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The Use of Collapsing Specific Differential Phase Columns to Predict Significant Severe Thunderstorm Wind Damage across the Northeastern United States

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ABSTRACT

The Storm Prediction Center (SPC) considers severe thunderstorms that produce measured or estimated wind gusts of at least 33.4 ms^{-1} (65 kt), hail 5.08 cm (2 in) in diameter or greater, or an EF2 or greater tornado to be significant. Pinpointing which particular severe thunderstorms will produce significant severe weather events can be a difficult challenge for the warning decision forecaster. Out of the 1423 severe wind reports received by the NWS Albany between 1 January 2012 and 31 December 2017, only 46 (about 3%) were considered significant. However, these particular storms had a major impact on the lives of many people in the region and these storms received a large amount of media attention. Doppler radar radial velocity data may not always provide a clear picture of a storm's severity due to inherent problems regarding the radar beam's height and angle. As a result, forecasters need to rely on something other than just radial velocity during radar interrogation.

This study examined the use of the dual-polarization product Specific Differential Phase (K_{DP}) during radar interrogation to diagnose the potential of significant severe thunderstorm winds. When examined in vertical cross-sections, elevated strong cores of K_{DP} were shown to lower towards the surface just prior to the reports of significant severe thunderstorm wind damage in 30 of 46 cases across the NWS Albany forecast area. This was statistically significant when compared with an examination of K_{DP} cores from 51 ordinary (non-significant) severe storms during the same case days. The use of K_{DP} columns can be a successful method to help forecasters predict when significant severe wind damage will occur, resulting in better lead times and more detailed information for impact-based severe thunderstorm warnings.

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1. Introduction

The Storm Prediction Center (SPC) considers severe thunderstorms that produce winds 33.4 ms^{-1} (65 kt) or greater, hail 5.08 cm (2 in) or larger in diameter, or an EF2+ tornado to be significant. Of the 1402 severe wind damage reports (50 kt or greater) received by the Albany NY Weather Forecast Office (WFO) between 1 January 2012 and 31 August 2017, about 3% (46) were considered significant and/or caused injuries. Despite being a rare occurrence, these events have had a large societal impact, receiving extensive media coverage and typically being more costly than low-end severe thunderstorm events (NOAA 2019).

Since 1 October 2016, the NWS has been using impact-based warnings nationally for severe thunderstorms and tornadoes. This updated warning format was developed based on results of the 2011 Joplin tornado service assessment, to help the public, media and emergency managers get clear and detailed information about the specific threats from imminent severe weather (U.S. Department of Commerce 2011). Under this new format, specific thunderstorm wind gust speeds and expected damage impacts are included within the warning text. Figure 1 provides an example of a severe thunderstorm warning, with the bulleted format displaying expected wind gusts and impacts.

Local research at WFO Albany over the past several years has helped improve knowledge on the potential for large hail (Frugis and Wasula 2011, Lee 2015) by using the critical reflectivity dBZ heights and examining dual-polarization parameters, but these techniques do not provide any information to help anticipate thunderstorm wind gust speeds. Studies have also been conducted, both nationally and locally, to help determine the potential strength of tornadic activity (Entremont and Lamb 2015).

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The National Weather Service in Albany has issued a

* Severe Thunderstorm Warning for...
  Southeastern Warren County in east central New York...
  Saratoga County in east central New York...
  Southeastern Fulton County in eastern New York...
  Central Washington County in east central New York...

* Until 815 PM EDT

* At 710 PM EDT, severe thunderstorms were located along a line
  extending from Lake Luzerne Campground to 6 miles east of Edinburg
  to Gloversville, moving east at 30 mph.

  HAZARD...60 mph wind gusts and quarter size hail.

  SOURCE...Radar indicated.

  IMPACT...Hail damage to vehicles is expected. Expect wind damage
           to roofs, siding, and trees.

* Severe thunderstorms will be near,
  Lake Luzerne Campground and Lake Luzerne-Hadley around 715 PM EDT.
  Lake George Village around 720 PM EDT.
  Glens Falls, Corinth, Glens Falls North and West Glens Falls
  around 725 PM EDT.
  Fort Edward and Northampton Beach Public Campground around 730 PM
  EDT.
  Hudson Falls around 735 PM EDT.
  Galway around 745 PM EDT.
  Hartford and Rock City Falls around 755 PM EDT.
  Milton, Ballston Spa, Greenwich and North Ballston Spa around 800
  PM EDT.

Other locations impacted by these severe thunderstorms include Parkis
Mills, Meco, Sweets Crossing, Lake Luzerne, Grangerville, West
Milton, Glenwild, Northumberland, Greenfield Center and Wiley
Corners.

PRECAUTIONARY/PREPAREDNESS ACTIONS...
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Figure 1. An example of an impact-based severe thunderstorm warning from 18 May 2017.

Determining specific thunderstorm wind gust speeds can be challenging for a warning decision meteorologist. Research on radar signatures associated with damaging wind gusts greater than 50 kt has focused on reflectivity patterns such as bow echoes and rear inflow notches (Houze et al. 1989, Przybylinski 1995), and velocity patterns such as meso-vortices (Trapp et al. 2003, Atkins et al. 2009) and Mid-Altitude Radial Convergence (MARC) zones (Schmocker et al. 1996). Note that the MARC has the same problems associated with any velocity product; that is, you need to have a good viewing angle to properly identify a MARC. However, little research has been attempted to assess signatures associated specifically with significant wind damage from wind speeds greater than 65 kt.

There are several challenges associated with using radial velocity alone as a warning indictor for severe thunderstorms, such as issues with beam broadening, beam height, beam angle and blockage from terrain (discussed in more detail in section 3). Taking these challenges into consideration, other datasets need to be examined to help make warning decisions regarding expected severe thunderstorm wind gust speeds and give the forecaster some indication to discriminate which storms will produce stronger winds compared to others.

2. Significant severe thunderstorm climatology results

Although previous local research associated with the Collaborative Science, Technology and Applied Research (CSTAR) project has focused on diagnosing tornado potential (Frugis and Wasula 2013), significant severe thunderstorms occur more often across the Northeastern United States. For this study, the Northeastern United States is considered to be New England, New York (NY), New Jersey (NJ), Delaware (DE), northeastern Maryland (MD), central and eastern Pennsylvania (PA). In addition to the SPC criteria for being a significant severe thunderstorm event, this study will also include any event that causes injuries or fatalities to be considered a significant event, as saving lives is the primary mission for NWS meteorologists.

