A severe weather event on 29 December 1997: Synoptic and mesoscale perspectives

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Abstract

On 29 December 1997 a severe hailstorm occurred over the eastern parts of the Free State. Hailstones with a diameter of 10 to 25 mm were reported. In this paper the authors try to establish the nature of the storm by looking at the synoptic and mesoscale analyses of the weather features at that time. Due to a lack of sufficient data, the South African version of the Eta model's 3 and 6 h forecast fields were used to establish the storm environment. Most of the model parameters indicated that severe weather could have been anticipated in the area of interest. Mesoscale analyses showed that steep temperature, pressure and dew point temperature gradients were evident over the area and that this contrast in air masses served as a good trigger mechanism for the development of thunderstorms. Analyses with the upper-air data showed that the air was very unstable at Bloemfontein earlier that afternoon, while Bethlehem was under the influence of an inversion (subsident motion in the upper layers of the atmosphere). The latter was removed during the early evening due to orographic forcing. With the high amount of energy available underneath the inversion, it exploded into a severe storm later that night. With the aid of software like TITAN and CIDD it was possible to analyse the radar data with much more detail than would have been the case under operational circumstances where forecasters did not have access to these software packages. Looking at all available data, the authors are of the opinion that this was an isolated severe thunderstorm which displayed several supercell characteristics.

Introduction

On 29 December 1997 between 20:00 and 22:00 (all times are SAST) a hailstorm passed over an area of about 80 km long and 30 km wide from Clarens, over Fouriesburg, Bethlehem, Danielsrus and up to Reitz and Petrus Steyn. Bethlehem's METARs (meteorological aviation reports) mentioned that hail fell between 20:00 and 21:00 and that it was accompanied by rain and thundershowers for most of the evening. According to the Volksblad (31 Dec 1997) the storm passed through Reitz at about 21:30 and grape to walnut sized hailstones (10 to 25 mm in diameter) caused R15 m. damage to crops in this area. Although this event was short-lived and resulted in relatively small rainfall amounts, the severity was responsible for a vast amount of structural damage to farm buildings, as well as the damage to corn, sunflower and wheat fields. Radar rainfall measured by Bethlehem's MRL5 radar over a 24 h period is shown in Fig. 1. This clearly depicts the swath of severe weather in a band stretching from south to north just east of the location of the radar. The radar rainfall usually overestimates the rainfall due to the hail stones' high reflectivity. Bethlehem measured a 24 h rainfall total of 20.8 mm (more detail in paragraph on 5 min AWS data), Deneysville (Vaaldam) reported 29.5 mm, while other rainfall totals for the Free State were less than 5 mm. Rainfall totals of more than 25 mm were also measured at: Johannesburg International Airport: 30.5 mm, Pretoria Weather Office: 33 mm, Alldays: 25.8 mm, Tzaneen: 26.2 mm, Doornlaagte: 43 mm, Lichtenburg: 42.5 mm. Most of the rainfall reported over the rest of the country was less than 10 mm, however.

In South Africa supercells are relatively rare. This is evident from studies surrounding the nature of hail producing thunderstorms in South Africa by various authors (Held, 1978; Held, 1982; Carte and Held, 1978). A comparative study of hailstorms in South Africa, Switzerland and Canada (Admirat et al., 1985) over a 5 to 20 year period revealed that very few supercells with a quasi-steady state were observed over South Africa (at least one in a 20 year period). Analysing the available data, the authors show that several supercell criteria were met, making this particular storm one of these rare supercell examples.

Data

Routine surface observations, 5 min AWS (automatic weather station) data, satellite imagery (mostly Infrared) and the MRL5 radar (stationed northeast of Bethlehem [Synoptic ID: 68461]) data were used to analyse the event. In addition to normal displays, TITAN (thunderstorm identification, tracking and nowcasting, Dixon and Wiener, 1993), RAOB (Rawinsonde observation system) and CIDD (Cartesian interactive data display) were used to interpret the raw data. Due to the lack of upper-air data the local version of the Eta model's 3 and 6 h forecast fields were also utilised to get an estimation of the model's short-term forecast ability in the storm's environment. For a more detailed description of the Eta model, the reader is referred to Mesinger et al. (1988). The South African version of the Eta model has a 48 km horizontal resolution and 38 levels in the vertical.

Analysis of the data

At the surface, at 14:00, a high pressure system was ridging in on the KwaZulu/Natal coast, advecting moist, cool air over the eastern parts of the country. A low pressure system was present over the central interior. A relatively steep pressure gradient was present between the higher pressures in the east and the low pressure system over the interior (Fig. 2). Pressure tendencies were mostly negative over the region of interest. Very high temperatures were recorded over the western Free State and Northern Cape. A steep

