A Mesoscale Analysis of the Development of Storms and Transition to Supercells during the Indiana and Ohio Tornado Outbreak of 24 August 2016

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1: Introduction and Motivation

- On the afternoon of 24 August 2016, an unexpected tornado outbreak struck portions of Indiana and Ohio, producing 24 confirmed tornadoes and 6 significant tornadoes (rated EF-2 or stronger on the Enhanced Fujita Scale; Fig. 1). This event was unusual in that it caught many meteorologists by surprise. For example, the outbreak occurred outside of the Storm Prediction Center (SPC) 2% Tornado Risk area from the 1630 UTC Day 1 Convective Outlook issued that day (Fig. 2).
- An analysis of surface, satellite, and radar data reveals that multiple mesoscale boundaries, morning convection, and a mesoscale convective vortex (MCV) were present over Illinois on the morning of the outbreak. These features moved eastward into Indiana in the afternoon. Below, we document how these features were important to this outbreak and contributed to the relative unpredictability of this event.

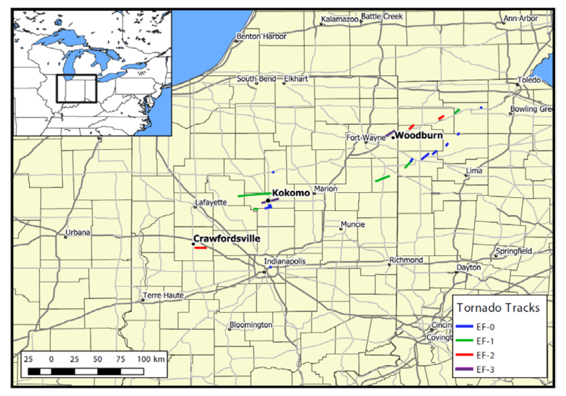

Figure 1: Tornado tracks from 24 August 2016. Colors indicate the Enhanced Fujita Scale rating. The towns nearest the three significant tornadoes in Indiana are in bold text.

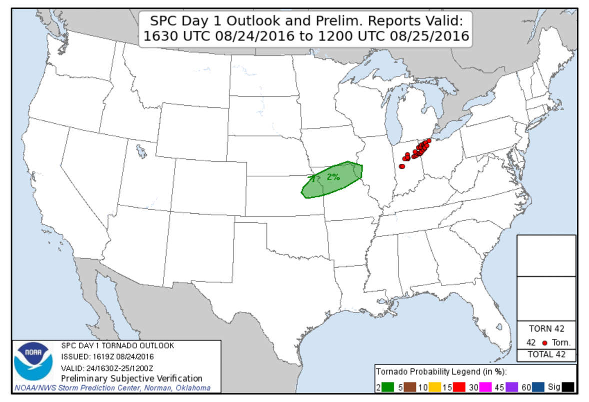

Figure 2: Tornado probabilities from the SPC Day 1 Convective Outlook issued at 1630 UTC 24 August 2016. Red dots are preliminary tornado reports.

2: Nocturnal Convection and Outflow Boundary

- On the evening of 23 August, a thunderstorm complex developed in eastern Nebraska and produced a well-defined cold pool as it crossed into southwestern Iowa (Fig. 3).
- By 0900 UTC, widespread elevated convection formed owing to large-scale ascent ahead of the outflow boundary (Fig. 4).
- At 1400 UTC, the leading elevated convection had reached eastern Illinois. Beneath the cloud shield from these storms, surface winds were SSE, while surface winds were SSW in the full sun (Fig. 5). New storms formed along the outflow boundary from the evening convection over north-central Illinois (Fig. 5). The MCV was near the Illinois/Iowa border (Fig. 6).

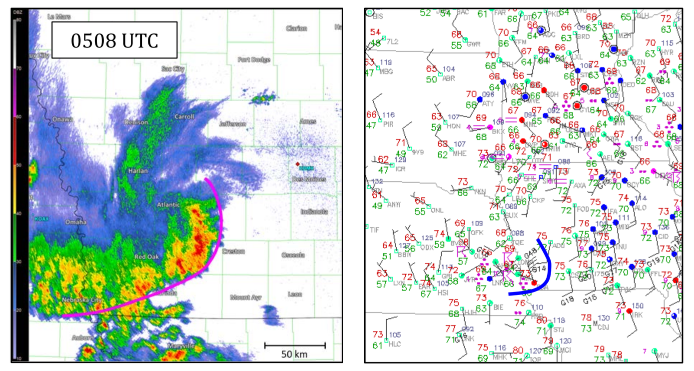

Figure 3: KDMX WSR-88D radar reflectivity (left) and surface station plot (right) at 0508 UTC 24 August. Pink (left) or blue (right) line indicates the outflow boundary.

