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VIL Density as an Indicator of Hail across Eastern New York and Western New England

Jonathan L. Blaes
Carl S. Cerniglia Jr.
Michael A. Caropolo
NOAA / National Weather Service Forecast Office
Albany, NY

Editor's Note: The lead author's current affiliation is NWSFO Raleigh, NC.

1. INTRODUCTION

The deployment and continued utilization of the Weather Surveillance Radar - 1988 Doppler (WSR-88D) network across the United States has resulted in an increase in severe local storm warning lead times and improved verification (Polger et al. 1994). As experience grows with the radar, new techniques are being developed to better utilize radar products and understand system limitations. Determining the likelihood of severe hail, currently defined as ≥ 0.75 inches (19 mm) in diameter, remains a significant forecast problem facing operational meteorologists monitoring the potential of severe local storms. Amburn and Wolf (1997) first compared maximum Vertically Integrated Liquid water content (VIL) values and associated Echo Tops (ET) to compute VIL densities (VIL / ET) which were successfully used as a predictor of large hail across the northeastern Oklahoma - northwestern Arkansas region.

A sample of hail events over 5 convective seasons from 1994 through early 1998 was examined at the NEXRAD Weather Service Forecast Office (NWSFO) in Albany, NY (ALY) using KENX WSR-88D radar data from Berne, NY. The study sought to determine if established VIL density techniques from other parts of the country were effective across eastern New York and western New England. The study also investigated whether new information and enhancements available in software Build 9 of the WSR-88D, such as Cell Based VIL (CBVIL) and Storm Top (ST), can improve the effectiveness of VIL density. Finally, with the proposed change in the severe hail size criteria (Purpura 1998) from ≥ 0.75 inches (19 mm) in diameter increasing to ≥ 1.0 inch (25 mm) in diameter, we sought to determine how this change would affect the usefulness of VIL density.

2. VERTICALLY INTEGRATED LIQUID

Greene and Clark (1972) proposed that Vertically Integrated Liquid water content (VIL) could be a useful tool for determining the potential for hail in the central Plains [hereafter, VIL and Grid Based VIL (GBVIL) refer to the same value]. They suggested that hail may produce false values of liquid water due to enhanced radar return. Operational forecasters have learned to use VIL in part to determine the potential severity of thunderstorms which are likely to produce severe hail.

There are several limitations in using VIL as an indicator of severe hail. Often, forecasters have no idea of what VIL value will correspond to severe size hail on a given day. Meteorologists often have to wait for ground reports of hail and then compare the location and time of the report to VIL. Based upon the correlation between the hail size reported and the VIL values displayed on the radar, forecasters can then estimate the occurrence and size of additional hail events. Forecasters at NWSFO ALY have observed that a colder, drier atmosphere can support severe hail with relatively low VIL values (20-30 kg m^{-2}), while a warmer, more moist atmosphere often requires larger VIL values (50-60 kg m^{-2}) to produce severe hail. This atmospheric and seasonal variation in VIL values associated with severe hail has led to various techniques and procedures to determine a representative VIL value that would produce severe hail for a particular event.

In an effort to anticipate thunderstorms which may produce severe hail, several studies have attempted to predict what VIL value on a particular day would result in severe hail. These values are commonly referred to as the "VIL of the Day." There are limitations inherent in using the VIL of the Day (VOD) approach. First, VOD values may be unrepresentative of the environment across a large forecast area with varying atmospheric conditions. Since the VOD requires forecast data, it is also subject to the biases and constraints of model forecasts. Finally, the VOD approach relies upon predictive data, failing to utilize real time observational data. Other studies have used VIL values in combination with other variables, to predict the occurrence of hail. Billet et al. (1997) developed a logistic regression model to act as a yes/no predictor of hail severity based on values of VIL, 850-hPa temperature, freezing level, and low-level storm inflow. Although this approach includes observed VIL values, it still relies upon forecast data or twice daily sounding data which may be unrepresentative of atmospheric conditions in the vicinity of thunderstorms. Recent research has centered on methods to eliminate the variability associated with VIL by "normalizing" VIL with the ET; which would result in a value that should be airmass independent.

3. VIL DENSITY

Amburn and Wolf (1997) first demonstrated the use of VIL density (VIL / ET) as a predictor of large hail across the northeastern Oklahoma - northwestern Arkansas region. Other studies have investigated VIL density across varying geographic locations. Turner and Gonsowski (1997) explored the utility of VIL density across northwestern Kansas, Roeseler and Wood (1997) investigated if VIL density was a useful predictor of severe hail across the northwestern Gulf of Mexico, and Troutman and Rose (1997) investigated VIL density across middle Tennessee.

Amburn and Wolf (1997) defined VIL density as the quotient of VIL (kg m^{-2}) divided by the ET (m) and then multiplied by 1000 to yield units of g m^{-3}.

$$\text{VIL density (g m}^{-3}\text{)} = \text{VIL (kg m}^{-2}\text{)} / \text{ET (m)} \bullet 1000$$

Amburn and Wolf (1997) hypothesized the VIL density concept after noting that high-topped thunderstorms with high VIL values do not always produce large hail, while low-topped thunderstorms with low VIL values occasionally do produce large hail. They suggested that dividing the VIL by the ET would "normalize" VIL with the ET. This would result in a value that can be used to identify thunderstorms which contain high reflectivities relative to their height and therefore possess a likelihood to produce large hail. By normalizing VIL with the ET, the VIL density value should be airmass independent and should be a useful predictor regardless of the thunderstorm's actual VIL or height and the local atmospheric characteristics.

