A snow forecasting decision tree for significant snowfall over the interior of South Africa

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Snowfall occurs every winter over the mountains of South Africa but is rare over the highly populated metropolises over the interior of South Africa. When snowfall does occur over highly populated areas, it causes widespread disruption to infrastructure and even loss of life. Because of the rarity of snow over the interior of South Africa, inexperienced weather forecasters often miss these events. We propose a five-step snow forecasting decision tree in which all five criteria must be met to forecast snowfall. The decision tree comprises physical attributes that are necessary for snowfall to occur. The first step recognises the synoptic circulation patterns associated with snow and the second step detects whether precipitation is likely in an area. The remaining steps all deal with identifying the presence of a snowflake in a cloud and determining that the snowflake will not melt on the way to the ground. The decision tree is especially useful to forecast the very rare snow events that develop from relatively dry and warmer surface conditions. We propose operational implementation of the decision tree in the weather forecasting offices of South Africa, as it is foreseen that this approach could significantly contribute to accurately forecasting snow over the interior of South Africa.

Significance:

- A method for forecasting disruptive snowfall is provided. It is envisaged that this method will contribute to the improved forecasting of these severe weather events over South Africa.
- Weather systems responsible for snowfall are documented and the cloud microphysical aspects important for the growth and melting of a snowflake are discussed.
- Forecasting methods are proposed for the very rare events when snow occurs over the interior of South Africa when the air is relatively dry and somewhat warmer.

Introduction

Snowfall sparks a particular interest in South Africa, especially when it descends from the mountain peaks to lower elevations. Snowfall events are well publicised by the media, and enthusiasts 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 event in winter. Weather forecasters in South Africa acknowledge that they are not familiar with forecasting snowfall on lower elevations, away from the mountains.[1,2] On 7 August 2012, snow fell in the cities of Johannesburg and Pretoria in the Gauteng Province (Figure 1). Snowfall is unusual in Gauteng and is exceptionally rare in Pretoria (Table 1).[2,3] This snowfall was the first in 44 years in Pretoria, but was not forecast. Weather forecasters from the South African Weather Service (SAWS) did foresee very cold conditions and the possibility of showers of rain, but they did not anticipate the severity of the event.[2]

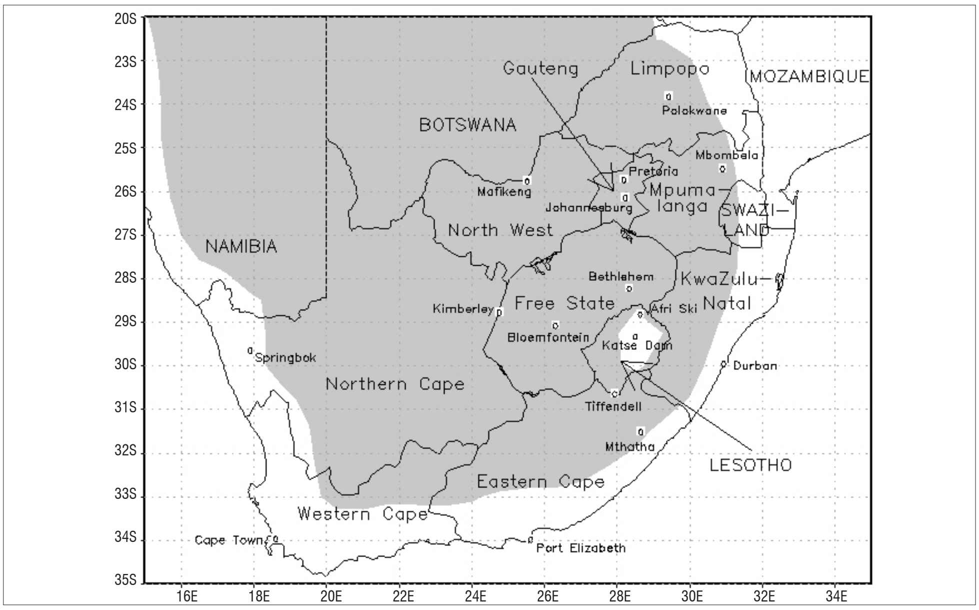

Figure 1: Location and geographical map of South Africa. The shaded area indicates where the height above mean sea level is less than 2000 m over the interior of southern Africa. Significant snowfall is defined as snowfall in this area.

Table 1: Dates of notable historical snowfall events over Johannesburg and Pretoria between 1909 and 2012[2,3]

Johannesburg	Pretoria
17 August 1909	
18 July 1915	
9 September 1921	
11 July 1926	
11 September 1936	
27 August 1962	
3 July 1963	3 July 1963 (Lyttelton)
18–19 June 1964	18 June 1964
14 July 1965	
18 October 1965	
11–12 June 1968	12 June 1968
10 September 1981	
2 July 1982	
21 July 1987	
28 June 1994	
2 August 2006	
27 June 2007	
7 August 2012	7 August 2012

Heavy snowfall is usually defined as that exceeding a threshold value. Threshold values are climate dependent and differ meaningfully by geographical and climatic region. For instance, in central Europe, heavy snowfall days are those on which the snow depth increases by 5 cm or more,[4] whereas in the mountains of Montana in the USA, heavy snowfall days are defined by 32.8 cm or more of snow.[5] Snowfall in South Africa is rare; and although snow is reported by SAWS when it occurs, the depth of the snow is not measured. An alternative definition of heavy or significant snowfall is therefore needed; in this paper, significant snowfall is defined as any amount of snowfall that occurs on the ground over the interior of South Africa in areas at an altitude of less than 2000 m above mean sea level (AMSL) (Figure 1). South Africa is characterised by an elevated plateau, rising to over 1500 m AMSL over extensive areas. The main escarpment of South Africa rises to 2000 m and higher over KwaZulu-Natal and the interior of the Eastern Cape, and in Lesotho to above 3000 m (Figure 1).[6] Snowfall is not uncommon during winter in the sparsely populated mountainous regions in South Africa; however, if snowfall occurs at lower elevations, it could be quite disruptive for the highly populated metropolises over the interior of South Africa.

