Radar Artifacts and Associated Signatures, Along with Impacts of Terrain on Data Quality

1.) Introduction:

The WSR-88D (Weather Surveillance Radar designed and built in the 80s) is the most useful tool used by National Weather Service (NWS) Meteorologists to detect precipitation, calculate its motion, estimate its type (rain, snow, hail, etc) and forecast its position. Radar stands for "Radio, Detection, and Ranging", was developed in the 1940's and used during World War II, has gone through numerous enhancements and technological upgrades to help forecasters investigate storms with greater detail and precision. However, as our ability to detect areas of precipitation, including rotation within thunderstorms has vastly improved over the years, so has the radar's ability to detect other significant meteorological and non meteorological artifacts. In this article we will identify these signatures, explain why and how they occur and provide examples from KTYX and KCXX of both meteorological and non meteorological data which WSR-88D detects. KTYX radar is located on the Tug Hill Plateau near Watertown, NY while, KCXX is located in Colchester, VT with both operated by the NWS in Burlington. Radar signatures to be shown include: bright banding, tornadic hook echo, low level lake boundary, hail spikes, sunset spikes, migrating birds, Route 7 traffic, wind farms, and beam blockage caused by terrain and the associated poor data sampling that occurs.

2.) How Radar Works:

The WSR-88D operates by sending out directional pulses at several different elevation angles, which are microseconds long, and when the pulse intersects water droplets or other artifacts, a return signal is sent back to the radar. From this return signal, the diameter of the object, along with distance, and intensity can be calculated, along if the object is moving toward or away from the radar. Based on the power of return from these objects or targets a value is assigned to establish precipitation rate and intensity. The return power is measured in decibels or dBZ, with strong returns >65dBZ may indicate not only heavy rain but hail, strong winds, or tornadoes, while weaker returns (20 dBZ to 50 dBZ) may indicate moderate snow or rain, and returns <20 dBZ may suggests drizzle, light snow, or insects. However, sometimes radar can detect other non meteorological objects such as mountains, buildings, or wind farms, which cause power returns with different intensity levels. In the next section we will examine meteorological targets detected by radar and their associated signature.

3.) Meteorological Targets/Objects:

a.) Hook Echoes/Tornado Signature:

The first and one of the most important meteorological signatures detected by WSR-88D radar is the hook echo and the associated velocity signature couplet, which can produce tornadic storms. The hook echo is a classic signal of a potential tornadic producing supercell and is most frequent across the Central Plains, but occasionally can occur in the North Country. These kidney bean shape supercells generally exhibit a strong and tight reflectivity gradient on the southwest flank portion of the storm, in the formation of a hook. In conjunction with the hook echo, is typically a tight cyclonic velocity couplet of inbound (toward the radar) winds and outbound (away from the radar) winds, indicating potential tornadogenesis. Figure 1 below is the KCXX 0.9° base reflectivity, which clearly shows a well defined hook echo reflectivity structure associated with a supercell thunderstorm near Brookfield, VT on 16 July 2009. This supercell thunderstorm did produce an EF0 (Enhanced Fujita) tornado of winds of 55 to 70 mph across central Orange County, VT. The reflectivity structure is very similar to supercell thunderstorms across the central Plains, and would provide NWS warning meteorologists with good indications of a potential tornado.

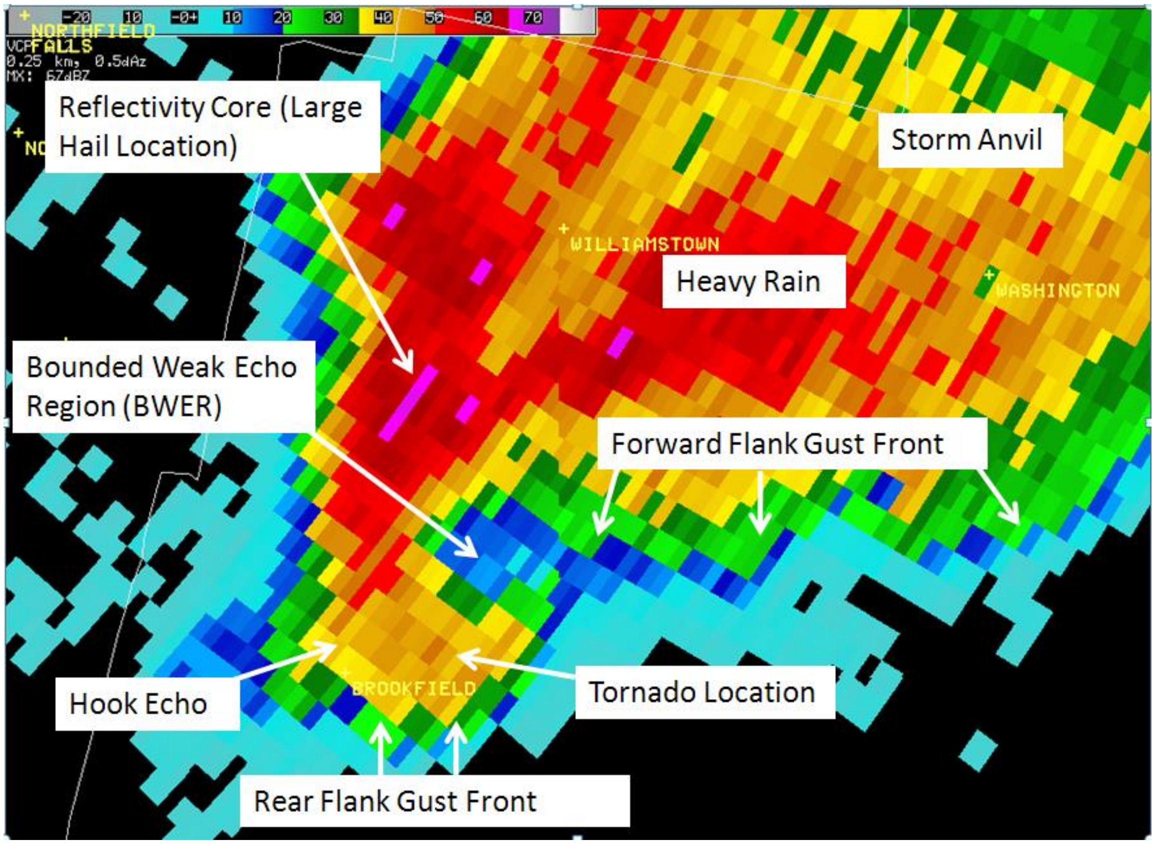
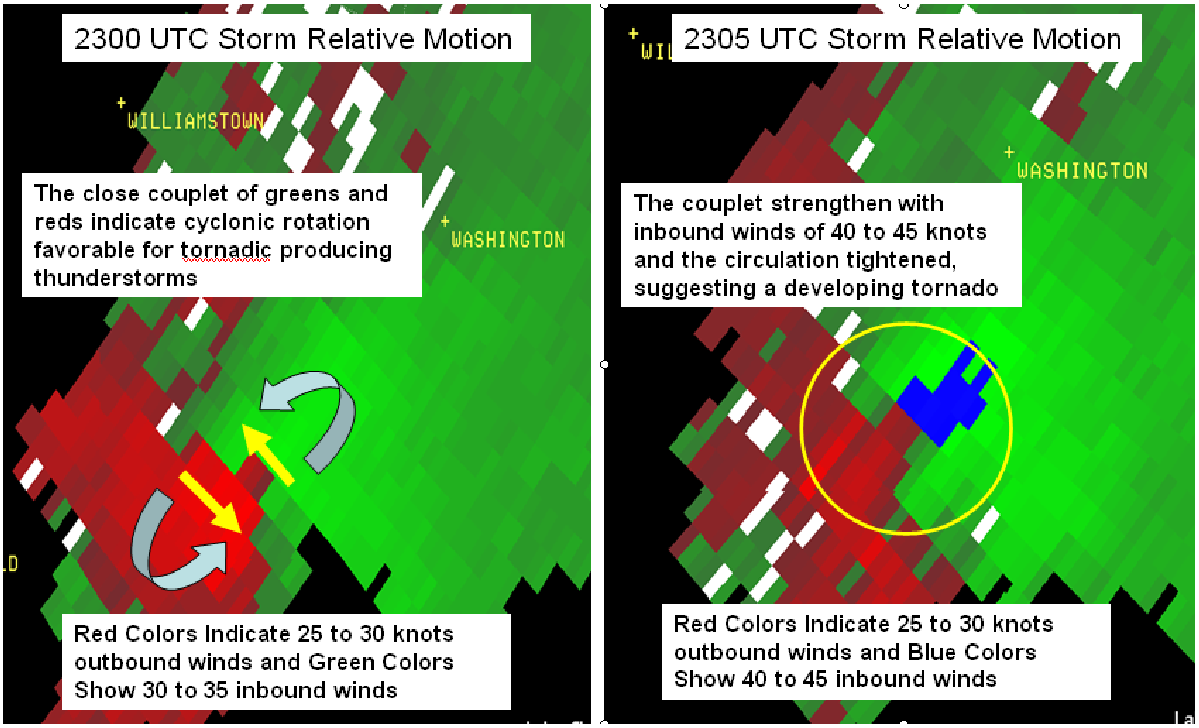


