P9.5 MESOSCALE ASPECTS OF THE 11 MARCH 2006 SEVERE WEATHER OUTBREAK

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1. INTRODUCTION

During the evening hours of 11 March 2006, a series of destructive and damaging tornadoes affected southeast Missouri and extreme southwest Illinois. This event however was largely overshadowed by severe weather which occurred during the following 18-36 hours on 12-13 March 2006 (*hereafter all dates 2006 unless noted*), when nearly 60 tornadoes produced 8 fatalities, 163 injuries, and over 75 million dollars in property damage across a large portion of the middle Mississippi Valley. The events on the evening of 11 March across southeast Missouri and southwest Illinois were equally as devastating for that region. Seven tornadoes were documented across southeast Missouri and extreme southwest Illinois (Fig. 1), resulting in 2 fatalities, 21 injuries, and around 6 million dollars in damage. The seven tornadoes were among a total of ten tornadoes produced by two cyclic supercells. Of these seven tornadoes, three were classified as strong with damage rated at F2 or greater. Two of the strong tornadoes, the Chloride tornado and the St. Mary tornado were large long-track tornadoes with path widths of ¼ to ½ mile and path lengths of 35.5 miles and 53.5 miles respectively.

Severe weather on 11 March was not confined to the evening hours. Several clusters of elevated thunderstorms produced primarily marginal severe hail across portions of southeast Missouri, southern Illinois, and the lower Ohio River Valley during the predawn hours. These thunderstorms occurred just to the north of a surface warm front, in response to weak large scale ascent associated with a mid-level low amplitude disturbance and low-level warm air advection/positive theta-e advection via the southerly low-level jet (LLJ). Thunderstorms within the surface warm sector comprised the remainder of the severe weather on 11 March, and this came in two distinct phases. During the afternoon and early evening hours, short-lived supercell thunderstorms and multicell thunderstorms produced large hail and two brief tornadoes from central Missouri into west-central Illinois. The character of the event changed dramatically by mid-evening when the two tornadic supercells traversed southeast Missouri and southwest Illinois. The southernmost of the two supercells was particularly long-lived with origins in southeast Oklahoma. Of particular interest is that significant tornado production was confined to the later part of both of the supercell's lifecycle.

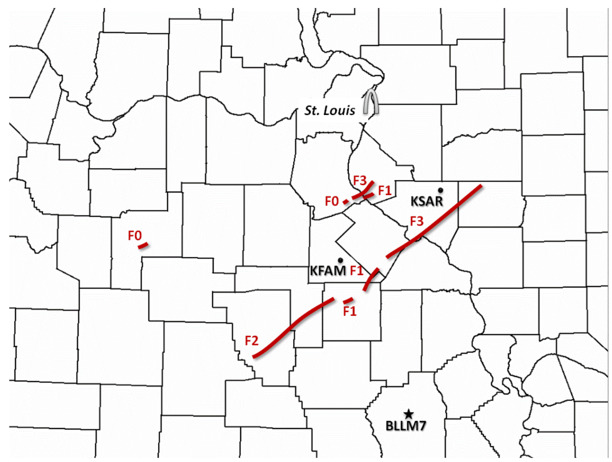

Figure 1. Map of tornado tracks (F-scale denoted) across southeast Missouri and southwest Illinois produced by two cyclic supercells. The locations of Farmington, Missouri (KFAM) and Sparta, Illinois (KSAR) surface observation sites, and the Bloomfield, Missouri (BLMM7) National Wind Profiler Network Site are annotated for reference.

This study examines the evolving environmental conditions which favored significant tornadoes across southeast Missouri and extreme southwest Illinois during the evening hours of 11 March. It will also take a close look at the lifespan of the two supercell thunderstorms, factors contributing to their longevity, as well as their ability to interact with the more favorable environmental conditions and hence produce significant tornadoes. Lastly, radar data from several National Weather Service WSR-88Ds are shown to highlight differences in radar viewing angles and emphasize the importance of utilizing multiple radars in warning operations.

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2. ENVIRONMENTAL CONDITIONS

The large scale pattern on the morning of 11 March featured a deep mid-upper level longwave trough centered across the far western U.S. with strong deep southwesterly flow aloft across the nation's midsection. An intense upper level jet streak (ULJ) with peak winds of 140 knots at 250 mb extended from Arizona into the lower Great Lakes. Embedded within the southwesterly flow aloft were a series of progressive low-amplitude shortwave troughs extending from the base of the longwave trough into the north-central Plains. At the surface, a low pressure center was located in southwestern Minnesota with an occluded front/cold front trailing southward across eastern Kansas into north-central Oklahoma where it intersected a north-south oriented dryline (Fig. 2). A retreating warm front was situated from the triple point in eastern Nebraska across the lower Missouri Valley into the lower Ohio Valley.

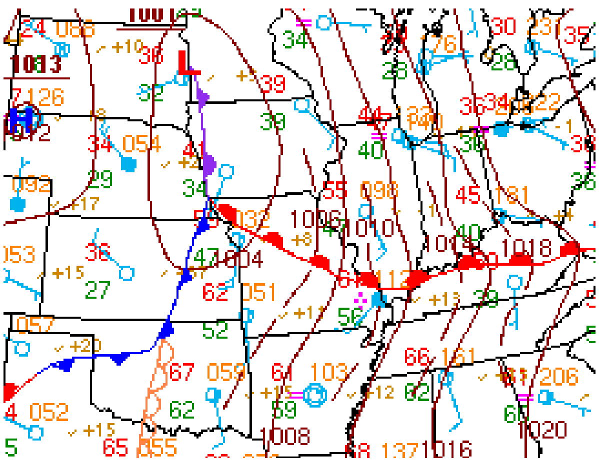

Figure 2. Surface analysis valid 1200 UTC 11 March 2006.

