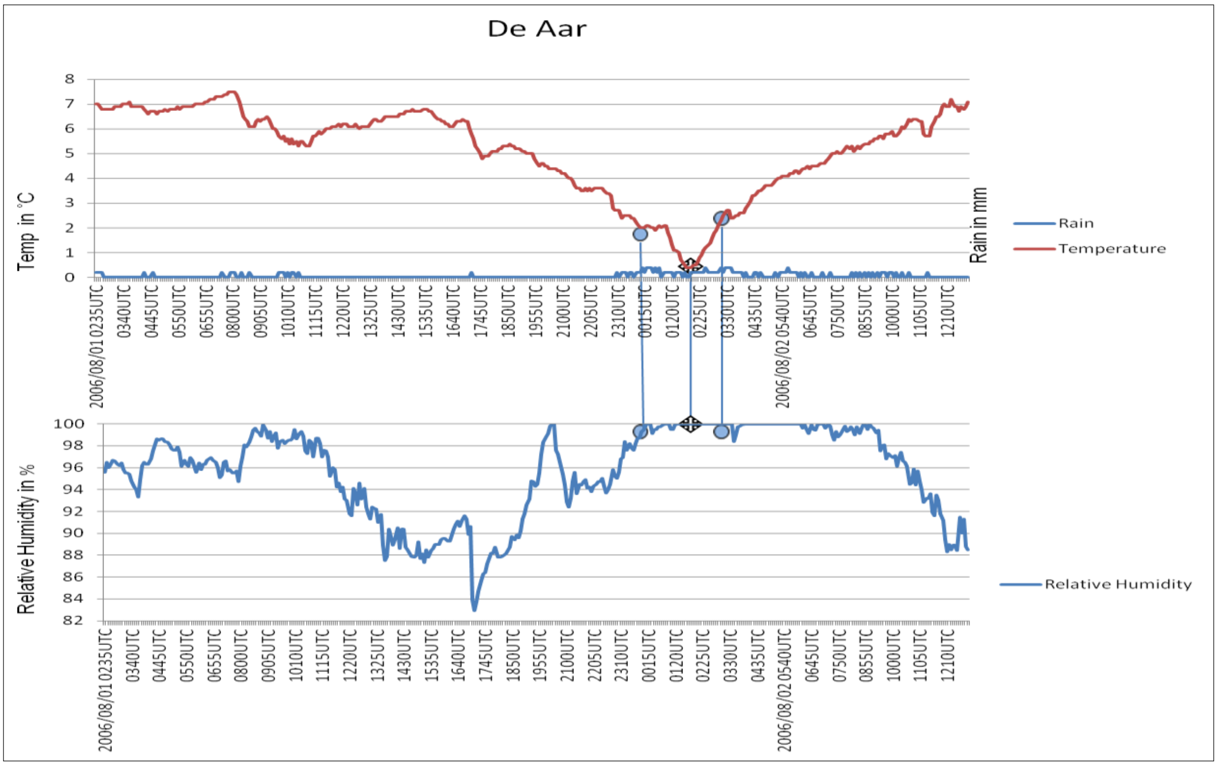


Figure 5.32: Same as Figure 5.26, but for South African Weather Service De Aar weather station on 1 and 2 August 2006; the blue circle is a confirmed report of drizzle or light rain and the star is snow

At Johannesburg International Airport, snow did not occur despite very cold surface conditions. The reasons for this are now explored. Between 0200 UTC and 0700 UTC (Fig. 5.33), surface temperatures were close to 0 °C and surface RH was below 85%, making surface conditions ideal for snow to reach the ground (see Section 3.2.5). This was because only three to seven eights of low level clouds between 300 and 500 m a.g.l were reported during this period with the unavailability of mid-level ice clouds.

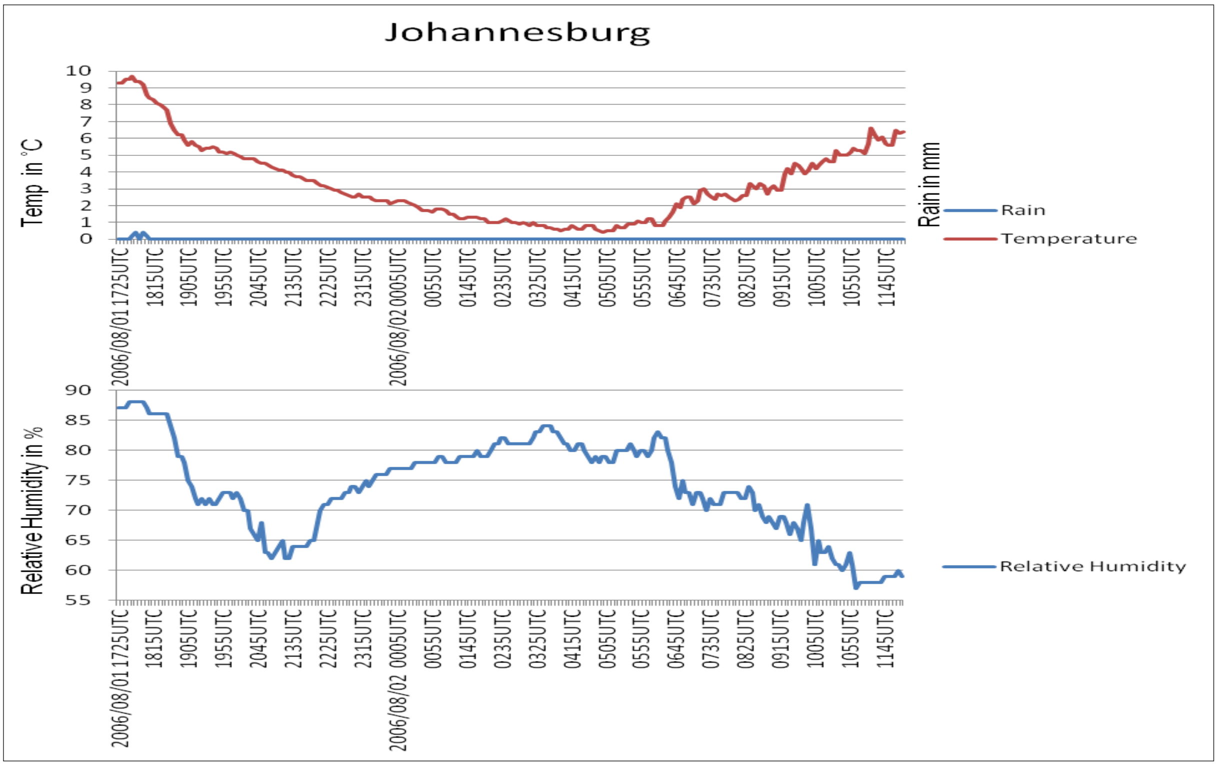


Figure 5.33: Same as Figure 5.26, but for South African Weather Service Johannesburg weather station for 1 and 2 August 2006

c. Upper air observations

The motivation for snowfall at De Aar lay in the difference between the vertical atmospheric ascents as depicted in Fig. 5.34. On 1 August 2006 at 1200 UTC (green lines and barbs), the vertical distribution of wind was north-westerly and the mid-levels were dry, reflecting that the surface cold front and upper COL still lay west of De Aar. By 2 August 2006 at 0000 UTC (red lines and barbs), the wind barbs throughout the whole atmosphere had turned south-westerly (Passage of cold front and upper COL) with the atmosphere moistening in the mid-levels and, consequently, snow occurred. Mid-level clouds were being reported on the ground at De Aar weather station. In the early hours of the morning on 2 August 2006, 150 cars were trapped between Reddersburg and Smithfield in the southern Free State because of snow (see Section 5.2.1). The red lines and barbs in Fig. 5.34 are indicative of this time of snowfall when the moisture at the atmospheric pressure level at -15 °C was saturated and the surface conditions below the melting level were cold enough to allow snowfall to reach the ground. The vertical distribution of moisture between -10 °C and 0 °C was also saturated, allowing further growth of falling snowflakes to occur by processes of aggregation; riming and accretion (see Section 1.4.2). On 2 August 2006 at 1200 UTC (blue lines and barbs), the atmosphere was still conducive to snowfall, however, the boundary layer conditions had warmed to above 6 °C in saturated air (RH = 100%), resulting in the melting of the snowflakes (see Section 3.2.4). This boundary layer is enlarged in Fig. 5.34 (right side), indicating these warmer surface conditions, although the freezing or melting levels were essentially the same in all three atmospheric ascents. This indicates that a forecaster must not be blinded by the height of the freezing level a.g.l alone to make a snowfall forecast but also consider the surface conditions. Snowfall at 1200 UTC was therefore restricted to the higher elevated mountains over the eastern Free State.

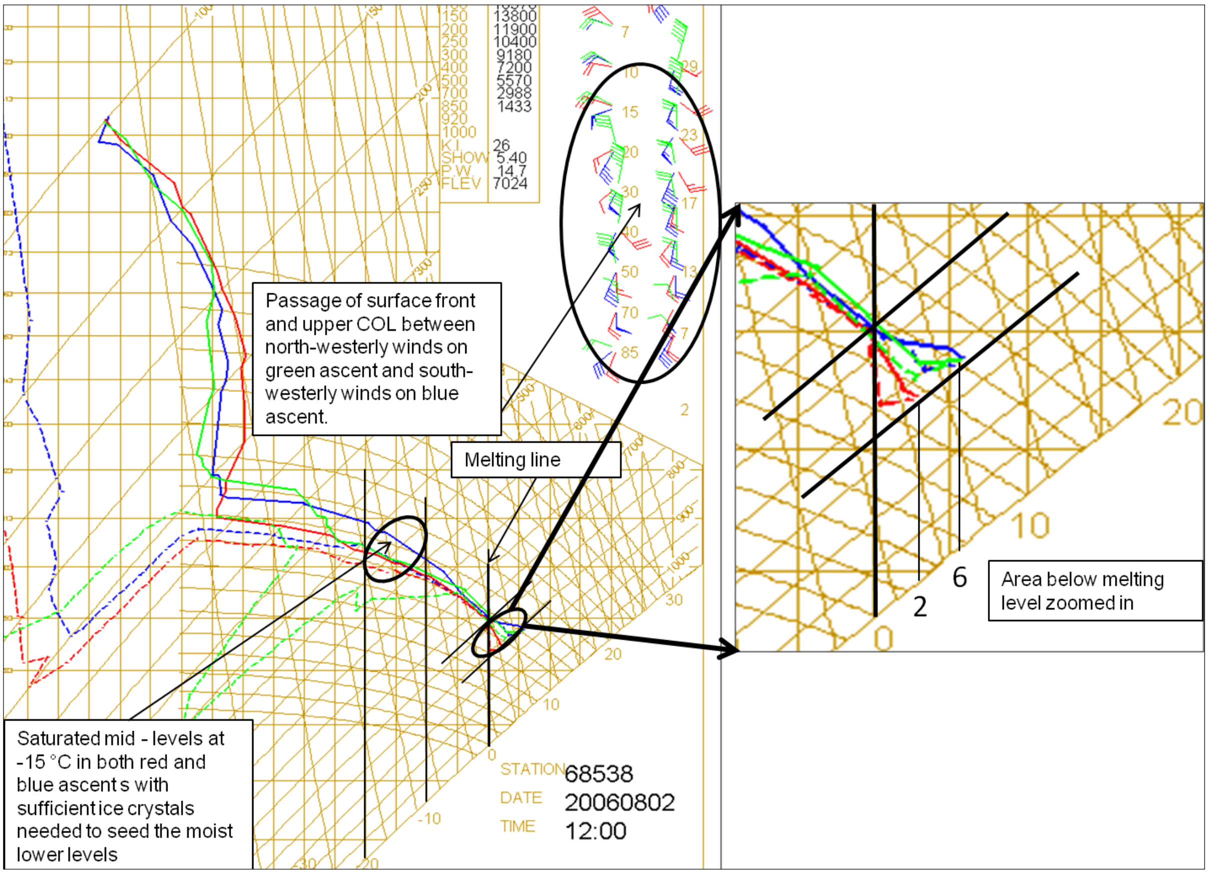


Figure 5.34: South African Weather Service De Aar tephigram for 2 August 2006 at 1200 UTC (blue lines and barbs), 2 August 2006 at 0000 UTC (red lines and barbs) and 1 August at 1200 UTC (green lines and barbs); the solid lines are temperatures and the dotted lines dew point temperatures

Light snow was reported in areas of Johannesburg such as Westonaria, Carletonville, Soweto and Sandton. Morningside reported a slight fall at 0800 UTC on 2 August 2006 (Flanagan, 2006). It is important to consider why no significant snow was reported over Gauteng during the morning of 2 August 2006 in order to understand the factors important in snowfall. Surface conditions were cold enough, yet no significant snow occurred. The answer lay in the unavailability of sufficient ice crystals in the mid to upper levels for the seeding of the lower level clouds (Fig. 5.35). Between 1 August 2006 at 1200 UTC (red lines and barbs) and 2 August 2006 at 0000 UTC (blue lines and barbs), spectacular cooling occurred at pressures higher than the 500 hPa level (Fig. 5.35, blue shaded region) but only a very thin layer of moisture was available for ice crystals near 500 hPa. At pressures lower than 500 hPa, the vertical distribution of moisture was extremely dry with no availability of ice crystals (Fig. 5.35).

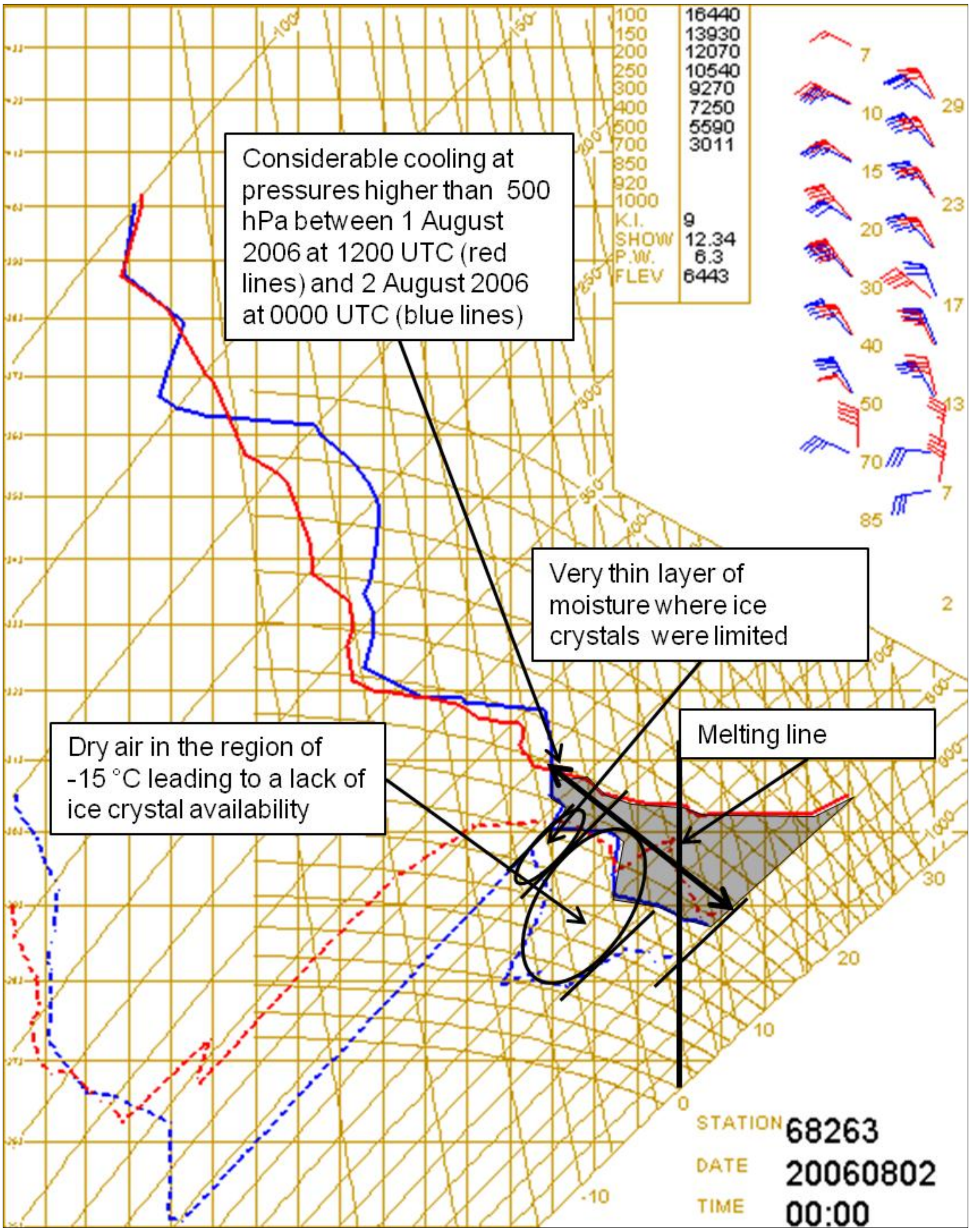


Figure 5.35: South African Weather Service Irene tephigram for 2 August 2006 at 0000 UTC (blue lines and barbs) and 1 August 2006 at 1200 UTC (red lines and barbs); the solid lines are temperatures and the dotted lines dew point temperatures

This is confirmed by the satellite image in Fig. 5.36 at 0200 UTC, indicating that there was no mid-level ice cloud available over Johannesburg. Surface conditions were cold enough (see Fig. 5.33) for snow to reach the ground with the height of the melting level at 270 m a.g.l (see Fig. 5.35) but significant snow did not occur because of a lack of precipitating ice clouds.

On 2 August 2006 at 0200 UTC, when snowfall was reported from De Aar, cloud top temperatures were in the range of -10 °C to -40 °C. This made the atmosphere conducive to the availability of ice crystals (Fig. 5.36). At 0200 UTC in Bethlehem, snow was also being reported with cloud top temperatures in the region of -10 °C to -20 °C. At Bloemfontein, most ice cloud was still to the south of the city.

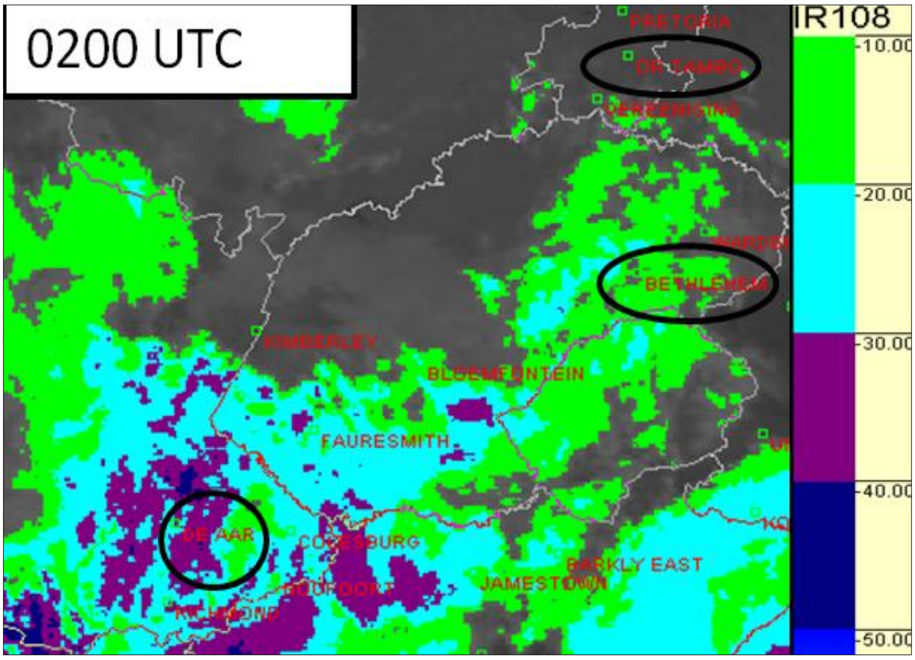


Figure 5.36: MSG satellite, IR 10.8 false colour for 2 August 2006 at 0200 UTC for De Aar, Bethlehem and OR Tambo International Airport (Johannesburg) © (2012) Eumetsat

On the 2 August 2006 at 0000 UTC, the COL was located between De Aar, Bloemfontein and Kimberley (Fig. 5.31 A) in a similar area to the one indicated in the satellite image of Fig. 5.37. The eastern part of the Northern Cape exhibits a bluish tinge, indicative of the cold air mass near the upper COL as well as the orange colour showing, the approximate location of the upper jet stream (Fig. 5.31 F and Fig. 5.37).

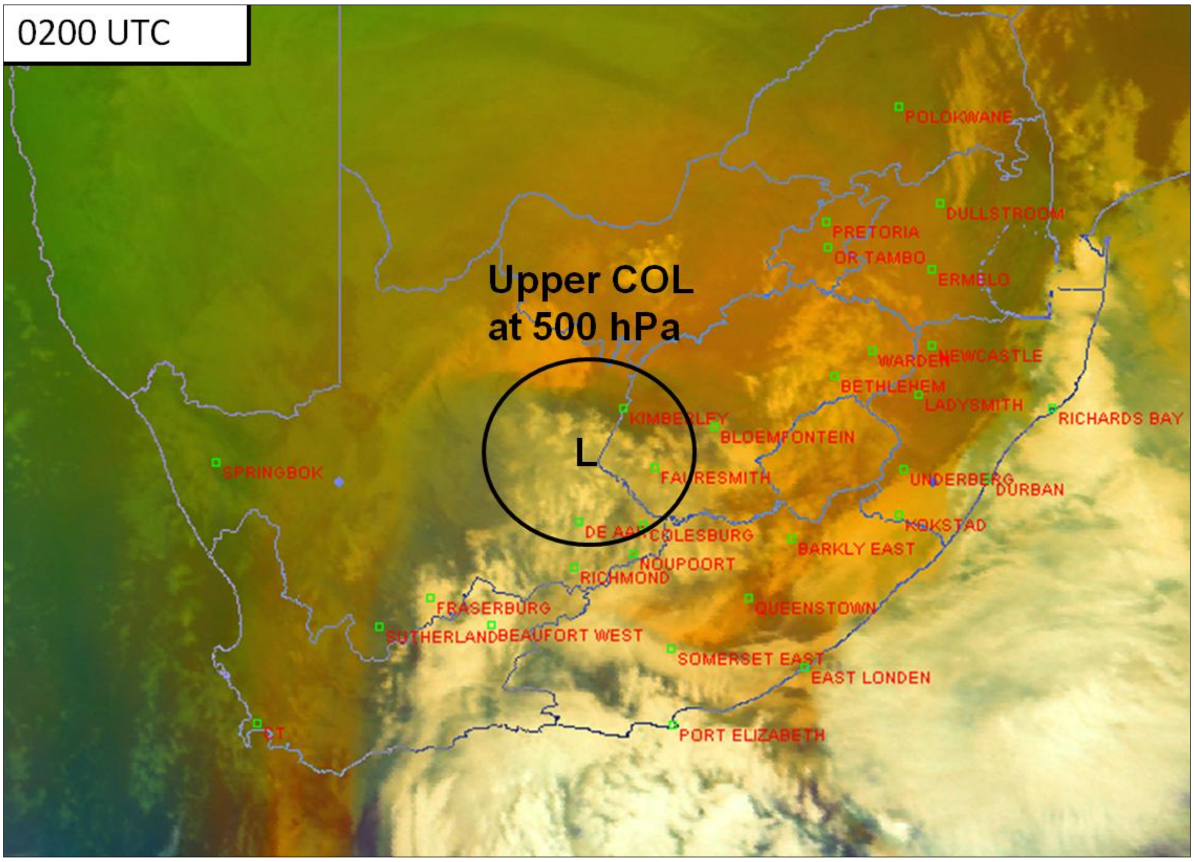


Figure 5.37: MSG satellite, Airmass RGB on 2 August 2006 at 0200 UTC indicating the position of the upper COL © (2012) Eumetsat

d. Partial atmospheric thickness

At this time, snowfall was occurring over De Aar and Bethlehem. The 850-500 hPa atmospheric thickness were below 4100 m (Fig. 5.38 A), the 850-700 hPa partial atmospheric thickness layer was below 1540 m (Fig. 5.38 B) and the 700-500 hPa partial atmospheric thickness was below 2560 m (Fig. 5.38 C).

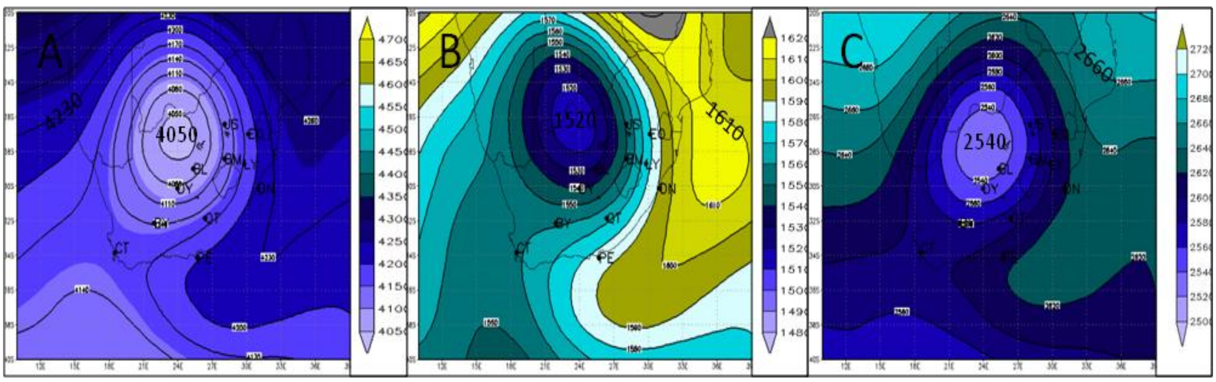


Figure 5.38: Same as Figure 5.27 but for 2 August 2006 at 0000 UTC

At Bloemfontein, partial atmospheric thickness were similar to De Aar and Bethlehem. However, because no ice clouds were present (Fig. 5.36) and the surface conditions were warmer, no snow occurred at this time. Therefore, partial atmospheric thickness cannot be used on their own to anticipate snow.

5.2.2.5 2 August 2006 at 0600 UTC

This period is discussed, since snow fell at Bloemfontein, Clarens, Fouriesburg, Harrismith, Paul Roux, Senekal, Bethlehem, Kestell, Ladybrand and Ficksburg (Volksblad, 2006a). It was the first snow in Bloemfontein since 1996 (Neethling, 2006). The synoptic circulation patterns will be discussed as the COL had moved over Bloemfontein in the presence of low level horizontal cold air advection but without vertical motion. The city of Bloemfontein will be discussed, indicating snowfall occurring at surface temperatures < 2 °C when the surface RH was 100%. The Bloemfontein tephigram is referred to in order to indicate the Passage of the cold front and COL and the availability of mid-level ice crystals. Satellite imagery is referred to, in order to validate the tephigram. The Bethlehem tephigram is used to indicate the vertical distribution of moisture throughout the troposphere, ensuring the availability of ice crystals. It is also used to indicate the Passage of the upper COL. The surface temperature and RH are used to emphasise snowfall in surface temperatures < 2 °C in the presence of 100% RH. When the temperature increased passed 2 °C, rain was reported. The city of Johannesburg is referred to in order to explain why snow did not occur when temperatures were close to 0 °C, surface RH close to 80% and low atmospheric thickness. Partial atmospheric thickness will be shown for Bloemfontein and Bethlehem, where snow occurred.

a. Synoptic circulation

On 2 August 2006 at 0600 UTC, the upper COL moved eastwards to be situated between Bloemfontein and Bethlehem over the Free State with the surface frontal low situated over the south-eastern part of the country near East London (Fig. 5.39 A). Cold air advection was prevailing over the De Aar, Bloemfontein and Bethlehem region as well as the north-eastern part of the Eastern Cape (Fig. 5.39 B). High amounts of RH > 80% (Fig. 5.39 C) was occurring in a similar area despite the little vertical motion.

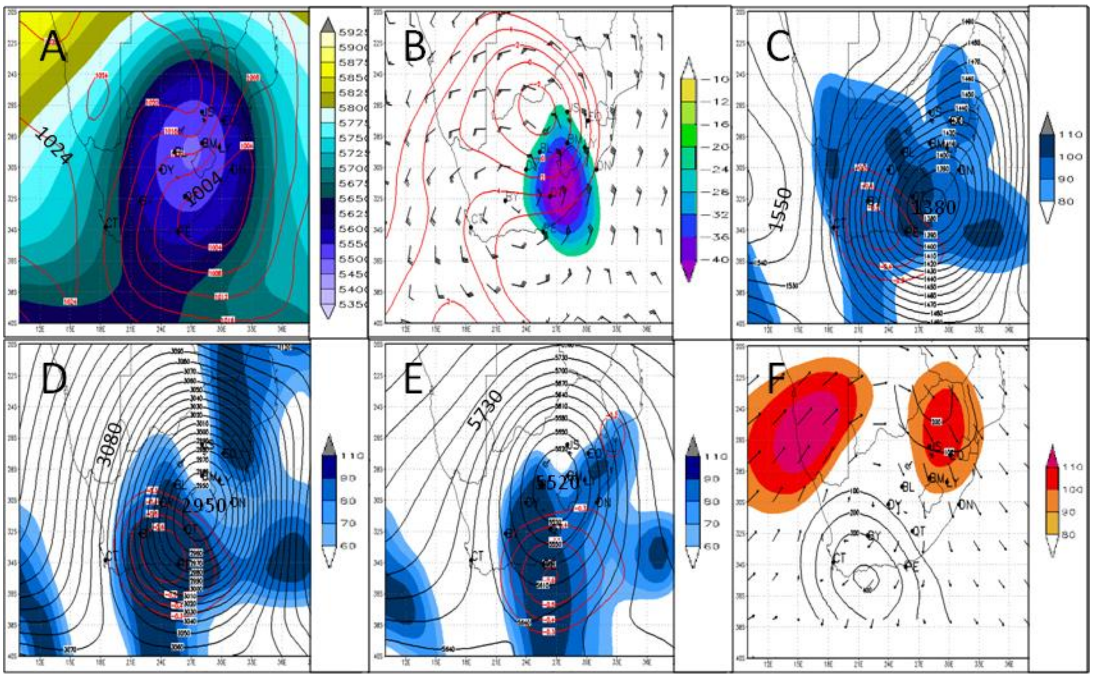


Figure 5.39: Same as Figure 5.23 but for 2 August 2006 at 0600 UTC

b. Surface observations

From 0200 UTC (Fig. 5.40) on 2 August 2006, it started to rain lightly at Bloemfontein with broken, low level cloud at 200 m a.g.l. Between 0300 UTC and 0400 UTC, drizzle was reported and at 0500 UTC, mist was reported. At 0600 UTC and 0700 UTC light drizzle, rain and snow was reported when the surface temperature dipped below 2 °C in 100% RH. At 0800 UTC and 0900 UTC, light drizzle was again reported when the surface temperature started to increase passed 2 °C.

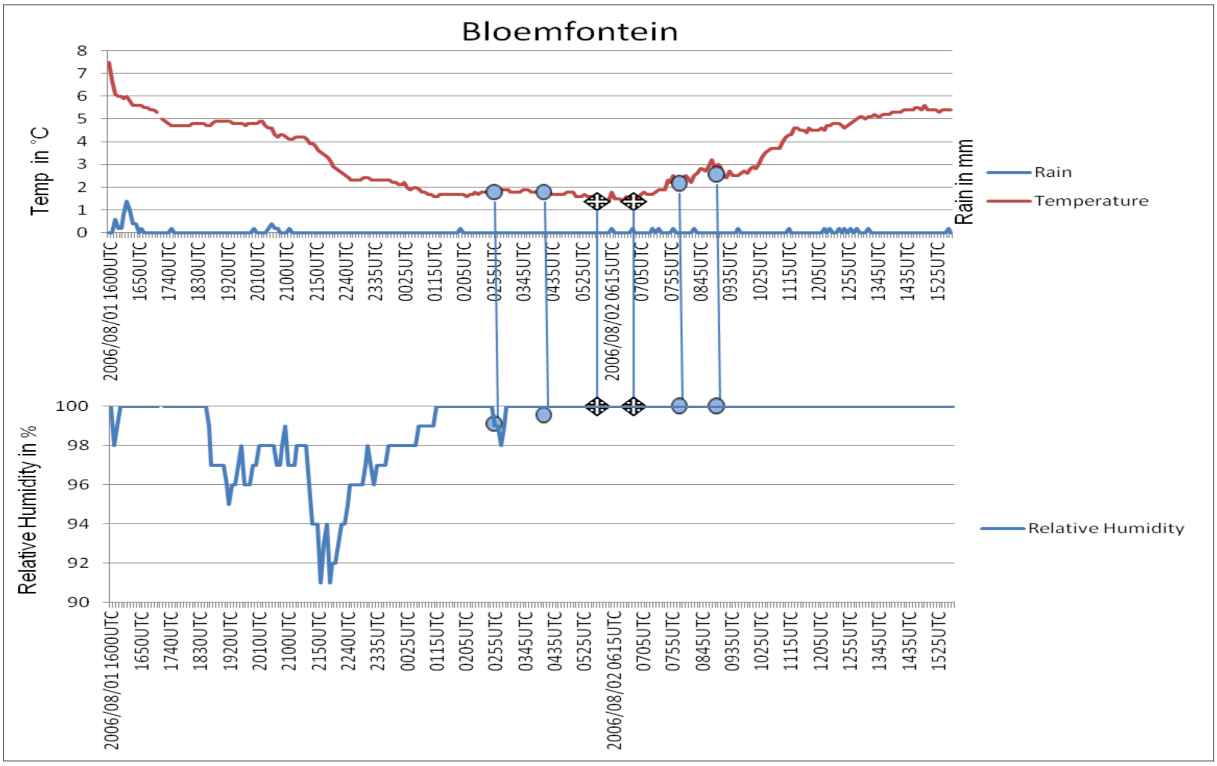


Figure 5.40: Same as Figure 5.26, but for South African Weather Service Bloemfontein weather station for 1 and 2 August 2006; the blue circle is a confirmed report of drizzle or light rain and the star is snow; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated.

During the time that it snowed at Bethlehem (Fig. 5.41), the surface RH was close to 100%. At 0300 UTC, there was a continuous fall of snowflakes when few Cumulonimbus clouds were reported and broken mid-level ice clouds at 2500 m a.g.l. From Fig. 5.36, it can be seen that at 0200 UTC, cloud top temperatures were between -10 °C and -20 °C indicating the presence of ice crystals. At 0600, 0800 and 1000 UTC, there was a light, continuous and intermittent fall of snowflakes (Fig. 5.41). At 0900 UTC, there were ice pellets and at 1100 and 1200 UTC, there was a continuous fall of snowflakes. It is important to note in this situation that, had the surface temperature been above 2 °C, it would not snow due to the melting of snowflakes in the high RH (see Section 3.2.4).

It was able to snow, because surface temperatures were close to zero despite the high surface RH. At 1300 UTC, there was rain when the temperature passed the 2 °C mark in surface RH of 100%.

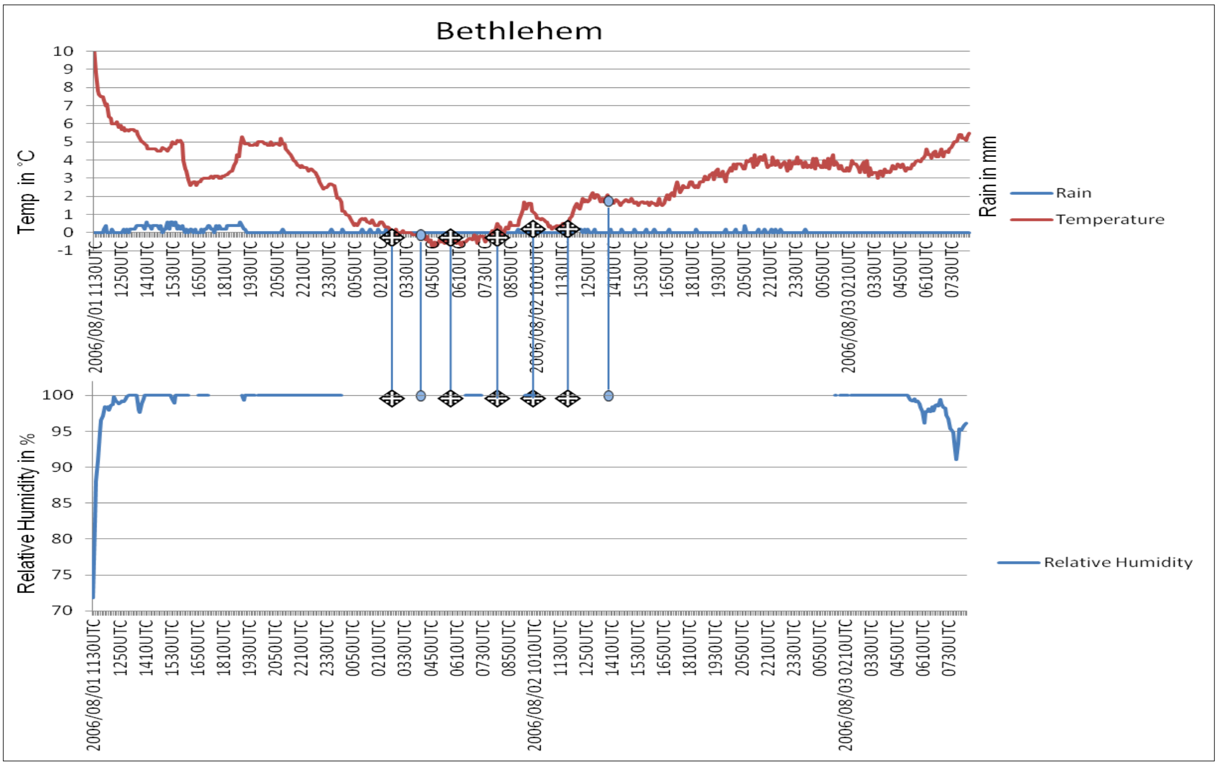


Figure 5.41: Same as Figure 5.26 but for South African Weather Service Bethlehem weather station for 1 August 2006 to 3 August 2006; the blue circle is a confirmed report of drizzle or light rain and the star is snow; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

c. Upper air observations

On 1 August 2006 at 0000 UTC, the height of the freezing level at Bloemfontein was still 3257 m a.m.s.l (not shown). On 1 August 2006 at 1200 UTC (red lines and barbs), it dropped to 2660 m a.m.s.l (Fig. 5.42 A). Between 1 August 2006 at 1200 UTC (red lines and barbs) and 2 August 2006 at 0000 UTC (blue lines and barbs) (Fig. 5.42 A), the vertical distribution of temperature cooled by more than 3 °C at pressures higher than 350 hPa, indicating the Passage of the cold front. The upper COL was still approaching with north-westerly winds in the upper air. At -15 °C (blue lines and barbs, Fig. 5.42 A) the air was moist but not saturated because the upper COL was still approaching.

On 2 August 2006 at 1200 UTC (blue lines and barbs, Fig. 5.42 B), the upper COL had passed Bloemfontein and the entire mid- and upper levels of the troposphere had moistened, creating a very good environment for the growth of ice crystals. However, at this time, no snow occurred because the surface conditions had warmed slightly to 5 °C in saturated surface conditions. Consequently snow that fell melted.

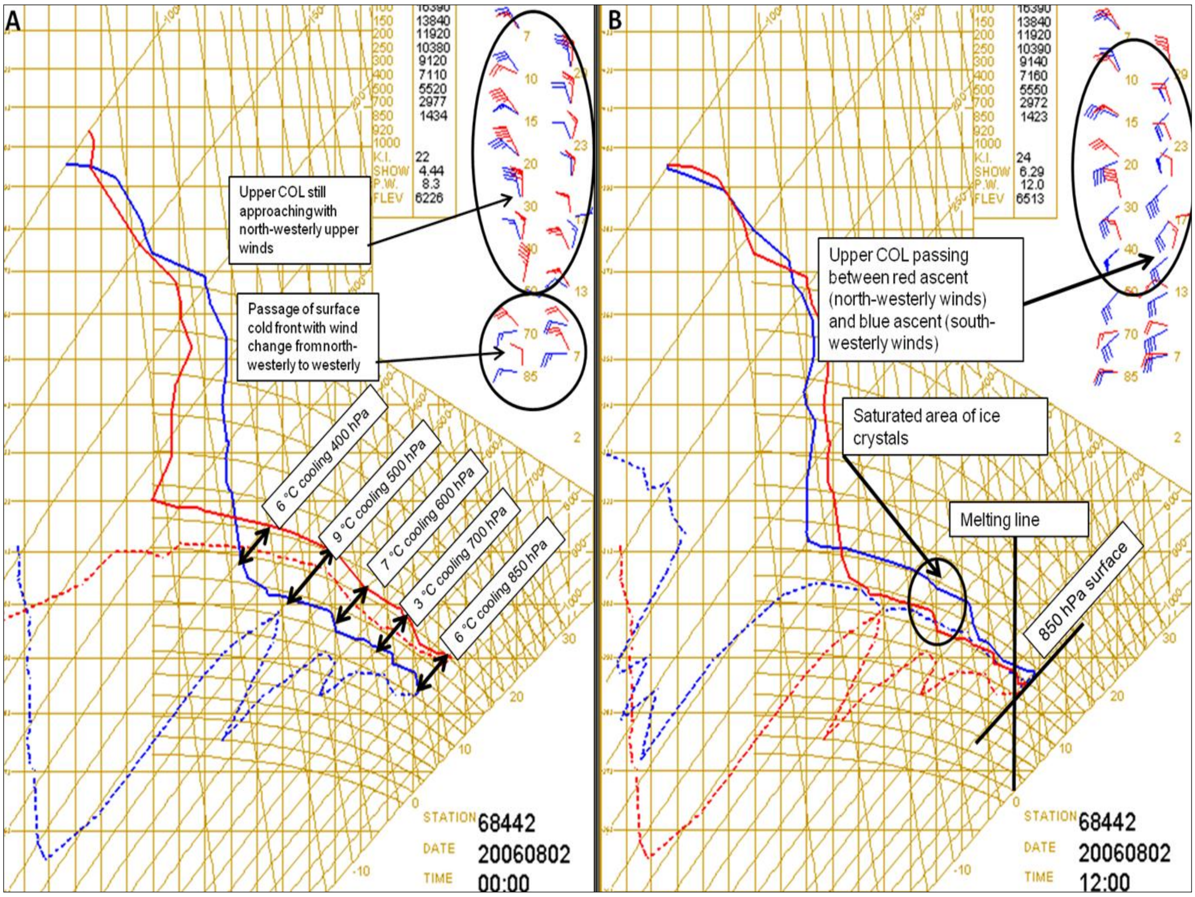


Figure 5.42: A): South African Weather Service Bloemfontein tephigram on 2 August 2006 at 0000 UTC (blue lines and barbs) and 1 August 2006 at 1200 UTC (red lines and barbs); and B): South African Weather Service Bloemfontein tephigram on 2 August 2006 at 1200 UTC (blue lines and barbs) and 2 August 2006 at 0000 UTC (red lines and barbs) (the solid lines are temperatures and the dotted lines dew point temperatures)

In Fig. 5.43, it can be seen that the temperatures of the cloud tops at 0700 UTC when it snowed at Bloemfontein (encircled), were around -20 °C (between -10 °C and -30 °C). This indicates the presence of ice in the cloud.

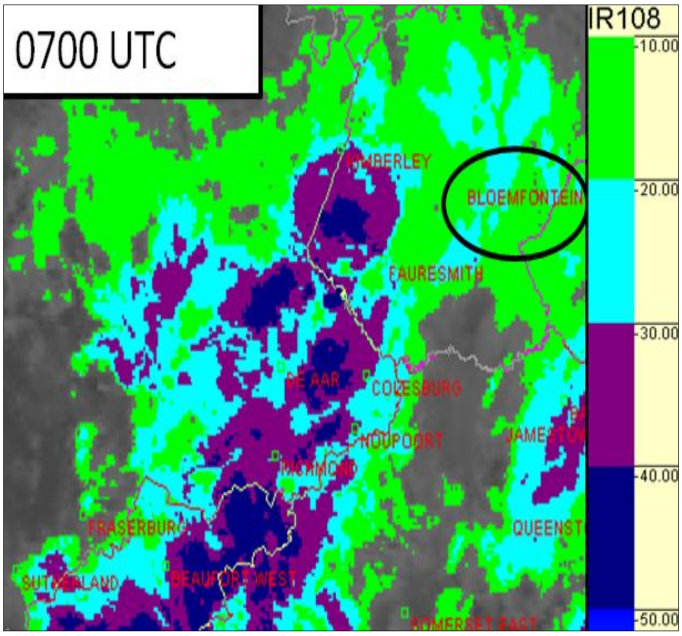


Figure 5.43: MSG satellite, IR 10.8 false colour for 2 August 2006 at 0700 UTC for Bloemfontein © (2012) Eumetsat

At Bethlehem, which is slightly higher elevated than Bloemfontein, the situation at this time (2 August 2006 at 1200 UTC) was different (Fig. 5.44). The surface cold front and upper COL passed between 1 August 2006 at 1200 UTC (green lines and barbs) and 2 August 2006 at 1200 UTC (blue lines and barbs). On 2 August 2006 at 1200 UTC, the air in the atmosphere was saturated at pressures higher than 450 hPa, resulting in Nimbostratus clouds extending down from the mid-levels to the surface. Consequently, there was sufficient ice crystals present around -15 °C which could grow by deposition and seed the lower level clouds so that snowflakes could further grow through aggregation and riming (see Section 1.4.2). At the surface, the height of the melting level was located at ground level, allowing the snowflakes to reach the ground in surface temperatures close to freezing.

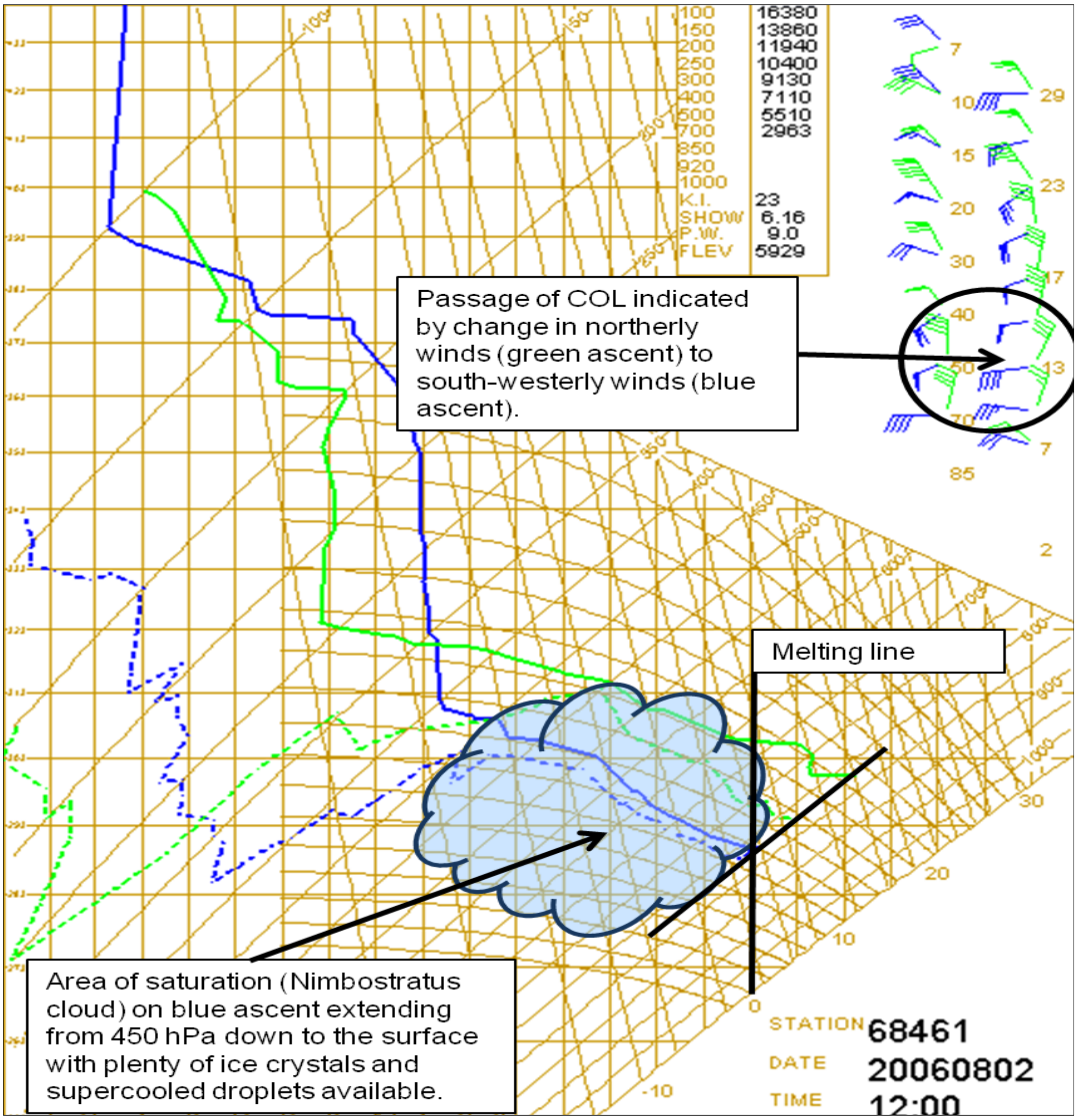


Figure 5.44: South African Weather Service tephigram for Bethlehem on 2 August 2006 at 1200 UTC (blue lines and barbs) and 1 August 2006 at 1200 UTC (green lines and barbs) (the solid lines are temperatures and the dotted lines dew point temperatures)

d. Partial atmospheric thickness

For the snowfall over the Bloemfontein and Bethlehem region, the atmospheric thickness for the 850-500 hPa layer were below 4100 m (Fig. 5.45 A), the 850-700 hPa partial atmospheric thickness was between 1540 and 1550 m (Fig. 5.45 B) and the 700-500 hPa partial atmospheric thickness was between 2540 and 2580 m (Fig. 5.45 C). During this time, the atmospheric thickness for Johannesburg were more favourable, yet it did not snow because of the reasons mentioned in section 5.2.2.4. Therefore, it is important not to consider atmospheric thickness in isolation when forecasting snow.

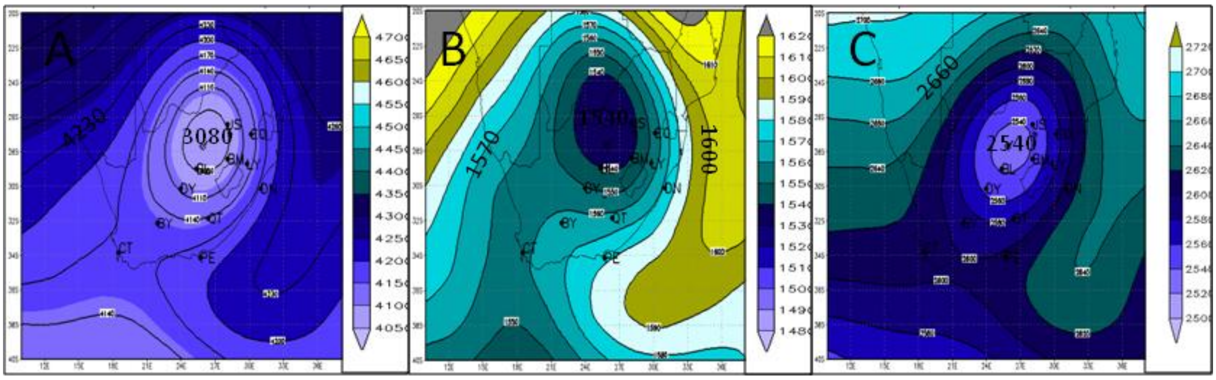


Figure 5.45: Same as Figure 5.27, but for 2 August 2006 at 0600 UTC

5.2.2.6 2 August 2006 at 1200 UTC

This period will be discussed, since snowfall was still being reported at Bethlehem and Barkly East in the north-eastern part of the Eastern Cape as the upper COL was moving through. Consequently, the synoptic circulation will be discussed. The town of Bethlehem will be discussed by referring to the partial atmospheric thickness thresholds during the snowfall. The surface and upper air observations for Bethlehem were discussed during the previous timeslot in section 5.2.2.5.

a. Synoptic circulation

At this time, snow was also reported from the Bethlehem weather office when the surface temperature and dew point were 0 °C (see Fig. 5.41). The upper COL continued to move eastwards over KZN, towards the surface low just to the east of the KZN coast, reducing the baroclinicity of the system and weakening it as a result (Fig. 5.46 A). The cold air advection was now limited to the area east of Bethlehem over southern KZN and the north-eastern part of the Eastern Cape where surface temperatures were still below 6 °C (Fig. 5.46 B). Moisture was still present over the aforementioned region (Fig. 5.46 C, D and E) with no vertical motion. The upper jet stream was exiting the country over Bethlehem and KZN where upper wind divergence was still occurring (Fig. 5.46 F).

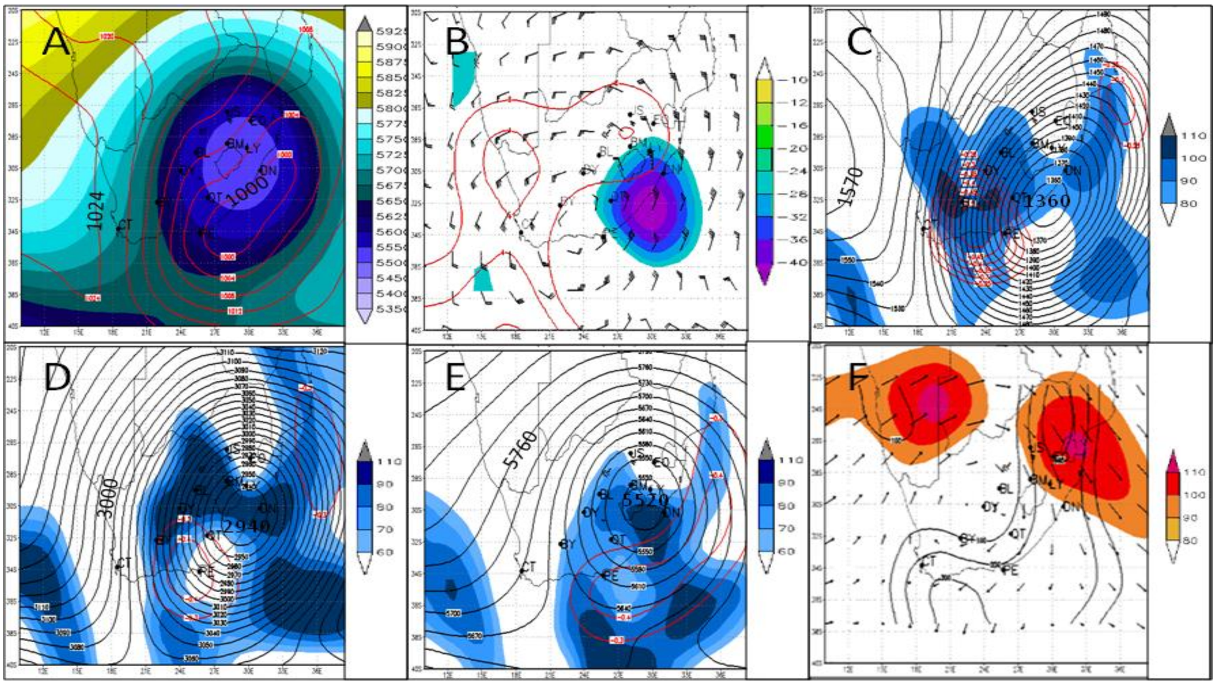


Figure 5.46: Same as Figure 5.23, but for 2 August 2006 at 1200 UTC

b. Partial atmospheric thickness

For snowfall over the Bethlehem region, the 850-500 hPa layer atmospheric thickness was 4120 m (Fig. 5.47 A), the 850-700 hPa partial atmospheric thickness was 1555 m (Fig. 5.47 B) and the 700-500 hPa partial atmospheric thickness was 2560 m (Fig. 5.47 C).

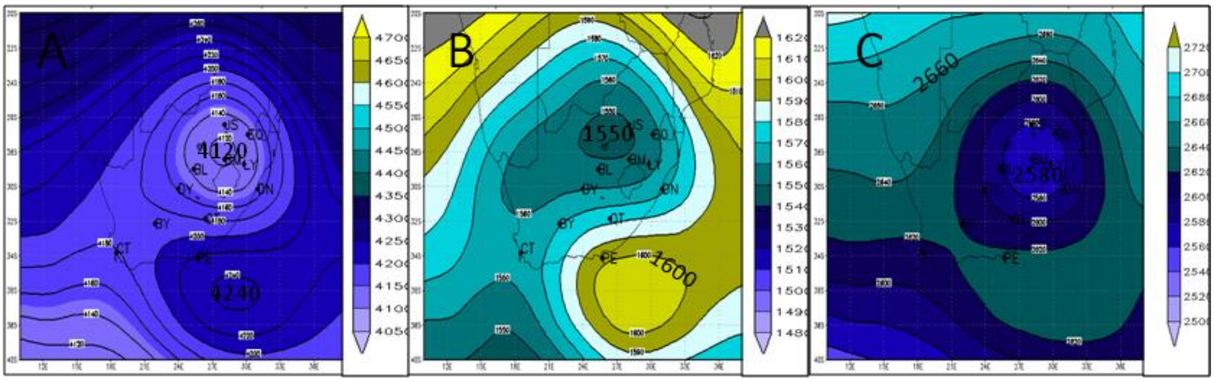
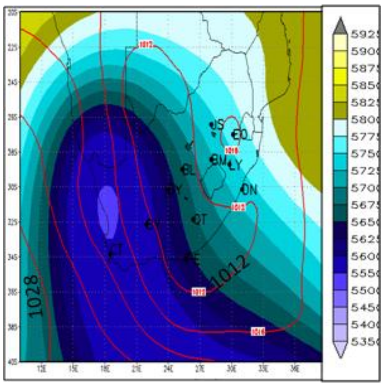
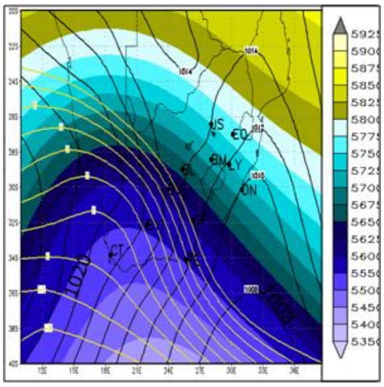
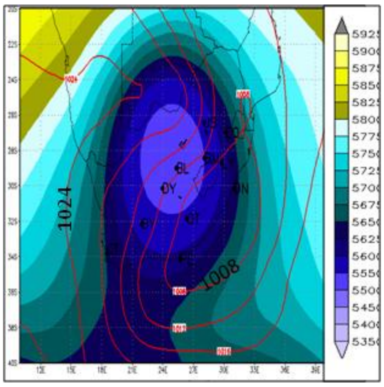
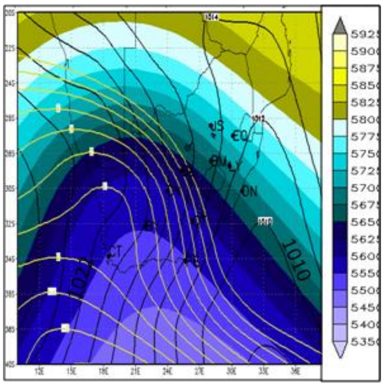
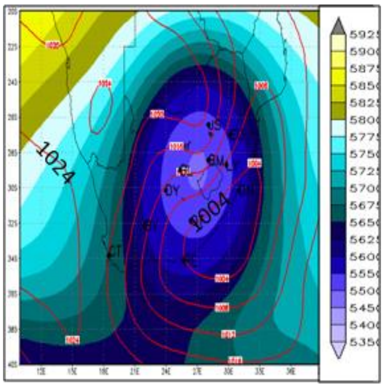
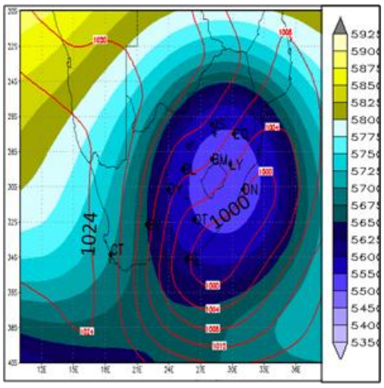
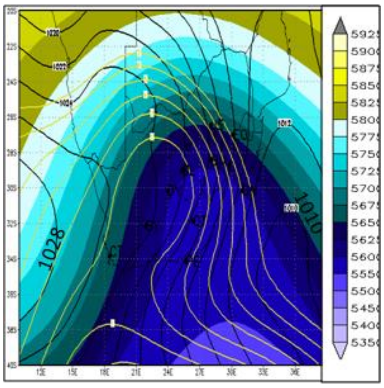


Figure 5.47: Same as Figure 5.27, but for 2 August 2006 at 1200 UTC

5.2.3 SOM node synoptic classification

This will be discussed in order to relate the synoptic classification of snowfall in Chapter 4.2 in Fig. 4.2 to the synoptic circulation of 1 and 2 of August 2006. This is indicated in Table 5.5.