Figure 2 shows the climatology of significant severe thunderstorms by events for the Northeastern United States from 2012 to 2019, when dual polarization-radar products became readily available. Significant severe wind events occur far more frequently than significant hail or EF-2 tornadoes across the Northeast. In addition, significant severe winds occur nearly twice as often as compared to *any* tornadic events across the Northeast between 2012 and 2019 (shown in Figure 3) with 409 events in total.

3. Radar limitations and considerations

When using Doppler radar for warning decisions, the warning decision meteorologist must keep several items in mind. First, the altitude of the centerline of the radar beam steadily increases with range away from the antenna. The 0.5° radar elevation slice will be centered around 1800 m (5905 feet) above ground level (AGL) at 70 nm from the radar site. Because of this, there is a portion of the storm below the beam that is not being sampled by the radar. Figure 4 shows the change in beam height with range from the radar site. The beam also broadens with range from radar, as adjacent radar bins become further apart. As a result, the sample volume of radar range bins increases with increasing range from the radar.

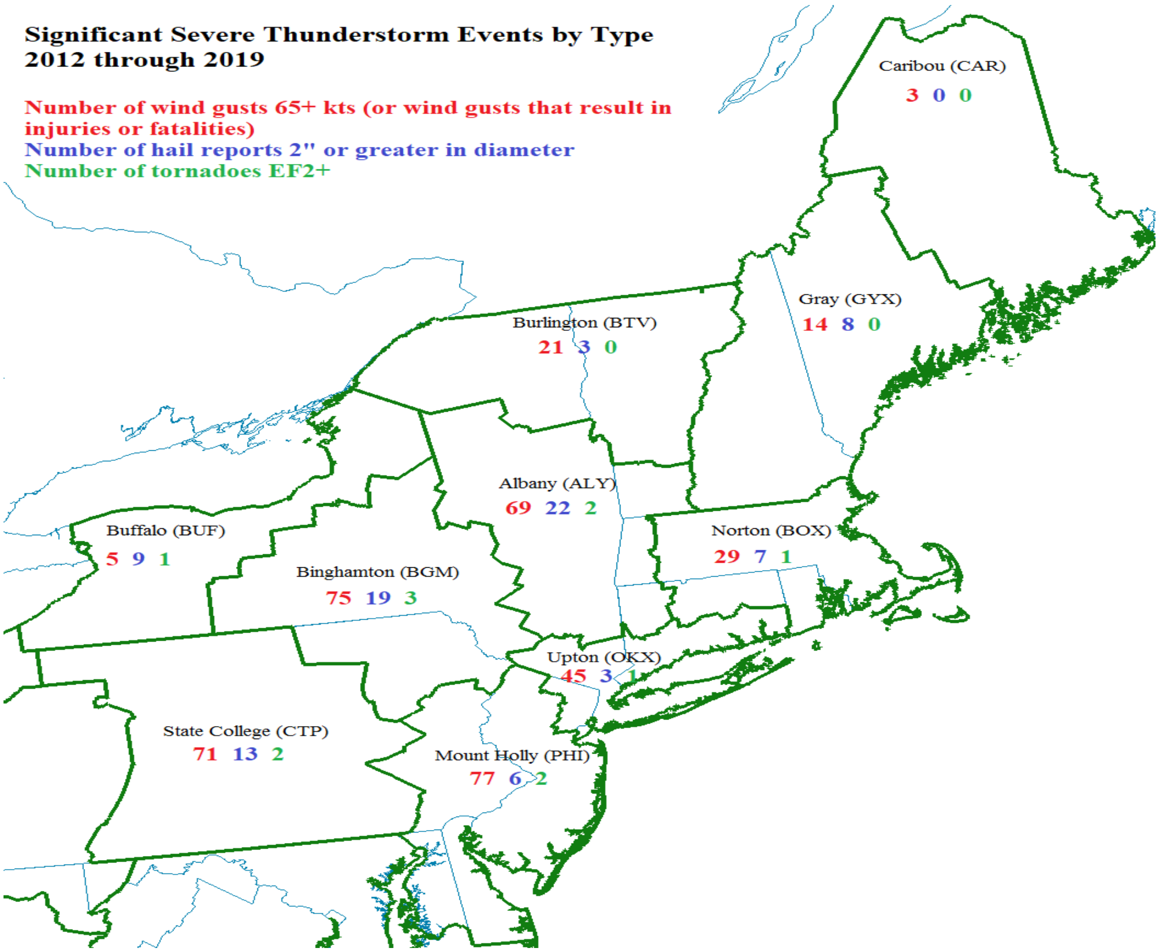

Figure 2. Climatology of significant severe thunderstorms across the Northeastern United States by weather forecast office county warning areas.

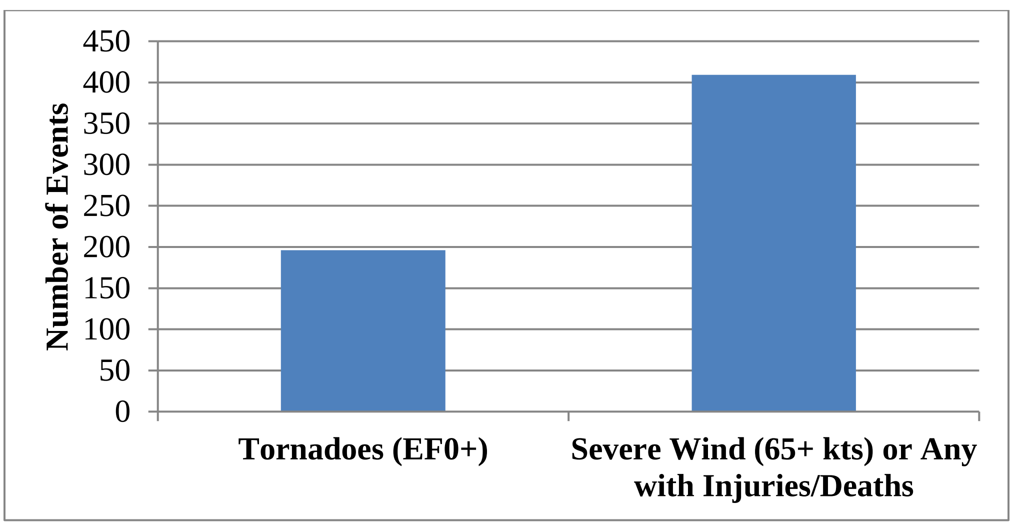

Figure 3. A comparison between tornadic events (EF0+) and significant severe thunderstorm wind gust events across the Northeast between 1 January 2012 and 31 December 2019.