Southerly low-level flow advected moisture and warm air northward during the morning hours leading to the continued retreat of the warm front and an expanding and destabilizing warm sector. By midday, the environment across the central U.S. was favorable for organized severe thunderstorms including supercells over a large region ahead of the cold front and dryline, with moderate instability and strong deep-layer shear (Rasmussen and Blanchard 1998; Rasmussen 2003). A special 1800 UTC sounding from KSGF showed mean-layer convective available potential energy (MLCAPE) of nearly 1000 J kg^{-1}, negligible convective inhibition (CIN), 0-6 km bulk shear of 29 m s^{-1}, and 0-8 km bulk shear of 34 m s^{-1}. Conditions however were less than optimal for significant tornadoes. A recent study by Thompson et al. (2003) found what could be described as preferred set of sounding parameters favorable for significantly tornadic supercells. Examining 40-km Rapid Update Cycle-2 (RUC-2) soundings in close proximity to tornadic and nontornadic supercells, they determined 0-1 km storm-relative helicity (SRH) and mean-layer lifting condensation level height (MLLCL) had the greatest ability to discriminate between environments favorable for significantly tornadic and nontornadic supercells. Though there was a range of preferred values for both parameters, a mean of 185 m^2 s^{-2} was found for 0-1 km SRH and 1029 m AGL for MLLCL height. A MLLCL height of 1105 m AGL and 0-1 km SRH of 46 m^2 s^{-2} was computed from the 1800 UTC KSGF sounding.

Strong heating and continued low-level moisture influx into the afternoon yielded moderately-strong instability (*by early March standards*) in the warm sector in advance of the cold front and dryline, with MLCAPE values increasing to around 1500 J kg^{-1} and little if any CIN. Storm Prediction Center (SPC) mesoanalyses showed little change in the parameters typically used to assess the potential for significant tornadoes with 0-1 km SRH values of ranging from 50-125 m^2 s^{-2} and MLLCL heights of 1200-1400 m AGL (Fig. 3). The combination of weak large scale ascent associated with an approaching low amplitude mid-level shortwave trough and associated ULJ, as well as a region of a broad region of low-level convergence ahead of the encroaching cold front, yielded extensive thunderstorm coverage between 2030-2200 UTC from west-central Missouri into west-central Illinois. A mixed convective mode was observed consisting of short-lived supercells and multicell storms. These severe thunderstorms were responsible for numerous reports of large hail. Columbia, Missouri received severe hail up to 2 inches in diameter from four different supercells between 2115-2245 UTC. Several short-lived F0 tornadoes were also reported in Pike County in west-central Illinois after a series of storm mergers. Upscale growth eventually led to the development of a mesoscale convective system (MCS) from central Illinois into east-central Missouri by 0000 UTC 12 March with an attendant southward sinking outflow boundary.

Storm initiation occurred earlier (1800-2000 UTC) in advance of the trailing portion of the cold front and dryline from southwest Missouri into

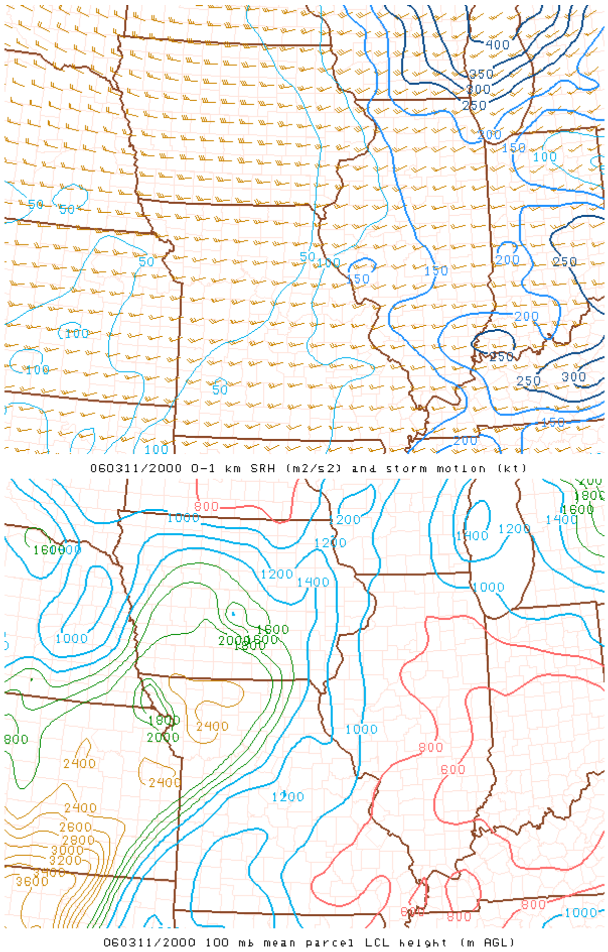

Figure 3. SPC mesoanalyses of 0-1 km SRH (top) and MLLCL height (bottom) valid at 2000 UTC 11 March.

