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An Examination of the Mesoscale Environment and Evolution of the Northern Indiana/Northwest Ohio Derecho of 29 June 2012

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ABSTRACT

A multicell cluster of thunderstorms moved into northern Indiana during the early afternoon hours of 29 June 2012, later evolving into a mature bowing mesoscale convective system (MCS) by the time it exited the County Warning Area of the Northern Indiana National Weather Service. This was the beginning of a derecho that would continue across the Appalachian Mountains and off the Atlantic coast, traveling 1000 km in 10 h and resulting in at least 18 fatalities. This derecho produced a measured wind gust of 41 m s^{-1} (79 kt) at Fort Wayne International Airport, the highest measured gust along the derecho's path. The mesoscale environment was characterized by a strong cold pool, extreme instability (including near-record steep midlevel lapse rates), and weak to moderate vertical shear. This paper examines the source of this extreme environment as well as the catalyst for the sustainability of the MCS.

1. Introduction

Severe-thunderstorm wind gusts (>50 kt [25.7 m s^{-1}]) are common in the NWS Northern Indiana County Warning Area (IWX CWA) during the late spring and summer. The peak month for severe wind events is June with a peak time of occurrence between 1500–1800 LT. Severe thunderstorm-wind events are responsible for 54% of all severe-weather reports for the area and for as many deaths (7) over the 30-y period as tornadoes (Lashley et al. 2014).

The southern Great Lakes region is favored climatologically for warm-season progressive derecho development and propagation (Johns and Hirt 1987, hereafter JH87; Bentley and Mote 1998; Coniglio and Stensrud 2004). The synoptic environment is typically characterized by a midtropospheric pressure high in the southeastern United States and a deamplifying midlevel ridge across the upper Midwest. A front across the region initiates convection that is organized by moderate shear generated by seasonably strong midtropospheric winds. Many derecho events are also associated with eastern and central U.S. heatwaves that provide the extreme instability and elevated mixed layer (EML) necessary for development (Corfidi et al. 2008).

While the synoptic-scale pattern favorable for derechos in the Great Lakes has been well studied and shows relative consistency, pattern recognition provides limited forecast utility due to the influence from mesoscale factors. Two similar multicell storm clusters in similar synoptic environments may yield drastically different storm modes due to differing meso-β- and meso-γ-scale influences such as outflow boundaries, lake breezes and horizontal convective rolls (Weckwerth and Wakimoto 1992). In addition, an unfavorable thermo-dynamic environment due to remnant clouds from the prior day's storms, or a strong capping inversion, can suppress convection completely in an otherwise ideal setup (Wakimoto and Murphey 2009).

By the morning of 29 June 2012, environmental parameters appeared favorable for severe weather, but questions remained regarding the northward extent of the severe risk,

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and the strength of the capping inversion. These inhibiting factors disappeared by midday, as elevated storms across northern Illinois realized the extreme surface-based instability and quickly organized into a bow echo. This persistent bow echo grew in size and strength, and continued for over 10 h, travelling as fast as 60 kt (31 m s^{-1})as it left a path of destruction from the southern tip of Lake Michigan to the Atlantic coast. (Fig. 1).

The aftermath of the event left around 3 billion dollars in damages (NCDC 2014), and over 4 million people without power over a 1000 km path during the heart of a record-breaking summer heat wave (USDC 2013). The heat claimed the lives of 34 people in areas without power following the derecho (USDC 2013).

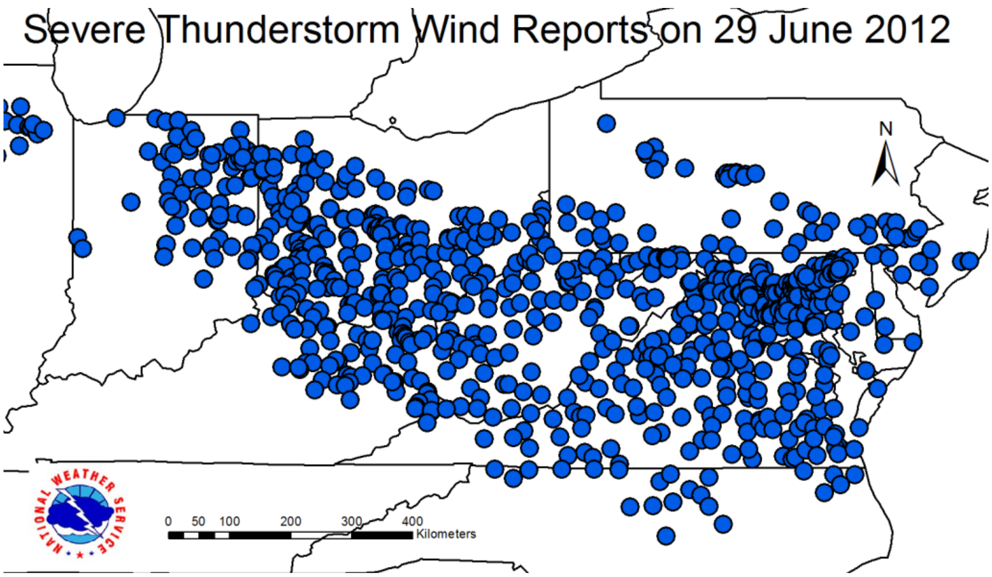

Figure 1: Storm Prediction Center (SPC) Storm reports on 29 June 2012. *Click image to enlarge.*

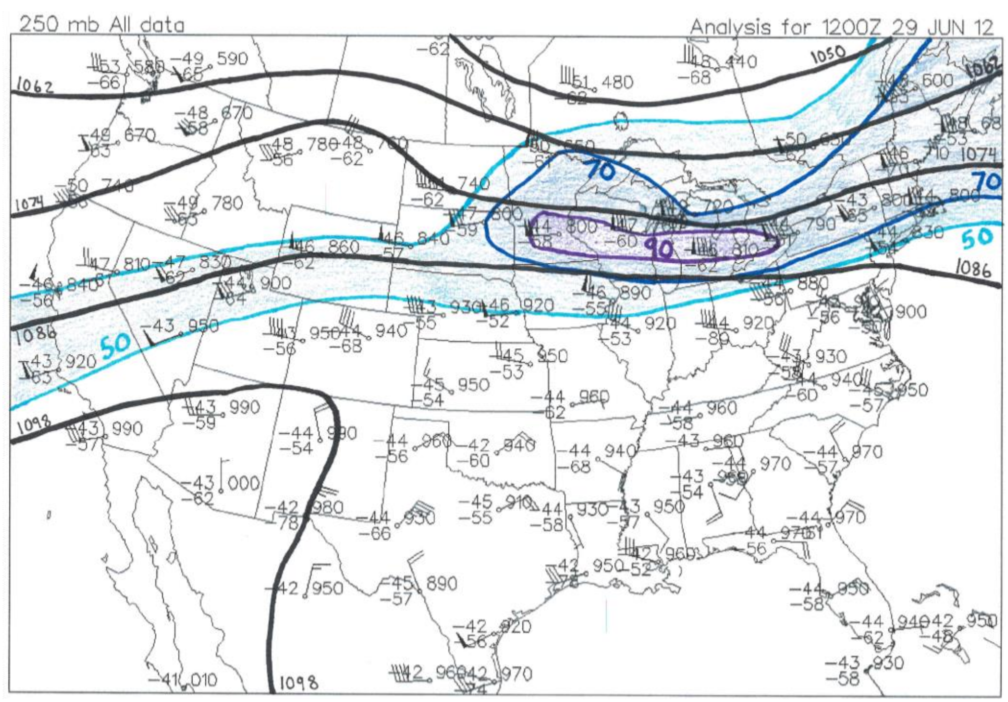

Figure 2: 1200 UTC 29 2012 250-hPa observations, black isohypses every 120 m, blue and purple isotachs >50 kt and shading. *Click image to enlarge.*

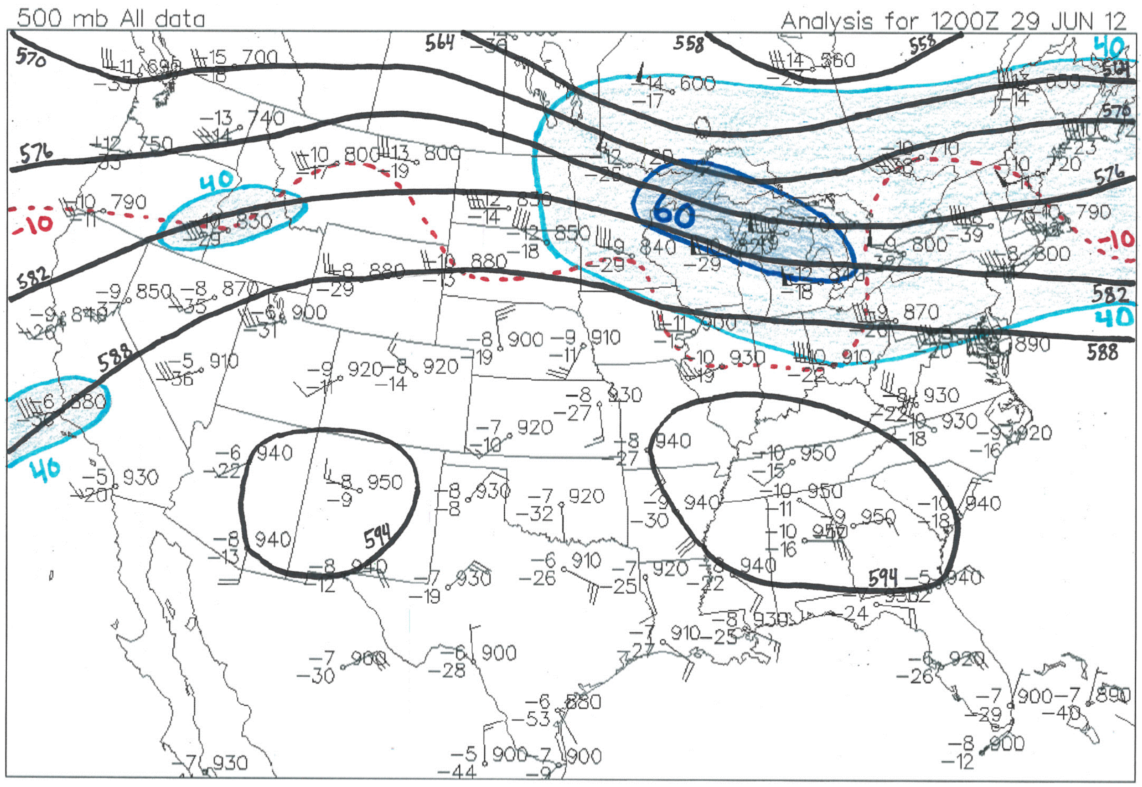

Figure 3: 1200 UTC 29 June 2012 500-hPa observations, black isohypses every 60 m, blue isotachs >40 kt (20 m s^{-1}) and shading, and red dashed isotherms every 10°C. *Click image to enlarge.*

2. Synoptic environment

a. 250 hPa

At 1200 UTC 29 June 2012, a seasonably strong upper-level jet streak had developed across the Great Lakes region in response to a tightening geopotential height gradient between a building ridge across the southeastern US and a trough moving through Ontario. The heart of this jet streak was oriented from near Minneapolis, MN to eastern Lake Erie with wind speeds over 51 m s^{-1} (100 kt). The right entrance region of this jet streak extended from northern Iowa to northern Illinois (Fig. 2).

b. 500 hPa

The midtropospheric pattern at 1200 UTC 25 June 2012 (not shown) featured a high-amplitude ridge centered across the central United States. This ridge was the catalyst for above-normal temperatures from the Great Plains into the southern Great Lakes for the days following the derecho. This ridge began to deamplify on 27 June as a closed low entered the western United States and traversed the Canadian plains. By 1200 UTC 29 June, winds in the 500-hPa layer increased to 26–31 m s^{-1} (50–60 kt) as the height gradient strengthened across the Great Lakes (Fig. 3). These midlevel winds were in the 23–26 m s^{-1} (45–50 kt) range across northern Indiana, which provided moderate deep layer shear for storm organization. There were no well-defined midlevel disturbances to support convection, which is consistent with JH87 findings regarding warm-season progressive derecho environments.