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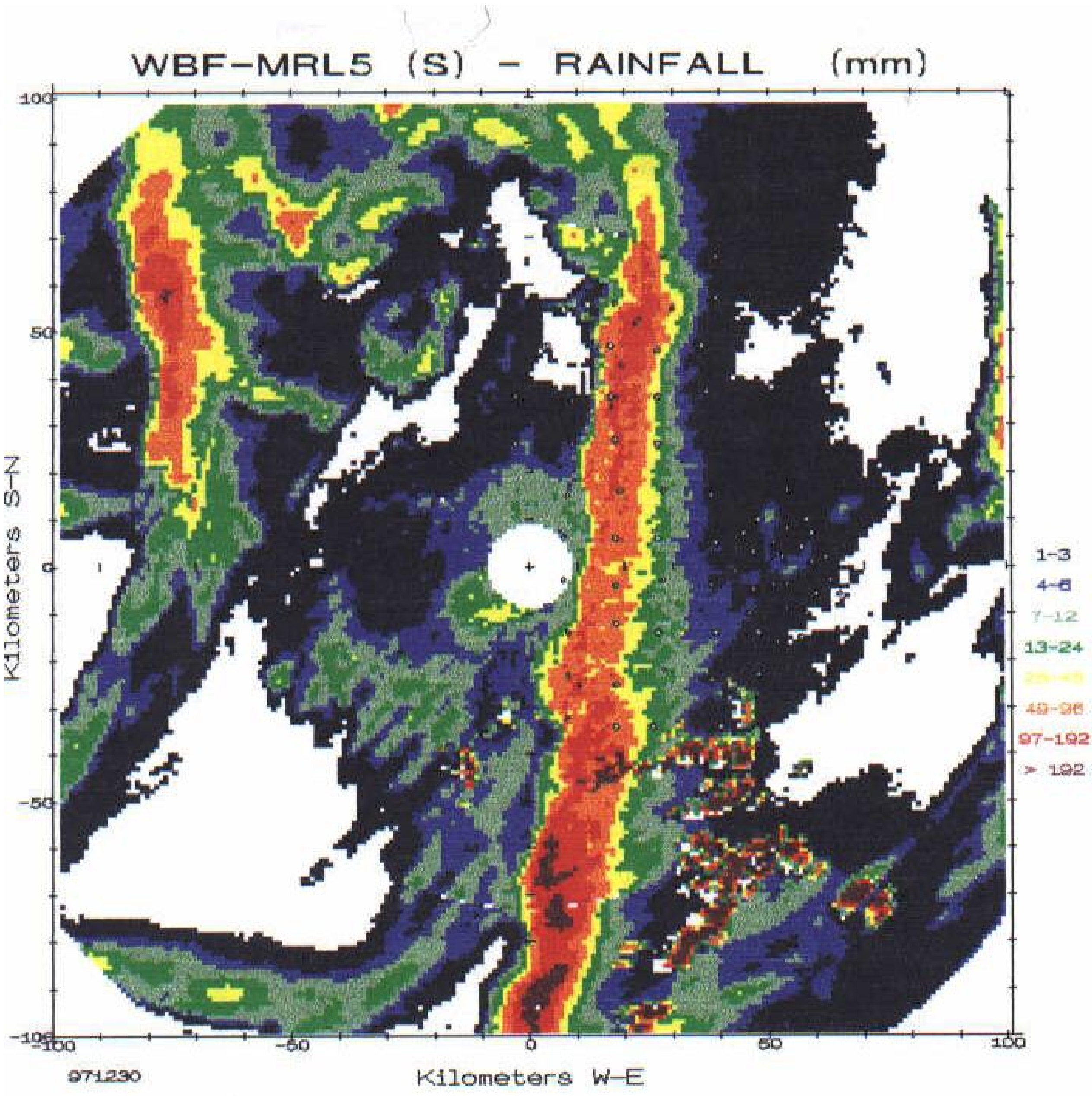

Figure 1
24 hour rainfall total from Bethlehem's dual wavelength, S-band, MRL5 radar

temperature gradient existed (Fig. 3) between the cooler south-eastern parts of the country (Eastern Cape and southern KwaZulu/Natal) and the interior (Free State and Northern Cape). Wet bulb potential temperatures were all above 22°C, but more than 26°C over the northern Free State and southern Gauteng. A tongue of drier air (dew point temperatures less than 10°C) pushed into northern Free State from the south-west to create a distinct dryline (i.e. an area where there is a steep gradient of dew point temperatures over a relatively small distance, see Fig. 4).

At 500 hPa, at 14:00, a high-pressure system dominated the circulation with west-southwesterly winds over the interior. Relative humidity at 500 hPa was in the order of 20 to 30% over the Free State. At 700 hPa it was 55 to 65% over this area and at 850 hPa the relative humidity was 29% at Bloemfontein and 94% at Durban. A westerly jet stream was present at 250 hPa with a velocity of 55 knots over Durban, which was the exit region of the jet stream.

Looking at the hodograph (adapted for the southern hemisphere by Forbes, after Doswell, 1991) for a typical cyclonic supercell in the southern hemisphere (Fig. 5), the wind directions measured at Bloemfontein at 14:00 are in close agreement with the theory, namely that the surface wind was from the north-east, the 3 km AGL (all heights in AGL unless otherwise stated) wind from the north, the 500 hPa winds were from the west-southwest with a westerly jet stream at 250 hPa. According to the hodograph model for cyclonic supercell motion, the storm would have been expected to move eastward. However, in this case the Drakensberg mountain range steered the storm in a northerly direction.

On the 21:00 Infrared satellite imagery at the time of the storm, the northern part of the country was covered by clouds where convective development was also evident. The southern half of the country was cloud-free. Cirrus clouds could clearly be seen blowing off in an easterly direction due to the upper level jet stream. The

