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# $Z_{DR}$ COLUMNS AS A PREDICTIVE TOOL FOR HAIL GROWTH AND STORM EVOLUTION

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## 1. INTRODUCTION

Within a storm cell updraft, raindrops are lofted to altitudes sometimes extending several kilometers above the environmental freezing level. If the strength of the updraft is such that large raindrops can be lofted, their oblate spheroid shape causes a columnar region of increased differential reflectivity $Z_{DR}$ values collocated with or on the fringe of the updraft. Typically, at S band these values range between 1 and 3 dB, although they can be upwards of 5 dB. Because of the columnar shape, this signature is referred to as the "$Z_{DR}$ column" and has frequently been reported throughout the literature (e.g., Caylor and Illingworth 1987, Illingworth et al. 1987, Meischner et al. 1991). A clear example of one is presented in Fig. 1.

Due to their association with updraft strength, $Z_{DR}$ columns have the potential to be a powerful tool for assessing and predicting short-term trends in storm evolution, including hail growth and tornadogenesis. Intuitively, a stronger updraft can loft large raindrops with greater intrinsic $Z_{DR}$ values to higher altitudes. Indeed, stronger updrafts prolong the freezing process, allowing liquid water (and thus positive $Z_{DR}$) to be lofted to higher altitudes (Kumjian et al. 2010), often several kilometers above the environmental freezing level. Therefore, one may reasonably expect with increasing $Z_{DR}$ values in a growing column that updraft intensification is underway, and, subsequently, heavier precipitation and perhaps larger hail could develop in the near future. Although large raindrops do not appear to be the primary contributor to large hail growth (Askelson 2002), they can reveal larger liquid water contents in updrafts that promote the accumulation of water mass by accretion on freezing drops and graupel, providing conditions that can lead to rapid growth of large hailstones (e.g., Nelson 1983). Hence, $Z_{DR}$ columns offer a possibility for improved short-term prediction of hail trends.

The second focus of this study is the relationship between $Z_{DR}$ columns and tornadic evolution in supercells. Past research has searched for correlations between updraft strength and tornadogenesis; naturally then, $Z_{DR}$ columns provide a clear and straightforward route to better understanding any correlations that do exist.

### *1.1 Cases*

For the hail growth section, four supercellular cases are presented (Table 1). These four cases were selected for their ease of analysis, as the $Z_{DR}$ columns representing each storm's main updraft remained fairly distinct for a sufficient time (> 30 minutes) to perform quantitative analyses.

The tornadic evolution section includes three supercellular cases (Table 1), two of which are also presented in the hail growth section. Once again, these cases involved $Z_{DR}$ columns that

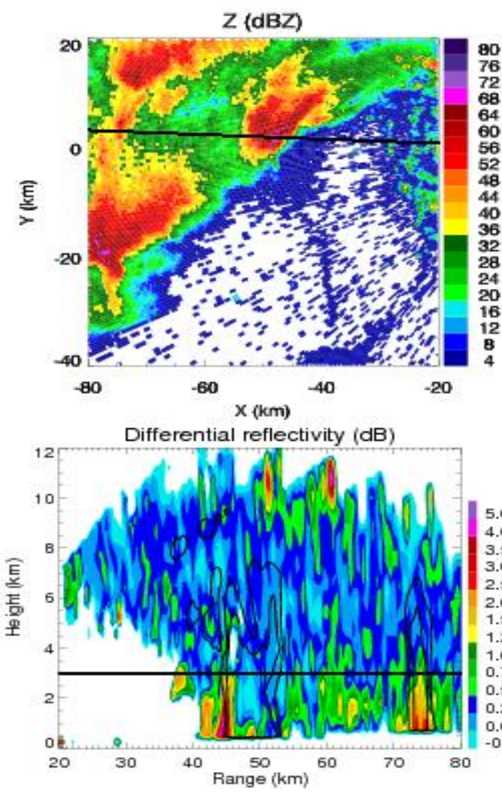


*Fig. 1: 0.5˚ $Z_H$ PPI and corresponding $Z_{DR}$ RHI (azimuth of 274˚) from 10 Feb 2009 at 2114 UTC. Approximate environmental freezing level (3 km) is indicated on the RHI. Note the $Z_{DR}$ column located at 45 km range.*

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| Case | Analysis Period (UTC) | Type |
|---|---|---|
| 29-30 May 2004 | 2350 – 0227<br>2330 – 0227 | H<br>T |
| 24 May 2008 | 2237 – 2309 | H |
| 31 March 2008 | 0600 – 0725 | T |
| 1 June 2008 | 0236 – 0318 | H |
| 10 February 2009 | 2003 – 2229<br>2027 – 2146 | H<br>T |

*Table 1: Details for the seven cases in this study. Type H indicates the case falls in the hail growth section, while Type T indicates the tornadic evolution section.*

| | |
|---|---|
| **Location** | Norman, OK |
| **Wavelength** | 10.9 cm |
| **Power** | 750 kW |
| **Azimuthal Resolution** | 1˚*, 0.5˚ |
| **Pulse Length** | 250 m |

*Table 2: Specifications for the KOUN data analyzed. Cases before 2008 have an azimuthal resolution of 1˚ (legacy resolution). Cases from 2008-2009 have a resolution of 0.5˚ (super resolution).*

persisted for a sufficient time such that correlations between them and tornadic evolution could be legitimately investigated. Additionally, each case produced at least two tornadoes during the analysis period, which provides further opportunity to observe possible correlations.