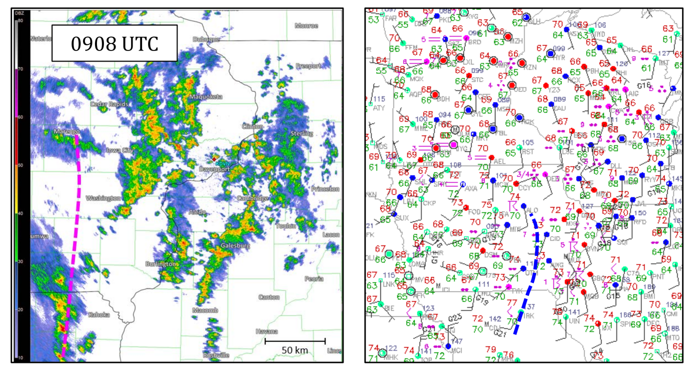

Figure 4: KDVN WSR-88D radar reflectivity (left) and surface station plot (right) at 0908 UTC 24 August. Pink (left) or blue (right) line indicates the outflow boundary.

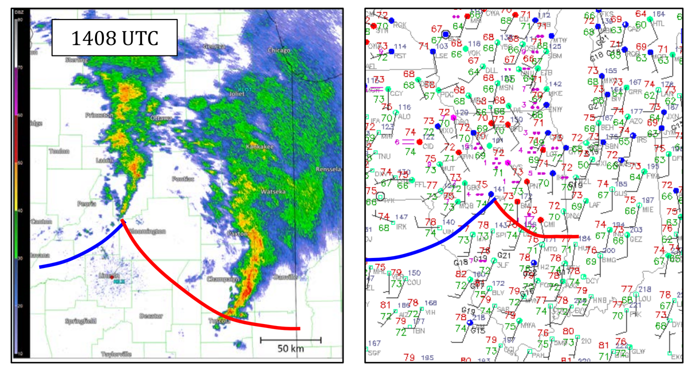

Figure 5: KILX WSR-88D radar reflectivity (left) and surface station plot (right) at 1408 UTC 24 August. Blue line indicates the outflow boundary and red line indicates the differential heating boundary.

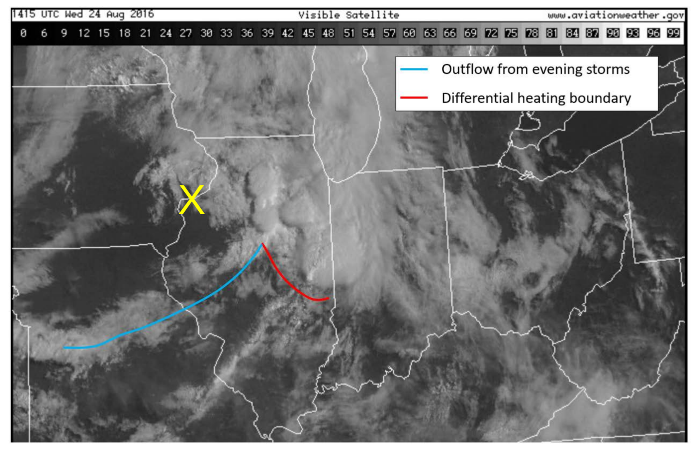

Figure 6: GOES-East visible satellite image at 1415 UTC 24 August. Blue line indicates the outflow boundary, red line indicates the differential heating boundary, and the yellow "X" indicates the MCV.

3: Environmental Parameters

- The 1200 UTC sounding from Lincoln, IL (KILX), sampled strong vertical wind shear in the surface to 950 mb layer, with little shear above this layer (Fig. 7).
- By 1800 UTC, enhanced flow on the southern flank of the MCV resulted in 30-40 kts of deep-layer shear over Illinois and Indiana (Fig. 8).

