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Operational Uses of Spectrum Width

PATRICK J. SPODEN
National Weather Service, Paducah, Kentucky

RAY A. WOLF
National Weather Service, Davenport, Iowa

LESLIE R. LEMON
University of Oklahoma, Cooperative Institute for Mesoscale Meteorological Studies, Norman, Oklahoma

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ABSTRACT

Spectrum width is a WSR-88D product that has been available to operational forecasters since the radar was deployed. In 2008, super-high-resolution reflectivity, velocity and spectrum width data became available. Six cases exemplifying operational use of spectrum width are presented; five are from after the upgrade. The cases were selected to depict the wide array of uses of spectrum width (SW). In one case, use of SW improved forecaster capability to evaluate the strength of horizontal shear within a bow echo's mesovortex. One case shows that SW can be extremely helpful in determining location of boundaries, which aids in overall situational awareness. In another case, SW aided forecaster confidence to issue a tornado warning with lead time. If a storm is close to the radar (55 km in this example), SW can be used to clarify the location of the rear flank downdraft, assess where its wind damage may be a threat, and discern subsequent cutoff of the tornado from the warm, moist inflow. Finally, when used in a derecho case, SW helped a forecaster to identify more quickly where wind damage threats were likely.

1. Introduction

Of the three Doppler radar moments, the second—base velocity spectrum width (SW)—is the least used in detection of severe local storms. This could be due to several factors, most importantly a lack of operational studies, which has led to under-training about the moment (L. Quoetone 2011, personal communication). Furthermore, if inappropriate color scales are incorporated in an operational setting, the ability to analyze the image quickly can be lowered dramatically.

The focus in initial National Weather Service (NWS) training was to use SW as a quality control for velocity data; typically, broad SW values indicate questionable velocity data. This is especially true when base reflectivity data are very weak, implying that the ratio of peak signal power to noise power (signal-to-noise ratio) is low. Operationally, data quality is also questionable and reflected in broad widths when areas of range-overlaid echoes are not properly identified and removed. This is particularly apparent when the SW values bordering range-overlaid echo are greatly broadened over the surrounding values.

Since the mid-1990s, a few studies have highlighted operational weather applications for these SW estimates, but these have been slow to gain acceptance in severe weather operations, even with an increase in NWS training. Lemon and Parker (1996) discussed SW values associated with deep convergence zone of the Lahoma, OK storm of 17 August 1994. Bohne

Corresponding author address: Patrick J. Spoden, National Weather Service, 8250 KY HWY 3520, West Paducah, KY 42086.
E-mail: pat.spoden@noaa.gov

et al (1997) discussed using SW to indicate storm features such as mesocyclones, boundaries, large hail, and tornadoes. Lemon (1998) showed large SW values associated with three-body scatter spike signatures. Lemon (1999) later suggested expanded operational uses, including detection of boundaries, intense updrafts, and estimating the depth of the orographically induced wind shear and turbulence.

This paper expands the list of case studies by showing six wide-ranging operational examples of SW usage. We stress here, as with any of the three Doppler moments, SW must be interpreted with frequent reference to the other two moments. Section 2 will define SW, while section 3 describes the six cases.

2. What is velocity spectrum width?

Before discussing additional SW applications, we will examine briefly what SW is and what contributes to its value. As with all weather radars, in precipitation, the echo power or the zero moment of the pulsed-Doppler weather radar, reflectivity, is an indicator of the liquid water content within the pulse volume. The first moment, mean radial Doppler velocity, is the mean radial motion of the power-weighted scatterers within the pulse volume. Finally, the SW is the square root of the second moment about the first of the normalized spectrum (Doviak and Zrnic 1984). More simply, it is a measure of the velocity dispersion within the pulse volume.

The SW within the pulse volume is produced by wind shear, turbulence, particle fall-speed dispersion, and antenna rotation. Moreover, clutter and clutter residue, system noise and radar artifacts all can contribute to observed returns and errors (Fang et al. 2004).

Because antenna elevation[1] is typically 20° or less for weather surveillance radars, precipitation fallspeed dispersion is ignored. Further, even though measured values are obtained as the antenna sweeps horizontally, contributing to measurement decorrelation, this contribution is typically small and also ignored. Thus, assuming sufficiently high signal-to-noise ratio in the absence of clutter or clutter residue, SW is reduced to wind shear and turbulence within the pulse volume. In most situations SW will increase with range from the radar. This is a natural consequence of the typical shear of the horizontal winds with height and the beam broadening with range.

Five of the six cases examined followed the 2008 implementation of super-resolution on the WSR-88D (Wood et al. 2009). The azimuthal sampling of the base products was reduced from 1.0º to 0.5º. Furthermore, 0.25-km range resolution replaced 1-km range-averaged values. In this paper, one study (3a) uses the older resolution.

3. Cases

a. 31 May 2000

1) Overview

In this case, SW was used operationally to assist in the warning decision.

During the daylight hours of 31 May 2000, a cluster of thunderstorms in central Iowa evolved into a bow echo and raced across eastern Iowa, Illinois, Indiana and Ohio. The bow echo produced a broad range of severe weather including nontornadic winds as high as 33 m s^{-1} (65 kt); hail up to 2.54 cm (1 in) in diameter; three tornadoes―including an F1 near Alburnett in east-central Iowa―and flash flooding (Fig. 1) (NCDC 2011). Two of the tornadoes in eastern Iowa developed south of the bow apex, rather than north of the bow apex, in the region typically associated with bow echo tornadoes.

The 1200 UTC (all times hereafter in UTC) sounding at Davenport, IA (KDVN) was contaminated by thunderstorms (not shown), but the Omaha, NE sounding (Fig. 2) provided a reasonable assessment of the storm environment when modified with surface data representative of southeast Iowa. The sounding indicated mid-level instability and vertical wind shear suggesting multicell evolution, the shear also evident in data from the KDVN WSR-88D velocity azimuth display wind profile (not shown). Modification of the Omaha sounding using surface observations from southeast Iowa produced CAPE of 2500–3500 J kg^{-1}, depending on parcel choice.

[1] Unless otherwise specified, units of degrees (º) are used for beam tilt herein.

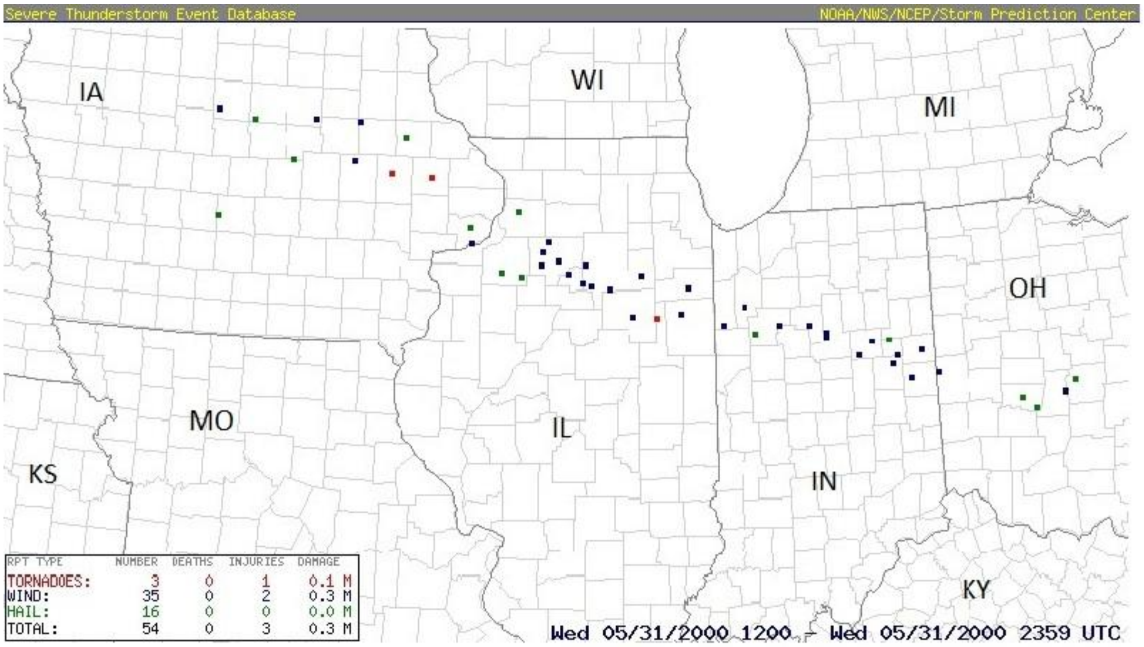


Figure 1. Storm reports associated with the 31 May 2000 bow echo (1200–2359 UTC 31 May 2000). Severe wind gusts are indicated in blue, large hail in green, and tornadoes in red.

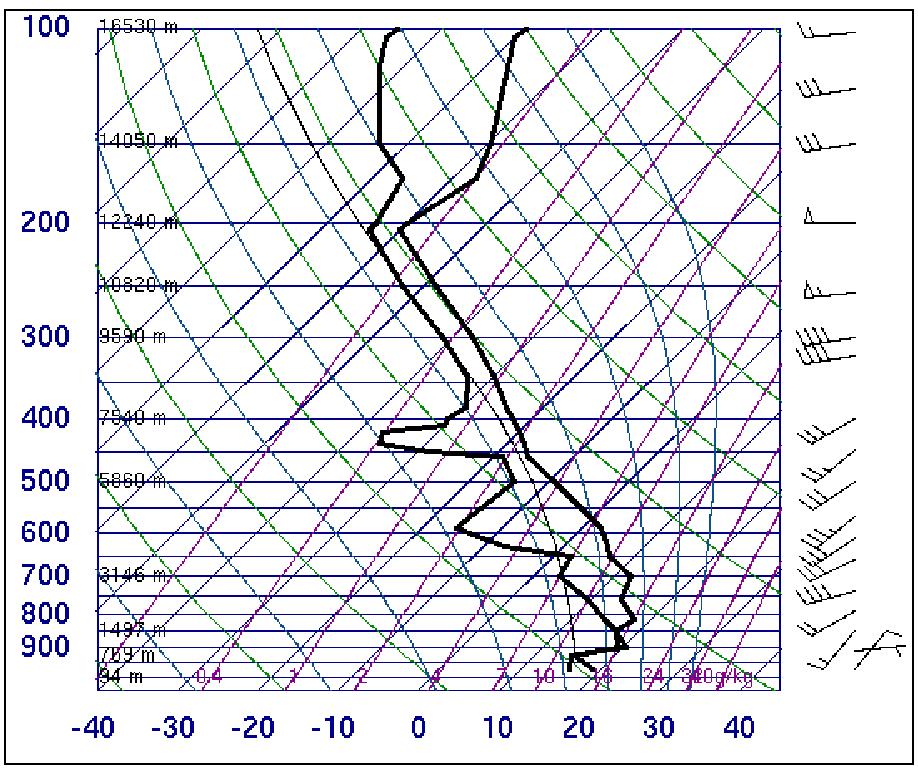


Figure 2. Skew *T*–log*p* diagram of the 1200 UTC 31 May 2000 Omaha, NE sounding, unmodified (temperature and dew point in °C, wind in kt). *Courtesy of University of Wyoming*.

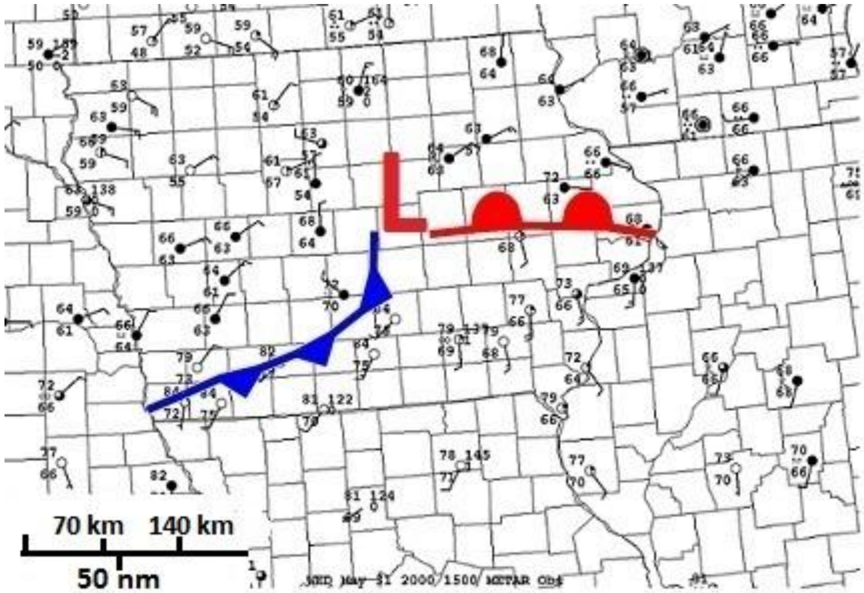


Figure 3. Surface weather observations and frontal positions (conventional symbols) at 1500 UTC 31 May 2000. Standard station plot with English units.

Surface observations at 1500 (Fig. 3) indicated that the thunderstorm complex was associated with a low pressure system and warm front in east-central Iowa. The track of the mesovortex and tornado in this event was located along the front in the area of implied convergence, where strong south winds in southeast Iowa were impinging on weaker east winds in northeast Iowa.

