Eastern Region Technical Attachment
No. 2011-05
August 2011

Development of Warning Thresholds for One Inch or Greater Hail in the Albany New York County Warning Area

Brian J. Frugis and Thomas A. Wasula*
NOAA/National Weather Service
Albany, New York

ABSTRACT

The National Weather Service (NWS) changed the criterion for severe hail from 0.75 in (1.9 cm) to 1.00 in (2.5 cm) on 5 January 2010. Many techniques have been developed for forecasting severe hail, such as examining echo tops of various reflectivity values, Vertically Integrated Liquid (VIL) Density, and using reflectivity echo (dBZ) heights relative to the -20°C level. However, hail forecasting techniques using these examples are all based on the legacy 0.75 in severe hail criterion. In an attempt to better warn for 1.00 in hail, 384 hail reports were examined from the NWS Albany County Warning Area (CWA) between 2005-2010. This study examined values for: the reflectivity echo height at various dBZ thresholds (50, 55, 60 and 65 dBZ), gridded and cell-based VIL, Storm Echo Top (ET), VIL Density and several other parameters at a storm-scale level. This study also calculated mean and median values for each parameter in connection with the new severe hail criterion, which would be potentially useful to a warning forecaster in an operational setting. For example, storms producing severe hail, on average, had reflectivity echo tops of 3.6-5.1 kilofeet (kft) higher than non-severe storms. Other parameters detailed in this paper can also be used in conjunction with each other to give warning meteorologists confidence of the existence of severe hail within a thunderstorm.

---

*Corresponding author address: Brian Frugis, NOAA/NWS 251 Fuller Rd. Suite B300 Albany, NY 12203. E-Mail: brian.frugis@noaa.gov

1. Introduction

On 5 January 2010, the NWS officially changed the criterion for severe hail from 0.75 in (1.9 cm) to 1.0 in (2.5 cm). This was based on research showing hail damage to roofing materials did not occur until hail was at least 1.0 in (2.5 cm) in diameter (Marshall et al. 2002). In addition, feedback from media and emergency managers in the NWS Central Region supported this change (http://www.weather.gov/oneinchhail/).

Differentiating between severe and non-severe thunderstorms can be difficult for operational warning meteorologists across eastern New York (NY) and western New England due to several factors. Often, limited instability causes many storms to have marginally strong updrafts, which makes for a difficult determination if a storm will produce severe hail or just fall short of the warning criterion. It is also unclear what role variable terrain plays in the storm process. Radar coverage is sometimes compromised due to nearby higher terrain as well. Finally, sparse population in rural or mountainous areas makes verification difficult or impossible for some storms. Despite not being as notorious as the Great Plains or Midwest for hail occurrence, the Northeast can still be quite active. According to the storm event database in *StormData*, the state of NY reported 323 events of hail 0.75 in. or larger in diameter in 2009 (U.S. Department of Commerce 2009). Out of this sample size, 132 events or reports were 1.0 in or greater, further showing the need for methods to accurately predict and warn for severe hail.

While there have been a few local studies conducted regarding the prediction of hail, they all were based on the legacy 0.75 in criterion (Blaes et al. 1998; Cerniglia and Snyder 2002). Also, previous studies have concentrated on just pulse storms (Cerniglia and Snyder 2002; Miller and Petrolito 2008), while the current study shows that the majority of hail producing thunderstorms are multicell in structure. Other studies conducted nationally have generally focused on the Southern Plains (Porter et al. 2005) or Central Plains and Midwest (Donovan and Jungbluth 2007), where storms frequently grow much taller than thunderstorms across the Northeast.

The most common methods of predicting severe hail for operational warning meteorologists are based off both base and derived radar products. Viewing the height of various distinct dBZ levels (e.g. 50, 55, 60 or 65 dBZ) within a storm, especially when compared to items such as the freezing level or -20°C level, can help instill confidence of a hail threat within a thunderstorm. This is supported by Donavon and Jungbluth (2007), which suggested that there is a linear relationship between hail size and the height of the 50 dBZ echo top. Other items, such as using Vertically Integrated Liquid (VIL), can give an indication of hail, although this will ultimately depend on the thermodynamic environment in place. To make up for this, VIL density can also be calculated to help normalize VIL values by taking into account both VIL and storm Echo Tops (Amburn and Wolf 1997). Lead time for severe thunderstorm warnings can be lost using derived products, such as VIL and VIL density, due to the requirement for the volume scan to complete prior to their production (Edwards and Thompson 1998). This study examines all of these various storm-scale based methods of predicting hail, to help best determine the difference between severe and non-severe hail for the Albany NY CWA using the new criterion.

2. Data and Methodology

A database was compiled of 384 hail events from 2005-2010 across the Albany CWA, as entered in *StormData* from local storm reports. Hail sizes ranged from 0.25 in to 2.60 in. Of the 384 events, 177 reports are considered severe under the new criterion (equal to or larger than 2.5 cm in diameter). While storm reports came from all counties in the Albany CWA, the majority of the reports were centered in and around the population centers of the Capital Region, mid-Hudson Valley, and Housatonic and Nagatuck valleys of northwestern Connecticut (CT). In addition, the freezing (melting) height and -20°C levels were recorded for each hail report from the most recent 00Z, 12Z or 18Z (when available) KALY sounding.

For each storm report, radar data from the local archive Digital Video Discs (DVDs) was loaded onto the Weather Event Simulator (WES). Radar data was principally from the Weather Surveillance Radar 88 Doppler (WSR-88D) (U.S. Department of Commerce 2009) located at East Berne, NY (KENX). Additional radar data from the WSR-88D at Binghamton, NY (KBGM), Upton, NY (KOKX), Colchester, VT (KCCX), and Montague, NY (KTYX) was also analyzed when cone of silence issues, beam blockage, and anomalous propagation (AP) made the principal radar site data suspect or unavailable. Figure 1 shows the locations of these radars in relation to the Albany CWA. This data was then analyzed using the Four-Dimensional Storm Investigator (FSI) from the Advanced Weather Interactive Processing System (AWIPS). The FSI software gives the user the ability to view the height of various dBZ levels in a storm in a four-dimensional (animate in three planar dimensions) perspective (Stumpf et al. 2006).

Radar data was examined at the time of the report, plus or minus one volume scan. This was to account for spotter errors in both place and time, as many spotters don't report their exact location or time. This helped ensure that the most accurate values were selected for each particular report. Changnon (1970) showed that a full-grown hail stone could take up to ten minutes to fall out of an updraft and reach the surface, which could fall within about a volume scan of a report, depending on the particular Volume Coverage Pattern (VCP) in use. Any reports that did not seem to logically match up with the radar data were thrown out to maintain the integrity of the study.

Various parameters were examined and recorded for each storm report. The Constant Altitude Plan Position Indicator (CAPPI) within the FSI software (Stumpf et al. 2004) gave the ability to obtain the top of the 50, 55, 60 and 65 dBZ echoes. The level of these various dBZ core heights were recorded to the nearest hundred foot. This was verified by using the Vertical Dynamic XSection (VDX), which gave a cross-section of reflectivity radar data for a line through the core of the storm. If a storm didn't have a particular echo core height, it was left blank for that report.

Essentially, the methodology for obtaining maximum grid VIL (GVIL) values was similar to what was done for other local studies (Cerniglia and Snyder 2002; Blaes et. al. 1998). GVIL values were provided by Display Two-Dimensions (D-2D) in AWIPS. GVIL is calculated by using the reflectivity value of a 4 km x 4 km grid for each elevation slice and integrating it through a vertical column. GVIL is displayed in a 5 kg m^{-2} range (i.e. 50-55 kg m^{-2}) for each 4 km box. The mid-point value of this range was recorded over the location in question, unless the storm was producing the maximum observed VIL value of that particular volume scan.

ETs were also obtained in a similar manner to GVIL, using the D-2D derived product graphic. ETs are displayed in 4 km boxes and reported in a 5 kft range (i.e. 30-35 kft). As with GVIL, the mid-point value was generally used for the ET, with the time and place based off the particular 4 km box that had been recorded for the GVIL value. This uses similar methodology to a hail study completed for the Burlington (BTV), VT office (Lahiff 2005).

Using the data obtained for the GVIL and ETs, VIL Density was calculated. VIL Density has become a popular method for predicting large hail and was the focus of several other Northeastern US Hail studies (Lahiff 2005; Blaes et al. 1998; Cerniglia and Snyder 2002). VIL Density was developed as research noted that high VIL values doesn't always produce large hail, and large hail can occur in the absence of high VIL values as well (Amburn and Wolf 1997). Using VIL Density, the values of VIL are normalized by the height of storm using ET, to help produce an effective hail indicator, regardless of season or air mass characteristics (Amburn and Wolf 1997). They defined VIL Density as:

$$\textbf{VIL Density} = \textbf{(GVIL/ET)} * \textbf{1000} \quad \textbf{(1)}$$

Since VIL is commonly measured in kg m^{-2}, a multiplication factor of 1000 is used to convert VIL Density to units of g m^{-3}. Using this simple equation, VIL Density was calculated for each of the hail reports in the study.

