21 MAY 2001: ENVIRONMENTAL AND RADAR ASPECTS OF A SIGNIFICANT LOW-TOPPED SUPERCELL TORNADO OUTBREAK ACROSS SOUTHERN LOWER MICHIGAN

Randy Graham

NOAA/National Weather Service
Weather Forecast Office
Salt Lake City, Utah

Abstract

On the afternoon of 21 May 2001, the southern portion of Lower Michigan experienced a record-breaking tornado outbreak associated with a series of low-topped supercell storms interacting with a warm front. There were nineteen tornados that afternoon with fifteen of those occurring in the twenty-three counties comprising the County Warning Area (CWA) of the National Weather Service Office in Grand Rapids, Michigan. These fifteen tornadoes are the most to have occurred on record in a single day in the counties included in the Grand Rapids CWA. The tornadoes all occurred in close proximity to a warm front that was lifting slowly northward across southern Lower Michigan. Several of the environmental signals associated with the outbreak such as very low level of free convection (LFC) heights, significant 0-1 km storm relative helicity (SRM) values, strong parcel accelerations near cloud base, and proximity to a surface warm front were classical in many respects. The storms that produced the tornadoes were very shallow. The majority of the storms exhibited storm tops below 20,000 feet above ground level (AGL). Some storm tops were as low as 9,000 feet AGL. All of these storms could generally be classified as mini-supercells since they typically contained relatively long-lived mesocyclones through a substantial depth of the storm. Although the intensity of the tornadoes was not impressive, the large number of tornadoes, as well as the small size and depth of the tornadic storms and the lack of other severe weather types (e.g. damaging winds or large hail), made the event unusual. This paper will examine the near storm environment that preceded and supported the tornado outbreak. In addition, the paper will briefly evaluate the radar signatures associated with several of the tornadoes.

1. Introduction

During the afternoon of 21 May 2001 between 1730 UTC and 2130 UTC, nineteen tornadoes were reported across southern Lower Michigan (National Climatic Data Center 2001). Fifteen of these tornadoes (Fig. 1) occurred in the counties that comprise the County Warning Area (CWA) of the NOAA/National Weather Service (NWS) Weather Forecast Office (WFO) in Grand Rapids (GRR). Historically speaking, this is the highest number of tornadoes ever recorded in one day in the GRR CWA. The nineteen tornadoes which occurred across southern Lower Michigan on 21 May 2001 exceeded the yearly average (1950-1995) of tornadoes for the entire state of Michigan (approximately sixteen per year). Damage surveys of the nineteen tornadoes determined that thirteen of the tornadoes were of F0 (40-72 mph) intensity, while four were rated as F1 (73-112 mph) and two were rated as F2 (113-157 mph). Of the nineteen tornadoes, the longest path length was 10.9 miles which occurred with a tornado that tracked through Livingston and Genesee Counties in southeast Michigan. *Storm Data* published by the NOAA/National Climatic Data Center (NCDC) (2001), estimated the tornadoes produced 5.8 million dollars in damage. While the tornadoes were not historically significant with respect to the damage they caused, the large number of tornadoes and the diminutive nature of the storms which produced them make this event noteworthy.

Many of the storms which produced the tornadoes could be classified as mini-supercells (Foster and Moller 1995). The occurrence of tornadoes from mini-supercells has been well documented since the early 1990s (e.g., Davies 1993; Guerrero and Read 1993; Vescio et al. 1993; Burgess et al. 1995), although the number of tornadoes associated with this outbreak of mini-supercells was unusually large. Although the majority of the storms on 21 May 2001 were clearly mini-supercells, several of the tornadic storms did not exhibit supercellular characteristics, and tornadogenesis in these cells appeared to result from a non-descending mode. Still many of the storms exhibited 'classic' radar characteristics such as reflectivity pendants, weak echo regions, and descending mesocyclones, although on a much smaller scale than is usually attributed to tornadic storms. Many of the tornadic storms exhibited storm tops below 6 km (20,000 feet) above ground level (AGL). In addition, the storms were not associated with any other types of severe weather (e.g., winds of 58 mph or greater or hail three-quarters of an inch or greater), and most cells did not produce any cloud to ground lightning strikes.

The tornadic storms occurred in close proximity to an active surface warm front that moved slowly northward across southern Lower Michigan during the afternoon hours. Early in the day several parameters

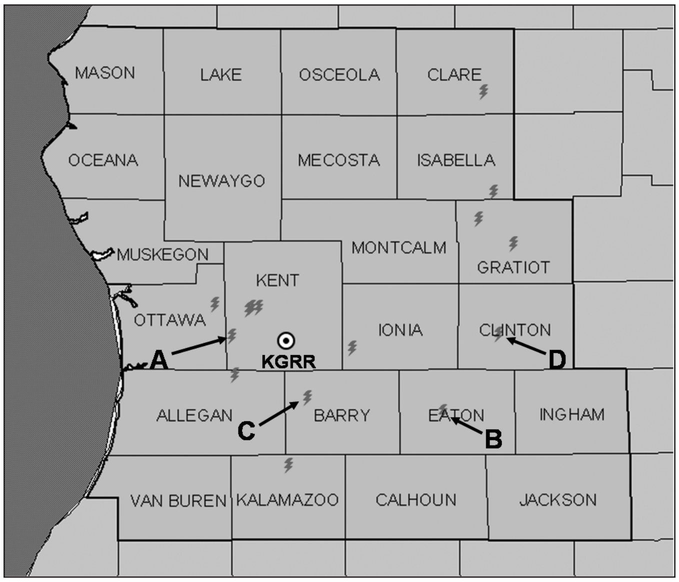

Fig. 1. Tornado locations as indicated by Storm Data across the Grand Rapids, Michigan CWA on 21 May 2001. The circle marks the location of the Grand Rapids (KGRR) RDA. The bold letters mark storms identified in the text; A – Grandville storm, B – Chester storm, C – Yankee Springs storm, D – Riley storm. County names are also identified.

