6.1 Observations and quantification of low-level mesovortex evolution within the 4 July 2004 southwest Missouri high wind event

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1. INTRODUCTION

Quasi-linear convective systems (QLCSs), or squall lines and bow echoes, are a well-known form of convective organization that often produce severe weather, including damaging surface winds and even tornadoes. It is well known that damaging straight-line winds at the surface are often caused by the descending rear-inflow jet at the bow-echo apex (Fujita 1978; Przybylinski 1995). However, recent observations indicate that many instances of damaging surface winds are associated with the development of leading-edge, low-level mesovortices, which have been shown to produce concentrated straight-line wind damage up to F1 intensity (Wheatley et al. 2006; Atkins et al. 2004).

A recent paper by Trapp et al. (2005) suggests that tornadoes formed from QLCSs from 1998-2000 accounted for nearly 20% of all tornadoes nationwide. This percentage rose to roughly 30% over Missouri, while an astounding 50% of tornadoes in Indiana during that time period formed within QLCSs. Studies have shown that the parent circulation of many bow-echo tornadoes are mesovortices (e.g., Funk et al. 1999; Arnott and Atkins 2002; Weisman and Trapp 2003). Based on the resultant damaging winds and tornadoes from QLCSs, mesovortices cannot be ignored as the aforementioned research highlights their significance. However, there is still a lack of detailed, radar-based detection of precursors of damaging straight-line winds and tornadoes caused by mesovortices. Without early detection, warning for these situations becomes very challenging for operational meteorologists.

One such event occurred on the morning of 4 July 2004. A line of hybrid supercells developed across central Kansas and later evolved into an intense bow echo as it moved southeastward into southwest Missouri. An observational analysis was performed on the portion of this QLCS that moved through the County Warning Area (CWA) (Fig. 1) of the National Weather Service (NWS) Forecast Office in Springfield, Missouri (SGF).

The 4 July 2004 bow echo produced intense straight-line wind damage and an F1 tornado.

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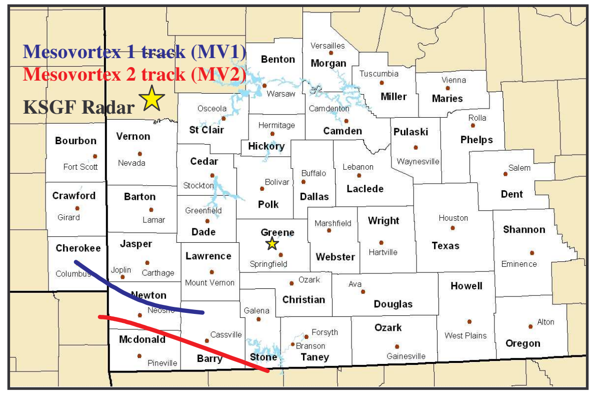

Fig. 1. Plot of the tracks of the two main mesovortices over the CWA of SGF on 4 July 2004.

Analysis from the KSGF WSR-88D Doppler radar indicated that four mesovortices developed along the leading edge of the QLCS. Only two mesovortices will be examined here (Fig. 1), as the northernmost mesovortex was quickly amalgamated by a northern line-end vortex (a fundamental, system-scale mid-level feature embedded within the precipitation field behind the leading edge of a bow echo (Weisman 1993)), and the southernmost one was too distant to be properly sampled.

Damage surveys from this event revealed that one mesovortex produced intense straight-line winds and a tornado, while the other produced marginal wind damage. Using WSR-88D radar data from KSGF, the main objective of this paper is to quantify the two dominant mesovortices in order to identify characteristics that may be relatable to damaging surface winds and tornadoes. Implications to NWS operational warning techniques will also be discussed.

2. SYNOPTIC AND MESOSCALE DISCUSSION

The synoptic environment in place that morning was that of a typical warm-season pattern for bow echoes described in Johns and Hirt (1987) and Johns (1993). This is represented by weak dynamics producing mid-level ridging or northwesterly flow, low-level warm, moist advection near the bow-echo initiation area, and a weak instability boundary usually oriented parallel to the mean wind direction, along which the bow echo typically advances.