2) Radar analysis

At 1559, a bow echo producing wind damage was moving across Buchanan County IA (Fig 4). The storm complex had a well-defined comma head and rear-inflow jet, the latter indicated by the weak-echo channel over the southwest part of that county. However, the area of subsequent tornadogenesis was south of the apex (Atkins et al. 2005), and just moving into western Linn County. While not evident in the reflectivity image at this time, the base velocity image at 0.5° indicated a strong convergence signature and incipient rotation, and was associated with high SW values of 10–13 m s^{-1} (20–25 kt; not shown) in the area of eventual tornadogenesis. Beam height at this location was ≈1.9 km (6500 ft) AGL (all radar beam heights AGL). This signature appeared to be at or near the intersection of the bow echo with the warm front shown in Fig. 3.

Figure 4. 1559 UTC 31 May 2000 KDVN 0.5° reflectivity image of the bow echo moving across eastern Iowa. *Click image to enlarge.*

Eleven minutes later at 1610 (Figs. 5 and 6), a pair of reflectivity hook echoes were evident at 0.5°. The southern hook echo was associated with the developing mesovortex and SW maximum, both of which had appeared *prior* to the development of the reflectivity hook. Note the spatial association of the reflectivity hook, mesovortex (apparent in both base and storm-relative velocity images), and SW maximum. At 0.5°, the SW had increased to 15 m s^{-1} (30 kt) while magnitude of rotational velocity (hereafter V_r) reached 22 m s^{-1} (43 kt). In this paper, V_r is defined as the average of the maximum inbound

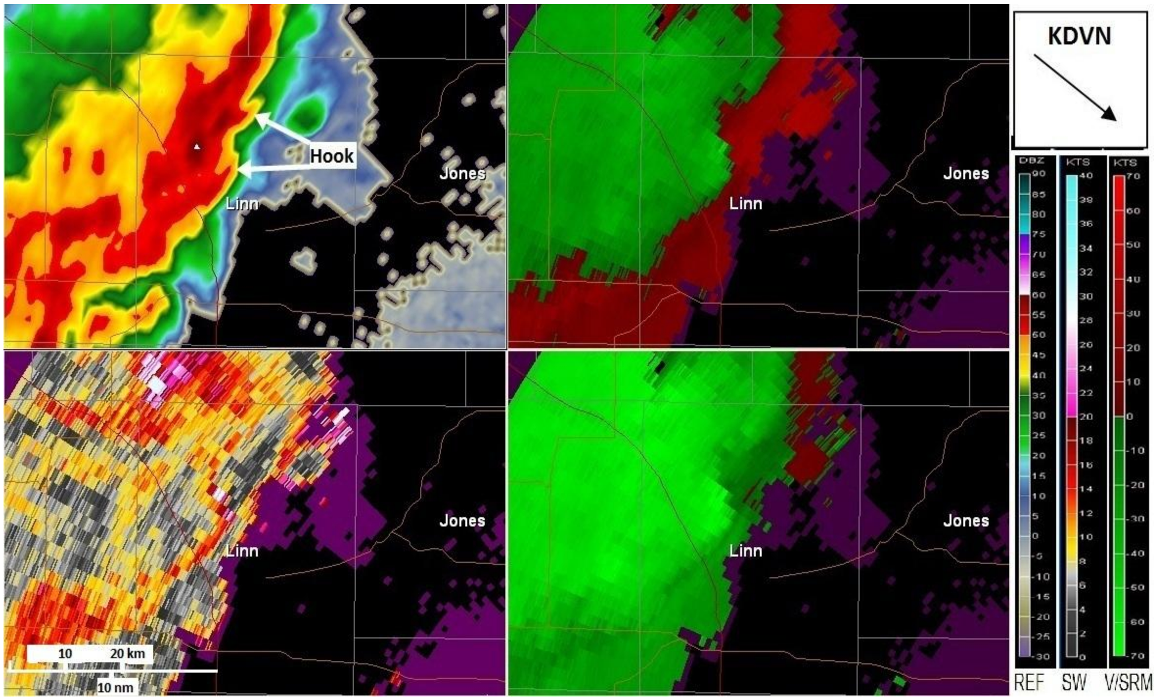


Figure 5. 1610 UTC 31 May 2000 KDVN 0.5° four-panel display of (clockwise from upper left) reflectivity, storm-relative velocity, base velocity, and SW (per scales at right) of the bow echo just before tornadogenesis. KDVN is located ≈100km (55 nm) to the southeast (lower right). *Click image to enlarge.*

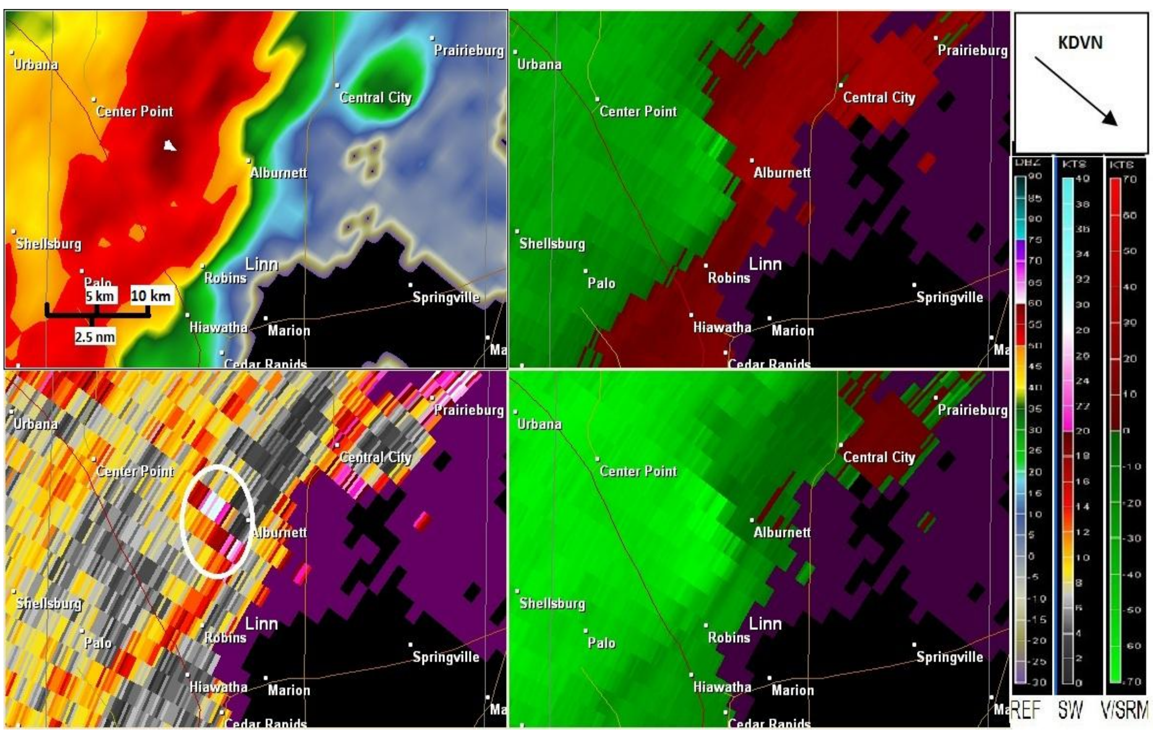


Figure 6. Zoomed version of Fig. 5 focusing on the tornadic mesovortex (circled) near Alburnett, IA. *Click image to enlarge.*

and outbound velocity values in the circulation. The initial tornado report was at 1612 near Alburnett, IA (middle of each Fig. 5 panel). An analysis of the mesovortex showed it developed in a non-descending mode (Trapp 1999): The mesovortex strengthened prior to the tornado, whereas mesovortex depth increased concurrent with tornado occurrence (Fig. 7). The tornado lasted about a minute. The reflectivity hook, mesovortex and SW maximum weakened shortly thereafter, but persisted for about another 40 min before dissipating.

In this case, the combination of SW and V_r provided confidence for the forecaster to issue a tornado warning prior to tornadogenesis. However, co-associated mesovortices and SW maxima do not always occur before tornadogenesis, so it should not be assumed that this signature will provide routine lead time.

b. 4 April 2008

1) Overview

This case showed how SW can assist in locating important boundaries.

During the overnight hours of 4 April 2008, a complex of thunderstorms moved across the mid-Mississippi Valley. The environment was characterized by 1000–2000 J kg^{-1} of mixed layer CAPE and 0–1 km bulk wind difference of 21 m s^{-1} (40 kt). As the storms progressed across the region, a northeast–southwest-oriented squall line developed. The squall line was associated with a fast moving cold front and accompanying low pressure area that moved from southeast Missouri into eastern Illinois between 0300–0600 (Fig. 8).

The exit region of a low level jet of 15–26 m s^{-1} (30–50 kt) was impinging upon the mid-Mississippi Valley area (not shown) at 0000, while the exit region of a 51 m s^{-1} (100 kt) 250 hPa jet streak was over central Illinois and Indiana. Echo tops were in the 9.1–12.2 km (30–40 kft) range. Unfortunately, representative observational soundings were not available near this event. The North American Regional Reanalysis (NARR, Mesinger et al. 2006) has shown viability for estimating environments of severe convection, including the region encompassing this case (Gensini and Ashley 2011). NARR data from the National Operational Model Archive and Distribution System, depicted 0600 mixed layer CAPE (Fig. 9) >2000 J kg^{-1} along the mid-Mississippi River Valley.

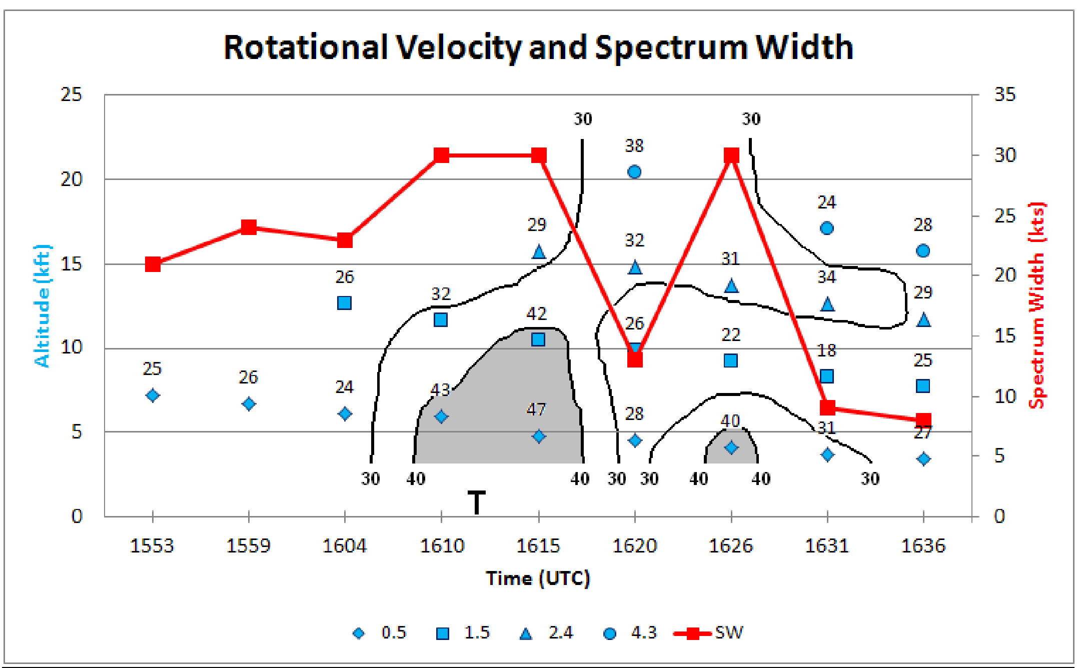


Figure 7. V_r (kt, blue) by radar elevation angle and beam height, and 0.5º SW (kt, red) vs. time for the tornadic mesovortex. Note the increase in SW and V_r prior to, and increase in circulation depth concurrent with the start of the tornado (T) at 1612 UTC. *Click image to enlarge.*

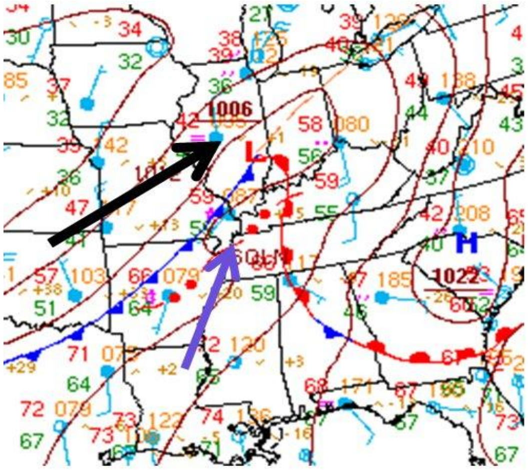


Figure 8. 0600 UTC 4 Apr 2008 surface analysis (*courtesy Hydrometeorological Prediction Center*). Black arrow is 250-hPa jet axis, purple arrow is 850-hPa jet axis. *Click image to enlarge.*

2) Radar analysis

At 0455 the squall line was entering extreme western Kentucky and northwestern Tennessee. The 0.5^{o} base reflectivity [height 1.1 km (≈3500 ft), Fig. 10], denoted a broken bowing line of convection along the Kentucky–Tennessee border which was ≈64.8 km (35 nm) south of the Paducah, KY (KPAH) WSR-88D. By 0523 (Fig. 11), the base velocity image indicated the location of the main boundary, with 0.5^{o} SW clearly showing a boundary merger near the state borders. An estimated wind gust of 33 m s^{-1} (65 kt) associated with the bowing line segment blew down some trees in Fulton County, KY around 0530. By 0557 (Fig. 12), a close examination of the SW image revealed a potential occlusion near the intersection of the bowing line segment and the main boundary. Although hints of the occlusion could be seen in base velocity, the super-high-resolution reflectivity image did not show this well. This occlusion, associated with the bowing line segment continued until 0614 (Fig. 13), ≈4–6 min before the tornado formed.

