P6.6 USING MAXIMUM STORM-TOP DIVERGENCE AND THE VERTICAL FREEZING LEVEL TO FORECAST HAIL SIZE

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1. INTRODUCTION

The use of storm-top divergence from Doppler weather radar has proven useful for the issuance of convective weather warnings, especially in anticipation of severe hail. Researchers at the National Severe Storms Laboratory (NSSL) in the 1970s documented the strong divergent flow at the summit of thunderstorms using early Doppler radars. The first detailed study that looked at the divergent flow at the storm summit was done by Snapp in 1979. Later, Lemon and Burgess (1980) looked at 2 supercells in Oklahoma that were sampled by high-resolution Doppler radar and produced large hail. They concluded that the use of storm-top divergence can be useful in real-time warning operations. This was also the conclusion of another study done by Witt and Nelson in 1984 which looked at additional hail storms and attempted to develop a relationship to storm-top divergence and hail size. The most comprehensive study into storm-top divergence was published in 1991 by Witt and Nelson where they looked at 49 cases of hail 1.9 cm and larger reaching similar conclusions to the previous studies.

This study was conducted using high-resolution velocity data from the National Weather Service's (NWS) WSR-88D to investigate the relationship between storm-top divergence and hail size. Recent changes in the WSR-88D have allowed for increased resolution in velocity data available to operational forecasters in real-time. Since 2003, this has included 8-bit velocity data with a resolution of 0.5 ms^{-1} from -55.2 to 54.3 ms^{-1}. For example, Fig. 1 shows both the 4-bit and 8-bit data for two thunderstorms producing severe hail. Although not the same thunderstorm, the increased resolution with the 8-bit velocity data is clearly visible. In this case, the maximum storm-top divergence was 201 kt which occurred 9 min before the corresponding hail report. In addition to changes in velocity resolution, there have been additional volume coverage patterns (VCP 12, 212, 211, and 121). These additions have allowed for additional scanning strategies when interrogating thunderstorms.

Further motivation for an updated study on the use of storm-top divergence in real-time warning decision making is the inclusion of a forecasted hail size with a particular storm in most National Weather Service (NWS) severe thunderstorm warnings and statements:

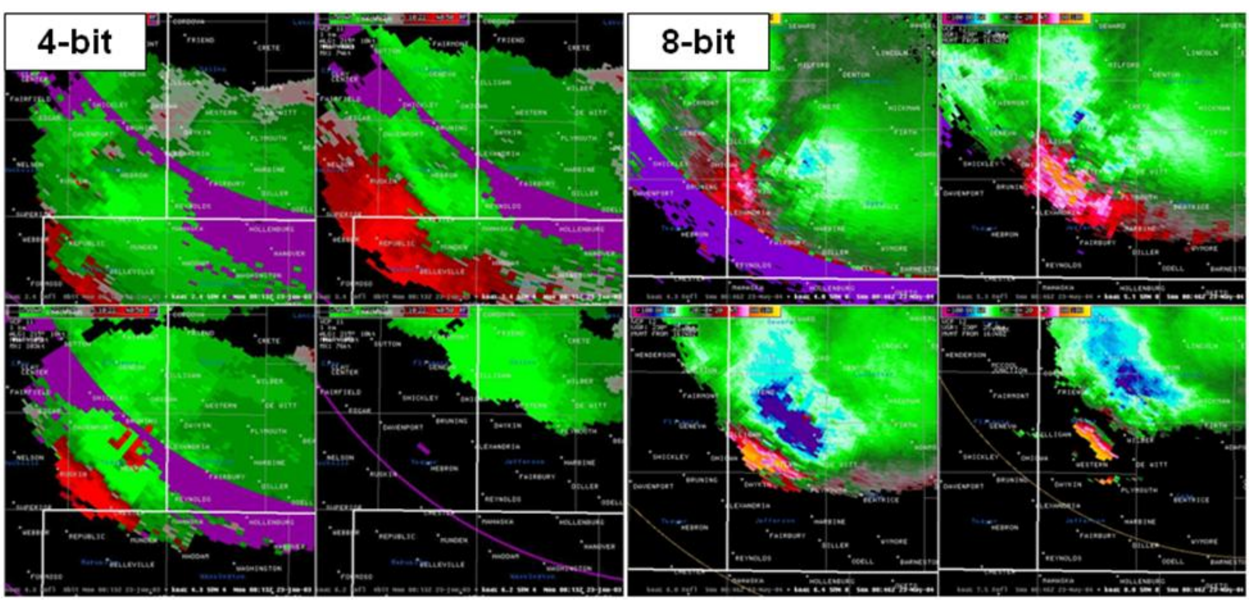

Figure 1. 4-bit and 8-bit radar data at 1821CST, 9 minutes before a corresponding hail report.