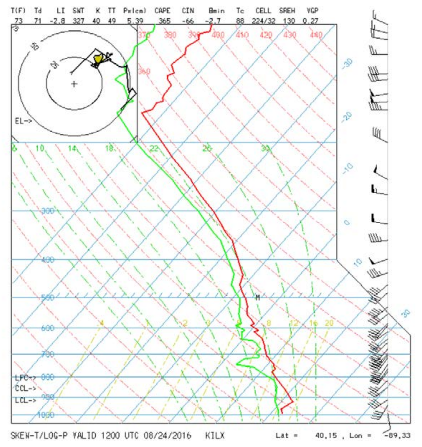

Figure 7: Skew-*T* log-*p* diagram depicting the 1200 UTC sounding from Lincoln, IL.

- 0-1 km storm-relative helicities were greater than 150 $m^2 s^{-2}$ north of the differential heating boundary (Fig. 9), with plentiful CAPE and little CIN remaining along and south of this boundary (Fig. 10). LCL heights were less than 1000 m (Fig. 11), suggesting an environment supportive of supercellular convection and possibly tornadoes.

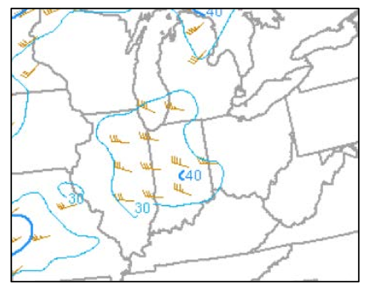

Figure 8: 0-6 km bulk shear (kts) at 1800 UTC 24 August.

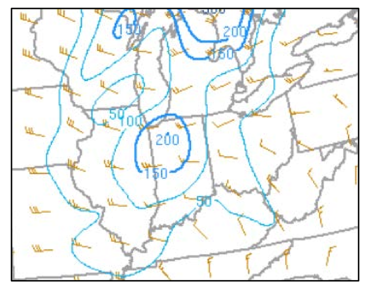

Figure 9: 0-1 km storm-relative helicity ($m^2 s^{-2}$) at 1800 UTC 24 August.

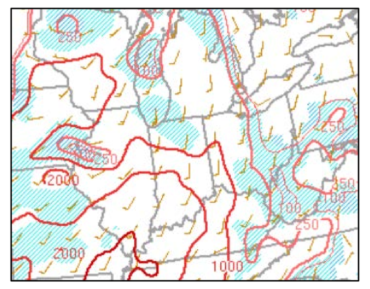

Figure 10: Mixed-layer CAPE (contoured; J kg^{-1}) and mixed-layer CIN (> 25 J kg^{-1} shaded) at 1800 UTC 24 August.

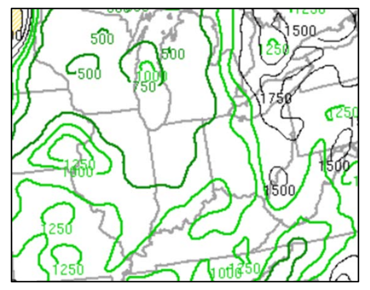

Figure 11: Lifting condensation level height (m) at 1800 UTC 24 August.

4: Transition to Surface-based Convection

- By 1700 UTC, the cluster of storms along the old outflow boundary (Fig. 5) reached the Illinois/Indiana border (Fig. 12). This convection was disorganized because it was likely elevated and rooted above the strongly-sheared near-surface layer (Fig. 7).
- Small cells continued developing south of this cluster through 1800 UTC (Fig. 13). These cells only exhibited weak rotation through this time, likely because they were still elevated.

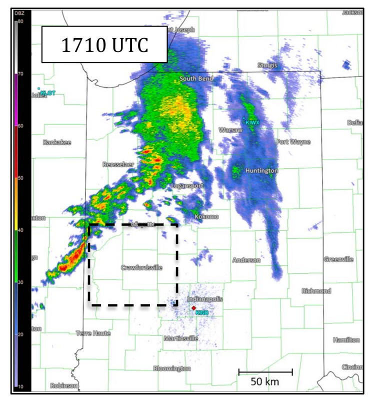

Figure 12: KIND WSR-88D radar reflectivity at 1710 UTC 24 August. Box is zoomed in area in Figs. 13-15.