c. 700 hPa

The 700-hPa pattern at 1200 UTC on 29 June 2012 featured a moist axis from eastern Iowa to southwest Ohio with dewpoints >5 °C. This was a good indicator of the deep moisture that was in place. In addition to the moist environment, westerly winds between 15 m s^{-1} and 21 m s^{-1} (30–40 kt) had developed in the same area, which contributed to sufficient 0–3-km shear (>15 m s^{-1} [30 kt]) for the maintenance of bowing segments (Fig. 4) (Schaumann and Przybylinski 2012).

d. 850 hPa

The vertical extension of the low-level moisture field is apparent at 850 hPa at 1200 UTC 29 June (Fig. 5). This moist airmass in the low to midlevels of the atmosphere alleviated moisture deficiencies that had been observed earlier in the summer with dewpoints decreasing amidst vertical mixing during the late morning and early afternoon. As a result, in this event, surface dewpoints actually increased as convective mixing initiated. Finally, warm-air advection was in place across Iowa, which is common in the source region of convection several hours before bow-echo organization (Fig. 5; Johns 1993).

e. Surface

At 1200 UTC 29 June 2012, a well-defined surface stationary front extended from the mid-Mississippi Valley to the mid-Atlantic (Fig. 6). A line of altocumulus castellanus clouds, indicating the presence of an EML (Corfidi et al. 2008), extended along this boundary on the 1400 UTC visible satellite image (Fig. 7). By 1800 UTC, a 1015-hPa cold-pool-generated mesohigh was established across northern Indiana with a sub-1010-hPa mesolow along the Indiana/Ohio border. In addition, a 1010-hPa wake low was evident across northern Illinois. A large outflow boundary from the morning convection extended from western Illinois into northern Indiana with a stationary front eastward from there into east central Ohio. North of this stationary front, temperatures were in the upper 80s °F to low 90s °F (low–mid 30s °C) with dewpoints in the low 60s °F (mid-teens °C). South of the front, temperatures were in the mid-90s to near 100 °F (mid–upper 30s °C) with dewpoints in the low to mid 70s °F (low 20s °C). The greatest moisture was evident ahead of the outflow boundary across central Indiana (Fig. 8).

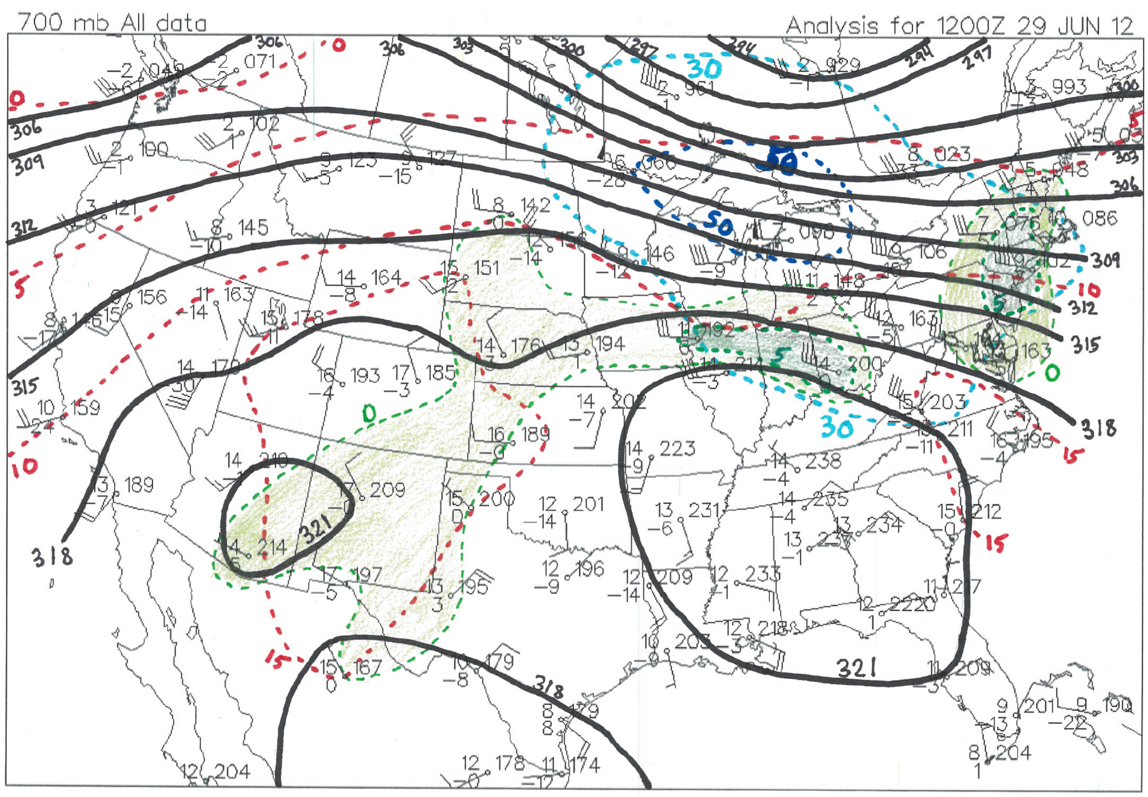

Figure 4: 1200 UTC 29 June 2012 700 hPa observations, black isohypses every 30 m, red isotherms every 5°C), isodrosotherms >0°C (light green shading >0°C, dark green >5°C), and blue dashed isotachs >30 kt (15 m s^{-1}). *Click image to enlarge.*

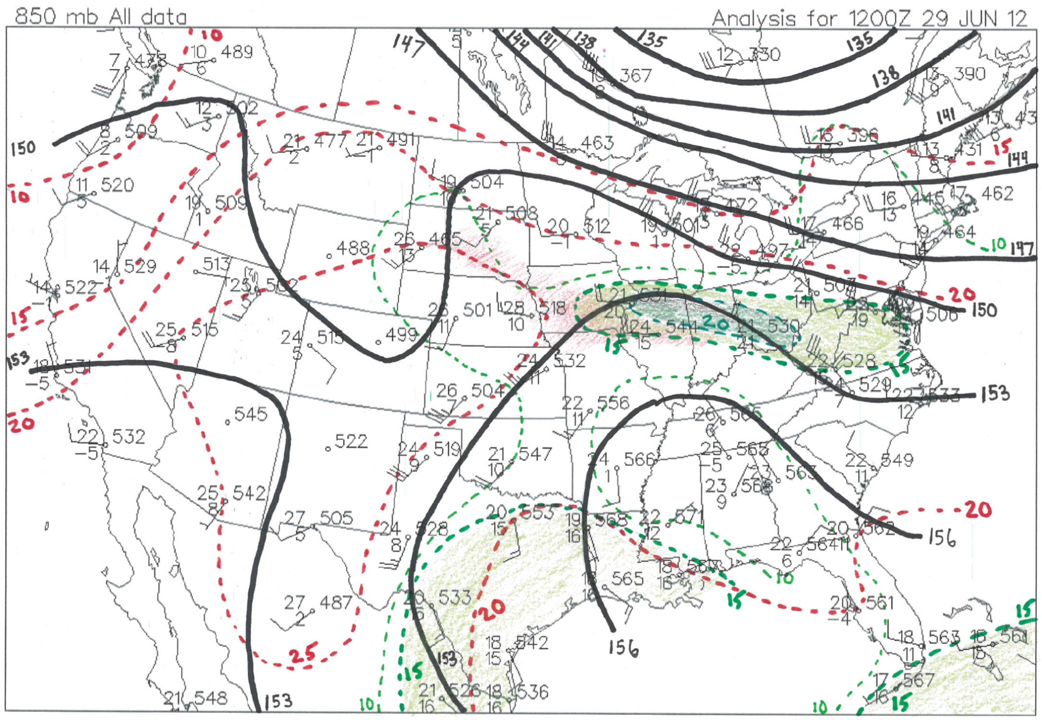

Figure 5: 850-hPa observations, black isohypses every 30 m, red dashed isotherms every 5°C, isodrosotherms >10°C (light green shading >15°C, dark green >20°C), and warm-air advection (red shaded area). *Click image to enlarge.*

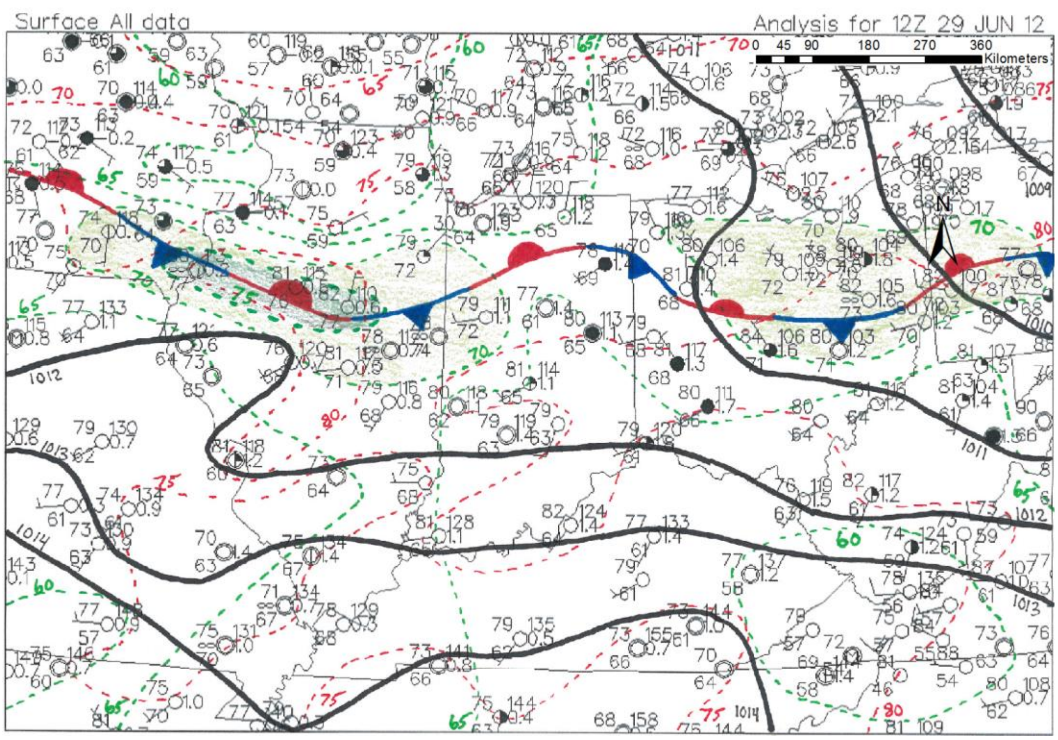

Figure 6: 1200 UTC 29 June 2012 surface observations, black MSLP isobars every 1 hPa, red isotherms every 5°F, (2.8°C) and green isodrosotherms shaded over 70°F (21°C) every 5°F (2.8°C). Hand-drawn stationary front extends from central Iowa to central Illinois, north-central Indiana and central Pennsylvania. *Click image to enlarge.*

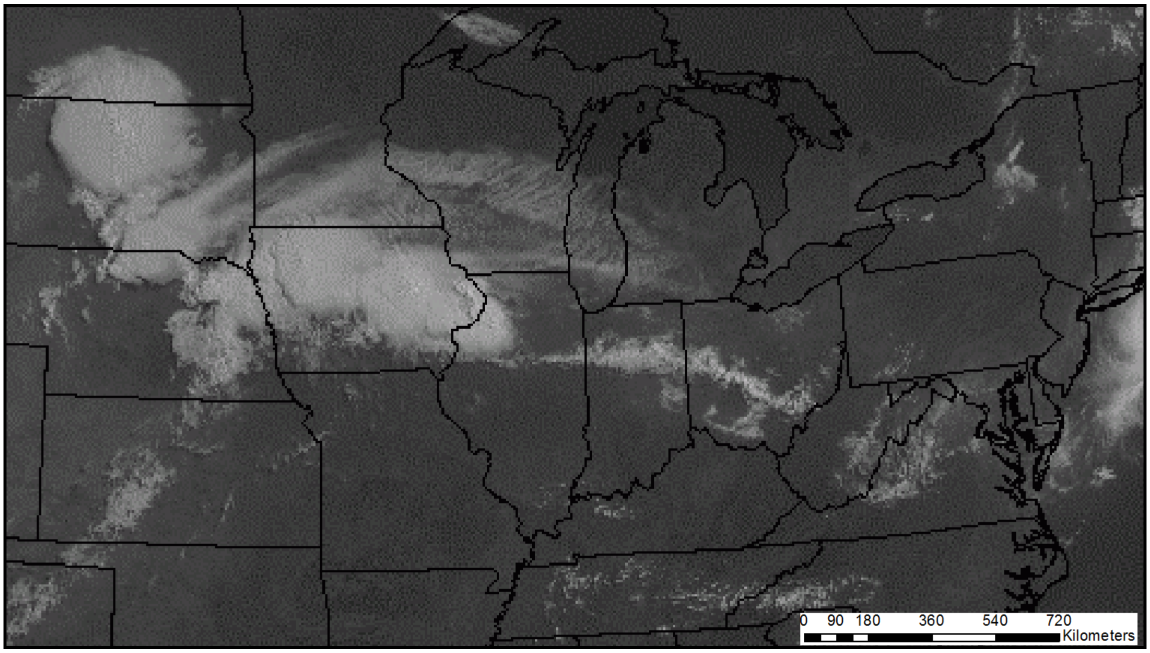

Figure 7: 1400 UTC 29 June 2012 GOES-East visible satellite image (courtesy SPC).

