EASTERN REGION TECHNICAL ATTACHMENT
NO. 2002-03
JUNE 2002

DEVELOPMENT OF WARNING CRITERIA FOR SEVERE PULSE THUNDERSTORMS IN THE NORTHEASTERN UNITED STATES USING THE WSR-88D

Carl S. Cerniglia and Warren R. Snyder
NOAA, National Weather Service Forecast Office
Albany, New York

1. Introduction

In recent years, identification and warning skill for significant, well organized severe convective systems have improved steadily in the northeast United States. Derechos, tornadoes, and supercell thunderstorms are relatively easily identified and often warned for with lead times in excess of 30 minutes as a result of improved understanding of these systems and the environments they evolve in. (LaPenta et al. 2000a; LaPenta et al. 2000b; Cannon et al. 1998).

From Storm Data, the majority of unwarned severe thunderstorm events are those that are not organized by a large scale feature, lack large scale dynamics, those that are scattered in areal coverage and appear random. Often within such environments a few storms become severe while most do not.

Lemon (1977) identified a class of storms as "Pulse" severe thunderstorms. These were generally characterized by weak flow and shear environments, slow movement, and the identification of an elevated core of high reflectivity. The storms themselves were characterized as short lived, on the order of 30 minutes to 2 hours, appeared random and not triggered by any organized dynamic feature. They typically produced severe weather (hail with diameter greater than 1.88 cm or wind gusts in excess of 25 ms^{-1}) for only a short period, often less than for 15 minutes.

Typically when the updraft weakened, the suspended area of large raindrops and hail rapidly descended, and accelerated toward the ground. This downward momentum transport produced a surge of winds and brought any significant hail to the surface. Some storms would go through several pulse cycles before producing severe weather.

Given this structure and organization, pulse type storms are often the most challenging storms to issue skillful warnings for. Lemon's technique identified the elevated cores, and with manual real time interrogation by the radars then in use, potential severe pulse storms were identified and warnings were issued. Even so, storms could not always be identified in time to issue a useful warning when numerous storms were on the scope. The automated scan strategy of the WSR-88D has made Lemon's technique for identifying pulse storms unworkable. Then, as is the case now, if one waits for the first report of

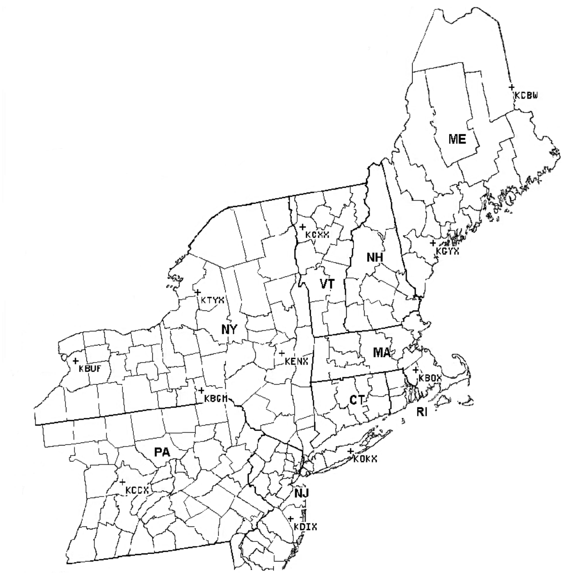

Figure 1. Northeast United States, study area.

severe weather at the ground, it is too late to warn for this class of storms.

2. Data and Criteria

Data from 1995, 1996, 1997 and 1998 were used for this study. The area of study was all of New England, New York, New Jersey, and Pennsylvania, excluding the Pittsburgh NWS office county warning area (Fig. 1). Extreme western Pennsylvania was excluded as the meteorological regimes in this region are often characteristic of the Midwest.

From *Storm Data*, every severe weather report in the defined geographical areas from 1995 through 1998 was examined. Each event was then compared to the National Radar Archive from National Climatic Data Center (NCDC). The data were sorted into storm types to extract severe and non-severe pulse storms. All events that were organized along a line, squall line, front, bow echo, or that were tornadic, were eliminated. Storms that contained a mesocyclone, whether algorithm or user defined, at any point prior to the severe report were also eliminated. Reports were disqualified from further study when there was a report, but no storm could be correlated to it in the radar data. Cases were eliminated when several storms were in the immediate vicinity near the time of the severe weather occurrence, and it was difficult to identify which storm produced the severe weather. Merging storms were also eliminated. Due to known time inconsistencies of logged severe weather reports, some severe weather report times were slightly adjusted to match the radar data.

Initially, 500 storms were identified, and out of those, 89 storms were deemed eligible to be included in this study. These included 64 severe thunderstorms. Twenty-five had severe hail of 1.88 cm or larger and 39 had wind gusts in excess of 25 ms^{-1}. There were 25 non-severe control cases.