The SW image indicated that the boundary was wrapping around the circulation's southern flank, forming an "S" shape as seen in the storm relative motion (SRM) image, but with more definition. The early identification of the characteristic S-shape, along with other factors, may aid in the potential to get a warning issued with lead time (e.g., McAvoy et al. 2000; Sabones et al. 1996).

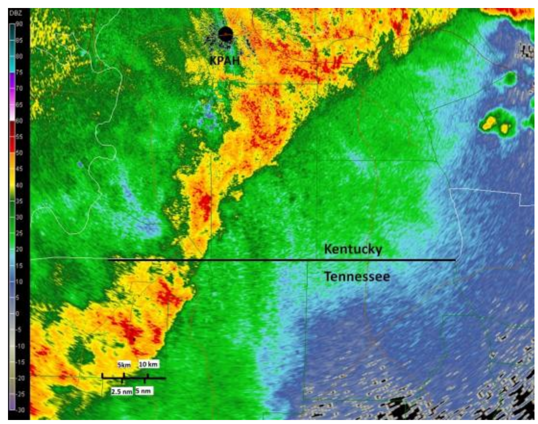


Figure 10. 0455 UTC 4 April 2008 KPAH 0.5° base reflectivity of the organizing line along the Kentucky-Tennessee border. KPAH location denoted by black dot. *Click image to enlarge.*

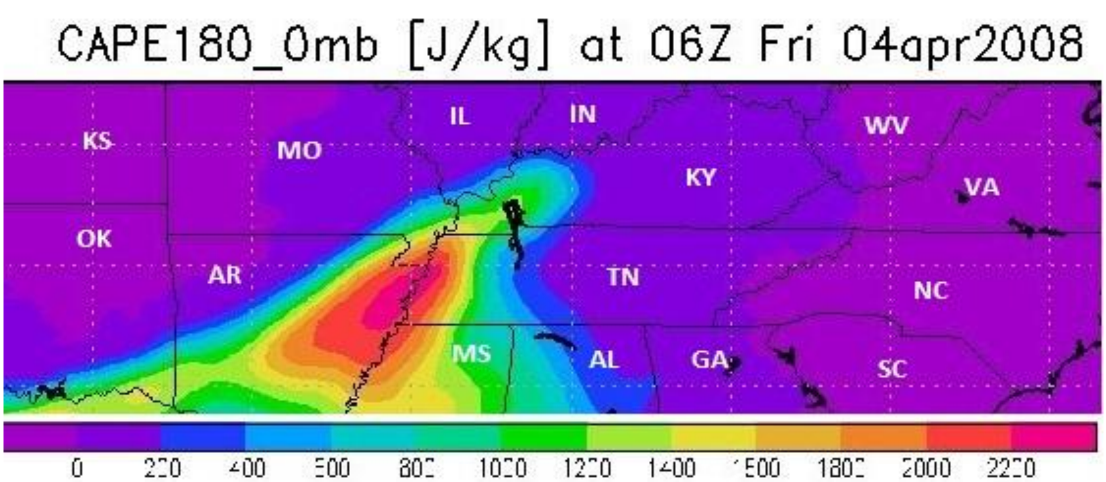


Figure 9. NARR surface to 100-hPa mixed-layer CAPE (J kg^{-1}), 0600 UTC 4 April 2008.

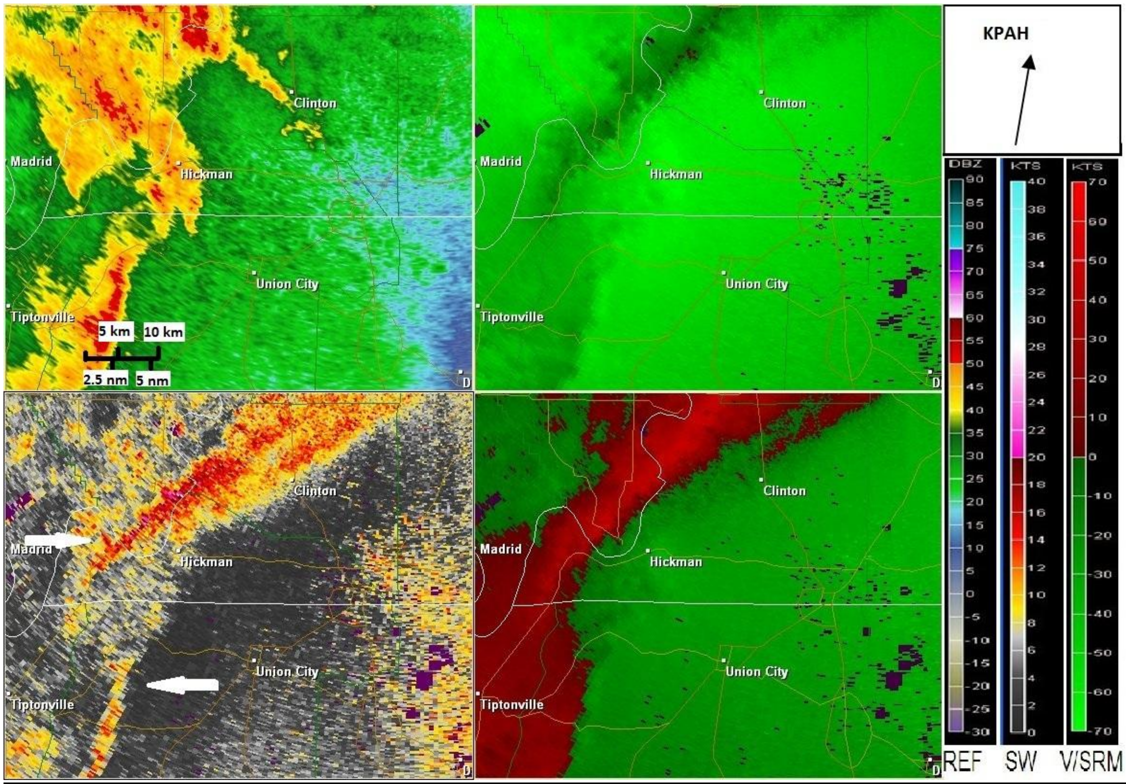


Figure 11. As in Fig. 5, but for 0523 UTC 4 April 2008 KPAH imagery at 0.5°. KPAH is located 74 km (42 nm) to the north-northeast in these images. Arrows point to boundary locations. *Click image to enlarge.*

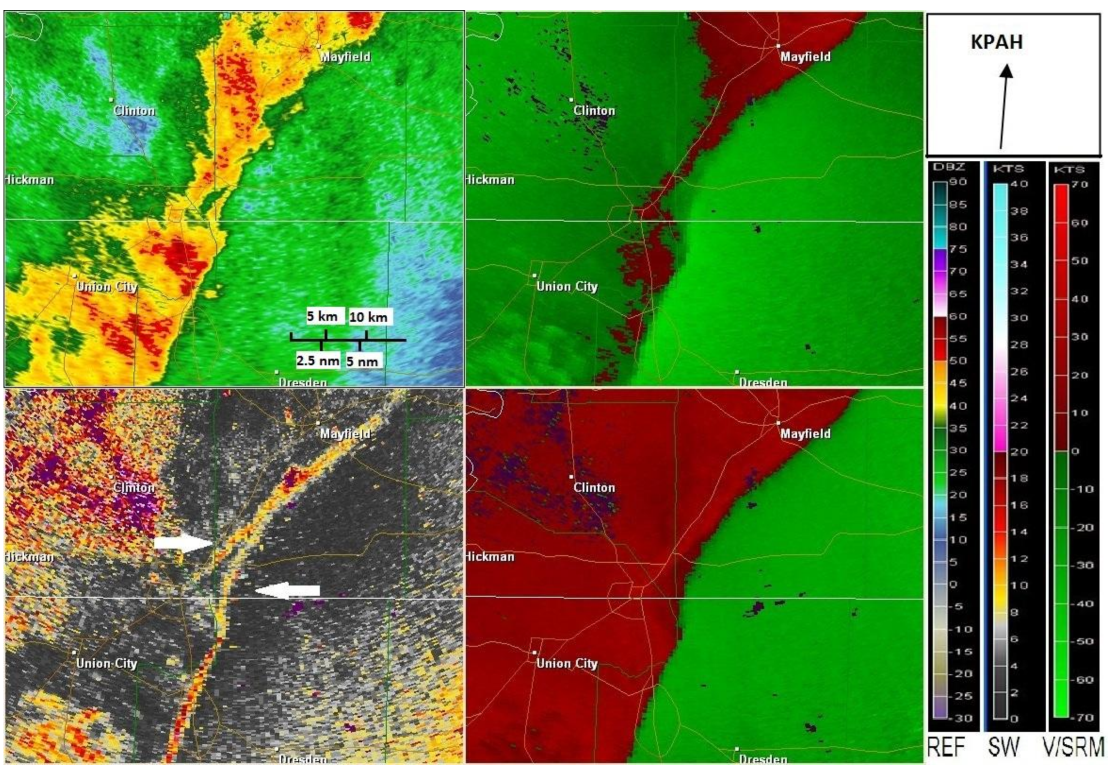


Figure 12. Same as Figure 11, except at 0557 UTC. Arrows point to area of potential occlusion. *Click image to enlarge.*

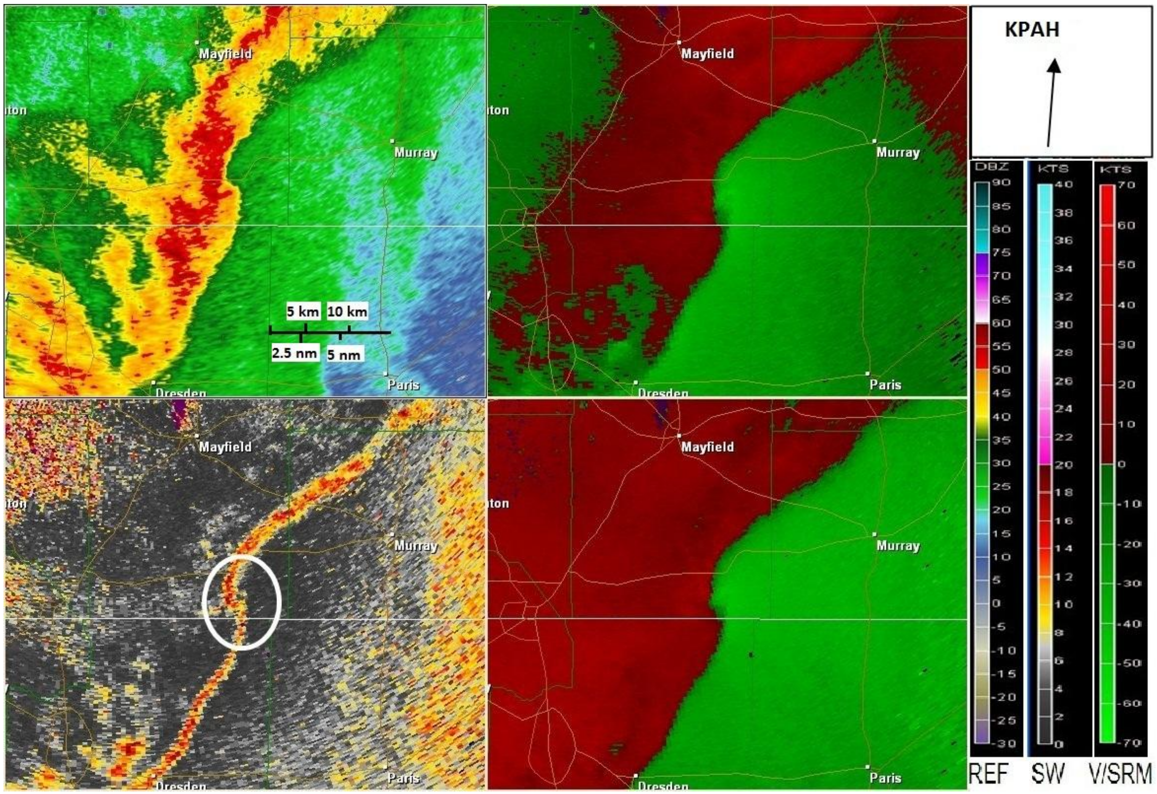


Figure 13. Same as Figure 11, except at 0614 UTC. Circle indicates the area of the occlusion. *Click image to enlarge.*

A post examination of the occlusion showed SW values ≥10 m s^{-1} (20 kt) were persistent from 0614–0622 at altitudes of 1.1 km and 1.6 km. Prior to 0614, SW values were generally <10 m s^{-1} along the boundary near the occlusion. These higher values descended down to 0.7 km by 0618, just before tornadogenesis.

The rotation associated with the occlusion began during the 0601 volume scan (not shown) through a depth of over 3.66 km (12 kft). The maximum V_r values of 22 m s^{-1} (42 kt) were at a height of 2.9 km (2.4^o). The circulation continued through 0618 with nearly constant strength, although by that time, the maximum V_r had descended to a height of 0.7 km (0.5^o).