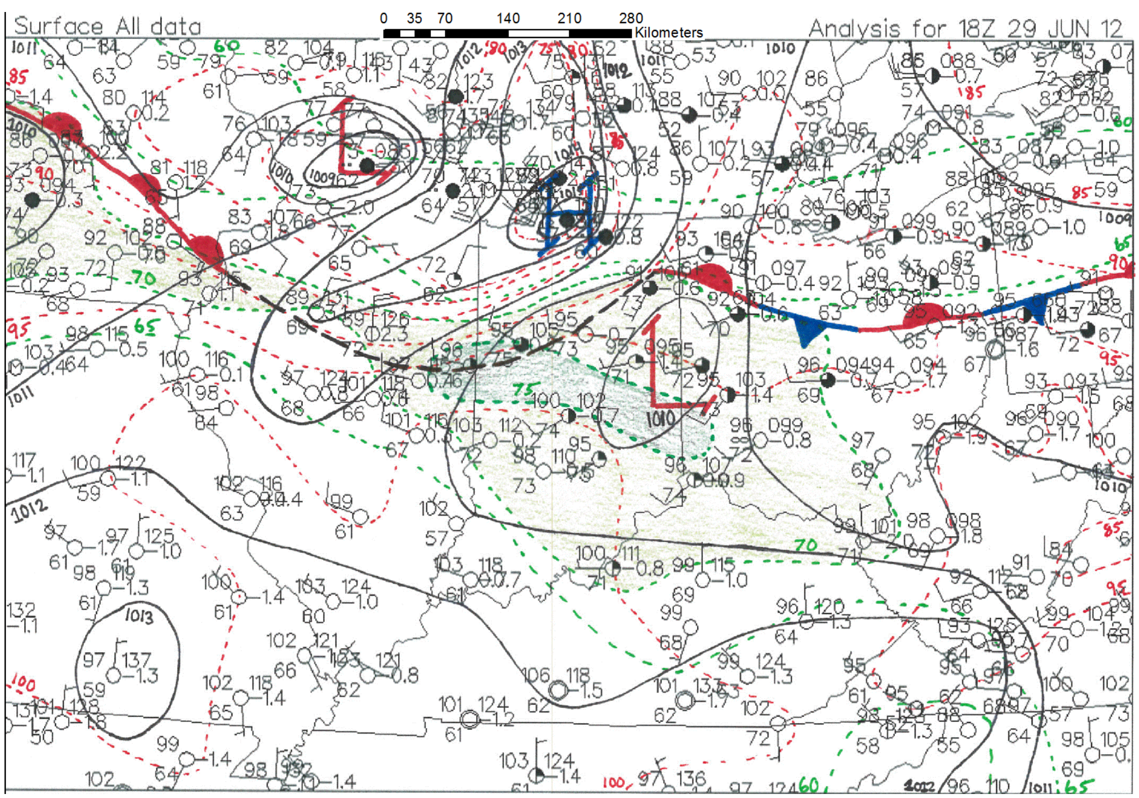

Figure 8: As in Fig. 6 but for 1800 UTC, warm front in eastern Iowa, outflow boundary from western Illinois to north central Indiana, and stationary front eastward into Pennsylvania. *Click image to enlarge.*

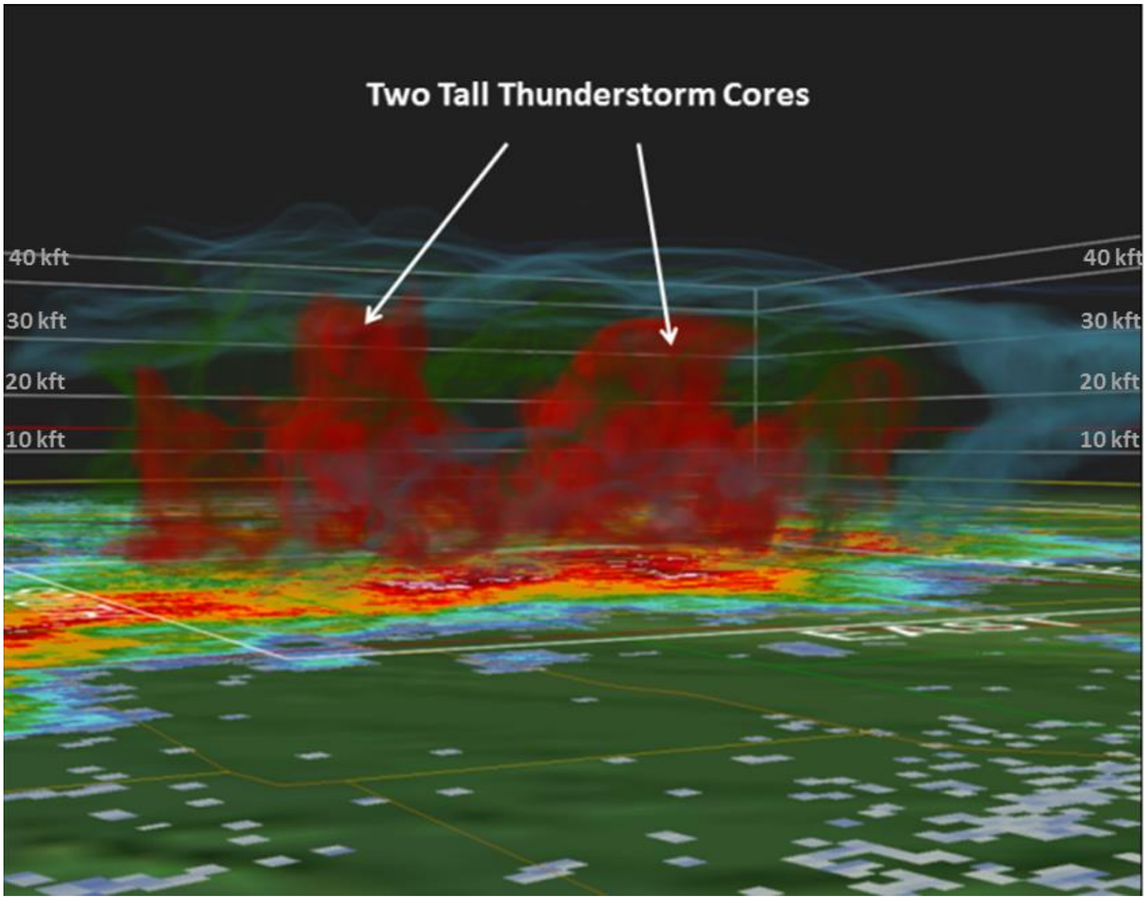

Figure 9: Three-dimensional volumetric scan of two thunderstorms in northern Illinois from the KLOT Doppler radar on 29 June 2012 at 1458 UTC. [Image courtesy of GRLevel2 Analyst®.] *Click image to enlarge.*

4. Radar evolution

On 1300 UTC 29 June, there was a broken line of convection in eastern Iowa where the warm-air advection and frontal zone interacted (see Fig. 5 & 6), and at the nose of the 850-hPa jet. A sharp low-level temperature inversion on the 1200 UTC Davenport, IA sounding (ejssm.org/ojs/public/vol11-1/12062912_SNDG-DVN.gif) and cloud bases above this inversion indicate these storms were mainly elevated over the next couple hours. The thunderstorms began to transition to surface-based by 1500 UTC as the boundary layer quickly destabilized through the morning. The 1458 UTC scan from the Romeoville, IL WSR-88D radar (KLOT) showed two tall reflectivity cores in north-central Illinois with 50 dB*Z* to 14.6 km above radar level (ARL) (Fig. 9). Both storms collapsed a few scans later with 1 cm (0.4 inch) hail and winds of 26–28 m s^{-1} (50–55 kt). That collapse led to the development of a short-lived bowing line segment with inbound velocities of 28–33 m s^{-1} (55–60 kt) measured by KLOT at 500–600 m (1.6–2.0 kft) above ground level (ARL).

This bowing reflectivity signature dissipated quickly, as the outflow boundary accelerated ahead of the convective line and cut off the inflow. By 1615 UTC, all that remained of the bowing segment was an outflow boundary with a few trailing showers. The winds along the boundary also had weakened as the Romeoville Automated Weather Observing Station only measured an 11-m s^{-1} (22-kt) wind gust. Despite the disorganization, two important features had already been established. A strong cold pool had developed, and an outflow boundary was moving southeastward towards the greater instability, leading to additional convection (Fig. 10).

By 1700 UTC additional storms developed along the instability gradient, once the outflow boundary interacted with greater surface-based instability as it entered Lake County, Indiana. 2.5–4.5-cm (1–1.75-in) hail was being reported with this cell, and the KLOT Doppler radar measured outbound velocity values near 28 m s^{-1} (55 kt) at ≈750 m (2.5 kft) ARL. Despite the strong outbound velocity values, the only storm report received was a 25-m s^{-1} (49-kt) wind gust at the Porter County, IN Municipal Airport.

Meanwhile, along the Lake Michigan shoreline in Michigan City, IN, the Great Lakes Environmental Research Laboratory marine station anemometer (located 21.3 m or 70 ft AGL) reported a wind gust to 34 m s^{-1} (66 kt), and local broadcast media passed on several reports of trees down throughout the city. This damage was due to a second cell that had traversed the southern portion of Lake Michigan and collapsed once it reached the shoreline.

The outflow of these two storms reinforced the cold pool and began a linear organization of the complex. One dominant cell along the line at 1800 UTC had evidence of a deep updraft with 50 dB*Z* to 14.8 km (48.7 kft) ARL and 60 dB*Z* to 12.3 km (40.5 kft) ARL from the Syracuse, IN (KIWX) WSR-88D (Fig. 11). The collapse of this storm in the next few scans accelerated the apex of the bowing segment towards KIWX, with 26–28 m s^{-1} (50–55 kt) winds estimated by the meteorologists onsite.

By 1830 UTC, a well-defined bow echo had developed. Rapid intensification and forward acceleration was accompanied by a major influx of widespread wind damage reports to the NWS as the line continued east. Two of these reports included downed radio towers in portions of northern Whitley County, with outbound KIWX velocities near 36 m s^{-1} (70 kt) between 150–200 m (500–650 ft) ARL. At 1850 UTC, Fort Wayne (KFWA) recorded a wind gust of 41 m s^{-1} (79 kt), as a mesovortex with an area of radar-derived winds of 33 m s^{-1} (65 kt) passed overhead (Fig. 12). WT03 observed the propensity for mesovortices to enhance nontornadic winds at the surface, which likely occurred in this case at KFWA.

