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Using Cell-Based VIL Density to Identify Severe-Hail Thunderstorms in the Central Appalachians and Middle Ohio Valley

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1. INTRODUCTION

Vertically integrated liquid (VIL) as an indicator of thunderstorm severity has been studied by researchers since the early 1970s (Greene and Clark 1972). With the arrival of the WSR-88D radar, VIL became operationally available at offices with warning responsibility as a tool for gauging the potential severity of thunderstorms. VIL density has also been shown to be useful in efforts to identify thunderstorms that have a high potential for producing severe hail (Troutman and Rose 1997, Amburn and Wolf 1997). However, for severe hail producing thunderstorms, a threshold VIL density was shown to be more consistent from season to season, and day to day than a threshold VIL (Amburn and Wolf 1997).

A threshold VIL density that could be used operationally at NWSFO Charleston WV was desired. However, previous studies done in different geographical areas have shown some variation in specific threshold grid-based VIL density values, with positive but differing amounts of success. With this in mind, a local study of VIL density was undertaken at the National Weather Service Forecast Office (NWSFO) Charleston WV, using data from the KRLX WSR-88D located in Ruthdale, 6 miles south of Charleston.

Since the implementation of Build 9.0 of the WSR-88D in 1996, cell-based VIL has been operationally available. Due to better accounting for storm tilt and storm movement, cell-based VIL can provide a better assessment of VIL for some storms than grid-based VIL (Operational Support Facility 1996; Johnson et al. 1998). Therefore, this study used cell-based VIL to find a threshold cell-based VIL density for the NWSFO Charleston, WV county warning area.

2. METHODOLOGY/BACKGROUND

VIL is calculated by vertically integrating reflectivity values from the top of a thunderstorm to the ground. The following is an equation for the calculation of VIL:

$$VIL = \Sigma 3.44 \times 10^{-6}[(Z_i + Z_{i+1})/2]^{4/7}\Delta h$$

Where VIL is liquid water content in kg m^{-2}, Z_i and Z_{i+1} are 2 subsequent radar reflectivity values in $mm^6\ m^{-3}$, and Δh is vertical distance between Z_i and Z_{i+1} in meters.

The variable for radar reflectivity (Z) used to find grid-based VIL is different than cell-based VIL. For grid-based VIL, radar reflectivity is found using the reflectivity value of a 4 km X 4 km (2.2 nm X 2.2 nm) grid in each elevation slice and then integrated in a vertical column. This methodology does not account for possible storm tilt or apparent tilt produced by fast-moving thunderstorms.

Cell-based VIL in Build 9.0 of the WSR-88D radar is determined by the Storm Cell Identification and Tracking (SCIT) algorithm (Operational Support Facility 1996). For each 3-dimensional cell identified on radar, SCIT determines a 3 bin average of the maximum reflectivity for each elevation slice. Cell-based VIL is then calculated by vertically integrating these maximum reflectivity values (Johnson et al. 1998). Unlike grid-based VIL, which is calculated for a 4 km X 4 km column, cell-based VIL is calculated using maximum reflectivity values from the core of the storm even if portions of that core are in different 4 km X 4 km columns. Therefore, cell-based VIL values may be higher than the highest grid-based VIL for a given storm. Due to the strict vertical assessment of grid-based VIL, tilted and fast-moving storms may result in unrepresentative, lower VIL values, while the core-following method of computing cell-based VIL attempts to compensate for both storm tilt and fast movement (Operational Support Facility 1997).

VIL density, which is calculated by dividing thunderstorm VIL by the height of the storm, has been found to be especially useful for identifying severe hail-producing thunderstorms (Troutman and Rose 1997, Amburn and Wolf 1997). A similar methodology was utilized at NWSFO Charleston WV, in an effort to determine the best severe hail threshold of VIL density for the central Appalachians and middle Ohio valley. Unlike the Amburn and Wolf study, which used the WSR-88D Grid-based VIL and Echo Tops products to determine VIL density, this study used the WSR-88D Algorithm Display and Testing System (WATADS) to simulate use of the WSR–88D Storm Structure product, which provides cell-based VIL and storm top. While the Echo Tops product uses an 18 dBZ threshold to define the top of a thunderstorm, the Storm Structure product uses 30 dBZ.

The following equation was used to calculate cell-based VIL density:

Cell-Based VIL density = (Cell-Based VIL/storm top) x 1000,

Where Cell-Based VIL density units are g m^{-3}, Cell-Based VIL units are kg m^{-2}, Storm top units are m, and 1000 is a conversion factor of 1000 g kg^{-1}.

3. DATA

Cell-based VIL and storm top data from the KRLX WSR-88D were acquired through processing level II archive data in the WATADS program, which uses a simulation of the WSR-88D Build 9.0 SCIT algorithm. The algorithm in WATADS that determines cell-based VIL yields an approximation of the values determined by the WSR-88D, with a potential error of a few percent (National Severe Storms Laboratory 1997).