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> AT 139 PM CDT…NATIONAL WEATHER SERVICE DOPPLER RADAR INDICATED A SEVERE THUNDERSTORM CAPABLE OF PRODUCING LARGE DAMAGING HAIL UP TO **GOLF BALL SIZE**. THIS STORM WAS LOCATED NEAR MARSVILLE…MOVING EAST AT 30 MPH.

Local verification studies of forecast hail size indicate the majority of warnings and statements have a low probability of detection of significant hail, or hail that is larger than 4.4 cm (1.75 in) in diameter (Fig. 2). Thus, a physically-based technique for estimating the maximum hail size in a storm would be useful when including forecast hail size in a warning.

Other recent studies, such as Donovan 2007, have shown the importance of using the vertical freezing level when determining when a storm is capable of producing severe criteria hail. With the increased availability of 3-dimensional numerical model output, and associated confidence in the height of the freezing level, incorporating the freezing level into a study based on storm-top divergence would have the potential to increase performance when warning for severe hail.

2. DATA AND METHODOLOGY

Thunderstorms from the 2003 to 2007 convective seasons were included in the study. In addition, numerical model data from the National Center for Environmental Prediction's Rapid Update Cycle (RUC) model were used to obtain the height of the freezing level in the convective environment. Relationships were then developed using storm-top divergence with a range of freezing level heights to predict a corresponding maximum hail size. Average lead times were also calculated to the maximum hail size from the time of the strongest divergence signature.

Thunderstorms were analyzed from the central and northern Plains, including Kansas, Nebraska, Iowa, South Dakota, and North Dakota, with 100 storms used in the study. Of these 100 storms, 62 were supercell thunderstorms which were characterized by a persistent mesocyclone and 38 were multicell thunderstorms. Nineteen of the supercells were associated with tornadoes.

Hail time and size data were obtained from the National Climatic Data Center's Storm Data. Only hail of penny size (~1.9 cm) or greater was used. The methodology for correlating maximum hail occurrence with storm-top divergence was largely taken from the Witt and Nelson (1991) research. Storms were analyzed from 15 minutes before to 5 minutes after the report of the largest hail. Individual velocity data points generally had to be within 15 ms^{-1} of the surrounding data. The study used the largest hail report received for each storm during the entire lifespan of updraft. A single Doppler radar was used in each case to analyze the storms.

Freezing level data were obtained using RUC analysis soundings. The freezing level one hour prior to the occurrence of the large hail report was used. Freezing levels were rounded to the nearest 1,000 ft level. Graphs were constructed to investigate the strength of the relationships between storm-top divergence and hail size for each freezing level. Finally, tables were constructed for each freezing level height.

Several of the thunderstorms used in the study were also analyzed from initiation to dissipation. This was done to compare the use of storm-top divergence as an initial warning technique to other studies such as the Donavan (2007) study. To do this, the height of the 50 dBz core and the maximum storm top divergence were compared. Then, the timing of when a warning would