eastern Oklahoma. Unlike the development further northeast where a mixed convective mode was observed and numerous storms were competing to become dominant, fewer thunderstorms developed and these evolved into discrete supercells. The southernmost of these storms became the long-lived supercell which impacted southeast Missouri and southwest Illinois. Environmental conditions were generally comparable to the region further northeast, however boundary layer convergence was slightly weaker at the time of initiation and the shear in the 2-8 km layer was more perpendicular to the initiating boundary/convergence zone (Fig. 4). The observed evolution and convective modes were consistent with work by Dial and Racy (2004). They found storms tend to be discrete when initiation occurs: along a dryline, in weak low-level convergence, and with 2-8 km shear oriented normal to the initiating boundary.

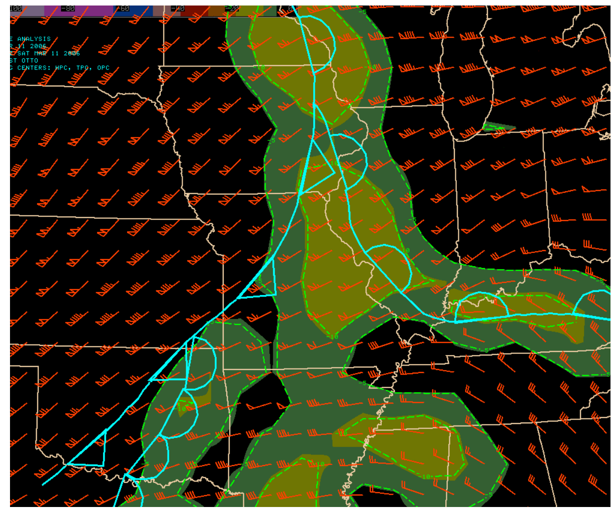

Figure 4. 00-h NAM 2-8 km bulk shear vectors (red), surface moisture convergence, and surface boundary positions valid at 1800 UTC 11 March.

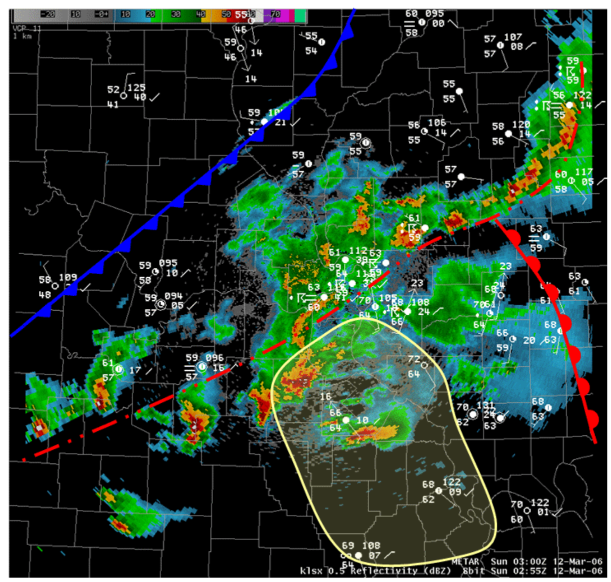

Figure 5. KLSX 0.5° reflectivity image with surface observations and subjectively analyzed boundaries. The region of locally backed surface winds are highlighted.

As discussed previously, the environment across the middle Mississippi Valley appeared unfavorable for significant tornadoes prior to 0000 UTC 12 March *(hereafter all times prior to 0000 UTC are 11 March and after 0000 UTC are 12 March)*. Environmental conditions changed dramatically across southeast Missouri and southwest Illinois after 0000 UTC, becoming increasingly favorable for significant tornadoes as the evening progressed. Surface data showed the surface winds backed by 20-40 degrees, while dew point depressions decreased in response to gradual cooling of the boundary layer (Fig. 5). Modified hourly Local Analysis and Prediction System (LAPS) soundings centered in southeast Missouri showed that LCL heights lowered below 600 m in response to the diurnal cooling (Table 1). CAPE also diminished but remained more than adequate for organized convection and supercells. Perhaps one of the most important changes was the development of an intense southerly LLJ. The Bloomfield (BLMM7) wind profiler in southeast Missouri (*located within the inflow sector 50-70 miles south of the track of the southernmost supercell*) documented the strengthening LLJ with winds increasing to over 50 knots between 1.0-1.5 km AGL (Fig. 6).

	2200	0000	0200	0400
MLCAPE (J kg^{-1})	2084	1398	1147	1016
MLLCL (m AGL)	891	686	594	505

Table 1. LAPS sounding values for the listed times (UTC).

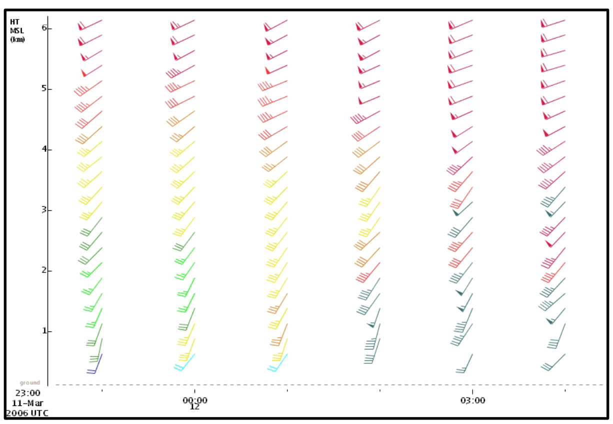

Figure 6. Time/height series of the vertical wind profiles from BLMM7 profiler site. Wind barbs are in knots.