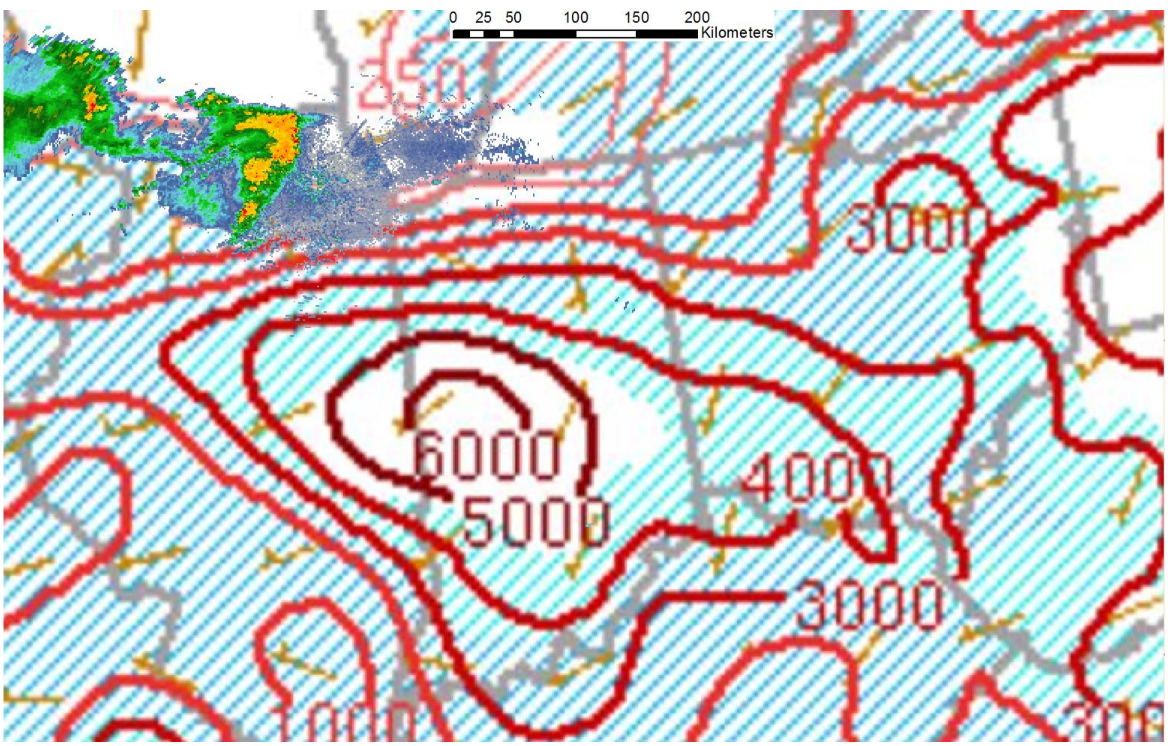

Figure 10: SBCAPE (J kg^{-1}) and KLOT radar reflectivity (upper left) at 1600 UTC 29 June 2012. [Map courtesy of SPC, radar imagery courtesy of Iowa Environmental Mesonet.]

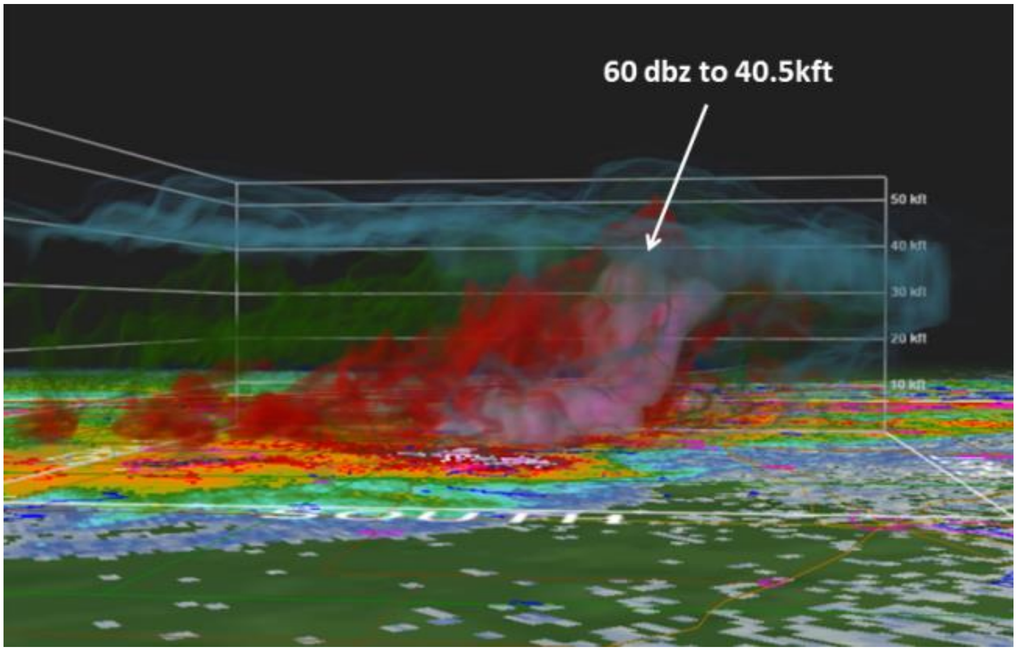

Figure 11: Three-dimensional volumetric scan of a thunderstorm in southwest Marshall County, IN from the KIWX Doppler radar, 1759 UTC 29 June 2012. Heights above radar level labeled in kft. [Image courtesy of GRLevel2 Analyst®.] *Click image to enlarge.*

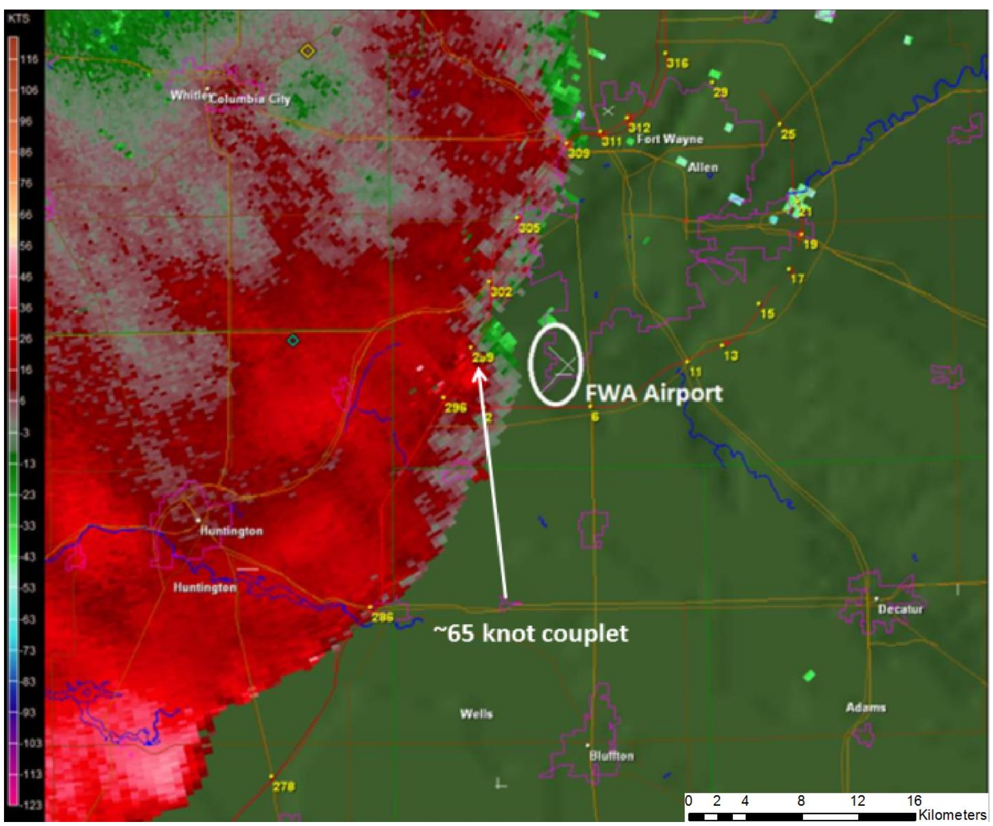

Figure 12: 1850 UTC storm-relative velocity from KIWX radar showing a mesovortex (arrow) with an area of radar-derived winds of 33.4 m s^{-1} (65 kt) as it impacted KFWA. [Image courtesy of GRLevel2 Analyst®.] *Click image to enlarge.*

Figure 13: Bricks lying on top of two cars after a second-story brick wall collapsed from a storefront in Columbus Grove, OH. [Photo credit: Eric Davis.]

As the bow echo moved east of KFWA and continued to mature, the KIWX radar detected outbound velocities of 41–51 m s^{-1} (80–100 kt) between 1–1.5 km ARL (~3–5 kft). The bow echo yielded reports of significant damage from measured 36–41 m s^{-1} (70–80 kt) wind gusts, numerous trees down, shingles off of roofs, and structural damage such as destroyed barns and sheds. The most substantial damage was in Columbus Grove, OH where the winds caused a failure of one of the walls of a two-story building in the downtown area and rubble buried two cars (Fig. 13).

While crossing the IWX CWA, the system exhibited all stages of a developing bow echo (Johnson and Hamilton 1988). A few multicellular storms entered northwest Indiana and evolved into a bow echo with >25.7 m s^{-1} (50 kt) wind speeds across northern Indiana before producing widespread winds in excess of 36 m s^{-1} (70 kt) across northwest Ohio, with a fully developed rear-inflow jet (Fig. 14 and 15). *The derecho went from little organization to maximum intensity in <1 h.*

5. Mesoscale environment

a. Thermodynamic environment

Derived instability parameters from the special rawinsonde observation (Fig. 16) taken at 1800 UTC at the Wilmington, OH (ILN) NWS office indicated large instability available to intensify surface-based storm development south of the stationary boundary. Lapse rates exceeded 8–9°C km^{-1} and SBCAPE in excess of 6000 J kg^{-1}.

A combination of factors contributed to the extreme lapse rates that were observed. A backward trajectory NOAA Air Resources Laboratory (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT; Draxler and Rolph 2003) model run for the 700-hPa air parcel over the previous 72 h shows that an EML advected from the source region of the desert and intermountain west (Fig. 18).

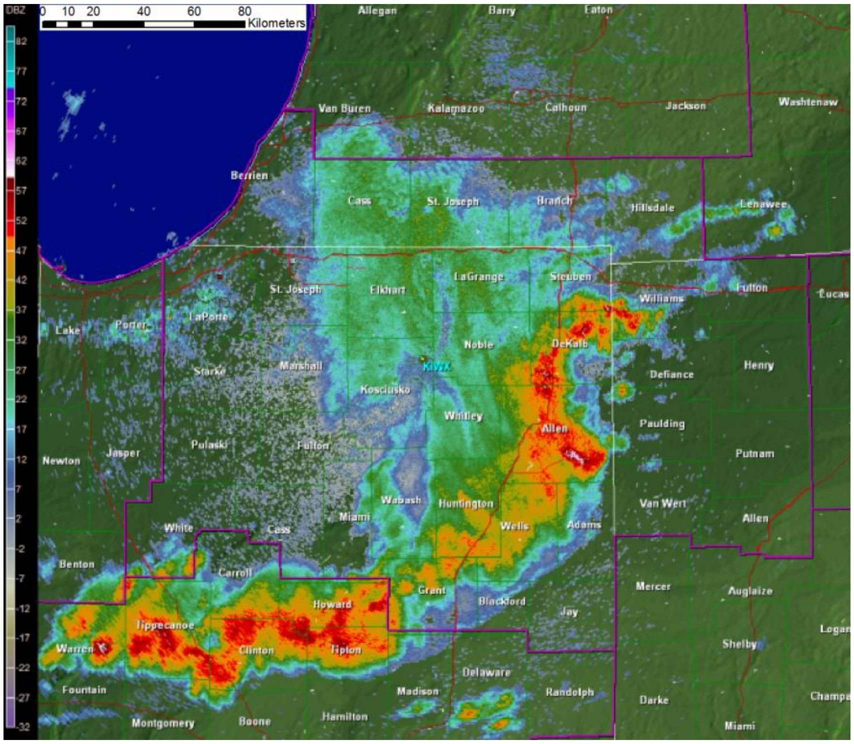

Figure 14: Base reflectivity from KIWX at 1908 UTC 29 June 2012. Base reflectivity loop from 1700–2030 UTC can be found at: www.ejssm.org/ojs/public/vol11-1/ref_animation.gif. *Click image to enlarge.*