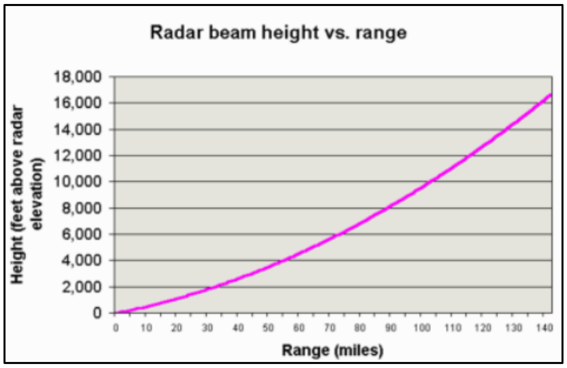

Figure 4. Radar beam centerline height vs. range, courtesy of the NWS Warning Decision Training Division (WDTD).

The radar beam is also impacted by terrain. While this is not an issue for some parts of the country, the interior Northeast features varied terrain due to numerous mountain ranges. Figure 5 shows the terrain surrounding the Albany radar (KENX) located in East Berne, NY in western Albany County. The KENX radar is especially impacted by the Catskill Mountains located just south of the radar site, which causes the lowest elevation slices to be blocked. Storms that develop across parts of the lower and mid-Hudson Valley are not fully sampled properly due to the high terrain to the north blocking the path of beam.

Also, an important consideration when examining velocity data is to determine the angle between the thunderstorm's wind gust direction and the radial beam of the radar. When the wind from a thunderstorm is blowing down the radial, parallel to the radar beam, the radar is able to sample it entirely. However, if the wind is blowing perpendicular to the radar, the radial velocity measurement will be zero. Usually, the angle is somewhere between these two scenarios. (US Department of Commerce 2018). Figure 6 shows how much percentage of the wind is measured depending on the exact angle between the wind vector and the radar radial.

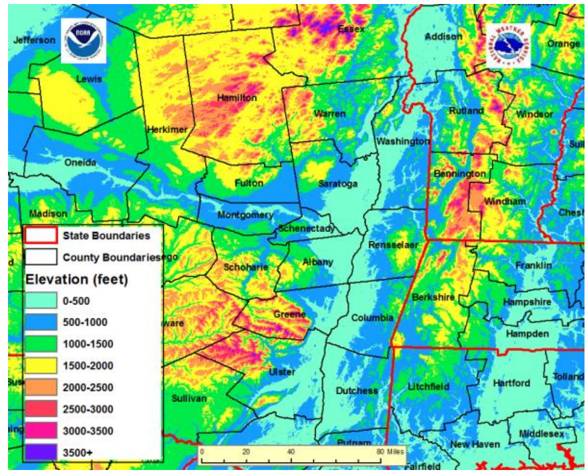

Figure 5. Elevation (in feet) of eastern NY and western New England. The KENX Radar is located in East Berne in western Albany County (near the A in Albany).

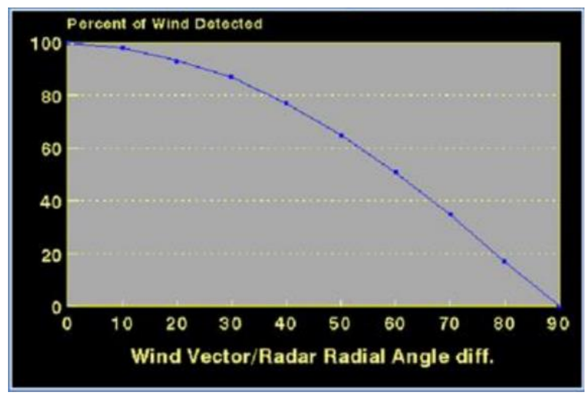

Figure 6. The percentage of wind measured depending on the difference of the angle of the wind vector and radar radial (from WDTD).

4. Consideration for polarized-radar products

The NWS Doppler radar network underwent a major upgrade in 2012 to include dual-polarization capabilities. This upgrade allowed for three new base products, Differential Reflectivity (Z_{DR}), Correlation Coefficient (ρHV) and Differential Phase Shift (Φ_{DP}), which is the basis for Specific Differential Phase (K_{DP}). Φ_{DP} is defined as the difference in 2-way attenuation for the horizontal and vertical phase shifts in a radar pulse volume (US Department of Commerce 2018).

K_{DP} is the range derivative of Φ_{DP} and is calculated at each range bin along the radar beam path. Large positive values of K_{DP} indicate an increase in the phase shift of the horizontal component of the radar beam relative to the vertical component, which suggests a large concentration of horizontally oriented targets, such as raindrops, at that range.

The K_{DP} product does have some limitations, as it does not plot when correlation coefficient is less than 0.90 due to the presence of non-Rayleigh scatters and areas of non-uniform beam filling. K_{DP} is also very unreliable in areas of low-signal to noise ratio. (US Department of Commerce 2018, Kumjian 2013).

Although K_{DP} is generally an indicator of heavy rainfall, analysis of K_{DP} was done to see if it can be an indicator of potential for damaging wind gusts. Kumjian and Ryzhkov (2008) mentioned that K_{DP} columns (elevated high K_{DP} values) are often seen within mature thunderstorms. Scharfenberg (2003) noted that high values of K_{DP} could indicate melting hailstones, which contribute to the condensate loading, a major factor in wet microbursts. At the time of the Scharfenberg study, operational radar data resolution was usually insufficient to adequately resolve many of these features. However, subsequent advances in spatial and temporal radar data processing that now provide 8 bit, super resolution (0.25 km range resolution) base data products, and 2 minute Supplemental Adaptive Intra-Volume Low Level Scan (SAILS) low level scans enable sampling/detecting a 1 km wide microburst downdraft.

Kumjian (2013) noted that low-level areas of high K_{DP} can be a good indicator of the downdraft region of the thunderstorm, driven by rain evaporation and melting hail. Considering that wet microbursts are often accompanied by heavy rainfall and melting hailstones, it is theorized that high elevated values of K_{DP} can be a precursor to strong and damaging thunderstorm downburst winds.

Kuster et al. (2019) examined the utility of K_{DP} for anticipating downbursts. Although they did not examine any Northeastern US thunderstorms, they did see a peak in K_{DP} values before downburst maximum intensity. While they did not see much difference in K_{DP} value between severe and non-severe downbursts, they did believe vertical gradients of K_{DP} may be useful during the warning process.