Figure 1: KCXX 0.9° Base Reflectivity of a Supercell Thunderstorm near Brookfield, VT on 16 July 2009 at 2300 UTC

Another very important radar product used by NWS meteorologists during severe weather warning operations is the storm relative motion or velocity data, which helps to determine storm rotation and the potential for producing a tornado. Figure 2 below shows the KCXX 0.9° storm relative motion product on 16 July 2009 near Brookfield, VT associated with a tornado producing thunderstorm. This product clearly shows a cyclonic gate to gate rotational couplet of inbound (green/blue colors) winds of 40 to 45 knots and outbound (red/orange colors) winds of 30 to 35 knots, indicating the potential for a tornado. This is a moderate signal of rotation and would alert NWS meteorologists, that Doppler radar is indicating a thunderstorm capable of producing a tornado. The closer the inbound and outbound couplet is, the smaller the diameter of circulation, and greater potential for a tornado.



2300 UTC Storm Relative Motion

The close couplet of greens and reds indicate cyclonic rotation favorable for tornadic producing thunderstorms

Red Colors Indicate 25 to 30 knots outbound winds and Green Colors Show 30 to 35 inbound winds

2305 UTC Storm Relative Motion

The couplet strengthen with inbound winds of 40 to 45 knots and the circulation tightened, suggesting a developing tornado

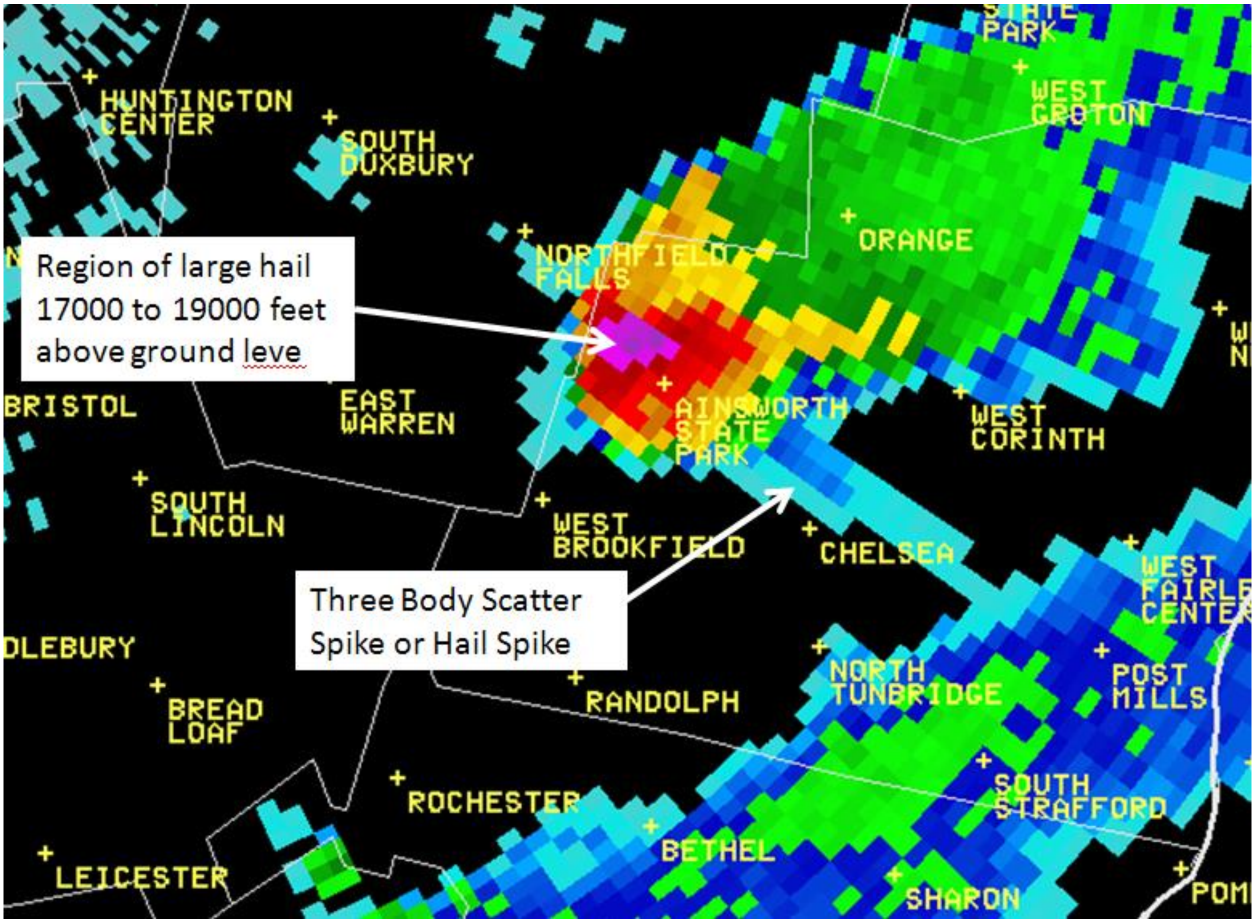
Red Colors Indicate 25 to 30 knots outbound winds and Blue Colors Show 40 to 45 inbound winds

Figure 2: KCXX 0.9° Storm Relative Velocity near Brookfield, VT 16 July 2009 at 2300 (left) and 2305 (right) UTC

b.) Hail Spike:

The next meteorological target we will discuss is the three body scatter spike (TBSS) or hail spike, which frequently indicates to warning meteorologist the potential for large hail. From the WIKI, “TBSS are the result of energy from the radar hitting hail and being deflected to the ground, then back to the hail and finally to the radar. The spike occurs because the energy took more time to go from the hail to the ground and back as opposed to directly from the hail to the radar. This results in the radar picking up the energy at a later time which places the echo further away from the radar than the actual location of the hail on the same radial path”.

Since hail cores are most intense in the storm core aloft, hail spikes only appear at the higher elevation scans that accompany the most intense hail. Another restriction to detection is that the signal of the radar beam has to do multiple reflections, each time weakening it. So hail spikes are usually noticeable only in extremely large hailstone cases. The development of a TBSS on radar, would likely indicate the potential for large, severe hail, and the NWS would issue a severe thunderstorm warning and mention the possibly of large hail in the warning. Figure 3 below shows KCXX 4.0° base reflectivity in western Orange County on 16 July 2009 at 2250 UTC. This figure clearly shows a hail spike line extending from the reflectivity core near Ainsworth State Park to Post Mills. This particular storm deposited numerous reports of large hail, with up to golf ball size reported near Brookfield, Vermont.