There have been noteworthy snowfall events and associated negative effects during the past two decades. In July 1996, 17 people died and damage to the value of millions of rand was caused as a result of snow. Widespread communication and power cuts occurred in KwaZulu-Natal and the Free State, while major routes between KwaZulu-Natal, the Free State and Gauteng became impassable.[7] On 22 July 2002, the very cold conditions associated with snowstorms resulted in 22 lives lost, livestock loss and infrastructure destroyed in KwaZulu-Natal.[8] On the same day, many areas in the Eastern Cape had to be declared disaster areas. In June 2007, very cold conditions caused numerous power failures in KwaZulu-Natal and several roads were closed to traffic. On 27 June 2007, flights from OR Tambo International Airport (Johannesburg) were delayed by 3 h in the morning because of snow on the wings of aircrafts. Snow can cause structural icing on an aircraft and could potentially affect the aerodynamic properties, performance and weight of the aircraft. Snow can also seriously reduce horizontal visibility at an airport, making it difficult or even impossible for aircraft to land without the correct instrumentation.[9] Because of the rarity of snow at this airport, systems to deal with the snow were not in place. In September 2008, roads in KwaZulu-Natal and the Eastern Cape were closed owing to heavy snowfalls after several motor vehicle accidents occurred.[10] August 2012 was the first time on record that snow occurred simultaneously in all nine provinces of South Africa.[2] On 6 and 7 August 2012, heavy snow occurred over many parts of the country with lighter falls as far north as Pretoria.

Snow also has some positive effects on the economy of South Africa. The melting of snow in the Drakensberg Mountains has an effect on the total water budget of the area, although the exact amount is not known.[11] The groundwater level in the Table Mountain group aquifer is enhanced by snowmelt.[12] A large percentage of water in the Katse Dam comprises snowmelt that originates in the Lesotho Highlands. Water from the Katse Dam fulfils the growing demand for water in the Vaal region of South Africa.[13] Tourism also benefits from snowfall – Tiffendell Ski Resort in the Eastern Cape and Afriski Ski Mountain Resort in Lesotho require snow to remain economically viable.[8]

Between 1981 and 2011, 60 significant snow events were identified over South Africa.[2] The frequency of significant snowfall events showed strong seasonality (Figure 2), with significant snowfall occurring from May to October. These events occurred most frequently in July (>30%) followed by June (25%) and August (15–20%). Less than 15% of these events occurred in September and less than 10% in May. Although not frequently, some events (<5%) occurred in October.

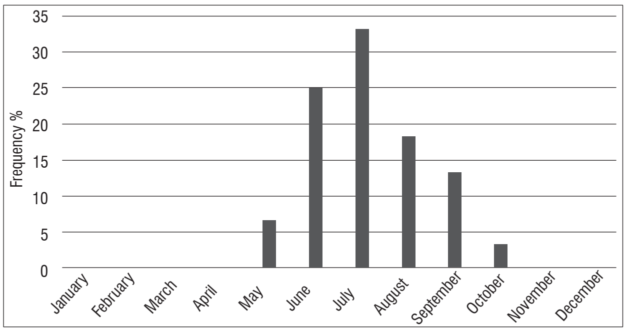

Figure 2: Frequency per month of 60 significant snow cases for the period 1981–2011.[2]

We aim to contribute to the forecasting of snowfall over South Africa by developing an operational snow forecasting decision tree (SFDT). The SFDT is especially useful to predict significant snowfall that occurs infrequently over South Africa but causes widespread disruption when it does occur. The SFDT consists of five steps or criteria that should all be met to reach a forecast of snow. The first two steps require subjective interpretation of synoptic circulation patterns and conditions conducive to the formation of precipitation. Steps 3–5 deal with ensuring that a snow flake is present in a cloud and will reach the ground without melting.

Snow forecasting decision tree

Various operational techniques or methods are used to guide forecasters in predicting the weather. Forecasters often use meteorological ingredients or decision trees to anticipate weather events. Inexperienced weather forecasters, in particular, benefit from a set of criteria or ingredients to follow in predicting rare severe events. Some examples include the ingredients that were identified to predict flash flooding.[14] Lift, instability and moisture were identified as the three main ingredients for convection.[15] A decision tree, together with threshold values, was developed to assess the potential and severity of thunderstorms.[16] Decision trees have also been used to aid in the forecasting of fog.[17,18] An ingredients-based winter season precipitation forecasting technique has been developed[19], as has a method proposed to distinguish between freezing rain, ice pellets, rain and snow.[20] The decision tree method was also used to determine the likelihood of lake effect snowfall over Lakes Erie and Ontario.[21]

The ingredients-based approach may be limiting as it is not specific about how much of each ingredient is needed to cause a certain weather outcome.[22] The process-based approach in which fundamental physical elements are required for the formation of a certain type of weather is preferred here over the ingredients-based approach. Forecasting should not only be a recipe of ingredients, but also a list of relevant, manageable parameters on which a forecaster can focus. A forecasting method should apply logical reasoning to atmospheric physics; and several case studies should be used to evaluate the method.[23]

The SFDT uses the basic physical attributes of snow formation to guide users through a five-step process in which all the steps should be met before snow is forecast. A logical flow of the key physical mechanisms that cause significant snowfall is used to create a chronological five-step SFDT. The first two steps require subjective input and some experience and expertise on the part of the user. The last three steps deal with distinguishing between solid and liquid precipitation (Table 2).

Step 1: Do the synoptic circulation patterns favour significant snowfall?