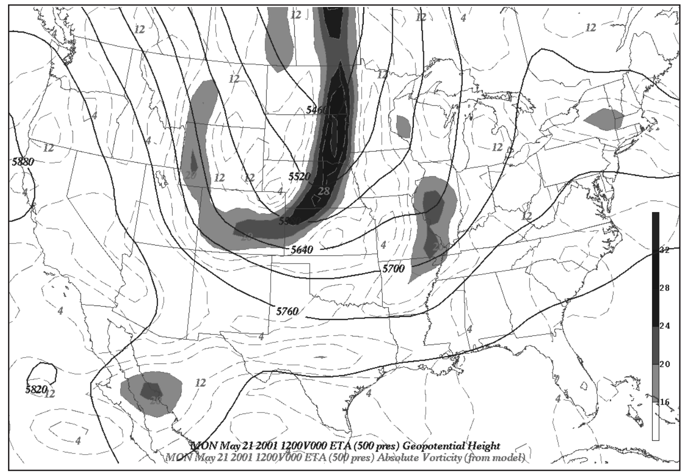

Fig. 2. Heights and absolute vorticity from 1200 UTC 21 May 2001. Solid lines represent the 500 hPa heights (60 gpm).

,such as lifting condensation level (LCL), level of free convection (LFC) heights, 0-1 km storm-relative helicity (SRH), and 0-6 km shear values, indicated the potential for low-topped supercells and possibly tornadoes. As the day progressed, the environment became even more favorable as surface-based instability developed north of the warm front and low-level winds backed, resulting in increased 0-1 km storm-relative helicity values in the cool sector.

This paper will examine the near storm environment that preceded and supported the tornado outbreak across southern Lower Michigan. In particular, the paper will focus on the evolution of the environment in the cool sector just north of the warm front. In addition, the paper will briefly review the radar signatures associated with several of the tornadoes, focusing on the relatively small scale and subtlety of some of the radar signatures.

2. Data and Methodologies

The data utilized for this case review of the 21 May 2001 tornado outbreak were obtained from a variety of sources and are listed in the Appendix. Weather Surveillance Radar-1988 Doppler (WSR-88D) data from the KGRR (Grand Rapids, MI) was obtained from the NCDC (Appendix A). The NOAA/National Severe Storms Laboratory (NSSL) WSR-88D Archive Level II data was interrogated utilizing the WSR-88D Algorithm Testing and Display System (WATADS) software (NSSL 2000). The Storm Cell Identification and Tracking (SCIT) algorithm was run in WATADS to determine storm motions which would be utilized in the generation of Storm Relative Mean (SRM) radial velocity images. The SRM data is traditionally utilized by NWS forecasters to assess the character and strength of rotation in thunderstorms, as well as to identify other important severe weather signatures, such as mid-altitude radial convergence and storm top divergence. Model and satellite data were provided by the Cooperative Program for Operational Meteorology, Education and Training (COMET) (Appendix A). Model fields and satellite data were examined utilizing the GEMPAK Analysis and Rendering Program (GARP) which is an X Windows/Motif software application developed by COMET (Appendix A). Surface observational data were displayed in the Digital Atmosphere software (Appendix A). All ambient temperature and dew-point temperature values mentioned in the text are given in degrees Fahrenheit. Model Soundings were interrogated utilizing BUFKIT software (Appendix A) available from the NWS's Warning Decision Training Branch (WDTB). Upper air soundings and plots were gathered from the NWS' Storm Prediction Center (SPC) Severe Thunderstorm Event Archive (Appendix A). Hodographs were developed utilizing an application developed by Matt Bunker of the NWS (see Acknowledgments).

3. Synoptic Overview

a. Upper air

The ETA model's analysis of upper air data valid 1200 UTC 21 May 2001 indicated a mid-tropospheric trough extending from the Province of Saskatchewan to the Southern Plains of the United States. The analysis also indicated a 500 mb short-wave trough stretching from northern Iowa to central Illinois moving up the east side of the trough axis toward Lower Michigan (Fig. 2). This short-wave moved across Lower Michigan during the afternoon hours contributing to large scale ascent via differential positive vorticity advection in the 500-300 mb layer (not shown). Isotach analysis at 250 mb (not shown) indicated a 40-45 m s^{-1} (80-90 knot) jet streak rounding the base of the trough in Kansas and eastern Nebraska at 1200 UTC on 21 May 2001. The 1200 UTC ETA model forecast indicated that the exit

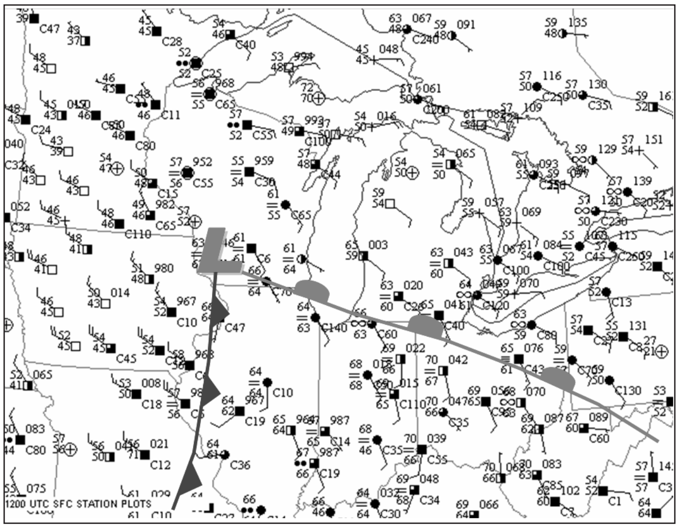

Fig. 3. 1200 UTC 21 May 2001 surface map showing location of surface low and approximate frontal positions. Station model in standard notation.