Region of large hail 17000 to 19000 feet above ground leve

Three Body Scatter Spike or Hail Spike

Figure 3: KCXX 4.0° Base Reflectivity Showing a Well Defined Hail Spike near Brookfield, VT on 16 July 2009 at 2250 UTC

c.) Low Level Boundary Detection:

Another very important feature detected by radar is low level boundaries, which can serve as focus areas for convective development or help forecasters identify an approaching surface front. Once convection develops, sometimes an outflow boundary or gust front is produced, and this can enhance low level shear or turning of the wind, and typically identifies the leading edge of rain cooled air and gusty winds, which can be detected by WSR-88D velocity and reflectivity products. Outflow boundaries can be seen as fine lines on WSR-88D, with weak reflectivity returns. The detection of low level boundaries can be difficult across complex terrain, due to poor radar sampling in the lowest elevation scans. Figure 4 below shows a composite mosaic reflectivity, along with 18 UTC surface observations on 25 August 2009. This image below clearly shows a weak defined Lake Champlain lake breeze boundary near Plattsburgh, New York, which is highlighted by the weak reflectivity returns and low level convergences of the surface winds.

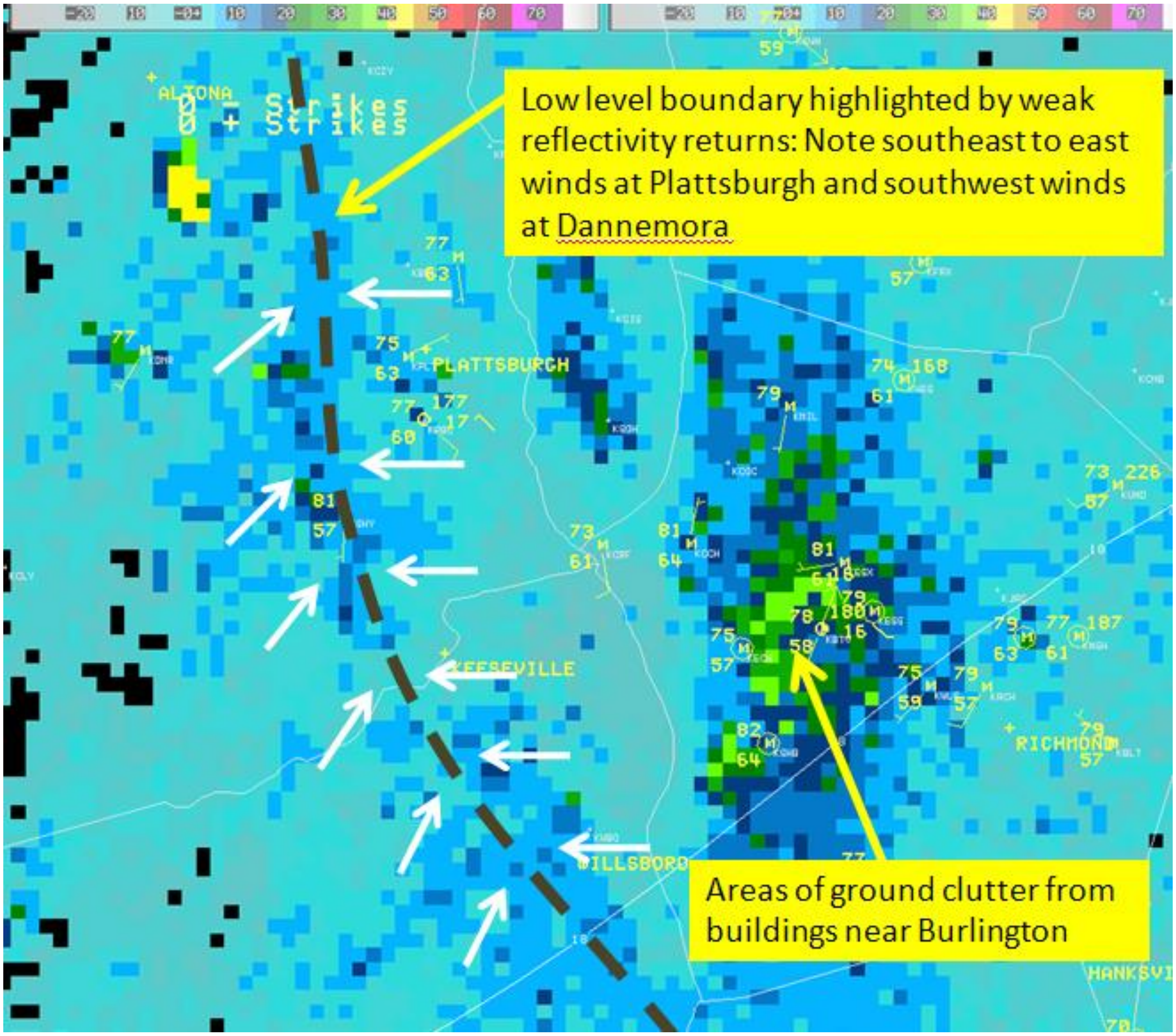
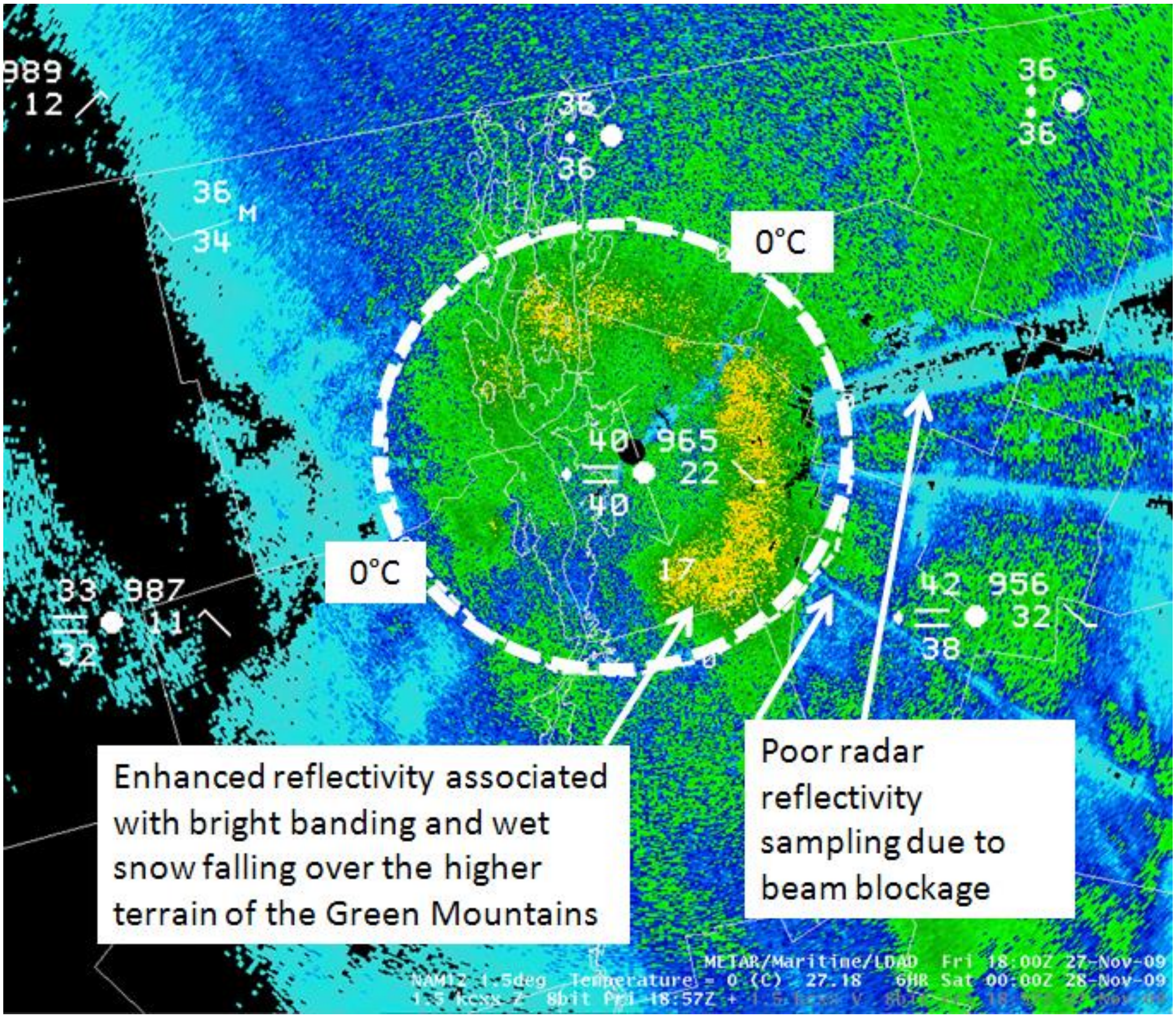