There is a rich heritage of South African synoptic climatologies and discussions of weather systems associated with rainfall.[4,24-28] Westerly wind disturbances associated with ridging anti-cyclones are important synoptic scale weather systems in winter over South Africa.[27] When an area of surface high pressure intrudes along its west–east axis into an area of lower pressure, it is said to ridge.[29] The winter rain-producing weather systems over South Africa are cold frontal troughs, low pressure systems close to land, cut-off lows (COLs) and long wave troughs.[26] Heavy precipitation in winter occurs almost exclusively from westerly wind troughs and COLs and nearly all winter rainfall in summer rainfall areas is caused by COLs.[25]

A COL is a cold-core low pressure system that is displaced equatorward (cut-off) from the westerly current. A closed low is formed in the upper troposphere and this circulation eventually extends to the surface.[25,28] COLs are weather systems of the subtropics and in the southern hemisphere are known to occur in Argentina, Uruguay, South Africa, Australia and New Zealand. An important ingredient in the development of COLs is surface cold air advection. In the South African region this cold air advection is often caused by the ridging surface high pressure system south of the land leading to cold air penetrating over the escarpment areas of the Eastern Cape and KwaZulu-Natal.[25]

Cold fronts are well defined in winter over the subtropical region of South Africa and may reach as far north as 15°S[24,30] when they are associated with upper air westerly troughs or COLs[27]. Cold fronts are normally followed by high pressure systems originating over the Atlantic Ocean. Atlantic Ocean highs (AOH) and the position and strength of these highs regularly determines the severity of the cold front. When the centre of the high is located south of the continent, the flow to its east is predominantly from south to north. The winds cross the isotherms nearly perpendicularly, causing strong cold air advection into South Africa. For the air temperature to drop by 5–10 °C over South Africa, the air is fetched by the AOH from as far south as 40–55°S.[26] It is the surface high pressure system following the cold front that sets up the horizontal pressure gradient necessary to drive cold air northwards over South Africa.

Table 2: The five-step snow forecasting decision tree

Step 1
Do the synoptic circulation patterns favour significant snowfall?

↓ If yes

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

↓ If yes

500 hPa — **500 hPa**

Step 3
Is the air close to saturation between -20 °C and -10 °C?

↓ If yes

Step 4
Are the geopotential thickness values lower than the critical values?
- 850–500 hPa thickness < 4170 m
- 850–700 hPa thickness < 1580 m
- 700–500 hPa thickness < 2590 m

↓ If yes

700 hPa — **700 hPa**

Step 5
Is the height of the melting level lower than 300 m above ground level and are surface temperature and relative humidity values favourable for the formation of snow?

Dry air scenario		Moist air scenario
Is the surface temperature from 3 °C to 6 °C and surface RH from 40% to 65%?	If yes, forecast snow	Is the surface temperature 2 °C or lower and surface RH from 60% to 100%?

850 hPa — **Surface** — **850 hPa**

The AOH and its counterpart over the Indian Ocean, the Indian Ocean highs (IOH), are generally associated with stable weather conditions (sinking air).[29] However, when they are associated with surface cold fronts and upper air westerly troughs and COLs they are responsible for the inflow of moist unstable air into the country that may lead to widespread precipitation. Under these circumstances, conditions for precipitation are further improved over the eastern escarpment as the moisture-laden air is forced to rise because of orographic forcing.[27]

Despite this body of evidence, little work has been done in South Africa to identify the synoptic circulation patterns associated with snow. Only in a recent study was a thorough synoptic climatology constructed for snow over South Africa.[2] COLs and cold fronts, as well as surface cold air advection, have been identified in case studies[31,32] as the main synoptic drivers associated with snow in South Africa. Globally, similar weather systems have been identified as important snow-producing systems. Steep upper air troughs and closed 500-hPa lows were identified as snow-producing weather systems on the east coast of the USA, in Andorra and in Tasmania.[33-35] In North Carolina in the USA, surface anticyclones were identified as the most frequent weather system causing cold air advection necessary for snowfall to occur.[36]

In recent years, self-organising maps have been used widely in South Africa to create climatologies and to associate weather events with certain synoptic states.[18,37-39] The synoptic climatology of significant snowfall over South Africa was created using 60 snow events (426 numerical model time steps) between 1981 and 2011.[2] The 24-node self-organising map provides archetypal synoptic states associated with snow for three variables: mean sea level pressure, 500-hPa geopotential heights and 850-hPa air temperatures (Figure 3). The map places nodes with similar characteristics adjacent to each other while nodes which are very different are placed far apart.

The nodes in the first two columns in Figure 3 show a cold frontal trough southeast of the country with a 500-hPa westerly trough situated slightly west of the positions of the surface low. In all of these examples, there is evidence of the AOH ridging behind the front causing a perpendicular onshore flow onto the south and/or east coast producing very cold conditions over the country with tight temperature gradients (dotted contours in Figure 3). In the nodes in the last two columns the IOH is dominant with a southeasterly onshore flow onto the east coast where at 500 hPa a COL is situated. The nodes in the two centre columns depict the transition from the dominant cold frontal trough to the IOH. Nodes 5, 6, 11 and 12 show a low pressure situated east of the country with diminished onshore flow and with weaker temperature gradients over the southern interior.

The advantage of using the self-organising map output is that it provides a wide range of synoptic patterns all associated with snow. Figure 3 shows that there are many different surface circulation patterns associated with snowfall, but in all instances an upper air COL, or at least a sharp trough, is present. Cold fronts are important contributors to the formation of snowfall but it is the location and strength of the surface anticyclones that cause the cold air necessary for snowfall to invade South Africa.

Therefore, the first step in the SFDT (Table 1) is to compare the synoptic circulation of a particular day with those provided in Figure 3 to determine if it is appropriate to proceed to the next step in the SFDT.