Hodographs were derived using the winds from BLMM7 and the mean surface wind from the surface observations sites at Farmington, Missouri (KFAM) and Sparta, IL (KSAR). Some of the BLMM7 winds were periodically unavailable from the lowest data gates. When the winds were unavailable or highly suspect, they were supplemented with values averaged from RUC-2 and LAPS hourly soundings. The hodographs depicted the impact of the strengthening southerly LLJ and the backed surface winds with the emergence of large low-level shear vectors and

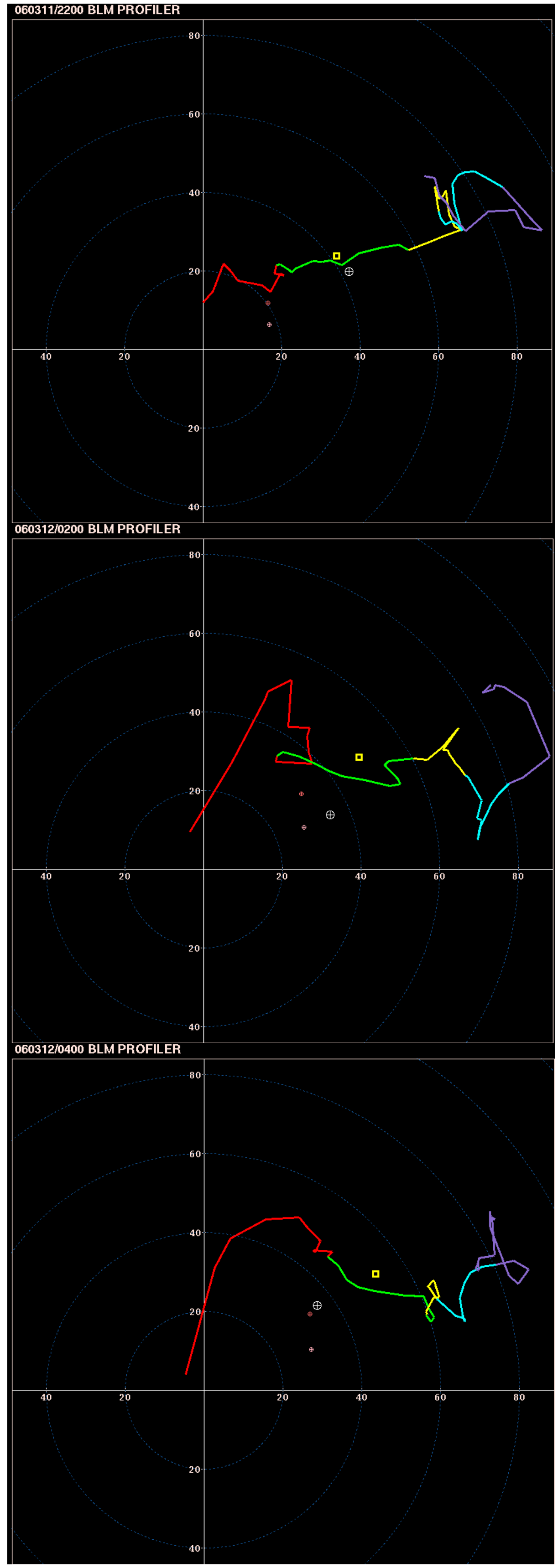

Figure 7. ***(Preceding page)*** Hodographs derived from the BLMM7 profiler site for 2200, 0200, and 0400 UTC 12 March *(from top to bottom).*

clockwise curvature between 0000-0400 UTC (Fig. 7). A time series of SRH values calculated from the BLMM7 hodographs using the observed storm motion of the southern long-lived supercell revealed a dramatic increase in 0-1 km SRH values from 63 $m^2\ s^{-2}$ at 2200 UTC to 321 $m^2\ s^{-2}$ by 0400 UTC (Fig. 8). Values of 0-3 km SRH showed a similar amplification, increasing from 48 $m^2\ s^{-2}$ at 2200 UTC to 399 $m^2\ s^{-2}$ at 0400 UTC.

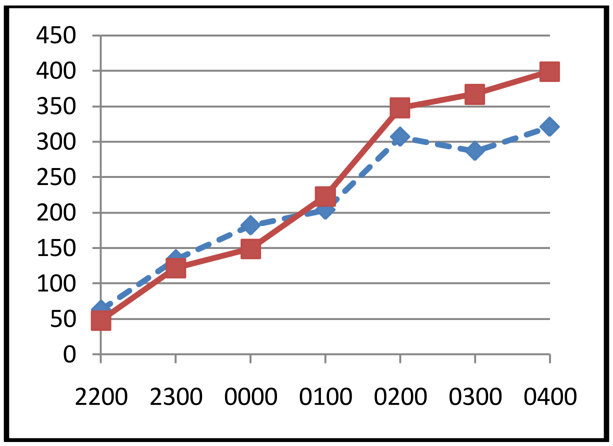

Figure 8. Time series of 0-1 km SRH (blue dashed) and 0-3 km SRH (red) calculated from the BLMM7 hodographs. Units are $m^2\ s^{-2}$.

