Investigating the Environment of the Indiana and Ohio Tornado Outbreak of 24 August 2016 Using a WRF Model Simulation

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INTRODUCTION

On 24 August 2016, a tornado outbreak impacted Indiana and Ohio with 22 confirmed tornadoes (Fig. 1a).

- Morning convection-allowing models did not depict cellular convection or significant updraft helicity across the area, resulting in a challenging forecast.
- Strong low-level shear, adequate deep-layer shear, low lifting condensation levels, and plentiful instability provided an environment favorable for the development of supercells and tornadoes.
- Convection transitioned from a linear mode to a cellular mode between 1700 and 1900 UTC, after which time tornadoes began to occur.

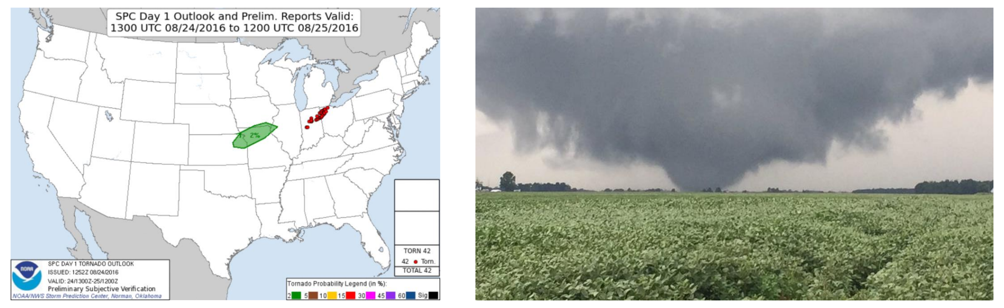
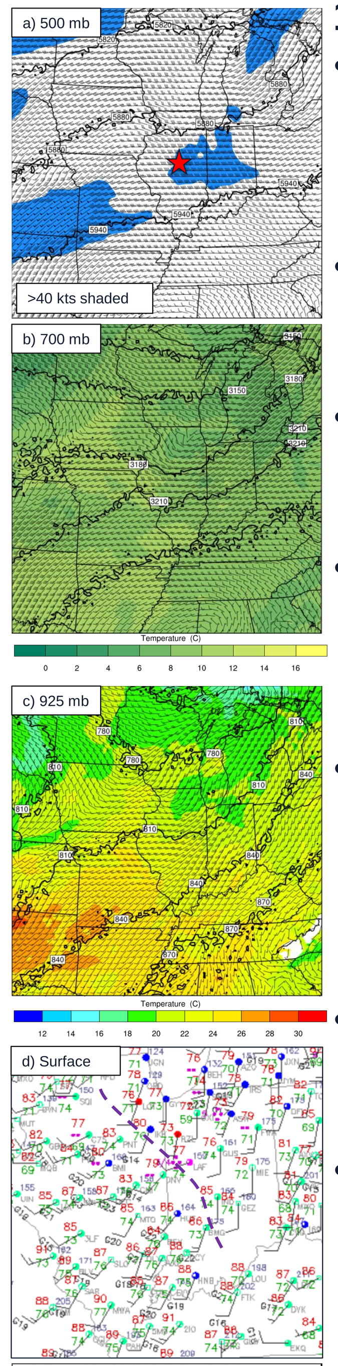


Figure 1: (a) Storm Prediction Center (SPC) 1300 UTC 24 August 2016 tornado outlook (green shading) and preliminary tornado reports (red dots). (b) Tornado near Sharpsville, IN (Photo credit: Dan Dawson).

MESOSCALE ENVIRONMENT



1800 UTC Analysis

- At 500 mb, a mesoscale convective vortex (MCV) over northern Illinois enhanced the flow over central Illinois and Indiana (Fig. 2a).
- At 700 mb, there was only a weak cap in place over Indiana, evidenced by temperatures of 8-10°C (Fig. 2b).
- At 925 mb, winds on the order of 30 knots over central Illinois and Indiana yielded strong low-level shear (Fig. 2c).
- A surface wind shift from southerly to southwesterly flow (purple line in Fig. 2d) moved northeastward amidst a moist air mass (Fig. 2d).
- The 1200 UTC sounding from Lincoln, IL (star in Fig. 2a), depicts significant low-level shear available to surface-based storms and only weak shear available to elevated storms (Fig. 2e).
- CIN was removed by 1800 UTC across most of central Indiana (Fig. 2f), with 2000-3000 J kg^{-1} mixed-layer CAPE.
- 0-1 km storm-relative helicity (SRH) was well above 100 m^2 s^{-2}, more than sufficient for rotating storms (Fig. 2g).