### *1.2 Data Collection and Analysis*

Data for all cases were collected by KOUN, a research polarimetric prototype WSR-88D S-band radar. KOUN volume scans consist of 14 or 15 elevation scans ranging from 0.5˚ (or 0.0˚) to approximately 19.5˚. Further details regarding the KOUN scanning strategies employed are provided in Table 2.

To create a volume file suitable for three-dimensional analysis, data from each scan undergo a Delaunay triangulation scheme and are linearly interpolated onto a three-dimensional Cartesian grid. For quantitative analysis in three dimensions (which is employed extensively in this study), constant altitude PPIs (CAPPIs) are produced every 250 m in the vertical. Following the production of a volume of CAPPIs, the strength of the $Z_{DR}$ column associated with the main updraft is estimated. To do so, above the estimated environmental freezing level each grid box that meets a certain $Z_{DR}$ threshold (> 1, 2, or 3 dB) is counted in a $Z_{DR}$ column volume. The temporal evolution of these values is then monitored and can be compared with $Z_H$ changes or tornadic development so any possible correlation can be better understood.

## 2. HAIL GROWTH ANALYSIS

To quantify hail intensity near the surface, grid boxes are also counted below the environmental freezing level. However, this process is performed for those boxes meeting or exceeding thresholds of 40 or 60 dBZ. The ratio of the 60 dBZ volume to the 40 dBZ volume is then used as a proxy for hail core intensity.

Previous research involving $Z_{DR}$ columns and hail growth has pointed towards a likely lag correlation between the column volume and $Z_H$ ratio (Picca and Ryzhkov 2010). Using the 24 May 2008 case, that study plotted a time series of both values and observed a trend where each "boost" in $Z_{DR}$ column volume was followed by an increase in $Z_H$ ratio approximately 15-25 minutes later.

To develop upon this previous work, the 24 May 2008 case along with the three other cases indicated are further investigated by analyzing any lag correlation existing between column volumes and $Z_H$ ratios. One likely explanation for this lag correlation involves an increase in hail and overall precipitation production due to a strengthening updraft. This process would result in a positive correlation. The other explanation is that a strengthening updraft is able to loft larger and simply more hydrometeors, in turn briefly decreasing the intensity of the surface $Z_H$ core. Conversely, a weakening updraft would allow more hydrometeors to descend, briefly increasing the intensity of the surface $Z_H$ core. This process would result in a negative correlation.

For the first possibility, a positive correlation between column strength and $Z_H$ ratio would be expected with a lag of 15-30 minutes, as there must first be an increase in hydrometeor production followed by descent to the surface. The second possibility would result in a negative correlation of approximately 5-10 minutes, as it is representing a change in the sorting of hydrometeors and not a change in production efficiency; therefore, the lag should be shorter.

To test these hypotheses, the volume and ratio values are determined for the four cases. For each case except 1 June 2008, correlation coefficients for the $Z_H$ ratio and each of the three $Z_{DR}$ volumes (1, 2, and 3 dB thresholds) are calculated for lag times from five minutes to as high as 60 minutes, in increments of five minutes.

Data from the 1 June 2008 were acquired using a special "rapid scan" technique (Kumjian et al. 2010b); in turn, lags are in increments of 1.2 minutes. Additionally, only the 1 dB volumes are calculated for this case.

### *2.1 Positive Correlation Results*

Three of the four cases exhibit a strong signal in support of the hypothesis that a maturing $Z_{DR}$ column is indicative of an intensifying updraft which could result in larger hail over the next 20-30 minutes (Figs. 2-4). Both the 24 May 2008 and 1 June 2008 cases exhibit significant positive correlations during the 20-30 minute period. At these lags, correlation values reach as high as 0.8, indicating a likely connection between the intensifying updraft and a greater production of precipitation (perhaps including larger hailstones), which tend to reach the surface 20-30 minutes later.

The 29-30 May 2004 case displays a positive correlation for all three thresholds extending to the 40-minute lag (Fig. 4). The cause for the extension of positive coefficient values is possibly due to the sheer strength and height of the updraft for this case. The weak-echo region frequently reached heights of 8 km above ground level (AGL), with echo tops peaking over 15 km AGL. Due to the longer distance of descent for the hydrometeors, as well as stronger upward velocities encountered, the positive correlation values are extended to longer lag times.

The 10 February 2009 case displays an all-positive correlation at the 35-minute lag, but primarily shows very weak correlations at times between the 15- and 30-minute lags (Fig. 5). Perhaps secondary updrafts along the rear flank of the storm, which are not taken into account in this analysis, could have influenced hydrometeor development and affected correlation values. Future studies could look into $Z_{DR}$ contributions from other updrafts as well, possibly clarifying the results.