The control cases in this data set were storms that were fairly similar in appearance, structure and magnitude to the severe storms in the base reflectively data. The intent behind this selection process was to gather non-severe storms that were as close in strength to the severe storms as possible, and then try to differentiate between the two, while not just adding a large number of weak storms to the data set. Control cases, while not having a severe weather report, had to meet all the criteria of the severe storms. They also needed to have occurred over relatively populated regions to avoid unreported severe storms contaminating the control data set in sparsely populated regions.

3. Methodology

Once all the storm dates were identified, Archive Level II data was obtained from radars throughout the Northeast. The storms were interrogated using the WATADS (Johnson 1998) software package. WATADS allows the operator to rerun the WSR-88D algorithms on historic data producing most of the WSR-88D products, plus several products under development for future WSR-88D builds. For each storm, cross sections were taken and the following parameters were obtained: Maximum Convergence, Maximum Grid Vertically Integrated Liquid (VIL), Cell VIL, VIL peak, Maximum Reflectivity, Maximum Reflectivity Height, Echo Top, Storm Top, Storm Speed and Direction, Storm Volume, VIL Density, Probability of Hail (POH), Probability of Severe Hail (POSH), and the top of the 45, 50, 55, 60 and 65 dBz reflectivity levels.

Each parameter was collected for five volume scans before the time of the severe weather event (T-5), to one volume scan after (T+1). Each WSR-88D volume scan is typically five (six) minutes in Volume Coverage Pattern (VCP) 11 (21). Due to the lack of a time of the event with the control cases (non-severe storms), the storms were carefully examined to determine the point when the downdraft would reach the surface. This time was declared to be T0. This method worked very well as the peaks in the severe and control cases of each parameter matched carefully.

VIL Density was tested in an effort to validate Blaes et al. (1998) and assess its utility as a warning criteria for Pulse Storms. Echo Top, Storm Top, and the top of the 45, 50, 55, 60 and 65 dBz echos were all derived by cutting multiple cross sections through the storms and choosing the maximum values. Maximum Reflectivity was obtained by selecting the highest value from the Composite Reflectivity Product. Maximum Reflectivity Height was derived using a combination of the algorithm output and close examination of cross sections. Storm speed and direction were also derived using a combination of the algorithm output and examination of the base data. The remainder of the parameters were logged as direct radar algorithm output.

As the analysis of the data progressed, several parameters were removed from further consideration in the study. Maximum Convergence was discarded because the algorithm rarely produced the data. Storm Volume was eliminated, as the calculated value tended to fluctuate dramatically depending on how the storm detection algorithm identified a cell. There was no apparent useful trend with this parameter.

Once the data set and parameters for further investigation were finalized, the process of analysis began. Severe and control cases were averaged separately at each time step, from T-5, to T+1. The control and severe events were compared for each parameter, for both the entire data set and for matched data sets of both severe and control events occurring the same event day. Also, the average of the maximum values of each parameter were calculated.

Bar graphs of the analysis data were produced. Trends and patterns became readily apparent. In nearly all cases, the values for the parameters for the severe cases were higher than the controls for each time step. Lead times were calculated for each parameter based on the difference between the time of the peak value obtained of that variable and the time of severe weather occurrence.

Absolute Lead Time (ALT) for this study is the number of volume scans from the time stamp of the product to the occurrence of the severe event. Effective Lead Time (ELT) is the number of volume scans from the time the product is actually made available to the radar operator to the occurrence of the severe event. With all products, the time stamp is the beginning time of the volume scan, even though volume products are not generated until the end of the volume scan. Typically ELT is one volume scan less than ALT for volume products, and is more representative of what a warning forecaster would experience from product arrival till the severe event. ALT for the volume products, ranged from 1.41 to 3.21 volume scans, or 7.1

minutes to 19.3 minutes. At first glance this looks pretty good. However when you adjust to EFT, this shrinks to 0.41 to 2.21 volume scans or 2 to 13.3 minutes.

4. Results

Several parameters demonstrated potential for increased warning lead time.

VIL peak used as a severe weather predictor has limited lead time. VIL peak has an ALT of 1.70 scans and ELT of 0.70 scans. Typically by the time the radar operator identifies a storm is severe by using the VIL peak, the warning will arrive coincident with the severe weather.

The ALT of the reflectivity parameters ranged from 1.0 to 2.07 volume scans. For non-volume products this lead time is representative, particularly in the lower elevation slices. At higher elevations, lead time begins to lag by the amount of time from the VCP start to the time the radar has reached the elevation in question.

To get the most benefit out of this lead time, it would be necessary to examine each elevation slice as it arrived. If you wait to look at a Layer Reflectivity Maximum product or cut a cross section, a good part of that lead time will be lost.

Finally, POD, FAR, and CSI were calculated for some of the parameters to determine the best possible points for which a warning/no warning decision can be based. The rest of this section will look at each parameter and its supporting data.

a. Grid VIL

Severe storms had significantly higher Grid VIL values on average, through the entire time series when compared to the control cases. On average, the severe storms had Grid VIL values around twice as high as the controls.