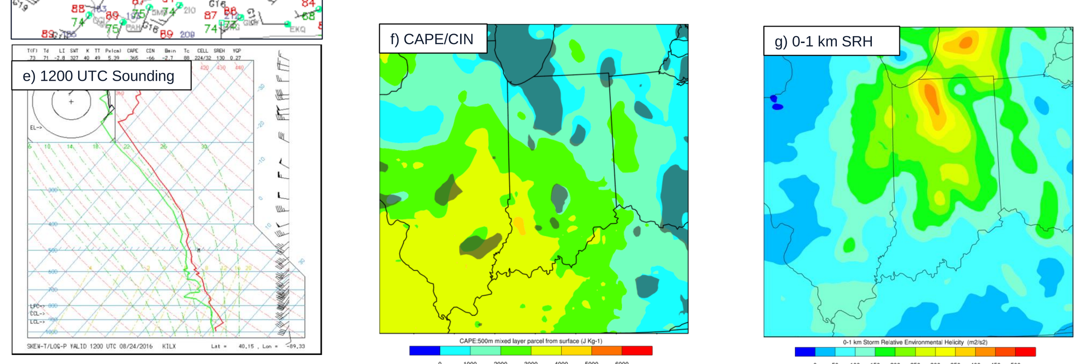


Figure 2: RAP analyses valid at 1800 UTC: (a) 500 mb height (m) and wind (kts; > 40 kts shaded); (b) 700 mb height (m), wind (kts), and temperature (°C); (c) 925 mb height (m), wind (kts), temperature (°C); (d) surface observations (°F); (e) 1200 UTC sounding from Lincoln, IL; (f) 500 m mixed-layer CAPE and CIN (> 10 J kg^{-1} CIN shaded gray); and (g) 0-1 km SRH (m^2 s^{-2})

RADAR ANALYSIS

Mesoscale Overview

- Between 1500-1700 UTC, elevated storms developed over eastern Illinois (Fig. 3a).
- A surging outflow boundary was not observed on radar (Fig. 3a) or in surface observations (Fig. 2d) with this convection as it moved into Indiana.
- The first supercell formed on the southern edge of this convection, near Crawfordsville, IN, between 1800-1900 UTC (Fig. 3b).
- Another supercell formed near Kokomo, IN, shortly afterward (Fig. 3b). This supercell produced an EF-3 tornado near Kokomo.
- These cells approached Indianapolis and Marion, IN, by 2000 UTC (Fig. 3c).
- A third supercell formed near Fort Wayne, IN, around 2100 UTC (Fig. 3d).
- Several other supercells formed west of the original supercells between 2000-2100 UTC (Fig. 3d). These storms also produced several tornadoes.