Table 5.5: SOM node synoptic classifications for 1 and 2 August 2006

1 August 2006 at 0000 UTC 	Node 19 	
2 August 2006 at 0000 UTC 	Node 7 	
2 August 2006 at 0600 UTC 	2 August 2006 at 1200 UTC 	Node 1 

This particular case was mapped to node 1, 7, 13 and 19. The synoptic circulation on 1 August 2006 at 0000 UTC (Fig. 5.23 A) was mapped to node 19. This pattern appears similar to node 19, although the depth of the COL and the surface low on the south-east coast is not as intense due to the generalisation of patterns. The synoptic circulation of 2 August 2006 at 0000 UTC (Fig. 5.31 A) was mapped to node 7. This node 7 was frequently associated with snowfall during the month of August. The fundamental synoptic systems are indicated by the classification. The synoptic circulation of 2 August 2006 at 0600 UTC (Fig. 5.39 A) and 1200

UTC (Fig. 5.46 A) was mapped to node 1. Once again, similarities appear in the circulations although the cold core of the COL is not so pronounced.

5.2.4 Summary

In terms of the synoptic circulation, this case study was different to case study 1 in the following way. The AOH never ridged around the South African coast as was found in the previous case (right hook) (Hurry and Van Heerden, 1995). Instead, a surface low pressure system developed in association with the upper COL along the southern and south-eastern coast essentially blocking the ridging of the AOH pressure system.

This gave rise to the left hook circulation pattern. This acted to enhance the surface pressure gradient force between the surface frontal low and the AOH further to the west and was the main contributor for the horizontal cold air and moisture advection across the country, especially the western interior. This was particularly the case in Sutherland on 1 August 2006. Due to the nature and location of the surface low pressure system south-east of the country, the surface wind flow was south-westerly during the snowfall events which is more typically the flow behind surface cold fronts. This was different from case study 1 when it was south-easterly due to the large pressure advection from the AOH.

The function of the surface low along the south-east coast had a similar purpose to that of the ridging AOH of case study 1 and will not be discussed in detail. The vertical distribution of temperature was cold throughout the troposphere. The lower atmosphere was cooled due to the cold air advection caused by the combined effect of the surface frontal low south-east of the country and AOH west of the country.

In this particular case, a cold front approached Cape Town and moved through it, making the cold air easily identifiable ahead of time. In case study 1, the cold front developed over the country as is typically the case when a strong ridging surface AOH is present south-west of Cape Town. Snowfall was limited to the central plateau in this case (1500 m a.m.s.l) as compared to case study 1 where snowfall occurred to the east of the escarpment (see Section 1.2, Fig. 1.1). Snowfall to the east of the Drakensberg escarpment occurs if there is a strong pressure advection from the AOH in the presence of a COL.

This case study also highlights the following significant factors during snowfall and reinforces findings made in case study 1. A forecaster must not be blinded by the height of the freezing level a.g.l alone to make a snowfall forecast but also consider the boundary layer conditions. At De Aar, two vertical atmospheric ascents had the same low freezing level height, however one atmospheric ascent produced snow. This was due to unfavourable conditions on the ground. It is thus important to determine surface conditions and not just consider freezing level heights in isolation.

The availability of precipitating ice clouds needs to be considered when anticipating snowfall, despite boundary layer conditions being cold enough. In this case, partial thickness were low but no snow occurred. Very low atmospheric thickness do not necessarily imply snowfall. At Bloemfontein, partial atmospheric thickness were very low. Due to the fact that no ice clouds were present and the surface conditions were warmer, no snow occurred at this time. Partial thickness alone cannot be used to anticipate snowfall.

The COL and upper jet stream served the same purposes as discussed in the previous case study and they were found to be instrumental in the occurrence of snowfall.

The precipitation type (liquid versus frozen) was identified following the same method as case study 1, by considering the partial atmospheric thickness, the height of the freezing (melting level) a.g.l and the surface boundary layer conditions. For this particular case, the following partial atmospheric thickness in Table 5.6 were conducive to snowfall, which were lower than the case study of 25 and 26 July 2011.

Table 5.6: Atmospheric thickness (850-500 hPa, 700-500 hPa and 850-700 hPa) during snowfall for 1 and 2 August 2006

Thickness layer	850-500 hPa	700-500 hPa	850-700 hPa
Thickness values	4100 m and 4120 m	2560 m	1540 m and 1555 m

The height of the freezing level a.g.l was calculated from upper air sounding data (Tephigrams). In the case of Sutherland, an approximation was taken from the Springbok and Cape Town upper air ascent data. In the case of Sutherland and Bethlehem, the freezing level height was < 250 m a.g.l (Table 5.7). In the case of Bloemfontein, it was 503 m a.g.l although snow occurred six hours after the time of the vertical ascent which meant that it could have been lower at this particular time.

Table 5.7: Atmospheric thickness (850-500 hPa, 700-500 hPa and 850-700 hPa) and freezing level height per region per synoptic station during snowfall on 1 and 2 August 2006

Region	Station in metres a.m.s.l	Time in UTC	850-500 hPa thickness in m	700-500 hPa thickness in m	850-700 hPa thickness in m	Freezing level height in m a.m.s.l	Freezing level height in m a.g.l
South-western part of the Northern Cape	Sutherland (1458)	1 August 2006 at 0000, 1200 and 1800	4120	2560	1550	1702	244
South-eastern Northern Cape	(De Aar) (1287)	2 August 2006 at 0200	4100	2560	1540	2134	847
Southern and Central Free State	Bloemfontein (1395)	2 August 2006 at 0600 and 0700	4100	2560	1540	1898	503
Eastern Free State	Bethlehem (1666)	2 August 2006 at 0600, 0800, 1000, 1100, 1200.	4120	2560	1555	1807	142

In this particular case, snowfall occurred with surface temperatures as high as 1.5 °C and surface RH close to 100% (saturated air). In the case of Sutherland, surface temperatures were below 0 °C and the surface RH around 80%. Due to this lower surface temperature and RH, the melting temperature of the snowflakes increased to 1.3 °C (Table 5.8).

Table 5.8: Surface temperature, surface relative humidity and melting temperature during snowfall per region per synoptic station during snowfall on 1 and 2 August 2006

Region	Station in metres a.m.s.l	Time of snowfall in UTC	Surface temp in °C	Surface RH (%)	Melting temperature in °C
South-western Northern Cape	Sutherland (1458)	1 August 2006 at 0000	-0.9	79	1.3
South-western Northern Cape	Sutherland (1458)	1 August 2006 at 1200	- 1.1	80	1.3
South-western Northern Cape	Sutherland (1458)	1 August 2006 at 1800	0.4	94	0.3
South-eastern Northern Cape	De Aar (1287)	2 August 2006 at 0200	0.4	100	0
Central Free State	Bloemfontein (1395)	2 August 2006 at 0600	1.4	100	0
Central Free State	Bloemfontein (1395)	2 August 2006 at 0700	1.5	100	0
Eastern Free State	Bethlehem (1666)	2 August 2006 at 0600	-0.4	N/A	N/A
Eastern Free State	Bethlehem (1666)	2 August 2006 at 0800	0	N/A	N/A
Eastern Free State	Bethlehem (1666)	2 August 2006 at 1000	1.2	100	0
Eastern Free State	Bethlehem (1666)	2 August 2006 at 1100	0.2	N/A	N/A
Eastern Free State	Bethlehem (1666)	2 August 2006 at 1200	0.9	N/A	N/A

5.3 Case study 3: 26 and 27 June 2007

5.3.1 Introduction

In Bloemfontein, snow fell on 26[t] June 2007 around lunchtime. Snow was also reported in Rhodes, Sterkspruit, Aliwal North, Tarkastad and Barkly East (Daily News, 2007b). Snow fell late on the afternoon of the 26 June 2007 in parts of Klerksdorp. The previous snowfall in Klerksdorp was in 1996 (Damons, 2007). On the night of 26 June 2007, it snowed in the east and west of Johannesburg. Vereeniging, Heidelberg and southern Mpumalanga also had reports of snow. Johannesburg woke up to snow on the morning of 27 June 2007 for the first time in 25 years. At Phineas McIntosh Park (Brixton) and Zoo Lake (Parkview) people played in the snow. At Johannesburg International Airport, flights were delayed for three hours due to snow on the wings of the aircraft (Damons and Moses, 2007).

Heavy snow fell in the KZN midlands, especially at Nottingham Road, Rosetta, Mooi River, Kokstad, Underberg and Sani Pass (0.15 m). The R103 from Nottingham road to Mooiriver, the R617 from Underberg to Kokstad, the N2 (national route) from Port Shepstone to Kokstad and the R56 from Umzimkhulu to Kokstad had to be closed due to the snowfall,

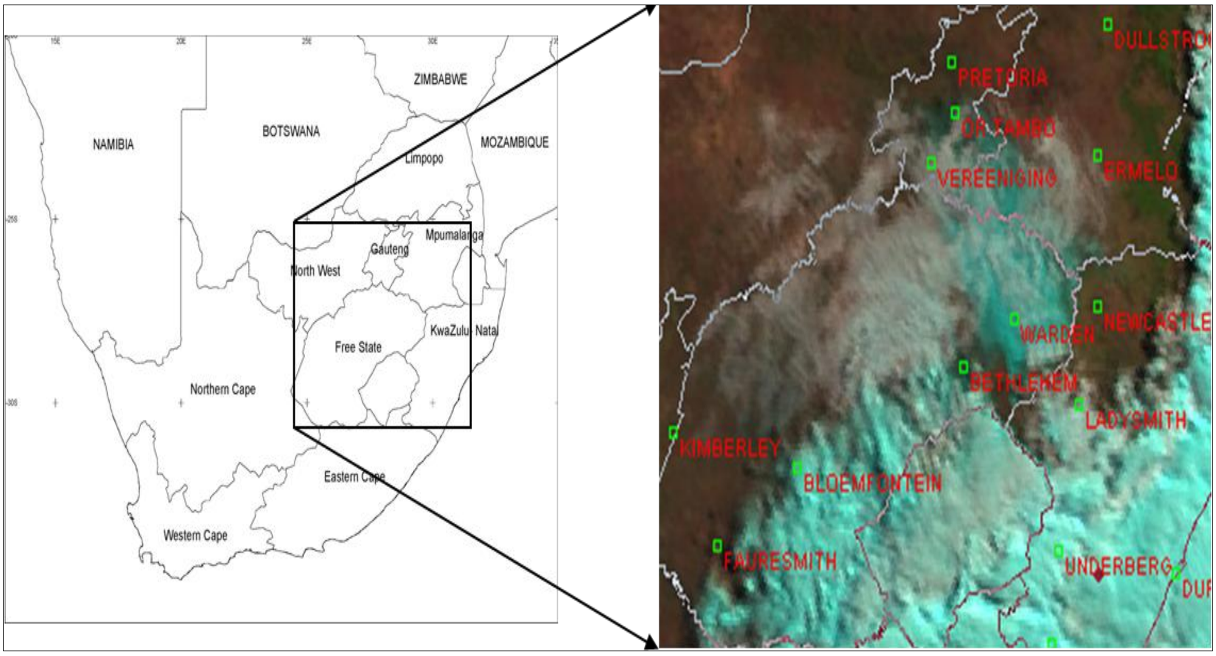


Figure 5.48: MSG satellite, Day Natural Colour RGB on 27 June 2007 at 0700 UTC; the cyan colour between Johannesburg, Bethlehem and Warden indicates snow on the ground in the area of interest © (2012) Eumetsat

Van Reenens Pass had to be closed on 27 June 2007 for two to three hours at 1330 UTC so that it could be made safe for vehicles. Halfway between Harding and Kokstad on the N2, the snow was a metre deep on the highway. The road outside Pietermaritzburg was closed for 44 km near Boston. The R103 between Nottingham Road and Mooiriver was also closed on the morning of 27 June 2007 (Liebenberg, 2007).

5.3.2 Atmospheric conditions during snowfall.

As snowfall occurred between 26 June 2007 at 1200 UTC and 27 June 2007 at 1200 UTC, this period will be discussed with reference to the regional distribution of snowfall. The importance of the large-scale synoptic circulation is emphasised as it provides the moisture and cold temperatures to form snowfall. The vertical temperature distribution and moisture content of the atmosphere which aid in the formation of snowfall are discussed. Partial atmospheric thickness, surface temperature and RH are important variables in snowfall and are discussed. Lastly, the SOM node synoptic classification of Chapter 4.2 is related to the case study synoptic circulation in order to show that the mapping was representative of the true synoptic situation within this case study.

5.3.2.1 26 June 2007 at 1200 UTC

This time step is discussed as the upper air pointed trough was developing into a COL and snowfall was occurring at Bloemfontein in the Free State. The surface conditions over Bloemfontein will be discussed to indicate that when the air was saturated with surface RH close to 100%, snowfall occurred in surface temperatures < 2 °C. At this time strong horizontal low level south-westerly cold air advection was occurring behind the cold front. The tephigram of Bloemfontein is referred to in order to explain the Passage of the cold front with the low level reversal in wind flow from north-westerly to south-westerly. This illustrates how snow occurred when the height of the melting level was below 300 m a.g.l. Satellite imagery is used to indicate the position of the surface front, upper COL and jet stream. The tephigram is used to compare ice cloud with that of the satellite image. Lastly, partial atmospheric thickness is referred to at Bloemfontein where the snow occurred.

a. Synoptic circulation

On 26 June 2007 at 1200 UTC, the cold front was Passing over the northern Free State extending down over the Eastern Cape into a low south of the country (Fig. 5.49 A and C). Associated with this cold front, was a pointed upper air trough situated over the Northern and Western Cape that was in the process of developing into a COL (Fig. 5.49 A). The AOH west of the country was starting to ridge south-west of Cape Town with cold air advection over the Free State, eastern part of the Northern Cape, southern KZN and the Eastern Cape occurring behind the cold front (Fig. 5.49 B). At 850 hPa, the frontal low was situated over Bethlehem (Fig. 5.49 C).

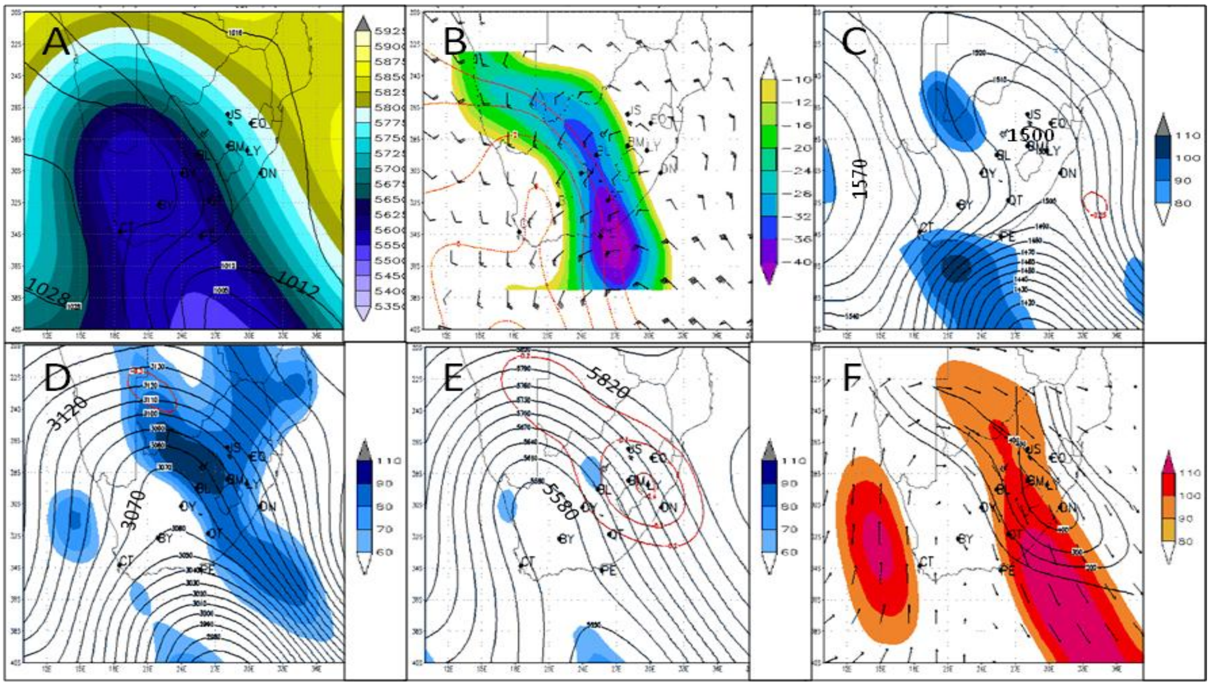


Figure 5.49: 26 June 2007 at 1200 UTC: A): mean sea level pressure in hPa black solid, 500 hPa geopotential heights shaded in metres; B): 850 hPa temperature < 6 °C in red, 850 hPa cold air temperature advection*10e^{6} in °C s^{-1} shaded, 850 hPa wind barbs in knots; C): 850 hPa relative humidity in % shaded, 850 hPa negative omega in Pa s^{-1} red, 850 hPa geopotential heights in metres solid black; D): 700 hPa relative humidity in % shaded, 700 hPa negative omega in Pa s^{-1} red, 700 hPa geopotential heights in metres solid black; E): 500 hPa relative humidity in % shaded, 500 hPa negative omega in Pa s^{-1} red, 500 hPa geopotential heights in metres solid black; F): 300 hPa jet stream > 80 knots shaded, 300 hPa wind divergence solid black (s^{-1})

The 700 hPa pointed trough that was located above the Northern Cape was associated with RH > 60% over the Free State, Gauteng, southern KZN and the eastern half of the Eastern Cape (Fig. 5.49 D). At 500 hPa, the pointed trough over the Northern Cape was coupled with vertical motion on its eastern flank, over the Free State, Gauteng, KZN and eastern half of the Eastern Cape (Fig. 5.49 E). The north-westerly jet stream was located over the Free State, Gauteng, western KZN and the eastern half of the Eastern Cape. Upper air wind divergence was occurring over the Free State and the Eastern Cape in the vicinity of the right exit region of the jet stream (Fig. 5.49 F) (see Section 2.3).

b. Surface observations

The surface cold front passed over Bloemfontein around 0535 UTC on 26 June 2007 (blue line and triangles in Fig. 5.50) .The wind direction changed rapidly from north-westerly to south-westerly with the surface temperature dropping rapidly after 0920 UTC due to the sustained south-westerly cold air advection (Fig. 5.50 and Fig. 5.49 B). Snow was confirmed during the 1130 UTC METAR and 1310 UTC SPECI reports when the wind direction was south-westerly and southerly respectively. In both observations, broken mid-level ice clouds at 2000 to 3000 m a.g.l which were caused by the upper COL were reported. At the time of the snow, the surface temperatures were between 1.3 °C and 1.5 °C while the surface RH was 100%. Since the surface temperatures were cold enough and the height of the melting level only 221 m a.g.l, snowflakes could make their way down to the ground despite saturated air at the surface (see Section 3.2.4). Snow was reported again at 1743 UTC and 1800 UTC when the surface temperature dropped below 2 °C and the surface winds were north-easterly (Fig. 5.50). Light snow was again reported at 0800 UTC on 27 June 2007 (not shown). The surface temperature then was 1.7 °C and the surface RH 100%.

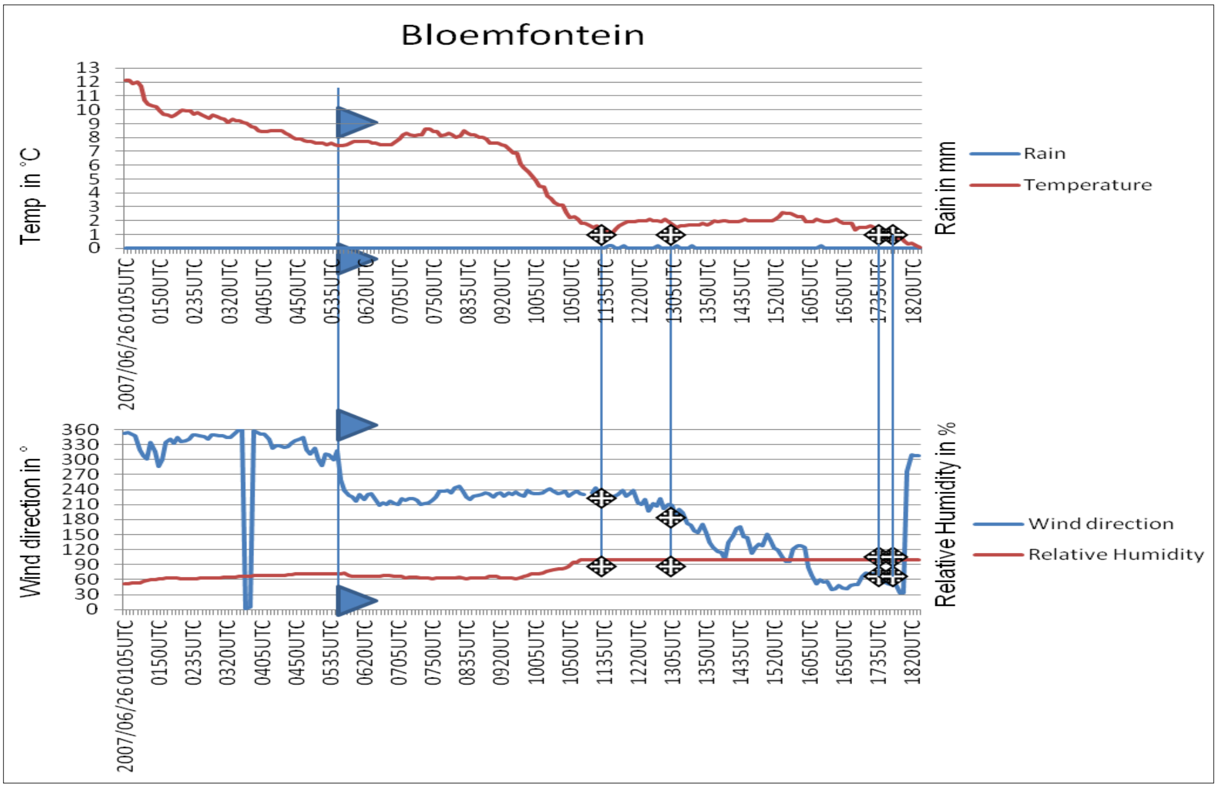


Figure 5.50: Temperature (°C), rain (mm), relative humidity (%) and wind direction (°) at the South African Weather Service Bloemfontein weather station on 26 June 2007; the stars indicate confirmed observations of snowfall and the blue line with triangles the cold front; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

c. Upper air observations and satellite imagery

The cold front passed over Bloemfontein between 26 June 2007 at 0000 UTC (red lines and barbs) and 26 June 2007 at 1200 UTC (blue lines and barbs) when considerable cooling occurred at pressures higher than the 350 hPa pressure level (shaded light blue) (Fig. 5.51) (note similar to surface cold front in Fig. 5.50).

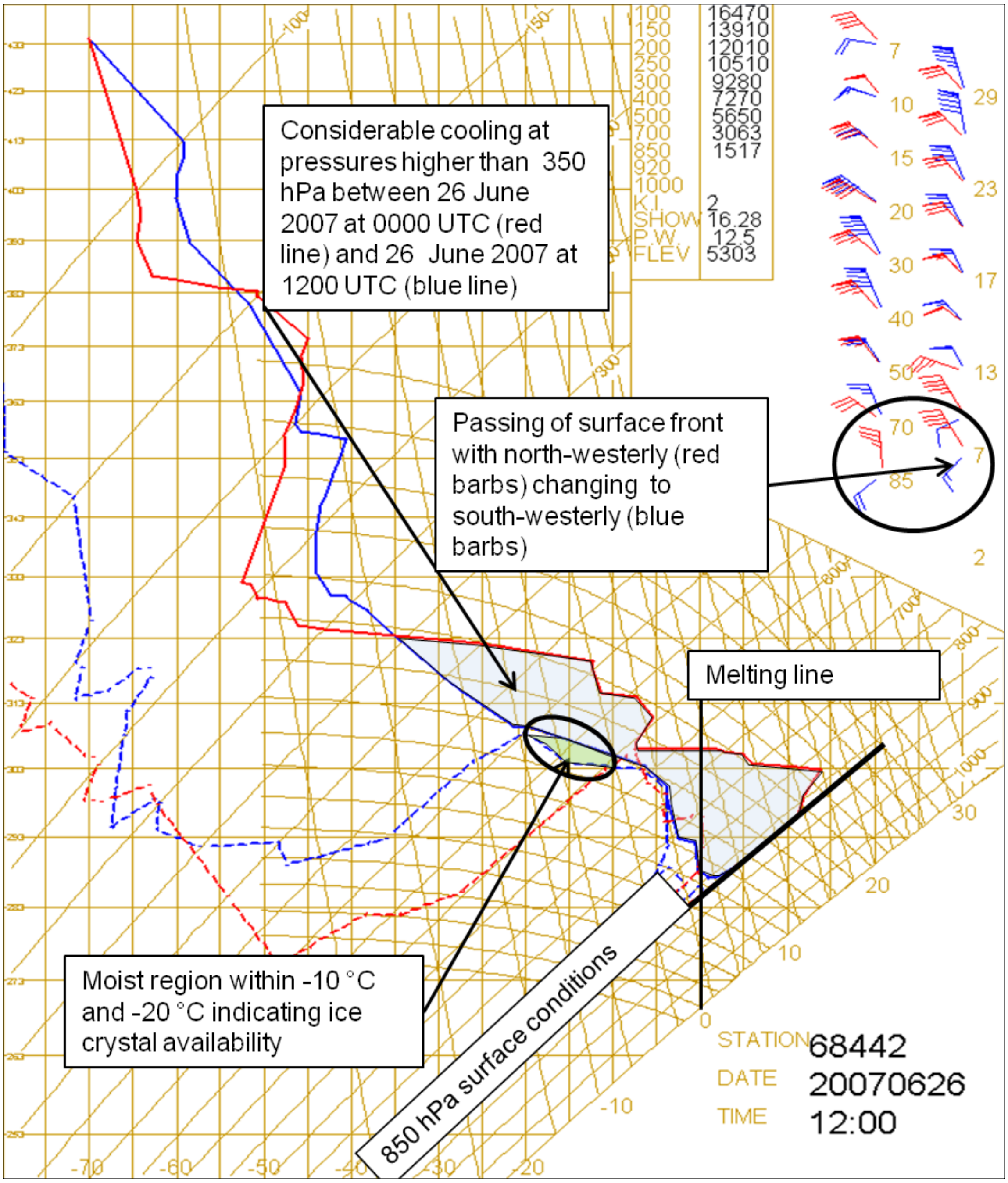


Figure 5.51: South African Weather Service tephigram for Bloemfontein on 26 June 2007 at 1200 UTC (blue lines and barbs) and 26 June 2007 at 0000 UTC (red lines and barbs) (the solid lines are temperatures and the dotted lines are dew point temperatures)

There was a pronounced wind shift at pressures higher than 700 hPa from north-westerly (red barbs) to south-westerly (blue barbs) indicating the Passage of the surface cold front during the morning (see surface data in Fig. 5.50 where the cold front passed at 0535 UTC). The height of the freezing level (melting level) dropped to 221 m a.g.l providing ideal near surface conditions for snowfall. The saturated air near -15 °C between 500 hPa and 600 hPa (green shaded) can be seen from the tephigram in Fig. 5.51 indicative of the presence of clouds containing ice crystals. The air in the atmosphere at pressures higher than 600 hPa between 0 °C and -10 °C was also saturated, allowing falling dendrite ice crystals to grow further into snowflakes by the process of aggregation (see Section 1.4.2).

Fig. 5.52 indicates cloud top temperatures between -10 °C to -20 °C over Bloemfontein (encircled) which was indicative of overcast ice clouds. This provided favourable upper air conditions for snow in agreement with the tephigram in Fig. 5.51.

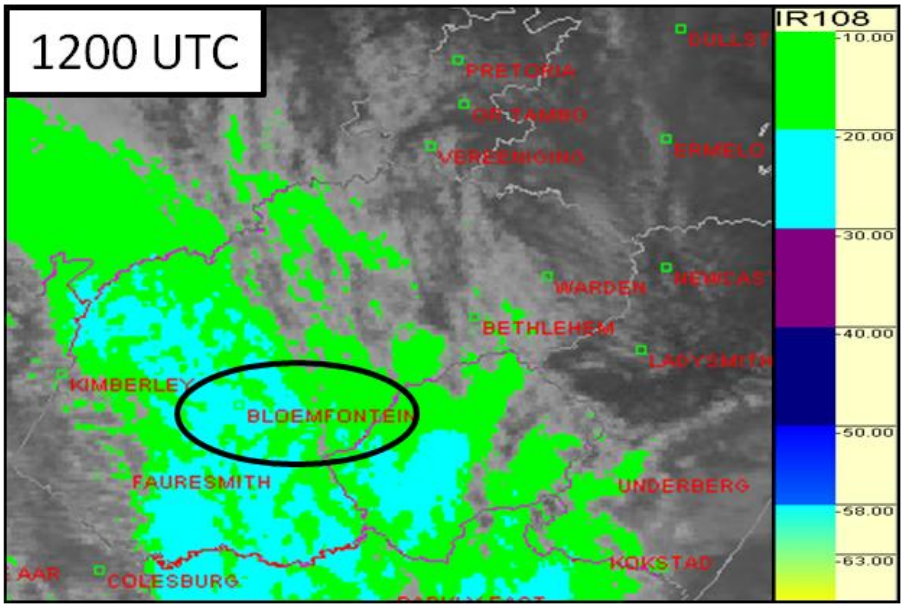


Figure 5.52: MSG satellite, IR10.8 false colour image for Bloemfontein (encircled) at 1200 UTC on 26 June 2007© (2012) Eumetsat

The Airmass RGB in Fig. 5.53 indicates that the COL was located at a similar geographic position at 500 hPa to that found in Fig. 5.49 A. The cold core is indicated by the bluish tinge in the Airmass RGB (encircled area of low pressure). The warm air mass (green) can be seen ahead of the cold front indicated by the light blue triangles. The orange colour in the image indicates horizontal advection of dry stratospheric air by the wind (Eumetsat, 2012). In this case, the south-westerly jet stream to the west of Cape Town and the north-westerly jet stream over the Free State just ahead of the cold front were responsible for this dry intrusion. This correlates well with the position of the jet stream in Fig. 5.49 F. The surface cold front was located below the large cloud band over the Free State and close to the upper north-westerly jet stream as indicated by the light blue triangles.

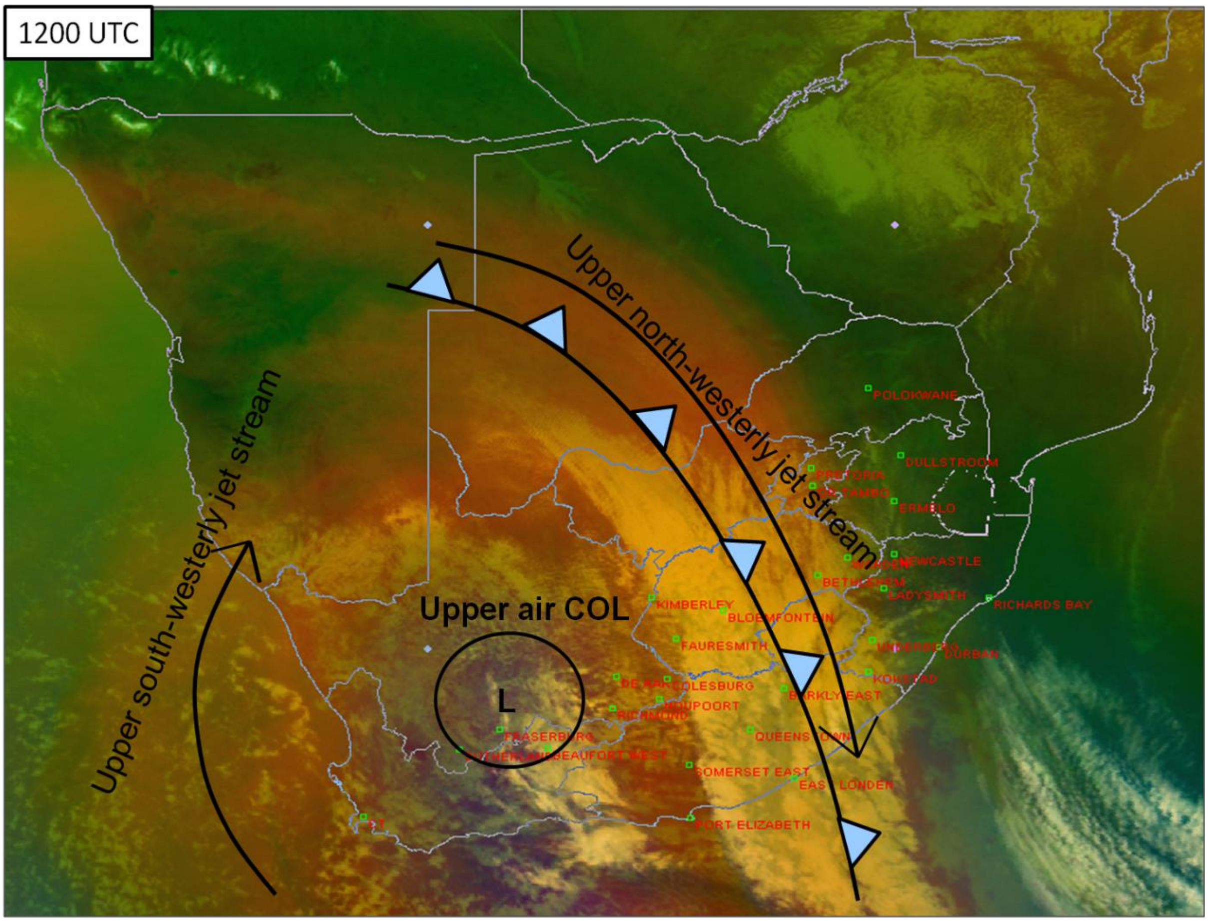


Figure 5.53: MSG satellite, Air Mass RGB for 26 June 2007 at 1200 UTC; the bluish colour indicates a cold air mass behind the cold front and within the cut-off low and the green colour a warm air mass; the orange colour indicates the location of the upper air jet stream and the blue triangles indicate the position of the surface cold front © (2012) Eumetsat

d. Partial atmospheric thickness

At Bloemfontein, where it snowed on 26 June 2007 at 1200 UTC, the 850-500 hPa atmospheric thickness were 4140 m (Fig. 5.54 A), for the 700-500 hPa partial atmospheric thickness it was 2550 m (Fig. 5.54 B) while for 850-700 hPa partial atmospheric thickness, it was 1560 m (Fig. 5.54 C).

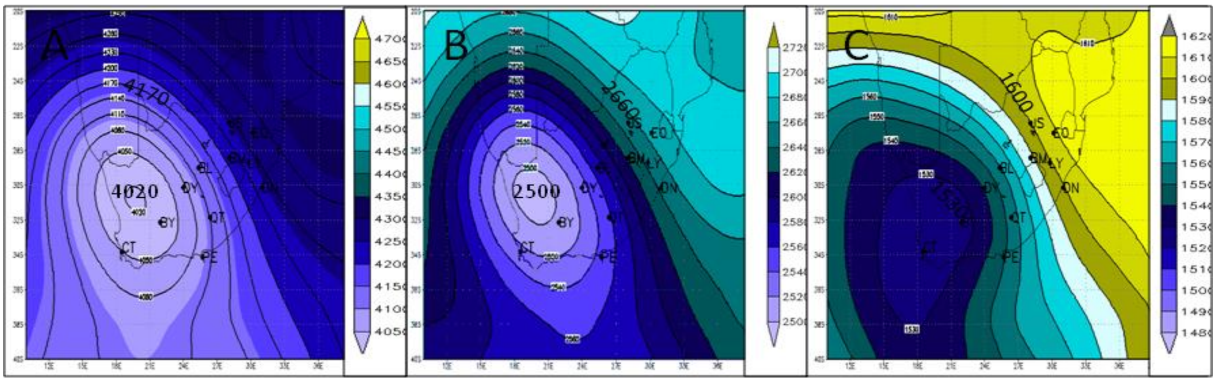


Figure 5.54: A): 850-500 hPa atmospheric thickness in metre; B): 700-500 hPa partial atmospheric thickness in metre; and C): 850-700 hPa partial atmospheric thickness in metre for 26 June 2007 at 1200 UTC

It is important to note that the area over Bloemfontein was not the region with lowest atmospheric thickness, but the area where a number of factors contributed to the occurrence of snow in the presence of low atmospheric thickness. These factors included availability of ice crystals, low atmospheric thickness and favourable surface conditions.

5.3.2.2 26 June 2007 at 1800 UTC

This time period will be discussed, since snowfall occurred at Bethlehem after the Passage of the cold front when there was significant low level cold air advection. The surface synoptic observations of temperature and RH will be discussed for the town of Bethlehem in order to indicate the occurrence of snowfall in temperatures below 2 °C when surface conditions are saturated (RH =100%). The tephigram of Bethlehem will be shown in order to indicate the reversal in wind direction from north-westerly to southerly throughout the troposphere with the Passage of the cold front and COL. This caused the subsequent lowering of the height of the freezing level closer towards the ground. The tephigram and cloud top temperatures in satellite imagery are referred to in order to indicate the occurrence of ice bearing cloud. Lastly partial atmospheric thickness values for Bethlehem are provided.

a. Synoptic circulation

The upper COL was situated between Beaufort West and De Aar in the Northern Cape with the surface AOH situated to the south-west of Cape Town (Fig. 5.55 A). Noteworthy cold air advection was occurring in the south-westerly wind flow behind the cold front over the Bloemfontein, Bethlehem, Johannesburg and Kokstad region (Fig. 5.55 B). In and to the south-west of this region, temperatures below 6 °C were occurring (Fig. 5.55 B). At 850 hPa, a small area of RH > 60% was located between Bloemfontein and Bethlehem south-eastwards towards Kokstad (Fig. 5.55 C). At 700 hPa, the COL was located just to the south-west of Bloemfontein with RH > 80% occurring on the eastern flank of this between Bloemfontein and Johannesburg south-eastwards towards Kokstad and the coast (Fig. 5.55 D). The COL was responsible for RH > 80% over the Bloemfontein and Bethlehem region down over Kokstad towards the coast (Fig. 5.55 E). Strong upper air wind divergence was occurring north and east of Bloemfontein in the vicinity of the right exit region of the north-westerly jet stream which was located over Johannesburg (Fig. 5.55 F).

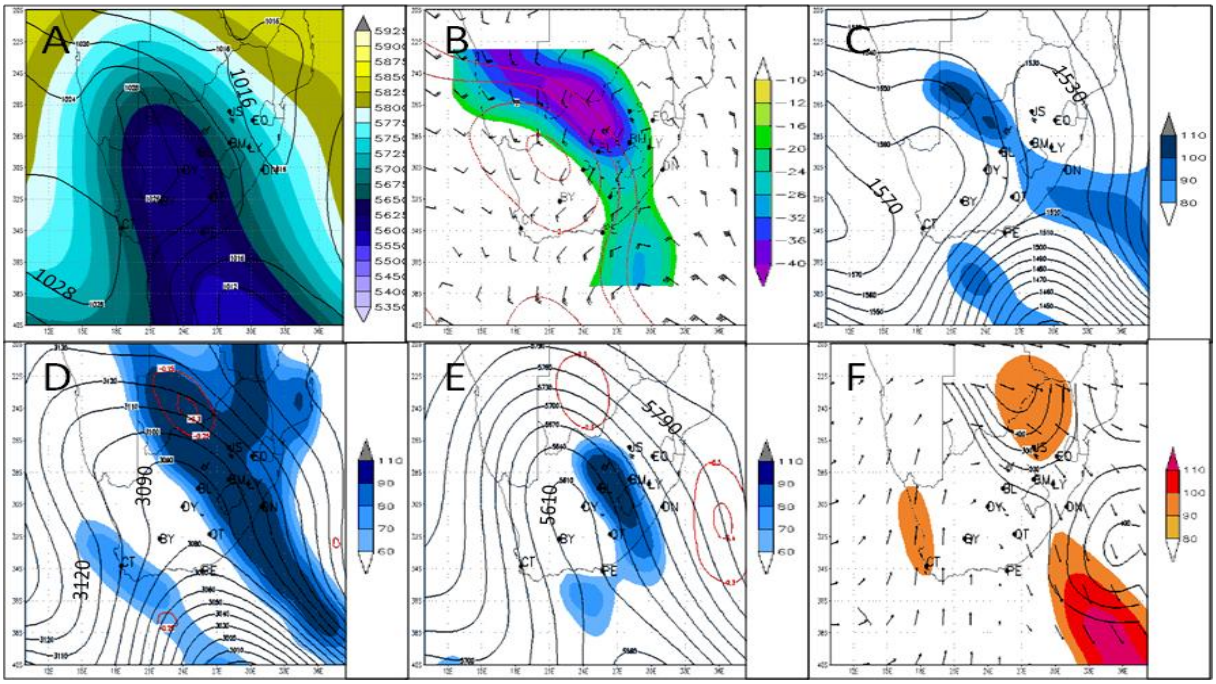


Figure 5.55: Same as Figure 5.49, but for 26 June 2007 at 1800 UTC

b. Surface observations

The surface cold front passed through Bethlehem at around 1400 UTC on 26 June 2007 when the surface wind direction changed to south-westerly and the surface temperature dropped dramatically at a rate of 14 °C in 4 hours (Fig. 5.56). It started to rain after 1600 UTC as the upper air COL approached. During this time, broken low level cloud at 500 m a.g.l and overcast mid-level ice clouds at 2000 m a.g.l were being reported. With surface temperatures below 1.8 °C at 1743 UTC and 1.2 °C at 1800 UTC, the rain turned into snow despite the RH being close to 100% (Fig. 5.56). It is important to note that this station closes after 1800 UTC and therefore snow could not be confirmed after this time, although the vertical distribution of temperature and moisture did support further snowfall. During the morning hours of 27 June 2007, the surface conditions were still favourable for snow but due to a lack of precipitating ice clouds, no snow occurred. Snow occurred again at 1200 UTC on 27 June 2007.

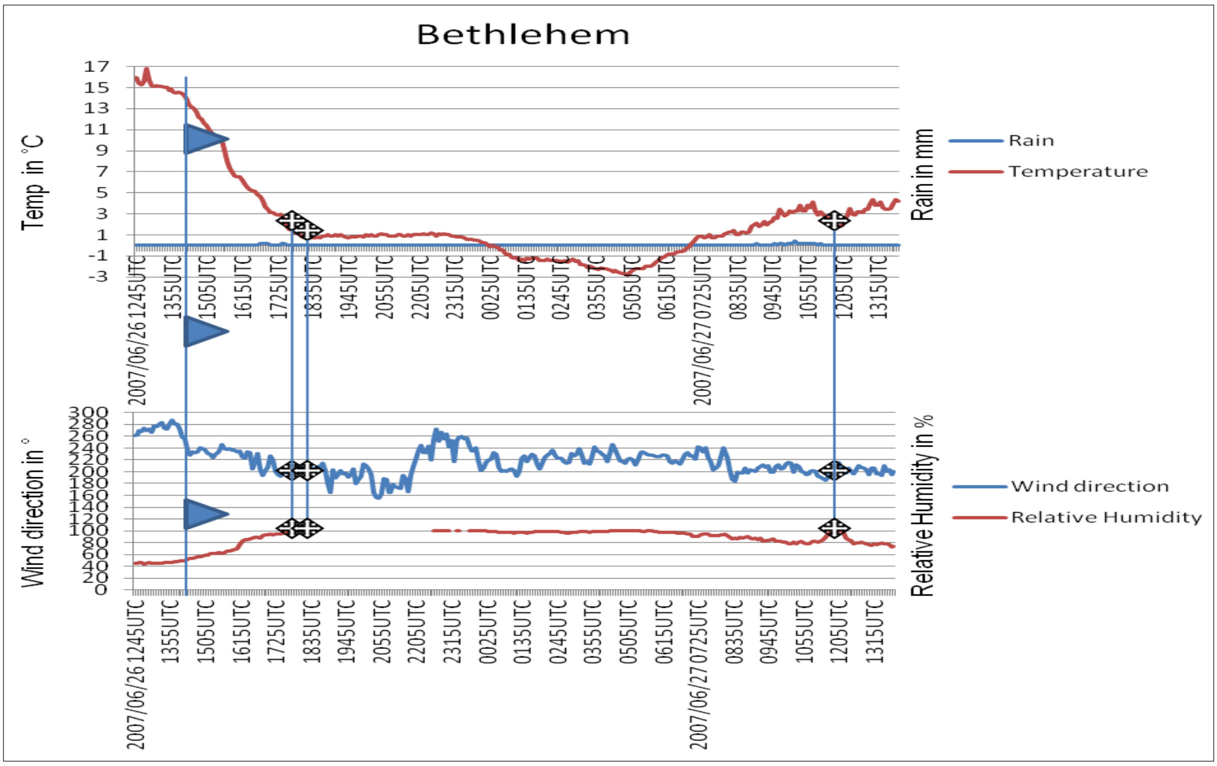


Figure 5.56: Same as Figure 5.50, but for Bethlehem on 26 and 27 June 2007; the stars indicate confirmed observations of snowfall and the blue line with triangles the cold front; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

c. Upper air observations and satellite imagery

The tephigram in Fig. 5.57 indicates that considerable cooling occurred from the surface up to 350 hPa in the vertical distribution of temperature (shaded region) between 26 June 2007 at 1200 UTC (green lines and barbs) and 27 June 2007 at 1200 UTC (blue lines and barbs). The passage of the surface cold front and upper COL through the station can also be seen in the vertical reversal of wind direction throughout the troposphere from north-westerly (green barbs) to south-westerly and south-easterly (blue barbs). On 27 June 2007 at 1200 UTC (blue lines and barbs), the vertical distribution of moisture indicated moist conditions in the region of -10 °C to -20 °C where ice clouds were present. At the same time, the height of the freezing level was virtually on the ground.

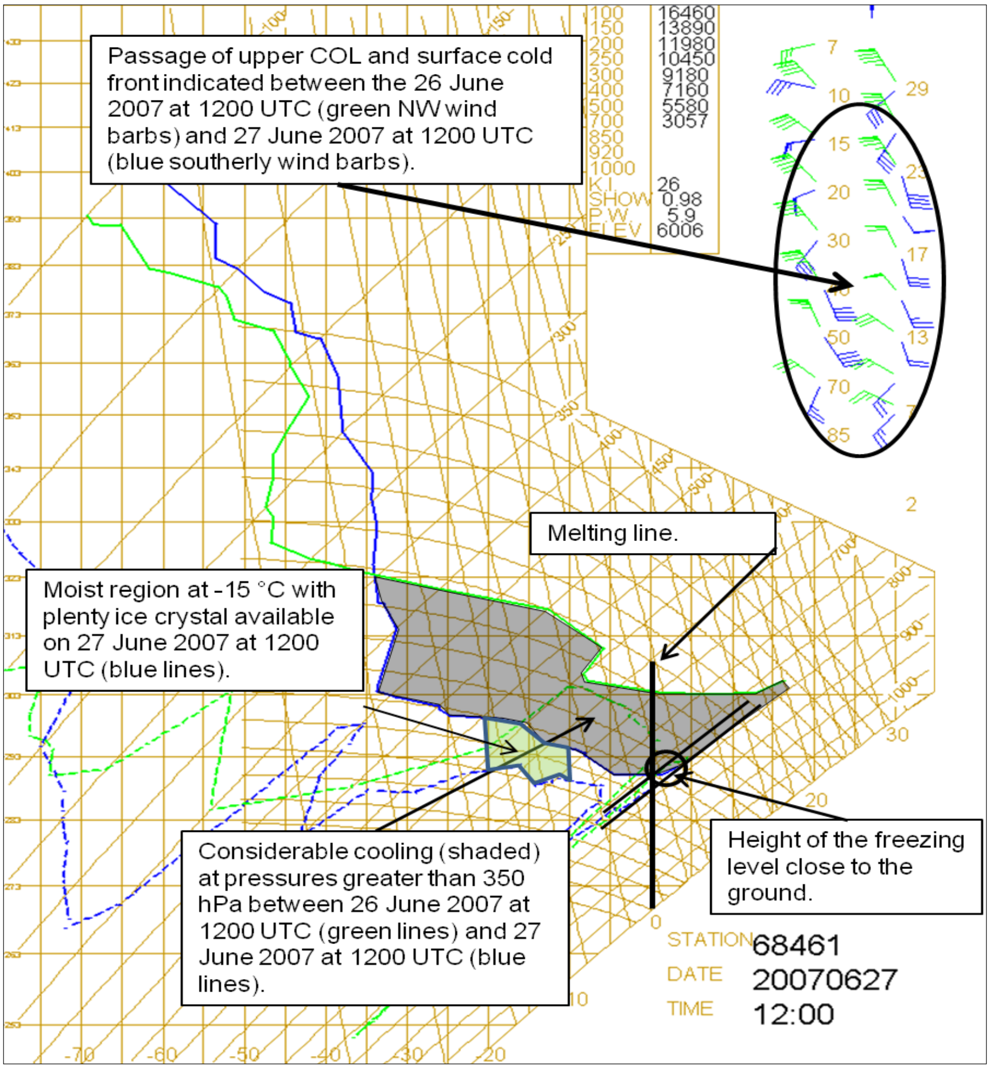


Figure 5.57: South African Weather Service tephigram for Bethlehem on 26 June 2007 at 1200 UTC (green lines and barbs) and 27 June 2007 at 1200 UTC (blue lines and barbs) (the solid lines are temperatures and the dotted lines dew point temperatures)

The cloud top temperatures over Bethlehem (encircled on Fig. 5.58) were around -20 °C as at 1800 UTC, indicating that conditions in the upper levels were conducive to ice crystals at Bethlehem.

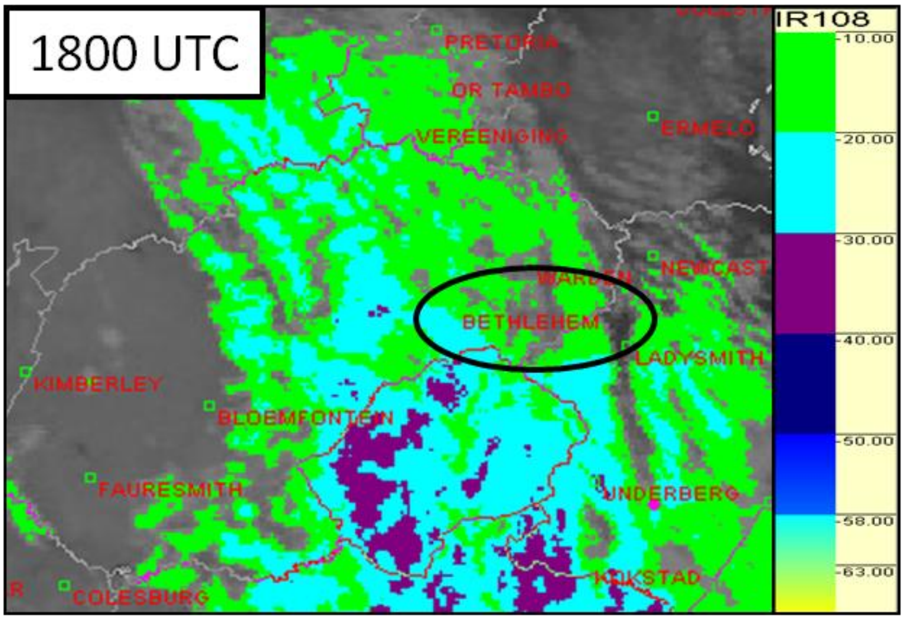


Figure 5.58: MSG satellite, IR10.8 false colour image for Bethlehem (encircled) at 1800 UTC on 26 June 2007© (2012) Eumetsat

d. Partial atmospheric thickness

When it was snowing at Bethlehem, the 850-500 hPa atmospheric thickness were 4150 m (Fig. 5.59 A), the 700-500 hPa atmospheric thickness were 2590 m (Fig. 5.59 B) and the 850-700 atmospheric thickness were 1570 m (Fig. 5.59 C). Note that the area where snowfall was occurring was not the area with the lowest atmospheric thickness. The lowest values were located to the west of De Aar.

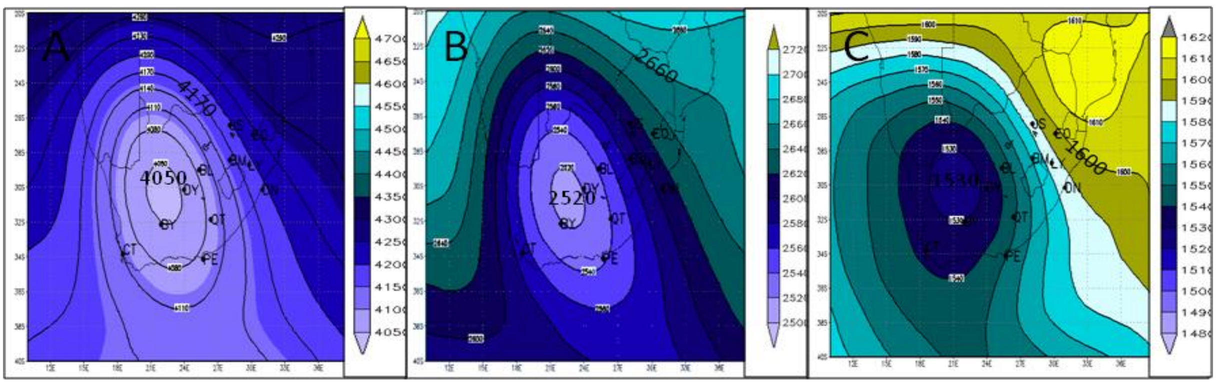


Figure 5.59: Same as Figure 5.54, but for 2 June 2007 at 1800 UTC

5.3.2.3 27 June 2007 at 0000 UTC

This time period is discussed as snow was occurring over Johannesburg (significant), Irene and Pretoria (light). The synoptic circulation is referred to because the COL was situated south-west of Johannesburg with large amounts of cold air advection occurring. The surface synoptic data of Johannesburg International Airport is used to indicate the passage of the cold front during the evening and the subsequent snowfall when surface temperatures were < 2 °C and surface RH close to 100%. The tephigram of Irene was representative of the snow and will be referred to in order to illustrate the passage of the cold front, the saturated air in the vertical distribution of moisture and the presence of ice crystals. Surface data from Irene will be shown to indicate snowfall at surface temperatures of <= 2 °C and 100% surface RH, while Pretoria will indicate snowfall at a surface temperature of 2 °C with a surface RH of 85%. Satellite imagery is used to reaffirm the presence of ice cloud over the snowfall area. The atmospheric thickness are shown and reveal that, when forecasting snow, one cannot identify low atmospheric thickness on their own.

a. Synoptic circulation

The upper COL had moved slightly south-eastwards to the south-eastern part of the Northern Cape and the north-eastern part of the Eastern Cape (Fig. 5.60 A). Strong cold air advection with surface temperatures below 6 °C was occurring over the North-West, Free State, Gauteng and southern KZN provinces behind the cold front (Fig. 5.60 B). To the south-west of the frontal trough between Johannesburg and Bloemfontein, RH > 60% was occurring due to the south-westerly onshore flow of moisture (Fig. 5.60 C). At 700 hPa, a pointed upper trough was present over the Free State into the Eastern Cape causing RH > 80% to the east of De Aar and Queenstown over the eastern interior. Vertical motion was confined to the south of Johannesburg, over the eastern Free State and western KZN (Fig. 5.60 D). At 500 hPa, the COL was situated between De Aar and Queenstown with RH > 80% to the east of this extending from Bloemfontein and Johannesburg south-eastwards over Bethlehem and Kokstad where vertical motion was also occurring (Fig. 5.60 E). The north-westerly jet stream was located over and to the north of Johannesburg causing large amounts of upper air wind divergence in the right exit region of the jet between Bloemfontein, Johannesburg, Bethlehem and southern KZN (Fig. 5.60 F).

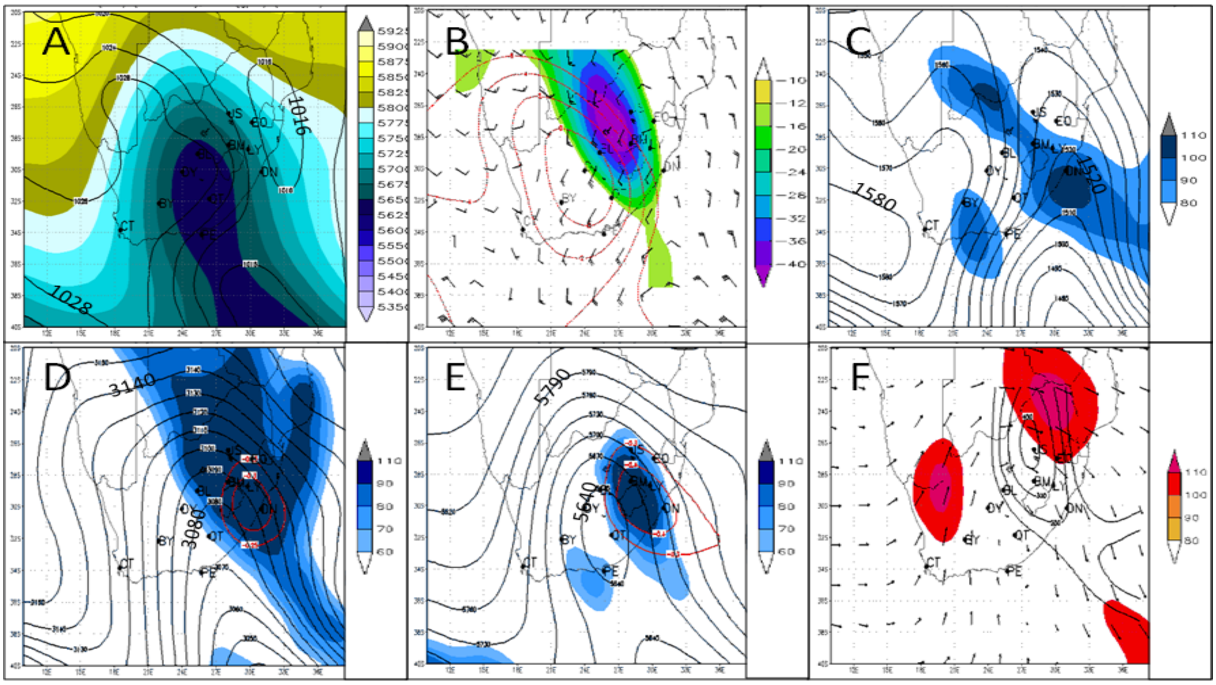


Figure 5.60: Same as Figure 5.49 but for 27 June 2007 at 0000 UTC

b. Surface observations

Fig. 5.61 indicates that the cold front passed through Johannesburg International Airport around 1700 UTC on 26[t] 2007 when the surface wind direction suddenly changed from a warm north-westerly to a cold southerly flow. As a consequence, the temperature drastically dropped as a consequence from 13 °C to below 6 °C due to the passage of the cold front (blue triangles). During the course of the night, the temperature continued to drop and a light continuous fall of snowflakes started at 2219 UTC when the surface temperature had reached 0.8 °C. It continued to snow until just after 0000 UTC. During this time, broken low clouds were reported between 200 to 300 m a.g.l and another layer of overcast cloud at 600 m a.g.l. At 0000 UTC, on 27 June 2007 broken Altostratus/Nimbostratus (ice clouds) were reported. During the period that snow was falling, the surface temperature was < 2 °C, the RH close to 100% and southerly winds were blowing. After the snowfall and up to 0800 UTC on 27 June 2007 surface temperatures remained < 2 °C, however, no further snowfall occurred. This is because the mid-level ice cloud which was causing the precipitation had cleared. This illustrates the importance of considering the entire troposphere when considering snowfall.