Also, storm convective mode was determined using a subjective analysis, with the categorization based off of common conceptual models. Storms were classified as pulse (ordinary), multicell or supercell. A storm classified as supercell was generally long-lasting, with a persistent rotating updraft or mesocyclone (Falk 1997). Multicell storms featured multiple updrafts and a strong reflectivity gradient on the leading edge of the storms (Falk 1997). Ordinary or pulse storms were generally short-lived, characterized by weak flow and shear environments, and featured only one updraft (Falk 1997; Lemon 1977).

In addition, two other parameters were also recorded, as displayed by the System for Convective Analysis and Nowcasting (SCAN) software. SCAN is a software program within AWIPS which assists the warning forecaster in detection, analysis, and monitoring convection in a quick and efficient manner (Filiaggi 2009). The two parameters obtained from SCAN were cell-based VIL (CBVIL) and maximum expected hail size (MEHS).

CBVIL is calculated with data from the Storm Cell Identification Tracking (SCIT) algorithm (Johnson et al. 1998). The SCIT algorithm scans reflectivity data to identify storm cells (Johnson et al. 1998). The calculation of CBVIL is different from the GVIL, as the CBVIL uses the maximum reflectivity values from the core of the particular storm cell, even if it is over a different 4 km x 4 km column (Johnson et al. 1998). This allows for the CBVIL to take into account storm tilt and movement, and may give a slightly higher value than the GVIL. Using the SCAN software, the CBVIL for each storm report was recorded, as provided for the particular storm cell as identified by the SCIT algorithm.

The MEHS is calculated from the Hail Detection Algorithm (HDA; Witt et. al

1998). HDA uses reflectivity data and numerical model output of the melting level to compute the Severe Hail Index (SHI). MEHS is a derived product of SHI using the following equation:

$$\mathbf{MEHS = 2.54(SHI)^{0.5}} \qquad \mathbf{(2)}$$

with MEHS measured in millimeters. The MEHS displayed in SCAN was recorded into the database in inches. MEHS data was obtained for the same time used for the VIL and ET for each particular hail report.

3. Limitations

Like other hail studies, there are several inherent issues when compiling a database of hail reports. Most importantly, the existence of hail can only be confirmed by storm spotters, who are located at the time and place of the actual hail event. Many parts of the Albany CWA are rural and mountainous, with some areas uninhabited and heavily forested, especially across the western and southern Adirondacks, eastern Catskills and southern Green Mountains of VT. This would allow for actual hail events to go unreported. Even in populated areas, hail that occurs during the overnight hours or accompanied by heavy rain could go unreported. While evidence of wind damage is left (i.e. trees and power lines down), hail can simply melt in the summer warmth, often leaving little proof that it occurred.

In addition, it cannot be confirmed that all hail reports are measured accurately with a ruler. It is more likely that hail is compared to other objects (such as coins) or is simply estimated. Also, many spotters may not report the exact time or location of their report. For example, just giving the name of a town could cause an error of over 10 miles for some parts of the Albany CWA. This forces even more estimation, which could have significant impacts on the report database.

There are also limitations due to the design of the WSR-88D. Lahiff (2005) noted that there are sampling issues due to the maximum height of elevation slices completed by the radar beam. With the highest slice only 19.5°, storms very close to the radar tower cannot be fully sampled. If hail reports were located too close to the radar's "cone of silence", and the storm didn't appear to fully sampled, the hail report was removed from the database. This similar methodology was used for other hail studies (Belk and Wilson 1998; Lahiff 2005).

Also, there are sampling issues with increases in distance from the radar site as well. As the beam goes further away from the radar, the vertical distance between the elevation slices increase. If a dBZ echo top or ET fell between these slices, some estimation was required to determine the numerical value. Luckily, nearly all the hail events studied occurred when the WSR-88D was in VCP-12, 11, 211, or 212. These VCPs feature 14 different elevation slices, with few or no gaps between elevation slices, allowing for better coverage. If an event was deemed to have poor radar sampling (such as the radar being in VCP-21), it was removed from the database. Figure 2 displays the various elevation slices of VCP 212.

The terrain of the Albany CWA imposes some limitations as well. With the rise of Catskill escarpment to the south of the radar site, the lowest elevation slice of the radar beam is blocked by the mountains. Figure 3 displays the prominent topographic features of the Albany CWA. This was also a limitation for a study for northern NY and central and northern VT due to similar terrain in the BTV CWA (Lahiff 2005). This "beam blockage" causes low reflectivity values to be returned for southern and southwestern parts of the CWA, causing unrealistic low VIL values for some events. Any hail reports associated with radar data that seemed to experience significant beam blockage was removed from the database.

Finally, a complete set of all radar data did not exist for every hail report in *StormData*. Because of limited radar data archives, some storms were simply not studied. Although it was the original intention to examine every hail report since the advent of 8-bit radar data in the Albany CWA, time and data constraints limited the total database to 384 hail reports. Despite these constraints, the amount of reports were still higher than other hail databases compiled for Northeastern U.S. studies, which helps validate the statistical significance of the study.

4. Results

a) dBZ Thresholds

The 50 dBZ echo top was the first of four different reflectivity thresholds examined for the study (Table 1, Figures 4 and 5). As expected, the average level of the 50 dBZ echo top was higher for the severe hail (30.9 kft AGL) as compared to the non-severe hail (27.3 kft AGL). On average, the 50 dBZ echo tops of the severe hail were 3.6 kft higher than the non-severe hail. Median values were similar (30.8 kft AGL for severe and 27.0 AGL for non-severe), which gave an indication that the reports were well distributed. Although there was a large range in the 50 dBZ echo tops of the severe hail (10.6 kft to 48.8 kft AGL), 75% of the events had a 50 dBZ echo top of at least 26.5 kft AGL.

When compared to the -20°C level, the 50 dBZ echo top for severe hail was on average 8.7 kft higher. Meanwhile, 50 dBZ echo tops of non-severe hail only averaged 5.5 kft higher than the -20°C level, a difference of 3.2 kft between the severe and non-severe hail. The median height of the 50 dBZ echo top above the -20° C level for severe (non-severe) hail was 9.4 kft (4.9 kft).

The 55 dBZ echo top was the next level examined. 97% of storms producing severe hail had dBZ values of 55 or higher. This level contained a similar signal as the 50 dBZ threshold, with the 55 dBZ echo top reaching a noticeably higher level for the severe hail events when compared to the non-severe. The average height of the 55 dBZ echo top was 27.4 kft AGL for the severe hail and 23.3 kft AGL for the non-severe hail, a difference of 4.1 kft. The median values for severe and non-severe were 27.9 kft AGL and 22.6 kft AGL respectively. 75% of storms producing severe hail had a 55 dBZ level of at least 22.5 kft AGL.

When examining the 60 dBZ echo top data, a similar pattern was observed. As was seen with the 55 dBZ echo tops, 97% of the storms that produced severe hail had reflectivity values reaching 60 dBZ or greater. The average height of the 60 dBZ echo top was 23.2 kft AGL for the storms producing severe hail, while the non-severe hail storms had an average of 18.3 kft AGL. This is a difference of 4.9 kft between the severe and non-severe hail at the 60 dBZ threshold level. Median values showed a similar pattern with severe and non-severe hail values of 23.5 kft AGL and 18.0 kft AGL respectively. 75% of the storms producing severe hail had a 60 dBZ echo top of at least 18.0 kft AGL.

The 65 dBZ echo top displayed a slight variation of the pattern, as only 81% of the storms producing severe hail had obtained dBZ values to this level or greater. Still, average values continued to maintain a strong separation between severe and non-severe hail. Severe hail had an average 65 dBZ echo top of 18.3 kft AGL, with non-severe hail 65 dBZ echo tops averaged 13.2 kft AGL, a difference of 5.1 kft. There was a similar pattern shown in the median values, with values of 18.5 kft AGL for severe hail and 11.9 kft AGL for non-severe hail. 75% of the severe storms had a 65 dBZ echo top of at least 11.8 kft AGL.