Nonetheless, the results of the previous three cases are quite promising in that they support the utility of using $Z_{DR}$ columns as a forecast tool for precipitation core intensity and hail size trends. Moreover, the 29-30 May 2004 case demonstrates that the lead time is likely dependent upon the updraft strength itself; hence, forecasters and potential algorithms using $Z_{DR}$ column data should be cognizant of the height of the updraft and significant hail growth regions.

### *2.2 Negative Correlation Results*

The overall trend among the four cases indicates a short-term negative correlation (5-15 minute lag) appears to exist as well. The 24 May 2008 and 1 June 2008 cases are the strongest among the four in exhibiting a relatively negative correlation at short time lags. Additionally, 10 February 2009 shows some negative correlation at 5 minutes. The smaller lag time is possibly a result of the same mechanism that resulted in the longer lag for a positive correlation with the 29-30 May 2004 supercell. Instead in this case, a shorter updraft (mixed phase region only 4-5 km AGL instead of 6-8 km with other cases) allowed decreases in upward velocities to be "felt" more rapidly at the surface as previously lofted hydrometeors reach the ground relatively quickly.

Interestingly, the 29-30 May 2004 case displays only positive values within the 5-15 minute lag. The cause is uncertain, but one possibility is that, similar to the 10 February 2009 case with positive correlations, secondary updrafts from developing turrets along the rear flank aided precipitation development enough to cause a noticeable effect on this analysis, which only considers the main updraft contribution.

Despite these results, the previous three cases support the belief that $Z_{DR}$ column intensity is negatively correlated to very short-term changes in surface $Z_H$ due to the updraft's ability to loft hydrometeors. An intensifying $Z_{DR}$ column indicates an intensifying updraft, which will loft more precipitation, resulting in a surface $Z_H$ decrease over the next several minutes. Conversely, a weakening $Z_{DR}$ column indicates a weakening updraft, which will loft less precipitation, resulting in a surface $Z_H$ increase over the next several minutes.

## 3. TORNADIC EVOLUTION

Previous research has searched for connections between updraft evolution and tornadogenesis. Trapp (1999) found that within tornadic supercells, low-level mesocyclones tend to have smaller radii and higher vertical vorticity than those of nontornadic supercells, which results in a weaker updraft for tornadic cells. Additionally, an occlusion of the main updraft into a divided mesocyclone phase has been considered a precursor to tornadogenesis (e.g., Brandes 1978; Lemon and Doswell 1979; Houze 1993; Adlerman et al. 1999). This occlusion also results in a weaker updraft.

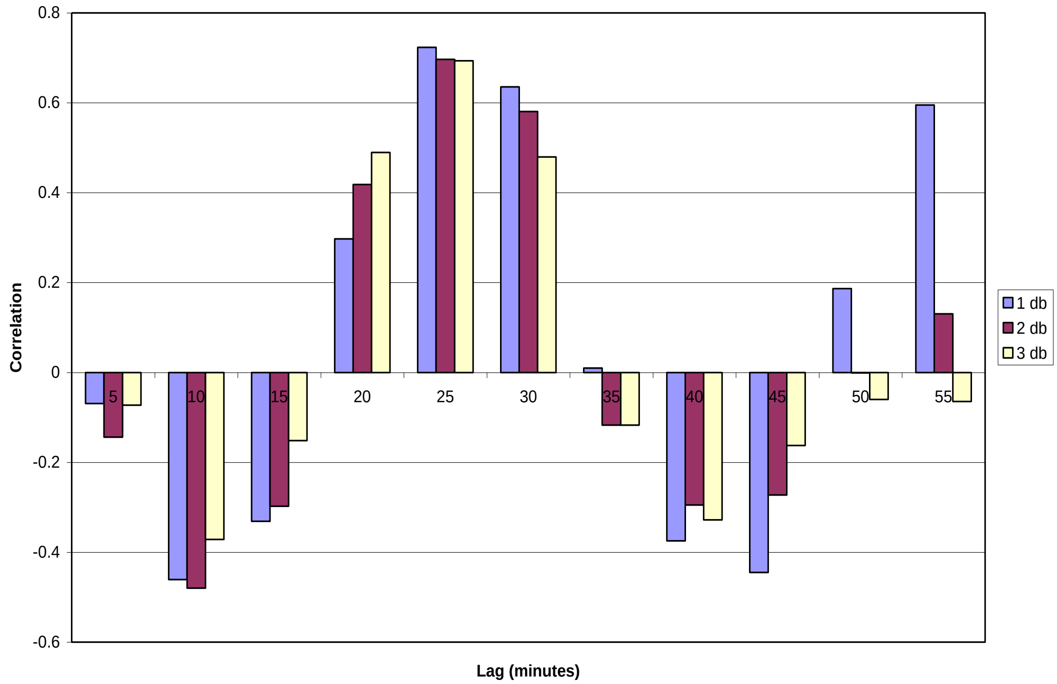


*Fig. 2: 24 May 2008 case lag correlations calculated between the $Z_H$ ratio and $Z_{DR}$ column volumes (one each for 1, 2, and 3 dB thresholds). Lag times ranged from 5 to 55 minutes, in increments of 5 minutes. Volume scans from 2201 to 2345 UTC are used.*