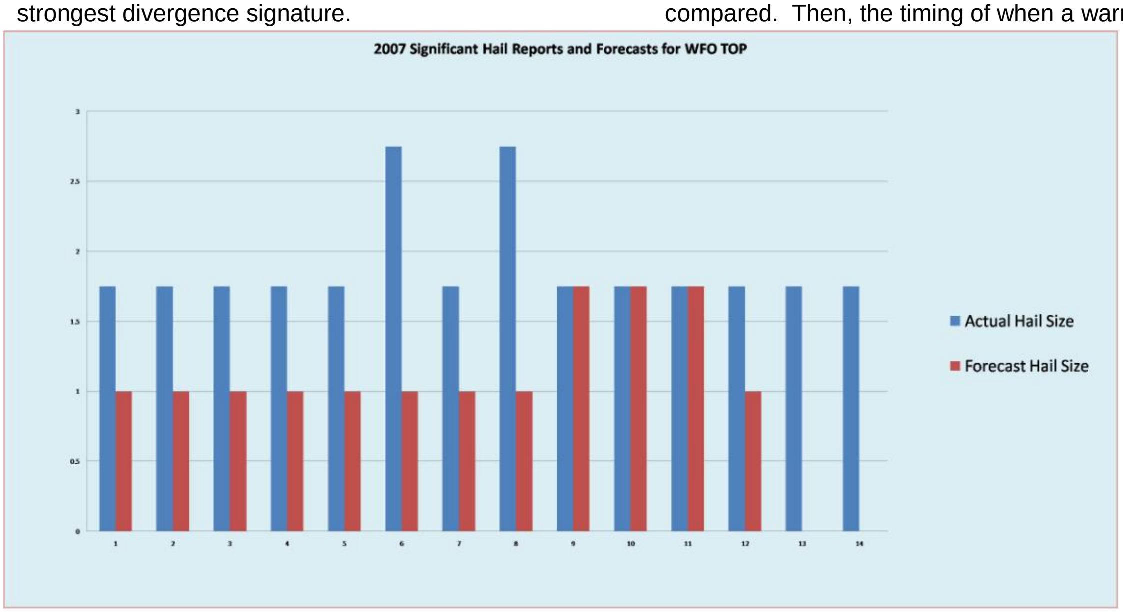

Figure 2. Number of hail reports, along with frequency of forecasts for each hail size, in the NWS Topeka CWA for 2007.

have been issued using just the minimum criteria for that freezing level was plotted.

Finally, verification of the results was conducted using data from the Severe Hail Verification Experiment (SHAVE) where high resolution hail reports were used in conjunction with Doppler radar data. SHAVE (Smith et al., 2006) obtains high resolution hail data for thunderstorms. It operates during a part of the spring and summer across the entire U.S. Numerous calls are made within the path of thunderstorms and residents are asked several about the hail that fell, and data are compiled into a database.

3. RESULTS

Results from all cases, at all freezing levels, are shown in Fig. 3a. The relationship between hail size and storm top divergence produces a correlation coefficient of 0.77. These results are not as strong as previous studies; possible complicating factors include limited hail reporting in sparsely populated areas, changes in NWS verification strategies, and the narrow nature of hail swaths. In addition, hail reporting is strongly tied to preset sizes. Reports are estimated and most easily conveyed by comparison to well known objects, such as coins (penny, nickel, quarter), sports balls (golf ball, tennis ball, baseball), and foods (walnut, hen's egg). For example, at a freezing level of 13,000 ft (Fig. 3b), the largest variability is around the golf ball size (1.75 in) hail. At this level, there were 18 total cases, with a correlation coefficient of 0.88.

Overall, adding the freezing level shows improvement in the correlation coefficient between storm-top divergence and hail size. For the 15,000 ft level (Fig. 3c), 17 cases were analyzed, with a correlation coefficient of 0.84. In addition, there was a significant increase in the minimum amount of storm-top divergence necessary to generate severe criteria hail.

Data from the SHAVE project was then used to test the results found in this study. There was 14 SHAVE hail reports used for the verification. Although this is a relatively small sample size, overall the reports are very representative of the results found using NCDC storm data. For example, at the ~15,000 ft freezing level, correlation from storm data was 0.85 and correlation from SHAVE was 0.88 (Fig. 3d). Likewise, for the ~14,000 ft freezing level (not shown), correlation from storm data was 0.94 and correlation from SHAVE was 0.93.

Finally, Fig. 4 is an example of one thunderstorm in which the updraft was analyzed from initiation to dissipation. In this case, a severe thunderstorm warning, using the minimum threshold criteria from results from this research and from the Donovan (2007) study, would need to be issued at the same time and would have provided the same amount of lead time to the first report of severe criteria hail. Further analysis of thunderstorms using this technique (not shown) indicated mixed results in that each technique sometimes gave better lead time than the other. Of note in all cases though is the