4. METHODOLOGY AND DATA

This study examined 154 thunderstorms which occurred from April 1994 through May 1998 in the NWSFO ALY County Warning Area (CWA). Thunderstorms ranged from 10 to 72 nm (19 to 133 km) from the radar; VIL values ranged from 15 to 77 kg m^{-2}, and ET values ranged from 17,000 to 52,000 feet (5.2 to 15.8 km). Of these 154 events, 97 produced severe hail [$\geq$ 0.75 inches (19 mm) in diameter], with 57 events producing non-severe [< 0.75 inches (19 mm) in diameter] or no hail. Hail sizes ranged from zero or no hail to 3.0 inches (76 mm) in diameter. There were two types of events included in this study, severe hail [$\geq$ 0.75 inches (19 mm) in diameter] and non-severe hail [< 0.75 inches (19 mm) in diameter] events.

Severe hail events were identified by reports of severe size hail. This information was retrieved from local storm reports, local severe weather logs, and *Storm Data* (U.S. Department of Commerce 1994-1997). Non-severe hail cases were identified from radar data and severe weather logs and then checked with *Storm Data* to ensure the events were of non-severe size. They were included in the study only if non-severe hail or no hail was observed over a significantly populated area during the time of day in which severe weather reports would normally be expected (0800 through 2000 local time). These events were included in the study if archived radar data was available.

Radar data used in this study was principally from archive IV data at the Berne, NY (KENX) WSR-88D. Echo Top data from the Taunton, MA (KBOX), Brookhaven, NY (KOKX) and Binghamton, NY (KBGM) radar sites were used for a few cases to fill in incomplete data sets. To be included in the study, the radar data had to be free of anomalous propagation and beam blockage. To be consistent with earlier studies, thunderstorms with maximum VIL values less than 15 kg m^{-2} were not included. Because of these methodology constraints, the total number of cases examined was significantly reduced from the overall number of hail cases available.

These methodology constraints limited the database significantly but they were necessary to eliminate sources of error in the data analyses. For example, thunderstorms with high VIL values may not have a corresponding verifying report of severe hail if they occurred in an area with a low population density. Additionally, non-severe hail events were included only if they occurred in a location and time of day in which severe weather reports would normally be expected. The absence of a verifying report does not necessarily mean that severe hail did not occur. As noted by Wyatt and Witt (1997), the largest source of potential error in a hail study arises from complications and errors inherent in spotter and verification reports. An accurate study requires that spotters accurately report the time, location, and size of the hail. Most thunderstorms within 15 nm (28 km) of the radar site and in areas subject to anomalous propagation as well as beam blockage were excluded since VIL and ET values would be unrepresentative due to "cone of silence" sampling limitations and clutter contamination, respectively. However, a few low topped thunderstorms that were within 15 nm (28 km) of the radar site were included after noting that the "cone of silence" was not a factor in observing these storms.

For each thunderstorm to be investigated, the time and location of each event, and the hail size was determined from local severe weather logs and *Storm Data*. The maximum observed VIL was recorded over the location of each hail report. The highest VIL value observed during the volume scan nearest the time of the report or during the previous volume scan was used. For this part of the investigation, the VIL value was specifically the WSR-88D GBVIL and was determined using mid point values of the data ranges unless the storm in question was producing the maximum observed VIL for that volume scan. In the latter case (approximately one-third of the events in this study), the VIL value that was explicitly displayed on the radar was used. The radar calculates GBVIL by estimating the liquid water content of the atmosphere for a vertical, square column, 2.2 nm (4.0 km) on a side. VIL values for each elevation angle, over a particular square, are summed to determine the VIL for a particular grid. This GBVIL value is often unrepresentative for fast moving and tilted storms.

After the location, time, hail size, and value of the GBVIL was determined, the WSR-88D ET was recorded for the same time at the same pixel or the next pixel down stream of the GBVIL. The down stream pixel was used to account for storm tilt and/or storm movement. Like the GBVIL, the ET has a 2.2 nm (4.0 km) resolution. The ET value is the highest sample volume that contains a minimum reflectivity value of 18.5 dBZ or greater. It is derived from each elevation angle, which makes it susceptible to several sources of error. For example, the ET is subject to truncation errors, especially at longer ranges from the radar and while the radar is using the VCP-21 scan strategy. This occurs where the true ET value lies between two radar scans (elevation slices). Interpolation is not used in the calculation of this product, and the ET is assigned to the lower radar beam height. The traditional VIL density value as defined by Amburn and Wolf (1997) was then computed for each event by dividing the GBVIL by the ET (GBVIL / ET).

Made operationally available with the Build 9 software installation in November 1996, the WSR-88D Storm Cell Identification and Tracking (SCIT) Algorithm (Witt 1990, Witt and Johnson 1993) continuously scans reflectivity data to identify storm cells and calculate various parameters of these cells. The algorithm calculates numerous values for each cell it identifies including; storm motion, maximum reflectivity of the storm, storm volume, CBVIL, and ST. Many of these values are displayed on the Principle User Processor (PUP) attribute table including CBVIL and ST. The PUP is a graphics display computer system that National Weather Service meteorologists use to view WSR-88D products. The attribute table provides an easy to read table of pertinent radar based values that are used by meteorologists at the radar to quickly determine the intensity of a storm. The VIL density of a particular storm cell could be easily calculated by dividing the CBVIL and ST values which are readily displayed on the PUP attribute table.