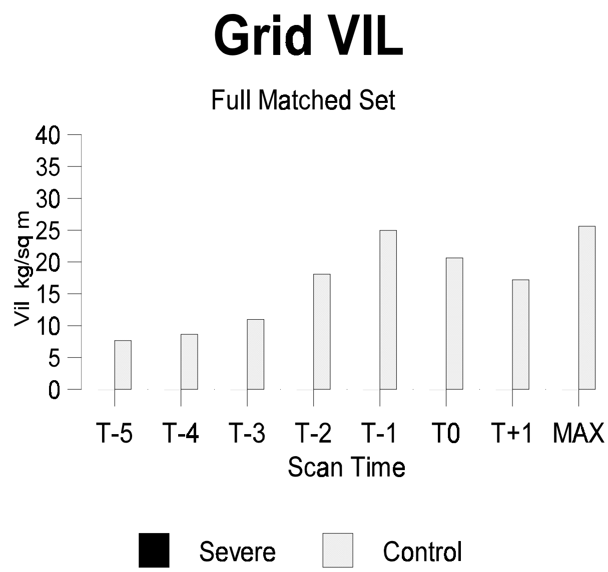

Figure 2. Grid VIL. Severe and control cases matched by date for T-5 volume scans to T+1 volume scans and max value.

When severe and control cases were matched for the same event day (Fig. 2), differences in the Grid VIL magnitudes were similar across the time series. The largest differences occurred at T-5, T-4, and T-3, where the Grid VIL for severe storms was two times higher than for the control cases. Grid VIL values for severe storms ranged from 19 k/gm^2 to 61 kg m^{-2} with an average maximum Grid VIL of 40.25 kg m^{-2}. The control case values ranged from 18 to 34 kg m^{-2} with an average maximum Grid VIL of 25.60 kg m^{-2}.

Grid VILs at or above (aoa) 25 kg m^{-2}, identified 61 of the 64 severe cases or 95%, but also 13 of 25 control cases or 52%. A threshold of 30 kg m^{-2} or above, identified 57 of 64 severe cases or 89%, while only 8 of 25 of the control cases, or 32% were identified. At the Grid VIL of 35 kg m^{-2} or greater threshold, 46 of 64, or 72% of the severe cases were identified, while there were no control cases identified.

Grid VIL is very airmass dependent and

therefore does not lend itself well to this type of direct comparison over different storm days. However, comparisons of severe and control cases on the same event day do show that VIL values for severe storms are higher than the controls, with very few instances of overlap.

The ALT of the peak Grid VIL value was 1.70 volume scans and ELT of 0.70 volume scans.

The most significant factor in this data, is that the severe pulse storms have Grid VIL values two to almost three times the control cases, in both matched and averaged modes, thus a potential warning threshold value for Grid VIL appears to be with VIL values in the 30 to 35 kg m^{-2} range.

b. Cell VIL

Cell VIL is calculated slightly differently, following the maximum value of reflectivity through a radar identified cell; whereas Grid VIL is calculated at a specific geographic point.
The Cell VIL generally mirrored the Grid VIL results with a few differences. The Cell VIL values were generally lower than the Grid VIL. Again, the largest differences between the severe and control cases occurred in the three scans prior to the event.

Cell VILs for the severe storms ranged from 14 to 56 kg m^{-2}, and for the controls from 8 to 34 kg m^{-2}. For comparison, VILs $\geq$ 25 kg m^{-2} identified 85% of the severe storms, but also identified 25% of the control cases. Cell VILs $\geq$ 30 kg m^{-2} identified 76% of the severe cases and only 8% of the controls.

The ALT for the Cell VIL peak was a little less than the Grid Vil at 1.56 volume scans and an ELT of 0.56 volume scans. However, VIL is generally not used in this manner, but rather warnings are routinely based on when the VIL reached a certain threshold (i.e. the VIL of the day).

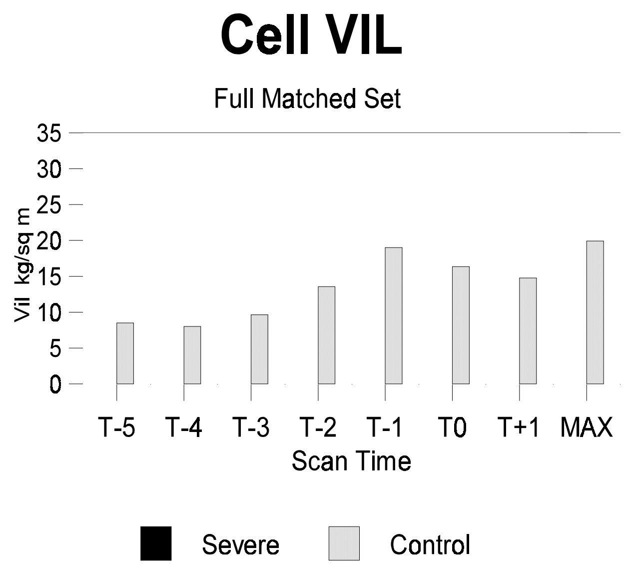

Figure 3. Cell VIL - Control and severe events matched by date for T-5 volume scans to T+1, and maximum value.