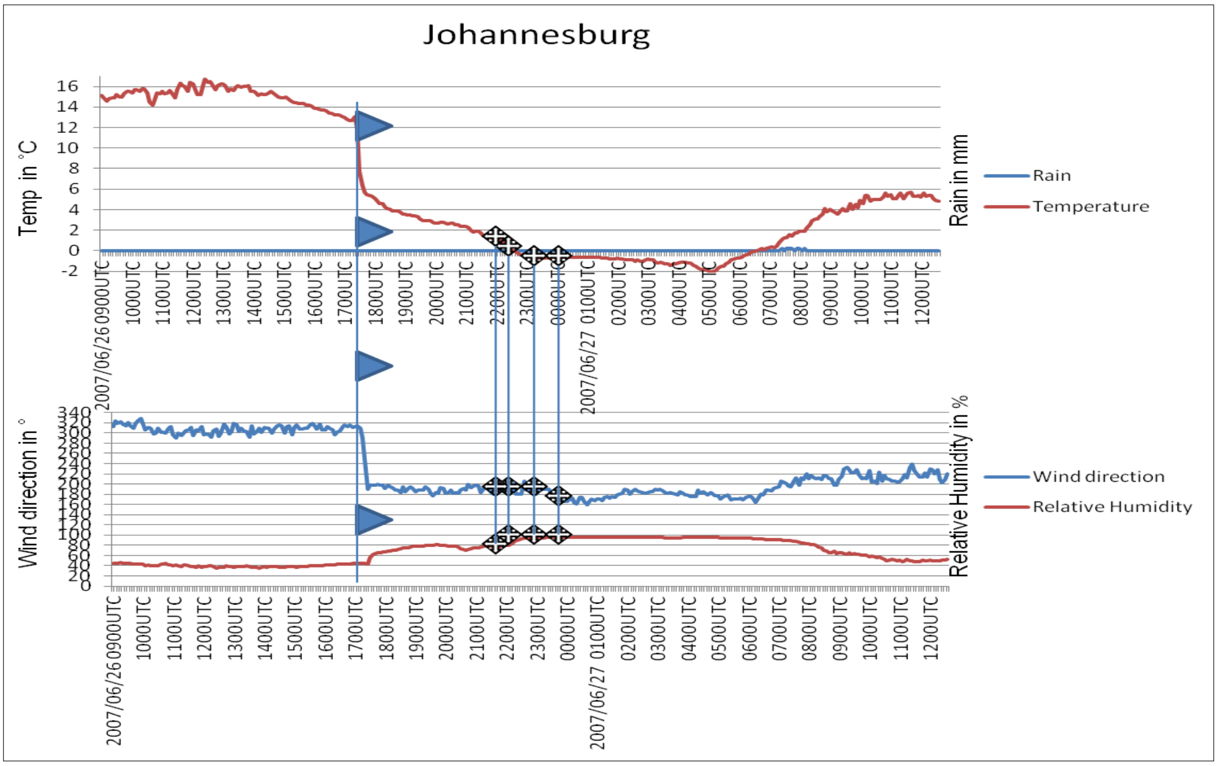


Figure 5.61: Same as Figure 5.50, but for South African Weather Service Johannesburg weather station on 26 and 27 of June 2007

At Irene weather office, recent snow was reported at 2300 UTC on 26 June 2007 up to 0000 UTC on 27 June 2007. During this time, scattered low level stratus cloud at 300 m a.g.l were being reported and broken mid-level clouds (Altostratus) at 3000 m a.g.l. This mid-level cloud is typically the cloud that contains ice crystals. At 0100 UTC on 27 June 2007, light, continuous snow was reported with snow also having been reported during the previous two hours. During the snowfall, surface temperatures dropped to < 2 °C while surface RH was between 85% and 92%. During the snowfall, the surface winds were southerly. From 0200 UTC to 0600 UTC, surface conditions remained favourable for snowfall. However, cloud conditions had cleared with no further chance of precipitation, similar to Johannesburg International Airport.

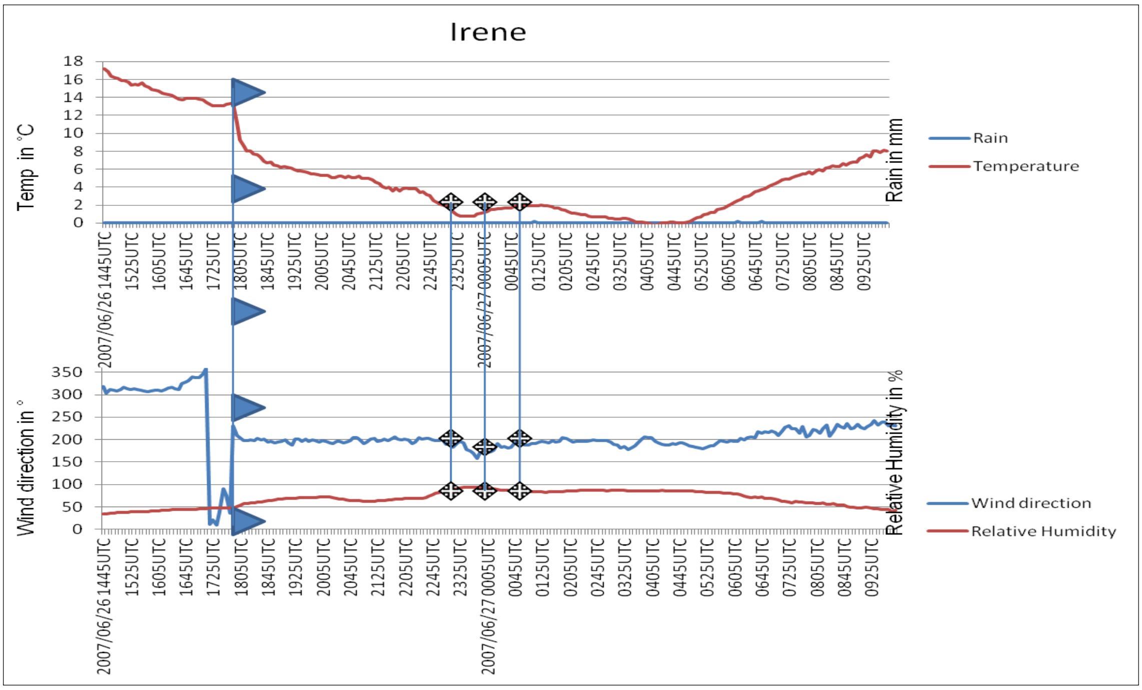


Figure 5.62: Same as Figure 5.50, but for South African Weather Service Irene weather station for 26 and 27 June 2007

In Pretoria, recent snow was reported in the 0000 UTC METAR and the 0200 UTC METAR on 27 June 2007.

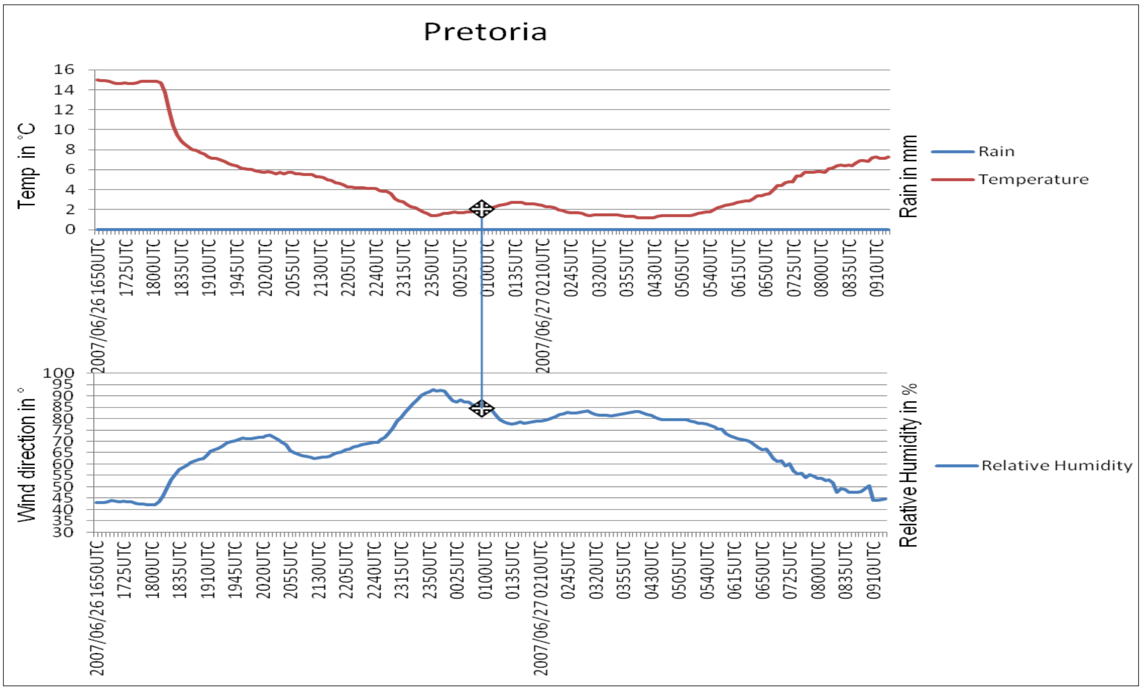


Figure 5.63: Temperature (°C), rain (mm), relative humidity (%) and wind direction (°) at the South African Weather Service Pretoria weather station on 26 and 27 June 2007 (the stars indicate confirmed observations of snowfall)

There were scattered stratus clouds reported at 300 m a.g.l and broken Altostratus clouds (ice cloud) at 1500 m a.g.l. At 0100 UTC, there was light and continuous snow at a temperature of 2 °C and a surface RH of 85%.

Light, intermittent snow occurred at Matatiele with a surface temperature of 1.2 ºC and a surface RH of 79% with overcast Nimbostratus clouds being reported. Barkly East had snow during the preceding hour with a surface temperature of -1.5 ºC and a surface RH of 90%. Light snow was also reported at Ermelo at 0244 UTC and lasted for about 12 minutes. During this time, the surface temperature was 0 °C and the surface RH was 100%.

c. Upper air observations

The cold front passed over Irene (close to Johannesburg) between 26 June 2007 at 1200 UTC (red lines and barbs) and 27 June 2007 at 0000 UTC (blue lines and barbs) when considerable cooling occurred (shaded blue region) and the surface wind direction changed from north-westerly to south-westerly (encircled blue barbs) (Fig. 5.64).

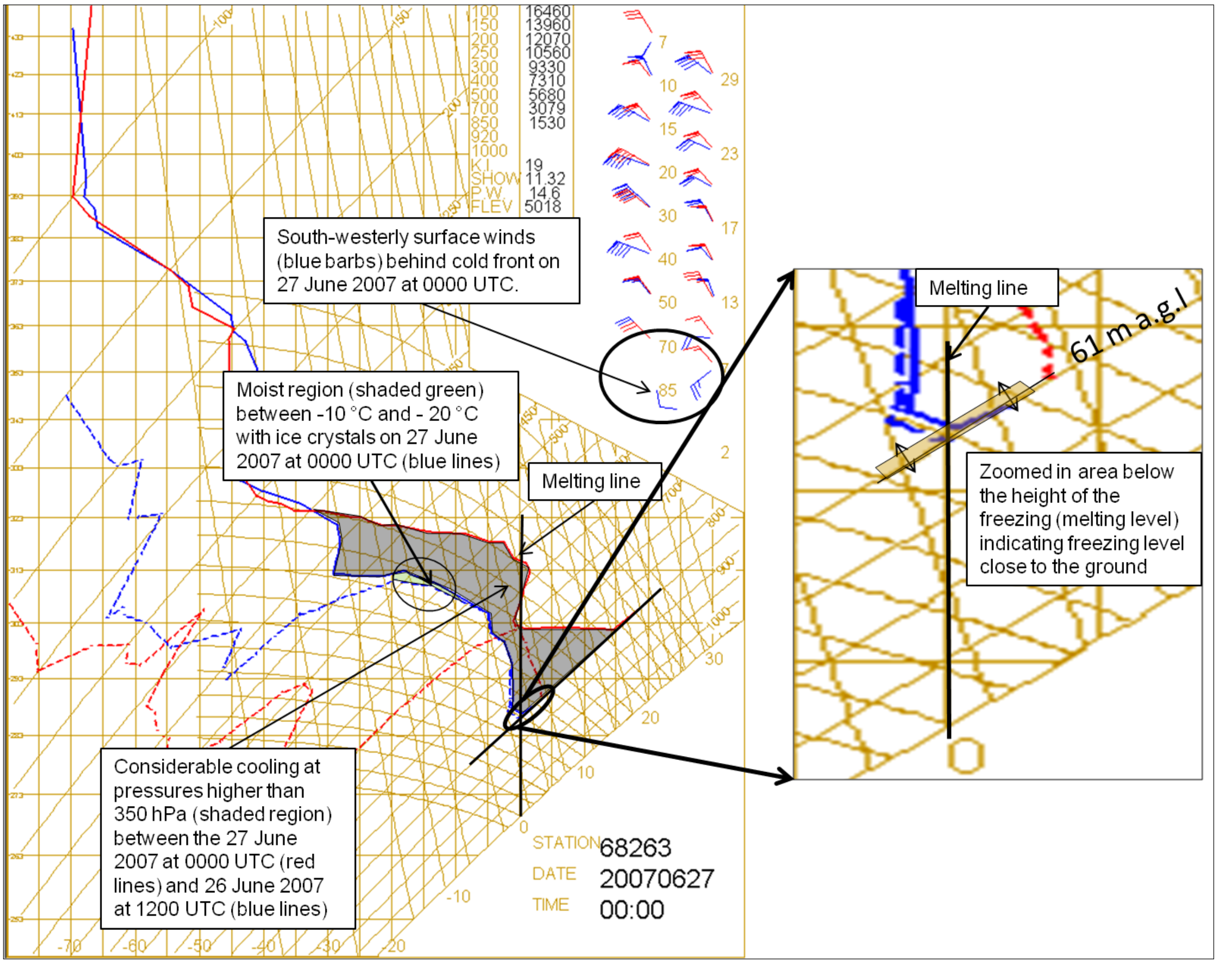


Figure 5.64: South African Weather Service tephigram for Irene on 27 June 2007 at 0000 UTC (blue lines and barbs) and 26 June 2007 at 1200 UTC (red lines and barbs) (the solid lines are temperatures and the dotted lines are dew point temperatures)

Fig. 5.64 indicates that the height of the freezing level was 61 m a.g.l and that the vertical distribution of moisture was saturated with ice crystals in the region of -15 °C. Consequently, ice crystals could grow through deposition and fall through the saturated air within the lower atmospheric layer between 0 °C to -10 °C; causing snowflakes to grow further through aggregation, accretion and riming.

The ice cloud at Johannesburg International Airport can be seen in Fig. 5.65 A (encircled) at 2300 UTC which indicates that cloud tops were around -20 °C during the snowfall. In Fig. 5.65 B at 0045 UTC, cloud top temperatures at Pretoria (encircled) were around -20 °C when snow occurred indicating the presence of ice crystals in the mid-levels.

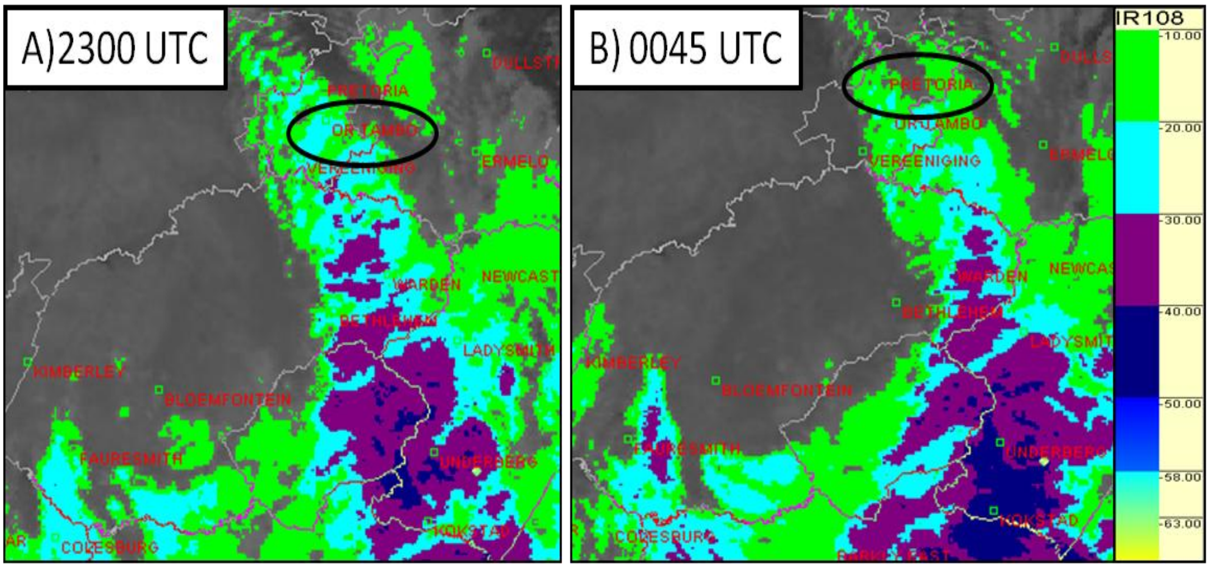


Figure 5.65: MSG satellite, IR 10.8 false colour image for A): Johannesburg International Airport at 2300 UTC on 27 June 2007; and B): Pretoria at 0045 UTC on 27 June 2007 © (2012) Eumetsat

d. Partial atmospheric thickness

When snow occurred over Johannesburg, Irene and Pretoria, the 850-500 hPa atmospheric thickness was 4170 m (Fig. 5.66 A). The 700-500 hPa partial atmospheric thickness was 2590 m (Fig. 5.66 B) and the 850-700 hPa partial atmospheric thickness was 1570 m (Fig. 5.66 C). It is interesting that Gauteng is not in the area of lowest atmospheric thickness. However, Gauteng was in a region where ice crystals were available, surface conditions were favorable and atmospheric thickness were low and cold enough for snow.

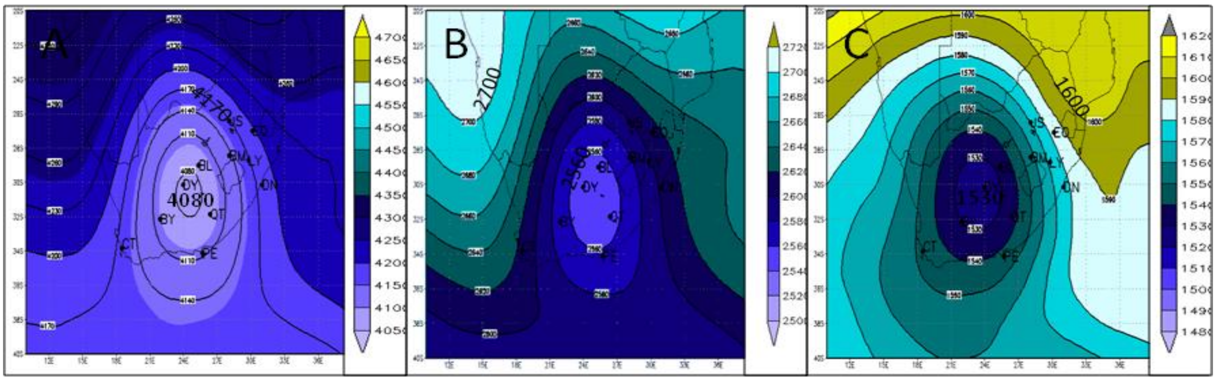


Figure 5.66: Same as Figure 5.54, but for 27 of June 2007 at 0000 UTC

5.3.2.4 27 June 2007 at 0600 UTC

This time period is discussed because light snow was reported at Bloemfontein at 0800 UTC. At this time the COL moved to Bloemfontein and Bethlehem with strong horizontal low level cold air temperature advection. The synoptic circulation is not discussed, as no major changes had taken place since the previous time slot at 0000 UTC.

a. Surface observations

Light snow was reported at Bloemfontein at 0800 UTC on 27 June 2007 when overcast mid-level (ice) cloud was reported at 2500 m a.g.l. The surface temperature at this time was 1.7 °C and the surface RH was 100%. It snowed overnight at Barkly East on 27 June 2007 when the surface temperature was -1.5 °C and the surface RH 90%.

b. Partial atmospheric thickness

Partial atmospheric thickness were very low over the Bloemfontein area when snow occurred. The 850-500 hPa atmospheric thickness were 4080 m (Fig. 5.67 A), the 700-500 hPa partial atmospheric thickness were 2550 m (Fig. 5.67 B) and the 850-700 hPa partial atmospheric thickness were 1530 m (Fig. 5.67 C). Although very low atmospheric thickness were occurring over a large area of the eastern interior, no snow occurred in all the areas due to the absence of ice cloud and precipitation. The probability of precipitation first needs to be considered before thickness are used to discriminate precipitation type.

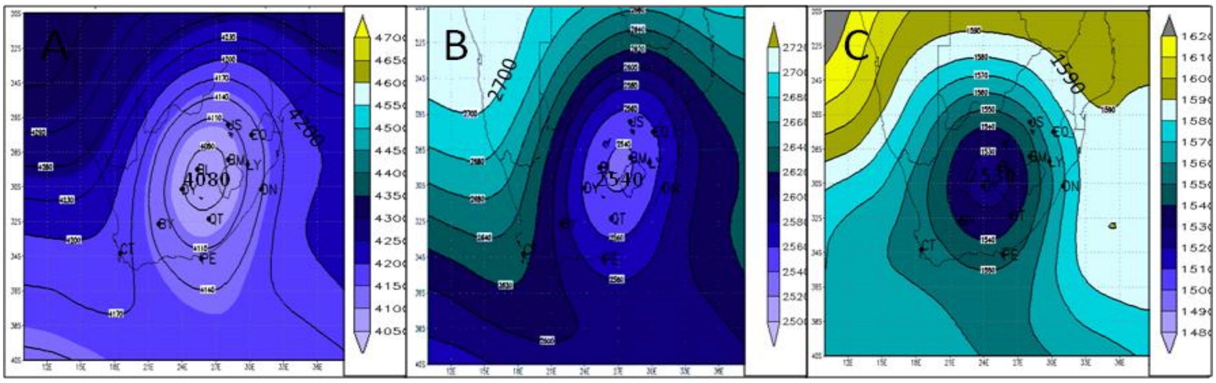


Figure 5.67: Same as Figure 5.54, but for 27 June 2007 at 0600 UTC

5.3.2.5 27 June 2007 at 1200 UTC

This time is discussed, since snowfall occurred at Bethlehem. The synoptic circulation is referred to, because the upper COL was moving over Bethlehem in the presence of low level horizontal temperature advection. Surface data is shown in order to explain the surface temperature and RH at which snowfall occurs. Finally, partial atmospheric thickness are given for the towns that received snow.

a. Synoptic circulation

At 1200 UTC on 27 June 2007, the COL had moved further eastwards to be situated between Bethlehem, Ermelo and KZN with the baroclinic surface frontal low situated to the east of Durban (Fig. 5.68 A). The entire synoptic weather system was decaying and becoming equivalent barotropic. Strong cold air advection was still occurring in the region between Bethlehem, Johannesburg and Ermelo (Fig. 5.68 B). As the system was exiting the KZN region, both 700 hPa and 500 hPa moisture and uplift were limited to the coast and adjacent interior of KZN (Fig. 5.68 D and E). The upper wind divergence was located in a similar area with a south-westerly jet present to the north and west of Bloemfontein and Johannesburg (Fig. 5.68 F).

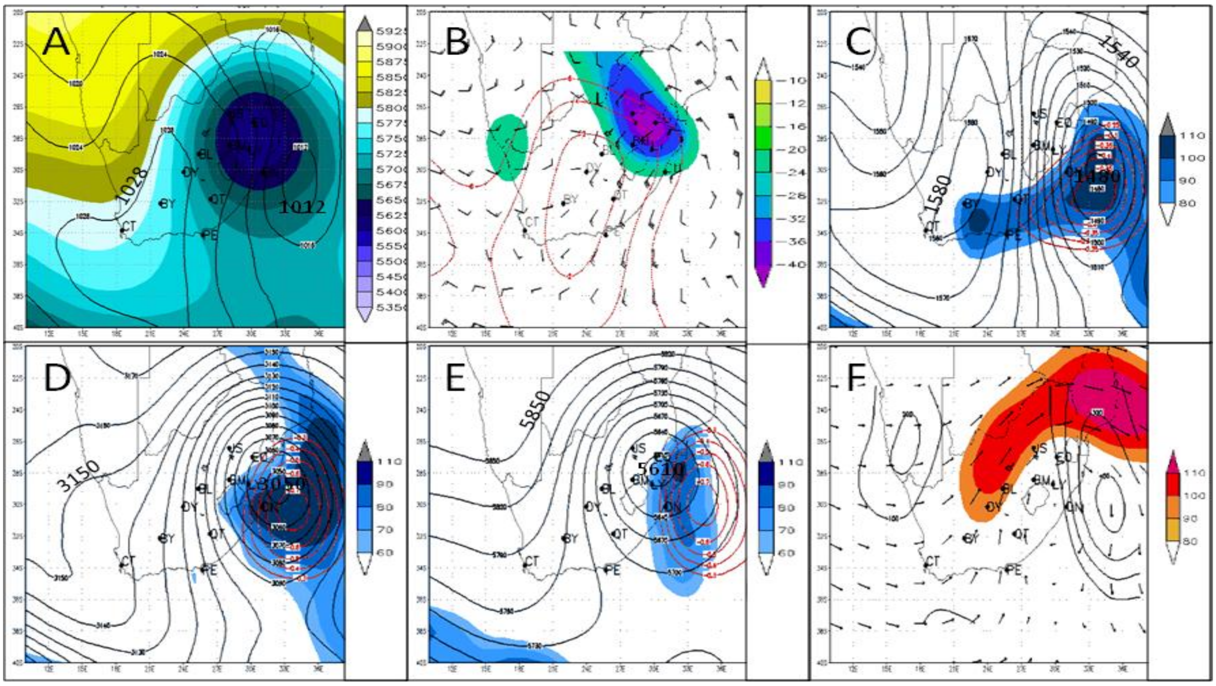


Figure 5.68: Same as Figure 5.49, but for 27 June 2007 at 1200 UTC

b. Surface observations

At 1200 UTC on 27 June 2007, light and intermittent snow occurred at Bethlehem with a surface temperature of 1.8 °C and surface RH of 100%. During the snowfall, there was broken low cloud (Stratocumulus) at 300 m a.g.l caused by the surface onshore flow behind the low pressure system east of Durban as well as mid-level clouds caused by the upper COL (Altocumulus ice cloud). By 1300 UTC, the surface temperature rose to 3 °C and no further snow occurred.

c. Partial atmospheric thickness

When it snowed at Bethlehem, the 850-500 hPa atmospheric thickness were 4050 m (Fig. 5.69 A), the 700-500 hPa partial atmospheric thickness was 2540 m (Fig. 5.69 B) and the 850-700 hPa partial atmospheric thickness was 1540 m (Fig. 5.69 C).

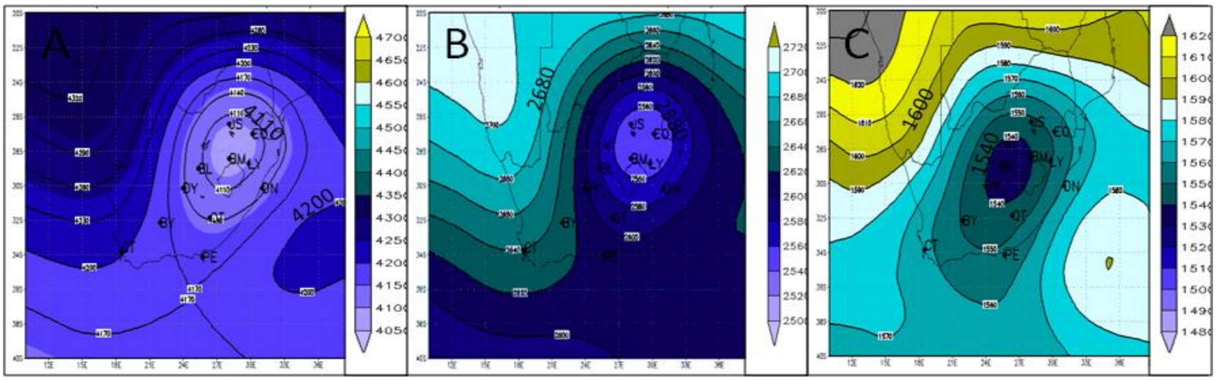
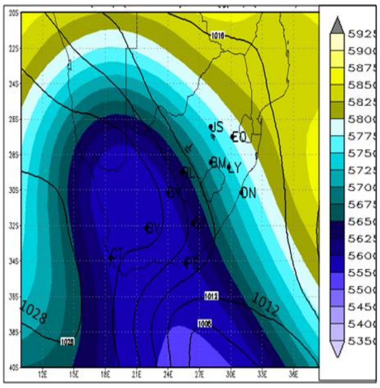
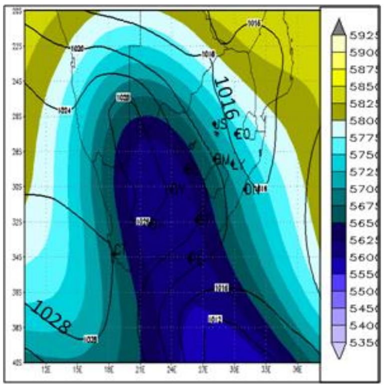
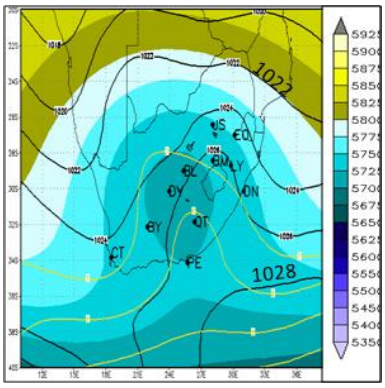
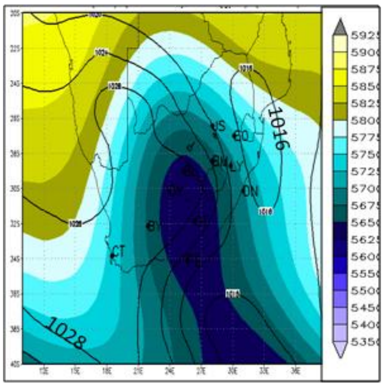
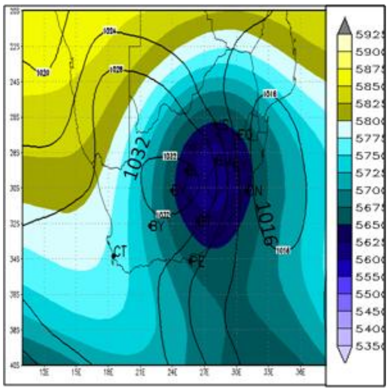
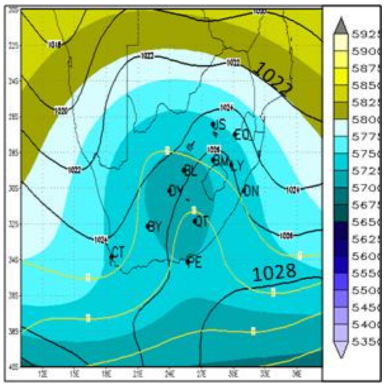


Figure 5.69: Same as Figure 5.54 but for 27 June 2007 at 1200 UTC

5.3.3 SOM node synoptic classification

The purpose of this discussion is to relate the synoptic classification of snowfall in Chapter 4 in Fig 4.2 to the synoptic circulation of 26 and 27 June 2007 in order to show that the mapping was representative of the synoptic situation in the case study.

Table 5.9: SOM node classification for 26 and 27 June 2007

26 June 2007 at 1200 UTC	26 June 2007 at 1800 UTC	Node 11
		
27 June 2007 at 0000 UTC	27 June 2007 at 0600 UTC	Node 11
		

The synoptic circulation of 26 June 2007 at 1200 UTC (Fig. 5.49 A) and 1800 UTC (Fig. 5.55 A) and 27 June 2007 at 0000 UTC (Fig. 5.60 A) and 0600 UTC was mapped to node 11. The results are summarised in Table 5.9 and shows that node 11 depicts a similar synoptic circulation to those within this case study. The COL is captured well over the south-eastern interior of the country.

5.3.4 Summary

This case study was similar to that of case study 1 as it indicated the importance of a ridging AOH in association with an upper COL in snowfall. However, there was a subtle variation on the previous identified patterns of case study 1 and 2. A surface low pressure system developed to the east of KZN in association with the upper COL system, enhancing cold air advection due to the established pressure gradient between the surface AOH and low pressure system. Taljaard (1995a) indicated that surface lows can develop between 25° S and 35° S and can then be manifestations of an upper air COL pressure system. The result was that the surface wind flow over the eastern interior was more southerly during snowfall, due to the location of this surface low pressure system of the east coast.

Similar factors were favourable for snowfall as within the previous two case studies. The areas with lowest atmospheric thickness are not necessarily the areas that can expect snowfall. Rather, snowfall should be viewed where a number of favourable factors coincide. The presence of precipitating ice clouds in the region of -15 °C is critical in snowfall and the probability of precipitation first needs to be established.

Similarly, atmospheric thickness were found to occur during snowfall as in the first two case studies. These results are summarised in Table 5.10.

Table 5.10: Atmospheric thickness (850-500 hPa, 700-500 hPa and 850-700 hPa) during snowfall on 26 and 27 June 2007

Thickness layer	850-500 hPa	700-500 hPa	850-700 hPa
Thickness values	4050 m and 4170 m	2540 m and 2590 m	1530 m to 1570 m

The height of freezing levels obtained during snowfall ranged from below ground level up to 221 m a.g.l. These results are summarised in Table 5.11.

Table 5.11: Atmospheric thickness (850-500 hPa, 700-500 hPa and 850-700 hPa) and freezing level height per region per synoptic station during snowfall on 26 and 27 June 2007

Region	Station in metres a.m.s.l	Time in UTC	850-500 hPa thicknes s in m	700-500 hPa thickness in m	850-700 hPa thickness in m	Freezing level height in m a.m.s.l	Freezing level height in m a.g.l
Central Free State	Bloemfontein (1395)	26 June 2007 at 1130, 1310 and 27 June 2007 at 0800	4140 4080	2550	1560 1530	1617	221
Eastern Free State	Bethlehem (1666)	26 June 2007 at 1743, 1800, 27 June 2007 at 1200	4150 4050	2590 2540	1570 1540	1568	-98
Gauteng	Johannesburg (1680)	26 June 2007 at 2219, 2300, 0000	4170	2590	1570	1530	-150
Gauteng	Irene (1523)	26 June 2007 at 2300 and 27 June 2007 at 0000	4170	2590	1570	1530	7
Gauteng	Pretoria East (1517)	27 June 2007 at 0000	4170	2590	1570	1530	13

In this case, the surface temperature during snowfall varied between -0.5 °C and 1.8 °C and the surface RH varied between 85.6% and 100%. Snowfall occurred with surface temperatures as high as 1.8 °C and surface RH close to 100%. In the previous two case studies, it was found that surface temperatures should be <=2 °C when conditions are saturated (RH = 100%). The surface conditions in the areas and times that received snowfall are summarised in Table 5.12.

Table 5.12: Surface temperature, surface relative humidity and melting temperature during snowfall per region per synoptic station during snowfall on 26 and 27 June 2007

Region	Station in metres a.m.s.l	Time in UTC	Surface temp in °C	Surface RH in (%)	Melting temperature in °C
Central Free State	Bloemfontein (1395)	26 June 2007 at 1130	1.3	100	0
Central Free State	Bloemfontein (1395)	26 June 2007 at 1310	1.5	100	0
Central Free State	Bloemfontein (1395)	27 June 2007 at 0800	1.7	100	0
Eastern Free State	Bethlehem (1666)	26 June 2007 at 1743	1.8	96.9	0.2
Eastern Free State	Bethlehem (1666)	26 June 2007 at 1800	1.2	100	0
Eastern Free State	Bethlehem (1666)	27 June 2007 at 1200	1.8	100	0
Gauteng	Johannesburg (1680)	26 June 2007 2219	0.8	85.6	0.9
Gauteng	Johannesburg (1680)	26 June 2007 at 2300	-0.5	94.6	0.3
Gauteng	Johannesburg (1680)	27 June 2007 at 0000	-0.6	95.4	0.3
Gauteng	Irene (1523)	27 June 2007 at 2300	2.1	85.6	0.9
Gauteng	Irene (1523)	27 June 2007 at 0000	1.1	92.8	0.4
Gauteng	Pretoria East (1517)	27 June 2007 at 0000	1.5	92.2	0.5
Eastern Cape	Barkly East	27 June 2007 at 0000	-1.5	90	0.6
Mpumalanga	Ermelo	27 June 2007 at 0244	0	100	0

5.4 Case study 4: 15 August 2011

5.4.1 Introduction

A COL was situated over the north-eastern Free State on 15 August 2011 which combined with a surface high pressure system in the north-east of the country to produce snow. It snowed lightly on the afternoon of 15 August 2011 in Vereeniging and the southern parts of Johannesburg but it was not enough to block roads (Motumi et al., 2011).

The cold conditions affected Gauteng, southern Mpumalanga, north-eastern Free State and KZN. The N3 highway had to be closed over Van Reenens Pass due to heavy snow. Snowfalls were reported from Volksrust, Ermelo and Dullstroom on 15 August 2011 (Van Rooyen, 2011). Roads between Bethlehem, Kestell, Harrismith as well as the Oliviershoek Pass had to be closed due to heavy snow (Swart, 2011). The N3 national road was closed to traffic from Harrismith to the Colenso/Frere road interchange due to the snowfall. The N11 national road at Ladysmith was also closed (Pretoria News, 2011b).

On the Day Natural Colour RGB indicated in Fig. 5.70, the towns of Dullstroom, Belfast and Ermelo can be seen on the Mpumalanga Highveld and will be discussed in this case study in terms of the occurrence of snowfall.

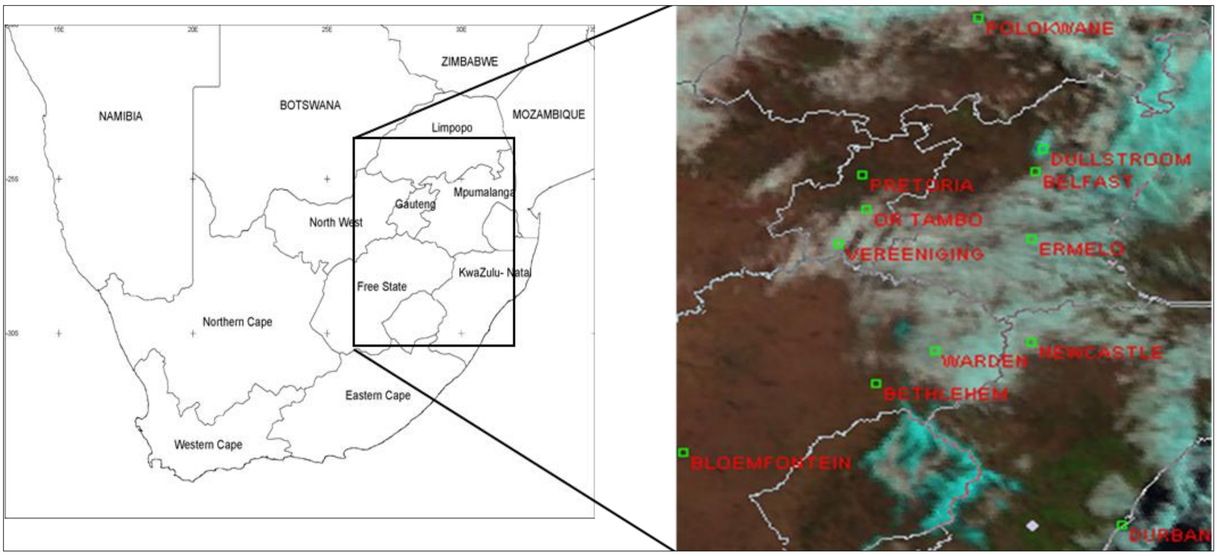


Figure 5.70: MSG satellite, Day Natural Colour RGB for 16 August 2011 at 0730 UTC; the cyan colour indicates snow on the ground in the area of interest © (2012) Eumetsat. Location names are indicated in red

The bright cyan colour near Dullstroom, the eastern Free State and Lesotho is indicative of snow lying on the ground. The light grayish colours indicate water cloud (see Section 3.1.5).

5.4.2 Atmospheric conditions during snowfall

Snowfall occurred over the Mpumalanga Highveld during the morning of 15 August 2011 and later in the evening over the Mpumalanga escarpment. Consequently, the period from 15 August 2011 at 0000 UTC to 16 August 2011 at 0600 UTC will be discussed, with special attention given to the Mpumalanga province where snowfall occurred. At Ermelo and Belfast, it will be shown how atmospheric conditions were conducive to snowfall. This case study is a good example of how an upper COL can develop over the eastern interior, without Passing over the entire country from west to east as in the previous three case studies.

5.4.2.1 15 August 2011 at 0000 UTC

The synoptic circulation during this period will be discussed because the COL was starting to develop over the eastern interior of South Africa which later had an impact on the occurrence of snowfall over the Mpumalanga province.

a. Synoptic circulation

On the 15 August 2011 at 0000 UTC, the surface IOH was situated to the south of the country (Fig. 5.71 A). It was causing an onshore flow of cool, moist air over the eastern interior indicated by RH > 60% (Fig. 5.71 C). Significant surface cold air advection was occurring over the central and western interior (Fig. 5.71 B). The influx of cold air in the lowest 3000 m a.m.s.l led to falling geopotential heights at the 700 hPa level resulting in the formation of a 700 hPa low pressure system over the eastern Free State where RH > 60% and vertical motion was present east of this (Fig. 5.71 D). At the 500 hPa pressure level, a COL was busy developing in the same region (Fig. 5.71 E). Upper wind divergence was present over Gauteng and Mpumalanga to the east (right exit region) of the upper south-westerly jet that was located over Botswana (Fig. 5.71 F).

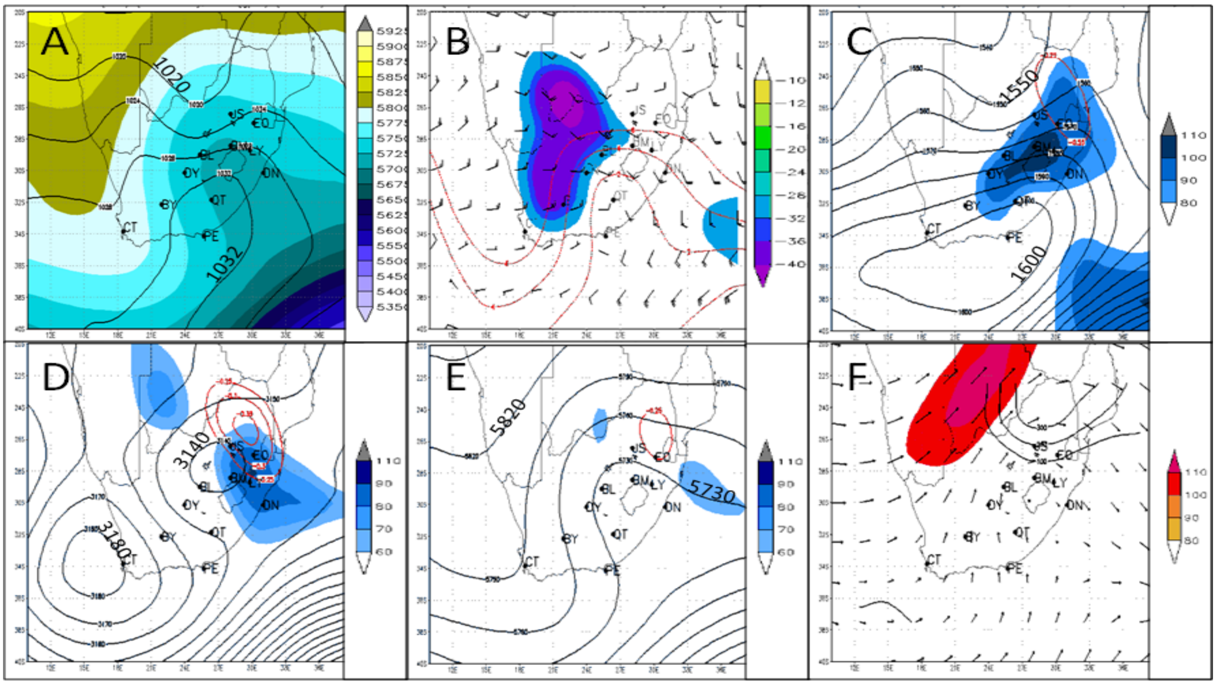


Figure 5.71: 15 August 2011 at 0000 UTC: A:) mean sea level pressure in hPa black solid, 500 hPa geopotential heights shaded in metres; B): 850 hPa temperature < 6 °C in red, 850 hPa cold air temperature advection*10e^{6} in °C s^{-1} shaded, 850 hPa wind barbs in knots; C): 850 hPa relative humidity in % shaded, 850 hPa negative omega in Pa s^{-1} red, 850 hPa geopotential heights solid black in metres; D): 700 hPa relative humidity in % shaded, 700 hPa negative omega in Pa s^{-1} red, 700 hPa geopotential heights in metres solid black; E): 500 hPa relative humidity in % shaded, 500 hPa negative omega in Pa s^{-1} red, 500 hPa geopotential heights in metres solid black; F): 300 hPa jet stream > 80 knots shaded, 300 hPa wind divergence solid black (s^{-1})

5.4.2.2 15 August 2011 at 0600 UTC

This period was characterised by a fully developed COL over the eastern interior and the subsequent snowfall at Ermelo weather station at 0900 UTC. For this reason, the synoptic circulation and partial atmospheric thickness for this time period will be discussed to ascertain the influence it had on snowfall.

a. Synoptic circulation

As the surface IOH continued to ridge further eastwards, the upper COL manifested itself over the eastern interior (Fig. 5.72 A). With the centre of the 850 hPa high pressure system just to the south of Port Elizabeth, there was a considerable influx of low level RH > 60% over the eastern interior around the north-eastern periphery of the high pressure system (Fig. 5.72 C). With the COL now evident through the 500 hPa and 700 hPa pressure levels, considerable moisture was present over Gauteng and Mpumalanga (RH > 60%, Fig. 5.72 D and E). There was no vertical motion at 500 hPa (Fig. 5.72 E), but at 700 hPa, vertical motion was occurring over and to the north of Johannesburg (Fig. 5.72 D). Wind divergence was still occurring in the right exit region of the upper jet over Gauteng, Mpumalanga and the Limpopo provinces (Fig. 5.72 F).

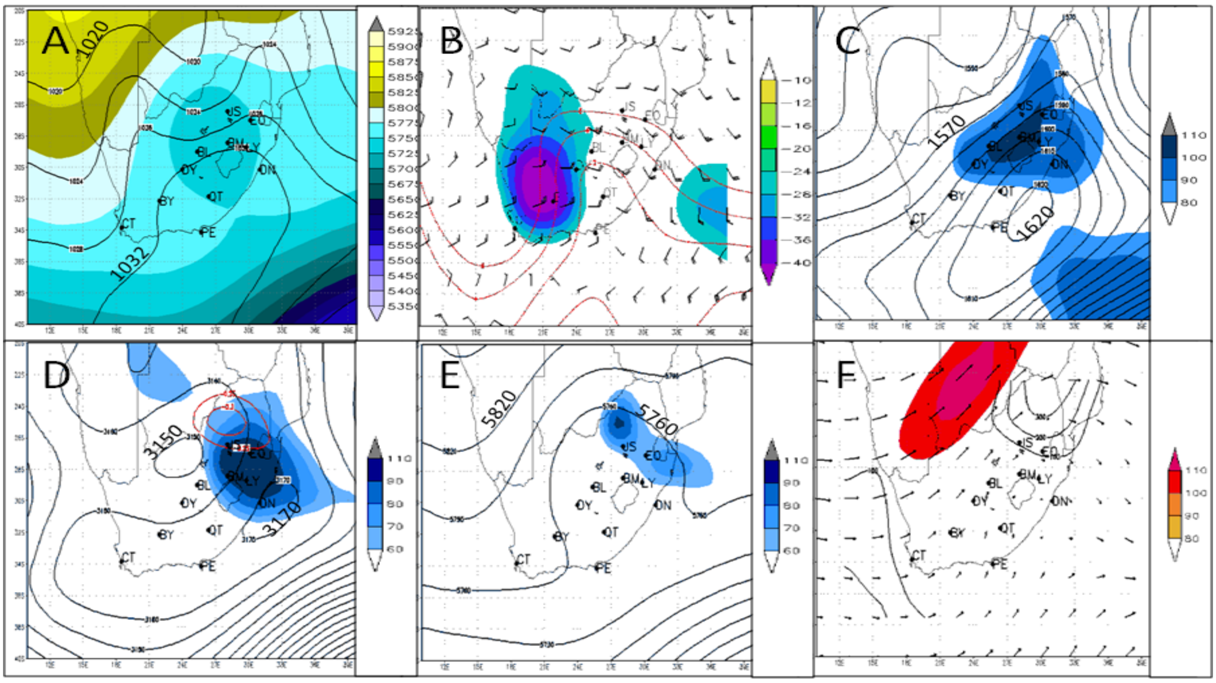


Figure 5.72: Same as Figure 5.71, but for 15 August 2011 at 0600 UTC

b. Partial atmospheric thickness

At Ermelo, the 850-500 hPa atmospheric thickness (Fig. 5.73 A) was 4160 m. For the 700-500 hPa layer, the partial atmospheric thickness was between 2580 m and 2600 m (Fig. 5.73 B) and for the 850-700 hPa layer, the partial atmospheric thickness was 1570 m (Fig. 5.73 C).

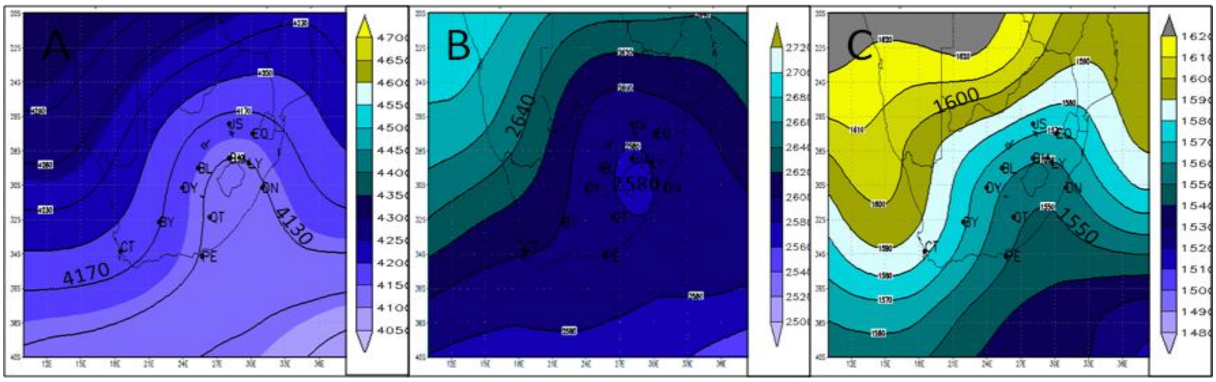


Figure 5.73 A): 850-500 hPa atmospheric thickness; B): 700-500 hPa partial atmospheric thickness; and C): 850-700 hPa partial atmospheric thickness for the 15 August 2011 at 0600 UTC

5.4.2.3 15 August 2011 at 1200 UTC

This period is discussed since snowfall occurred three hours prior to this over Ermelo. The surface conditions resulting in snowfall in Ermelo at 0900 UTC will be discussed during this time step, as significant cold air advection was occurring over the area of interest which helped to contribute to the falling surface temperature at Ermelo during the course of the morning. The satellite imagery will be referred to in order to place the position of the COL and establish the presence of ice crystals. Lastly, partial atmospheric thickness are referred to.

a. Synoptic circulation

At 1200 UTC on 15 August 2011, the IOH that was situated to the south-east of Port Elizabeth was producing a significant onshore south-easterly flow over the Mpumalanga and Gauteng region helping to intensify the upper COL over the aforementioned region (Fig. 5.74 A) (see Section 3.2.4). The extent of the cold air advection over Mpumalanga and Gauteng can be seen in Fig. 5.74 B and the extent of the moisture advection can be seen in Fig. 5.74 C where RH > 60% was occurring over the Ermelo, Belfast and Dullstroom region. At 700 hPa, the RH was > 80% and vertical motion was now starting to develop over the Mpumalanga region (Fig. 5.74 D).

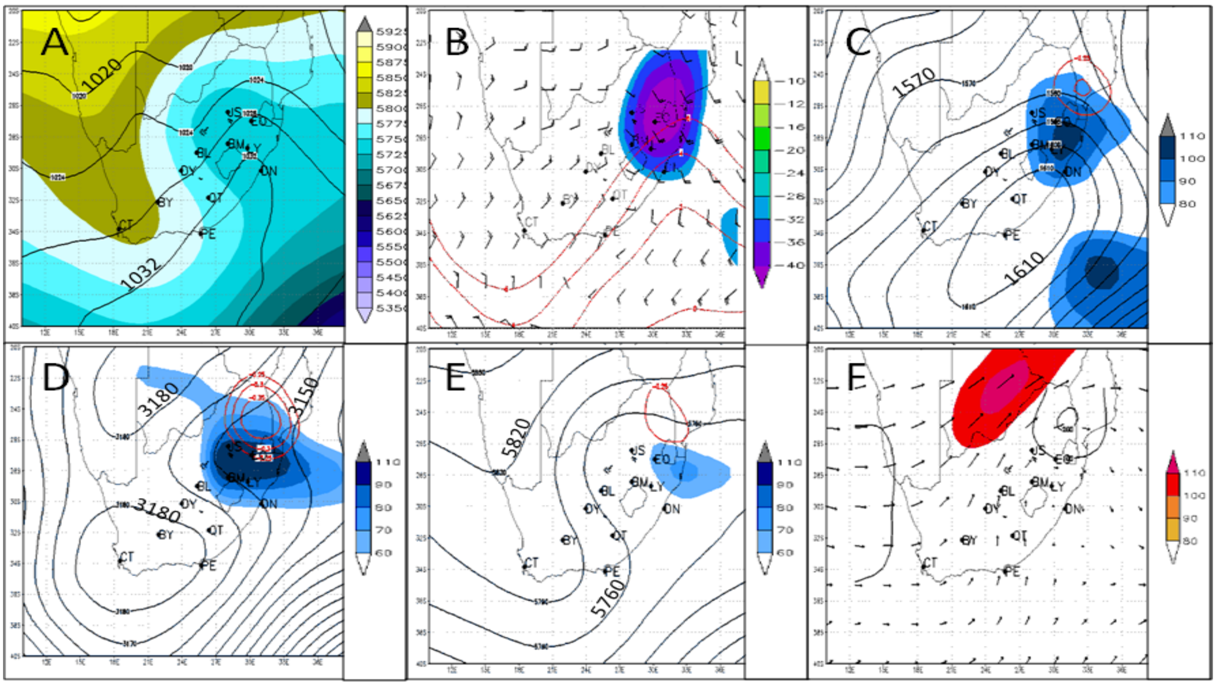


Figure 5.74: Same as Figure 5.71, but for 15 August 2011 at 1200 UTC

At 500 hPa, moisture and uplift was less impressive with RH > 60% occurring over the Ermelo region (Fig. 5.74 E). To the north of Ermelo, upper air wind divergence was occurring over the right exit region to the south-east of the upper south-westerly jet stream located over Botswana (Fig. 5.74 F).

b. Surface observations

Snow was reported at Ermelo at 0855 UTC as well as at 0900 UTC on 15 August 2011 (Fig. 5.75). On the 15th, the wind direction remained mainly south-easterly due to the ridging of the IOH, resulting in overcast low Stratus cloud being reported at 300 m a.g.l causing saturation of the lower atmospheric levels (see Fig. 5.74 C). This, together with the precipitation, contributed to the continuous drop in surface temperature during the morning until it started snowing around 0900 UTC at Ermelo (Fig. 5.75). At this stage, the surface RH was 99.2% and the surface temperature was 1.1 °C. It snowed for a short while after which the temperature rose dramatically to above 3 °C, causing the falling snow to melt and be reflected as liquid precipitation.

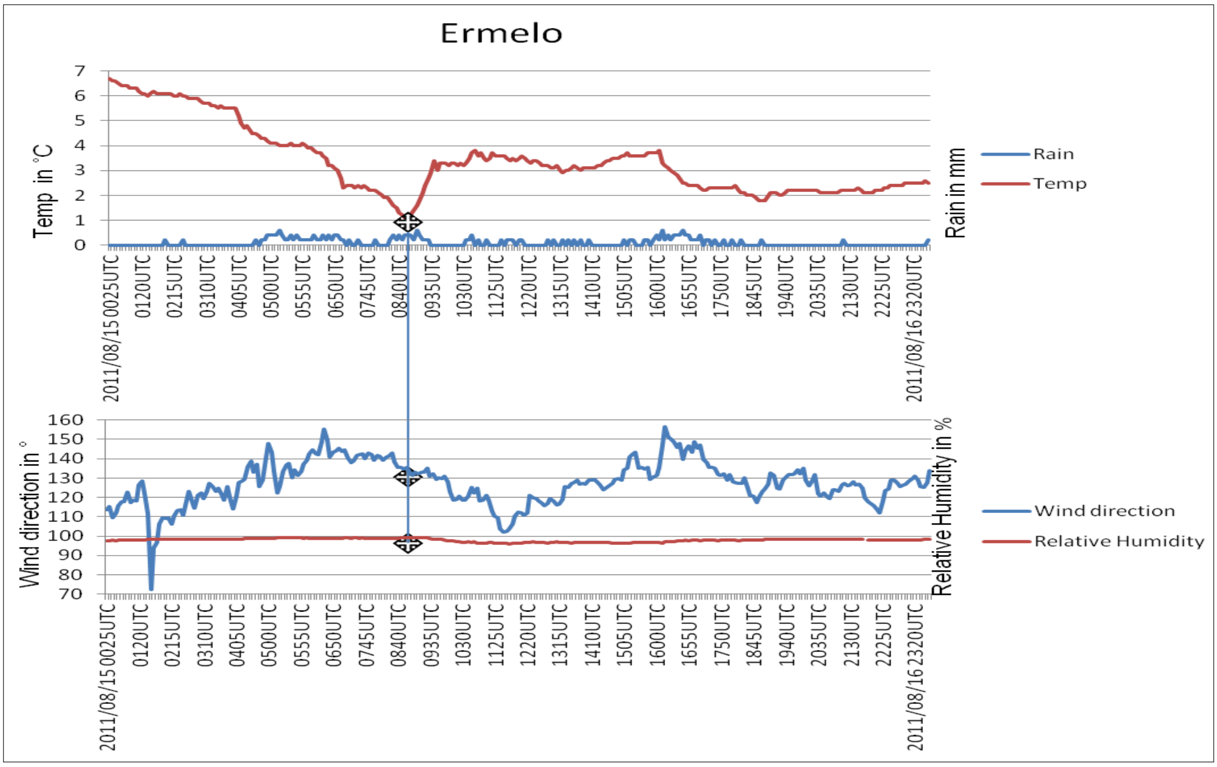


Figure 5.75: Temperature (°C), rain (mm), relative humidity (%) and wind direction (°) at the South African Weather Service Ermelo weather station on 15 and 16 of August 2011; the stars in the figure indicate confirmed observations of snowfall; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

c. Satellite imagery

The Airmass RGB on 15 August 2011 at 1200 UTC in Fig. 5.76 indicates the presence of the COL over the eastern Free State. The bluish tinge of the cold air mass can be seen over Lesotho with plenty of advection of dry stratospheric air around the COL (orange) (Eumetsat, 2012). The whitish cloud mass can be seen to the east of the upper COL over the snowfall region of Mpumalanga.

