Golf Ball Hail and Damaging Wind Event on 11 September 2013

1.) Introduction

On 11 September 2013 several lines of strong to severe thunderstorms impacted the North County with damaging winds and large hail. These lines of storms formed along a pre-frontal trough and surface cold front, which interacted with temperatures well into the 80s to near 90 and dewpoint values near 70. A record high temperature of 88 degrees was observed at both Montpelier, VT and Massena, NY on September 11th prior to the arrival of these storms. The highest concentration of damaging winds occurred from northern New York into parts of central and southern Vermont, including portions of the Champlain Valley and Northeast Kingdom of Vermont. A goal of this post-storm write up is to identify the Elevated Mixed Layer (EML) through sounding analysis and how the pre-storm wind and instability profiles were favorable for organized bow like and mini supercell storm structures and their associated radar signatures.

Figure 1 below shows a map of Local Storm Reports (LSRs) received by the National Weather Service (NWS) Burlington (BTV), VT Weather Forecast Office (WFO). Click here for a complete listing of all the severe weather reports across WFO BTV county warning area (CWA). In Bridgewater Corners, VT a 60 mph wind gust was estimated, along with golf ball size (1.75") hail at Louisville and North Lawrence, NY and Alburgh, VT. The primary severe weather threat observed was damaging winds, which resulted in over 20,000 people losing power across Vermont and numerous trees down across the North Country from multi lines of storms with embedded bowing segments.

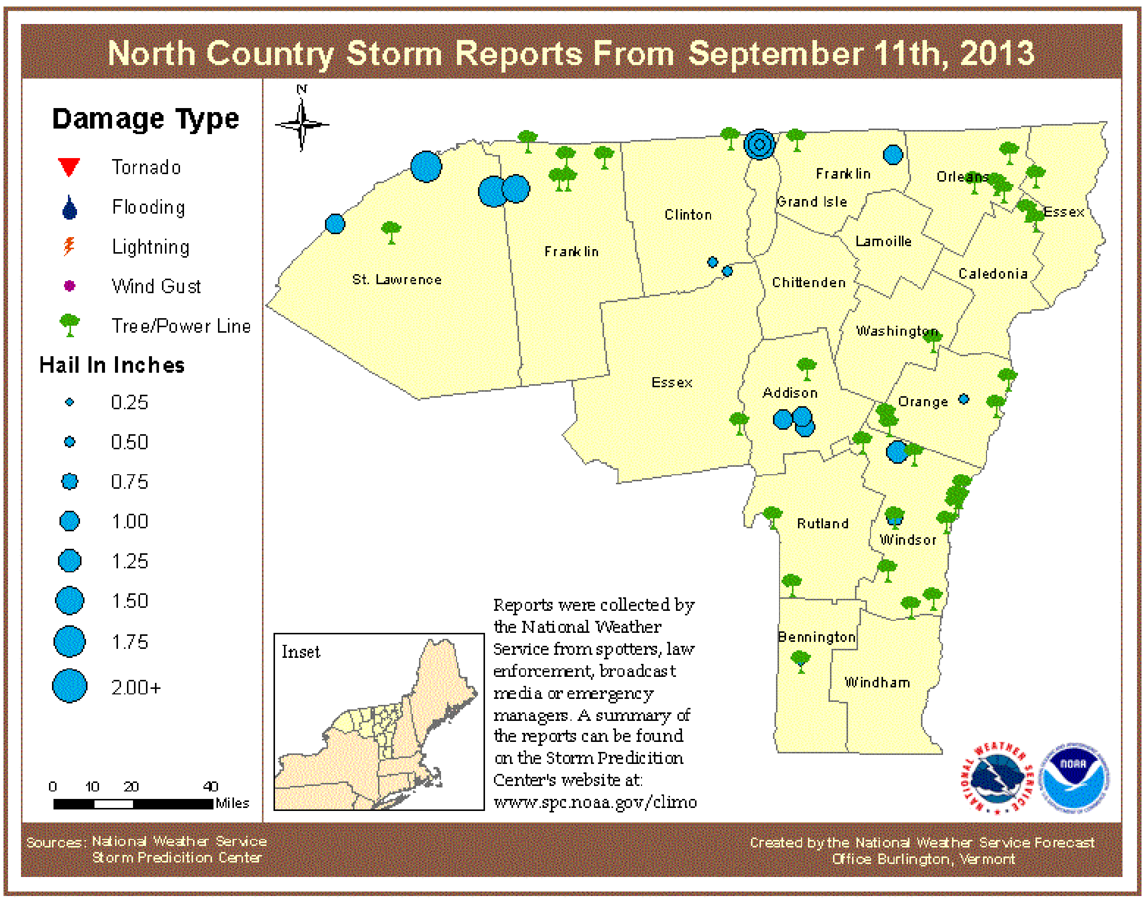

Figure 1: Map of Local Storm Reports on 11 September 2013. Green trees indicate trees or power lines down and the light blue circles show where hail occurred.

2.) Storm Prediction Center Outlook Information

In this section we will discuss the products issues by the Storm Prediction Center (SPC) leading up and during the event, which will include the Day 1 outlooks and Mesoscale Discussions. Figure 2 below shows the SPC Day 1 categorical outlook (left image), day 1 wind outlook (middle image), and day 1 hail outlook (right image) on 11 September 2013 at 1630 UTC, which shows all of the BTV CWA was in a slight risk for severe thunderstorms. From SPC, a slight risk implies well-organized severe thunderstorms are expected, but in small numbers and/or low coverage. Depending on the size of the area, approximately 5-25 reports of 1 inch or larger hail, and/or 5-25 wind events, and/or 1-5 tornadoes would be possible. The probabilistic wind and hail forecast from SPC, showed a 30% chance of severe thunderstorm winds and 15% hail within 25 miles of a given point during the outlook period across northern New York and most of Vermont. Click here for the 1630 UTC convective outlook text product from SPC on 11 September 2013.

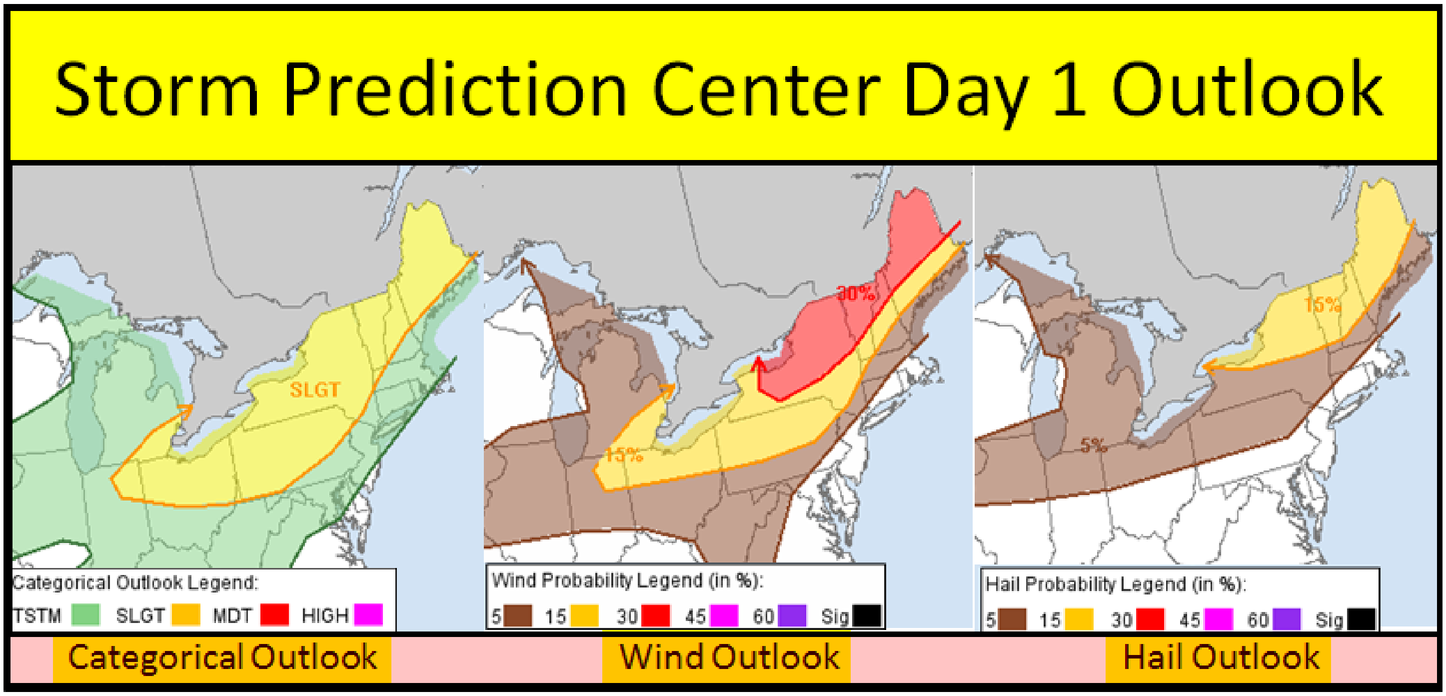

Figure 2: The Storm Prediction Center (SPC) Day 1 categorical outlook (left), SPC Wind Outlook (middle), and SPC Hail Outlook (right) issued at 1630 UTC 11 September 2013.

3.) Pre-storm Environment (Upper Air, Sounding, and Rapid Refresh CAPE and Shear)

In Section 3 of this post-storm write up we will investigate the pre-storm environment, including the upper air data, sounding, and Rapid Refresh (RAP) most unstable CAPE and effective shear. The 500 hPa (20,000 feet above ground level) showed a developing deep trough across the northern Plains, with a ribbon of enhanced winds greater than 55 knots lifting from near Chicago, IL to Detroit MI to southern Ontario Canada on 11 September 2013 at 12 UTC. In addition, Figure 3 below shows a potent shortwave trough across the eastern Great Lakes, which moved into the Saint Lawrence Valley by 18 UTC. This shortwave helped to produce large-scale lift for thunderstorm development, while the stronger winds aloft helped in the organization of storms and provided the severe weather wind threat across the WFO BTV CWA. In addition, helping to enhance the fast flow across the Mid-Atlantic States into southern Canada was the placement of the Bermuda high pressure off the East Coast and digging trough over the northern Great Lakes. This is clearly shown in Figure 3 below, with low pressure over the Great Lakes and high pressure off the East Coast.

