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VERTICALLY INTEGRATED LIQUID DENSITY AND ITS ASSOCIATED HAIL SIZE RANGE ACROSS THE BURLINGTON, VERMONT COUNTY WARNING AREA

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ABSTRACT

Since 1997 when Vertically Integrated Liquid (VIL) density was introduced as a tool for assessing hail potential in thunderstorms, much research has focused on making better use of this method in operational forecasting during severe weather events. To assess the usefulness of this method in the Burlington, Vermont county warning area, thunderstorm VIL and echo tops were analyzed for a number of severe thunderstorm events, and VIL density was calculated. VIL density was then correlated to the observed reports of hail. The results showed that above a VIL density threshold value of 3.28 g m^{-3}, severe hail occurred in a substantial number of thunderstorm events. Further, results also showed that above a VIL density threshold value of 4.22 g m^{-3}, severe hail occurred in almost every thunderstorm.

1. INTRODUCTION

Forecasting hailstorms has been a popular topic of research for the past 2 decades, because of their physical damage and financial costs to society. In an attempt to improve warning lead times for thunderstorms producing severe hail, much research has focused on making greater use of vertically integrated liquid water content (VIL). Amburn and Wolf (1997) were the first of many to study VIL density and showed that it is a useful method for assessing hail potential in thunderstorms.

A sample of 156 severe thunderstorm events from 1997 to 2004 was examined using radar data from the National Weather Service Forecast Office (NWSFO) Burlington, Vermont (BTV) Weather Surveillance Radar -1988 Doppler (WSR-88D) located in Colchester, Vermont (KCXX). The data was used to determine if the VIL density method established by Amburn and Wolf is an effective tool for forecasting hail across the WFO BTV County Warning Area (CWA) in the state of Vermont and Northern New York. This study also sought to compare the VIL density method to the WSR-88D's Hail

Detection Algorithm (HDA), to investigate the relative accuracies of the VIL density method and other radar algorithms.

2. VERTICALLY INTEGRATED LIQUID

Clark and Greene (1972) were the first to introduce the idea that the concentration of liquid water in a cloud could be a useful tool for assessing the severity of a thunderstorm. They noted that rapid increases in liquid water content appeared to indicate "explosive development" of severe storms. Liquid water content is calculated by the WSR-88D software and depicted in the VIL product. It is a nonlinear function of reflectivity which converts radar reflectivity data into estimates of equivalent liquid water content based on theoretical studies of drop size distributions and empirical studies of reflectivity factor and liquid water content (Amburn and Wolf 1997). The VIL equation used in the WSR-88D software is

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

where Z_i and Z_{i+1} are two radar reflectivity values and Δh is the vertical distance between Z_i and Z_{i+1} in meters. The units of VIL are in kg m^{-2}. It is calculated using the reflectivity value of a 4 km x 4 km horizontal grid in each elevation scan and then is integrated through a vertical column (U.S. Department of Commerce 1991). This method of computing of VIL is also referred to as grid-based VIL (GBVIL).

3. VIL DENSITY

Amburn and Wolf (1997) first pioneered the idea of using VIL density to assess the presence of large hail in a thunderstorm after noting that high-topped thunderstorms with high VIL values did not always produce large hail, while low-topped thunderstorms with low VIL values sometimes did produce large hail. They hypothesized that dividing a storm's VIL value by its Echo Top (ET), VIL would be "normalized" and produce a common value for thunderstorms producing large hail, independent of air mass characteristics (Amburn and Wolf 1997). They defined VIL density as:

$$\mathbf{VIL\ Density = (GBVIL / ET) * 1000} \quad \mathbf{(2)},$$

where GBVIL is measured in kg m^{-2}, and ET is measured in meters. The ratio is then multiplied by a factor of 1000 to yield units of g m^{-3}. The resulting VIL density value would be independent of air mass characteristics, and could be used to quickly identify thunderstorms with high reflectivity values relative to their height. Amburn and Wolf (1997) also hypothesized that as VIL density values increased, the hail core should become deeper and more intense, and thus reported hail sizes should tend to be larger.

4. METHODOLOGY & DATA

One hundred fifty-six severe thunderstorm events from June 1997 through August 2004 in the WFO BTV CWA were analyzed. For the purposes of this study, severe hail was defined as hail greater than or equal to 1.9 cm (0.75 in), which is the NWS standard criteria for verifying severe hail. The events were divided into two groups based on hail size: a severe group with severe thunderstorm events that produced severe sized hail greater than or equal to 1.9 cm (0.75 in) in diameter, and a non-severe group with severe thunderstorm events which produced high wind or damage related to high wind such as downed trees, and non-severe sized hail (≤1.9cm [0.75 in]), but did not produce severe sized hail.

Severe thunderstorm events were identified from local storm reports (LSR) retrieved both in real time and from the National Climatic Data Center's (NCDC) storm event database. After an event was identified as severe or non-severe, VIL and ET values were then acquired from the KCXX archive IV data, the Advanced Weather Interactive Processing System (AWIPS), or from data archived on digital video disk (DVD) from the Weather Event Simulator (WES; Magsig and Page [2003]). The maximum VIL value observed nearest to the time and location of each hail report was recorded using values from the GBVIL product computed by the WSR-88D. Since GBVIL values are displayed by the radar in a 5 kg m^{-2} range (i.e., 40-45 kg m^{-2}), the lower VIL value was used due to data ambiguity. The maximum ET value observed nearest to the maximum GBVIL value was then recorded. VIL density values were then computed for each storm using equation (2).
The WSR-88D ET algorithm computes ET by locating the maximum height where reflectivity is greater than or equal to 18.3 dBZ for each 2.2 km x 2.2 km grid box. The mean sea-level height of the radar is then added to the above-mentioned height and the final height value is the storm's echo top.

In 1996, the Storm Cell Identification Tracking (SCIT) algorithm (Johnson et al. 1998) for tracking storm cells was introduced with the WSR-88D build 9.0 software release. The SCIT algorithm provides storm cell structure attributes and tracking information. For purposes of this study, two storm structure attributes, Cell-based VIL (CBVIL), and Storm Top (ST), were used to calculate a new value of VIL density. CBVIL and ST are calculated differently than GBVIL and ET. Typically, GBVIL is calculated within a vertical 4 km x 4 km column. In SCIT, CBVIL is calculated using the maximum reflectivity values from the core of the storm, even if portions of that core are in different 4 km x 4 km columns (Belk and Wilson 1998). By using this method, storm tilt and movement are accounted for, which may capture the liquid water content of the reflectivity core better than the GBVIL calculation. ET is usually calculated using the height of the 18 dBZ reflectivity echo, whereas ST uses the height of the 30 dBZ echo. With the availability of this data, a cell specific method (CBVIL/ST) was also used to compute the VIL density for each thunderstorm event.