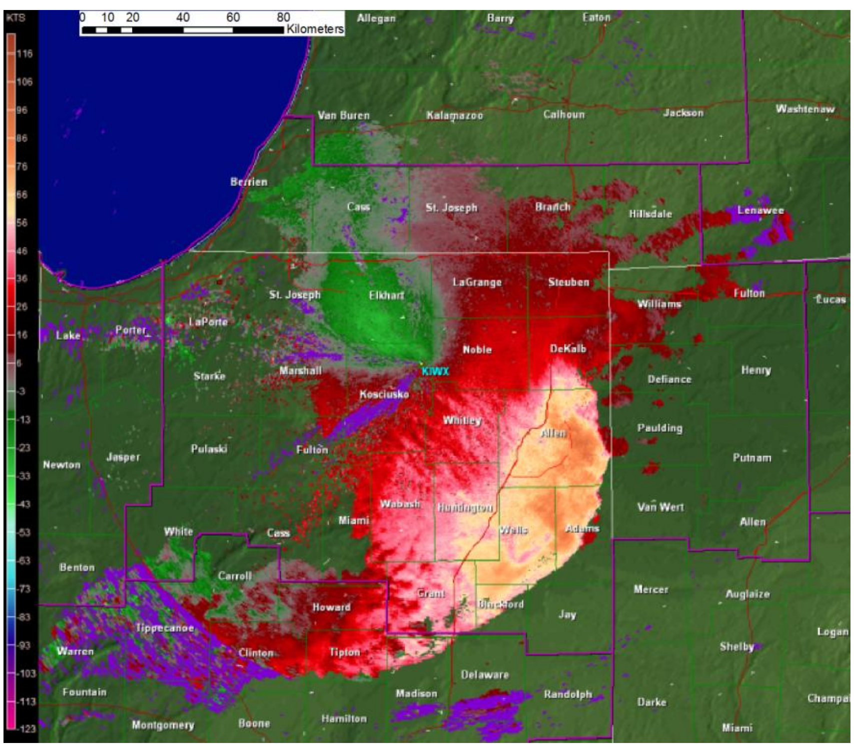

Figure 15: Base velocity from KIWX at 1908 UTC 29 June 2012. Base velocity loop from 1700–2030 UTC can be found at: www.ejssm.org/ojs/public/vol11-1/vel_animation.gif. *Click image to enlarge.*

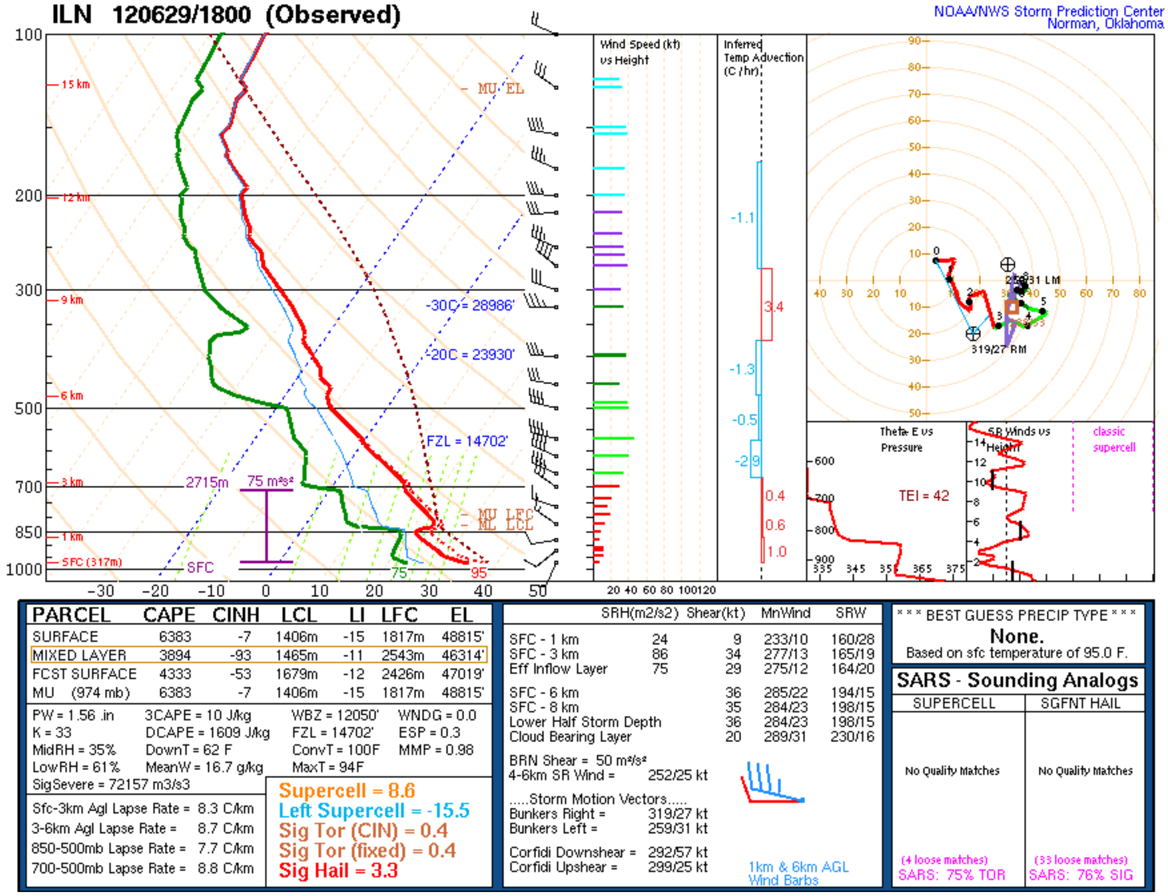

Figure 16: Skew *T*–log*p* diagram and hodograph of 1800 UTC 29 June 2012 ILN sounding, with tabular parameter computations (bottom). [Image courtesy SPC.] *Click image to enlarge.*

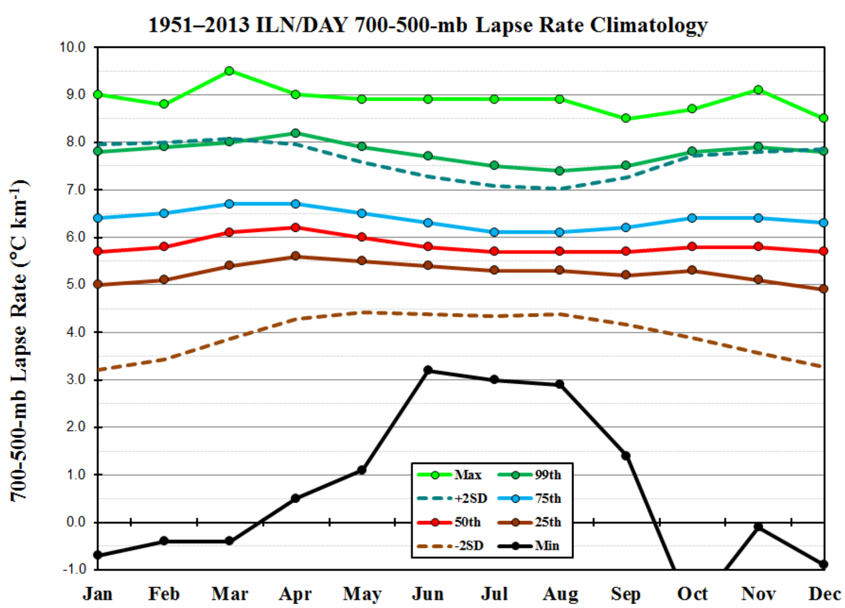

Figure 17: Climatological graph of ILN and DAY 700–500-hPa lapse rates from 1200 UTC, 0000 UTC and special soundings, 1953–2013. [Courtesy M. Bunkers, NWS WFO Rapid City.] *Click image to enlarge.*

This EML was relatively undisturbed due to subsidence across the Great Plains which helped to maintain the strength of the EML (Banacos and Ekster 2010). This can be seen in the bottom graph of Fig. 18 where the parcel began at 5000 m over southern California and encountered gradual subsidence up until 24 h before the event. This typically only occurs when there is a strong capping inversion in the Great Plains beneath a strong midlevel ridge. This synoptic pattern also places northern Indiana in a climatologically favorable area for northwest flow (NWF) severe weather outbreaks (e.g., Fig. 19; Johns 1984).

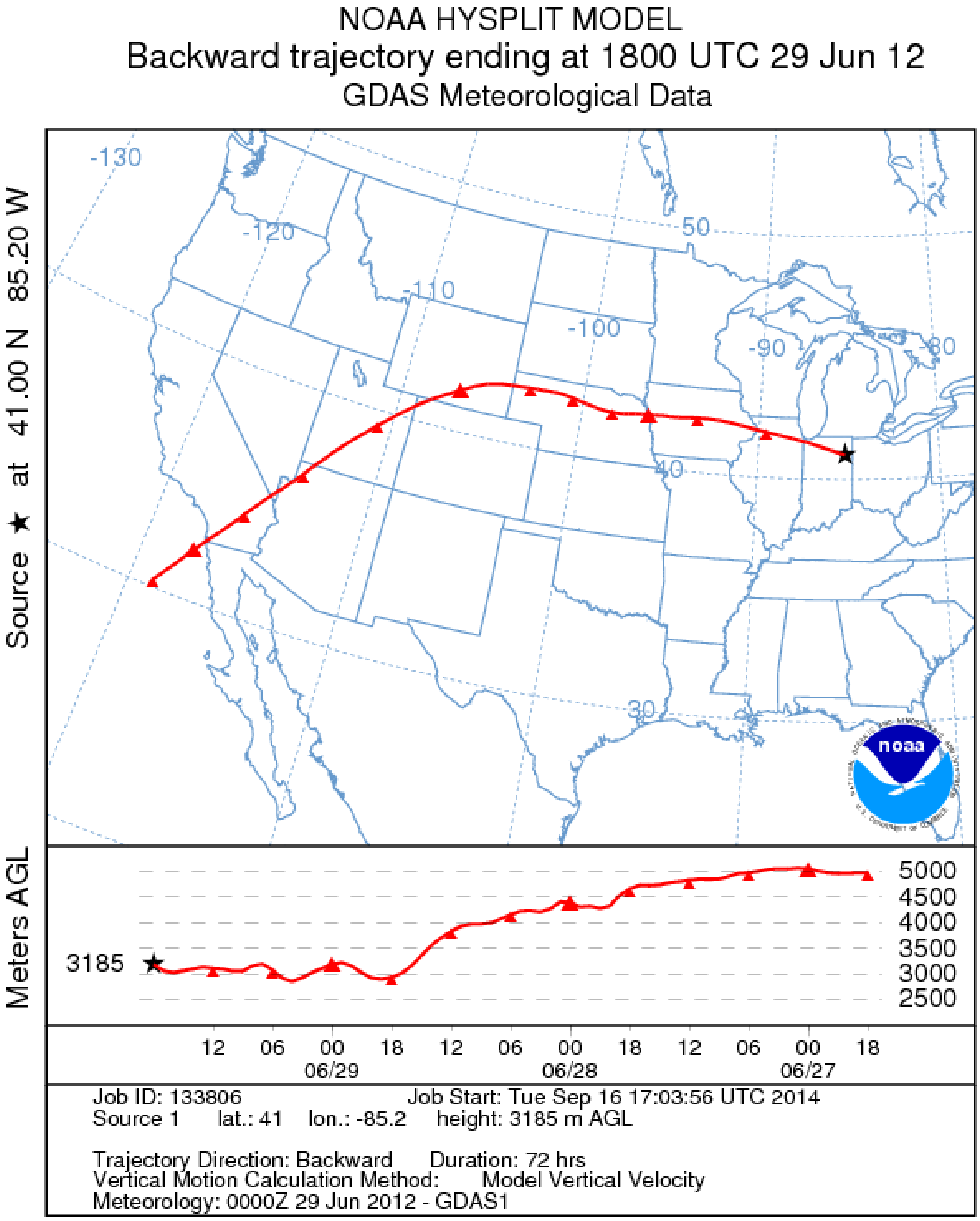

Figure 18: 72-h backward NOAA HYSPLIT model trajectory of a ≈700-hPa parcel over KFWA ending at 1800 UTC 29 June 2012.

