Comparisons of hail kinetic energy derived from radar reflectivity with crop damage reports over the eastern Free State

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Abstract

Hail kinetic energy (HKE) derived from radar reflectivity is used to identify hail on the ground over the eastern Free State. The location of crop damage reports is used for validation. Three case studies on days with the highest crop damage claims are analysed. HKE corresponds well with hail on the ground under moist atmospheric convective development, but failed to detect hail under dry atmospheric convective development. The duration and intensity of hail events above farms are also analysed. Several reflectivity threshold levels for hail identification were investigated. A threshold between 45 dBZ and 50 dBZ with a scaling factor resulted in the best correlation between HKE and crop damage location, while a reflectivity cut-off at 50 dBZ or 55 dBZ underestimated hail occurrence.

Introduction

Convective storms, also known as thunderstorms, are an almost daily occurrence over the summer rainfall regions of Southern Africa. Despite their generally short duration of less than an hour over a location, they are responsible for significant damage and interference in the lives of humans. Hail spawned from these storms destroys approximately 2.1% of the total annual agricultural production in South Africa (Theron et al., 1973) and causes millions of Rands in property damage. On average, locations over the eastern Free State receive between 3 and 5 hail days per year. This increases to between 5 and 7 d over the southern and eastern regions of the eastern Free State (Le Roux and Olivier, 1996).

Carte and Held (1978) studied convective storms over the Witwatersrand area and observed hail to be produced by single, multicell storms and linear arrays of thunderstorms. Most of the multicell storms (77%) propagated to the left or front of the existing storm. These convective storms are often responsible for significant hail damage, gusting winds and flash floods (Held, 1981). Research on the frequency and distribution of hail was done with the help of close to a thousand volunteers, distributed over the Witwatersrand area, reporting hail sizes and location during 1960-1970 (Carte and Kidder, 1970; Carte and Basson, 1970).

A hail suppression project initiated in December 1971 in the Nelspruit area of Mpumalanga, used the strict guideline of the height of the 45 dBZ contour exceeding 7.5 km for the identification of hail storms (Mather et al., 1976). This guideline was expanded by Held (1978) to include cloud top height and temperature for identifying severe hail storms. However, no such strict relationship for the height of the 45 dBZ contour and cloud tops was found and it was concluded that most likely a variety of characteristics must be used to separate hail and no-hail convective storms. Carte and Held (1978) found that in 86% of hail storms a strong horizontal reflectivity gradient existed, but that the use of echo characteristics are not reliable in determining the probability of hail. This was further illustrated when two apparently similar storms were investigated, one causing a cloudburst and the other severe hail (Held, 1981).

The detection of hail is difficult due to the complex spatial distribution and temporal distribution of hail. The most common method used to measure hail was by means of extensive hailpad networks (Sleusener and Jennings 1960; Changnon, 1977). Hailpads were used to identify location, hail distribution sizes and impact kinetic energy. Hailpad data are limited by instrumental problems due to the saturation of the pads, physical problems due to unknown hail shapes and drag, and statistical problems as to the representivity of the hailpad to the events in the nearby area (Waldvogel et al., 1978b). To operate such an extensive network requires a large logistical effort at large cost.

The use of radar to detect hail was found to be a very feasible option in comparison to operating a hailpad network. The comparison between HKE($\dot{E}$) ($J \cdot m^{-2} \cdot s^{-1}$) and radar reflectivity (Z) was extensively researched by Waldvogel et al. (1978a; b). Assuming Rayleigh scattering of cloud particles and an exponential hail distribution spectrum, semi-empirical and theoretical estimates of this relationship were made from several case studies. This resulted in a HKE-Z relationship:

$$E = 5.0 \times 10^{-6} Z^{0.840} \quad (1)$$

with dBZ defined as 10 log Z. The empirical relationship is similar to the well-known Z-R relationships (Marshal and Palmer, 1948). Waldvogel et al. (1978a; b) concluded that Z-E relationships between different hailstorms show surprisingly similar behaviour and that such a relationship is within 25% of the real energy values at a point. Geotis (1963) found the 55 dBZ surface contour to be a good cut-off for hail detection on the ground in New England. Similar results using hailpads, hail spectrometers and radar reflectivity with a 60 dBZ cut-off for hail, provided the best criteria for Switzerland as determined by Waldvogel et al. (1978a). Wotjic and Ewing (1983) did several comparisons between hail and crop damage and found the best relationship at 49 dBZ. It is thus clear

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that the cut-off value for comparing HKE with reflectivity might be climatologically dependent. By making use of threshold with a scaling factor between 55 and 65 dBZ and a cut-off threshold at 60 dBZ, Waldvogel et al. (1981) presented very similar correlations between radar reflectivity and hailpads. When the displacement of radar elements at the surface due to storm movement was included, this correlation improved to 0.9. This was reaffirmed by Schmid et al. (1992) who concluded that a conventional hail-measuring network could be replaced by a S-band radar and that it could be used for the verification of hail prediction models. He also suggested that this method is equal in its validation of hail occurrence to more sophisticated dual-polarisation radar methods.

