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HAIL IN THE GRAY MAINE COUNTY WARNING AREA

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1. INTRODUCTION

The occurrence of hail is an important forecast concern, due mainly to the damage caused and the resulting financial cost. While most of the parameters for severe weather in the Northeast are well known, not much research has been devoted solely to the forecasting of hail (LaPenta et al. 2002).

In order for hail to form, deep moist convection (DMC) is necessary. Given DMC, three conditions are required for the formation of hail: adequate updraft, sufficient supercooled water, and an ice or snow nuclei to act as an embryo.

Traditionally, parameters used to forecast the occurrence of hail have included CAPE, shear, and freezing level information. CAPE is considered a measure of the updraft potential and stronger updrafts (parameterized as larger CAPE values) should support larger hailstone sizes (Edwards and Thompson 1998).

Recently, more focus has been placed on the importance of low-level lapse rates and CAPE in the development of large hail. Steep low-level lapse are important to allow parcels to become positively buoyant, and high CAPE is important to ensure sufficient updraft velocity for hail growth. Grenier et al. (1983) and Foote (1984) state that much of the hail growth occurs between -10° C and -25° C, and large CAPE in this region suggests rapid hail growth. This results in "recycling" of small hailstones within the updraft.

Strong shear supports the development of organized convection, which in turn should lead to stronger updrafts. Typically, 0-6 kilometer shear values of greater than 40 knots favor supercell development, which imply stronger updrafts and the potential for large hail (Wicker and Cantrell 1996).

Freezing level information is important in determining the amount of melting that falling hail would encounter. The environmental wet-bulb zero (WBZ) level approximates the freezing level height of the downdraft air, where the hail is likely to be found (Johns and Doswell 1992). Because of this, most hail forecasting studies reference values of the wet-bulb zero height. The occurrence of large hail tends to be clustered around a WBZ height of 9000 feet, and is mostly likely when the WBZ is between 7000 and 9000 feet (Miller 1972).

The goal of this study was to develop a synoptic climatology of hail days in the Gray, ME (GYX) County Warning Area (CWA). Additionally, "traditional" thermodynamic parameters for hail forecasting were reviewed, in order to determine their utility in the GYX CWA.

2. DATA AND METHODOLOGY

All hail reports (severe and non-severe) in the Gray, ME CWA for the period 1998 to 2006 were collected. Severe hail reports were obtained from *Storm Data* (National Climatic Data Center 2006) and office significant weather logs. Non-severe hail reports were obtained from office significant weather logs.

Archived WSR-88D Level III radar data (or its equivalent) were obtained from the National Climatic Data Center (NCDC) for each hail report. Radar data was viewed using NCDC's Java NEXRAD Viewer (Del Greco and Ansari 2005; available at: http://www.ncdc.noaa.gov/oa/radar/jnx/index.html), and each hail report was checked to ensure the accuracy of the timing and placement of the report.

If the hail report could not be verified, it was removed from the dataset. Similarly, if archived radar data was not available for a report, it was also dropped from the dataset. In all, 287 hail reports were used in the study, 134 of which were severe hail reports. For each hail report, the grid based VIL and Echo Top were gleaned from the radar data.

Selected thermodynamic parameters were calculated from "proximity" soundings for each hail report. The "proximity" soundings consisted of RUC native vertical resolution BUFR soundings closest in time and space (from either the RUC analysis or 1 hour forecast projection) to the hail report. RUC model soundings have been used as a basis for "proximity" soundings in studies produced by the Storm Prediction Center (SPC) (Thompson et al. 2003). Surface conditions were interpolated from available surface observations, and used to modify the RUC model soundings. It should be noted, the horizontal resolution of the RUC model was increased from 20 km to 13 km in 2005 (Benjamin et al. 2004).

The soundings were modified using the RAOB PC program (Shewchuk 2006). This software was employed to utilize parameters that GYX forecasters use in an operational setting. Due to the limited availability of RUC model soundings prior to 2002, the thermodynamic parameters were calculated for all hail reports from 2002 through 2006, inclusive. Table 1 shows the parameters collected from the RAOB-analyzed soundings.

Finally, in order to develop pattern recognition for hail days, a synoptic climatology for hail days was created. This was done using data from the Daily Average NCEP NARR Composites web page at the Climate Diagnostic Center (http://www.cdc.noaa.gov/cgi-bin/NARR/plotday.pl).

The composites were computed using the North American Regional Reanalysis (NARR; Mesinger et al. 2006). Average meteorological conditions based on the list of hail days were examined using this dataset. The daily composites are averages of the 00, 06, 12, and 18 UTC data, and the anomalies are based on means between 1979 and 2006. From this dataset, via the website, daily composites and anomalies were computed for geopotential height, temperature, specific humidity, zonal wind, meridional wind and total wind at all mandatory levels. In addition, mean sea level pressure and precipitable water were also computed.

3. RESULTS

The results were broken down into three sections: overview of hail days, synoptic climatology of hail days in the GYX CWA, and thermodynamic parameters.

3.1 Overview of Hail Days

For the purpose of this study, a hail day constituted any calendar day for which at least one hail report, either severe (e.g., ≥ 0.75 inches), or non-severe was received. During the study period, there were 75 "hail days" (calendar days during which hail, severe or non-severe, was reported). Eleven days had severe hail reports only; 36 days had non-severe hail reports only. The remainder (27) had both severe and non-severe hail reports. During the 1988-2006 period of study, there was an average of six hail days per year (Figure 1).

The number of hail days increased dramatically during the last two years of the study. This is attributed to the marked increase in the total number of severe weather events during these two years, as well as a more concentrated effort to collect severe weather reports.

Not unexpectedly, the peak months for hail reports were June through August (Figure 2). The month with the highest number of hail days was July, with just over two and one-half days. These results are similar to those presented by SPC on their Online Severe Weather Climatology Page (http://www.spc.noaa.gov/climo/online/rda/GYX.html).

Figure 3 shows a plot of the number of severe hail reports across the GYX CWA by county. Not surprisingly, many of the reports came from more populated areas. Previous studies have stated that hail reporting is strongly biased to population centers, and that not all hail that occurs is reported (Kelly et al. 1985).

3.2 Synoptic Climatology of Hail Days in the GYX CWA

The mean sea level pressure (MSLP) composite for all hail days is shown if Figure 4. The two main features are the pre-frontal trough across the Northeast and the cold front across Quebec. Most of the severe weather in the GYX CWA occurs not with the cold front, but with the pre-frontal trough. This is typical of many severe weather events in the Northeast.

Figure 5 depicts the 925 mb mean meridional flow and anomaly. The largest negative anomaly occurred near Hudson Bay, with the largest positive anomaly centered near Nova Scotia. The mean flow shows more southerly flow than climatology over the GYX CWA, implying an increased source of warm and moist air for the development of deep moist convection. The 850 mb mean wind and anomaly (m/s) are shown in Figure 6. As was the case with the 925 mb meridional flow, the largest anomaly occurred near Hudson Bay.

Figure 7 shows the 500 mb mean height composite and anomaly. The mean shows a broad trough centered over Quebec, with the GYX CWA in a west southwest flow. The anomaly shows the greatest height departure from climatology centered over western Quebec. This pattern is also prevalent for other types of severe weather in northern New England (Cannon 2002).

The 500 mb mean temperature composite and anomaly is shown in Figure 8. The negative anomaly stretches from near Hudson Bay into western New York. The mean temperature at 500 mb over the GYX CWA is -14^{o}C.

The 250 mb mean wind composite and anomaly are depicted in Figure 9. The largest anomaly was centered over eastern Quebec, with a secondary anomaly over the Great Lakes. The composite and anomalies depict a stronger than climatology 250 mb cyclonic jet across New England into the Canadian Maritimes during hail days in the GYX CWA. Also note the implied coupled jet structure, which is significant considering it appears in the mean composite.

3.3 Thermodynamic Parameters

Table 1 summarizes the thermodynamic parameters calculated for the study. Thermodynamic parameters were calculated for all hail events between 2002 and 2006. The BUFR files for the RUC before this time were not readily available, thus no thermodynamic parameters were calculated for hail events prior to 2002.

Median values were calculated for severe hail reports and non-severe hail reports. This was done in an attempt to determine "threshold" values for discriminating severe hail from non-severe hail producing thunderstorms. In addition, each parameter was compared to hail size. This was done to determine which, if any, parameters have skill in forecasting hail size.

3.3.1 CAPE

The CAPE calculated for this study was for a surface-based parcel (SBCAPE). SBCAPE was used since it is commonly used in operations, and the RAOB software at GYX calculates SBCAPE by default. As a result, both severe and non-severe hail reports occurred with zero SBCAPE. However, the zero RUC-based SBCAPE illustrates that there are times when reliance on surface-based CAPE can be problematic (i.e., elevated convection). All SBCAPE severe hail reports with SBCAPE values of 500 J/kg or less (six in all) were reanalyzed for elevated CAPE using BUFKIT. Table 2 shows SBCAPE and elevated CAPE for all severe hail reports. While this subset is small compared to the entire severe hail dataset, it does show that elevated severe hail does indeed occur in northern New England. Note, for the remainder of this paper, all references to CAPE is SBCAPE.

Figure 10 shows hail size vs. CAPE for all hail reports. There is large variability in the data (the correlation coefficient is 0.288) as hail reports occurred with a wide range of CAPE values (including zero). All hail reports of half-dollar size (1.25 in) or greater occurred with CAPE values greater than 1200 J/kg.

Box and whisker plots are used to compare data for each category (severe and non-severe hail reports). On a single graph, the plots can show information about range, variance and median values for each parameter. The plot shows the lower extreme (bottom whisker), 25th (bottom of the box), 50th (center line), 75th percentiles (top of the box), and the upper extreme (top whisker) for the data. Comparing box and whisker plots in different categories yields information about the similarity of the data.

Figure 11 shows box and whisker plots of CAPE for severe and non-severe hail reports. The median value for severe hail reports is more than 400 J/kg higher than non-severe reports, and the spread between the 1st quartile and 3rd quartile is smaller. This result makes sense, as CAPE is considered to be an indicator of the strength of the updraft, and the larger CAPE values for severe hail suggest this expected relationship.

3.3.2 Shear

Vertical wind shear is important for strong updraft rotation. Rasmussen and Blanchard (1998) and Thompson et al. (2003) both found 0-6 km shear greater than 40 knots were sufficient for supercell development (and presumably the potential for large hail). Figure 12 shows a plot of 0-6 kilometer shear vs. hail size. Hail (both severe and non-severe) occurred with a variety of 0-6 km shear values. While a tendency for larger hail with higher shear values is present, the correlation is quite low (0.088).