5. Data and methodology

Radar data from the Albany KENX radar was examined for 46 thunderstorms that produced significant wind damage and for 51 thunderstorms that produced ordinary (non-significant) severe wind damage across the Albany WFO County Warning Area (CWA) between 2012 and 2017. Event dates for the ordinary storms were matched to the significant event days to allow for similar thermodynamic environments for both data sets. Level 2 radar data for a several hour period surrounding each damage report was downloaded from the National Center for Environmental Information (NCEI) website and loaded into the GR2Analyst software for evaluation. Several radar-based parameters, such as radial velocity and K_{DP}, were examined for the ordinary and significant wind-producing storms at the time of and just prior to the time of the damage report. The maximum value (in deg/km) and height (in feet above ground level) of the elevated K_{DP} cores were noted for several scans prior to the damage report, and the time was recorded when these elevated values of K_{DP} descended towards the surface. The depth of the surface-based mixed layer was also recorded around the time of damage using that day's

12 UTC North American Mesoscale (NAM) model-based sounding, valid at Albany, NY, from BUFKIT software (Mahoney and Niziol 1997) valid at the time of convective initiation.

Storm type was also noted, with classifications of supercell, squall line/quasi-linear convective system (QLCS) or other. Storms were classified as supercells if they were discrete, contained mid-level rotation and were generally long lived. Figure 7 shows the majority of the significant events (27) were supercells, but QLCS/squall line events make up a notable amount as well (17). There were two other events that were classified as other, which were generally discrete non-supercell storms.

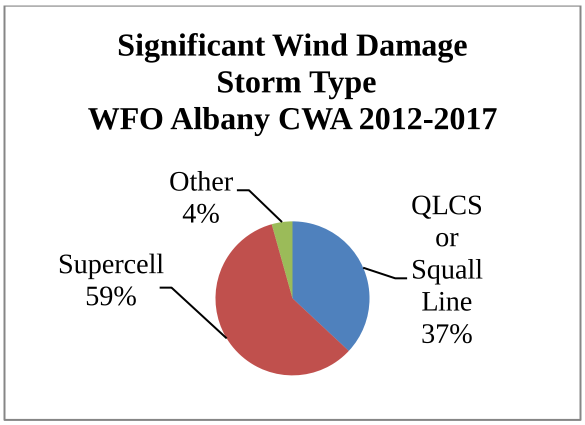

Figure 7. Significant Wind Damage Storm type across the Albany CWA 2012-2017.

Figure 8 shows the 0.5° KENX radial velocity values at the time of significant severe thunderstorm wind damage over the location of the wind damage. The median value was 36 kts and the average value was 37 kts. Significant wind damage is not always associated with high radial velocity values due to the earlier mentioned radar limitations, especially viewing angle and distance. This shows that radial velocity cannot be used alone as a warning indicator, as many of these events produced wind surface gusts of 65 to 85 kts.

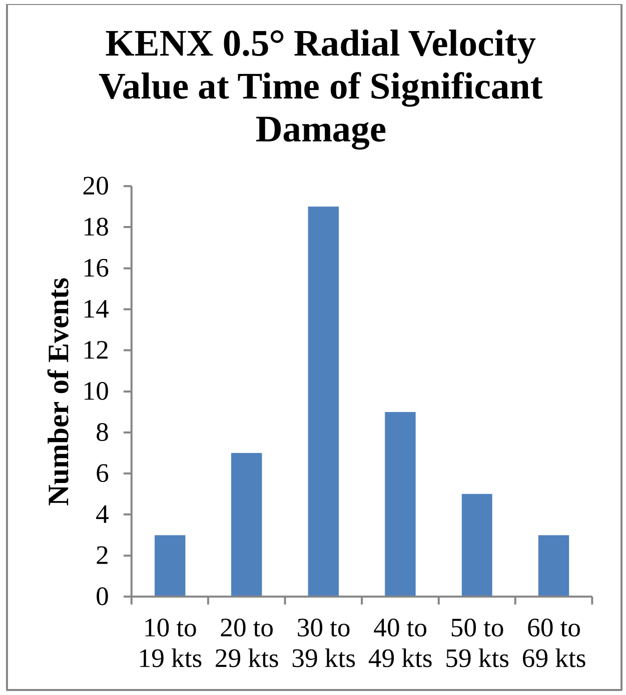

Figure 8. 0.5° KENX radial velocity value (kts) at the time of significant severe thunderstorm wind damage.

6. Analysis

Out of the 46 significant cases examined, 30 (65%) were seen to have high values of K_{DP} (at least 5 deg/km) collapse towards the surface at the time of the significant severe thunderstorm wind damage report. Collapsing was considered to have taken place when the maximum K_{DP} core aloft (containing values above 5 deg/km) lowered toward the surface (to an elevation under 5000 ft AGL) within two radar volume scans of the wind damage report and eventually became indistinguishable from the rest of the storm. Within the other 16 cases, K_{DP} cores were either associated with a lower maximum value (less than 5 deg/km), were not present, and/or did not lower towards the surface. For the 30 cases when collapsing was observed, the maximum values within the K_{DP} column averaged 7.6 deg/km. The median value was 7.0 deg/km. Figure 9a shows a box and whisker plot of the maximum K_{DP} values aloft within the 30 storms that contained a collapsing K_{DP} column. The forecaster on the warning desk could utilize this data during the warning process to compare the real-time data to the historical dataset of this study.

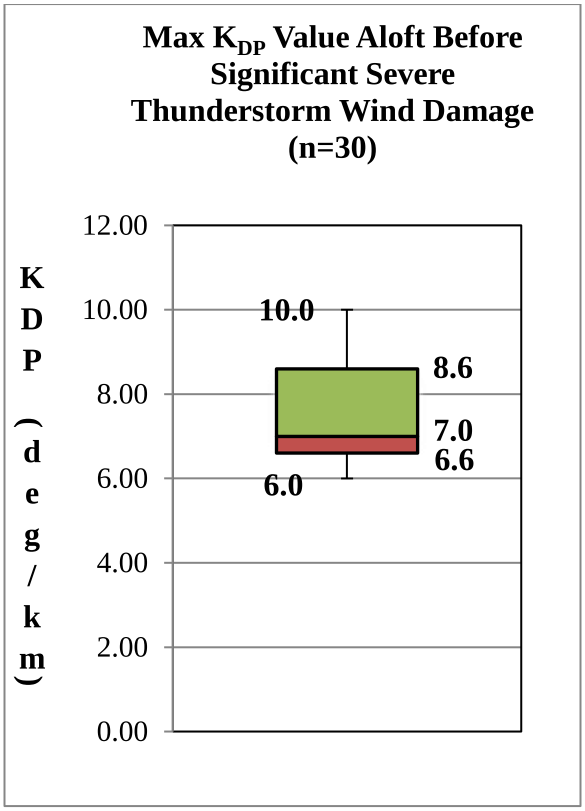

Figure 9a. Box and Whisker plot of maximum K_{DP} value aloft prior to column collapse for significant thunderstorms. The median value was 7.0 deg/km, 75th percentile was 8.6 deg/km, 25th percentile was 6.6 deg/km, 10th percentile was 6.0 deg/km and 90th percentile was 10.0 deg/km.