Studies relating crop damage with HKE (Wotjic and Ewing, 1983; 1985) followed and arrived at correlations of 0.75 between time integrated reflectivity and percentage crop damage. A complete study of hail damage on various crops by Schiesser (1990), making use of total hail kinetic energy (THKE) by integrating HKE with time, established a non-linear damage function. He used THKE against percentage crop damage and estimated possible crop damage from radar reflectivity measurement in real time. No comparisons have been done in South Africa, regarding the use of THKE as detector of hail.

For the hail growth process to be efficient, Browning and Ludlam (1960; 1962) developed the concept of a combination of vertical wind shear and a tilted updraft, enabling the updraft and downdraft to be maintained continuously without serious interference. According to a numerical model (Foote, 1984), hail stone sizes were randomly spread where radar reflectivity exceeded 50 dBZ. The preference of hail fall-out coinciding with high reflectivity regions of storms was also detected by Nelson (1983). HKE fields calculations take this important factor into account.

The MRL-5 dual wavelength weather radar (X and S band) is owned by the Water Research Commission and is located 20 km northwest of the town Bethlehem, in the eastern Free State. Owing to the cost of infrastructure involved in hail studies, projects of this nature have not been attempted for several years. The utilisation of S-band weather radar for the determination of HKE needs to be investigated to determine the applicability of HKE for hail estimates. The climatological dependancy of HKE has already been mentioned. This study investigates how well HKE fields represent the presence of hail damage at the surface for the eastern Free State.

Data and methods

Wheat is extensively cultivated in the region and represented most of the crop damage reported to insurers. The three days with the highest amount of crop damage during the 1995/96 summer season, 16 October 1995, 28 November 1995 and 22 December 1995, were selected for this analysis. On all these days the upper air soundings at 1 200 Z displayed significant unstability above the level of free convection. The troposphere was relatively moist with relative humidity at 500 hPa above 50% on 28 November 1995 and 22 December 1995. These days were characterised by scattered convective development over the region. On 16 October 1995 the layer above 650 hPa was dry with relative humidity below 30% at 500 hPa, resulting in only isolated convective development. Multicellular storms caused most of the crop damages and lasted for several hours. The trajectories of the severe storms in all the cases were from southwest to northeast and deviated to the left of the 500 hPa wind flow.

TABLE 1
RADAR CHARACTERISTICS OF MRL-5 RADAR

	X-Band	S-Band
Receiver sensitivity	-104 dBm	-106 dBm
Receiver dynamic range	70 dB	70 dB
Transmitter frequency	9.603 GHz	2.954 GHz
Pulse duration	2 µs 1µs	2 µs 1µs
Peak transmitter power	200 kW	600 kW
	200 kW	600 kW
Pulse repetition frequency	250 Hz	250 Hz
	500 Hz	500 Hz
Pulse coincidence	within 0.2 µs	within 0.2 µs
Antenna gain	40 dB	39 dB
Side lobes	> 22 dB down	> 22 dB down
Beamwidth	1.5° at 3 dB	1.5° at 3 dB
	one-way points	one-way points
Polarisation	Vertical	Horizontal

The MRL-5 weather radar

The S-band reflectivity data from the dual-wavelength MRL-5 radar were used in this investigation. The radar characteristics are shown in Table 1. Antenna control for volume scanning capabilities, data storage and processing are done with RDAS (radar data acquisition system) (Terblanche et al., 1994). The radar was set to execute 18 elevation steps with base scan at 1.5° and top scan at 55°. The radar range used for data storage was set to 146.6 km. An initial skip of 80 µs is used, resulting in a blank range 12 km around the radar. The azimuth rotation speed was set to 5.2 $r \cdot min^{-1}$, resulting in the completion of the volume scans in less than 5 min.