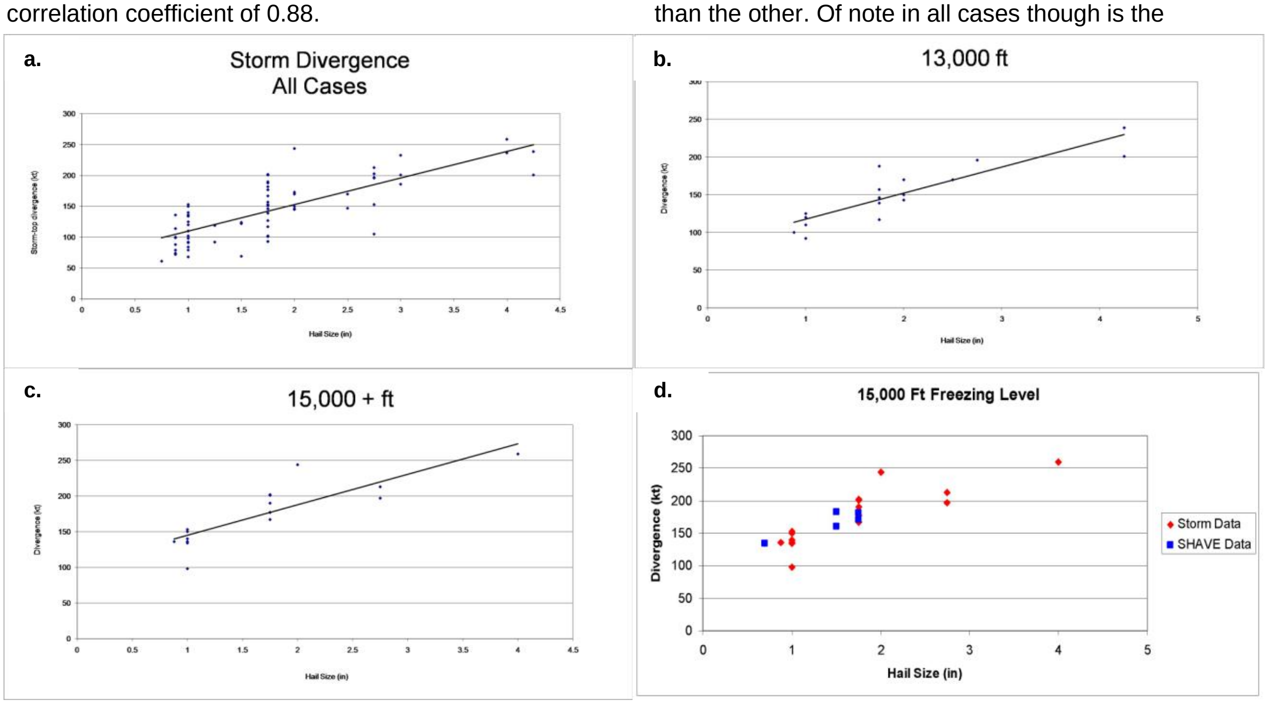

Figure 3. Correlation graphs between hail size and storm top divergence for (a) all cases, (b) cases at a freezing level of 13,000 ft, (c) cases at a freezing level at or above 15,000 ft, and (d) both storm data and SHAVE data for cases at or above a freezing level of 15,000 ft.

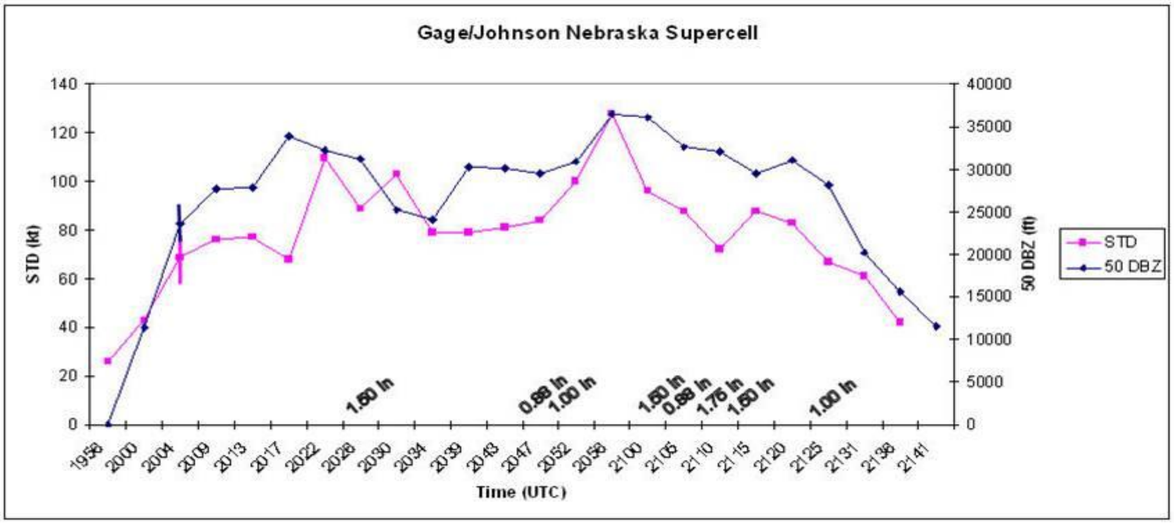

Figure 4. Storm-top divergence and height of 50 dBz core for an individual thunderstorm, along with hail reports.