A brief EF1 tornado occurred at approximately 0620 in southeast Graves County, KY. The notch in both SW and SRM images remained until 0644. No additional severe weather was reported with this line. This case demonstrates the ability to use SW to see key boundary intersections.

c. 19 August 2009

1) Overview

In this case, SW was used operationally to assist in making a warning decision.

Two different areas of thunderstorms developed during the afternoon across eastern Iowa and northwest Illinois producing a mix of flash flooding, nontornadic wind damage, and a few weak tornadoes (NCDC 2011). The convective mode was mixed with both supercell and quasi-linear convective storm structures, but all storms were "low-topped" with 18 dBZ echo heights below 10.6 km (35 kft) AGL.

Shear and instability were sufficient for organized severe convection in eastern Iowa. At 2100, surface-based CAPE estimates ranged between 1000 and 1500 J kg^{-1} (Fig. 14a) and effective bulk wind difference (Thompson et al., 2007) was 15–21 m s^{-1} (30–40 kt: Fig. 14b).

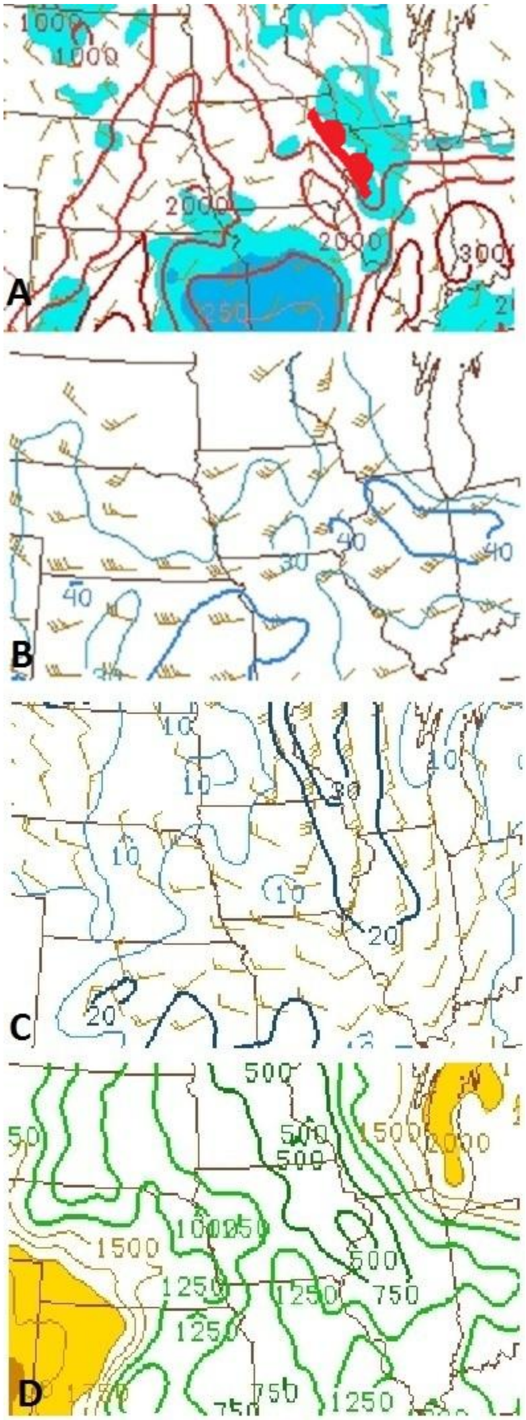


Figure 14. Automated mesoanalyses (Bothwell et al. 2002) valid 2100 UTC 19 August 2009, for: a) surface-based CAPE and convective inhibition (J kg^{-1}) shaded (25, 100); b) effective bulk wind difference (kt); c) 0–1-km AGL bulk wind difference (kt); and d) lifted condensation level height (m, 100-hPa layer) shaded (1000, 2000). *Courtesy of the Storm Prediction Center. Click image to enlarge.*

Also in Fig. 14a, a warm front is indicated by the surface wind shift line and gradient of CAPE. Two brief tornadoes occurred on the boundary, with estimated 0–1-km AGL bulk wind difference of 10–12.9 m s^{-1} (20–25 kt, Fig. 14c) and lifted condensation level around 500 m AGL (Fig. 14d). Both parameters were within the range found to support significant tornadoes (Craven and Brooks 2004). At 2214 (Fig. 15), a squall line was apparent with two areas of interest noted: Storm A and Storm B.

Storm A was located on the southern part of the line and was developing a distinct comma-head shape in the reflectivity pattern. This resulted from a circulation apparent in both the SRM and base velocity images, but V_r was low, only about 12–13 m s^{-1} (23 kt). Also associated with this area were SW maxima of 2.5–7.7 m s^{-1} (10–15 kt). However, no severe weather was reported from spotters monitoring this part of the squall line.

2) Radar analysis

Meanwhile, Storm B was undergoing a merger with a supercell located ahead of the line. Inbound velocity magnitudes of ≈17 m s^{-1} (34 kt) were apparent in the SRM image, although the circulation was unbalanced with much weaker outbound velocities, and weaker overall than the circulation with Storm A. However, SW within this circulation peaked between 7.2–11 m s^{-1} (14–21 kt) at this time, higher than Storm A.

At 2218, SW values decreased slightly to between 4–7 m s^{-1} (8–13 kt) in Storm A's circulation, while values in Storm B's circulation increased to 12.9 m s^{-1} (25 kt, Fig. 16). Storm B's circulation was both cyclonic and convergent while Storm A's circulation showed no indication of convergence. At 2220, a brief EF0 tornado was reported with Storm B that snapped and uprooted trees, flattened part of a corn field, and caused minor damage to a storage building.

In summary, the rotational velocities of both storms' circulations were weak and of similar values, but the SW of Storm B was higher and maximized very shortly before tornadogenesis.

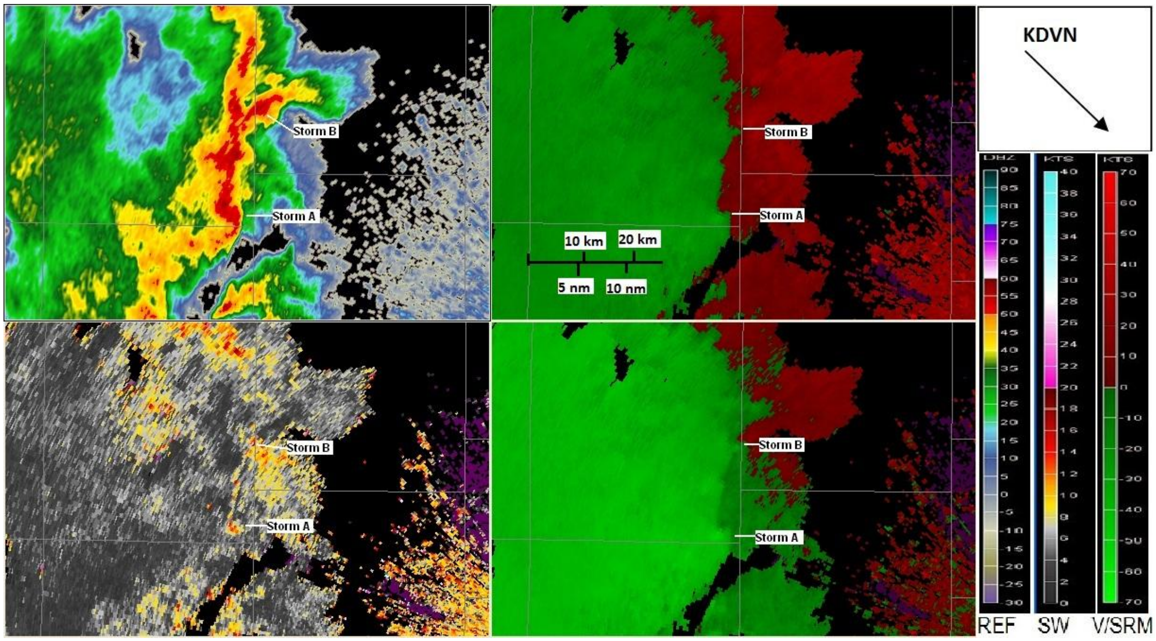


Figure 15. As in Fig. 5, but for 2214 UTC 19 August 2009 KDVN imagery at 0.5°. The KDVN radar is located about 83km (45 nm) to the southeast (lower right). *Click image to enlarge.*

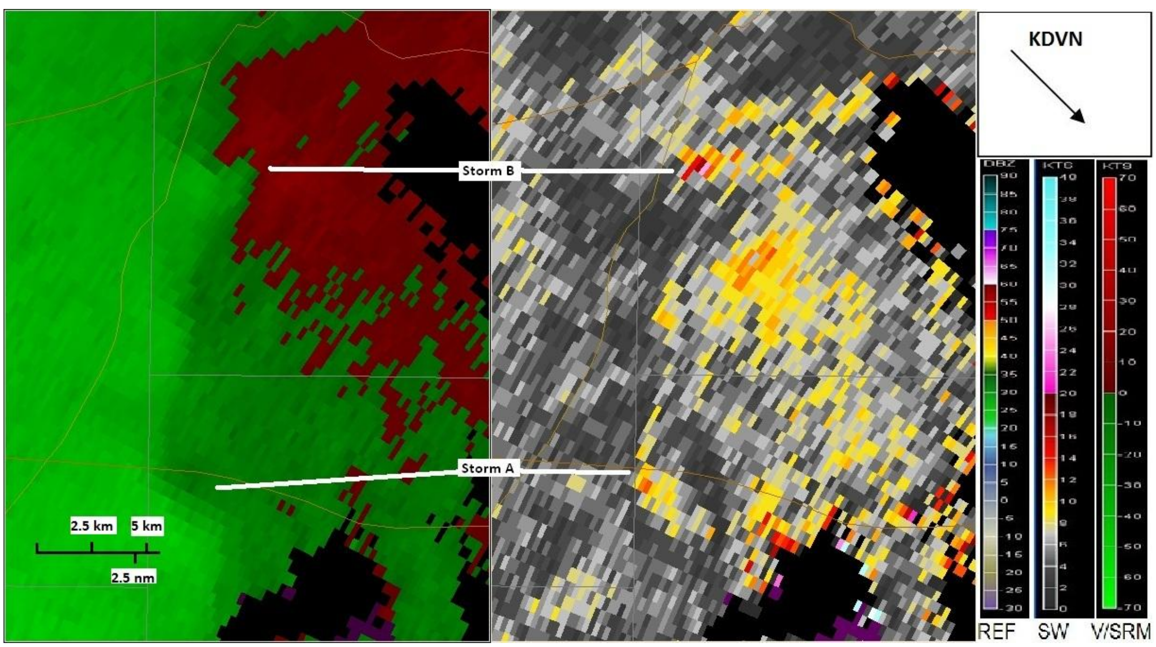


Figure 16. 2218 UTC 19 August 2009 KDVN 0.5° two-panel display of base velocity (left) and SW (right) of the squall line during tornadogenesis in Storm B. KDVN is located about 83 km (45 nm) to the southeast (lower right). *Click image to enlarge.*

d. 2 May 2010 mid evening

1) Overview

In this case SW was used operationally to assist in making a warning decision.

A mixture of broken thunderstorm line segments and clusters moved through southeastern Missouri on 2 May 2010. A supercell, initially embedded within a short line segment, produced a brief EF0 tornado in Butler County around 0300. A sounding released from Little Rock, AR at 0000 (Fig. 17) depicted an environment with surface-based CAPE close to 2500 J kg^{-1} and 0–3 km AGL storm-relative helicity (SRH) of 272 $m^2 s^{-2}$. In this case, the forecaster used the SW image to enhance confidence in the location and strength of the rotation seen in SRM data, for issuing a tornado warning 20 min prior to the tornado (D. Spaeth 2010, personal communication). This storm was ≈185 km (100 nm) west of the KPAH WSR-88D with the lowest slice at 2.9 km (9500 ft) AGL.

2) Radar analysis

At 0220 a short S-shaped line segment had moved into southeast Missouri from Arkansas. Rotation already had developed in the forward notch with a maximum V_r of 17 m s^{-1} (33 kt), increasing to 20 m s^{-1} (39 kt) at 0224 and 0229. SW values of ≥10.3 m s^{-1} (20 kt) grew in coverage at both the 0.5^o and 0.9^o during this time. The 0229 volume scan showed the S-shape had evolved to cellular.

By 0233 (Fig. 18), a new circulation developed just north of the inflow notch, on the southern flank of the storm. The maximum V_r was 17.5 m s^{-1} (34 kt) and the grouping of higher SW values ≥10.3 m s^{-1} (20 kt) remained at 0.5^o and 0.9^o. By 0238, the SW values increased dramatically in coverage at 0.5^o (Fig. 19) while remaining just north of the reflectivity inflow notch. Rotation values also increased to 21.6 m s^{-1} (42 kt) near the notch. An inflow jet was observed on base velocity (not shown), moving through the southern flank of the storm during the period. By 0242, the inflow notch on the southern flank dissipated. The rotation continued within the higher reflectivities, with V_r of 18.5 m s^{-1} (36 kt), while the higher associated SW pattern became less organized. By 0246 (Fig. 20) a new inflow notch had developed on the southern flank of the storm. The V_r values remained the same, but the higher SW values appeared to reorganize into a more circular shape.