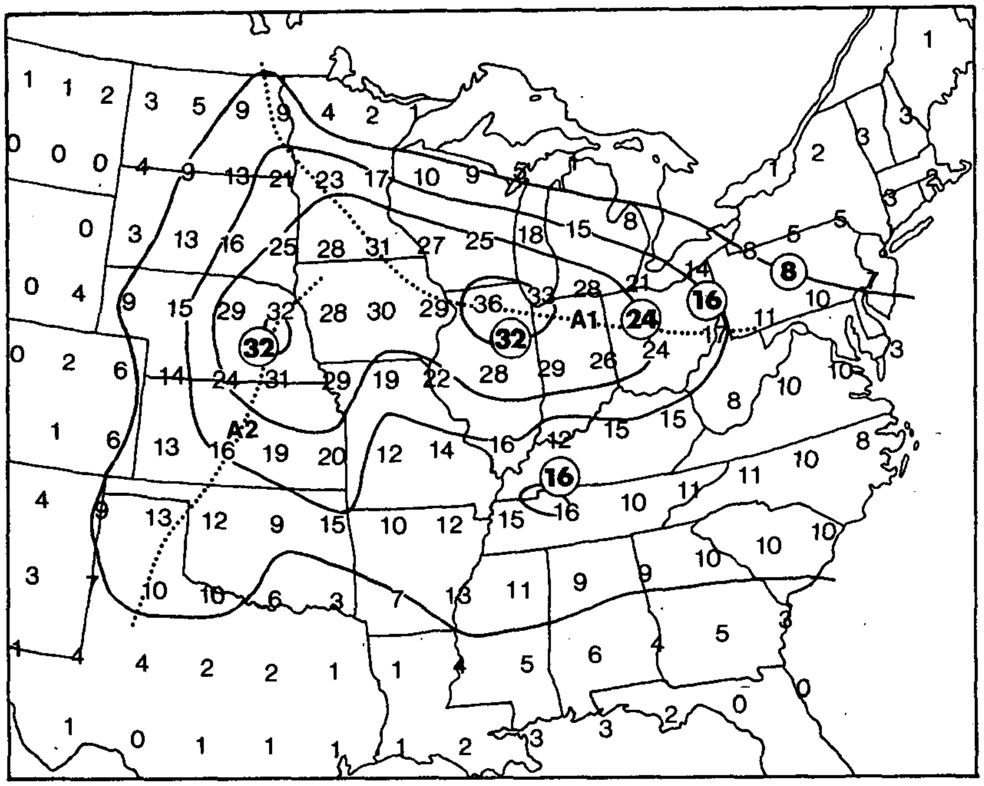

Figure 19: Total number of NWF severe weather outbreaks occurring in 2° Marsden squares for the period 1962–1977. Dotted lines indicated major high-frequency axes (Johns 1984).

b. Kinematic environment

Rotunno et al. 1988 (RKW88) (Fig. 20) discuss the balance between the cold-pool strength and the environmental shear, increasing potential for upright convection along an updraft-downdraft convergence zone (UDCZ) and maintenance of linear storm segments.

When the cold pool (*C*) and environmental shear are in balance, $C = \Delta u$ (RKW88), vertical updrafts are favored along the UDCZ. The strength of the *C* can be calculated by using either the hydrostatic pressure difference:

$$c \approx \left(2\,\frac{\Delta p}{\rho}\right)^{0.5} \qquad (1)$$

where Δp represents pressure change between the cold-pool-generated high and the pre-storm environment and ρ represents the standard density of the atmosphere, or by using potential temperature (Θ) between the ambient environment and the cold pool. In this paper, pressure change is used to calculate the cold-pool strength since archived 1-min ASOS data are available for many sites in the path of the derecho.

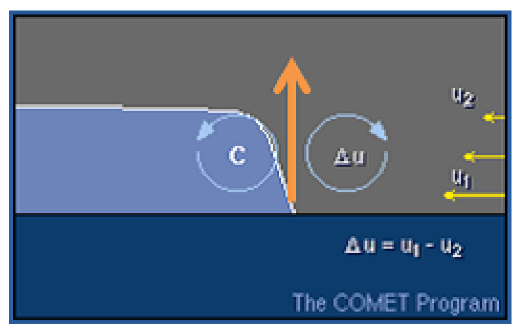

Figure 20: Conceptual diagram showing a perfectly balanced environment between a cold pool and environmental wind shear, where *C* represents the cold pool vorticity, u_1 represents surface wind, u_2 represents the wind at the top of the cold pool, Δu represents environmental shear across the cold pool depth, and the orange arrow represents the direction of air movement. [Figure provided by the Cooperative Program for Operational Meteorology, Education and Training (COMET).]

KFWA was impacted directly by the apex of the bow echo, and the 1-min pressure trace (Fig. 21) at the site depicts the rising pressure in the wake of the line. The total pressure rise at KFWA was 4.10 hPa. Other sites across northern Indiana and northwest Ohio detected similar values of 4–5 hPa as the cold pool moved overhead. Goshen Airport, IN (KGSH) rose 5.38 hPa, Warsaw Airport, IN (KASW) rose 4.40 hPa rise, and Defiance Airport, OH (KDFI) rose 4.67 hPa. Once the derecho moved east of KFWA, the cold pool strengthened further which was evident by pressure rises of 8.16 hPa at DAY, 7.42 hPa at Ohio State University Airport (KOSU), 7.96 hPa at Columbus, OH (KCMH), and 8.50 hPa at Fairfield County Airport in Lancaster, OH (KLHQ). This pressure differential (7–9 hPa) correlates to cold-pool strength of 19–21 m s^{-1} using Eq. 1.

The ambient vertical environmental wind difference, Δu, was calculated using the formula $\Delta u=\sin(\phi)*m$ where ϕ= the angle between the direction of storm motion and the 0–3-km shear vector and m = magnitude of that vector. Since the 0–3-km shear vectors were normal to the convective line, ϕ has a value of 90°. Using that and m = 15.4 m s^{-1} yields Δu of 15.4 m s^{-1}. This value of m was calculated by approximating the depth of the cold pool, and then using the velocity azimuthal display wind profile (VWP) from KIWX to calculate the shear across the depth of the cold pool. The top of the cold pool is the point in the vertical where negative and positive buoyancy meet (Bryan et al. 2005). Using 3D radar analysis, an approximate depth of a cold pool can be estimated where the wind direction abruptly changes—in this case, where the top of the strong radial-velocity outbounds end and weaker inbounds (associated with the updraft) begin (Fig. 22).

Once the cold pool depth is known, an "effective" layer wind difference can be used when calculating the environmental shear needed to balance the cold pool. In this case, the cold-pool depth was ~3 km. Using the 1621 UTC VWP from KIWX, the 0–3-km wind difference is ≈15 m s^{-1}(30 kt) (Fig. 23).

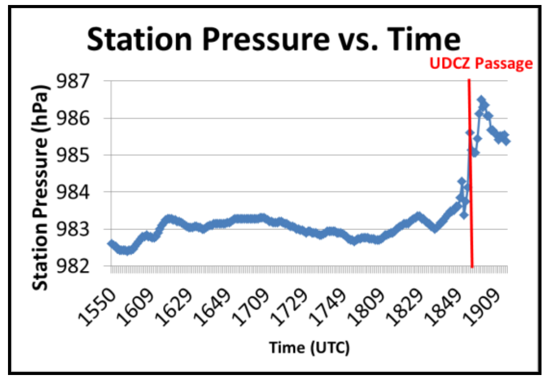

Figure 21: Barograph trace from 1550–1909 UTC, which shows rising pressure caused by the passage of a cold-pool-generated mesohigh at KFWA. *Click image to enlarge.*

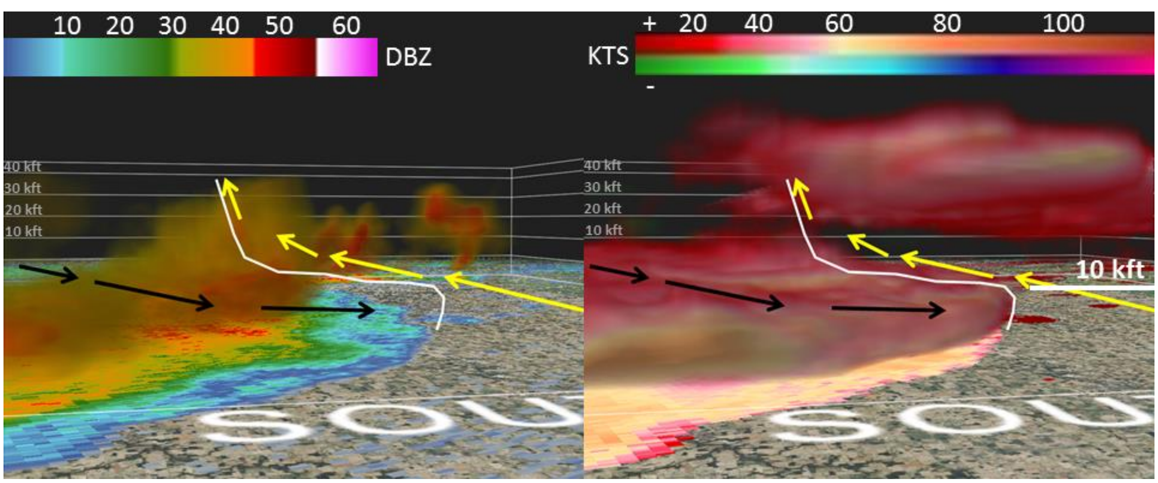

Figure 22: 3D view of the bow echo at 1855Z from KIWX as the line passed over KFWA, with base reflectivity on the left and base velocity on the right. Yellow arrows indicate the updraft, and black arrows indicate the downdraft. The white line shows the updraft/downdraft convergence zone (UDCZ). [Image courtesy of GRLevel2 Analyst®.] *Click image to enlarge.*

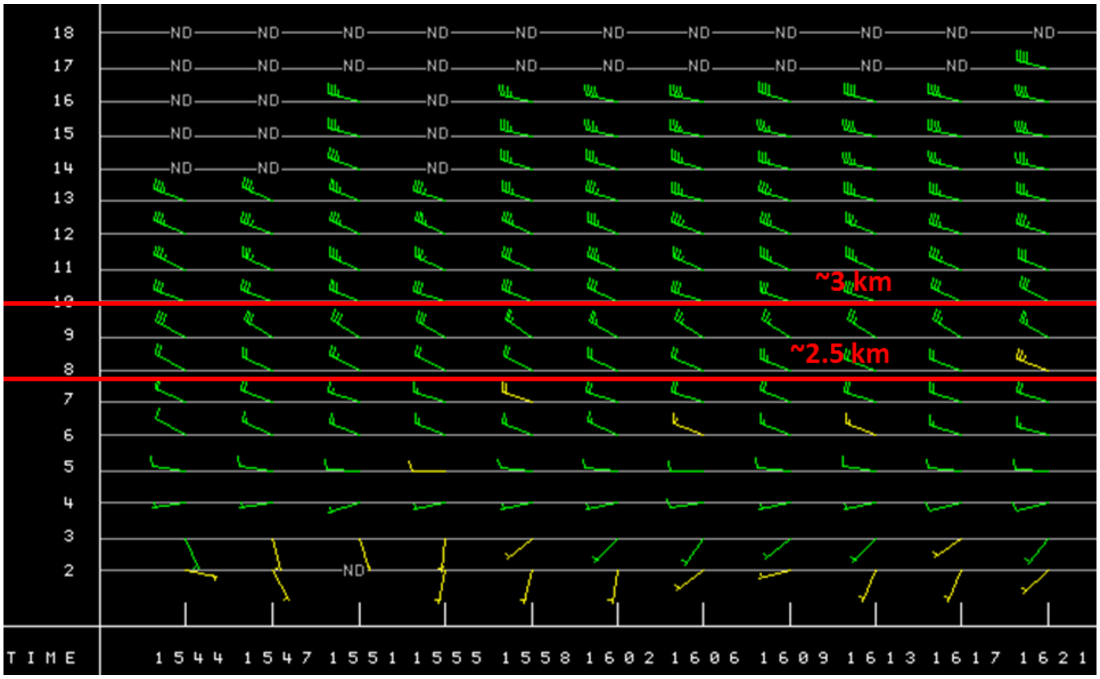

Figure 23: 1621 UTC VWP from KIWX on 29 June 2012. *Click image to enlarge.*

Table 1: Mesoanalysis convective parameters on 29 June 2012 compared to JH87 and ED01. Columns show the minimum, maximum, and 25th and 75th percentile for all cases. ED01 values are from 113 proximity soundings from 67 derecho events.

Variable	Min	25%	75%	Max	Jun 29
0–6 km shear (kt[m s^{-1}])	2.2 (1.1)	20.4 (10.5)	38.8 (20)	54 (28)	**36 (19)**
0–3 km shear (kt[m s^{-1}])	1.9 (1.0)	15.6 (8)	29.2 (15)	46.7 (24)	**34 (17.5)**
MUCAPE (J kg^{-1})	1286	2664	4194	8512	6383
DCAPE (J kg^{-1})	601	698	1352	1758	1609
MLCAPE (J kg^{-1})	741	1578	2924	5611	3894
θ_e deficit (K)	6	18	28	33	45
θ deficit (K)	3	6	10	17	18

Calculating an "effective" layer wind difference provides a more accurate calculation of the balance between cold-pool and environmental shear. In this case, if a 0–2.5-km wind difference were used, the calculation of Δu would have yielded a much lower value [≈10 m s^{-1} (≈20 kt)] (Fig. 23). Nevertheless, Δu of 15.4 m s^{-1} coupled with a cold pool strength value, *C*, of 18–23 m s^{-1} indicates that the updraft likely would be sloped towards the precipitation (as would be expected in a cold-pool-dominant system). Observations on radar showed a gust front that was ahead of the strongest reflectivity returns, indicating that the convective line was indeed cold-pool-dominant (Fig. 24).