The 65 dBZ echo top threshold or greater was examined in comparison to the -20°C height. 59 hail events in the database had a 65 dBZ echo top higher than -20°C level and 45 of those (76%) produced severe hail. While it doesn't guarantee severe hail, having a tall 65 dBZ echo, especially one above the height of the -20°C level, certainly increases confidence in the potential for severe hail.

b) Vertically Integrated Liquid

The next item examined was VIL. As mentioned earlier, VIL has its limitations, as particular values can have different implications due to day to day differences in the thermodynamic environment. However, when examined in a database over time, differences between the severe and non-severe hail can easily be seen in the data. GVIL values for the severe hail ranged from 17 kg m^{-2} to 80 kg m^{-2}. ET values for the severe hail ranged from 28 kft to 53 kft. GVIL values for severe hail averaged 50 kg m^{-2}, while non-severe hail averaged 44 kg m^{-2} (Table 1). These mean values were the same as the median values for GVIL, and 75% of the severe hail events had a GVIL of at least 43 kg m^{-2}. CBVIL values showed a similar pattern. The average CBVIL for severe hail was 45 kg m^{-2}, while non-severe hail averaged 40 kg m^{-2}. These values were somewhat surprising, as one would expect higher values for CBVIL, since it should better capture tilted and quickly moving storms.

c) VIL Density

After taking into account ETs, VIL Density was calculated for each hail report. As shown in research (Amburn and Wolf 1997), VIL Density helps "normalize" the values to be used in different seasons and environments. Using the GVIL and ET values, VIL Density for severe hail computed to a range from 1.86 g m^{-3} to 5.41 g m^{-3}. The average VIL Density for severe hail was found to be 4.07 g m^{-3}. Meanwhile, VIL Density for non-severe hail averaged to be 3.77 g m^{-3}. Median values were very close to the averages, with 4.09 g m^{-3} and 3.84 g m^{-3} for severe and non-severe hail respectively.

d) Supercells vs. Multicells

Out of the 384 hail events in the database, 77% (295) of the events were classified as multicell, 21% (81) of the storms were classified as supercell, and 2% (8) hail events were classified as pulse. A study from Hayes in 2008 showed that northern New England typically receives hail of any size from pulse thunderstorms. However, nearly all hail cases examined in this study across eastern NY and western New England were produced by multicell or supercell storms. Because of the small sample of pulse storms, the only significant comparisons are the parameters for severe multicell and supercell storms.

On average, the supercell storms produced slightly larger hail than the multicell storms, with the hail size around 1.20 in for multicell storms and 1.24 in for supercell storms. This is also seen in the reflectivity values for each of the various dBZ thresholds. The 50 dBZ echo top, on average, reached 29.8 kft for the multicell storms, while it reached 34.2 kft on average for the supercell storms. This pattern was also seen at the 55, 60 and 65 dBZ levels as well, with the supercell storms on average about 5 kft higher, as shown in Figure 6. In addition, storms classified as multicell that produced severe hail had an average GVIL of 49 kg m^{-2}, while storms producing severe hail classified as supercell had an average GVIL of 54 kg m^{-2}. When taking into account ET, the average VIL Density for multicell and supercell storms was 4.04 g m^{-3} and 4.21g m^{-3} respectively.

e) Maximum Expected Hail Size

Witt et al. (1998) state that most hail reports do not reach the MEHS, as it was developed such that around 75% of reports would be less than the predicted size. This was done so the figure represented the highest possible size hail from the particular storm. This trend was also noted in our data, as more than half of the reports (55%) were smaller than the size predicted by the MEHS. For example, the MEHS predicted golf ball size or larger hail (1.75 inches) for 102 events. In reality, only 19 of these events produced golf ball or larger size hail. Out of these 102 potential events, 58 (57%) were severe. Still, there is some value in evaluating the MEHS when trying to estimate the potential size of hail.

The MEHS can increase a forecaster's situational awareness of severe hail, even though the algorithm isn't designed to predict the exact deterministic size of the hail. This can be done by allowing the forecaster to focus on which particular storms potentially would have the largest hail at any particular time. Although, this parameter must be used with caution due to its sensitivity in over predicting severe hail size. As with the VIL Density, MEHS can be a helpful tool in increasing confidence of the existence of large hail. However, when used on its own, it may allow for high false alarm rates and is best utilized when combined with other interrogation methods.

5. Discussion

There are several items from the reflectivity data worth noting in regards to gaining confidence for warning for severe hail. Nearly all storms had reflectivity values over 60 dBZ and the majority reached 65 dBZ as well. Considering that the cursor readout function in FSI gives the warning meteorologist an instant dBZ value, this is a quick safeguard when interrogating storms for severe hail, as error due to estimating the value from the color scale won't occur.

Figure 7 displays a box and whisker plot of all four studied dBZ thresholds for severe hail. As previously shown in Figures 4 and 5, the median values were close to the mean values, which show that there is a symmetrical Gaussian distribution across the range of values. The box plot clearly shows the median and quartile values for each threshold level, allowing warning forecasters to use these values in an operational setting. When warning for severe hail, the median values can be used by the forecaster as a starting point when looking to issue a warning. The median level gives a better measure of the central tendency of the hail dataset (Banacos 2011). In addition, the lower quartile level (25th percentile) represents the height below which one quarter of the events produced severe hail. This can be used as a "cautionary level" for issuing severe thunderstorm warnings as most events contained dBZ echo tops at higher levels.

An item of interest displayed in the data is seen when the median levels for each of the thresholds of the non-severe storms are compared to the first quartile (25%) of the severe storms data. The values are quite close (Figure 8). Using these values as a "cautionary level" could give the warning meteorologist an indication that severe storms are a possibility, although not a certainty. As the storm evolves, the higher the dBZ levels extend through the storm; the increased confidence the warning meteorologist can have that severe hail is occurring. Also, comparing the levels in real-time to the values obtained in the database can help make warning decisions in a quick manner, without having to wait for processed derived products or algorithm output.

While many meteorologists continue to use VIL, its limited use can easily be seen in the database. Although the average GVIL for severe storms is about 6 kg m^{-2} higher than for non-severe storms, the particular values depend on the thermodynamic setup. Forecasters will need to keep in mind that abnormally high or low freezing levels and/or -20°C heights will affect what particular GVIL values to use in the warning process.

Since VIL Density takes into account both VIL and ET, it is a more useful application for warning for severe hail when compared to pure VIL, although is still far from perfect. A linear regression line was run for the average VIL Density against each particular hail size in the database (Figure 9). There is certainly a correlation (*r*) between increasing VIL Density and increasing hail size. However, the *r* value of 0.90 shows that this correlation isn't perfectly linear, but is positively associated.

As with the dBZ thresholds, the VIL Density first quartile values for the severe hail (3.81 g m^{-3}) matched quite closely with the median value for the non-severe data (3.84 g m^{-3}). This continues to show that confidence can increase significantly in the existence of severe hail, as VIL Density increases from the 1st quartile value for severe hail (3.81 g m^{-3}) towards the median value for severe hail (4.09 g m^{-3}).

A local study (Blaes et al. 1998) stated a VIL Density of 3.70 g m^{-3} as a warning threshold correctly identified 91% of severe storms meeting the new 1.00 in hail criterion, but they admit that their small sample-size database of only 40 storms was too limited to draw valid correlations. This is due to the fact that when the study was done, the severe criterion was still only 0.75 in (1.9 cm), and it was difficult to obtain copious amounts of large hail reports. This threshold also incorrectly identified storms as severe 48% of the time in their database. In the current study, using a VIL Density of 3.70 g m^{-3}, 80% of the storms would be correctly identified. Also, 60% of the non-severe storms would also be classified as severe. While VIL Density has some skill in showing correlation with severe hail, it needs to be used with caution, as high false alarm rates can still occur, especially if not used in conjunction with other warning thresholds and methods.

As shown in Figure 10, increasing echo heights of the 50 dBZ level is well correlated (*r* = 0.9678) with increasing hail size. Only hail sizes that contained 10 or more reports were included in this diagram.

This helps show the usefulness of the study, as the warning meteorologist can quickly compare the various echo top of a storm in question to the measures of center (medians) of other elements in the study to help gain confidence in the existence of severe hail.

Lastly, the results of the study have shown that the majority of storms (98%) producing hail across eastern NY and western New England were from multicells and supercells. Although the study has shown that supercells produce larger hail on average, it should not be assumed that this storm convective mode exclusively produces very large hail (such as golfball size or larger). This can be seen when examining the data for golf ball size (1.75 in) or larger hail. In the entire database, multicell storms produced hail 1.75 in or larger 17% of the time compared to 25% for supercells. While the results of this study have shown that supercells are more likely to produce larger hail, it is not exclusive to them, and multicells are certainly capable of producing very large hail as well.

6. Conclusions

Preliminary lessons learned from this study appear to have been helpful to warning forecasters at the Albany NWS Office. For the 2010 convective season, forecasters were challenged with the change in the severe warning criterion from 0.75 to 1.00 in. Although 2010 proved to have a lower frequency of hail events as previous years, warning forecasters were armed with the knowledge that severe hail, on average, had a 50 dBZ echo top of 30.9 kft (with a median of 30.8 kft) and an average GVIL of 50 kg m^{-2} (Table 1). In addition, knowing that severe hail, on average, had a 50 dBZ echo top of 8.7 kft (with a median value of 8.6 kft) above the -20°C level (Table 1) was a useful piece of knowledge when making warning decisions. In 2010, NWS Albany warning meteorologists used the preliminary results of the study during operational warning situations. As a result, the office had a very high Probability of Detection (POD) and a False Alarm Rate (FAR) lower than recent years, according to the “Stats on Demand” interface from the Performance Branch of the Office of Climate, Water and Weather Services (OCWWS). While the total success in the POD and FAR cannot be completely accredited to just the knowledge learned from the hail study, it appears that the study at the very least has been a helpful tool in accurately predicting severe hail.