Figure 13 shows a box and whisker diagram of 0-6 km shear values for severe and non-severe hail reports. Surprisingly, there is little difference in the median value and spread between severe and non-severe hail reports. This implies that shear is not as important for large hail as instability.

Figure 14 shows 0-6 km shear and CAPE for severe hail reports. Surprisingly, the correlation between the two was quite low (-0.138). Figure 15 shows shear and CAPE for non-severe hail reports. Not surprisingly, a least squares fit analysis show little or no correlation between the two parameters, with a correlation coefficient of -0.07.

3.3.3 Other Parameters

Several other "traditional" and "non-traditional" thermodynamic parameters were investigated. Figure 16 shows freezing level vs. hail size. Interestingly, all but four severe hail reports occurred with freezing levels above 8000 feet and all of the hail reports of half dollar (1.25 in) or larger occurred with freezing levels above 9500 feet. Figure 17 shows a box and whisker diagram of freezing level for severe and non-severe hail. The results seem somewhat counterintuitive, as severe hail reports have a higher mean freezing level than non-severe hail reports.

Wet bulb zero height vs. hail size is depicted in Figure 18. All but one severe hail report occurred with a wet bulb zero height above 6000 feet, and all golf ball (1.75 in) or larger reports occurred with wet-bulb zero heights above 9000 feet. These heights are well above the "traditional" values expected for severe hail (Miller 1972). Figure 19 shows a box and whisker chart of wet bulb zero height for severe hail reports and non-severe hail reports. Again, these results almost seem counterintuitive, with severe hail reports having a higher median value. In addition, spread between the 1st quartile and the 3rd quartile is much less for severe hail reports. These results would imply that large hail is, to some extent, invariant of wet bulb zero height. It is possible that the limited data size is affecting the results; thermodynamic parameters were not calculated for hail before 2002, due to the limited availability of RUC model soundings.

Figure 20 shows precipitable water vs. hail size. While severe hail reports occurred with a wide variety of precipitable water values, the majority of events occurred with values greater than 1.25 inches (which is higher than climatology for the warm season in northern New England). The variability of precipitable water values for severe hail reports and non-severe hail reports are depicted in Figure 21. As might be expected, the median value for severe hail reports is much higher, with a smaller spread. The median climatological value of precipitable water for July (the month with the highest number of hail days, as well as the highest monthly precipitable water value) is plotted on the box and whisker chart as well. The third quartile value of precipitable water for July and the two standard deviations above climatology value for July are also indicated (NWS 2005). The median value of precipitable water for July is almost identical to the median value for non-severe hail reports. The median value of severe hail reports is on the high end of the climatological spectrum, but still well below the two standard deviation value for climatology.

4. DISCUSSION AND CONCLUSION

Typically, hail in northern New England is produced by "pulse" thunderstorms. These thunderstorms tend to develop in an environment that is not characterized by large scale features or forcing. While most of these storms do not produce severe weather, occasionally some do (Cerniglia and Snyder 2002).

Table 3 shows a summary of the thermodynamic parameters calculated from proximity soundings. The much higher mean value for CAPE for severe hail reports was expected, since higher CAPE values imply a stronger updraft, enhancing the potential for larger hail. However, the mean CAPE value for severe hail reports is lower than is typically seen in other parts of the country (Gensini 2008).

The higher median value for precipitable water for severe hail reports is also not surprising. In fact, the value for severe hail reports is nearly two standard deviations above normal for July. This supports the idea that that substantial supercooled water is necessary for large hail formation.

Surprisingly, there was little difference in the median values for shear between severe hail and non-severe hail reports. In general, higher shear values suggest better storm organization, stronger updrafts and the potential for large hail. The values found here were below the values generally accepted as important for supercell development (Rasmussen and Blanchard 1998).

The most striking results, however, are the somewhat surprising freezing level and wet-bulb zero heights. Typically, one would expect lower values of each, since higher freezing levels would increase the melting effect, especially on marginally severe hail. Again, it is possible that the limited data size is affecting the results; thermodynamic parameters were not calculated for hail before 2002, due to the limited availability of RUC model soundings.

It is also possible that the severe hail is occurring primarily with supercells or mini-supercells. Supercells, with strong updrafts in the presence of strong instability, transport warm and moist air higher than non-severe hail producing storms. This might explain the higher freezing level and higher wet bulb zero values.

Some of the results from the examination of thermodynamic parameters seem to contradict traditional "conventional" wisdom. However, hail occurs with a wide variety of values for most parameters, and Edwards and Thompson (1998) found that on a nationwide basis, commonly used hail predictors showed little or no skill in predicting hail size. This study of northern New England hail events appears to be consistent with their findings for a number of commonly used parameters such as freezing level, wet bulb zero height, and 0-6 km shear.

Obviously, many factors are responsible for hail production, so the relationship of most parameters and hail size is likely non-linear. It is also likely that multi-variant based parameters are necessary for better correlations to hail size. Thermodynamic parameters may offer some hope, but examination of soundings in total is necessary.

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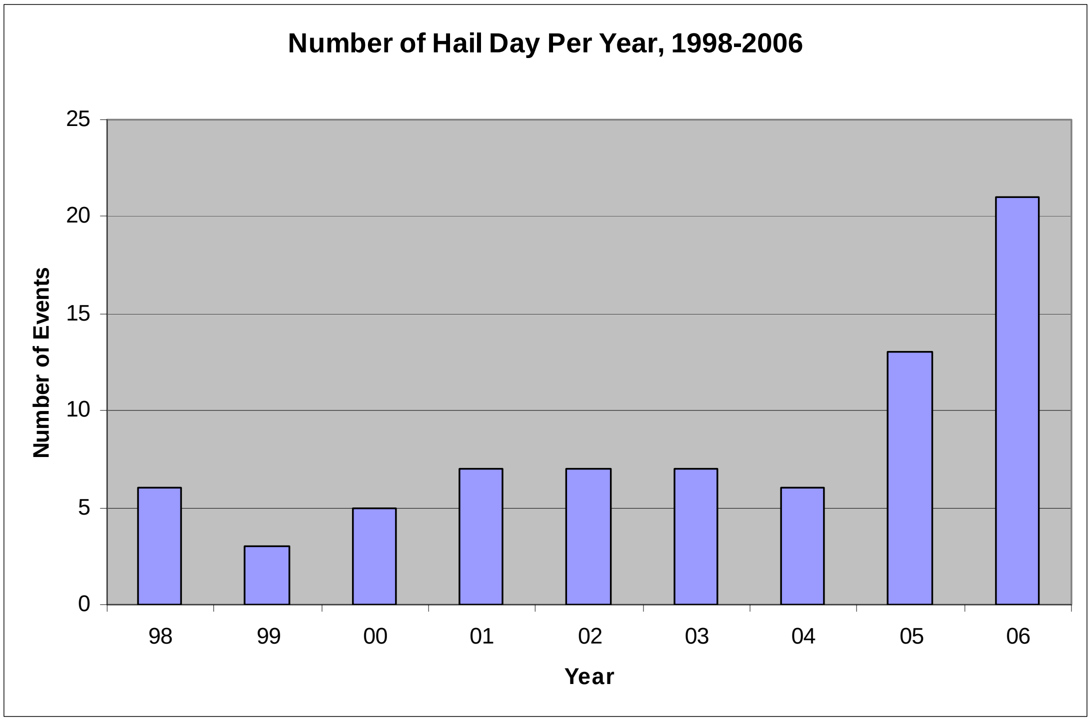


Figure 1. Number of hail days per year, 1998-2006.

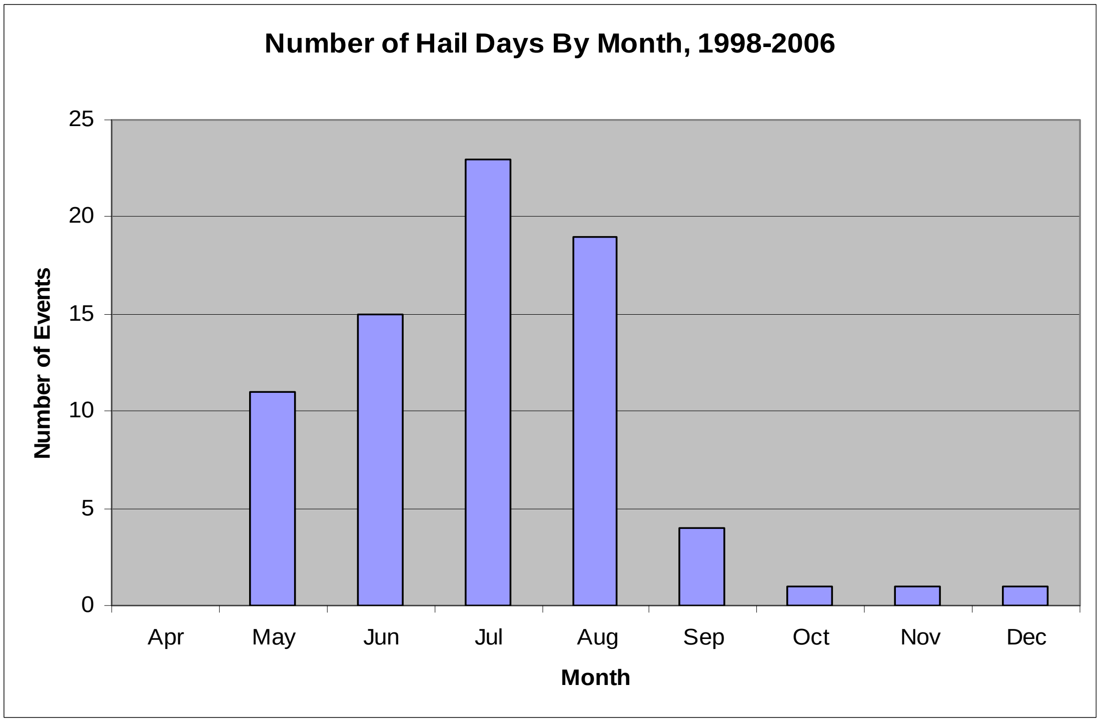


Figure 2. Number of hail days per month, 1998-2006.