- A WRF simulation of this event (paper 6B.6) reveals that these updrafts gradually ingested more near-surface air as diurnal destabilization progressed.
- An intense surface-based updraft developed by 1821 UTC on the southern end of this cluster as evidenced by the sharp gradient in reflectivity and convergence in radial velocity (arrows in Fig. 14).
- This storm developed a hook echo and intense rotation by 1834 UTC (Fig. 15). Four minutes later, at 1838 UTC, this storm produced an EF-2 tornado near Crawfordsville, Indiana, that lasted for 10 minutes.

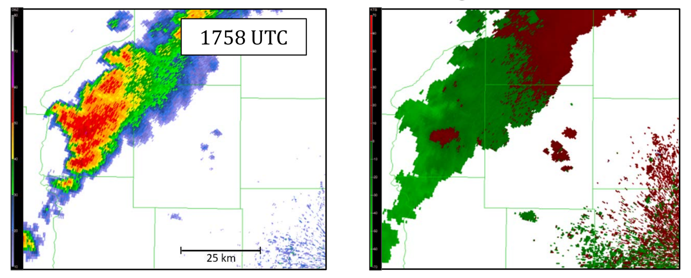

Figure 13: KIND WSR-88D radar reflectivity (left) and radial velocity (kts; right) at 1758 UTC 24 August.

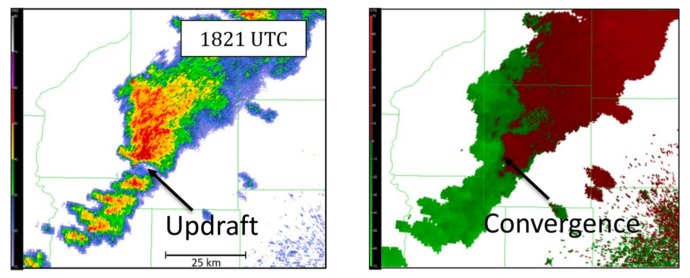

Figure 14: KIND WSR-88D radar reflectivity (left) and radial velocity (kts; right) at 1821 UTC 24 August.

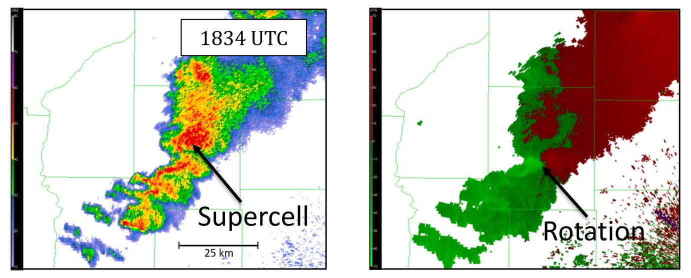

Figure 15: KIND WSR-88D radar reflectivity (left) and radial velocity (kts; right) at 1834 UTC 24 August.

5: Tornado Production

- At 1810 UTC, the storm that became the Crawfordsville supercell was near the intersection of the differential heating and outflow boundaries in west-central Indiana (Fig. 16). About 30 minutes later, at 1838 UTC, this supercell produced an EF-2 tornado.

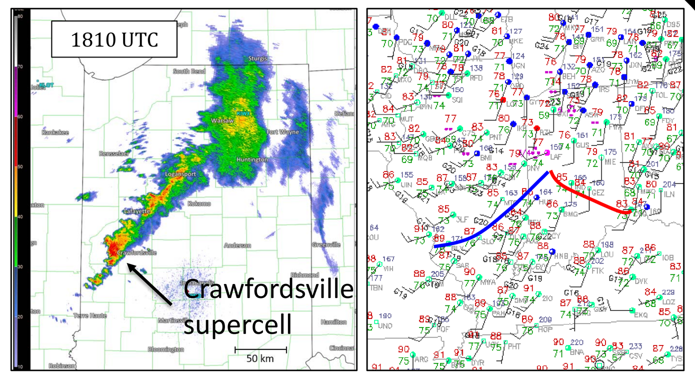

Figure 16: KIND WSR-88D radar reflectivity (left) and surface station plot (right) at 1810 UTC 24 August. Blue line indicates the outflow boundary and red line indicates the differential heating boundary.

- By 1907 UTC, another supercell developed from previously elevated convection in north-central Indiana, near Kokomo, also close to the intersection of the differential heating and outflow boundaries (Fig. 17). This storm produced an EF-3 tornado in Kokomo at 1920 UTC.