On the morning of 4 July 2004, a mid-level ridge was located over the bow-echo initiation region in the central Plains, with cyclonic flow over the Midwest and Intermountain West. The 500mb flow consisted of a 20 m s^{-1} northwesterly jet over eastern Kansas and northwest Missouri at 0000 UTC 4 July 2004 backing to west-northwesterly by 1200 UTC. This mid-level jet was located north of the bow-echo initiation region, which is in harmony with the findings of Johns (1993). Also consistent with Johns (1993) was the advection of warm, moist air at 850mb, likely aided by a 15 - 20 m s^{-1} southwesterly jet. The maximum 850mb temperatures, dewpoints, and equivalent potential temperatures advecting into the bow-echo initiation region of central Kansas were nearly 25°C, 20°C, and 360 K, respectively.

It was hard to discern a frontal boundary, however a weak instability gradient was located across central and southern Kansas, extending eastward from a low pressure center over southeast Colorado (Fig. 2). South of this boundary, surface winds were generally southerly as dewpoints ranged from 20-24°C, with one reading up to 26°C. The highest dewpoints were co-located with the most unstable air, indicated by lifted indices less than -6°C (Fig. 2).

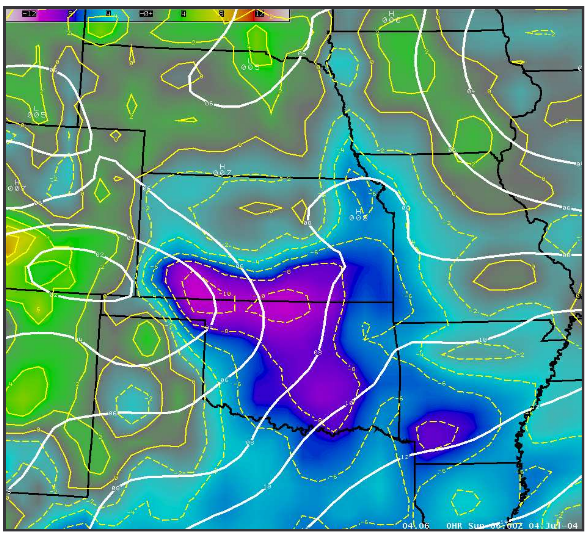

Fig. 2. Surface RUC analysis of mean sea-level pressure (mb) and lifted index (°C) valid at 06 UTC 4 July 2004. The image is of lifted indices (yellow dashed lines are negative values and yellow solid lines are positive values), with mean sea-level pressure identified by white solid lines.

The environment within the warm sector was moderately unstable as indicated by the 1200 UTC 4 July upper-air soundings from Oklahoma City, OK and Springfield, MO, which had mixed-layer convective available potential energy (MLCAPE) values of roughly 2400 J kg^{-1} and 2300 J kg^{-1}, respectively. Given the time of day, however, surface convective inhibition values (CIN) were less than -300 J kg^{-1}. The Topeka, KS and Lamont, OK soundings from 0000 UTC 4 July (approximately six hours prior to bow-echo initiation) indicated this instability, with surface-based lifted indices of -8°C and -12°C, respectively. The warm-sector environment was also moderately sheared, with surface southeasterly winds from 2.5 – 5.0 m s^{-1} and 925-850mb southwesterly winds around 20 m s^{-1}. The winds above this were roughly unidirectional from the west-northwest and slightly increased to 25 m s^{-1} with height.

3. RADAR DISCUSSION

As previously mentioned, the bow echo across southwest Missouri initialized as a line of hybrid supercells across central Kansas (Fig. 3a). The supercells formed along an outflow boundary generated from weakening convection across Nebraska and northern Kansas, which was initially associated with a 500mb vorticity maximum embedded within the northwest flow. The line of convection transitioned into an intense bow echo over southeast Kansas (Fig. 3b) and southwest Missouri.