Within the 51 ordinary (non-significant) severe cases, only 20 (39%) of these were seen to have a collapsing K_{DP} signature. The same criteria for a collapsing core was used as compared to the significant events. For the 20 events where collapsing occurred, the maximum value within the K_{DP} column averaged 6.9 deg/km and the median value was 6.4 deg/km. Figure 9b shows a box and whisker plot of maximum K_{DP} values within the ordinary severe thunderstorm events. This data seems to suggest that K_{DP} collapses occur more often within significant events compared to ordinary events and maximum values are slightly higher. A chi square test was computed to assess this difference and it was found to be statistically significant (Pearson 1900). In addition, all of the collapsing ordinary events occurred with supercell type storms (no QLCS or pulse type events).

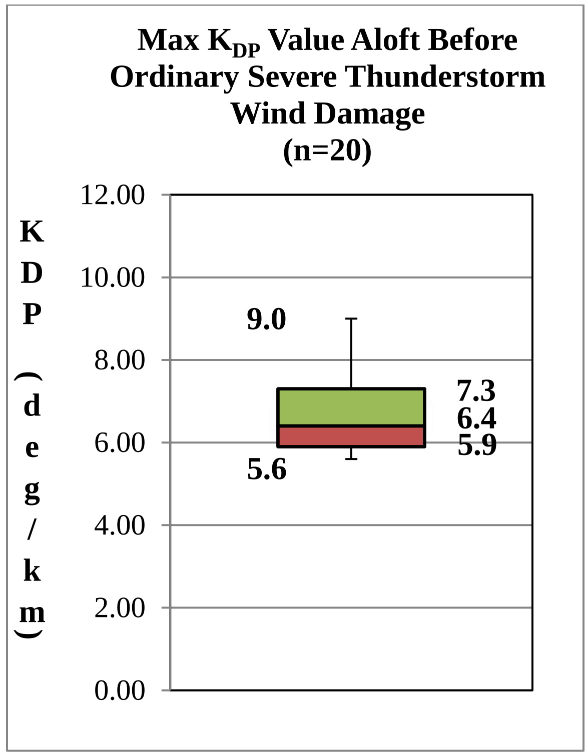

Figure 9b. Box and Whisker plot of maximum K_{DP} value aloft prior to column collapse for ordinary (non-significant) severe thunderstorms. The median value was 6.4 deg/km, 75th percentile was 7.3 deg/km, 25th percentile was 5.9 deg/km, 10th percentile was 5.6 deg/km and 90th percentile was 9.0 deg/km.

Within both the significant and non-significant events, the K_{DP} columns were typically seen between the surface and the freezing level, with the highest elevated values generally around 5,000 to 10,000 feet above ground level (AGL). These results are intuitive, as above the freezing level, the quantity of liquid water would be decreasing with height due to some of this water being converted into ice, graupel, or hail.

Based on these results, it is possible that a warning meteorologist can identify and anticipate a collapsing K_{DP} column during the warning process. This could be an imminent sign of a wet microburst, especially once the K_{DP} cores enter the surface-based mixed layer. High values of K_{DP} could signal the potential for a significant event, allowing the warning forecaster to use more enhanced wording within the impact-based warning. Figure 10a shows how these high values of K_{DP} lower towards the surface by the time of the damage report. The median height of the maximum K_{DP} value lowers about 1000 feet AGL with each radar volume scan (~5 minutes).

In 22 of the 30 cases (~73%) that saw a collapsing K_{DP} column lead to significant damage, the storm type was supercell. Although this methodology may work best within supercells, it may occasionally be seen within very strong QLCS or squall line events as well. The general trend of K_{DP} cores lowering towards the surface depicted for all events in Figure 10a was evident for both supercell and squall line events (not shown).

Figure 10b shows the lowering of K_{DP} core heights within ordinary severe thunderstorms. As seen with the significant events, there is a lowering trend in height towards the time of the severe weather report. The core heights seem to lower around 1000-2000 feet per radar volume scan (about 5 minutes in duration using most common scan strategies), which is typical in both the significant and non-significant events.

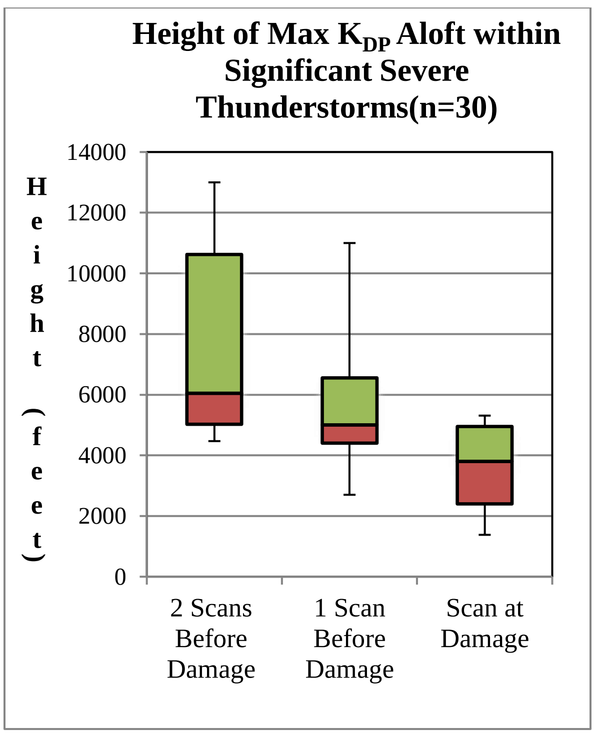

Figure 10a. Box and Whisker plot of height of maximum K_{DP} value aloft for one and two radar volume scans prior to column collapse within significant thunderstorms.

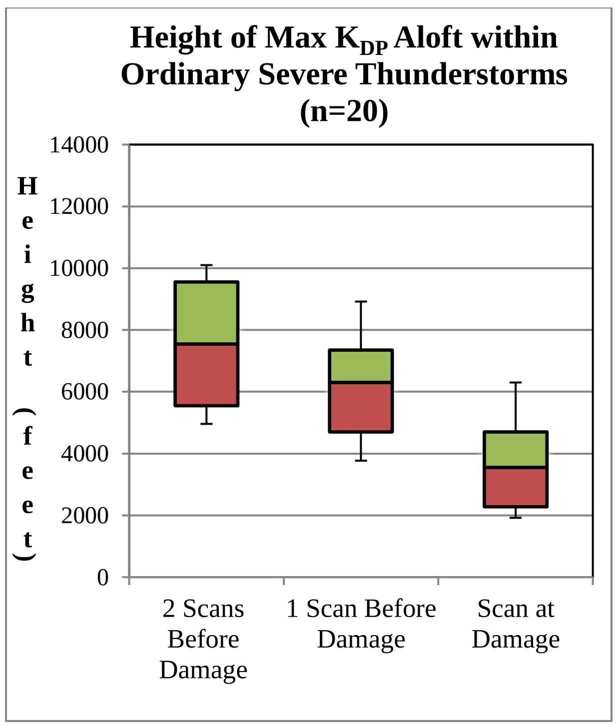

Figure 10b. Box and Whisker plot of height of maximum K_{DP} value aloft for one and two radar volume scans prior to column collapse within ordinary (non-significant) thunderstorms.

