Observations of the Z_{dr} Column During Two Severe Weather Events

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Abstract

The Z_{dr} column was studied using data collected by the KOUN prototype polarimetric WSR-88D on 8 May and 9-10 May 2003 severe weather events. Eight storms were chosen for detailed study. The height above the 0°C level, width, location, maximum values of Z_{dr} within the column, and time of appearance were recorded for each of these storms. There were differences in the height of the Z_{dr} column from storm-to-storm but when beamwidth error was considered the differences were not significant. The width of the Z_{dr} column also varied from storm-to-storm, with the widest column nearly 6.3 km across and while the narrowest was 2.2 km across. When a bounded weak echo region was present, the Z_{dr} column was usually colocated with it. Z_{dr} values within the column ranged from 0.9 dB to 5 dB. Comparisons were made between the time of the first Z_{dr} column appearance and the first National Weather Service issued severe thunderstorm warnings and severe weather reports. It was found that the appearance of the Z_{dr} column preceded the first warning by 15 minutes and the first severe weather report by 39 minutes.

1. Introduction

Within the next 10 years, polarization diversity capability will be applied to the National Weather Service WSR-88D radars. For this reason, it is important that forecasters given this new technology are able to interpret observed polarimetric radar signatures. The advantages of polarimetric radar include the ability to classify hydrometeor type, distinguish nonmeteorological scatterers, and better estimate rainfall amounts (Zrnić and Ryzhkov 1999). Hydrometeor classification allows forecasters to better locate regions of different types of hydrometeors within storm.

Differential reflectivity, or Z_{dr}, is one of the base products of polarimetric radar that is valuable for distinguishing the dominant hydrometeor type in a sample volume. Z_{dr} is the ratio between horizontal and vertical reflectivity and allows better indication of the general shape and orientation of hydrometeors (Straka et al. 2000; Vivekanandan et al. 1999). For example, negative values of Z_{dr} indicate the presence of vertically-oriented hydrometeors such as graupel, while positive values indicate horizontally-oriented hydrometeors such as rain (Straka et al. 2000). For hail, as well as other spherical hydrometeors, Z_{dr} is nearly 0 dB (Aydin et al. 1986).

In most thunderstorms, positive values of Z_{dr} are found in a relatively narrow region extending above the ambient 0°C level. This is called a *Z_{dr} column*. Values of Z_{dr} within this region typically range from 1 dB to 5 dB (Straka et al. 2000). According to aircraft measurements, the Z_{dr} column usually contains large drops of liquid water and is associated with an updraft (Brandes et al. 1995). This paper explores characteristics of several Z_{dr} columns from two severe weather events and discusses the implications of the Z_{dr} columns relevant to an operational warning forecaster.

2. Data and Methodology

On 8 May and again on 9-10 May 2003, severe weather occurred across much of central Oklahoma. The Oklahoma City metropolitan area was affected by tornadoes on two consecutive days. A total of eight storms from both events are examined in this study (Figure 1), including two left-moving storms, four right-moving storms, and two failed storms (Table 1). A failed storm was defined as a storm that did not go on to produce reported severe weather. On 8 May, one isolated right-moving supercell produced most of the severe weather, but there was also one report of hail from a short-lived left-moving storm that split from the parent supercell. The dominant right-moving supercell went on to produce a long-track F4 tornado that began in Moore, moved through southeast Oklahoma City, and finally dissipated in Choctaw. 9-10 May were characterized by numerous splitting supercells, many of which contained large hail. As the event evolved, one right-moving supercell became dominant and produced an F3 tornado from Edmond to Luther. Polarimetric radar data were collected during the course of both severe weather events with the KOUN prototype polarimetric WSR-88D using 15 quasi-horizontal scans stepped in elevation angle. The data were collected during the Joint Polarization Experiment (JPOLE) in 2003. There were six minutes between volume scans.

For each storm, observations of the Z_{dr} column were made using the Warning Decision Support System – Integrated Information (WDSS-II) program (Lakshmanan 2002). These observations included the maximum height above the 0°C level, width, location relative to other features in the storm, time of appearance, and maximum Z_{dr}

values within the column at each elevation. Observations were only taken while a storm was within 120 km of the radar because of the increasing height of the beam with greater distance from the radar. The times of the observations were then compared with the first warnings issued by the National Weather Service Weather Forecast Office (WFO) in Norman, Oklahoma. The times were also compared to the first severe weather reports. Z_{dr} columns were compared between storms. The height of the 0°C level was determined by soundings from Norman, Oklahoma at 00Z on 9 May and from 00Z on 10 May. The severe weather reports were obtained from the National Climate Data Center Publication Storm Data.

Membership functions (Straka et al. 2000) were used to determine whether any positive Z_{dr} values above the 0°C level were in fact liquid water (Figure 2). In this case, the membership functions for horizontal reflectivity (Z_h) and differential reflectivity from a prototype hydrometeor classification algorithm. The categories containing liquid water were big drops, rain, heavy rain, and a mixture of rain and hail. First, Z_h and Z_{dr} in the region of interest were noted. Next, the corresponding weights were found in each of the four categories for both Z_h and Z_{dr}. The two weights from each category were then averaged together and the category with the greatest average was chosen. If the resulting average was greater than 0.6, the region was considered to contain liquid water, but if it was less than 0.4 it was considered to contain no liquid water. If the average was between 0.4 and 0.6 then it was not known if the region contained liquid water. To be confident of the existence of liquid water, the membership functions for the correlation coefficient, ρ_{hv}, were used and the corresponding weight was used in the overall average.

After the final average, only values greater than 0.5 were considered to contain liquid water and thus be defined as part of the Z_{dr} column.

3. Results

One of the properties of each Z_{dr} column examined was the horizontal width. There were large storm-to-storm differences in the width of the Z_{dr} column. The width of the Z_{dr} column in the 8 May tornadic supercell was a maximum of 6.3 km wide and was the widest of all the observed storms. For comparison, the width of the Z_{dr} column on 9-10 May tornadic supercell was an average of 4.4 km during the early part of the observation period. Most other storms had Z_{dr} columns between 4 and 4.6 km wide. The exceptions were the failed storm on 9 May with a maximum Z_{dr} column width near 2.5 km and the multicellular storm with an average Z_{dr} column width near 2.2 km.