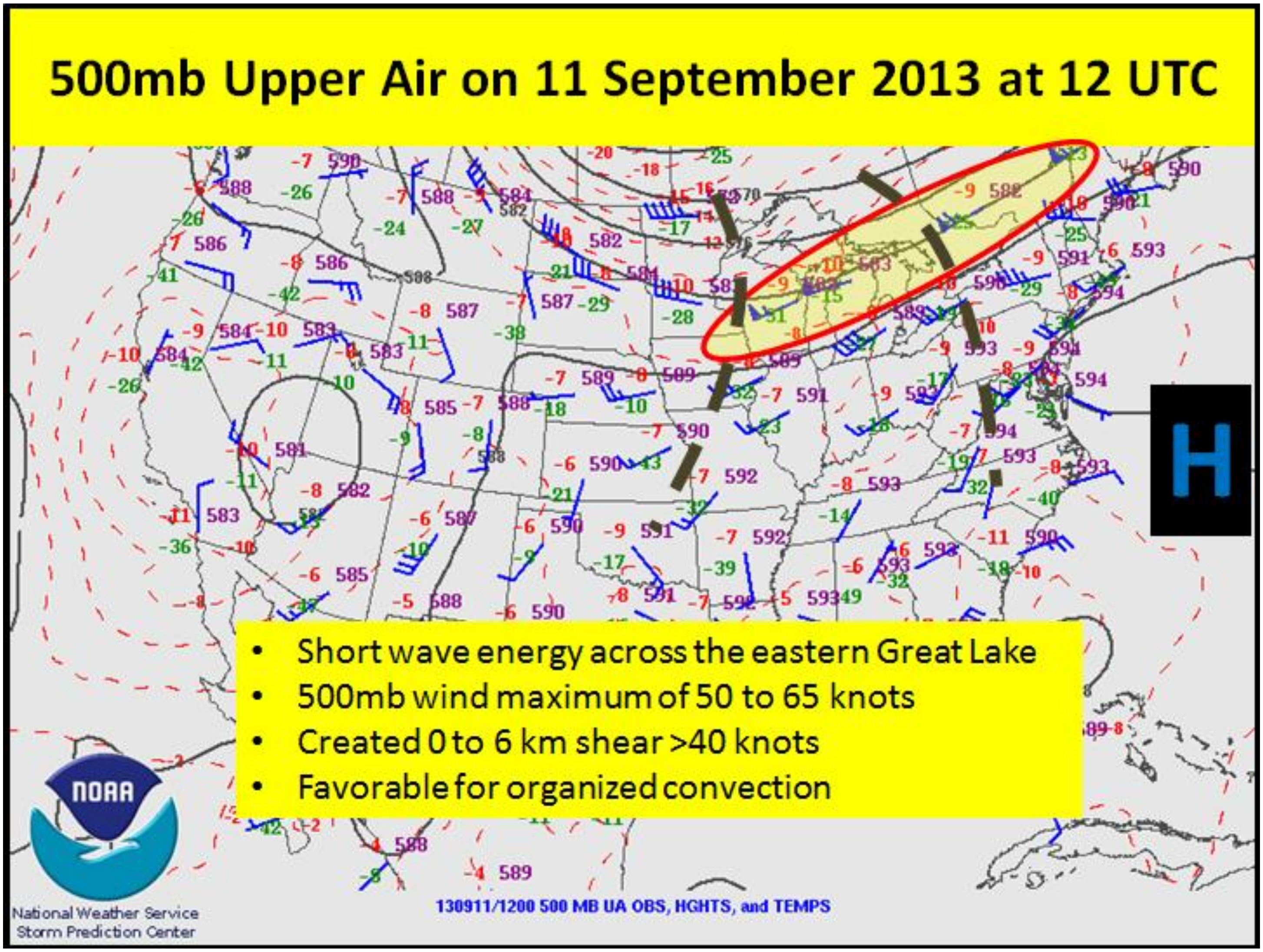

Figure 3: The 500 hPa (20,000 feet above ground level) upper air analysis on 11 September 2013 at 12 UTC. Wind barbs, (plotted in blue, 1 arrow=50 knots, 1 barb=10 knots, 1/2 barb=5 knots), 500 hPa heights (black lines), and temperatures (dotted red).

Figure 4 below shows the 250 hPa (40,000 feet above ground level) upper air analysis on 11 September 2013 at 12 UTC. A potent ribbon of 75 to 100 knot jet stream winds were pushing southeast toward the eastern Great Lakes as a mid/upper level trough deepened over the northern Plains. This helped place our northern and central CWA in the right rear quadrant of favorable upper level divergence by 00 UTC on 12 September 2013. This ribbon of strong winds aloft and several embedded short waves at 500 hPa, helped to promote deep-layer ascent across northern New York into Vermont on the evening of September 11th, for the development of tall thunderstorms capable of producing severe weather.

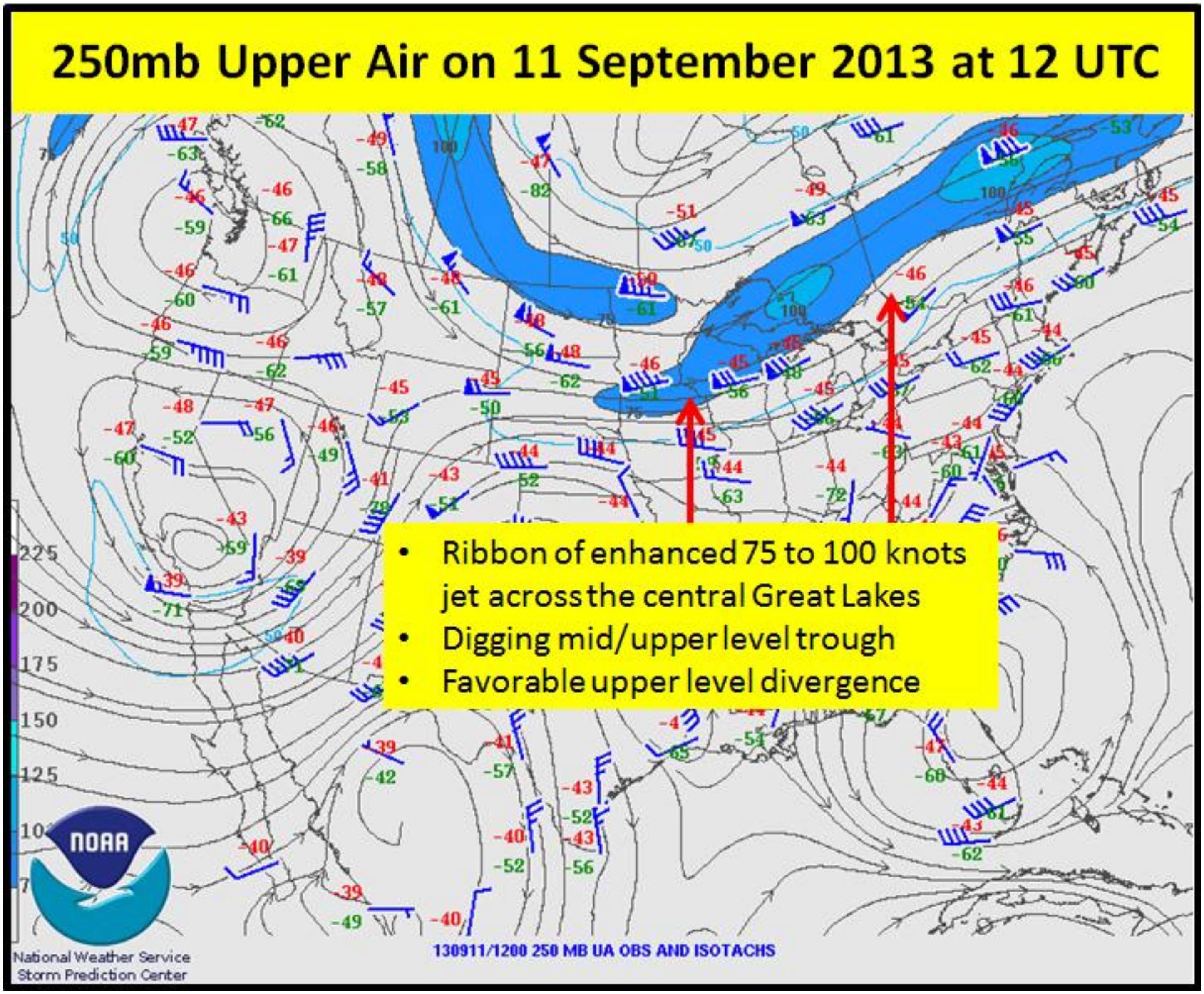

Figure 4: The 250 hPa (40,000 feet above ground level) upper air analysis on 11 September 2013 at 12 UTC. Wind barbs, (plotted in blue, 1 arrow=50 knots, 1 barb=10 knots, 1/2 barb=5 knots), Isotach (dark blue>75 knots, and lighter blue>100 knots, streamlines (black), and temperatures (red).