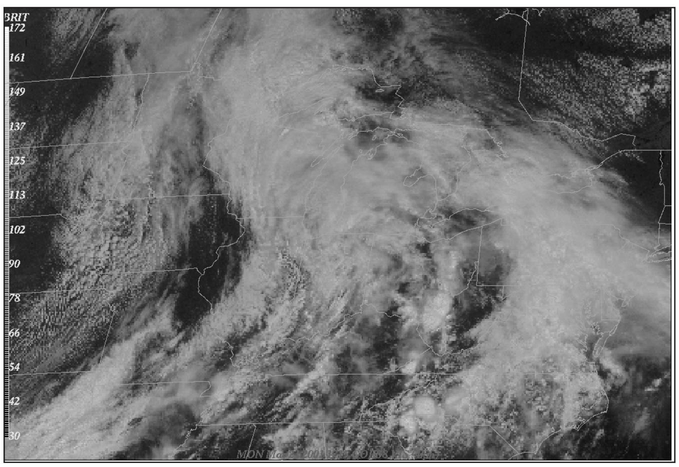

Fig. 4. Visible satellite imagery from 1715 UTC 21 May 2001 showing widespread cloud cover over Lower Michigan.

region associated with this jet streak would remain well south of Lower Michigan through the afternoon. However, weak 300 mb divergence was forecast in the ETA model over Lower Michigan for the afternoon of 21 May 2001, and was expected to contribute to the large scale upward vertical motion over Lower Michigan in the afternoon. Ageostrophic wind vectors at 300 mb (not shown) implied that the divergence was associated with curvature effects between the upper trough over the Central Plains and a weak upper-level ridge axis over Quebec.

At 850 mb the ETA model indicated that a strong (20 m s^{-1}) south to north oriented low-level jet would stretch from southern Indiana into southern Lower Michigan by 1800 UTC. The nose of this jet would be approximately collocated with a bull's-eye of upper-level divergence over Lower Michigan during the afternoon hours. While the warm air advection associated with this low-level jet would be modest, the ETA model forecast indicated a solid area of convergence at

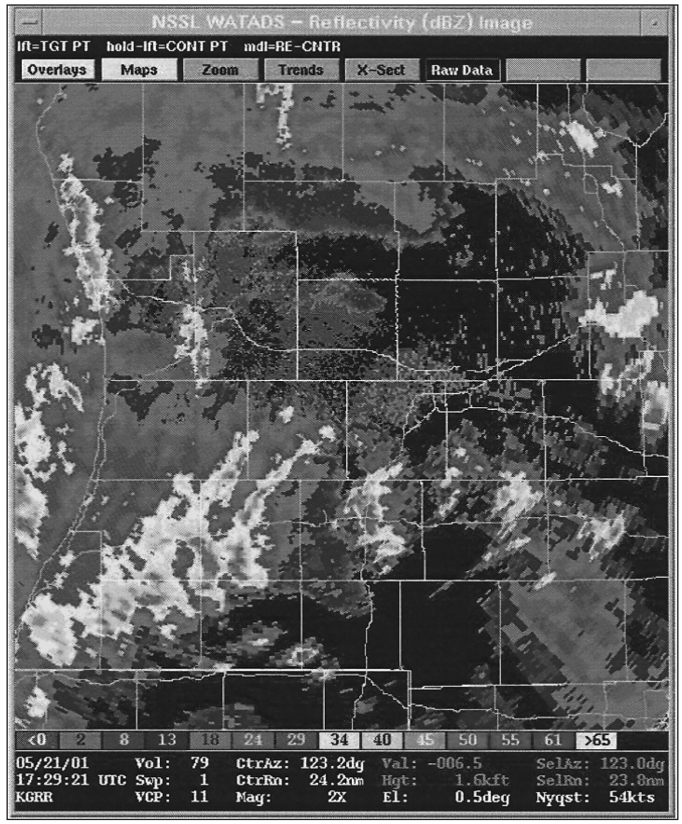

Fig. 5. KGRR 0.5 degree base reflectivity image from 1729 UTC 21 May 2001 showing coverage of precipitation across southwestern Lower Michigan.

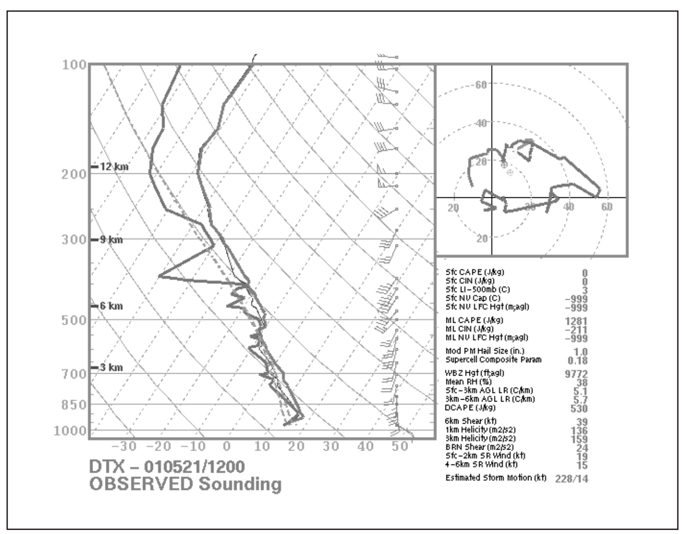

Fig. 6. Upper air sounding from White Lake, Michigan (DTX) at 1200 UTC 21 May 2001. Image from SPC archive.

the nose of the low-level jet across southern Lower Michigan which would contribute to deep upward vertical motion in the vicinity of the surface warm front.

b. *Surface analysis*

At 1200 UTC, a surface low was located across southwestern Wisconsin with a warm front stretching

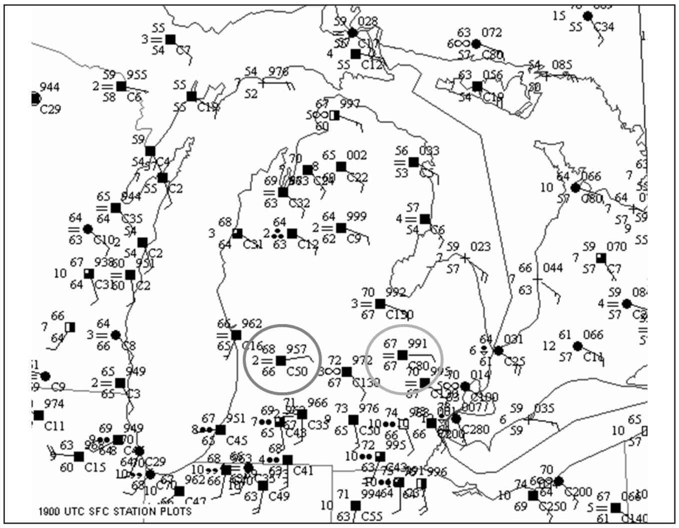

Fig. 7. Surface observations across southern Lower Michigan at 1900 UTC 21 May 2001. Grand Rapids (KGRR) is the observation encompassed by the circle to the left while Flint (FNT) is the observation site encompassed by the circle to the right. Flow is sharply backed at both of these sites which are situated just north of the surface warm front at this time. Station model in standard notation.