The CBVIL is calculated for each storm cell identified by the SCIT algorithm. The algorithm calculates CBVIL by vertically integrating maximum reflectivity values of an identified cell's components. These components are vertically correlated by comparing the centers of each component in adjacent elevation angles. If a component's center overlaps a component in the adjacent elevation angle, they are linked and a cell is created. The CBVIL is then calculated using this algorithm defined cell rather than just using reflectivities stacked vertically above a fixed point. This method of cell identification and VIL calculation enables the CBVIL to be adjusted for storm tilt and storm motion, unlike the GBVIL.

The arrival of Build 9 also resulted in an improvement to the ST value which has been available since the installation of the WSR-88D radar. The SCIT algorithm installed with Build 9 more accurately identifies individual storm cells which results in an improvement in all the derived cell attributes, including ST. This is especially true of lines or clusters of storms which the earlier software would frequently identify as a single, large cell instead of individual storms. The ST value is a quantity somewhat similar to the ET, however the intensity threshold for this value is higher. Storm Top is defined as the height of the beam center point at the center of the highest component detected for each identified storm. The minimum reflectivity value used to create a component is 30 dBZ, therefore the ST value is the highest radar identified echo that contains a reflectivity value of 30 dBZ or greater (U.S. Department of Commerce 1991). Storm top values will generally be lower than ET values except when truncation errors occur. In this situation, which occurred in less than 8 % of the events examined, the two values will be nearly the same. The ST values were recorded for events investigated subsequent to the release of Build 9.

A database containing hail size, GBVIL, ET, as well as CBVIL and ST (when available) was created for the 154 investigated events. A traditional VIL density value (GBVIL / ET) was computed for each of these events. VIL density values were also calculated using cell specific data (CBVIL and ST) when available. This resulted in three additional methods to calculate VIL density using a combination or a portion of CBVIL and ST (GBVIL / ST, CBVIL / ET, and CBVIL / ST). Various statistical parameters were then calculated, for both traditional and cell specific VIL density values, in order to determine the thresholds that possess the greatest skill in forecasting severe hail events.

5. LIMITATIONS

As noted earlier, the largest source of potential error in a hail study arises from complications and errors inherent in spotter and verification reports (Wyatt and Witt 1997). The collection of data can introduce errors into the data set through various means. First, the exact time and location of the hail event may be inaccurate, making it difficult to correlate the event with radar data. Second, hail sizes are nearly always estimated, often inaccurately. Even if the location, time and size of the hail event is accurate, the report may not be representative of the actual severity of the particular thunderstorm. Larger hail may have fallen elsewhere and gone unobserved or unreported. Similarly, a thunderstorm without a report of hail or specifically severe hail, does not necessarily mean that hail or severe hail did not occur. These potential sources of error can be limited, but not eliminated, by carefully correlating the hail reports with the radar data and using storms that occur over a reasonably populated area at a time of day in which reports normally would be expected.

Due to design limitations of the radar system, the actual radar data may contain errors. The radar is designed to scan the atmosphere at discrete elevation angles allowing only portions of a thunderstorm to be sampled directly. Portions of a thunderstorm between the elevation angles are often not sampled and result in missing data. The missing data affects the calculation of volume products such as VIL and results in truncation errors in products such as ET and ST (U.S. Department of Commerce 1991).

At short distances from the radar, generally less than 15 nm (28 km), thunderstorm tops may exceed the highest elevation scan of the radar leading to unrepresentative calculations of GBVIL and ET since the radar is unable to sample the entire storm. Since VIL density normalizes reflectivities (GBVIL) with the height of the storm (ET), the truncation of GBVIL and ET values should generally not pose a problem. However, if the reflectivity core exceeds the highest elevation scan, the VIL density value would be unrepresentative and result in a VIL density value that is too low.

Grid Based VIL values are often underestimated in thunderstorms that tilt excessively or move rapidly. In these situations, portions of a thunderstorm may be present in more than one of the 2.2 nm (4.0 km) grid boxes used in the calculation of the GBVIL product. This results in diminished GBVIL values that are unrepresentative of the thunderstorms severity. This problem is especially noticeable in cool season, fast moving convective events which often occur in a strong synoptic scale wind regime.

6. RESULTS

Traditional VIL density values (GBVIL / ET) as defined by Amburn and Wolf (1997) are shown in a scatter diagram (Fig. 1) of ET (thousands of feet) versus GBVIL (kg m^{-2}) and was created using 97 severe hail cases (✖) and 57 non-severe hail cases (●). A VIL density threshold of 3.50 g m^{-3} correctly identified 82 % (80 of 97) of severe hail cases in this study and incorrectly identified 7 % of non-severe cases (4 of 57) as severe. In an operational setting, forecasters would find the VIL density value of 3.80 g m^{-3} significant since it serves as the upper limit of non-severe cases; 99 % (69 of 70) of events with a VIL density value greater than or equal to 3.80 g m^{-3} were of severe size. Conversely, the VIL density value of 3.28 g m^{-3} serves as a lower limit for severe size hail; only 11 % (5 of 45) of events less than 3.28 g m^{-3} were severe. Fig. 2 illustrates the distribution of severe and non-severe hail frequencies versus VIL density.