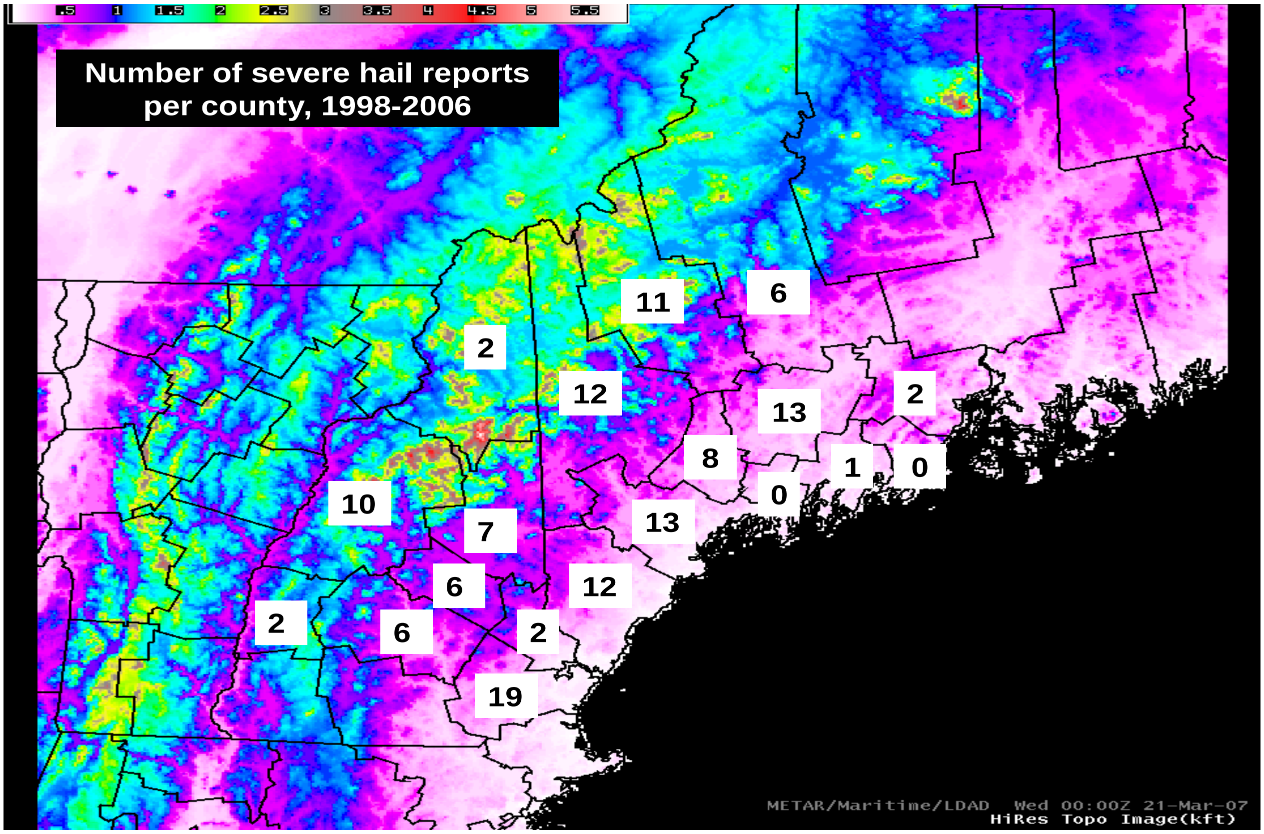


Figure 3. Number of severe hail reports by county. Color shading represents terrain height (kft).

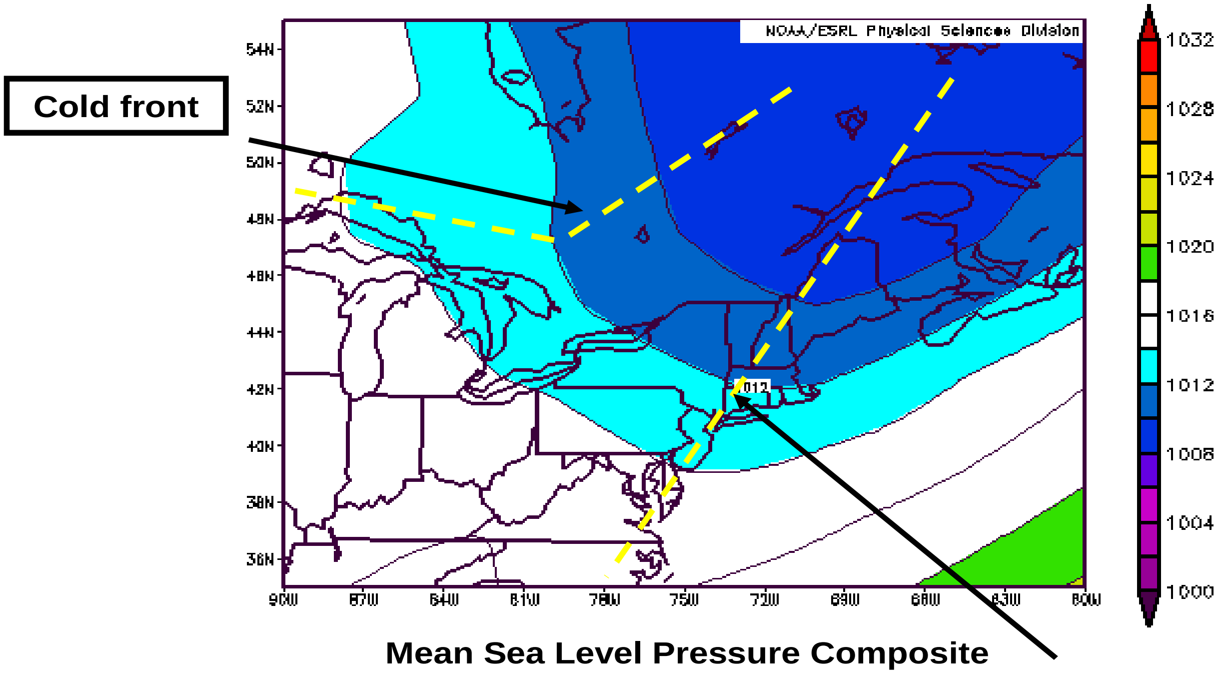
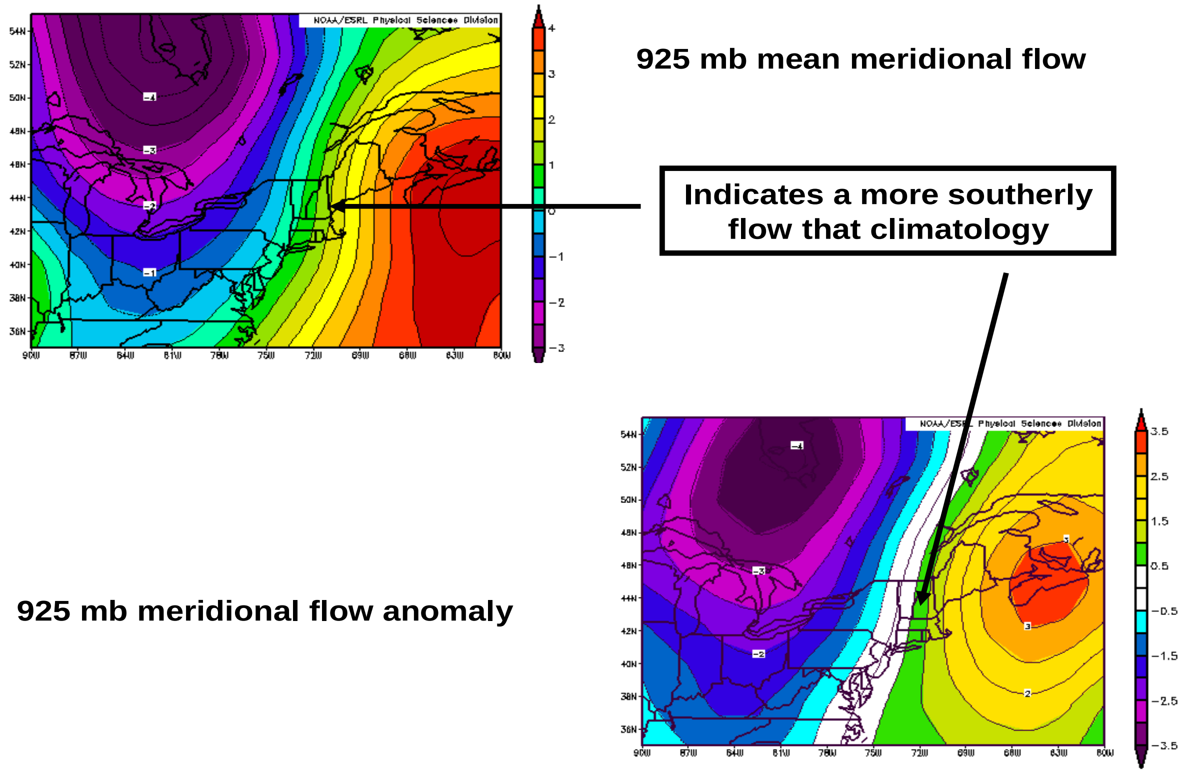


Figure 4. Mean sea level pressure (MSLP) composite for all hail days.