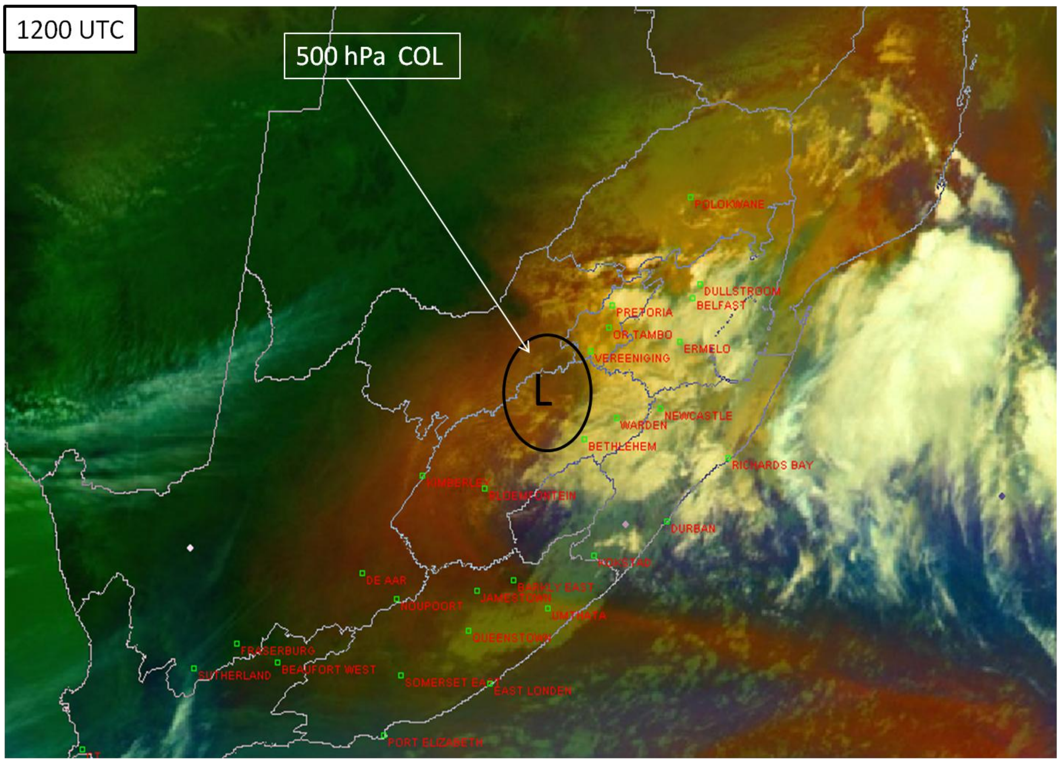


Figure 5.76: MSG satellite Airmass RGB on 15 August 2011 at 1200 UTC with the COL over the northern Free State © (2012) Eumetsat

At Ermelo, when it snowed at 0845 UTC on 15 August 2011, where the cloud top temperatures were in the region of -20 °C to -30 °C. This was indicative of temperatures cold enough to support plenty of ice crystals needed for the growth of snowflakes (Fig. 5.77). This, together with favourable surface temperature and RH made snowfall possible over Ermelo.

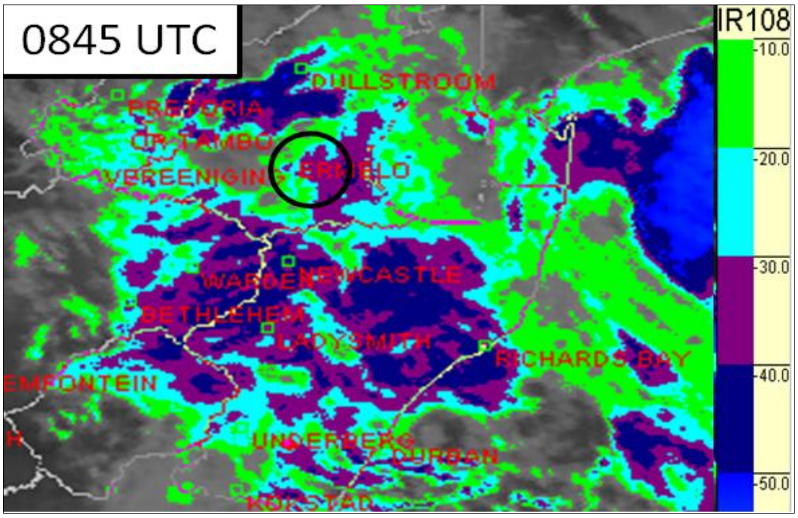


Figure 5.77: MSG satellite, false colour IR 10.8 at Ermelo on 15 August 2011 at 0845 UTC © (2012) Eumetsat

d. Partial atmospheric thickness

Over the eastern Highveld of Mpumalanga, where it had recently snowed, the atmospheric thickness in the 850-500 hPa layer was 4150 m (Fig. 5.78 A), the 700-500 hPa partial atmospheric thickness layer was 2580 m (Fig. 5.78 B) and the 850-700 hPa partial atmospheric thickness layer was 1565 m (Fig. 5.78 C).

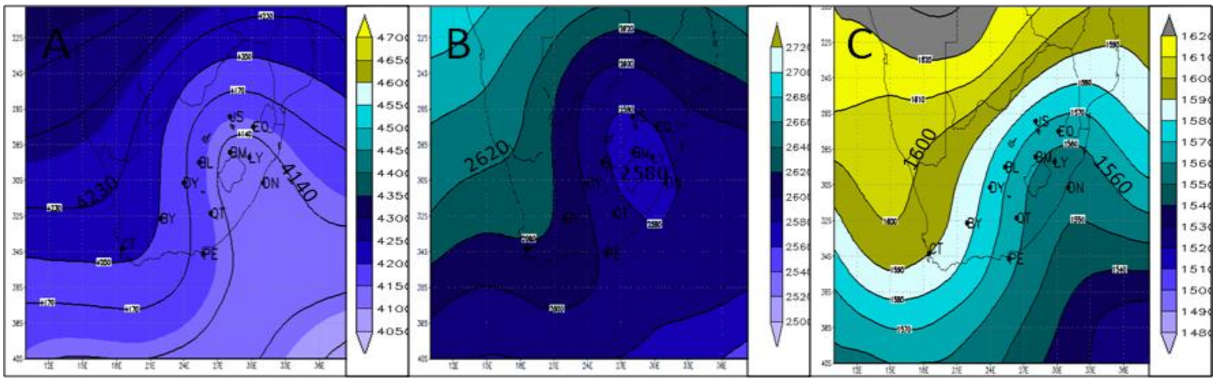


Figure 5.78: Same as Figure 5.73, but for 15 August 2011 at 1200 UTC

5.4.2.4 15 August 2011 at 1800 UTC

This time period will be discussed since snowfall started in Dullstroom in Mpumalanga. The surface and upper level atmospheric conditions will be discussed during the period which it snowed in Dullstroom, emphasising the important factors during snowfall.

a. Synoptic circulation

The IOH pressure system had moved slightly eastwards together with the upper COL, which exhibited a smaller regional extent than six hours previously (Fig. 5.79 A). With a sustained south-easterly flow of cool, moist air around the periphery of the 850 hPa high (Fig. 5.79 C), considerable cold air advection was occurring over the Highveld of Mpumalanga which further cooled the lower vertical distribution of temperature (Fig. 5.79 B) in that area with RH > 80% (Fig. 5.79 C). The upper COL was visible at 700 and 500 hPa with RH > 60% in a similar area but with no vertical motion indicated on the synoptic scale. Orographic uplift was most likely the cause of vertical motion in the area of Dullstroom which is located on the eastern escarpment of Mpumalanga (see Section 1.2, Fig. 1.1 for a topographic map). The upper winds were now less than 80 knots with no significant upper air wind divergence (Fig. 5.79 F).

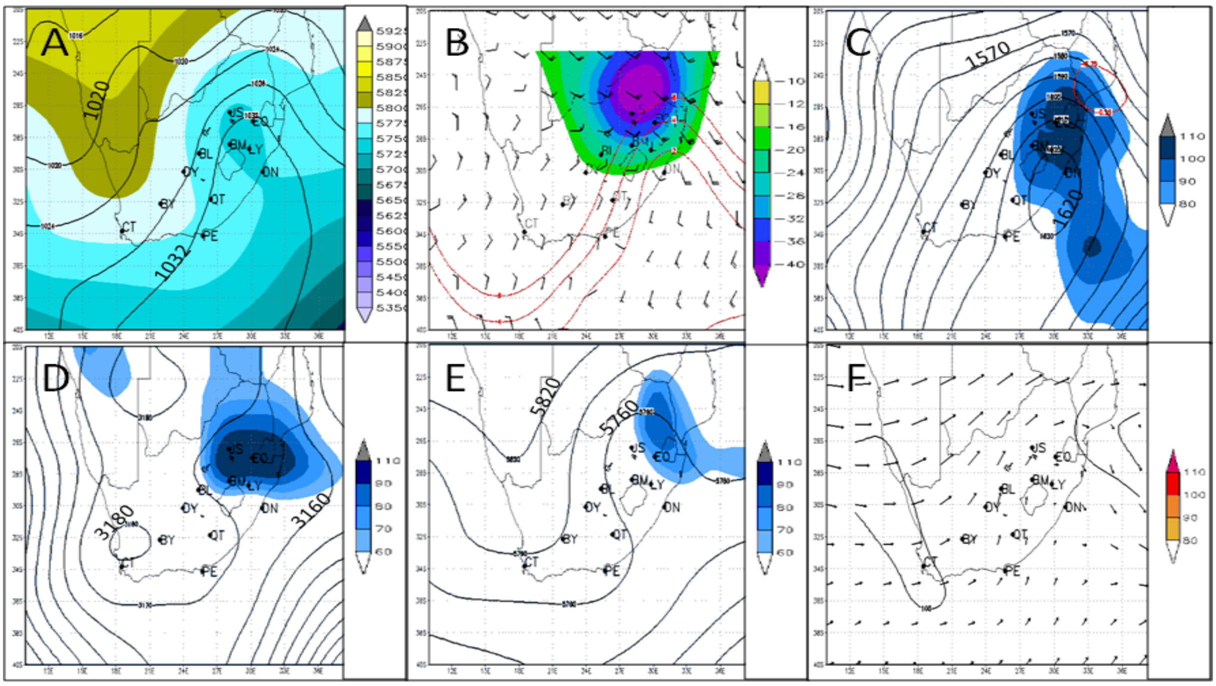


Figure 5.79: Same as Figure 5.71, but for 15 August 2011 at 1800 UTC

b. Surface observations

Snow started falling at Dullstroom around 1800 UTC on 15 August 2011. The closest observations available were at Belfast, which is located 36 km from Dullstroom. Fig. 5.80 indicates a large drop in temperature after sunrise on 15 August 2011. Rain started falling from the active COL. Towards sunset, the surface temperature fell further to below 2 °C when snow started to fall. Although no measurements of RH were available, it can be assumed that the air was saturated (RH = 100%) during snowfall given the surface synoptic conditions with moist air being fed in over the Indian Ocean by the IOH (Fig. 5.79 C).

Figure 5.80: Temperature (°C) and rain (mm) at the South African Weather Service Belfast weather station on 15 and 16 August 2011; the stars in the figure indicate snowfall; the deviations from zero on the rain graph depict only when rainfall occurred and the actual amount of rainfall is not indicated

c. Satellite imagery

At 1915 UTC during snow fall at Dullstroom, cloud top temperatures were similar to those found for Ermelo (-20 °C), which are conducive to the growth of ice crystals through deposition (Fig. 5.81) (see Section 1.4.2).

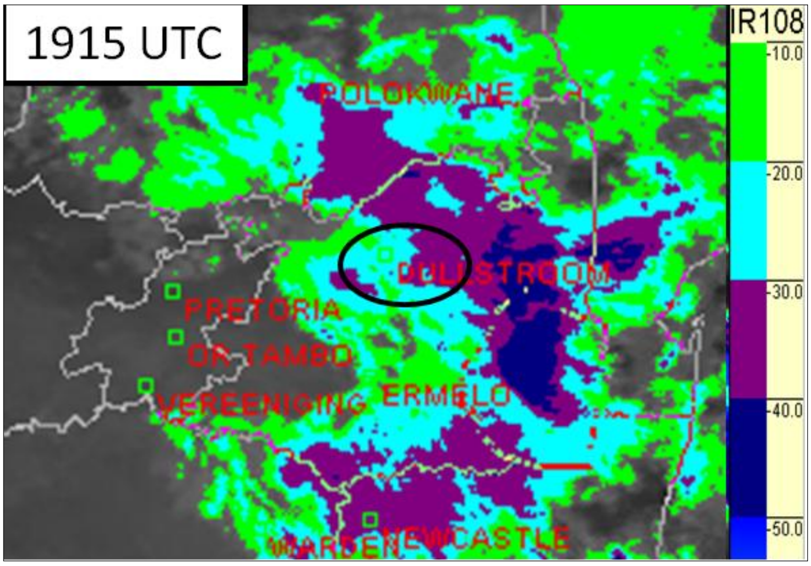


Figure 5.81: MSG satellite, false colour IR 10.8 at Dullstroom on 15 August 2011 at 1915 UTC © (2012) Eumetsat

d. Partial atmospheric thickness

At the time of the snowfall in the Dullstroom region, the atmospheric thickness for the 850-500 hPa layer was between 4140 to 4160 m (Fig. 5.82 A). For the 700-500 hPa partial atmospheric thickness layer, it was 2540 to 2560 m (Fig. 5.82 B) and for the 850-700 hPa partial atmospheric thickness layer, it was 1560 m (Fig. 5.82 C).

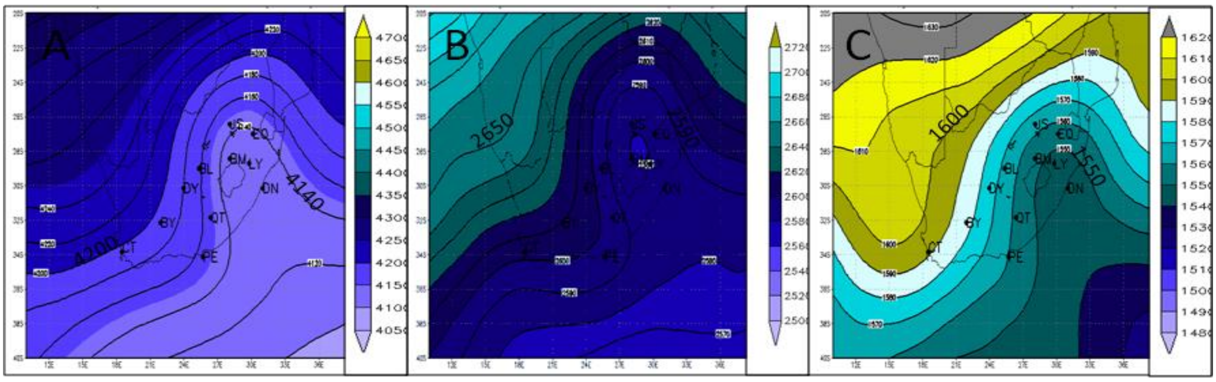


Figure 5.82: Same as Figure 5.73, but for 15 August 2011 at 1800 UTC

5.4.2.5 16 August 2011 at 0600 UTC

Although no snowfall occurred during this specific time period, the partial atmospheric thickness will be discussed, since out of all the time periods within this case study, these values were the lowest.

a. Partial atmospheric thickness

The atmospheric thickness was 4150 m for the 850-500 hPa layer (Fig. 5.83 A), 2590 m for the 700-500 hPa partial atmospheric thickness layer (Fig. 5.83 B) and 1560 m for the 850-700 hPa partial atmospheric thickness layer (Fig. 5.83 C).

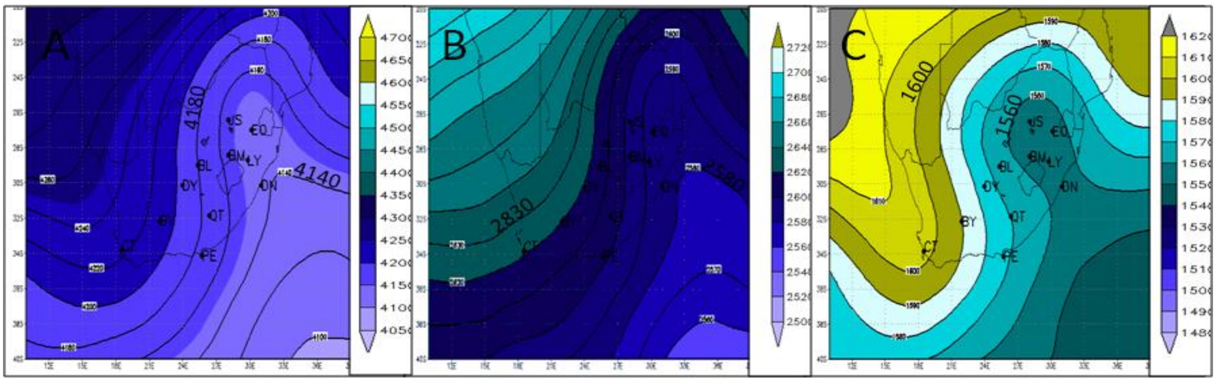


Figure 5.83: Same as Figure 5.73, but for 16 August 2011 at 0600 UTC

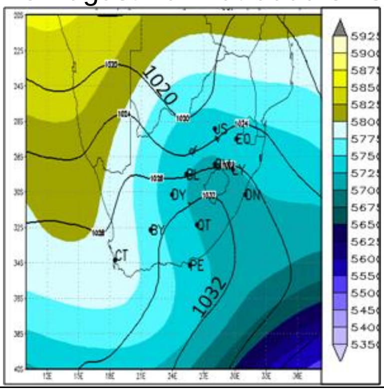
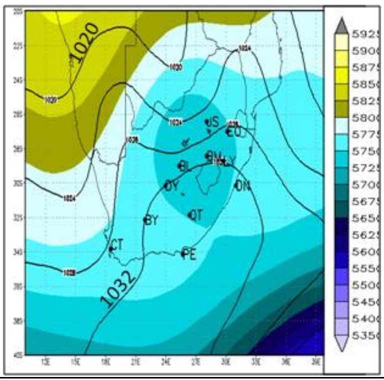
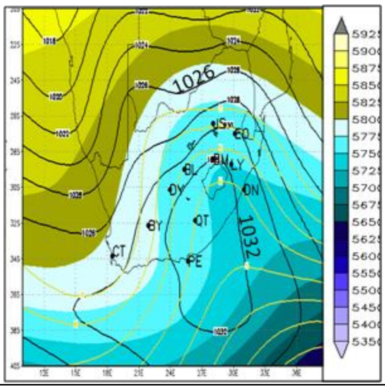
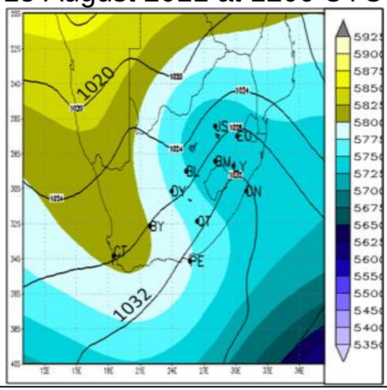
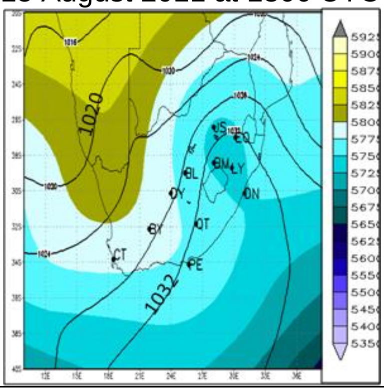
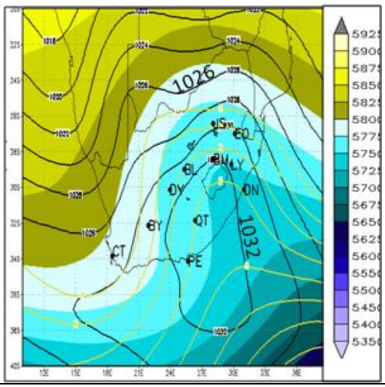
A significant reason for no snowfall at this time period was the unavailability of ice crystals and precipitation due to the fact that the weakening COL had moved further eastwards. It is essential that partial thickness are not the only consideration when forecasting snow.

5.4.3 SOM node synoptic classification

The purpose of this discussion is to relate the synoptic classification of snowfall in Chapter 4 in Fig. 4.2 to the synoptic circulation on 15 August 2011 in order to show that the synoptic classification made was indeed representative of the synoptic circulation within this case.

The synoptic circulation of the 15 August 2011 at 0600 UTC, 1200 UTC and 1800 UTC was mapped to node 18 in Table 5.13. The node circulation is very similar to the actual synoptic circulation that occurred and can be seen as a good mapping.

Table 5.13: SOM node classification for 15 August 2011

15 August 2011 at 0000 UTC	15 August 2011 at 0600 UTC	Node 18
		
15 August 2011 at 1200 UTC	15 August 2011 at 1800 UTC	Node 18
		

5.4.4 Summary

This case was unique to the previous three case studies in the sense that there was no significant snowfall over the Western, Northern and Eastern Cape as well as the Free State. This is because the COL only developed to the east of this region over the northern Free State. The consequence was that significant snowfall was limited to the Mpumalanga province, which is rare. This is an example where forecasters need to be vigilant of a developing upper air COL system across the country making, it more difficult to predict. This is in contrast to a fully developed synoptic system that moves across the country from the west to the east.

The factors important to snowfall in this case study reaffirm those that have been diagnosed during the previous three case studies. In this case, snowfall occurred along the escarpment region of the Mpumalanga Highveld. For topographically sensitive areas such as the eastern escarpment areas of South Africa, a mesoscale model would have been more appropriate in order to determine the effect the orographic forcing had on the snowfall at Dullstroom.

The atmospheric thickness thresholds are within a similar range to those obtained within the previous three case studies and are indicated in Table 5.14.

Table 5.14: Atmospheric thickness (850-500 hPa, 700-500 hPa and 850-700 hPa) during snowfall for 15 August 2011

Thickness layer	850-500 hPa	700-500 hPa	850-700 hPa
Thickness values	4140 to 4160 m	2540 to 2600 m	1560-1570 m

Stranz and Taljaard (1965) found values between 2520 and 2560 m for the 700-500 hPa partial atmospheric thickness during snowfall over Bloemfontein and Johannesburg in June 1964, which correlates well with the findings of Table 5.14.

Table 5.15 indicates that during the snowfall surface temperatures were above freezing but < 2 °C with surface RH close to 100%, allowing snowfall to reach the ground (see Section 3.2.4). Once again, the upper threshold for snowfall was 1.8 °C with a surface RH of 100%. This, together with the results from the previous cases, confirms a strong argument that snowfall can occur in saturated air in temperatures <= 2°C.

Table 5.15: Surface temperature, surface relative humidity and melting temperature per region per synoptic station during snowfall on 15 August 2011

Region	**Station in metres a.m.s.l**	**Time in UTC**	**Surface temp in °C**	**Surface RH (%)**	**Melting temperature in °C**
Mpumalanga escarpment	Dullstroom (2000)	15 August 2011 at 1800 to 2200	1.8	N/A	N/A
Mpumalanga Highveld	Ermelo (1769)	15 August 2011 at 0855 and 0900	1.1	99.2	0

Chapter 6: Snow forecasting decision tree

6.1 Introduction

In weather forecasting, various operational techniques or methods are used to guide forecasters in anticipating future weather events. Very often forecasters use rules of thumb to anticipate weather events such as thunderstorms, heavy rain or snow. Schultz et al. (2002) suggests that a process-based approach to forecasting should be followed instead. A process-based approach makes use of fundamental physical elements. Schultz et al. (2002) suggests that forecasting should not be a recipe of ingredients but rather a list of relevant, manageable things that a forecaster can focus on. Chaston (1989) advises that any forecasting method should apply logical reasoning to atmospheric physics with several case studies used to evaluate the method. This chapter first describes the work of other authors proposing weather forecasting processes, methods or ingredients. A systematic snow forecasting decision tree is then proposed for forecasting significant snow over the lower elevations of South Africa. This can be used as a guide for operational forecasters so that they can have a situational awareness of expected severe weather involving snow.

6.2 Forecasting methods

Doswell et al. (1996) proposed the first ingredients and process-based approach for convection and flash flood forecasting. They noted that each case may have a different mixture for forecasting ingredients. However, the ingredients-based method was a logical one and it was required that the forecaster considered the atmospheric processes or mechanisms that bring these ingredients together to create the flash flood scenario. It is important that a flash flood event can be recognised and predicted ahead of time. Even though it might be the forecaster's first experience of such an event, using ingredients or a forecasting process aids with this. By having an understanding of the physical processes involved in a specific weather event, forecast ingredients can be devised. Schultz et al. (2002) warn that the ingredients based approach is however, limiting in that it is not specific as to how much is needed of each ingredient to give rise to a certain weather outcome. Some examples of ingredients based approaches is that of Schultz and Schumacher (1999) where an ingredients-based methodology for convection was suggested by identifying the three main ingredients (lift, instability and moisture) needed to forecast slantwise convection. Mills and Colquhoun (1998) used a thunderstorm decision tree together with threshold values to assess the potential and severity of thunderstorms. Forecasting methods have been used within various spheres of weather forecasting. Tardiff and Rasmussen (2007) devised a decision tree encompassing various scientific mechanisms important in the formation and dissipation of fog in the New York region. This decision tree was adapted by Van Schalkwyk and Dyson (2012) for fog forecasting at Cape Town International Airport and outlines the threshold values and decisions that forecasters need to make during their thought process. Similar methods exist for the forecasting of snow.

Wetzel and Martin (2001) proposed a winter season precipitation forecasting technique which is ingredients based. The method is based on the five physical ingredients necessary for the formation of precipitation, namely vertical ascent, moisture, instability and precipitation efficiency which included cloud microphysical properties and temperature. At various levels in the atmosphere, the forecaster has to evaluate vertical motion in the presence of moisture to determine precipitation. Atmospheric variables were used to assess the intensity of precipitation and the snow was dependent on temperature. Moisture was evaluated with RH at various levels throughout the atmosphere with at least 80% required for the formation of precipitation within vertical motion. Bourgouin (2000) suggested a method in which precipitation type can be forecasted and it is in operational use at the Canadian Meteorological Centre. It is based on applying the area method on the vertical distribution of temperature in the decision making process. Two types of areas were indentified, those that are above freezing (positive area) and those that are below freezing (negative area). By identifying these areas the forecaster could ascertain whether freezing rain, ice pellets rain or snow would occur. Niziol (1987) developed a decision tree that can assist forecasters in determining whether lake effect snowfall over lakes Erie and Ontario would occur.

A similar approach can be followed with the forecasting of snow in South Africa. Although it does not happen frequently, the forecaster should still be able to anticipate this weather event ahead of time.

6.3 Physical mechanisms important in a snow forecasting decision tree

A snow forecasting decision tree should include scientific based factors that are important in the formation and growth of snowflakes and the subsequent precipitation of snow. The physical mechanisms important for the formation of snowfall were dealt with in Chapter 1.4.2. The main findings in this dissertation are repeated in Table 6.1 and are used to create a snow forecasting decision tree. This process approach follows a logical sequence of events. The process starts in the middle to upper atmosphere by identifying physical mechanisms important in the formation of ice crystals and its subsequent growth into snowflakes. The process follows snowflakes down through the atmosphere until they reach the surface. A snow forecasting decision tree can be devised, taking into account the important synoptic circulation types, cloud microphysical and surface conditions necessary to allow snowflakes not to melt on their way down to the surface. These important factors have been identified and applied within the case studies of Chapter 5. The key factors or physical mechanisms to consider when creating a snow forecasting decision tree are addressed in Table 6.1.

Table 6.1: Logical sequence of key physical mechanisms in the snow forecasting decision tree

Fundamental physical mechanism or process	**Critical pattern or value**	**Scientific reference in literature**
Synoptic surface and upper air patterns associated with significant snowfall.	Deep pointed troughs/COL associated with a surface cold front and AOH/IOH. (Chapter 4.2, Fig. 4.2).	Van Heerden and Hurry (1995), (1994a), (1995a); Taljaard (1995b); Tyson and Preston-Whyte (2000); Kocin and Uccellini (2004); Chapter 2.1, 2.2 and 2.3; Chapter 4 and Chapter 5.
Sound forecasting principles to determine the likelihood and location of precipitation.	Some of these principles are referred to in Chapter 5: Moisture, uplift, surface convergence, upper wind divergence. Atmospheric instability?	Taljaard (1985a); Petterssen (1956) Kocin and Uccellini (2004); Tyson and Preston-Whyte. (2000).Chapter 2.3, Chapter 3.2.4, Chapter 4 and 5.
Precipitation type forecasting: Degree of saturation in cloud, availability of ice in cloud and ice crystal growth	Depositional growth of ice crystals in near saturated to saturated air between -12 °C and -15 °C.	(AMS, 1996); Wetzel and Martin. (2001); Ahrens (2007) Pruppacher and Klett (2010); Chapter 1.4.2.
Elimination of warm layers in the atmosphere (>0 °C) by investigating thickness values	Threshold thickness values**:** • 850-500 hPa < 4170m. • 700-500 hPa < 2590m. • 850-700 hPa < 1580 m. (Lowest layer critical).	Lamb (1954) ; Wagner (1957); Koolwine (1975) ; Keeter and Cline (1991) Heppner (1992) Chapter 1.4.2, Chapter 5
Melting effect on falling snowflakes close to the surface.	Height of the freezing level a.g.l < 300 m Moist air scenario: Are surface temperatures <= 2 °C and surface RH 100% <= RH >= 40% Dry air scenario: Are surface temperatures 3 °C >= T <= 6 °C and surface RH 65% <= RH >= 40%	Chapter 3.2.4 Matsuo and Sasyo (1981); Pruppacher and Klett (2010); Chapter 5 (Case study 1-4)

The logical flow of the key physical mechanisms with regard to snowfall in Table 6.1 is used to create the five main steps important in the formulation of a snow forecasting decision tree.

Careful consideration needs to be given to each of the five steps (questions) before proceeding to the next step. A visual representation of this process is given in Fig. 6.1.

Step 1: Does the combined MSLP, 500 hPa geopotential height and 850 hPa temperatures synoptic pattern favour significant snowfall?
Step 2: Is precipitation likely to occur in the area of interest?
Step 3: Is there maximum depositional ice crystal growth around -15 °C?
Step 4: Are the atmospheric thickness less than the critical values given in Table 6.1? Also see Fig 6.1.
Step 5: Is the height of the freezing level a.g.l, surface temperature and RH within threshold values given in Table 6.1 and Fig. 6.1 for either moist or dry scenarios?

Step 1: Does the combined MSLP, 500 hPa geopotential height and 850 hPa temperatures synoptic pattern favour significant snowfall?

Step 1 is the starting point for identifying the synoptic patterns associated with snowfall in the snow forecasting decision tree (Fig. 6.1). The forecaster needs to answer the following question during winter when anticipating a potential significant snowfall event.

"Does the combined MSLP, 500 hPa geopotential height and 850 hPa temperatures synoptic pattern favour significant snowfall"?

Ascertain if the synoptic weather pattern is one which favours snow (see Section 4.2, Fig. 4.2). If the answer is yes, then the forecaster may proceed to Step 2. If the synoptic pattern is not favorable for snow the forecaster should remain vigilant of the potential change in the synoptic circulation patterns given by the NWP model guidance.

Step 2: Is precipitation likely to occur in the area of interest?

In **Step 2** the forecaster needs to determine the likelihood and location of precipitation (Fig. 6.1).The likelihood of precipitation needs to be determined by using sound forecasting principles (see Section 3.2.4 and Chapter 5).The forecaster cannot continue with Step 3, without there being a likelihood of precipitation. During this step, the forecaster should carefully consider those areas that are normally prone to snowfall. These areas have been indicated in Appendix A for the period 1981-2011.

Step 3: Is there maximum depositional ice crystal growth around -15 °C?

In **Step 3,** the forecaster needs to determine the level of saturation of the atmosphere in the region of -15 °C (Fig. 6.1). This step is essential in precipitation type forecasting as this temperature identifies the atmospheric level where ice crystals have the highest growth rate by deposition (see Section 1.4.2).

The Bergeron-Findeison cold cloud process is an integral part of the main snow forecasting decision tree. Supercooled water droplets live in co-existence with ice crystals between temperatures of -10 °C and -20 °C (AMS, 1996). Ahrens (2007) indicated that this is also the temperature where dendrite crystals, which are typically the crystals that form snowflakes, are found. Schultz et al. (2002) state that cloud top temperatures less than -10 °C can be viewed as a cross over temperature for determining the presence of ice crystals, there are few cases where snowfall occurred where cloud top temperatures were between -10 °C and -5 °C. In these instances, ice crystal growth occurred by aggregation.

The vertical distribution of temperature and moisture should be scrutinised to establish whether ice clouds exist or not. If the air in the atmosphere is saturated between -10 °C and -20 °C, the likelihood of fast growing dendrite crystals through deposition is very good. In addition, saturation of the atmosphere between 0 °C and -10 °C is crucial for the growth of snowflakes through aggregation. The forecaster needs to keep the growth of snowflakes through aggregation in mind when dealing with saturating between 0 °C and -10 °C, as this can further enhance the growth of snowflakes.

The MSG Day Microphysical RGB is useful in determining the different cloud properties within a cloud such as droplet size, presence of ice and supercooled water droplets (see Section 3.1.5). Channel 9 (IR10.8) can be used to obtain cloud top temperatures (Eumetsat, 2012). Upper air ascents are only done at 12 hourly intervals (at most) and MSG geostationary satellite imagery is available every 15 minutes. As a consequence, this imagery provides an excellent way for forecasters to fill in the gaps between atmospheric soundings or to verify the conclusions made from upper air sounding data. Once the forecaster has established that ice crystals are present and can optimally grow, Step 4 can be investigated.

Step 4: Are the atmospheric thickness less than the critical values given in Table 6.1?

Step 4 assesses the vertical distribution of temperature with regard to the presence of warm layers (T > 0 °C) which could alter precipitation type. The snow forecasting decision tree needs to make provision for determining whether the snowflakes will make it all the way down from the upper atmosphere to the ground without melting. This is done by determining the atmospheric thickness for the 850-500 hPa layer and the partial atmospheric thickness for the 700 500 hPa and 850-700 hPa layers.

As a consequence of the first three steps having been satisfied, the likelihood that ice crystals are fast growing into snowflakes is good. When they become heavy enough, they will fall to the ground under the influence of gravity. Snow can fall to the ground when the entire vertical distribution of temperature is at or below freezing (T<= 0 °C) (Beckman, 1987). The purpose of determining atmospheric thickness is to ensure that the temperature of the layer through which the snowflakes fall is less than 0 °C and to identify warmer layers that may cause the snowflakes to melt. Koolwine (1975) and Heppner (1992) found that looking at the 1000-850 hPa, 850-700 hPa and 700-500 hPa atmospheric thickness layers can help to distinguish liquid from frozen precipitation. The critical thickness values found in this dissertation are given in Fig. 6.1 and Table 6.1. Heppner (1992) indicated that the 850-700 hPa layer could help in identifying frozen precipitation, especially if the thickness of this layer was more than the 1550 m threshold which would then cause the snowflakes to melt through this warmer layer and reach the surface as rain. The 850-700 hPa atmospheric thickness associated with snow obtained in this dissertation were slightly higher (30 m) than those suggested by Heppner (1992).

It is critical that the lowest atmospheric layer be evaluated thoroughly within this snow forecasting decision tree. This is addressed in Step five where the surface temperature and RH are determined that could lead to the melting of snowflakes in temperatures above freezing.

Step 5: Is the height of the freezing level a.g.l, surface temperature and RH within the threshold values given in Table 6.1 and Fig. 6.1 for either moist or dry scenarios?

In **Step 5** the height of the freezing level above the ground, surface temperature and RH are investigated in the areas where precipitating ice clouds exist (Step 2 and Step 3). Lamb (1954) found that both the height of the freezing level a.g.l and the vertical distribution of temperature near the surface of the earth is critical in determining whether snow or liquid precipitation will develop. Matsuo and Sasyo (1981) found that when surface temperatures were below 2.5 °C and surface RH below 90% snowfalls were frequent. They also found that snowfall can occur when surface temperatures were higher, between 4 °C -6 °C but then surface RH has to be below 60%. In all of the cases analysed in Chapter 5, snowfall occurred frequently when surface temperatures were 0 °C <= T <= 2 °C and surface RH was close to 100% (saturation).

According to Pruppacher and Klett (2010), the height of the freezing level a.g.l should not be more than 300 m for snow to occur. However, in this dissertation, freezing level heights as high as 500 m a.g.l occurred during snowfall. However, due to the limited number of cases investigated here, it was decided to use the established height of 300 m in the decision tree. Further case studies and operational implementation of this decision tree will reveal whether this criterion is to limiting.

The forecaster needs to ascertain if the vertical distribution of moisture lends itself to a moist or dry air scenario (Fig. 6.1). These two scenarios are now briefly explained.

In moist air scenarios, the air is saturated close to the surface. Nimbostratus cloud extends from the mid-levels down to the lower levels where stratiform clouds are found. These cloud types can be identified using MSG satellite imagery as layered stratiform clouds have a uniform appearance in satellite imagery (Eumetsat, 2012). If the air in the atmosphere is saturated from the surface to the mid-levels with the presence of Nimbostratus clouds, then the forecaster must calculate if the surface temperature is <= 2 °C and 100% >= RH >= 40%. If these surface conditions prevail, snow can be forecasted, provided that the previous four steps are also true. The 40% minimum value for surface RH was found to be the minimum value of RH needed for precipitation to occur in Chapter 5.

In dry air scenarios, the atmosphere near the surface should be very dry. Cold air Cumulus (convective) clouds occur with a moist atmosphere within the Cumulus or cumulonimbus cloud layer. On satellite imagery, these clouds will appear more cellular in structure interspersed with clearer regions (Eumetsat, 2012). According to Kain et al. (2000), one of the biggest challenges that forecasters face is to determine whether or not melting will affect the precipitation type. Melting occurs typically when cold air advection and vertical motion in the lower levels are fairly weak. Heppner (1992) identified such cases where the rate of cold air advection in the upper air (unstable cases) exceeds that in the lower layers. In these cases, snow could melt into raindrops. This is typical of the dry air scenario. According to Kain et al. (2000), in areas where it has been raining for a while, cooling due to melting will be strongest and these areas need to be monitored as this causes release of latent heat and further cooling of the atmosphere which can lead to snow. In the dry scenario, when cold air Cumulus clouds are present, the forecaster needs to calculate if surface temperature is 3 °C >= T <= 6 °C with surface RH between 40 and 65%. If these criteria are met, snow can be forecast, provided that the criteria of the previous four steps have been satisfied.

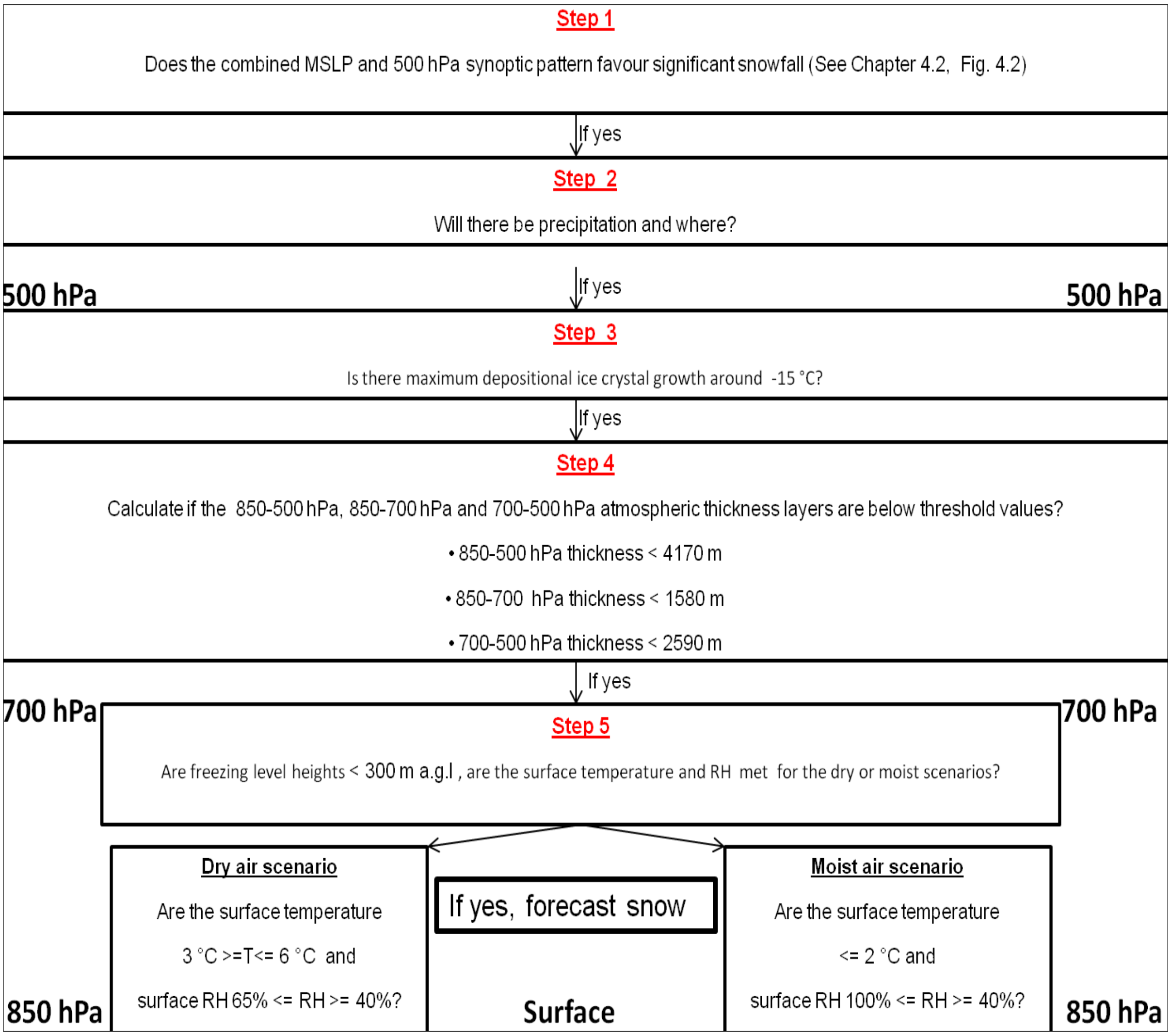


Figure 6.1: Snow forecasting decision tree

If the answer is no at any point at each of the steps in Fig. 6.1, the forecaster should monitor weather conditions till such a stage that conditions change so that a decision can be reached.

6.4 Application of the snow forecasting decision tree

On 7 August 2012, widespread snowfall occurred over the Gauteng Province. Some of the weather stations which recorded snowfall were Rand Airport, OR Tambo International Airport (ORTIA), Pretoria east (SAWS) and Wonderboom Airport. This was the first time on record that snow had occurred in all nine provinces of South Africa (News24, 2012). The snowfall over Gauteng fell from Cumulus clouds in dry surface conditions. At Rand Airport, Pretoria east and Wonderboom, snow occurred with surface temperatures between 3 and 6 ° C. The case studies that were described in Chapter 5 were moist air scenarios with snowfall due to Nimbostratus clouds where surface temperatures were <= 2 °C and surface RH close to saturation (100%). The purpose of the 7 August 2012 case study over Gauteng will be to test the snow forecasting decision tree (Fig. 6.1) with specific reference to the dry air scenario where snowfall occurred in temperatures between 3 and 6 °C and with surface RH values from 40-60%. Special emphasis will be placed on Step 5.

In order to illustrate the *snow forecasting decision tree* on 7 August 2012, the conditions at 0000 UTC will represent the time of observation while a forecast is prepared for 1200 UTC. NCEP reanalysis data are used here as an example of an NWP forecast in order to illustrate how NWP data could be used in the *snow forecasting decision tree*. Forecasts are routinely issued at 0500 UTC from the National Forecasting Center of SAWS and the discussion will expand on how observed data could be incorporated into the *forecasting process* as they become available. In the final section of this discussion, observed data will be used to indicate the atmospheric conditions when the snowfall occurred.

6.4.1 Using the snow forecasting decision tree to predict a snowfall event for 1200 UTC by using NWP data.

Step 1: Does the combined MSLP and 500 hPa synoptic patterns favour significant snowfall?

The NWP forecast for 7 August 2012 at 1200 UTC indicates that the COL would be situated over Gauteng with a cold frontal surface low east of KZN. The ridging surface AOH was predicted to be located near 40° S (Fig. 6.2).

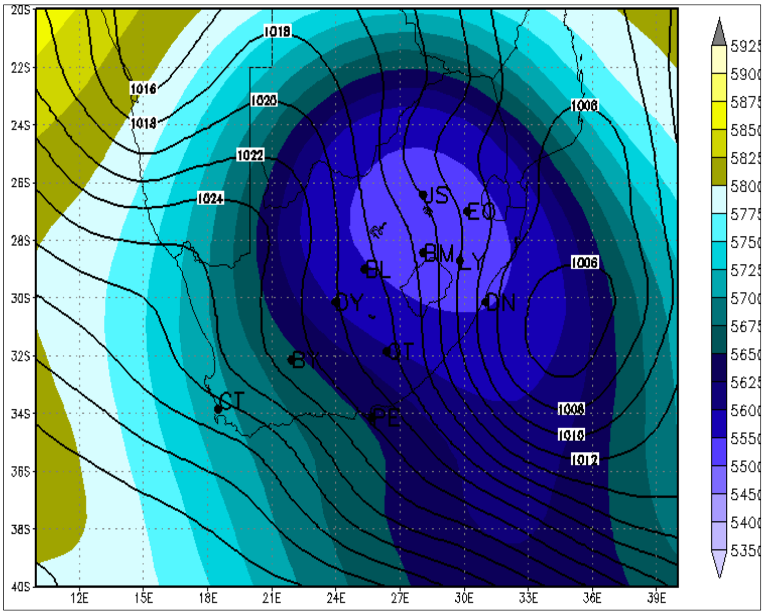


Figure 6.2: 12 hour model forecast of mean sea level pressure in hPa (black solid), 500 hPa geopotential heights in metres (shaded) for 7 August at 1200 UTC (NCEP reanalysis data)

This will result in the strengthening of the surface pressure gradient south of the country, enhancing the cold air advection into South Africa. This is a typical snow producing synoptic pattern. This pattern bears resemblance to the left hook (Van Heerden and Hurry, 1995) and is similar to node 3, 9, 15 and 21 of Fig. 4.2 in Section 4.2. Step 1 has been positively identified.

Step 2: Is precipitation likely to occur in the area of interest?

The NWP forecast at 0600 UTC on the 7 August 2012 for Gauteng is unfavourable for the formation of precipitation. Even though the forecast shows surface convergence, there is a lack of upper air divergence (300 hPa) and moisture throughout the column, making it unfavorable for the formation of precipitation.

For 1200 UTC, the NWP forecast shows that at 850 hPa (Fig. 6.3 A) surface conditions are relatively dry over Gauteng with RH values of between 50 to 60%. Surface convergence is occurring over Johannesburg (Fig. 6.3 A). In Fig. 6.3 B, the jet stream is shown to pass over Gauteng with upper wind divergence over the right exit region. Fig. 6.3 D indicates that the 700 hPa COL is situated just south to south-east of Johannesburg with RH values in excess of 70%. Fig. 6.3 E and Fig. 6.3 F show that the 600 hPa and 500 hPa levels are moist with vertical motion close to Gauteng. Fig. 6.3 C points to the fact that there is not much cold air advection near the surface, resulting in surface temperatures between 4 and 6 °C over Gauteng.

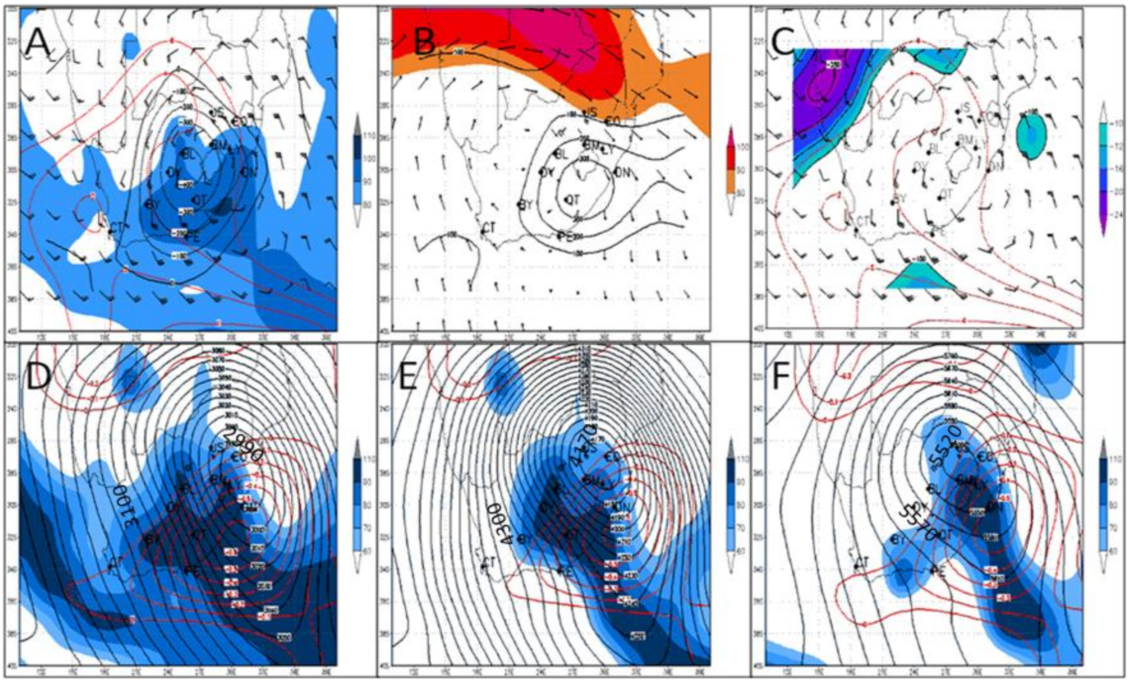


Figure 6.3: The NWP forecast for 1200 UTC on 7 August 2012 A) 850 hPa relative humidity (%) shaded, 850 hPa convergence in solid black (s^{-1}), 850 hPa wind barbs in knots black B) 300 hPa jet stream >80 knots shaded, 300 hPa wind divergence solid black (s^{-1}) C) 850 hPa temperatures < 6 °C (red), 850 hPa cold air temperature advection *10e^{6}(°C s^{-1}) (shaded), 850 hPa wind barbs in knots D) 700 hPa relative humidity in % shaded, 700 hPa negative omega in Pa s^{-1} red, 700 hPa Geopotential heights solid black E) 600 hPa relative humidity in % shaded, 600 hPa negative omega in Pa s^{-1} red, 600 hPa Geopotential heights solid black F) 500 hPa relative humidity in % shaded, 500 hPa negative omega in Pa s^{-1} red, 500 hPa Geopotential heights solid black

This is an example of a case where the rate of cold air advection in the upper air exceeds that in the lower layers (see Fig. 6.3 C) and if this happens, the snow could melt into raindrops (Heppner, 1992). Due to favourable synoptic conditions (COL close to Johannesburg through 700 hPa to 500 hPa with upper air jet stream), the presence of sufficient moisture in the atmosphere, the availability of surface convergence and upper air divergence and some uplift at 700 hPa the forecaster proceeds to forecast precipitation for 1200 UTC over Gauteng.

Step 3: Is there maximum depositional ice crystal growth around -15 °C?

Considering that conditions over Gauteng are favourable for the development of precipitation at 1200 UTC, it will be now be determined if ice crystals will grow near -15 ° C. In Step 2, the NWP in Fig. 6.3 C, D and E indicates the availability of sufficient moisture between the atmospheric layers of 700 hPa and 500 hPa for cloud development. In order to establish whether the predicted clouds over Gauteng contain ice crystals and if conditions are favourable for their growth through deposition around -15 °C, the vertical temperature distribution between the 700 hPa and 500 hPa levels at 1200 UTC are investigated. At 700 hPa (Fig. 6.4), the expected temperature over Gauteng is around -10 °C which is where the atmosphere now starts to contain ice crystals. At 600 hPa (Fig. 6.4), the temperature will be -15 °C which indicates that ice crystals will grow by depositional growth. The NWP output for 1200 UTC thus confirms the presence of ice crystals (sufficient moisture and cold enough temperatures) between -10 °C to -16 °C. The absence of strong vertical upward motion throughout this layer limits the growth of the ice crystals and excludes intense prolonged snow showers. The deposition process of ice crystal growth occurs at temperatures between -12 °C and -16 °C and are typically found in winter between the layers of 700 to 500 hPa, where the air in the atmosphere is saturated and vertical motion is maximised (NOAA, 2013). At 500 hPa and around -16 °C, the growth rate of ice crystals are at a maximum (Pruppacher and Klett, 2010).

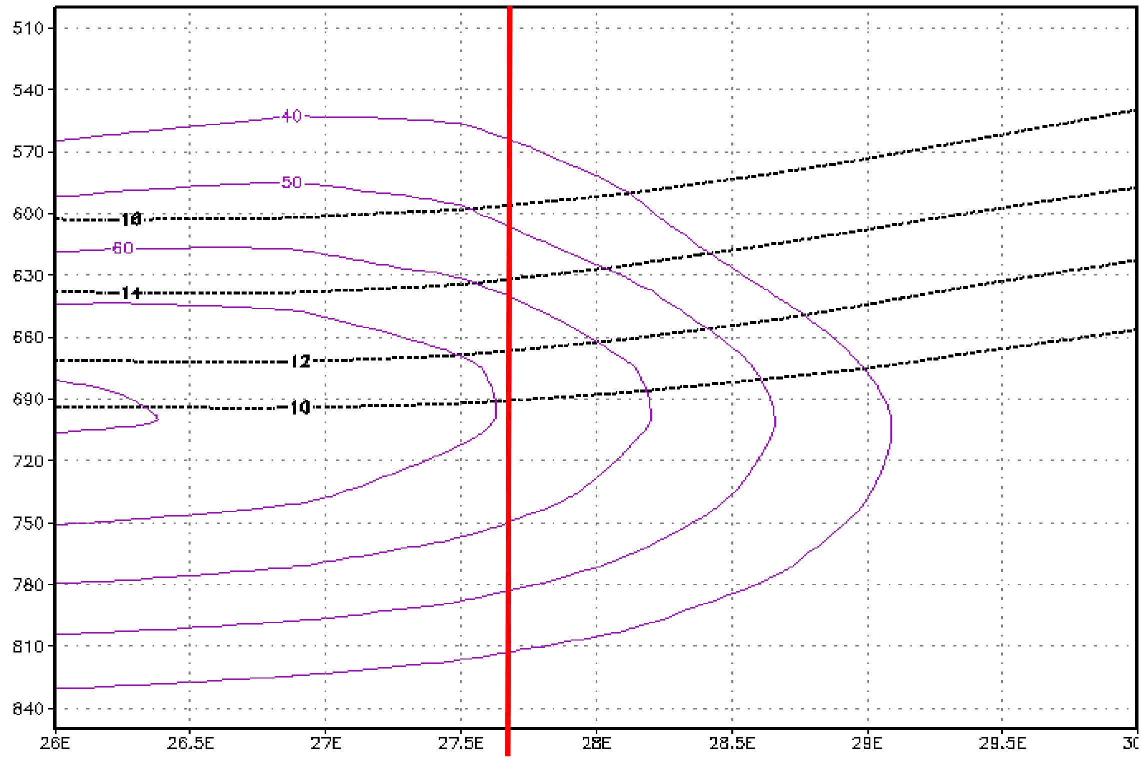


Figure 6.4: A vertical cross section of the NWP forecast of relative humidity greater than 40% (purple) and temperatures between -10 °C and -16 °C (dotted black lines) over Gauteng on 7 August 2012 at 1200 UTC. The vertical red line indicates the location of Gauteng

The IR 10.8 false colour image at 0445 UTC (Fig. 6.5) is investigated (in practice this would be the last image available to the forecaster before issuing the weather forecast).

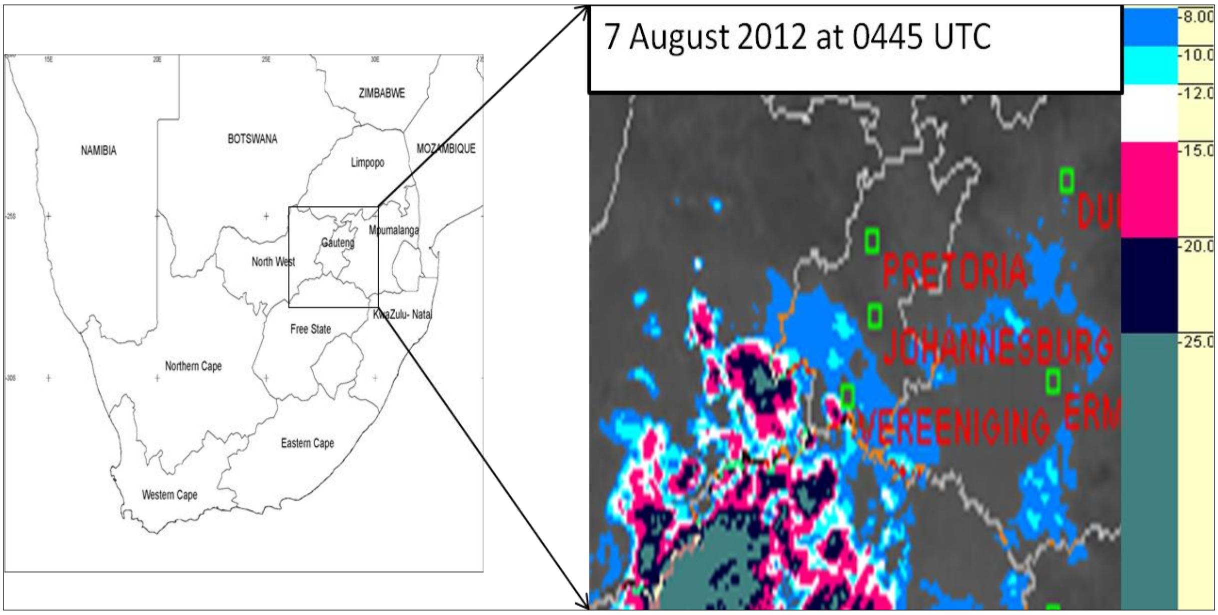


Figure 6.5: MSG satellite false colour IR 10.8 image over Gauteng at 0445 UTC on 7 August 2012© (2012) Eumetsat

The false colour IR temperature scale distinguishes between cloud top temperatures in the ranges of -8 °C to -10 °C (supercooled droplets), -12 °C to -15 °C (ice crystals and depositional growth), -15 °C to -20 °C (ice crystals and depositional growth) and -20 °C to -25 °C (ice crystals). To the south-west of Johannesburg, supercooled droplets are present (-8 °C to -10 °C, dark blue) with Cumulus cells south-west of Gauteng to the west of the upper COL (Fig. 6.5). These Cumulus clouds have a cellular structure with colder cloud tops. The Cumulus cells have cloud top temperatures between -12 °C and -25 °C (compare to NWP discussion). An animation of the satellite imagery (not shown) confirms that the Cumulus cells are developing and moving from the south-west over Gauteng.