A second property of Z_{dr} columns noted was the maximum height above the 0°C level. The 9-10 May tornadic supercell had the highest Z_{dr} column of any storm in this study. It extended to approximately 8.2 km above the radar level (ARL), or 4 km above the 0°C level, at its maximum height (Figure 3). The Z_{dr} column was above 7.5 km ARL, or 3.3 km above the 0°C level, shortly after the beginning of the observation period. After 0155 UTC, the height slowly descended to 7 km ARL or less. For comparison, the Z_{dr} column in the 8 May tornadic supercell was less than 7 km ARL, or 2.8 km above the 0°C level, during the observation period. The Z_{dr} columns in two other storms also had maximum heights over 7.5 km ARL, but those altitudes were more short-lived. During most of the observations times, the maximum Z_{dr} column heights were less than 7.5 km ARL, or 3.3 km above the 0°C level. The beam width was measured using VCP Ray

Path Explorer to determine the amount of possible error in the measured height of the Z_{dr} column. Although a difference in height between the 9-10 May tornadic supercell and the rest of the storms was noted, it was much less than the measured beamwidth of nearly 2 km.

The Z_{dr} column was generally located on the upshear side of the observed storms, but it was located on the left flank of the storm in left-moving storms and on the right flank of the tornadic right-moving supercells. Two of the storms showed a well defined bounded weak echo region, or BWER (Figure 4). The Z_{dr} column was colocated with the BWER most of the time (Figure 5). When they were not colocated, the Z_{dr} column was upshear of the BWER.

The height, width, and position of the Z_{dr} column did vary with time within some storms. The Z_{dr} column in the 9-10 May tornadic supercell slowly decreased in height after consistently obtaining the highest values observed in any storm in this study (Figure 3). In one of the "failed" storms from 9 May (Figure 6), the Z_{dr} column had relatively high penetration above the 0°C level during part of its life that showed a pattern similar to the first part of the 9-10 May tornadic supercell. The height of the Z_{dr} column, however, did not stay this tall as long as the 9-10 May tornadic supercell This storm did not produce any reported severe weather. In storm 4 (Figure 1) from 9 May, the maximum height of the Z_{dr} column through time takes on a sinusoidal pattern (Figure 7). The storm took a path directly away from the radar soon after it developed, which may explain this observation. Due to increasingly poor vertical resolution aloft with range, the top of the Z_{dr} column was often underestimated. The result is that the height of the Z_{dr} column appears to oscillate.

The width and location of the Z_{dr} column in the 9-10 May tornadic supercell varied during the observation period. The Z_{dr} column grew wider, took on an oblong appearance, and moved from the right-flank of the storm more toward the upshear side of the storm at 0300 UTC. This was the same time that the storm produced a significant tornado.

The values of Z_{dr} within the columns ranged from 0.9 dB to 5 dB. The membership functions were helpful in borderline Z_{dr} values, such as near 0.9 dB, where there is more uncertainty about the existence of liquid water. There were some cases where the values of Z_{dr} within the column exceeded those allowed by the membership functions, mainly in the 8 May and 9-10 May right-moving tornadic supercells. For example, the supercell on 8 May had values of Z_{dr} near 5 dB in the center of the Z_{dr} column above the 0°C level (Figure 3), outside of the range given by the membership functions. This region was surrounded by lower Z_{dr} values determined by the membership functions to be liquid water. The values in the region of higher Z_{dr} were as liquid water. Another interesting occurrence was the presence of low negative Z_{dr} in a shallow region immediately above the top of the Z_{dr} column. Values in this region were as low as -1.6 dB. This was a result of the presence of vertically-oriented graupel (Straka et al. 2000). Due to the very shallow nature of this feature, it may be difficult to observe at longer ranges from the radar, where vertical resolution is poor.

The time of appearance of the Z_{dr} column was compared to the first warnings and time of the first severe weather reports. Four of the eight storms developed within 120 km of the radar and severe thunderstorm warnings were issued for all four storms. The time between Z_{dr} column appearance and the first warnings was, on average, 15 minutes for these four storms. The longest time between the appearance of the column and the first warning was 20 minutes storm 4 on figure 1. The shortest time was 7 minutes for the left-moving storm on 8 May.

Of the four storms mentioned above, three produced reported severe weather. The first type of reported severe weather from each storm was hail. The average time between the appearance of the Z_{dr} column and the first hail report was 39 minutes. The longest time between the appearance of the Z_{dr} column and the first hail report was 60 minutes while the shortest time was 26 minutes.

A few obstacles were encountered while trying to find the Z_{dr} column. The main problems were data artifacts, differential attenuation, and the cone of silence. The artifacts encountered were the three-body scatter spike and nonuniform beamfilling. The first artifact to be discussed is the three-body scatter spike (TBSS). It is caused when the radar radiation is scattered from the hail core to the ground, back to the hail core, and finally back toward the radar again (Lemon 1998). When present, the three-body scatter spike is usually at middle elevations and always on the downrange side of the storm (Figure 8). It is often observed collocated with a region of extremely high Z_{dr}, sometimes exceeding 12 dB. If the updraft is on the downrange side of the storm, the Z_{dr} column can be hidden by the TBSS. This was observed in a left-moving supercell on 9-10 May (Figure 5). The Z_{dr} column should have been on the left flank of the storm but a three-body scatter spike was in the same location so the Z_{dr} column was not visible through most of the life of the storm.

Another problem with finding the Z_{dr} column was attributed to nonuniform beamfilling, usually caused by a high gradient in reflectivity within a sample volume

(Ryzhkov and Zrnić 1998; Zrnić and Ryzhkov 1996). Such large gradients can artificially produce positive values of Z_{dr}, and were sometimes observed along the edges of the storm. The anomalously large Z_{dr} sometimes overlapped the region where the Z_{dr} column was expected, making it more difficult to observe. Differential attenuation sometimes made it difficult to obtain accurate Z_{dr} values in the Z_{dr} column. When the Z_{dr} column was downrange of a large amount of heavy rain, the horizontally polarized beam became attenuated, and the Z_{dr} was near 0 dB or negative where rain was expected to be present. The cone of silence, an unsampled region aloft near the radar, was only a problem when the storm became too close to the radar. The 8 May supercell came within 20 km of the radar and the 19.5 degree elevation was not high enough to resolve the height of the Z_{dr} column.