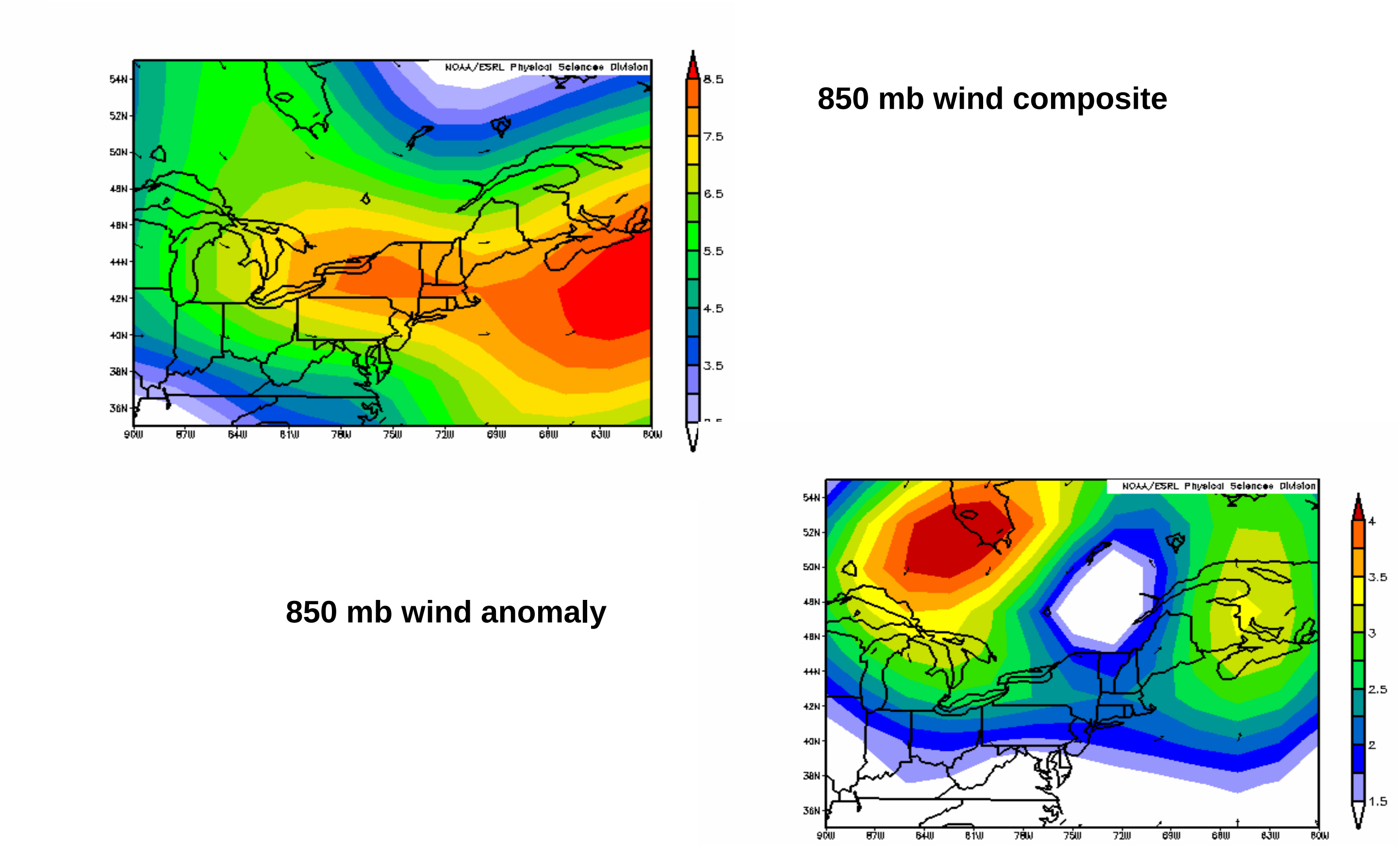


925 mb mean meridional flow

Indicates a more southerly flow that climatology

925 mb meridional flow anomaly

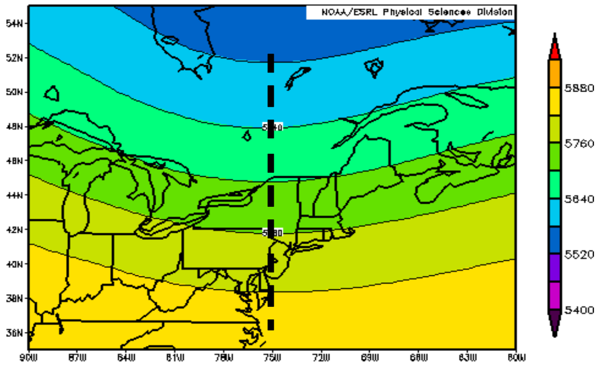
Figure 5. 925 mb mean meridional flow (upper left) and anomaly (lower right) (ms^{-1}) for all hail days.



850 mb wind composite

850 mb wind anomaly

Figure 6. 850 mb mean wind (upper left) and anomaly (lower right) (ms^{-1}) for all hail days.



500 mb height composite

500 mb height anomaly. The maximum anomaly just to the northwest is about 40 meters

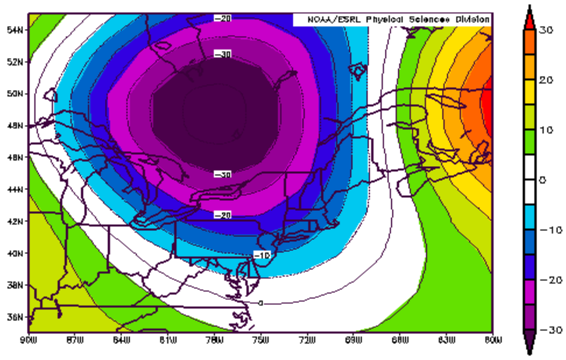
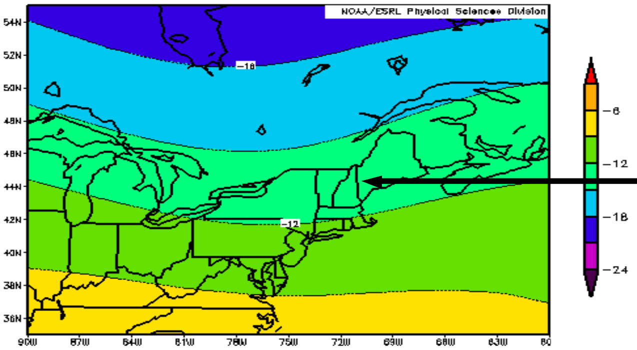


Figure 7. 500 mb mean height composite (upper left) and anomaly (lower right) (m) for all hail days.



500 mb temperature composite.

Note the value of -14 Celsius over the CWA

500 mb temperature anomaly

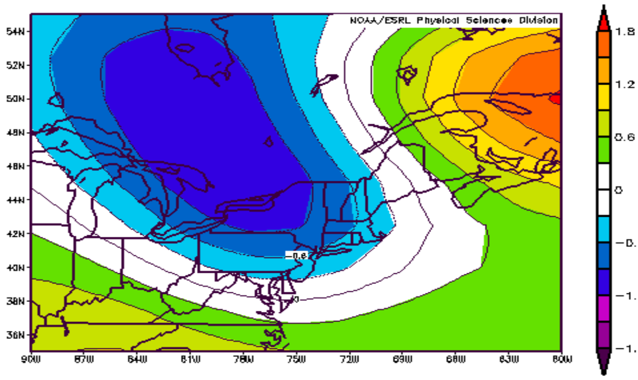
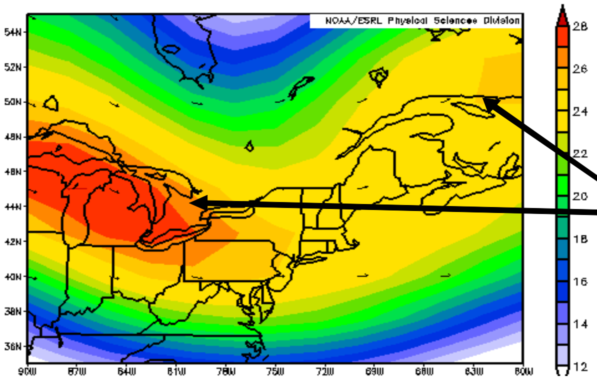


Figure 8. 500 mb mean temperature composite (upper left) and anomaly (lower right) (^{o}C) for all hail days.



250 mb wind composite.

Note the implied jet coupling

250 mb wind anomaly

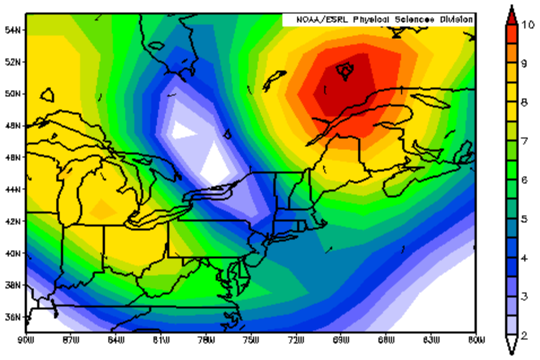
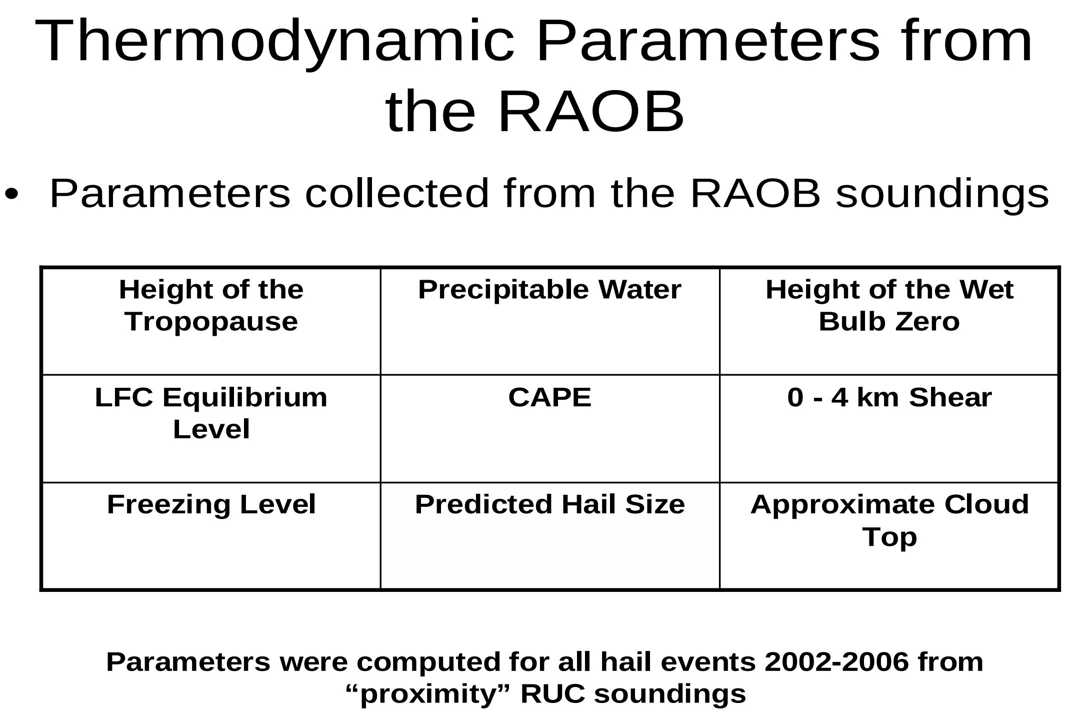


Figure 9. 250 mb mean wind composite and anomaly (ms^{-1}) for all hail days.