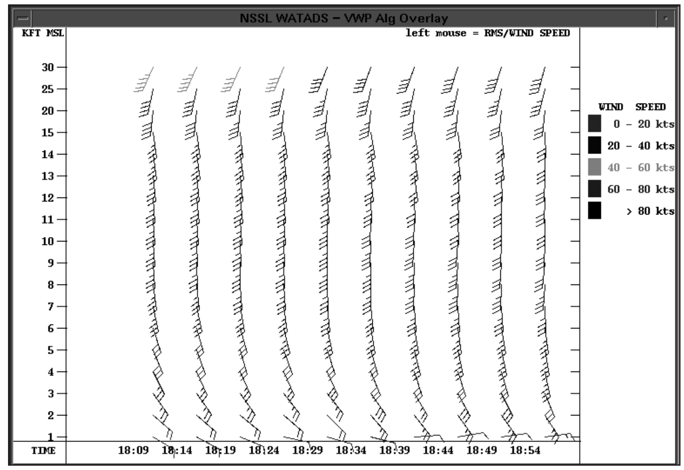

Fig. 8. KGRR VAD wind profile from 1854 UTC 21 May 2001 indicates how the low level flow backed to just north of east as the warm front approached.

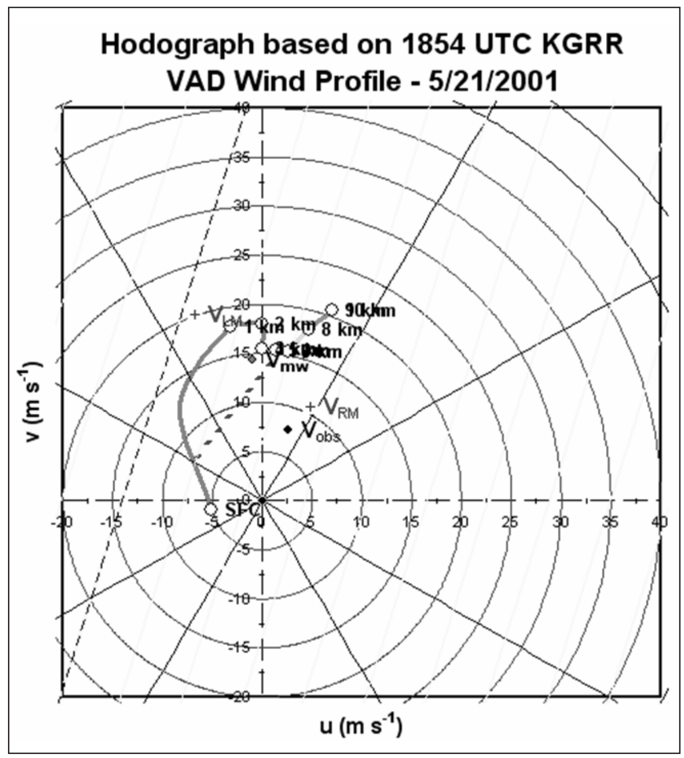

Fig. 9. Hodograph based on the 1854 UTC KGRR VAD wind profile and the surface wind from the Grand Rapids ASOS at 1856 UTC.

eastward to near the Michigan/Indiana border and a trailing cold front extending southward through extreme eastern Iowa and western Illinois (Fig. 3). The surface low was forecast to move from near Lacrosse, Wisconsin at 1200 UTC 21 May 2001 to west of Green Bay by 0000 UTC 22 May 2001 as the warm front lifted slowly northward through southern Lower Michigan. As the low moved to the northeast and the warm front lifted to the north, surface winds north of the front, which were largely from the southeast across southern Lower Michigan at 1200 UTC, were expected to back slowly to just south of east by afternoon.

At 1200 UTC, temperatures were generally in the lower to middle 60s and dew-points were in the upper 50s and lower 60s across southern Lower Michigan (Fig. 3). At 1700 UTC, in response to the large scale lift in the vicinity of the warm front ahead of the approaching upper-level short-wave, there was a significant amount of cloud cover (Fig. 4) and shower activity (Fig. 5) across southern Lower Michigan and northern Indiana through the morning and early afternoon hours. Due to this extensive cloud cover and showers, significant surface heating was not anticipated. Still by 1800 UTC, the temperatures had slowly risen to around 70 degrees across most of southwestern Lower Michigan with dewpoints climbing into the middle to upper 60s. The combination of increasing low-level temperatures and dewpoints, although modest, helped to destabilize the surface-based layer north of the warm front.

4. Mesoscale Aspects of the Convective Environment

Several aspects of the mesoscale environment were supportive of low-topped supercell storms and indicated the potential for tornadic development on 21 May 2001. Of note were the presence of strong deep-layer shear, low LCL and LFC heights, significant 0-1 km storm-relative helicity, and the presence of the warm front. As the warm front lifted northward across southern Lower Michigan, the environment north of the front became more supportive of tornadic development as the low-level winds backed to near due east. increasing the low-level storm-relative helicity.