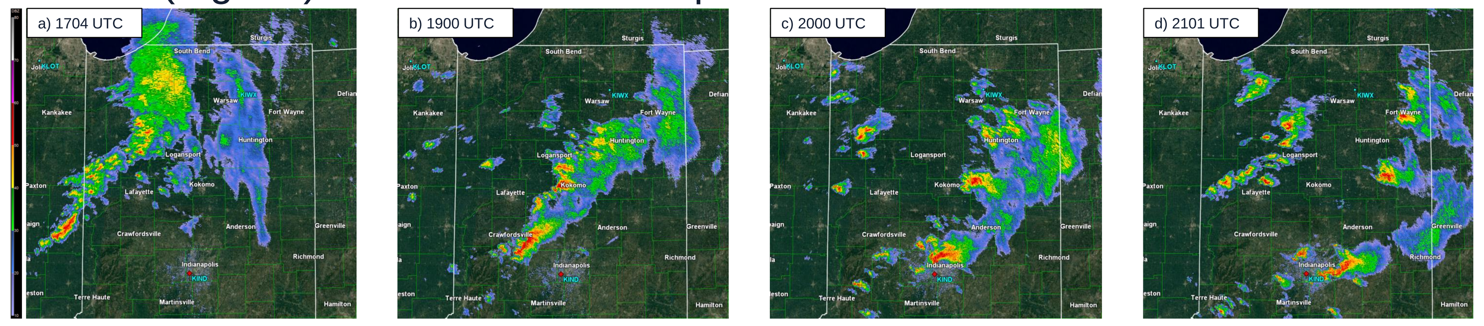


Figure 3: Indianapolis, IN (KIND), WSR-88D radar reflectivity at (a) 1704, (b) 1900, (c), 2000, and (d) 2101 UTC.

Development of Initial Supercell

- The southernmost storm was initially disorganized, with new cell formation to its south and cell decay to its north (Fig. 4a). Weak rotation developed within this cell around 1300 m above ground level (AGL; see white circle in Fig. 4b).
- This storm began to exhibit supercellular structure by 1821 UTC (Fig. 4c). At this time, the area of rotation weakened and shifted rearward, while low-level convergence strengthened ahead of the storm in the inflow region (Fig. 4d).
- As a small cell south of the developing supercell approached it (Fig. 4e), the convergence and rotation associated with the storm increased significantly, possibly owing to the development of a rear-flank downdraft (Fig. 4f). As convergence continued to increase, the vertical vorticity was likely amplified via stretching.

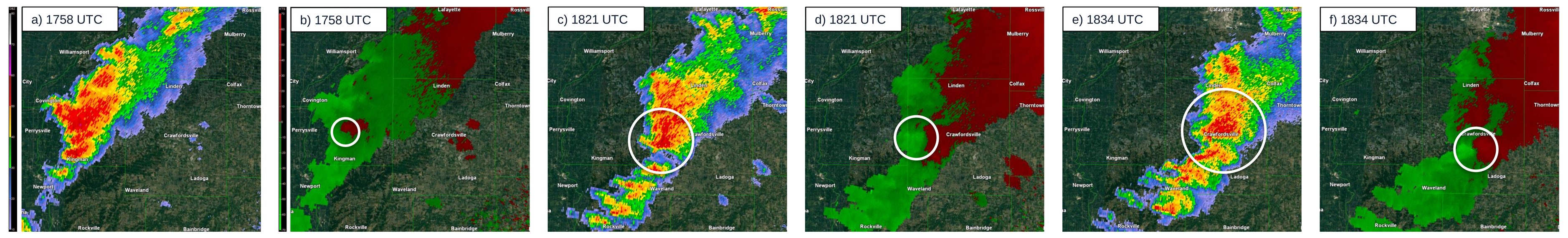


Figure 4: Indianapolis, IN (KIND), WSR-88D (a) radar reflectivity (dBZ) at 1758 UTC, (b) radial velocity (m s^{-1}) at 1758 UTC, (c) radar reflectivity at 1821 UTC, (d) radial velocity at 1821 UTC, (e) radar reflectivity at 1834 UTC, (f) radial velocity at 1834 UTC. Radar is to the southeast of the storm.

WRF MODEL SIMULATION

Model Configuration

- Initialized from 0600 UTC 24 August 2016 NAM analysis
- Three nested grids (Fig. 5)
- Δx = 12 km, 4 km, 1 km
- 60 vertical levels
- Microphysics: Morrison 2-moment
- Boundary Layer: YSU
- Cumulus Physics: Kain-Fritsch (12 km domain)

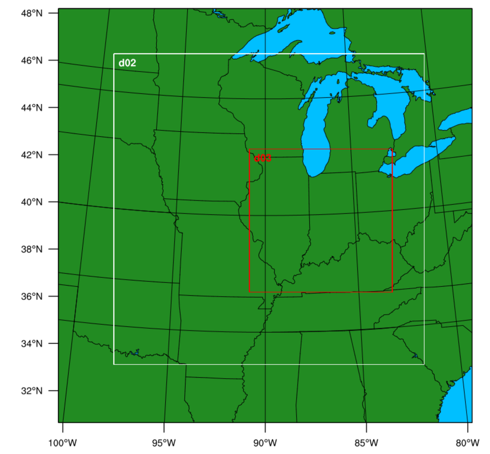


Figure 5: Map of the three nested WRF domains with horizontal resolutions of 12 km, 4 km, and 1 km.