Table 1. Parameters collected from RAOB-analyzed soundings.



Thermodynamic Parameters from the RAOB

- Parameters collected from the RAOB soundings

Height of the Tropopause	**Precipitable Water**	**Height of the Wet Bulb Zero**
LFC Equilibrium Level	**CAPE**	**0 - 4 km Shear**
Freezing Level	**Predicted Hail Size**	**Approximate Cloud Top**

Parameters were computed for all hail events 2002-2006 from “proximity” RUC soundings

Table 2. Hail size, SBCAPE and elevated CAPE (computed in BUFKIT) for the six severe hail reports with SBACPE values less than 500 J/kg.

Hail Size	SBCAPE (J/kg)	Elevated CAPE (J/kg)
¾ inch	344	596
¾ inch	344	312
1 inch	109	554
0.88 inches	59	414
¾ inch	20	243
¾ inch	0	101

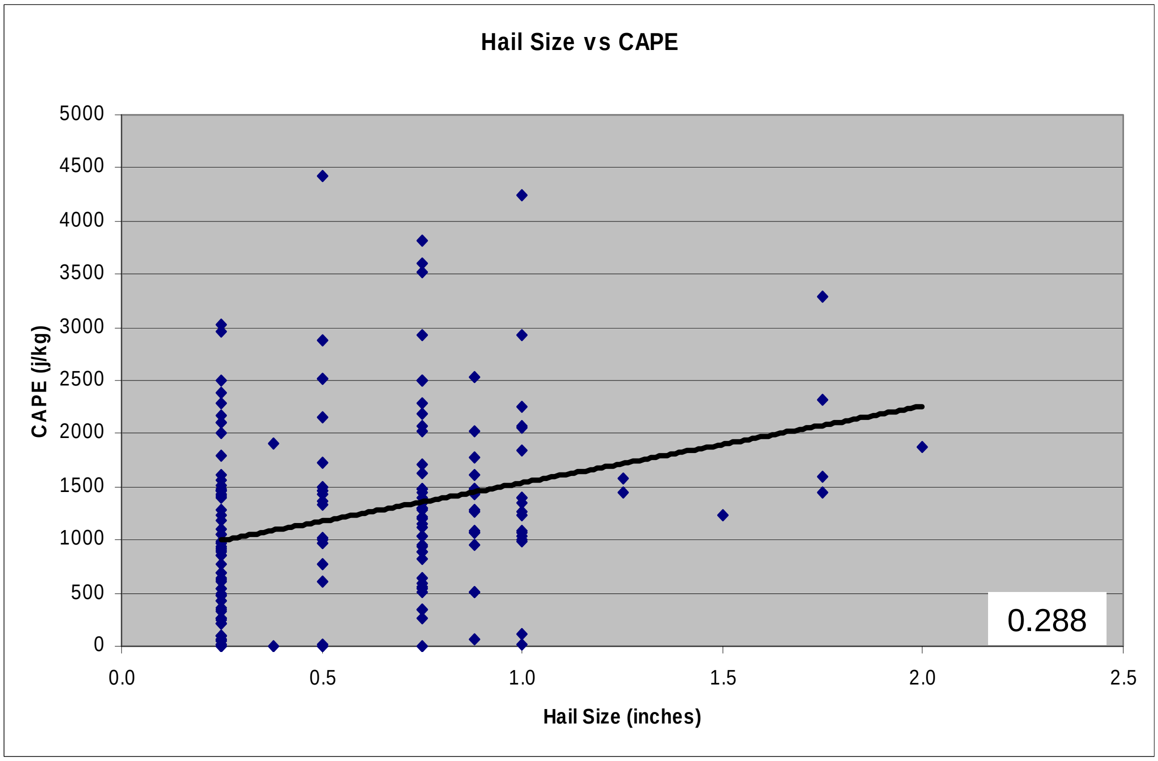


Figure 10. Scatter diagram of CAPE (J/kg) vs. hail size (in).

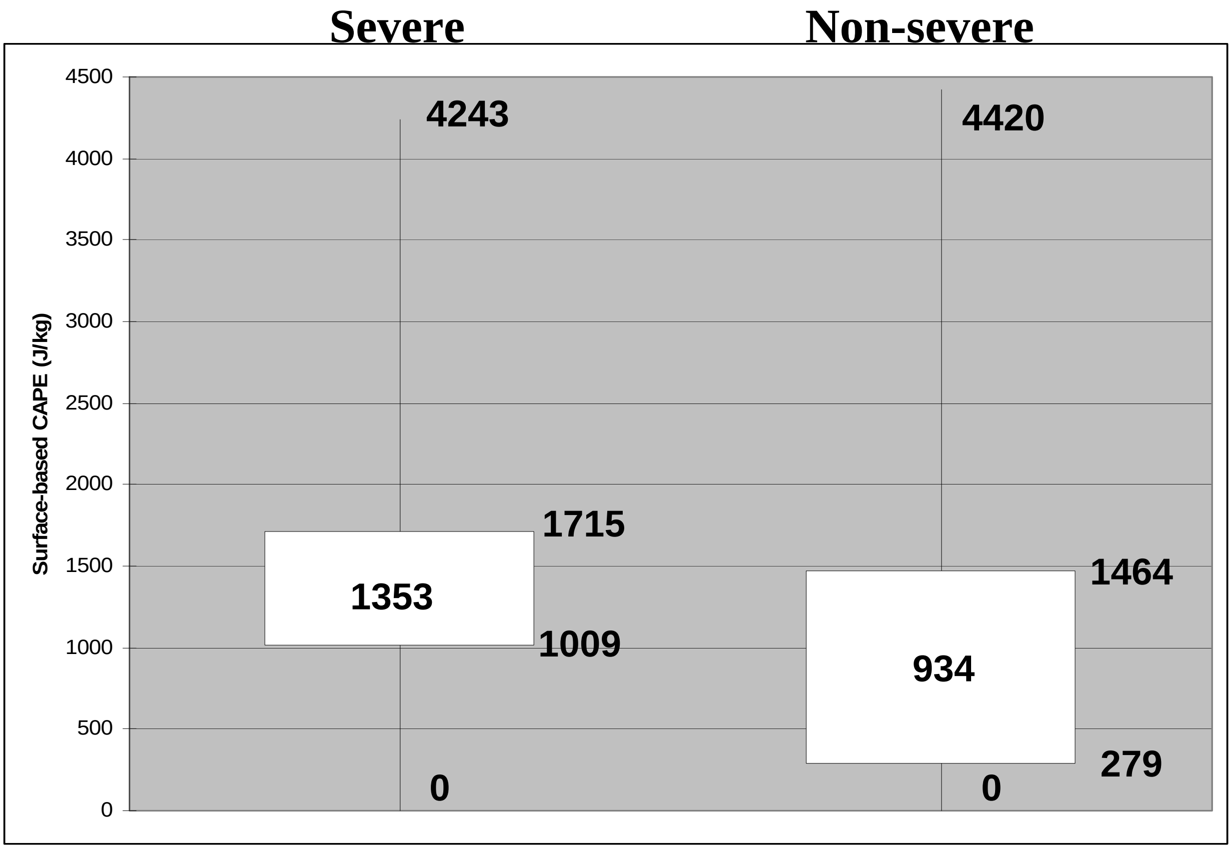


Figure 11. Box and whisker diagram of surface based CAPE (J/kg) for severe and non-severe hail. The median value is plotted in the center of the box. The box is bounded by the first and third quartile values. The maximum and minimum values are plotted at the tails of the whiskers.

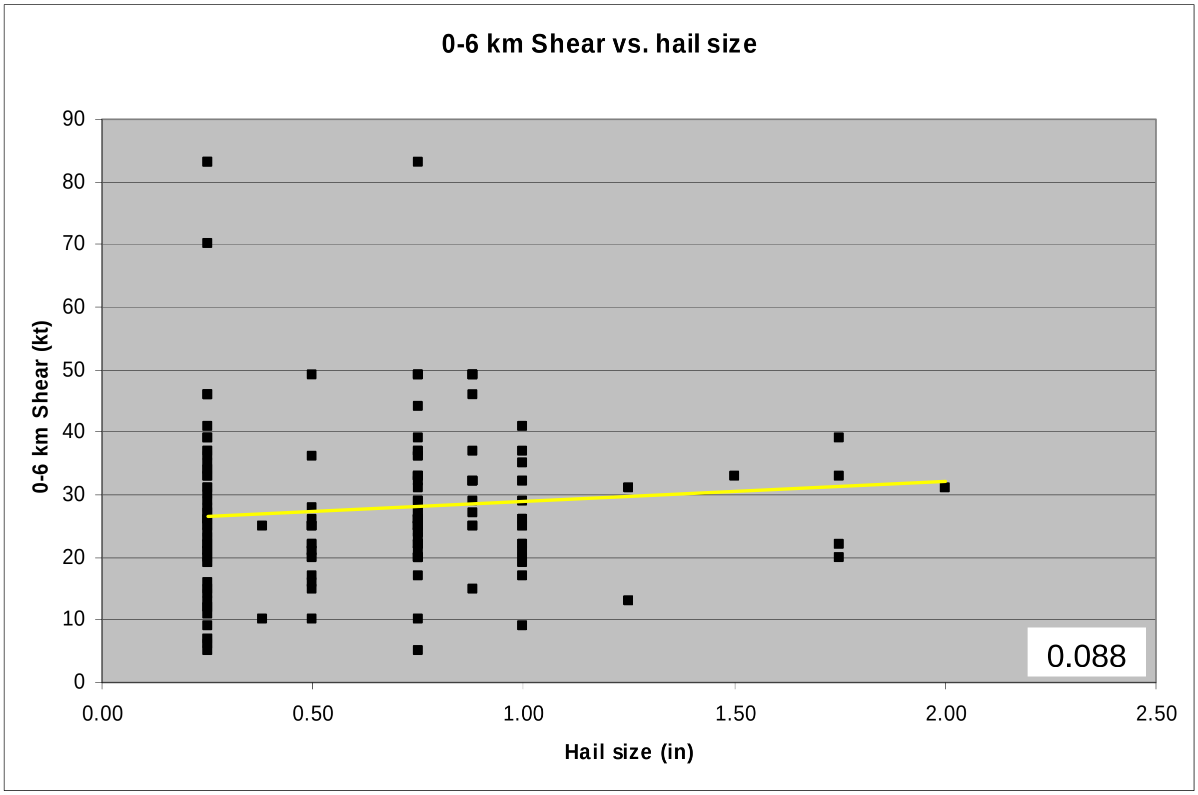


Figure 12. Scatter diagram of 0-6 km shear (kt) vs. hail size (in).