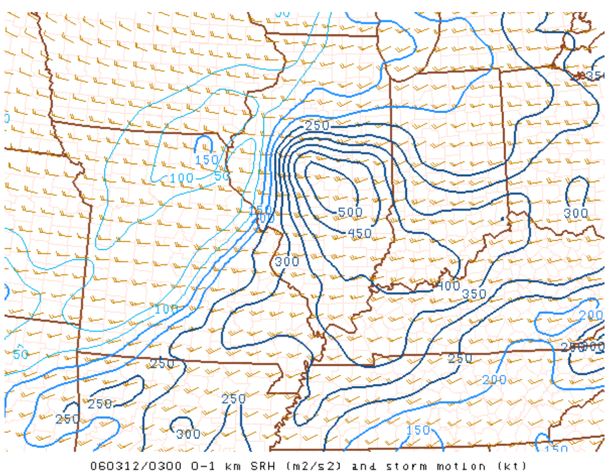

Figure 9. SPC mesoanalysis of 0-1 km SRH valid at 0300 UTC 12 March.

Figure 9 shows the spatial distribution of large 0-1 km SRH values favoring significant tornadoes across southeast Missouri and southern Illinois. A "kink" in the hodograph trace at a height of 1.0-1.5 km AGL was also periodically observed during the evening. Similar "kinks" were noted in hodographs across central Oklahoma during the 3 May 1999 tornado outbreak (Thompson and Edwards 2000), and in a collective study of low-level wind shear profiles and significant tornadoes by Miller (2006). Miller discussed the presence of large low-level bulk shear vectors from the surface to the height of this kink and through 1 km AGL. For the 14 significant tornado cases examined, he found a mean value of 14.4 $m\ s^{-1}$ for the 0-1 km AGL bulk shear magnitude. A time series of 0-1 km bulk shear magnitudes computed from the BLMM7 data showed magnitudes increased to even greater values than the mean value of Miller (2006) with 19.5 $m\ s^{-1}$ by 0200 UTC (Fig. 10).

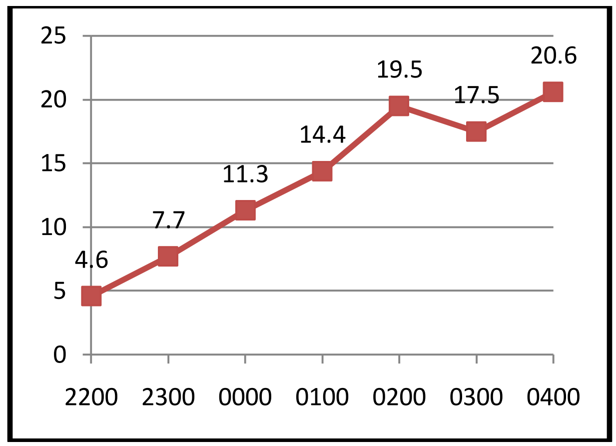

Figure 10. Time series of 0-1 km bulk shear for BLMM7profiler site. Units are $m\ s^{-1}$.

Studies by Kocin et al. (1986) and Glass (1993) have documented the enhancement of the local severe storm environment due to an ULJ and the associated ageostrophic circulations. The mass adjustment process within the exit region of the ULJ forces an indirect thermal circulation whose lower branch can enhance the low-level wind. Glass found the lower branch of the indirect thermal circulation increased the low-level shear through amplification of the LLJ and backing of the boundary layer winds with the 1991 Nixa-Springfield F4 tornado. LAPS and RUC-2 data during the evening of 11 March suggest an ULJ may have played role in the production of the strong LLJ and the region of locally backed surface winds across southeast Missouri and extreme southwest Illinois. Figure 11 depicts the ULJ exit region across the mid Mississippi Valley at 0300 UTC and the attendant upper and lower branches of the indirect circulation. Ageostrophic flow at 300 mb was directed southeast towards higher heights, while the ageostrophic flow at 850 mb was directed north towards lower heights and coincident with the narrow zone of southeast surface winds.

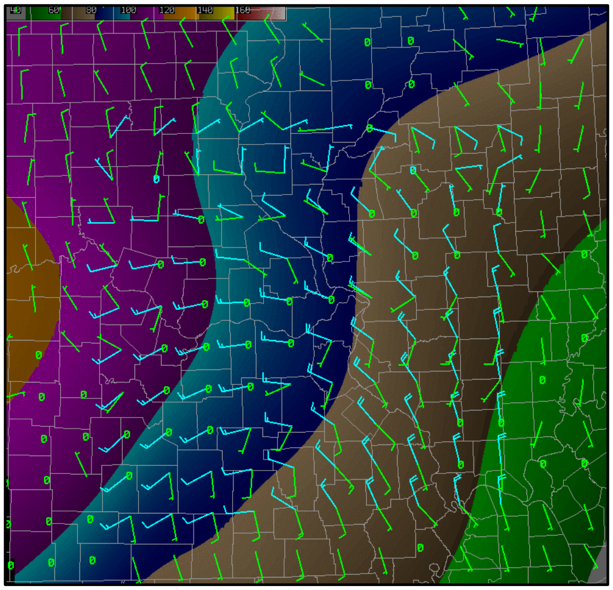

Figure 11. LAPS 300 mb wind speed image with 300 mb ageostrophic wind (blue) and 850 mb ageostrophic wind (green), valid at 0300 UTC 12 March.