Thunderstorms in the non-severe group with ET values of less than 9144 m (30,000 ft) were not considered for this study, unless the thunderstorm produced hail, since severe thunderstorms rarely occurred in the BTV CWA with storm top heights of less than 9144 m. To be consistent with previous studies of VIL density (Amburn and Wolf 1997; Blaes et al. 1998; Rose and Troutman 1997), thunderstorms with maximum VIL values of less than 15 kg m^{-2} were also not included.

Finally, the probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) were computed for several VIL density thresholds to assess the best threshold to use for severe hail warnings in the BTV CWA. POD is defined as

$$\textbf{POD = A / (A+B)} \quad \textbf{(3),}$$

where (A) is the number severe hail events with a VIL density greater than or equal to a particular threshold, and (B) is the number of severe hail events with a VIL density less or equal to the same threshold. FAR is defined as

$$\textbf{FAR = C / (A+C)} \quad \textbf{(4),}$$

where (A) is the same as in equation (3) and (C) is the number of non-severe hail events with a VIL density greater than or equal to the same threshold. CSI is a combination of POD and FAR scores, and is defined as

$$\textbf{CSI = A / (A+B+C)} \quad \textbf{(5)}$$

5. LIMITATIONS

Several limitations exist in the data used for this study including a limited number of ground-truth hail reports and the design and location of the KCXX WSR-88D. One of the largest sources of potential error in any hail study is the verification of actual hail size in spotter reports. As noted by Witt and Wyatt (1997), hail reporting requires spotters in be in the location where the hail is falling, and also have the ability to measure the size of the hail and accurately pinpoint its location and the time it fell. They hypothesized that hail reports were better in areas of high population density compared to areas where there are few people to report it. This is especially true for the WFO BTV CWA, where large portions of the forecast region are uninhabited or forested and have no weather spotters and large hail from a storm could potentially go unreported. Similarly, even if hail is reported, the exact time and location of the event may not be accurate, which makes it difficult to correlate the report with radar data.

The design and location of the WSR-88D radar is another important limitation of this study. The highest elevation scan performed by the WSR-88D is at an angle of 19.5º, so data within a radius of 15 nautical miles from the radar are not sampled well, if at all. Additionally, the location of the KCXX WSR-88D poses a sampling problem. The KCXX WSR-88D is located in the town of Colchester, Vermont at the Camp Johnson Army National Guard Base, in the Champlain Valley at an elevation of 97 m (318 ft). Located 35 nm to the west and southwest of the radar are the Adirondack Mountains of New York (Fig. 1), which rise to an elevation of 1629 m (5345 ft). To the east are the Green Mountains of Vermont, which reach a maximum elevation of 1339 m (4,393 ft). Both mountain ranges present a radar data quality problem, creating large areas of beam blockage at low elevation angles. East of the radar over the Green Mountains, greater than 60% of the radar beam is blocked at an elevation angle of 0.5° for the entire eastern half of Vermont. In addition, for the northeast section of the radar range, greater than 60% of the beam is blocked even at an elevation angle of 1.5°. With beam blockage at lower elevation angles, radar calculations of reflectivity will be limited and will be lower than the actual value.

Radar reflectivity observation error can cause uncertainty in the calculation of VIL. Radar reflectivity is a measure of the amount of power backscattered by raindrops in a volume of the atmosphere sampled by the radar (French et al. 1995). While the uncertainty of a single reflectivity measurement may be low, for a product derived from this data such as VIL, the uncertainty associated with it may be much larger. This problem became evident when looking at data from storms that occurred in the northeast portion of the CWA study area, where 60% of the radar beam from KCXX is blocked by the higher terrain of the Green Mountains at the elevation angle of 1.5º. Lack of reflectivity data in the lower elevations in this sector will lead to substantially lower VIL values resulting in lower VIL density values and under representing the hail potential in a thunderstorm. For this reason, storms that occurred in Northeast Vermont where beam blockage occurred at the 1.5º elevation angle were not used for this study.

An example of lack of reflectivity data in the lower levels due to beam blockage can be seen from data taken during a hailstorm over Lyndonville, Vermont on 7 July 2001, which produced hail 3.8 cm (1.5 in) in diameter. Figure 2 shows the lack of reflectivity data at the lower elevation scans due to radar beam blockage. Due to the absence of reflectivity data, the GBVIL value computed by the radar is unrepresentative. The GBVIL value given by the radar in this case was only 30 to 35 kg m^{-2} (Fig. 3), a very unlikely value to be associated with hail of 3.8 cm (1.5 in), as results of this study show typical GBVIL values for hail greater than or equal to 1.9 cm (0.75 in.) would be greater than 35 kg m^{-2}.

Another limitation was the availability of data from the radar archives. Several events worthy of inclusion in the NCDC's storm database were not available in the radar archives. This is likely due to the fact that older versions of the WSR-88D software required immediate archiving at the beginning of an event, or the data would be lost.

6. RESULTS

Of the 156 severe thunderstorm events identified, 72 events (the "severe group") produced severe sized hail greater than or equal to 1.9 cm (0.75 in) in diameter, and 84 events (the "non-severe group") produced non-severe hail less than 1.9 cm in diameter or produced wind damage, but no hail. Thunderstorm values of VIL and ET for all events ranged from 10 to 75 kg m^{-2} and 6,096 to 16,764 m (20,000 to 55,000 ft), respectively. It was found that 90% (65 of 72) of the severe hail events occurred with a VIL value greater than or equal to 35 kg m^{-2}, and 94% (68 of 72) occurred with an ET value greater than or equal to 9144 m (30,000 feet). No severe hail occurred with a VIL value less than 25 kg m^{-2} or an ET value less than 6096 m (20,000 feet). VIL density for severe hail events ranged from 2.81 g m^{-3} to 5.62 g m^{-3}.

POD, FAR and CSI scores were calculated for a broad range of VIL density thresholds for severe versus non-severe events (Table 1). A VIL density threshold of 3.28 g m^{-3} was found have a POD of 0.99, a FAR of 0.24, and a CSI of 0.75 for all events. A threshold of 3.69 g m^{-3} was found have a POD of 0.88, a FAR of 0.16, and a CSI of 0.75 for all events. Both thresholds offer the same CSI, though the 3.28 g m^{-3} threshold has a much better POD, and only slightly larger FAR. It was for this reason that 3.28 g m^{-3} was chosen as the threshold value to use to assist in making warning decisions for severe versus non-severe hail. It was noted in the data that only one severe hail event occurred with a VIL density of 3.0 g m^{-3} or less.