Crop damage reports

Crop damage reports from the crop insurance company SENTRAOES were used in this study to identify the location of hail reports. Data provided by SENTRAOES were:

- date of crop damage
- farm name
- approximate time of hail occurrence
- amount claimed
- daily amount per district of the type of crop damaged by hail.

The data used were for the period September to December 1995, in the districts covered by the MRL-5 radar. Several farms could not be located on the topographical maps and had to be excluded from the study. No information on the size or the percentage of crop damage were available. The time when hail damage was inflicted on the produce was not of prime importance to the data collectors and often did not correspond with radar-determined time of hail.

Calculation of hail kinetic energy

Three different radar reflectivity thresholds is used to compare THKE with locations of crop damage. The threshold is used to differentiate between hail and rain. The first threshold uses a scaling function F(Z) in the HKE calculation. It is assumed here that radar reflectivity between 46 and 49 dBZ, originates from a combination of liquid water droplets and of hail. Reflectivity of

TABLE 2
HKE(E) VALUES FOR SPECIFIC RADAR REFLECTIVITY (dBZ)

dBZ	45	48	51	53	57	60	63	66	69
$\dot{E}$ $J \cdot m^{-2} \cdot s^{-1}$	0.0	0.032	0.096	0.172	0.307	0.548	0.979	1.749	3.12

50 dBZ and higher is assumed here to be resulting only from hail with no liquid water present. The scaling function is thus:

$$F(dBZ) = \begin{cases} 0 \text{ if } dBZ < 46 \\ (dBZ - 45) \times 0.2 \text{ if } 45 \leq dBZ \leq 50 \\ 1 \text{if } Z > 50 \end{cases} \qquad (2)$$

resulting in the following equation exclusively used in this study for determining HKE ($J \cdot m^{-2} \cdot s^{-1}$):

$$\dot{E} = 5.0 \times 10^{-6} \; F(Z) \; Z^{0.840} \qquad (3)$$

The second radar reflectivity threshold used for HKE calculations was 50 dBZ and the third threshold was 55 dBZ.

The HKE is calculated from radar reflectivity using values at the 4 km CAPPIs (constant altitude plan position indicator) or higher levels, depending on the range. Higher altitude CAPPI levels than 4 km are used in cases where the 4 km CAPPI is below the radar base scan at 1.5°. Table 2 presents the values for HKE for specific radar reflectivity as used with the sloping threshold.

THKE ($J \cdot m^{-2}$), E in Eq. (4), is determined by integrating the HKE in time. The period in time is the length in seconds the storm remained active above a point.

$$E = \int \dot{E} \, dt \qquad (4)$$

THKE represents the total amount of kinetic energy supplied at the ground during the passage of a storm over a location. THKE fields were generated for each of the 3 d evaluated. The HKE fields were integrated over the period when the convective storms were positioned over the farms. The maximum THKE value in a 3 x 3 min horizontal grid with the farm location at the centre was used as the representative HKE value.

Crop damage reports

Farmers sustained close to R1 m. of crop damage on 16 October 1995. Most of this occurred in the Ficksburg and Fouriesburg districts. In the Ficksburg district, damage to apple orchards of between 97 and 99%, peaches between 32 and 100% and wheat between 17 and 70%, was caused by hail. In contrast to other case studies, wheat was responsible for less than half the total amount. Of the 23 farms that reported damage on this day, 17 were located on topographical maps. Table 3 shows the amount of damage per district, the distribution of claims per district and the number of farms located on the topographical maps.

TABLE 3
DAMAGE AMOUNT SUSTAINED PER DISTRICT AND NUMBER OF FARMS WHICH REPORTED CROP DAMAGE PER DISTRICT ON 16 OCTOBER 1995

District	Amount of crop damage reported	Number of farms that indicated crop damage	Number of farms located with crop damage
Bethlehem	R27 000	3	2
Ficksburg	R689 000	14	10
Fouriesburg	R180 000	4	3
Senekal	R4 600	2	2

Hail damage to the value of R5.5 m. was reported to SENTRAOES for damage sustained on 28 November 1995. This day was the most damaging hail day of the 1995/1996 summer season in the eastern Free State. Crops affected were mainly wheat, while about R200 000 worth of claims were received due to damage to other crops, such as maize and sunflower. Table 4 lists the amount of crop damage reported by farms per district as well as the number of farms reporting against the number identified on the topographical maps. Most of the damage occurred in the magisterial districts of Senekal and Bethlehem. Of the 149 farms which reported damage in the Bethlehem districts, only 62 could be located on the topographical maps. Thirty-seven out of a total of 66 were located in the Senekal district. Two farms with the same names in the same district were located on the topographical map. The farmers were contacted where possible to clarify the location of the farm.