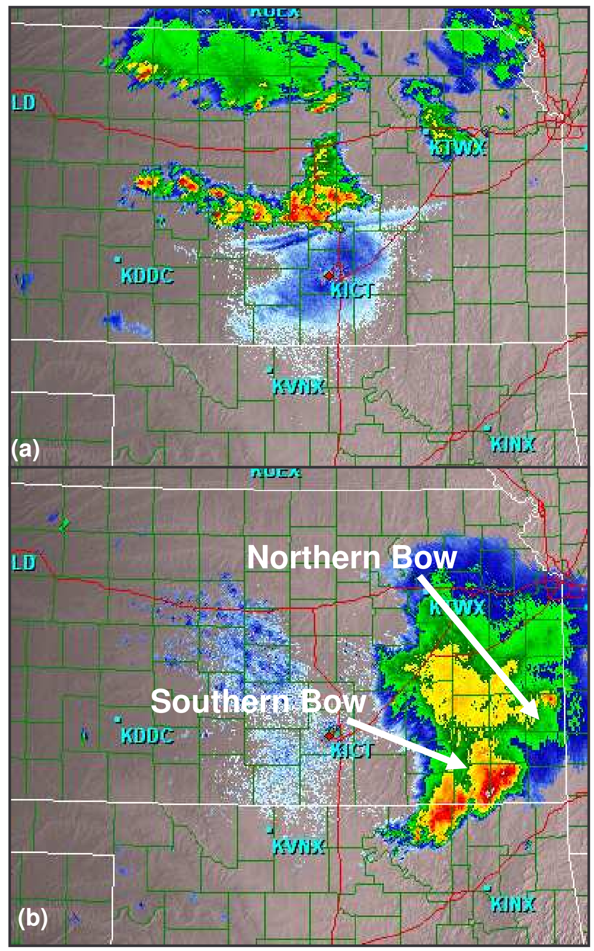

Fig. 3. 0.5° reflectivity image from the WSR-88D at KICT (Wichita, KS) valid at (a) 0648 UTC and (b) 1101 UTC 4 July 2004. The northern bowing segment (eastern Kansas) and southern bowing segment (southeast Kansas) are labeled in (b). State borders (white), interstates (red), county outlines (green), and regional radars (blue) are also identified.

The entire QLCS was split into a small, northern bowing segment and a large, primary bowing segment further south (Fig. 3b). The northern bow reached the northern Kansas counties of the SGF CWA by 1024 UTC. However, these cells quickly dissipated thereafter, and produced a southeastward progressing outflow boundary. Concurrently, the stronger southern bowing segment sustained itself as it reached the SGF CWA by 1119 UTC. Straight-line wind damage was reported with the latter bowing segment as early as 1126 UTC over Cherokee County, KS, where winds in excess of 60 KT and numerous accounts of structural damage occurred (golf ball size hail also was reported). The severe straight-line winds accompanied the bow as it moved into southwest Missouri.

The outflow boundary from the dying northern cells intersected the main bow echo near the apex (Fig. 4). Near this conjunction at 1205 UTC, an F1 tornado formed in NW Newton County, which was initially assumed to be entirely due to the intersecting boundary. However, closer radar interpretation revealed that a leading-line mesovortex was located in the same vicinity at the same time.