Figure 4: Composite Mosaic Reflectivity and METAR Surface Observations (Yellow) on 25 August 2009 at 1800 UTC

d.) Bright Banding (rain/snow line):

Figure 5 below shows the KCXX 1.5° base reflectivity, along with surface observations (white text), and the LAPS (Local Analysis and Prediction System) 0°C (Celsius) line (dotted white line). This image below clearly shows enhanced reflectivity in the darker green and yellow colors closely associated with the LAPS 0°C line. This enhanced reflectivity structure is called bright banding, and notifies to forecasters the elevation at which snow falling through the atmosphere is melting and turning to rain. This technique of identifying the bright banding signature is extremely helpful to forecasters in predicting snow levels and locations at which snow is falling versus rain, especially during early or late season snowstorms, when the valleys are typical warmer and receive mostly rain. Also, note in the radar image below the stronger reflectivity (darker green and yellow colors) returns are occurring mostly along the spine of the Green Mountains, where the elevation increases quickly. By using the sampling tool and area soundings, forecasters can quickly determine the exact elevation of the rain/snow line, which greatly helps in predicting the location and amount of potential snowfall in the higher elevations.



Enhanced reflectivity associated with bright banding and wet snow falling over the higher terrain of the Green Mountains

Poor radar reflectivity sampling due to beam blockage

Figure 5: KCXX 1.5° Base Reflectivity, METAR Surface Observations (white) and LAPS 0°C line (white) on 27 November 2009 at 1800 UTC

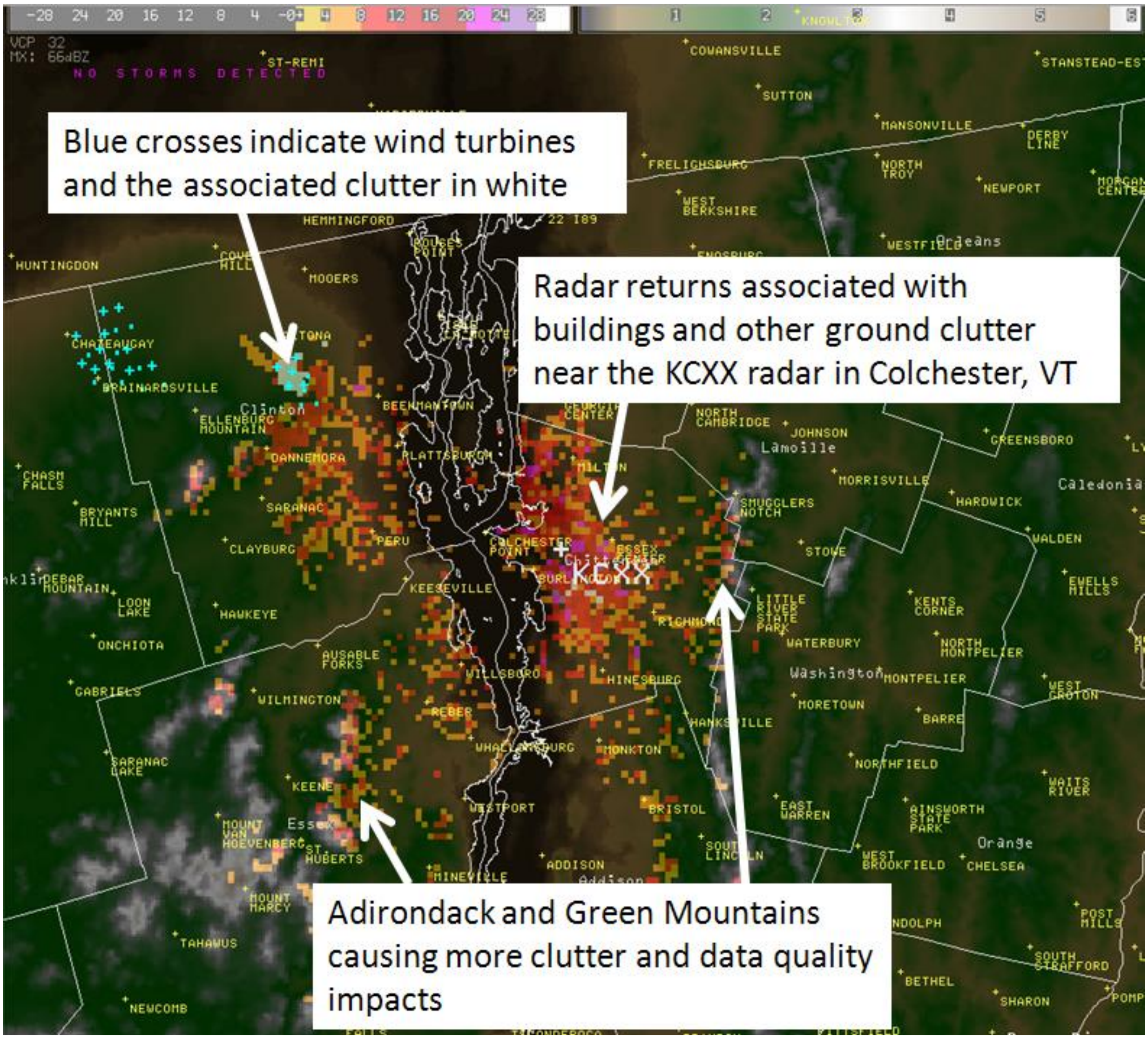
4.) Non Meteorological Targets/Objects:

In this next section we will discuss non meteorological targets and objects which are detected by NWS WSR-88D radar, such as mountains, buildings, wind farms, sun spikes, migrating birds, and traffic along with their associated signals. These non meteorological objects can impact both the reflectivity and velocity data. Furthermore, these objects can produce anomalously high precipitation estimates if the incorrect clutter suppression or precipitation exclusion zones are used. Meteorologists must continuously monitor the radar for potential ground clutter and the associated impacts.

a.) Mountains/Buildings Impacts:

The first non meteorological target we will examine which is detected by our KCXX radar in Colchester, Vermont is clutter produced by mountains and buildings. This clutter is detected everyday by the radar and can severely impact data quality, especially if incorrect clutter suppression maps are used. During strong low level temperature inversion (warmer air above a cold dome close to the surface) the radar beam is refracted or bends back toward the earth’s surface, causing an increase in anomalous propagation (AP). This produces persistent and quasistationary returns of high reflectivity, which can result in over-estimates of (false) precipitation accumulation. This has more operational impact and is more difficult to suppress when AP echoes are imbedded in precipitation echoes.

Removing all clutter detected by the radar is extremely difficult to achieve, especially associated with wind farms, because of the movement of the wind turbines. This movement and detection can greatly influence precipitation estimates and velocity data. Figure 6 below shows the KCXX composite reflectivity with topography as the background image and the blue crosses indicate wind turbines. From the image below you can see increased reflectivity returns across the Champlain Valley, especially near the KCXX radar site in Colchester, VT from buildings and other non meteorological objects. In addition, more reflectivity returns are generated from the wind farm in central Clinton County and from the Adirondack and Green Mountains. As you increase the distance from the radar, less ground clutter is detected due to the radar beam being higher above the ground and passing above the obstructions. This ground clutter caused by the mountains, buildings, and wind farms is very persistent and does not move through time; therefore we can invoke precipitation exclusion zones to prevent the accumulation of precipitation from occurring. When precipitation is occurring sometimes it’s difficult to determine the regions of ground clutter from areas of precipitation.