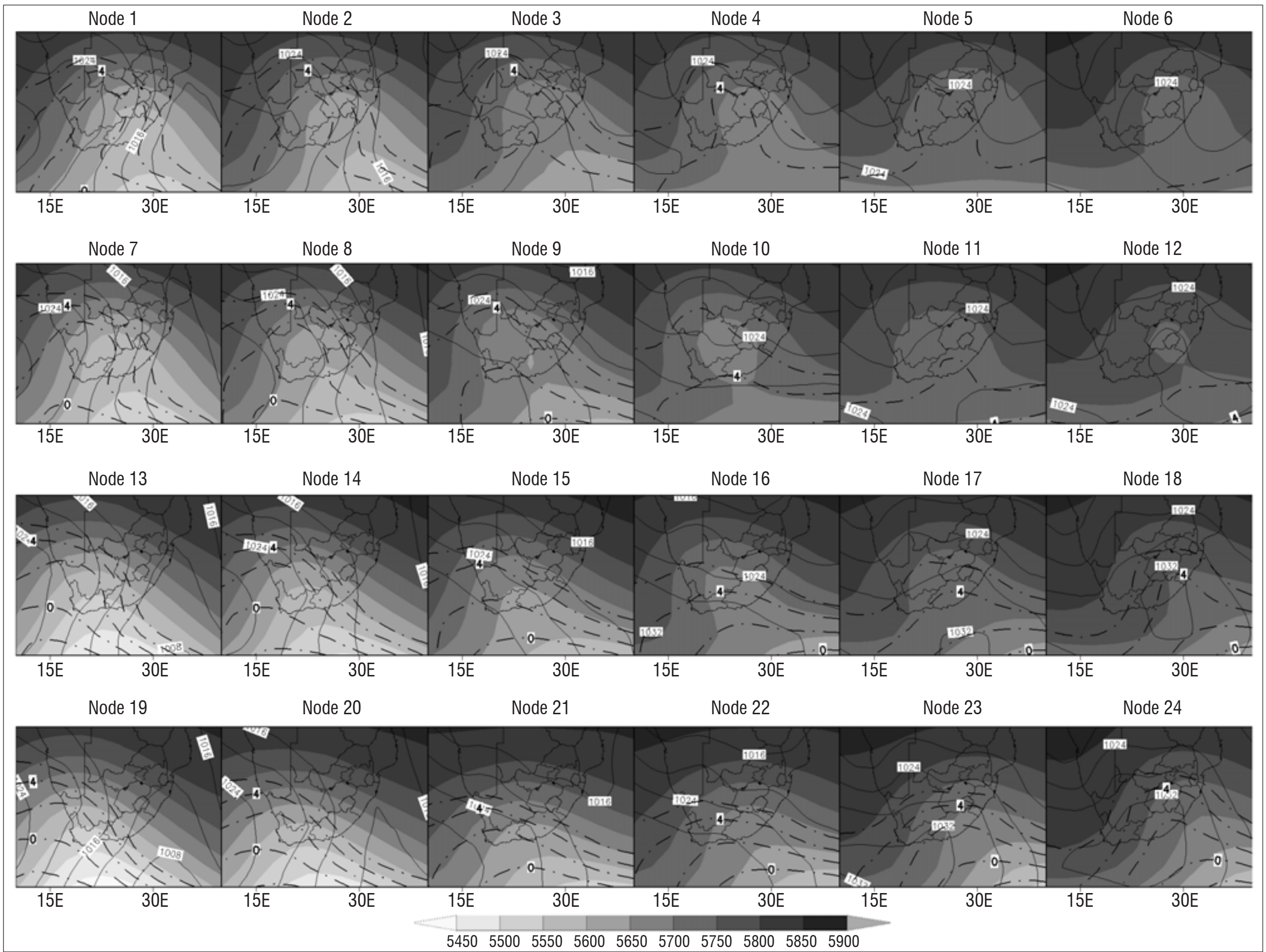

Figure 3: Archetypal self-organising maps showing sea level pressure (solid contours), 500-hPa geopotential heights (shaded) and 850-hPa temperatures lower than 6 °C (dotted/dashed contours) for 60 snow events between 1981 and 2011.

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

In Step 2, the user needs to determine the likelihood of precipitation using sound forecasting principles. Forecasting precipitation remains one of the major challenges for an operational meteorologist. In recent times there have been tremendous advances in the ability of numerical weather prediction products to accurately identify areas of precipitation.[40-43] However, operational weather forecasters do not exclusively rely on numerical precipitation prognoses to identify areas of precipitation – they utilise a wide variety of variables and techniques. Classical forecasting theory was developed during World War II[43] and further developed during the second part of the 20th century[14-19,20,22,44]. It is outside the scope of this paper to discuss forecasting techniques in detail, suffice to say variables such as wind divergence, vertical velocity, geopotential heights and relative humidity (RH) are investigated on several pressure levels to diagnose current and future states of the atmosphere to predict precipitation.

Once it has been determined that precipitation is likely, the user may proceed to distinguish between solid and liquid precipitation.

Step 3: Is the air close to saturation between -20 °C and -10 °C?

In the free atmosphere, water does not necessarily freeze at 0 ºC but can remain in liquid form at temperatures as low as -40 °C in the absence of nucleation nuclei.[45] Liquid water at temperatures less than 0 °C is referred to as supercooled water. Ice crystals may form and grow as a result of deposition, aggregation and riming within cold clouds (clouds with cloud top temperatures <0 °C).[45]

Deposition is the process whereby snow crystals grow by diffusion of water vapour in an environment in which the air is saturated with ice crystals. This process is also referred to as the Bergeron–Findeisen process.[45] In essence, this process takes place when water vapour changes phase to ice and the ice grows quickly when the air is saturated. Deposition normally occurs in the mid-atmosphere (700–500 hPa)[19] and where temperatures are between -16 °C and -12 °C.[45] Dendrite crystals are most likely to grow under these circumstances.[46] Dendrite ice crystals are crystals with open spaces between them that effectively cause water vapour to condense on them and to grow by deposition.[46]

When ice crystals collide and stick together to form a snowflake it is called aggregation (clumping). The efficiency of the aggregation process is greatest when the air is saturated and temperatures are between -10 °C and 0 °C.[19,47]

Riming or accretion occurs when water freezes onto ice. This process often happens when ice particles fall through supercooled droplets; the more ice crystals that are available for seeding into the low level cloud, the better the chance of producing snowflakes with larger diameters. The process is also referred to as the seeder feeder mechanism and typically occurs when ice-bearing clouds with cloud top temperatures of -15 °C (seeder clouds) move over warmer clouds containing supercooled water droplets and with cloud top temperatures of about -6 °C (feeder clouds). When the ice particles in the seeder clouds are large enough, they fall through the supercooled droplets of the feeder clouds and grow, provided the distance between the two cloud types is 1500 m or less.[19,47] 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.[47] In the absence of feeder clouds there is little chance of the ice crystals riming and forming snowflakes. The presence of low level feeder clouds increases the precipitation efficiency. In cases in which seeder clouds are absent, and only feeder clouds such as cumulus are present, light snow might be observed. However, when thick convective feeder clouds are present, heavy snowfall might occur.[47]

Cloud top temperatures of less than -10 °C indicate the presence of ice crystals in the cloud.[22,19] If the cloud top temperatures are between -15 °C and -12 °C, there is a 70–90% likelihood of ice in the cloud, while at -20 °C ice is guaranteed in the cloud. Snow can also occur with cloud top temperatures of between -10 °C and -5 °C; in these instances ice crystals grow by aggregation.[47]

In Step 3, the vertical profile of temperature and moisture should be scrutinised to establish whether ice clouds exist. If the atmosphere is close to saturation between -20 °C and -10 °C, the likelihood of fast-growing dendrite crystals through deposition is very high. In addition, saturation of the atmosphere between -10 °C and 0 °C is needed for the growth of snowflakes through aggregation.