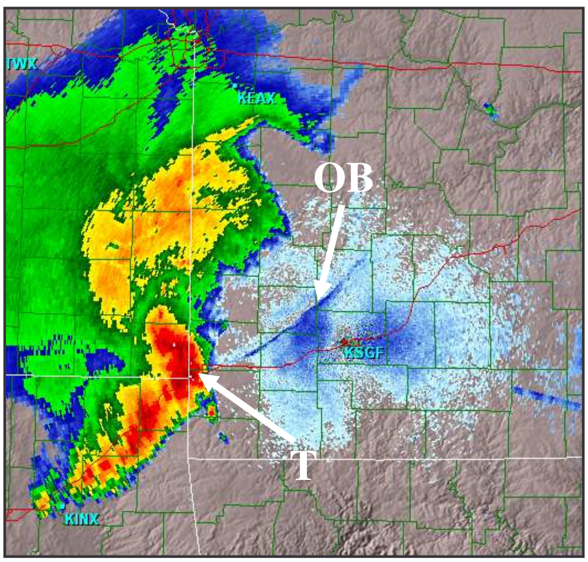

Fig. 4. 0.5° reflectivity image from the WSR-88D at KSGF valid at 1206 UTC 4 July 2004, one minute past tornado report. State borders (white), interstates (red), county outlines (green), outflow boundary (OB), and tornado location (T) are all identified.

Velocity data valid at 1222 UTC and 1252 UTC show MV1 and MV2, respectively (Fig. 5). Also identified is the mid-level line-end vortex (LEV) and rear-inflow jet (RIJ). MV1 can be seen near the bow-echo apex, coincident with the strong rear-inflow jet, while MV2 formed south of the apex as the bow echo continued east-southeastward. Both mesovortices continued on their southeastward progression along the leading edge of the bow echo until they dissipated before 1330 UTC, when the strongest portion of the bow echo had exited the SGF CWA to the southeast.

Although there were many wind damage reports, especially surrounding the bow apex, the intensity of

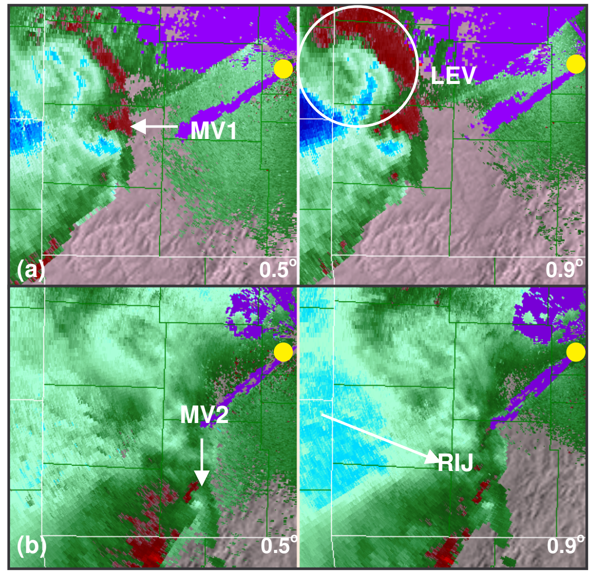

Fig. 5. 0.5° and 0.9° ground-relative velocity from the KSGF radar valid at (a) 1222 UTC and (b) 1252 UTC. The northern mesovortex (MV1) is identified in (a), while the southern mesovortex (MV2) is shown in (b). The line-end vortex (LEV), rear-inflow jet (RIJ), and KSGF WSR-88D radar (yellow circle) are also identified. Inbound velocities are blue and green, while outbound velocities are red.

the damage was not fully understood until three separate damage surveys were conducted. The first survey targeted the tornado damage in Newton County, MO, and the straight-line wind damage upstream in Cherokee County, KS. The second survey targeted locations along and around MV1, while the third was concentrated along and around the path of MV2. The last two surveys revealed that the most intense straight-line wind damage and the F1 tornado were in some way associated with MV1. Moreover, the MV1 survey indicated a swath of F0 straight-line wind damage anywhere from 8 to 11 miles wide, with embedded F1 straight-line wind damage in Cherokee County, KS, eastern Newton County, MO, and northwestern Barry County, MO. Mobile homes were damaged and rolled, numerous power lines were downed, and many large trees were uprooted. Conversely, weaker and much more sporadic damage occurred with MV2. This large difference was not discernable from *Storm Data* (NCDC 2004), as many of the reports lacked detail (i.e., county-wide damage) and were lacking from the region of most intense damage (this will be revisited in the final discussion). Thus, it was necessary to research the possibilities of why MV1 produced intense straight-line wind damage and an F1 tornado, while MV2 only produced minor wind damage.

