19.1 Analysis of the 2 April 2006 Quasi-Linear Convective System (QLCS) over the Mid-Mississippi Valley Region: Storm Structure and Evolution from WSR-88D data

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1. Introduction

The 2006 convective season across the Mid-Mississippi Valley region was one of the busiest in recent memory. The number of severe weather reports received within the Weather Forecast Office (WFO) St. Louis (LSX) County Warning Area (CWA) in 2006 has become one of the largest within recent years. A widespread damaging wind and tornado event occurred during the afternoon and early evening of 2 April 2006 and affected much of the WFO LSX CWA. Ten tornadoes occurred within the WFO LSX CWA with the greatest concentration of tornadoes and subsequent structural damage occurring over parts of central and southwest Illinois. Three of the tornadoes caused F2 damage, one - F1 damage while the remaining six tornadoes produced F0 damage. The storm system was responsible for two fatalities and twenty injuries. The majority of the injuries occurred across southwest Illinois where one large department store, nearby businesses and homes were severely damaged by a tornado in the Fairview Heights – O'Fallon area in St. Clair County Illinois.

It is well known that bow echoes and quasi-linear convective systems QLCSs often produce swaths of strong to severe straight-line winds generally F0-F2 in damage intensity (Fujita 1978). Recent numerical simulations have shown that damaging surface winds may be created by meso-y scale vortices or mesovortices that often form along the leading edge of the bow echo (Trapp and Weisman, 2003). These mesovortices have been observed along the leading edge of QLCSs at low-levels (generally 0-3/4 km) at or north of the bow apex (Funk 1999, Przybylinski et al. 2000**,** Atkins and Przybylinski 2000**,** and Atkins et al. 2005). In addition to the damaging winds mainly focused along the southern periphery of the mesovortex, non-supercell tornadoes have also been documented during the life time of these circulations. However, not all mesovortices become tornadic. The characteristics between non-tornadic and tornadic mesovortices are not well understood.

During the early afternoon two lines of discrete storms with a few embedded supercells formed over parts of north-central through central Missouri. As the line traversed east into east-central Missouri several storm mergers and interactions lead to a nearly solid QLCS with embedded bowing segments within the line. The merger of the two convective lines to the north occurred as the system crossed the Mississippi and Illinois Rivers. Extensive wind damage occurred over the immediate St. Louis metropolitan area while non-supercell tornadoes and wind damage occurred over parts of west-central and southwest Illinois. Some of the greatest structural damage occurred along the path of the tornadic mesovortices over the Fairview Heights – O'Fallon Illinois area similar to the 10 June 2003 St. Louis bow echo event. A brief description of the mesoscale environment is discussed in Section 2. Section 3 provides a radar overview of the event and the damage that was created. Detailed radar and damage survey / mesovortex track information will be presented in this section. This is followed by a survey of the structural characteristics of the mesovortices that were identified and a comparison to other tornadic and non-tornadic circulations from previously studied cases.

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2. Synoptic and Mesoscale Environment

The synoptic-scale environment on 2 April 2006 was similar to the "Dynamic Pattern" described by Johns (1993). This pattern is typically associated with strong, migrating low-pressure systems and has the characteristics of a classic "Great Plains" tornado outbreak pattern. Prominent thermal advection is present at low-levels while mid-levels winds are stronger than those in the warm season Derecho-type patterns.