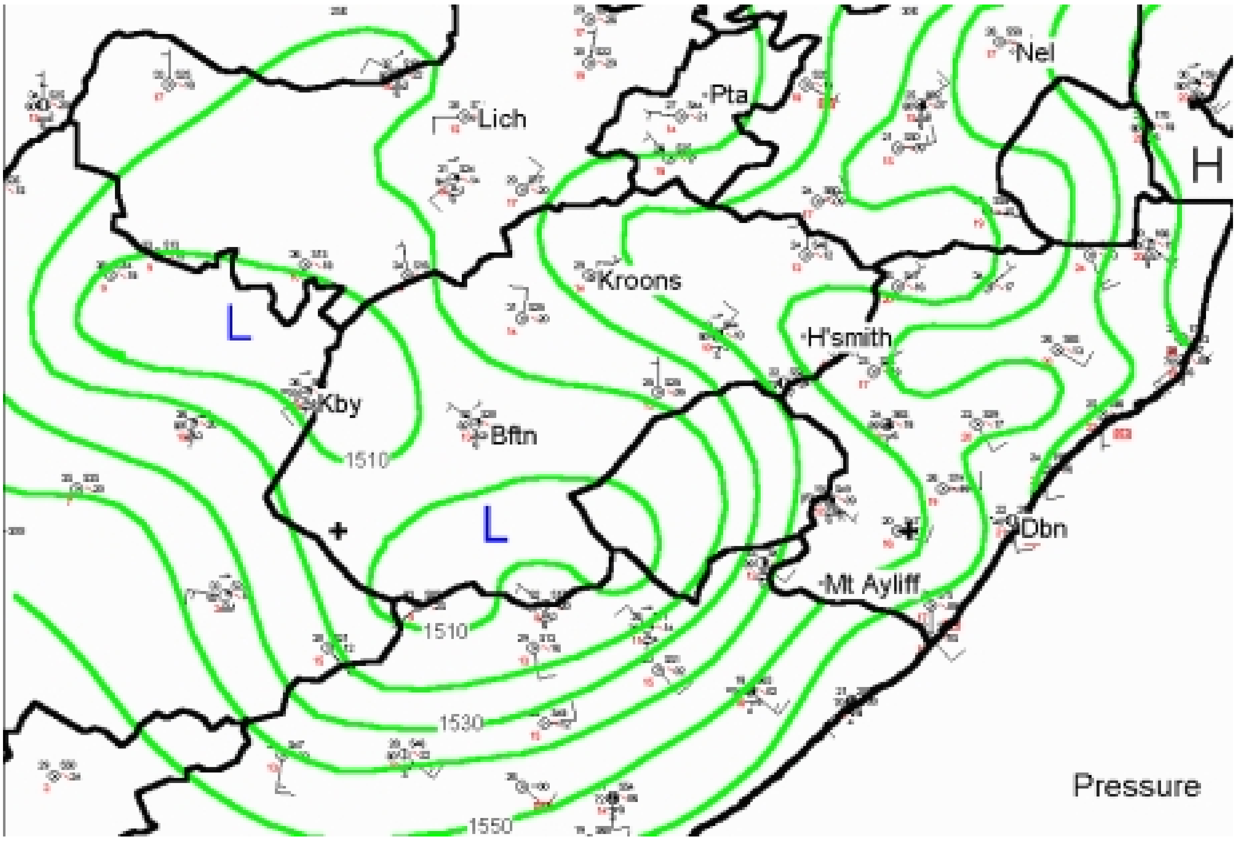

Figure 2
Mesoscale analysis of the pressure data over the region of interest on 29 December 1997 at 14:00

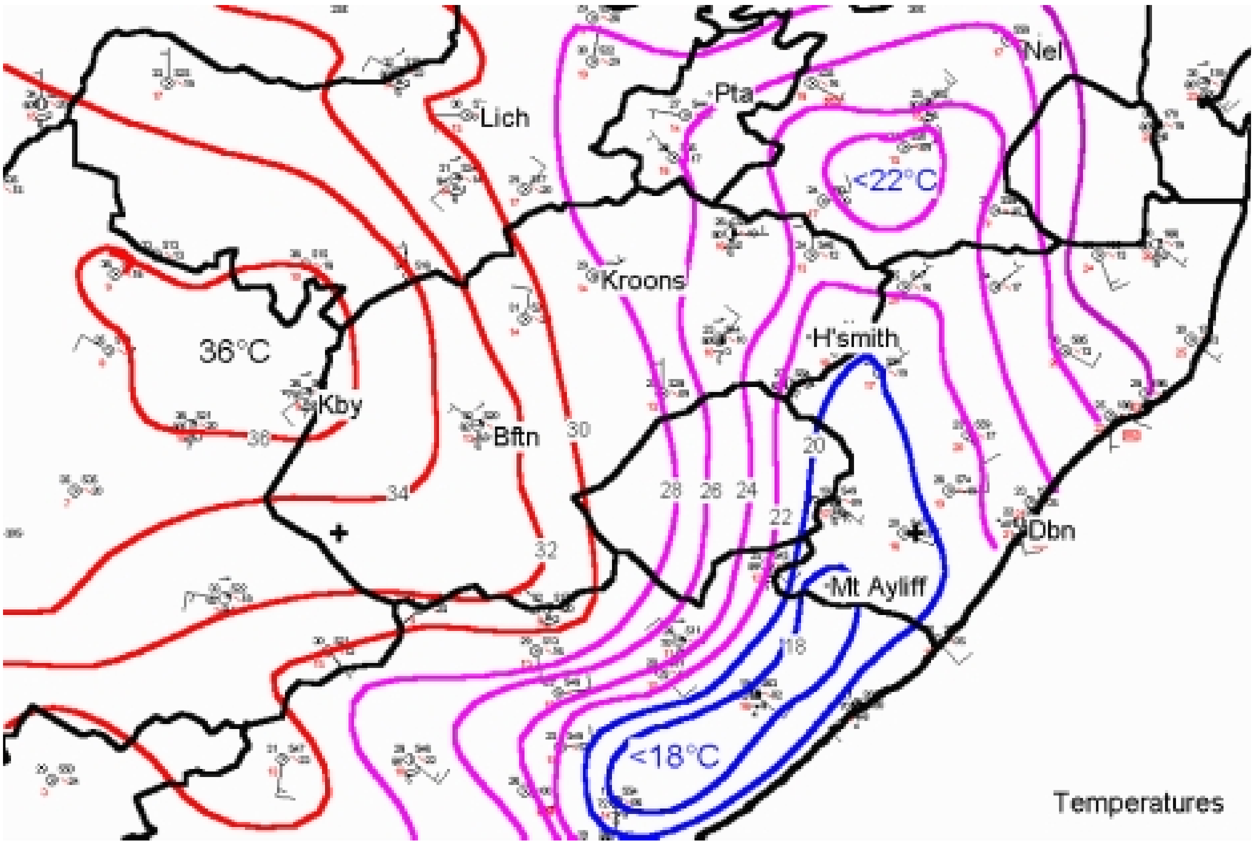

Figure 3
Analysis of the temperature data (isotherms at 2° intervals) over the region of interest on 29 December 1997 at 14:00