Step 4: Are the geopotential thickness values lower than the critical values?

The SFDT needs to make provision for determining whether the snowflakes will make it all the way down to the ground without melting. This determination is done by considering the geopotential thickness for several layers in the atmosphere. The geopotential thickness is defined as the difference in geopotential heights of two pressure levels and it is proportional to the average column temperature in that layer.[44]

If the first three steps of the SFDT have been met (Table 2), the likelihood that ice crystals will be fast growing into snowflakes is high. When the snowflakes become heavy enough, they will fall to the ground under the influence of gravity. Snow will reach the ground as long as the temperature through which it falls is at or below freezing.[48] The purpose of determining geopotential thickness is to evaluate whether the temperature of the layer through which the snowflakes are falling is less than 0 °C and to identify the presence of thin warm layers that may cause the snowflakes to melt.[49]

Using thickness to identify precipitation type is a method employed widely, although threshold values vary by geographical location. In the UK the transition from rain to snow occurs when the 1000–500-hPa thickness is about 5310 m and the 1000–700-hPa thickness is 2788 m.[50] In the western USA, heavy snowfall is associated with 1000–500-hPa geopotential thickness values of 5340–5460 m.[51] Cold outbreaks with snow in Tasmania were associated with 1000–500-hPa thickness values of 5320 m.[52] Because of the height AMSL of the interior of South Africa, a pressure level close to the ground surface must be used for the higher pressure threshold in the calculation of thickness values. Surface pressures over the interior plateau are close to 850 hPa[6] and this pressure level is used as the surface pressure threshold. The 850–500-hPa geopotential thickness of less than 4170 m was found to occur in conjunction of significant snowfall over the interior of South Africa.[2]

Examining the values of thinner geopotential thicknesses or partial thicknesses is important to ensure that there are no thin warm layers in the atmosphere that could cause the snowflakes to melt. The partial thickness in the layer between the ground and the freezing level is especially significant as it is indicative of cold air close to the ground in support of frozen precipitation. An 850–700-hPa partial thickness value of less than 1552 m implies that the average column temperature in that layer is less than 0 °C and therefore favourable for snow. In a New York study, the thickness of the same level was less than 1550 m for snow to occur.[49] Over the interior of South Africa, significant snowfall was associated with 850–700-hPa thickness values of less than 1580 m.[2]

When the average column temperature in the 700–500 hPa layer is 0 °C, the thickness is 2690 m. However, during the snow event over Bloemfontein and Johannesburg in June 1964, a 700–500-hPa thickness map was analysed from upper air sounding data at Bloemfontein, Irene and Durban. The thicknesses in this instance were 100 m less than the 2690 m threshold and varied between 2520 m and 2560 m.[53] Significant snowfall over the interior of South Africa was found to occur when the 500–700-hPa thickness values were less than 2590 m.[2]

Step 4 of the SFDT requires that the geopotential thickness for the 850–500-hPa layer, as well as that for the 700–500-hPa and 850–700-hPa layers, needs to be less than the critical values in Table 2.

Step 5: Are the melting level height, surface temperature and relative humidity values suitable for snow?

Snow is more likely to reach the ground when the melting level is not more than 300 m above ground level (AGL).[45,54] The melting level is the height of the 0 °C isotherm AGL. Snow can still reach the ground when the temperature between the ground and the freezing level is greater than 0 °C. This happens when snowflakes start to melt once they fall through the melting level into the dryer air close to the ground. Melting leads to the absorption of latent heat that cools surrounding temperatures, allowing some flakes to make it to the ground.[36] The absorption of latent heat by melting could also cause the air surrounding the snowflake to be cooled to freezing. The snowflake can fall several hundreds of metres below the melting level before melting completely when the environmental temperature is 5 °C. When surface RH is less than 90% and the temperature lapse rate is wet adiabatic, the snowflakes can fall approximately 600 m in above freezing temperatures before melting. As the RH increases, the distance that a snowflake can fall before melting becomes shorter.[45]

The RH in the lower levels of the atmosphere is a determining factor in the surface temperature required for snow to reach the ground. When surface RH is close to 100%, snow occurs in temperatures below 1 °C and rainfall is more likely than snow when temperatures are greater than 1 °C. For surface RH values less than 90%, snow occurs regularly when surface temperatures are lower than 2.5 °C.[55] Snow occurs at temperatures lower than 2 °C when surface RH exceeds 60%, because in high RH environments, 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. When surface RH values are less than 60%, surface temperatures must be between 4 °C and 6 °C for snow to occur.[45] In environments with low 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.[45,55]

In Step 5, two snowfall scenarios are defined. The moist air scenario and the dry air scenario. When the surface temperature is 2 °C or lower and surface RH is between 60% and 100%, the moist air scenario occurs. In moist air scenarios, the air is saturated close to the surface with the presence of stratiform and nimbostratus clouds that extend from close to the surface to mid-levels. The dry air scenario occurs when the surface is dry (RH<65%) and surface temperatures are 3–6 °C. (Table 2). In dry air scenarios, the atmosphere near the surface is dry and clouds which can form in low RH environments should be present, such as cold air cumulus[56] (convective) clouds which develop behind cold fronts.[57] The user of the SFDT has to determine whether the snow will melt. Melting typically occurs when cold air advection and upward motion in the lower levels are fairly weak.[49,58] Furthermore, in areas in which it has been raining for a while, cooling from melting will be strongest and the absorption of latent heat in these areas further cools the atmosphere, which can lead to snow.[58]

Case study: 7 August 2012, Gauteng

On 6 and 7 August 2012, snowfall occurred in all nine provinces of South Africa. On 7 August 2012, widespread snowfall occurred over nearly the entire Gauteng Province. Virtually all of the aerodromes over the province reported snowfall, including OR Tambo International, Rand, Lanseria and Wonderboom Airports. Reports of snow came from all the metropolises in the province. Between 1909 and 2012, snowfall has been reported on only three occasions in both Pretoria and Johannesburg (Table 1). Prior to 7 August 2012, the last report of snowfall in Pretoria was 12 June 1968. One of the reasons that makes the snowfall of 7 August 2012 over Gauteng exceptional, is that it occurred in relatively warmer yet distinctively drier surface conditions. It is shown that by applying the SFDT, this very rare snow event could have been anticipated. The snow that occurred in Bloemfontein on 7 August 2012 is also analysed using the SFDT, as it is an example of the moist snow scenario. The two contrasting conditions are used to demonstrate the effectiveness of the SFDT.