A more detailed depiction of the mesoscale environment is shown in **Fig. 1** where the surface station plot and frontal positions are superimposed on the visible Geostationary Operational Satellite-E (GOES-E) satellite imagery. At 1900 UTC, (hereafter all times UTC) a warm front extended east-southeast from an area of low pressure over northwest Missouri to north of St. Louis and into southwest Indiana. A dry-line and pre-frontal trough stretched south across west-central and southwest Missouri into northwest Arkansas. A broad southern flow was advecting moist unstable air into the region ahead of the dry line as surface dew points south of the warm front reached 17° C. The visible satellite imagery shows two bands of convective towers developing along the dryline and prefrontal trough. At 500 hPa southwest flow was observed over Missouri with speeds of 20 – 30 m s^{-1}. The 1800 sounding launched from Springfield MO shown in **Fig. 2** clearly shows a highly unstable atmosphere with surface-based convective available potential energy (CAPE) values of 2829 J Kg^{-1}. The hodograph reveals a strong shear environment with magnitudes of 0 – 3 / 0 – 6 km bulk shear of 16 and 22 m s^{-1} respectively. The shear vector was oriented to the east-southeast within the 0 – 3 km layer and east within the 0 – 6 km layer. Two hours later (2000), the Winchester profiler showed strong shear within both layers (20 and 25 m s^{-1}) with the strongest shear within the lowest layer (0 – 3 km).

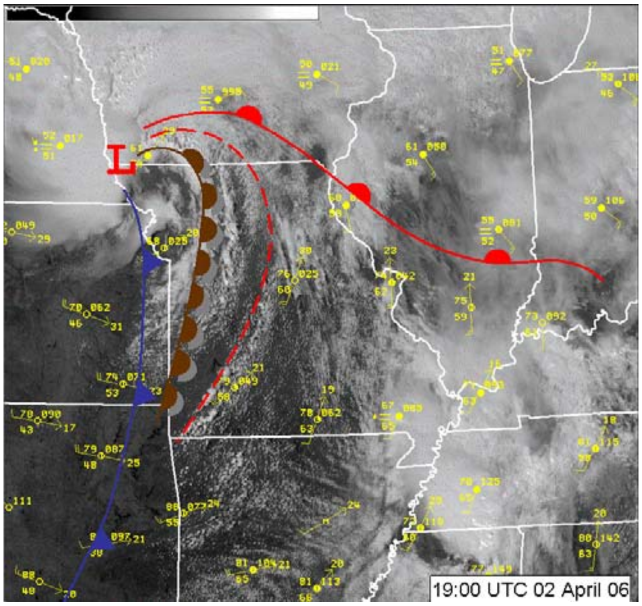

Fig. 1. Visible satellite imagery with surface station plots and conventional frontal symbols.

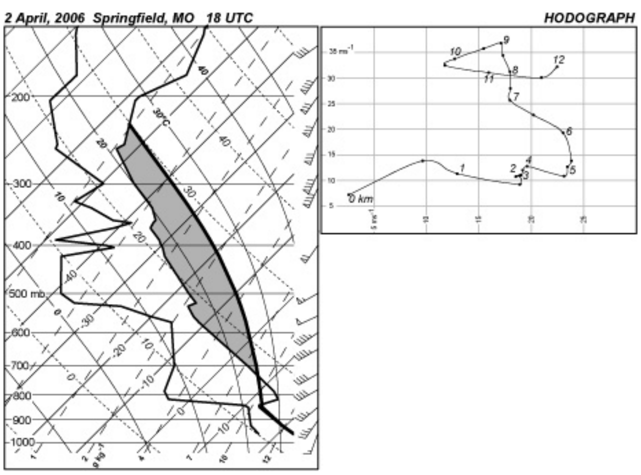

Fig. 2. Sounding and hodograph at 1800 UTC from Springfield MO. The gray shaded area represents the CAPE for the lifted parcel.

3. Radar and Damage Overview

Detailed ground-based damage surveys were performed the following day on six of the ten mesovortex tracks identified from WSR-88D data. Survey teams carefully traversed the tornadic damage paths mapping the damaged surface wind field based on observed tree fall along with damage to structures.

Two active lines of thunderstorms initiated over central Missouri between 1930 and 2000. The leading convective line extending from northeast Missouri through south central sections of the state at 2033 revealed stronger cells compared to the second weaker line of cells **(Fig 3).** During the following 30 minutes many of the storms intensified with a few exhibiting supercellular characteristics. Hail ranging in size from 2 to 4 cm were common with the leading line as they moved across central and parts of south-central Missouri. One supercell located 110 km northwest of KLSX at 2058 exhibited strong low and mid-level rotation for a period of 15 minutes. However, no tornadic activity was observed. After 2058 storm interactions and mergers were common across the central part of the line while discrete cells persisted over the southern part. Severe hail was still reported across much of the line.