The reflectivity notch became more prominent at 0250 (not shown), with the V_r remaining nearly steady at 19 m s^{-1} (37 kt). The higher SW values at 0.5^o shrunk in coverage, while increasing and becoming more circular in shape at 0.9^o. Between 0254 and 0259, the circulation moved into range-obscured data and became difficult to decipher.

The forecaster on duty noticed that the velocity couplet originally over Ripley County at ≈0238 was strong enough to investigate further. At that distance, 176–185 km (95–100 nm) from KPAH, the radar bins are quite large, and the lowest elevation angle is >3 km AGL, so more information (i.e., SW) was needed to make a confident warning decision.

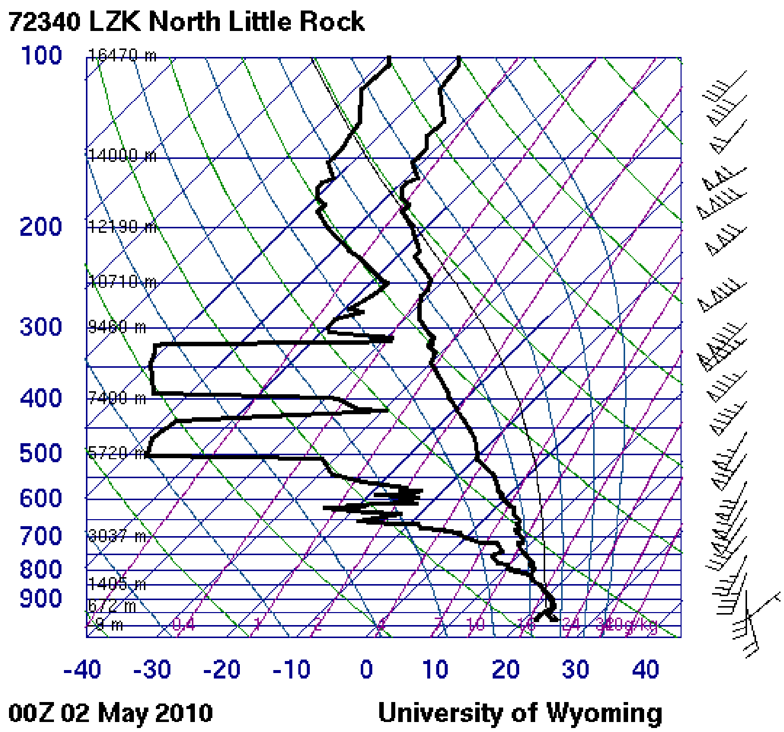
In this case, the SW image provided the extra piece of information needed to prompt the tornado warning. The bulls-eye that was associated with the velocity couplet indicated to the forecaster that the actual circulation was stronger and smaller in size than was depicted in the velocity image. The forecaster continued the tornado warning until the bulls-eye of SW had weakened. The tornado occurred around 0300 in the warning.

e. 2 May 2010 late evening

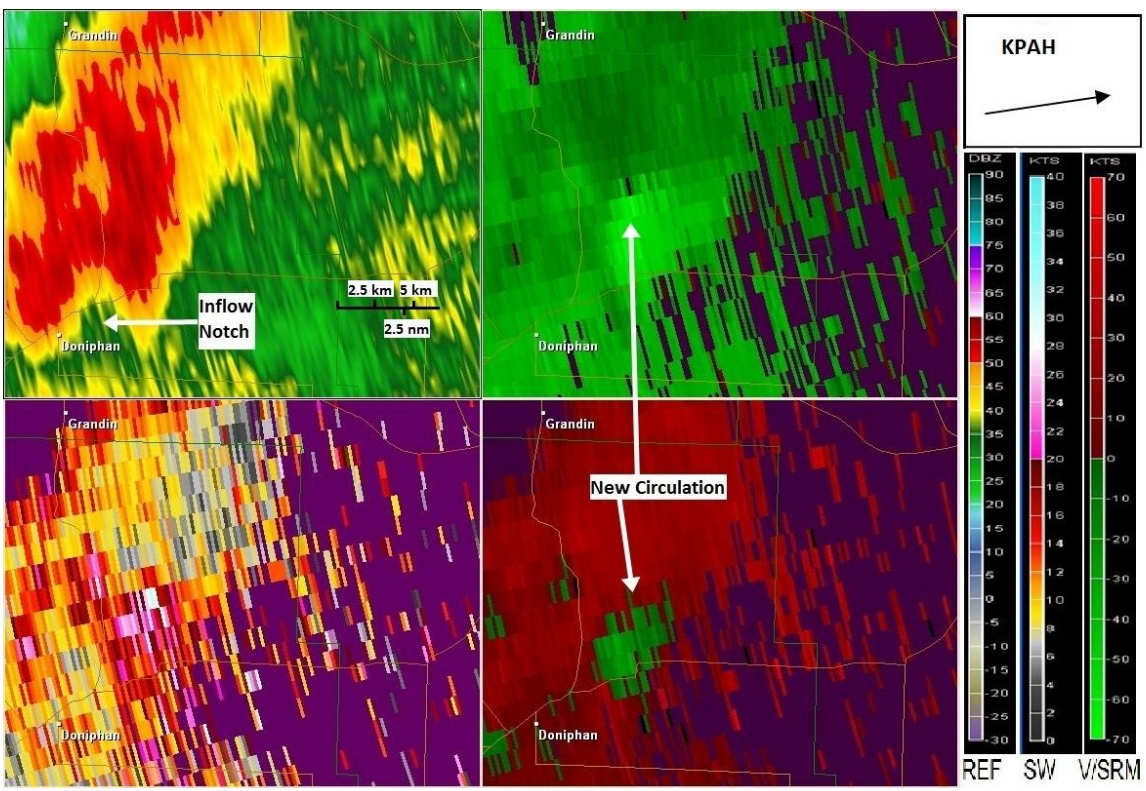
1) Overview

This case shows how SW can assist in locating important storm-structure features, such as the rear-flank downdraft (RFD) of a supercell, if a storm is relatively close to the radar.

Isolated supercells ahead of and embedded within a squall line moved across the lower Ohio Valley on 2 May 2010. Mesoanalyses from the Storm Prediction Center depicted mixed-layer CAPE near 3000 J kg^{-1} and 0–1 km bulk wind difference of 18–21 m s^{-1} (35–40 kt). One of the supercells embedded within the squall line exhibited classic characteristics including a mesocyclone and associated hook echo. The SW image depicts the location of the RFD (see Markowski 2002 for a thorough review) as it wrapped around the mesocyclone and subsequent tornado.



<u>Figure 17</u>. Skew *T*–log*p* diagram of the 0000 UTC sounding from KLZK (Little Rock, AR). *Courtesy of University of Wyoming.*



<u>Figure 18</u>. As in Fig. 5, but for 0233 UTC 2 May 2010 KPAH imagery at 0.5° about 28 min prior to tornadogenesis. The KPAH radar is located ≈185 km (98 nm) to the right. *Click image to enlarge.*

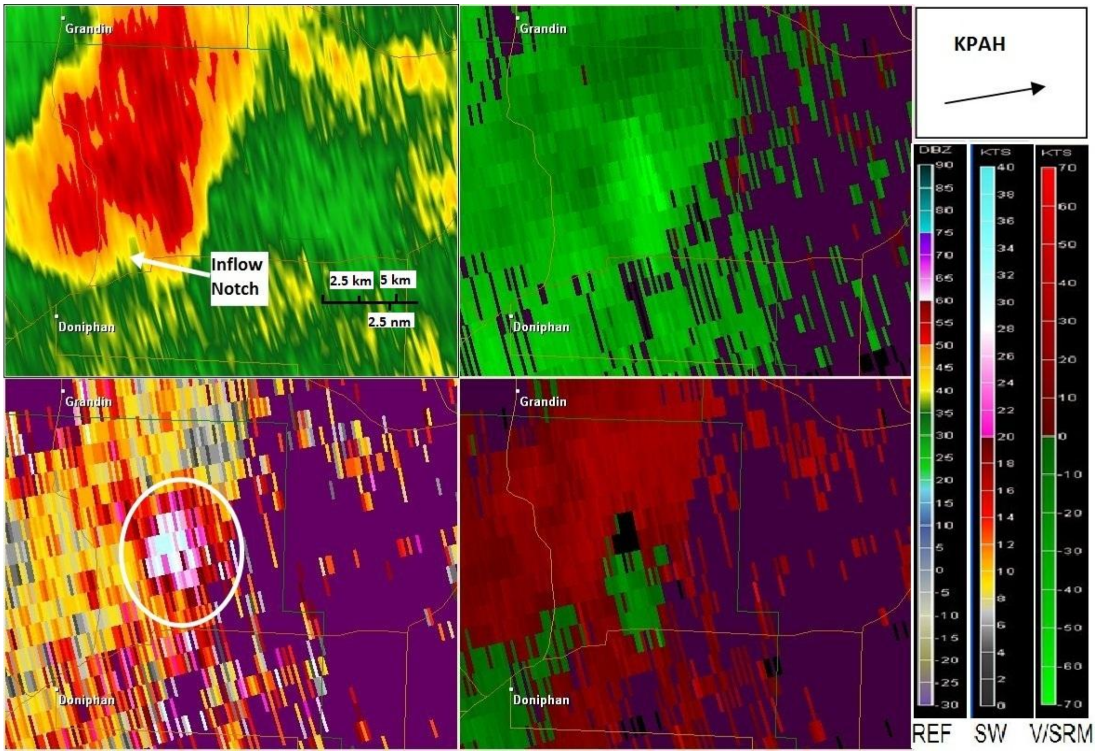


Figure 19. As in Fig. 18 but for 0238 UTC 2 May 2010, about 22 min before tornadogenesis. The KPAH radar is located ≈185 km (98 nm) to the right in these images. Circle indicates the area of concern. *Click image to enlarge.*

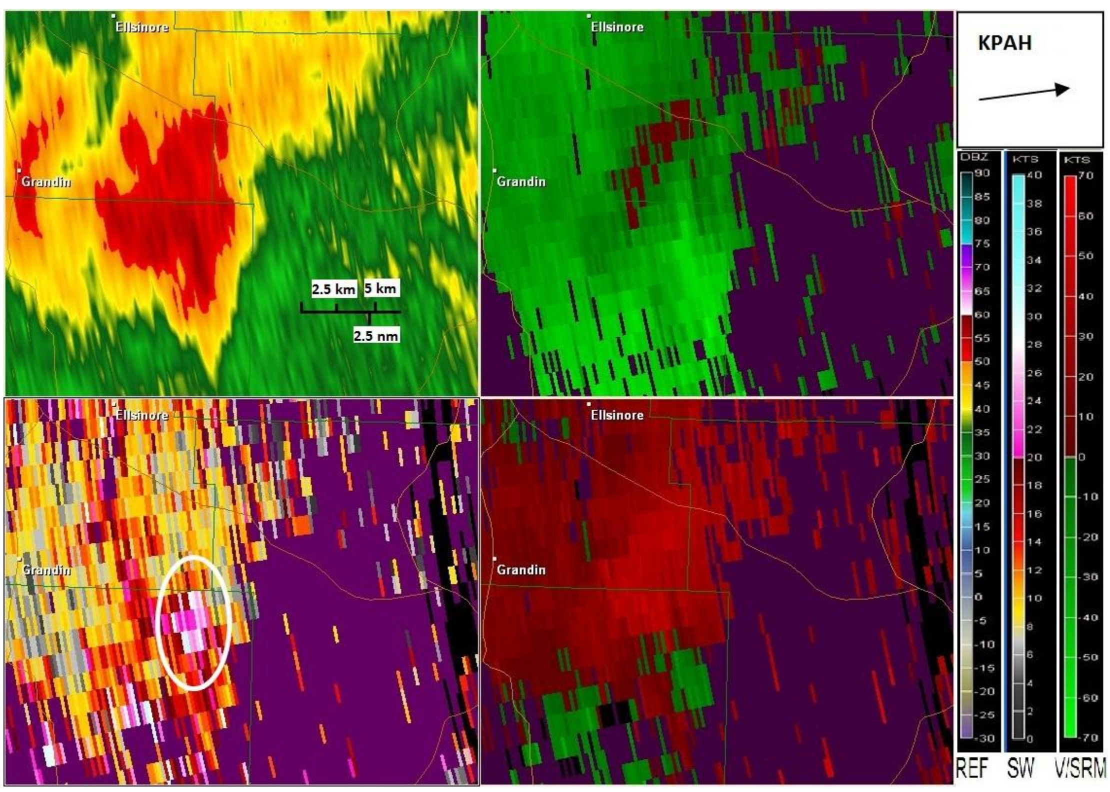


Figure 20. Same as figure 18 except at 0246 UTC.

A National Weather Service storm survey of the event found two damage paths: 1) the tornado, which produced EF2 damage, and 2) apparent RFD damage (Fig. 21).

2) Radar analysis

At 0612 a large supercell with a hook, strong mesocyclone and subsequent tornado was located ≈55.5 km (30 nm) south-southwest of the KPAH radar (Figs. 22–23). Base velocity, reflectivity, and SW images suggested that the rear-flank downdraft already was beginning to wrap around the mesocyclone. The tornado was not yet at its peak rating. Rotational velocities at .64 km (2100 ft) AGL were 35 m s^{-1} (67 kt) with a 4-km (13 kft) deep mesocyclone.