Data used in the case study

The synoptic circulation patterns on 7 August 2012 are illustrated using National Centers for Environmental Prediction reanalysis two (NCEP 2) data.[59] Vertical profiles of temperature, dew point temperature and RH at Irene (situated between Pretoria and Johannesburg) and Bloemfontein were obtained from SAWS upper air ascents. The geopotential thicknesses and melting level heights at Irene and Bloemfontein were also calculated from these data. Surface temperature and RH values were measured by SAWS automatic weather stations.

Meteosat Second Generation satellite data from EUMETSAT were used to determine the properties of the clouds.[60] The infrared (IR) 10.8-μm channel is useful to determine cloud top temperatures. High reflectivity of clouds on the high-resolution visual images indicates the presence of ice in clouds. Furthermore the cloud structure of clouds in the visual image are used to distinguish between convective and layered cloud. Convective cloud has a clear cellular pattern whereas layered cloud appear as uniformly grey sheets of cloud.[60]

Application of the snow forecasting decision tree

Step 1: Do the synoptic circulation patterns favour significant snowfall?

Figure 4 depicts the synoptic circulation pattern on 7 August 2012. The surface cold front was located east of the country with the 500-hPa COL over the eastern interior of South Africa. There was a strong onshore flow of moisture onto the south and southeast coasts and an AOH ridging at 40 °S behind the cold front. This circulation pattern is very favourable for significant snowfall and represents the synoptic patterns depicted in the top right-hand corner of Figure 3. Although surface temperatures were quite cold, there was a weak temperature gradient over the eastern half of the country. Step 1 of the SFDT is therefore met.

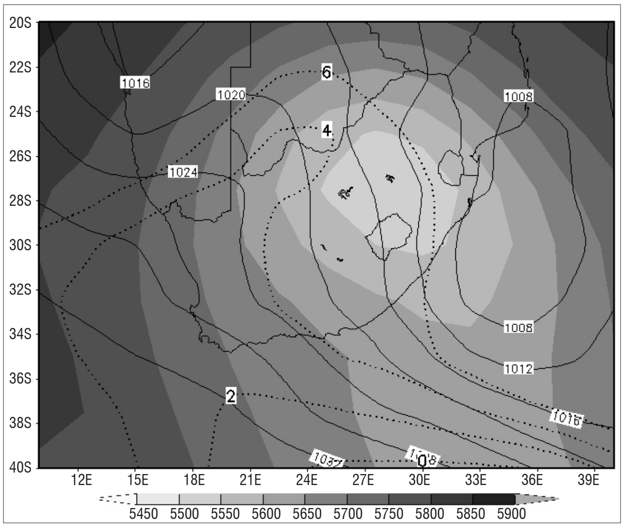

Figure 4: Sea level pressure (solid contours), 500-hPa geopotential heights (shaded) and 850-hPa temperatures lower than 6 °C (dotted contours) on 7 August 2012 at 1200 UTC.

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

The cyclonic circulation of the 850-hPa winds indicate that the 850-hPa low was situated over the coast of KwaZulu-Natal, causing large areas of surface convergence (negative divergence) over the eastern parts of the country – including Gauteng and the eastern Free State (Figure 5). The cyclonic circulation around the low caused a strong onshore flow of moisture over the southeast and east coasts, resulting in RH values in excess of 80% over the southern half of South Africa but with drier conditions over Gauteng. Over the Free State, the RH values were 50–70%. At 500 hPa, the low was situated over the eastern interior (Figure 4) with areas of upper air divergence over the eastern half of the country (not shown). Conditions for precipitation were therefore quite favourable over Bloemfontein and Gauteng.

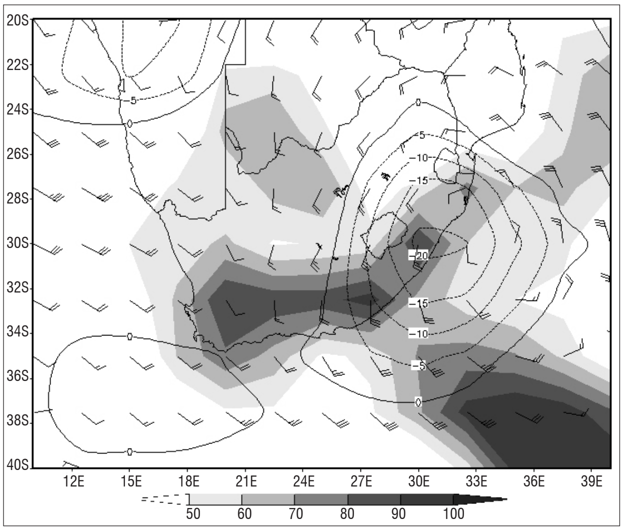

Figure 5: The 850-hPa winds (knots), relative humidity (%, shaded) and horizontal wind convergence (x10^5 s^{-1}, contour values) on 7 August 2012 at 1200 UTC.

Step 3: Is the air close to saturation between -15 °C and -12 °C?

Data from Irene upper air sounding at 1200 UTC on 7 August 2012 is depicted in Figure 6. The surface temperature was 6 ºC with RH values less than 50% in the surface layers. In those layers in the atmosphere (600–700 hPa), at which temperatures were between -20 °C and -10 °C, RH values varied from 54% to 60%. Conditions were therefore favourable for fast-growing dendrite crystals through deposition.