Step 4: Are the critical values of partial thickness achieved?

The 1200 UTC NWP forecast is used to calculate the atmospheric thickness (Table 6.2). These are compared to the critical threshold thickness values of the snow forecasting decision tree. The values are all lower than the critical threshold thickness values and therefore no warm layers exist in the atmosphere, making conditions favourable for the formation of snowfall.

Table 6.2: Partial atmospheric thickness for 7 Aug 2012 at 1200 UTC compared to threshold values of snow forecasting decision tree

Atmospheric thickness	1200 UTC thickness forecast	Critical threshold thickness values
850-500 hPa atmospheric layer	4050-4080 m	<4170 m
700-500 hPa partial atmospheric layer	2520-2540 m	<2590 m
850-700 hPa partial atmospheric layer	1540 m	<1580 m

The forecaster now proceeds to the final step.

Step 5: Is the height of the freezing level a.g.l, surface temperature and RH below threshold values given in Table 6.1 and Fig. 6.1 for either moist or dry scenarios?

Considering that the first four steps of the *snow forecasting decision tree* was favourable, it now has to be determined if a moist or dry snow case scenario exists. The air in the atmosphere is not predicted to be saturated (RH = 100%), especially in the lower layers where the NWP is indicating dry conditions. The RH at 850 hPa is predicted to be less than 60% at 1200 UTC (Fig. 6.3 A). Furthermore, at 700 hPa (Fig. 6.3 D), 600 hPa (Fig. 6.3 E) and 500 hPa (Fig. 6.3 F) the RH is close to 70%, indicating the potential of clouds within this layer. In this particular case, the height of the Cumulus cloud base in metres a.g.l can be obtained by multiplying the dewpoint depression by 125 (SAWB, 1982). In this particular case, a cloud base of 2274 m a.m.s.l can be calculated, which is close to 750 hPa. Surface temperatures are forecast to be in the region of 4 °C (Step 2, Fig. 6.3 C) at 1200 UTC which excludes the moist snow scenario. Additionally, the satellite image at 0445 UTC does not indicate Nimbostratus clouds but Cumulus type clouds. Considering the predicted surface temperatures (3-6 °C) and RH values (< 65%), the dry air snow scenario is most probable.

6.4.2 Atmospheric conditions during the time of the snowfall event

The 1200 UTC observed data is used to confirm the occurrence of snow over Gauteng. The surface observations at 1200 UTC are indicated in Table 6.3. Snow is already occurring at most stations where visual weather observations are done in Gauteng. The surface temperatures are between 2 °C and 5 °C and surface RH between 44% and 65%.

Table 6.3: Surface observations during snowfall over Gauteng on 7 August 2012

Observation station	Time observed in UTC	Surface temperature in °C	Dew point in °C	Surface RH in %	Cloud type
Rand Airport	Light snow at 1200	4	-4	44	Cumulus
OR Tambo International Airport	Light snow at 1200	2	-5	59	Cumulus
Wonderboom Airport	Light snow at 1200	5	-2	60	Cumulus
Pretoria East SAWS	Light snow at 1200	4	-2	65	Cumulus

The 1200 UTC Irene tephigram indicates south-westerly winds in the low levels (encircled on Fig. 6.6), causing the advection of drier continental air which helps to provide the drier conditions necessary for snowfall at the surface. These drier conditions are also reflected in the surface RH values in Table 6.3. These drier conditions are important for the snowflakes to survive in above freezing temperatures (see Section 3.2.5). These drier surface conditions are in stark contrast to the moist examples described in Chapter 5. The 1200 UTC Irene tephigram and satellite image is used to verify the vertical distribution of moisture and temperature which was present during the snowfall event. The increase in dew point temperatures from 700-560 hPa (Fig. 6.3), together with surface cloud observations and satellite imagery confirms the presence of Cumulus cloud between these levels. The tephigram also indicates that the temperature range in the 700–560 hPa levels was between -12 °C and -25 °C (Fig. 6.6). The height of the freezing level at Irene is 400 m a.g.l (Fig. 6.6).

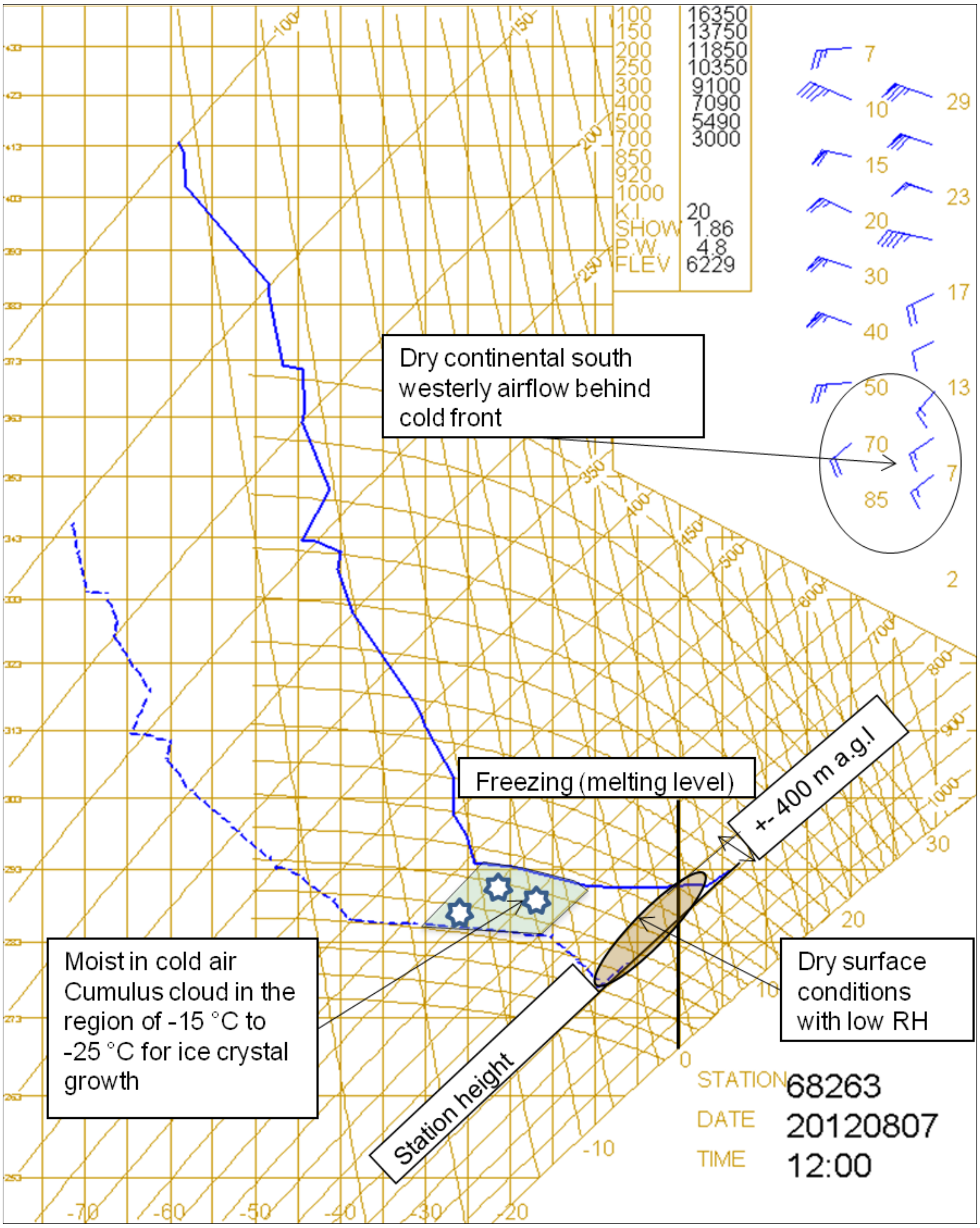


Figure 6.6: South African Weather Service tephigram for Irene weather station at 1200 UTC on 7 August 2012

The false colour IR 10.8 in Fig. 6.7 indicates the cloud top temperatures of the Cumulus cloud cells at 1200 UTC. The temperature of these Cumulus cells cloud tops over Gauteng are between -10 °C and -22 °C which compares well with the values of -12 °C and -25 °C where Cumulus clouds are indicated on the tephigram (Fig. 6.6). Temperatures of around -15 °C (white and pink colour) are good for the growth of dendrite ice crystals and the subsequent formation of snow (see Table 6.3).

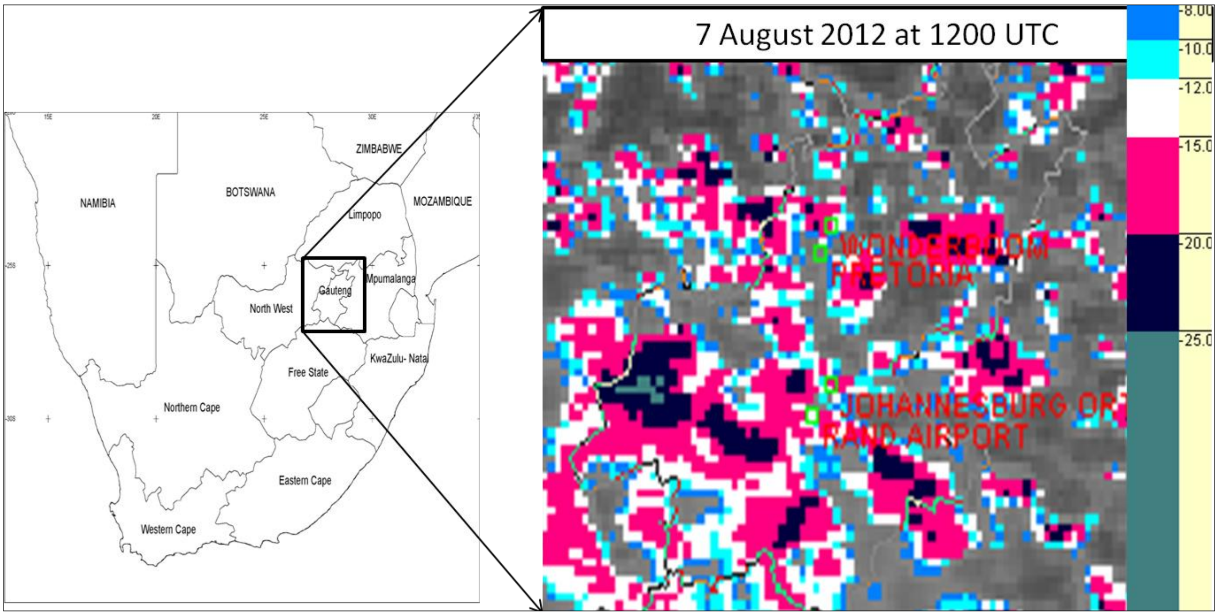


Figure 6.7: MSG satellite IR 10.8 false colour cloud top temperatures on 7 August 2012 at 1200 UTC© (2012) Eumetsat

The 1200 UTC Airmass RGB in Fig. 6.8 indicates the intrusion of dry descending stratospheric air over Gauteng province (orange colour) to the north-east of the upper COL due to the upper level jet stream. The deep blue colour over the central interior is indicative of the cold air mass (Eumetsat, 2013). The enlarged Day Microphysical RGB in Fig. 6.8 indicates that the pinkish cellular clouds over Gauteng contain ice (see also Fig. 6.7). This is a case where seeder clouds are absent and only spender clouds are observed, which are normally winter Cumulus clouds that may cause light snow. According to Jiusto and Weickmann (1973), when thick convective spender clouds are present, heavy snowfall may occur (see Section 1.4.2). This is in contrast to the case studies of Chapter 5 where both seeder and spender clouds were observed.

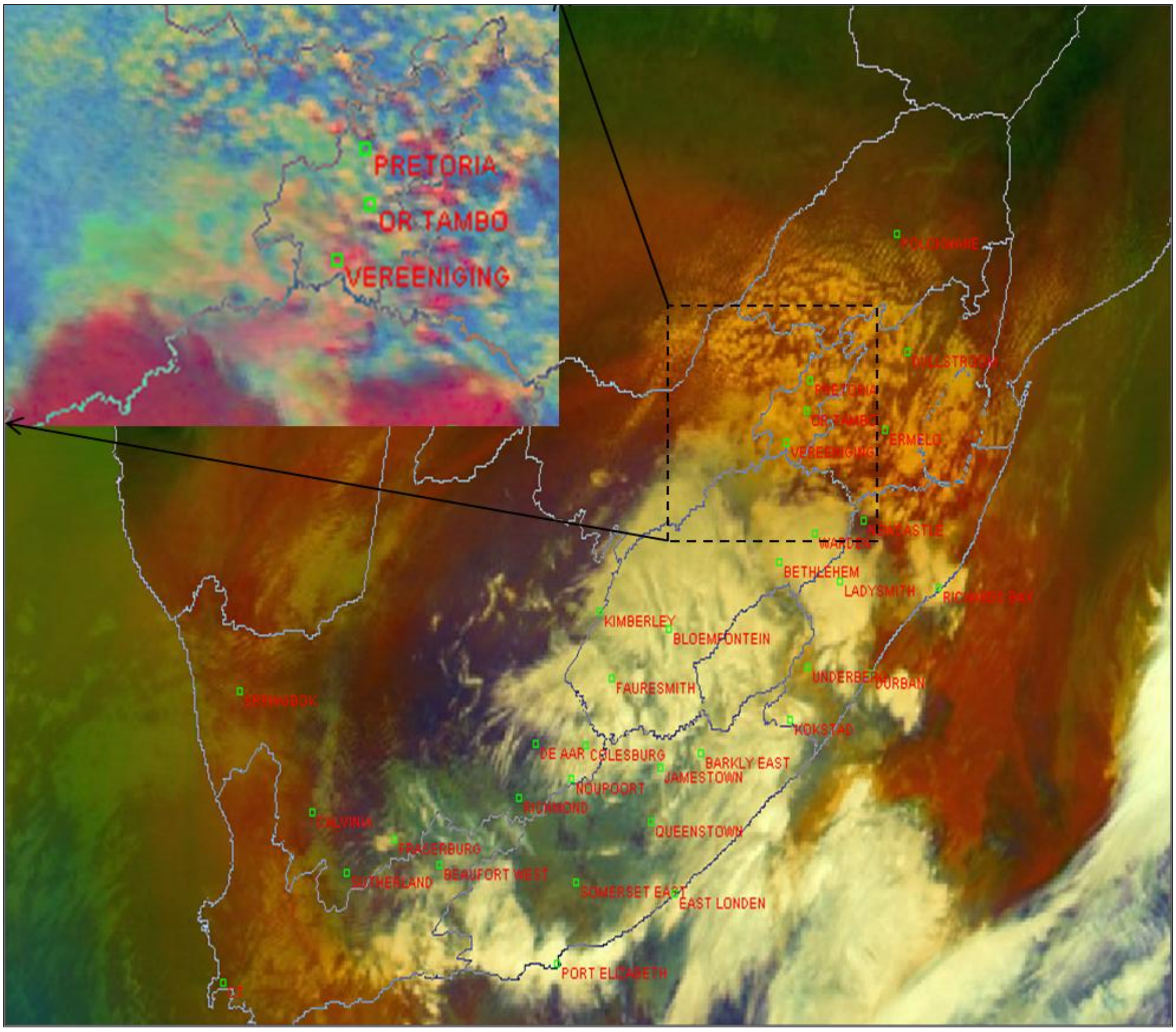


Figure 6.8: MSG satellite, Airmass RGB for 7 August 2012 at 1200 UTC with the zoomed in Day Microphysical RGB for the same time over Gauteng province© (2012) Eumetsat

Fig. 6.9 indicates the fluctuation of surface temperature and surface RH throughout the day at Pretoria east (SAWS). The snowfall at 1116 UTC was due to a Cumulus cloud when the surface temperature was close to 6 °C and the surface RH 53%. After this snowfall, the temperature dropped to around 4 °C and the surface RH rose to 65%. The next Cumulus cell was located east of Pretoria at 1200 UTC (Fig. 6.7) and snow was reported with a surface temperature of 4 °C and surface RH of 65%. Another Cumulus cell moved over Pretoria east (SAWS) at around 1320 UTC when it snowed and the surface temperature was close to 5 °C and the surface RH 60% (also see Fig. 1.2 in Chapter 1.3 which indicates a photo of the snowfall at Pretoria east (SAWS) at 1321 UTC). After this snowfall, the surface temperature dropped to just below 4 °C and the surface RH rose above the 65% critical threshold to nearly 80%. Consequently, no more snowfall was observed.

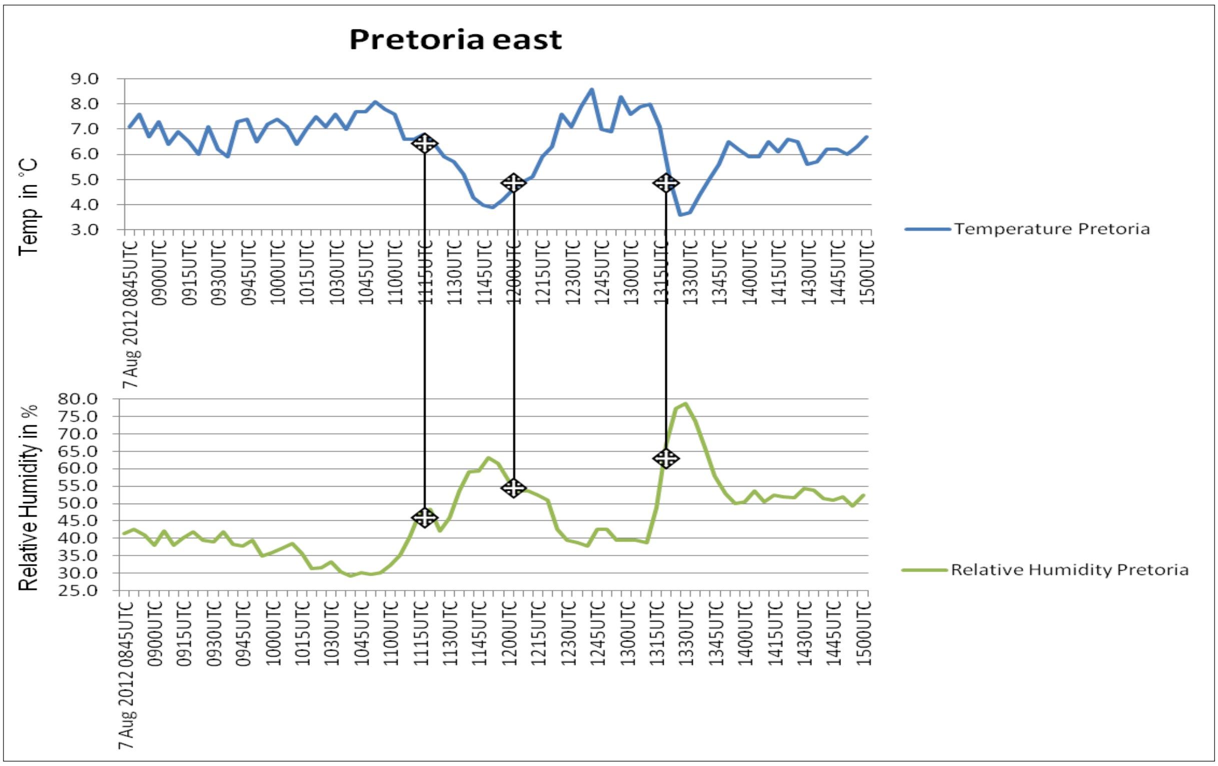


Figure 6.9: Surface temperature and surface relative humidity at South African Weather Service, Pretoria east station on 7 August 2012; black lines and stars indicate snow at Pretoria (SAWS)

At ORTIA the surface temperature remained below 4 °C during the entire day while surface conditions were moister than at Pretoria east (SAWS) and Wonderboom, but not saturated (Fig. 6.10). Most of the snowfall occurred at surface temperatures below and equal to 2 °C. It is of interest to note that at 1005 UTC and 1200 UTC snowfall occurred with surface temperature above 2 °C and closer to 3 °C. On these two occasions, the surface RH was lower than 70%. The lower RH made it possible for snow to occur, despite the surface temperature being above 2 °C. From 1300 UTC, surface RH started to increase until nearly 100% but light snow continued to fall as temperatures were around the 1 °C mark which is more representative of a moist air scenario.

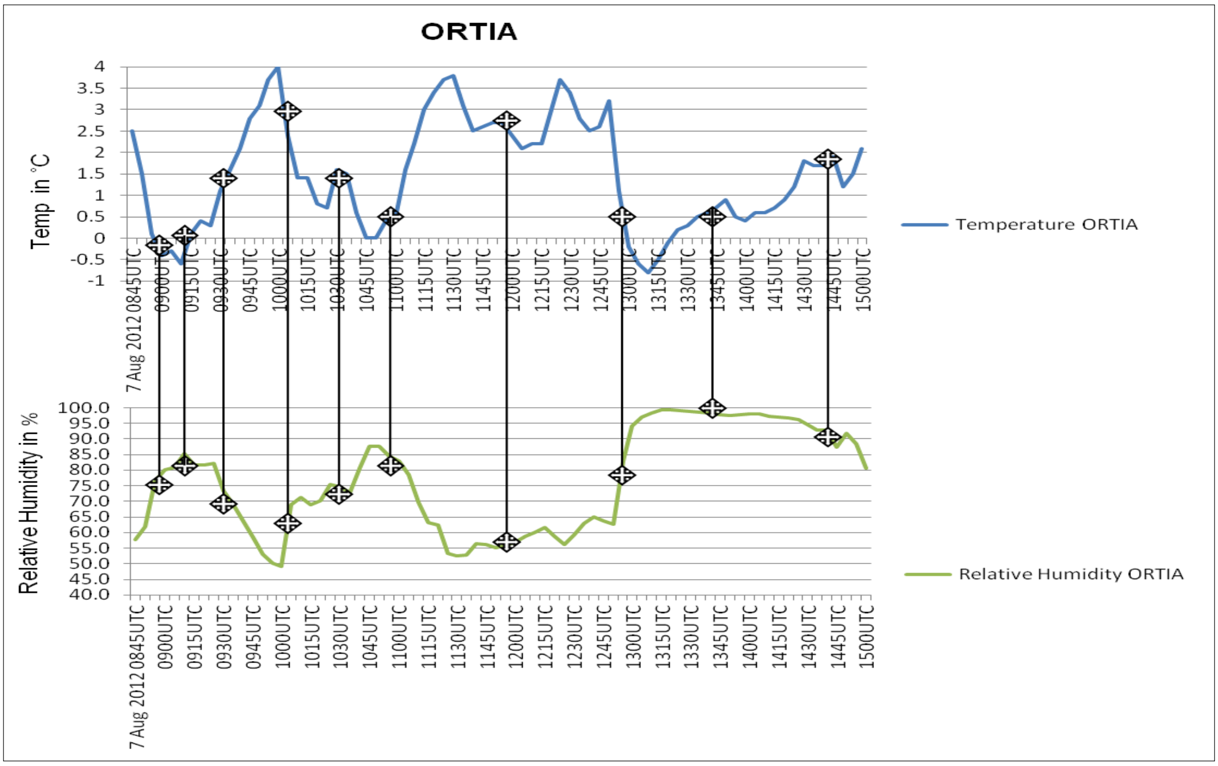


Figure 6.10: Surface temperature and surface relative humidity at South African Weather Service, OR Tambo International Airport weather station on 7 August 2012; black lines and stars indicate snow

Rand airport which is close to Germiston to the south-west of ORTIA, reported heavy snow at 1000 UTC when a Cumulus cloud with cloud tops close to -20 °C moved over the airport. At 1200 UTC, light snow was reported when the surface temperature was 4 °C and the surface RH 44% (Table 6.3) confirming the dry air scenario.

At Wonderboom Airport, snow was reported at 1200 UTC with a surface temperature of 5 °C and a surface RH of 60% (Fig. 6.11). At 1145 UTC, the edge of a Cumulus cloud was starting to invade the airport. At 1200 UTC (Fig. 6.7), the Cumulus cloud with cloud top temperatures of -14 °C to -18 °C was located over the airport.

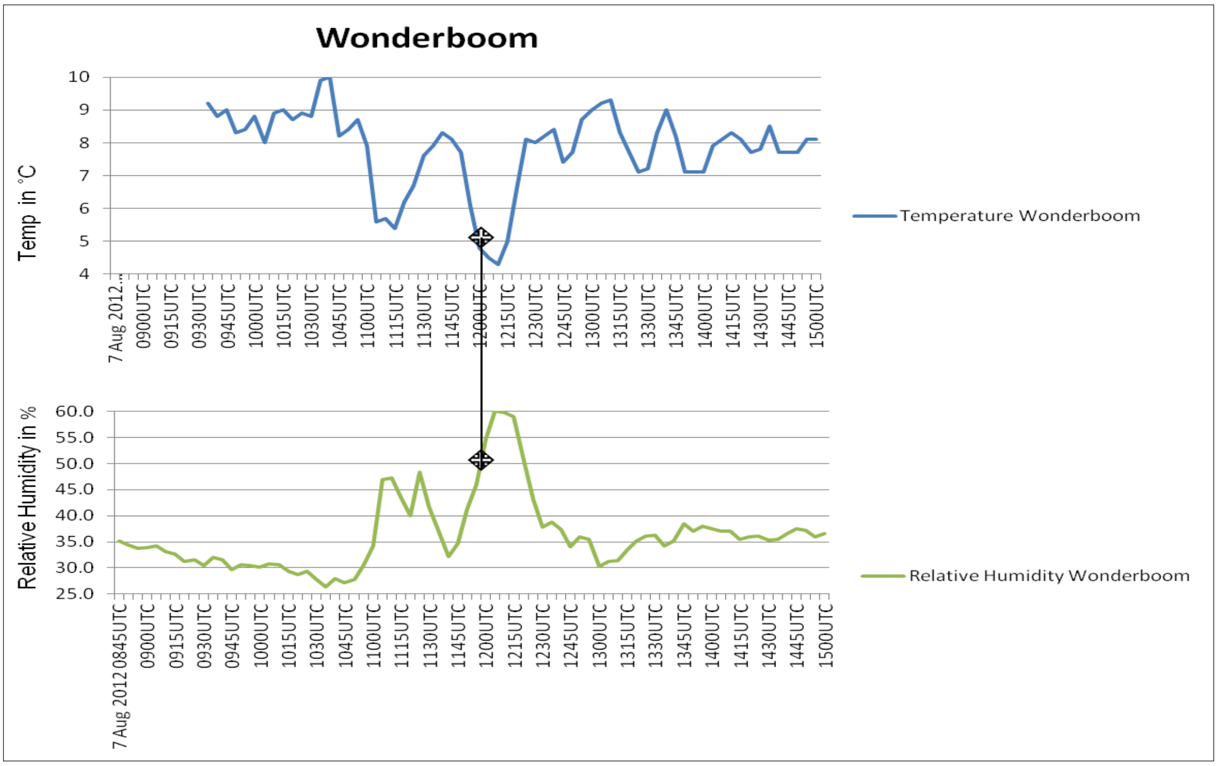


Figure 6.11: Surface temperature and surface relative humidity at South African Weather Service, Wonderboom weather station on 7 August 2012; black line and stars indicate snow

6.5 Summary

Snowfall occurred at 1200 UTC from Cumulus clouds over Gauteng. Surface observations showed that during the snowfall, surface RH was below 65% and surface temperatures varied between 2 °C and 5 °C. No snow had been forecast over Gauteng by the SAWS on this particular day, most probably due to the warm surface conditions (T > 2 °C). Although snow occurred in dry surface conditions with temperatures above 3 °C, following the *snow forecasting decision tree* would have enabled a forecaster to predict snow. The common moist air snow scenarios (Chapter 5) can also be forecasted using this same snow forecasting decision tree.

The snow forecasting decision tree can assist in creating situational awareness of the physical processes involved during the forecasting of snow in winter. This forecasting process can help forecasters to anticipate and nowcast snow by providing them with sound scientific and logical based forecasting steps. The process also incorporates readily available NWP output with clear threshold values making it easy to use.

Chapter 7: Summary, conclusions and recommendations

7.1 General summary

Significant snowfall events in this research were defined as those cases where snowfall reached the ground in areas with an altitude of less than 2000 m a.m.s.l. Snowfall in South Africa normally occurs in the sparsely populated mountainous regions with altitudes greater than 2000 m a.m.s.l. In the lower altitudes, the snow often melts before reaching the ground. However, during significant snowfall events as defined in this dissertation, snowfall reaches the more populated lower elevated regions. The average height of the interior of South Africa is 1500 m a.m.s.l and significant snowfall can therefore impact on the livelihood and daily activities of people (see Section 1.2, Fig. 1.1).

The aim of this research was to investigate synoptic circulation patterns and atmospheric variables associated with significant snowfall over South Africa in winter. Five objectives were identified, namely:

Objective 1: Identify significant snowfall cases over South Africa for the period 1981-2011.
Objective 2: Identify surface and upper air synoptic scale weather systems associated with significant snowfall subjectively in order to identify atmospheric variables that play an important role in the occurrence of significant snowfall.
Objective 3: Create an objective climatology of surface and upper air synoptic scale weather patterns as well as 850 hPa temperatures for significant snowfall cases using self-organising maps (SOMs).
Objective 4: Conduct several case studies to create a better understanding of the local atmospheric variables conducive to snowfall over the interior of South Africa.
Objective 5: Provide a snow forecasting decision tree to forecast significant snowfall over the interior of South Africa.

Snow producing synoptic scale circulation patterns were identified for a 30 year period for the months of May to October. Four case studies were conducted and were chosen due to the significant snowfall, which occurred in several regions over South Africa. These case studies investigated the factors giving rise to significant snowfall and resulted in a snow forecasting decision tree. This decision tree was illustrated by investigating the very significant snowfall event in August 2012.

7.2 Summary of results

7.2.1 Significant snowfall cases over South Africa (Objective 1)

South Africa is affected by weather systems that are capable of producing significant snowfall. The results of this dissertation show that, over the past 30 years, there have been 60 significant snowfall cases (see Appendix A). South Africa is situated in the subtropics between 25 and 35° S (Taljaard, 1972) and snow does not occur frequently over South Africa in winter as the snow often melts when it reaches the warmer layer close to the ground. Therefore, snowfall is very often limited to the mountains of the sub-continent during the winter months.

On average there are two significant snowfall events per year over South Africa but the results indicate that these events do not happen every year but are clustered together in certain years. For instance, there were three events in 1981, one in 1982 and none in 1986 (see Appendix A). During the winters of 2011 and 2012, there were four significant snowfall events. As snow occurs irregularly with only, at most, a few events per year, it becomes important to understand the synoptic conditions and atmospheric variables causing snowfall in lower elevations.

7.2.2 Synoptic classification of snowfall circulation patterns in winter (Objective 2 and 3)

7.2.2.1 Subjective synoptic classification

The month with the highest frequency of snow is July, followed by June and August. Snow occurs infrequently in May and October.

During the subjective synoptic classification of weather systems over South Africa (see Section 4.1) the Atlantic Ocean High (AOH), Indian Ocean High (IOH), cold fronts and upper cut-off low (COL) were found to be major role players in the occurrence of significant snowfall in winter. These weather systems were previously identified as important winter circulation systems by Taljaard (1995b) and Tyson and Preston-Whyte (2000). In this dissertation, it was found that the combination and interaction of surface (AOH, IOH and cold front) and upper air synoptic circulation systems (COL) were critical in sculpting the ideal synoptic pattern for significant snowfall to occur. Many of the significant snow cases were long lasting and took two to three days to progress across the country, due to the slow moving nature of the weather systems. Taljaard (1985a) noted the importance of the slow moving surface AOH in the creation of an upper COL. The role of the AOH and IOH following the cold front are critical in the occurrence of snow as the latitudinal position and strength of the surface high pressure systems was found to be instrumental in the formation of the upper COL which was associated with significant snowfall.

Five synoptic patterns were classified subjectively and the results are summarised in Table 7.1. Pattern 1 and 2 contributed to more than 80% of the snowfall events. These two patterns contained the surface high pressure system located around 35° S latitude between 1024 hPa to 1036 hPa in strength. In pattern 1, the surface AOH was dominant while in pattern two it was the surface IOH which was dominant. In both patterns, there was a cold front which was associated with an upper COL. Table 7.1 indicates that when COLs occurred, the AOH and IOH were situated between 35 and 40°S.

The position of the AOH and IOH formed the basis of the subjective classification into patterns 1 and 2. Moreover Van Heerden and Hurry (1995) indicated that the strong advancing AOH behind the cold front (pattern 1) lead to the formation of the right hook which caused an influx of moist cool air over the north-eastern interior and when associated with an upper COL could cause heavy rain or snow due to enhanced uplift and condensation. Tyson and Preston-Whyte (2000) indicated that, when a ridging surface high pressure system is associated with an upper COL it, often leads to widespread precipitation over the country, since, the surface anticyclone promotes a strong pressure gradient leading to a strong influx of surface moisture over the country.

Table 7.1 Summary of results obtained during the subjective synoptic classification for the winter period 1981 to 2011.

Pattern 1: (37 cases)	**Pattern 2: (13 cases)**	**Pattern 3 (3 cases)**	**Pattern 4 (5 cases)**	**Pattern 5 (2 cases)**
Pointed upper trough/COL, cold front with associated surface low south or east of the country. AOH (1024 to 1036 hPa) between 30° to 40° S. Average pressure gradient 21 hPa.	Pointed upper trough/COL, cold front followed by ridging IOH 1028 to 1036 hPa) between 36° to 40° S).	Pointed upper trough/COL, cold front with surface low over the south-eastern Cape coast.	COL	Unknown

On average, a surface pressure gradient of 21 hPa was found between the AOH and the low pressure in pattern 1 during significant snowfall. Patterns 3, 4 and 5 made up 17% of the cases but with the upper COL still prominent.

7.2.2.2 Objective synoptic classification

The synoptic weather systems associated with snowfall were classified objectively by using Self Organising Maps (SOMs). Two distinct synoptic patterns emerged from the objective classification scheme and these were similar to pattern 1 and 2 of the subjective classification.

The two synoptic patterns which most frequently occur when snowfall happens lie on opposite sides of the SOM and are very different. On the one side (left pattern) of the SOM (node 19) a very deep 500 hPa pointed trough or COL is present with an intense surface cold front extending from a low south-east of the country. An AOH near 40° S causes south-westerly to southerly flow producing horizontal cold air and moisture advection into the southern parts of South Africa. On the other side (right pattern) of the SOM (node 6) a weaker COL is found at 500 hPa with the IOH located south of the country close to 40° S this time producing southerly to south-easterly flow over the Indian Ocean into the eastern parts of South Africa. The result of this airflow over the warmer Indian Ocean was that the 850 hPa temperatures were warmer with less intense frontal boundaries.

The dominant snow-producing weather systems were thus found to be a combination of a ridging high pressure system located around 35° S (Either AOH/IOH) following a cold front with a pointed upper air trough or COL. This infrequent pattern where the surface high followed a cold front at 35° S was also found by Taljaard (1995a) (see Section 2.1.1.2) and normally lead to the development of a COL (Taljaard, 1985a). In this dissertation, it was also found to be associated with significant snowfall over South Africa. In the objective classification, a strong AOH and IOH of 1030 hPa or more in strength was located between 34° S and 38° S in the presence of a COL.

7.2.3 Case studies (Objective 4)

The main findings of the case studies of Chapter 5 and 6 will be summarised as follows. The findings will be explained by referring to the synoptic circulation, upper air soundings, atmospheric thickness and surface observations.

a. Synoptic circulation

COLs have been associated with heavy rainfall in winter over South Africa; however, no synoptic classification of significant snowfall producing weather systems existed prior to this research. De Villiers (2001) noted the important role that the upper air circulation played in snowfall over the north-eastern Cape in South Africa and stated that more research was needed into this particular area. (Taljaard, 1982a) found that an important ingredient in the development of COLs is the surface ridging high pressure system south-west and south of the country leading to strong advection from the south and south-east over the escarpment areas of the Cape to KZN.

The case studies pointed out that it is not necessary for an existing cold front associated with an upper COL to move in from the Atlantic Ocean over Cape Town. Cold fronts can develop over the interior of South Africa when COLs form and the AOH ridges strongly near 40° S south-west of the country. The development of a COL normally occurs overland between Cape Town and Port Elizabeth and on occasion over the eastern interior.

In the case studies of Chapter 5, the surface synoptic weather patterns were well developed cold fronts followed by an AOH or IOH with an upper air COL or where an intense surface low was located along the south-east coast. In this dissertation, it was found that the combination of surface and upper level weather systems lead to snowfall over the usually dry summer rainfall areas in winter.

This surface AOH/IOH and the frontal low were responsible for creating a strong pressure gradient causing low level horizontal moisture and cold air temperature advection into South Africa. Snow occurred where low level cold air advection was prevalent helping to cool the lowest boundary layer. The case studies emphasised how the ridging high behind a cold front could contribute positively or negatively on the occurrence of snow. It is responsible for creating very low surface temperatures but at the same time also increasing the surface RH to 100%. Under circumstances where RH values approach 100% snow cannot occur when the surface temperatures are greater than 2 °C (Matsuo and Sasyo, 1981). On the other hand, the IOH south-east of South Africa produces the low level south-easterly flow perpendicular to the Drakensberg mountain range causing orographic lift enhancing snowfall in the narrow corridor of southern KZN and the north-eastern part of the Eastern Cape and even the eastern escarpment of Mpumalanga. The importance of orography in creating precipitation was also noted by Stranz and Taljaard (1965); Budin (1985); Tyson and Preston-Whyte (2000) and Kocin and Uccellini (2004). The north-eastern part of the Eastern

Cape and the southern part of KZN is situated in the narrow channel between the highly elevated Drakensberg range to the north-west and the warm Indian Ocean to the south-east (Fig. 1.1). When a strong surface anticyclone is situated to the south of the country, colder air is advected from the south-east perpendicular to this mountain range as in the *right hook* case (Van Heerden and Hurry, 1995) and this area becomes an enhanced focused region of thermal advection, convergence and orographic lift, increasing heavy snowfall in that area.

All cases in Chapter 5 and 6 were associated with an upper air jet stream of at least 80 knots in strength causing upper level wind divergence. Kocin and Uccellini (2004) found jet streams to play an instrumental role in contributing to favourable atmospheric conditions for snow. Budin (1985) found that high snowfall over the Australian highlands was related to the strong westerly sub-tropical jet.

b. Upper air soundings

The analysis of upper air soundings during snowfall revealed that in all instances a change in air mass occurred throughout the troposphere due to the combined effects of the surface cold front and upper COL. In the horizontal, the change in temperature was greater than 5 °C, while in the vertical, the change in temperature occurred throughout the middle and lower atmosphere with the passage of cold fronts. These findings are consistent with Taljaard (1961; 1972; 1994b) who stated that the passage of a cold front is visible at a depth greater than 3 km on an aerological diagram, while the horizontal temperature change was more than 5 °C in the mid-latitudes. Normally the wind at the surface will change from north-westerly ahead of the cold front, to south-westerly behind the cold front (Taljaard, 1985a; Tyson and Preston-Whyte, 2000) and this was also found in the case studies. However, in this dissertation, it was also found that when a strong surface ridging high was present behind a cold front, the change in wind direction was very often instantaneously from north-westerly to south-easterly due to the rapid rise in surface pressure behind the cold front. The upper air ascents also indicated vertical wind shear typical of baroclinic weather systems. The strong vertical wind shear was often caused by the high pressure system and cold front at the surface and COL in the upper troposphere. This corresponds to Glickman (2000) who described a cold front as a weather system which has a strong horizontal temperature gradient with strong vertical wind shear in the presence of an upper air jet stream.

Upper air troughs and COLs produce mid- and high-level clouds such as altostratus and cirrostratus which are effective in producing ice crystals (Jiusto and Weickmann, 1973). In the case studies, it was found that the upper COL lead to the formation of cloud in the mid-levels causing saturation of the air between the 700 hPa and 500 hPa pressure levels where clouds were within the -10 °C to -20 °C temperature range corresponding to the values of a case study conducted by Taljaard (1985a) involving snow. This temperature range was found to be critical in producing ice crystals for seeding the lower cloud layers. The depositional growth of ice crystals was the largest in the region of -15 °C. This is similar to the findings of Pruppacher and Klett (2010). This alludes to the fact that the main mechanism for ice crystal growth between 700 and 500 hPa was that of deposition of dendrite crystals due to the presence of the COL.

The onshore flow from the ridging AOH/IOH or surface frontal low pressure system caused strong advection of moisture with supercooled cloud droplets leading to the saturation of the atmosphere at pressures higher than 700 hPa. Taljaard (1985a) indicated that the effect of the AOH was accentuated in a similar region of the atmosphere. The 0 °C to -10 °C temperature range occurred typically between the 850 hPa and 600 hPa pressure levels during snowfall events. This made the lower atmosphere favourable for further snow crystal growth through the process of aggregation similar to the findings of Baumgardt (1999) and NOAA (2013). This alludes to the fact that the main mechanism for ice crystal growth between 850 and 700 hPa was that of aggregation due to the surface AOH/IOH.

It was found that in the case studies of Chapter 5, ice crystals could grow through the seeder feeder mechanism which is similar to the findings of Jiusto and Weickmann (1973) and Baumgardt (1999). The upper COL provided the ice crystals necessary (seeder cloud) for the subsequent growth of snowflakes by deposition while the onshore flow of low level warmer clouds (feeder clouds) creates the environment for cloud seeding and further growth of snowflakes through aggregation due to the saturation of the lower atmosphere.

c. Atmospheric Thickness

Koolwine (1975) and Heppner (1992) found that the 1000-850 hPa, 850-700 hPa and 700-500 hPa atmospheric thickness can assist in the identification of liquid or frozen precipitation by identifying warmer atmospheric layers that could cause snowflakes to melt. Of the five case studies investigated, threshold values for the 850-500 hPa atmospheric thickness layer varied between 4060 to 4170 m. For the 700-500 hPa partial atmospheric thickness layer threshold values were near 2540 to 2600 m similar to the values found by Stranz and

Taljaard (1965). The threshold values for the thickness of 850-700 hPa atmospheric layer were between 1530 and 1580 m.

Keeter and Cline (1991) indicated that the 850-700 hPa atmospheric thickness of less than 1540 m was good for snow. Heppner (1992) used a critical 850-700 hPa thickness value of 1550 m to forecast snow in Pennsylvania in the USA at an altitude of 347 m a.m.s.l. This is more in agreement with 1 and 2 Aug 2006 and 7 Aug 2012 case studies. In the forecasting offices in South Africa, a thickness value of less than 1570 m for the 850-700 hPa layer is used to forecast snow which agrees well with the results obtained in this dissertation.

d. Surface observations

The case studies in Chapter 5 describe the so called *moist air* scenarios. The formation of snowfall under these moist conditions is the most common form of snowfall in South Africa. In moist air scenarios, the air has to be saturated for some depth with the presence of Nimbostratus clouds extending from the mid-levels to the surface where RH has to be close to 100% and surface temperature less than 2 °C. In the case studies discussed in Chapter 5, the surface temperatures varied mostly between 0 and 2 °C and were very seldom negative. These events were saturated (RH close to 100%) or near saturated (RH > 85%) in the lowest layers due to the strong onshore moisture advection from the Ocean. During this dissertation, the highest temperature that was found to occur during snowfall in saturated or near saturated conditions was 2.1 °C. Similarly Matsuo and Sasyo (1981) found snowfall to be less frequent in temperatures above 2.5 °C and surface RH above 90% although when surface temperatures were below 2.5 °C and surface RH below 90%, snowfall were more frequent.

The height of the freezing level was found to be within 500 m a.g.l and when conditions were as such, snowflakes could make it to the ground. There were exceptions when it was as high as 800 m a.g.l but in these situations the snowfall was short lived. Pruppacher and Klett (2010) indicated that in saturated conditions snowflakes can fall approximately 600 m in above freezing temperatures below the height of the freezing level before melting.

The case of Chapter 6 was a rare snowfall event at Pretoria which indicated the so called *dry air scenario*. In this scenario very dry surface conditions should prevail but the air has to be near saturation in the region of Cumulus clouds between 700 hPa and 500 hPa. Snowfall occurred with surface RH <= 65% and surface temperatures more than 3 °C. In the case of

Pretoria, snow fell at 4 °C but with a RH of 65%, similar to results obtained by Matsuo and Sasyo (1981). Mitra et al. (1990) and Pruppacher and Klett (2010) indicated that snow could fall several hundred metres before melting and that this distance was higher when RH was lower. Similar results were obtained within this dissertation.

7.2.4 Snow forecasting decision tree (Objective 5)

The synoptic circulation patterns provide very good guidance as to whether ice crystals will grow in the atmosphere to form snow. To assess whether snow will fall and reach the ground involves taking into account several other factors. All these factors can be taken into account by following several steps in a snow forecasting decision tree. Should the decision to forecast snow fail at any one of the five steps, the forecaster should monitor weather conditions and start again at step 1.

Step 1: Does the combined MSLP, 500 hPa geopotential height and 850 hPa temperatures synoptic pattern favour significant snowfall? If yes, proceed to the next step.
The characteristic synoptic patterns were found during the SOM analysis and included various combinations of deep pointed upper troughs/COL associated with a surface cold front and AOH/IOH.

Step 2: Is precipitation likely to occur in the area of interest? If yes, proceed to the next step.
The forecaster needs to employ sound forecasting principles by ensuring that there is sufficient moisture in the presence of vertical motion, surface convergence and upper wind divergence.

Step 3: Is there maximum depositional ice crystal growth around -15 °C? If yes, proceed to the next step.
Depositional growth of ice crystals in near saturated to saturated air occurs around -12 °C to -15 °C. When the lower atmospheric levels between 0 °C and -10 °C are saturated, further growth can occur via aggregation.

Step 4: Are the atmospheric thickness less than the critical values. If yes proceed to the next step.
*Threshold thickness values are**:***
850-500 hPa thickness < 4170 m
700-500 hPa thickness < 2590 m

850-700 hPa thickness <1580 m (lowest layer critical)

Step 5: Identify whether this is a wet or dry snow scenario by considering the following critical values.
Threshold values are:
Height of the freezing level a.g.l < 300 m (<u>both scenarios</u>)
<u>Moist air scenario</u>: Are surface temperatures <= 2 °C and surface RH 100% <= RH >= 40%. If yes forecast snow.
<u>Dry air scenario</u>: Are surface temperatures 3 °C >= T <= 6 °C and surface RH 65% <= RH >= 40%. If yes, forecast snow.

The decision to forecast snow or not is often related to the temperature and RH in the narrow layer close to the ground. It makes the analysis of this layer critical, especially over the sub tropical regions when dealing with snowfall events. Two scenarios were devised for snowfall, a moist air scenario and a dry air scenario. Although, most cases analysed in this dissertation are moist air scenarios, dry air scenarios do occur as was the case over Gauteng in 2012. The snow forecasting decision tree is capable to provide guidance to forecast both moist and dry air scenarios.

7.3 Conclusions

In saturated conditions, the ridging high pressure system behind the surface cold front acts to drive down the surface temperatures close to zero, yet causing RH close to 100%. This causes snowfall to occur in temperatures <= 2 °C.

In dry conditions when surface RH is <= 65%, snow can occur at surface temperatures between 3 °C >= T <= 6 °C.

The most prevalent synoptic circulation associated with snowfall is a well developed cold front followed by a ridging surface AOH/IOH pressure system around 35° S in association with an upper COL. Other circulation types involve a surface frontal low pressure off the KZN coast with the IOH south-east of the country with a COL located over the eastern interior.

In the moist air scenario, the saturation of the atmosphere between 700-500 hPa layer was caused by a pointed upper trough or COL at that level. This saturation enables the growth of dendrite ice crystals by deposition in the mid-levels in the region of -10 °C (approximately 700 hPa) to -20 °C (approximately 500 hPa. This suggests that the main mechanism for ice crystal growth in the 700-500 hPa layer is that of deposition of dendrite crystals due to the COL synoptic scale weather system.

In the moist air scenario, the saturation of the atmosphere between 700-500 hPa is complemented by the saturation of the air in the lower 850-700 hPa atmospheric layer. This is caused by the onshore flow from the AOH or IOH synoptic scale weather system behind the cold front. This saturation enables further growth of falling snowflakes from the mid-levels to the surface through the process of aggregation between 0 °C (850 hPa surface) and -10 °C (approximately 700 hPa). This suggests that the main mechanism for snowflake growth in the 850-700 hPa layer is aggregation of snowflakes due to the AOH/IOH synoptic scale weather systems.

The combined interaction of synoptic surface and upper air weather patterns creates the atmospheric environment conducive to ice crystals growth via the seeder feeder mechanism where ice bearing clouds with cloud tops of -15 °C (seeder clouds caused by COLs) move over warmer clouds with cloud tops of -6 °C (feeder clouds caused by the ridging AOH/IOH) that contain supercooled water droplets.

The most important atmospheric thickness layer to consider during snowfall is the 850-700 hPa layer, which corresponds to the difference in the height between the mountain tops of Lesotho (700 hPa or 3000 m a.m.s.l, see Fig. 1) and the height of the interior plateau of South Africa (850 hPa or 1500 m a.m.s.l). When this layer is sufficiently cold and all other favourable factors considered, it will result that snow not only falls over the mountain tops of Lesotho but also over the lower elevations of South Africa.

The height of the freezing level can be as high as 500 m a.g.l during snowfall.

The horizontal pressure gradient can be used as a forecasting tool to determine the amount of low level cold air and moisture advected across the country. A surface pressure gradient of at least 22 hPa was found to be associated with significant snowfall.

When the surface flow from the ocean is perpendicular to the eastern escarpment areas of South Africa, orographic induced vertical motion enhances snowfall on the eastern side of the escarpment.

Intense surface cold fronts can progress to the northern interior of South Africa when a COL is present in the upper air.

Significant snowfall over South Africa is rare, but when it does occur it causes wide spread disruption to infrastructure and even loss of life. Understanding the processes which lead to snow formation is therefore important, as it could also facilitate the prediction of the severe weather.

Forecasters can predict snowfall by knowing what weather systems cause snow and using the snow forecasting decision tree to forecast these events.

7.4 Assessing the scientific contribution of this study

No comprehensive research has been undertaken in South Africa to identify the synoptic surface and upper air weather systems responsible for snowfall in winter. This research contributes not only to a better understanding of the synoptic circulation systems but also adds insight into the cloud microphysical and surface conditions during snowfall. The research results culminate in a snow forecasting decision tree where the synoptic circulation patterns, cloud microphysical aspects and other atmospheric variables are condensed into a user-friendly product.

The research results confirm the importance of a COL as a precipitation producing weather system over South Africa, especially with regard to snowfall in winter. Different surface circulation patterns are associated with snowfall but in all instances are supported by an upper air COL or at least a sharp trough. Cold fronts have been shown to be an important contributor to the formation of snowfall but it is the location and depth of the surface anticyclone which cause the cold and moist air to invade South Africa. The research also indicates that a high situated south-east of the country and which is associated with relatively warmer temperatures, can still cause snowfall as the air is forced to rise over the eastern escarpment.

This research relies on several data sources. The output from Numerical Weather Prediction (NWP) is utilised as is several observation data sets. It was shown how surface, upper air and satellite observation can be integrated to identify the atmospheric conditions conducive to snowfall. By specifically employing MSG satellite data, the most recent observational technology is integrated into the research results and enables the analysis of the atmosphere in otherwise data scarce areas.

One of the most important conclusions of this dissertation is the emphasis on distinguishing between *wet snow* and *dry snow.* Most of the analysed snowfall events over South Africa are wet snow scenarios (high surface RH and surface temperatures <= 2 °C). But it is specifically the dry snow scenario (surface temperatures 3 °C >= T <= 6 °C and surface RH 65% <= RH >= 40%) which contributes to the local understanding of the processes involved in the formation of snowfall. These are very rare occurrences but when they do occur they are quite severe.

The snow forecasting decision tree has the potential to guide the accurate forecasting of snowfall over South Africa. Several products and concepts are summarised into a five-step procedure which can easily be applied in forecasting offices. This decision tree brings the forecasting of snowfall in South Africa in line with international methods but with local application.

A 30-year archive of snowfall cases was created. This archive identifies 60 significant cases and can in future be used as an easy reference into further snow research.

7.5 Recommendations

The results of this dissertation should be made available to weather forecasters, especially the snow forecasting decision tree. The input from weather forecasters can be used to further refine this process.

The snow forecasting decision tree is based on sound theoretical principles and was tested and developed by detailed analysis of four significant moist air scenario cases and one significant dry air scenario. It is recommended that the decision tree be tested on more cases and in the operational environment in order to verify and adapt the process where necessary. In order to understand the value of the forecasting decision tree statistical scores such as the Probability of Detection or False Alarm Rate needs to be calculated. However, due to the subjective judgments in the first part of the decision tree calculating objective scores will be difficult. Operational weather forecasters can add value to this decision tree by providing feedback on its usefulness in an operational environment.

The snow forecasting decision tree could also be applied by using the output of NWP to automate steps 1 to 5. An interactive process is proposed where the forecaster could manually change the surface temperature and surface relative humidity. It is important that the process has human intervention and reasoning.

It is recommended that a mesoscale model which has a resolution fine enough to deal with the topographic effects of South Africa should be used to make Step 5 of the snow forecasting decision tree more efficient. This will assist a more complete study of the topographical influences on snowfall over the eastern escarpment areas of South Africa.

Further research is encouraged in the following areas.

- Perform research into significant snowfall using a mesoscale model which has a finer grid resolution and more vertical atmospheric layers, especially within the 850-700 hPa atmospheric layer. This will lead to a better topographic and surface simulation as well as enable finer atmospheric thickness and freezing level height calculations.

- Determine what effect climate change will have on the occurrence of snowfall by running a climate model taking into account the synoptic weather systems that contribute to snowfall and the surface temperature and RH in terms of a moister versus drier climate simulation.

- Consider what effect El Nino and La Nina events have on the occurrence of snowfall over South Africa.

- The concept of cold air damming can be investigated over the narrow corridor between the north-eastern part of the Eastern Cape and southern KZN which, receives significant snowfall more often.