While the 1200 UTC NWS WFO White Lake, MI (DTX) sounding (Fig. 6) indicated no surface-based

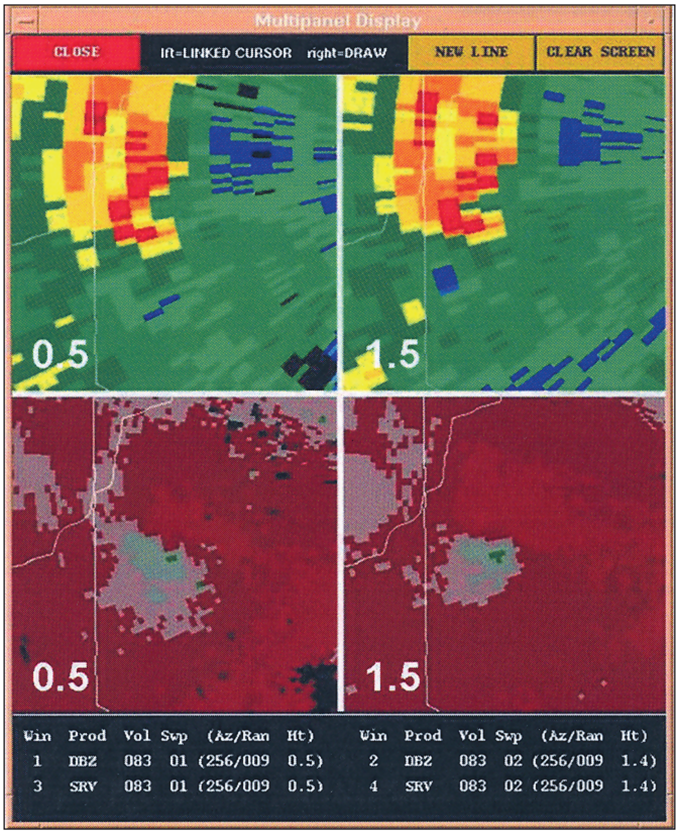

Fig. 10. KGRR 1749 UTC Base Reflectivity (dBZ) and Storm-Relative Velocity (SRM) display of the Grandville storm. RDA is located approximately 10 nm east (to the right of image) of this cell. Upper left (dBZ) and lower left (SRM) quadrants are from the 0.5 degree elevation slice while the upper right (dBZ) and lower right (SRM) quadrants are from the 1.5 degree elevation slice.

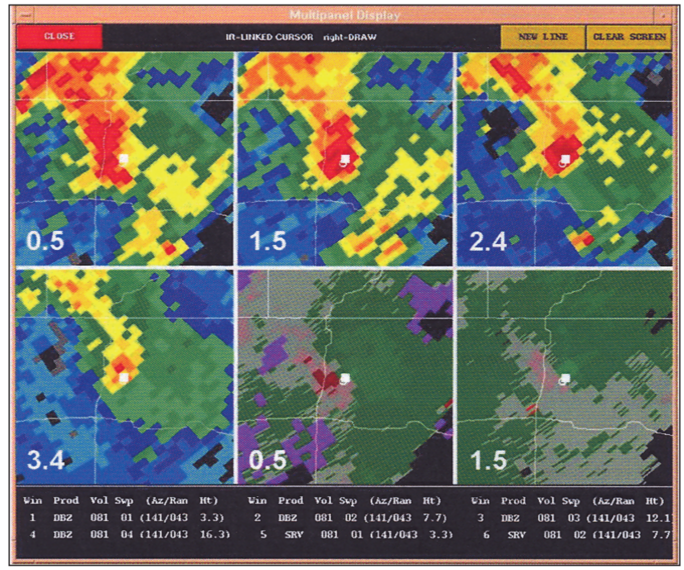

Fig. 11. Six-panel display of the Chester cell from 1739 UTC 21 May 2001. The top three panels (from left to right) are the 0.5, 1.5, and 2.4 degree Base Reflectivity images, respectively. The bottom three panels (from left to right) are the 3.4 degree Base Reflectivity image, and the 0.5 and 1.5 degree Storm-Relative Velocity images. The white dot on the panels marks at the same geographical location on all of the panels and depicts the location of the echo overhang and circulation associated with this cell.

convective available potential energy (SBCAPE), it did support mean-layer (lowest 100mb) convective available potential energy (MLCAPE) with values of 1200 J kg^{-1}. Meanwhile, the mean-layer convective inhibition (MLCIN) from the DTX sounding was a substantial 211 J kg^{-1}; however, only modest surface-based heating would be required to eliminate this low-level inhibition. Modifying the 1200 UTC DTX sounding to account for surface temperatures and dew-points near Grand Rapids at 1900 UTC yielded a SBCAPE of approximately 1400 J kg^{-1} and only 5 J kg^{-1} of convective inhibition (CIN). In support of this, the soundings from nearby Grand Rapids at 1800 UTC from the Local Analysis and Prediction System (LAPS) analysis software (based on observed data and a RUC model initialization) in AWIPS (Advanced Weather Interactive Processing System) indicated SBCAPE values of 1000-1500 J kg^{-1} (not shown) and less than 50 J kg^{-1} of CIN. Correspondingly, LAPS analyses indicated that surface-based lifted indices (LIs) were typically +1 to -1 across central and southern Lower Michigan at 1300 UTC. However, by 1800 UTC LAPS analyses indicated that the surfaced-based LIs had destabilized with values ranging from to -2 to -5 across much of southwestern Lower Michigan.

As is frequently the case in low-topped supercell events, the CAPE values on 21 May 2001 were relatively modest. However while the total CAPE was not impressive, the distribution of CAPE appeared to be supportive of strong parcel acceleration near cloud base as a substantial portion of the CAPE was confined to the 0-3 km level. Modeling work by Wicker and Cantrell (1996) demonstrated the importance of the distribution of CAPE in the vertical profile. They found that the combination of CAPE and shear in the low-levels of the storm (lowest few kilometers) were more important to the development of rotation than was deep, large CAPE. Substantial CAPE values in the vicinity of cloud base are supportive of strong parcel accelerations in the low-levels that may play a role in the stretching of low-level vertical vorticity into the updraft. Another consideration is that there was still significant SBCAPE north of the warm front as it lifted northward through Lower Michigan. LAPS soundings north of the warm front indicated SBCAPE values in excess of 1000 J kg^{-1}. In other words, as storms developed and crossed the warm front, they did not quickly become elevated as they moved into the vorticity-rich cool sector. As the storms crossed the warm front into the region where the greatest 0-1 km storm-relative helicity was present, they were able to maintain a surface-based updraft.

While CAPE values were supportive of significant low-level parcel acceleration, the deep-layer shear values appeared capable of supporting supercells during the afternoon of 21 May 2001. Several observational studies including Markowski et al. (1998b), Rasmussen and Blanchard (1998; hereafter RB98), Thompson et al. (2002), and Bunkers et al. (2000) have indicated that a vector shear magnitude of approximately 20 m s^{-1} over the lowest six kilometers is supportive of supercell development. The 1200 UTC White Lake (DTX), MI sounding (Fig. 6) on 21 May 2001 showed a favorable deep-layer vector shear magnitude of approximately 20 m s^{-1}.