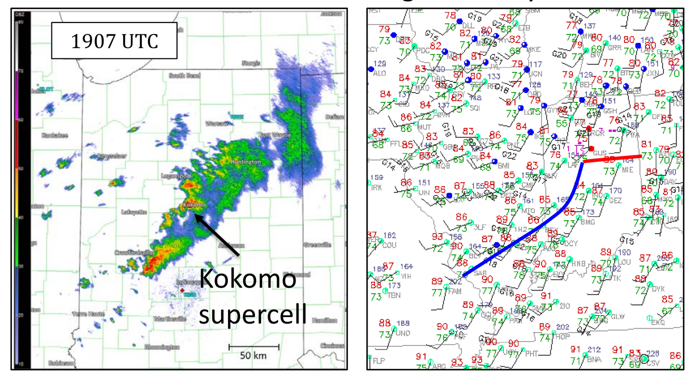

Figure 17: KIND WSR-88D radar reflectivity (left) and surface station plot (right) at 1907 UTC 24 August. Blue line indicates the outflow boundary and red line indicates the differential heating boundary.

- A third supercell began to organize near Fort Wayne by 2105 UTC (Fig. 18). This storm produced an EF-3 tornado near Woodburn, Indiana, at 2127 UTC, also in the vicinity of the northward-moving differential heating boundary. This storm produced additional tornadoes in NW Ohio.

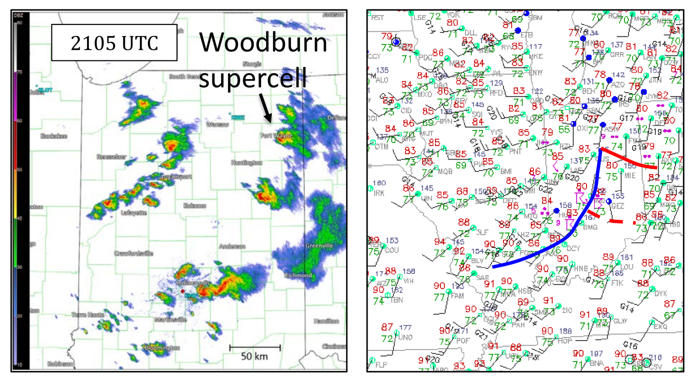

Figure 18: KIND WSR-88D radar reflectivity (left) and surface station plot (right) at 2105 UTC 24 August. Blue line indicates the outflow boundary red line indicates the differential heating boundary, and dashed red line is a secondary differential heating boundary.

6: Conclusions

- Two clusters of disorganized elevated thunderstorms developed over Illinois on the morning of 24 August 2016. Cloud shading from the leading cluster led to an east-west oriented differential heating boundary over central Illinois and Indiana by mid-morning.
- The trailing cluster formed south of an MCV and along an outflow boundary from convection the previous evening.
- As updrafts within the trailing cluster ingested highly-sheared air from near the surface, the storms became surface-based supercells. The MCV augmented the vertical wind shear, permitting supercell development.
- The supercells developed from south to north and each supercell produced a significant tornado shortly after its formation, coinciding with the northward movement of the differential heating boundary (Fig. 19).
- Less solar heating north of the differential heating boundary led to less vertical mixing and preserved high SRH there.
- Every significant tornado during this event occurred in proximity to the differential heating boundary (Figs. 1 and 19).

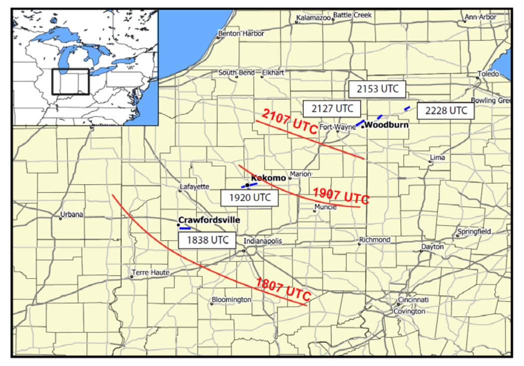

Figure 19: Map depicting the tracks (blue lines) of all significant tornadoes on 24 August 2016. The time each tornado began is listed in the white boxes. Red lines indicate the approximate locations of the primary differential heating boundary, as determined from surface and satellite observations. Towns nearest the three significant tornadoes in Indiana are in bold text. The westernmost significant tornado track in Ohio was two separate tornadoes according to *Storm Data*. The secondary differential heating boundary at 2107 UTC is not shown for clarity.