TABLE 4
DAMAGE AMOUNT SUSTAINED PER DISTRICT AND NUMBER OF FARMS WHICH REPORTED CROP DAMAGE PER DISTRICT ON 28 NOVEMBER 1995

District	Damage amount in Rands	Number of farms with crop damage	Number of farms in district located with crop damage
Bethlehem	R3 200 000	149	62
Kroonstad	R12 000	1	1
Ficksburg	R680 000	10	7
Fouriesburg	R40 000	4	3
Senekal	R1 250 000	66	37
Lindley	R53 000	2	0
Reitz	R150 000	11	7
Harrismith	R250 000	16	11

Crop damage totalling R4 m. was reported on 22 December 1995. Damage in the district of Lindley was the highest, followed by Frankfort and Senekal. Damage to the total of R400 000 was caused to maize, sunflowers and potatoes, while damage to wheat crops totalled R3.6 m. Wheat is usually harvested during December and is then very susceptible to hail. The distribution of the hail damage reports on 22 December 1995 is shown in Table 5. The hail damage reports were concentrated in the Frankfort, Senekal, Lindley and Reitz districts. A number of 64 out of a total of 184 farms could be identified on the topographical maps. From a total of 81 farms in the Lindley district, which reported crop damage on this day, only 23 farms were identified. Only 2 farms were located within the radar blank area closer than 12 km from the radar.

Results

Using the threshold with a scaling factor, 85 of the 92 farms on the 28 November 1995 case which reported hail were located within the THKE field generated. Figure 1 shows the THKE field generated with the threshold with a scaling factor and the locations of the crop damage reports for 28 November 1995. Most of the

TABLE 5
DAMAGE AMOUNT SUSTAINED PER DISTRICT AND NUMBER OF FARMS WHICH REPORTED CROP DAMAGE PER DISTRICT ON 22 DECEMBER 1995

District	Crop damage amount	Number of farms with crop damage reports	Number of farms located with crop damage reports
Heilbron	R150 000	4	1
Frankfort	R288 000	16	9
Kroonstad	R33 000	4	4
Lindley	R2 535 000	81	23
Reitz	R821 000	38	12
Senekal	R288 000	29	12
Bethlehem	R84 000	10	3
Fouriesburg	R45 000	1	0

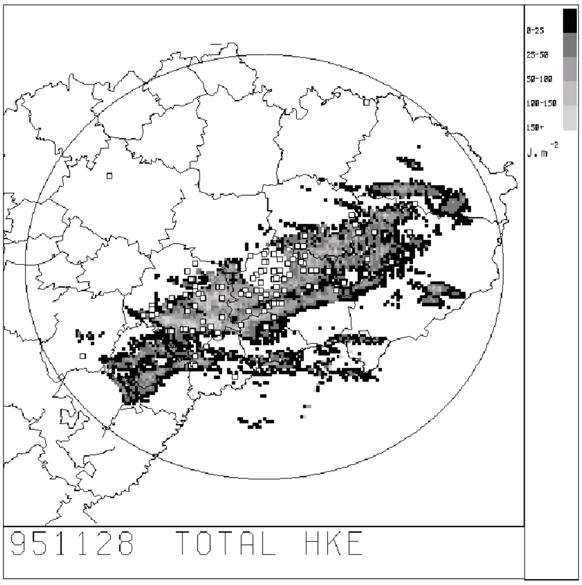

Figure 1 (top)
The THKE field determined with a threshold with a scaling factor on 28 November 1995. The squares indicate the location of the farms which reported crop damage.

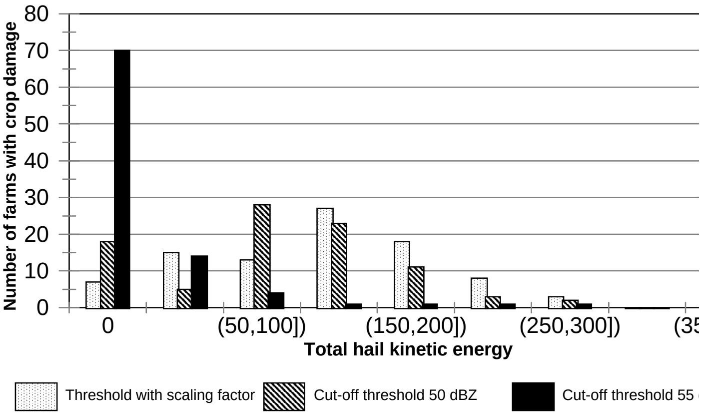

Figure 2 (left)
The distribution of THKE with a scaling factor, 50 dBZ and 55dBZ thresholds at the farms located with crop damage on 28 November 1995