Despite low-level (0–3 km) shear that was not sufficient to balance the strong cold pool, the derecho persisted for over 10 h. Coniglio and Stensrud 2001 (hereafter CS01) showed that many derechos were able to persist in an unbalanced RKW system and that they were more dependent on the instability than the shear in those cases. As witnessed in CS01, mostly vertical updrafts were observed in the elevated cells that formed behind the initial UDCZ (Fig. 22). The vertical growth of these cells helped to reinforce the cold pool and rear-inflow jet. Stronger 0–6 km wind difference (~21 m s^{-1} or ~40 kt) likely aided in the sustainability of these cells which also contributed to the longevity of this derecho (Weisman and Rotunno 2004).

c. Comparison to past research

Given the extremely favorable environment for severe storm development on 29 June 2012, the 1800 UTC ILN sounding parameters were compared to past derecho proximity soundings researched by Evans and Doswell (2001; hereafter ED01); see Table 1. The comparison yielded impressive results as every quantity except for 0–6 km wind difference was well above the 75th percentile for previous events. Two variables (Θ_e and Θ deficits) exceeded the previous maximum value, the latter by 12 K.

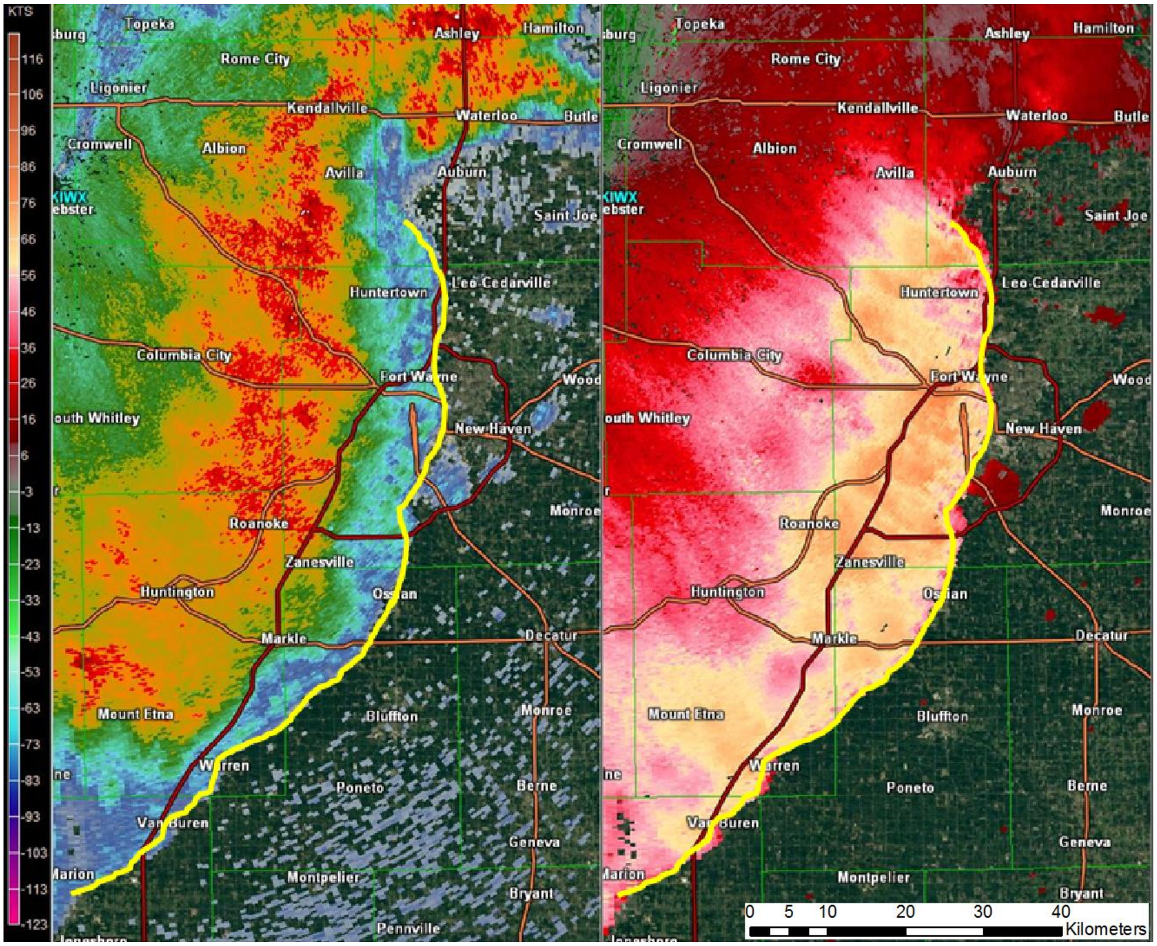

Figure 24: KIWX 0.5° beam-tilt reflectivity (left) and base velocity (right). UDCZ indicated by the yellow line. [Image courtesy of GRLevel2 Analyst®.] *Click image to enlarge.*

6. Discussion

The historical derecho of 29 June 2012 was characterized by a cold pool that exceeded the strength of any other documented cases to date. The cold pool developed in a preexisting environment with a Θ_e gradient of 30–35 K. The maximum Θ_e deficit of 46 K exceeded those observed in the previous research of ED01 by 12 K. This anomalously strong cold pool was virtually impossible to balance by the observed 0–3 km shear, which resulted in a cold-pool-dominant derecho.

Despite the lack of upright convection along the leading edge of the line, the extreme instability and midlevel lapse rates coupled with stronger deep-layer shear allowed this system to remain organized eastward to the Atlantic Ocean. (Fig. 25).

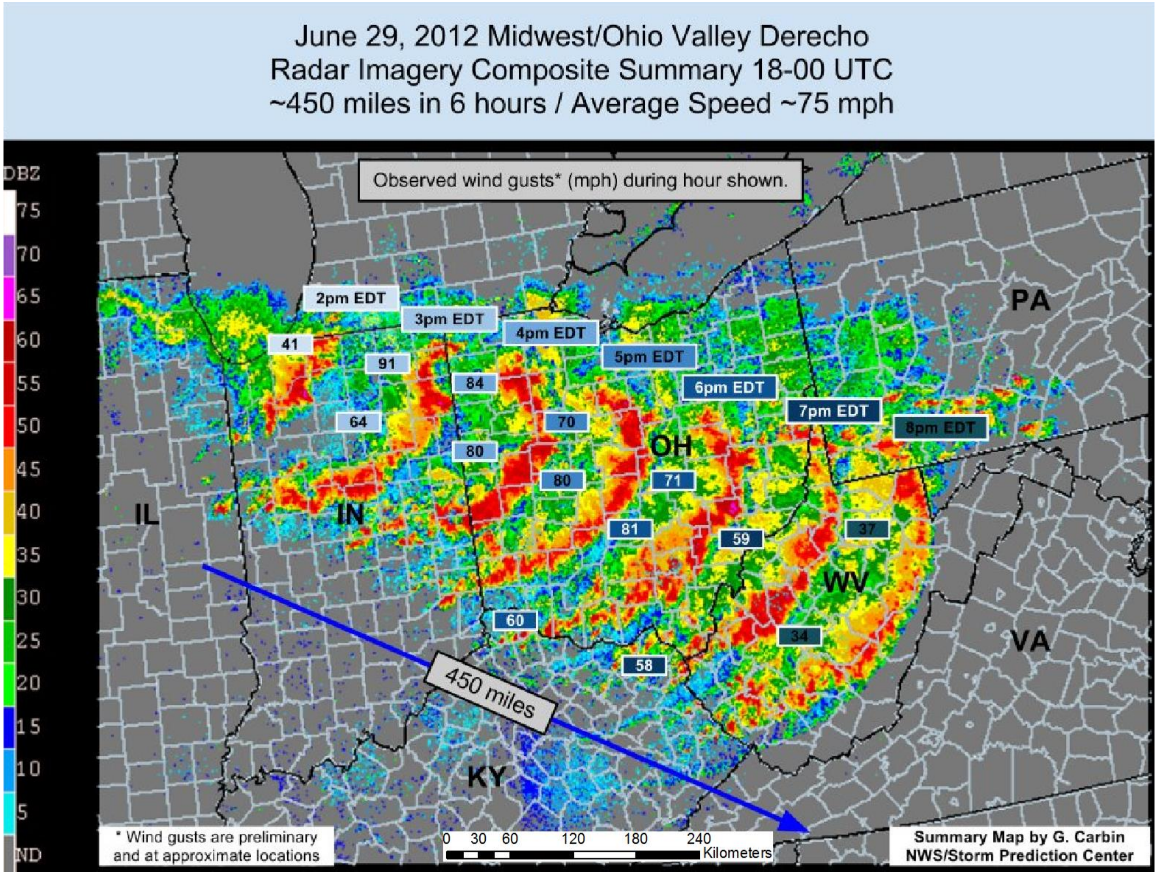

Figure 25: Radar reflectivity composite on 29 June 2012. Radar and surface observations loop can be found at: www.ejssm.org/ojs/public/vol11-1/12jun29_loop_rflecbase_pingpong.gif. [Image and loop courtesy of SPC.] *Click image to enlarge.*

The authors of this paper see this case as an important reminder to operational forecasters that calculating the strength of a cold pool can be important for forecasting the sustainability of an MCS. In addition, calculation of Θ_e deficit both across a boundary and in the vertical can help a forecaster to estimate the potential strength, if a well-established cold pool can be generated. To calculate estimated cold-pool strength in real time, operational forecasters can use the tool provided by the NWS Warning Decision Training Branch at the URL: http://www.wdtb.noaa.gov/tools/misc/boundary/index.htm.

In addition, operational forecasters should use 3D radar velocity analysis to better analyze cold-pool depth. Once the cold-pool depth is known, an "effective" layer wind difference can be used when determining the environmental shear needed to balance the cold pool.

7. Future research

While investigating the evolution of this derecho, and comparing it to other studies, we believe more research is necessary to further understand the complex mesoscale processes that are involved with these convective systems. Convection near Lake Michigan hypothetically was an important factor in the organization and development of this derecho. To test this theory, model simulations for this event will be analyzed both with and without the existence of Lake Michigan to examine whether the thermodynamic and kinematic effects of the lake had any influence on the development of this derecho. The strength of the cold pool and the location of the first storms (possibly along a lake breeze) may be impacted by Lake Michigan. A similar scenario was observed over the IWX CWA on 12 June 2013 when initial convection collapsing near Chicago initiated a derecho which moved across northern Indiana. These initial storms formed close to the initial storms on 29 June 2012.

In addition, the derecho composite parameter on the SPC mesoanalysis page accurately displayed the risk for derecho development, but the location of the highest probability was too far south. This southward placement was due to the parameter's overdependence on the magnitude of the CAPE. Work has begun locally to experiment with the creation of a modified derecho-probability parameter that will take into account the gradient of instability to improve the accuracy of our forecast derecho parameter, especially for warm-season frontal derecho events.

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All hand-analyzed surface and upper air maps were generated using the Plymouth State Weather Center map archive.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Barry E. Schwartz):

Initial Review:

Recommendation: Accept with major revisions.

General comments: In general this is a well thought out paper that forecasters would be interested in. The paper could use some reorganization as it is a bit difficult to follow in places and I will try and make some recommendations that the authors might consider.

Although the authors say that the paper is an "examination of the forecast process" that occurred prior to the event, I am not sure all readers would agree that the "dry bias" the authors claim was in the mind of the forecasters was a reason this event was not predicted a few days, and even 24 h prior to the event. As the authors included in their manuscript, many factors, mainly on the mesoscale, effect how convection will form, evolve, and propagate. These mesoscale features, such as the development of a strong cold pool from early convection, can only be noticed at most hours (6–12?) in advance of an event. Expecting SPC to issue a high risk of mesoscale convection 2 days before a small scale driven event is unrealistic. So from this perspective, I suggest the authors leave a good part, if not most of, section 2 out of the paper. A paragraph could be added to section 3 discussing the unusually dry spring that had inhibited daily convection but it seems to me that once the strong thermal gradient had been established with rich θ_e air in place, I doubt the forecasters were not tuned into the potential for strong convection. I think the paper is just fine discussing the development and evolution of the derecho without getting into why it was not predicted or anticipated days before the event.