While any of these parameters have limited use on their own, confidence of severe hail can be increased when using these parameters in conjunction with each other. When examining various dBZ echo tops, VIL and VIL Density, as well as other algorithm-based derived products together, strong confidence can be gained in the potential for severe hail for each volume scan, especially when compared to historical values.

When interrogating a storm for severe hail, it is imperative that the warning forecaster maintains situational awareness and adjusts warning thresholds and decisions based on results of the ongoing convective episode. It’s worth noting that atypical situations (such as very low freezing levels or cold season events) will have much different warning thresholds than the “typical” storms, which comprised a majority of this study. While both the 50 dBZ echo top height and average VIL Density showed a positive correlation with identifying hail size, there still were particular events that went against the trend. It is also important to note that all of the values in this study have been developed for severe hail only and damaging winds and/or tornadoes may occur at any time, even in the absence of hail. It's for this reason that the warning forecaster must be vigilant in studying all base and derived products and never issue any warnings solely off these mere statistics.

Finally, the advent of the dual-polarization radar will considerably change how operational forecasters interrogate thunderstorms and make warning decisions. Statistical data, such as that included in this study, will only help with this transition as the landscape of hail prediction rapidly changes over the next several years.

Acknowledgements

The authors would like to thank Warren Snyder, Albany WFO SOO and Eastern Region SSD and MSD for their thorough and timely review of this publication. In addition, the authors would like to thank former University at Albany students Rihaan Gangat, Rebecca Darrow, and Sara Ganetis for their help with data analysis and the creation of figures for both this paper and previous presentations. This paper is an unfunded component under the Severe Weather topic of CSTAR IV, grant **NA01NWS4680002**.

References

Amburn, S., and P. Wolf, 1997: VIL density as a hail indicator. *Wea. Forecasting*, **12**, 473-478.

Banacos, P.C., 2011: Box and whisker plots for local climate datasets: Interpretation and creation using Excel 2007/2010. *Eastern Region Technical Attachment*, **No 2011-01**, National Weather Service, NOAA, Department of Commerce, 20 pp., Bohemia, NY.

Belk, N.M. and L.D. Wilson, 1998: Using cell-based VIL density to identify severe-hail thunderstorms in the central Appalachians and middle Ohio Valley. *Eastern Region Technical Attachment*, **No 98-9,** National Weather Service, NOAA, Department of Commerce, 7 pp., Bohemia, NY.

Blaes, J. L., C. S. Cerniglia Jr., and M. A. Caropolo, 1998: VIL density as an indicator of hail across eastern New York and western New England. *Eastern Region Technical Attachment*, **No 98-8**, National Weather Service, NOAA, Department of Commerce, 17 pp., Bohemia, NY.

Cerniglia, C.S. and W.R. Snyder, 2002: Development of warning criteria for severe pulse thunderstorms in the northeastern United States using the WSR-88D. *Eastern Region Technical Attachment*, **No 2002-03,** National Weather Service, NOAA, Department of Commerce, 14 pp., Bohemia, NY.

Changnon, S. A., 1970: Hailstreaks. *J. Atmos. Sci.*, **27**, 109-125.

Donavon, R.A., and K.A. Jungbluth, 2007: Evaluation of a technique for radar identification of large hail across the upper Midwest and central Plains of the United States. *Wea. Forecasting*, **22**, 244-254.

Edwards, R., and R.L. Thompson, 1998: Nationwide comparisons of hail size with WSR-88D vertically integrated liquid water and derived thermodynamic sounding data. *Wea. Forecasting*, **13**, 277-285.

Falk, K.W., 1997: Techniques for issuing severe thunderstorm and tornado warnings with the WSR-88D Doppler radar. *NOAA Tech. Memo.*, NWS SR-185, NWFO Shreveport, LA.

Filiaggi, T., 2009: SCAN: System for convection analysis and nowcasting, guide for users, Version OB8.3. NOAA/NWS Meteorological Development Laboratory, Silver Spring, MD.

Hayes, J.C., 2008: Hail in the Gray, Maine county warning area. *Eastern Region Technical Attachment*, **No 2008-04,** National Weather Service, NOAA, Department of Commerce, 22 pp., Bohemia, NY.

Johnson, J.T., P.L. MacKeen, A. Witt, E.D. Mitchell, G.J. Stumpf, M.D. Eilts, K.W. Thomas, 1998: The storm cell identification and tracking algorithm: an enhanced WSR-88D algorithm. *Wea. Forecasting*, **13**, 263-274.

Lahiff, C.T., 2005: Vertically integrated liquid density and its associated hail size range across the Burlington, Vermont county warning area. *Eastern Region Technical Attachment*, **No 2005-01,** National Weather Service, NOAA, Department of Commerce. 20 pp., Bohemia, NY.

Lemon, L.R., 1977: New severe thunderstorm radar identification techniques and warning criteria. *NOAA Tech Memo.* NWS NSSFC-1. Kansas City, MO. NOAA National Severe Storms Forecast Center.

Marshall, T.P., R.F. Herzog, S.J. Morrison, S.R. Smith, 2002: Hail damage threshold sizes for common roofing materials. Preprints, *21st Conference on Severe Local Storms*, San Antonio, TX. Amer. Meteor. Soc.

Miller, D. and A. Petrolito, 2008: Anticipating pulse severe thunderstorms using the WSR-88D all-tilts display: a case study. *Eastern Region Technical Attachment*, **No 2008-02**, National Weather Service, NOAA, Department of Commerce, 11 pp., Bohemia, NY.

Porter, D.L., M.R. Kramar, S.D. Landolt, 2005: Predicting severe hail for the southern High Plains and West Texas. Preprints, *32nd Conf. on Radar Meteorology*, Albuquerque, NM, Amer. Meteor. Soc.

Stumpf, G.J., M.T. Filiaggi, V. Lakshmanan, W.F. Roberts, M.J. Istok, S.B. Smith, 2004: A four-dimensional radar analysis tool for AWIPS. Preprints, *22nd Conf. on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc.

Stumpf, G.J., M.T. Filiaggi, M.A. Magsig, K.D. Hondl, S.B. Smith, R. Toomey, and C. Kerr, 2006: Status on the integration of the NSSL four dimensional stormcell investigator (FSI) into AWIPS. Preprints, *23rd Conf. on Severe Local Storms*, St. Louis, MO, Amer. Meteor. Soc.

U. S. Department of Commerce, 2005-2010: Storm Data, **47-*52.*** National Climatic Data Center, Federal Building, 151 Patton Ave., Asheville, NC 28801-5001.

U.S. Department of Commerce, Doppler Radar Meteorological Observations, *Federal Meteorological Handbook No. 11*. [Available online from http://www.ofcm.gov/fmh11/fmh11parta/pdf/2009-PartA_FMH11.pdf]

U.S. Department of Commerce, One Inch Hail (2010). Retrieved 18 July 2011, from National Weather Service: http://www.weather.gov/oneinchhail/

U.S. Department of Commerce, Stats on Demand Interface, Office of Climate, Water, and Weather Services, Performance Branch, Silver Spring, MD.

Witt, A., M.D. Eilts, G.J. Stumpf, J.T. Johnson, E.D. Mitchell, K.W. Thomas, 1998: An enhanced hail detection algorithm for the WSR-88D. *Wea. Forecasting*, **13**, 286-303.

Table 1. Average height of 50, 55, 60 and 65 dBZ echo tops (kft), average height above -20°C height (kft), and average GVIL values (kg/m^2) for both severe and non-severe hail.

	SEVERE **1.00"+ (Quarter or Larger) Hail**	**NON-SEVERE** **0.25"- 0.88" (Nickel or smaller) Hail**	**Difference**
Average Height of 50 dBZ Echo Top	**30.9 kft**	**27.3 kft**	**3.6 kft**
Average Height of 55 dBZ Echo Top	**27.4 kft**	**23.3 kft**	**4.1 kft**
Average Height of 60 dBZ Echo Top	**23.2 kft**	**18.3 kft**	**4.9 kft**
Average Height of 65 dBZ Echo Top	**18.3 kft**	**13.2 kft**	**5.1 kft**
Average Height of 50 dBZ Echo Top above -20° C Isotherm	**8.7 kft**	**5.5 kft**	**3.2 kft**
Average GVIL (kg/m^2)	**50 kg/m^2**	**44 kg/m^2**	**6 kg/m^2**