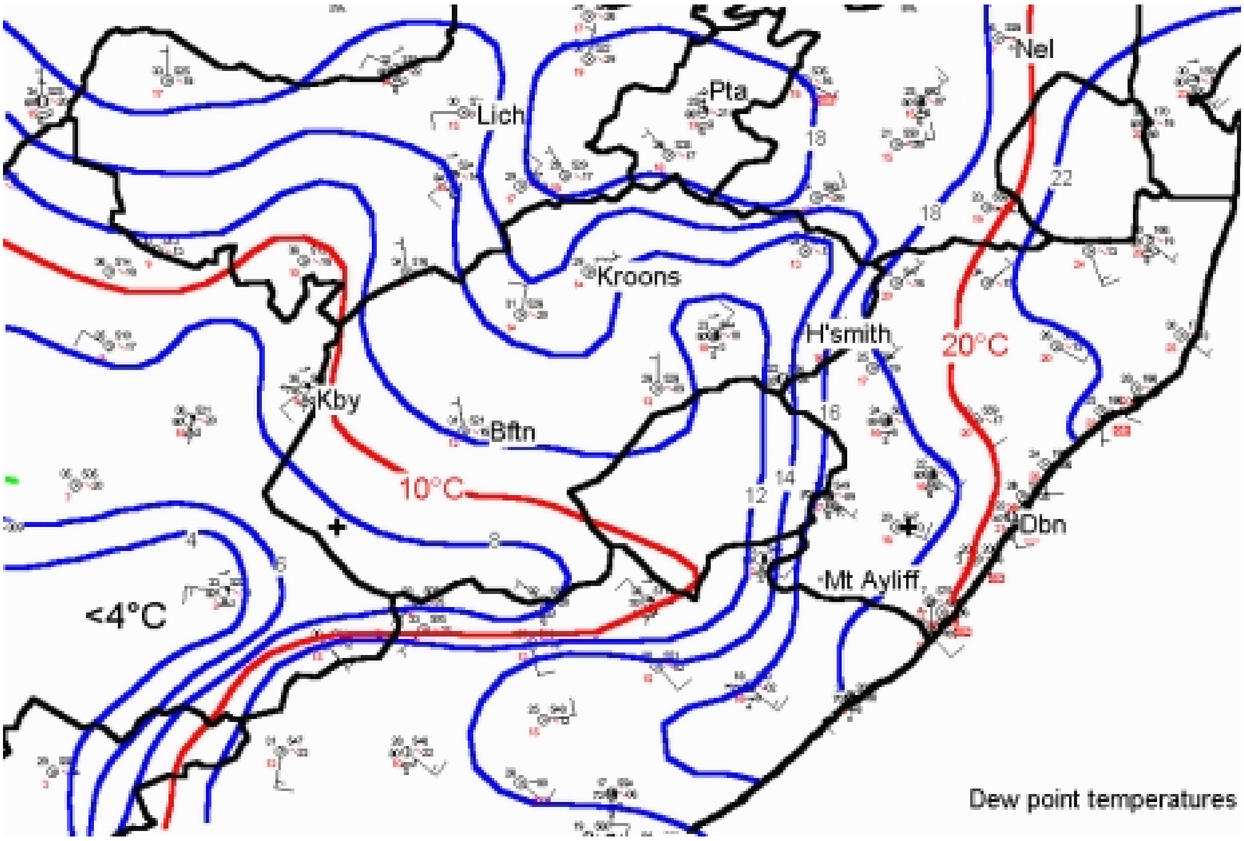

Figure 4
Analysis of the dew point temperature data (isotherms at 2° intervals) over the region of interest on 29 December 1997 at 14:00

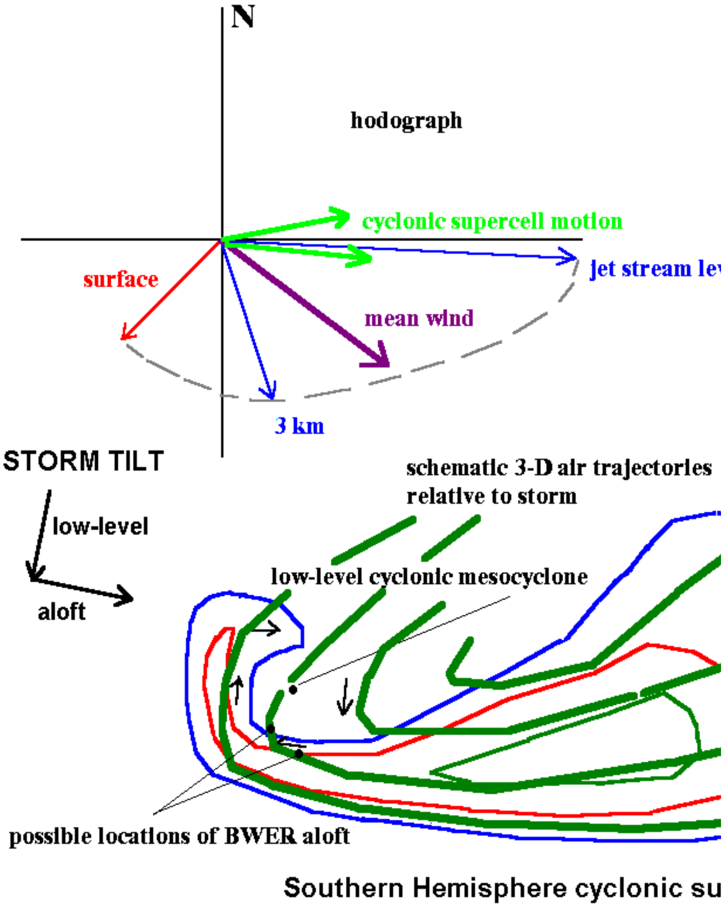

Figure 5
Schematic representation of the cyclonic supercell in the southern hemisphere (adapted by Forbes after Doswell, 1991)

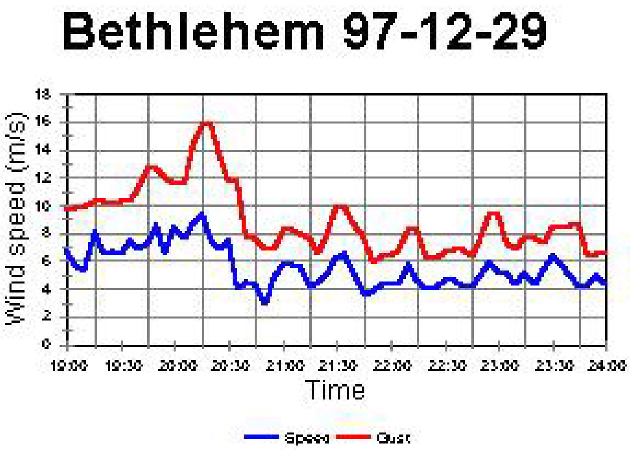

Figure 6
Wind speed (m·s⁻¹) data from the AWS for Bethlehem from 19:00 to 24:00 on 29 December 1997

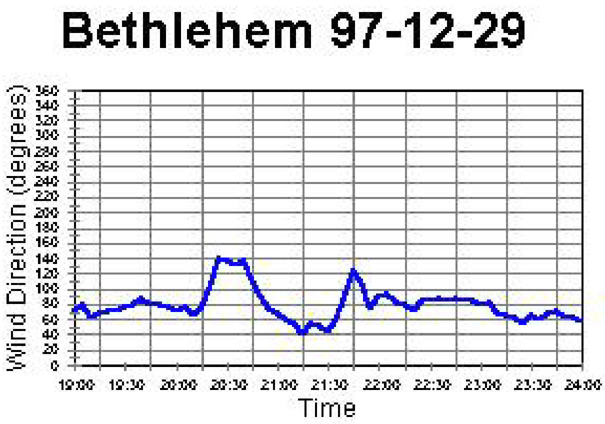

Figure 7
Wind direction (degrees) data from the AWS for Bethlehem from 19:00 to 24:00 on 29 December 1997