4. ANALYSIS OF MESOVORTICES

Both MV1 and MV2 were compared in the post-event analysis to discern differences between them in order to understand the resulting damage pattern. Characteristics such as lifetime, width, depth, maximum inbound and outbound velocities, rotational velocities, and radar signatures were compared.

The first step was to identify any radar signatures or characteristics that may have helped expose differences between the intense and tornadic MV1 and the marginally severe MV2. The first and primary feature is the intersecting outflow boundary. Although the outflow boundary was a product of the weakening northern bowing segment (Fig. 3b), the boundary had oriented itself nearly perpendicular to the advancing stronger, southern bow (Fig. 4), which corresponded to the location of MV1. In past cases, it is evident that boundary intersections are not necessary for mesovortices to become tornadic (e.g., Atkins et al. 2004, Funk et al. 1999). However, it is possible that this boundary added a source of low-level vorticity which is often the case (Maddox et al. 1980). At the time of tornado occurrence, a secondary, yet small boundary extended southeast from MV1 (Fig. 6a). Whether this is a product of the mesovortex (such as an inflow band), or a mesoscale warm front, or some other phenomenon is uncertain. While a similar feature was seen with MV2 (Fig. 6b), this element (Fig. 6a) intersected, or was adjoined to MV1, near the outflow boundary intersection. This interaction may have aided in tornadogenesis. Lastly, it is noted

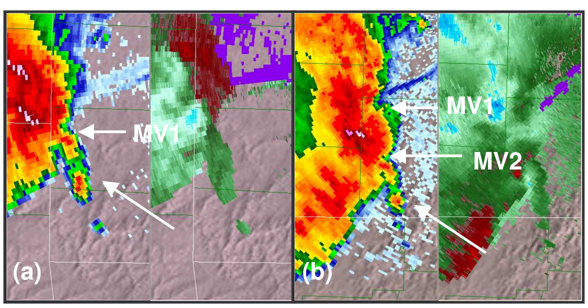

Fig. 6. 0.5° reflectivity and ground-relative velocity two-panels for (a) MV1 valid at 1201 UTC, and for (b) MV2 valid at 1248 UTC. White arrows identify appendages extending from the mesovortices.

that MV1 formed at or just north of the bow-echo apex, whereas MV2 formed just south of the apex. Recent case studies have identified that most tornadic mesovortices form north of the apex (e.g., Atkins et al. 2004), most likely due in part to enhanced cyclonic shear north of the apex (Weisman and Trapp 2003). It appears as though the same situation occurred in this event.

The next step was to quantify all aspects of MV1 and MV2. First, the lifetime, depth, and width of the mesovortices were compared. Similar to previous findings, the tornadic MV1 was much deeper and wider than MV2. The maximum depth of MV1 was over 7km, compared to a maximum depth of about 3km for MV2. Similarly, the maximum width of MV1 at 0.5° was roughly 12km versus the 7km of MV2 (not shown). One finding that was not consistent with recent studies is that both mesovortices had nearly the same lifetime (about one hour each); recent studies have shown that tornadic mesovortices tend to last longer than non-tornadic mesovortices.

The velocity data from MV1 and MV2 were also quantified at several elevation slices, though only 0.5° data are shown here. Figure 7 displays the inbound, ground-relative velocities of MV1 and MV2. For much of their lifetimes, the inbound velocities hover around 20-25 m s^{-1}. However, prior to tornadogenesis, the inbound velocities of MV1 rise above 30 m s^{-1} for two volume scans. The rotational velocities, and the inbound velocities at 0.9° and 1.3° also displayed the same behavior for MV1 (not shown).