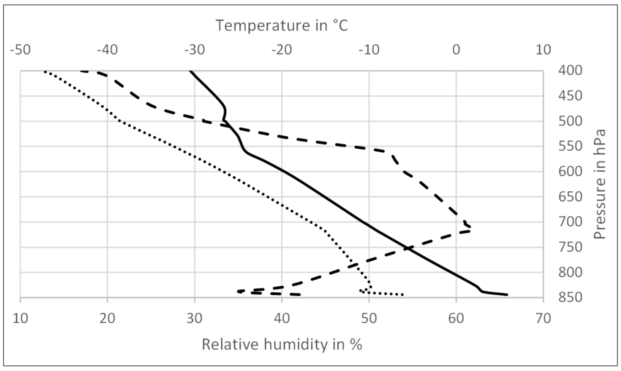

Figure 6: The vertical profile of temperature (solid), dew point temperature (dotted) and relative humidity (dashed) as obtained from upper air ascent at Irene on 7 August 2012 at 1200 UTC.

The IR 10.8-μm Meteosat Second Generation satellite image indicates that the temperatures of the cloud tops over Gauteng were between -10 °C and -20 °C (Figure 7). Cloud top temperatures in this range indicate the presence of ice in the clouds.[22] The high reflectivity of these clouds (bright white colours) is further evidence of ice in the clouds. The convective nature of the clouds is illustrated by the cellular structure of the clouds over Gauteng (Figure 7 inset). The satellite image shows that there were no higher (seeder) clouds present over Gauteng and this is also reflected in the very dry conditions at pressure levels lower than 550 hPa (Figure 6). Over Gauteng, ice crystals primarily formed by deposition and aggregation were not dominant in this instance.

Over Bloemfontein the atmosphere was saturated throughout, with surface temperatures lower than 2 °C and RH values greater than 90%

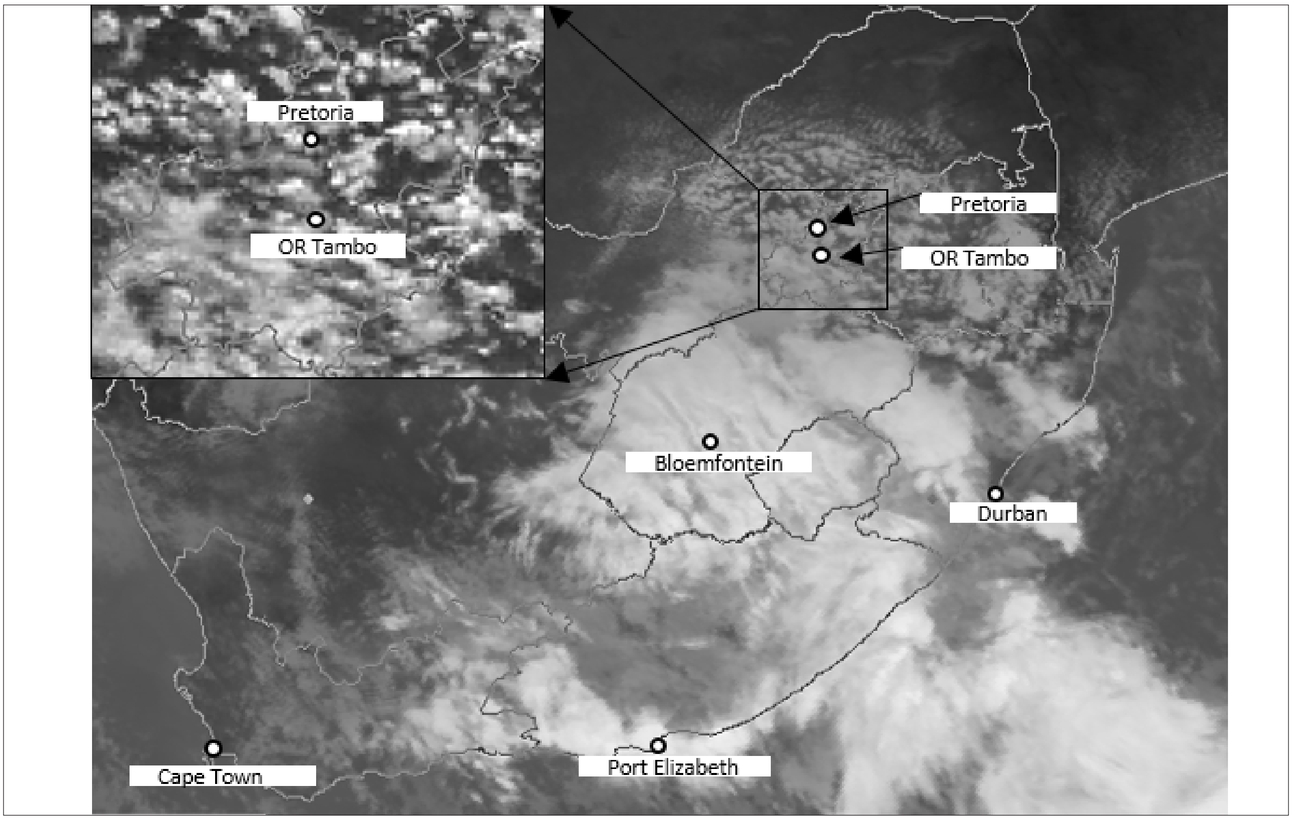

Figure 7: Meteosat Second Generation satellite IR 10.8-μm image over South Africa on 7 August 2012 at 1200 UTC. Inset: High-resolution visible image zoomed in over Gauteng.

(Figure 8). Considering the uniformly grey sheet of cloud in Figure 7, it is clear that seeder and feeder clouds were present over the Free State, causing ice crystals to grow by both deposition in the higher seeder clouds and aggregation in the low-level feeder clouds. Snow occurred during the late morning and early afternoon in Bloemfontein, but continued until the evening at Bethlehem.