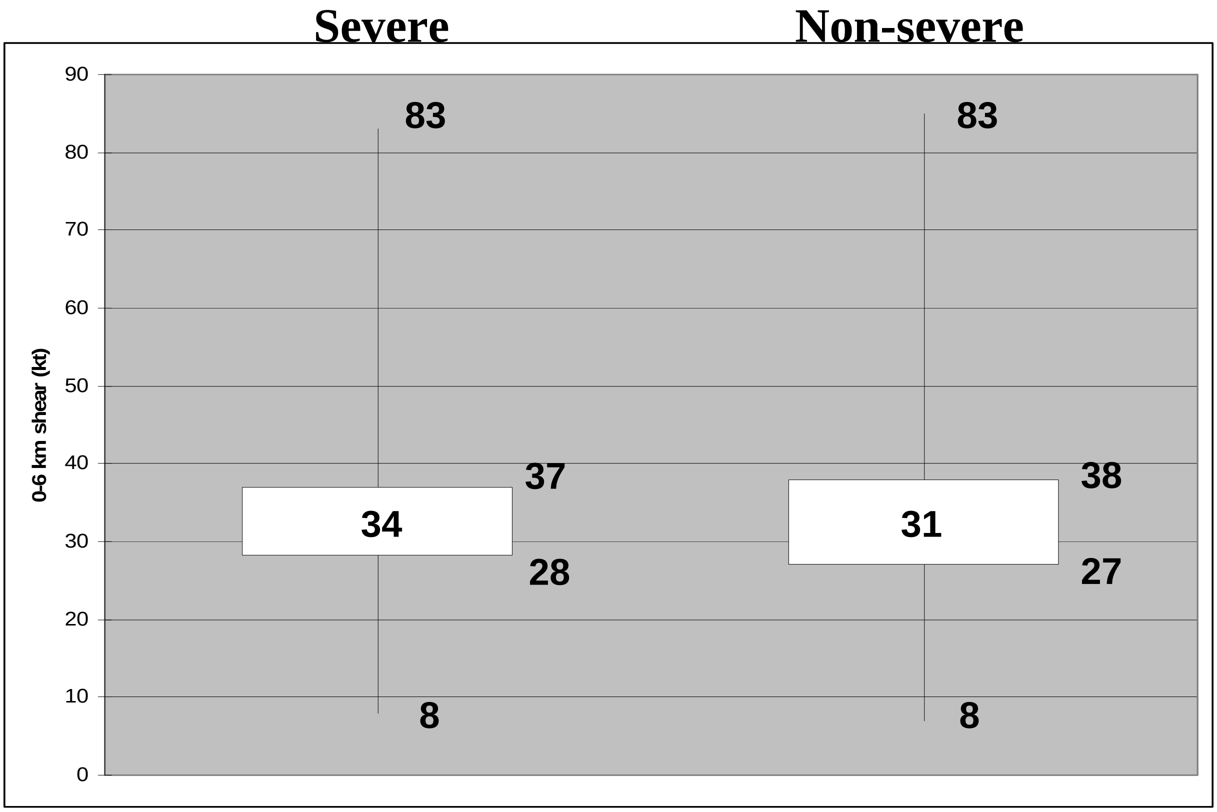


Figure 13. Box and whisker diagram of 0-6 km shear (kt) for severe and non-severe hail reports.

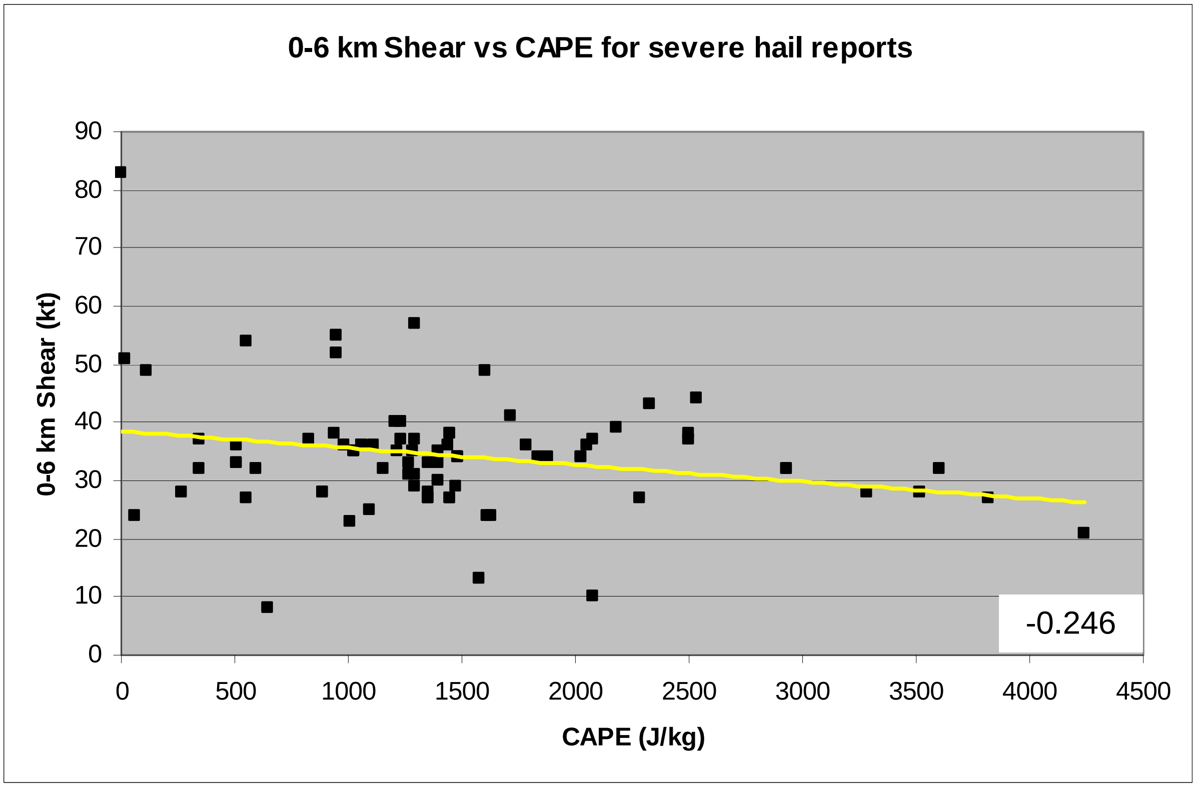


Figure 14. Scatter diagram of 0-6 km shear (kt) vs. CAPE (J kg^{-1}) for severe hail reports.

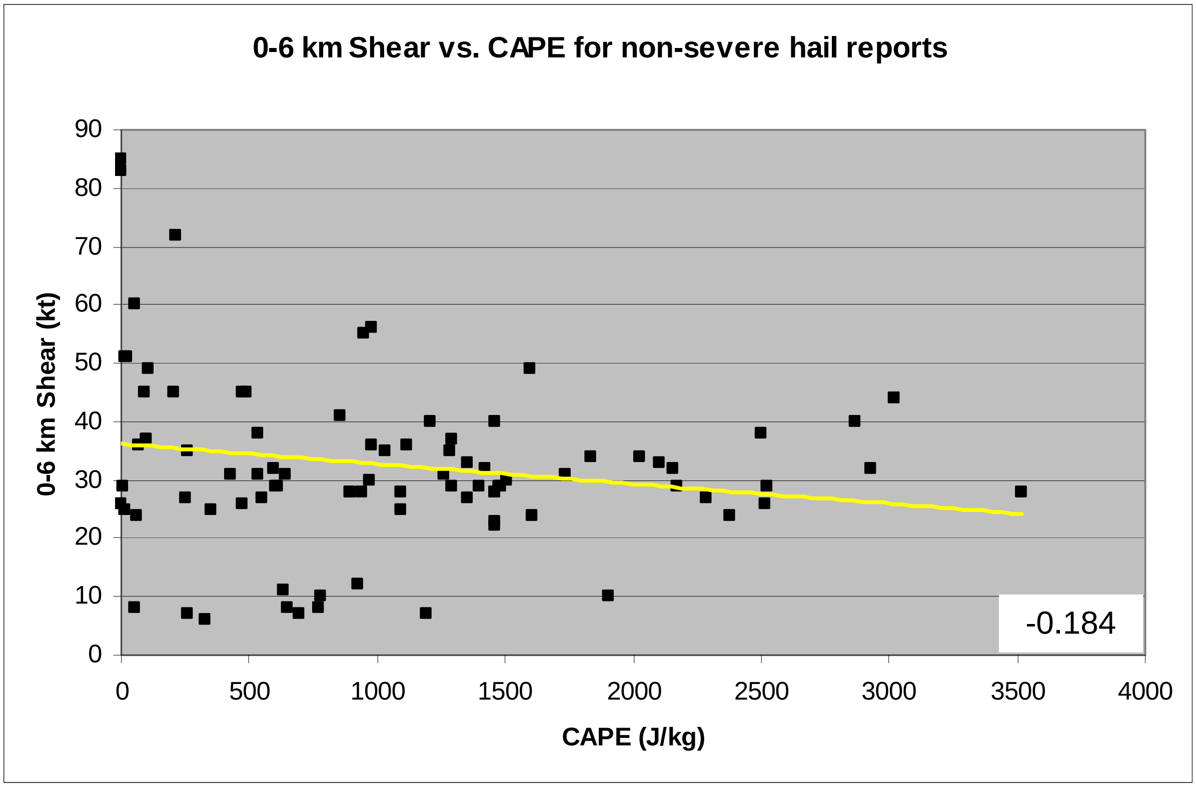


Figure 15. Scatter diagram of 0-6km shear (kt.) vs. CAPE (J kg^{-1}) for non-severe hail reports.