In the matched data sets (Fig. 3) the Cell VIL of the severe events was often two to three times that of the control cases, thus a potential warning threshold for Cell VIL appears to be at values in the 25 to 30 kg m^{-2} range.

c. Maximum Reflectivity

The Maximum Reflectivity parameter peak value had an ALT of 1.33 volume scans. The maximum reflectivity is generally reached at the point when the updraft is decaying into a downdraft, with this point being the maximum loading of the storm. This is also around the same time that VIL is maximized. Maximum Reflectivity values earlier in the life cycle of the storm are several dBz greater in the severe storms than the control cases, typically on the order of 6-7 dBz. This difference narrows to 2-3 dBz by T-2 through T+1.

The number of controls began to quickly drop off with increasing reflectivity. Only 20% (12%) of the control cases reached exceeded 60 (61) dBz, while 69% (50%) of the severe cases reached 60 (61) dBz. The data are shown in Table 1.

In the overall averages, and in a particular case where a storm was well sampled by two radars, there appears to be a slight range dependency (Table 2). This may be due to beam resolution characteristics. The effect was subtle in the averages and more dramatic in the dual radar sampled storm with a difference of 5 dBz. However, this trend was not observed in the height of certain dBz thresholds which will be discussed later.

Table 1. Maximum Reflectivity at or above various dBz levels for Severe and Control Cases

≥ Max dBz	Severe	Control
55 dBz	98%	88%
56 dBz	98%	90%
57 dBz	97%	60%
58 dBz	92%	36%
59 dBz	78%	32%
60 dBz	69%	20%
61 dBz	50%	12%
62 dBz	39%	0%

Table 2. - Maximum reflectivity for storms with values ≥ 60 dBz at different ranges from the radars.

	Severe	Control
Dataset	69%	20%
<75 nm	75%	20%
<60 nm	72%	33%

d. Maximum Reflectivity Height (MRH)

The data for MRH shows there is not much difference in MRH between the severe and control cases, at least when all of the storms are averaged together. Even the average of the maximum values does not indicate a difference when as low as 2000 ft. This parameter was highly variable through the life cycle of the storms. It generally fluctuated from the mid-levels to the base of the storm several times, before settling near the base from scans T-1 through T+1.

There was a tendency for the severe storms to have a more substantial drop in the MRH from T-2 through T0 than the controls, even in the averages. From T-2 to T0, the severe storms had an average drop of around 4000 ft., and the controls dropped nearly 2500 ft. From T-1 to T0 the severe storms dropped 2950 ft., and the controls dropped around 1700 ft.

When the data was viewed with a MRH of 18,000 ft. or greater the Probability of Detection (POD) was 0.547 and False Alarm Rate (FAR) was 0.103 for this data set. Values at or above this height identified just over half of the severe events while falsely warning on 16% of the control storms. The numbers are better when the MRH was broken down to only include storms with a height aoa 18 thousand feet and reflectivity near 50 dBz, and then near 55 dBz. Near 18 thousand feet and 50/(55) dBz the POD was 0.52 (.44) and FAR 0.03 (0), and CSI 0.51 and (.44). However, overall, there are better warning tools than MRH based on the CSI's obtained.

One area that shows promise would be to combine the Maximum Reflectivity and MRH terms into a single value. Later sections use a paired value approach successfully as a warning criteria with these two parameters. This principle was central to Lemon (1978).

e. Echo Top

Severe storms were found to have higher average tops than the control cases. The severe storms had Echo Tops on average 5,000 to 7,000 ft above the non severe ones. The greatest difference occurred at T-2. This trend showed up in both matched and average data-sets.

This result would be expected with severe storms having stronger updrafts. Severe tops ranged from 23,000 to 49,500 ft., while controls ranged from 23,000 to 38,500 ft. As with other parameters, there was some overlap in the ranges, and this was again due to differences in the airmass in which the storms developed. Even though there was overlap, there was a point in the data that appears to be a useful break-point, 35,000 ft.(Table 3) Only two, or 8% of the control cases reached or exceeded this level, while 67 % of the severe cases reached or exceeded it.

Table 3. Echo Top at or above various heights in feet for severe and control Cases.