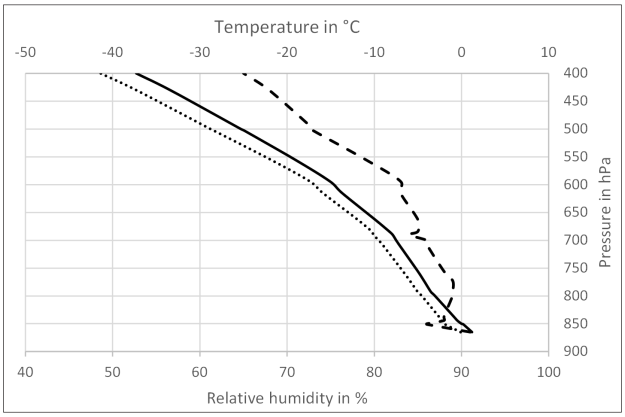

Figure 8: The vertical profile of temperature (solid), dew point temperature (dotted) and relative humidity (dashed) as obtained from upper air ascent at Bloemfontein on 7 August 2012 at 1200 UTC.

Step 4: Are the geopotential thickness values lower than the critical values?

Table 3 depicts the geopotential thickness values over Irene and Bloemfontein for the three critical levels identified by the SFDT. Over both Bloemfontein and Irene, the thickness values for all three levels were well below the critical values identified for significant snowfall over South Africa (Table 2). This indicates that the snowflakes would not have fallen through warm layers that may have caused it to melt.

Step 5: Are the melting level height, surface temperature and relative humidity values suitable for snow?

At Irene and Bloemfontein, the first four steps of the SFDT were met and the difference between the moist and dry air scenario is illustrated by considering the surface conditions at these two locations. The height of the melting level at Irene was 420 m AGL – higher than the threshold value[45,54] of 300 m (Table 2). Considering all the other favourable factors over Gauteng, this value alone is not enough to reject the possibility of snowfall. At Bloemfontein, the melting level was only 141 m AGL and therefore well within the critical value.

Over Irene the surface RH was only 42% and according to the SFDT snow will occur in the dry air scenario if surface temperatures are between 3 °C and 6 °C. Surface temperature at Irene was 5 °C (Table 3) and even lower in Pretoria and Johannesburg (not shown). Surface conditions therefore met the criteria for the dry air snow scenario. Snow occurred at 1200 UTC in Pretoria and Irene. At OR Tambo International Airport light snowfall started before midday and continued well into the evening.

At Bloemfontein the surface RH was 91%, which clearly indicates that this was a moist snow scenario. The surface temperature was only 1 °C, which meets the criterion needed for snow to occur during a moist air scenario. Snow occurred through most of the morning in Bloemfontein, with heavy snow showers reported from time to time during the day.

Discussion and conclusions

The World Meteorological Organization defines a snow day as a day with a snow depth greater than a certain threshold.[61] For instance, in Switzerland this threshold is set at 1 cm.[62] Because of the rarity of snow in South Africa, the snow depth is not measured; however, the occurrence of snow is noted at SAWS offices. The absence of snow depth measurements necessitates an alternative definition of significant snowfall over South Africa. Significant snowfall is therefore defined in this paper as snow that reaches the ground in areas at an altitude of less than 2000 m AMSL. Snowfall in South Africa normally occurs in the sparsely populated mountainous regions. At lower altitudes, the snow often melts before reaching the ground, but when it does reach the ground it causes widespread disruption to infrastructure and even loss of life. Significant snowfall events are rare and irregular. On average there are two significant snowfall events per year over South Africa[2] and these events do not occur every year. In comparison, there were 160 snow days on average at Semedan in the central Alps.[62] As significant snow occurs irregularly with only, at most, a few events per year, it becomes important to understand the synoptic conditions and atmospheric variables which cause snowfall at lower elevations in order to predict it when it does occur. A snow forecasting decision tree (SFDT) is proposed, in which the synoptic circulation patterns, cloud microphysical aspects and other atmospheric variables are condensed into a user-friendly product.

The SFDT consists of five steps that should all be met to forecast snowfall. The first step identifies the snow synoptic circulation type and the second step requires the user to determine if precipitation is likely to occur. Steps 3 to 5 distinguish between solid (snow) and liquid (rain) precipitation by first ensuring that ice crystals are present in the cloud and then investigating if the snow will melt on the way to the ground. In the last step, the user needs to differentiate between *wet* and *dry* snow conditions by examining surface temperature and RH values.

The synoptic circulation systems associated with significant snowfall over South Africa are COLs or sharp troughs at 500 hPa together with surface systems which cause strong cold air advection into the subcontinent. The surface circulation is broadly categorised into cold frontal troughs followed by the ridging AOH and the IOH southeast of the country. These weather systems are similar to those that have been identified elsewhere in the world.[33-36]

Critical geopotential thickness values associated with snow have been identified for several layers in the atmosphere (Table 2), but were specifically developed for the interior of South Africa which lies close to the 850-hPa pressure level. Comparable threshold values have been developed internationally. For instance, the UK Met Office gives a 90% chance of snow if the 1000–500-hPa thickness is less than 5180 m and the 1000–850-hPa thickness is less than 1281 m. The UK Met Office considers the melting level to be at about 108 m above the ground, whereas we identified 300 m as the threshold value.[63]

Forecasting snow under wet surface conditions is a well-known technique in weather forecasting offices in South Africa.[2] The real value of the SFDT is in aiding in the identification of the very rare dry snow conditions.

Table 3: Geopotential thickness values, melting level heights and surface temperature and relative humidity values at Irene and Bloemfontein on 7 August 2012 at 1200 UTC

	Thickness (m)			Surface		
	850–500 hPa	850–700 hPa	700–500 hPa	Melting level height (m)	Temperature (°C)	Relative humidity (%)
Irene	3967	1477	2490	420	5	42
Bloemfontein	4065	1532	2533	141	1	91

This paper contributes to a better understanding of the synoptic circulation systems associated with significant snow and adds insight into the cloud microphysical and surface conditions during snowfall. It is recommended that the SFDT is implemented in forecast offices of the SAWS, which will allow further fine-tuning of critical values. Operational weather forecasters can add value to the SFDT by providing feedback on its usefulness in an operational environment. Steps 3 to 5 could be automated and made available through numerical weather prediction output. However, subjective and human interpretation of Steps 1 and 2 remains a necessity.

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Authors' contributions

This paper emanates from the work that J.H.S. conducted to obtain his MSc at the University of Pretoria under the supervision of L.D. J.H.S. conducted all the research and constructed the forecasting decision tree. L.D. provided scientific guidance, and helped with the preparation of the manuscript. C.J.E. developed the initial Fortran code used in this study and provided feedback on the manuscript.

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