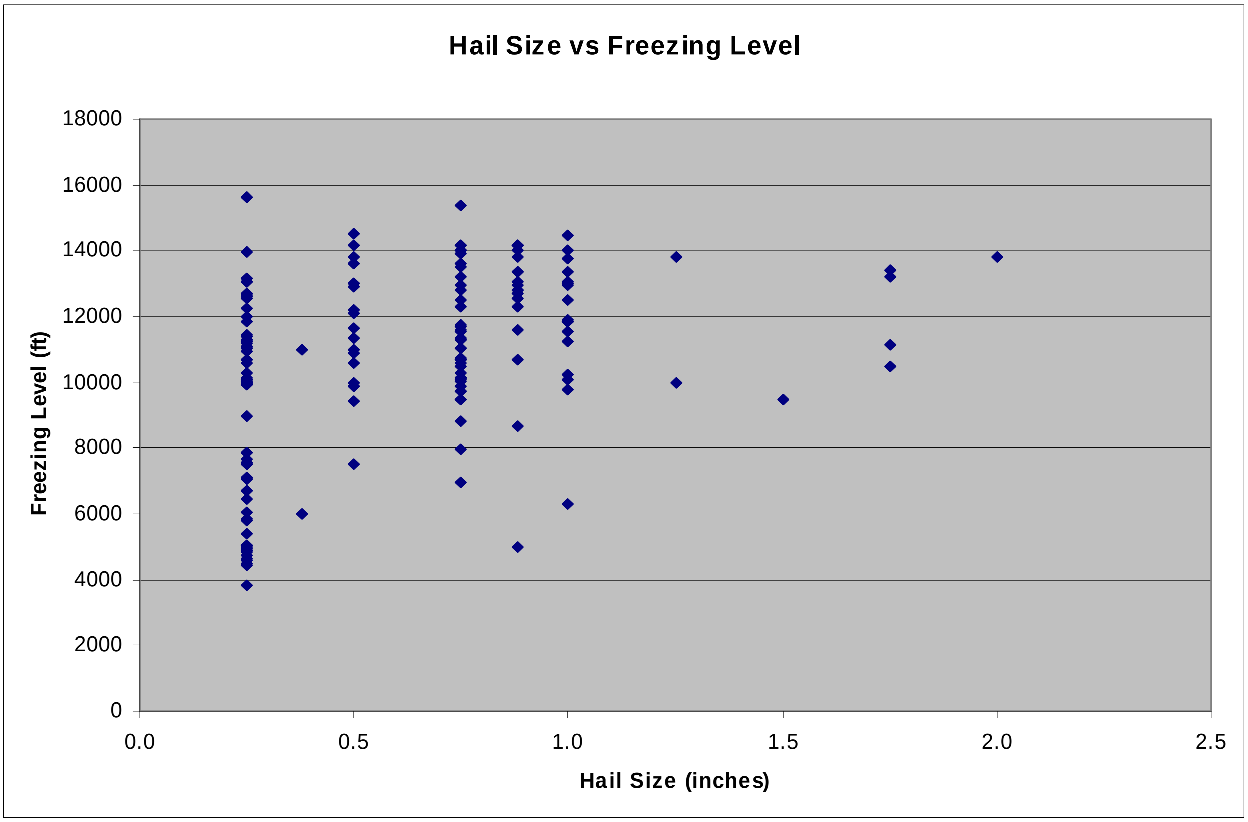


Figure 16. Scatter diagram of hail size (in.) vs. freezing level (ft.). All hail reports greater or equal to one-half dollar size occurred with freezing levels above 9500 feet.

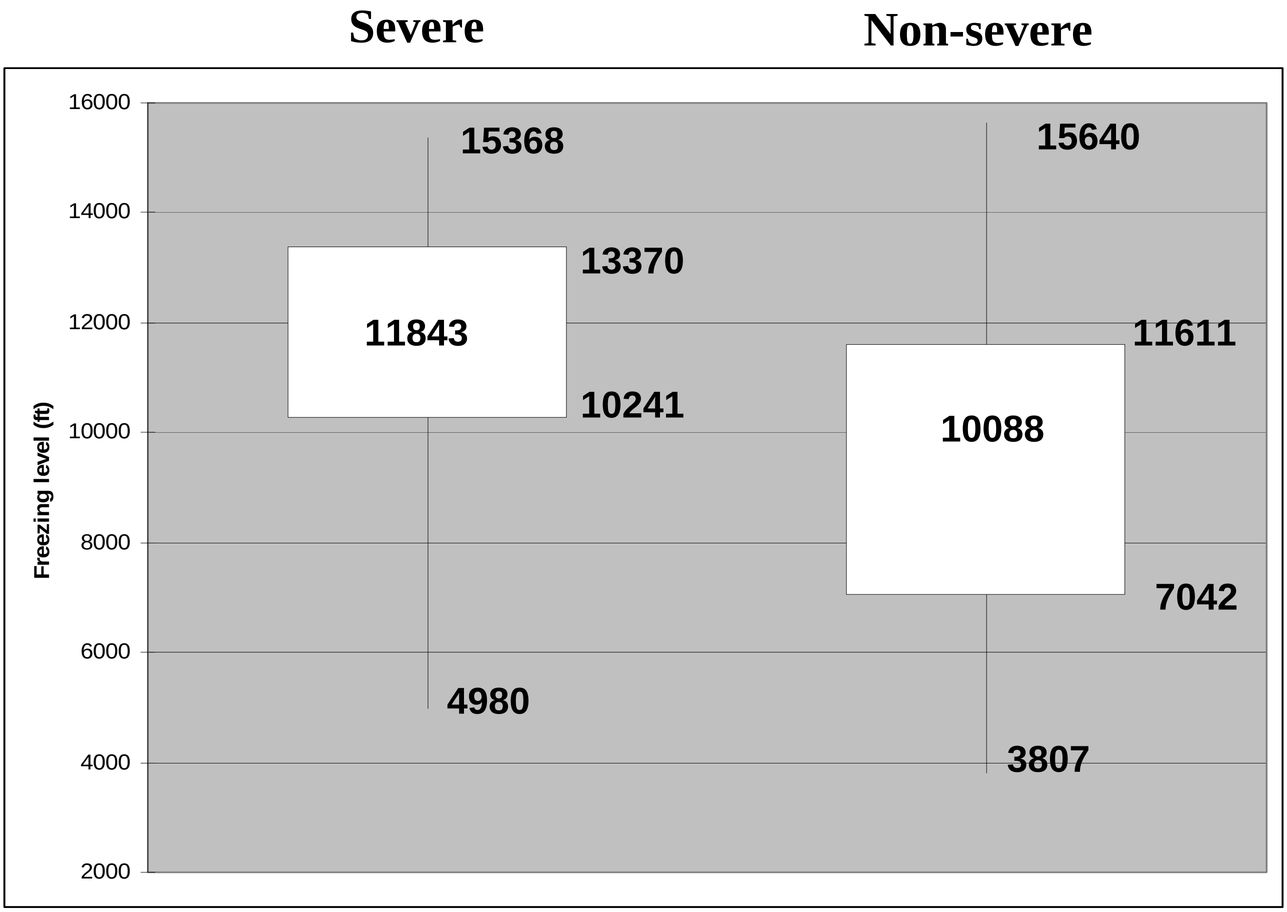


Figure 17. Box and whisker diagram of freezing level (ft.) for severe and non-severe hail reports.

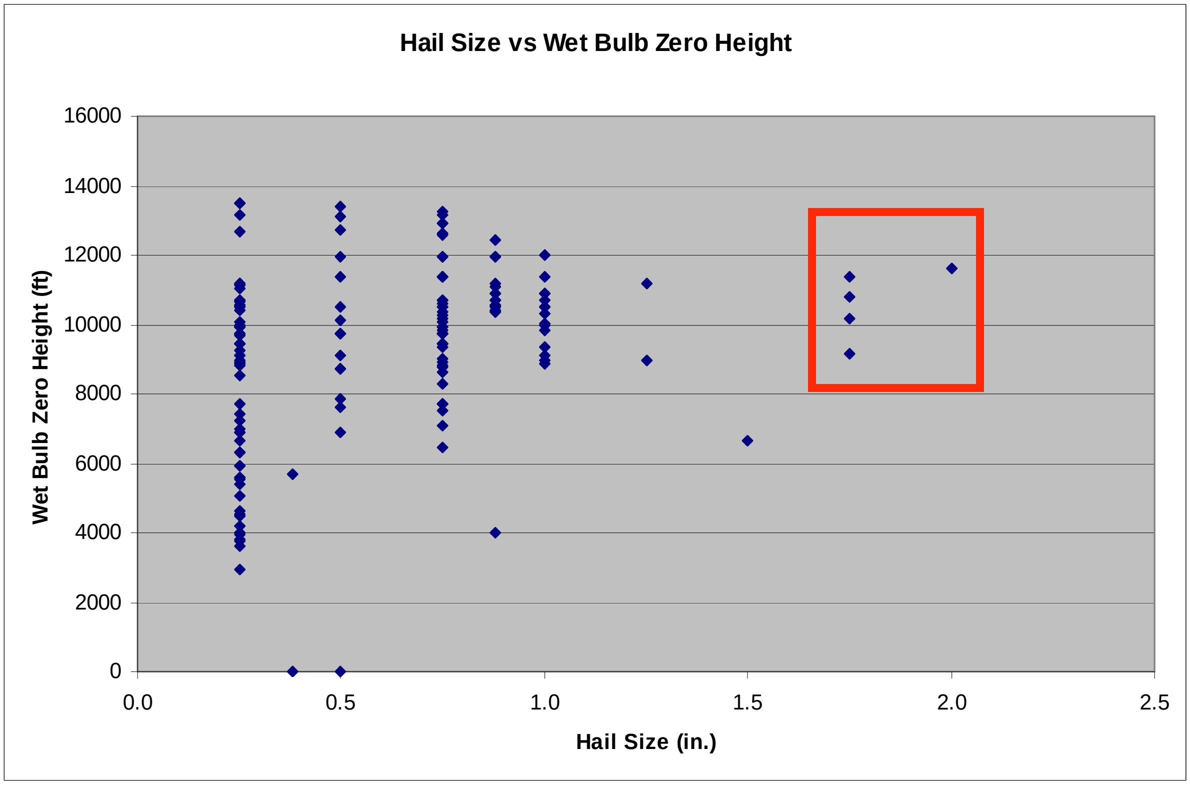


Figure 18. Scatter diagram of wet bulb zero (WBZ) values vs. hail size. All golf ball or larger hail events occurred with WBZ greater than 9000 feet (denoted by the red box).