These calculations have led to the subjective development of a nomogram (Fig. 3) for use by meteorologists at NWSFO ALY as guidance during potential severe weather events. The nomogram utilizes a VIL density value of 3.28 g m^{-3} as the upper limit of non-severe hail events while a VIL density value of 3.50 g m^{-3} is used as the lower limit of severe hail events. The area on the nomogram between the 3.28 g m^{-3} and the 3.50 g m^{-3} values is a region in which the severe hail potential is indeterminate. This nomogram should be used as a part of the warning decision making process and not used exclusively to predict the occurrence of severe hail.

Our results compare to the Tulsa study by Amburn and Wolf (1997) in which a VIL density of 3.50 g m^{-3} correctly identified 90 %

of severe hail events and falsely identified 5.5 % of non-severe hail cases as severe. The Albany study investigated 154 total cases during 5 convective seasons. The Tulsa study investigated 221 total cases (185 severe cases) in one convective season. The better performance of the 3.50 g m^{-3} VIL density threshold in the Tulsa study as compared to our investigation was likely enhanced by the greater number of severe cases investigated by Amburn and Wolf. The Tulsa study was comprised of many events with a generally larger hail size than our study. Our study investigated only 43 events with a hail size of 1.0 to 1.75 inches (25 to 45 mm) compared to 63 events of similar size in the Tulsa study. The Tulsa study also included 6 cases with hail $\geq$ 2.5 inches (63 mm) compared to only one case of similar size in our investigation. The larger hail size included in the Tulsa investigation compared to our study would allow an easier identification of severe hail, resulting in a better performance of VIL density in the Tulsa study.

Our results are more similar to an investigation by Troutman and Rose (1997) across middle Tennessee in which a VIL density of 3.50 g m^{-3} correctly identified 81 % of severe hail cases. Our findings are preferable to the Roeseler and Wood (1997) study across the northwest Gulf Coast in which a VIL density threshold of 3.50 g m^{-3} correctly identified 72 % of severe hail cases. At the same threshold our study correctly identified 82 % of severe hail cases. The Turner and Gonsowski (1997) study across northwestern Kansas used a VIL density threshold of 3.25 g m^{-3} to correctly identify 91 % of severe events. However, this threshold falsely identified 43 % of the non-severe events as severe.

Our findings are consistent with studies by Troutman and Rose (1997), Roeseler and Wood (1997), and Turner and Gonsowski (1997) which indicate that VIL density is operationally useful across the climatic regimes of eastern New York and western New England, northwestern Kansas, northwestern Gulf of Mexico, and across middle Tennessee respectively. The VIL density approach appears to be effective as an indicator of hail across various geographical locations, across areas of varying climatology, and in both cool and warm seasons.

Previous VIL density studies showed that as the VIL density increased, the maximum reported hail size also increased. Results from this investigation indicate that as the average VIL density (averaged for each particular hail size), increased from 3.95 g m^{-3} to 4.49 g m^{-3}, the average hail size generally increased from 0.75 inches (19 mm) to 1.5 inches (38 mm) in diameter (Fig. 4). Average VIL density values fluctuated somewhat as hail size increased above 1.5 inches (38 mm) to 3.0 inches (76 mm); this is likely a result of the limited number of cases investigated with a hail size greater than 1.5 inches (38 mm).

This study also sought to determine whether enhancements and new cell specific values and information (CBVIL, improved ST, and enhanced SCIT algorithm) provided subsequent to the delivery of Build 9 could improve the effectiveness of VIL density. VIL density values were calculated using a combination or a portion of CBVIL and ST (GBVIL / ST, CBVIL / ET, and CBVIL / ST). It was hoped that VIL density calculations using cell specific data would result in improved VIL density utility.

Analysis of VIL density values using GBVIL / ST, CBVIL / ET, and CBVIL / ST indicate that there is little if any improvement over traditional VIL density calculations using cell specific values. VIL density calculations using GBVIL / ST showed the least skill of all of the VIL density calculations using cell specific data. There appears to be no definite trend in the distribution of non-severe hail cases [< 0.75 inches (19 mm)] in the data set. The majority of severe hail cases [≥ 0.75 inches (19 mm)] occurred with a VIL density value of 5.0 g m^{-3} or greater.

VIL density calculations using CBVIL / ET (Fig. 5) and CBVIL / ST (Fig. 6) performed better than the GBVIL / ST but still without the skill present in the traditional VIL density calculations (GBVIL / ET). In both the CBVIL / ET and CBVIL / ST calculations, the number and occurrence of non-severe events decreases as VIL density increases. For both of these VIL density calculations, the number of severe cases increases to a maximum as the number of non-severe cases decreases. This is a pattern similar to calculations using the traditional VIL density methodology (Fig. 2). However, there is significant overlap of severe and non-severe cases for a given VIL density, resulting in an unacceptable rate of incorrect identifications of non-severe hail events as severe. For this reason, VIL densities calculated using cell specific data appear to be ineffective in identifying severe hail events.

This study contained only 55 events (31 severe and 24 non-severe) in which the cell specific data needed to calculate VIL densities using a combination or a portion of CBVIL and ST was available. The relatively small number events appears to be too limited for an effective analysis. We will continue to expand the data set with additional post Build 9 cases in order to effectively analyze the potential utility of VIL density calculations using cell specific data.