4. Conclusions

Storms during the severe weather events on 8 May and 9-10 May 2003 showed some variations in Z_{dr} columns from storm to storm. The column was wider in the 8 May supercell than in any other storm. One failed storm showed a very narrow Z_{dr} column and the other failed storm showed a Z_{dr} column over 4 km wide but was not consistent. Storm 6 in figure 1 had a narrow Z_{dr} column but also had multiple Z_{dr} columns during part of its life. The rest of the storms had Z_{dr} column widths between 4 km and 4.3 km. The differences in the width of the Z_{dr} columns may be helpful in determining if a storm has severe potential.

The average height of the Z_{dr} column was similar for many of the storms over both days but the 9 May tornadic supercell had a slightly higher Z_{dr} column for part of its life. The height of the Z_{dr} column did not differ significantly enough between storms to draw any definite conclusions. The maximum Z_{dr} values within the Z_{dr} column above the ambient 0°C level were typically as high as 3 dB for the non-tornadic storms, however, in the 8 May tornadic supercell and the 9-10 May tornadic supercell values exceeded 5 dB at times.

The time of the Z_{dr} column appearance can give forecasters some lead time for severe weather. In an average between four storms in this study, the Z_{dr} column appeared 15 minutes prior to the first severe thunderstorm warning and 39 minutes prior to the first hail report.

The Z_{dr} column was susceptible to being hidden in some storms by data artifacts, such as the three-body scatter spike and nonuniform beamfilling. Attenuation and the cone of silence also became obstacles in finding the Z_{dr} column in some instances. For this reason, care should be taken when looking for the Z_{dr} column signature.

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Table 1. Storms observed with the date of r, start, and end of the observation period in UTC. Notes about the storm and types of severe weather are listed in the comments column.

Storm Number	*Date*	*Start Time (UTC)*	*End Time (UTC)*	*Comments*
1	8 May	20:29	21:21	"Failed" storm
2	8 May	20:55	21:51	Long-track tornado, hail
3	8 May	21:14	22:06	Split from 2. Hail
4	9 May	21:36	23:07	Hail
5	9 May	22:09	23:46	"Failed" storm
6	9-10 May	22:59	00:44	Multicellular. Hail
7	9-10 May	22:59	01:03	Left-moving supercell, split from 6. Hail.
8	10 May	01:10	03:25	Long-track tornado, wind, hail