Another important feature that likely supported the development of tornadoes across southwestern Lower Michigan on 21 May 2001 was the presence of the warm front. As storms crossed the warm front, they moved into a richer storm-relative helicity environment and rapidly developed rotation. It is likely that the storms ingested low-level horizontal vorticity associated with the surface boundary. A study by Markowski et al. (1998a) examining significant tornadoes from the VORTEX-95 data set showed that 70% of the tornadoes in the data set occurred near low-level boundaries not associated with the forward or rear flank downdrafts. Typically these tornadoes occurred on the cool side and within 30 km of the boundary. They speculated that the horizontal vorticity generated along boundaries was an important vorticty source for the development of low-level mesocyclones via tilting and stretching. By comparing the location of the reported tornado touchdown to surface analyses of the warm front at the hour closest to the time of touchdown, it is estimated that on 21 May 2001, all fifteen tornadoes in southwestern Michigan developed within 30 km of the boundary. Due to the lack of high-resolution surface data sets, there is some subjectivity as to the location of the boundary, but detailed analyses were completed to determine the location of the warm front. The fact that storms crossed or developed very near the warm front in a region of enhanced low-level storm-relative helicity is an important consideration in this case.

In addition to the significant deep-layer shear available on 21 May 2001, the environmental background storm-relative helicity appeared supportive for the development of low-level mesocyclones in the vicinity of the warm front. The 1200 UTC DTX sounding exhibited low-level winds that veered with height in the lowest 1 km and showed modest speed shear, the combination of which contributed to moderate low-level storm-relative helicity (SRH). While the 0-3 km SRH in the 1200 UTC DTX sounding was only 159 m^2 s^{-2}, the 0-1 km SRH was 136 m^2 s^{-2}, indicating that the majority of the storm-relative helicity was in the 0-1 km layer. As the warm front lifted into southern Lower Michigan during the afternoon, the surface winds backed to the east in a narrow corridor just north of the front. This is clearly visible in the 1900 UTC surface observations where the surface winds have backed to just north of east at Grand Rapids (GRR) and to near due east at Flint (FNT) (Fig. 7). The backing of the low-level winds was also well observed in the velocity-azimuth display (VAD) wind profile from the KGRR WSR-88D where the winds at 1000 feet AGL became almost due east just north of the warm front at 1854 UTC (Fig. 8). This backing of the low-level winds served to increase the low-level SRH values north of the warm front. A hodograph based on the observed surface winds at Grand Rapids, Michigan and the VAD wind

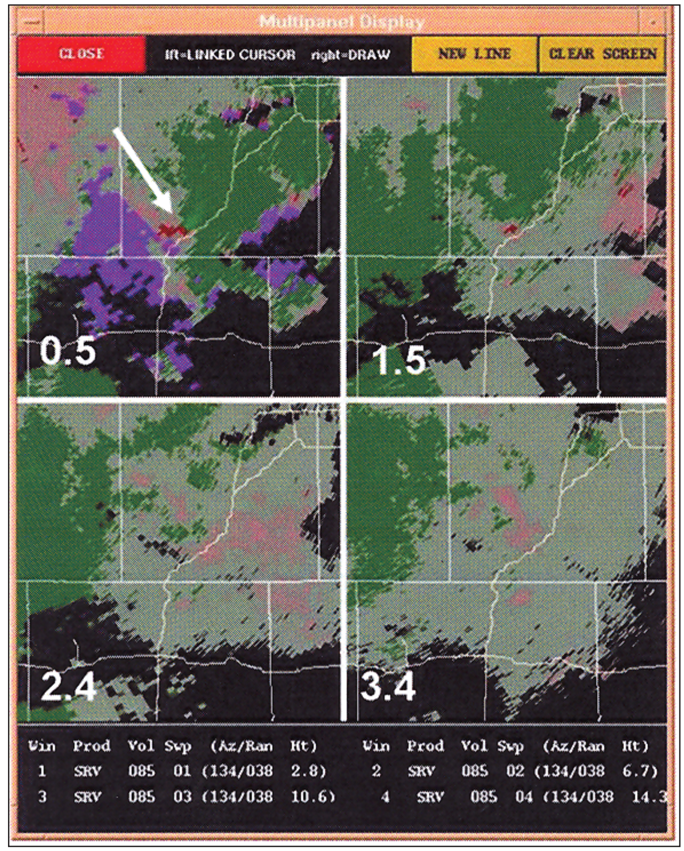

Fig. 12. KGRR Storm-Relative Velocity four-panel of the Chester Storm at 1759 UTC 21 May 2001. The top two quadrants (from left to right) are from the 0.5 and 1.5 degree slices respectively while the bottom two quadrants (from left to right) are from the 2.4 and 3.4 degree slices. Arrow in the upper left hand quadrant points to strong rotational velocity (40 m s^{-1}) in the 0.5 degree slice. The RDA is located roughly 38 nm to the northwest of this cell.

profile from the KGRR WSR-88D at 1854 UTC yielded a 0-1 km SRH of approximately 150 m^2 s^{-2} (Fig 9) with a 0-3 km SRH of 205 m^2 s^{-2}. In a mesoscale discussion, forecasters at the SPC noted that the VAD wind profile from the KDTX (White Lake, MI) WSR-88D combined with an easterly surface wind of 15 knots, yielding a 0-3 km SRH of 450 m^2 s^{-2}. Edwards and Thompson (2000; hereafter ET00) and Rasmussen (2003) showed that the 0-1 km SRH is a better discriminator between significant tornadic and non-tornadic supercells than is 0-3 km SRH. These studies have indicated that soundings associated with tornadoes preferentially have 0-1 km SRH that is much larger than the SRH contained in the 2-3 km layer. Based on the modified hodograph utilizing the KGRR surface observation and the KGRR VWP, the resulting 0-1 km SRH helicity was nearly 75% of the 0-3 km total. So, as the warm front lifted north and the low-level winds backed, the 0-1 km SRH became quite supportive of low-level mesocyclogenesis. The majority of the 0-3 km SRH was confined to the 0-1 km layer where low-level mesocyclogenesis and tornadogenesis occur. Additional research by Thompson et al. (2003) indicated that the supercell environments which support F2 or greater tornadoes exhibit 0-1 km