The Storm Structure product from the WSR-88D uses 30 dBZ to define the storm top of a thunderstorm. However, the WATADS reflectivity display does not produce a 30 dBZ data level, but does indicate a 29 dBZ data level. Therefore, the highest elevation where 29 dBZ was found was used as the storm top.

Station policy at NWSFO Charleston requires WSR-88D implementation of Volume Coverage Pattern (VCP) 11 during severe weather events. VCP 11 provides 14 elevation slices with continuous vertical coverage for the lowest 6 slices and with a temporal update rate of 5 minutes. This allowed this study to reap the benefits of the best-available sampling of the storms. Cell-based VIL was found for 75 thunderstorms during 28 thunderstorm events. Severe hail was reported in 56 cases. The thunderstorms occurred during 1996 and 1997, mainly during May through July (Fig. 1). All thunderstorms analyzed occurred in the Charleston NWSFO county warning area.

a. Limitations

There were several limitations to this study. First, due to the sparse population of most areas in the central Appalachians and middle Ohio valley, many episodes of large hail were likely to go unreported. In addition, time and resources typically do not allow extensive searching for "non-reports", thus non-hail cases were limited to storms that tracked over highly populated areas when reports of severe weather would most likely occur (between 8 AM and 10 PM). This severely limited the number of non-severe hail cases included in the study. Even in those episodes where large hail was reported, in many cases it is unlikely that the largest hail that occurred was reported, making an accurate correlation of hail size to VIL density difficult. This study was therefore primarily concerned with finding a threshold cell-based VIL density which would correctly identify nearly all severe hail cases with a minimum of false alarms.

The cell-based VIL of one severe thunderstorm in this study could not be determined with certainty, and was hence discarded from the study. In this case, the thunderstorm under analysis was close by to a stronger thunderstorm. A gap occurred in the identification of the weaker thunderstorm near the hail report time, hence a maximum VIL value for this cell could not be fully determined. The stronger storm was continuously identified by WATADS.

Storms within the cone of silence were not included in the final results of the study. A previous study has shown that VIL density can be useful when attempting to identify severe hail producing thunderstorms in the cone of silence (Amburn and Wolf 1996). However, as neither cell-based VIL nor storm top can be accurately determined for these storms, they were omitted from this study.

4. RESULTS

Figure 2 shows a scatter plot of cell-based VIL versus severe storm top. The cell-based VIL density values of the 56 severe hail thunderstorms in the study were consistently high, with 91% yielding a cell-based VIL density of 4.0 g/m^3 or greater, and 64% yielding a cell-based VIL density of 4.5 g m^{-3} or greater (Fig. 3). No severe hail-producing thunderstorm in this study was found to have a cell-based VIL density less than 3.2 g m^{-3}, and all thunderstorms with hail 1.25 inch in diameter or greater had a cell-based VIL density of 4.1 g m^{-3} or greater (Table 1). Storm tops from the severe hail thunderstorms analyzed ranged from 22,700 ft (6,919 m) to 54,800 ft (16,703 m), with cell-based VILs ranging from 34 to 88 kg m^{-2}. Storm tops of the non-severe hail thunderstorms varied from 20,800 ft (6,340 m) to 53,900 ft (16,429 m), with cell-based VILs of 10 to 54 kg m^{-2}. VIL densities for the non-severe hail-producing thunderstorms ranged from 1.6 to 4.4 g m^{-3} (not shown).

Based on the data set used in this study, using a threshold cell-based VIL density of 4.0 g/m^3

would yield a probability of detection (POD) of 0.91, and a false alarm ratio (FAR) of only 0.019. If warnings had been issued based on a threshold cell-based VIL density of 4.0 g/m^3, a total of 51 severe storms would have been warned for and verified, 1 storm would have prompted a warning for which verification of severe hail was not found, and 5 severe hail storms would not have been warned for. This yields a critical success index (CSI) of 0.89. However, it should be noted that both the FAR and the CSI may be skewed somewhat due to the limited number of non-severe hail thunderstorms in the database. A more telling statistic may be the percentage of non-severe storms that would have prompted false warnings using a threshold of 4.0 g/m^3, which in this case is only 5%.

The thunderstorms analyzed for cell-based VIL density in this study appeared to show a trend of increasing hail size with increasing cell-based VIL density. This trend is consistent with other recent studies on VIL density, including studies done by Turner and Gonsowski (1997), Troutman and Rose (1997), and Amburn and Wolf (1997). Both Table 1 and Fig. 3 show that larger hail in this study was more frequently associated with larger cell-based VIL density values. Several reports of smaller severe hail (less than 1 inch in diameter) were also associated with large cell-based VIL density values. This may be due at least in part to the sparse population of most locations in the central Appalachians and middle Ohio valley, potentially inhibiting reports of larger hail.