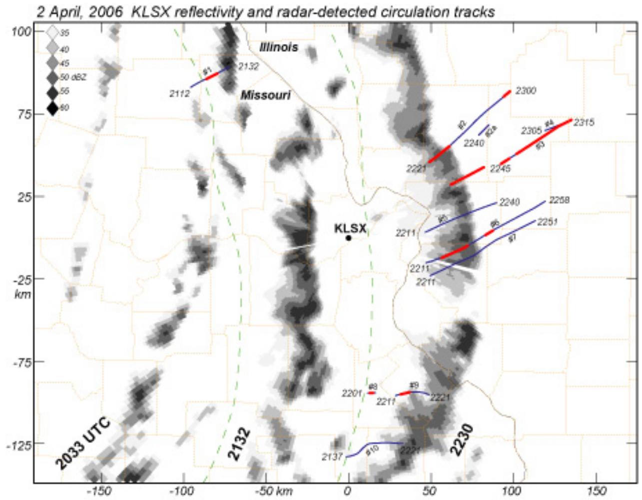

Fig. 3. Radar reflectivity data from the KLSX radar at 2033, 2132 and 2230 UTC. Solid lines represent the location of radar detected tornadic and non-tornadic mesovorticies. The thick red lines along the tornadic mesovortex paths represent the location of observed tornado damage.

The northern part of the trailing line of storms extending from northeast Missouri to 15 km east of Columbia, Missouri (KCOU) intensified after 2058 as they became more discrete in character. One of three storms entering Ralls County Missouri (25 km west-southwest of Hannibal Missouri) showed supercellular characteristics and contained a weak mesocyclone with rotational velocities (Vr) of 09 – 11 m s^{-1} and had a depth of 6 km. As the mesovortex height significantly lowered to a depth of 2 km, a tornado occurred at 2125. Damage survey information revealed F0 – F2 damage intensity where machine sheds, buildings and trees were damaged on several farmsteads. Burgess et al. 1982 has shown that tornadogenesis often occurs preceding and during the period of rapid lowering in mesocyclone height. The small line of storms continued to produce damaging winds and large hail across eastern Missouri (over and east of Hannibal) after 2130.

Shortly after 2115, storm interactions and mergers along the central part of the leading line resulted in the development of three small bowing segments west of KLSX within the larger line. Swaths of damaging winds occurred with the development of the bowing segments (**Fig. 4).** Between 2200 and 2215 a large bow echo formed just east of the Mississippi River across much of southwest Illinois. Curiously, many of the mesovortices after 2200 became tornadic across this region. This large broad bow echo pattern persisted through 2300.

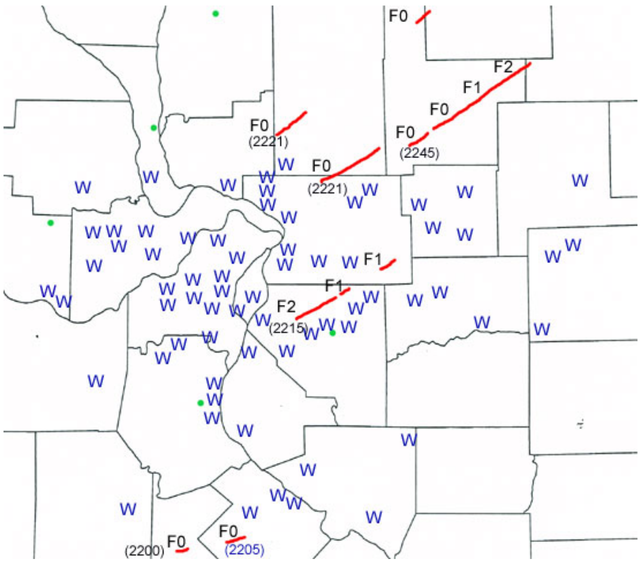

Fig. 4. Map of wind damage (W), hail reports (**.**) and tornadic damage tracks from the 2 April 2006 QLCS.