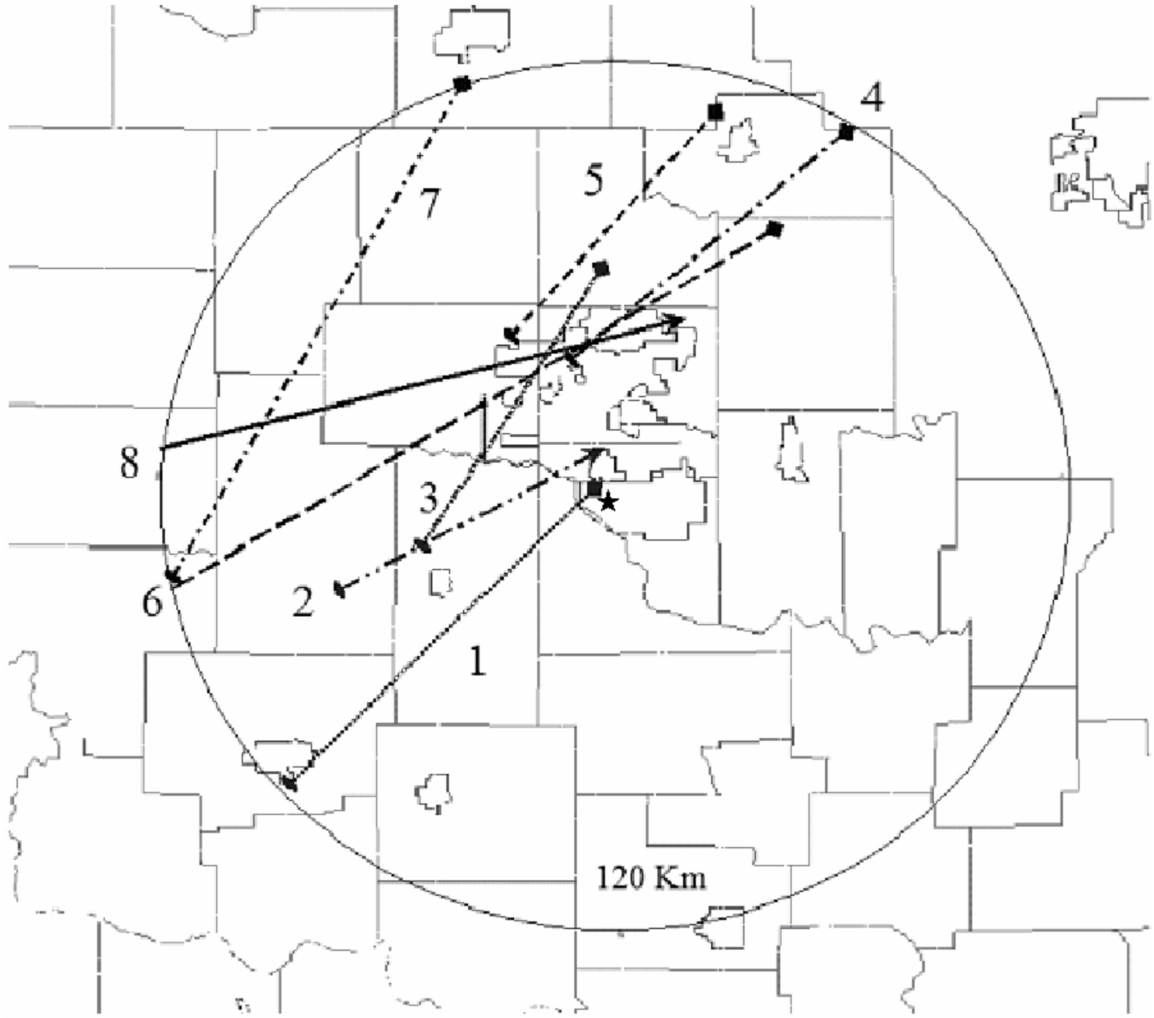

Figure 1. Tracks of studied storms from 8 May and 9-10 May 2003. The circle marks the 120 km range ring. Storms 1-3 are from 8 May and storms 4-8 are from 9-10 May. Storms 2 and 8 produced long-track tornadoes. Tracks 1 and 5 are "failed" storms. Storms 3, 4, 6, and 7 were associated with hail reports. Storm 7 is a left-moving supercell that split from storm 6. Storm 3 split from storm2. The tracks for the duration of each storm's observation period are shown.

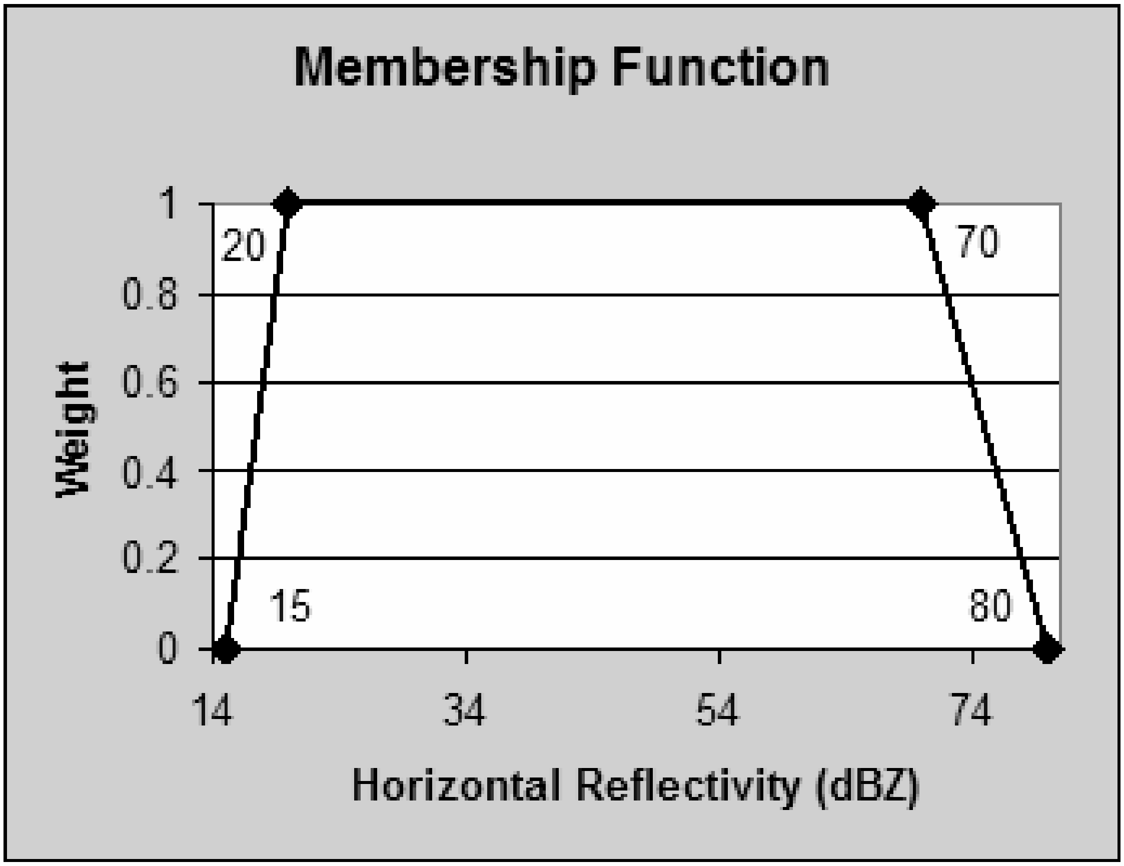

Figure 2. An example membership function using reflectivity to classify big drops. There are four numbers involved in a membership function, in this case 15, 20, 70, and 80 dBZ. Weights are assigned to each number. In this case, horizontal any reflectivity of 15 dBZ or less is given a weight of zero. The same is done for any horizontal reflectivity of 80 dBZ or more. 20 dBZ and 70 dBZ are assigned a weight of one. Anything between 20 dBZ and 70 dBZ is also given a weight of one. Between 15 dBZ and 20 dBZ the weight increases linearly from zero to one. Between 70 dBZ and 80 dBZ the weight decreases linearly from one to zero. The result is this trapezoid-shaped graph.