Per your recommendation and that of others, we kept out a majority of the section talking about the dry bias. In addition, we took out most of the discussion about the forecast process.

Obviously, the kinematic environment section is the most important and most interesting part of the paper. In the summary section, they mention the use of a computed derecho "parameter" that was developed at the training center. I think this should be mentioned in this earlier section. Was this the technique that was used and discussed in the Kinematic Environment section? The discussion on page 9 has me believe they did something different. [Then] Table 1 is not necessary as it gives no more information than what is discussed in the text. Figure 14 should label the pressure as "station pressure" and the starting hour/min should be shown. Finally, I was left a bit confused over the final choice of wind shear that was used by the authors to compute the balance. Was it 0–3 or 0–2.5 km, and is the difference important?

We spent more focus on the kinematic section to improve things including more discussion on using 0–3-km shear rather than 0–2-km shear.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Accept with minor revisions.

Substantive comments: This paper is in considerably better shape. Nice job! As usual for me, I have some comments and further suggestions.

Does the lift have to be generated by a stationary front? Would not any boundary where you have surface convergence do? I ask because you make a point of mentioning stationary front and then towards the end of the paper you refer to the boundary as a warm front.

You mention observed dewpoint values along the front: what front? First mention of a front...might say along the stationary front to make this clear and refer to Fig 6. I would discuss the surface dewpoints in e) not in the 850-hPa section as you did.

We changed this to front and kept the discussion more broad here per your recommendations.

What is considered a cool-pool-dominated system? That is, how many m s^{-1} cool pool strength > shear defines whether the system is dominated by the cool pool?

There is no exact value for what ratio constitutes cold pool dominant or shear document. Only that a ratio of $c/\Delta u$ is near 1 when it is balanced, and the further away from 1 the value gets, the less balanced the cold pool is with the environment. Hopefully the rewording we did in that section per your comments and those of the other reviewers makes this more clear.

After Fig. 16 I would reword [that] sentence to not imply a link between the 0–3- and 0–6-km shear. When I first read this sentence I wondered what does the cool-pool domination of the system have to do with the longevity of the system. If you want to link these, then you need a sentence or two more to explain.

This entire section has been reworded significantly. Hopefully you will find it clearer. We agree that this depth of cold pool information needs to be moved up in the paper [and] have completed this action.

[Minor comments omitted...]

REVIEWER B (Ernest J. Ostuno):

Initial Review:

Reviewer recommendation: Accept with minor revisions.

Substantive comments: The long-lived, destructive derecho of 29 June 2012 is certainly worthy of a case study and the authors have done well to describe the environmental conditions and storm morphology of this event. I believe they have identified the physical basis for the persistent and intense nature of the derecho; a strong cold pool resulting from a storm environment featuring an extreme θ_e deficit. There are some issues I would like to see addressed before the paper is published, however.

Section 2 discusses the antecedent conditions, specifically the drought that had developed during the spring of 2012 and intensified during the summer. The claim is made that, "extreme drought conditions observed across most of the Midwest during June made it difficult to anticipate a high-end event," and describes a dry bias that forecasters had adopted by late June. This is the classic "drought begets drought" (until it doesn't) forecast philosophy that can, and in this case did, result in significant rains sneaking in under the radar, as it were.

I would also like to see a reference that quantifies how drought conditions affect MCS precipitation coverage and amounts to provide some context to the discussion of the impact of drought conditions on convection in Section 2. I was able to find a paper (Fritsch et al, 1986) that compared one drought year (1983) to a single non-drought year (1982), but ideally, I'd like to see a more comprehensive climatology cited, if one exists.

We decided to take a majority of the discussion about the antecedent conditions and the forecasting process out of the paper.

[Minor comments omitted...]

Second Review:

Reviewer recommendation: Accept with minor revisions.

General Comments: The authors have addressed the issues noted in the first review to my satisfaction. I think this paper will be helpful to operational forecasters in recognizing conditions favorable for the development of derechos and assessing their potential severity. A separate paper about antecedent conditions might still be useful, since, if my memory serves me correctly, the dry bias resulting from "persistence forecasting" had a strong influence on the local forecast for precipitation and severe storms during this event, despite signs that conditions would be favorable for organized, possibly severe, convection.

[Minor comments omitted...]

REVIEWER C (Robert J. Trapp):

Initial Review:

Recommendation: Accept with major revisions.

General comments: I like the general topic of this paper, and what it reveals about the forecast process from the perspective of operational meteorologists. It raises several interesting points about the 29 June event, including the potential impact of the drought, and the relative rarity of the environmental lapse rates. What I struggle with is the focus. I think the paper tries to cover too many aspects of the event, and as a consequence doesn't go deeply enough into any one of them. This is confirmed to me by the significant disconnect between the abstract and the summary.

I would recommend modifying the paper to focus almost exclusively on the impact of the drought on the meteorology as well as on the situational awareness of the forecasters. In the abstract, the authors note the occurrence of "several rounds of overnight/early morning convection which dissipated quickly before it could reach the northern Indiana CWA as surface dewpoints frequently mixed into the mid-50s ^{o}F by afternoon." I would be interested in a comparison/contrast between these events and the 29 June event, and think this would be a worthy addition to the paper, especially if it included some radar analysis. I don't think the RKW-type analysis adds much to the paper, and in fact worry a bit about the methodology. The results are inconclusive. I like the concept of a radar analysis, but it didn't necessarily convince me that: "the collapse of one storm in northern Illinois laid out an outflow boundary from which a historical derecho emanated".

You mentioned that the paper lacked focus as it tried to cover too many aspects of the event. Therefore, we took out most of the section talking about the drought. We decided that topic would be better suited for a standalone paper. Also, evidence that the drought played a significant role in this event became less clear the deeper we dug into the data.

We cleaned up the RKW analysis to make its focus more clear and the methodology more organized. We see your point about saying the collapse of one storm was responsible for the entire derecho. That type of wording was not our intent, so we cleared up the wording to make it clearer.

Second Review:

Reviewer recommendation: Accept for publication pending major revision.

General comments: My previous recommendation was as follows: [See initial review above.]

The authors have modified the manuscript so that the focus seems to be on whether or not the MCS met the RKW balance conditions. I found this new focus to be confusing and contradictory. Adding to the confusion is the order of the presentation. I can understand why the authors might want to include an evaluation of the RKW balance within a 'mesoscale environment' section. However, I suggest instead that they present the radar analysis first, and then proceed with this evaluation.

In the first round of edits it was suggested by the other two reviewers to remove all mention of the antecedent conditions/forecasting from this paper. In round 2, one of the other reviewers echoed this sentiment by saying that the antecedent conditions would be better suited in another paper. After discussing it for a while during the first round of edits, and digging further into the data, we don't see that discussion best suited within this paper. We may look at doing an additional paper about the drought impact on local summer convection and discuss this case, but we decided not to do that at this time.

Your insight regarding RKW theory into this paper is much appreciated. After reading your comments and reading a few more journal articles to fill the voids in our paper, we feel that this portion of the paper is now easier to follow and more scientifically relevant.

Your suggestion to move the radar analysis section before the RKW section is one that was mentioned by a[nother] reviewer in the first round of edits. At the time, we preferred to stay with what we have. We wanted to show how extreme the environment was before we showed what happened, but we can see how this may not be best for the focus of this paper.

Specific substantive comments: The RKW balance is, strictly speaking, between the horizontal vorticity in the environmental shear, and the horizontal vorticity that's baroclinically generated in the horizontal density gradient associated with the cold pool. An alternative way of interpreting this is that the speed (c) of the cold pool is essentially balanced by the low-level environmental winds (in the derivation of the balance criteria, you'll find that u^2 is set to zero).

Your insight regarding RKW theory into this paper is much appreciated. After reading your comments and reading a few more journal articles to fill the voids in our paper, we feel that this portion of the paper is now easier to follow and more scientifically relevant.

This is arguable – to really do this correctly, you need the buoyancy (via θ) over the depth of the cold pool, which you don't usually have (i.e., you need a sounding through the cold pool). This has been the main criticism of the Evans & Doswell approach. The pressure approach removes this need, although implicit in (1) is the need for hydrostatic pressure, which is not what we measure, but total pressure suffices.

Agree with your comments about using θe for calculations. This is an issue we ran into ourselves when trying to calculate "c" using θe. Therefore just removed the line about it being a preferred method.

I understand this reasoning, but the subsequent discussion about the cold pool is all in terms θ_e. I assume that this is because past quantifications (Evans & Doswell) used θ_e. The question here, though, is whether this pressure-based calculation of a c = 19–21 m s^{-1} can be reconciled with a θ_e deficit of 45 K (i.e., do you get the same c)?

We now only mention theta-e in the paper when comparing this event to the ED 2001 paper.

I don't quite understand why you jumped from 0–3 to 0–6 [km depth]. You note on the previous page that Δu represents the shear across the cold pool. You argue that 0–2.5 is too shallow, and that the cold pool depth is in excess of 3 km based on the radar data. So what happens if you used 0–3.5, or 0–4? It seems to me that you're looking for values to make the RKW theory work here. Weisman '93 (I think) discusses how a mature bow echo may need to be "rebalanced" by including the elevated rear-inflow-jet speed.

We understand your use of 0–2.5 in your paper regarding mesovortex formation. We were using this as just one example of the many papers that use 2.5 km rather than 3 km. Instead of addressing this individual issue, we took things a different direction and focused specifically on the relevant value for this case rather than an arbitrary value from past research that is generalized for many cases.

I'm confused about how to reconcile the statement in the conclusions: "(cold pool was) virtually impossible to balance by the observed 0–3 km shear which resulted in a cold-pool dominant derecho system". I understand the 0–3 km part, but it seems to me that by "sustain the derecho" you're implying that the system is balanced by virtue of the 0–6 km shear?

To answer your question about how accurately we can quantify the cold-pool depth using this approach. While an exact value is tough, a relative value within a few hundred meters of the actual depth seems very attainable. Bryan et al. (2005) uses this method to estimate cold-pool depth which increases our confidence that it is a valid method. Looking at the radar more, this depth seems consistent through the life of the system in our forecast area, but that is tough to show with a few figures in our paper.

This is not very apparent to me from the 3D rendering that these were mostly upright. I'm also confused about how to reconcile this with the statement in the conclusions: "lack of upright convection at the UDCZ". I'm assuming that this refers to other times?

The lack of upright convection along the UDCZ was referring to along the leading edge of the UDCZ. Where the outflow boundary begins. To help rectify this, we changed the wording in the conclusion section to say along the leading edge rather than along the UDCZ.

[Minor comments omitted...]

Third Review:

Reviewer recommendation: Some revisions still needed.

Specific substantive comments: [You present] one way of thinking about bow echoes. But I would argue that the cold pool is part of the highly coupled bow-echo **system**. Yes, the cold pool plays a role in the convective organization, but it is present in the first place because of the convection, and is reinforced as the convection—and other components such as the RIJ—become more organized. [see Trapp (2013): *Mesoscale Convective Processes in the Atmosphere*, Cambridge Univ. Press.]

The authors agree this is a bit confusing, so we took out cold-pool induced and it now says, "All stages of a developing bow echo were exhibited..."

A more appropriate interpretation is that this imbalance should, theoretically, case updrafts to be less vertically erect/more sloped. The implication is the updrafts in an unbalanced state are also weaker. One note about the RKW "balance" condition in a bow-echo is that it neglects the effect of the RIJ. There's a discussion of this in Weisman (1992), *J. Atmos. Sci*. He argues that inclusion of the surface component of the RIJ can "re-balance" the MCS.

The authors changed the wording to more accurately reflect the expected slope of the updraft due to the cold-pool-dominant nature rather than saying the updraft was mainly driven by the cold pool. Your note about RKW "balance" condition neglecting the effect of the RIJ is important. We feel the discussion of this point a few paragraphs later (Coniglio and Stenstrud 2001) is adequate.

We did read both of the papers suggested by Reviewer C, but we did not directly use any information from those papers in the final manuscript which is why these papers are not cited.

[Minor comments omitted...]