a: Madison – Macoupin and Montgomery County tornadoes

After 2215, a line-echo wave type reflectivity pattern (Hamilton 1969) formed over parts of southwest Illinois (90 to 65 km north to northeast of KLSX). The bowing part of this line, south of the inflection point, rapidly moved northeast at greater than 25 m s^{-1} across southern Macoupin and northern Madison counties in Illinois. Strong low-level reflectivity gradients were present along the leading edge of the bowing segment while Rear Inflow Notches (RINs) comprised the trailing flank of the line segment. At 2221 Mesovortex #2 (MV 2) formed near the northern part of the accelerated bowing segment within the larger convective line. **Figure 5** shows the reflectivity and base velocity fields with MV 2 track overlaid for 2226. Two weak tornadoes occurred immediately after the formation of MV 2 while a third weak tornado occurred between 2226 and 2235. Several machine sheds, barns, other structures and trees were either damaged or destroyed by the tornadoes. Scattered wind damage was reported along MV 2's track during the following 15 minutes. The Vr time-height cross-section shown in **Fig. 6** reveals a deepening mesovortex during the time of tornado occurrence with the strongest magnitudes noted at 2226. These findings are similar to results from the 10 June 2003 bow echo cases where tornadoes occurred during the period of mesovortex deepening with strongest rotation confined to the lowest 2 km (Atkins et al. 2005, Przybylinski et al. 2000). MV 2 also

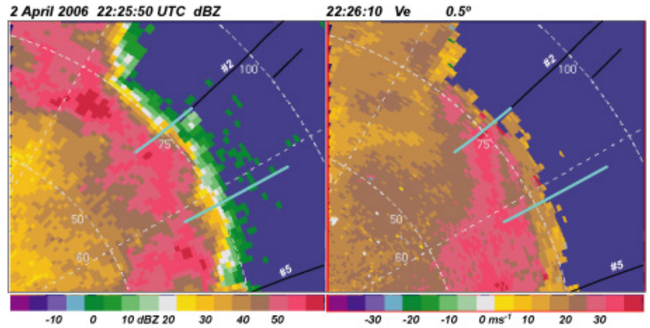

Fig. 5. KLSX reflectivity (dBZ) (left) and base radial velocity (m s^{-1}) (right) in plan view (0.5°) for 2226 UTC. Thin solid black lines represents the location of mesovortex tracks #2 and #5. Thin solid blue lines are the tornado tracks superimposed on mesovortex tracks.

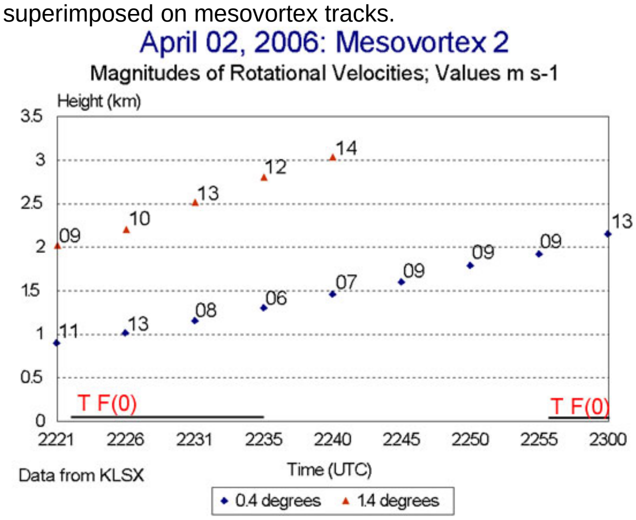

Fig. 6 Time-height Rotational Velocity trace of MV 2.