The criteria for severe hail [current criteria ≥ 0.75 inches (19 mm) in diameter] is expected to increase to a new criteria by the spring of 2000 [future criteria ≥ 1.0 inch (25 mm) in diameter] (Purpura 1998). Traditional VIL density values (GBVIL / ET) are shown in a scatter diagram (Fig. 7) of ET (thousands of feet) versus GBVIL (kg m^{-2}) using the future severe hail criteria [≥ 1.0 inch (25 mm) in diameter]. The scatter plot includes 44 severe hail cases (✖) and 110 non-severe cases (●). Results from this study indicate that a VIL density threshold of 3.70 g m^{-3} correctly identified 91 % (40 of 44) of the future severe hail events. However, the 3.70 g m^{-3} threshold falsely identified 48 % (37 of 77) cases of non-severe hail as severe. In fact, the false alarm rate does not drop below 40 % until the VIL density value increases to 4.80 g m^{-3}. The 3.50 g m^{-3} VIL density threshold associated with the current severe hail criteria performed much better than the 3.70 g m^{-3} VIL density threshold associated with the future severe hail criteria. Fig. 8 illustrates the decrease in the occurrence of non-severe events as VIL density values increase. Fig. 8 also shows that the number of severe events gradually increases as VIL density increases up through a VIL density value of 4.50 g m^{-3}. Beyond the 4.50 g m^{-3} VIL density value, the trend is not clear; likely a result of a limited data set.

The overall poorer performance of the ≥ 1.0 inch (25 mm) in diameter hail threshold likely results from at least two factors. First, the number of cases included in this study with hail ≥ 1.0 inch (25 mm) in diameter is limited. Second, spotters, law enforcement officials, and verification procedures are all biased to the ≥ 0.75 inches (19 mm) in diameter threshold. For example, a report of hail 0.88 inches (22 mm) in diameter would satisfy current verification requirements. Because of workload restrictions during severe weather, NWS personnel may elect not to seek out reports of larger hail, even though larger hail may have occurred, since the verification requirement has already been met. Due to the limitations previously mentioned, it is difficult to develop reliable thresholds or even a nomogram to predict the occurrence of severe hail ≥ 1.0 inch (25 mm) without additional cases and further research.

7. SUMMARY

Results from this study indicate that there is a strong correlation between VIL density as defined by Amburn and Wolf (1997) and the occurrence of severe hail in eastern New York and adjacent western New England. These results indicate that meteorologists during potential severe weather events could use VIL density as a significant input into the warning decision making process. A VIL density threshold of 3.50 g m^{-3} correctly identified 82 % (80 of 97) of severe hail cases in this study and incorrectly identified 7 % of non-severe cases (4 of 57) as severe. The VIL density value of 3.80 g m^{-3} is significant since it serves as the upper limit of non-severe cases; 99 % (69 of 70) of events with a VIL density value greater than or equal to 3.80 g m^{-3} were of severe size. Conversely, the VIL density value of 3.28 g m^{-3} serves as a lower limit for severe size hail; only 11 % (5 of 45) of events less than 3.28 g m^{-3} were severe. A resulting nomogram (Fig. 3) has been used successfully by meteorologists at NWSFO ALY, during both severe and potential severe weather events.

VIL density also appears useful as a means to approximate the size of the severe hail event. Although indisputable evidence is lacking, findings from this study and other studies noted earlier indicate that there is a correlation between increasing VIL density and increasingly large hail. However, some caution should be used when using VIL density to predict the size of severe hail.

Further investigation is required to more completely determine the role, if any, that cell specific values (CBVIL and ST) can play in improving the VIL density concept. In our study, VIL density calculations using CBVIL / ET and CBVIL / ST preformed the best among all of the VIL density calculations using cell specific data. However, these cell specific VIL density calculations were inferior to the traditional VIL density calculations using GBVIL and ET.

The criteria for severe hail is expected to increase to ≥ 1.0 inch (25 mm) in diameter by the spring of 2000. First, our study indicates that there are far fewer events of hail ≥ 1.0 inch (25 mm) in diameter than ≥ 0.75 inches (19 mm) in diameter. Second, the VIL density technique had much less skill with the larger severe hail criteria. A VIL density value of 3.70 g m^{-3} correctly identified 91 % (40 of 44) of the ≥ 1.0 inch (25 mm) in diameter severe hail events but falsely identified 48 % (37 of 77) cases of non-severe hail as severe. The overall inferior performance of the ≥ 1.0 inch (25 mm) in diameter hail threshold is likely a result of the limited number of cases included in this study with hail ≥ 1.0 inch (25 mm) in diameter. Continued investigation is also necessary to determine the viability of using VIL density in the future after a larger severe hail criteria [≥ 1.0 inch (25 mm) in diameter] is enacted.