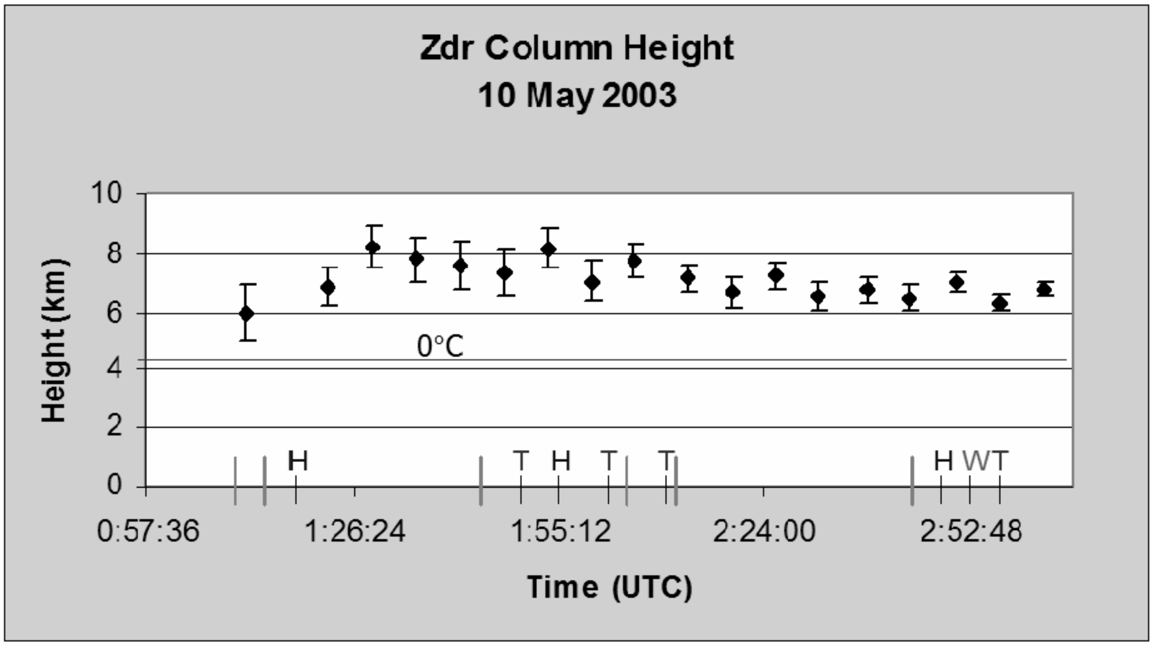

Figure 3. The height of the Z_{dr} column in kilometers above radar level (ARL) in storm 8 from Table 1 and Figure 1. Error bars represent the beamwidth at the observed range and altitude. The horizontal line just above 4 km ARL represents the 0°C level. Long, grey vertical lines represent warnings and short, black vertical lines with letters represent severe weather reports. An "H" is a hail report, a "W" is a wind report, and a "T" is a tornado report. The highest Z_{dr} column heights of any storm in this study were recorded between 0126 UTC and 0155 UTC. Shortly after 0155 UTC, the height slowly decreased.

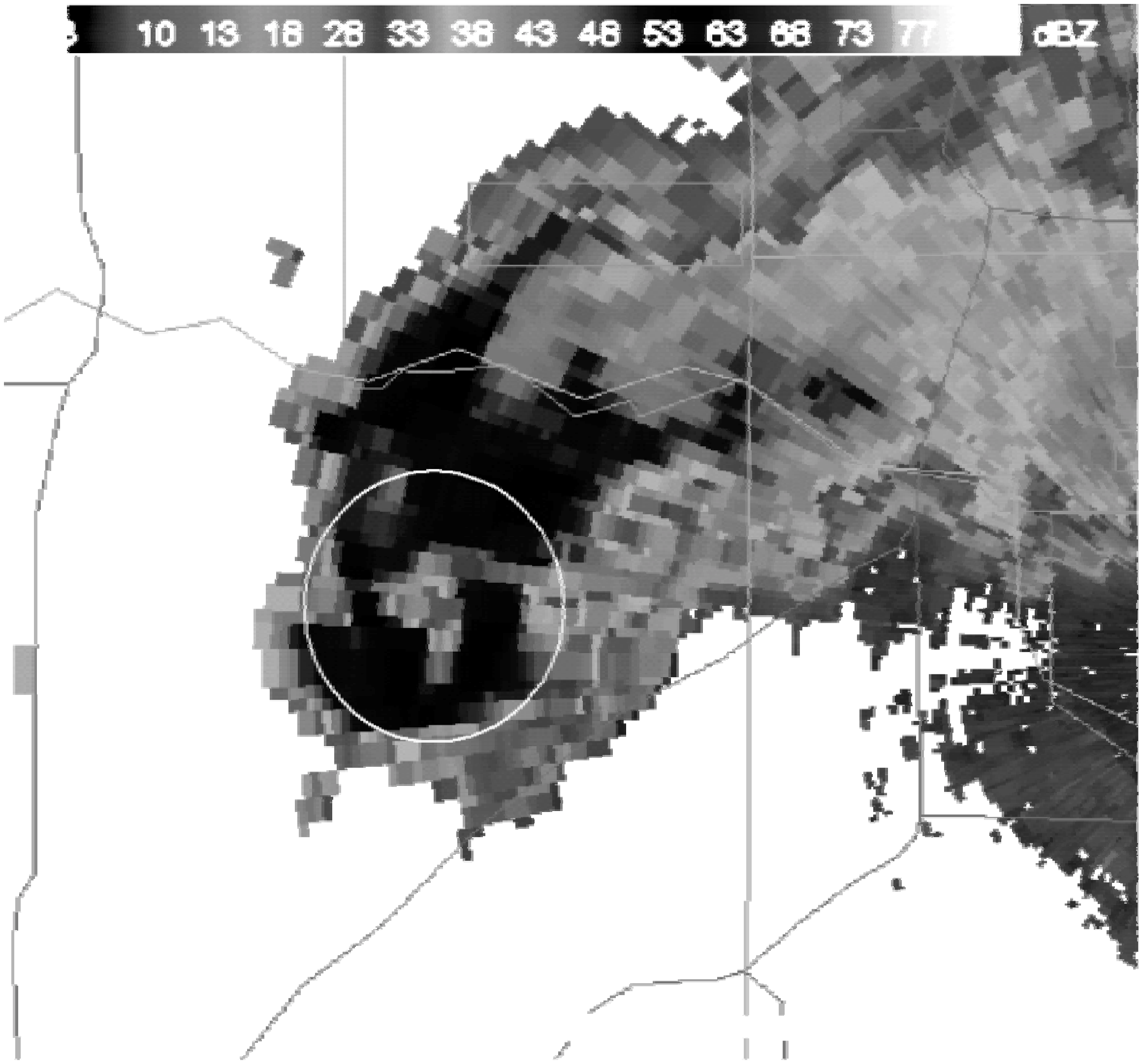

Figure 4. Bounded weak echo region (BWER, circled) in storm 2 in Table 1 and Figure 1. This image is a horizontal reflectivity image from 2144 UTC at the 12.00° elevation. The height of this feature is approximately 6.5 km ARL. The darker grey colors represent horizontal reflectivity of at least 53 dBZ. The lighter regions in the center of the feature depict horizontal reflectivity as low as 28 dBZ.