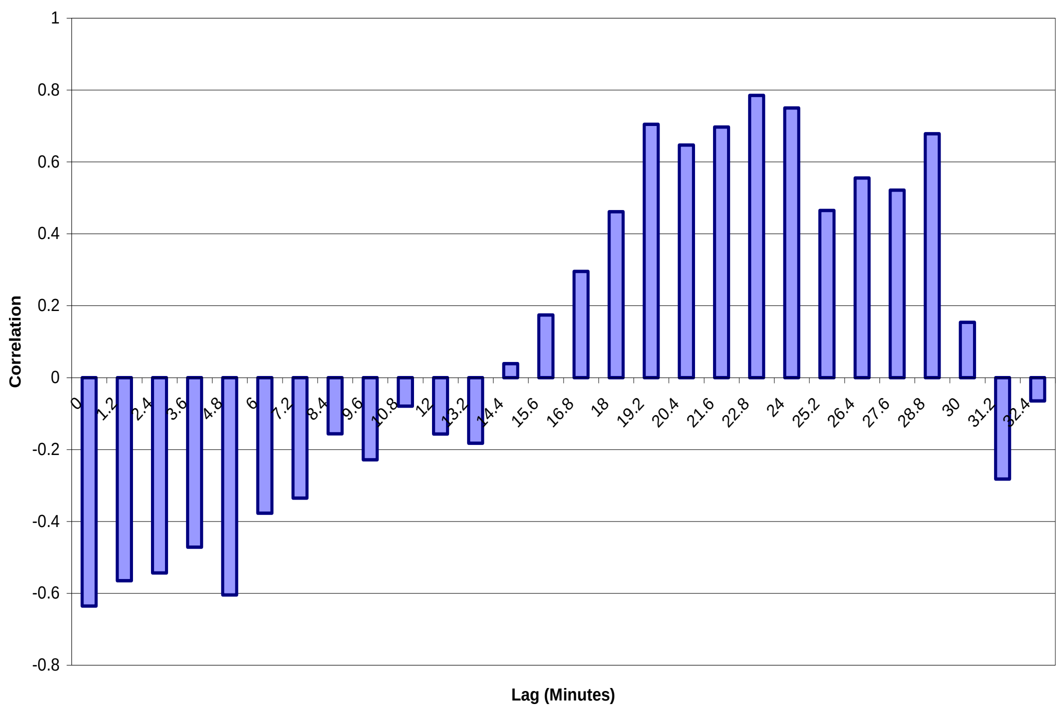


*Fig. 3: 1 June 2008 Rapid Scan case lag correlations from 1.2 to 32.4 minutes, in increments of 1.2 minutes. For this case, only the 1 dB threshold was calculated. Volume scans from 0236 – 0318 UTC are used.*

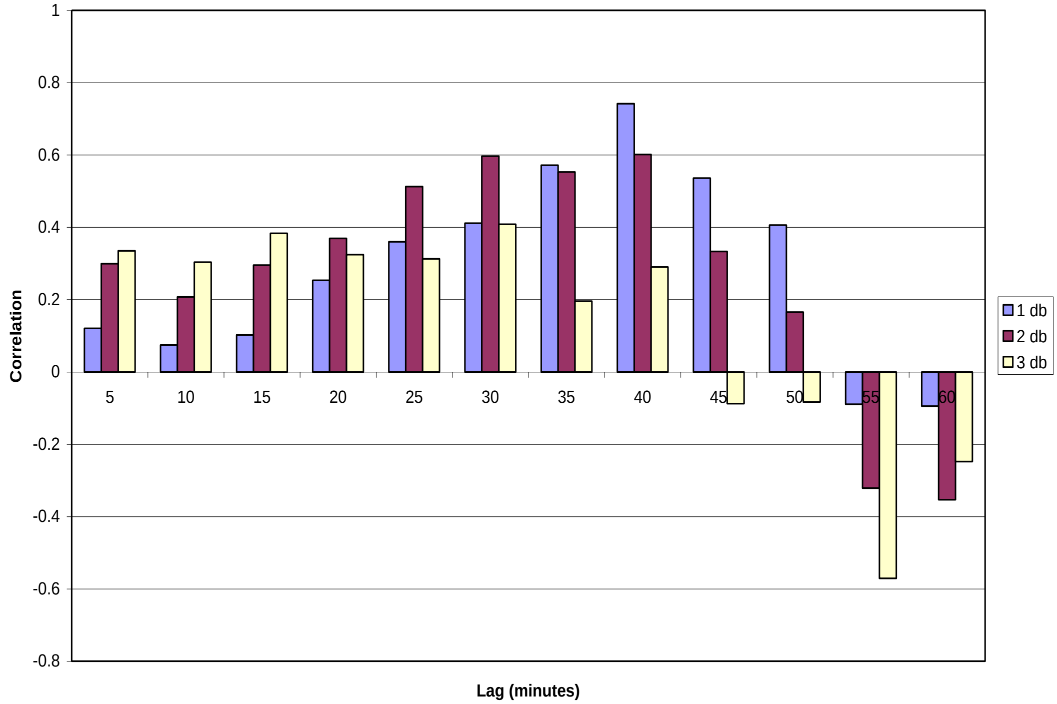


*Fig. 4: 29-30 May 2004 case lag correlations from 5 to 60 minutes, in increments of 5 minutes. Volume scans from 0012 to 0227 UTC are used.*