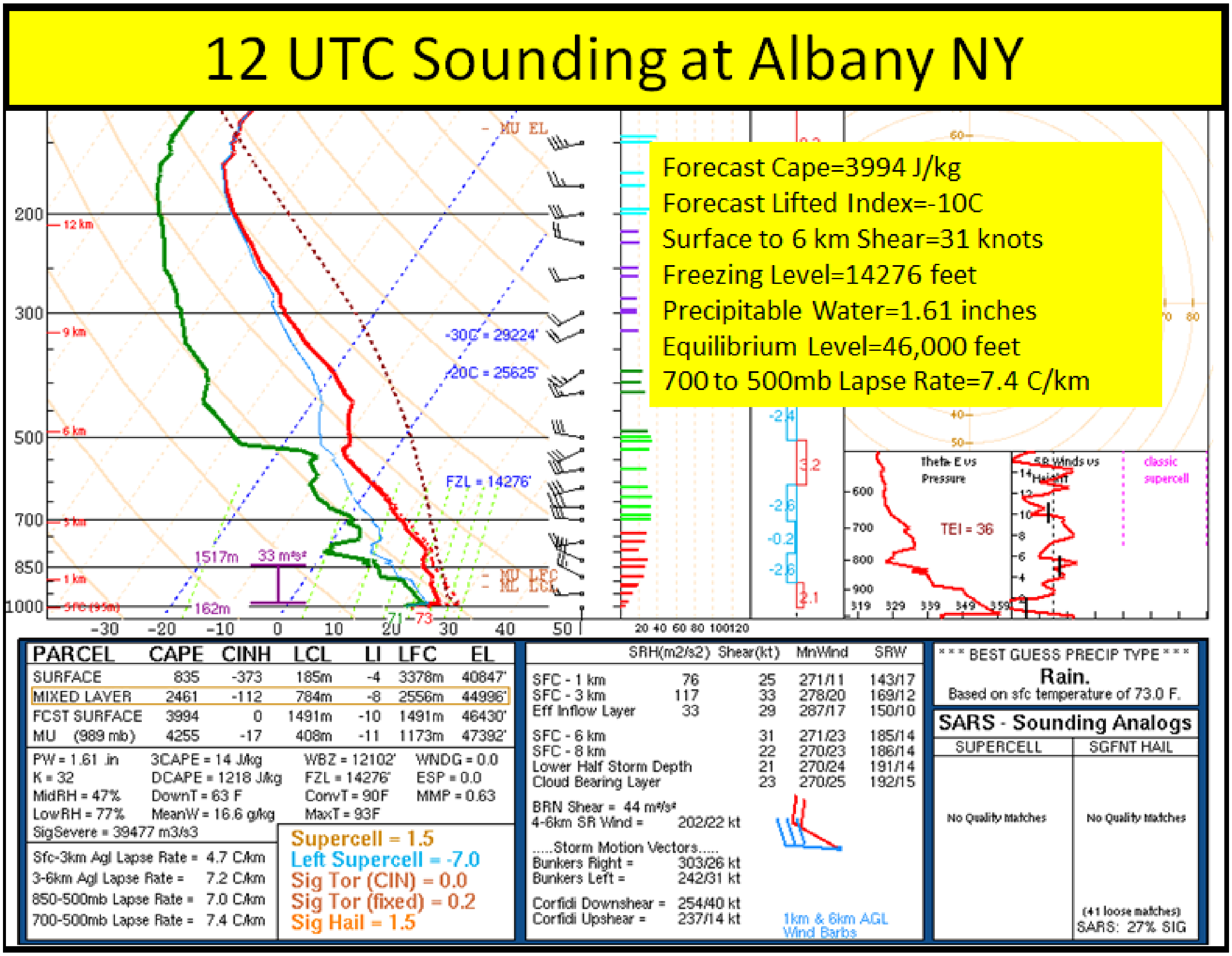

Figure 5: Albany, New York observed sounding on 11 September 2013 at 1200 UTC.

The Albany, New York (ALB) sounding on 11 September 2013 at 1200 UTC (Figure 5) showed the very favorable thermodynamic environment in place for severe convective storms, with early morning 100-hPa mixed layer CAPE values already approaching 2500 J kg^{-1}. A surface dewpoint value of 71°F was observed, indicative of the rich low-level moisture in place across eastern and northern New York into New England. Steep mid-level lapse rates – approaching dry adiabatic values - are apparent from 800-550 hPa. These steep lapse rates are associated with a residual EML plume that advected from the Intermountain West over a period of several days on the northern periphery of a strong 700hPa ridge centered over the Tennessee River Valley. By the morning of 11 September 2013, this EML plume had made it all the way to the New England coast. The EML plume had the effect of producing substantial CIN early in the day to allow strong surface heating to occur unabated through mid-afternoon. This contributed to the buildup of unusually large CAPE values, especially for this time of year. As forcing for ascent increased from the west and northwest, the weakening of the capping inversion allowed for explosive convective development late in the day. The steep lapse rates also had the effect of increasing buoyant/convective accelerations, which were supportive of large hail with very strong updrafts and localized damaging winds with strong downdrafts.

Figure 6 shows Rapid Refresh (RAP) analysis of CAPE and 0 to 6 km effective shear from SPC on 11 September 2013 at 2100 UTC. As the mid-level jet approached the region the deep layer shear increased to between 45 and 55 knots, while CAPE values ranged between 3000 and 4000 J/kg across parts of our CWA. Note, the best combination of deep layer shear and highest instability (CAPE) was located across northern New York into parts of central Vermont and closely matches the region of greatest concentration of damage.

This pre-storm environment was conducive for well-organized and persistent convection to develop, capable of producing damaging winds associated with a bow echo storm structure. Also, from Figure 6, you can see the Convective Inhibition (blue shaded areas) decreased significantly as surface temperatures warmed into the 80s and was only present over the cooler Lake Ontario and Atlantic Ocean waters and areas of rain cooled air.

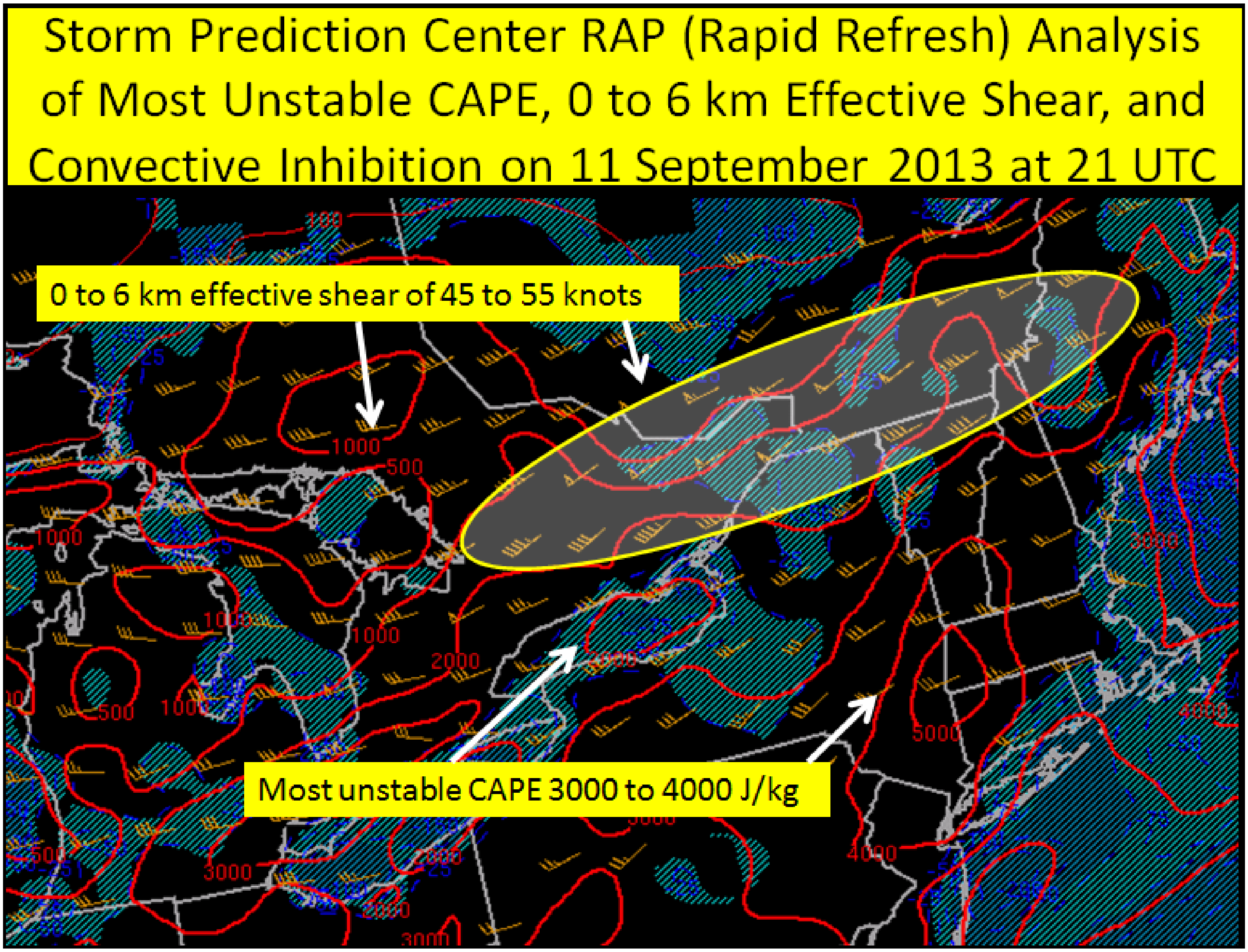

Figure 6: Storm Prediction Center (RAP) Rapid Refresh analysis of CAPE (red lines), 0 to 6 km effective shear (orange wind barbs), and Convective Inhibition (light blue shading) on 11 September 2013 at 2100 UTC.

4.) Storm Prediction Center Mesoscale Graphics and Discussion

Figure 7 below shows SPC's two mesoscale graphics issued prior to and during the severe weather event on 11 September 2013. The image on the left indicates severe storms are likely with a severe thunderstorm watch warranted soon. The right image shows several intersecting outflow boundaries and the continued threat for mainly isolated damaging winds across eastern New York into most of central and northern New England through 2200 UTC on September 11th. Click here for the detailed mesoscale convective discussions #1872 and #1875, which were issued by SPC. At 1835 UTC the SPC issued severe thunderstorm watch #521 until 2200 UTC on 11 September 2013 for WFO BTV entire CWA, with damaging winds as the primary threat. Click here to view severe thunderstorm watch box information.