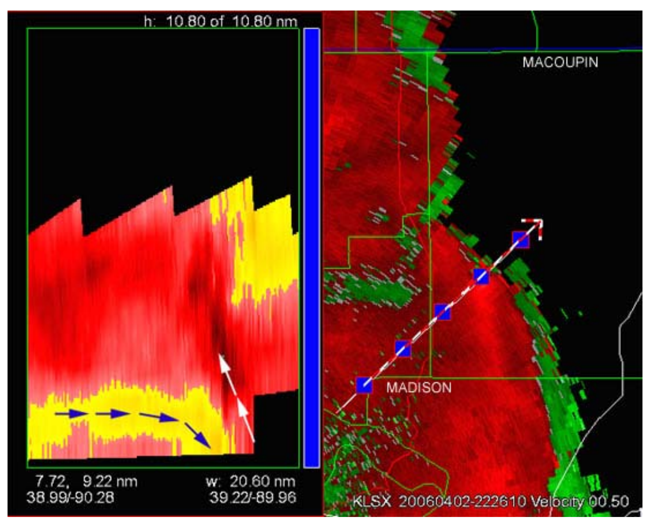

Fig. 7. KLSX storm-relative radial velocity (right) in plan view and base velocity cross-section (left) at 2226 UTC using WDSS program from NSSL. Dark blue arrows signify descending RIJ. While white arrows denotes ascending branch.

formed in the presence of multicell evolution and the mature stages of a mesoscale rear inflow jet (RIJ) shown in **Fig. 7.** The breadth of the RIJ extended across the entire trailing flank of the line. The vertical cross-section suggest that convergence may have increased near the leading edge of the nose of the descending RIJ core where magnitudes reached 35 m s^{-1}. The enhanced convergence likely aided in the formation of MV 2 and subsequent tornadogenesis. As the bowing convective line and MV 2 approached the warm frontal boundary over central Illinois, the mesovortex intensified a second time and spawned a fourth weak tornado over northeast Montgomery County Illinois.

At approximately 2221, a non mesocyclonic weak tornado formed over far northern Madison County and moved northeast into extreme southeast Macoupin County (Wakimoto and Wilson 1989). No discernable mesovortex was identified along the tornadic damage path. As the bowing convective line approached southwest Montgomery County, a weak and shallow mesovortex (MV 3) formed at 2245 and moved northeast. MV 3 spawned a weak tornado causing F(0) damage across much of central and northeast Montgomery County. A new mesovortex (MV 4) formed over northeast Montgomery county and merged with MV 3 at 2305 strengthening MV#3's rotational characteristics. The longevity of MV 2 and 3 and the continuous tornadic damage associated with MV 3 may have been influenced by the presence of increasing 0-1 km storm-relative helicity values (200 m^2 s^{-2}) over this region at 2200. Both MV 2 and MV 3 also further intensified as they moved northeast towards the warm frontal boundary over central Illinois. Tornadic damage rated F1 to F2 intensity was common near the warm frontal boundary over central sections of Illinois.

b. St. Clair – Madison – and Bond county tornadoes

At 2132, as the QLCS approached the St. Louis metropolitan area, three distinct bowing structures were evident on KLSX radar. The two northern most bowing segments merged as they reached KLSX (southwest St. Charles County) around 2145, while the third and most southern segment entered Jefferson County, Missouri (south of St. Louis). After the aforementioned merger, a stronger, more intense bowing structure traveled east-northeast across the St. Louis metropolitan area producing severe wind gusts greater than 30 ms^{-1} (Table I). This intense bowing segment continued northeast across the Mississippi River into southwest and south-central Illinois (see Section 3a).