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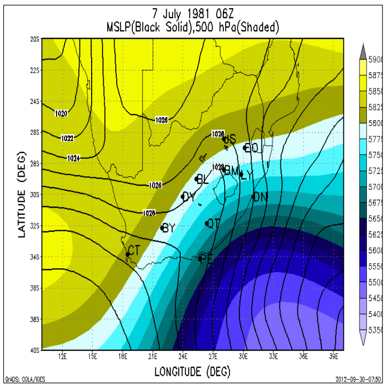
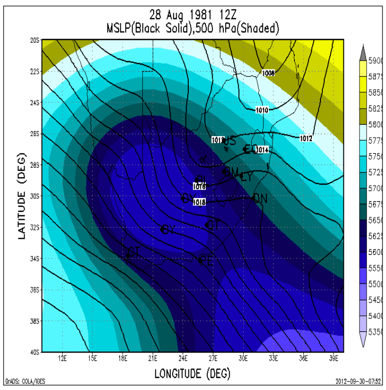
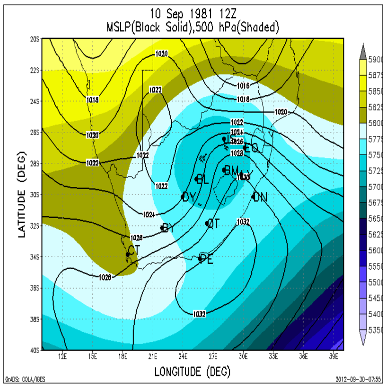
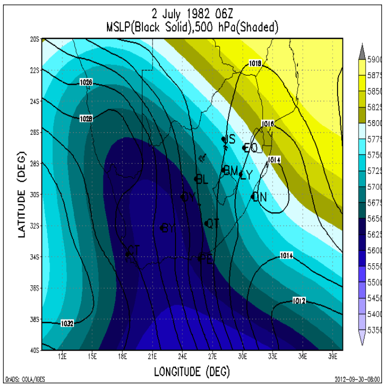
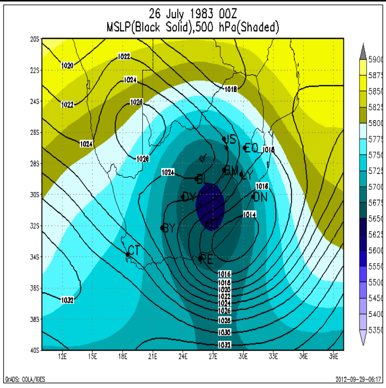
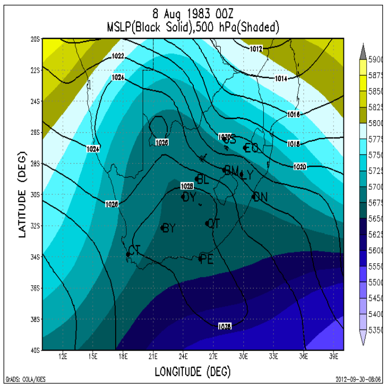
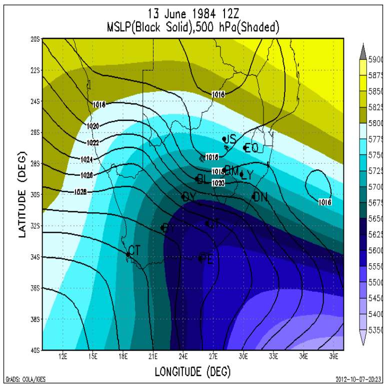
APPENDIX A

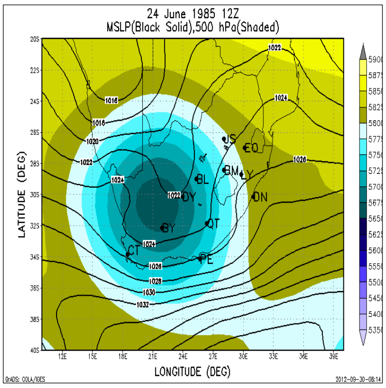
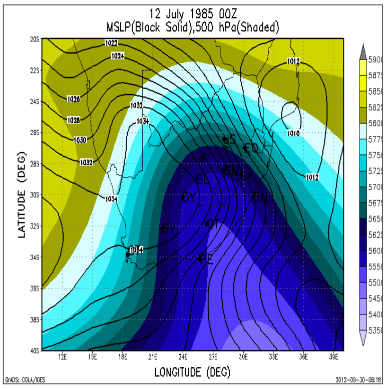
Synoptic circulation patterns of significant snowfall over South Africa for 1981-2011

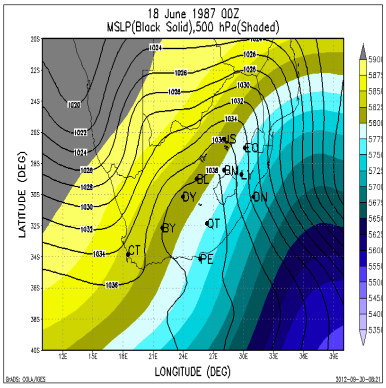
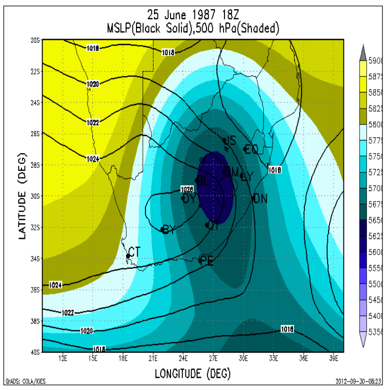
Significant snowfall Case Study Dates over South Africa *(NCEP Reanalysis Derived data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/*

1981	
1) 7-8 July 1981 **Regional areas affected by snowfall:** Zastron, Pearston, Sutherland, Fraserburg, Beaufort West, Willowmore, Swartberg Pass Aasvoëlberg near Villiersdorp, Somerset East, Ladysmith, Porterville, Burgersdorp, Middelburg, Colesburg, Cradock, Molteno road between Middelburg and Graaf Reinet. **Basic System Identification:** Pointed trough, cold front with low of 1010 hPa south-east of the country followed by ridging AOH of 1035 hPa at 40° S. W/E horizontal Pressure gradient between high and low: 1035 -1010 = 25 hPa.	
2) 28-29 August 1981 **Regional areas affected by snowfall:** Cape Province, Vanwyksvlei, Pofadder, Upington, Kenhardt, Keimoes, De-Aar, Beaufort West, Aberdeen, Table Mountain, Canon Island in Upington, Jansenville, Burgersdorp, Pofadder, Outeniqua and Robinson passes, Sandvlei in the Koo, Barkly Pass (Elliot to Barkly East), Boesmanshoek Pass (Sterkstroom to Molteno), Robertson pass (Mosselbay to Oudshoorn) Indwe, Aberdeen and Noupoort. **Basic System Identification:** Deep COL, cold front with low of 1014 hPa south-east followed by ridging AOH of 1040 hPa at 40° S. W/E horizontal Pressure gradient between high	

and low: 1040 hPa – 1014 hPa = 26 hPa.	
3) 10-11 September 1981 **Regional areas affected by snowfall:** North Eastern interior, Long Tom Pass, Amersfoort, Bethal, Witbank, Standerton, Ermelo, Springs, Delmas, Harrismith, Warden, East Rand, Kempton Park, South Eastern Transvaal, North Eastern Orange Free State, Van Reenens Pass, Boksburg, Brakpan, Braamfontein, outskirts of Pretoria, Nigel, Boksburg, Balfour, Heidelberg, Leandra, Secunda, Evander, Greylingstad, Turfontein race course. Roads linking Transvaal, OVS and Natal. **Basic System Identification:** Weak COL, cold front followed by ridging IOH of 1032 hPa at 38° S.	
1982	
4) 1-3 July 1982 **Regional areas affected by snowfall:** Thaba Nchuberg near Bloemfontein, Eastern Cape passes, Winterberge and Stormberge, Witwatersrand, south and south-western Cape Province, the Orange Free State and the southern parts of the Transvaal, Johannesburg, Eastern Cape and the higher lying parts of the Orange Free State, mountains near Elliot, Florida on the West Rand, Molteno, Dordrecht, Burgersdorp, Barkly East ,Lady Frere, Indwe, Hofmeyer, Elliot, and Colesburg Penhoek Pass, Carlton Heights Pass, Wapadsberg Pass, Boesmansnek Pass, Lootsberg Pass, Naudes Barkly Pass. **Basic System Identification:** COL, strong cold front with low of 1012 hPa South East of the country followed by ridging AOH of 1032 hPa at 38° S. W/E horizontal Pressure gradient between AOH	

and frontal low = 20 hPa.	
1983	
5) 24-26 July 1983 **Regional areas affected by snowfall:** Drakensberg, Witsieshoek. **Basic System Identification:** COL, cold front with surface low over SE Cape coast of 1014 hPa and AOH of 1032 hPa at 38° S.	
6) 7-8 August 1983 **Regional areas affected by snowfall:** Belfast in the Eastern Transvaal **Basic System Identification:** Pointed trough, cold front followed by IOH of 1028 hPa at 38° S south of the country.	
1984	
7) 13-14 June 1984 **Regional areas affected by snowfall:** Eastern Cape and KZN interior (several mountain passes), Bethlehem, Kestell, Richmond, Hilton, Lootsberg Pass Wapadsberg Pass, Coetzeesberg, Longhill, Hangklipberge, Eastern Transvaal Highveld, Eastern Free State, southern and south-eastern parts of the Cape Province, Rhodes Pietermaritzburg, Mooiriver, Underburg, Kokstad, Nottingham Road Hilton, Boston, Bulwer, Curries Post, Ixopo, Highflats Dargle, Karkloof, Springfontein, Zastron, NaudesNek Pass, Barkly pass, Dordrecht, Laingsburg Pass between Newcastle and Vryheid, Vrede, Bethlehem, Kestell, Bethulie, Natal Midlands, Volksrust, Memel, Witsieshoek,	

Van Reenens Pass, Mooiriver, Ladysmith, Perdekop, Standerton, Ermelo, Secunda, Bethal, Amersfoort, Wakkerstroom, Breyten and Nigel **Basic System Identification:** Pointed trough, cold front with 1016 hPa low followed by ridging AOH of 1036 hPa at 40° S. W/E horizontal Pressure gradient between high and low: 20 hPa.	
1985	
8) 24-25 June 1985 **Regional areas affected by snowfall:** Eastern Cape and the southern Orange Free State, Carnarvon. **Basic System Identification:** COL, cold front with ridging IOH of 1040 hPa at 40° S.	
9) 11-12 July 1985 **Regional areas affected by snowfall:** Southern and Eastern Cape, Langkloof, Orange Free State, Transvaal Highveld. Natal interior, Van Reenens and the Majuba Pass closed, Matatiele, Franklin, Swartburg, Cedarville, Kokstad, Dargle, Tweedie, Greytown, Karkloof, Mooiriver, Nottingham Road, Vryheid, Glencoe, Dundee, Volksrust, Perdekop, Amajuba Pass, Matroosberg between De Doorns and Ceres, Cedarberg near Citrusdal and at Franschoek, Worcester, Villiersdorp, Bethal, Ermelo, Standerton, Rhodes, near Bloemfontein, Table Mountain, Skurweberge, Gydo Pass, Swaarmoed Pass, Sutherland, Queenstown, New Bethesda, Somerset East, Pearston, Harrismith, Ladysmith, Laingsnek Pass closed, Amersfoort, Harrismith, Smithfield and Frankfort.	

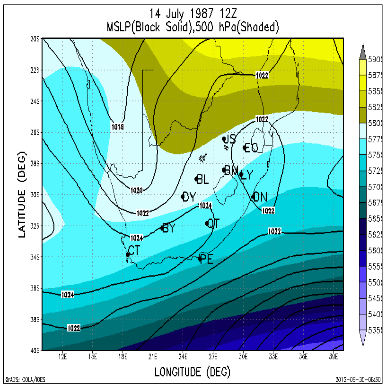
Basic System Identification: COL, cold front with surface low of 1012 hPa South East of the country and AOH of 1036 hPa at 35° S. W/E pressure gradient between high and low: 24 hPa.	
1987	
10)17-18 June 1987 **Regional areas affected by snowfall:** Eastern interior, Van Reenens Pass, southern Cape, Eastern Cape mountains, Southern Drakensberg, eastern Free State, Loodsberg Pass, Wapadsberg Pass, Coetzeesberg Mountain's, Orange Free State, Western Cape, Champagne Castle, Mont ex Sources, Sani Pass, Witsieshoek, Cathedral Peak, Matatiele, Himeville, Bulwer, Kokstad, Impendle, Swartberg, Nottingham Road, Rosetta, Ladysmith, Underberg, Babanango, Ixopo, Dordrecht and Steynsburg, Graaf Reinett, Rhodes and Lady Grey. **Basic System Identification:** Pointed Trough, strong cold front with ridging IOH of 1038 hPa at 40° S.	
11)25-26 June 1987 **Regional areas affected by snowfall:** Eastern parts of the Orange Free State, Southern and Eastern Cape mountains, Barkly East, Underberg area, Loteni Nature Reserve, East Griqualand, Kingscote Pass, Underberg, Matatiele and Kokstad. **Basic System Identification:** COL, cold front followed by overland ridging high of 1026 hPa at 32° S.	

12)14-15 July 1987

Regional areas affected by snowfall:

Ermelo, Breyten and Piet Retief. Johannesburg Eastern Cape and Natal Trompsburg, Wepener and Ladybrand.

Basic System Identification: Moderate trough with overland ridging high behind cold front.



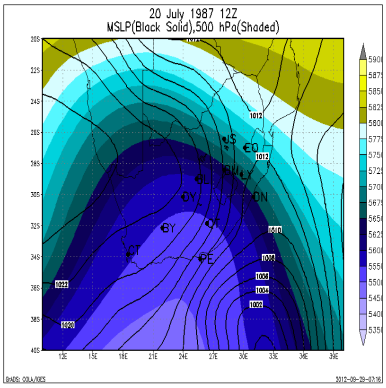
13)20-21 July 1987

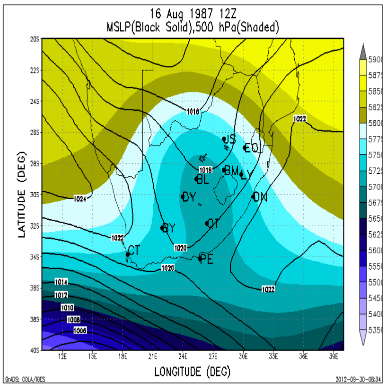
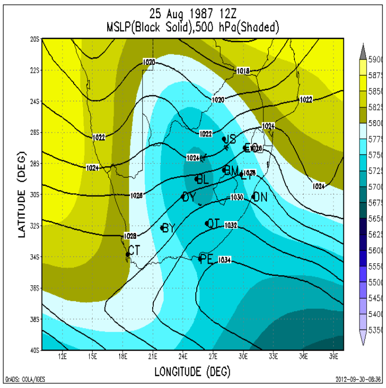
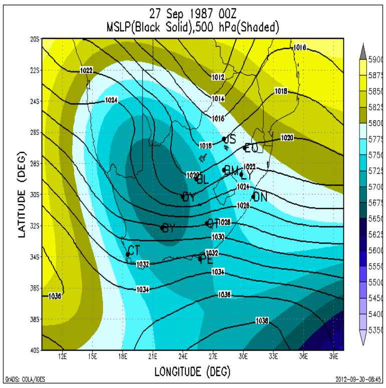
Regional areas affected by snowfall:

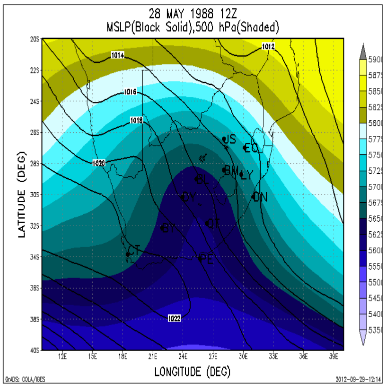
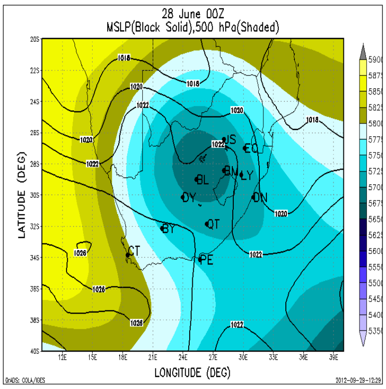
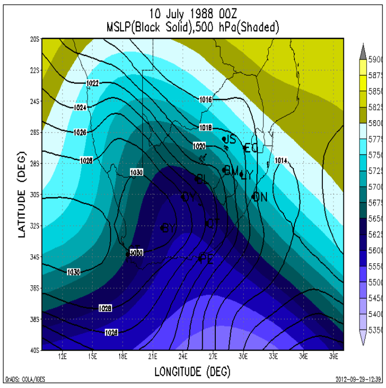
Boland, Sarelskop at Tulbach, Karoo, Eastern Cape, Eastern Orange Free State, Natal ,south eastern Transvaal, Oliviershoek Pass, Naudesnek Pass, Longtom Pass, Kestell, Warden, Harrismith, Boland Mountains, Swartberge in the Little Karoo, Graskop Trompsburg, Ficksburg, Smithfield, Fouriesburg, Aliwal North, Springfontein, Burgersdorp, Zastron, Ladybrand, Rouxville, Dordrecht, Harrismith, Qwa Qwa, Dordrecht, Molteno, Barkly East, Burgersdorp, Aliwal North, Lady Grey, Cradock, Colesburg, Steynsburg, Spring Valley near Tarkastad, White River at Trompsburg, Wepener, Molteno and Ugie.

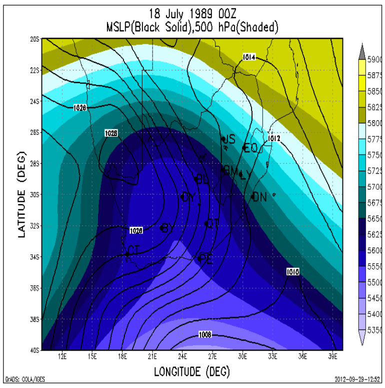
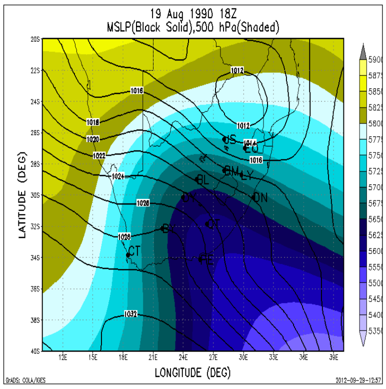
Basic System Identification: Pointed trough, strong cold front with deep low of 1000 hPa south-east of the country followed by ridging AOH of 1024 hPa at 30° S.

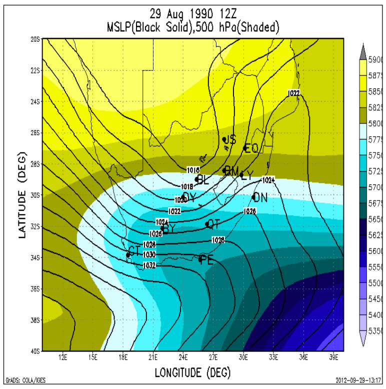
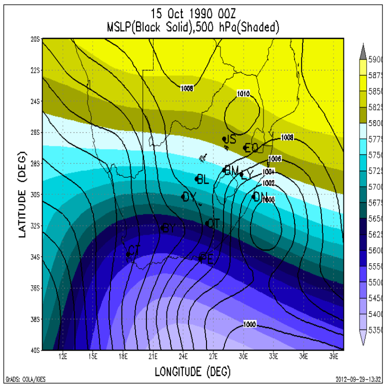
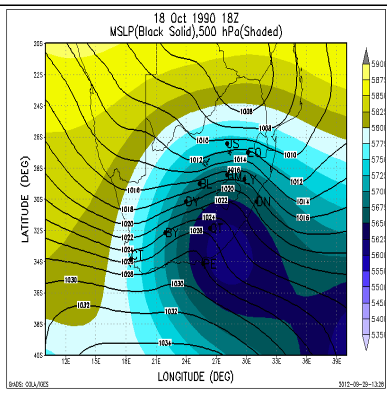
W/E pressure gradient between high and low = 24 hPa.

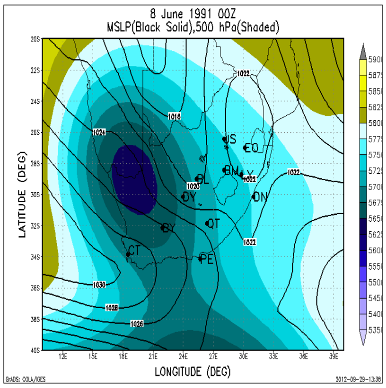
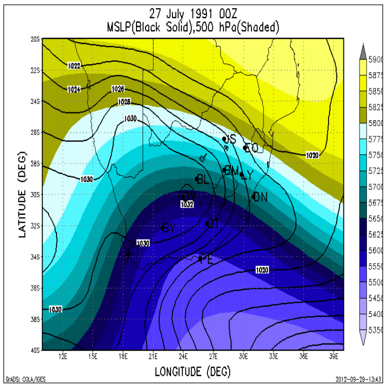
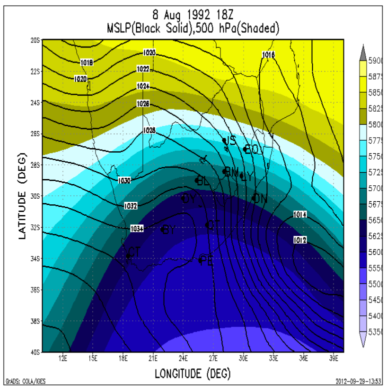


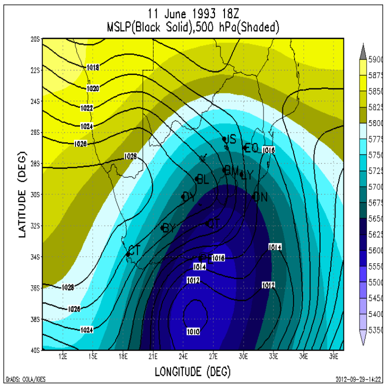
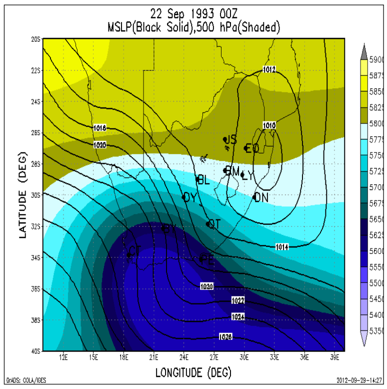
14)16 August 1987 **Regional areas affected by snowfall:** Swartberg, Kings Cote Pass near Underberg, Matatiele, Kokstad, southern Natal and the Drakensberg. **Basic System Identification:** COL, surface trough and IOH of 1022 hPa at 35° S.	
15)25-26 August 1987 **Regional areas affected by snowfall:** Eastern Orange Free State, Natal interior, Memel, Fochville, Van Reenen Pass, Matatiele, Cedarville, Sani Pass, Potchefstroom and Golden Gate. **Basic System Identification:** COL, cold front followed by ridging IOH of 1036 hPa at 39° S.	
16)27-28 September 1987 **Regional areas affected by snowfall:** NE Cape, Dordrecht, Lady Grey, Queenstown, Molteno, Rhodes, Steynsburg, Drakensberg, Eastern Cape, Eastern Free State, Lootsberg Pass, Wapadsberg Pass and Penhoek Pass, Sterkstroom, Elliot, Barkly East, Maclear, Indwe and Ugie. **Basic System Identification:** COL, cold front followed by ridging IOH of 1038 hPa at 40° S.	
1988	

17)28 May 1988 **Regional areas affected by snowfall:** North Eastern Cape, Dordrecht **Basic System Identification:** Pointed Trough, cold front with low of 1012 hPa followed by ridging AOH of 1024 hPa at 38° S. W/E horizontal Pressure gradient between high and low =12 hPa.	
18)27-28 June 1988 **Regional areas affected by snowfall:** Bethal and in places in the Orange Free State east of Bloemfontein, Witsieshoek resort, Drakensberg at QwaQwa. Bethlehem, Ficksburg and Bloemfontein. **Basic System Identification:** COL, cold front in surface low of east coast of 1018 hPa followed by ridging IOH of 1024 hPa at 38° S.	
19)9-11 July 1988 **Regional areas affected by snowfall:** Volksrust, high lying areas of the Eastern Cape, Nottingham Road, southern interior of the Eastern Cape, Eastern Free State, Lesotho, Natal highlands, south western, southern and Eastern Cape provinces, mountain peaks near Springbok, Drakensberg and Natal midlands Ladysmith, southern and south-western Cape Mountains, mountains near Ceres, Paarl, Tulbach and the Hex river valley, Matroosberg, Witzenberg and Theronsberge Outeniqua Mountains, Warden, farms at Curry's post and Karkloof, Boston, Swinburne, Newcastle, Vrede, Road (N3) was closed between Nottingham Road and Mooiriver, Roads from Kokstad to Underberg, Botha's and Oliviershoek Pass, Harrismith, Memel, Clarens, Dordrecht,	

Fouriesburg, Golden Gate, Ermelo, Amersfoort, Volksrust and Piet Retief. **Basic System Identification:** Pointed trough, strong cold front with 1008 hPa low South East of the country followed by AOH of 1032 hPa at 34° S. W/E pressure gradient between high and low:24 hPa.	
1989	
20)17-18 July 1989 **Regional areas affected by snowfall:** High lying areas of the Eastern Cape, Free State, southern, central, and eastern parts of the country, Winburg, Kokstad, Matatiele and Underberg, Table Mountain, High lying areas of the Western Cape, Matroosberg, Waboomsberg on Gydo Pass near Prince Albert, Michells Pass near Ceres, Piketberg, little Swartland Range, Kamieskroon range, Barkly East and Lady Grey. Bloemfontein, Kimberley and Prieska. **Basic System Identification:** Pointed trough, strong cold front with 1008 hPa low south of the country followed by ridging AOH of 1028 hPa at 34° S. W/E horizontal Pressure gradient between high and low: 20 hPa.	
1990	
21)19-20 August 1990 **Regional areas affected by snowfall:** Interior of KZN, Underberg, mountains near Volksrust, Ermelo, Wakkerstroom, Harrismith Lady Grey, Zastron, Reitz, Lootsberg, Sneeuberge, Eastern Cape and the Drakensberg **Basic System Identification:** Pointed Trough, cold front with low of 1016 hPa followed by ridging AOH of 1032 hPa at 40° S.	

W/E horizontal Pressure gradient between high and low: 16 hPa.	
22)29-30 August 1990 **Regional areas affected by snowfall:** Several Natal and East Griqualand towns. Himeville, Swartberg, Matatiele, Franklin and other centers in Southern Natal Lesotho and the central and Northern berg Dordrecht, Elliot, Jamestown, Indwe, Underberg, Graaf Reinet. **Basic System Identification:** Pointed Trough, strong cold front with 1020 hPa low South East of the country followed by ridging AOH of 1040 hPa at 40° S. W/E horizontal Pressure gradient between high and low: 20 hPa.	
23)15 October 1990 **Regional areas affected by snowfall:** Uniondale, Graaf Reinet and Middelburg. **Basic System Identification:** Moderate trough, strong cold front with 1002 hPa low South-East of the country followed by ridging AOH of 1024 hPa at 40° S. W/E pressure gradient between high and low: 22 hPa.	
24)18-19 October 1990 **Regional areas affected by snowfall:** Cradock, Dordrecht, Eastern Free State, Graaf Reinet, Harrismith, Middelburg in the Cape, Eastern Orange Free State, QwaQwa, Eastern Cape and parts of Natal. **Basic System Identification:** COL, cold front with 1008 hPa low followed by ridging AOH of 1034 hPa at 40° S. W/E horizontal Pressure gradient between high and low:26 hPa.	
1991	

25)7-8 June 1991 **Regional areas affected by snowfall:** Southern Cape Mountains, Mountain's of the Eastern Cape and Southern Cape, Beaufort West, Drakensberg, Boland, W Cape, Klein Karoo, Matroosberge, Skurwe and Theronsberge, Klein Swartberge near Ladysmith and the Lootsberg Pass **Basic System Identification:** COL, cold front with 1018 hPa low and overland AOH ridge of 1030 hPa at 35° S. W/E horizontal Pressure gradient between high and low: 12 hPa.	
26)26-27 July 1991 **Regional areas affected by snowfall:** Ceres, Matroosberg, Sutherland, Phillipolis, Bethulie, Trompsburg, Verlatenkloof Pass Zastron and Bethulie. **Basic System Identification:** Pointed Trough, cold front with1010 hPa low followed with overland AOH ridge of 1032 hPa at 34° S. W/E horizontal Pressure gradient between high and low: 22 hPa.	
1992	
27)8-10 August 1992 **Regional areas affected by snowfall:** Aberdeen, Kareedouw, southern and eastern mountain areas, Kokstad, Ngeliberge, Zastron, Lady Grey, Barkly East, Lootsberg Pass, Hogsback Jamestown, Dordrecht, Cathcart, Molteno, Stutterheim, Queenstown, Drakensberg near Barkly East and at Rhode's, Nico Malan Pass, Penhoek Pass, New Bethesda, southern Drakensberg and Drakensberg Gardens Hotel **Basic System Identification:** Moderate trough, cold front with low of 1012 hPa east of the	

country followed by ridging AOH of 1030 hPa at 40° S. W/E pressure gradient between high and low = 18 hPa.	
1993	
28)11-12 June 1993 **Regional areas affected by snowfall:** Bloemfontein, De Aar, Noupoort, Swartberg Barkly East, Cape mountains and southern Drakensberg, Burgersdorp, Goedemoed, Dewetsdorp, Edenburg, Reddersburg, Zastron, Verkeerdevlei, Trompsburg, Springfontein, Phillipolis, Brandfort, Smithfield, Strydenburg, Colesburg, Maseru, Western Lesotho and Aliwal North. **Basic System Identification:** COL, cold front low south of the country of 1010 hPa and overland AOH ridge of 1030 hPa at 34° S. W/E pressure gradient between high and low: 20 hPa.	
29)21-22 September 1993 **Regional areas affected by snowfall:** Molteno Pass closed and Nuweveld Mountains near Beaufort West. **Basic System Identification:** Pointed trough/COL, cold front with 1010 hPa followed by ridging AOH of 1034 hPa at 40° S. W/E horizontal Pressure gradient between high and low: 24 hPa.	
1994	

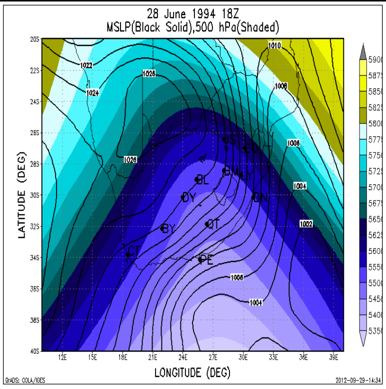
30)28-29 June 1994

Regional areas affected by snowfall:

Swartland, Drakensberg, Klerksdorp, Lichtenburg, Ottosdal, Paarl, Potchefstroom, Springbok, Theronsberge Pass between Ceres and Touws River, Springbok, De Aar, Bloemfontein, Sutherland, Kimberley, Windhoek, Table Mountain, Jonkerhoek mountains, Simonsberg, Dordrecht, Springfontein, Phillippolis, Zastron, Campbell, Bulwer, Ficksburg, Fouriesburg, Secunda, Carletonville, Westonaria, Randfontein, Krugersdorp, Lanseria to Waterkloof, Johannesburg CBD, Vanderbijlpark, Boston and Giants Castle.

Basic System Identification: Pointed Trough/COL, strong cold front with low of 1004 hPa south of the country and overland AOH ridge of 1028 hPa at 33° S.

W/E pressure gradient between high and low = 24 hPa.



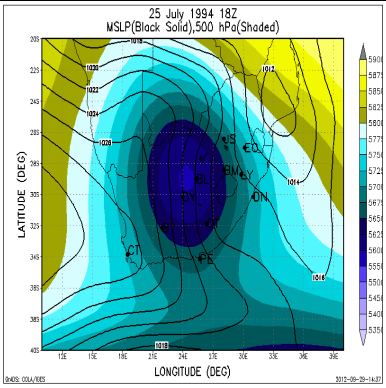
31)25-26 July 1994

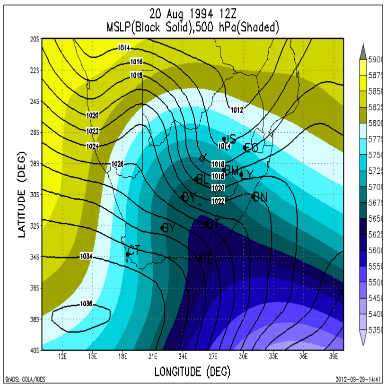
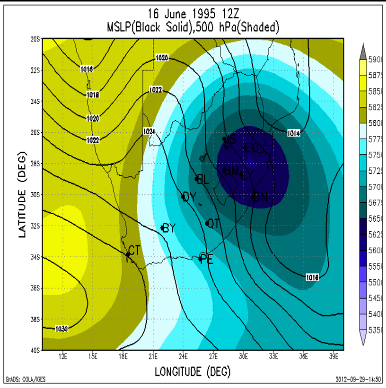
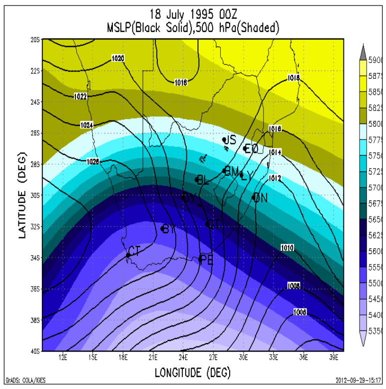
Regional areas affected by snowfall:

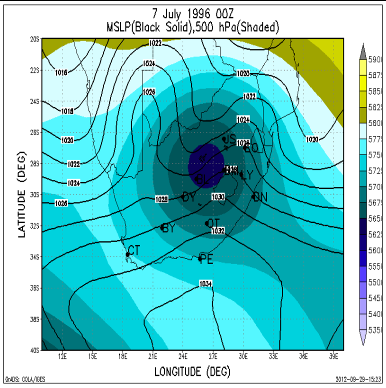
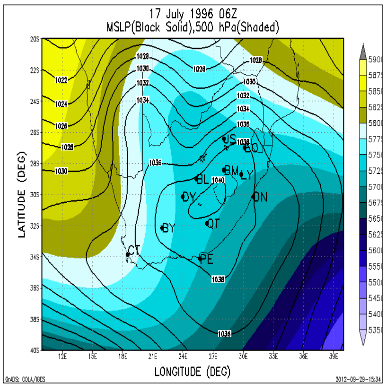
Zastron, East Rand, Bethlehem, Clarens southern parts of KZN, Witwatersrand, Oranjeville, Wepener, Senekal, Clarens, Ficksburg, Fouriesburg, Sasolburg, Viljoenskroon, Oranjeville, Lady Grey, Heilbron and Matatiele.

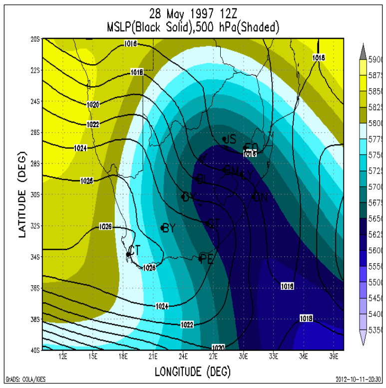
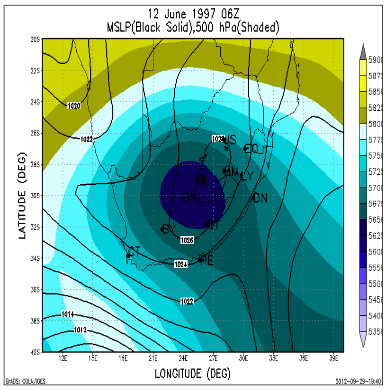
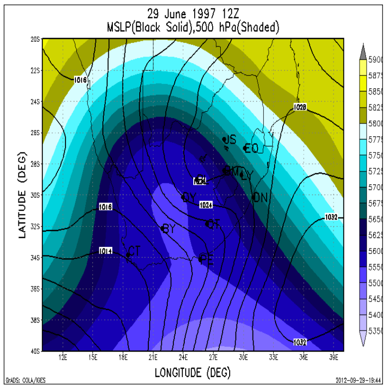
Basic System Identification: COL, cold front with 1014 hPa low followed by AOH of 1030 hPa at 34° S.

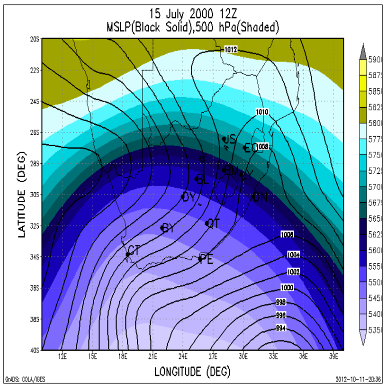
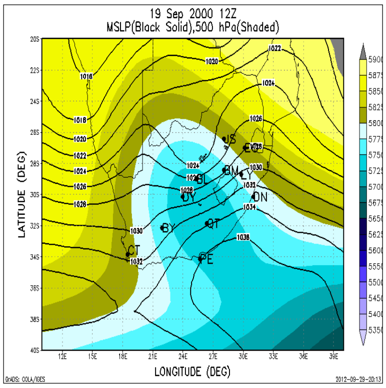
W/E horizontal Pressure gradient between high and low: 16 hPa.



32)20-21 August 1994 **Regional areas affected by snowfall:** Eastern Cape, KZN and Ermelo. **Basic System Identification:** Pointed Trough, cold front with 1014 hPa low with ridging AOH of 1036 hPa at 39° S. W/E horizontal Pressure gradient between high and low: 22 hPa.	
1995	
33)15-17 June 1995 **Regional areas affected by snowfall:** Bethlehem, Reitz, Harrismith, Belfast, Bethlehem to Kestell, Harrismith to Warden, Harrismith to Bethlehem, the R103, the road between Reitz and Bethlehem, Cradock, Lady Grey, Molteno, Dordrecht, Graaf Reinet, Drakensberg, Malutis, Free State areas of Qwa Qwa, Clarens, Golden Gate, Zastron, Reitz and Memel. **Basic System Identification:** COL, cold front with surface low south-east of KZN coast of 1014 hPa and ridging AOH of 1030 hPa at 38° S. W/E pressure gradient between high and low:16 hPa.	
34)17-18 July 1995 **Regional areas affected by snowfall:** Eastern Cape, Table Mountain, Western Cape, Ceres, Koue bokkeveld, Franschoek, George, Montagu, Oudshoorn, Piketberg, Cradock, Graaf Reinet, Maclear, Oudshoorn, Tarkastad, Bloemfontein, Wepener, Edenburg, Verkeerdevlei, Zastron, Petrusville, Luckhoff, Koffiefontein, between De Aar and Philipstown, Piketberg, Franschoek, Free State, Cradock and Tarkastad. **Basic System Identification:** Deep Moderate	

Trough, cold front with 1004 hPa low and overland ridging AOH of 1028 hPa at 34° S. W/E horizontal Pressure gradient between high and low: 24 hPa.	
1996	
35)6-10 July 1996 **Regional areas affected by snowfall:** Ceres, Touws River, Franschoek, Montaqu, especially Theronsberge and Matroosberg, Hogsback, Molteno, Rosendal, snow thick at Welkom, Mooiriver, Harrismith, Eastern Free State, South-east Gauteng, Southern Mpumalanga, interior of KwaZulu-Natal, Lesotho, North Western parts of KwaZulu-Natal. Klerksdorp, Virginia, Henneman, Wesselsbron, Bultfontein, Hoopstad, Kroonstad, southern and east Rand, Amalia, Lydenburg, Dullstroom, Belfast, Volksrust, Ermelo, Memel, Bethulie, Senekal and Paul Roux, Bethal, Standerton, Hendrina, Secunda, Ermelo, Queenstown, Jamestown, Dordrecht, Ladysmith, Vryheid, Dundee and Newcastle. **Basic System Identification:** COL, cold front followed by ridging IOH of 1034 hPa at 40° S.	
36)16-18 July 1996 **Regional areas affected by snowfall:** Magoebaskloof, Longtom Pass between Lydenburg and Sabie, Rowerspas, Belfast, Ermelo, Pilgrimsrest, Dullstroom and the Drakensberg. **Basic System Identification:** Pointed trough/COL, cold front followed by ridging overland high of 1040 hPa at 32° S.	
1997	

37)27-29 May 1997 **Regional areas affected by snowfall:** Swartberg up to the Malutis Barkly East, Lady Grey, Somerset East, Steynsburg, Hogsback and the Long Tom Pass. **Basic System Identification:** COL, cold front with 1016 hPa low followed by ridging AOH of 1026 hPa at 32° S. W/E horizontal Pressure gradient between high and low = 10 hPa.	
38)10-12 June 1997 **Regional areas affected by snowfall:** Drakensberg, Underberg, Eastern Cape interior, Southern Drakensberg, Lesotho, Southern Free State, southern KwaZulu-Natal, Kokstad, Matatiele, Brook's Nek, Stafford's Post Swartberg and Underberg. **Basic System Identification:** COL with surface low over eastern interior.	
39)29-30 June 1997 **Regional areas affected by snowfall:** Bo Swaarmoed Pass, Klein Swartberge in the Karoo, du Toitskloof Pass, Zastron, Wepener, Elliot, Lady Grey, Queenstown, Sutherland, De Aar, Barkly East, Bloemfontein, Nottingham road, Van Reenens Pass, Merrivale, Donnybrook, Ixopo roads, Bethlehem, Harrismith, Reitz, Sasolburg, Kokstad, Malutis, Lady Grey, Ladybrand, Harrismith and Colesburg. **Basic System Identification:** Pointed Trough/COL, strong cold front followed by ridging IOH of 1032 hPa at 38° S.	
2000	

40)14-15 July 2000 **Regional areas affected by snowfall:** Mountains of the SW Cape, Drakensberg, Calvinia, Sutherland, Western and SW parts of the Northern Cape, Theronsberge Pass, SE Free State higher regions of the Western Cape and other provinces Koue Bokkeveld area Graaf Reinet, Hogsback, Elliot, Dordrecht, Jamestown and Tiffendell. Groot Swartberge near Oudshoorn, Calitzdorp and De Rust Swartberg Pass Theronsberge and Swartberg Pass Sneeu and Winterberge up to Rhodes Matroosberg and Waboomsberg Galgeberg at Montagu Theronsberge district, Koue bokkeveld, Tiffendell ski resort. **Basic System Identification:** Deep Sharp Trough with cold front with deep low south of the country of 994 hPa and ridging AOH at 1024 hPa at 36° S. W/E pressure gradient between high and low: 30 hPa.	
41)18-19 September 2000 **Regional areas affected by snowfall:** Table Mountain, Pofadder, Nieu Bethesda in the Eastern Cape, Queenstown, Matatiele, Northern Drakensberg, Kokstad Underberg, Evatt police station, R617 between Swartberg and Kingscoat Swartberg and Kokstad **Basic System Identification:** COL, cold front followed by IOH of 1036 hPa at 38° S.	
2001	

42)20-23 July 2001

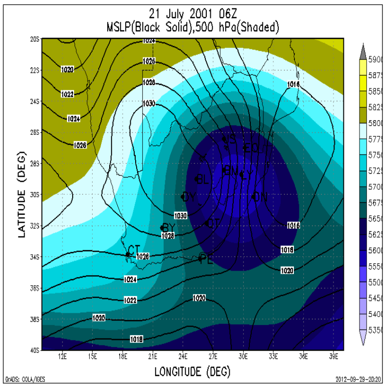
Regional areas affected by snowfall:

Ottosdal, Danielskuil, Gauteng (Kempton Park, Sandton, Benoni, Auckland Park),Ermelo, Bethlehem in the North Eastern Free State

Van Reenens Pass, Olivierhoek Pass, Amajuba Pass, Tiffendell, Cradock, Graaf Reinet high ground of the Eastern Cape, Kokstad, Mooi River, Drakensberg, Harrismith, Klondyke cherrie farm at Ceres, The Eastern Free state, Kestell, Clarens, Golden Gate, Rosendal, Fouriesburg, Bethlehem, Ficksburg, Warden, Melville, Mayville, Benoni, Kempton park, Barkly Pass, Lootsberg Pass, Wapadsberg Pass and Brookes Nek Pass.

Basic System Identification: COL, cold front with low east of the KZN coast of 1014 hPa followed by overland AOH of 1032 hPa at 30° S.

W/E pressure gradient between high and low = 18 hPa.



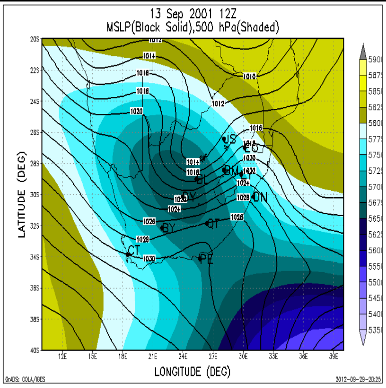
43)12-14 September 2001

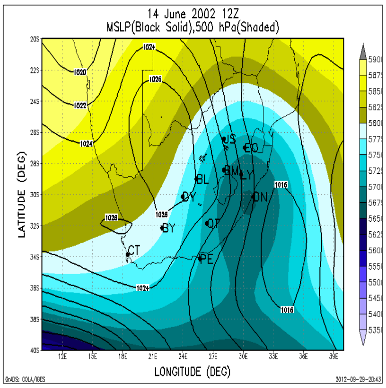
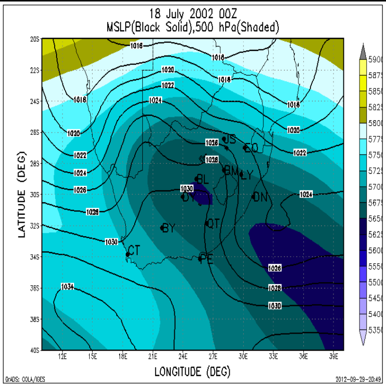
Regional areas affected by snowfall:

Drakensberg and adjacent high ground, Mooi River, Underberg, Bulwer, Van Reenens Pass, Western Cape Mountains, Amersfoort, Cornelia, Drakensberg, Dundee, Frankfort, Harrismith, Memel, Reitz, Standerton, Volksrust, Vrede, Warden, Harrismith, Olivershoek Pass, Nottingham road, Loteni road to Sani Pass, Kokstad, Drakensberg, Malutis and Mpumalanga Highveld.

Basic System Identification: COL, cold front with 1016 hPa low followed by ridging AOH of 1038 hPa at 40° S.

W/E horizontal Pressure gradient between high and low: 22 hPa.



2002	
44)14-15 June 2002 **Regional areas affected by snowfall:** Lootsberg, Graaf Reinet, Matatiele, Giant Castle, Bergville, QwaQwa, Tiffendell Barkly East, Dordrecht, Ficksburg, Fouriesburg, Jamestown, Kestell, Molteno, Phuthadithaba, Queenstown, northern parts of the Eastern Cape, Penhoek Pass on the N6, Boesmanshoek Pass on the R56, Dordrecht, Platberg near Harrismith, Aliwal North. **Basic System Identification:** COL, cold front with low south-east of KZN of 1016 hPa followed by ridging AOH of 1028 hPa at 32° S. W/E pressure gradient between high and low = 12 hPa.	
45)16-20 July 2002 **Regional areas affected by snowfall:** Barkly East, Cala, Drakensberg, Queenstown, Satansnek Pass, Ugie, Sneeuberge, Mountains near Nieu Bethesda, Goods Motel, Lootsberg Pass R61, Matroosberg near De Doorns, interior of the Eastern Cape, Penhoek Pass, Tiffendell ski resort, Lady Grey, Sterkspruit, Joubertina, Somerset East, Elliot, Indwe, KwaZulu-Natal, southern Drakensberg, Kokstad. **Basic System Identification:** Pointed Trough/COL, cold front with surface low south-east of KZN of 1022 hPa followed by ridging AOH of 1034 hPa at 38° S. W/E pressure gradient between high and low = 12 hPa.	

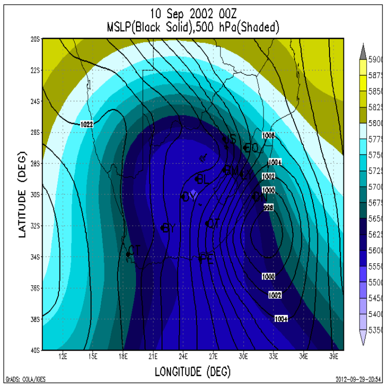
46) 9-11 September 2002

Regional areas affected by snowfall:

Queenstown, Elliot, Barkly East, Kokstad, Drakensberg, QwaQwa, Zastron, Queenstown district, Middelburg, Graaf Reinet Barkly Pass road between Queenstown and Jamestown, Lady Grey, Aliwal North, Mount Frere, Matatiele, Cedarville, Dordrecht, between Cala and Lady Frere, Penhoek Pass and Tiffendell,

Basic System Identification: COL, cold front with surface low south-east of KZN of 998 hPa followed by strong ridging AOH of 1028 hPa at 38° S.

W/E pressure gradient between high and low:30 hPa.



2003

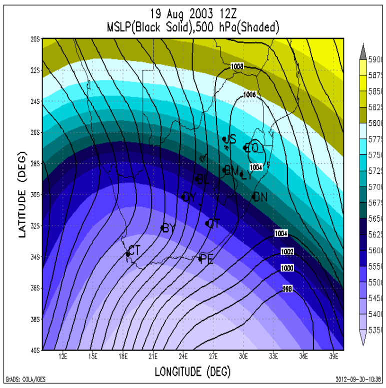
47) 19-20 August 2003

Regional areas affected by snowfall:

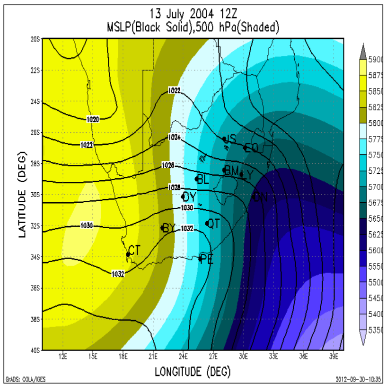
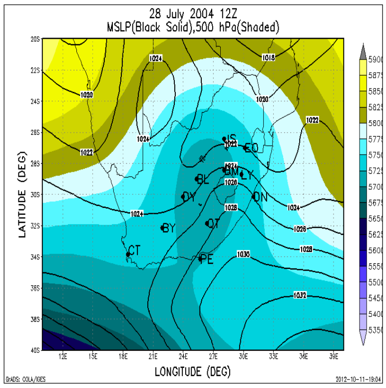
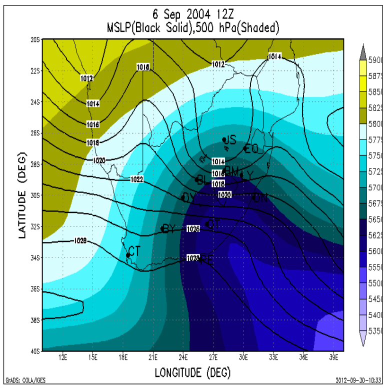
Matroosberg, Gydo Pass, Theronsberge Pass, Prince Alfred Hamlet, Simonsberg, Sederberg near Uitkyk Pass, Matroosberg Pass outside Ceres, Devils Peak, Ceres, Franschoek, Table Mountain, Devil's Peak, Hottentotsholland mountains, Tulbach ,Riebeek-Kasteel, Calvinia, Sutherland, Springbok, mountains by Clanwilliam between Bloemfontein and Petrusburg.

Basic System Identification: Deep Pointed trough, cold front with low south-east of the country of 998 hPa followed by AOH of 1026 hPa at 34° S.

W/E pressure gradient between high and low = 28 hPa.



2004

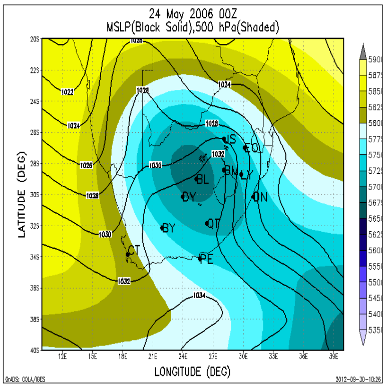
48)13-14 July 2004 **Regional areas affected by snowfall:** Sani Pass hotel, Underberg region, Kokstad, Sinjisi, R617 between Underberg and Impendle, Adelaide, Tarkastad, Barkly East, Elliot, Queenstown. Underberg, Himeville, Rhodes Tiffendell, Van Reenens Pass, Long Tom Pass, Belfast, Lydenburg, Sabie, Dullstroom and Drakensberg Gardens Hotel. **Basic System Identification:** Pointed trough, cold front with 1014 hPa low followed by ridging AOH of 1034 hPa at 40° S. W/E horizontal Pressure gradient between high and low = 20 hPa.	
49)27-29 July 2004 **Regional areas affected by snowfall:** Kingscote Pass between Underberg and Swartberg, Kokstad, Matatiele, Cedarville near Kokstad, Matatiele, Drakensberg, Southern KZN and NE Cape. **Basic System Identification:** COL, cold front followed by ridging IOH of 1034 hPa at 40° S.	
50)6-7 September 2004 **Regional areas affected by snowfall:** Harrismith, Kokstad, Matatiele, Underberg, Himeville, Mooi River, Lions River areas, Boston and Impendle. **Basic System Identification:** Pointed trough, cold front with 1012 hPa low with ridging AOH of 1030 hPa at 38° S. W/E horizontal Pressure gradient between high and low = 18 hPa.	
2006	

51)23-25 May 2006

Regional areas affected by snowfall:

E Cape, NE Cape, Lesotho, Lootsberg Pass, Wapadsberg mountains in E Cape, Drakensberg around Bethlehem, Matroosberg, Winterberge near Aberdeen, Cradock, Queenstown, Drakensberg near Elliot, Barkly East, Cala, Ficksburg, Clocolan, Paul Roux, Ladybrand, Tweespruit, Wepener, Thaba Nchu, De Wetsdorp, Harrismith, Van Reenens Pass, Ladybrand and Clarens.

Basic System Identification: COL, cold front followed by ridging IOH of 1034 hPa at 40° S.



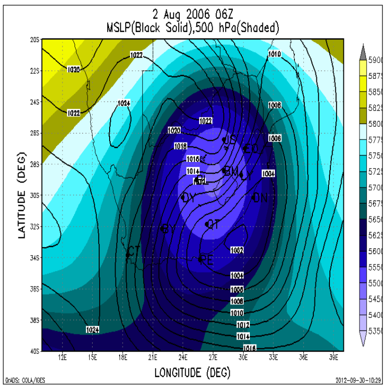
52)1-3 Aug 2006

Regional areas affected by snowfall:

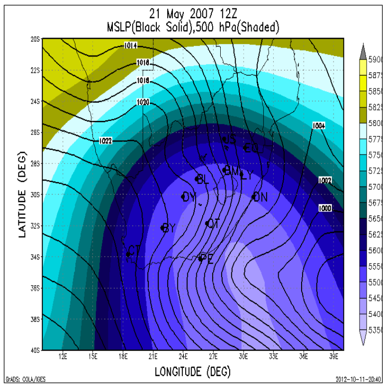
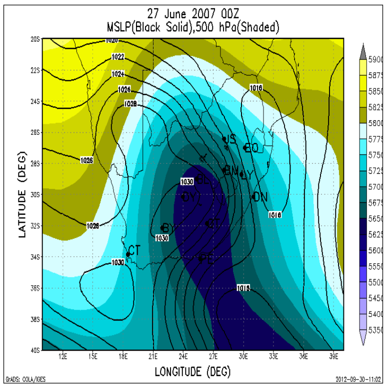
NE Cape, Lesotho, SW Cape, Swart berge, Sutherland, Verlatekloof Pass, Matroosberg, Sutherland, Hex River Mountains at De Doorns, Johannesburg areas such as Westonaria, Carletonville, Soweto, Sandton, Morningside, Bloemfontein and surrounds, Clarens, Fouriesburg, Harrismith, Paul Roux, Senekal, Bethlehem, Kestell, Ladybrand, Ficksburg Philipstown N6 between Reddersburg and Smithfield, Wepener, Paul Roux, Lootsberg Pass, De Aar, Hanover Orania, Willistown, Calvinia, Joubert Pass near Lady Grey, Graaf Reinet, Nieu Bethesda, Colesburg, Burgersdorp, Smithfield, Reddersburg, De Wetsdorp snow near Touws River.

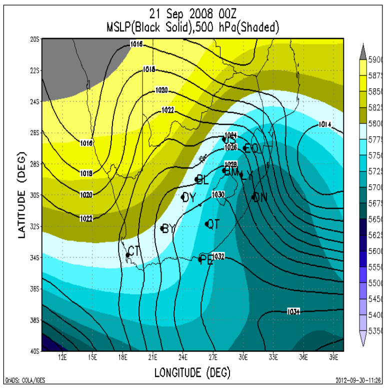
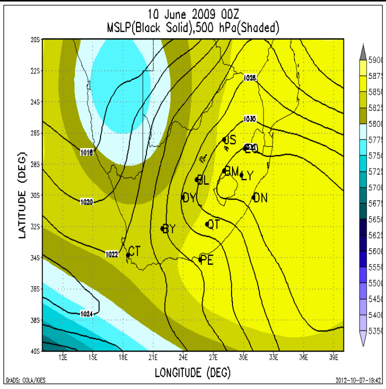
Basic System Identification: Deep COL with surface low on the south-east coast of 1002 hPa followed by ridging AOH of 1024 hPa at 38° S.

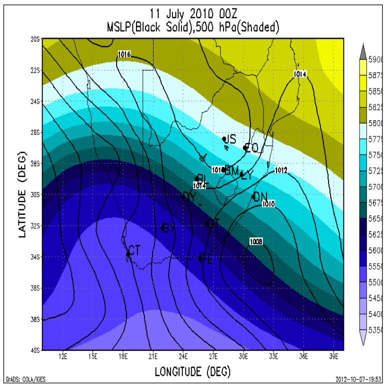
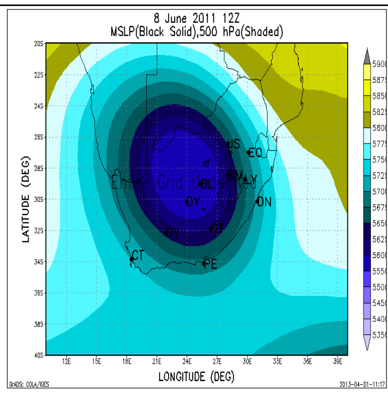
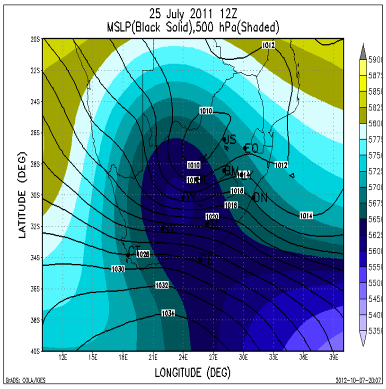
W/E pressure gradient between high and low = 22 hPa.

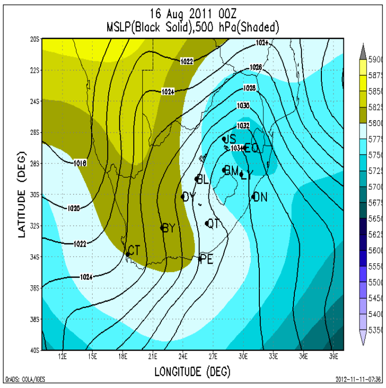


2007

53)21-22 May 2007 **Regional areas affected by snowfall:** Western Cape, Eastern Cape, Lesotho, Matroosberg, Hottentots Holland Mountains, Simonsberg, Swartberge, Swartberg Pass near Ladysmith, Southern Cape, Eastern Cape high ground, Southern Drakensberg, Bamboes berge at Joubertina, Tsitsikama berge, Kouga Mountains at Hogsback, N9 in the Lootsberg Pass, Vryheid and Hlobane. **Basic System Identification:** Deep Pointed trough, cold front with surface low over Indian Ocean of 996 hPa and ridging AOH of 1032 hPa at 40° S. W/E pressure gradient between high and low = 36 hPa.	
54)26-27 June 2007 **Regional areas affected by snowfall:** Western Cape, Eastern Cape, Lesotho,Eastern Highveld,100 km south of Bloemfontein on the N1, Sutherland, Bloemfontein, KZN midlands, Nottingham road, Rosetta, Mooi River, Kokstad, Underberg, Sani Pass, R103 from Nottingham road to Mooiriver, R617 from Underberg to Kokstad, N2 from Port Shepstone to Kokstad, R56 from Umzimkhulu to Kokstad, Rhodes, Sterkspruit, Aliwal North, Tarkastad, Barkly East, Reddersburg, Klerksdorp Johannesburg In Phineas McIntosh Park (Brixton), Zoo Lake (Parkview), Matroosberg Auckland Park, Germiston, Roodepoort, Grootvlei, Mpumalanga, Brakpan, Brakendowns in Alberton, Harding, Kokstad on N2, Boston, Nottingham road, Mooiriver, Underberg and Zastron. **Basic System Identification:** Pointed trough, cold front with low south of the country of 1016	

hPa followed by ridging AOH of 1030 hPa at 36° S. W/E pressure gradient between high and low =14 hPa.	
2008	
55)20-21 September 2008 **Regional areas affected by snowfall:** Kokstad, Underberg, Giants Castle, Sani Pass, mountains of the Eastern Cape, Lesotho and Southern KZN, Drakensberg, Nottingham road region, Lesotho, Nottingham Road, Escourt, N2 between Kokstad and Harding, Underberg, Bulwer to Franklin, R612 over Ixopo, near Ixopo and Table Mountain. **Basic System Identification:** COL, cold front with low east of the country of 1014 hPa followed by ridging IOH of 1036 hPa at 40° S.	
2009	
56)9-10 June 2009 **Regional areas affected by snowfall:** Eastern Free State. Platberg near Harrismith and along the N3 highway. Northern Drakensberg, 3cm on N3 highway according to the AA, Harrismith, Kestell and Van Reenens, QwaQwa and Lesotho. **Basic System Identification:** COL and overland IOH ridging high of 1032 hPa.	
2010	

57)10-11 July 2010 **Regional areas affected by snowfall:** Little Switzerland, De Aar, Victoria Wes, between Three Susters and Richmond in the Northern Cape, Matroosberg near Ceres and the Swartberg Pass. **Basic System Identification:** Moderate Trough, cold front with low SE of country of 1008 hPa and ridging AOH of 1026 hPa at 36° S. W/E pressure gradient between high and low = 18 hPa.	
2011	
58) 8 June 2011 **Regional areas affected by snowfall:** Snow fell in South-west Namibia. Spreetshoogte Pass between Sossusvlei and Windhoek and Drakensberg. **Basic System Identification:** Cut-off low.	
59)25-27 July 2011 **Regional areas affected by snowfall:** Eastern Cape, Karoo, Somerset –East, Beaufort west, Queenstown, Bedford, Tarkastad, Hogsback, Barkly East, Richmond, Victoria West, Molteno Pass, southern KZN, Kokstad, Underberg, Matatiele, Newcastle, Paardekraal farm between Middelburg and Graaf-Reinet, Franschoek mountains, Free State, KwaZulu-Natal, Van Reenens Pass, Harrismith, Newcastle , Ermelo, R56 between Kokstad and Matatiele, N2 by Brookes Nek in the Eastern Cape, Oliviershoek Pass on the R74, R617 between Bulwer and Underberg, N11 between Ladysmith and Newcastle, Charlestown in Mpumalanga, and the R34 near Memel on the way to	

Newcastle. **Basic System Identification:** COL, cold front with 1012 hPa low followed by ridging AOH of 1034 hPa at 40° S. W/E horizontal Pressure gradient between high and low: 22 hPa.	
60)15-16 Aug 2011 **Regional areas affected by snowfall:** Elliot, Vereeniging, southern parts of Johannesburg, Gauteng, southern Mpumalanga, north-eastern Free State, KZN ,Volksrust, Ermelo, Dullstroom, Little Switzerland resort between Harrismith and Bergville, Olivierhoek Pass, N3 was closed to traffic from Harrismith to Colenso/Frere interchange, Roads between Bethlehem and Kestell, Bethlehem and Harrismith and the Longtom Pass at Lydenburg. **Basic System Identification:** COL, cold front with low east of the country followed by ridging IOH high of 1036 hPa at 38° S.	

APPENDIX B

Significant snowfall cases over South Africa for 1981-2011

(Note all times stated in this appendix are UTC + 2)
The following case studies were considered to be significant for this study.

1) 7–8 July 1981

It was reported from the Cape Town weather office that during the night of the 6th of July 1981 the freezing level fell to 4000 ft, with thick snow over the south west Cape Mountains with a light covering on Table Mountain (Nuus van die Weerkantore, 1981a).