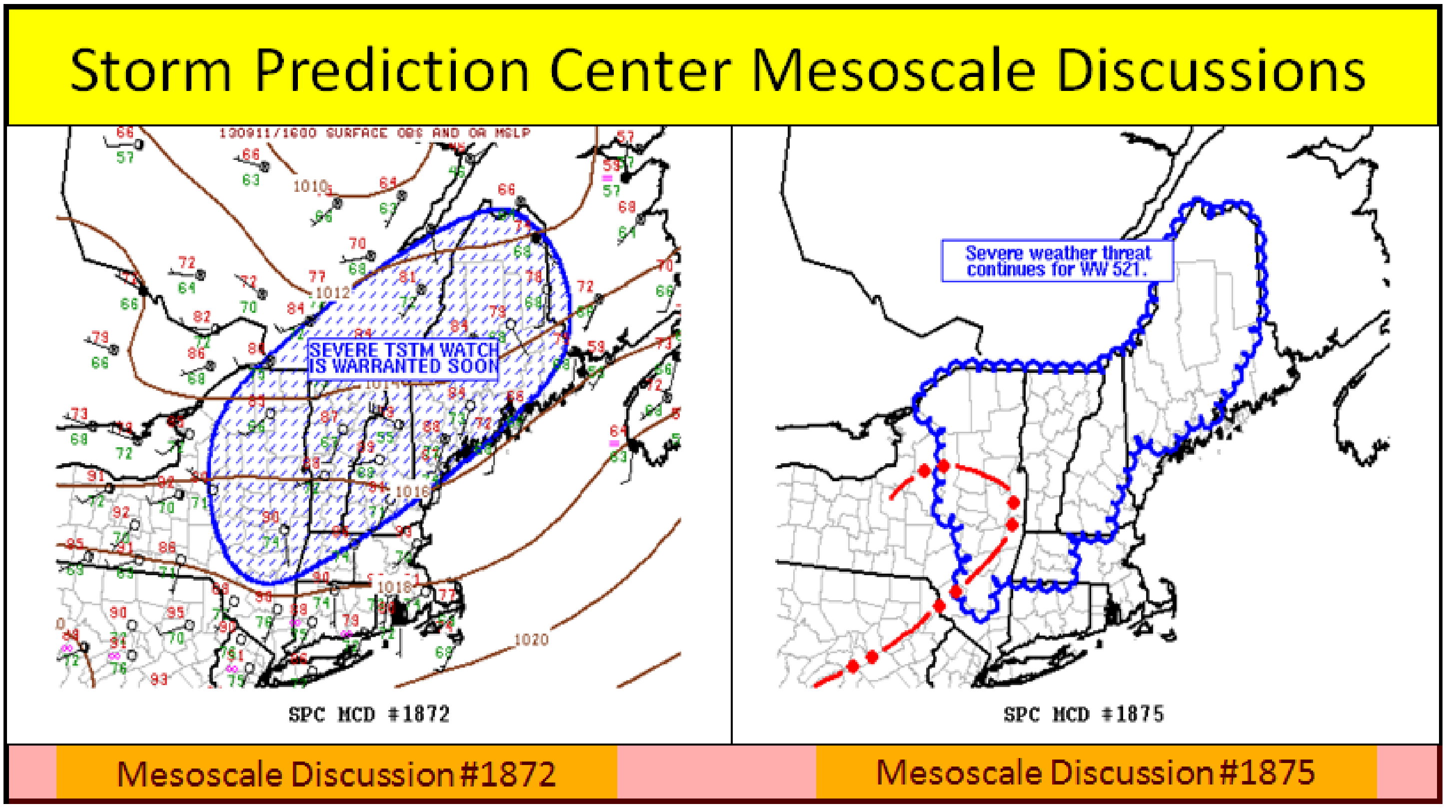

Figure 7: Storm Prediction Center Mesoscale Discussion #1872 (left image) and #1875 (right image).

5. Satellite/Radar overview

In this section we will discuss the satellite and radar data and closely investigate the well-defined bow echo that impacted southern Vermont with damaging winds and several of the stronger storms over northern New York which produced golf ball (1.75”). Image 8 below shows a visible satellite on 11 September 2013 at 1945 UTC. From the image you can clearly see the towering cumulus clouds across the pre-frontal trough from the central Champlain Valley into western New York. The combination of a warm unstable air-mass associated with temperatures in the 80s and dewpoints near 70, created CAPE values between 2000 and 3000 J/kg, which interacted with the higher terrain of the Adirondack Mountains, to produce thunderstorms during the afternoon hours of September 11th. A surface cold front across the eastern Great Lakes helped in additional thunderstorm development during the evening hours, especially across the Saint Lawrence Valley. The brighter/whiter clouds in the image below indicate the taller and stronger areas of thunderstorms.

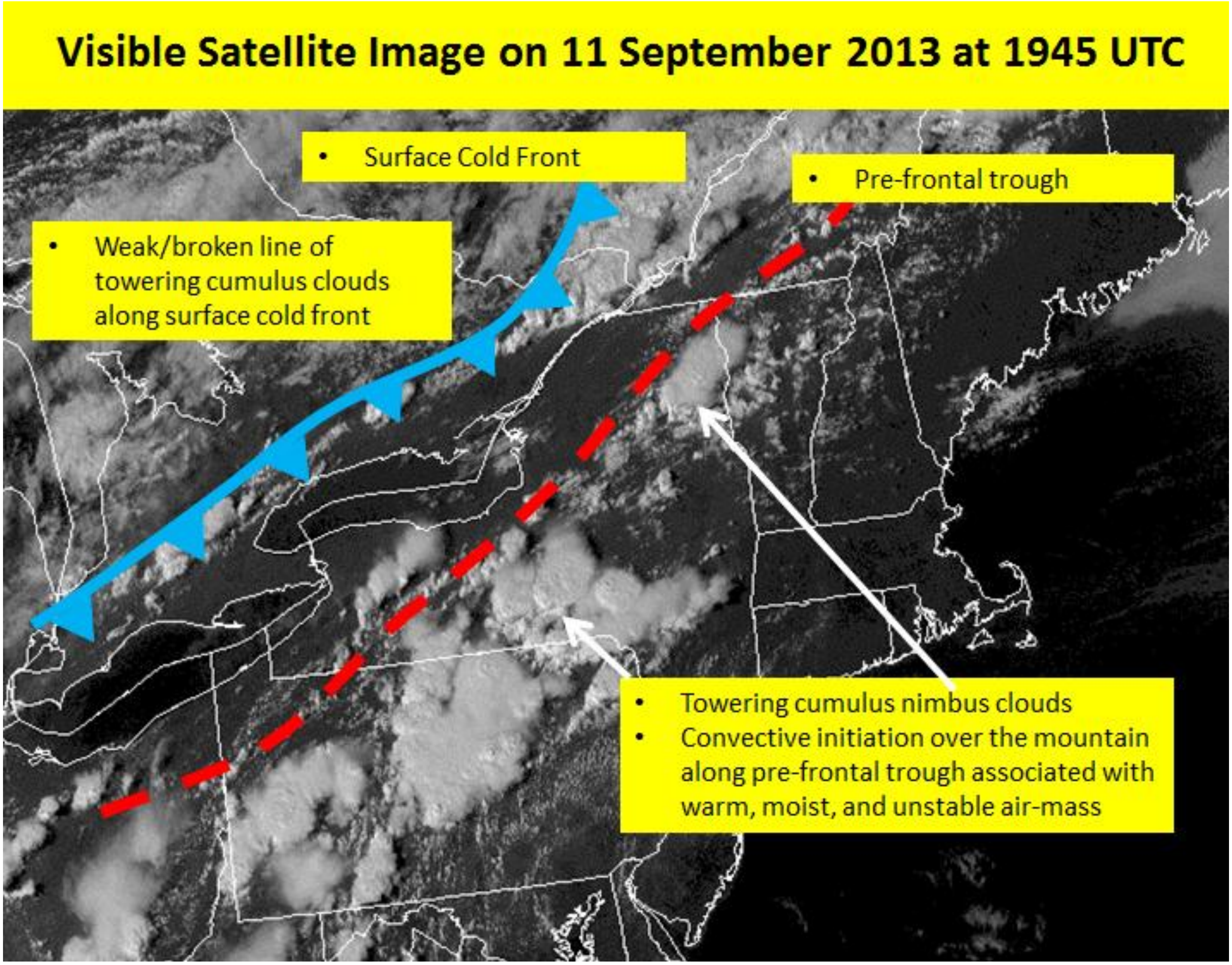

Figure 8: Visible Satellite Image on 11 September 2013 at 1945 UTC, with pre-frontal trough (red dotted line) and surface cold front (light blue line with triangles).

The mosaic composite reflectivity loop (see figure 9 below) from 1912 UTC to 2354 UTC (2:12 PM to 7:54 PM EDT) shows the transition of multi lines of thunderstorms across northern New York into most of Vermont. In addition, a well-defined bow echo signature developed across eastern New York around 2200 and impacted central and southern Vermont by 2300 UTC as this line raced northeast at 35 to 40 knots. The combination of favorable wind and instability profiles and quick movement of storms produced widespread wind damage across Rutland, Windsor, and Orange Counties of Vermont on the evening of September 11th. Also, noted from the image below the abundant lightning associated with these lines of strong to severe thunderstorms.