Near kFT	Severe	Control
25	98%	96%
30	92%	64%
32.5	80%	28%
35	67%	8%
40	34%	0%

f. Storm Top

The storm top data basically mirrored the echo top data other than having lower overall heights. This would be expected due to the different criteria used to define an echo top (18 dBz), and storm top (30 dBz). For severe thunderstorms, storm tops ranged from 20,000 ft. to 44,500 ft. The storm tops for the control cases ranged from 20,500 to 33,500 ft. A threshold of 30,000 feet appeared to be useful. This level was met or exceeded by 69% of the severe storms, and only 12% of the control cases.(Table 4)

Table 4. Storm Top at or above various heights in feet for severe and control Cases

Near kFT	Severe	Control
20	100%	100%
22.5	98%	92%
25	97%	68%
27.5	84%	44%
30	69%	12%

g. 45 dBz Echo Top

This is the first of five different reflectivity thresholds that were examined for usable signals as warning thresholds. For each storm, the height of the top of this reflectivity value was recorded. The values were again higher on average for the severe storms than the controls through the life cycle of the storms and maximized around T-3. The severe storms ranged from 18,000 to 40,500 ft while the controls ranged from 18,000 to 25,500 ft. The optimum CSI for this parameter occurred at 23,000 feet with a CSI of 0.816, POD was 0.906, and FAR 0.108. For this value the ALT was 1.69 volume scans or 8 to 10 minutes.

h. 50 dBz Echo Top

This level had the same basic signal as the 50dBz echo top. However, as would be expected the values were at slightly lower altitudes. The range for severe storms was 15,500 to 38,500 ft. while the controls were from 15,500 to 23,500 ft. All storms in this study having 50 dBz reach or exceed 24,000 feet were severe. Optimum

CSI for this parameter was 0.765 at or above 20 thousand feet. At this point POD was 0.921, and FAR 0.181. The full range is shown in Table 5. The ALT was 1.66 or 8-10 minutes.

Table 5. POD, FAR, CSI for 50 dBZ Echo Top at or above various thresholds in kFT.

Height (kft) at or above	POD	FAR	CSI
24	0.594	0	0.594
23	0.703	0.043	0.681
22	0.734	0.078	0.691
21	0.828	0.117	0.746
20	0.921	0.181	0.765
19	0.953	0.208	0.762
18	0.969	0.235	0.747

i. 55 dBz Echo Top

This level had the same basic signal as the previous two echo top parameters, although it appeared to be more definitive. The range for severe storms was 12,500 to 36,500 ft., and the controls, from 6,000 to 20,000 ft. Three of the control cases never reached 55 dBz. Of the remaining control cases that did reach 55 dBz, none of them extended above 20,000 ft.

Optimal CSI for this parameter occurred for values at or above 18 thousand feet with a CSI of 0.789, POD 0.875, and FAR 0.111. The full range is shown in Table 6. The ALT for reaching the maximum value in this parameter is 1.75 volume scans or 9 to 11 minutes. Comparisons from the full dataset to points within 75 nm and 60 nm, showed no range variation.

Table 6. POD, FAR, CSI for 55 dBZ Echo Top at or above various thresholds in kFT.

Height (kft) at or above	POD	FAR	CSI
21	0.625	0	0.625
20	0.734	0.021	0.723
19	0.813	0.088	0.754
18	0.875	0.111	0.789
17	0.906	0.147	0.783
16	0.938	0.189	0.769
15	0.953	.208	0.762

j. 60 dBz Echo Top

Major changes took place by this level. This data points to the fact that if a pulse storm is capable of producing reflectivities over 60 dBz, it is highly probable the storm will produce severe weather. Few (5 out of 25) of the controls had reflectivity levels near 60 dBz at any point in the storms life cycle, while 64% of the severe cases reached 60 dBz. The highest reflectivity value attained by a control storm was 61.5 dBz.

Working through the POD and FAR numbers for various altitudes were not very revealing due to the limited number of cases (Table 7). Thus for 60 dBz top, occurrence is a sufficient threshold.

Table 7. POD, FAR, CSI for 60 dBZ Echo Top at or above various thresholds in kFT.

Height (kft) at or above	POD	FAR	CSI
18	0.281	0	0.281
17	0.391	0.038	0.385
16	0.422	0.069	0.409
15	0.500	0.059	0.485
14	0.531	0.055	0.515
13	0.578	0.075	0.552
12	0.609	0.093	0.573

k. 65 dBz Echo Top

Only eight storms had reflectivity of near 65 dBz, and all were severe, with a lead time of 1.0 volume scan. For storms in this study, the occurrence of 65 dBz or greater reflectivities in a pulse non-rotating storm, is a sufficient threshold.

l. Center of Mass

With 2.66 volume scans of potential lead time, this parameter originally seemed promising. Also, when working with the data, there appeared to be a relationship emerging where the higher center of mass heights could become a good severe weather indicator. This is consistent with conventional thinking; a stronger updraft should hold a core at a higher altitude when compared to a weaker updraft in a non-severe storm. A problem was discovered upon further examination of the data. This is a very range dependent parameter. This is the result of the radar beam becoming more elevated with increasing distance from the radar, artificially elevating the center of mass height with range. An example follows, for center of mass heights above 15,000 ft. for the full data set, 53% of the severe and 16% of the controls exceeded this level. However, limiting the range to storms within 60 nm results in only 28% of the severe storms and 13% of the control storms Center of Mass exceeding 15,000 ft. This is true regardless of the altitude selected.