3. SUPERCELL CHARACTERISTICS AND EVOLUTION

The two cyclic supercells which produced the tornado families *(including the significant tornadoes)* were among a number of supercells across southern Missouri on the evening of 11 March. Their longevity and ability to remain both discrete and free of any detrimental cell/storm mergers, then move into favorable environmental conditions appears critical in this event. Lee and Finely (2006) and Lee et al. (2006) also found that supercell isolation was an important component in two tornado outbreaks they studied.

Figure 12 is a plot of the tracks for the two supercells. The southern supercell (A) was particularly long-lived with a supercell lifespan of 10.5 hours, placing in the upper-echelon of its class. The northern supercell could almost be classified as a long-lived supercell with a supercell lifespan of 3.75 hours, just short of the 4 hour criteria established by Bunkers et al. (2006a). Table 2 is a list of tornadoes produced the two storms. Interestingly, the two supercells, separated by around 20 miles, both produced strong tornadoes which simultaneously crossed

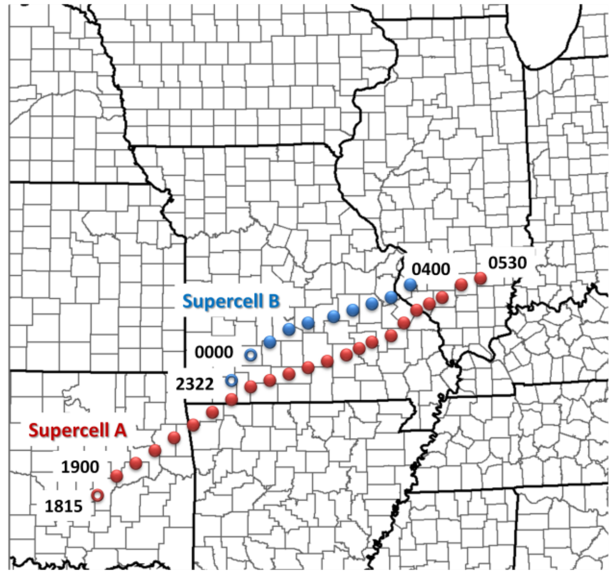

Figure 12. Plot of tracks for the two cyclic supercells. The open circle represents the initial cell or the pre-supercell storm position. Solid circles represent the supercell positions every 30 minutes.

Interstate 55 in southeast Missouri (Fig. 13). A more detailed account of the supercells is given in the two subsections below.

a. Southern Supercell (A)

The southern supercell was the most prolific tornado producer generating a family of six tornadoes including two strong large long-lived tornadoes. Important elements contributing to its longevity include strong 0-8 km bulk shear in excess of 30 m s^{-1}, 0-8 km storm-relative winds in excess of 15 m s^{-1}, weak forcing, and isolation from other thunderstorms until late in its lifecycle (Bunkers et al. 2006b).

The initial cells that grew into the supercell developed between 1800-1815 UTC in Hughes County, Oklahoma within a convergent zone ahead of the dryline. Around 1900 the ensuing storm began to display supercell characteristics, including mid-level rotation, a weak echo region, and tight reflectivity gradient on the southeast flank. Following some cell shedding/splitting around 2000 UTC, the supercell intensified exhibiting low-level rotation. The supercell moved northeast around 50 mph across northeast Oklahoma and into northwest Arkansas through 2130 UTC, remaining discrete and isolated. Between 2130-2200 UTC the supercell became very intense with deep regions of 65-75 dBz and a three-body scatter spike (TBSS). From 2200-0000

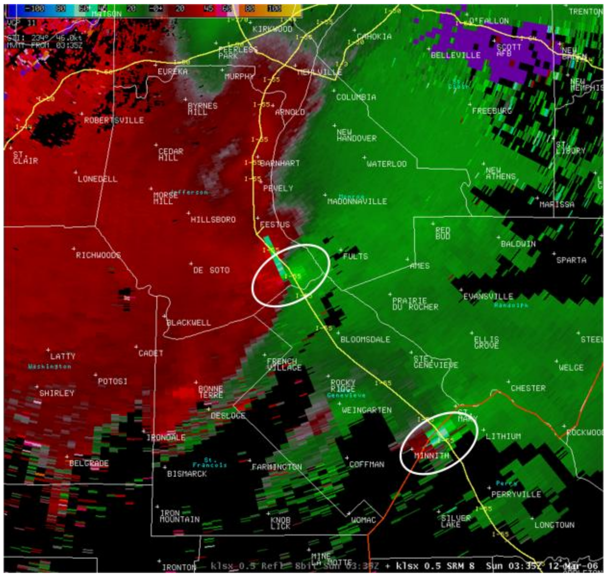

Figure 13. KLSX 0.5° storm-relative velocity image for 0335 UTC 12 March when large strong tornadoes were simultaneously crossing Interstate 55.

Southern Supercell (A)		
F-scale	**Path Length (mi)**	**Time (UTC)**
F0	8.0	2234
F0	0.1	2349
F2	35.5	0155
F1	0.7	0247
F1	6.0	0301
F3	53.5	0319
Fatalities 2	Injuries 20	Damage $5.1M
Northern Supercell (B)		
F0	3.0	0149
F0	0.1	0340
F3	5.1	0342
F1	2.4	0346
Fatalities 0	Injuries 1	Damage $1.1M

Table 2. List of tornadoes produced by the two supercells.