Simulated Environment – 1700 UTC

- Simulation captures the MCV at 500 mb over northern Illinois with winds on the order of 40 kts on its southern flank (Fig. 6a).
- 0-1 km SRH greater than 100 m^2 s^{-2} existed across most of Indiana, more than sufficient for rotating surface-based storms (Fig. 6b).
- The environment is characterized by over 2000 J kg^{-1} of CAPE (Fig. 6c).
- Model soundings (red star in Fig. 6c) reveal that the environment near the storms becomes uncapped between 1630-1725 UTC (Figs. 6d and 6e).

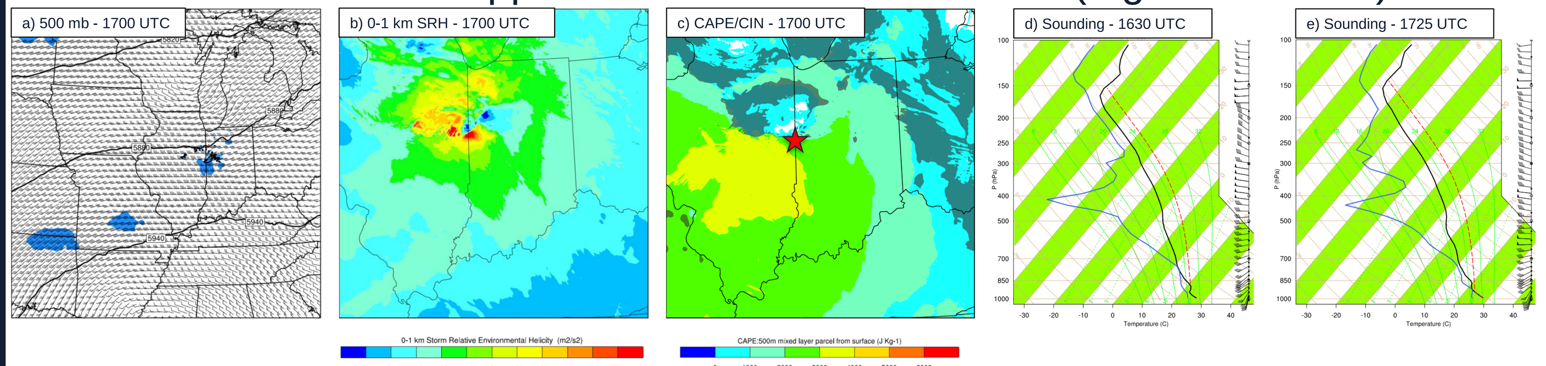


Figure 6: WRF model simulated (a) 500 mb height (m) and wind (kts; > 40 kts shaded) at 1700 UTC; (b) 0-1 km SRH (m^2 s^{-2}) at 1700 UTC (c) 500 m mixed-layer CAPE and CIN (> 10 J kg^{-1} CIN shaded gray) at 1700 UTC; model soundings at the red star in (c) at (d) 1630 and (e) 1725 UTC.

Mesoscale Evolution of Simulated Convection (1 km Resolution)

- Quasi-linear convection crosses from Illinois into Indiana at 1630 UTC (Fig. 7a). This is slightly earlier than was observed (Fig. 3a).
- A dominant supercell develops and persists on the southwestern end of the line (Figs. 7b and 7c).
- Although slight embedded rotation develops farther northeast (Figs. 7c and 7d), the model fails to develop additional supercells from this initial convection in northeastern Indiana.
- Too much stratiform precipitation ahead of the linear convection (Figs. 7a and 7b), or too much or too cold outflow may have limited instability farther north, preventing the development of additional supercells in northeastern Indiana.