By 0616, a large "debris ball" (Burgess et al 2002) appeared in reflectivity as the tornado was reaching its peak rating of EF2, while crossing the Fulton–Hickman County line (Fig. 24). Ahead of the RFD, SW was 4–10 m s^{-1} (8–20 kt). Within the RFD, the SW image was relatively smooth with values ≤4 m s^{-1} (8 kt). One could infer the location of the RFD using base velocity at this time; however, the SW image assisted in RFD identification. The V_r at 0.64 km AGL had decreased to 24 m s^{-1} (46 kt).

Figure 21. Map of damage survey for the 2 May 2010 event. The red line represents the tornado path while the blue line represents the RFD wind damage path. The boxes around the tornado path are used to depict tornado rating (EF0, EF1, EF2, EF0 from southwest to northeast). Yellow lines are roads labeled with highway numbers. *Click image to enlarge.*

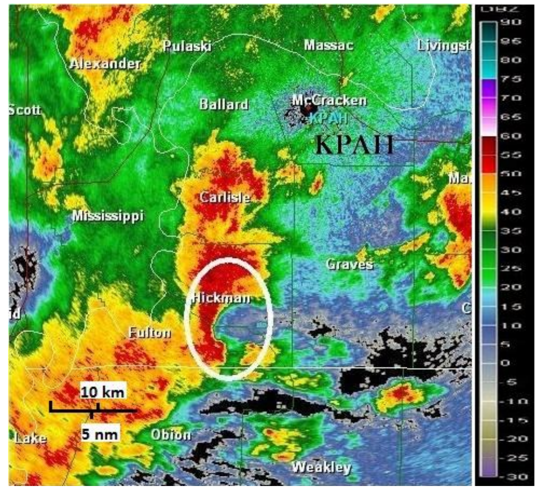


Figure 22. 0612 UTC 2 Nay 2010 KPAH 0.5° reflectivity image of supercells moving across western Kentucky and northwest Tennessee. The supercell of concern (circled) is ≈60 km (32 nm) SSW of KPAH WSR-88D (location as labeled). *Click image to enlarge.*

At 0621, the hook no longer was clearly identifiable. The mesocyclone had begun to occlude and the tornado damage was EF1. The tornado was wrapped in heavy rainfall at this time, when wind damage was starting to occur south of the circulation. The reflectivity image did not aid in the identification of the RFD, which the base velocity may have allowed. However, using the SW image, one easily could see the RFD conceptual model occurring (Fig. 25). The SW near the mesocyclone had increased to 13 m s^{-1} (26 kt). Figure 26 from 0625 indicates a decrease in V_r [15 m s^{-1} (30 kt)] and an area of SW [max value still >10 ms^{-1} (20 kt)] that is cut off from the warm, moist inflow by the RFD.

This area of SW correlates with the end of the tornado, according to the damage survey. The RFD advanced 7.4 km (4 nm) northward during the previous volume scan. While the velocity images showed the eastward movement of the RFD, the northward extent could not be determined easily. However, the SW did show the northward extent of the RFD. By 0630 the RFD still could be identified in the SW and base velocity images, but not in the reflectivity. The mesocyclone had weakened greatly, as one would expect.

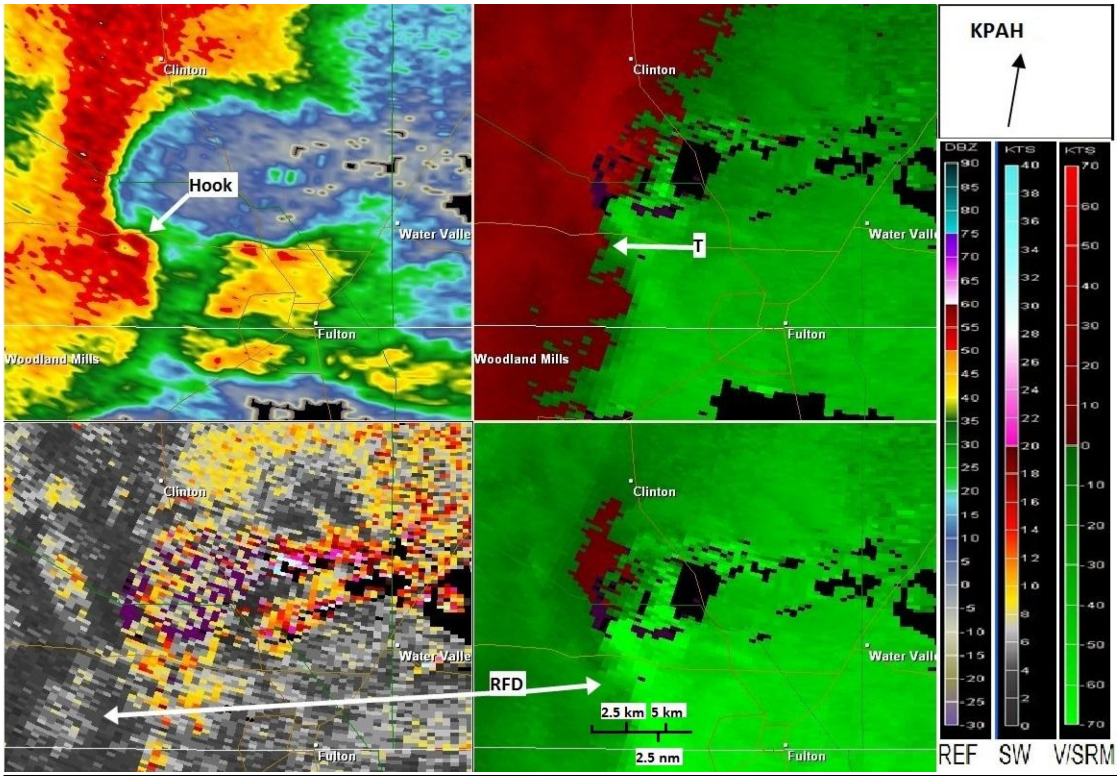


Figure 23. As in Fig. 5, but for 0612 UTC 2 May 2010 KPAH imagery of the supercell at 0.5°. KPAH is located 59 km (32 nm) to the upper right. *Click image to enlarge.*