A well defined rear inflow notch on the 0.5° reflectivity radar data marked the southernmost bow echo as it accelerated northeast across Jefferson County Missouri and into St. Clair County Illinois. Sporadic severe wind damage and large hail were observed along the path of the bow echo. At 2211, shortly after entering St. Clair County, two mesovortices (MV 6 and MV 7) developed along the forward flank of the convective segment, north of the bow's apex (Fig. 8). These mesovortices paralleled each other for nearly 90 km through four counties in southwest Illinois, exhibiting characteristics similar to the numerical simulations that Trapp and Weisman displayed

Observation Site ID	Peak Wind Gust	
KSTL ASOS (Saint Louis MO)	61 kts	31 m s^{-1}
KSUS ASOS (Chesterfield, MO)	64 kts	32 m s^{-1}
KSET ASOS (Saint Charles MO)	55 kts	28 m s^{-1}
KSAR AWOS (Sparta IL)	56 kts	28 m s^{-1}
KUIN ASOS (Quincy IL)	54 kts	27 m s^{-1}
KBLV (Belleville IL)	52 kts	26 m s^{-1}
KENL AWOS (Centralia, IL)	50 kts	25 m s^{-1}

Table I. Peak wind gusts at observation sites.

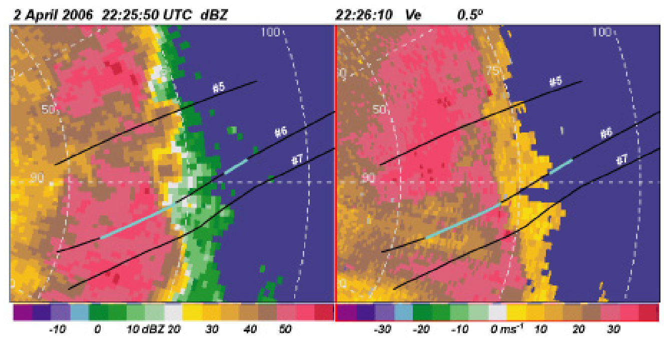

Fig. 8. Same as figure 5 except for 2216 UTC east of KLSX.

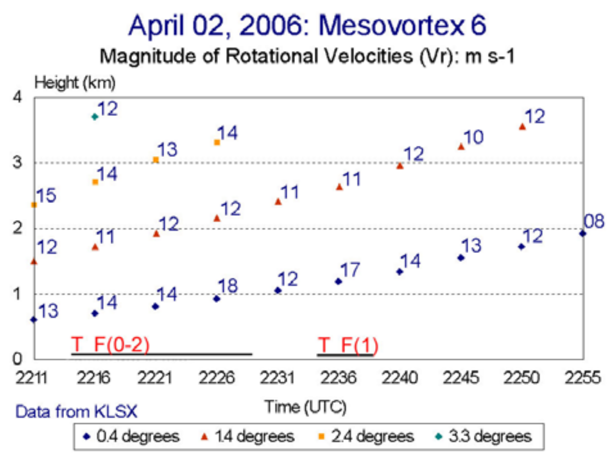

Fig. 9. Same as figure 6 except for MV 6.

in 2003. Both circulations exhibited core diameters less than 0.7 km throughout their existence, which made it difficult to discern during warning operations.

Two tornadoes causing F2 and F1 damage were associated with MV 6, while MV 7 only caused damaging winds. Time height Vr cross section of MV 6 revealed a deepening mesovortex with the strongest cyclonic rotation confined to the lowest 1 km during the time of tornadogenesis (**Fig. 9**).

The circulation depth and Vr intensity briefly decreased between 2226 and 2231 upon the demise of the first tornado. Although by 2236, Vr values increased once again, to 17 m s^{-1} at the 0.5° elevation slice (1.2 km), marking the genesis of the second tornado.

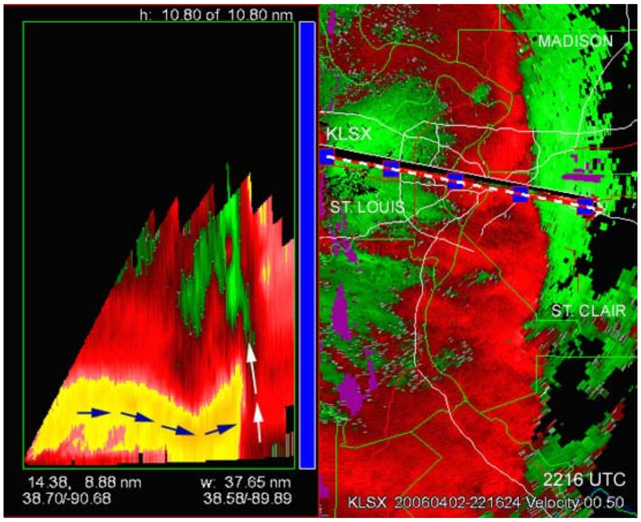

Fig. 10. Same as figure 7 except for 2216.