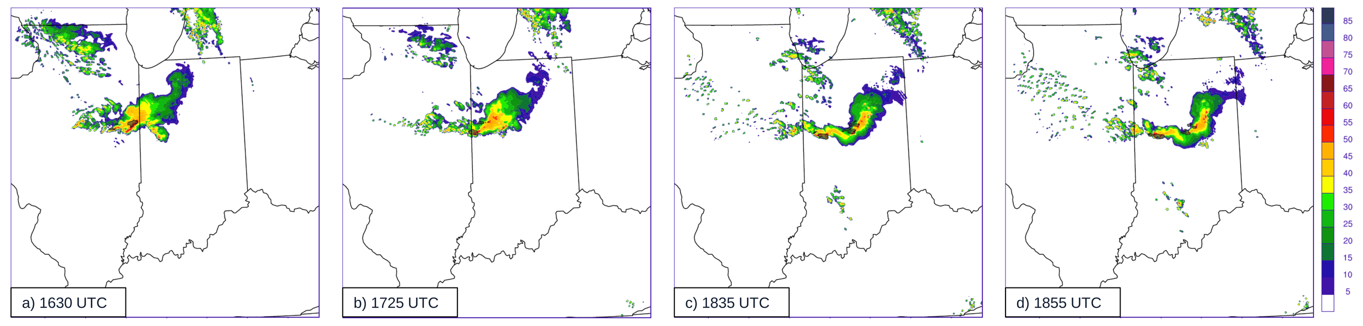


Figure 7: Simulated 1 km radar reflectivity and updraft helicity greater than 300 m^2 s^{-2} over the past 30 minutes (dark shading) at (a) 1630, (b) 1725, (c) 1835, and (d) 1855 UTC.

Storm-Scale Analysis (1 km Resolution)

- Convection is quasi-linear with only weak outflow at 1700 UTC. Any vertical relative vorticity (ζ) is generated by horizontal shear across the gust front at this time (Fig. 8a).
- Small cells form south of and merge with the southwestern end of the stronger convection. A localized area of convergence develops at the far southwestern end of the strong convection, focusing ζ in this region (Fig. 8b).
- An inflow notch forms and ζ becomes concentrated near the inflow notch (Fig. 8c).
- By 1745 UTC, the storm is a mature supercell with strong ζ, a hook echo, and forward-flank and rear-flank gust fronts as indicated by the temperature and wind fields (Fig. 8d).

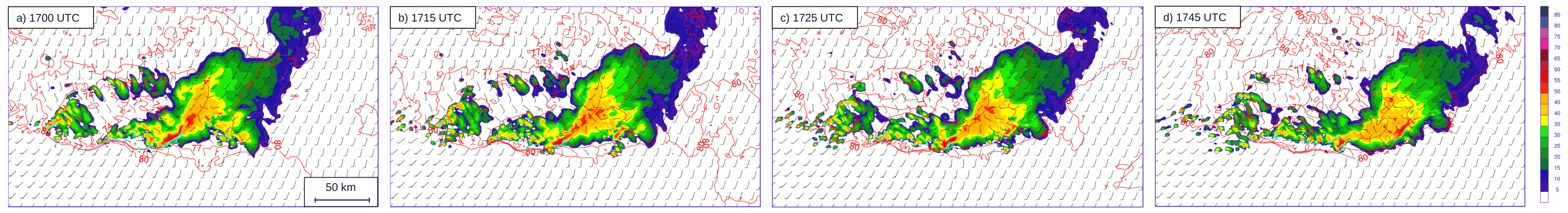


Figure 8: Simulated 1 km radar reflectivity (shaded), 10 m winds (barbs; kts),1 km vertical vorticity contoured only at 0.005 s^{-1} (cyan), and isotherms contoured between 74-80°F every 3°F (red) at (a) 1700, (b) 1715, (c) 1725, and (d) 1745 UTC. State borders removed for clarity.

CONCLUSIONS

- On 24 August 2016, a surprise tornado outbreak impacted parts of Indiana and Ohio.
- Convection transitioned from disorganized elevated convection to discrete tornadic supercells as it became surface based and gained access to strong near-surface vertical wind shear.
- A WRF simulation of this event captures the thermodynamic and kinematic environment, including the MCV, which regionally augmented the vertical wind shear.
- As in the observations, robust supercellular convection did not develop in the simulation until the storms became surface based. The lack of strong outflow in both the observed and simulated storms likely aided in this transition to a supercellular mode.

FUTURE WORK

- Explore additional cloud microphysics options in the WRF simulation.
- Perform additional analysis of the transition from elevated to surface-based convection.
- Examine why many operational models failed to develop supercellular convection in this regime.

ACKNOWLEDGEMENTS

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