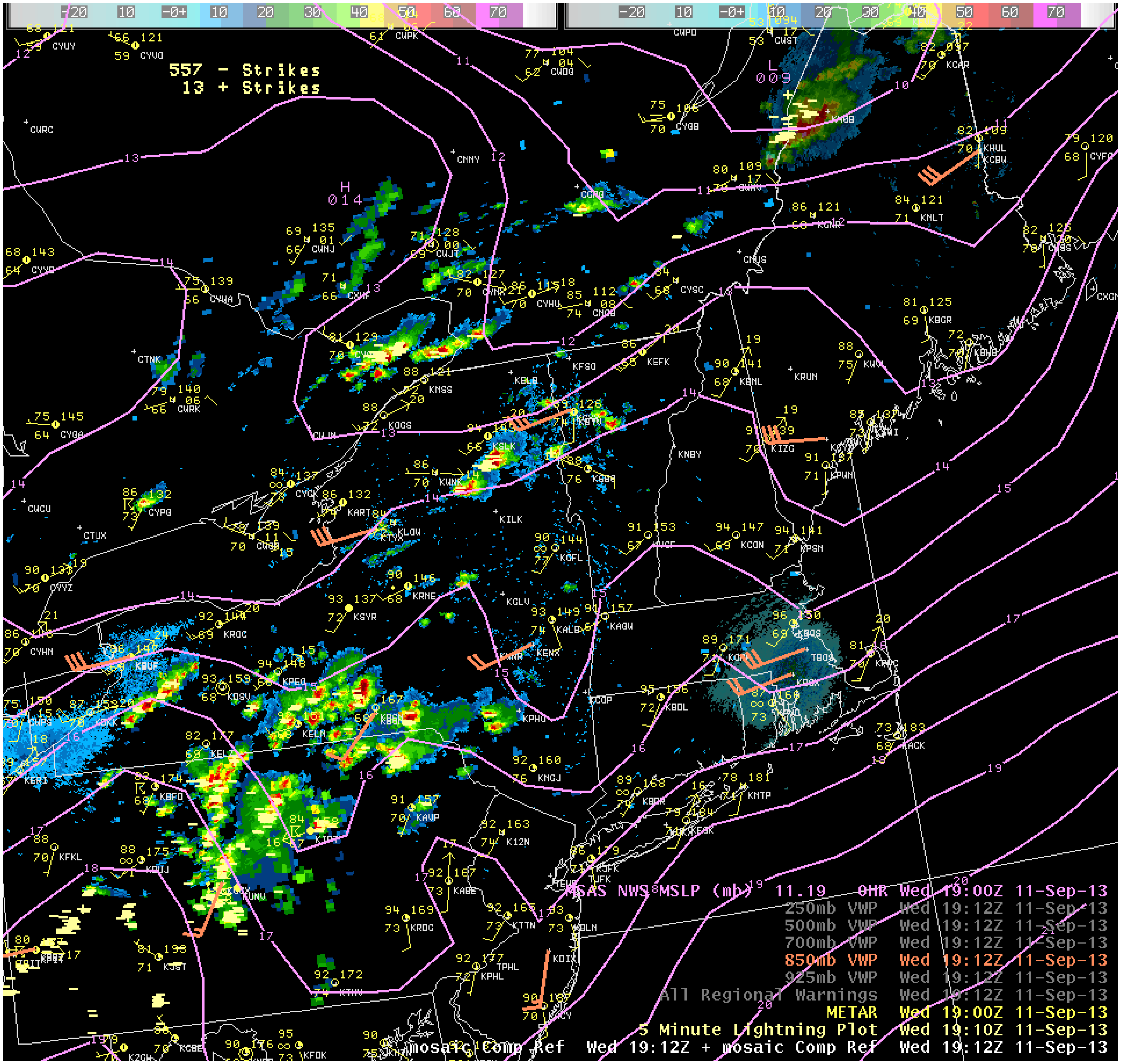

Figure 9: Mosaic composite reflectivity (dBZ) loop from 1912 to 2354 UTC 11 September 2013 with surface observations (yellow plots), NWS mean sea level pressure (light purple lines) and Lightning (yellow). Click to launch radar reflectivity loop. (Click image to animate)

Figure 9a below shows a 1 hour lightning plot on 12 September 2013 at 00 UTC. The intense cloud to ground lightning strikes clearly show the tracks of the multi mini supercells and bow echo storms across our CWA on the evening of Sept 11th. In addition, this plot shows 3,633 negative and 199 positive strikes occurred during this one hour period, indicating how intense the storms were at their peak.

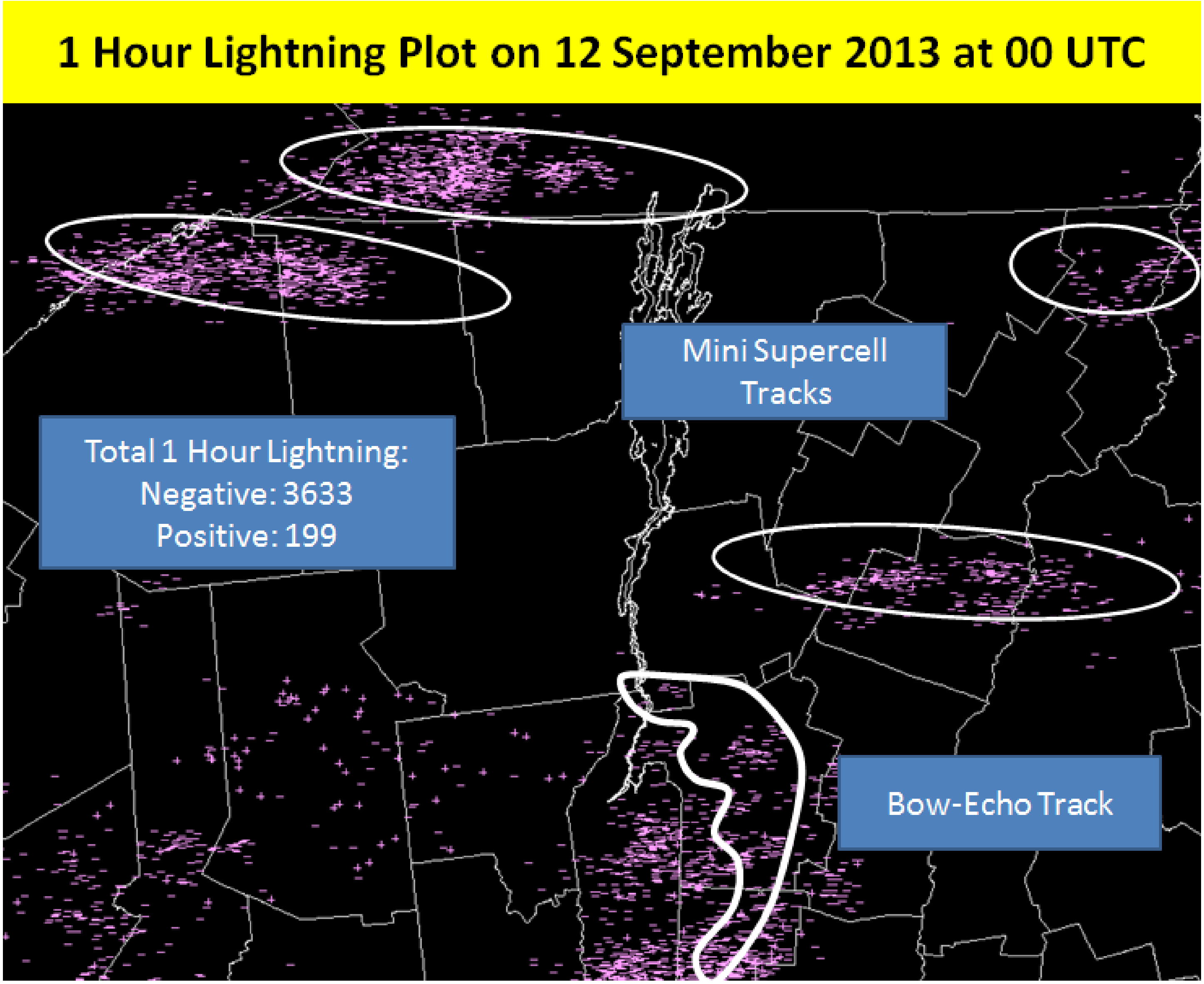

Figure 9a: 1 Hour lightning plot (negative and positive in purple) at 00 UTC on 12 September 2013.

5a.) Bow Echo (Rutland/Windsor Counties):

As is common with lines of convection in high instability environments, evaporatively cooled air stemming from heavy rainfall creates a mesoscale cold pool, which induces strong pressure gradients and accelerates the convective line. The rain-cooled air is evident in the overlaid surface observations; at 22 UTC note the temperature of 82°F as the line passes Glens Falls, NY while temperatures in advance of the line were still in the lower 90s. Consistent with the cold pool, a pressure jump occurred at Glens Falls (+1.2 mb in 1 hour) as the thunderstorms passed, owing to relatively dense, convectively cooled air trailing the leading edge of thunderstorms activity.

The convective line evolved into a broken bow echo across eastern New York and impacted southern Vermont, especially Rutland and Windsor counties between 2300 UTC and 0015 UTC (see Figure 10 below), in which the reflectivity structure resembled that of an archer's bow.

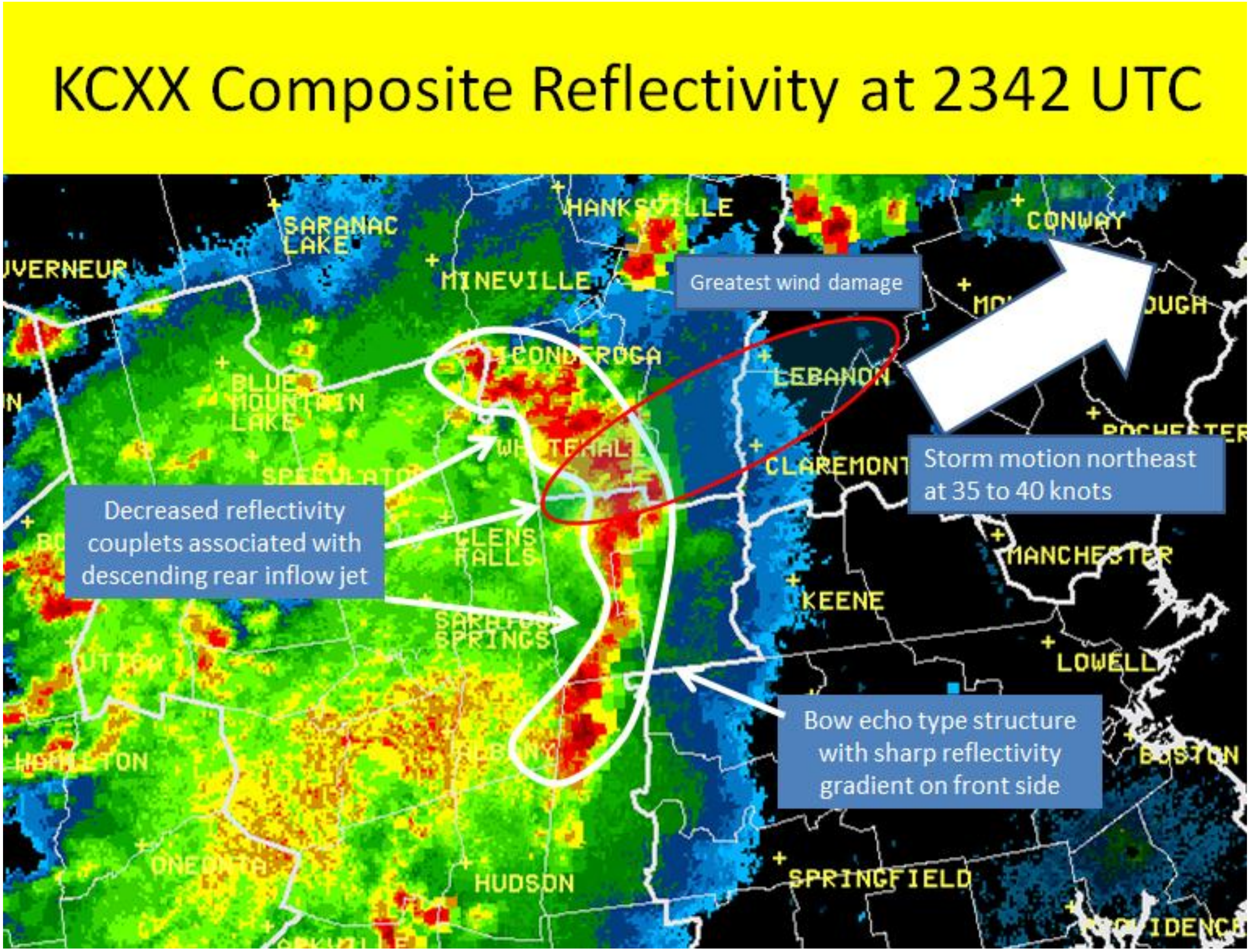

Figure 10: KCXX composite reflectivity (dBZ) at 2342 UTC 11 September 2013.