UTC it exhibited a pattern of periodic new intense updraft development on the southeast flank, which lead to a slight rightward deviation in the storm motion. After being in existence for 3.5 hours, the supercell produced its first weak tornado at 2234 UTC near Branson in extreme southwest Missouri. The tornado occurred following the appearance of a new intense updraft on the southeast flank and the ensuing development of a tight low-level mesocyclone. Despite continuous structural evolutions, a deep core of extreme reflectivity values (70+ dBz) and a TBSS remained present through 0010 UTC. Between 0010-0100 UTC the supercell displayed some rather dramatic evolutions, first weakening and elongating after a series of cell mergers and new cell development on the southern flank (RFD) gust front, then finally reorganizing and intensifying with the development of a new strong updraft on the southeast flank. This brief period was the only one in the history of the long-lived supercell where it was not completely isolated on the southern flank and potentially detrimental cell mergers occurred. Following the re-intensification the supercell remained discrete and largely isolated. The storm displayed smaller overall dimensions as it gradually evolved into a classic supercell exhibiting cyclic mesocyclogenesis and a reflectivity hook echo.

The first strong long-tracked tornado touched down in Reynolds County in southeast Missouri at 0155 UTC, nearly 7 hours after supercellgenesis. The cyclic supercell proceeded to produce tornadoes nearly continuously through 0445, including the 53.5 mile path length killer F3 tornado. The initial strong tornado development and subsequent tornado production coincided with the movement of the supercell into favorable environmental conditions for strong tornadoes present across southeast Missouri and extreme southwest Illinois (*discussed in section 2*). The supercell remained discrete but became less isolated as it moved northeastward into southwest Illinois through 0400 UTC. Between 0400-0500 UTC the supercell experienced a series of storm mergers, and the storm evolved into a hybrid high-precipitation supercell complex with several co-existent mesocyclones. The supercell met its demise between 0530-0545 UTC after additional cell and storm mergers transpired, and a distinct mesocyclone was no longer identifiable.

b. Northern Supercell (B)

The northern supercell produced a family of four tornadoes including one strong short-track tornado. Important elements contributing to its longevity and allowing it to move into more favorable conditions include strong deep layer shear, the ability to remain south of a progressive cold outflow boundary, and limited interaction with other storms/cells until late in its lifespan.

The storm initiated around 2322 UTC from a small southwest-northeast oriented band of weak cells just southwest of Springfield, Missouri. The storm intensified slowly as it moved northeast

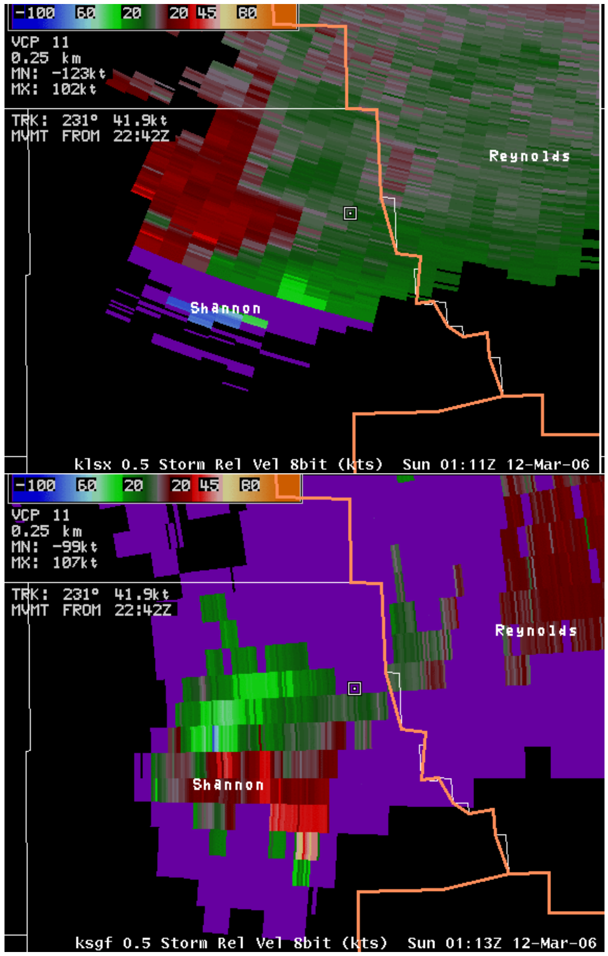

Figure 14. KLSX 0.5° storm-relative velocity image for 0111 UTC (top) and KSGF 0.5° storm-relative velocity image for 0113 UTC (bottom).