Blue crosses indicate wind turbines and the associated clutter in white

Radar returns associated with buildings and other ground clutter near the KCXX radar in Colchester, VT

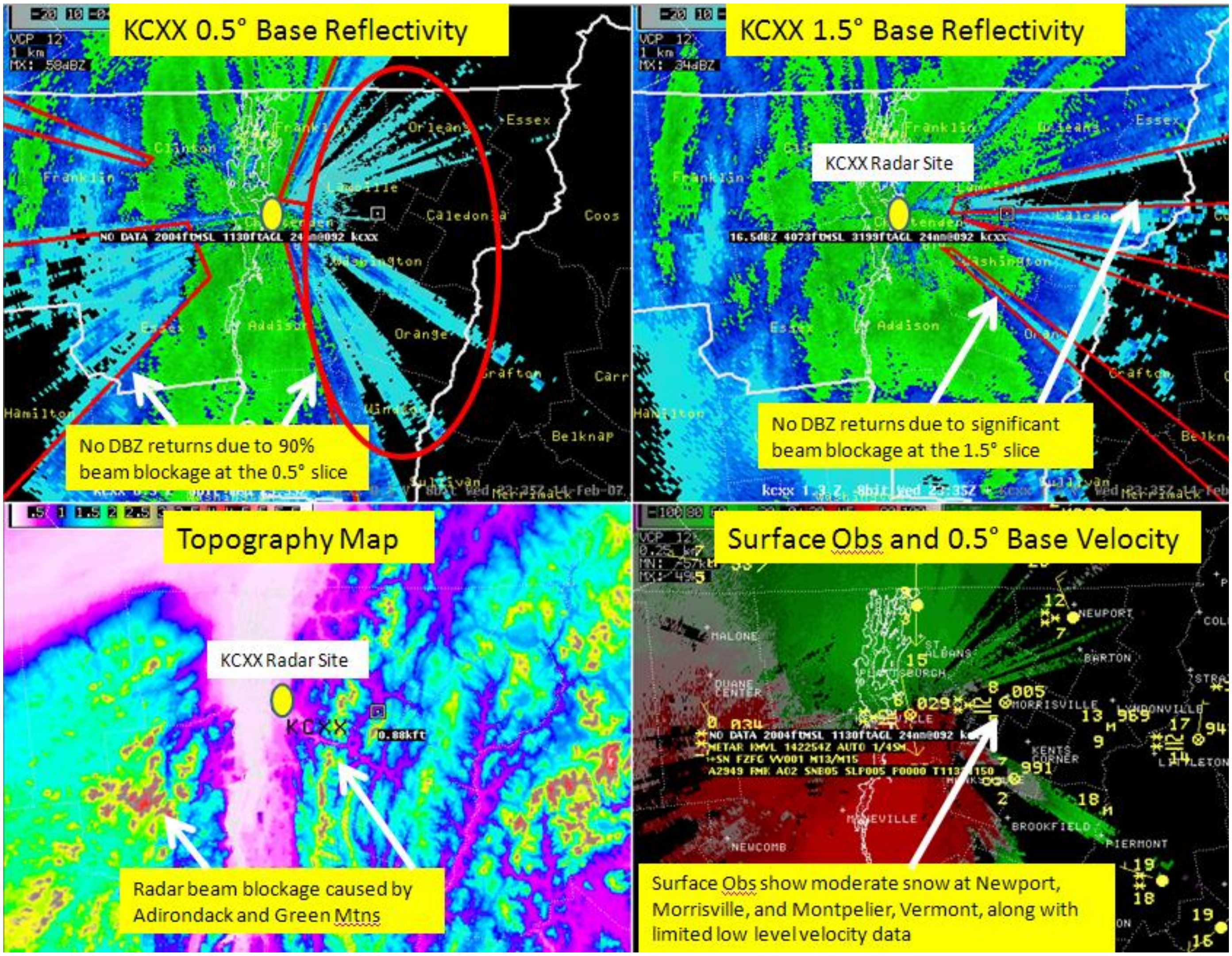
Adirondack and Green Mountains causing more clutter and data quality impacts

Figure 6: KCXX Composite Reflectivity with Topography (background image) and Wind Turbines (blue crosses)

b.) Beam Blockage by Mountains:

Given the position of the KCXX radar located in Colchester, VT, which is in the Champlain Valley and surrounded by the Green Mountains to the east and the Adirondack Mountains to the west, a significant amount of beam blockage occurs, especially in the lowest elevation scans. This considerably reduces data sampling in the 0.5°, 0.9°, 1.3°, and 1.5° elevation scans across central, eastern, and northern Vermont, as well as parts of the northern Adirondack Mountains. Meteorologists especially notice a reduction in dBZ returns during light to moderate snow events, because the vertical development of snow is much less and takes place closer to the surface, where radar coverage is limited and higher elevation scans over shoot the precipitation. Many times you will see moderate snow falling at such places like Newport or Morrisville, Vermont, but the radar is showing very weak or no radar returns, due to the beam blockage caused by the mountains. Figure 7 below shows the KCXX 0.5° Base Reflectivity (Upper Left), Topography Map (Lower Left), KCXX 1.5° Base Reflectivity (Upper Right) and Surface Observations and KCXX 0.5° Base Velocity (Lower Right). From this figure you can clearly see the beam blockage which occurs across central , eastern, and northern Vermont, as well as parts of the northern Adirondack Mountains in New York, resulting in much less activity being detected by the radar. In addition, the velocity data is poorly sampled in the example below, with no winds being detected in the blockage area, which makes determining winds with thunderstorms very difficult. In addition, a significant reduction in storm total precipitation results from this poor radar sampling, which can greatly impact hydro operations during the summertime.

The red circle and red squares across northern New York and eastern Vermont in figure 7 (upper left) shows the large area with nearly 90% beam blockage in the 0.5° base reflectivity scan. The upper right image is the 1.5° base reflectivity, with the red squares showing areas of reduced precipitation caused by Mount Mansfield and Camel’s Hump of the Green Mountains. Notice no beam blockage occurs over northern New York at the 1.5 slice, because the beam is propagating above the mountains, which are at a greater distance from the radar. Note the observations at Newport and Morrisville, Vermont indicates moderate snow is falling, but the radar shows limited activity over this region, especially in the 0.5° base reflectivity.