The heaviest snowfall in years occurred over the Western Cape, Porterville and Ladysmith with some areas having their worst snowfall in years. It was reported from the Port Elizabeth weather office that very cold air on the 7th and 8th of July 1981 caused snow showers over the Eastern Cape interior. On the 8th of July 1981 a big cold front with snow passed over the southern and south-eastern mountains causing several mountain passes to be closed (Quinn, 1981). The road from Graaf Reinet to Middelburg was closed because of heavy snowfalls on the night of the 7th of July 1981 and they were still closed on the 9th of July 1981 although it had stopped snowing (E.L.D Dispatch, 1981). Pearston, Somerset East, Middelburg, Molteno had their heaviest snow in years (Nuus van die Weerkantore, 1981b). The snowfall in the Eastern Cape reached a depth of 15 cm in Pearston (Viljoen, 1981a). Snow had fallen at Sutherland, Fraserburg, Beaufort West, Middelburg and Willowmore according to the South African Weather Bureau (SAWB). Heavy snowfalls closed the Swartberg Pass (Walker, 1981). Heavy snow occurred in the Cape Province with many roads having to be closed. In Ladysmith the snow was 15 cm thick and it was the worst in 20 years. In Porterville it snowed for the first time in 24 years. The Swartberg Pass was closed for 3 days. Snow covered Burgersdorp, Pearston, Middelburg, Somerset East, Colesburg, Cradock and Molteno. Agriculture and livestock were affected. The road between Middelburg and Graaf Reinet had to be closed on the 7th of July 1981. People had to turn back due to the accumulation of snow on their windscreens. At Pearston branches of trees were torn off by the snow and farmers feared stock losses (Oosterlig, 1981). Snow caused the main power lines to break in the Karoo town of Pearston (Citizen, 1981). In Rouxville and Smithfield where snow seldom fall's the ground was covered with a 12 cm thick layer on the 8th of July 1981 (E.L.D Dispatch, 1981).

2) 28-29 August 1981

It was reported from the Cape Town weather office that a COL developed on the 25th August 1981 to the north west of Cape Town, with the Atlantic high with an intensity of 1040 hPa driving the COL northwards to Upington with snowfalls occurring over the southern parts of South West Africa, now referred to as Namibia (Moir, 1981). It had snowed for the first time in many years in the north western part of the Cape with 30 cm at Vanwyksvlei. At De-Aar it was the worst in living memory and at Aberdeen and Beaufort West it was the worst in 50 years. It also snowed in Pofadder, Upington, Kenhardt and Kanoneiland (Viljoen, 1981b; Viljoen, 1988). The Outeniqua and Robinson Passes were closed to traffic. Snow on the Langeberg/Swartberge fell on Wednesday night, the 26th of August 1981 and further falls occurred on Thursday night the 27th of August 1981. Record falls had last occurred in 1964 in Beaufort West. Two cars and a bus were involved in an accident while the national road was closed for a 2 hour period on the morning of the 28th of August 1981. Snow fell in low lying areas (Cape Times, 1981). It was reported from the Cape Town weather office that on the 28th of August 1981 the heaviest snowfall in years occurred on Table Mountain. It however did not last long but it was visible from the airport for a short period (News from the weather offices, 1981a).

Heavy snowfalls occurred in the Cape Province. In Vanwyksvlei the snow was 30 cm deep. Snow was also reported at Pofadder, Upington, Kenhardt and Keimoes (Cape Times, 1981). Places like Canon Island in Upington had snow for the first time in living memory (News from the weather offices, 1981b).

Possibly the heaviest snowfall in 50 years hit Beaufort West on the morning of the 28th of August 1981 as a number of roads had to be closed. In Pofadder it was the first snowfall in 20 years (Cape Times, 1981).

The Port Elizabeth weather office reported that a COL pressure system developed on the 26th and 27th of August 1981. Heavy snowfalls caused Passes to be closed, some up to 2 days. Jansenville had its worst snowfall since 1933, and the Oosterlig newspaper reported that the snow at Burgersdorp lay up to 1 metre deep (News from the weather offices, 1981c). Snowfalls adversely effected roads in the Eastern Cape. The Barkly Pass (Elliot to Barkly East), Boesmanshoek Pass (Sterkstroom to Molteno), Robertson Pass (Mosselbay to Oudshoorn) which were all closed due to heavy snowfall (E.P. Herald, 1981a).Snow fell as far south as the Winterhoek and Hanekom mountain ranges. Indwe, Aberdeen and Noupoort had continuous snow on the 28th of August 1981, it lay 20 cm deep in Noupoort. Stock losses were feared by farmers in the area (E.P. Herald, 1981b).

The Bloemfontein weather office reported that a deep low pressure developed in the upper air over the interior, with a strong surface high pressure system south of the country (News from the weather offices, 1981b).

It had snowed in Escourt in the Natal midlands (The Star, 1981b).

3) 10-11 September 1981

Heavy snow fell Thursday the 10th of September 1981 over the north eastern interior (Viljoen, 1981c). The Johannesburg weather office reported that a COL developed the 9th of September 1981, with rain and thundershowers between 9:00 am – 10:00 am in the morning (Nuus van die Weerkantore, 1981d). Snow began falling over the east of Johannesburg just before 9:00 am and lasted for about 15 minutes. It also snowed in Kempton Park where it had last snowed this heavily in 1964. The cause of the heavy snow was a strong surface high pressure south of the country and a trough of low pressure over the country (Vaderland, 1981a). The temperature was 9 °C but dropped to 1 °C at 10:00 am. Twenty five mm of precipitation occurred with snow at intervals from 10:00 am to 19:00 pm. Snow reached a depth of 15 cm. The airport was closed for flights with 108 flights affected. The previous major snowfall event occurred in June 1964 (Nuus van die Weerkantore, 1981d). It snowed the whole day in Johannesburg extending close to Pretoria (Viljoen, 1981c). In Boksburg, 600 tons of snow caused the roof of a popular skating rink to collapse. Damage was estimated at R200000. In Brakpan, the roof of the market collapsed crushing a car and damaging another. The town was blacked out for the night. Four hundred stranded motorists had called the AA by 5:00 pm on the 10th of September 1981. An international SAA flight was diverted from New York to D.F. Malan Airport in Cape Town because of the snow. It had snowed in Braamfontein (The Star, 1981d). All incoming flights to Jan Smuts airport (now ORTIA) were cancelled on the 18 June 1964. On the 10th of September 1981, 60 incidents were reported by the Automobile Association. The snow was 15 cm deep, in 1964 it was 5 cm deep and in 1962 it was 7.6 cm (The Star, 1981e). The Durban weather office reported that because of the snow, ice and crosswinds many flights to Johannesburg were cancelled (Nuus van die Weerkantore, 1981c). There were massive increases in demand for electricity after the snow and very cold conditions. There was a 16 hour power cut over the eastern parts of Johannesburg that ended at 4:00 am on the morning of the 11th of September 1981. Heidelberg, Balfour and Germiston also had power failures after 12:00 pm on the 10th of

September 1981 (The Star, 1981f). There were several hours of snow on the 10th of September 1981 in which at least 8 lives were claimed. Air traffic shut down at Jan Smuts (Johannesburg) and Louis Botha (Durban). Forty international flights were affected.

In Warden 180 children were stranded in a school bus and Escom reported power cuts. Snow fell on the outskirts of Pretoria, Springs, Nigel, Boksburg, Balfour, Heidelberg, Standerton, Leandra, Secunda, Evander and Greylingstad. There were heavy snows on the Drakensberg. Telephone services too many Transvaal towns were disrupted. Five trains between Durban and Johannesburg were cancelled because of heavy snow at Van Reenens Pass (Feinstein and O'Connor, 1981). The Vaderland (1981b) also reported snow in Johannesburg.

Trains were disrupted and hospitals had to make use of emergency power. Telephone lines were affected and hundreds of telephone poles gave way under the snow. There had been reports of stock losses. Roads were opened again on the 11th of September in the Transvaal, OVS and Natal. At 2:00 pm on the 11th of September 1981 the power need was 14000 megawatt while Escom could only provide 12000 megawatt (Beeld, 1981). Snow also fell at the Turfontein race course on 11 September 1981 (Tshabalala, 1981).

The Bloemfontein weather office reported that snow affected the northern Free State and Transvaal (Nuus van die Weerkantore, 1981e). Snow occurred over the south eastern Transvaal and the north eastern Orange Free State (Fourie, 1981). The Long Tom Pass, Amersfoort, Bethal, Witbank, Standerton, Ermelo, Springs and Delmas all reported snow. Between the towns of Harrismith and Warden telephone poles broke under the weight of the snow (Viljoen, 1981c).

It was reported that for the first time in 17 years the Witwatersrand was blanketed in snow, 20 car smashes were reported in an hour after the first snow fell around 09:45 am. Flights were also disrupted. Pretoria did not have any snow. Heavy snowfalls on the Drakensberg trapped 20 heavy trucks on Van Reenens Pass (The Star, 1981c).

4) 1–3 July 1982

A strong cold front followed by a strong surface high pressure system caused snow to spread as far north as the Witwatersrand and the central parts of South-West Africa. According to reports it was the first time in 18 years that snow fell on the mountains south of Windhoek. Passes had to be closed over the south and south-western Cape Province. Snow was also reported as far north as the southern and central parts of South West Africa, the Orange Free State and the southern parts of the Transvaal (Quinn, 1982).

Heavy snow fell in the Eastern Cape and parts of the Orange Free State. Light snow fell in Johannesburg on Friday morning the 2nd of July 1982 (Viljoen, 1981a).The Bloemfontein weather office reported that on the 2nd and 3rd of July 1982 snow covered the Thaba Nchuberg near Bloemfontein (Nuus van die Weerkantore, 1982a).

The Port Elizabeth weather office reported that heavy snow showers occurred over the Eastern Cape on the 2nd and 3rd of July 1982. Passes had to be closed in the Winterberge and Stormberge where it lay 60 cm deep (Nuus van die Weerkantore, 1982b). Heavy snow fell in the Eastern Cape and the higher lying parts of the Orange Free State. Snow had been falling since the afternoon of the 1st of July 1982 on the mountains near Barkly East and Elliot in the Eastern Cape. The Thaba Nchu Mountains near Bloemfontein were covered on the morning of the 2nd of July 1982 with thick snow. In Florida on the West Rand there was light snow on the morning of the 2nd of July 1982 before it began to rain (Terblanche, 1982). Snow closed Passes in the Eastern Cape. Ten centimetres of snow fell at Molteno, 10 cm at Dordrecht, 2 cm at Burgersdorp and 14 cm in Barkly East where there were skiers in the streets. In Lady Frere, 15 cm of snow fell between 1:00 pm and sunset on the 2nd of July 1982. Snow also fell in Indwe, Hofmeyer, Elliot, and Colesburg. The Penhoek Pass was closed at 11:00 am on the 2nd of July 1982 as it was snowing too heavily for cleaning equipment to keep the road clean. Several other passes had to be closed such as: Carlton Heights between Noupoort and Middelburg, Wapadsberg between Cradock and Bethesda road, Boesmansnek between Sterkstroom and Molteno, Lootsberg between Bethesda and Middelburg, Naudes Pass between Graaf Reinet and Bethesda and Barkly Pass between Eliot and Barkly East. Mountains in the vicinity of Clarens and Hobhouse in the Orange Free State were covered (E.P. Daily Dispatch, 1982).

It snowed in the Eastern Cape and Free State as well as Johannesburg during the morning of the 2nd of July 1982 (Viljoen, 1988).

5) 24–26 July 1983

Bad weather occurred in KZN from Saturday the 23rd of July 1983 (Vaderland, 1983). It began snowing Saturday night the 23rd of July 1983 (Oertel, 1983). Heavy snow fell on Sunday the 24th of July 1983 over the Drakensberg, it was more than a metre deep and 22 climbers were stranded near Witsieshoek (Viljoen, 1983). Children were trapped on the mountains near Tshakgolo and Qwa Qwa. The snow was more than a metre deep on the Drakensberg, hampering efforts by helicopters to find mountain hikers (Vaderland, 1983). In Witsieshoek on the 26th of July 1983, two helicopters went searching for 22 people.

6) 8 August 1983

A cold front passed over the Western Cape on the 4th of August 1983. A secondary development took place behind the cold front and it was followed by a ridge of high pressure. A low pressure trough developed in the upper air (Vallance, 1983). It was reported from the Bloemfontein weather office that an active cold front passed over the region on the 6th of August 1983 (News from the Weather offices, 1983). It snowed in Belfast in the Eastern Transvaal on the 8th of August 1983. Buses and trains were delayed and school lessons started late.

7) 13–14 June 1984

It snowed on the 13th of June 1984 over the Eastern Cape with heavy snow covering the Natal midlands. On the 14th the snow spread to the eastern Free State and the southern Transvaal Highveld (Viljoen, 1988).

The Deputy Director of the South African Weather Bureau, Mr. G.Schulze said that the snow was caused by a strong surface high that was ridging south of the country with a low pressure system in the upper air (van der Westhuizen, 1984). During the period of the 12th of June 1984 to the 14th of June 1984 there were heavy snowfalls over the eastern Transvaal Highveld, Natal, Eastern Orange Free State, and the southern and south-eastern parts of the Cape Province (Jooste, 1984).

On the 13th of June 1984 heavy snow occurred in the Eastern Cape and Natal and several mountain passes were closed. On the 14th of June 1984 it snowed at Volksrust, Memel, Vrede, Bethlehem and Kestell (Viljoen, 1987a).

It snowed in Vrede, Bethlehem, Kestell and Bethulie. Heavy falls occurred in the Natal midlands, Volksrust and Memel (Volksblad, 1984). The heaviest snowfalls in years were reported in some places. Snow fell in the Cape, Orange Free State and Natal. It snowed in Richmond for the first time since 1922. The town of Rhodes near the Transkei border could not be reached by road because of heavy snow. In the north-eastern Cape snow lay 60 cm thick. From Tuesday night the 12th of June 1984 it also snowed in the Western and southern

Cape and Karoo. The Malutis dividing the Orange Free State and Lesotho were covered with heavy snow in the southern Orange Free State (Citizen, 1984).

It was reported from the Port Elizabeth weather office that heavy snow showers fell over high lying areas and many towns in the Eastern Cape were completely blanketed in snow (News from the weather offices, 1984a). Snow that fell in the Eastern Cape, was heavy enough to close roads. The Lootsberg Pass was closed early in the morning of the 13th of June 1984 after snow started falling the previous night in the area. It was snowing in the Wapadsberg Pass near Cradock. The Coetzeesberg range near Pearston and the Longhill and Hangklipberge near Queenstown were covered in snow. Snow was lying at the foot of the mountain. Power had been interrupted since 3:00 pm at the town. Light snow fell at the Kamdeboberg range near Aberdeen and the Garslandkloof area near Cradock (Kellerman, 1984). The NaudesNek Pass between Rhodes and Maclear and the Barkly Pass between Barkly East and Elliot was still closed to traffic after heavy snowfalls the previous day (the 13th of June 1984). It was reportedly still snowing in Dordrecht early in the morning of the 14th of June 1984. In some parts the snow lay 60 cm deep (Evening Post, 1984).

The Durban weather office reported that on the evening of the 12th and the 13th of June 1984 widespread snow fell over the interior. Freezing levels dropped as low as 1800 m a.m.s.l. Snow was reported at Richmond and Hilton, only 80 km inland from the coast (News from the weather offices, 1984b). Heavy snow began falling in the Drakensberg and Natal interior on the 13th of June 1984. Pietermaritzburg, Mooiriver, Underburg, Kokstad and Nottingham Road reported snowfalls. Telephone lines were down in some areas. At noon of the 13th of June 1984 driving snow was falling in the Natal midlands. Heavy falls occurred over the Drakensberg as far south as Matatiele. Soft snow fell at Hilton, the heaviest at Boston, Bulwer, Curries Post, Ixopo and Highflats. Snow was also falling in Dargle and Karkloof in the Howick area and Nottingham Road. At 3:00 pm the temperature at Mooi River was -2 °C. In Escort the cold claimed 4 lives. The Transvaal - Natal train was delayed by more than 2 hours because of the snow. Heavy snow fell at Volksrust and the Natal midlands was covered by more than 200 km with snow. Heavy snow also fell at Newcastle, Memel and Vryheid (First time in 50 years). Snow also fell at Witsieshoek, Van Reenens, Mooiriver, Ladysmith, Newcastle, Volksrust and Perdekop (Beeld, 1984). Laingsburg Pass between Newcastle and Vryheid was closed on the 14th of June 1984 because of heavy snow (Evening Post, 1984). Newcastle awoke to a snowy covering for the first time in 13 years and got another fall during the day that covered trees, grass and roofs. Road were closed on Wednesday night the 13th June 1984 between Newcastle and Volksrust and again on the morning of the 14th of June 1984. Van Reenen was also closed for a short while on the 14th of June 1984. Snow covered Standerton, Piet Retief, Volksrust, Wakkerstroom and Ermelo and was still falling late in the afternoon on the 14th of June 1984. In Ermelo 15 cm had fallen, the largest since 1967. Piet Retief had 3 cm on the ground early yesterday, the 14th of June 1984 and there was 15 mm in Matatiele, the first time in 50 years (Natal Mercury, 1984).In the Orange Free State snow fell at Springfontein and Zastron (Citizen, 1984).

The maximum temperature at Standerton on the 14th of June 1984 was only 0.6 °C. On the 13th of June 1984 the cold front moved to Transvaal with snowfalls over the Drakensberg, mountains of the Eastern Cape and the high lying regions. On the 14th of June 1984 there were snowfalls in places over the Eastern Highveld (Jooste, 1984). Widespread reports of snow were received from the eastern Highveld and the South Eastern Transvaal. Farmers in Ermelo reported 5 cm of snow on the ground early on the 14th of June 1984, but it began melting soon after (The Star, 1984a). The road was closed between Standerton and Volksrust where it snowed on the night of the 14th of June 1984. Secunda, Bethal, Amersfoort, Wakkerstroom, Breyten and Perdekop had snow. Branches of trees broke because of the snow at Ermelo. In Nigel it snowed for 2 min (Beeld, 1984; The Star, 1984b).

8) 24–25 June 1985

The Port Elizabeth weather office reported that the snow was caused by a COL west of Kimberley and a very intense surface high of 1042 hPa south of the country (News from the weather offices, 1985). It was reported that towards the end of the month of June 1985 snow fell over the Eastern Cape and the southern Orange Free State (Poolman, 1985). It snowed for the first time in 14 years in the town of Carnarvon. It started on the 24th of June 1985 at 11:00 am and continued for an hour without stopping. Roofs were covered in white, while branches were bent by the snow (Die Burger, 1985).

9) 11–12 July 1985

A strong cold front moved over the country between the 10th and the 13th of July 1985.and caused the most noticeable snow of the month. The cold front passed over the south west Cape on the 10th of July 1985 and was followed by a strong surface high pressure system (Fourie, 1985).

Heavy snowfall was reported on the 11th of July 1985 over the southern and eastern Cape. The Langkloof had snow and 5 cm deep in Sutherland. On the 12th of July 1985 the snow spread to the Free State, Natal and the Transvaal Highveld blocking several routes (Viljoen, 1988).

The mountains in the Western Cape were blanketed in snow. Sleet and snowflakes fell on Table Mountain in the morning of the 11th of July 1985. The heaviest falls occurred in the Matroosberg, Cedarberg, Villiersdorp, Worcester and Franchoek areas. On a farm, bokveldskloof in the Skurweberge where it snowed heavily on the 11th of July 1985, farmer Mr. Pierre du Toit said it was the second time it had snowed in 20 years during the day. Gydo Pass, Swaarmoed Pass and Sutherland also had snow (Cape Argus, 1985). Heavy snow fell over the Southern and Eastern Cape on the 11th of July 1985. It snowed in several towns and the Langkloof. Snow occurred on the Matroosberg between De Doorns and Ceres, on the Cedarberg near Citrusdal, Franschoek, Worcester and Villiersdorp (Natal Witness, 1985).

On the night of the 11th of July 1985 snow was reported to be falling in Queenstown. In Barkly East intermittent snow fell during the day. At New Bethesda snow had fallen in the town in the morning of the 11th of July 1985, but stopped by night. There was a small snowfall at Cathcart and Somerset East in afternoon and evening. Somerset East and Pearston farmers reported heavy falls during the night of the 11th of July 1985. Snow fell on mountains near Graaf Reinett, Murrayburg and the Lootsberge on the 11th of July 1985. Sleet fell at Middelburg and snow fell on Swaershoek and on Wapadsberg. Heavy falls of snow fell in the Langkloof and mountains between Avontuur and Louterwater. Snow also fell on Formosa Peak, the highest in the Tsitsikama Range near Plettenberg Bay on the morning of the 11th of July 1985 (E.P. Herald, 1985).

On the 12th of July 1985 the snow moved to Natal, Orange Free State and the Transvaal Highveld. Mountain Passes between Natal and the Transvaal had to be closed (Viljoen, 1987a). The Van Reenens and the Majuba Pass were closed to heavy vehicles. Road scrapers were sent to the passes on early on the 12th of July 1985, most of East Griqualand was blanketed by snow which began falling late on the 11th of July 1985 and spread to Matatiele, Franklin, Swartburg, Cedarville and Kokstad. Snow covered higher regions near Dargle, Tweedie, Greytown and Karkloof. There was a continuous blanket of snow across parts of Mooiriver and Nottingham Road. The towns of Vryheid, Glencoe and Dundee had light snow (Daily News, 1985).

The road between Harrismith and Ladysmith, Van Reenens, Laingsnek Pass and Amajuba Pass were closed to traffic. Two people died in the morning of the 12th of July 1985 on their way from Volksrust to Standerton when their car slipped on the ice and went into a lorry. Late on Thursday the 11th of July 1985 the temperature in Potchefstroom was 20 °C and Friday morning -2 °C. At Volksrust it snowed from 8:00 am to 11:00 am on the 12th of July 1985. It was reported to have reached a depth of 4 cm. It also snowed at Standerton and Amersfoort. A lorry fell over on Van Reenen due to ice (Ebersöhn and Pienaar, 1985).

The Johannesburg weather office reported that an active cold front moved through the area at 16:00 pm on the 11th of July 1985 (Nuus van die Weerkantore, 1985a). The Bloemfontein weather office had a maximum temperature of 11 °C on the 11th of July 1985 with a 23 knot wind (Nuus van die Weerkantore, 1985b). The Durban weather office reported snow over the Natal interior on the 12th of July 1985 (Nuus van die Weerkantore, 1985c).

Snow was reported at Volksrust, Perdekop and Amajuba. Snow fell over most of the Eastern Cape Mountains during the night of the 11th of July 1985 (Stretch, 1985).

Light snowfalls occurred in the morning of the 12th of July 1985 in the areas of Bethal, Ermelo and Standerton. The heaviest snowfalls of the winter occurred in the Cape. Snow was reported over the Orange Free State and expected to move over the Drakensberg. It began snowing early on the 12th of July 1985 at Rhodes in the Eastern Cape. The Outeniqua had a light dusting on the morning of the 12th of July 1985. Near Bloemfontein large areas were covered in snow (The Star, 1985).

Bloemfontein was under snow. There had also been a search for four Belgium's on a small plane which disappeared in the snow covered area of the Groot Drakenstein mountain range on the 11th of July 1985. There were fears for Angora goats which had been sheared near Cradock (van Dyk, 1985). It was reported from Bloemfontein that residents awoke to snow on snow Friday morning the 12th of July 1985, the first time in more than 20 years after a light snowfall during the night. There was a 7 car pileup due to ice on the road. Two traffic officers fell off their bikes. In the Harrismith area 15 cm fell. It was reported at 11:30 am on Friday the 12th of July 1985 that snow covered the road. Snow also fell at Smithfield and Frankfort (The Friend, 1985).

10) 17–18 June 1987

Double fronts and lows formed south-east of the country on the 17th of June 1987. Strong cold air advection behind it caused a sharp drop in temperatures. Widespread snowfalls occurred over the Southern Cape, Eastern Cape and Southern Drakensberg on the 18th of June 1987 and the high ground of the eastern Free State on the 19th of June 1987 (de

Villiers, 1987). Heavy falls occurred over the eastern interior closing several routes (Viljoen, 1988).

Two mountain passes were closed in the Eastern Cape. In the Lootsberg Pass where 6 cm of snow fell the pass was closed on the 18th of June 1987. The Wapadsberg Pass was also closed. The heaviest falls in 7 years occurred on the Coetzeesberg Mountain's and Bruintjieshoogte near Pearston. There were reports of snow in parts of the Orange Free State and the Western Cape (Daily News, 1987a).

The Lootsberg Pass was closed at 7:00 am on the morning of the 18 June 1987. The Wapadsberg Pass was also closed later. In places in the pass the snow was 10 cm deep. Coetzeesberg near Pearston had its most snow in 7 years. Bosberg at Somerset East and the mountains near Cradock also had snow. Barkly East and Mortimer were also covered in snow. Light snow was reported from Dordrecht and Steynsburg, 8 mm thick. At Graaf Reinett, snow fell widely. Snow fell north-east of the town in the morning on the 18th of June 1987. At Barkly East the snow was 80 mm thick in the morning with more on the mountains. At Cradock it was reported to be 30 cm thick on farms (Spies, 1987a). On the night of the 17th of June 1987 Rhodes had 8 cm and Lady Grey 7 cm (Evening Post, 1987).

Heavy snowfalls occurred over the eastern interior (Viljoen, 1988). The N3 highway between Ladysmith and Van Reenen's Pass had to be closed for 20 minutes due to heavy snowfalls. By 10:25 am the weather cleared (Daily News, 1987a). Snow disrupted traffic on the 18th of June 1987 in Kestell (Erasmus, 1987). Snow was falling early on the 18th of June 1987 over the Drakensberg and several midlands areas. Road's were reported to be dangerous n poor visibility and sleet. Champagne Castle, Mont ex Sources, Sani Pass, Witsieshoek, Cathedral Peak and Matatiele had heavy snow in their areas. Snow also reported at Himeville, Bulwer, Kokstad, Impendle, Swartberg, Nottingham Road, Rosetta, Ladysmith, Underberg, Babanango and Ixopo. It was still snowing in several areas by 9:00 am on the 18th of June 1987. The Little berg near Champagne Castle was also covered in snow on the 18th of June 1987. In Witsieshoek thick snow was falling from 6:30 am. At Sani Pass it began snowing at 2 am, snowing on and off (Daily News, 1987a).

11) 25–26 June 1987

The southern and Eastern Cape Mountains received snow on the 24th of June 1987 with fairly heavy falls in the Barkly East area while the Drakensberg and Underberg area had heavy falls on the 25th of June 1987. On the 24th of June 1987 a cold front moved over the country. An upper air trough that deepened over the country helped produce heavy snowfalls over the Eastern Cape Mountains and the Drakensberg (de Villiers, 1987). Heavy snowfalls occurred over the eastern Free State (Viljoen 1988).

Grazing, bush and farmlands were covered by the heaviest snow in 3 years over southern Natal. It snowed high on the Underberg and Swartberg road. No vehicles could pass there since 4:00 am on the 26th of June 1987. Snow started at 6:00 pm at Sani Pass border post. At Van Reenen Pass and Swinburne there was no snow. Snow blanketed Loteni Nature Reserve and was still falling there early on the 26th of June 1987. During the course of the last week four passes had to be closed because of snow (Daily News, 1987b).

Thick snow covered the Drakensberg on the 26th of June 1987. Consumers drew a record 20000 MW at 9:00 am, the highest ever. Snow lay deep over East Griqualand, most of the 26th of June 1987 and in southern KZN. It was still snowing in the higher elevations on the morning of the 26th of June 1987. Rain and snow on Thursday the 25th of June 1987 made some roads impassable. Kingscote Pass on the Underberg/Swartberg road was closed for some time on the 26th of June 1987 and at midday snow was still thick at the side of the road. A resident of Cathedral Peak said it was heaviest snow in 3 years. Snow fell in Underberg, Matatiele and Kokstad areas. Lesotho Airways Corporation cancelled all domestic flights into the Maluti Mountains because of heavy snow hampering landing on mountain strips (Natal Mercury, 1987a).

12) 14-15 July 1987

On the night of the 15th of July 1987 it started snowing at Ermelo, Breyten and Piet Retief. Few snowflakes were recorded in the night in Johannesburg. Heavy snow showers on the 15th of July 1987 disrupted traffic in the Eastern Cape and Natal. On the night of the 14th of July 1987 it snowed in Trompsburg, Wepener and Ladybrand (Beeld, 1987a).

13) 20–21 July 1987

A cold front and upper COL moved to the south of the country with an influx of cold air over the country. The maximum intensity was on the 20th of July 1987 with cold air over the Drakensberg. The cold front caused a 15 °C drop, with many places having maximum temperatures not much more than 7 °C (Wolfaardt, 1987). Heavy snow fell on the 19th of July 1987 over the Boland and Sarelskop at Tulbach. Snow fell on the 20th of July 1987 over the Karoo, Eastern Cape, eastern Orange Free State, Natal and south eastern Transvaal. The

Oliviershoek Pass and Naudesnek Pass was closed and the Longtom Pass even received snow. The area between Kestell and Warden was covered with snow and at Harrismith it was the heaviest fall in years (Viljoen, 1987a). Snow occurred over the Boland Mountains and Swartberge in the Little Karoo. Light snow was reported on the week-end on the Coetzeesberg range near Pearston and higher areas surrounding Cradock (Spies, 1987b; Viljoen, 1988).

The Naudesnek Pass at Lady Grey was closed on the 20th of July 1987 because of 20 cm of snow. In the Dordrecht area the snow lay 10 cm deep. It snowed on the Swartberg near Ladysmith. The heaviest snow in 5 years occurred on the Witzenberg, Winterhoekberge and Sarelskop near Tulbach. The Boland Mountains near Worcester, Ceres, and Stellenbosch were covered in the morning of the 20th of July 1987 in a blanket of snow. Light snow fell at Villiersdorp, Wellington, Franchoek and Sutherland. Table Mountain was lightly covered with snow on the 20th of July 1987.

Parts of the Drakensberg reported the heaviest snow fall in 20 years-8 cm deep. By 9:00 am on the 21st of July 1987 snow was reported over most of the mountains and still falling. Champagne Castle, Sani Pass, Dragon Peaks, Sanford Lodge and the The Nest reported snow on surrounding peaks. The manager of the Champagne Castle hotel, Mr. Conor Ward said “It hasn’t snowed like this in 20 years”. “Huge flakes are falling and snow must be at least 8 cm deep already” At Sanford lodge near Bergville, paths were white. The Weather office in Durban reported that this was the 6th snowfall of the season (Daily News, 1987c). It also snowed in Lesotho (Beeld, 1987b).

The mountains of the Eastern Cape had their heaviest falls in years with many passes being closed. Benjaminshoogte and Naudesnek Pass were closed near Lady Grey. The Witteberge and Stormberge in the east were covered in snow. The Lootsberg and Renosterberge in the central areas and Kamdeboberg range in the west were also covered. In the north-east many towns were covered in snow as well. These towns included Dordrecht, Molteno, Barkly East, Burgersdorp and Aliwal North (10 cm). At Motkopstasie, beyond Lady Grey as much as 20 cm fell. The other districts that recorded snow were Cradock, Colesburg, Steynsburg and Spring Valley near Tarkastad. Snow fell on Table Mountain on the 20th of July 1987 but melted soon after falling at 8:45 am. Parts of the southern Namib dessert in South West Africa were also blanketed in snow after a freak snowfall in the Aus area for the first time in 24 years. It also snowed in the Boland, Sandveld and southern Namaqualand. Heavy snow also fell on the Riviersonderend Mountains and the Swartberg near Ladysmith in the Little Karoo. Tulbach had its heaviest snow in 5 years on the Witzenberg and the Winterhoek mountains. Snow was reported at Porterville, Villiersdorp, Wellington and Franschoek (E.P. Herald, 1987a).

The Lootsberg Pass and Wapadsberg Pass were opened on the afternoon of the 21st of July 1987. There were 2 accidents. The road between Barkly East and Rhodes and Queenstown and Aliwal North was also closed for a while. Van Reenens Pass was also temporary closed and Oliviershoek Pass was also closed late in the afternoon of the 21st of July 1987. On the 20th of July 1987 the snow was a metre deep around the Barkly East area and the whole day it snowed on and off. Snow also fell on the 21st of July 1987 in the lowveld in the region of White River. It snowed on the night of the 20th of July 1987 at Trompsburg, Wepener and Ladybrand. It snowed lightly in Maseru and the Malutis (Spies, 1987c).

Snow fell at Molteno, Barkly East, Ugie and Dordrecht. From 5:00 pm to 10:00 pm on Monday night the 20th of July 1987 the snow really set in over Dordrecht with 10 mm falling (E.P. Herald, 1987b).

Van Reenens Pass was closed on the morning of the 21st of July 1987. It was re-opened after workers cleared the snow on the 21st of July 1987 but by the afternoon the melting snow had formed ice on the road causing 2 trucks to collide and slip. Three people were killed on the 21st of July 1987 in accidents. Snow started melting on the 22nd of July 1987 in the low lying resorts (Daily News, 1987d).

The Bloemfontein weather office reported a big dust storm between 3:00 pm and 5:00 pm on the 19th of July 1987 with the nearest snow 60 km away on Thaba Nchu-berg (Nuus van die Weerkantore, 1987b). The weather office at Bethlehem recorded a maximum temperature of 1.5 °C on the 22nd of July 1987 with most of the snow occurring at Harrismith (Nuus van die Weerkantore, 1987c).It snowed at Trompsburg, Ficksburg, Smithfield, Fouriesburg, Aliwal North, Springfontein, Burgersdorp, Zastron, Ladybrand, Rouxville, Dordrecht, Harrismith and Qwa Qwa (Beeld, 1987b). It had last snowed that heavily in Zastron in 1954 (Viljoen, 1988).

It was reported from the Johannesburg weather office that light snowflakes fell between 5:00 pm to 6:00 pm. It was too little to be measured (0.0 mm) (Nuus van die Weerkantore, 1987a). At Graskop snow fell 5 cm deep on the 19th and 20th of July 1987 as per Mr. Nico Smith (Nuus van die Weerkantore, 1987e).

The office in South West Africa recorded snow over the southern interior on the 19th/20th of July 1987 for the first time in 23 years (Nuus van die Weerkantore, 1987d).

14) 16 August 1987

The snowfall was caused by a COL that formed over the Western Cape where it caused no weather. Once the Atlantic high ridged across the Eastern Cape on the 15th of August 1987, the upper low moved to the Orange Free State where it absorbed moist surface air, advected from the Indian Ocean High. The Geopotential heights at 500 hPa fell and the low deepened and caused instability with thunderstorms, small hail, rain and extensive snow (Laing, 1987). Heavy snowfalls occurred over the Drakensberg regions and the interior of Natal on the 15th and 16th of August 1987 (Viljoen, 1988).

The Swartberg was transformed into a winter wonderland. Heavy falls occurred at Kings Cote Pass near Underberg. Snow fell in Underberg on the 16th of August 1987 but melted quickly. Heavy snowfalls were reported from Matatiele on the morning of the 16th of August 1987 where snow was 15 cm deep. It covered the ground by 8:00 am. Snow and rain was also reported from Kokstad. Snow blanketed the Sani Pass mountain range (Natal Mercury, 1987b). It was the heaviest falls in southern Natal and the Drakensberg in years. A blanket of snow covered Champagne Castle, Cathkin Peak, Dragons Peak and Sterkhorn on the 17th of August 1987. It snowed on the Amphitheatre and more snow fell at Cathedral Peak on the night of the 16th of August 1987. At Sani Pass it snowed heavily until midday on the 16th of August 1987 and the area was covered in snow. Matatiele had its heaviest fall in 23 years and snow was more than 10 cm thick in the town (Daily News, 1987e).

15) 25–26 August 1987

Heavy snow once again occurred over the eastern Orange Free State and the Natal interior. At Memel the roads to the town were closed after overnight snow. At Van Reenen the snow lay 32 cm deep. Fochville recorded it first snow since 1967 (Viljoen, 1988). At Memel there was heavy snow. Farm children could not get to their schools, since the roads had been snowed in. Telephones were not working for a while. Numerous farmers in the Bothas Pass range were cut off on the morning of the 26th of August 1987 after it had snowed them in overnight. They had to take snow of the roofs of the barns in the night so that they did not cave in. There was also heavy snow at Matatiele, Cedarville and Sani Pass. About 32 cm of snow fell on the road at Van Reenens Pass. It also snowed at Golden Gate. Flakes fell on the road between Fochville and Potchefstroom in the morning of the 26th of August 1987 and snow started in the town around 9:00 am (Beeld, 1987c).

16) 27–28 September 1987

Between the 26th to the 28th of September 1987 significant snowfalls occurred over the north-eastern Cape especially on the 26th of September 1987. Hikers were trapped in the Drakensberg, especially Lesotho (Viljoen, 1988). The Eastern Cape had heavy snowfalls that caused stock losses, closure of roads and mountain passes, flight delays and cancellation of sporting events. Dordrecht and Lady Grey had been isolated by the heavy snow. Dordrecht and Queenstown roads were closed over the Penhoek Pass where the snow laid a metre thick. Snow ploughs helped to dislodge a number of vehicles stranded in the snow. It had also snowed at Molteno, where a man was stuck in the snow overnight on the 27th of September 1987. In the Molteno district, 350 sheep were lost with further losses of new born sheep in the Colesburg area. The temperature on Saturday the 26th of September 1987 never rose above 5 °C (Barkhuizen, 1987).

It snowed on the mountains near Rhodes, Lady Grey, Dordrecht, Molteno, Steynsburg and the Drakensberg. It snowed on the Platberg near Harrismith and near Qwa Qwa (Beeld, 1987d). The Platberg near Harrismith was covered with snow. Mountains of the Eastern Cape, eastern Free State and Drakensberg all had snow. Passes had to be closed in the north eastern Cape due to snow a metre thick. Several roads in Natal were closed. Snow also occurred in the mountains at Rhodes, Lady Grey, Dordrecht, Molteno and Steynsburg. At Tarkastad there were losses of stock. A big lorry had been stuck on the Penhoek Pass since Saturday night, the 26th of September 1987 with Sunday paper deliveries. The Lootsberg Pass, Wapadsberg Pass and Penhoek Pass were all closed (Volksblad, 1987).

Eight towns were cut-off for more than 48 hours because of heavy snow and rain. Sterkstroom, Dordrecht, Elliot, Molteno, Barkly East, Maclear, Indwe and Ugie could still not be reached by road or telephone. Boesmanshoek Pass between Jamestown and Queenstown was closed. Two hundred lambs and recently shaved goats had been lost at Dordrecht until Friday the 25th of September 1987 (Spies, 1987d).

In the Eastern Cape a passenger train was stuck in the snow near Queenstown. Electricity was cut and telephone lines were down. Lady Grey and Dordrecht were still cut-off on the morning of the 28th of September 1987. Heavy snow fell in the mountains of the Eastern Cape. Platberg at Harrismith and the Drakensberg also had snow. Roads that were closed over the week-end were the Penhoek Pass and Wapadsberg Pass. The Lootsberg Pass was re-opened on the 27th of September 1987. Telephone lines were still down in the morning in the Sterkstroom, Molteno, Dordrecht, Indwe, Elliot, Maclear and Ugie areas. Main routes were damaged near Dordrecht and Queenstown. Snow fell on the Lootsberg, Nadoesberge and Toorberg between Graaf Reinet and Murraysburg, there was also snow on Coetzeesberg. The heavy snow occurred Saturday night on the 26th of September 1987 with Dordrecht and Ugie cut-off. Eleven overhead power lines broke under the weight of the snow. The Witteberge were covered for the 4th time this year with snow (Oosterlig, 1987).

17) 28 May 1988

An active cold front reached the Western Cape on the night of the 25th of May 1988. Due to a sharp upper trough, snow occurred over the high lying parts of the Eastern Cape and the southern Drakensberg (Kroese, 1988). The East Londen weather office reported that the weather of the week-end 27th to the 29th of May 1988 was due to an upper low over the interior and a surface ridging high (Nuus van die Weerkantore, 1988b). Heavy falls of snow occurred over especially the north-eastern Cape. At Dordrecht it snowed all day and at 12:00 pm the temperature was still below freezing point (Viljoen, 1988). The Bloemfontein weather office reported that on the 28th of May 1988 a cold front moved through causing snow over the north-eastern Cape (Nuus van die Weerkantore, 1988a).

18) 8 June 1988

The weather office in Port Elizabeth reported that snow, mainly light occurred on 3 occasions but heavier falls were reported in the Barkly East, Rhodes and Dordrecht areas (News from the weather offices, 1988a). In the Agtersneeu Mountains west of Cradock it snowed heavily on the 8th of June 1988. On the morning of the 8th of June 1988 more snow fell at Barkly East, but melted quickly (Kolbe, 1988a). The mountains near Graaf Reinet, Cradock, Langkloof and Kougaberge were all covered in snow. Snow fell on the 12th of June 1988 on Nadoesberg east of Graaf Reinet in the direction of Cradock (Kolbe, 1988b).

The Durban weather office reported that on an inspection to Underberg and Matatiele Fanie Terblanche's car was bogged down in snow and he had to spend the night in his car in southern Natal (News from the weather offices, 1988b).

19) 27-28 June 1988

The heaviest fall of the winter occurred over the Drakensberg and the border post to Lesotho had to be closed on the 27th and 28th of June 1988 (Viljoen, 1988). More than 0.1m of snow fell at Witsieshoek resort. Snow still fell late on the afternoon of the 28th of June 1988 on the

Drakensberg at Qwa Qwa. A group of students were trapped at Mont ex Sources (Volksblad, 1988a).

Snow also fell at Bethal and in places in the Orange Free State east of Bloemfontein (Viljoen, 1988).

20) 9-11 July 1988

Heavy snowfalls occurred from the 8th to the 10th of July 1988 over the Drakensberg and Lesotho. A well developed upper low formed over the Cape on the 8th of July 1988. By the 9th it had moved over the central interior with snow over the southern and south-western Cape Mountains. By the 10th of July 1988 the surface high moved northeastwards causing more snow over the eastern parts (Olivier, 1988).

For the first time in many years snow fell on the mountain tops near Springbok. Heavy snow fell over the weekend on the mountains near Ceres, Paarl, Tulbach and the Hex river valley. Snow also fell on the Matroosberg, Witzenberg and Theronsberge. At Leliesfontein in Namaqualand, the Kamiesberge was covered. On the Boland Mountains snow was a metre thick on Saturday the 9th of July 1988. At Ceres the snow reached the lower sides of the mountains. The Swartberge had its second snowfall of the winter. On the high parts of the Outeniqua Mountains near George there was even light snow (Die Burger, 1988).

The Port Elizabeth weather office reported that the week-end of the 9th and 10th of July 1988, heavy snowfall occurred over the high-lying areas of the Eastern Cape. Light snow occurred on the foothills of the Winterberge, a rare phenomenon. Deaths were also reported because of the cold (Nuus van die Weerkantore, 1988d). The East London weather office reported snow over the southern interior of the Eastern Cape (Nuus van die Weerkantore, 1988f).

Heavy snow fell over the south western, southern and Eastern Cape provinces on the 9th of July 1988. There was also some snow on the mountain peaks near Springbok as well as the 10th of July 1988 early morning east of the Drakensberg and Natal midlands. Later that day all the passes over the Drakensberg were closed. At Ladysmith the heaviest snow since 1922 fell. Snow was also heavy over Lesotho. The storm was similar to one of the 4th and 5th of June 1987 (Triegaardt, 1988).

Snowflakes appeared on windscreens near Warden 6:00 am on the 10th of July 1988. Four hours later motorists were bogged down in a blizzard near Escourt. Traffic on the N3 came to a halt. After a hour it started to move again at 30 km/h. Near Pietermaritzburg the snow disappeared. It snowed near farms at Curry's post and Karkloof and Boston road on the 10th of July 1988 (Graham, 1988).

It snowed heavily in the higher mountains Saturday night the 9th of July 1988. Roads between Graaf Reinet and Cradock and Graaf Reinet and Middelburg had to be closed for a few hours. Two people died as telephones, electricity and roads were cut-off (Schoeman, 1988).

At 10:30 am on the 10th of July 1988 the Van Reenen Pass was closed on the Harrismith side. Outside Vrede the first snowflakes fell on the morning of the 10th of July 1988. Verkykerskop near Harrismith was covered in a thick layer of snow. Roads were closed the whole day on the 10th of July 1988. The N3 was opened during the night as well as the route from Volksrust to Newcastle (van der Westhuizen, 1988).

The Durban weather office reported that a cold front passed on the 10th of July 1988 followed by a strong surface high pressure system with snow up to Nottingham Road (Nuus van die Weerkantore, 1988e). At least 2 people were killed. In Underberg telephone lines were down. Railway lines between Kokstad and Pietermaritzburg were closed because of heavy snow falls. Nottingham Road, Mooiriver, Underberg still had power problems on the 11th of July 1988. Power cuts were caused by the weight of the snow. The N3 road was closed between Nottingham Road and Mooiriver. All routes to the Drakensberg were closed. Roads from Kokstad to Underberg were closed too including Botha's and Oliviershoek Pass. Late on the 10th of July 1988 it was still snowing (The Star, 1988). Hikers were trapped in the Cobham area near Himeville-Ioteni-Kamberg and Coleford where it was snowed in. Six hikers were stranded on Thursday night the 7th of July 1988 on a Cathedral Peak Ridge. They were rescued at 10:00 am Saturday morning the 9th of July 1988 (Daily News, 1988a).

The eastern Free State was blanketed in snow. The Oliviershoek Pass was still closed. The Underberg area received more than 1.5 m of snow. Several towns such as Bulwer, Elandskop, Greytown and Ixopo were still without power on the morning of the 11th of July 1988. The heaviest snow fell at Harrismith, Memel, Clarens, Dordrecht and the Drakensberg. It snowed nearly the whole day on the 10th of July 1988 in Harrismith (0.1m deep). At Dordrecht 0.15m fell and at Memel 0.1m. Fouriesburg had snow for the first time in many years. Snow fell on the surrounding mountains near Ficksburg. Light snow fell in Warden, Vrede, Ladybrand, Newcastle and Hobhouse (Volksblad, 1988b).

The Bethlehem weather office reported that on Sunday, the 10th of July 1988 snow occurred over the whole eastern Free State, Lesotho and Natal highlands. At Bethlehem snow fell for 2 hours (Nuus van die Weerkantore, 1988g). The road was closed at Swinburne early on the 11th of July 1988 after the heaviest snowfalls in living memory on the 10th of July 1988. Snow was falling at Newcastle early on the 11th of July 1988 with many farmers over the Natal interior snowbound. Berg villages were without power since early on the 10th of July 1988. The weight of the snow broke trees. A record 17205 MW power was used on Sunday the 10th of July 1988. It snowed in the Curry's post area, near Karkloof and Midmar dam (Daily News, 1988b).

There were 13 deaths because of the cold and around 100 hikers trapped. Late on the 11th of July 1988, 14 people were rescued at Loteni. Forty skiers were trapped at Club Maluti. It had snowed in the Nottingham Road area. Farmers at Dundee, Newcastle, Glencoe and Volksrust were without power. Later on the 11th of July 1988 it still snowed at Newcastle. Light snow occurred in the morning of the 11th of July 1988 at Ermelo, Amersfoort, Volksrust and Piet Retief that melted by early afternoon (Beeld, 1988a).

The Johannesburg weather office at the airport reported that a cold front passed in the night of the 9/10th of July 1988 and caused 200 mm of snow at Volksrust (Nuus van die Weerkantore, 1988c).

21) 17–18 July 1989

A cold front passed over the Cape on the 16th of July 1989 introducing bitterly cold conditions over the country on the 17th of July 1989 spreading to the northern parts of the country on the 18th of July 1989 due to the strong advection of cold air. Heavy snowfall occurred over the southern and central interior with most places in the Free State between 3 °C and 5 °C on the 18th and Sutherland reaching only 2 °C on the 17th (Triegaardt et al., 1989).

Snow started falling at 3:00 pm on the 17th of July 1989. A little bit covered the roof of cableway on Table Mountain. There was light snow at Sutherland on the morning of the 17th of July 1989. It snowed on the Matroosberg (Cape Times, 1989). It has snowed between Barkly East and Lady Grey next to the railway line (Beeld, 1989). The heaviest snow in many years occurred on the Matroosberg and Waboomsberg on Gydo Pass near Prince Albert and Michells Pass near Ceres. Snow occurred on the mountains of the Piketberg, little Swartland Range and Kamieskroon range. Snow fell on Tafelberg near the Skurweberge in the koue bokkeveld (Holiday, 1989).

The Port Elizabeth weather office reported that a cold front followed by a 1040 hPa surface high pressure system caused heavy snow over the high-lying areas of the Eastern Cape. All mountain passes were closed for at least 2 days (Nuus van die Weerkantore, 1989a). The Bloemfontein weather office reported that snow had occurred over large areas, but light at many places. On the 18th of July 1989 the maximum temperature was only 6.2 °C (Nuus van die Weerkantore, 1989b).

Widespread rain and snow occurred over the southern, central, and eastern parts of the country. The surface high pressure system followed the cold front and spread cold over the whole country with snow up to Winburg (Kroese, 1989). Snowfalls occurred in Kokstad, Matatiele and Underberg. It was some of the heaviest snowfall in years. Snow occurred on the 17th of July 1989 on top of Table Mountain. High lying areas of the Western Cape also reported heavy falls (Daily News, 1989).

22) 19-20 August 1990

The Durban weather office reported that between the 19th and 20th snow falls were reported over the interior. Andrew van der Merwe from the Durban weather office tried to build a snowman at the first order station in Underberg (News from the weather offices, 1990).

The cause was a cold front that moved on the 20th of August 1990 over the Transvaal because of a strong high south of the country feeding cold arctic air northwards. Snow covered the mountains near Volksrust, Ermelo and Wakkerstroom on the morning of the 19th of August 1990. At Harrismith snow was 0.05 m deep and the Platberg was covered on the 19th of August 1990. It was also thick at Lady Grey and Zastron, 0.25 m. Light snow fell at Reitz. Snow fell on the Lootsberg and Sneeuberg. A cold front moved over the Cape on the 17th of August 1990, the upper trough intensified and a wave developed on the cold front close to the south coast. The system intensified on the 19th of August 1990 spreading snow over the Eastern Cape and the Drakensberg. Cold air reached Ermelo on the morning of the 20th of August 1990 where light snow was reported. On the 29th of August 1990 snow fell on the mountains of the Eastern Cape with max temps around 9 °C. Snow continued on the Eastern Cape Mountains on the 30th of August 1990 with heavy falls on the Drakensberg (de Villiers, 1990).

The area of Volksrust received snow, 0.03 m deep. Due to the extreme weather dairy farmers were going to lose 200 liters of milk per day due to the effect the cold had on the cows. Snow started falling at about 8:00 am on the 20th of August 1990 and continued till noon when rain melted it (Templeton, 1990).

The snow lay thick in the mountains around Volksrust, Ermelo and Wakkerstroom on the 20th of August 1990. At Harrismith and Platberg the snow lay 0.05m thick. It also snowed at Lady Grey, Zastron, Lootsberg and Sneeuberge. There lay thick snow on the farm Rooipoort between Volksrust and Utrecht (Beeld, 1990).

23) 29-30 August 1990

Heavy snow fell in several Natal and East Griqualand towns. Snow fell in Underberg, Himeville, Swartberg, Matatiele, Franklin and other centers in southern Natal. By late morning on the 30th of August 1990 the snow was ankle deep. Snow also fell in Lesotho and the central and northern berg (The Star, 1990).

24) 15 October 1990

Garth Sampson at the Port Elizabeth weather office reported that the cold spell of the 15th of October 1990 was short-lived with snow at Uniondale, Graaf Reinet and Middelburg (Sampson, 1990). Raymond Thorpe from the Durban weather office reported that between the 15th and 21st of October 1990 several frontal systems blanketed the Drakensberg in snow (Thorpe, 1990).

25) 18-19 October 1990

The cold spell between 14th of October 1990 and the 19th of October 1990 saw snow falling on the Eastern Cape and Drakensberg. On the 15th of October 1990 the cold front crossed Cape Town. A low developed over the Orange Free State, moving northeastwards. Snow occurred over the south-eastern and eastern mountains as well as north-eastern Orange Free State Mountains (Medcalf, 1990). A second cold spell on 18th of October 1990 brought snow to Middelburg itself, which is very rare (Sampson, 1990). Fanus du Preez at the Bloemfontein weather office reported that there was a low over the central interior on the 17th of October 1990 with a surface cold front followed by strong surface high pressure system. Snow occurred over the mountainous areas (du Preez, 1990).

It snowed in parts of the eastern Orange Free State, Qwa Qwa, Eastern Cape and parts of Natal. The Van Reenens Pass at Harrismith was closed in the morning of the 19th of October 1990 for lorries because of a layer of snow on the road surface (Volksblad, 1990).

26) 7-8 June 1991

On the 7th of June 1991 there was strong cold air advection behind the cold front that caused the first snow of the season over the southern Cape Mountains. An Upper COL formed over Cape Town. Snow occurred over the Mountain's of the Eastern Cape. On the 8th of June 1991 further snowfalls occurred over the southern Cape with Beaufort West having its heaviest fall in 20 years (Myburgh, 1991).

The first snow of the winter fell over the Boland, Western Cape and Klein Karoo. Mountains at Ceres had heavy snow that lay low down on the Matroosberge, Skurwe and Theronsberge with snow on the Klein Swartberge near Ladysmith. There was a light snowfall on Table Mountain and Sneeukop. Snow occurred on the 7th of June 1991 on the Klein Swartberge near Ladysmith and was still falling at 3:00 pm in the afternoon (Die Burger, 1991).

The Lootsberg Pass was closed on the morning of Saturday the 8th of June 1991. The snow lay thick on Saturday night the 8th of June 1991 over the Lootsberg and in the plain below the mountain (Oosterlig, 1991).

Fanus du Preez from the Bloemfontein weather office reported that the low moved over the Western Cape on the 7th of June 1991.The Lootsberg Pass was closed temporarily due to snow (du Preez, 1991).

The heaviest snowfall in 20 years occurred in Beaufort West. Snow also occurred on southern mountain ranges and the Drakensberg (Notable weather related events in 1991, 1992).

27) 26-27 July 1991

On the 25th of July 1991 a well developed weather system moved over the Western Cape. A new front developed on the 26th of July 1991 that caused snow over Ceres, Matroosberg and Sutherland (Strydom, 1991). Light snow fell at Phillipolis, Bethulie and Trompsburg. On Saturday, the 27th of July 1991 it snowed at Champagne Castle. The Verlatenkloof Pass between Sutherland and Matjiesfontein was closed over the week-end due to heavy snow (van der Westhuizen, 1991).

On Saturday night, the 27th of July 1991 the higher Drakensberg from Cathedral to Cathkin Peak was covered in snow (Daily News, 1991).

28) 8-10 August 1992

Andy Davidge from the Durban weather office reported about extreme weather, with snow fall on the Drakensberg on the 8th and 9th of August 1992 (Davidge, 1992).

It snowed over the southern and eastern mountain areas. On the 5th of August 1992 there was a cold front South-west of the Cape, with a strong upper air trough on the west coast. On the 7th of August 1992 the cold front moved to East London and by the 8th of August 1992 it was over Durban. By this time a COL developed over the Eastern Cape interior, followed by a strong surface high pressure system of 1040 hPa (Nigrini, 1992).

Near Graaf Reinet, the Spandaukop was covered in snow. The Lootsberg Pass and the passes to Cradock and Murraysburg were closed for hours on Saturday the 8th of August 1992 after the heaviest snow in 25 years in this area. A luxury bus was trapped in the Lootsberg Pass on Friday night the 7th of August 1992. The snow lay 0.36 m deep. Cradock also had its heaviest snow in years. On the 9th of August 1992 people were building snowmen on their cars. At Hogsback telephone lines were down due to the snow. Snow also fell at Jamestown, Dordrecht, Cathcart, Barkly East and Molteno (Die Burger, 1992).

Heavy snowfalls were reported from Cathcart where it began snowing early on Saturday the 8th of August 1992. Mr. Piet van der Vyver of Woodhouselea farm said it continued to snow till 9:00 am on the 9th of August 1992. Heavy falls were also reported from Hogsback. Snow fell at Stutterheim on Friday night the 7th of August 1992 and continued till Saturday morning the 8th of August 1992. Snow began falling at Queenstown early on Saturday the 8th of August 1992. It snowed for 4 hours but soon melted. There were also reports of snow from Dordrecht and near Molteno. Snow fell in the Drakensberg near Barkly East and at Rhodes. At Hogsback 7 cars were trapped in the snow. Cars had to be pulled out with a tractor. A Translux bus was trapped for 7 hours in the Lootsberg Pass, it had to reverse 11 km on Saturday morning the 8th of August 1992 to bring the 49 passengers to safety. The Nico Malan Pass was closed Saturday and re-opened on the 9th of August 1992. The Penhoek

Pass was closed for a short while on Saturday the 8th of August 1992. Telephone lines were damaged near Cathcart and Hogsback (Daily Dispatch, 1992a).

The Lootsberg, Wapadsberg and Nico Malan Passes were closed to traffic on the night of the 9th of August 1992. Up to one metre of snow was measured on the Lootsberg Pass. A Large truck jackknifed on Ouberg Pass on Saturday the 8th of August 1992 in snow. On the Lootsberg Pass the snow was halfway up to car doors with several cars being stuck. There was 45 cm of snow at Nieu Bethesda on Saturday morning, the 8th of August 1992 (Schoeman, 1992). A thousand Angora goats died on an Eastern Cape farm during the week-end. Many farmers suffered heavy stock losses. Most badly affected areas were near the Winterberge. Many goats were shaved the previous month and it was start of lambing season (Sparks, 1992). One thousand angora goats were lost near Aberdeen with a value of about R80000. Near Pearston, 80 new born lambs were lost and 20 adult goats (E.P. Herald, 1992). Telephone lines in Hoggsback snapped under 0.3m of snow. Snow continued to fall Sunday the 9th of Aug 1992 in Hoggsback (Daily Dispatch, 1992b).

It snowed heavily near Kokstad in the Ngeliberge. It also snowed in Zastron. Light snow fell in Lady Grey and Barkly East (Beeld, 1992). There were heavy snowfalls in the southern Drakensberg on the 10th of August 1992. At Drakensberg Gardens Hotel light snow was falling late on the 10th of August 1992 and was visible on the higher peaks (Natal Mercury, 1992).

29) 11-12 June 1993

The most important cold front was that of the 10th to the 13th of June 1993 with snow falling in Bloemfontein for the first time in 25 years and the first time in 10 years in De Aar. Snow also fell over Drakensberg on the 11th of June 1993 (de Villiers, 1993). Snow blanketed Drakensberg mountains on the 11th of June 1993 with the snow starting late in the afternoon on the berg near Underberg (Saturday News, 1993).

Tonie Rossouw from the Bloemfontein weather office reported that there was a very light snowfall on the morning of the 11th of June 1993 at the airport. However in the south western suburbs the countryside was covered in a blanket of snow (Rossouw, 1993).

The De Aar weather office reported light snow on the morning of the 11th of June 1992, the surrounding mountains and hills were covered in snow. At Noupoort up to 0.12 m fell in places. The George weather office reported that light snow occurred on the peaks of the Swartberg (Wolvaardt, 1993).

On the 11th of June 1993 snow was reported in the Cape and Natal. Thick snow covered the Cape Mountains and southern Drakensberg, De Aar had snow for the first time in 10 years, and it snowed in Bloemfontein (Notable weather related events in 1993, 1994). Snow fell in De Aar region for the first time in 10 years. It started early on the morning of the 11th of June 1993. The heaviest snowfalls this year were recorded over the Eastern Cape Mountains (Cape Times, 1993a). Early on the 11th of June 1993 light snow was recorded in Bloemfontein for the first time in 25 years but melted quickly. There was also snow reported from other places in the Orange Free State, north-eastern Cape and Lesotho. It snowed in Burgersdorp, Goedemoed, Dewetsdorp, Edenburg, Reddersburg, Zastron, Verkeerdevlei, Trompsburg, Springfontein, Phillipolis, Brandfort, Smithfield, Strydenburg, Colesburg, Noupoort, Maseru, Western Lesotho, De Aar, Aliwal – North and Barkly East where 0.18 m fell (Carstens, 1993).