Using POD, FAR and CSI scores, a VIL density threshold for hail events greater or equal to 1 inch in diameter was calculated (Table 2). Based on CSI, a VIL density threshold of 4.22 g m^{-3} was identified to assist in discerning hail events 1 inch or greater. It was also noted that only one non-severe hail event occurred with a VIL density of 4.22 g m^{-3} or greater.

Using the traditional method of computing VIL density, as defined by Amburn and Wolf (1997), a scatter diagram was constructed (Fig. 4) of Echo Tops and GBVIL using 72 severe hail events and 84 non-severe events. Values of VIL density (g m^{-3}) are also plotted on this diagram shown as solid lines, labeled 3.28, 3.69, and 4.22. As VIL density increases, more of the severe events meet or exceed the indicated VIL density threshold. Comparing the number of severe and non-severe events versus VIL Density (Fig. 5), it is evident that as VIL density increased, the number of non-severe events decreased. Also, from inspection of hail size versus VIL density (Fig. 6), it can be seen that as average VIL density increased, the hail size increased.

The results of this study are similar to other recent studies of VIL density across the country such as Albany, NY (Blaes et al. 1998), Tulsa, OK (Amburn and Wolf 1997), Nashville, TN (Rose and Troutman 1997), Peachtree City, GA (Hart and Frantz 1998), Goodland, KS (Turner 1998), and Lake Charles, LA (Roeseler and Wood 2001). Of interest are the similarities and differences between this study's results and a VIL density study performed by Blaes et al. (1998) at the WFO in Albany, NY. Although the two CWA's are physically close in proximity and contain similar terrain and climate features, the critical threshold for each office was found to be different. The Albany study found a VIL density of 3.5 g m^{-3} correctly identified 82% of severe hail events, and incorrectly identified 7% of non-severe events, whereas the BTV study found a VIL density of 3.28 g m^{-3} correctly identified 99% of severe hail events, and incorrectly identified 27% of non-severe events in the BTV CWA using KCXX radar data. This slight difference in results might be the result of the number of hail events included in this study: the 154 total events (97 severe and 57 non severe) over 5 convective seasons in the Albany study, compared to the 156 events (72 severe and 84 non severe) over 8 convective seasons in the BTV study. In the Albany study, there was a greater number of hail events (43) producing larger hail (2.5 to 4.5 cm [1 to 1.75 in]) than in the BTV study with 29 events of hail greater than or equal to 2.5 cm (1.0 in). Larger hail sizes would result in increased VIL density values and thus a larger VIL density threshold would be expected. Another explanation for differences in results could be due to the fact that the Albany radar is not as beam blocked as the Burlington radar.

This would account for lower VIL density values in the Burlington CWA, and thus a lower VIL density threshold.

The Albany study's results are similar to those of a Tulsa study performed by Amburn and Wolf (1997), where a VIL density of 3.5 g m^{-3} correctly identified 90% of severe hail events. Similar studies performed in the WFO Nashville, Tennessee CWA (Rose and Troutman 1997); the WFO Peachtree City, Georgia CWA (Hart and Frantz 1998); the WFO Goodland, Kansas CWA (Turner 1998); and the WFO Lake Charles, Louisiana CWA (Roeseler and Wood 2001) also had similar results as Amburn and Wolf's findings. Differences did arise however when comparing results to similar studies performed in the Western and Mid-Western states. A study performed in the WFO Sacramento, California CWA (Tardy 2001) found similar results to the Amburn and Wolf study for the mountains in the Sierra Nevada. However, studies performed in the WFO Salt Lake City, Utah CWA (Graham and Struthwolf 1999) and the WFO Springfield Missouri CWA (Taggart 1997) found a much lower VIL density value, 3.07 g m^{-3} and 3.1 g m^{-3} respectively, to be more useful for their specific CWA.

From the results of all these studies, there is a range (3.1 to 3.7 g m^{-3}) for which VIL density threshold values correctly identify storms containing severe hail; however, other variables such as elevation of the radar above mean sea level and topography can affect threshold values for a specific radar coverage area. As such, it appears that for optimum operational use of VIL density for a specific radar coverage area, a local study needs to be performed to discover the threshold value for that area. Without a local study, use of generic VIL density values in hail forecasting can potentially have an adverse effect on severe weather verification scores.

7. COMPARISON WITH THE WSR-88D HAIL DETECTION ALGORITHM

The WSR-88D HDA became operational in the WSR-88D build 9.0 software release in 1998, which contained an entire suite of storm detection algorithms (Lenning et al. 1998). The HDA is broken down into 3 component algorithms: the probability of hail (POH), the probability of severe hail (POSH), and the maximum expected hail size (MEHS). These values can be found on AWIPS in the Combined Attribute Table associated with the composite reflectivity product.

To compute the probability of hail (POH,) the HDA only needs reflectivity data and numerical model output of the melting level (Davis 2002). The algorithm uses the height of the 45 dBZ echo above the height of the environmental melting level to statistically calculate the POH (Witt et al. 1998). The height of the 45 dBZ echo is obtained from radar reflectivity data, while the height of the melting level is normally obtained from an observed sounding or numerical model output. To compute POSH, the HDA relies on the Severe Hail Index (SHI). The SHI is based on reflectivity values of at least 40 dBZ at altitudes above the melting level (Lenning et al. 1998). Finally, like the POSH algorithm, the HDA uses the SHI for the calculation of MEHS. However, this calculation is much simpler than that for POSH, as it uses only SHI for calculation hail sizes in millimeters shown in equation 6.

$$\mathbf{MEHS = 2.54(SHI)^{0.5}} \quad \mathbf{(6)}$$

For each storm cell producing hail in the study, the POH, POSH, and MEHS were also recorded. After all VIL density values were computed using the traditional method (GBVIL/ET), Table 3 was created as a guideline for predicting hail size range based on VIL density. The ranges for severe hail in Table 3 were determined using the best CSI value for each hail size. For the range beginning with 1.9 cm (0.75 in) diameter hail (severe criteria), 3.28 g m^{-3} was chosen as the lower limit because it was found to have the highest CSI for all hail diameters of severe size (Table 1). For the range beginning with 2.5 cm (1 in) diameter hail, 4.22 g m^{-3} was chosen as the lower limit because it was found that this threshold had highest CSI 0.46 (Table 2). The upper limit for this range was chosen to be 4.45 cm (1.75 in), because it was found that in the past 75 years there were only 10 hail cases in the BTV CWA where hail greater than or equal to 5.08 cm (2 in) was reported (NCDC). For the range of non-severe hail the lower limit of 2.0 g m^{-3} was chosen because only 1 non-severe hail event had a VIL density of less than 2.0 g m^{-3}.