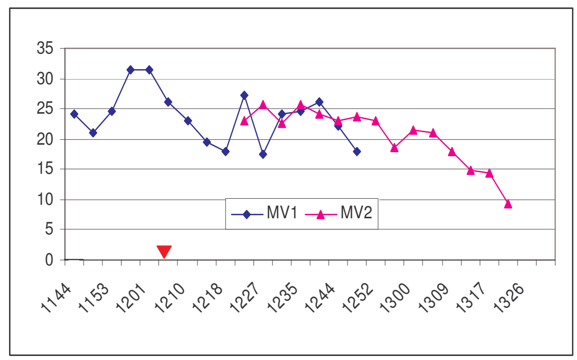

Fig 7. This graph displays inbound, ground-relative velocity (m s^{-1}) versus time (UTC) for MV1 (blue) and MV2 (pink) at the 0.5° elevation slice. Red triangle denotes time of tornadogenesis (1205 UTC).

5. SUMMARY AND DISCUSSION

This paper detailed the evolution of the 4 July 2004 high wind event across extreme southeast Kansas and southwest Missouri. This intense bow echo produced damaging straight-line winds and an F1 tornado. Although damaging straight-line winds were the most widespread aspect of the bow echo, most of the intense damaging winds coincided with the presence of a low-level, leading-edge mesovortex (MV1). A second mesovortex (MV2) formed as well, but damage surveys proved that this, along with the rear-inflow jet and line-end vortex, produced less intense and much less concentrated wind damage.

For operational meteorologists, it is important to be able to not only identify the existence of these leading-line vortices, but to also be able to distinguish between the tornadic and non-tornadic, or the intense and the marginally severe mesovortices. Although MV1 did produce an F1 tornado, the swath of F0 to F1 intensity straight-line wind damage was the most devastating result. Thus, MV1 and MV2 were compared to see if there were any differing characteristics to determine why MV1 was more extreme. It was found that MV1 and MV2 had similar lifetimes, and for the most part, rotational velocities. However, MV1 was deeper and wider, and the inbound and rotational velocities pulsed up just prior to tornadogenesis. In addition, the intersecting outflow boundary may have aided in tornadogenesis, or just strengthening of MV1 itself. Both mesovortices also exhibited an appendage or inflow band of some sort during a portion of their existence, although the appendage associated with MV1 (MV2) was present for about 11 (5) volume scans. Finally, it was also shown that tornadic MV1 formed at or just north of the bow-echo apex, whereas MV2 formed south of the apex. This is similar to recent studies where most of the tornadic mesovortices form at or north of the apex of a bowing segment rather than south (though the latter can occur).

From an operational standpoint, it is necessary to continue to identify and research these leading-line mesovortices. This case, in addition to many previous cases, showed that mesovortices pose a large threat and are capable of producing intense straight-line wind damage and tornadoes. In contrast, this case was somewhat unique in that the damaging surface winds occurred within a decoupled boundary-layer environment. Despite the surface CIN, damaging winds were able to mix down through the shallow stable layer. Also noteworthy is that the intersecting boundary may have aided in the strength of MV1 and perhaps the tornadogenesis as well. Kent Knopfmeier and Dr. Robert J. Trapp (Purdue University) have continued research on this case study to investigate the possible effects of the boundary on the evolution of the bow echo and tornadic mesovortex (Paper 6.2).

Although it is beneficial to characterize differing mesovortices, this post-event quantification and analysis may not prove useful in a real-time event. Researchers need to strive to find precursory features and trends that will enable operational meteorologists to identify a mesovortex ahead of time, and then accurately differentiate the threats. Until then, future case studies should be continued. Meteorologists from NWS forecast offices need to be aware of these features, and be willing to conduct detailed damage surveys even beyond the typical tendency to only survey possible tornado damage. Increased and improved damage surveys may help to mitigate nonspecific storm reports, or compensate for the lack of any storm reports, which may skew future results.

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