In the koue bokkeveld there was snow on Tafelberg, Sneeukop and Skurweberg. Snow also fell on Riviersonderend Mountains and De Aar. The Matroosberge in the Hex River valley were covered and it was still snowing in the afternoon of the 11th of June 1993. It also snowed at Dordrecht (0.75 m) and Molteno (15 mm) Snow also fell at Trompsburg, Springfontein, Phillipolis, Edenburg, Noupoort, Brandfort, Smithfield, Zastron, Strydenberg, Colesburg, Barkly East and Aliwal North (Cape Times, 1993b).

30) 21-22 September 1993

Heavy snowfalls occurred on the Nuweveld Mountains which closed the Molteno Pass, thousands of Angora goats, sheep and ostriches were lost in the cold (Notable weather related events 1993, 1994).

31) 28-29 June 1994

There were 2 cold fronts between the 26th and 30th of June 1994 producing widespread snowfalls. On the 25th of June 1994 snow was reported on the south west Cape Mountains. The first cold front was situated over the south-eastern Cape on the 27th of June 1994 with a second cold front over the south west Cape associated with an upper air COL. The cold front reached up to Namibia on the 28th of June 1994. Another cold front reached the Cape on the 28th of June 1994 bringing snow to the Franschoek Mountains. This cold front moved over the country causing snow over large parts of the country, for some places it was the first in 50 Years. There was snow on Table Mountain, in Namibia and Johannesburg. By the 30th of June 1994 heavy snow was reported from KwaZulu/Natal (Fletcher, 1994). Snow was reported on the 28 June 1994 from Johannesburg. It was caused by a cold front and upper air trough according to the Bloemfontein weather office. A second cold front caused it to start snowing again late on the 28th of June 1994 in the south-west Free State (Dedekind, 1994). Sydney Marais from the Cape Town weather office reported that in some places in the Swartland the highest snowfalls in 50 years were recorded (Marais, 1994).

Eleven people were trapped in Lorries in the Theronsberge Pass between Ceres and Touws River in a metre of snow. Snow fell on Table Mountain and there were reports from Springbok, De Aar, Bloemfontein, Sutherland, Kimberley and even Windhoek. A weather bureau spokesman said it was very unusual and he can't remember when last it had snowed in Windhoek. Four lorries were stuck high in the pass 40 km from Ceres. It was bitterly cold and snowing continuous. Snow on the Du Toitskloof Mountains was lower than in other years. The Jonkerhoek Mountains and Simonsberg near Stellenbosch were heavily covered. All passes to Ceres, except Mitchell's Pass were closed. Light snow fell in parts of Free State and Northern Cape including Bloemfontein, Springfontein, Phillippolis, Zastron, Kimberley and De Aar. Campbell in the Northern Cape had its first snow in 26 years (Malan and Sorour, 1994).

Danie Ferreira from the De Aar weather office reported that on the morning of the 28th of June 1994 the little hills had some snow that fell in the early morning. That afternoon residents experienced small snowflakes falling to the ground (Ferreira, 1994). Gys Botes from the Bloemfontein weather office reported that a big cold front passed on the morning of the 28th of June 1994 and Bloemfontein only reached a maximum of 5.7 °C. Cloudy conditions with light snowfalls occurred on the 28th and 29th of June 1994 (Botes, 1994). Frank Adam from the Bethlehem weather reported that the maximum temperature at Bethlehem on the 29th of June 1994 was only 2.8 °C (Adam, 1994).

Gerhard Venter from the Johannesburg office reported that on the 29th of June 1994 the temperature dropped by 20 °C in places. There were reports of snow from a few places in Johannesburg, nothing significant was observed (Venter, 1994). Jan Taljaard from the Irene weather office reported that on the 28th of June 1994 the cold front surged over Irene, instead of temps increasing through the day, it kept dropping. In Johannesburg the temperature was down to 3 °C with occasional snow showers (Taljaard, 1994a). Laing (1994) described the snowfall as unusual because of the fact that it has spread as far north as Windhoek which previously had snowfall in 1967. This system was different to the cold outbreak of 1964 in that it was not a COL but a deep trough. Only the 500 hPa charts were used during his comparison.

At Stellenbosch snow fell the night of the 26th of June 1994 and it was low against the mountains. It was also low down the mountains near Tulbach (Volksblad, 1994a). Franschoek had it s heaviest snowfall in years with snow low against the mountains and 70 mm of rain measured in the town. It was caused by 2 cold fronts following each other closely (van der Merwe, 1994).

Brief flurries to heavy falls of snow reached the Cape, Free State, the Karoo, Lesotho, North-West Province and the southern region of the Eastern Transvaal. The Highveld had its first significant falls since 10 September 1981. Many roads in the Free State were under snow and impassable on the 29th of June 1994 (Cape Argus, 1994).

Snow fell on Table Mountain, the edge of the Namib, Free State and the Transvaal. In several areas it was the heaviest and the lowest above sea level in 50 years. Kimberley and Campbell had light snow. The Drakensberg was covered, Sani Pass was closed and Bulwer had several centimetres. Bloemfontein, Ficksburg and Fouriesburg had light snow. The South African Weather Bureau reported that it snowed on the 28th of June 1994 for the first time in 30 years in Windhoek. Johannesburg received snow for the first time since 1987. In Waterkloof a few flakes fell. It snowed in Potchefstroom, Klerksdorp and Lichtenburg. Secunda had snow for the first time in 13 years. Passes that had to be closed were Bainskloof, Theronsberge and the Bo-Swaarmoed Pass at Ceres. It was the worst snow in 50 years in the Ceres district. Snow fell for the first time in 20 years in Springbok with 2.5 cm in the town. The mine town Carolusberg looked like something out of Europe with 65 mm of snow in the town. It snowed the whole day on farms in the Sederberg (Volksblad, 1994b).

It snowed in Lanseria, Potchefstroom, Lichtenburg, and Klerksdorp and according to residents it was the first time since 1970. Snow fell on Drakensberg late on the afternoon of the 28th of June 1994 (Beeld, 1994a).

On the 28th of June 1994, South Africa was under a blanket of snow. Areas on the highveld reported swirling snowflakes that melted upon contact with the ground. Snow with sleet was reported at Carletonville, Westonaria, Randfontein, Krugersdorp, Johannesburg and Vanderbijlpark (Elsas et al., 1994). Snow covered much of the southern Drakensberg on the morning of the 29th of June 1994 after heavy falls the previous night at Devil's Peak, Chapman's Peak and Champagne Castle. There were knee deep falls at Boston, Bulwer and Giants Castle. Several snowbound roads were closed in the Natal Midlands at night on tthe 28th of June 1994 to avoid accidents. At Boston motorists were trapped in heavy snow and some cars slid of roads (Daily News, 1994).

Roads were closed on the 28th of June 1994 due to snow and ice. The power usage was up to 23993 MW It snowed on Gydo Pass (Cape Times, 1994a). Snow fell in central Johannesburg for the first time in 13 years. Windhoek in Namibia had its heaviest fall in 30 years (Cape Times, 1994b). On the morning of the 29th of June 1994 the cricket field in Bloemfontein was covered in snow (Volksblad, 1994c).

32) 25-26 July 1994

Snow fell in the last week over the Free State, Eastern Cape and KwaZulu-Natal. On the 23rd of July 1994 an intense cold front passed over the Western Cape. It moved over the country on the 24th and 25th of July 1994 in association with a very intense upper air trough. On the 26th of July 1994 another cold front moved over the Cape followed by a strong ridging surface high pressure. Snow occurred over the Orange Free State, Eastern Cape and KZN with light snow and hail reported from the Witwatersrand (de Vleeschauwer, 1994).

Willie Pretorius from the Durban weather office reported that a strong cold front on 25th and 26th of July 1994 caused heavy snow to occur over the southern parts of Natal (Pretorius, 1994).

Tonie Rossouw from the Bloemfontein weather office reported that it snowed over parts of the interior with the passage of a cold front on the 25th and 26th of July 1994 (Rossouw, 1994). Karel de Waal of the Bethlehem weather office reported that it had snowed the night of the 25th and 26th of July 1994 and the following morning it was a like a fairy tale landscape of 20 - 40 mm of snow. Clarens had 500 mm of snow (de Waal, 1994). Light snow fell in most towns in eastern Free State on the 29th of July 1994. Temperatures did not rise to more than 2 °C in the day. The heaviest snow fell in Clarens. It was the heaviest fall in Bloemfontein since 1964. Also Welkom, Smithfield and Bethulie had snow (Volksblad, 1994d).

Snow covered the area from Zastron to Oranjeville in the north on the 26th of July 1994. Twelve centimetres of snow fell in Zastron. It also snowed at Wepener, Senekal, Clarens, Ficksburg, Fouriesburg, Sasolburg, Viljoenskroon, Oranjeville, Lady Grey and Heilbron. The mountains near Lesotho and Thaba Nchu were also covered (Beeld, 1994b).

There were record snows in Lesotho and parts of Natal since Monday night the 25th of July 1994. A British Airways flight was delayed for 12 hours on the 26th of July 1994 because of ice on the wings at Jan Smut's airport. The Lesotho Weather Bureau reported its heaviest falls in 20 years in the north-east. Maseru had 50 cm deep snow and telephone and electricity lines were down. Matatiele was snowed in on the 26th of July 1994 (Louw et al., 1994).

Andries Bester of the Johannesburg weather office reported ice rain and light snow on the 25th of July 1994. Light snow fell on the East Rand and at the airport. In the night between 19:50 pm and 21:18 pm, 5 flights had to delay their departure due to ice accumulation on the wings. Another plane the following morning at 7:30 am (Cessna 402) had to make an emergency landing due to ice accumulation on the wings (Bester, 1994).

33) 20-21 August 1994

Snow fell in the Eastern Cape and KwaZulu-Natal on the 20th of August 1994. An upper air COL was also present during this episode which caused the heavy snowfalls (Rae, 1994). It snowed lightly on the morning of the 21st of August 1994 in Ermelo (Beeld, 1994c).

34) 15-17 June 1995

It snowed in Cradock, Lady Grey, Molteno, Dordrecht and Graaf Reinet. The Natal Drakensberg and Malutis in Lesotho were also blanketed in snow (E.P. Herald, 1995a).

Karel de Waal from the Bethlehem weather office reported that on the morning of the 16th of June 1995 snow covered the landscape. Snow fell for about 4 hours in the town till it lay 20-50 mm deep. To the north and east heavier snowfalls were reported. The road between Bethlehem and Reitz and Bethlehem and Harrismith was closed to traffic most of the morning of the 16th of June 1995 (de Waal, 1995).

Andy Davidge from the Durban weather office reported that for the period 16th-18th of June 1995 a deep low followed by strong surface ridge of Atlantic high pressure caused the snow on the mountains (Davidge, 1995). On the 16th of June 1995 a ridge of high pressure produced cloudy conditions over Natal and an upper air COL developed over the Drakensberg (Nigrini, 1995).

On the night of the 16th of June 1995 it snowed in Belfast in the Eastern Transvaal. On the 16th of June 1995 several roads in the Free State were closed to traffic including the road from Bethlehem to Kestell, Harrismith to Warden, Harrismith to Bethlehem, the R103 and the road between Reitz and Bethlehem (Natal on Saturday, 1995).

Heavy snow fell in the Drakensberg and Malutis, in the Free State areas of Qwa Qwa, Bethlehem, Harrismith, Kestell, Clarens and Golden Gate. In some areas 15 cm was measured. Light snow fell at Zastron, Lady Grey, Reitz and Memel (Cape Argus, 1995a).

In the Eastern Free State several roads were closed on the 16th of June 1995 due to heavy snowfalls. Heavy snowfalls occurred Thursday night the 15th of June 1995 over the Drakensberg, Malutis, Qwa Qwa, Bethlehem, Kestell, Clarens and Golden Gate. There was light snow at Reitz, Zastron, Memel and Lady Grey (Jordaan, 1995). Snow fell the 16th of June 1995 over a wide area. Kestell, Reitz and even areas in Bethlehem had snow. Roads between Kestell and Bethlehem were closed and between Bethlehem and Reitz (Volksblad, 1995a).

35) 17-18 July 1995

It snowed near Cradock, Somerset East and Tarkastad. At Hawekwaberg it was the first snow since 1972. Near Wellington, Groenberg received snow for the first time. Snow fell on De Rustberg near Grabouw. Near Stellenbosch the Botmaskop and Simonsberg had snow. Around Worcester it was the first snow since 1979 on Brandwag-, Lange-and Badsberg. Swartberg Pass was closed on the morning of the 16th of July 1995 because of heavy snow. Snow also fell at Riebeek-Kasteel, Porterville, Sutherland, Hermanus, Botrivier and Koue Bokkeveld (de Klerk and Theron, 1995).

Snowfalls occurred over the higher regions of the Eastern Cape on the 17th of July 1995 (Koegelenberg, 1995). Johan Labuschagne from the Cape Town weather office reported that several mountains in the area including Table Mountain had snow (Labuschagne, 1995).

On the night of the 16th of July 1995 a cold front reached the Cape, with a secondary development reaching the Cape on the 17th of July 1995. There was a well developed upper trough associated with this system and freezing levels fell to below 1250 m. Table Mountain received snow. Snow also fell over most of the high-lying areas of the Western Cape. By the 18th of July 1995 it moved over the Eastern Cape with snow over the Eastern Cape Mountains (Dyson, 1995).

The snow was visible in the ravines above Newlands and even Devils Peak had a light sprinkling. Snow closed mountain passes to Ceres with 25 cm at Klondyke cherry farm outside Ceres. The Koue bokkeveld also reported snowfalls. Stellenbosch and Somerset west residents said that they had never seen snow as thick on the lower slopes of the mountains of the Jonkerhoek Valley and Helderberg Range. Ian Teek of manor farm in Koue Bokkeveld said it started snowing on the 17th of July 1995 at 5 pm. Piet Kruger, municipal water pipeline overseer at Woodhead dam on Table Mountain said early on the 18th of July 1995 snowfalls had continued on and off through the night of the 17th of July 1995 and his family were making snowmen and snowballs on the evening of the 17th of July 1995. Snow fell in the mountains near Ceres on the afternoon of the 17th of July 1995 (Cape Argus, 1995b).

Snow occurred on Table Mountain. It happened on the night of the 17th of July 1995. The Kruger family at Woodhead dam said snow had covered 4 square kilometres and was the first time they had seen snow there in 10 years of living on the mountain. Snow fell at around 7:00 pm and was about 6 cm thick. All the trees were full of snow (Granger and Templeton, 1995).

Light snow fell on the 18th of July 1995 in Bloemfontein, Wepener, Edenburg, Verkeerdevlei, Zastron, Petrusville, Luckhoff and Koffiefontein. Snow fell between De Aar and Philipstown (Volksblad, 1995b).

It snowed at Piketberg, Franschoek, Oudshoorn, George and the Free State. Montagu had snow in the mountains for first time in10 years. Snow began falling at 7 pm on Monday the 17th of July 1995 and was 15 cm thick on the morning of the 18th of July 1995 (The Star, 1995).

Snow and light rain was reported in high lying areas of Maclear, Cradock, Graaf Reinet and Tarkastad. Snow also covered Oudshoorn (E.P. Herald, 1995b).

36) 6-10 July 1996

Snow fell around Ceres and Touws River. It was the first snow there since 1957. Theronsberge Pass was closed on the 10th of July 1996. A 40 ton truck got stuck in snow.

Snow was also covering the Matroosberg, Theronsberge and Waboomsberg (Aranes and Blignaut, 1996). Johan Singleton from Cape Town reported that Ceres was popular since snow occurred on numerous occasions. Snow had also been visible from the weather office (Singleton, 1996).

Heavy snow occurred on the 6th and the 7th of July 1996 over the high-lying parts of the eastern Free State, south-east Gauteng, southern Mpumalanga and the interior of KwaZulu-Natal. There were numerous deaths, roads and passes had to be closed. There was a cold front on the 1st of July 1996 followed by another over the Cape on the 4th of July 1996. This front was followed by strong surface high south of the country. Freezing levels fell to 5000ft a.m.s.l and snow was reported from high lying regions of the Western Cape and Eastern Cape. The upper trough deepened and developed into a COL over the eastern interior that was also visible at the surface. The surface high to the south of the country ridged further east and fed cold moist air into the eastern parts. From the night of the 6th of July 1996 and for the following 2 days widespread snow occurred over Lesotho, the north east Free State and the north western parts of KwaZulu-Natal. All passes over the Drakensberg were closed. Snow was also reported from the south-eastern part of the Northern Cape, Free State and KZN midlands. It also snowed on the Highveld as far west as Klerksdorp. The next cold front arrived on the 14th of July 1996 followed by a strong surface high of 1036 hPa and accompanied by an upper COL. Snow was again reported from several places in Mpumalanga. The Long Tom Pass was also closed to traffic due to heavy snowfalls (Nel and Strydom, 1996).

Niek Koegelenberg from East Londen reported that on the 6th of July 1996 the max temperature at Buffelfontein and Barkley East was -0.5 °C. This was when heavy snow fell over eastern interior (Koegelenberg, 1996). There were 9 accidents around Queenstown, Jamestown and Dordrecht because of ice and snow. Three buses in the Lootsberg and Wapadsberg Pass had to be pulled out of snow. The Lootsberg Pass was closed for 17 hours over the week-end. Late afternoon on the 7th of July 1996 it was still snowing in Molteno (Volksblad, 1996b).

Thousands of motorists were stranded on the 7th of July 1996 between the KZN midlands and the Free State because of snow and ice. Police had to save people from a Translux bus on the Van Reenens Pass. Late afternoon of the 7th of July 1996 they will still trying to get to stranded lorries. Six buses were stranded in Harrismith. In the Northern Cape the cold weather cost 4 lives. There were snowfalls in the Western and Eastern Cape, Mpumalanga, Free State and KwaZulu-Natal. At Harrismith it was snowing since the night of the 6th of July

1996 and on the afternoon of the 7th of July 1996 it was already 10 cm deep. In the northern and western Free State it snowed heavily for the first time in 60 years. Welkom, Virginia, Henneman, Wesselsbron, Bultfontein, Hoopstad and Kroonstad were covered in a white sheet of about 6 cm of snow. On the afternoon of the 7th of July 1996 in Harrismith more than a 1000 people were stranded without accommodation because the N3 was closed from early morning on the 7th of July 1996 from Howick. All alternative routes were also closed during the day. The hotel at Villiers was fully booked with people who had to return to Gauteng. The traffic department in Pietermaritzburg had not experienced something like that in 20 years of service (Beeld, 1996a).

Willie Pretorius from the Durban weather office reported that it was an exceptional month. On Saturday the 6th of July 1996 the first snow started falling over southern KwaZulu-Natal. It continued till the 9th of July 1996. Many roads were cut-off. In western KZN the roads were brought to a standstill. Many people were trapped in the snow. Many millions of rands worth of damage had been caused by the snow and it was described as one of the biggest snowfalls in living memory. Three weeks after the snow Sani Pass was still closed to traffic (Pretorius, 1996). People that had attended the July handicap in Durban could not return to Gauteng. The Mooiriver area was covered in snow. The area from Harrismith to 30 km near the Vaal Toll plaza was covered in snow (Louw, 1996).

The towns of Ladysmith, Vryheid, Dundee and Newcastle were completely cut-off by snow storms. Snow lay 15 cm thick in Van Reenens and was still falling on the afternoon of the 7th of July 1996. The roads were packed with ice, in some instances 18 cm thick. There was snow up to 1 m deep in the Amajuba Pass. The Van Reenens Pass, Botha and Oliviershoek Pass was closed. The snow was caused due to a cold front and a moist high pressure system over the eastern parts causing favourable conditions for snow. It snowed near Standerton (Pretoria News, 1996a).

Karel de Waal from the Bethlehem weather office reported that from the 6th of July 1996 to the 8th of July 1996 the worst snow in more than a decade fell in Bethlehem. It was 50 cm thick in the high=lying parts of the town. The snow started Saturday the 6th of July 1996. At 11:00 am there was ice rain and by 2:00 pm in the afternoon it had turned into snow with 100 mm falling in the afternoon and evening. Very early Sunday morning the 7th of July 1996 there was another heavy fall which added another 200 mm. It then continued uninterrupted till Monday afternoon the 8th of July 1996 when it started to clear. On the Monday the roads were impassable, only 4x4 vehicles could safely navigate. All cars that passed through the town were prevented from passing to KZN till Tuesday the 9th of July 1996. The Coca Cola pack house roof caved in causing 3 million rands in damage (de Waal, 1996). There were widespread communication and powers cuts in KZN and the Free State (Pretoria News, 1996b).

The town of Amalia in the North-West Province had its first snow in history. In Nelspruit it snowed for the first time in 34 years. It also snowed in Lydenburg, Dullstroom, Belfast, Volksrust and Ermelo. People driving by road from Johannesburg to Bloemfontein on the 7th of July 1996 had to wait 2 hours in Kroonstad till the road was navigable to Bloemfontein. In Henneman snow lay 11 cm thick and in the district 18 cm. It had snowed heavily on the morning of the 7th of July 1996 in Bethlehem and in Reitz late in the morning there was 20 cm of snow, the most since 1964. In Welkom the snow was 20 cm thick and branches broke because of the weight of the snow. A roof collapsed onto a vehicle because of the weight of the snow. In Bultfontein and the district 3 cm of snow fell. There were also snowfalls in Memel, Bethulie, Senekal and Paul Roux. Snow also fell in the western Free State. Light snow fell in Bloemfontein but melted quickly. The hills north of Bloemfontein and Thaba Nchu berg were still covered in snow on the 8th of July 1996 (Volksblad, 1996a).

The Johannesburg weather office reported that there was heavy snow over the eastern interior in July 1996. On the 7th of July 1996 snow was reported over the southern and east Rand. On the 17th of July 1996 it nearly reached Johannesburg, there was a few flakes at Kaalfontein, 10 km north of the airport (Nuus van die Weerkantore, 1996).

Bethal, Standerton, Hendrina, Secunda and Ermelo were covered in snow. In the town of Bethal in Mpumalanga the snow lay between 1 cm and 10 cm deep. There had been light snow in 1981 but on the 7th of July 1996 it was incomparable of the last 2 days snow when branches broke (Kuhn, 1996).

It started snowing in Standerton in the afternoon of the 6th of July 1996. At 5:00 pm on the 7th of July 1996 it was still snowing and lay 30 cm deep. It had last snowed like that in the fifties. The Majuba Pass was closed on the morning of the 7th of July 1996 because of ice. In Volksrust it started snowing at 21:00 pm on the 6th of July 1996 and was still snowing in the afternoon of the 7th of July 1996. All roads were closed on the morning of the 7th of July 1996 between Volksrust, Vrede, Newcastle, Amersfoort and Wakkerstroom. It had snowed 12 years ago in the area. Ermelo received 17 cm of snow on the 7th of July 1996. It had been snowing since Saturday night the 6th of July 1996 without end. It snowed lightly at Lichtenburg, and Orkney had 6 cm by the afternoon of the 7th of July 1996. It snowed lightly on the 7th of July 1996 in Daspoort and Groenkloof and also in the vicinity of Johannesburg in the late afternoon. It snowed on the 7th of July 1996 in the Natal midlands (Gibson and Jonker, 1996).

Seventeen people died and 44 were missing in the worst snowstorms since 1964 (Beeld, 1996c).

Prof. Robert Preston-Whyte stated that these events normally occur in September. The weather resulted from a COL pressure system that occurred 2-3 times a year and normally passed south of the country. In July a powerful surface high normally blocks these systems and steers them away. The fact that this one arrived in the colder season means that we are getting more snow and ice instead of rain. The KZN province was ill prepared to deal with heavy snow that normally occurs in the mountains. It was the heaviest snow in 40 years (Daily News, 1996).

37) 16-18 July 1996

On the 17th of July 1996 light flakes fell around Johannesburg and Pretoria. In Magoebaskloof the snow was 25 cm deep on the morning of the 17th of July 1996. At the Magoebaskloof hotel people last saw snow in 1974. In Pietersburg and Tzaneen a few flakes fell. On the night of the 16th of July 1996 snow and rain led to the closure of the Longtom Pass (R37) between Lydenburg and Sabie and the Rowerspas (R533) between Rusplaas and Graskop. Reports of light snow were received from Belfast, Ermelo and Pilgrimsrest. In Dullstroom it was deep enough to build snowmen. In Elandshoogte and Sabie it was ankle deep. Snow occurred on the night of the 16th of July 1996 and on the morning of the 17th of July 1996 on Van Reenens Pass and in Harrismith. All hiking routes in the Drakensberg had also been closed (Beyers, 1996; Hattingh, 1996). Light snow was reported in Gauteng on the 17th of July 1996. Suburbs affected were Bapsfontein east of Pretoria, Witbank, Sandton, Middelburg, Benoni and Thembisa. Snowfall over south-east and east Pretoria was so light that it melted as it hit the ground. It snowed at Dullstroom (Beeld, 1996b).

At Houtbosdorp, east of Pietersburg in the Northern Province, the first snow in 40 years fell on the 17th of July 1996. Pietersburg had a noon temperature of only 6 °C. Snow also fell in the Hwite and Spitskop mountains at Tzaneen and in the Magoebaskloof, Vee-kraal and Haenertsburg. Heavy snowfalls were reported in Dullstroom (10 cm), Lydenburg and Belfast. Light snow was reported on the 17th of July 1996 from Bapsfontein, Witbank, Sandton, Middelburg, Benoni and Thembisa but melted as it reached the ground. The Long Tom Pass and Robbers Pass were closed to traffic most of the 17th of July 1996. At Houtbosdorp east of Pietersburg the first snow fell on the 17th of July 1996 in 40 years (Johnson et al., 1996).

38) 27-29 May 1997

Snow fell on the Swartberg up to the Malutis. Snow was reported at Barkly East, Lady Grey, Somerset East, Steynsburg and Hogsback. A second upper low developed over the interior on the 28th of May 1997 with further snowfalls on the high ground in these areas. On the 29th of May 1997 these conditions spread further eastwards with snow on the Long Tom Pass (Brookes, 1997).

Garth Sampson from the Port Elizabeth weather office reported that on the 27th and 28th of May 1997 snow occurred over the entire area because of a series of cold fronts. Lady Grey, Somerset-East, Barkly East, Rhodes, Steynsburg, Hogsback and Dordrecht all reported snow. Barkly East was cut-off because of the snow on the roads (Sampson, 1997a).

Niek Koegelenberg from the East Londen weather office reported that on the 27th and 28th of May 1997 snow occurred over that area due to the passage of cold fronts. Barkly East and the Lady Grey districts were effected where roads were closed because of the snow (Koegelenberg, 1997).

Light snow fell over parts of Gauteng on the 28th of May 1997. Reports of sleet were received from Centurion, Alberton and Sandton. Snow also fell over Lesotho, north-eastern Free State, south-eastern Mpumalanga and KZN (Feris, 1997a).

Charne Reyneke from the Bloemfontein weather office reported that during the last week of May 1997 very cold conditions occurred and snow could be enjoyed from Golden Gate (outside Bethlehem) up to the Malutis (Reyneke, 1997).

Schools in northern KZN were forced to close early on the 28th of May 1997 in Dundee where 10 cm of snow fell. Sani Pass was closed and Mokhotlong in Lesotho was completely cut-off. Snow was still falling at noon on the 28th of May 1997 at the Little Switzerland resort. Mooi River, Nottingham Road, Glencoe, Escort and Danhauser had reported snowfalls. A thick mantle of snow covered Towerkop in the Eastern Cape on the 28th of May 1997. The Prince Albert Mountains near Oudshoorn and the Swartberg range near Oudshoorn were also covered (Pretoria News, 1997c).

39) 10-12 June 1997

It was a month of extreme weather, news paper articles like “200 cars trapped in thick snow”. A cold front reached the Cape on the 7th of June 1997 and progressed to KZN on the 9th of June 1997 and remained quasi stationary as the low deepened of the east coast and an upper air disturbance moved over the eastern interior. The first snowfalls for June were reported over the Eastern Cape interior on the 10th of June 1997 and also the southern Drakensberg and Lesotho. Snowfalls occurred over the Eastern Cape interior, southern and eastern Free State and thick snow over Bethlehem. The KZN interiors roads were closed again with people trapped in their cars. The snow reached Amersfoort in Mpumalanga (Myburgh, 1997).The Swartberg/Underberg road was snowed under (Daily News, 1997a).

Andy Davidge from the Durban weather office reported that 3 cold fronts crossed the province of KZN depositing snow over the interior and Drakensberg Mountains. On 2 of the 3 occasions roads leading to KZN had to be closed because of snow and ice (Davidge, 1997).Garth Sampson from the Port Elizabeth weather office reported that real winter conditions were felt on the 12th of June 1997 and the 29th of June 1997 (Sampson, 1997b).

Three towns in southern KZN were cut-off due to the snow. Motorists were trapped by the snow. Motorists were freed at Brooke’s Nek and between Harding and Kokstad. Hundreds of cars were stuck in the snow near Kokstad. Kokstad, Cedarville and Matatiele were cut off by snow. The snow started falling at Matatiele after 5:00 am and was still coming down by late afternoon. Four major roads in southern KZN were closed (Feris, 1997b).

Kokstad was hardest hit with 200 cars trapped. Roads to Kokstad, Matatiele, Swartberg, Underberg and Harding were closed. The R617 between Boston and Bulwer and Impendle and Rosetta-Kamberg turnoff on the R103 had to be closed (Daily News, 1997b).

Sixty motorists were trapped between Kokstad and Matatiele. As many as 200 vehicles were stuck outside Kokstad the previous afternoon (The Natal Mercury, 1997a). The roads between Kokstad and Matatiele, Brook’s Nek and Stafford’s Post and between Swartberg and Underberg remained closed on the night of the 12th of June 1997 (Pretoria News, 1997a).

The Bloemfontein weather office reported that the southern Free State was blanketed by snow at the beginning of June with the passage of a cold front. Some patches of snow were still visible over the Lady Grey areas (Oageng, 1997). Hein Pienaar from the Bethlehem weather office reported that mild snowfalls were recorded on the 10th and 11th of June 1997 (Pienaar, 1997).

40) 29-30 June 1997

Mariana Olivier from the Cape Town weather office reported that after the 28th of June 1997 snow started falling on the Boland Mountains (Olivier, 1997). The first snow of the season fell on the Boland Mountains. Snow fell on Saturday the 28th of June 1997 on a farm in the Bo Swaarmoed Pass. Snow fell on the Klein Swartberge in the Karoo (Nicholas, 1997).

The night of the 29th of June 1997 saw the heaviest snow fall of the winter in the Stormberge. It was still snowing on the morning of the 30th of June 1997 over the Lootsberg. At 11:00 pm on the 30th of June 1997 the pass was re-opened after being closed for 16 hours. There was little snow on Spandauskop. There was also snow near the mountains of Elliot, Somerset East, north of Aberdeen, Lady Grey, Graaf Reinet and Queenstown. It Snowed on the 29th of June 1997 in Elliot, Lady Grey and Queenstown. Snow also fell on the mountains of Somerset East and Aberdeen (Morgenrood, 1997). There were reports of snow on the 29th of June 1997 from Sutherland, De Aar, Barkly East and Bloemfontein (Fourie, 1997).

Heavy snowfalls closed may roads in the KZN region on the 30th of June 1997. The N3 highway at Van Reenens was closed for at least 4 hours on the 30th of June 1997. The traffic had to be diverted through Oliviershoek Pass. Kokstad became a ghost town for the second time in 3 weeks, as businesses were closed. Routes that were closed were Rhodes to Kokstad and Kokstad to Matatiele. Most were reopened late on the afternoon of the 30th of June 1997 (The Natal Mercury, 1997b). There was snow on the Nottingham road side of the N3 which came in on Sunday night the 29th of June 1997. The northbound lane from Howick onwards was closed for several hours. The Merrivale, Donnybrook and Ixopo roads were also closed due to snow (Cooper, 1997). The towns of Kokstad, Matatiele and Cedarville were cut-off for 24 hours from the outside world (Beeld, 1997).

Snow fell widely on the 30th of June 1997 in the southern and eastern Free State. At Lady Grey, Ladybrand, Harrismith and Colesburg it was still snowing on the morning of the 30th of June 1997. The road between Harrismith and Verkykerskop and roads near Lindley and Bethlehem were closed to traffic on the 30th of June 1997 (Die Burger, 1997). Snow was reported in the Free State towns of Bethlehem, where 10 cm had fallen by 11:00 am on the 30th of June 1997. Snow was also reported from Harrismith, Reitz, Sasolburg, Kokstad and the Malutis (Pretoria News, 1997b). In the Zastron and Wepener area there was light snow falls (Morgenrood, 1997).

41) 14-15 July 2000

The period from 13th to the 16th of July 2000 saw a series of cold fronts moving over South Africa causing heavy snowfalls over the mountains of the south-west Cape and the Drakensberg. By Saturday the 15th of July 2000 snow was already falling over the mountains of the south-west Cape. It was also snowing at Calvinia and Sutherland. A secondary cold front reached the Cape causing widespread snowfalls over the Western and south-western parts of the Northern Cape. Theronsberg Pass had to be closed. Light snowfalls occurred over the south-east Free State (Stander, 2000).

Widespread snow fell over the higher regions of the Western Cape and other provinces. The heaviest fall in 40 years occurred in the Koue Bokkeveld. Farms in the Sutherland area were cut-off from the rest of the world. On the night of the 14th of July 2000, 25 cm fell in the town with 10 cm at Graaf Reinet, Hogsback, Elliot, Dordrecht, Jamestown and Tiffendell. The mountains that were blanketed on the night of the 14th of July 2000 were the Groot Swartberge near Oudshoorn, Calitzdorp and De Rust. Snow fell low into the Swartberg Pass. The road on the Theronsberge and Swartberg Pass was closed. Snow fell on the Sneeu and Winterberge up to Rhodes including the slopes of the Drakensberg. The biggest fall occurred on the 15th of July 2000 on the Matroosberg and Waboomsberg. Galgeberg at Montagu was covered by snow (van Rensburg, 2000).

Sutherland had its heaviest snowfall since 1950. The temperature went down to -19 °C. The Verlatenkloof Pass had to be closed to traffic. The 15 km stretch between the town of Sutherland and the observatory was closed because of snow (Die Burger, 2000).

Bloemfontein saw snow again for the first time in years. Heavy snow fell on the Friday night of the 14th of July 2000 over the Western Cape, Eastern Cape and Lesotho (Kok, 2000).

42) 18-19 September 2000

On the 14th of September 2000 there was snow fall from Table Mountain, to Pofadder to Nieu Bethesda in the Eastern Cape. The first snow in 65 years fell in Pofadder with only light snow on Table Mountain. At Tulbach the mountain peaks were covered. At Pofadder snow began at 6:00 am and covered cars, parks and flowers (Beeld, 2000). The cause for the heavy snowfall was the presence of an upper air COL associated with a surface cold front which was followed by strong ridging high pressure system. On the Monday afternoon, the 18th of September 2000 snow was reported at Queenstown and Matatiele and it spread to the northern Drakensberg where 0.5 m was reported (de Villiers, 2000).

Snow knocked out electricity, telephone lines, closed roads and gave school children the day off on Tuesday the 19th of September 2000. The Evatt police station is located just 5 km from the Lesotho border and 15 cm fell at Evatt station on Tuesday morning the 19th of September 2000. Snow began falling on Monday night, the 18th of September 2000 and was still falling the 19th of September 2000 (Cole, 2000). Snowfalls of up to a half a metre fell in the Drakensberg on the 19th of September 2000. The R617 between Swartberg and Kingscoat was closed to traffic. The road from Matatiele to Swartberg and to Kokstad was also impassable on the 19th of September 2000 (van Zyl, 2000).

43) 20-23 July 2001

The COL deepened on the 20th of July 2001 leading to widespread snowfalls. Widespread snowfalls were reported even at Ottosdal and Danielskuil. There were reports of light snowfall early on Saturday the 21st of July 2001 over some parts of Gauteng (Kempton Park, Sandton, Benoni and Auckland Park). Snow was reported briefly at Ermelo, with 10 cm of snow at Bethlehem in the north eastern Free State. The N3 over Van Reenens Pass was still closed on the 21st of July 2001 following 22 cm of snowfall which was still falling at 11:00 am on the 21st of July 2001. The Oliviershoek Pass and the Amajuba Pass were also snowed in (Rae, 2001).

Snow fell Monday (23rd of July 2001) in the morning on the high ground of the Eastern Cape, 17 mm at Tiffendell. Snow was also reported at Kokstad in the early morning, and later in the morning light snow was reported at Mooi River (de Villiers, 2001b). At Tiffendell it snowed a further 15 cm from 4:00 pm on the 22nd of July 2001 till early afternoon on the 23rd of July 2001. The Barkly Pass, Lootsberg Pass and Wapadsberg Pass were closed on the 23rd of July 2001 after an ice layer formed on the road (Stiemie, 2001).

The N2 highway was closed at Brookes Nek Pass on the 24th of July 2001 due to heavy snow. Slippery conditions occurred in the Penhoek Pass near Sterkstroom on the N6 (Pretoria News, 2001a).

Heavy snowfalls occurred in Harrismith. The eastern Free State, Kestell, Clarens, Golden Gate, Warden, Rosendal, Fouriesburg, Bethlehem and Ficksburg were under snow on the 22nd of July 2001. According to residents it was the heaviest since 1995 (Floris and Harrison, 2001).

44) 12-14 September 2001

Very cold conditions occurred on the 11th of September 2001. On Wednesday the 12th of September 2001, Underberg was 1 °C at 2:00 pm. Snow fell on the Drakensberg and adjacent high ground. There were reports of snow from Mooi River and knee deep snow between Underberg and Bulwer. The N3 over Van Reenens was closed. Light snow occurred over the Western Cape Mountains on the night of the 11th of September 2001. Snow was expected to spread over the northern Drakensberg and Volksrust later on the 12th of September 2001. The weather systems that was responsible for this event was an upper air COL and surface ridging high. There was a similar event the previous year from 18 to 19 September 2000. These events tend to catch people unawares because of the characteristic expected warmer weather in August and September (de Villiers, 2001c).

Residents awoke on the morning of the 13th of September 2001 in Harrismith to find the town covered in snow. The Van Reenens Pass was closed for more than 5 hours for safety reasons. By 7:00 pm on the night of the 13th of September 2001 there was still more that 40 lorry's waiting (Floris, 2001). There was knee deep snow in KwaZulu-Natal. On the night of the 13th of September 2001, the N3 freeway and alternative N11 route was closed. The Van Reenens Pass, Oliviershoek Pass, Nottingham road, Mooi River, Loteni road to Sani Pass was covered in snow on the night of the 13th of September 2001. The cause was a pronounced surface high pressure system (Pretoria News, 2001b).

The N3 highway was still closed on the night of the 14th of September 2001 because of people trying to clear it of the snow. Snow had fallen on the Drakensberg, Malutis, and Mpumalanga Highveld since Wednesday night the 12th of September 2001. There was not much snow over the Eastern Cape Mountains with only 0.5 cm measured at Tiffendell. At least 200 people were rescued on Thursday night the 13th of September 2001 that were trapped in the Oliviershoek Pass. Kokstad, Swartburg, Franklin, Underberg, Nottingham road, Kamberg, Escourt and Dundee were without power (Pretoria News, 2001c).

45) 14-15 June 2002

A cold front made landfall over the Cape on the 12th of June 2002 accompanied by an upper air COL. It snowed over the Lootsberg in the Graaf Reinet area. Reports of snow were received from Matatiele (Lesotho), Giant Castle, Bergville, Qwa Qwa and Tiffendell (Bulo and Sebego, 2002).

There were heavy snowfalls in the north Eastern Cape on the 14th of June 2002 closing the Penhoek Pass, Boesmanshoek Pass and the Lootsberg Pass. In Dordrecht it snowed all day on the 14th of June 2002 (Pretoria News, 2002). The N6 and the R56 had to be closed to traffic. Late on the 14th of June 2002 the Boesmanshoek Pass was re-opened but the Barkly Pass still remained closed, which had been open earlier. The Lootsberg Pass was also closed later in the morning. At Dordrecht snow fell throughout Friday the 14th of June 2002 with all outgoing roads closed. The snow was 15 cm thick at Buffelsfontein farm near Molteno (Cape Argus, 2002).

Snow was visible on the 15th of June 2002 on the South-Eastern mountains tops and the Malutis in the eastern Free State as well as on Platberg near Harrismith. Snow at Aliwal North was 20 cm deep on the morning of the 15th of June 2002. About 20 mm of rain preceded the snow. On the farm Berlyn between Burgersdorp and Aliwal North snow was 10 cm deep at 11:00 am (Kruger, 2002).

46) 16-20 July 2002

The Matroosberg was covered by snow on the night of the 15th of July 2002. Heavy falls that occurred in the Eastern Cape closed roads between Cradock, Graaf Reinet and Middelburg on Tuesday the 16th of July 2002 (Cape Times, 2002).

There was snow on the Sneeuberge Mountains near Nieu Bethesda. The Lootsberg Pass was closed between 2 am and 1 pm on the 16th of July 2002. Hogsback did not receive any snow (Bantam, 2002). Heavy snowfalls occurred on the 18th of July 2002 in the interior of the Eastern Cape causing power cuts, road closures and roofs to collapse. The Penhoek Pass, Barkly Pass, Satansnek Pass and road to Tiffendell ski resort were closed because of the snow. Elliot, Ugie, Indwe Dordrecht, Cala and Cofimvaba were without power early on the 18th of July 2002. Snow in the area was between 30 and 40 cm deep. In Queenstown store roofs collapsed because of the weight of the snow. In Barkly East snow started falling overnight and by mid morning lay 10 cm thick. Snow was also reported at Lady Grey, Sterkspruit and Ugie. The Port Elizabeth weather office reported snow near Joubertina, Somerset East and the Lootsberg Pass (Citizen, 2002a).

The high ground of the Eastern Cape, Free State and KZN were hit by very cold conditions with the heaviest snowfalls in 40 years. Approximately 150 motorists were trapped for 24 hours on their way to the Tiffendell ski resort. Elliot received 0.5 m of snow and power lines were down. Barkly East was cut-off with the Rhodes area having its heaviest fall in 40 years (Bamford, 2002). Elliot had been cut-off since early on Thursday the 18th of July 2002 without electricity. By the afternoon of the 19th of July 2002 nearly 20 shops roofs had collapsed due to the weight of the snow. The Super Spar in the town roof also collapsed (Fourie, 2002). Township homes were flattened in Elliot due to the weight of the snow. There was a metre of snow on the morning of the 20th of July 2002. There was a snowstorm on Thursday the 18th of July 2002. At midday on the 20th of July 2002, Elliot was still cut-off. Roads were closed on Friday the 19th of July 2002 in KZN as snow covered the interior. The heaviest falls occurred in the southern Drakensberg with Kokstad cut-off due to heavy snow. The Penhoek Pass and Satansnek Pass were also blocked (Horner and Philip, 2002).

47) 9-11 September 2002

A cold front moved on Sunday the 8th of September 2002 over the central parts of the country. It snowed in Elliot, Barkly East and Kokstad. Snow also occurred in the Drakensberg area of QwaQwa on the afternoon of the 10th of September 2002 (Scholtz, 2002). On the evening of the 10th of September 2002 at 10:00 pm it had already snowed 25 cm in the Barkly East area. According to the South African Weather Service it snowed heavily in the Queenstown district and at Indwe. The road between Middelburg and Graaf Reinet was very dangerous and it was still snowing there. Barkly Pass was closed and the road between Queenstown and Jamestown, Lady Grey and Aliwal North. The N2 between Mount Frere and Kokstad and Matatiele and Cedarville was also closed to traffic. The road to Dordrecht and between Cala and Lady Frere was also closed (Muller, 2002). The Barkly and Penhoek passes were closed to traffic due to snow on the 10th of September 2002. Early morning on the 10th of September 2002 the Hangklip Mountain at Queenstown was covered with snow falling on the higher ground in the Sterkspruit district. At 7:00 pm Monday evening the 9th of September 2002, snow started falling at Tiffendell which was still falling on the 10th of September 2002. In the Elliot district light snow fell on the 10th of September 2002 (Citizen, 2002b).

48) 19–20 August 2003

Matroosberg, Gydo Pass and Theronsberge Pass were all closed to traffic due to heavy snow. The roads were being scraped clean while it was still snowing. Access to the Matroosberg farm was cut-off. It was snowing on the morning the 19th of August 2003 at 4:00 am. People said that it was the heaviest in 10 years. At Prince Alfred Hamlet snowflakes were falling in the town, for the first time. Snow on the Simonsberg was the lowest it had been in 50 years (Thiel, 2003). It snowed in Ceres, Franschoek, Table Mountain, and Devil's Peak and near Hermanus. There was a light sprinkling of snow on rooftops at Franschoek in the town on the morning of the 19th of August 2003 at 7:30 am but it melted quickly. The Matroosberge and Hottentots Holland Mountains were also covered in snow. The Gydo and Theronsberge Passes were closed but Bo Swaarmoed and Onder Swaarmoed Passes were open. It started snowing on the night of the 19th of August 2003 at Ceres. There was even snow on Voëlklip Mountain near Hermanus (Mathys and Smith, 2003).

It snowed for the first time in 80 years in Tulbach and for the first time in 40 years in Riebeek-Kasteel. According to the South African Weather Service snow was still falling at Calvinia, Sutherland and Springbok by the morning of the 20th of August 2003. Snow was still covering Table Mountain, mountains by Clanwilliam, Riebeek Kasteel, Tulbach, Ceres, Stellenbosch, Franschoek, Somerset West and Caledon on the 20th of August 2003. The Theronsberge Pass was closed to traffic (Die Burger, 2003).

49) 13-14 July 2004

By the afternoon of the 13th of July 2004 around 50 cm of snow fell in the Underberg region of KZN (Zwecker, 2004a). The N2 road between Kokstad and Sinjisi and the R617 between Underberg and Impendle was closed to traffic (Russouw, 2004). According to the South African Weather Service snow fell in the mountains between Adelaide and Tarkastad, Barkly East, Elliot and Queenstown. Snow was also reported from Underberg, Himeville, Rhodes Tiffendell and Van Reenens (Zwecker, 2004b). It snowed in the Long Tom Pass (de Nysschen, 2004).

On Tuesday, the 13th of July 2004 snow fell on the mountain tops of the Drakensberg. Snow also fell in Belfast and Lydenburg (Russouw, 2004). Snow fell in the area of Sabie, Dullstroom and Lydenburg (Zwecker, 2004b).

50) 27-29 July 2004

In the Kingscote Pass between Underberg and Swartberg, 400 cars were trapped for nearly 8 hours. Forty kilometres outside Underberg the snow was 1.7 m deep in places on the Pass. The road between Kokstad and Matatiele was also closed due to snow (Cape Times, 2004).

51) 6-7 September 2004

It began to snow around 7:00 am on the 6th of September 2004 in several areas of the Drakensberg. At the Nek Berg and Trout resort it was the 3rd time in 2004 that they had snow. It snowed near Harrismith, Kokstad, Matatiele and Underberg (Sewsunker and Singh, 2004). Schools had been closed since Tuesday the 7th of September 2004. In total there were 8 schools closed in the Mooi River and Lions River areas, 11 around Boston, and 27 around Impendle.

52) 23-25 May 2006

The first snow of the season fell over the Matroosberg and Klein Swartberg near Ladysmith. It also snowed over the Winterberge near Aberdeen, Cradock, and Queenstown and on the Drakensberg near Elliot, Barkly East and Cala. Light ice rain fell Saturday the 20th of May 2006 in Bethlehem and Harrismith with snow in QwaQwa. Snow fell the 21st of May 2006 on the southern Drakensberg, Tiffendell, Rhodes, Barkly East and the Lootsberg Pass (Beeld, 2006).

Snow fell a short while in some Free State towns. According to the South African Weather Service snow fell on the 24th of May 2006 in Ficksburg, Clocolan, Paul Roux, Ladybrand, Tweespruit, Wepener, Thaba Nchu and De Wetsdorp. According to Mrs. Corrie Labuschagne of the Volksblad in Harrismith, snow fell there and in Van Reenen late in the afternoon of the 24th of May 2006. In Ficksburg it snowed on the afternoon of the 24th of May 2006 for an hour after which it started to rain. It was the first time that it had snowed there in 5 years. It had melted quickly in the town but was still visible outside the town. At Ladybrand snow had started falling at 10:00 am in the morning of the 24th of May 2006 (van Wyk, 2006). In Clarens in the Free State there was 5 cm of snow in the morning of the 25th of May 2006 after it fell on the Wednesday night the 24th of May 2006 (Fraser, 2006). It snowed Wednesday the 24th of May 2006 over the Drakensberg, Lesotho and Free State (Tau, 2006).

53) 1-2 August 2006

The snow was 30 cm deep in Sutherland on the 1st of August 2006 and was reported to be the worst since 1988. The Verlatenkloof Pass to the town had to be closed because of the snowfall. It had also snowed on the Matroosberg and was still snowing in Sutherland late on the 1st of August 2006 (Gosling, 2006).

Snow was reported in areas in Johannesburg such as Westonaria, Carletonville, Soweto and Sandton. Morningside reported a slight fall at 10:00 am on the 2nd of August 2006. It had reportedly snowed in Gauteng for the first time in at least 8 years.

Border posts had to be closed in Lesotho after Blizzard conditions occurred there (Flanagan, 2006). The first snow for more than a decade fell in Bloemfontein and surrounds. Clarens, Fouriesburg, Harrismith, Paul Roux, Senekal, Bethlehem, Kestell, Ladybrand and Ficksburg all received snow. Monantsa Pass in Qwa Qwa also had to be closed. Snow also fell in Philipstown in the Northern Cape on the morning of the 2nd of August 2006. The N6 between Reddersburg and Smithfield and the road between Wepener and Paul Roux also had to be closed on the 2nd of August 2006 due to snowfall. The Lootsberg Pass was also closed due to snowfall. Snow also fell at De Aar, Hanover, Orania and Sutherland in the Northern Cape. At Sutherland snow was 30 cm deep on the 1st of August 2006. The road between Willistown and Calvinia also had to be closed due to snowfall (Volksblad, 2006a). Snow fell in towns like Graaf Reinet, Nieu Bethesda, Colesburg, Burgersdorp, Smithfield and Reddersburg (Volksblad, 2006b).

On Wednesday the 2nd of August in the early hours of the morning, 150 cars were trapped between Reddersburg and Smithfield because of snow. Snow started falling late on the Tuesday night the 1st of August 2006. By 23:00 pm Tuesday night the first bus was trapped. The last car was pulled from a metre of snow on the 2nd of August 2006 at 12:00 pm (Fourie, 2006). It was the first snow in Bloemfontein since 1996 (Neethling, 2006).

54) 21-22 May 2007

The South African Weather Service (SAWS) said there was snow over the southern Cape, eastern Cape high ground and southern Drakensberg. Hugh van Niekerk from the SAWS of the Port Elizabeth regional weather office stated that it had snowed on the Bamboes berge at Joubertina, Tsitsikama berge and Kouga Mountains at Hogsback, on the Outeniqua and Winterberge mountains in the Barkly East and Molteno area. Forty five people were stuck on

N9 in the Lootsberg Pass. They became stuck at 6:00 pm on Monday the 21st of May 2007. The Lootsberg, Wapadsberg, Barkly Pass and Nico Malan Pass were closed to traffic. The N2 near Kokstad was closed on the 22nd of May 2007 after heavy overnight falls. There were also reports of snow at Vryheid and Hlobane (Bateman et al., 2007).

55) 26-27 June 2007

Sutherland was covered in snow on Monday the 25th of June 2007. Sleet was falling in Bloemfontein on the 26th of June 2007 (Business Day, 2007).

Residents in Johannesburg woke up to snow on the morning of the 27th of June 2007. The last time was 10th of September 1981. At Phineas McIntosh Park (Brixton) and Zoo Lake (Parkview) people played in the snow. On the night of the 26th of June 2007 in snowed in Johannesburg, the East and West rand. Vereeniging, Heidelberg and southern Mpumalanga also had reports of snow. Mark Todd from the SAWS reported that in some places in Johannesburg it was 3 cm deep. At OR Tambo flights were delayed for 3 hours due to snow on the wings of the aircraft (Damons and Moses, 2007b).

The Van Reenens Pass and roads around Kokstad were closed on the 27th of June 2007 due to snow. Van Reenens Pass had to be closed on the 27th of June 2007 for 2-3 hours at 15:30 pm in the afternoon so that it could be made safe for vehicles. Halfway between Harding and Kokstad on N2, the snow was knee deep on the highway. Forty four kilometres outside Pietermaritzburg the road was closed near Boston. The R103 between Nottingham road and Mooiriver was also closed on the morning of the 27th of June 2007 (Liebenberg, 2007).

Heavy snow fell in the KZN midlands, reports from Nottingham road, Rosetta, Mooi River, Kokstad, Underberg and Sani Pass areas. Roads closed were the R103 from Nottingham road to Mooiriver, R617 from Underberg to Kokstad and N2 from Port Shepstone to Kokstad. The R56 from Umzimkhulu to Kokstad also had to be closed. It had been reported to be still snowing in Kokstad. Bloemfontein had sleet falling on the 26th of June 2007 around lunchtime. Snow was also reported in Rhodes, Sterkspruit, Aliwal North, Tarkastad and Barkly East (Daily News, 2007a). Snow fell late in the afternoon on the 26th of June 2007 in parts of Klerksdorp. It had been reported that it had last snowed in 1996 in Klerksdorp (Damons, 2007a).

56) 20-21 September 2008

On the morning of the 19th of September 2008 at 10:30 am the temperature in Cape Town fell from 6 °C to 2 °C, hard droplets of ice were followed by flakes. It had snowed on Table Mountain and could be seen in places between the rocks (Volksblad, 2008).

Snow occurred on the mountains of the Eastern Cape, Lesotho and southern KZN. Snow fell over the week-end in the foothills of the Drakensberg and many people went to look on the 21st of September 2008 in the Nottingham road region. Snow started falling on Friday night the 19th of September 2008. It also snowed over Lesotho. The snow was heavy in the Kokstad, Underberg, Giants Castle and the Sani Pass region. Light falls were recorded at Nottingham Road and Escourt. Several roads were closed on Saturday the 20th of September 2008 due to snow. The closed roads included the N2 between Kokstad and Harding, Underberg, Bulwer to Franklin and the R612 over Ixopo (Liebenberg, 2008).

57) 9–10 June 2009

Snow fell over the eastern Free State over the southern part of the Platberg near Harrismith and along the N3 highway (Sowetan, 2009). Snow fell in the northern Drakensberg, 3 cm on N3 highway according to the Automobile Association which occurred around Harrismith, Kestell and Van Reenens Pass (Aliseev, 2009).

58) 10-11 July 2010

There was snow at De Aar, Victoria West and between Three Susters and Richmond in the Northern Cape (Botha, 2010). At Little Switzerland snow started falling at 09:00am on Monday and stopped later in the afternoon (Smith, 2010).

59) 8 June 2011

Snow fell in south-west Namibia. It snowed on the Spreetshoogte Pass between Sossusvlei and Windhoek (Mare’, 2011).

60) 25-27 July 2011

Snow fell on the night of the 25th of July 2011 over the Eastern Cape, KZN, south and east Free State, Lesotho and the Highveld of Mpumalanga (van Rooyen, 2011a). The snow was caused by a COL pressure system (Cape Times, 2011). It snowed on the Franschoek mountains (Williams, 2011). Three provinces were affected by the snowfall that left many people stranded in their cars and homes. Many roads had to be closed in the Eastern Cape, Free State and KwaZulu-Natal. The N3 near Wilge Plaza had to be closed on the 26th of July 2011 with 220 km of road being inaccessible (Pretoria News, 2011a).

There was snowfall over the Karoo. It snowed in Beaufort west for the first time in 30 years (Marais and Spoormaker, 2011). On the morning of the 25th of July 2011 the road between Beaufort West and Richmond had to be closed including the alternative route via Victoria west. The road was closed up to 3 pm in the afternoon. Beaufort West awoke on the morning of the 25th of July 2011 to a snow covered landscape (Cape Times, 2011).

In the Eastern Cape several towns, schools and businesses were snowed in (Pretoria News, 2011a). It has snowed for the first time in 75 years in the town of Somerset-East. Queenstown had its first snow in 35 years. It snowed in Bedford, Tarkastad and Hogsback. There were power failures in Cala, Dordrecht and Mthatha. At Barkly east; between 35 to 40 cm of snow had accumulated by the afternoon of the 25th of July 2011 (Marais and Spoormaker, 2011). It snowed at Paardekraal farm between Middelburg and Graaf-Reinet (Williams, 2011). The N9 had to be closed between Colesburg and Middleburg. On Monday the 25th of July 2011 the N1 was also closed between Colesburg and Three Sisters. It was the worst snow since 1992 (Gibson et al., 2011).

Many motorists were trapped on Van Reenens Pass. Harrismith awoke to snow and residents said it was only the third time in 21 years that so much snow had fallen. The snow started falling on Monday the 25th of July 2011(Pretoria News, 2011a). By the afternoon of the 26th of July 2011 cars and lorries stood for more than 10 km between the Tugela Plaza and Van Reenens Pass. There were heavy snowfalls in southern KZN on the 25th of July 2011. A few people were killed on the KZN roads with the N3 (between Van Reenens Pass and the Tugela toll plaza, both directions) and N1 being closed. Snow covered the high ground of Kokstad, Underberg and Matatiele. Snow was also reported from Newcastle (Moolla and Venktess, 2011). Train services from Gauteng to the Eastern Cape and KZN also had to be cancelled (Pretoria News, 2011a). It snowed in Harrismith, Newcastle and Ermelo where up to 5 cm of snow fell. The N3 between Villiers and Howick was closed the whole of the 26th of July 2011. Roads that were closed were the R56 between Kokstad and Matatiele, N2 by Brookes Nek in the Eastern Cape, Oliviershoek Pass on the R74, R617 between Bulwer and Underberg, N11 between Ladysmith and Newcastle, also near Charlestown in Mpumalanga, and the R34 near Memel on the way to Newcastle (van Rooyen, 2011a). It snowed near Nottingham Road (Gibson et al., 2011).

61) 15 August 2011

A COL was situated over the north-eastern Free State on the 15th of August 2011 which combined with a surface high pressure system in the north-east of the country to cause snow (van Rooyen, 2011b). The cold conditions affected Gauteng, southern Mpumalanga, north-eastern Free State and KZN. It snowed lightly on the afternoon of the 15th of August 2011 in Vereeniging and the southern parts of Johannesburg (van Rooyen, 2011b). The snow in the south of Johannesburg started at 11:00 am and lasted for 30 minutes on the 15th of August 2011 but was not enough to block roads but caused several accidents. It reportedly also snowed in Sasolburg and in Orlando east in Soweto (Motumi et al., 2011). It snowed in Columbine road in the south of Johannesburg (Beeld, 2011).

Snowfall led to the closure of the Van Reenens Pass after it fell in the early hours of Sunday night the 14th of August 2011 (Motumi et al., 2011). Snowfalls were reported from Volksrust, Ermelo and Dullstroom on the 15th of August 2011(van Rooyen, 2011b). It snowed at Little Switzerland resort between Harrismith and Bergville on Oliviershoek Pass (Beeld, 2011). Van Reenen and alternate routes were closed on the 15th of August 2011. The N3 was closed to traffic from Harrismith to Colenso/Frere interchange due to the snowfall with the N11 at Ladysmith also closed (Pretoria News, 2011b). People on the Van Reenens Pass were stranded up to 3 pm on the 15th of August 2011. Roads between Bethlehem and Kestell, Bethlehem and Harrismith, as well as the Oliviershoek Pass had to be closed due to heavy snow. The roads had been closed in the early morning of the 15th of August 2011 (Swart, 2011).

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