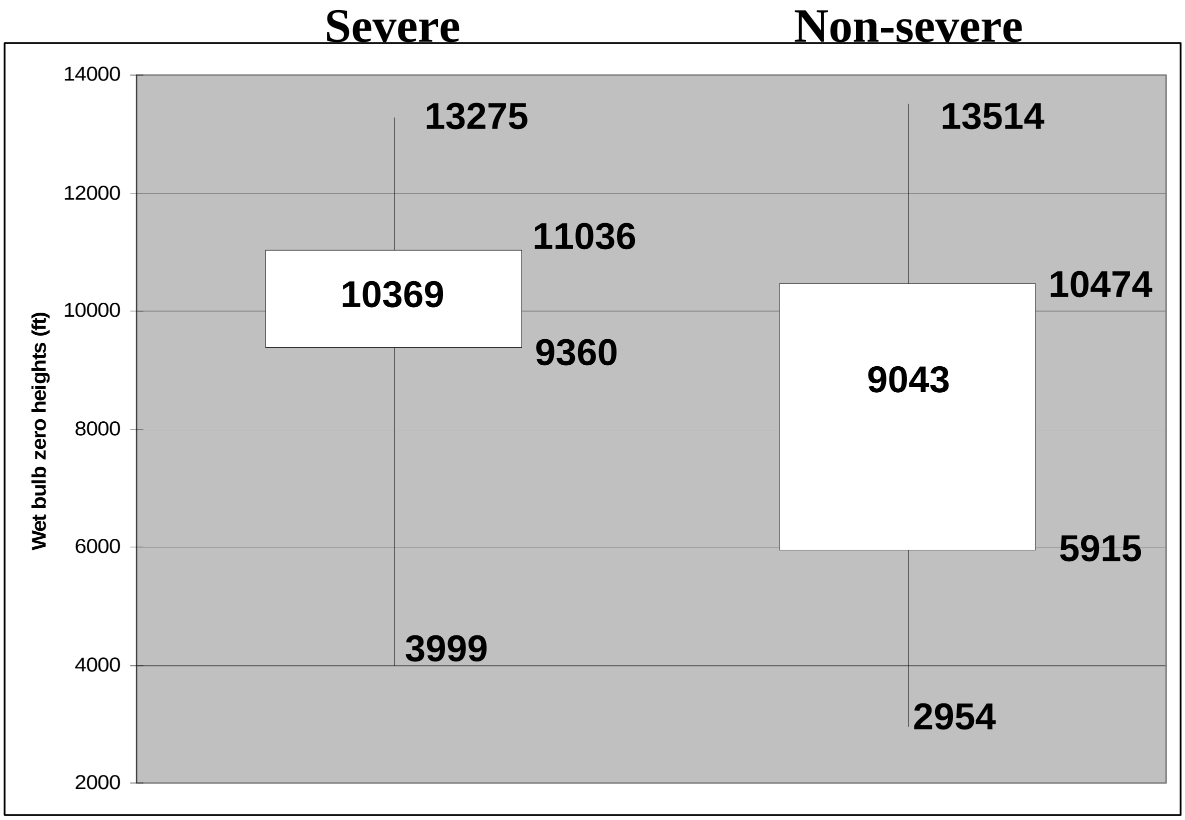


Figure 19. Box and whisker diagram of wet bulb zero heights (ft.) for severe and non-severe hail reports.

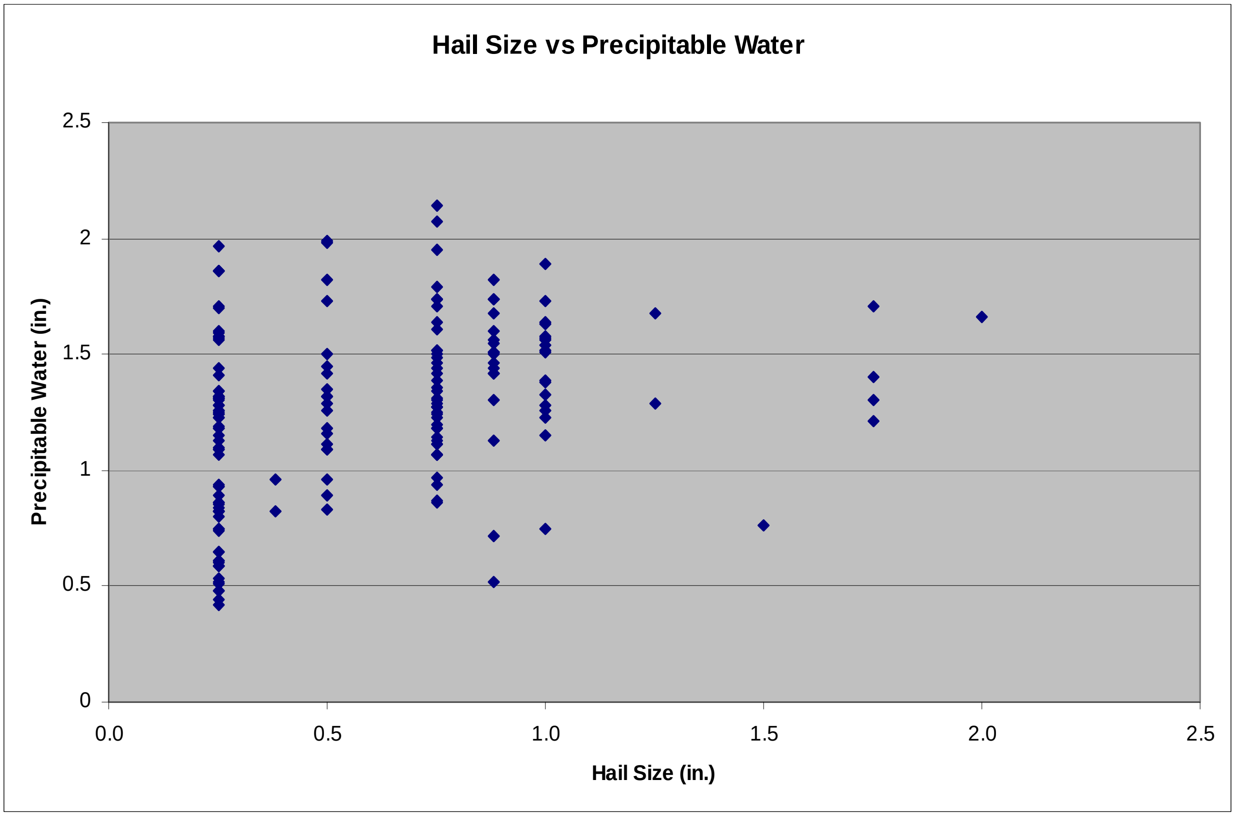


Figure 20. Scatter diagram of precipitable water (in.) vs. hail size (in.).

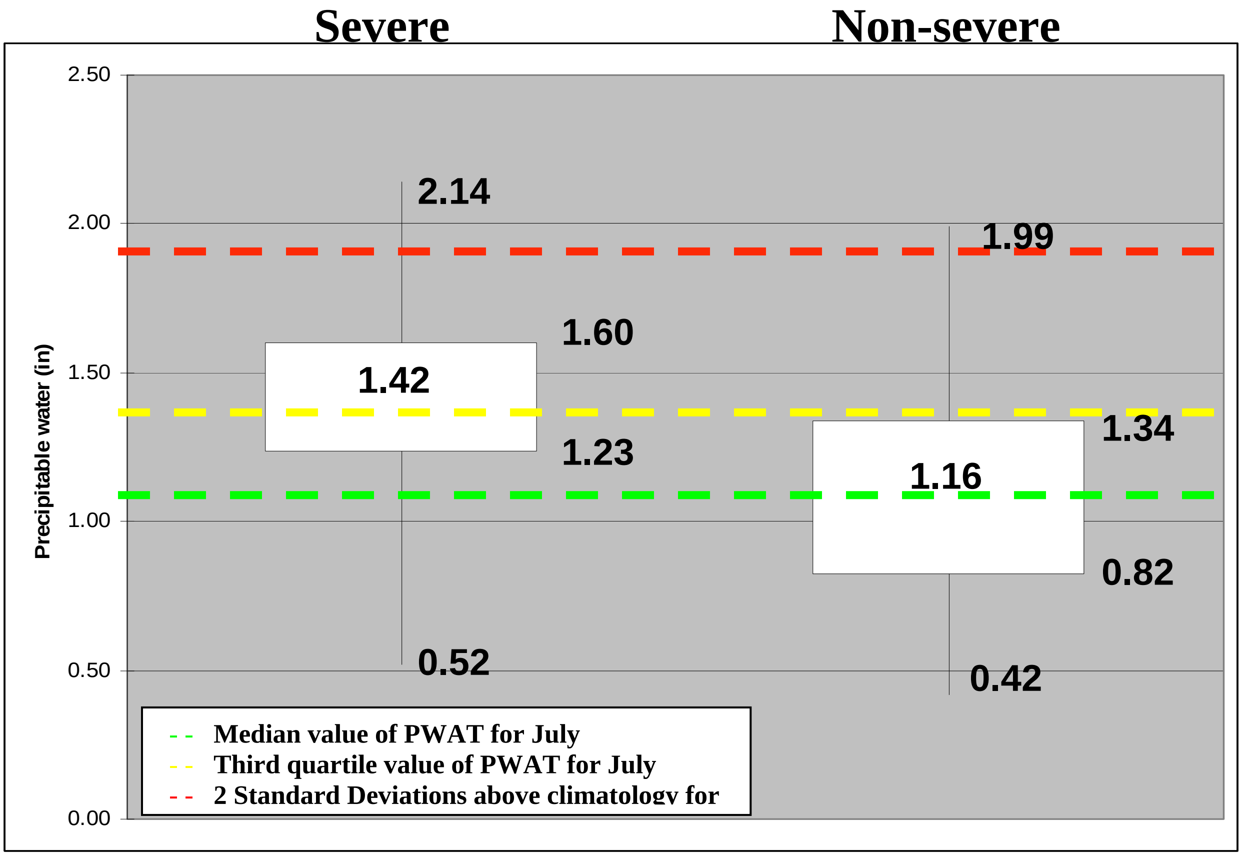


Figure 21. Box and whisker chart of precipitable water (in.) for severe and non-severe hail. Climatological values of precipitable water for July for GYX were added for comparison.

Table 3. Summary of mean thermodynamic parameters obtained from proximity soundings

Parameter	Severe	Non-Severe
SBCAPE (J/kg)	1353	934
Freezing Level (ft)	11843	11030
Wet Bulb Zero (ft)	10369	9043
Precipitable Water (in)	1.42	1.18
0-6 km shear (kt)	27	25