This second tornado was short lived as the circulation correspondently weakened at 2240, and the tornado dissipated. Similar to the Macoupin County tornadoes, the nose of the mesoscale RIJ at this part of the convective segment likely enhanced the local convergence along the leading edge and initiated MV 6 and MV 7 and tornadogenesis with MV 6. The RIJ structure is quite impressive revealing magnitudes up to 40 m s^{-1} just behind the nose of the jet leading to '*forced ascent*.' Wind damage primarily occurred along the path of MV 7 (**Fig. 10)**.

The bow echo continued to move northeast into south-central Illinois, with the majority of the severe wind damage being confined to the tracks of the two mesovortices. The correlation between observed wind damage and mesovortex tracks in this case further strengthens work done by Atkins et al. 2005, where it was also shown that the greatest straight-line wind damage occurred along the paths of the mesovortices.

c: Iron – St Francois – Ste Genevieve County tornadoes

The storms which developed across portions of southeast Missouri were initially discrete in nature, mainly multicell and a few supercell storms. Although the storms were initially discrete there were numerous storm interactions and mergers resulting in the development of a organized linear convective line. There were many reports of large hail (10 cm in diameter), numerous reports of damaging straight line winds, and two reported tornadoes producing F(0) damage. At 2201 a tornado causing F(0) damage occurred in Park Hills Missouri (**Fig. 11**). The damage path was short compared to the tornadic damage paths east and northeast of St. Louis. Tornadogenesis appeared to occur during storm merger within a developing line. A low-level mesovortex (MV 8) was briefly identified (for only one volume scan) during the time of tornado touchdown. The most unusual aspect of this circulation linked to the weak tornado was the anticyclonic rotational character of the mesovortex. After storm merger, this storm appeared to take on the characteristic of a small

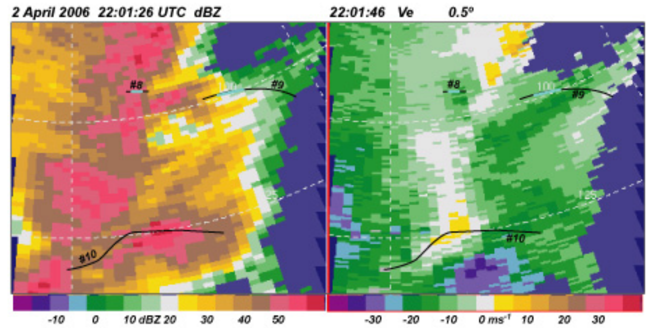

Fig. 11. Same as figure 5 except for 2201 UTC – south of St. Louis.

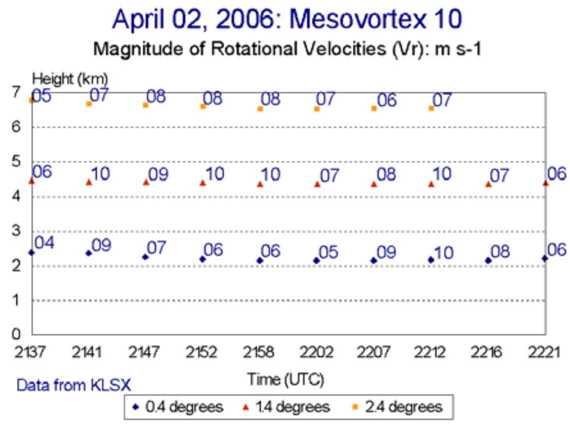

Fig. 12. Same as figure 6 except for MV 10.