KCXX 0.5° Base Reflectivity

No DBZ returns due to 90% beam blockage at the 0.5° slice

KCXX 1.5° Base Reflectivity

KCXX Radar Site

No DBZ returns due to significant beam blockage at the 1.5° slice

Topography Map

KCXX Radar Site

Radar beam blockage caused by Adirondack and Green Mtns

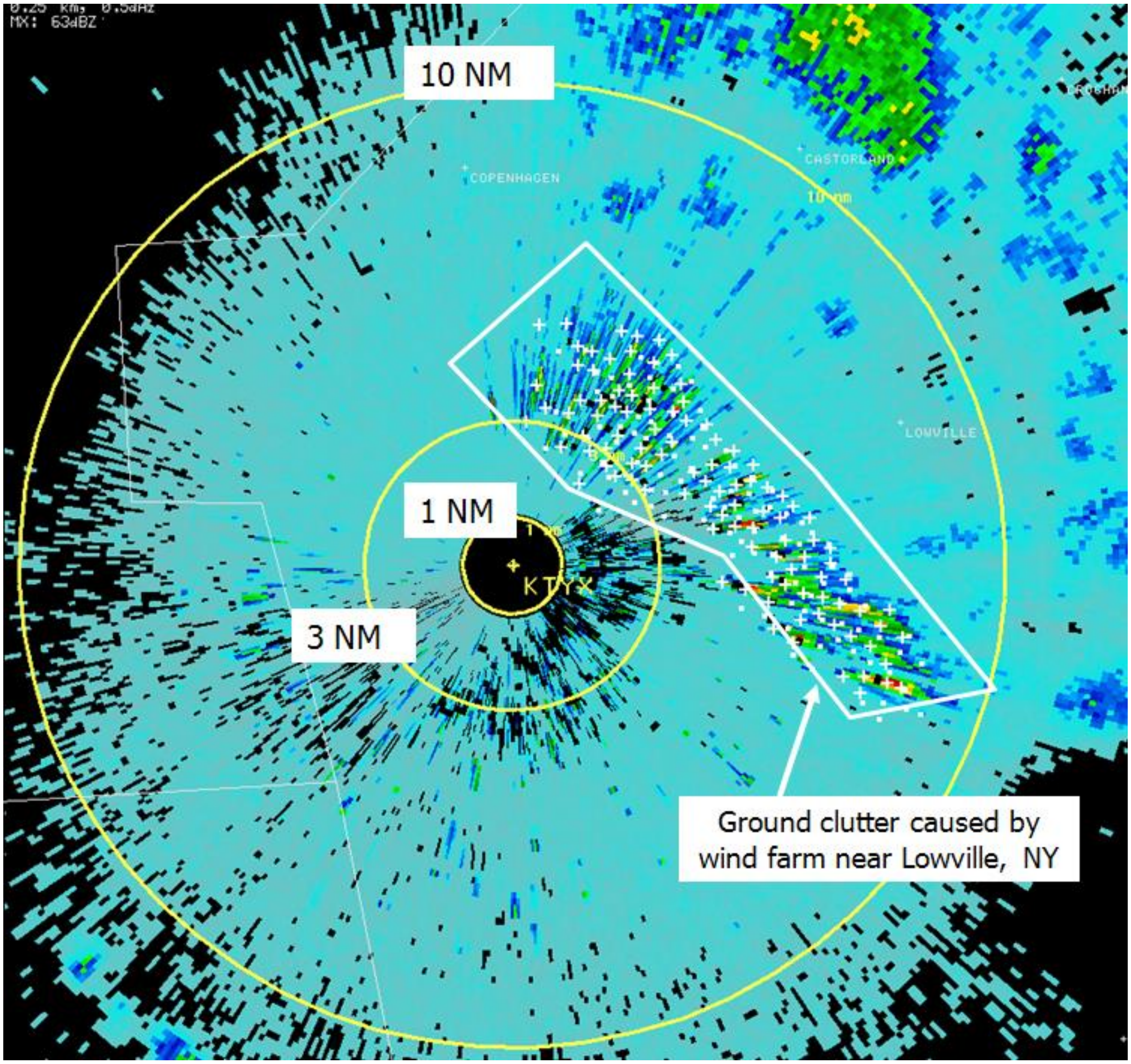
Surface Obs and 0.5° Base Velocity

Surface Obs show moderate snow at Newport, Morrisville, and Montpelier, Vermont, along with limited low level velocity data

Figure 7: KCXX 0.5° Base Reflectivity (Upper Left), Topography Map (Lower Left), KCXX 1.5° Base Reflectivity (Upper Right) and Surface Observations and KCXX 0.5° Base Velocity (Lower Right)

c.) Wind Farms:

Figure 8 below is a composite reflectivity image from the KTYX radar near Montague NY on the Tug Hill Plateau, with wind turbines (white crosses) and range rings (yellow circles). From the image you can see the wind farm is located between 2 nautical miles and 10 nautical miles from the KTYX radar, which greatly impacts the radar data. Given the wind turbines move, but the towers are stationary, both velocity and reflectivity data is impacts with areas of ground clutter being detected. In addition, the return signal power from the wind turbines greatly reduces the radars ability to detect precipitation returns downstream across the western Adirondack Mountains, which can reduce radar rainfall estimates. The brighter greens and yellows from figure 8 below suggest stronger reflectivity returns caused by the wind farm near KTYX radar.



Ground clutter caused by wind farm near Lowville, NY

Figure 8: KTYX near Montague, NY Composite Reflectivity (Image) with Wind Turbines (white crosses) and Range Rings (yellow circles)

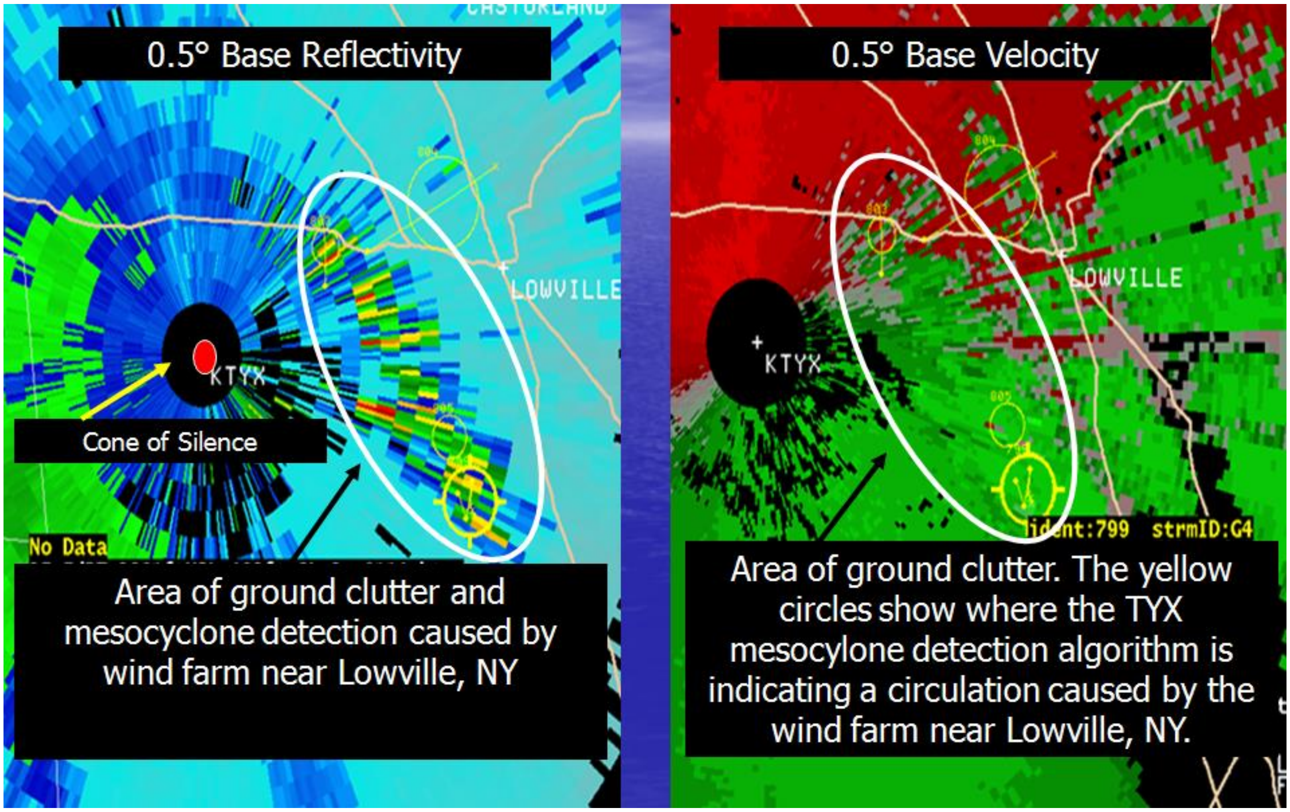


Figure 9: KTYX 0.5˚ Base Reflectivity with Mesocylones (yellow circles) Left Image and KTYX 0.5˚ Base Velocity with Mesocylones (yellow circles) Right Image

Figure 9 shows KTYX 0.5˚ base reflectivity with mesocylones (yellow circles) left image and KTYX 0.5˚ base velocity with mesocylones (yellow) right image and clearly shows the impacts caused by the wind farm located near the radar. These images show the clutter produced by the wind farms, along with the poor velocity data, with the mesocylone detection alogirthm highlighting a circulation by the yellow circles. Furthermore, the wind farm blocks the beam from downstream locations, which results in limited detection of precipitation and velocity signatures in the lowest level scans. This greatly impacts the magnitude of velocity signatures and strenght of reflectivity returns in the lowest elevation scans. During severe weather events, radar warning meteorologists must be aware of the wind farms and potential impacts to the radar data quality. Invoking clutter suppression maps to remove the erroranous returns is nearly impossible due to the closness to the radar and movement of the turbines. We have produced numerous precipitation exclusion zones in and around the wind farm to prevent erroranous precipitation amounts from accumulating.

d.) Sunrise/Sunset Spikes:

In this section we will discuss sunrise and sunset spikes detected by the WSR-88D radar network. These spikes occur twice a day, once at sunrise and again at sunset. The radar experiences interference from the energy emitted by the sun, especially during sunrise and sunsets when the radar dish points directly at the sun. Figure 10 below is a northeast composite radar mosaic, which clearly shows several sunset spikes. Notice in the image below that the sunset is slightly north of due west, because of the August 17th date, meanwhile in wintertime the sun spikes will set slightly south of due west. On the fall and spring equinox the sun will set due west.