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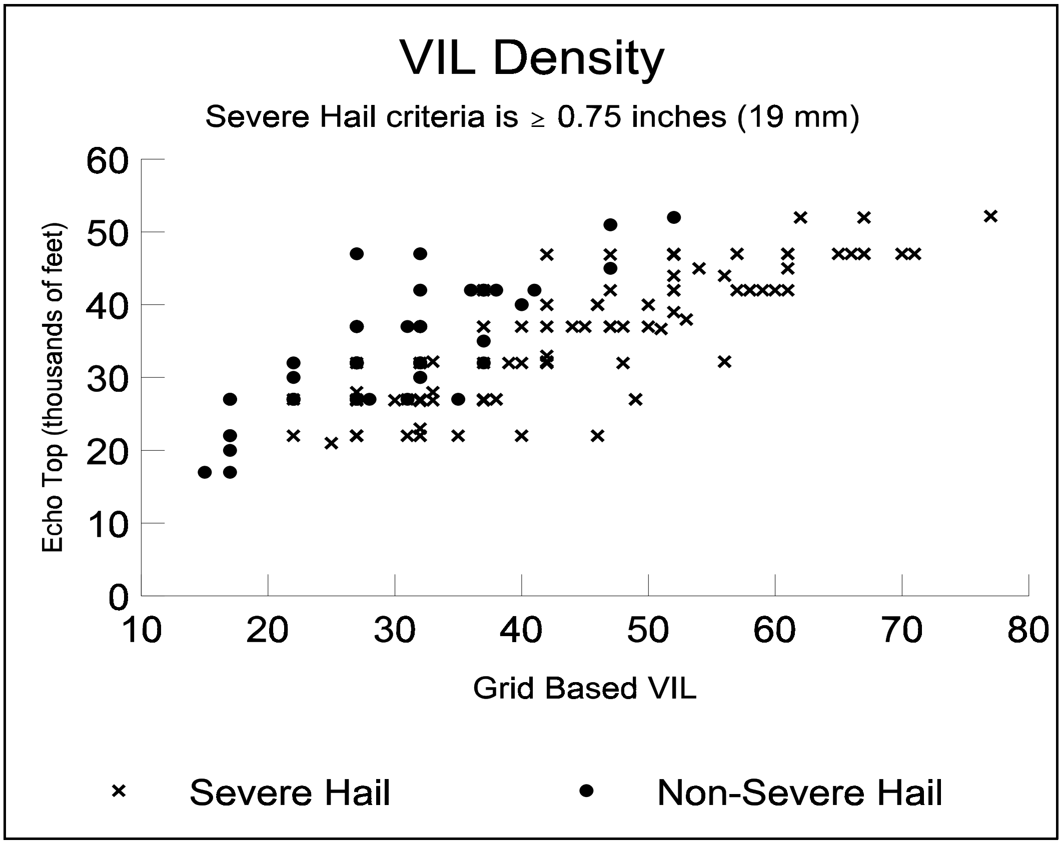

Figure 1. Scatter diagram of Echo Top (thousands of feet) versus Grid Based VIL (kg m^{-2}) for 97 severe hail (✖) cases and 57 non-severe hail cases (●). A few data points are composed of multiple events. Severe hail criteria is ≥ 0.75 inches (19 mm).

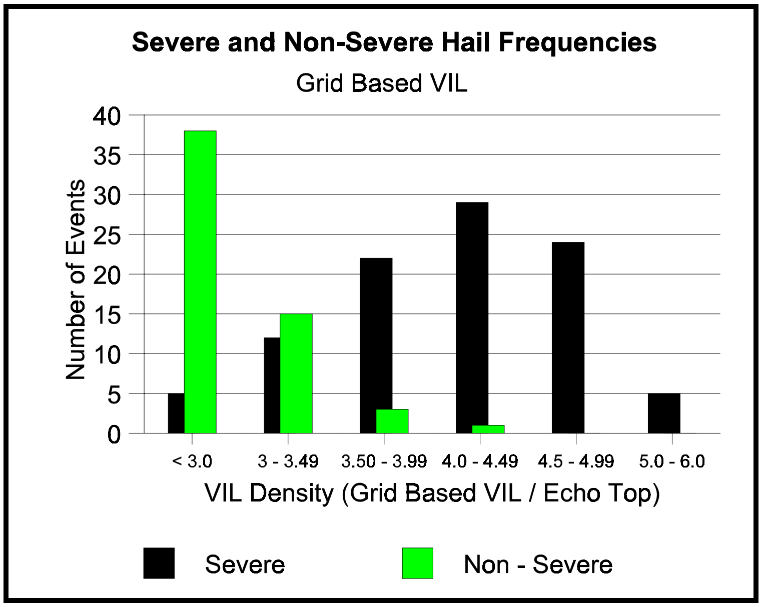

Figure 2. The number of severe and non-severe events versus VIL density (Grid Based VIL / Echo Top) indicating a decrease in the occurrence of non-severe events as VIL density increases. Severe hail criteria is $\geq$ 0.75 inches (19 mm).

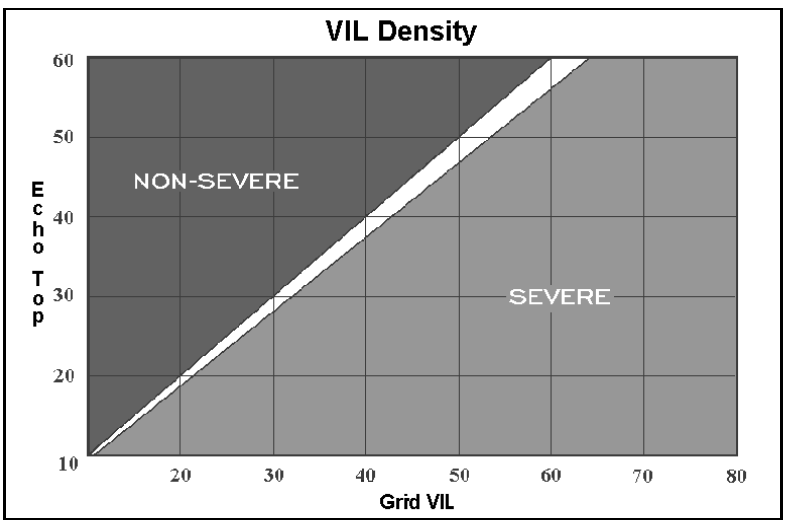

Figure 3. Nomogram for operational use depicting Echo Top (thousands of feet) and Grid Based VIL (kg m^{-2}) with the derived warning thresholds. Area in white between severe and non-severe regions represents indeterminate events with limited confidence. This nomogram should be used as guidance only and not used exclusively in the warning decision making process. Severe hail criteria is $\geq$ 0.75 inches (19 mm).