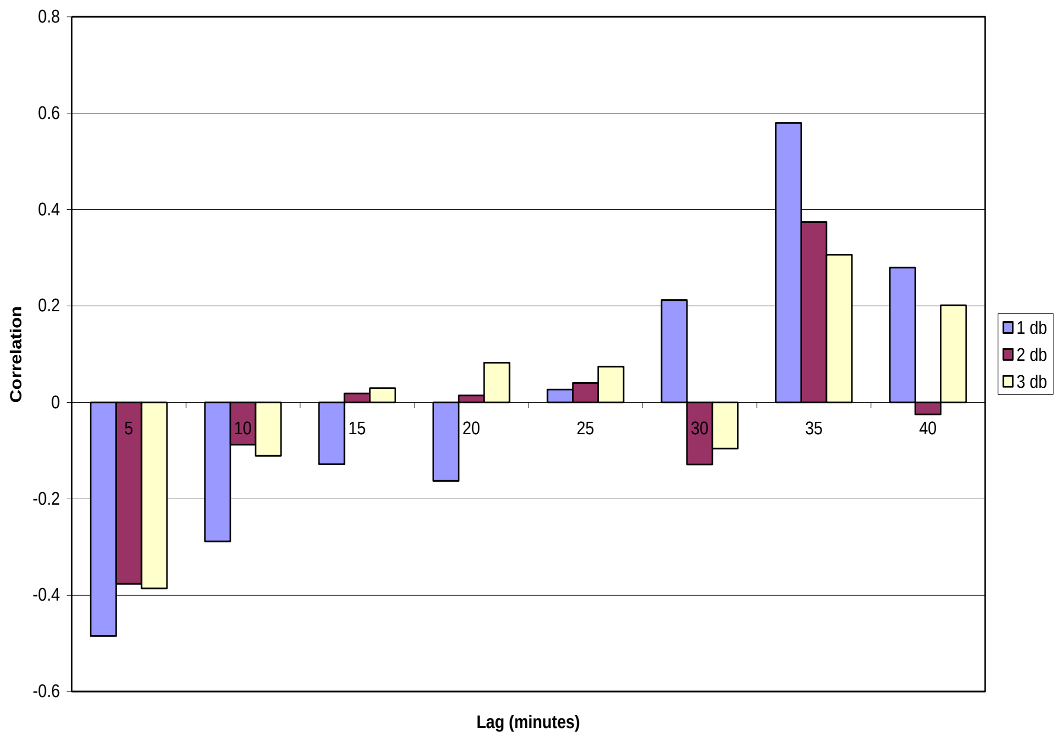


*Fig. 5: 10 February 2009a lag correlations from 5 to 40 minutes, in increments of 5 minutes. Volume scans from 2027 to 2157 UTC are used.*

In their dual-Doppler analyses of a supercell, Beck et al. (2006) observed a rapid cycling of mesocyclogenesis with an approximate period of six minutes, which is much shorter than the findings of previous studies (e.g., Doswell and Bluestein 2002; Johnson et al. 1987). During the analysis period, the supercell did not produce a tornado, and the authors theorized that the rapid cycling limited the ability of each low-level mesocyclone to develop sufficiently for tornadogenesis to occur.

Naturally, as $Z_{DR}$ columns offer insight into updraft strength, this study searches for weakening or cycling trends in the column volume calculations for three cases and then compares them with the reported tornado times. Indeed, the 1-dB volume magnitudes show some periodic cycle for all three cases, which may represent the cycling of the mesocyclone (Figs. 6-8).

The 29-30 May 2004 case exhibits the strongest relation between $Z_{DR}$ column strength and tornadic evolution. During the analysis period, prior to the development of each of the four tornadoes, there is a very prominent weakening of the $Z_{DR}$ column. Most likely, these volume minima are a result of the occlusion of the low-level mesocylone, which in turn weakens the updraft and reduces the number of large raindrops present in the updraft, subsequently reducing $Z_{DR}$ within the column. Each tornado develops following this weakening period and then dissipates within a few minutes of or during the next weakening period. Therefore, it seems plausible that we are observing tornadogenesis following an occlusion of the low-level mesocyclone and then dissipation with the next occlusion.

A quick analysis of the $Z_{DR}$ volume trends indicates an approximate period of 20-30 minutes for the cycling, with $Z_{DR}$ reaching each minimum fairly rapidly after peaking in intensity (on the order of 5-10 minutes). The 10 February 2009 case exhibits a similar cycling period around 20-30 minutes (Fig. 7). Interestingly, however, the tornado with the longest lifespan among all three cases occurs on the backside of a peak where column values reach a minimum nearly 20 minutes after the maximum, which is much longer than with the cycles of the 29-30 May 2004 case. Perhaps this longer time is a result of a better balance between inflow and outflow, as the rear-flank gust front does not surge ahead of the low-level mesocyclone as quickly. In turn, this balance would enable the tornado to persist longer.