bowing segment. The bow echo spawned a second tornado at 2214 southwest of Weingarten Missouri or approximately 25 km east of Park Hills Missouri. A weak cyclonic circulation (MV 9) was identified at 2211 just before tornado touchdown. MV 9 exhibited low Vr values of 6 m s^{-1} between 1.5 and 3.5 km at this time. Vr magnitudes slightly increased to 8 m s^{-1} at 1.5 km and 9 m s-1 as 3.2 km level at 2216. The mesovortex further intensified to 12 m s^{-1} as it moved east-northeast towards the Mississippi River. However no additional tornado touchdowns were reported.

The strongest mesovortex to occur over the southern part of the WFO LSX CWA developed over Iron County in southeast Missouri. This circulation (MV 10) developed near the southwest flank of a supercell storm at 2137 and was detected within the lowest three elevation scans (0.5°, 1.5° and 2.4° slices) between 2 and 7 km. Initially the strongest Vr values (6 m s^{-1}) were detected at mid-levels of the storm near 4.4 km (**Fig 12**). The Vr values increased to 10 m s-1 at 2141 during the subsequent volume scan at this level. MV 10 moved slowly northeastward through Iron County, then appeared to accelerate eastward over Madison County after 2202 after a convective line merged along the western flank of the supercell. Slightly higher Vr values (10 m s^{-1}) were identified at the two lowest elevation slices at 2212.. This was the strongest of the three mesovortices over this area during this period. However, there were no reported tornadoes or wind damage in the vicinity of MV 10. MV10 did travel through a relatively sparsely populated area in Madison County Missouri.

4. Summary

The 2 April 2006 squall line event became one of the more challenging severe weather episodes that warning forecasters at WFO St. Louis have experienced in recent years. The rapid convective line motion, weak rotational velocities and very small mesovortex core diameters associated with a number of tornadic mesovortices lead to the complexity and challenge. The storm system was responsible for two fatalities and twenty injuries over the region with the majority of injuries occurring over southwest Illinois. Ten tornadoes were reported with this system with the majority of tornadoes occurring with the bowing convective line over southwest Illinois. Tornadic damage ranged from F0-F2 intensity. Widespread wind damage appeared after the mesoscale rear inflow jet descended to near the surface over parts of east-central Missouri including the immediate St. Louis metropolitan area and parts of southwest Illinois. The more concentrated wind and tornadic damage was focused along the path of the mesovortices over parts of central and southwest Illinois.

Mesovortex growth and subsequent tornadogenesis likely formed in response to enhanced convergence along the leading edge of the nose of the RIJ where velocity values were highest. These observations are similar to the numerical simulations shown by Trapp and Weisman (2003). Even though many of the mesovortices over parts of central and southwest Illinois showed weak to moderate magnitudes of Vr, motion along the line exceeding 25 m s-1 may have played a critical role in mesovortex longevity and tornado damage intensity. Many of the tornadic damage tracks on 2 April 2006 were considerably longer compared to the 10 June 2003 St. Louis Bow Echo event (Atkins et al. 2005) The longevity and intensification of MV's 2, 3 and 4 over parts of central Illinois may have also been enhanced by the warm frontal boundary and 0-1 km storm-relative helicity where values increased to 250 $m^2 s^{-2}$ over central sections of Illinois. Close examination of the Vr data suggest that it was difficult to distinguish between tornadic and non-tornadic mesovortices. Mesovortices 1, 2, and 6 compared to 7 however did provide limited clues to mesovortex strength and depth to time of tornado occurrence. There is a limited number of cool to transitional season QLCS cases that have been studied since the installation of the WSR-88D. Many more cases will be needed to study the mesovortex–tornado genesis mechanisms through the use of Doppler radar and detailed storm assessments. The role of line motion and storm-relative helicity to mesovortex longevity and damage intensity will equally need to be closely examined in future cases.

5. Acknowledgements

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