7. Radar data from 13 August 2016

During the late afternoon and early evening on 13 August 2016, severe thunderstorms occurred across eastern NY. A squall line produced significant severe thunderstorm wind damage, especially in the town of Caroga in Fulton County, NY. Significant damage occurred at the Pine Lake Campground, resulting in over one million dollars' worth of damage, with damage to 59 structures and 18 vehicles. Seven people were also injured during this event, which was one of the highest injury totals for one particular severe thunderstorm event within the last 30 years across eastern NY (NOAA 2019).

Figure 11 shows a K_{DP} vertical cross section from a thunderstorm squall line over Herkimer County, which was quickly moving eastward into Fulton County, NY as seen through GR2Analyst. At 22:14Z, maximum K_{DP} values were elevated around 12,800 feet AGL and the maximum values were recorded around 5.6 deg/km. The values and height were determined using the cursor readout with GR2Analyst. The K_{DP} core was located just below the freezing layer, which was around 15000 ft based off the 00 UTC upper-air sounding at Albany, NY. In addition, the mixing layer depth was approximately 6000 ft. Using the K_{DP} warning methodology, the warning forecaster would be noting the significantly high values of K_{DP} located within the column and would be anticipating this to begin descending towards the surface soon.

At the next full radar scan at 22:20Z (Figure 12), the K_{DP} column is starting to collapse. The highest values are now around 5,000 feet AGL and the column is showing signs of lowering towards the surface. The maximum value at this time is greater than 3.0 deg/km. Using the warning methodology, the warning forecaster could consider issuing their warning (or most likely updating if it was already issued) to include more enhanced wording, especially considering that the K_{DP} core has lowered into the surface-based mixed layer.

Figure 13 shows a cross-section of K_{DP} from 22:26Z on 13 August 2016. By this time, the strong K_{DP} values are no longer seen, implying that the K_{DP} column has collapsed to the surface. Based on spotter reports, significant damage occurred at the Pine Lake Campground at 22:25Z, which would be around the time of the K_{DP} column collapsing to the surface. Although this case only featured a K_{DP} max value of 5.6 deg/km (one of the lowest in the study's database), it was a good example of how lowering heights over time can lead to significant damage.

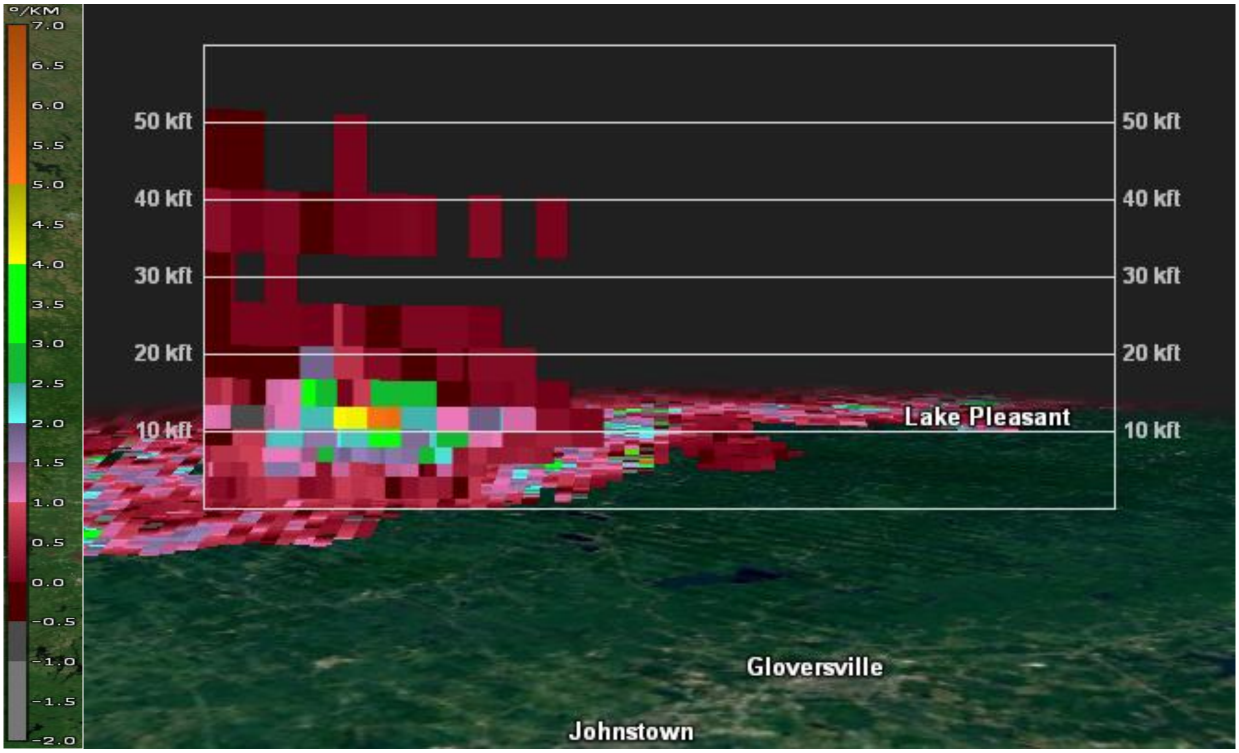

Figure 11. K_{DP} vertical cross-section of a thunderstorm squall line over Herkimer and Fulton Counties, NY from KENX radar at 22:14Z on 13 August 2016.