Stratifying the Center of Mass results by several range rings may very well result in a useful set of values for differentiating between severe and non-severe pulse storms. However this process would be fairly cumbersome as a tool in the warning decision process process.

m. Probability of Hail

Probability of Hail did a credible job of identifiying the severe thunderstorms, for both large hail and wind damage. The average lead time for the peak of the POH was 2.42 volume scans, and ELT was 1.42 volume scans (about 7-8 mins), and about 1/3 of the time this was at a 100% probability of hail. Severe cases in matched data sets exceed controls by 40 to 50% (Fig. 4).

None of the control cases exceeded an 80% probability of hail. There was overlap, with the severe storms ranging from 0 to 100% and the controls from 0 to 80%. Only 5 of 61 severe storms where this parameter was produced, had values below 50%. POH values near 70%, correctly identified 85% of the severe storms while only mis-identifying 20% of the control cases. For probability of hail values near 80%, severe storms were correctly identified 70% of the time and controls 12% of the time.

There appears to be a slight relationship between the probability of hail and increasing range from the radar (Table 8), but not to the extent of the center of mass example. Storms further from the radar tended to have higher values of probability of hail, more so near the

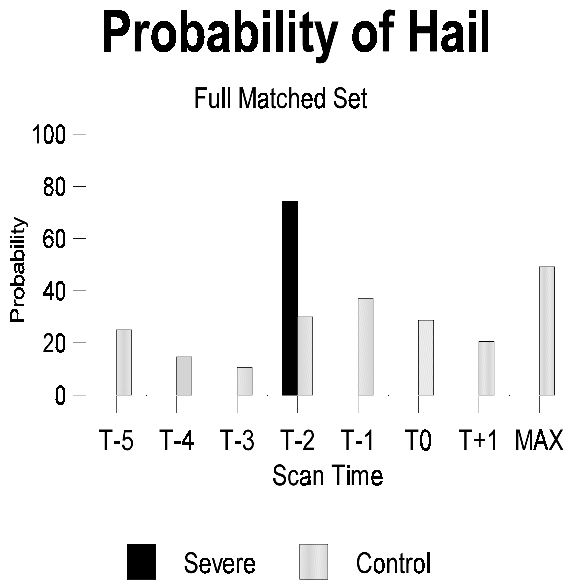

Figure 4. Probability of Hail from five volume scans prior to time of severe event or peak of storm to one volume scan after.

80% probability than near the 70%. This is probably an artifact of the increasing height of the radar beam with increasing range, as well as decreasing beam resolution with range.

Table 8. Probability of Hail at or above 70% and 80% within 75 nm and 60 nm of radar.

POH near 70%	Severe	Controls
Full Set	85%	20%
<75 nm	85%	25%
<60 nm	80%	20%
POH near 80%	Severe	Controls
Full Set	70%	12%
<75 nm	67%	15%
<60 nm	56%	7%

n. Probability of Severe Hail

Probability of Severe Hail (POSH) like POH did well in identifying pulse severe storms for both

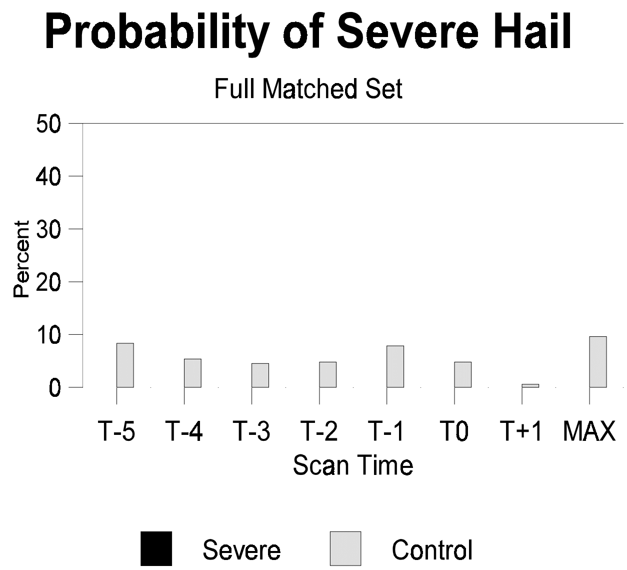

Figure 5. Probability of Severe Hail (POSH) from five volume scans prior to time of severe event or peak of storm to one volume scan after.

wind and hail events. There was a respectable amount of lead time with an ALT of 2.13 volume scans or 1.13 volume scans ELT from the point of the peak of POSH. Only (Fig. 5) two of the 25 control cases exceeded 20% probability of severe hail.

Of those that did not, only one was at 20%. The other 22 cases were either zero or 10%. Using near 20% as a break, 70% of the severe cases and 12% of the controls reached or exceeded this value.

As with the probability of hail, there was a range dependency with this parameter, although it was minimal(Table 9).