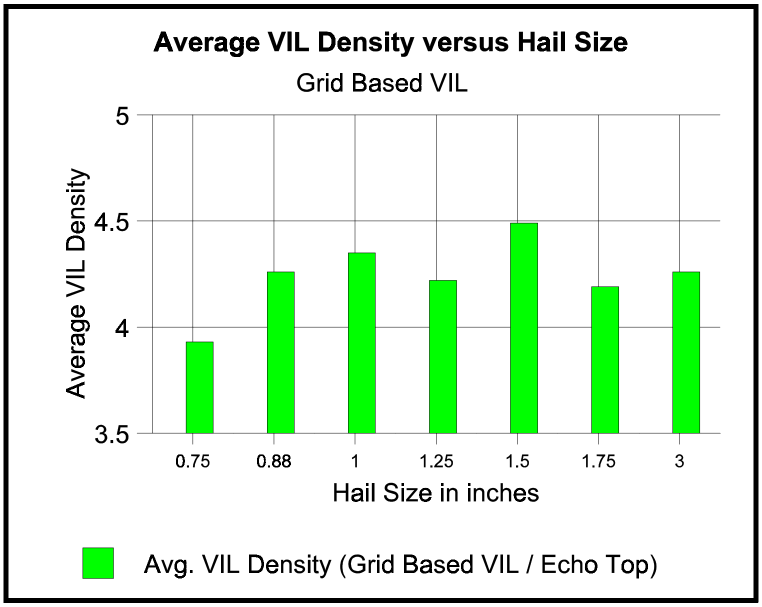

Figure 4. Average VIL density (Grid Based VIL / Echo Top) versus hail size in inches. VIL density generally increases as hail size increases up through 1.5 inches (38 mm).

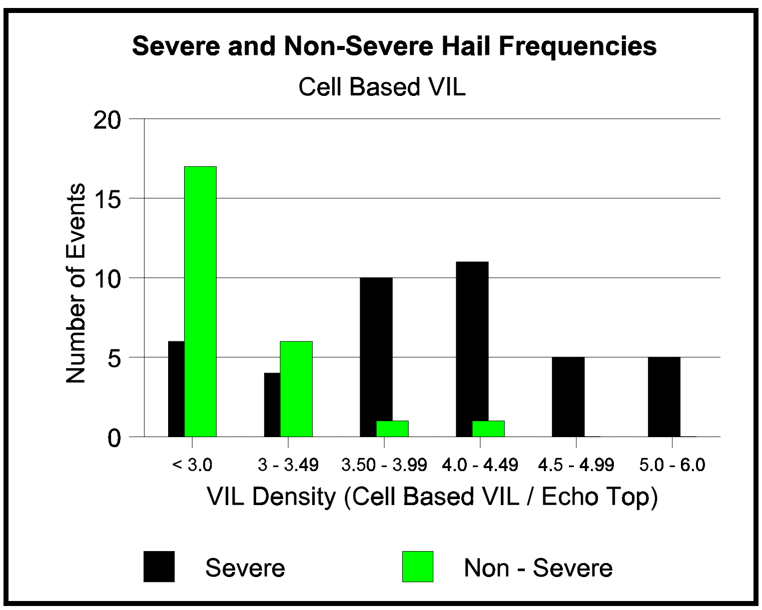

Figure 5. The number of severe and non-severe events versus VIL density (Cell Based VIL / Echo Top) indicating a significant decrease in the occurrence of non-severe events as VIL density increases. Severe hail criteria is $\geq$ 0.75 inches (19 mm).

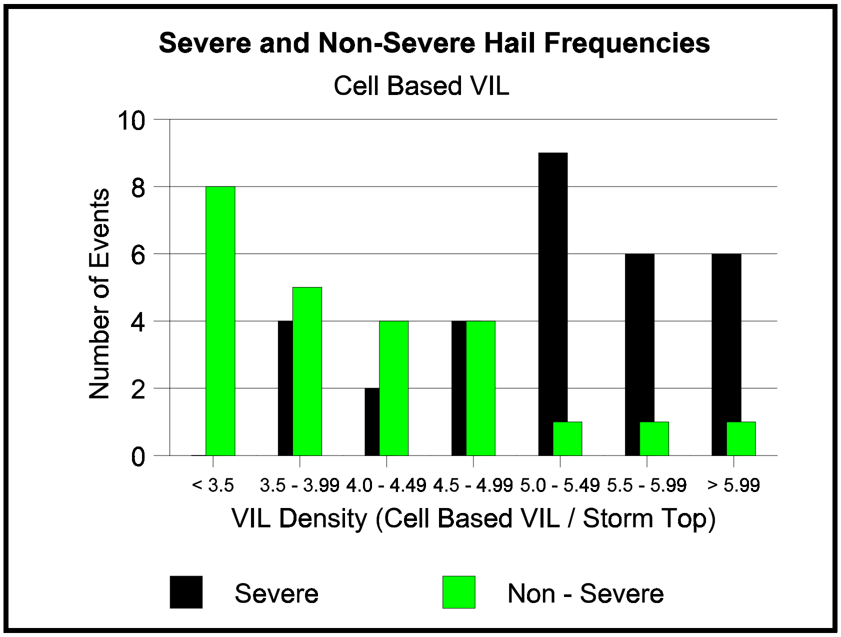

Figure 6. The number of severe and non-severe events versus VIL density (Cell Based VIL / Storm Top) Severe hail criteria is ≥ 0.75 inches (19 mm).