This is an indication of potentially damaging straight line winds where a portion of the convective line "bows out" where downburst winds are strongest, typically near the apex of the bow echo (Figure. 10).

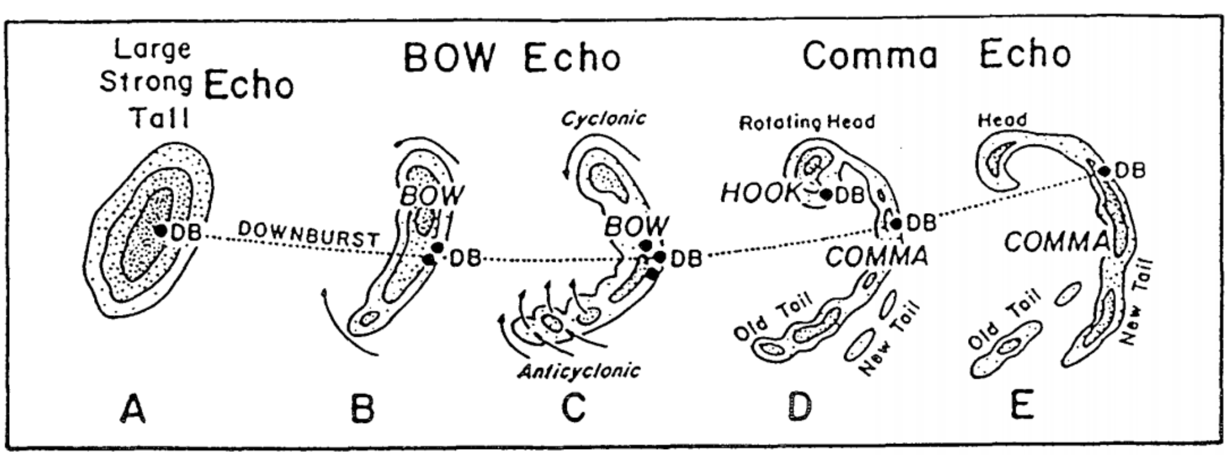

Figure 11: Idealized morphology of an isolated bow echo associated with strong and extensive downbursts. (from Johns 1993)

The direction of the highest winds occur perpendicular to the convective line, or from the southwest, in this case. The average forward speed of the bow echo was near 40 knots (45 mph) across Rutland and Windsor counties, with the apex of the bow moving up to 50 knots (58 mph) across that region. The forward speed of linear convective structures typically provide a rough estimate of the associated surface winds, and the forward motion met NWS severe criteria of 50 knots in this case. Of course, Doppler velocity data is also utilized to remotely sense wind speeds within convective storms. Since the Doppler radar measures the speed of reflectors (e.g., raindrops) toward or away from the radar, the best velocity estimates occur when the line motion is perpendicular to the radar beam. In this event, the line moved down the radial of the ENX radar, located near Albany, NY and provided excellent sampling of the velocity data. The ENX radar, observed Doppler velocities were near 60 knots at 4000 feet AGL across extreme southern Rutland County at (See Figure 11). This bow echo structure produced a measured 47 mph wind gust at Rutland Regional Airport at 2355 UTC along with numerous areas of trees and power lines down across southern Vermont on the evening of September 11th.

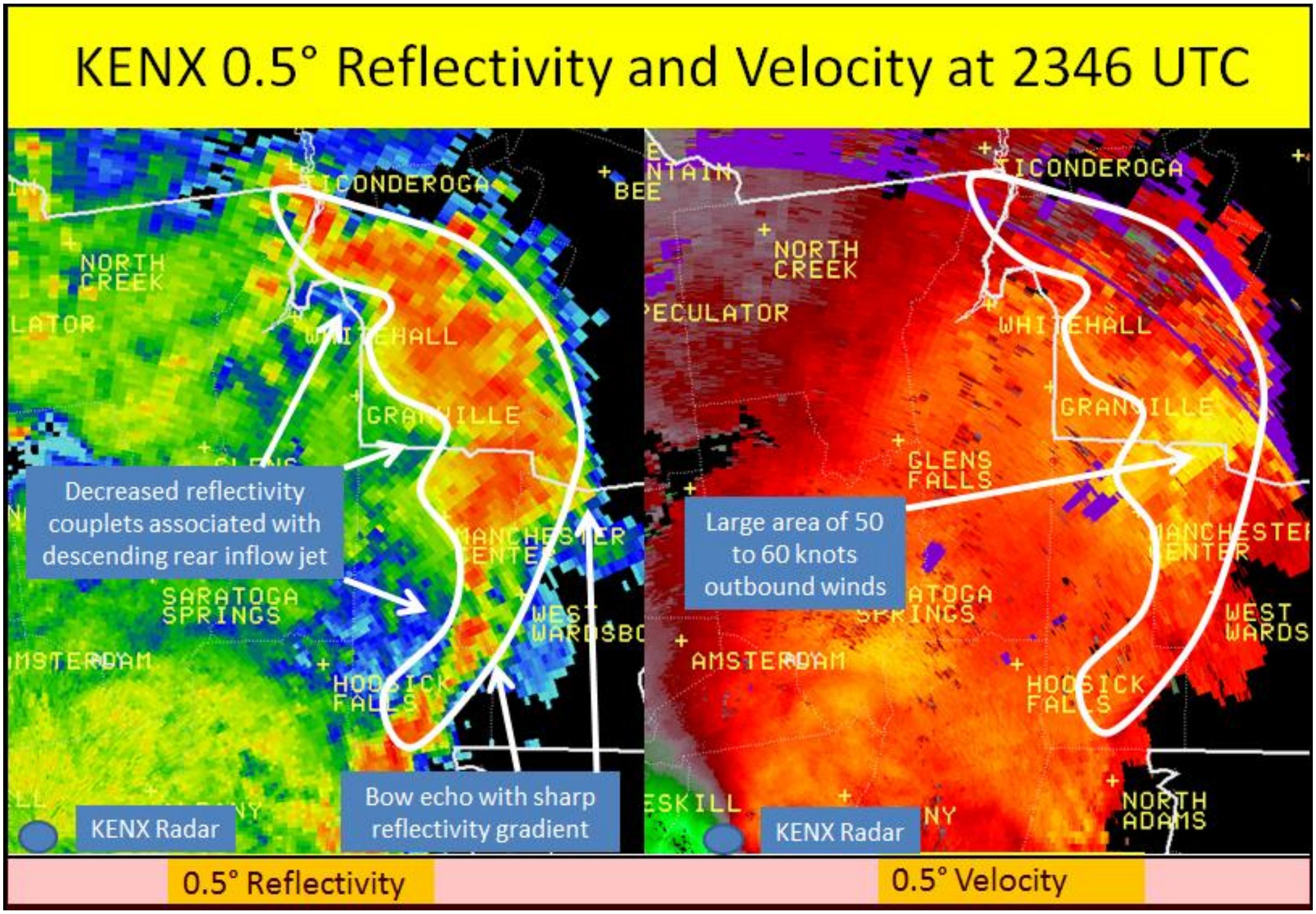

Figure 12: KENX 0.5° reflectivity (left) and velocity (right) at 2346 UTC 11 September 2013.

Other organization structures that prompted forecasters to the severity of this bow echo included: (1) a sharp reflectivity gradient on the leading edge of the box echo, and (2) weak echo channels on the upstream side of the bow, an indication of a descending rear inflow jet that is resulting in locally enhanced winds along the line (Fig. 11).

The 19 July 2013 bow echo approached, but did not reach, the oft-cited criteria for a *derecho* (see: http://www.spc.noaa.gov/misc/AbtDerechos/derechofacts.htm for more information). While the wind-producing convective system covered a distance around ~200 miles from northeast Pennsylvania to central New Hampshire, at least 3 measured wind gusts to hurricane force ≥ 65 kt (≥74 mph) spaced at least 40 miles apart are also needed in the traditional definition (see Johns and Hirt, 1987). It didn't appear from reports received and observations that this wind-producing system reached the significant wind speed criteria. That said, it is worth noting that the physical processes involved are the same between the bow echo on 19 July 2013 and higher-end systems that may be classified as derechos. Examples of rare derechos affecting portions of the North Country include the 14-15 July 1995 Adirondack derecho and 4-5 July 1999 derecho. The 19 July 2013 bow echo was more in line with the magnitude of the "Route 7 Runner" event observed on 26 May 2010.

5b.) 2.0" Hail North Lawrence, New York:

The next storm we will examine is the mini supercell which developed over the Ottawa Valley in southern Canada and tracked east into the Saint Lawrence Valley, then weaken over northern Vermont during the late evening hours on September 11th. This storm produced severe hail across Saint Lawrence and Franklin Counties, along with areas of wind damage and abundant lightning. Figure 13 below shows the KCXX 2.4° reflectivity at 0016 UTC on 12 September 2013, along with the hail detection algorithm. From the image below you can clearly see a three body scatter spike (TBSS) out the backside of the strongest reflectivity core, suggesting large hail. In addition, the hail algorithm was indicating almost 2.0" diameter hail was possible, associated with this core of 65 dBZ reflectivity up to 20,000 feet above ground level. Click here for additional information on TBSS. Generally known as hail spikes, these are the result of energy from the radar hitting hail, or very heavy rain, and being reflected to the ground, where they reflect back to the hail and then to the radar. The multipath echoes are then analyzed on the radar display as echoes extending in a radial direction behind the actual location of the hail/heavy rain core. Hail spikes usually appear at the levels aloft that accompany the most intense hail.