Table 9. Probability of Severe Hail near 20%

	Severe	Controls
Full Data	70%	8%
<75 nm	64%	5%
<60 nm	60%	13%

o. VIL Density

VIL Density was calculated to see if VIL Density was applicable with Pulse thunderstorms, and to provide additional validation to Blaes et al (1998) and Amburn & Wolf (1997) for this parameters utility in the Northeast United States. After reviewing the data, this study validated the previous work with very favorable data for both wind and hail severe criteria.

VIL Density is defined as the quotient of VIL (kg m^{-2}) divided by the Echo top (m) and then multiplied by 1000 to yield units of gm^{-3}. In the previous studies, the echo top was determined by choosing the value off the Echo Top product produced by the WSR-88D algorithms. The echo top for this study had to be manually determined using WATADS while viewing the reflectivity cross-sections. Although this might make a subtle difference, the numbers in this study, very closely reflected the results arrived at in Blais et al. (1998) and Auburn and Wolf (1997).

At first glance, the lead time for this parameter does not look impressive at 1.77 volume scans. This lead time was determined by calculating the lead time from the peak of the VIL Density in the storm's life cycle. If the lead time is based on reaching or exceeding a VIL Density of 3.28 gm^{-3}, the critical value determined in previous studies, then the ALT jumps to 2.88 volume scans. Again, these are based on volume products, which means one additional volume scan by the time the data is available, so the ELT is 1.88 volume scans. This still provides 9 to 11 minutes lead time. When applied to hail cases only, stratified for distance from the radar, the ELT actually increased from 2.64 for all hail cases, to 2.79 for cases within 75 nm and 3.22 for cases within 60 nm. This trend did not show up in the wind cases.

Since this parameter was originally used for the detection of hail, numbers were calculated separately for severe hail, severe wind, and combined wind and hail, the numbers were compared with the control cases.

Out of the 64 severe storms, 25 produced hail equal to or exceeding severe criteria. These storms had an average peak VIL Density of 4.23 g m^{-3} and ranged from 3.38 g m^{-3} to 5.53 g m^{-3}. Therefore, using the 3.28 g m^{-3} (Table 10) threshold, all of the hail cases exceeded this value for a POD of 100%, and as will be shown in more detail, only 12% of the control cases reached or exceeded this value.

The wind cases accounted for 39 of the severe storms and overall had lower VIL Density values than hail events. The average peak VIL Density for these storms was 3.38 gm^{-3}, and ranged from 2.19 gm^{-3} to 4.76 gm^{-3}.

Table 10. POD, FAR, CSI for VIL Density for Hail Cases for above various thresholds in g m^{-3}

VIL Density (*g m^{-3}*) at or above	**POD**	**FAR**	**CSI**
3.75	0.800	0	0.800
3.50	0.920	0.080	0.852
3.28	0.422	0.107	0.893
3.25	1.00	0.107	0.893
3.00	1.00	0.286	0.714
2.75	1.00	0.375	0.625
2.50	1.00	0.432	0.568

The 3.28 gm^{-3} threshold was met or exceeded in 59% (Table 11) of the wind cases with an ALT of 3.13 and ELT of 2.13 volume scans.

For the 25 control cases, overall VIL Density values were even lower than the wind events. The average peak VIL Density for these storms was 2.85 gm^{-3}, and ranged from 2.02 gm^{-3} to 3.71 gm^{-3}

Only 3 of the cases (12%) were greater than 3.28 gm^{-3}, with 10 cases (40%) near 3.00 gm^{-3}.

VIL Density was originally devised as a way to predict hail size potential for thunderstorms. This method has more difficulty predicting wind damage due to the number of variables involved with the production of strong thunderstorms winds, some of which are not related directly to high reflectivities.

Table 11. POD, FAR, CSI for VIL Density for Wind Cases for above various thresholds gm^{-3}

VIL Density (gm^{-3}) at or above	POD	FAR	CSI
3.75	0.256	0	0.256
3.50	0.410	0.111	0.390
3.28	0.590	0.115	0.548
3.25	0.590	0.115	0.548
3.00	0.770	0.250	0.613
2.75	0.846	0.313	0.611
2.50	0.897	0.352	0.603

As has been shown in previous studies and confirmed here, using VIL Density values equal to or greater than 3.28 gm^{-3} is a very useful warning tool for severe hail prediction. However, as this study has shown, this VIL Density value is also very useful for predicting severe thunderstorms in general. Using 3.28 gm^{-3} for all severe cases identifies 75% of the severe storms (Table 12) while producing a FAR of 0.06. If 3.00 gm^{-3} is used as a threshold, 86% of the severe storms were detected correctly. However the FAR increased to 0.15.

Table 12. POD, FAR, CSI for VIL Density for All Cases for above various thresholds in gm^{-3}

VIL Density (gm^{-3}) at or above	POD	FAR	CSI
3.75	0.469	0	0.469
3.50	0.609	0.049	0.590
3.28	0.750	0.059	0.716
3.25	0.750	0.059	0.716
3.00	0.859	0.154	0.743
2.75	0.906	0.205	0.734
2.50	0.938	0.241	0.723

5. Conclusions

While many of these parameters have potential as warning criteria for pulse severe thunderstorms, the most significant and useful were height of the Maximum Echo top of the 45, 50, 55, 60 & 65 dBz series, VIL Density, POH and POSH.