The 31 March 2008 case exhibits a cycling period of 10-20 minutes (Fig. 8), and indeed the two tornadoes here persist for less than one minute and approximately six minutes, which agrees with the relatively short period observed.

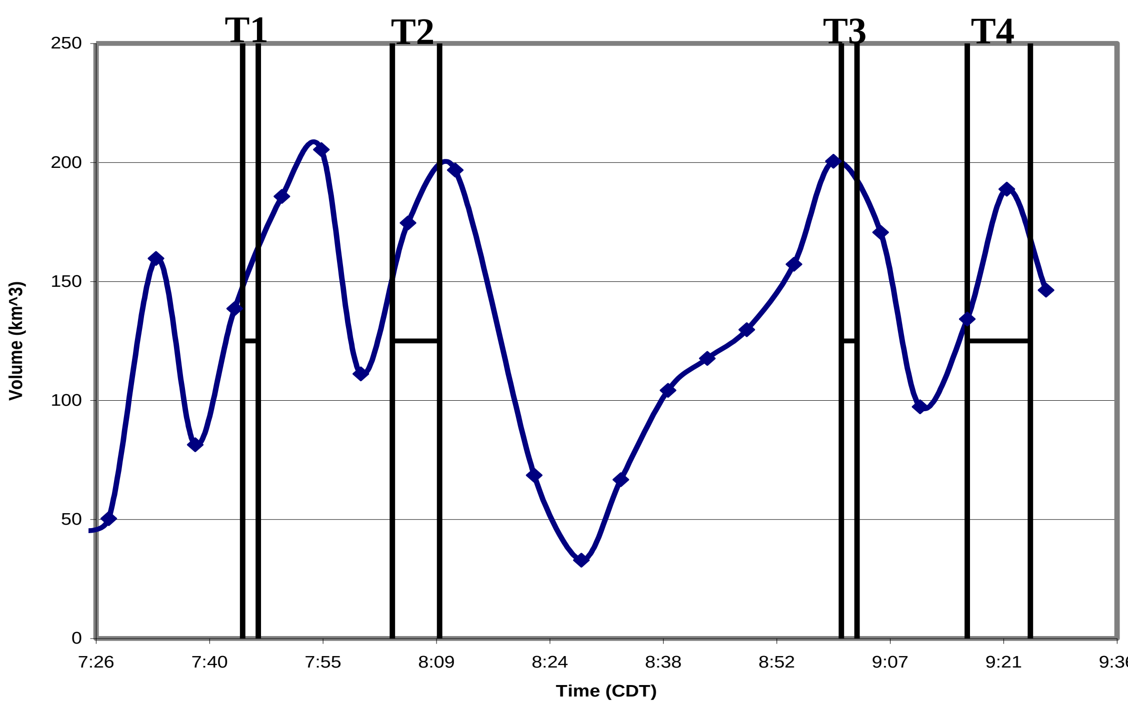


*Fig. 6: 29-30 May 2004 time series of 1-dB $Z_{DR}$ column volumes (blue curve) and tornadoes with vertical black lines indicating the reported begin and end times for each (Storm Data). Indicated times are PM.*