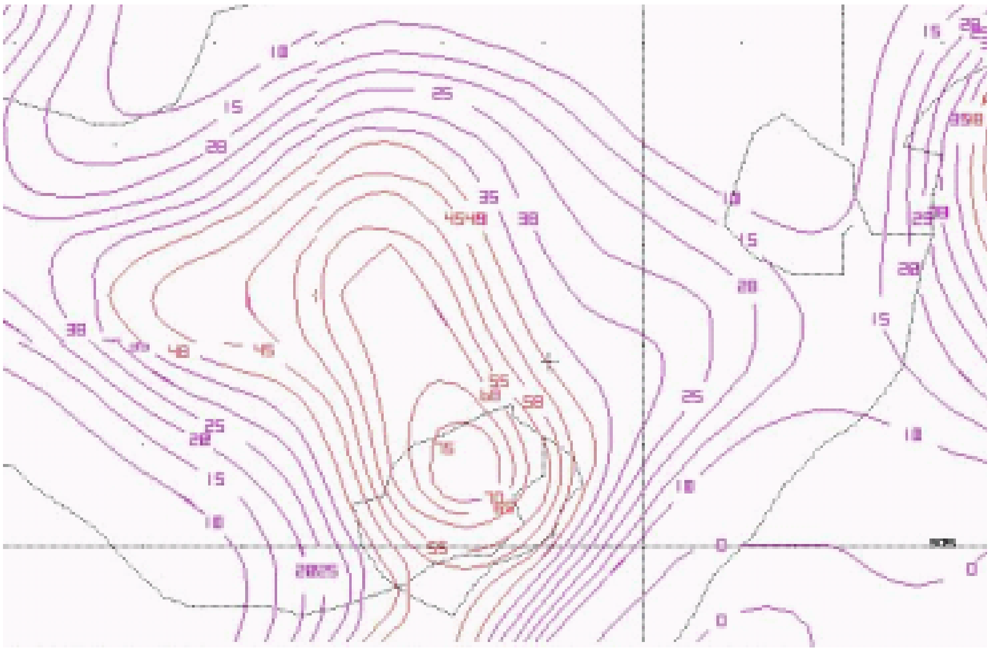

Figure 8
Eta model 6 h forecast field for Bulk Richardson number (interval 3), valid for 29 December 1997 at 20:00

cloud patterns associated with the storm showed a wedge shape, which is favourable for the development of heavy precipitation (Conway, 1997; Bader et al., 1995).

Bethlehem's 5 min AWS data between 19:00 and 24:00

An AWS averages wind speed over a 10 min time interval, with the data being logged every 5 min (bottom line in Fig. 6).The gust is measured as an instantaneous maximum gust (top line in Fig. 6). Although there was a steady increase in average wind speed leading up to the passage of the storm over the Bethlehem Weather Office, the most significant indication of the storms presence was the marked increase in the wind gusts at 20:15. The wind direction veered by about 80° as the storm moved over the Bethlehem Weather Office (around 20:15) and maintained this direction for approximately 25 min before backing to its original direction again at 21:15.

Temperature and relative humidity values are averaged over 5 min periods by an AWS. A significant drop in temperature coincided with the passage of the storm at the Bethlehem Weather Office. At around 20:20 the temperature dropped by nearly 3°C within 5 min. At the same time the relative humidity showed a marked increase, but never reached 100% due to the relatively little liquid precipitation. Once the storm had passed, the temperature again increased.

The onset of precipitation was in the form of a short shower at 20:20, with 6.8 mm recorded in 5 min and another 6 mm during the following 10 min, thereafter the precipitation decreased significantly. The total precipitation for the evening amounted to 18.8 mm.

The analysis of Bethlehem's 14:00 upper air temperature and humidity profiles (there were no wind data available for this sounding) showed that the atmosphere in the lowest 300 m was unstable, above it up to 3 km, it was conditionally unstable and above 3 km stable. A strong inversion existed, which means that an air parcel's ascent would have been limited due to subsiding air in the upper layers of the atmosphere. Convective available potential energy (CAPE) represents the amount of buoyant energy available to accelerate a parcel vertically (Louisville Science Page, hereafter LSP). CAPE values at Bethlehem were very low (66 $J \cdot kg^{-1}$). The

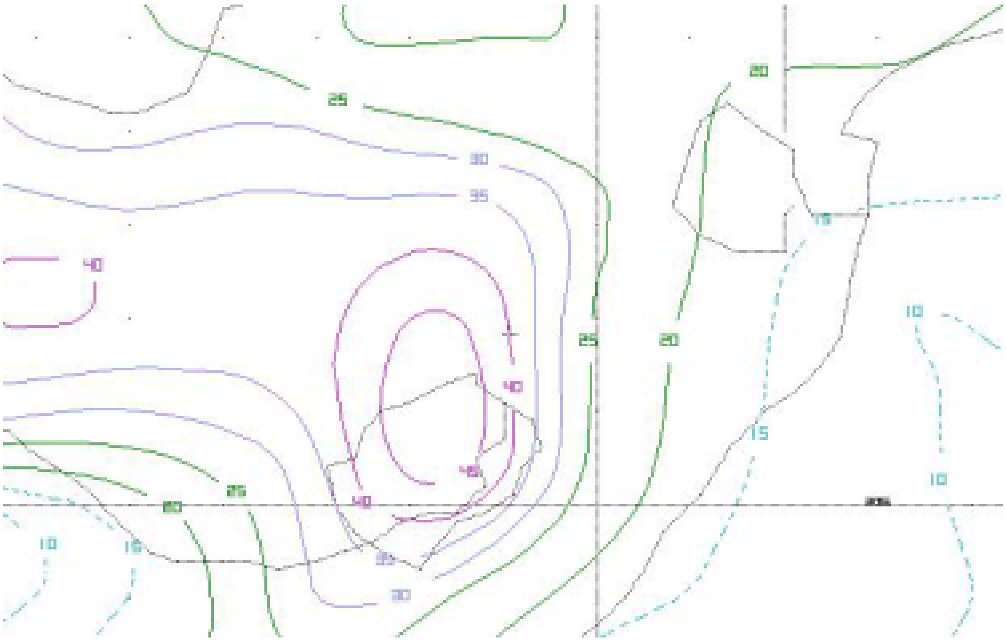

Figure 9
Eta model 6 h forecast field for SWEAT Index (interval 50), valid for 29 December 1997 at 20:00