Using Table 3, the 90 thunderstorm events where severe and non-severe hail fell were examined to compare the hail size ranges predicted by the VIL density method and the HDA MEHS. For VIL density, a hit was scored if the VIL density value and its corresponding range of predicted hail sizes (Table 3) matched the reported hail size. The HDA was scored using the same predicted hail size ranges as VIL density in Table 3. If the MEHS fell within a range of predicted hail sizes from Table 3 that matched the reported hail size, the HDA was scored a hit. For example, if the HDA predicted hail 4.45 cm (1.75 in) in diameter, and only 2.5 cm (1 in) hail fell, the HDA was scored a hit. If the HDA predicted hail 7.62 cm (3 in) in diameter, and only 2.5 cm (1 in) hail fell, the HDA was scored a miss.

The results were unexpected. VIL density and the HDA were nearly equal in their ability to discern between severe versus non-severe hail events, with POD scores of 0.99 and 0.96 and CSI scores of 0.89 and 0.83, respectively. The VIL density method correctly identified the hail size range of 62% (56 of 90) of the events, compared to the HDA MEHS, which correctly identified the hail size of only 36% (32 of 90) of the events. Furthermore, the VIL density method correctly identified the hail size range of 65% (47 of 72) of the severe hail events, and 50% (9 of 18) of the non-severe hail events, compared to the HDA, which correctly identified the hail size of only 35% (25 of 72) of the severe hail events, and only 39% (7 of 18) of the non-severe hail events.

With the data available from this study, it was found that the use of the VIL density method to predict hail size range is superior to the WSR-88D HDA MEHS over most of the Burlington CWA. The HDA will likely predict the hail size range more accurately than the VIL density method over the beam-blocked northeast portion of the CWA. The HDA is relatively unaffected by beam blockage; only reflectivity values above the melting level are sampled, which in most instances, is above the lower elevations where the beam is blocked. Therefore, hail size values predicted by the HDA will be more accurate than the VIL density method where radar beam blockage occurs.

8. COMPARISON OF GBVIL AND CBVIL DERIVED VIL DENSITY

Enhancements to the WSR-88D radar in the build 9.0 software release, specifically CBVIL and ST values, were examined and compared to the traditional method of calculating VIL density (GBVIL/ET). VIL density values were computed using a cell specific method of cell-based VIL divided by storm top (CBVIL/ST). The results indicated that this method showed little or no improvement in predicting severe vs. non-severe hail over the traditional method of computing VIL density (Fig. 7). Figure 7 shows that as VIL density values increased, the number of severe events increased, but the number of non-severe events remained somewhat constant, in contrast to the traditional method (Fig. 5). For this reason, it was concluded that using cell-based data did not improve the VIL density utility, and should not be used operationally in the BTV CWA.

9. DISCUSSION

Results from this study imply that there is a strong relationship between VIL density and the occurrence of severe hail in the Burlington, Vermont County Warning Area. The results indicate that VIL density could be a very useful operational tool during a severe thunderstorm event to accurately identify storms that have the potential to produce severe or non-severe hail, and to predict the size range of the hail associated with the storms. It was found that a GBVIL/ET computed VIL density value of 3.28 g m^{-3} served as the optimum threshold value between identifying severe and non-severe hail events. This value was also important because it served as the lower limit of severe hail events. Only one event with a VIL density value less than 3.28 g m^{-3} produced hail of severe size. A VIL density value of 4.22 g m^{-3} is important for warning purposes because it served as the upper limit of non-severe hail events. Only one non-severe hail event occurred with a VIL density value greater than or equal to 4.22 g m^{-3}. These values are important to warning purposes because they provide a forecaster with guidance when considering whether or not to warn for a thunderstorm if they feel it has the potential to produce hail of any size.

This study also found that VIL density appears to be superior to the MEHS produced by the WSR-88D HDA as a forecast tool for predicting hail size range in the BTV CWA. Of all the hail events examined, the VIL density method correctly identified the hail size of 62% of the events, and incorrectly identified only 38% of the events. Conversely, the MEHS from the HDA only correctly identified the hail size of 36% of the events, and incorrectly identified 64% of the events. From these results, it can be noted that the VIL density method of predicting hail size range may be a better forecast tool compared to the MEHS.

Some caution should be used though when using VIL density to predict the size of severe hail, as it cannot always accurately predict the correct hail size, especially in the northeast portion of the CWA where beam blockage is known to occur. It may be more useful to use the HDA in that area. As with any other product, VIL density should not alone be used to forecast the occurrence of severe hail.

The results of this study have been incorporated into to warning operations at NWSFO BTV. A UNIX-based warning decision aid program was created for use at NWSFO BTV during severe and potentially severe weather events to help forecasters accurately predict the occurrence of hail. The forecaster can calculate a storm's VIL density by entering in VIL and ET values into the program. The results will display the VIL density, the expected hail size, and whether or not the hail size is severe.

11. CONCLUSION

Amburn and Wolf (1997) first introduced the idea of using VIL density to forecast severe hail, and since then many studies across the country have been performed to test their hypothesis. The VIL density method involves "normalizing" the VIL product by combining it with echo top values. The resulting VIL density value is air mass independent, and can be used to quickly identify thunderstorms with the potential to produce hail of severe size.

Storm data from 8 convective seasons from 1997 to 2004 in the Burlington, Vermont CWA was studied to assess whether the VIL density method would prove as a useful tool for predicting severe hail in Vermont and Northern New York. The results indicated that VIL density could be a very useful tool used operationally by meteorologists in the BTV CWA during a severe thunderstorm event to accurately identify storm cells producing severe and/or non-severe hail, and even accurately forecast the correct hail size range.

The VIL density method and the WSR-88D HDA MEHS were compared. The study found that the VIL density method was superior to the HDA MEHS. In the future, meteorologists at the WFO BTV may find it more useful to use the VIL density method to properly assess the severity of hail during a severe thunderstorm event in non-beam blocked areas. Furthermore, other NWS offices may find these results useful in helping to determine a VIL density threshold for severe hail for their CWA. Future advances in the WSR-88D HDA will assist in better application to specific topographical areas and better analysis of the VIL and ET products, improving the VIL density method.