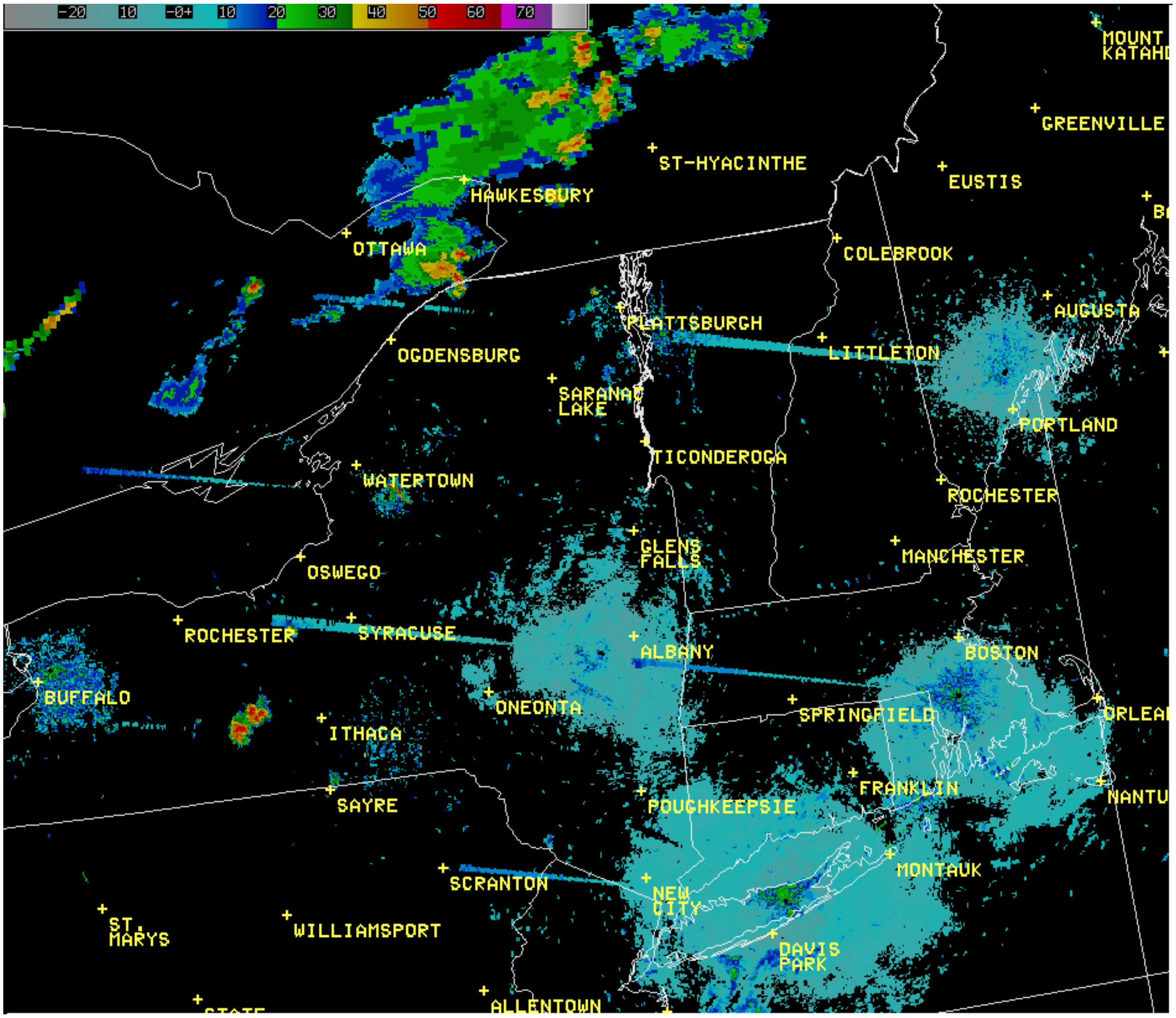


Figure 10: Northeast Mosaic Radar Composite Reflectivity 17 August 2009 at 738 PM EDT and the Associated Sunset Spikes

e.) Migrating Birds:

In the following section we will briefly discuss the pattern detected by radar from migrating birds. These signatures are most common in the fall months when bird gather for seasonal migration, and typically occur around bodies of water, which usual have temperatures warmer than the surrounding land at night. At night, birds rest and nest in and around bodies of water. Just before sunrise, there is often a coordinated lift off and dispersion of the birds out into the surrounding fields for feeding during the day or migration south. Figure 11 below is a KTYX 0.5˚ base reflectivity loop on 1 August 2010 from 239 AM EDT to 616 AM EDT, showing a circular reflectivity pattern near the head of the Saint Lawrence River Valley associated with birds lifting off around sunrise. The signature develops around 530 AM EDT (930 UTC) and continues to spread out in a circular pattern for the next several volume scans. The birds act as a target and reflect energy back to the radar, which results in reflectivity signatures being displayed on the radar as if it was precipitation. In the radar loop you can see the initial reflectivity returns are in a very concentrated area, but spread out through time, as the birds disperse from their nesting grounds.