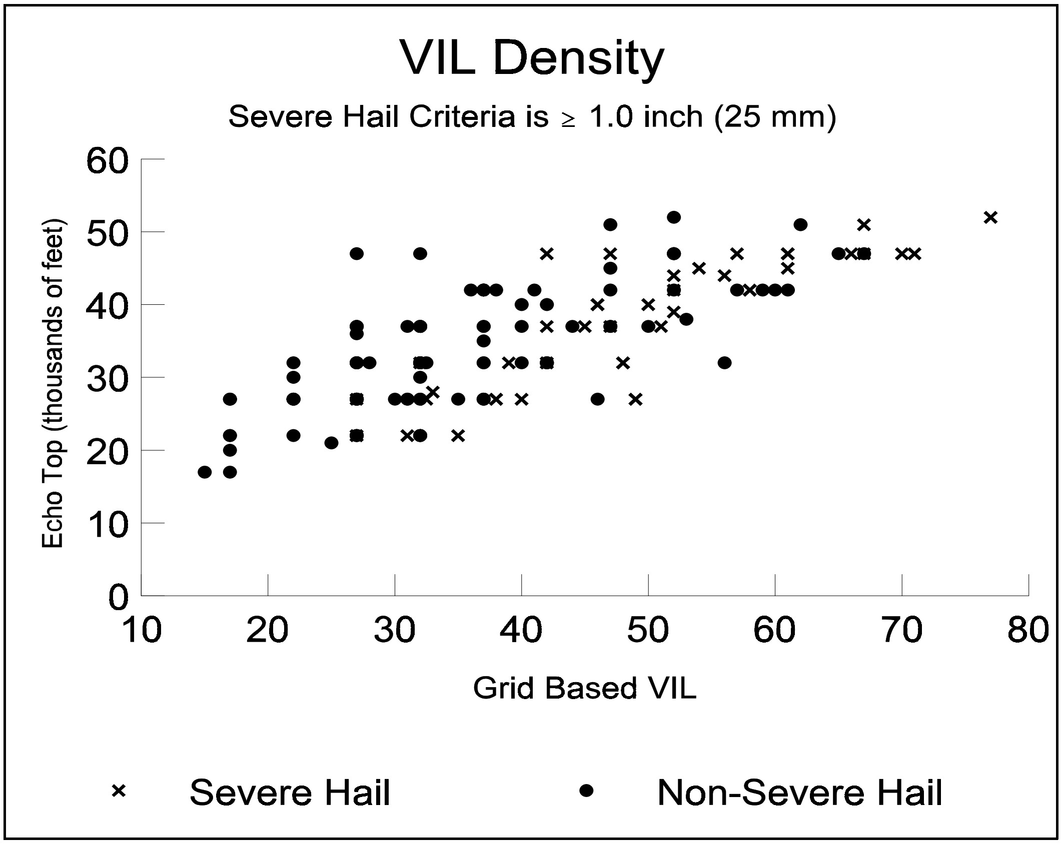

Figure 7. Scatter diagram of Echo Top (thousands of feet) versus Grid Based VIL (kg m^{-2}) for 44 severe hail (✖) cases and 110 non-severe hail cases (●). A few data points are composed of multiple events. Severe hail criteria is ≥1.0 inch (25 mm).

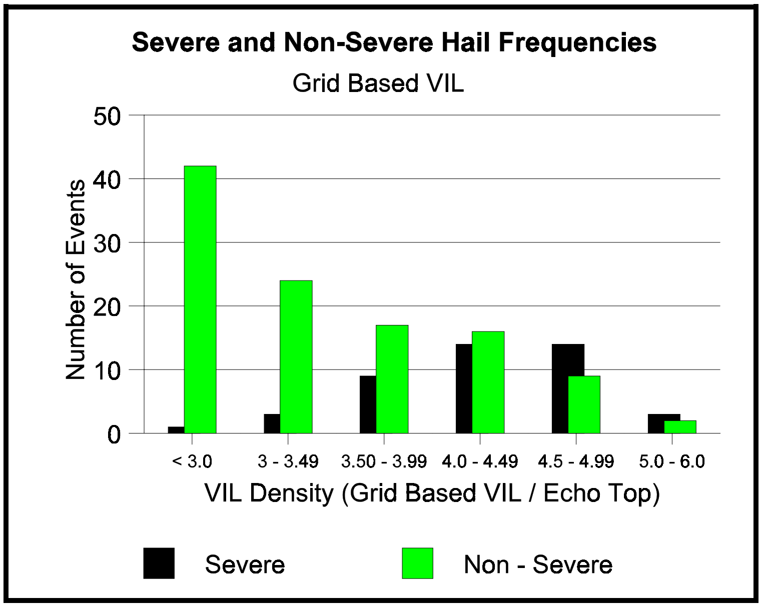

Figure 8. The number of severe and non-severe events versus VIL density indicating a decrease in the number of non-severe events as VIL density increases. Severe hail criteria is ≥ 1.0 inch (25 mm).