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FIGURES

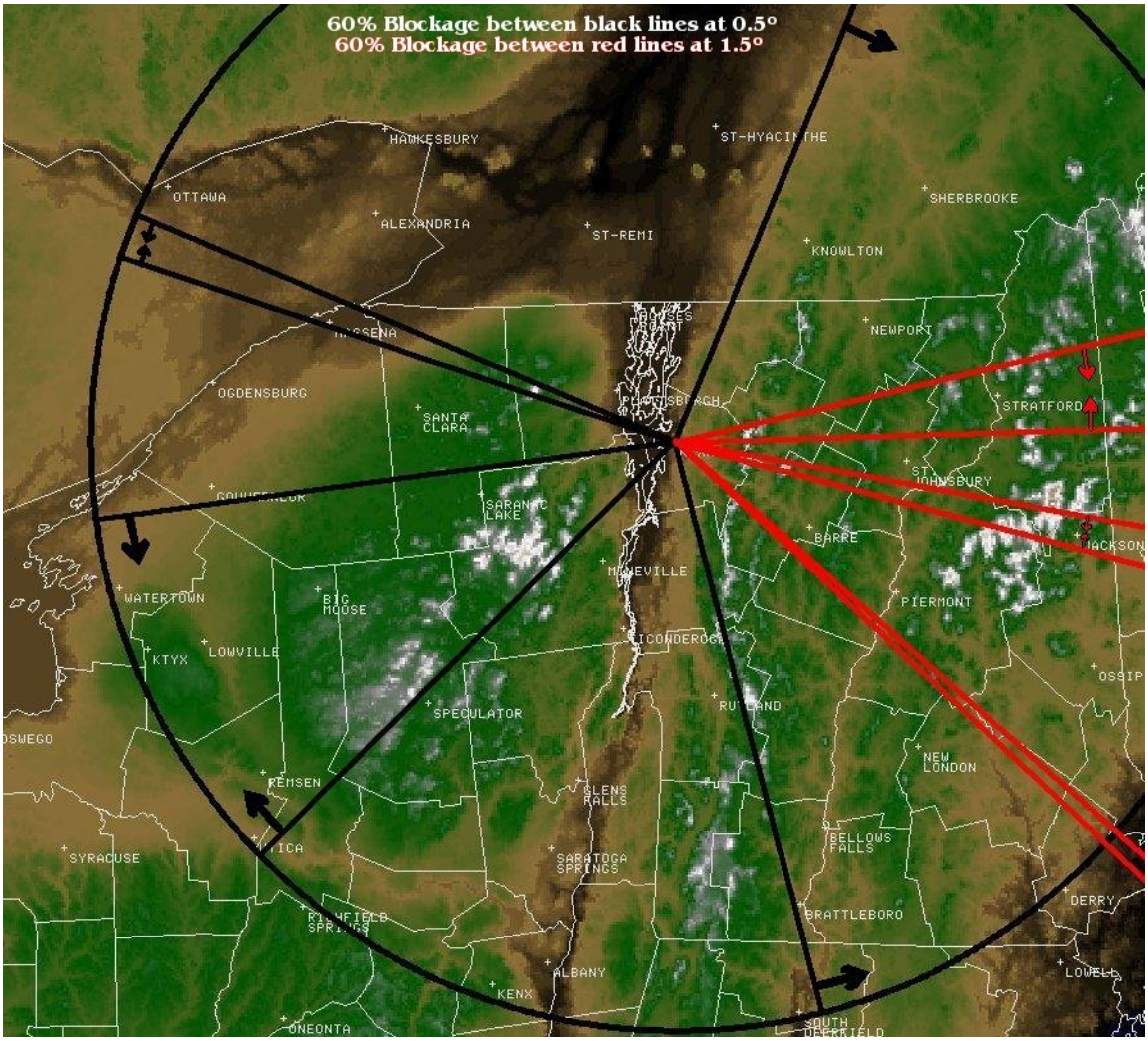

Figure 1. Display of beam blocked regions of the KCXX (Colchester, VT) WSR-88D radar. Black lines with arrows pointing towards each other indicate the areas where the beam is 60% blocked at 0.5º. Red lines with arrows pointing towards each other indicate the areas where the beam is 60% blocked at 1.5º.