Figures

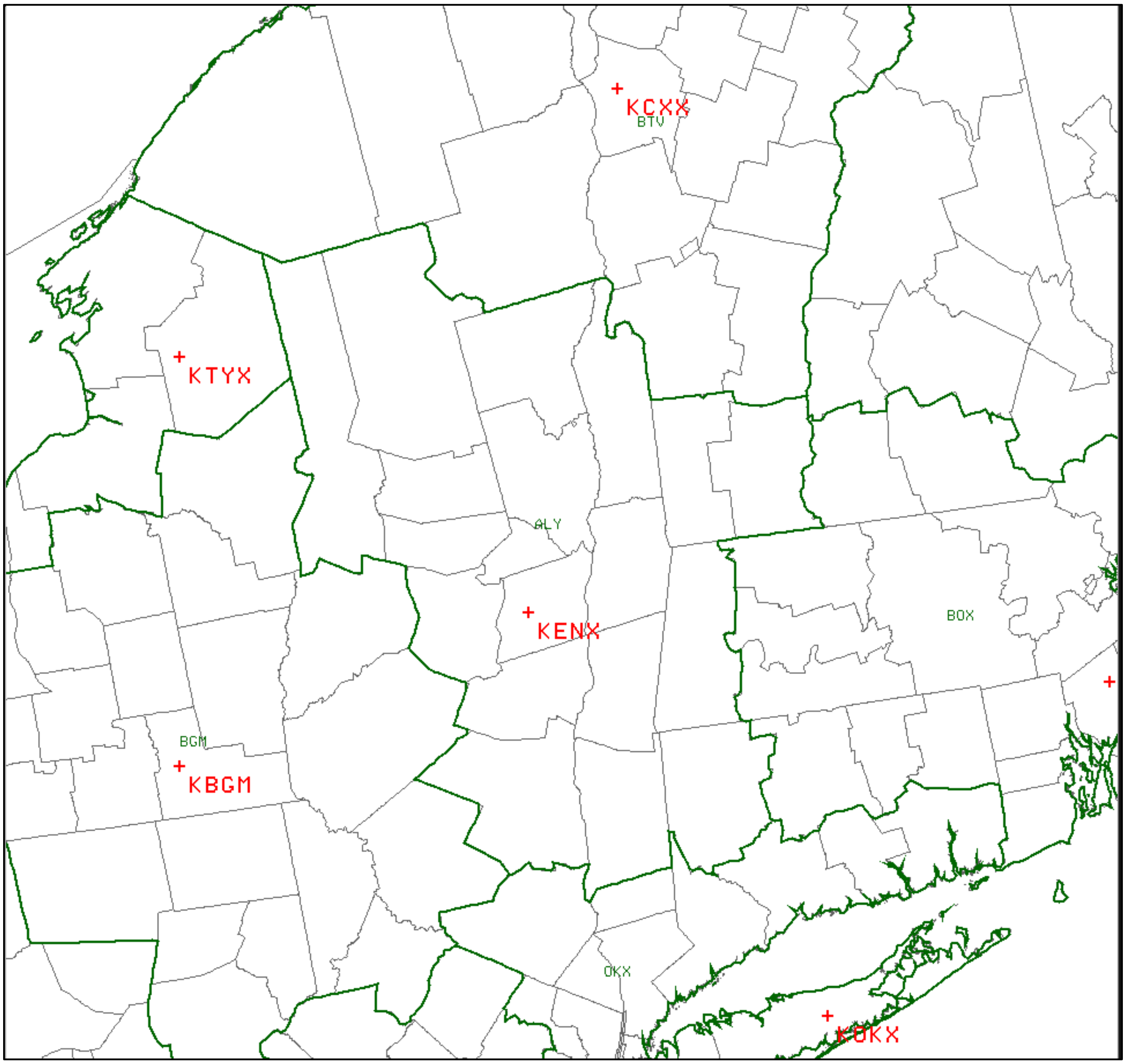

Figure 1. The various radar sites surrounding the Albany CWA utilized for the hail study.

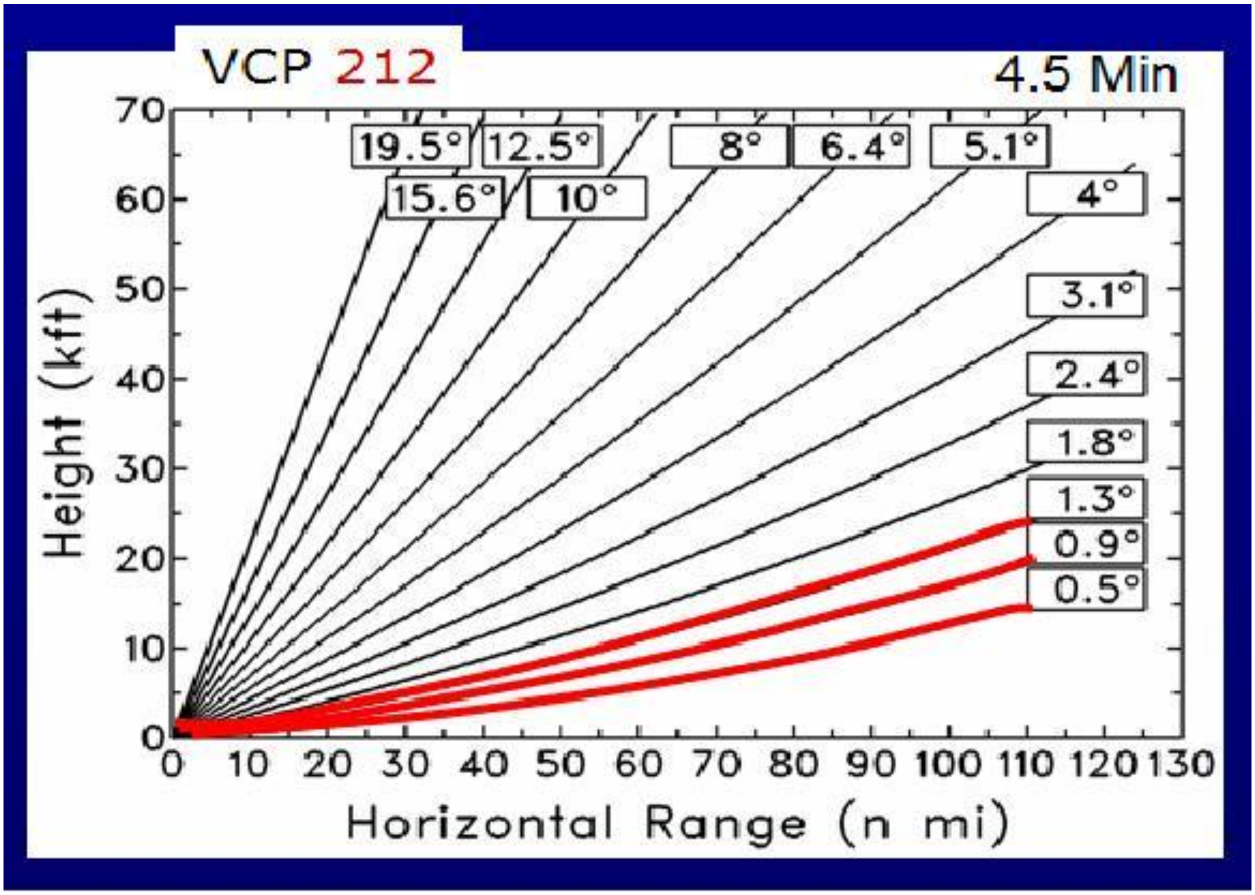

Figure 2. The elevation slices of VCP-212, as provided by the Warning Decision Training Branch (WDTB). The bottom three elevation slices, known as split cuts, are scanned multiple times during a VCP-212 volume scan to help produce better velocity results.