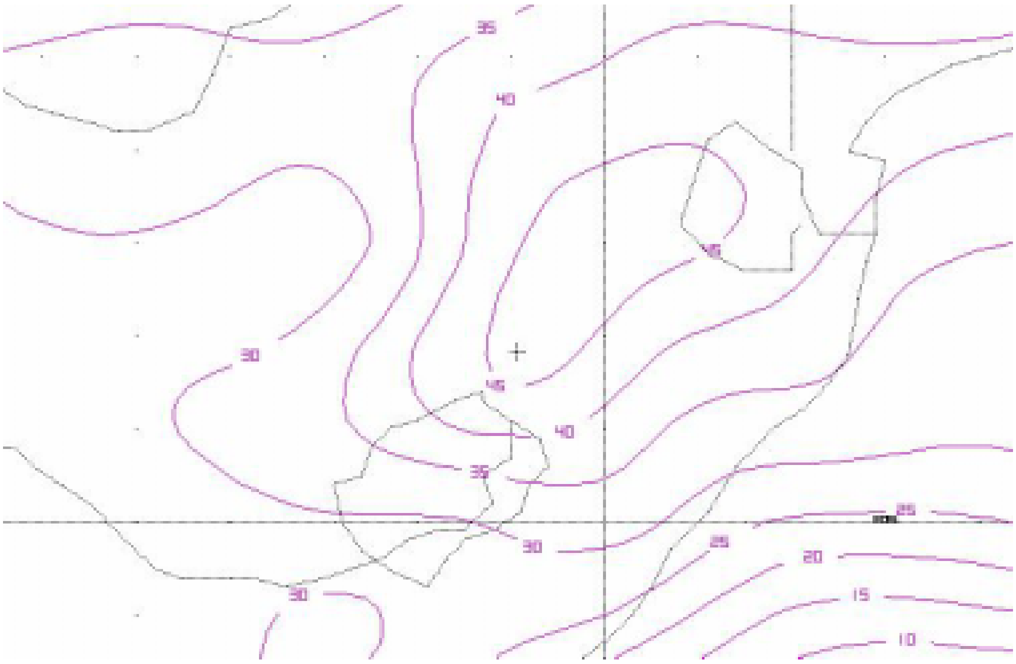

Figure 10
Eta model 6 h forecast field for vertical wind shear (interval 0.5 x 10^{-3} s^{-1}), valid for 29 December 1997 at 20:00

Lifted Index measures the difference between a parcel's temperature compared with the environmental temperature at 500 hPa, after the parcel had been lifted from the lifting condensation level (LCL) (AWS, 1990). In this case the Lifted Index was -1 which is considered to be marginally unstable (LSP). The maximum vertical velocity of the potential convective updraft calculated by the RAOB software was 11 m·s^{-1}. It is calculated as the square root of twice the CAPE value and CAPE values of 1500 to 2500 J·kg^{-1} give a maximum updraft velocity of 50 to 70 m·s^{-1} (LSP). This value does not take into account the fact that entrainment and mixing occur and is thus overestimated and should be halved to obtain a more realistic value (LSP).

Bloemfontein's ascent was much more favourable for development with a CAPE value of 2 458 J·kg^{-1}. A CAPE value greater than 1 500 J·kg^{-1} is suggested by Rasmussen and Wilhelmson (1983) as being necessary for supercells to form, but Johns and Doswell (1992) found that a number of supercells over the United States also arise in situations with CAPE values less than 1 500 J·kg^{-1}. There was no inversion present at Bloemfontein, while the Lifted Index was -7.6 (very unstable, LSP). The **Showlater Index** is calculated by lifting a parcel dry adiabatically from 850 hPa to its LCL, then moist adiabatically to 500 hPa and comparing the parcel versus environmental 500 hPa temperature (LSP). For Bloemfontein the Showalter Indexwas -2.2 (moderately unstable, LSP). The lowest

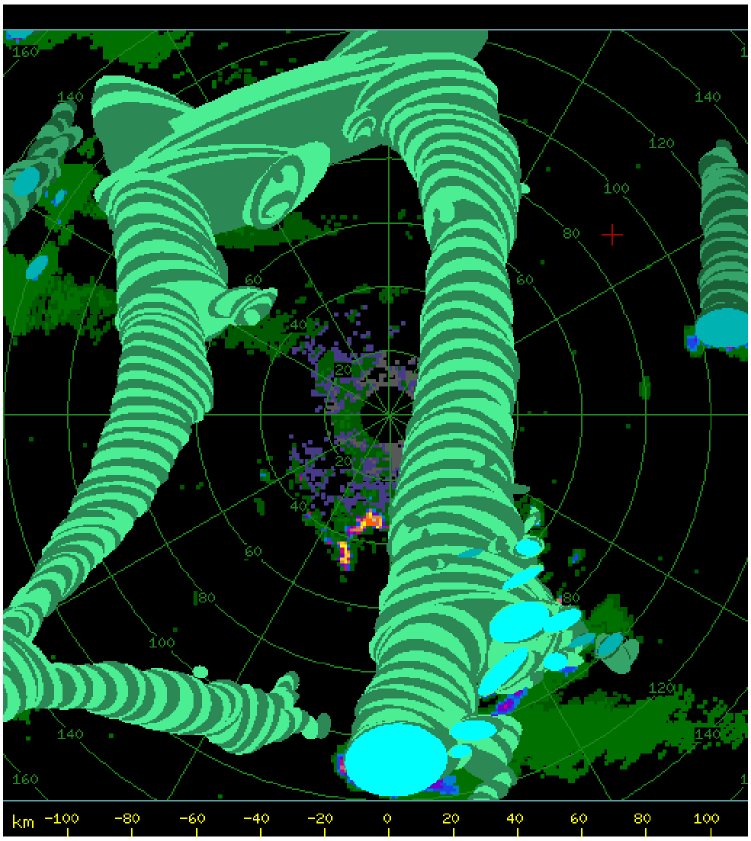

Figure 11

Storm tracking showing the passage of the storm by means of 30 dBz volume scans taken at ~ 5 min intervals from south to north and the mainly connected core of uniform size

700 m of the atmosphere was unstable, the next 4 km conditionally unstable and above that predominantly stable. The maximum vertical velocity for the potential convective updraft according to RAOB software was 70 m·s^{-1}, which more realistically implies 35 m·s^{-1}. The level of zero wet bulb potential temperature was around 2 500 m for both Bethlehem and Bloemfontein, which is favourable for large hail production (LSP).

The forecast issued by the Central Forecasting Office in Pretoria on that day included isolated to scattered thundershowers over the region of interest.