5. CONCLUSIONS

This study found that severe hail producing thunderstorms in the Charleston WV county warning area had consistently high values of cell-based VIL density. A threshold cell-based VIL density of 4.0 g m^{-3} appeared to work well with the data set used in this study, correctly identifying 91% of severe-hail cases and falsely identifying as severe only 5% of the non-severe hail cases. Amburn and Wolf's Oklahoma study found a threshold grid-based VIL density of 3.5 g m^{-3}, with a nearly identical POD and FAR. The higher threshold density value found in this study is likely due to three factors. First, using the storm top value instead of echo top value to define the top of the storm results in lower average storm tops, and thus higher density values. Second, as stated earlier, cell based VIL values may on average be higher than grid-based VIL, leading to higher density values. Finally, the differences inherent to differing geographic locations, also may explain some of the variation in density values.

There was some indication that cell-based VIL density tended to increase with increasing hail size. However, few hail reports in this data set were larger than an inch, likely due to the sparse population of the central Appalachians and middle Ohio valley. Therefore, the relationship of increasing VIL density with increasing hail size cannot be demonstrated with certainty.

Quick identification of severe hail thunderstorms using cell-based VIL density values has the potential to improve warnings of severe thunderstorms. Since both the cell-based VIL and storm top are readily available on one product (Storm Structure), calculation of cell-based VIL density can be done very quickly in an operational setting. Further study of cell-based VIL density could determine whether or not severe hail producing thunderstorms in Charleston's county warning area could have cell-based

VIL density values less than 3.0 g m^{-3}. However, this lack of lower values may attest to the improved accountability of storm tilt and fast-moving thunderstorms with the WSR-88D Build 9.0 SCIT algorithm.

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Hail Diameter (inches)	Cell-based VIL Density Categories (g/m^3)				
	3.0 - 3.49	3.5 - 3.99	4.0 - 4.49	4.5 - 4.99	$\geq$ 5.0
$\geq$ 1.25"	0	0	3	2	3
1.00"- 1.24"	0	2	3	5	5
0.75"- 0.99"	2	1	9	14	7

Table 1. Number of events for various categories of cell-based VIL density versus hail diameter associated with severe thunderstorms. Note that as the hail diameter increases, the cell-based VIL density category also increases.

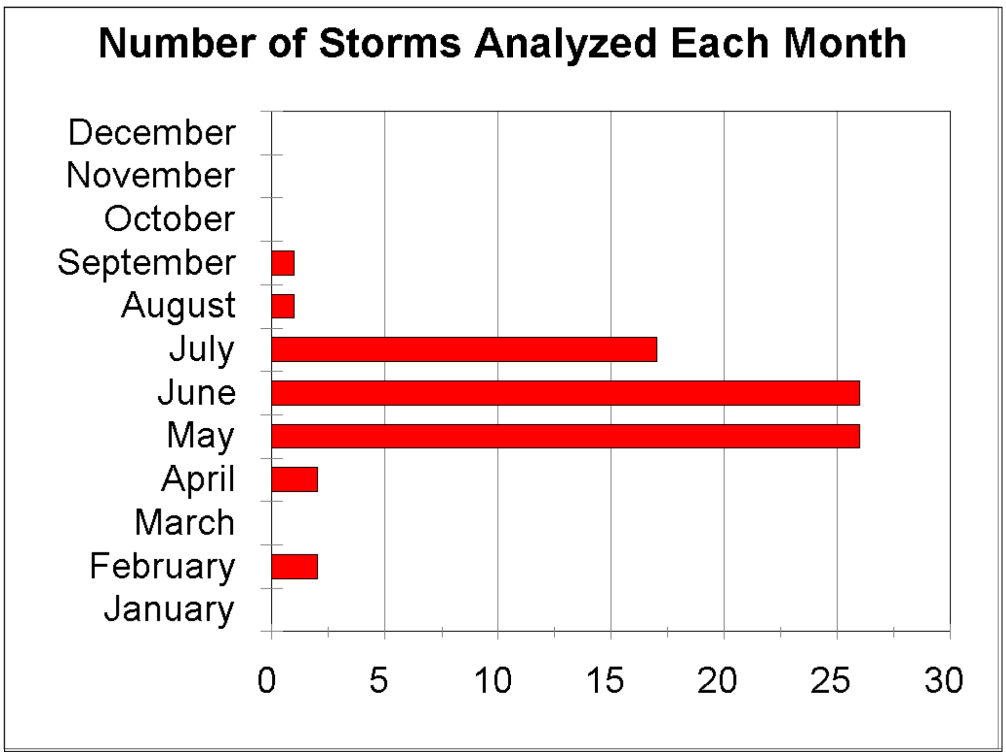

Figure 1. Number of storms in each month that were analyzed in this study. Note that most of the hail producing thunderstorms occurred during May through July.