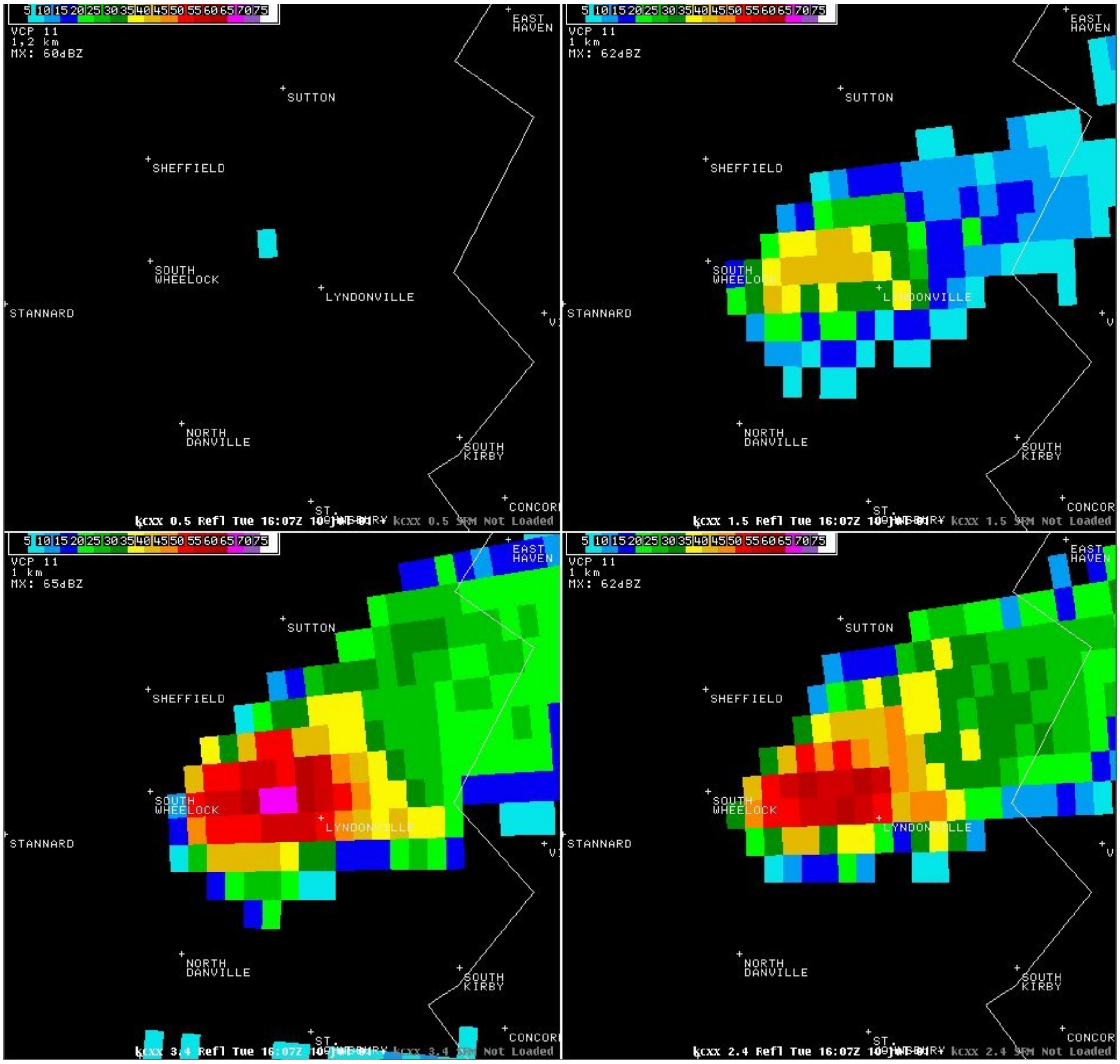

Figure 2. KCXX-WSR-88D 4-panel base reflectivity during a hailstorm over Lyndonville, VT, from 1607 UTC 7 July 2001. Upper left panel is 0.5º elevation, upper right is 1.5º elevation, lower right is 2.4º elevation, and lower left is 3.4º elevation.

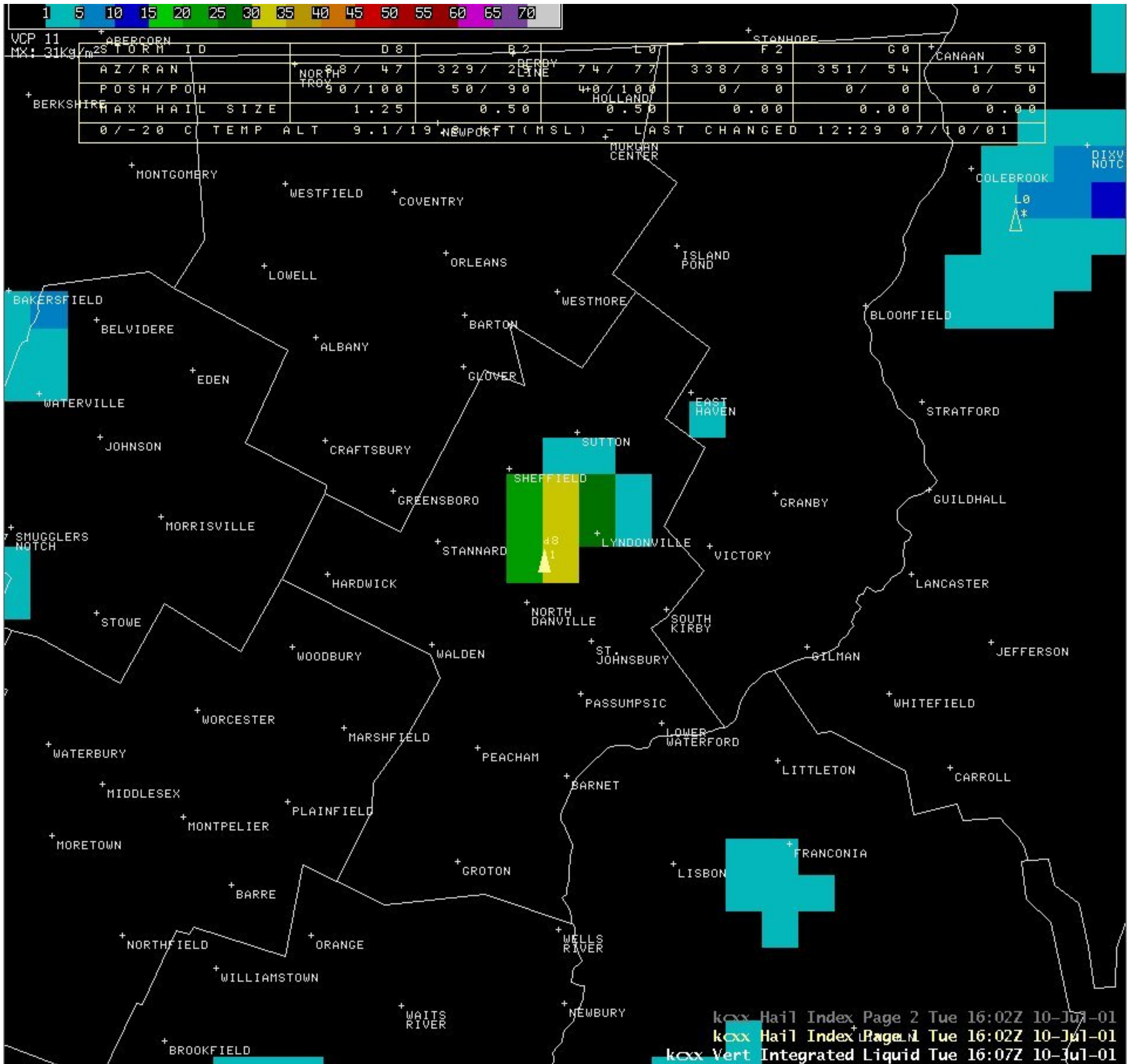

Figure 3. KCXX WSR-88D VIL product from 1607 UTC 7 July 2001 in kg m^{-2} during hailstorm over Lyndonville, VT.