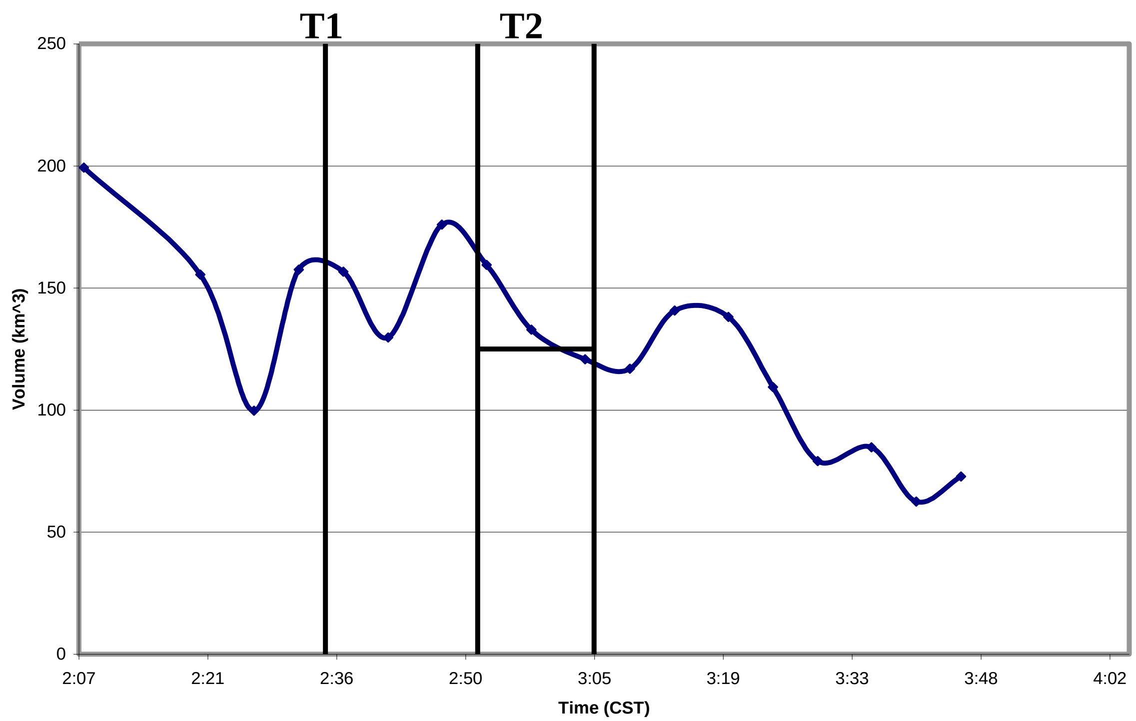


*Fig. 7: 10 February 2009 time series of 1-dB $Z_{DR}$ column volumes (blue curve) and tornadoes with vertical black lines indicating the reported begin and end times for each (Storm Data). Note for T1 that the tornado was reported as "brief" with the same begin and end time. Indicated times are PM.*

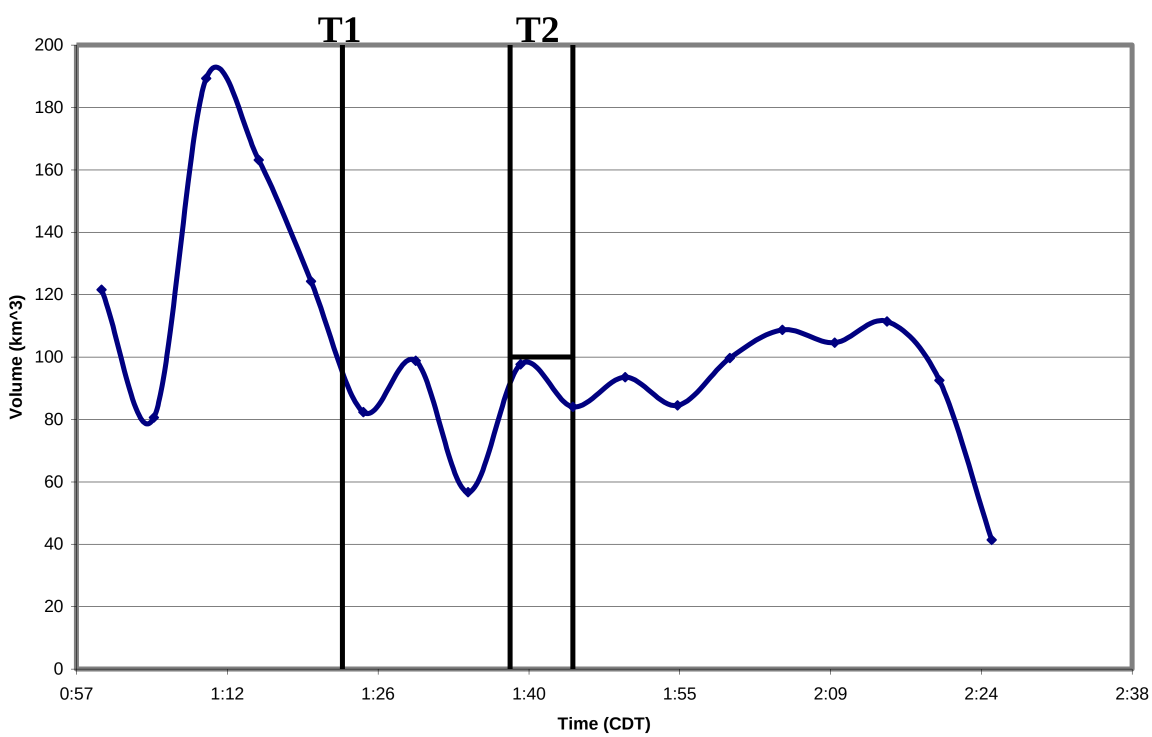


*Fig. 8: 31 March 2008 time series of 1-dB $Z_{DR}$ column volumes (blue curve) and tornadoes with vertical black lines indicating the reported begin and end times for each (Storm Data). Note for T1 that the tornado was reported as "brief" with the same begin and end time. Indicated times are AM.*

Like the tornadoes in the other cases, the second tornado develops relatively soon after a volume minimum. It then appears to dissipate with the next possible occlusion. With the first tornado, its brief lifespan occurs during an extended time of decreasing volume.

Initially, this observation appears to disagree with our hypothesis regarding the lifespan of the second tornado from 10 February 2009. However, Fig. 8 shows that the tornado develops only a few minutes before the minimum is reached. Therefore, perhaps other factors which are beyond the scope of this study delay tornadogenesis until a time when the lifespan could only be relatively short. Additionally, the rate of volume decrease is much larger—around 8 $km^3$ $min^{-1}$—than with the second tornado from 10 February 2009, where it averages about 4 $km^3$ $min^{-1}$. Perhaps this rate is representative of the balance discussed above, which would certainly influence the length of a tornado's lifespan.