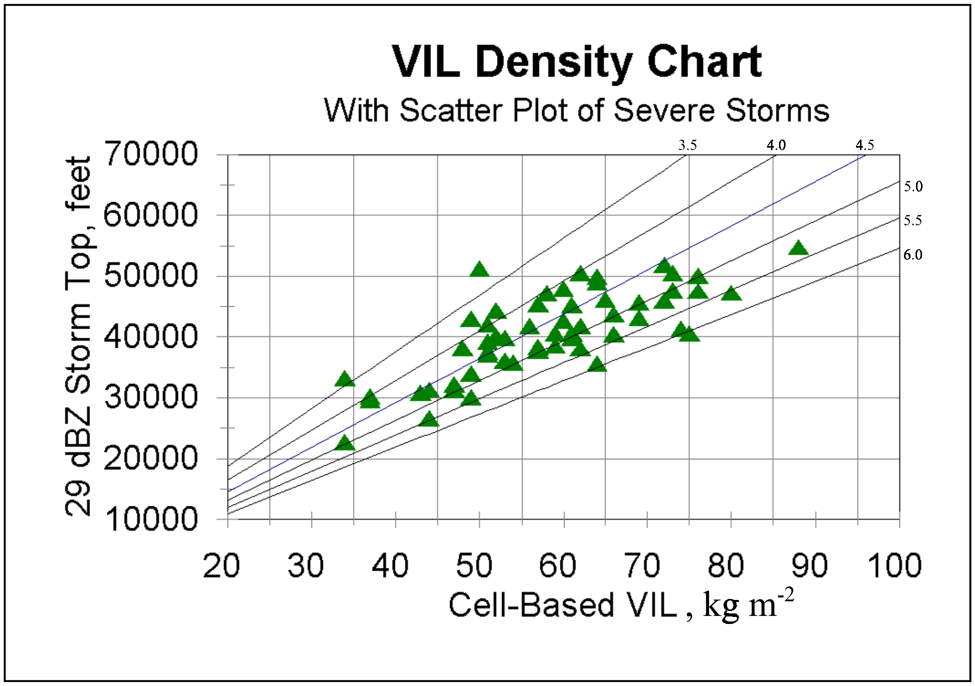

Figure 2. VIL density chart, with a scatter plot of severe hail producing thunderstorms analyzed in this study. Diagonal lines on this chart represent lines of constant VIL density, calculated using the VIL density equation stated in this paper. VIL density units are g m^{-3}.

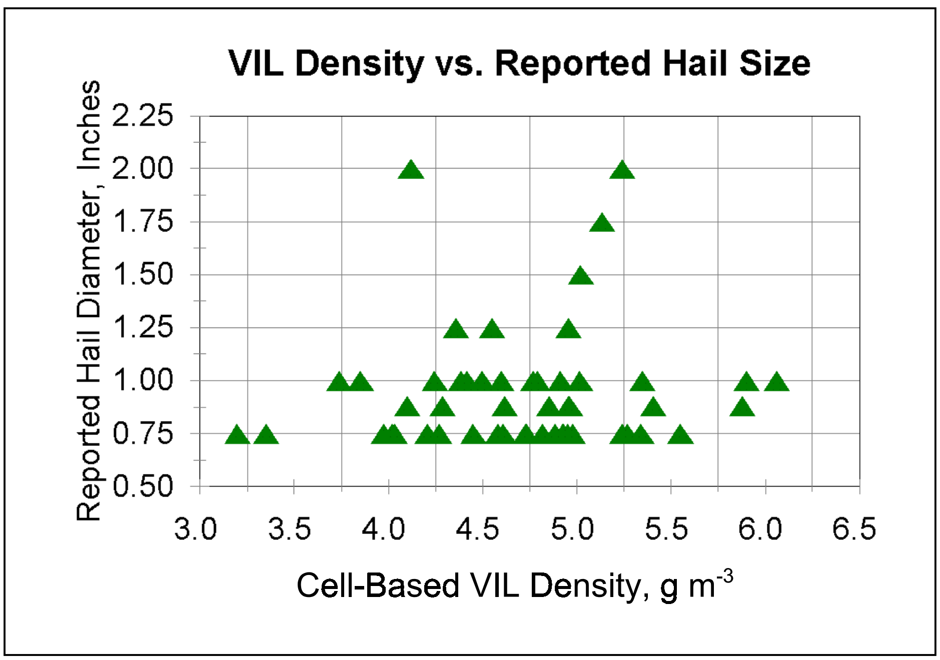

Figure 3. Cell-based VIL density versus reported hail size for 56 severe hail producing thunderstorms that occurred in 1996 and 1997**.**