Eta model analysis

Due to the insufficient upper-air data provided by upper-air soundings, the Eta model's 3 and 6 h forecasts were utilised to get additional information about the instability and severe weather potential of the atmosphere. The midday run (starting at 14:00) was used to obtain forecasts for late afternoon (3 h forecast is for 17:00) and early evening (6 h forecast is for 20:00). The charts displayed here (Fig. 8 to 10) are of the eastern parts of the country and Bethlehem's location is indicated by a cross (+).

The **Bulk Richardson Number** (BRN) is used to quantify the relationship between buoyant energy and vertical wind shear (Weisman and Klemp, 1982), both of which are critical factors in determining storm development, evolution and organisation. The Eta model calculated BRN values of 20 to 60 for 17:00 for an area south of Lesotho. Later that evening, at 20:00, BRN at Bethlehem was 40 (Fig. 8). This is in the range that is favourable for supercell development (Moller et al. 1994).

Miller (1972) introduced the **Total Totals Index** for identifying areas of potential thunderstorm development. It accounts for both static stability as well as the presence of 850 hPa moisture. For 17:00 the Total Totals Index was forecast as 56 south-east of Lesotho and between 55 and 60 at 20:00. These values are viewed as favourable for the development of strong to severe thunderstorms (AWS , 1990).

The **K-index** is a measure of thunderstorm potential based on vertical temperature lapse rate, moisture content of the lower atmosphere and vertical extent of the moist layer (AWS, 1990). For 17:00 the K-index was more than 40 in the region of development and more than 44 at 20:00. Values above 40 are viewed as the best potential for thunderstorms with heavy rain (AWS, 1990).

The **CAPE** values forecast by the model were between 1 000 and 1 500 J·kg^{1} at the relevant times over the area of interest. The **maximum updraft velocity** values southeast of Lesotho were >45 m·s^{-1} at 17:00 as well as at 20:00 which are reasonable values for thunderstorm development.

The **Showlater Index** was calculated from 800 hPa instead of 850 hPa for the purpose of this article, since Bethlehem's surface pressure is 840 hPa. The values predicted by the model were in the order of -4 south-east of Lesotho at 17:00 and -4 to -6 in the Bethlehem region at 20:00. These values indicate the possibility for severe thunderstorms (AWS, 1990).

The **Lifted Index** values varied between -4 (at 17:00) and -5 (at 20:00) which indicates moderately unstable conditions (LSP).

The **SWEAT Index** evaluates the potential for severe weather by combining several instability parameters like low level moisture, instability, low level jet, upper level jet and warm advection into one index (AWS, 1990). The predicted values were 350 to 400 at 17:00 and more than 400 at 20:00 (Fig. 9). This would indicate the possibility of strong or extreme thunderstorm development (LSP) because values between 300 and 400 are given as adequate for severe thunderstorms.

Layer weighted vertical wind shear calculated for the cloud layer (700 to 250 hPa, as per thermodynamic diagram at Bethlehem), at 17:00 was between 2.5 and 3 x 10^{-3}s^{-1} southeast of Lesotho and between 3.5 and 4.0 x 10^{-3}s^{-1} at 20:00 (Fig. 10). These values are consistent with well-documented supercell environments according to Marwitz (1972).

The 3 h forecast (for 17:00) of **surface layer moisture flux convergence** showed that moisture was converging in the area where the storm developed. This situation improved towards 20:00 when the moisture flux convergence was also combined with 700 hPa upward motion.

Radar interpretation by means of TITAN and CIDD

Using TITAN/CIDD tracking facilities the 30 dBz volume scans taken at ~5 min intervals are fitted into a composite field. From

Fig. 11 it is clear that the storm moved in a northerly direction due to the alignment of the topography as well as the upper air winds which changed from west-southwesterly at 14:00 on the 29th to southerly at 02:00 on the 30th. The storm cloud was mainly a connected, continuous core which lasted for more than an hour.

The storm developed south of Lesotho and moved in a north-easterly direction initially. At 16:05 the storm was visible on the southern part of the radar image, and 55 dBz reflectivities were already evident. At this stage the storm tops were above 16 km. Lemon and Doswell (1979) stated that during the first stage of supercell formation the left rear flank of the storm (in the southern hemisphere) develops a mid-level overhang and weak echo region (WER). This overhang is the consequence of a strong, persistent updraft and correspondingly strong divergence in the upper layers. At 19:09 the storm moved into South Africa (from Lesotho) and a WER could be distinguished on a vertical cross section through the storm. At 20:05 maximum reflectivities reached the lower levels of the storm and strong reflectivity gradients were also evident on the north-western flank of the storm. According to Lemon and Doswell (1979) the second stage of the supercell life cycle is most clearly defined when a bounded WER (or BWER) is detected. This is an indication of increasing water and ice content around the core of the updraft and also of continued updraft intensification. A mesocyclone usually forms at this stage. A vault, associated with a strong updraft region, and a BWER were visible at 20:55 (Fig. 12a) on the northern side of the storm. The existence of a mesocyclone cannot be accurately verified without Doppler radar, but by using CIDD at the 3 km CAPPI level in a time loop, weak signs of a cyclonic rotation (Fig. 12b) could be seen. Also evident in the 3 km CAPPI at 20:55 in Fig. 12b is the hook echo on the northern side of the storm. This pattern correlates well with the hodograph model for a supercell shown in Fig. 5. The horizontal extent of the storm was about 5 km at 21:03, after which it gradually dissipated.

Summary

According to Moller et al. (1994) **supercell** characteristics can be summarised as:

- Supercells are 'steady state' convective storms
- A supercell is a single, continuous cell
- Supercells have deviate motion, although this is not an absolute prerequisite
- Supercells have a deep, persistent mesocyclone and a BWER.

Mesocyclones are defined (Moller et al., 1994) as having vertical vorticity greater than or equal to $10^{-2}\ s^{-1}$, lifetimes at least on the order of tens of minutes and are present through a substantial fraction (more than a third) of the storm's depth. Burgess (1990) was of the opinion that it is extremely unlikely for a convective storm with a *bona fide* BWER NOT to have a mesocyclone.

The storm on 29 December 1997 displayed the following radar characteristics:

- High reflectivities (>60 dBz)
- A mainly connected core for longer than an hour
- A WER and BWER visible
- A hook echo on the northern flank
- A possible mesocyclonic circulation
- Good correlation with typical Southern Hemisphere cyclonic supercell hodograph.

All of these point toward a good correlation with the typical characteristics of a supercell environment based on findings by Moller et al. (1994).