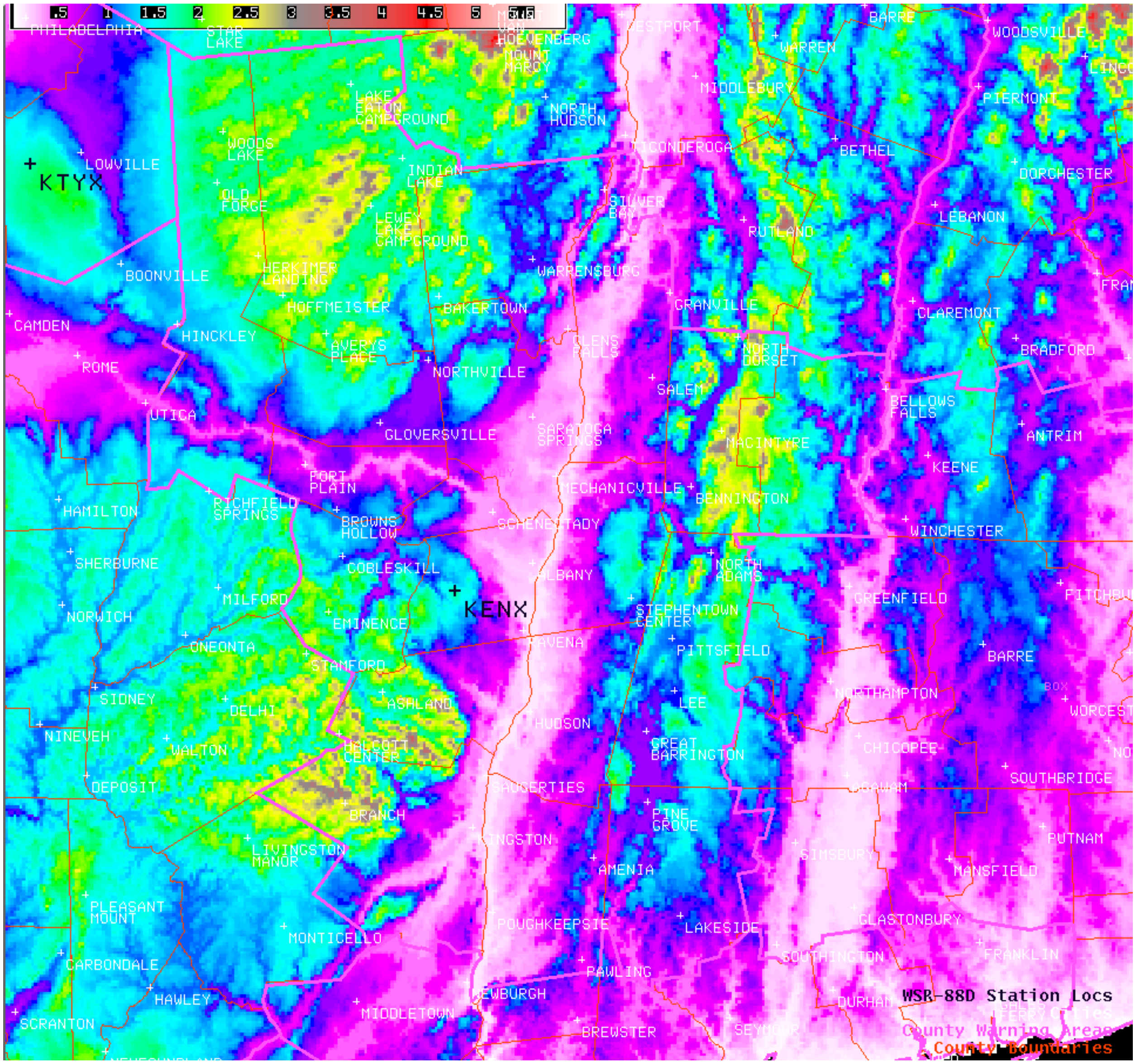

Figure 3. The topography of the Albany CWA, featuring the Adirondacks, Catskills, Green Mountains and Berkshires surrounding the Hudson and Mohawk Valleys. The Catskill Escarpment is located just to the south of the KENX radar site. Elevation above sea level is color coded (kft).

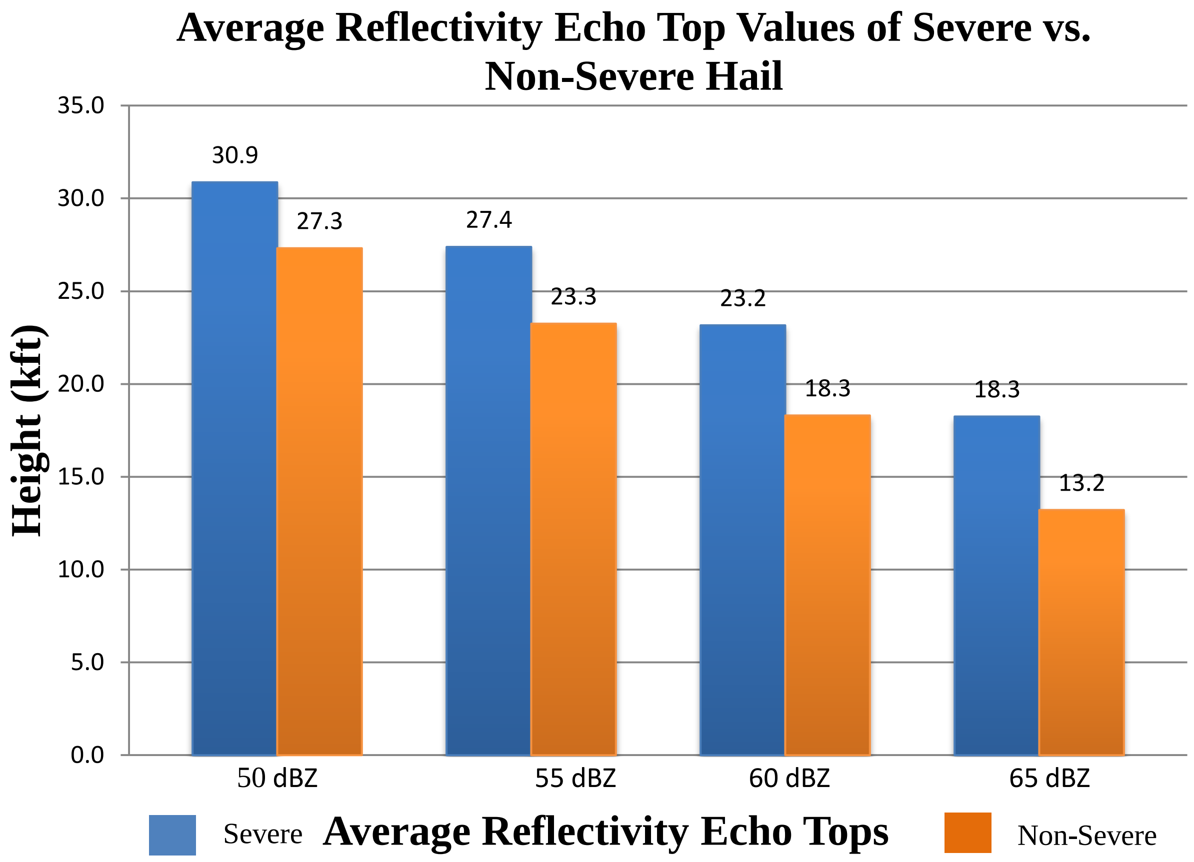

Figure 4. Average reflectivity echo top values for severe vs. non-severe hail (kft).

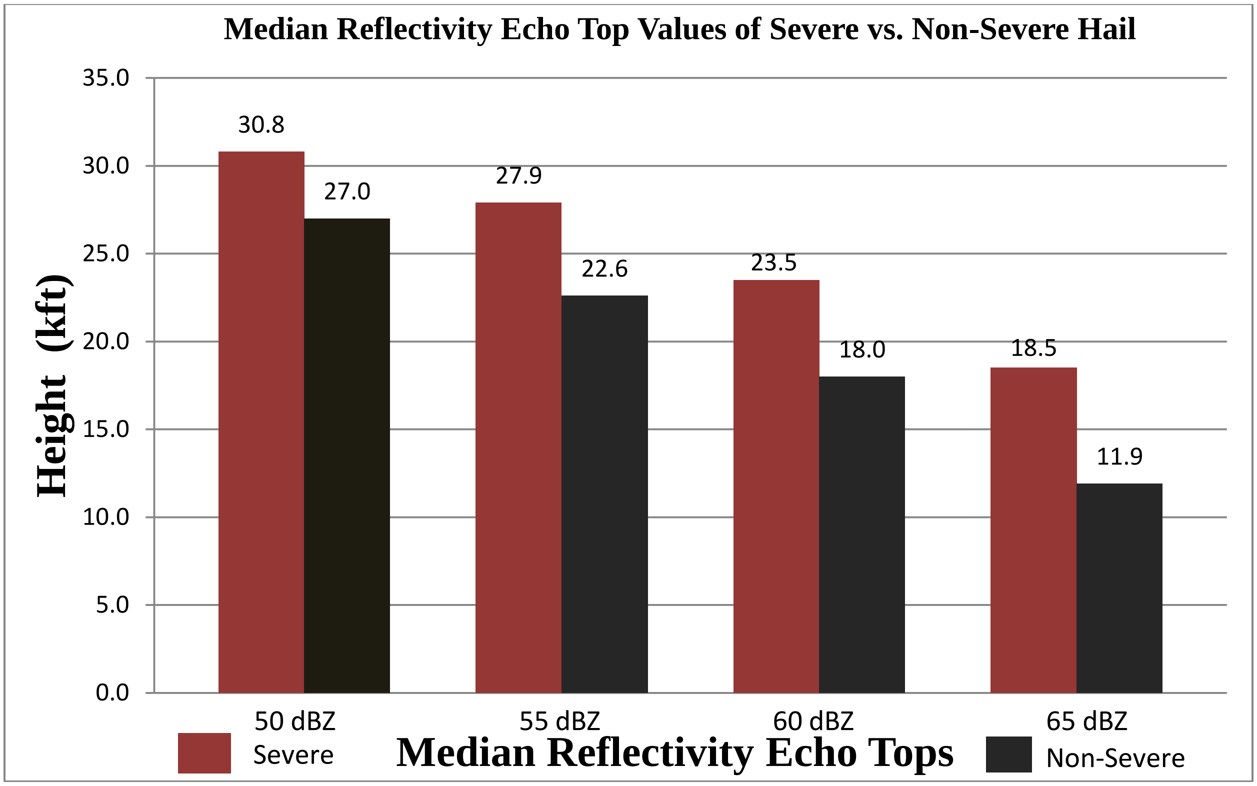

Figure 5. Median reflectivity echo top values for various thresholds for severe vs. non-severe hail (kft).