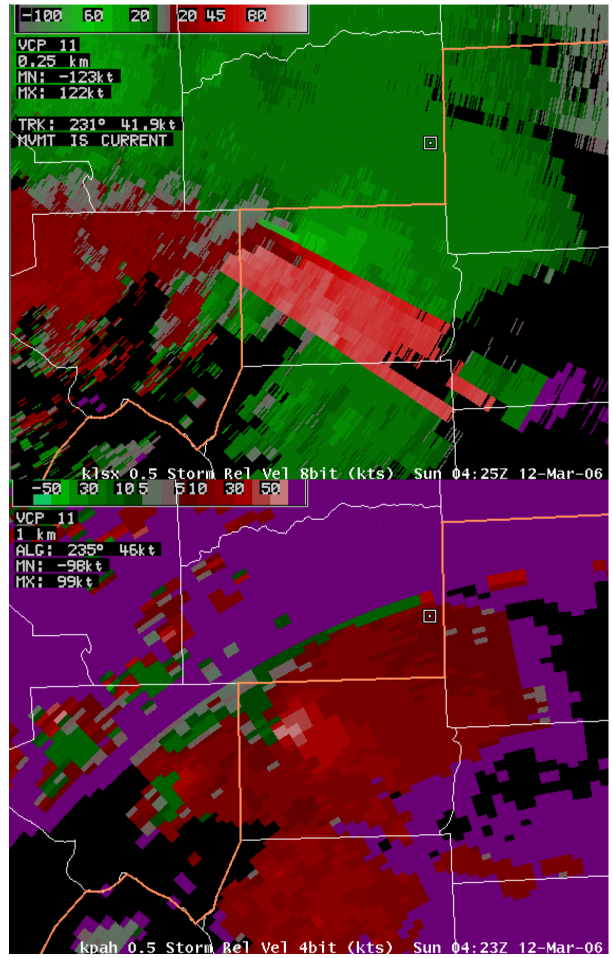

Figure 15. KLSX 0.5° storm-relative velocity image for 0425 UTC (top) and KPAH 0.5° storm-relative velocity image for 0423 UTC (bottom).

exhibiting a mid-level mesocyclone and supercell reflectivity characteristics shortly before 0030 UTC. Moving to the northeast at 50 mph, the supercell came into close proximity to a cold southward sinking boundary outflow generated by the MCS across northeast Missouri. However around 0100 UTC, a weak cell merger on the forward flank resulted in an intensification of the supercell *(reflectivity values aloft increased to 70+ dBz)* and rightward deviant motion away from the outflow boundary. The supercell produced its first weak short-track tornado at 0149 in Phelps County. The storm remained discrete and relatively isolated until 0230 UTC when a series of cell mergers occurred, leading to continued intensification and the appearance of a reflectivity hook echo and bounded weak echo region. Despite continued mergers, the supercell remained relatively discrete producing a series of tornadoes (including a strong F3 tornado) between 0340-0350 within the zone of more favorable environmental conditions. The supercell met its demise a short-time later when continued mergers lead to the transformation into a small bow echo absent of any low-mid level rotation.

4. RADAR CONSIDERATIONS

Wood and Brown (1997, 2000) discussed the impacts of radar sampling on observed mesocyclones and intensity. They showed the position of the radar beam with respect to the vortex can result in variations in the appearance of the mesocyclone and the magnitudes of the peak Doppler velocity values. Spoden et al. (2006) recently examined radar sampling issues and mesocyclone intensity with the November 2005 Evansville, Indiana F3 tornadic supercell. Their investigation revealed dramatic intensity differences of the observed mesocyclones when comparing nearby WSR-88D radars. Velocity dealiasing failures and range folding are other problems observed requiring radar adjustments or alternate radar views. The southernmost long-lived tornadic supercell on March 11 is a good illustrative case emphasizing the importance of examining multiple nearby WSR-88Ds during warning operations *(and research)*.

Figure 14 illustrates the impact of range folding and long-range velocity sampling on velocity magnitudes and mesocyclone intensity as the supercell approaches Reynolds County in the extreme southwest portion of the NWS St. Louis County Warning Area (LSX CWA). The images are nearly equidistant from both radars (~95 nm). The KLSX WSR-88D radar data suffers from range folding with a rotational velocity of only 29 knots. Alternatively, the KSGF WSR-88D located to the west shows an intense mid-level mesocyclone with a peak rotational velocity of 65 knots. Figure 15 is a good example of the impacts of velocity dealiasing failures as the supercell exits the southeast portion of the LSX CWA. The appearance of the mesocyclone is compromised in the KLSX data, while the KPAH WSR-88D clearly depicts the mid-level mesocyclone with a rotational velocity of >30 knots.

5. CONCLUDING REMARKS

Two cyclic supercell thunderstorms produced tornado families including strong tornadoes across southeast Missouri and southwest Illinois on the evening of 11 March. Cumulatively the tornadoes resulted in 2 fatalities, 21 injuries, and around 6 million dollars in damage. Below is a summary of the important aspects of this event presented in this study:

- The initial environment was not favorable for significant tornadoes.
- Noteworthy changes occurred during the evening with the development of a strong southerly LLJ, locally backed surface winds, and cooling of the boundary layer. These changes resulted in strong low-level shear and lowering LCL heights which transformed the environment into one supportive of significant tornadoes.
- A long-lived supercell which initiated in eastern Oklahoma and a short-lived supercell which initiated in southwest Missouri produced significant tornadoes upon moving into the more favorable environment.
- Significant tornado production did not occur until late in the supercell's lifecycles.
- Isolation was a key component in the longevity of the supercells and their ability to interact with the more favorable environment.
- Environmental conditions which favored supercell isolation and longevity include strong deep layer shear oriented normal to the initiating boundary, strong 0-8 km storm-relative winds, and weak forcing.

6. ACKNOWLEDGEMENTS

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