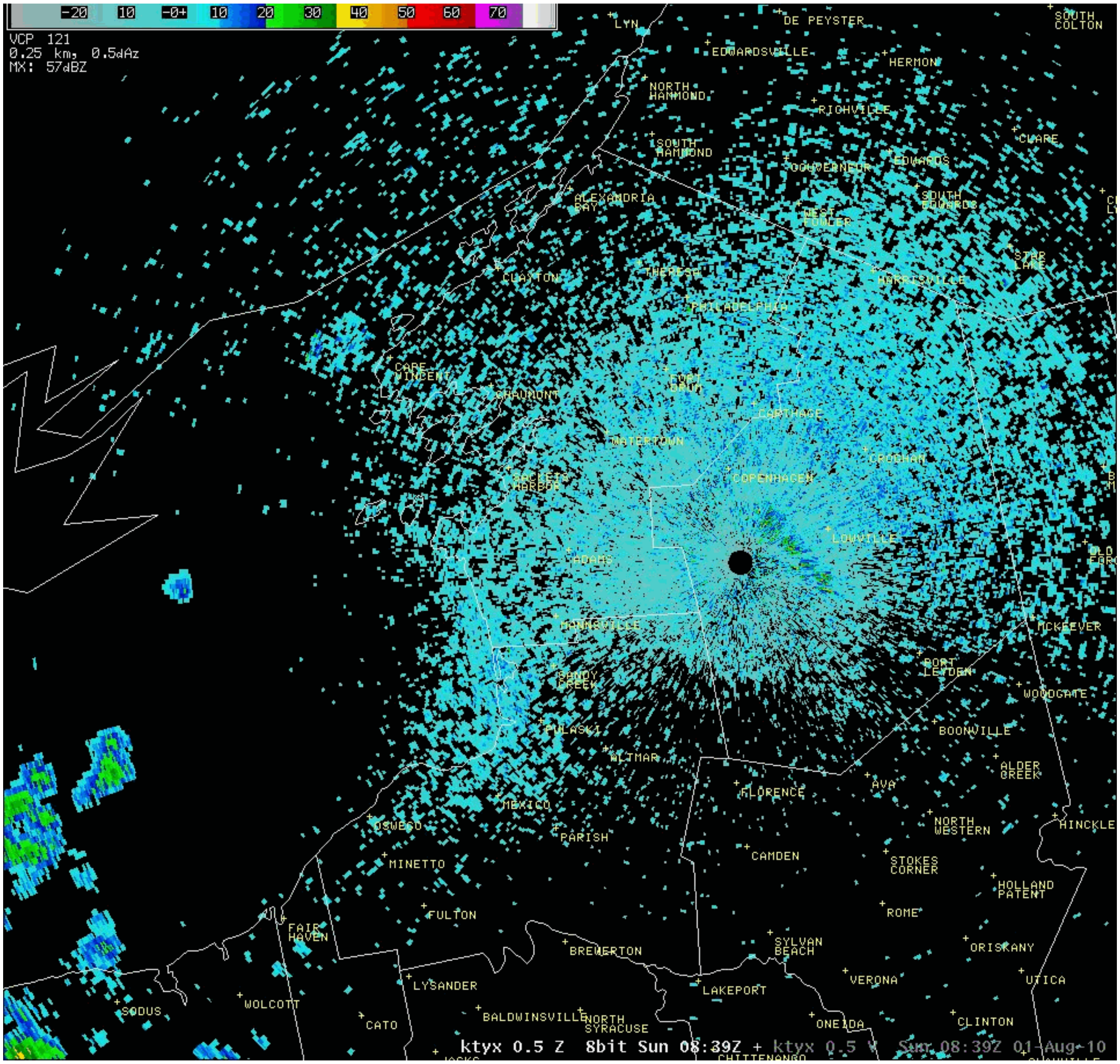
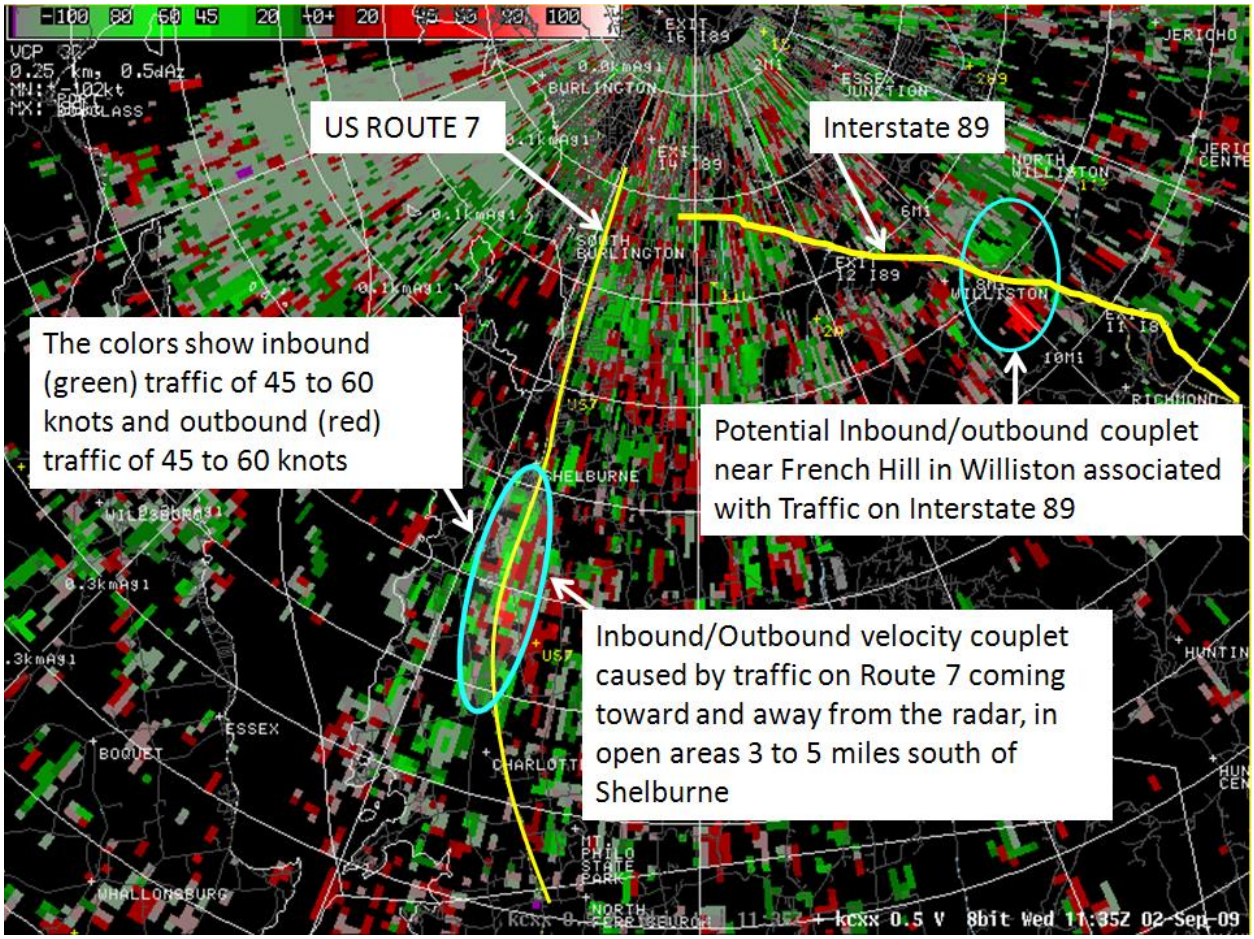


Figure 11: KTYX 0.5˚ Base Reflectivity Loop on 1 August 2010 from 239 AM EDT to 616 AM EDT

f.) Route 7 Traffic:

In the final section we will briefly discuss the WSR-88D's ability to detect traffic moving toward and away from the radar. Figure 12 below shows the KCXX 0.5˚ velocity data along with Route 7 and Interstate 89 highlighted in yellow lines. The green colors on the image below indicate air moving toward the radar, while the red colors denote air moving away from the radar. Note the light blue circles, highlighting inbound and outbound velocities associated with traffic moving toward and away from the radar on Route 7 and Interstate 89. This couplet occurs just south of Shelburne where there is a slight increase in surface elevation of Route 7, and along Interstate 89 just east of Williston, VT near French Hill. This increase in surface elevation helps the radar beam detect objects very close to the ground, especially when the radar is scanning in the lowest degree slice. These inbound and outbound couplets have to be recognized by our meteorologists, and not be confused with actual storm rotation during severe weather events.



The colors show inbound (green) traffic of 45 to 60 knots and outbound (red) traffic of 45 to 60 knots

Potential Inbound/outbound couplet near French Hill in Williston associated with Traffic on Interstate 89

Inbound/Outbound velocity couplet caused by traffic on Route 7 coming toward and away from the radar, in open areas 3 to 5 miles south of Shelburne

Figure 12: KCXX 0.5˚ Velocity with Route 7 and Interstate 89 (yellow lines)

The WSR-88D radar obtains weather information (precipitation and wind) based upon returned energy. The radar emits a burst of energy and if the energy strikes an object (rain drop, snowflake, hail, bug, bird, traffic, etc), the energy is scattered in all directions; with a small fraction of the emitted energy traveling directly back toward the radar. The structure and location of the returned energy, along with the reflectivity or velocity signature helps meteorologists determine if the object is a meteorological or non meteorological target and the potential threat. It's extremely important to have proper radar training and knowledge of these targets, especially during warning operations. The WSR-88D is an extremely useful tool in the protection of life and property, in which NWS meteorologists use every day. As you can see, mountains greatly impact the quality of data sampling, especially in the lowest elevation scans, which makes for difficulties in determining the intensity or amount of precipitation falling and strength of the wind. NWS meteorologists at WFO BTV continue to work with these radar issues, while providing the citizens of the North Country with the best possible warnings of potentially upcoming hazardous weather.

References:

Information on radar and how Doppler Radar works:
http://www.srh.noaa.gov/jetstream/doppler/doppler_intro.htm

WIKI Page on Doppler Radar:
http://en.wikipedia.org/wiki/Weather_radar