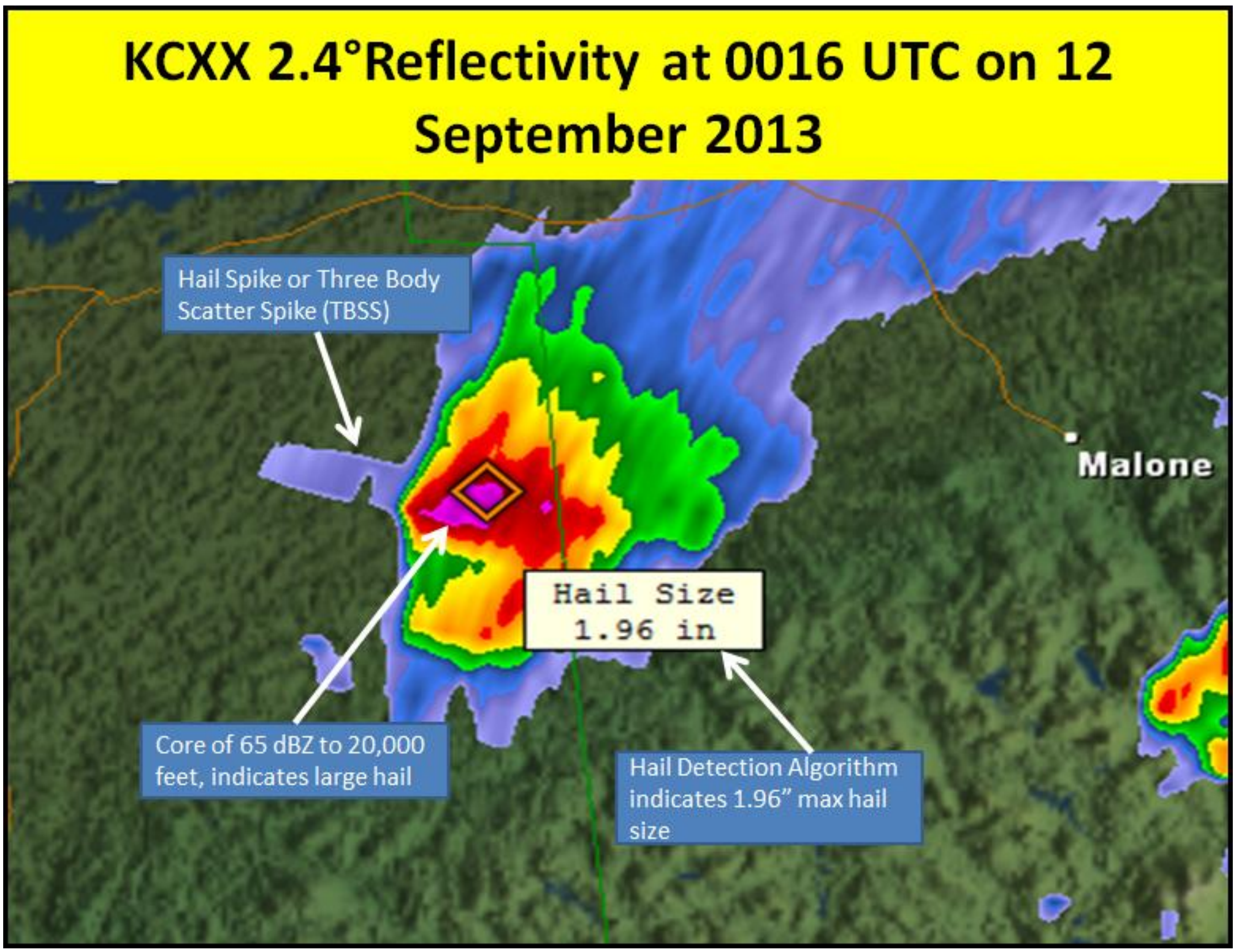

Figure 13: KCXX 2.4° reflectivity at 0016 UTC on 12 September 2013.

Figure 15 below shows a KCXX reflectivity cross section of the 2.0” diameter hail producing mini supercell across east-central Saint Lawrence County at 0016 UTC on 12 September 2013. This storm was 10 miles tall in the atmosphere with storm top reflectivity over 50,000 feet above ground level (AGL). In addition, a solid 60 to 70 dBZ reflectivity core was present to 30,000 feet AGL, indicating a very warm and unstable air mass was being lifted into the storm’s updraft. Soundings showed a very unstable profile with tall equilibrium levels to 46,000 feet and favorable shear for organized and persistent convection capable of producing severe hail and damaging winds.

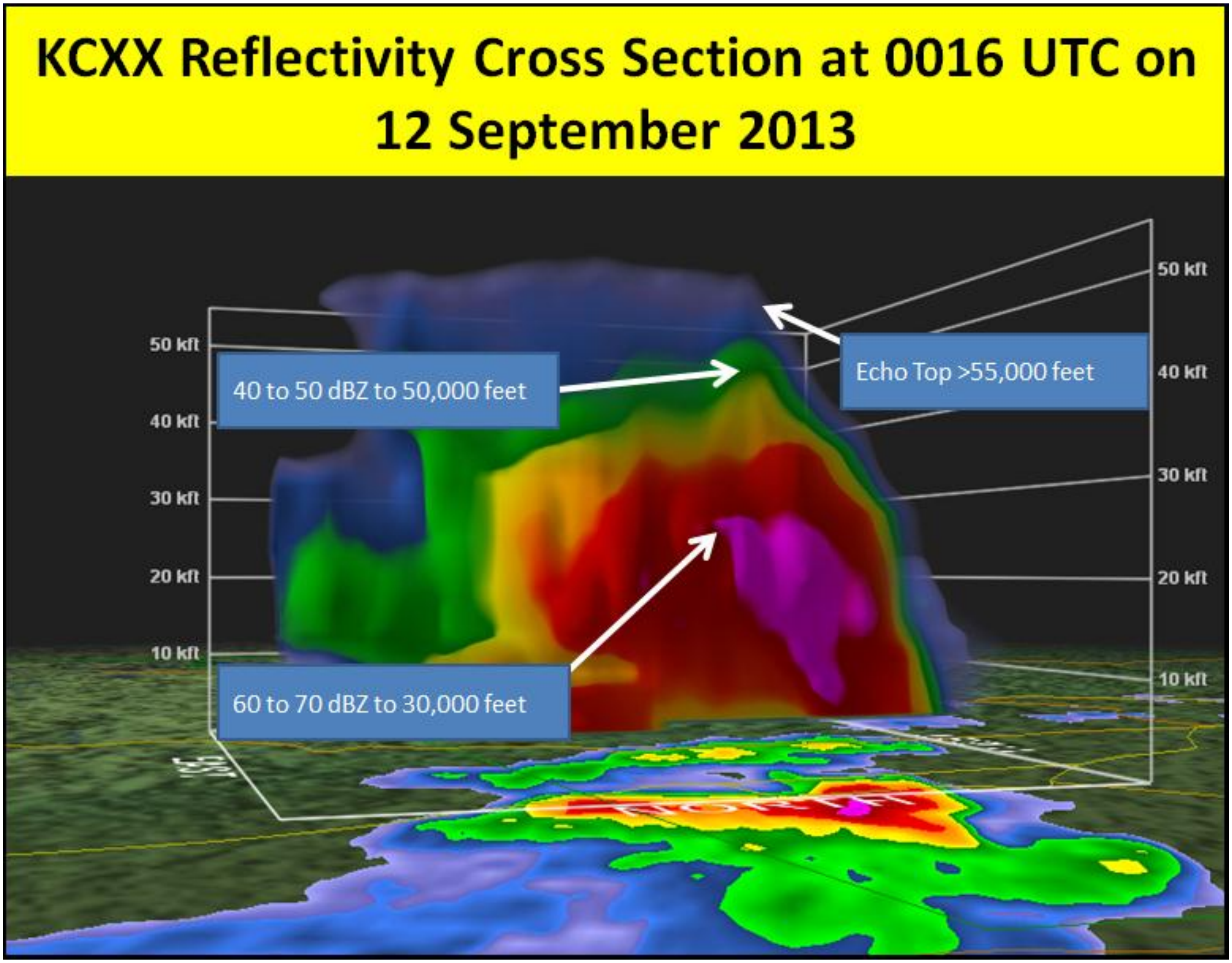

Figure 14: KCXX reflectivity cross section at 0016 UTC on 12 September 2013.

Figure 15 below shows the KCXX Vertical Integrated Liquid (VIL) at 0016 UTC on 12 September 2013 near North Lawrence, NY. VIL is an estimate of the total mass of precipitation in the clouds. The measurement is obtained by observing the reflectivity of the vertical column as obtained by radar. This measurement is usually used in determining the size of hail, the potential amount of rain under a thunderstorm, and the potential downdraft strength when combined with the height of the echo tops. When VIL values quickly fall, it may mean that a downburst is occurring, a result of a weakening of the storm's updraft and the storms inability to hold the copious amounts of moisture/hail within the storm's structure. This means greater potential for the storm to produce damaging winds as the downburst descends to the surface. Figure 15 shows VIL (pink/purple and white color) values between 65 and 75 kg/m2 west of Malone, New York. This indicates a very well developed updraft, which produced near 2.0” diameter hail in North Lawrence, NY, which is located in east-central Saint Lawrence County. This mini-supercell storm continues to track east and produced 1.50”size hail near Moira, NY in Franklin County at 0027 UTC.