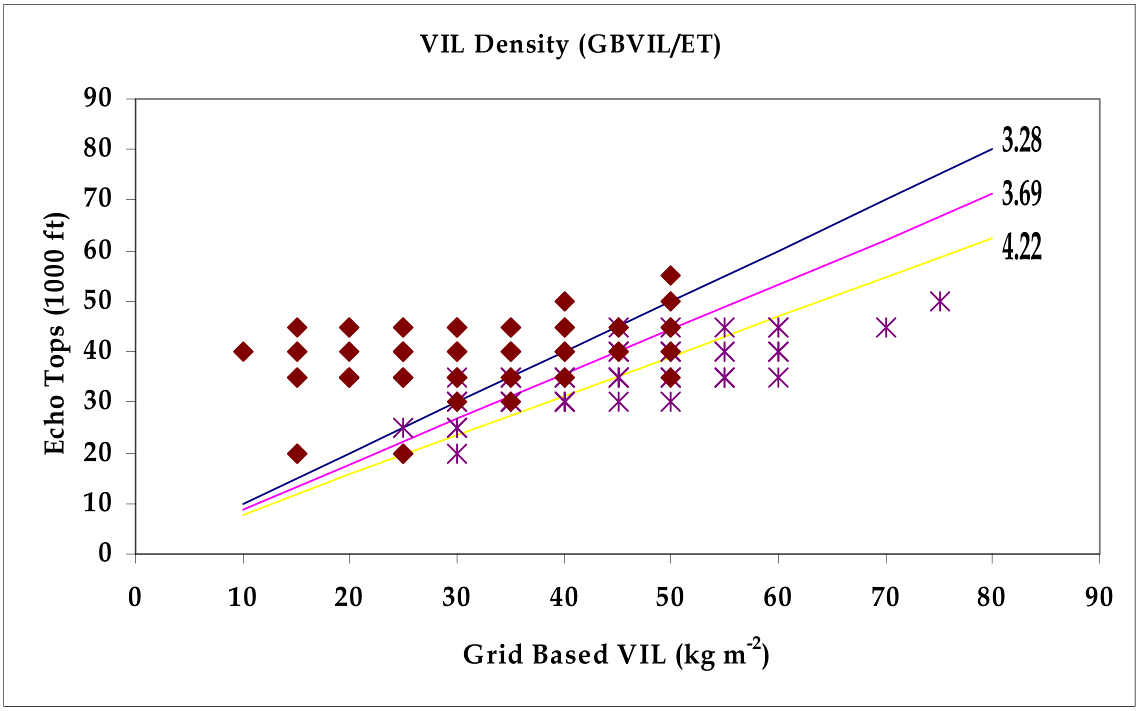

Figure 4. Scatter diagram of grid-based VIL (kg m^{-2}) vs.Echo Top (ft) for 72 severe hail events (✳)and 84 non-severe hail events (◆). A few data points are comprised of multiple events (◆), severe hail event and non-severe hail event occurring with the same GBVIL. Values of VIL density (g m^{-3}) are shown as solid lines labeled 3.28, 3.69, and 4.22.

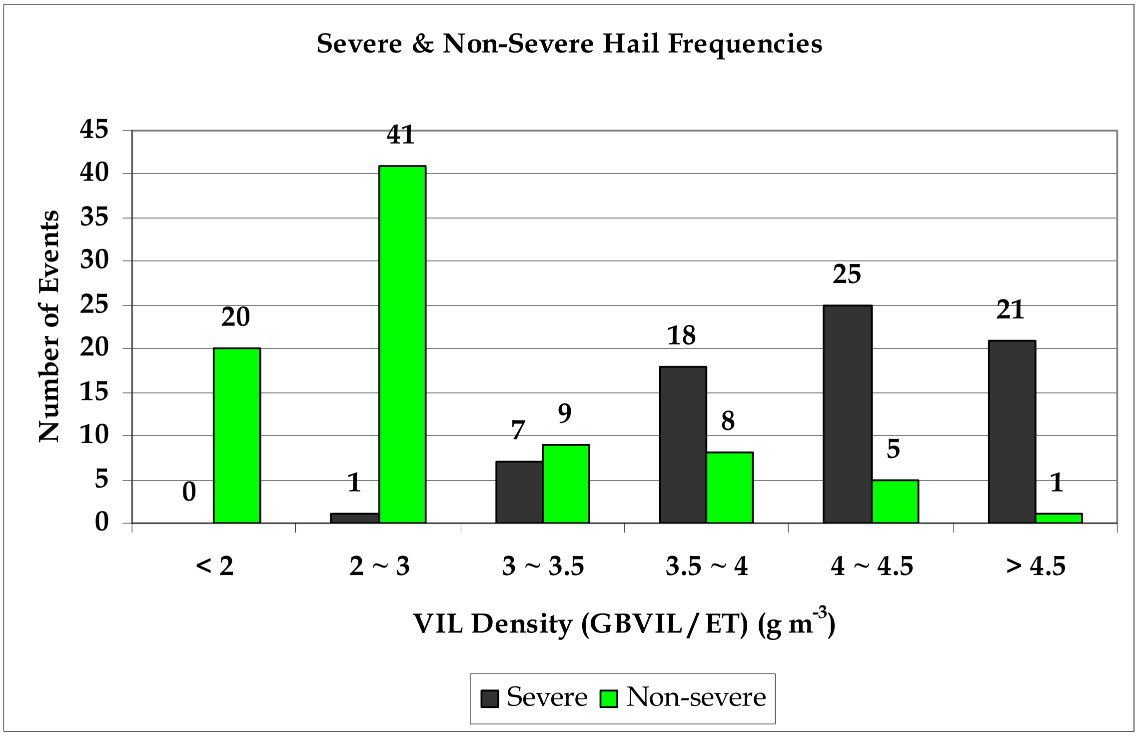

Figure 5. The VIL Density (GBVIL/ET) values vs. number of severe and non-severe events.