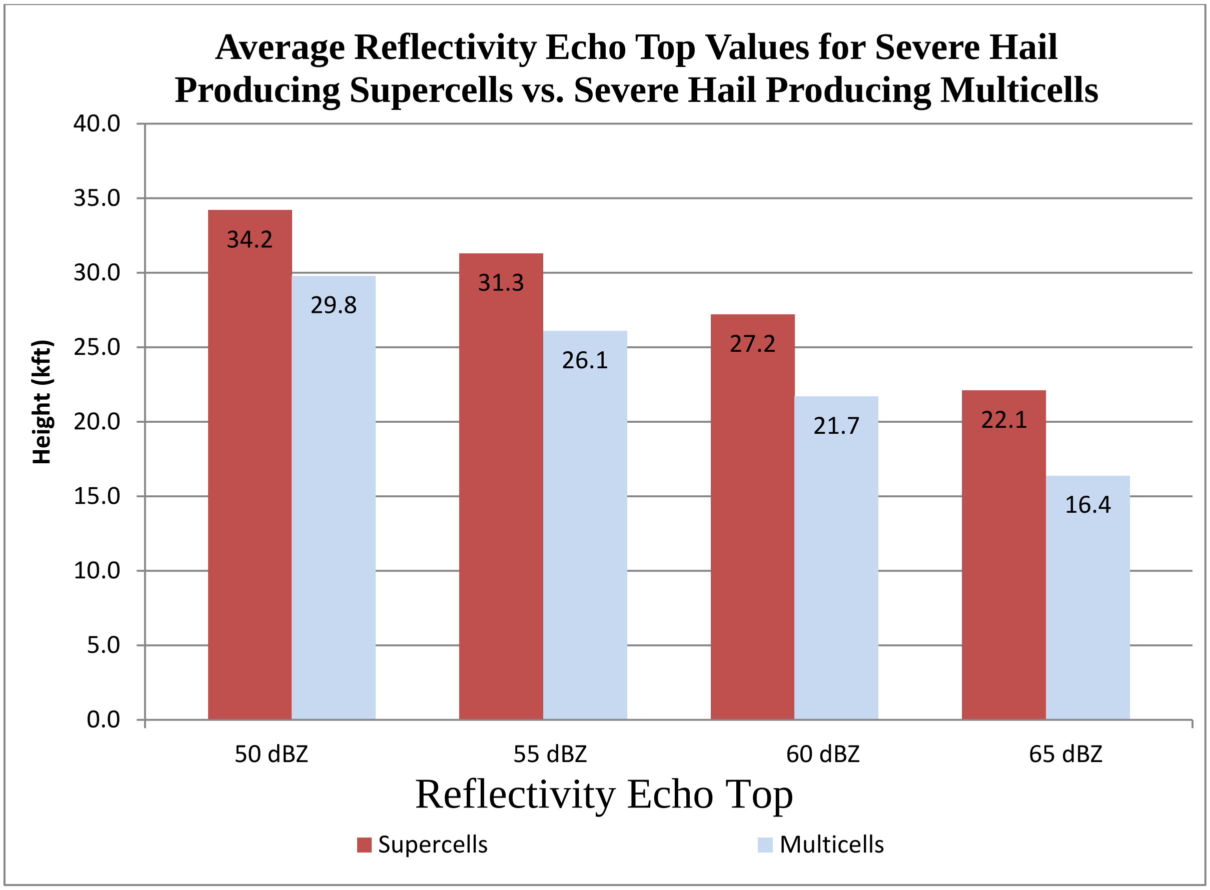

Figure 6. Average reflectivity echo top values for severe hail producing supercells vs. severe hail producing multicells (kft).

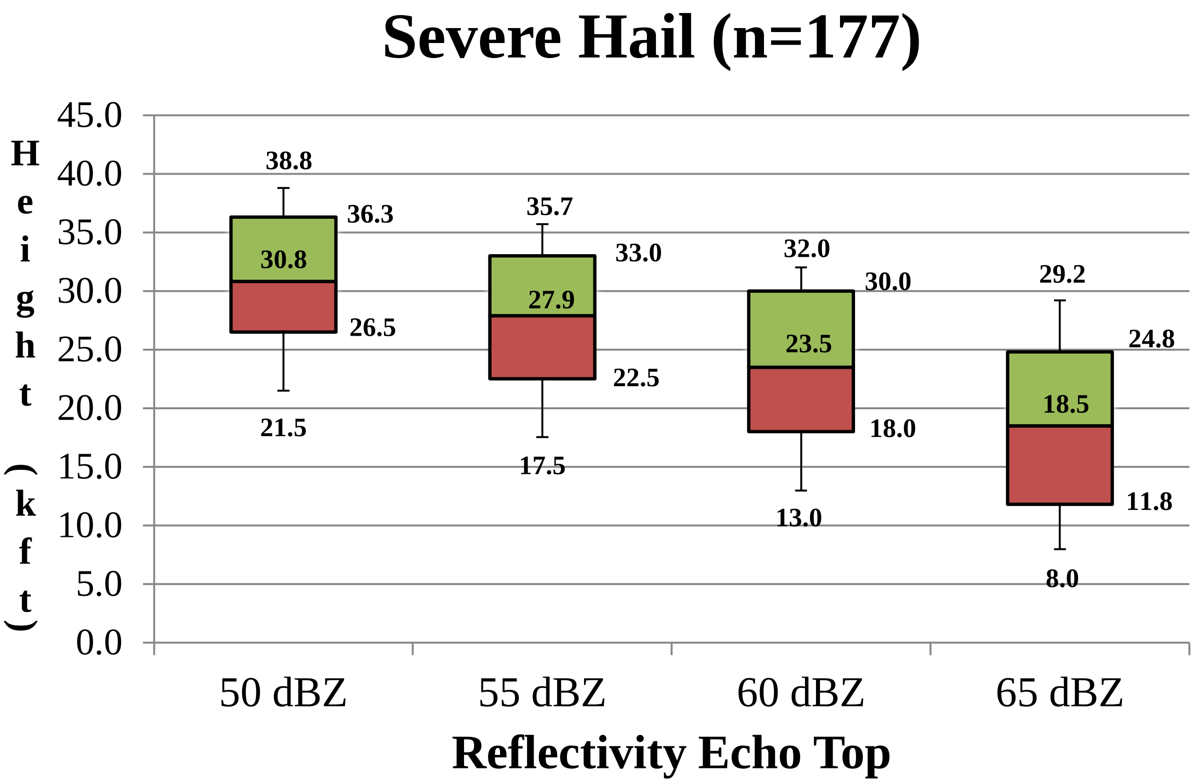

Figure 7. Box and whisker plot of various reflectivity echo top thresholds for severe hail (kft).