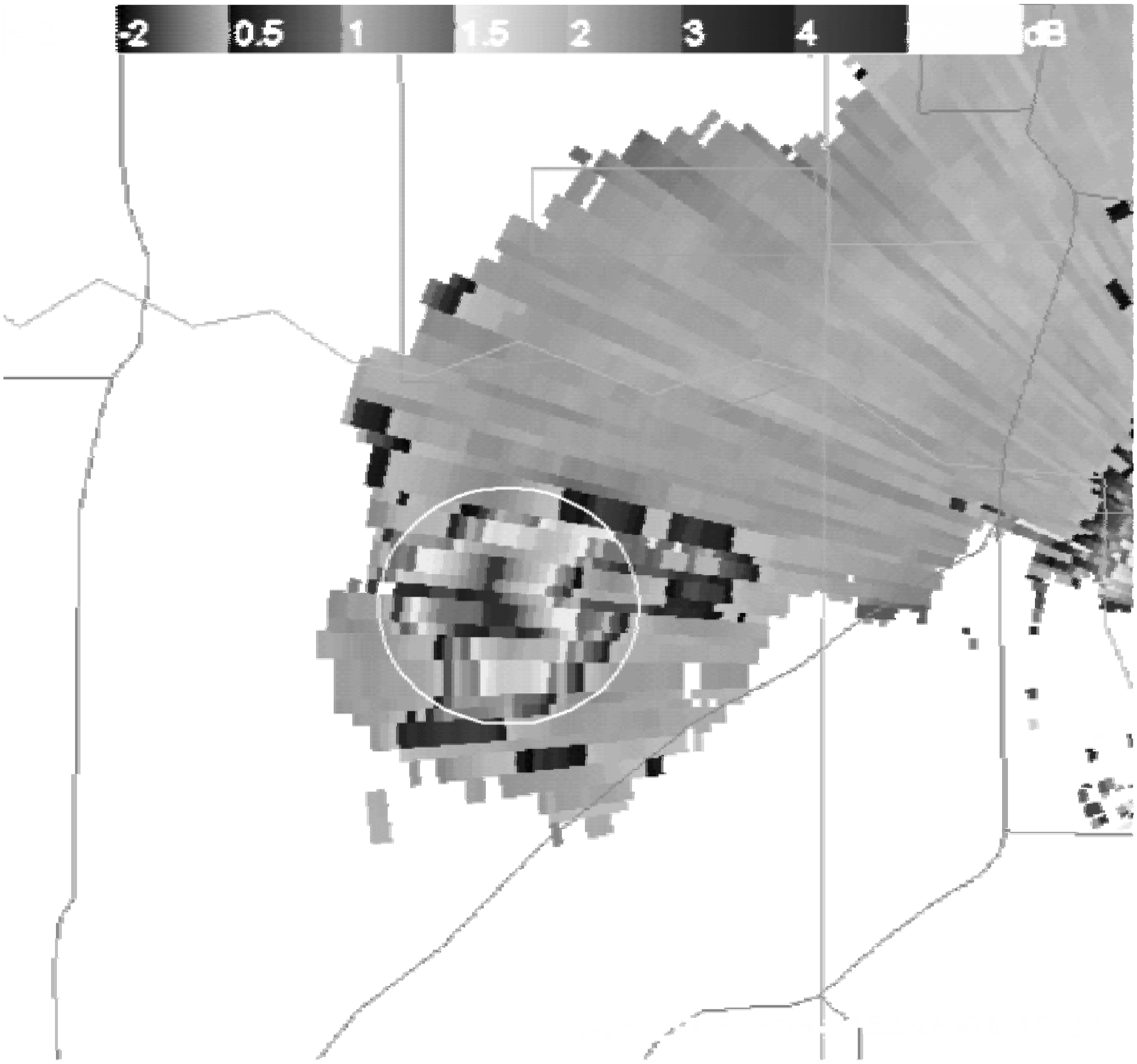

Figure 5. Z_{dr} column (circled) in storm 2 in Table 1 and Figure 1. This is Z_{dr} at an elevation of 12.00° and a height of 6.5 km. The circle is in the same location as in Figure 4. This is one case where the Z_{dr} column and the BWER are colocated. Peak values within this Z_{dr} column were near 4 dB.