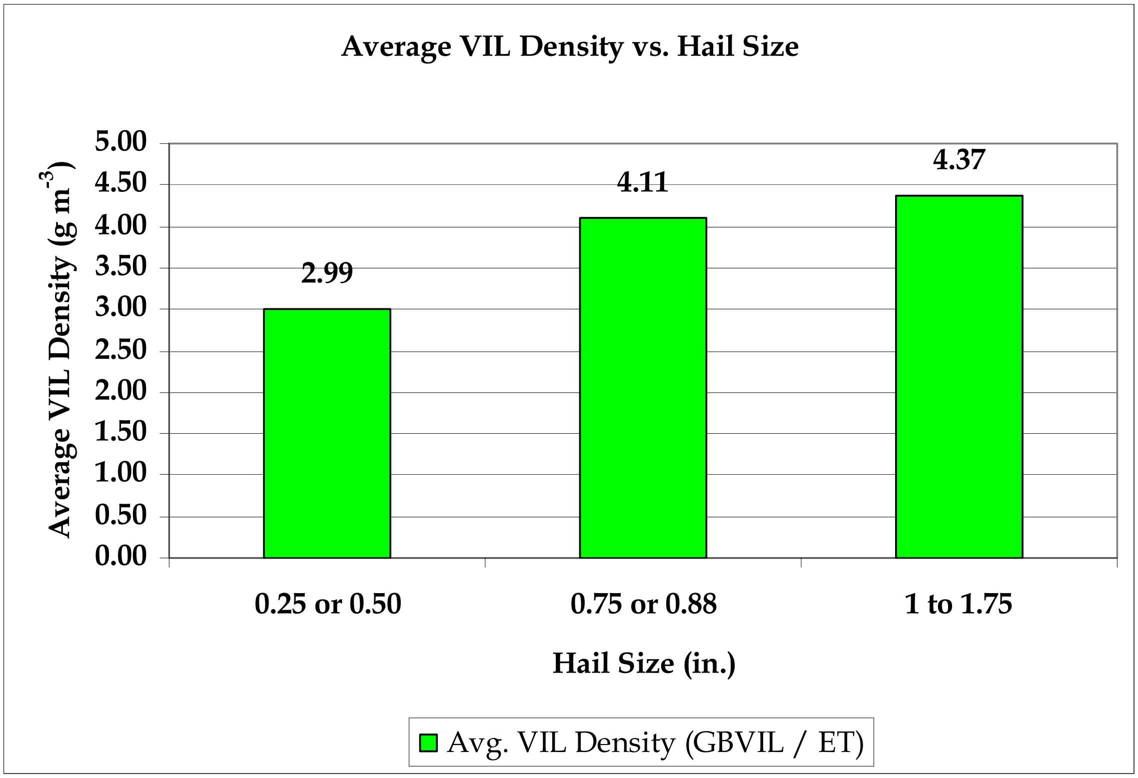

Figure 6. Reported hail size vs. average VIL Density (GBVIL/ET) with average VIL density atop each bar.

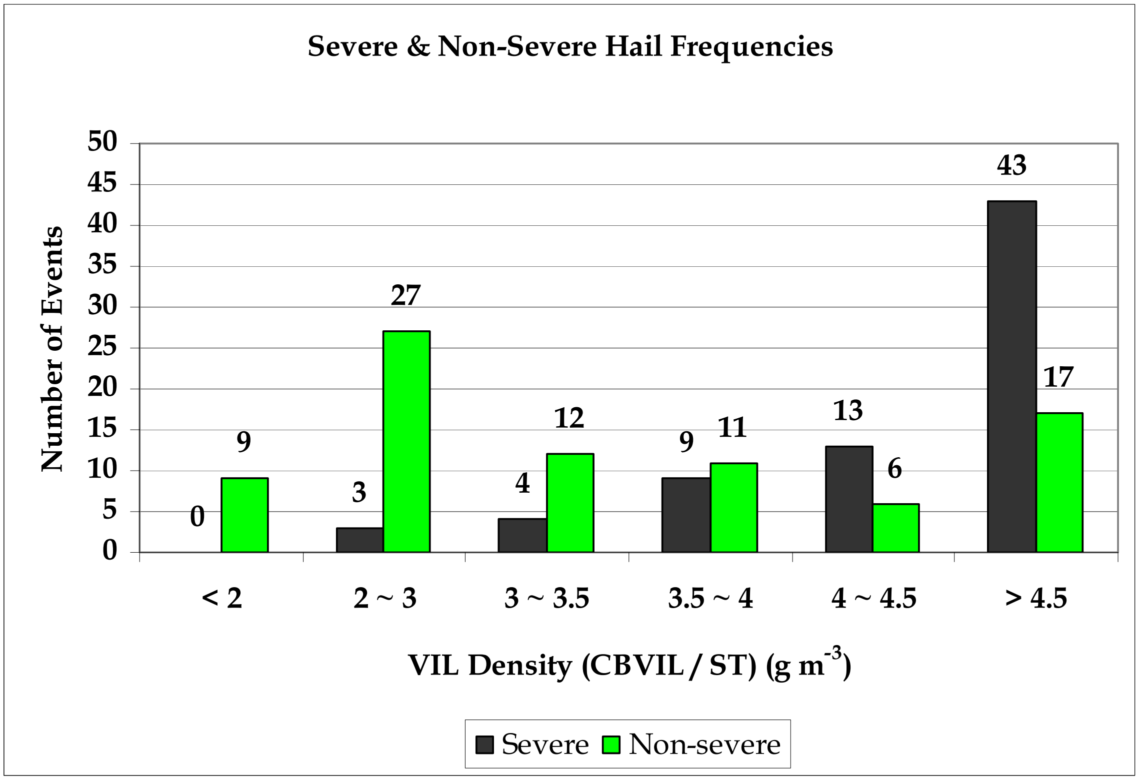

Figure 7. The VIL Density (CBVIL/ST) values vs. number of severe and non-severe events with the number of events atop each bar.

Table 1. POD, FAR, and CSI values for all events.

VIL Density ($g\ m^{-3}$)	POD	FAR	CSI
4.20	0.56	0.02	0.55
4.00	0.64	0.12	0.59
3.69	0.88	0.16	0.75
3.50	0.89	0.18	0.74
3.28	0.99	0.24	0.75
3.00	0.99	0.24	0.75
2.50	1.00	0.37	0.63
2.00	1.00	0.47	0.53
< 2.00	1.00	0.54	0.46

Table 2. POD, FAR, and CSI values for 1" to 1.75" hail events.

VIL Density ($g\ m^{-3}$)	POD	FAR	CSI
5.00	0.14	0.50	0.12
4.50	0.34	0.55	0.24
4.22	0.76	0.46	0.46
4.00	0.83	0.54	0.42
3.69	0.93	0.64	0.35
3.50	0.97	0.64	0.35
3.28	0.97	0.70	0.29
3.00	0.97	0.70	0.29
2.00	1.00	0.79	0.21
< 2.00	1.00	0.81	0.19

Table 3. VIL density values using the traditional method (GBVIL/ET) and associated VIL density predicted hail sizes.

VIL Density Value ($g\ m^{-3}$)	**Predicted Hail Size (in)**
< 2	**No hail**
2 – 3.27	**0.25 or 0.50**
3.28 - 4.21	**0.75 or 0.88**
≥ 4.22	**1.00 to 1.75**