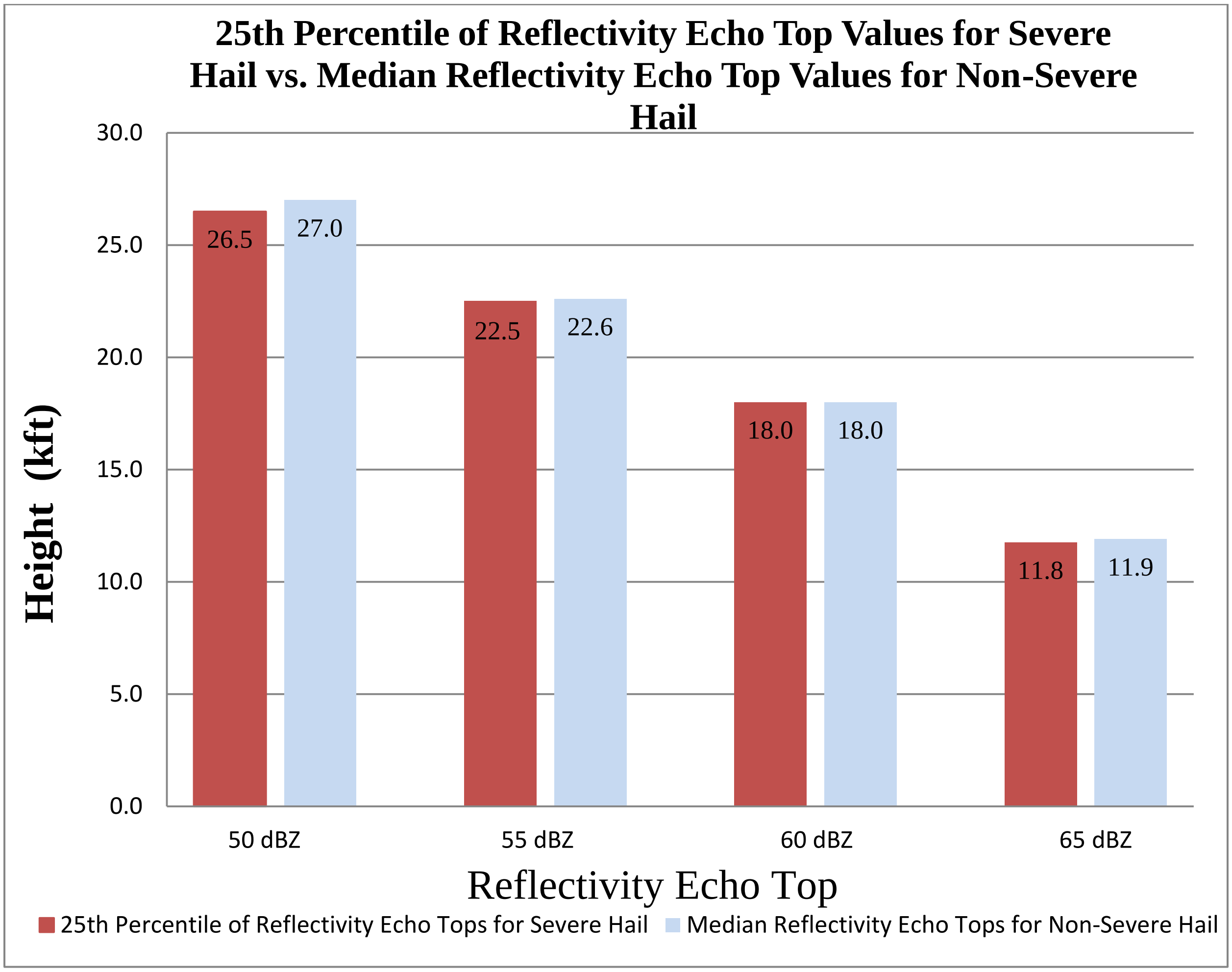

Figure 8. A comparison of the various reflectivity echo tops thresholds using the 25th percentile values for severe hail vs. the median values for non-severe hail (kft).

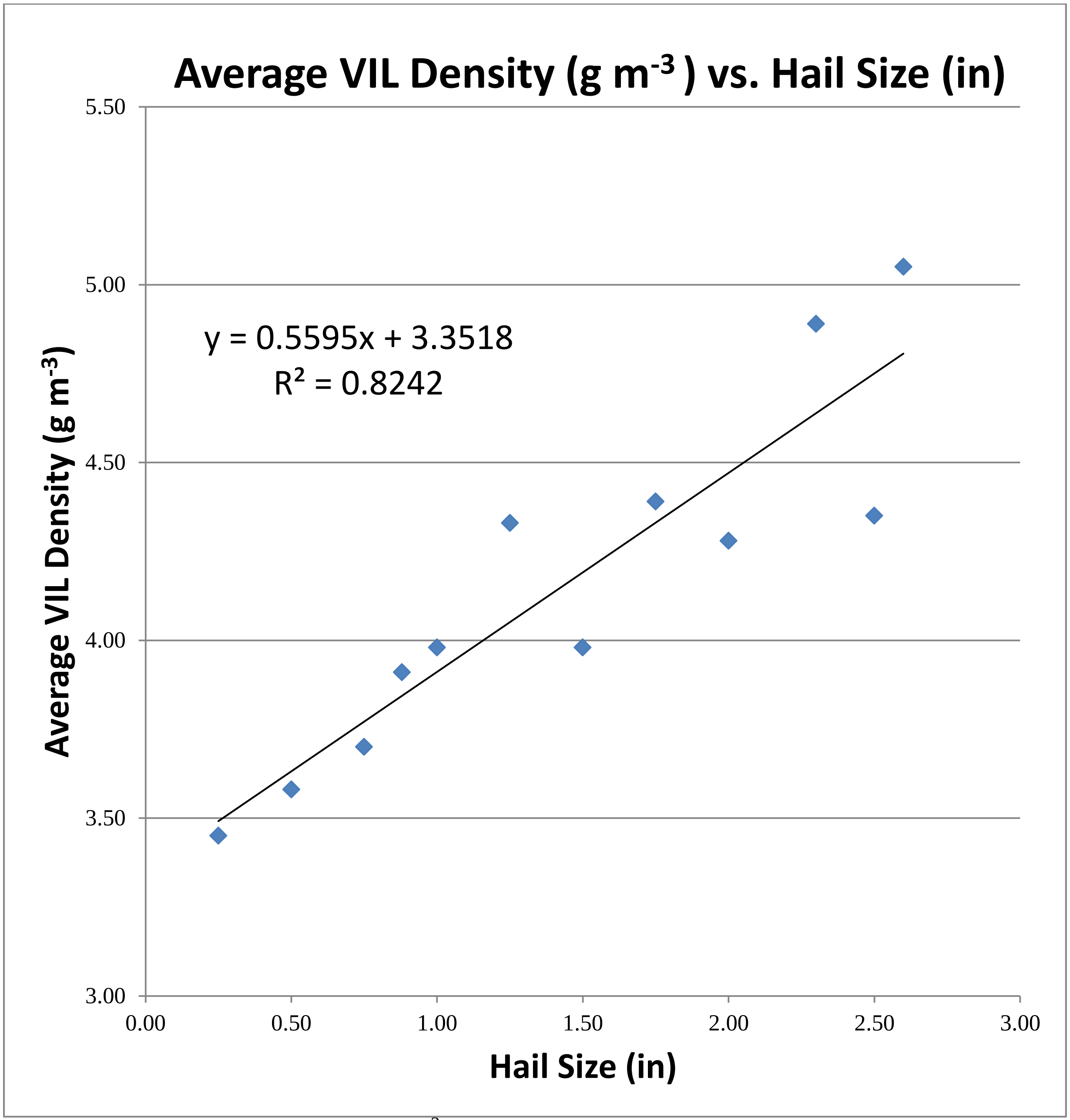

Figure 9. Average VIL Density (g m^{-3}) vs. Hail Size (in) with a linear regression line and coefficient of determination.

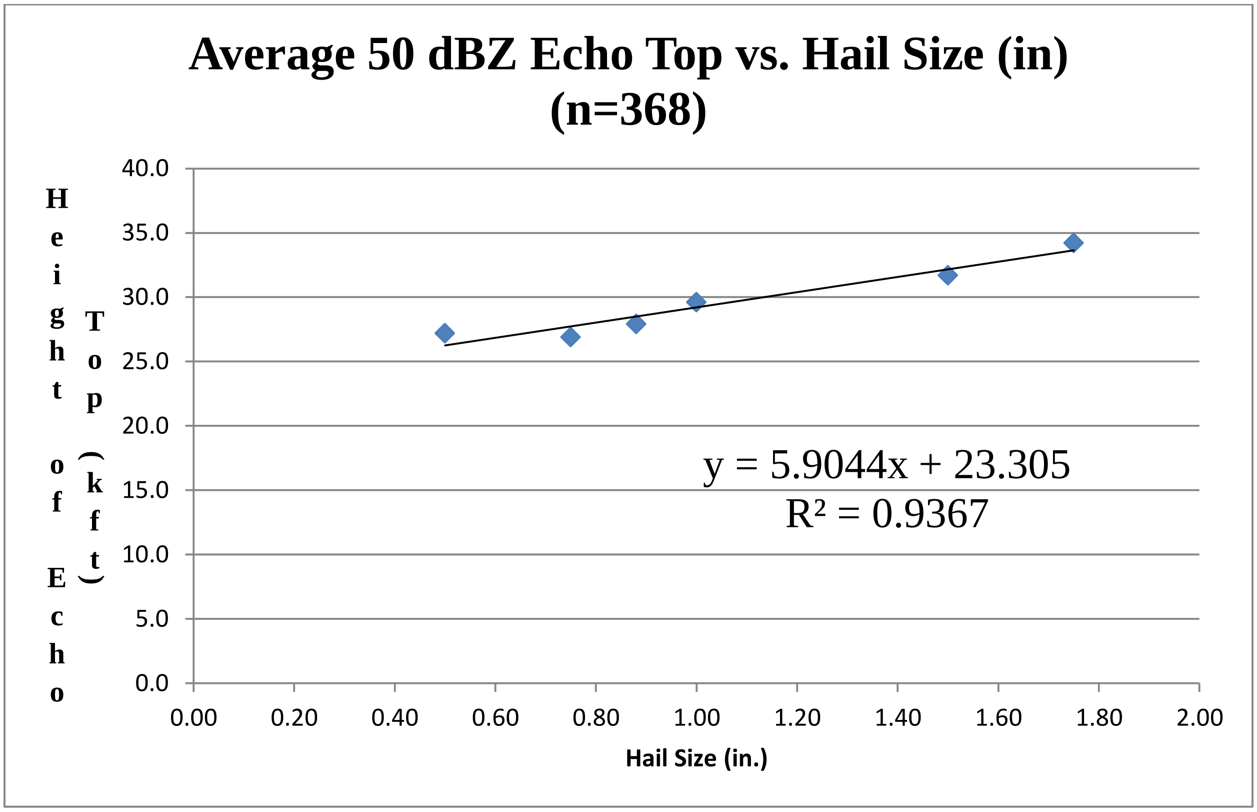

Figure 10. Average 50 dBZ Height of Echo Top (kft) vs. Hail size (in.) with a linear regression line and coefficient of determination.