weakening of the storm-top divergence prior to the decrease in reflectively aloft in the thunderstorms. This may indicate using storm-top divergence in determining future strength of a particular updraft could prove useful in warning operations.

Resulting tables were constructed for each 1,000 ft of freezing level between 11,000 ft and 15,000 ft (Fig. 5), utilizing the relationship between storm-top divergence and hail size determined in this study. The results show the least variability with the more significant hail of 5 cm or greater. This could be due to inaccurate reporting of hail of smaller sizes or that stronger updrafts produce more predictable hail sizes.

4. CONCLUSIONS

This study confirms that storm-top divergence continues to have utility in an operational warning environment. The inclusion of the vertical freezing level data in this study does result in an increase in correlation between storm-top divergence and maximum hail size. The results from the comparison with the high resolution SHAVE experiment data appear to confirm our findings that stratifying storm-top divergence and hail size by freezing level height results in a better correlation between the two. The results from this study appear to indicate the most utility for the use of storm-top divergence is in the larger hail stones 5 cm or greater. Thus warning forecasters using the tables may have increased confidence in including very large hail sizes into a severe thunderstorm warning. In addition, supercells that produced the largest stones (>7.6 cm) all had continuous high values of storm-top divergence in the 15 min prior to the report.

Other advantages to using storm-top divergence include no significant delay in obtaining SRM data compared to radar derived algorithms, so forecasters are able to assess information as data is received. Next, analyzing random storms in the study from development to dissipation does seem to indicate storm-top divergence provides information not only about the current strength of the updraft, but also about whether it is weakening or intensifying. Thus the warning forecaster can use the evolution of storm-top divergence to forecast if a storm will continue to produce severe criteria hail. Finally, the study results indicated the technique provides an average lead time of 8.0 min before the largest hail stone occurs.

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Storm top divergence
10500 - 11500 ft freezing level
8- bit SRM
STD = VR-shear *2

55 - 74	0.75" - 1.00"
74 - 115	1.00" - 1.75"
115 - 126	1.75" - 2.00"
126 - 148	2.00" - 2.50"
148 - 172	2.50" - 3.00"
175	> 300"

Storm top divergence
11500 - 12500 ft freezing level
8- bit SRM
STD = VR-shear *2

60 - 80	0.75" - 1.00"
80 - 120	1.00" - 1.75"
120 - 135	1.75" - 2.00"
135 - 155	2.00" - 2.50"
155 - 184	2.50" - 3.00"
185	> 300"

Storm top divergence
12500 - 13500 ft freezing level
8- bit SRM
STD = VR-shear *2

91 - 110	0.75" - 1.00"
110 - 143	1.00" - 1.75"
143 - 152	1.75" - 2.00"
152 - 170	2.00" - 2.50"
170 - 188	2.50" - 3.00"
195	> 300"

Storm top divergence
13500 - 14500 ft freezing level
8- bit SRM
STD = VR-shear *2

100 - 115	0.75" - 1.00"
115 - 147	1.00" - 1.75"
147 - 160	1.75" - 2.00"
160 - 180	2.00" - 2.50"
180 - 208	2.50" - 3.00"
215	> 300"

Storm top divergence
14500 + ft freezing level
8- bit SRM
STD = VR-shear *2

120 - 135	0.75" - 1.00"
135 - 178	1.00" - 1.75"
178 - 188	1.75" - 2.00"
188 - 209	2.00" - 2.50"
209 - 230	2.50" - 3.00"
231	> 300"

Note: Storms that produce the largest hail (i.e. >2.50 ") tend to have very highs storm top divergence for an extended period of time. Storms that show a short spike in storm top divergence generally have corresponding hail sizes in the lower range of possible sizes. Also, storm top divergence can provide some value as to the future strentgh of your updraft. Storm top divergence generally decreases quicker than your core height.

Figure 5. Table of storm top divergence and hail size for different freezing levels.