farms which reported crop damage are located within close proximity of the storms footprint. One farm, located in the Kroonstad district, could not be placed in proximity of the main storm track area. The radar did not detect any significant convective development over this farm on this day. 72% of the farm locations had THKE exceeding 100 $J \cdot s^{-1}$. When a time series above the farms were analysed, some farms had a radar reflectivity exceeding 45 dBZ for close to 3 h, while maximum radar reflectivity only exceeded 55 dBZ at short intervals. The THKE was thus generated not from the severity of the storms alone, but due to the prolonged persistence of reflectivity exceeding 45 dBZ. This occurred due to continuous redevelopment of the convective storm on the rear flank of the storm complexes. This led to the continuous favourable conditions for persistent hail. The reflectivity values also indicate that the hail was most likely smaller than 15 mm in diameter. Hail of this size can still cause extensive damage to wheat. Figure 2 shows the distributions of THKE on 28 November 1995 at the farms with crop damage with the 3 radar reflectivity thresholds used. When the radar reflectivity threshold was increased to 50 dBZ, 17 of the 92 farm locations did not correlate with the THKE field. 45% of the locations has THKE exceeding 100 $J \cdot s^{-1}$. With a threshold of 55 dBZ, the detection rate fell dramatically to only 25% of the cases. Clearly, the usage of 55 dBZ as a threshold would be too strict criteria in this case.

Using the threshold with a scaling factor, 58 of the 62 farms which reported hail were located within the THKE field generated for 22 December 1995. Figure 3 shows the THKE field with the locations of the crop damage reports for 22 December 1995. 62% of the locations had THKE exceeding 100 $J \cdot s^{-1}$. The convective storm of this day, was less organised compared to the 28 November 1995 case and storms were located over the farms for less than an hour. Figure 6 shows the THKE field with the locations of the crop damage reports for 22 December 1995. Figure 4 shows the distributions of THKE for 22 December 1995 at the farms with crop damage with the 3 radar reflectivity thresholds used. When the threshold was increased to 50 dBZ, 10 farms did not correspond with the THKE field and 42% had THKE exceeding 100 $J \cdot s^{-1}$. With the threshold increased to 55 dBZ, 60% of the farms with crop damage were missed by the THKE field.

The THKE field for 16 October 1995 only corresponded with 1 out of a total of 17 farms with crop damage when a threshold with a scaling factor was used. Figure 5 shows the THKE field generated with the threshold with scaling factor and the locations of the crop damage reports for 16 October 1995. When the thresholds were increased, none of the farm locations corresponded with the THKE field. What seems more disturbing, was the fact that the farms reported damage to orchards of more than 90%. Clearly, HKE failed to detect hail at the surface in this case. Data from the automatic weather station close to Fickburg were investigated with corresponding radar data. The convective storms over the Ficksburg district, coincided with the strongest wind gusts reported for the month. This indicated strong downdrafts. It also suggests that the hail which occurred on 16 October was too small for a threshold of even 45 dBZ. The hail was, however, accompanied by surface winds gusting at 90 $km \cdot h^{-1}$. This combination of strong surface wind and small hail, could devastate orchards with small fruit.

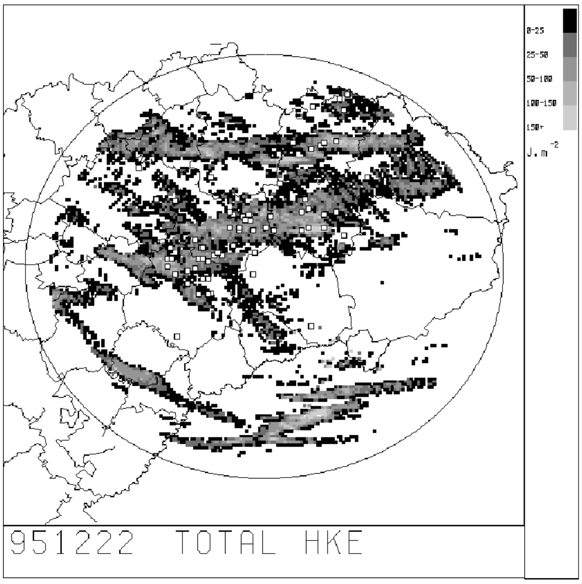

Figure 3
The THKE field determined with a threshold with a scaling factor at the farms located with crop damage on 22 December 1995. The black squares indicate the location of the farms which reported crop damage.