Marwitz (1972) summarised the **environmental conditions surrounding supercells** as:

- Severe thermal instabilities with a thermal buoyancy at 500 hPa of +4°C
- The mean subcloud environmental winds are strong (>10 $m{\cdot}s^{-1}$) and veer by 60° from the mean environmental winds, with more than 50° veering within the subcloud layer
- The environmental wind shear through the cloud layer is strong (2.5 to 4.5 $x10^{-3}\ s^{-1}$), but not extreme.

Moller et al. (1994) said that the lift needed to initiate deep, moist convection in supercell environments is provided by mesoscale or storm-scale processes (including drylines).

The 5 min AWS data at Bethlehem showed that the average wind speed was between 8 and 10 $m{\cdot}s^{-1}$ during the storm and dropped to 4 $m{\cdot}s^{-1}$ after the passage of the storm. Wind gusts of up to 16 $m{\cdot}s^{-1}$ were, however, measured during the storm. The wind direction veered from 66° to 140° (>70°) during the storm and then backed to 40°. This is in agreement with Marwitz' ideas of subcloud layer wind direction and speed for supercell environments. Confirming the prerequisite with regard to moisture content (Moller et al., 1994), it was clear that Bethlehem had ample moisture (relative humidity > 70% prior to the storm, increasing to 90% during the storm).

Using the Eta model's output of instability parameters for 3 and 6 h predictions, it was clear that an above-normal thunderstorm could develop in the area where the storm occurred. More than one of the indicators had values which would take thunderstorm development into the strong or extreme category. The Showalter indices for the relevant area and time were between -4 and -6 for the 800 to 500 hPa layer. This gives the buoyancy required according to Marwitz (1972) for supercell environments. The vertical wind shear values in the cloud layer were in close agreement with Marwitz's ideas for vertical wind shear in the cloud layer and ideal for supercell development.

Examination of the storm features and environment on 29 December 1997 showed that steep pressure, temperature and dewpoint gradients were evident in the area where the storm developed and moved to. This is in agreement with Moller et al. (1994) ideas about supercells developing due to mesoscale boundary forcing (like drylines). Bluestein and Crawford (1998) presented evidence from two case studies that an isolated supercell formed along a dryline in a region of elevated terrain. They argued that when a number of storms are initiated along a dryline, the most severe activity may be associated with those cells initiated over higher terrain. The steep gradient in dewpoint temperatures (or the so-called dryline) which was present in the area along with the proximity of the Drakensberg to the east of the storm proved to be important role players in this case.

Conclusions

Based on all the above-mentioned information, the authors believe that this could well be one of the few rare supercell events over South Africa. The Eta model's 3 and 6 h forecasts provided good indicators of the severe weather potential of that evening and by using the mesoscale analyses and radar tools like TITAN and CIDD, it would have been possible to monitor the real time development and movement of the storm. Without the optimal utilisation of the mentioned tools and methodologies, it would not be possible for operational forecasters in South Africa to recognise and forecast severe weather events such as the one described in this article.

One of the aims of the recently developed research programmes in the South African Weather Bureau - the Weather Forecasting Research (WFR) Programme - is to gain knowledge and to develop tools in order to improve forecasting accuracy of severe weather events. Some of the key elements in this kind of research is to have enough observations (surface and upper-air) and good radar coverage. Although conventional radars can be a great help, the future of severe weather forecasting lies in Doppler radar. Meteorologists in the USA can detect the existence of mesocyclones and tornadoes by merely looking at the screen since built-in algorithms exist to identify these phenomena.

Further case studies and relevant software (composite radar imagery, better quality satellite imagery, CIDD and RAOB) will be utilised by the WFR programme to provide the vital ingredients to successful mesoscale and severe weather forecasting in South Africa with our limited resources.

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NB

The printing costs of printing Figs. 1 (p. 138) and 12 (p. 146) in full colour are borne by the authors.

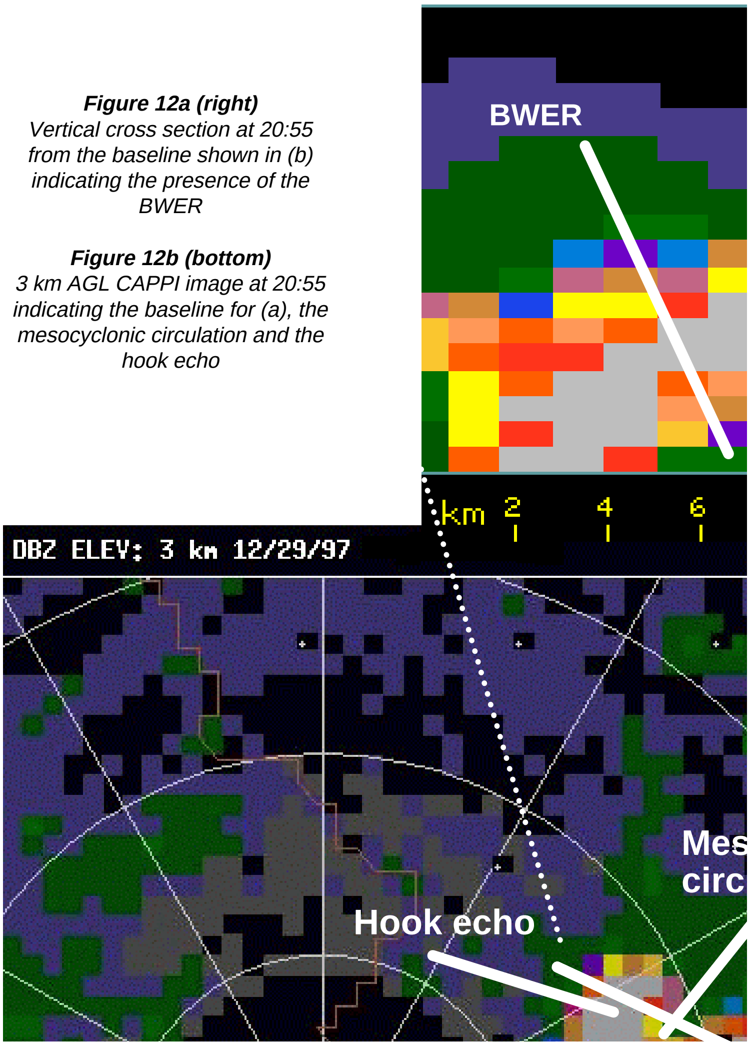

Figure 12a (right)
Vertical cross section at 20:55 from the baseline shown in (b) indicating the presence of the BWER

Figure 12b (bottom)
3 km AGL CAPPI image at 20:55 indicating the baseline for (a), the mesocyclonic circulation and the hook echo