Certainly, there are many more avenues to explore with possible correlations between $Z_{DR}$ columns and tornadogenesis. For example, velocity data can be analyzed in conjunction with volume trends to gain a better understanding of what the time series data actually represent. Furthermore, perhaps there is a connection between column trends and the intensity of the tornadoes. And, of course, more cases should be examined in a similar manner as was done here. The three cases here definitely support the continuation of such studies, as there appears to be a possibility to gain significant operational benefit from $Z_{DR}$ column analysis.

## 4. CONCLUSION

$Z_{DR}$ column signatures offer unique and straightforward insight into the evolution of storm cell updrafts. As they are closely related to the strength of upward motion, changes in updraft intensity will very likely manifest themselves as changes in the $Z_{DR}$ column. Furthermore, the identification of this signature only requires one radar; therefore, they provide a feasible means for better estimation of updraft strength in an operational setting. And because the updraft is such an integral part of any storm and its related features, such as hail growth or tornadogenesis, the importance of utilizing $Z_{DR}$ columns for forecast purposes is clear.

In terms of hail growth, the cases presented within this study generally indicate a negative correlation between $Z_{DR}$ column strength and low-level hail core intensity at a lag of approximately 5-10 minutes. Conversely, a positive correlation tends to exist at a lag of 20-30 minutes. With the existence of such correlations, there is great promise for improving short-term forecasts of precipitation / hail intensity.

Although a connection between tornadic development and $Z_{DR}$ columns is not as clear, the data presented here very much support the continuation of such studies. Clearly, processes that affect the strength of low-level mesocylones and tornadoes also affect the evolution of the $Z_{DR}$ column. Therefore, this type of polarimetric analysis of updrafts has the potential to offer significant benefit to the operational community.

## 5. ACKNOWLEDGEMENTS

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## 6. REFERENCES

Adlerman, E.J., K.K. Droegemeier, and R.P. Davies-Jones, 1999: A numerical simulation of cyclic mesocyclogenesis. *J. Atmos. Sci.*, **56**, 2045-2069.

Askelson, M.A., 2002: Hydrometeor structures observed in supercells. Ph.D. dissertation, University of Oklahoma, 246 pp.

Beck, J.R., J.L. Schroeder, J.M. Wurman, 2006: High-resolution dual-Doppler analyses of the 29 May 2001 Kress, Texas, cyclic supercell. *Mon. Wea. Rev.*, **134**, 3125-3148.

Brandes, E.A., 1978: Mesocyclone evolution and tornadogenesis: Some observations. *Mon. Wea. Rev.*, **106**, 995-1011.

Caylor, I.C., and A.J. Illingworth, 1987: Radar observations and modeling of warm rain initiation. *Quart. J. Roy. Meteor. Soc.*, **113**, 1171-1191.

Doswell, D.C. and H.B. Bluestein, 2002: The 8 June 1995 McLean, Texas, storm. Part I: Observations of cyclic tornadogenesis. *Mon. Wea. Rev.*, **130**, 2626-2648.

Houze, R.A., 1993: *Cloud Dynamics*. Academic Press, 573 pp.

Johnson, K.W., P.S. Ray, B.C. Johnson, and R.P. Davies-Jones, 1987: Observations related to the rotational dynamics of the 20 May 1977 tornadic storms. *Mon. Wea. Rev.*, **115**, 2463-2478.

Kumjian, M.R., S. Ganson, and A.V. Ryzhkov, 2010: Polarimetric characteristics of freezing drops: Theoretical model and observations. *6th European Conf. on Radar in Meteorology and Hydrology*, Sibiu, Romania. Available online at http://erad2010.org/pdf/oral/friday/micro/07_ERAD2010_0159.pdf

Kumjian, M.R., A.V. Ryzhkov, V.M. Melnikov, and T.J. Schuur, 2010b: Rapid-scan super-resolution observations of a cyclic supercell with a dual-polarization WSR-88D. *Mon. Wea. Rev.*, **138**, 3762-3786.

Illingworth, A.J., J.F. Goddard, and S.M. Cherry, 1987: Polarization radar studies of precipitation development in convective storms. *Quart. J. Roy. Meteor. Soc.*, **113**, 469-489.

Lemon, L.R., and C.A. Doswell, 1979: Severe thunderstorm evolution and mesocyclone structure as related to tornadogenesis. *Mon. Wea. Rev.*, **107**, 1184-1197.

Meischner, P.F., V.N. Bringi, D. Heimann, and H. Höller, 1991: A squall line in southern Germany: Kinematics and precipitation formation as deduced by advanced polarimetric and Doppler radar measurements. *Mon. Wea. Rev.*, **119**, 678-701.

Nelson, S.P., 1983: The influence of storm flow structure on hail growth. *J. Atmos. Sci.*, **40**, 1965-1983.

Picca, J.C., and A.V. Ryzhkov, 2010: Polarimetric signatures of melting hail at S and C bands: Detection and short-term forecast. Extended Abstracts, *26th Conference on Interactive Information and Processing Systems (IIPS)*, Atlanta, GA, Amer. Meteor. Soc., 10B.4.

Trapp, R.J., 1999: Observations of nontornadic low-level mesocyclones and attendant tornadogenesis failure during VORTEX. *Mon. Wea. Rev.*, **127**, 1963-1705.