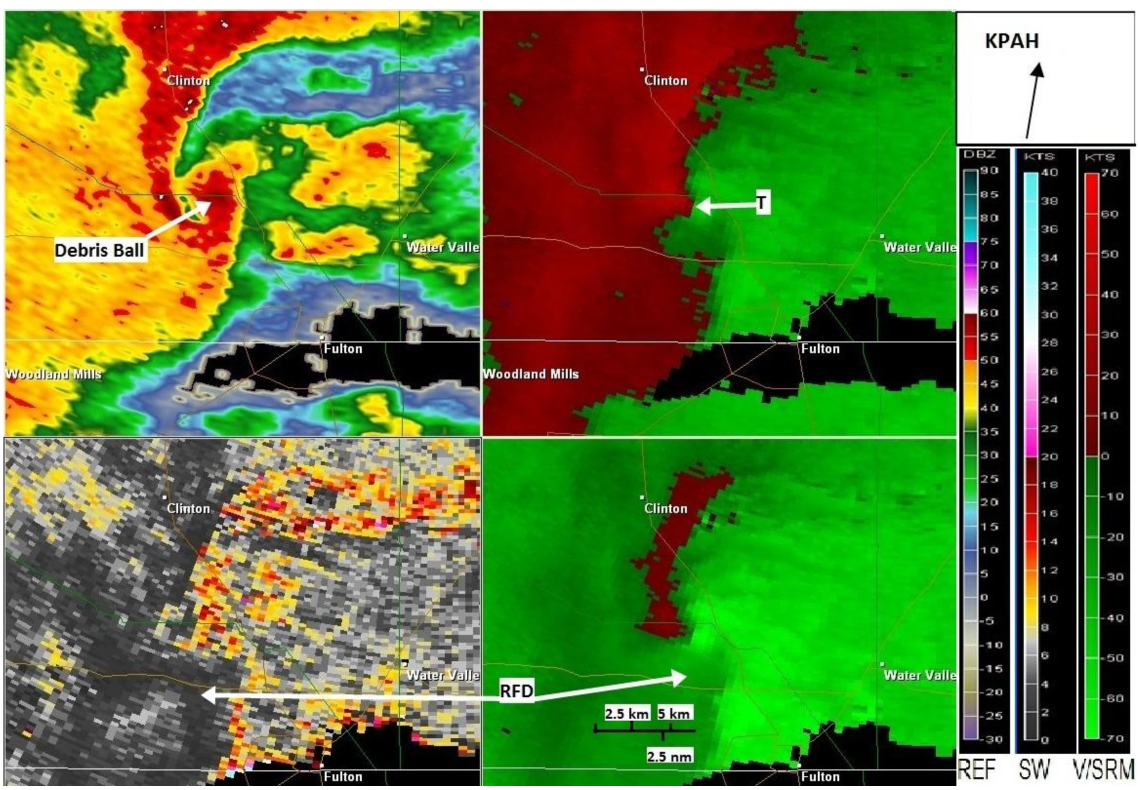


Figure 24. Same as Figure 23 except at 0616 UTC. *Click image to enlarge.*

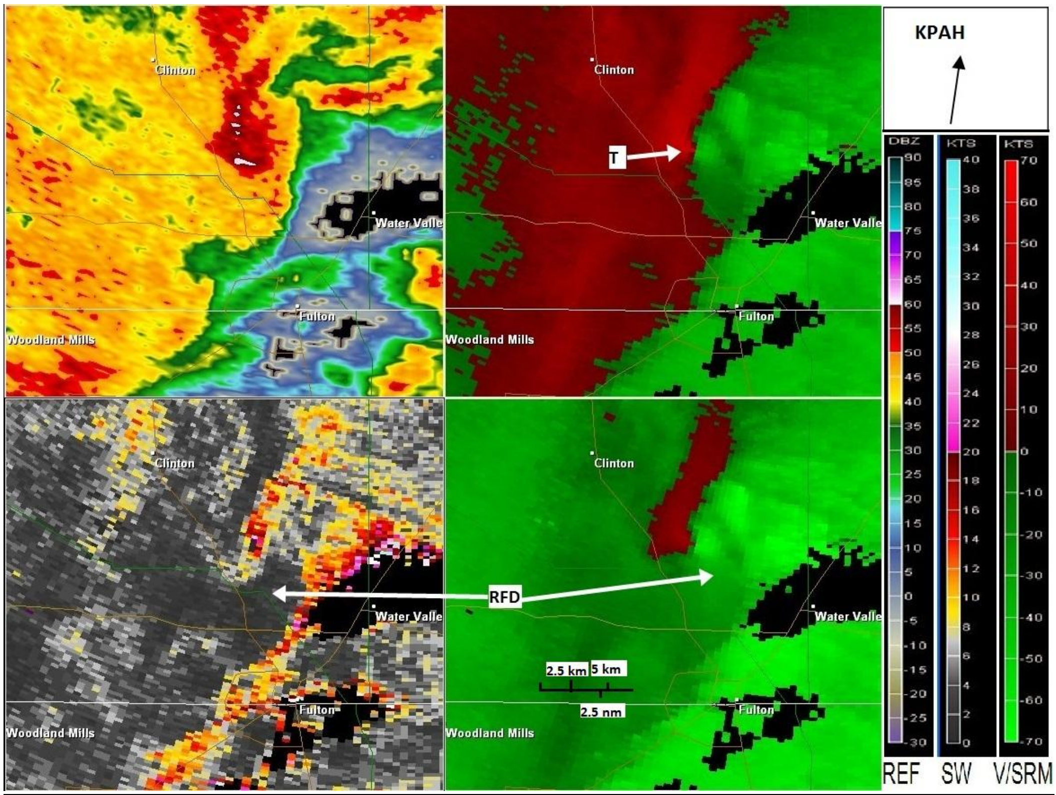


Figure 25. Same as Figure 23 except at 0621 UTC. *Click image to enlarge.*

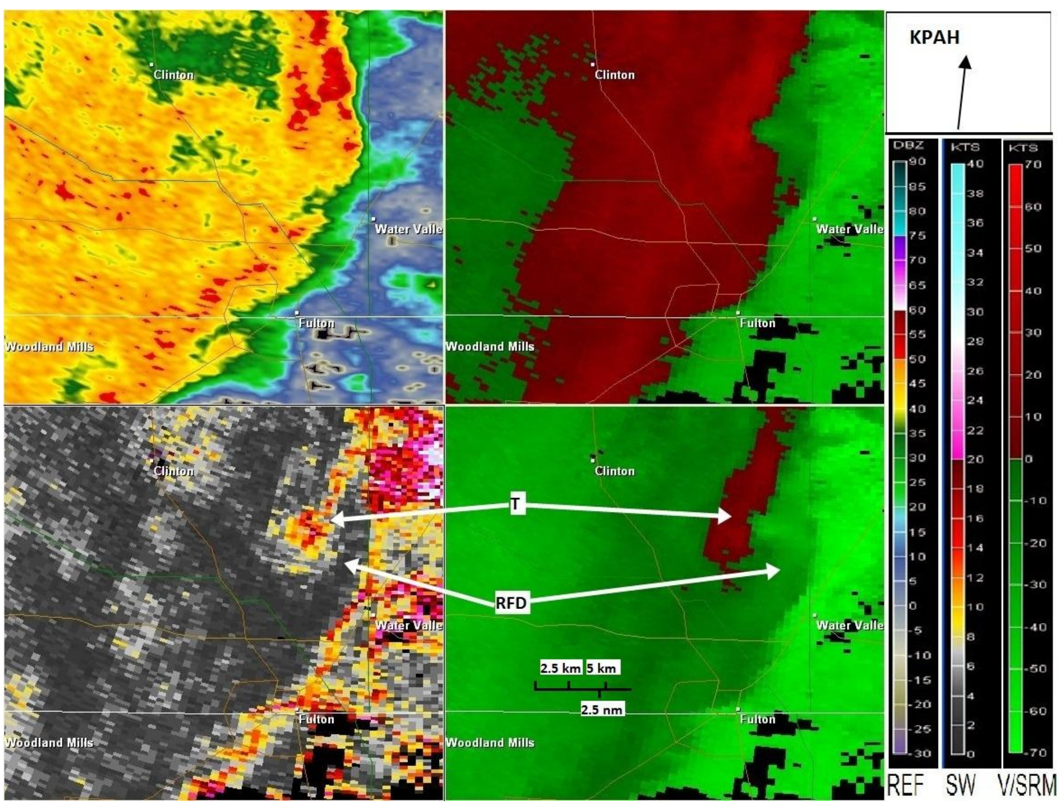


Figure 26. Same as Figure 23 except at 0625 UTC. *Click image to enlarge.*

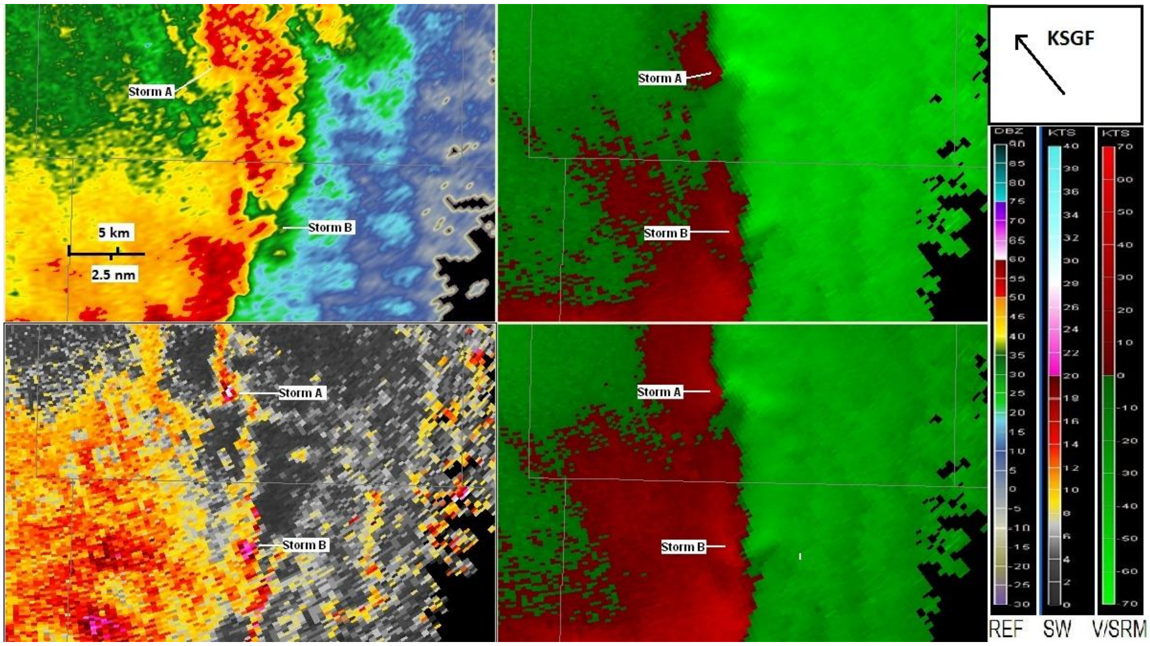


Figure 27. As in Fig. 5, but for 1321 UTC 8 May 2009 KSGF imagery at 0.5°, showing the squall line just prior to tornadogenesis. The KSGF radar is located about 56 km (30 nm) north-northwest of the storms. *Click image to enlarge.*

f) 8 May 2009

1) Overview

This case illustrated how SW can assist in determining locations of wind damage in a derecho.

A powerful mesoscale convective system developed in the Central Plains and was supported by an unusually strong and deep low-level jet, high precipitable water, and very large mid-tropospheric lapse rates (Corfidi et al. 2010). The system tracked across southeast Kansas, into southern Missouri and through southern Illinois, producing swaths of wind damage 75–100 km (≈45–60 miles) in length and 30–40 km (≈20–25 miles) wide (Przybylinski et al. 2010). In addition, numerous tornadoes were reported, including one rated EF3.

2) Radar analysis

At 1321, the KSGF WSR-88D indicated a pair of mesovortices, both with high values of SW (Fig 27). The northern mesovortex, designated Storm A, had developed within the past two volume scans and was embedded within the squall line which exhibited a leading stratiform type configuration (Parker and Johnson 2000). The southern mesovortex, designated Storm B, was at the leading edge of the squall line where most of the reflectivity echoes lay behind the circulation. Used operationally together with velocity images, SW not only indicated that both circulations were quite strong with high horizontal shear values, but most importantly, aided identification of the mesovortex embedded in the precipitation. In this case, the collocation of mesovortices with high SW values [>10.3 m s^{-1} (20 kt)] helped to determine locations where wind damage was a likely threat.

Storm A produced a 32-km (20-mi) swath of wind damage but no reported tornadoes. A few minutes after the images in Fig. 27, Storm B produced an EF1 tornado (Przybylinski et al. 2010).

In this case, SW helped to identify more quickly where wind damage threats were likely. SW values were sufficiently high to suggest tornadic potential; although it did not help to discriminate tornadic vs. nontornadic wind threats, since the higher SW values actually were associated with the nontornadic mesovortex. SW maximum values at 1321 reached 12 m s^{-1} (24 kt) with the tornadic mesovortex vs. 16 m s^{-1} (32 kt) for the mesovortex associated with nontornadic wind damage.

4. Conclusions

The SW product available from the WSR-88D is a useful diagnostic tool for operational forecasters. Examples provided in this paper detail the ability, in some cases, to relate high SW values of 10.3 m s^{-1} (20 kt) to the occurrence of tornadoes. This observed association may assist the warning forecaster in differentiating between some tornadic and non-tornadic circulations, especially at long distances from the radar. One case showed that boundaries sometimes can be easier to locate in SW than in base reflectivity. In some cases, high SW can be used to assess the persistence and strength of a circulation, and to aid in the tornado warning process. If the storm is close enough (in this case 59 km (32 nm)) to the radar, highly detailed storm features can be seen in the super-high-resolution SW, such as the RFD. This information can be critical to help warning forecasters with understanding the storm structure, morphology, and evolution. The authors strongly urge operational forecasters to integrate SW in their storm interrogation and warning assessment.

ACKNOWLEDGMENTS

Special thanks go to Beverly Poole, MIC of WFO Paducah, KY and Steve Kuhl, MIC of WFO Quad Cities for their support in this research. Thanks also go to Dan Spaeth of WFO Paducah for his recommendation to include the mid evening case from 2 May 2010 in this research. Dan also assisted in the review of this paper along with Mary Lamm and Rachel Trevino of WFO Paducah. Special thanks go to Jeff Manion of CRH. All radar images were created using Gibson Ridge software. A thanks also goes to our formal reviewers whose comments resulted in significant improvements to the paper.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Pamela L. Heinselman):

Initial Review:

Recommendation: Accept with major revision.

General comments: The purpose of the manuscript is to illustrate operational uses of spectrum width. This goal is addressed by illustrating spectrum width, velocity, and reflectivity signatures associated with six tornado events. Spectrum width signatures depicting boundaries and an RFD are also shown. Though the case studies presented have the potential to fulfill the author's goals, and are of interest to the meteorological community, as a whole the paper falls short of fulfilling some of the basic, scientific standards of a refereed publication. Most importantly, the manuscript fails to acknowledge previous refereed publications on the paper's primary topic, spectrum width.

Substantive comments:

1. Manuscript ignores several previously published meteorological studies on spectrum width and other topics.

A quick search of the AMS journals on the AMS website reveals seven articles with "Spectrum Width" in their title and 136 articles with the term in their abstract. While not all of these articles are directly related to the topic of this paper, some of them are, and those articles reveal a historical record of the use of this moment in the field of meteorology. Some previous conference papers on applications of spectrum width in storm analysis, such as Bohne et al. (1997; 28th Conf. on Radar Meteor), are also absent from the text. Reading this submission's Introduction, one is led to believe, incorrectly, that only two conference papers on applications of spectrum width exist in the literature: Lemon (1999) and Lemon and Parker (1996). Interestingly, Lemon's 1998 article in *Wea. Forecasting*, "The Radar "Three-Body Scatter Spike": An Operational Large-Hail Signature", is one of the papers that, though relevant to the submitted study, is not cited. Section 2's explanation of spectrum width is also devoid of relevant references, such as those that discuss errors associated with this moment (see Fang et al. 2004; JAOM).

Another example of a topic without citations is super-resolution sampling; this concept is demonstrated in Wood et al. (2009; JTECHA).

To be acceptable for publication, I would expect this manuscript to:

a. Introduce this research topic in context of previous studies,
b. Discuss what is unique about this study relative to other works,
c. Cite papers that support the discussion of spectrum width strengths and limitations found in Section 2 (limitations would ideally be more specifically stated as such in the text),
d. Discuss findings in light of other works, and
e. Include all other relevant references on other topics discussed in the manuscript.

We have re-worked the introduction to add more references. However, we do not have access to several of the references you cite. We would be happy to add them if you feel they are still necessary.

2. The abstract states that two operational cases demonstrate impact of the use of spectrum width on forecaster confidence: (a) and (e). In the text I only noticed one specific mention of a forecaster having used this moment during operations, and that instance is case (d). The associated radar analysis, though, does not demonstrate how the forecaster used the field in his decision making. Revising the cases to make clear operation use and resulting decisions made would definitely strengthen the paper.

We have addressed these concerns in the revision.

A related question that came to mind while reading the paper is how the cases were chosen. I think that a brief description of how/why the six cases were chosen would be of interest to your audience. It would be informative to tell readers the number and types of cases examined, and that the focus is on spectrum width signatures within tornadoes that develop primarily within convective lines and mergers (abstract and introduction).

These cases were chosen based upon what we have seen operationally. We did mention that we were focusing on severe weather related signatures only. The idea was to broaden the reader's scope to include looking at SW during severe weather events.

3. There is a lack of consistency in quality of presentation across the six cases, including the degree to which the three moments are analyzed (see below).

a. 31 May 2000
Although the focus of the paper is on spectrum width, the discussion of this case focuses much more on velocity signatures and their evolution during the event (like Fig. 7; a figure I do like, by the way). While it is good to know that a maximum in spectrum width existed at the time of the tornado, from an operational perspective it would be more useful to know if this signature also co-existed with the circulation seen in the velocity data prior to tornado occurrence and how the field evolved during the same time frame as the analyzed velocity data (Fig. 7). The magnitudes of spectrum width are also important to include since a quantitative value of spectrum width associated with tornadoes is given in the conclusion.

Concerning the interpretation of Fig. 7, it seems to me that the mesovortex began to weaken much earlier than 30 min after tornado occurrence.

We have worked to address these concerns. All cases were revised to give more detailed information on SW itself. Where you asked for additional velocity data, this too has been enhanced. We attempted to present about the same information for each case. This should address several of the sections below.

b. 4 April 2008
This case nicely shows the strong depiction of boundaries in the spectrum width data. What it does not mention, as in the 31 May 2000 case, is the magnitude of spectrum width at the time of the tornado. Again, this is needed to substantiate (or not) the value noted in the conclusion.

The description of circulation's evolution suggests that it was first observed at the lowest elevation angle (0.5 deg) at 0610 UTC, yet later in the text (0618 UTC) descent of an intensifying circulation to 0.5 deg is noted. Was this latter circulation separate from the first one described or did the intensification occur w/in a broader circulation? Also, at 0610 UTC magnitude of the circulation is given, but is absent from the 0618 UTC description.

We hope this confusion has been addressed.

c. Nice description of the trend in spectrum width over two volume scans. Compared to the previous two cases, the discussion of velocity signatures is sparse.

d. We are told that spectrum width data contributed to a forecaster's decision to issue a tornado warning, yet the case doesn't tie the forecaster's use of the data into the case description. Though a tornado occurred at the end of the case, this point is left out, leaving the reader hanging and a bit disappointed at the lack of closure. The velocity and spectrum width signatures are treated more equally in this case than in previous cases.

We have enhanced this section with exact details given to the authors directly from the forecaster.

e. Like (c), the discussion of velocity signatures is sparse compared to the discussion on spectrum width. A question that came to mind two while reading this section is how an event written as being "subsequent" can also be occurring at the reference time (Radar Analysis: sentence 1 and then description of evolution at 0625 UTC; at 0625 UTC, how does the analysis of the radar data show the end of the tornado?)

This has been addressed.

f. Like (a) and (b), values of spectrum width are not given. A question that arose while reading this section is when and for how long did Storm A produce a swath of [nontornadic] winds; was this swath one of those discussed in the overview of this case?

4. The conclusions section contains a supposition that is not addressed in this paper. Given that the manuscript doesn't show any data supporting the comment that spectrum width "may be able to assist the warning forecaster in differentiating between some tornadic and non-tornadic circulations", this speculation seems inappropriate, especially since analysis of one of the cases (f) showed that spectrum width values were not useful for differentiating between potential for tornadoes and straight-line wind damage.