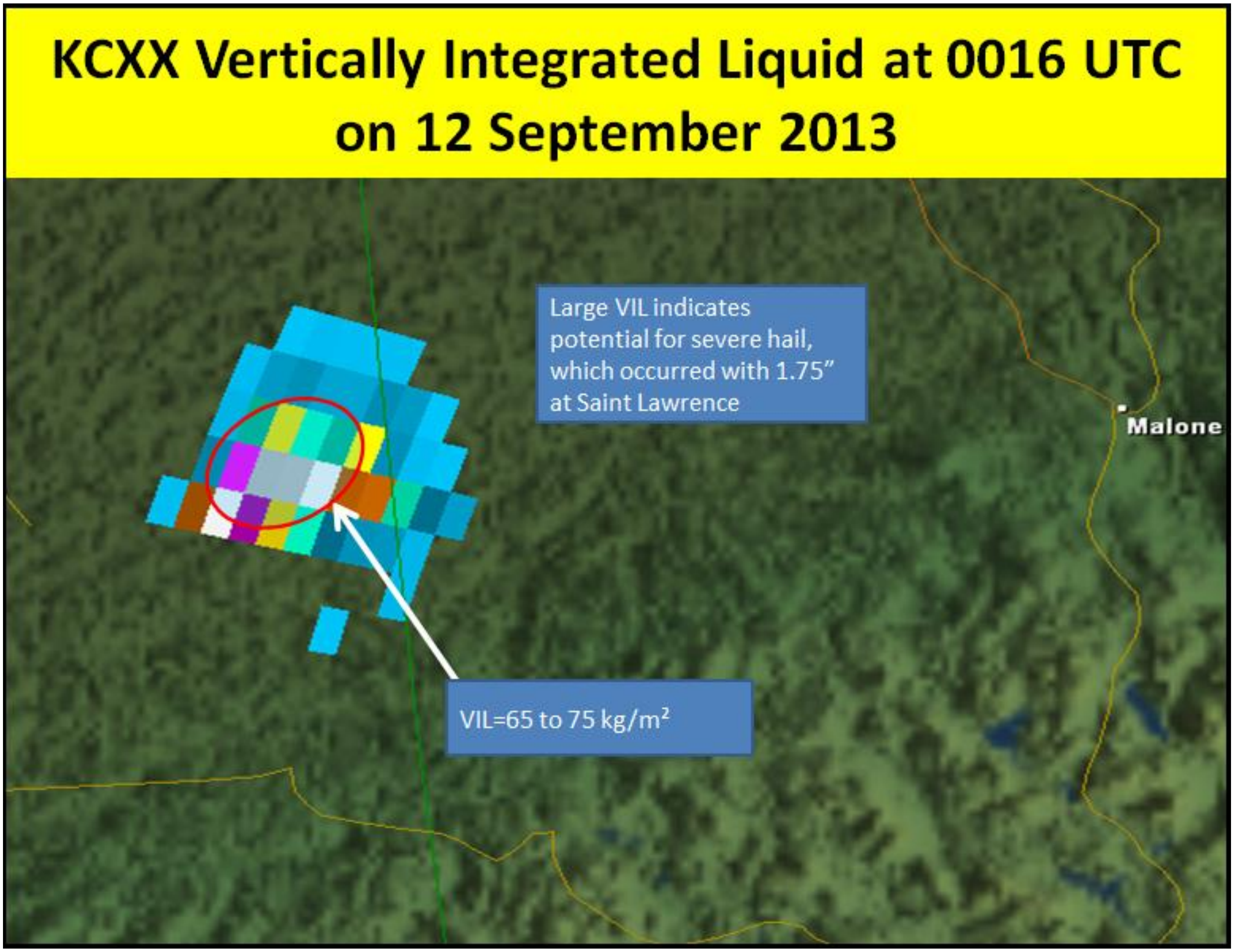

Figure 15: KCXX Vertically Integrated Liquid (VIL) at 0016 UTC on 12 September 2013.

5c.) Golf Ball Hail Alburgh, Vermont:

The final storm that we will investigate is the mini-supercell that would go on to produce golf ball size hail in the town of Alburgh, VT at 2130 UTC on 11 September 2013. This storm originated south of Montreal, but would move southeastward and track along extreme northern Grand Isle and Franklin Counties, adjacent to the U.S./Canada international border. Based on KCXX radar, this storm was actually at its most intense while tracking north of the international border. However, Figure 16 shows a Reflectivity Cross Section of the storm at 2123 UTC on September 11th, 7 minutes before the storm would produce golf ball size hail in Alburgh.

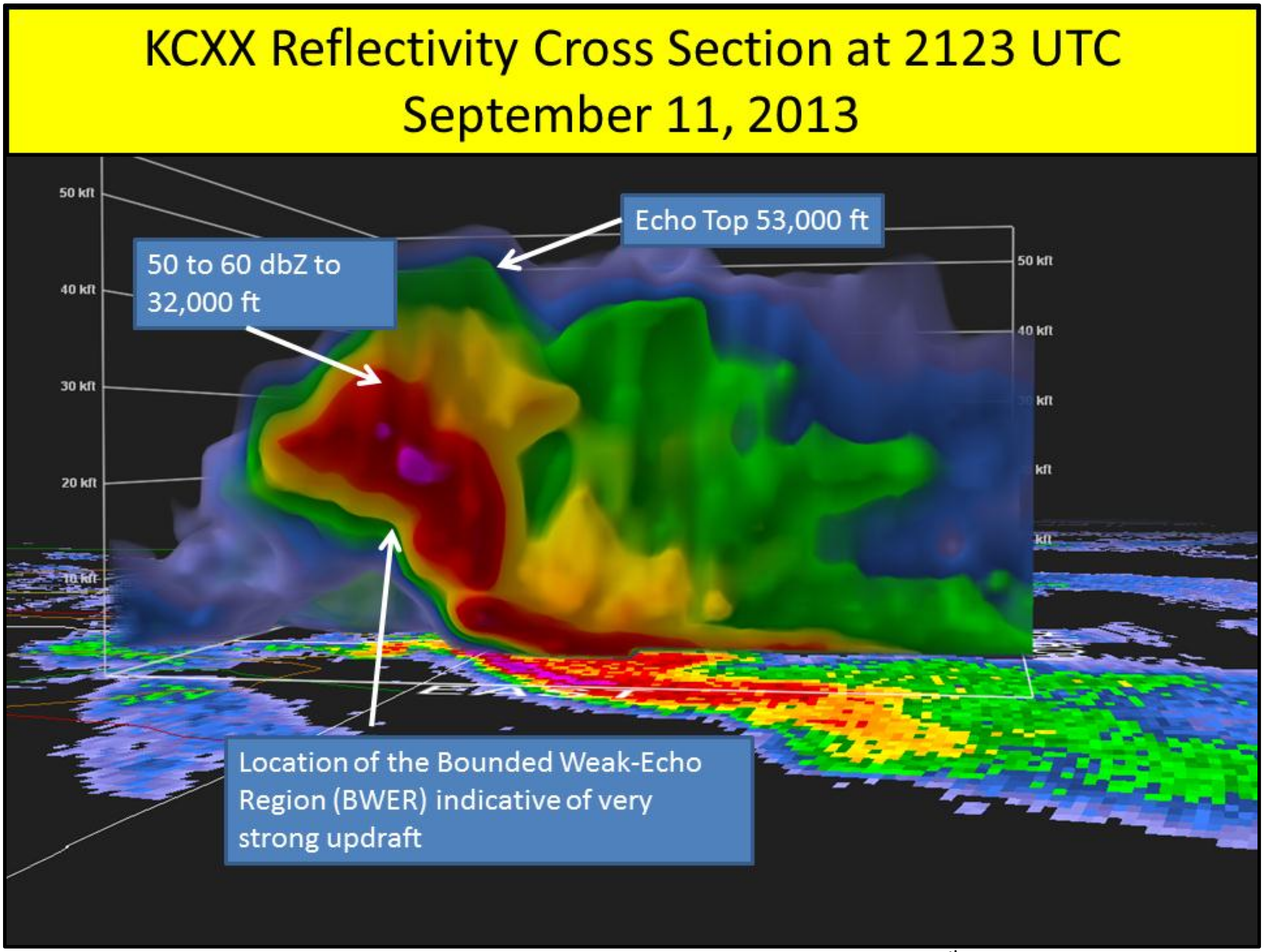

Figure 16: KCXX Reflectivity Cross Section at 2123 UTC September 11th, 2013.

Although the storm was stronger while in Canada, there are still a few indicators that the storm was still capable of producing severe weather. The Echo Top (ET) of this particular storm was around 53,000 ft. The storm's updraft remained strong, with 50 to 60 dBZ reflectivity core extending upward to 32,000 ft. Finally, there is evidence of what forecasters refer to as a Bounded Weak-Echo Region (BWER). In Figure 16, note how the strongest reflectivity core is elevated above an area where radar echoes are weak to non-existent. It is this region that is referred to as a BWER. You can compare Figure 16 to Figure 17, which is a classic example of a BWER. Meteorologists can infer that the updraft is so strong that it is able to suspend rain and/or hail aloft, and not fall to the ground (hence, the lack of echo returns below the strong reflectivity core). Storms that have this particular signature are capable of producing severe weather.

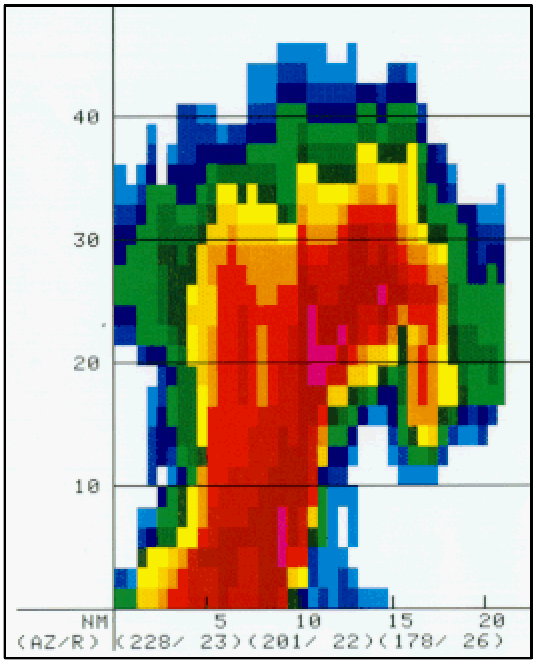

Figure 17: Reflectivity cross section of a Bounded Weak Echo Region (BWER).

6. Summary:

Several modes of severe weather took place in the September 11th, 2013 severe weather episode. These include a bow echo mesoscale convective system which produced numerous reports of damaging winds across central and southern Vermont, as well as mini-supercells which produced hail up to 2" in diameter. The atmosphere was ripe for the development of severe thunderstorms on this day with temperatures well into the 80s to lower 90s and dewpoints near 70, creating an unstable environment. An elevated mixed layer (EML) helped to steepen lapse rates in the mid-levels of the atmosphere and contribute to large instability values, and several jet streaks in the mid- to upper-levels of the atmosphere provided sufficient vertical shear necessary to maintain the persistence of severe thunderstorms. Figures 18 and 19 below show some photos that we received which show some of the large hail.

Figure 18: Large hail near North Lawrence in Saint Lawrence County. Photo taken by Nancy La Clair-Dimick

Figure 19: Golf ball hail at Louisville, NY.

References

Johns, R. H., 1993: Meteorological conditions associated with bow echo development in convective storms. *Wea. Forecasting*, **8**, 294-299.

Johns, R. H., and W. D. Hirt, 1987: Derechos: widespread convectively induced windstorms. *Wea. Forecasting*, **2**, 32-49.