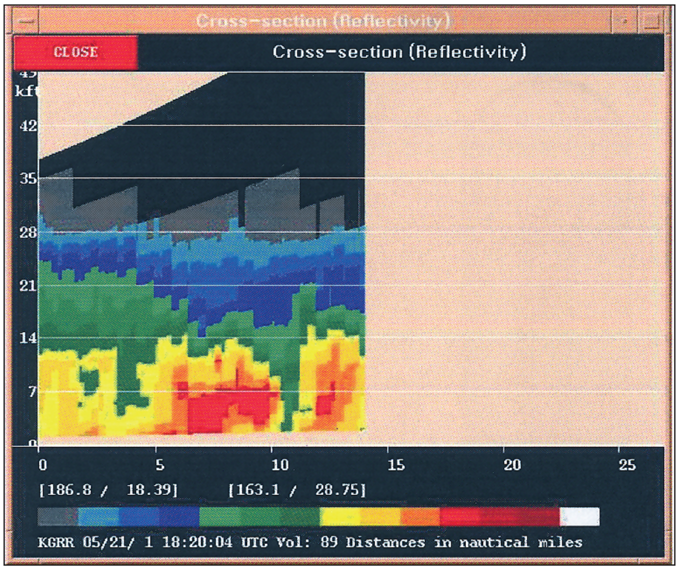

Fig. 13. KGRR Base Reflectivity cross-section highlighting the Bounded Weak Echo Region (BWER) associated with the Yankee Springs tornadic low-topped supercell at 1820 UTC 21 May 2001. The top of the BWER vault in this cell is only at roughly 5000-6000 feet AGL.

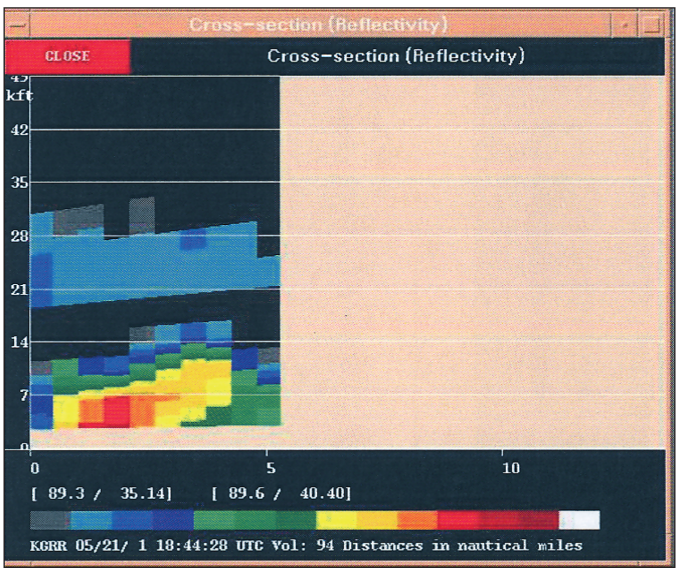

Fig. 14. KGRR Base Reflectivity cross-section of the Weak Echo Region (WER) associated with the Riley storm at 1844 UTC 21 May 2001. Note that the height of the 30 DBz echo (storm top) only extends to approximately 12000 feet AGL.

SRH values greater than 100 m^2 s^{-2}, 75% of the time. While there were only two F2 tornadoes associated with this event, the low-level environment was clearly supportive of relatively high background SRH values and fit the profiles identified by Rasmussen (2003) and Thompson et al. (2003). It should be noted that while background 0-1 km SRH values were supportive of low-level mesocyclone development in this case, RB98 suggested that even though large-scale environments may be characterized by instability and shear values that support supercells, local augmentation of these values may determine whether or not supercells become tornadic. Markowski et al. (1998a, 1998b) have shown that mesoscale storm-relative helicity in close proximity to tornadic supercells may be an order of magnitude larger than ambient large-scale values, and that local values of SRH vary greatly over short temporal and spatial scales. LCL and LFC heights were also very favorable for low-level mesocyclone development north of the warm front on 21 May 2001. Several recent studies including RB98, ET00, and Thompson et al. (2003) have indicated LCL heights are an important discriminator between significantly tornadic (F2 or greater) and non-tornadic supercells. Utilizing proximity soundings from the Rapid Update Cycle (RUC), Thompson et al. (2003) showed that 75% of the supercells in their data set that produced significant (F2 or greater) tornadoes were associated with mean-layer LCL heights less than roughly 1150 m. This and other research lends support to the hypothesis that low-level humidity may play a role in increased buoyancy of the rear flank downdraft and result in a correspondingly increased threat of tornadoes. On 21 May 2001 as surface temperatures rose to near 70° north of the warm front, surface dew-points climbed into the middle and upper 60s. At 1800 UTC dew-point depressions of zero to eight degrees F were in place across most of southern Lower Michigan, indicating low LCL heights. The 1200 UTC DTX sounding modified for the temperature and dew-point at Grand Rapids at 1900 UTC yielded a mean-layer LCL of less than 750 m.