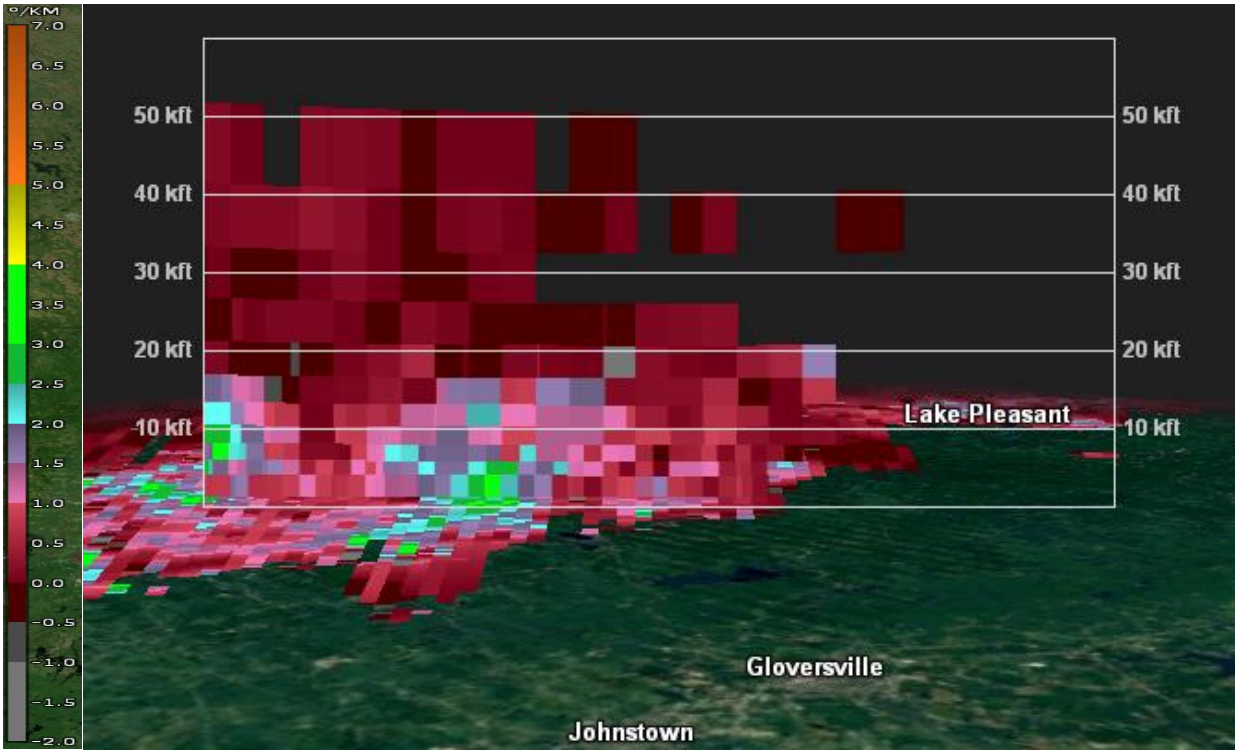

Figure 12. K_{DP} vertical cross-section of a thunderstorm squall line over Herkimer and Fulton Counties, NY from KENX radar at 22:20Z on 13 August 2016.

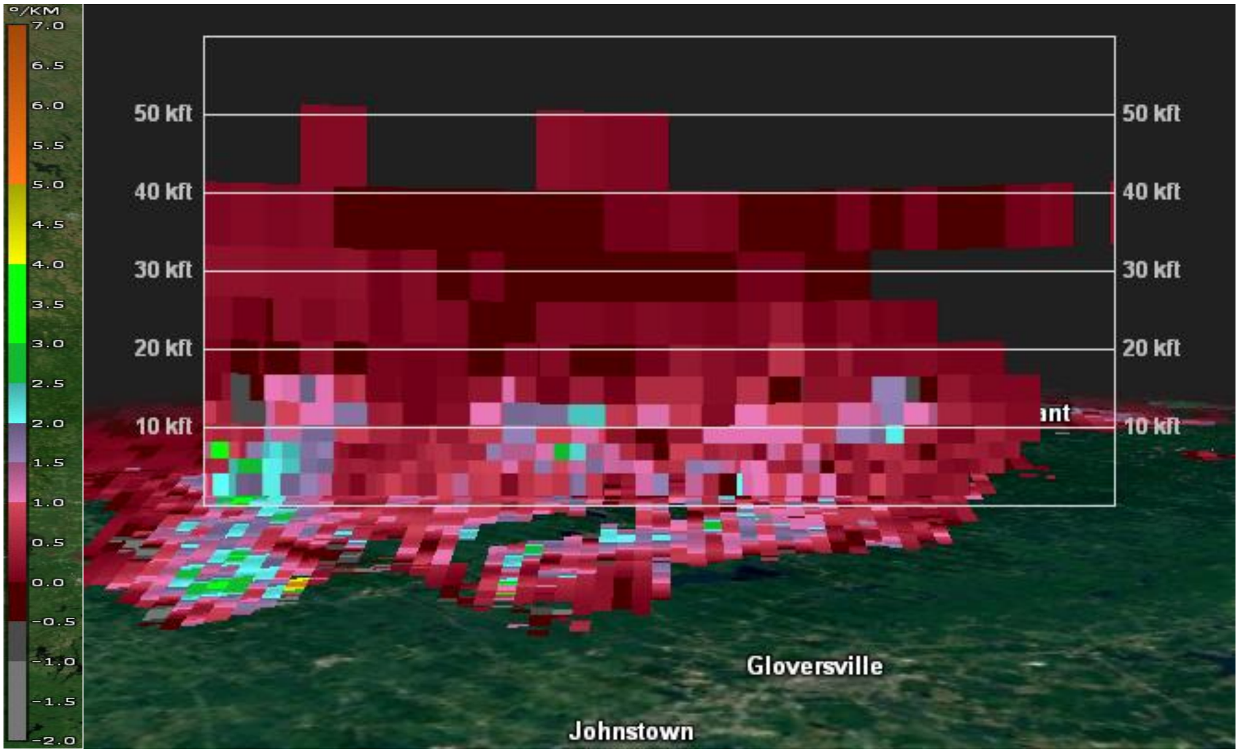

Figure 13. K_{DP} vertical cross-section of a thunderstorm squall line over Fulton County, NY from KENX radar at 22:26Z on 13 August 2016.

8. Discussion and future work

Based on the 46 significant cases and 51 ordinary severe events analyzed, the use of collapsing K_{DP} columns appears to be a helpful component of the warning decision process when anticipating severe thunderstorm wind gusts, particularly significant events. While a warning forecaster is interrogating other base data products, they can look for building columns of K_{DP} within a thunderstorm. If values appear to remain elevated and reach critical values (around 5 to 6 deg/km based off this study), a warning decision forecaster can anticipate an increased chance for significant damage when this column collapses towards the surface.