The conclusions section also states that some cases show a correlation between "SW values of 10 m s^{-1}" and occurrence of tornadoes. How many of the cases? Did this correlation only exist for the cases for which SW values were shared with the reader? How did the magnitude of values found in this study compare to the magnitude of values found in other published studies looking at squall line and supercells? It seems that a more specific treatment of the degree to which (in how many cases?) spectrum width provided additional information versus complementary information would be worth stating as well. Finally, I am curious to know if the term "continuity" is meant in the same sense as "persistence" (repetitive), or if the author's mean to say "vertical continuity?"

The conclusion has been re-worked to use your comments. Again, this paper only deals with these cases. We do not know of any published work that even mentions the 10 m s^{-1} correlation. It was just something seen in our cases. It would take numerous cases to verify that this is a viable warning threshold. It was not meant to be a threshold, rather something that we have noted. SW provides complementary information to help the forecaster see additional details (clearer than with velocity or reflectivity). It is meant to be one more piece of information to help them decipher what is seen on radar. In the case where the forecaster actually used SW to aid in a tornado warning, SW was not used alone, it was an aid.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General comments: The purpose of the manuscript is to illustrate operational uses of spectrum width. This goal is addressed by illustrating spectrum width, velocity, and reflectivity signatures associated with six tornado events. Spectrum width signatures depicting boundaries and an RFD are also shown. Though the case studies presented have the potential to fulfill the author's goals, and are of interest to the meteorological community, as a whole the paper falls short of fulfilling some of the basic, scientific standards of a refereed publication. Most importantly, the manuscript fails to acknowledge previous refereed publications on the paper's primary topic, spectrum width.

The quality of this paper has been improved by 1) the inclusion of most relevant referred publications, 2) a more balanced description of the six cases, and 3) more focus on how the spectrum width data were used operationally. The writing is a bit rough around the edges. Using track changes, I've offered suggestions to improve the clarity, flow, etc. of the paper.

Substantive comments:

1. Manuscript ignores several previously published meteorological studies on spectrum width and other topics.

I would think that the NWS would have access to AMS journals through the AMS website. Is this not the case?

Just became the case today 10/11/11—we have added additional papers as references

In section 3, I agree that this concern [impact on forecaster confidence] has been addressed in (a), and (d)–(e), but not in (b) or (c). In the latter two case studies, a clear statement as to how SW data were useful to the forecaster is still lacking. The content of the abstract is improved, but would benefit from further revisions. (see attached file)

[Minor comments omitted…]

We have decided to introduce each example with a statement that explains whether the SW helped operationally or in a post mortem sense.

Thank you so much for the suggested inline changes—very helpful.

a. 31 May 2000: Nice job producing more balanced analyses, here and in the cases that follow. In the new draft, though, Fig. 6 appears to have been replaced w/ an incorrect one. It looks quite similar to Fig. 15. Also, the end of the first paragraph in this section, which discusses location of the mesovortex relative to the bow echo, should reference relevant papers from BAMEX field program.

Done.

b. 4 April 2008: The revised text contains more details of the storm evolution, but has lost its prior organization. Please revise with chronological description of the event. Still unclear is the operational use of the data; the text reads more like a research case study. Based on content in the abstract, this case appears to be the one helped in the identification of boundaries, aiding situational awareness. Please include a clear statement of SW operational benefit in this section. The comment about S-shape of SW possibly aiding warning lead time begs the question, "Did it in this case?"

It is a research case study. This was a more "after the fact" finding. We have included a sentence at the start of each section stating that states whether the case was "operationally used" or a research based case.

Information added from the forecaster is good. I am left wondering, though, if the warning verified?

Yes it did.

REVIEWER B (Jon W. Zeitler)

Overview:
This paper provides a brief refresher on base velocity spectrum width (hereafter SW), and offers six focused case studies on the application of SW data for mesoscale analysis, short-term forecasting, and severe storm warnings. While solid in premise and scope, the paper can still be significantly improved.

Recommendation: Accept with Major Revisions

Substantive comments:

1. Section 1, paragraph 2: What is the reference for "Apart from convective storms, it was also suggested that SW may be used to provide clues to trends in tropical storm strength." ?

The paragraph refers to both Lemon (1999) and Lemon and Parker (1996), but the placement of the above statement is right after the reference to Lemon and Parker (1996), for which it seems unlikely to be *attributed to. Moreover, considering that WSR-88D coverage of the lifetime of tropical cyclones is very limited, and in the near-shore environment where significant changes in tropical cyclone structure occur, I'd like to review the reference.*

We have re-worked the introduction and removed the reference to tropical cyclones.

2. Sections 2 and 3: Nearly all of the figures are too small, some to the point of illegible. While the standard format for ESSJM is dual-column, that cannot be at the expense of legible figures. I notice that Lindley et al. [2011, *Electronic J. Severe Storms Meteor*., **6** (1), 1–27], has multiple figures that encompass both columns. I strongly urge the authors to utilize that technique, zoom in, or split some figures into parts (a) and (b) and zoom in.

In addition, all figures should have a distance scale, which is especially critical since a variety of map scales are shown. I also strongly urge a north arrow, for the reasons cited here: http://eloquentscience.com/2010/02/when-to-use-north-arrows-on-maps/.

We have re-worked almost all figures to have distance from RDA, directional arrows, and color scales. It should be a given that north is up in all radar images. We have never seen this be a problem in other publications.

Last and most important, the authors can greatly increase the value of the paper by annotating features discussed in the text. They do a good job of this for Figs. 15 and 16, but so much more could be done. For example, on Fig. 3, show the surface low center and the warm front. Yes, there can be endless quibbling by some about the placement of those features, but not annotating those does not *de facto* nor *de jure* make it more scientific or helpful to the reader.

To recap, all figures need a distance scale, a north arrow, and annotation of features discussed in the text. Additional specific ideas for some figures follow:

[Minor comments omitted...]

3. Section 2, paragraph 2: I am intrigued by this sentence: "...a strong convergent signal which was associated with high SW values (not shown) in the area of incipient tornadogenesis."

This should be shown, I'd find it one of the more valuable contributions of the paper!

4. Bunkers and Lemon (2007) completed a preliminary analysis of updrafts using spectrum width, cited here: http://nwas.org/meetings/nwa2007/index.php.

Two suggestions for the authors/editors:
a. Since Lemon is a co-author of both papers, add a section to the paper with the findings from Bunkers and Lemon (2007). Including Bunkers as a co-author (presuming he contributes to the revised paper) would be appropriate.

He did not contribute to the revised paper. I have been in personal communication with Matt Bunkers about this study. He essentially said that it became a dead end. The SW was too noisy for this type of analysis.

b. Refer to Bunkers and Lemon (2007) as prior work in Section 1 and add it to the reference list. However, the title of the paper should then be changed to reflect the emphasis on detecting boundaries, damaging straight-line winds, and tornadogenesis with SW—it would be misleading to leave as is, implying all operational uses of SW would be addressed in the paper.

We can change the title, if you think that is necessary.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions.

General comments: This paper provides a brief refresher on base velocity spectrum width (hereafter SW), and offers six focused case studies on the application of SW data for mesoscale analysis, short-term forecasting, and severe storm warnings. The authors have addressed most of the issues from the first review.

[Minor comments omitted...]

REVIEWER C (James R. Johnson):

Initial Review:

Reviewer recommendation: Accept with major revisions

General Comments: The authors have built a substantial case for increased operational use of velocity spectrum width based on sound science and six case studies of various meteorological events using both the standard resolution and the super-high-resolution data displays. Velocity spectrum width plan view displays and image loops are, in this reviewers, experience rarely used by operational forecasters. Part of the reason appears to be data quality issues associated with the older, coarser displays as the authors correctly point out and they are to be congratulated on attempting to remedy this situation by producing case studies where use of these data have greatly clarified the meteorological situation.

Despite the above and doubtless the authors best intentions, there are organizational and visualization issues with the manuscript in its current form. Most of the difficulty lies in figures that are difficult to read and, in some cases, not well presented leaving the reader confused. Organizational problems in the text are relatively minor and only a few suggestions are offered there. When these issues are corrected this reviewer will have no difficulty at all recommending publication of the work.

Substantive Comments:

Figures: With few exceptions, the figures are extremely difficult to read, requiring much study and puzzling.

Generally this reviewer suggests the authors study the presentation of EJSSM Vol. 5, No. 5 (2010), Finch and Bikos, for excellent examples of how the capabilities of online publication with EJSSM can enhance figures. making them easily and quickly understandable by the reader. In virtually every case for this manuscript an embedded link to a full screen version of the figure with caption would greatly benefit readability.

[Editor's note: While the figure-expansion capabilities of EJSSM are very advantageous, as the reviewer suggests, figures also should be legible at the size presented in the manuscript. This means that

1. *Some images can be spread across both columns (abundant precedent in EJSSM), and*
2. *Wherever needed for either one- or two-column figure legibility, fonts should be expanded, line widths thickened, zooming and cropping employed, and so forth.*

The "Click image to enlarge" capability is intended to direct readers to a larger, higher-resolution version of each figure where more detail and/or information can be displayed; but every figure in the manuscript itself still should be decipherable. Please keep that in mind as you attend to the requests by the reviewer below.]

All figures have been enhanced and should be readable.

[Numerous specific figure comments omitted...]

Text: The Abstract is not clear that the authors are going to present a total of six case studies. Please try to re-word it to that effect. Along those lines, the individual case studies need to indicate more clearly in the text as to which are using the super-high-resolution data and which are not.

In the description of spectrum width and its origin, there should be some mention that the units of SW are knots or m s^{-1}. *[Editor's note: Since EJSSM is a formal, international journal, any English units used in the text must be accompanied by metric equivalents.]*

In all of the radar imagery offered, there is no indication of WSR-88D algorithm output, leaving the reader to wonder if the radar actually identified any of these features. If algorithm output is not available, perhaps a statement to that effect in the introduction somewhere. Has anyone considered creating algorithms which us spectrum width input to identify features? (Possible future study?)

We view algorithm outputs as "last chance" type of information. Forecasters are taught to interrogate the base data and not rely on any algorithm output. Forecasters should be able to recognize features such as mesocyclones and TVS's without any algorithm output.

For case "b" the second sentence mentions "relatively high shear" yet no shear depth/value is offered to the reader. Please at least provide a value. If that is not available for calculation from soundings, you should delete mention of it. The next paragraph cries out for a diagram of the jet structure on the principle that a picture is better than a lot of text. Perhaps some sort of simple composite image?

Done.

Your comment that the forward notch seen in the reflectivity was located approximately 3.2 km (10.5 kft) farther north than the notch on the SW and the location of the rotation. Speculation is usually inappropriate in a scientific paper, but indication that this unusual discrepancy may be the subject of future investigation may be appropriate. If you do not wish to do so, it may be best to omit this sentence.

Omitted.

For case "c", the paragraph beginning with "Meanwhile, Storm B...": Just a suggestion that you might provide actual values (or a range) for the "Strong inbound velocities" in the SRM... V_r perhaps?

[Minor comments omitted...]

Second review:

Recommendation: Accept with major revisions. I need to see this one again before publication.

General comments: As mentioned in the original review, this is a very worthy subject. The manuscript when finalized will be useful not only for assisting the operational meteorologist in using velocity spectrum width as a warning tool, but also for educational purposes and numerous other applications throughout the international meteorological community. The science is sound throughout and the authors clearly know their subject well. I want to see this paper published.

That said, there are still a number of quality-of-presentation and visualization problems with the manuscript as it stands. Not the least of these are some rather confusing figures. While the authors appear to identify features and geography in the figures, they must make those identifications clear to the reader, especially to new forecasters, academia and the international community. Although the authors have improved the figures during the first review there is still much that needs attention in order to make the paper more readable and the concepts easier to understand. My wish here is not to "ding" the authors but to help make the published product the best it can be.

Here are some things which are needed to greatly improve the manuscript.

Substantive Comments:

Terminology:
The authors use the terms "spectrum width", "velocity spectrum width", "SW", "spectrum width image" and "spectrum width data" interchangeably throughout the manuscript and in the captions. This terminology needs to be consistent throughout. I suggest the first sentence of the Introduction be altered slightly to read, "The second moment, the base velocity spectrum width (hereafter, SW)...." You then can replace all of the references to this Doppler moment throughout the paper with a simple "SW".

Done.

There is also somewhat of a quandary concerning the term "spectrum width data". Nowhere in the manuscript do you use the actual "digital" spectrum width data. While this term may be understood in the operational forecast environment to mean the image, parts of academia and the international radar community do in fact work with the actual digital data and not the computer generated rendering of said data into the image you refer to. Simply replace the term (where used) "data" with "image" and that potential confusion is cleared up.

Done in sections that referred directly to images.

Figures:
A number of figures still require much study and puzzling to understand the associated comments in the text. Figures should appear in support of the discussion and clearly show the desired feature with a minimum of examination. Many of the current figures are somewhat enigmatic and left to the imagination of the reader to figure out. These must be improved as follows:

[Numerous specific figure comments omitted...]

Text:
The issues in the text have been successfully addressed.

Third review:

Recommendation: Accept.

General comments: Congratulations to the authors on a top-quality manuscript. All concerns have been addressed satisfactorily. I sincerely hope the operational community and academia put this to good use.