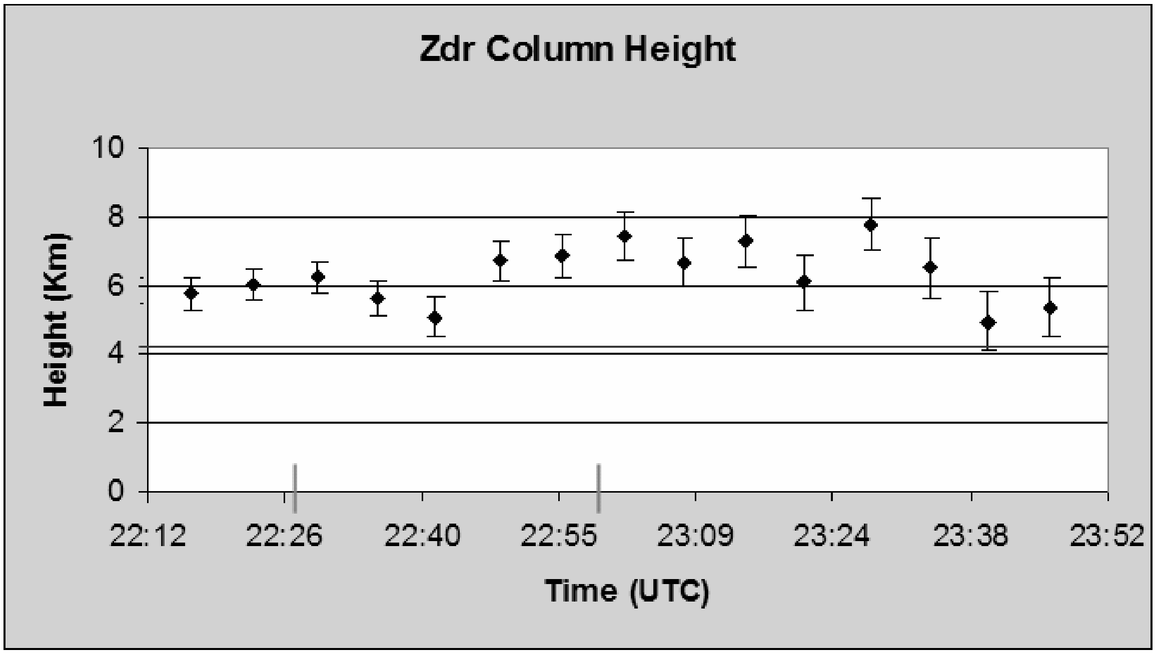

Figure 6. Z_{dr} column height for a "failed" storm on 9 May. As in Figure 3 but for storm 5 in Table 1 and Figure 1. The first severe thunderstorm warning was at 2228 UTC. Notice the heights were similar to the 9-10 May tornadic supercell (Figure 3).

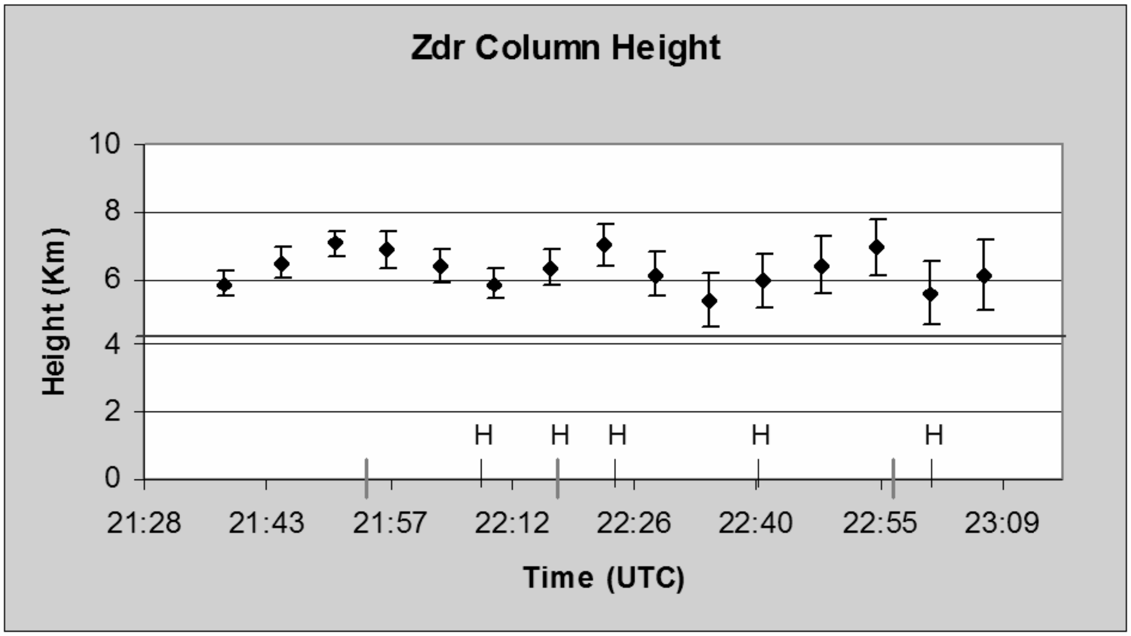

Figure 7. Height of the Z_{dr} column in storm 4 from Table 1 and Figure 1. As in Figure 3. The first severe thunderstorm warning was at 2156 UTC and the first hail report was at 2208.