When compared to cross-sections of reflectivity, K_{DP} is often easier for the warning meteorologist to examine lowering cores of high liquid water content. Figure 14 shows a comparison between cross-sections of K_{DP} and reflectivity at the same time for a storm in Ravena, NY on 30 June 2017 at 20:16Z. This storm would go on to produce significant damage in South Schodack, NY at 20:28Z. While the K_{DP} cross-section shows an elevated core with max values around 8 degrees/km at 10,000 ft, the corresponding reflectivity cross-section doesn't appear to show anything overly threatening, with just a broad area of 50+ dBZ located close to the surface. This shows the advantage of evaluating K_{DP} cross-sections, as reflectivity can be misleading at times. While elevated reflectivity cores are sometimes indicative of strong wind potential, the cases in this study indicate that for many significant wind events, elevated K_{DP} cores provide a more robust signature.

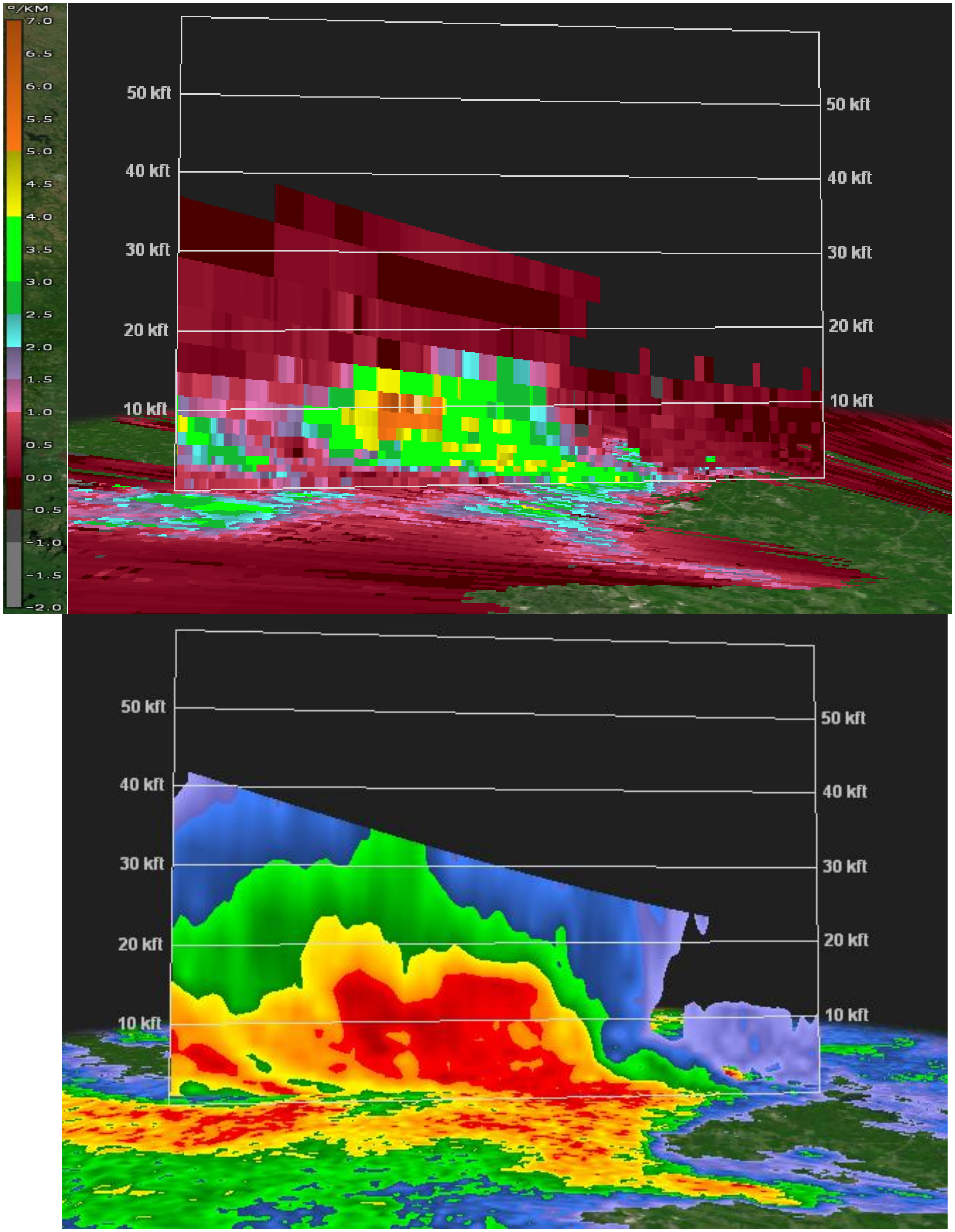

Figure 14. A comparison of cross-sections from K_{DP} (top) and Z (bottom) from 30 June 2017 at 20:16Z near Ravena, NY.

Although the Kuster et al. (2019) study wasn't able to differentiate between severe and non-severe storms using K_{DP}, this study included a criteria for lowering columns and collapsing towards the surface. Since Kuster et al. (2019) did note that K_{DP} could have better utility when examined for wet microbursts and when considering the vertical gradient, the use of the criteria for a lowering K_{DP} column within this study could be the additional piece needed to make interrogation of K_{DP} values aloft useful during the warning process.

The utility of base velocity can be limited at times due to issues involving beam angle and direction, however it appears that identification of elevated K_{DP} cores can help alleviate these limitations. Still, inherent issues with beam width will result in some range limitations when evaluating K_{DP}. Although lower elevations will be impacted, elevated radar slices will not suffer from beam blockage, allowing the diagnosis of K_{DP} columns aloft within a storm. In addition, storms that contain large hail may not always show K_{DP} columns, as K_{DP} is not plotted when associated with low values of correlation coefficient (<0.90).

It should be cautioned that this methodology is not meant to be used alone and should be complemented with other interrogation methods. Other items within new research, such as the evaluation of lightning jumps, could be useful pieces of information when making warning decisions (Eck 2017).

The NWS WFO at Albany has already begun to implement this preliminary work into the office severe weather operations. Examining K_{DP} column strength and determining the potential for significant severe thunderstorm wind gusts was a key training component of the office spring severe weather training in 2018 in weather event simulated cases.

Additional cases will need to be examined, including null cases, to better confirm and further quantify these results. It can be hypothesized that elevated K_{DP} cores may only lead to surface wind damage when the core reaches an elevation corresponding to the top of the surface-based mixed layer. Null events could occur when the core remains above the mixed layer, or when the low-level lapse rates are not sufficiently steep. An examination of null cases would be needed to test this hypothesis. Also, the correlation between maximum wind speed at the surface and maximum K_{DP} values aloft could be studied. Additional supplementary radar scans, such as the Mid-Volume Rescan of Low-Level Elevations (MRLE) scanning strategy that was deployed in 2019 (Build 18.2), will provide more frequent radar data sampling within the low to mid-levels of the atmosphere, which will help this methodology greatly as well.

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