Compiled from previous tables, Table 13 shows the height top dBz where the optimal CSI is obtained, as well as the height that would represent a reasonable warning criteria for each dBz.

Table 13. Warning Criteria Suggestions. Height of Echo Top of dBz thresholds.

Echo Top dBz	Height Near in Kft	Optimal CSI CSI/POD/FAR
45	23	0.82/0.90/0.11
50	20	0.77/0.92/0.18
55	18	0.79/0.88/0.11
60	12	0.57/0.61/0.09
65	any	

Table 14. Warning Criteria suggestions for VIL Density.

Parameter	Near VIL Density kgm^{-3}	Optimal CSI
Hail	3.28	0.89
Wind	3.00	0.61
ALL	3.00	0.74

Table 14 shows the VIL density values corresponding to optimum CSI for hail, wind and all events. The value of 3.28 kgm^{-3} was validated as a significant threshold for warning decisions however for pulse type events as defined by this study a warning decision should be considered at a VIL Density of 3.00 or greater.

Using POH of 70% or greater and POSH of 20% or greater produces acceptable results for warnings, while limiting false alarms.

For Echo Tops, severe cases showed values of 5,000 to 7,000 ft greater than the control cases in both averages of all data and matched data by event. This suggests that Echo Tops of potentially severe Pulse storms could identify storms up to 5 volume scans before the event. For Echo Tops near 35,000 feet, we would identify 67% of the severe cases, but only mis-identify 8% of the control cases. Storm Top showed a similar pattern for both average and matched data sets and near 30,000 feet identify 67% of the severe cases and mis-identify 12% of the control cases.

Grid and Cell based VIL also show the Pulse severe storms have VIL values 2 to 3 times the controls, particularly when the values exceed 30 kgm^{-3}. This is another indicator to monitor from the warning desk.

One of the key break points for using criteria from this study was the point at which a storm developed a mesocyclone. At that point, the storm ceased to be a pulse storm in this study, and then these approaches no longer apply. At that point, the storm severity needs to be assessed using different methods.

Only 12 of 64 pulse thunderstorms produced severe weather directly from the first pulse or updraft. This concurs with the earlier work of Lemon (1979). Most of the cases developed the severe weather as a direct result of the second or third pulse (updraft) which was stronger than the original pulse. It appears as though the second or third updraft receives a boost on the nose of the outflow of the original pulse, which is enough to generate the severe weather.

Acknowledgments

The authors would like to thank Thomas Wasula, Vasil Koleci, John Quinlan and Ken LaPenta for their assistance to this project. This work was an unfunded component of COMET Cooperative Grant UCAR 09915806, Advanced Forecast and Warning Criteria for Tornadoes and Severe Thunderstorms in the Northeastern United States.

References

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

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,__pp., Bohemia, NY

Cannon, J. W., K. D. LaPenta, J.S. Quinlan, L. F. Bosart, W. E. Bracken and A. Seimon, 1998: Radar characteristics of the 15 July 1995 northeastern derecho. *Preprints 19th Conf. on Severe Local Storms*, Minneapolis, MN, Amer. Meteor. Soc.,__pp.

Cacciola, A.C., LaPenta, K.L., J. S. Quinlan, L. F. Bosart, S. F. Honikman, and T. J. Galarneau, 2000: Northeast severe weather distribution as a function of flow regime. *Preprints 20th Conf. on Severe Local Storms*, Olando, FL. Amer. Meteor. Soc., 453-460.

Johnson, J. T. and J. Janish, 1998: WATADS - WSR88D Algorithm Testing and Display System reference guide., Norman, OK. Stormscale Research and Applications Div., National Severe Storms Laboratory,__pp.

LaPenta, K.L., G. J. Maglaras J.S. Quinlan, H. W. Johnson, L. F. Bosart and T. J. Galarneau, 2000: Radar observations of northeastern United States tornadoes. *Preprints 20th Conf. on Severe Local Storms*, Olando, FL. Amer. Meteor. Soc., 356-359.

Lemon, L. R., 1977: New severe thunderstorm radar identification techniques and warning criteria. *NOAA Tech. Memo*. **NWS NSSFC-1**,. Kansas City MO, National Severe Storms Forecast Center, 60 pp.

Lemon, L. R., 1978: On the use of storm structure for hail identification. *Preprints 18th Conf. on Radar Meteorology*, Boston MA, Amer. Meteor. Soc. 203-206.

Wilk, K. E. L. R. Lemon, and D. W. Burgess, 1979: Interpretation of radar echoes from severe thunderstorms: a series of illustrations with extended captions. FAA Contract Report, Unpublished, Excerpts provided by L. Lemon,__pp.