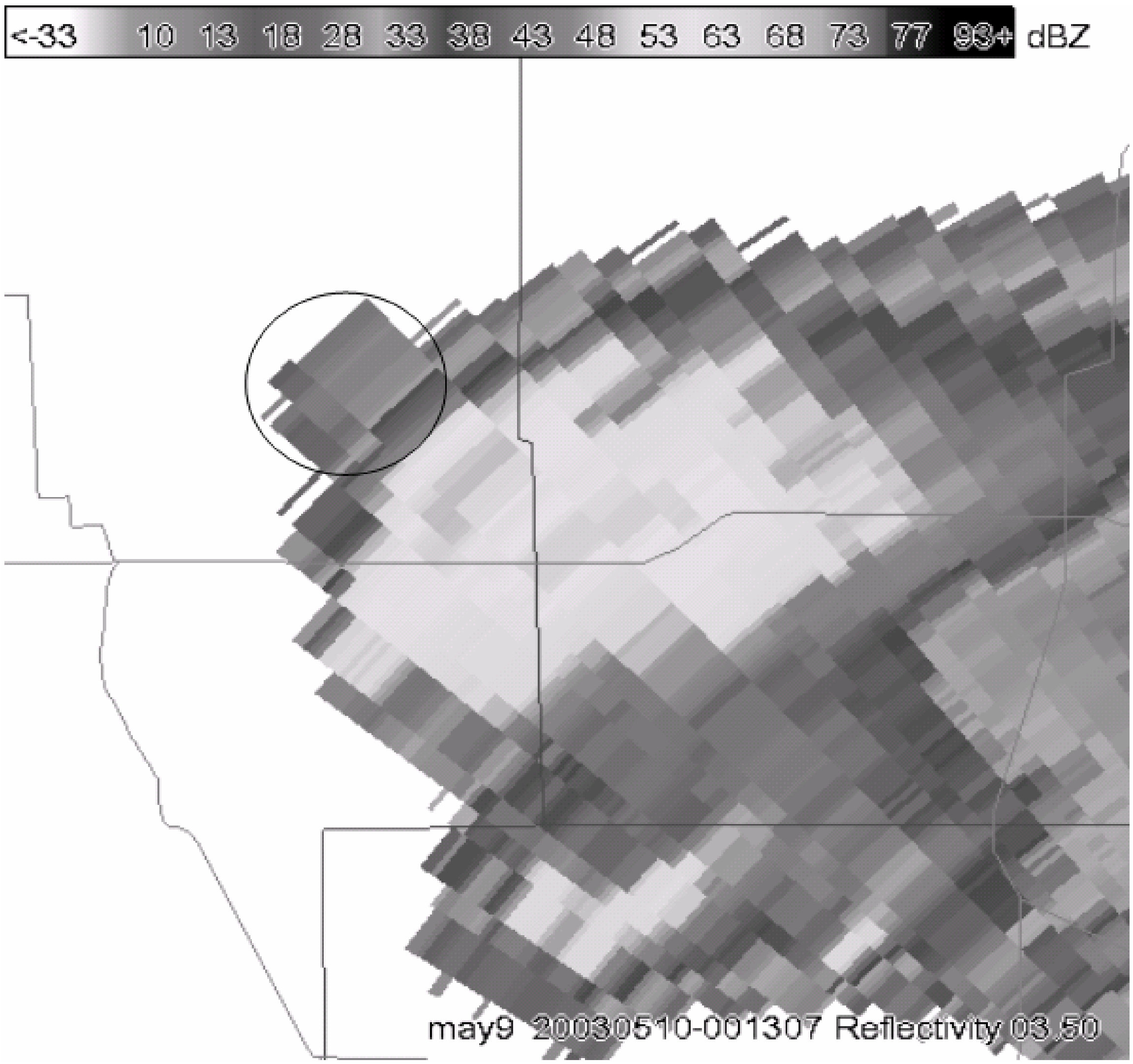

Figure 8. Three-body scatter spike (TBSS) on storm 7 from Table 1 and Figure 1. This is a horizontal reflectivity image at a 3.5° elevation and a height of 7.3 km ARL. The TBSS appears in the circle and contains reflectivity near 20 dBZ on the left-flank of the storm. Higher reflectivity is shown in the light grey shades toward the center of the storm.

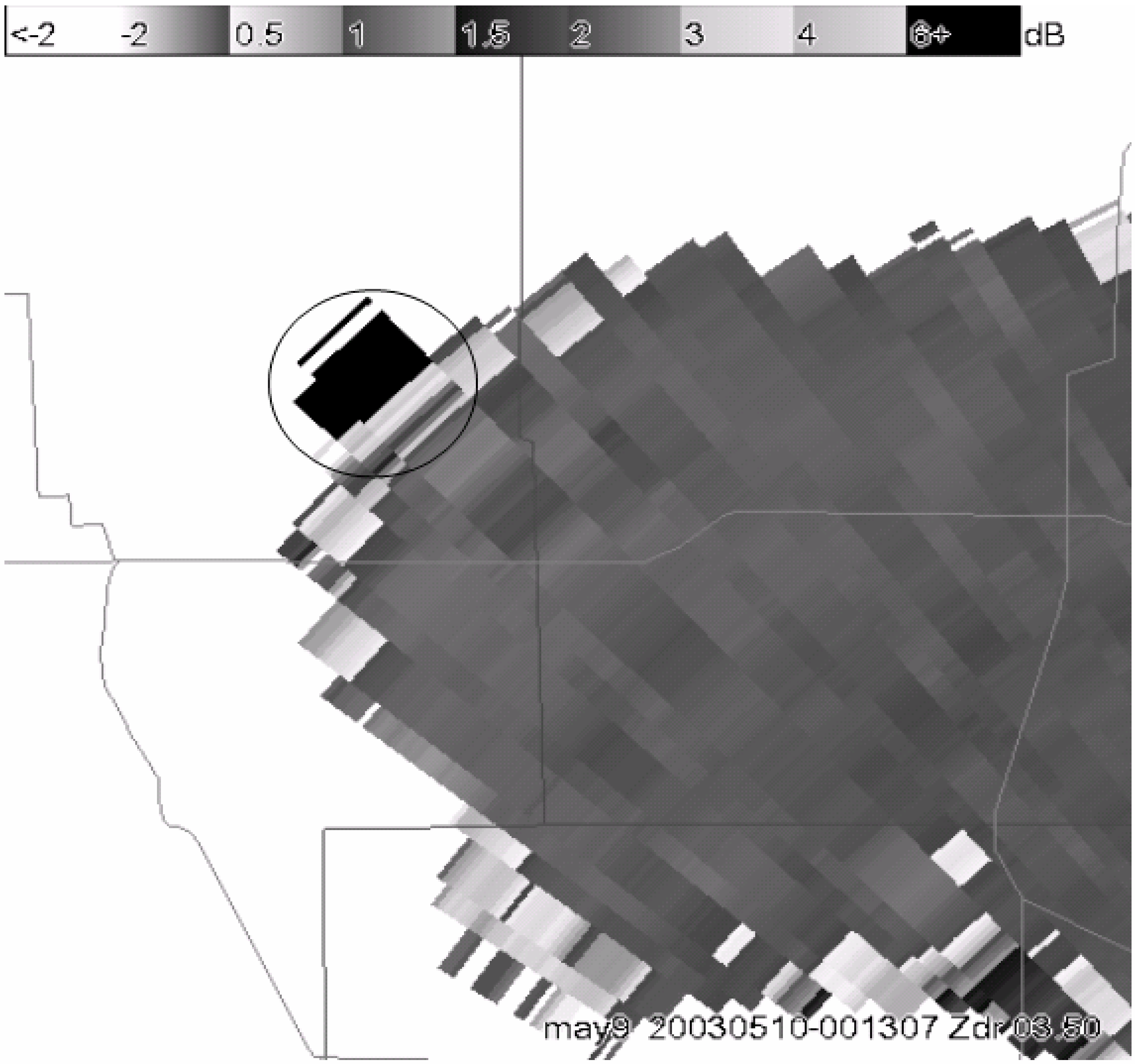

Figure 9. Three body scatter spike in storm 7 in Table 1 and Figure 1. This is a Z_{dr} image at 3.5° elevation and a height of 7.3 km ARL. The Z_{dr} values within the spike (circled) are greater than 6 dB. The dark grey colors in the rest of the storm depict areas with Z_{dr} near 0 dB.