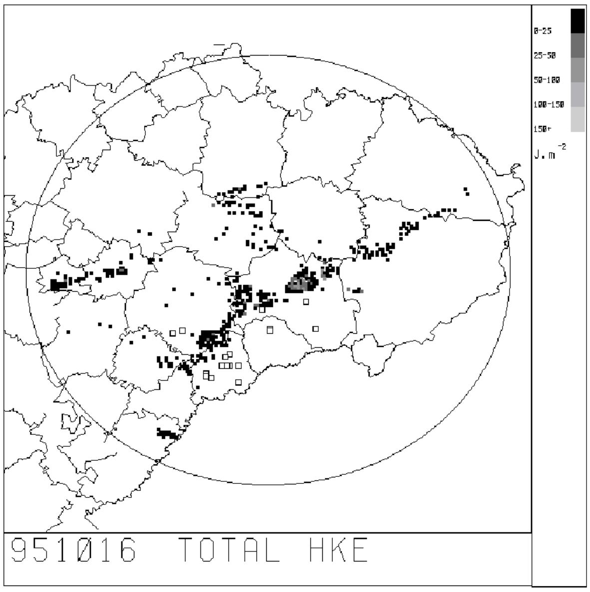

Figure 5
The THKE field determined with a threshold with a scaling factor on 16 October 1995. The black squares indicate the location of the farms which reported crop damage.

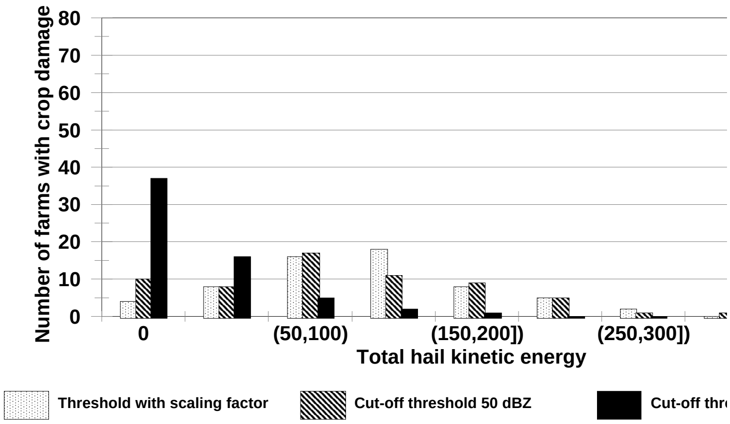

Figure 4
The distribution of THKE with a scaling factor, 50 dBZ and 55dBZ thresholds at the farms located with crop damage on 22 December 1995

Conclusions

Three cases of the most severe hail days of 1995/1996 over the eastern Free State summer season were taken to investigate the detection of hail with radar-derived HKE. Three thresholds were used to determine HKE. The threshold with a scaling factor proved to be the most reliable in detecting ground truth hail reports. However, under dry upper air circulation, such as the case of 16 October 1995, it failed to detect hail. On this day the hail was most likely too small for radar detection, but the accompanying strong winds assisted in increasing hail damage. The 55 dBZ hail threshold for HKE determinations resulted in a very poor probability of detection. Therefore rather than a fixed threshold, a threshold with a scaling factor should be used to calculate HKE. Storm structure can also play an important part in validating a convective storm as exhibiting characteristics of a hail producing storm. A combination of storm structure with HKE determination could assist in generating improved hail fields. The lack of information regarding percentage crop damage needs to be addressed and co-operation with insurance companies is needed to improve hail-crop damage relationships.

Because of the complexities of identifying hail producing convective storms, care must be taken against the utilisation of a very low radar reflectivity threshold value of 45 dBZ. Tropical precipitation with high precipitation rates can exceed 45 dBZ in reflectivity and be interpreted as hail. Information on the vertical structure of a convective storm to identify the existence of a tilted updraft could assist in isolating hail producing convective storms. This can improve the relationship between HKE and crop damage reports. As indicated by this study, a threshold of more than 50 dBZ risk the chance of missing most hail at the surface.

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