In addition to the minimal LCL heights, LFC heights were very low on 21 May 2001. A 1600 UTC LAPS sounding for a point taken near Grand Rapids, Michigan indicated that the Surface Based LFC (SBLFC) was around 900 m (3000 feet), and a 1900 UTC LAPS sounding at Grand Rapids indicated that the SBLFC height had dipped below 500 m. Modifying the 1200 UTC DTX based on the 1900 UTC surface observation at Grand Rapids yielded an mean-layer LFC of around 1000 m. It has been suggested that high LFC heights may inhibit low-level parcel ascent and stretching near the ground, thereby reducing the likelihood of tornadoes (Davies 2004), while lower LFC heights suggest that rapid parcel acceleration (given sufficient CAPE) begins closer to the surface increasing the likelihood that low-level vorticity can be stretched into the updraft. Research by Davies (2004) showed a correlation between mean layer LFC height and the occurrence of F1 or greater tornadoes. He found that supercells producing F1 or greater tornadoes typically have lower mean-layer LFC heights than supercells that do not produce tornadoes. In his data set, he found that roughly 87% of the supercells which produced F1 or greater tornadoes were associated with mean-level LFC heights below 2000 m. The distribution was similar when he calculated the values for surface-based LFC (SBLFC) heights. LAPS soundings indicated very low SBLFC heights (around 1000 m at 1600 UTC dropping to below 500 m by 1900 UTC) were present in the vicinity of the warm front on 21 May 2001 across southwestern Michigan. These low SBLFC heights may have been an important aspect of the environment that supported the development of numerous tornadoes that day. The combination of low LFC heights and significant 0-1 km SRH appear to have significantly enhanced the tornado potential. The near storm environment which supported the development of numerous tornadoes across southern Lower Michigan on 21 May 2001 was typical in many ways of mini-supercell environments. Foster et al. (1995), and Davies (1993) reported that conditions favorable for mini-supercells included a low equilibrium level at approximately 25,000 to 30,000 feet (7-9 km), CAPE between 200 to 1500 J kg^{-1}, lifted indices 0 to -4, wind shear greater than 20 m s^{-1} in the 0-5 km layer, and 0-3 km storm-relative helicity values of 200-400 m^2 s^{-2}. On 21 May 2001, all of these conditions were satisfied with equilibrium levels ranging from 3-7 kilometers (10,000-25,000 feet), SBCAPE generally in the 1000-1500 J kg^{-1} range, lifted indices of -2 to -5, and 0-6 km wind shear values around 20 m s^{-1}.

5. Radar Signatures

From a radar perspective there were numerous challenges in handling this event. Most of the tornadic storms did not exhibit strong shear as many of the mesocyclones associated with the tornadic storms exhibited rotational velocities of only 10-15 m s^{-1} (20-30 knots), and classic supercell reflectivity structures were non-existent, subtle, or very short-lived in some cases. In addition, the cells tended to be very small and the large number of cells on the radar made real-time assessment of all the significant circulations a challenge. However, several of the cells that produced tornadoes on 21 May 2001 did exhibit classic supercellular radar signatures such as weak echo regions, reflectivity pendants, and descending mid-level mesocyclones. One complicating factor was the limited depth of the updrafts during this particular event. Storm tops were typically below 20,000 feet AGL and in a few cases were less than 12,000 feet AGL. Given the shallow nature of the storms, it is possible that cells located a substantial distance from the KGRR WSR-88D would be sampled only in the mid levels, making low-level mesocyclone trends very difficult, if not impossible, to reliably ascertain. The evolution of several storms will be examined to illustrate these points. This is not meant to be a thorough review of all storms or significant radar signatures that occurred on this date, but rather a summary of the most pertinent and noteworthy storms and signatures. Radar data were analyzed utilizing the WATADS 10.2 (NSSL 2000) radar display software.

a. *Grandville storm*

The first tornado in southwest Michigan on 21 May 2001 occurred in the city of Grandville (Fig. 1) in Kent County at approximately 1800 UTC. This cell was very small (~2-3 nm wide) and was situated roughly ten nautical miles from the KGRR WSR-88D. Even at this close range, the cell is unimpressive in most respects. A close look at the storm indicates that the initial circulation developed above the lowest elevation slice at a height of approximately 5000 feet AGL (not shown) at about 25 minutes prior (~1735 UTC) to the tornado.

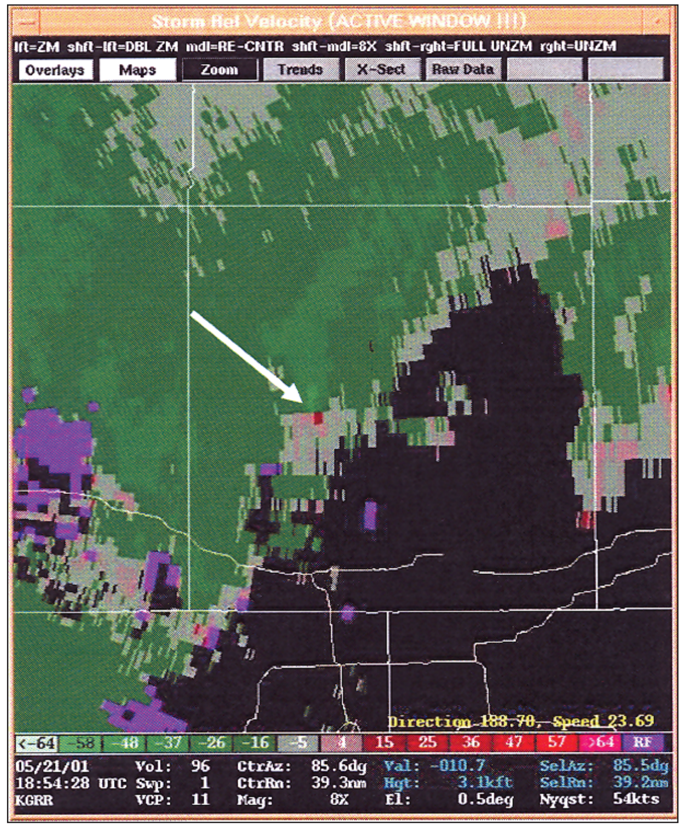

Fig. 15. KGRR Storm-Relative Velocity image from the 0.5 degree elevation slice of the Riley storm at 1854 UTC 21 May 2001. The image shows a tight low-level circulation of approximately 22 m s^{-1} associated with this cell.

With time, the circulation descended and the rotation was approximately 5000 feet deep at the time of the tornado while the storm top varied between 12,000 and 15,000 feet. At the time of the tornado, the mesocyclone in the 0.5 degree slice contained a rotational velocity of 22 m s^{-1} (45 knots). The cell, while very small, did exhibit a pronounced inflow notch and a small weak echo region that coincided with the mesocyclone (Fig. 10). These features are so small that they could easily be overlooked in a real-time environment. The tornado associated with this storm was an F0 that was on the ground for less than a mile knocking down numerous trees. Of note in this case is that the cell was so close to the radar that the descending nature of the shallow mesocyclone could be observed. If this cell had been located approximately 55 nm or farther from the radar, not only would the descending nature of the mesocyclone not have been detected, but the beam would have overshot the circulation completely.

b. *Eaton County (Chester) storm*

The most impressive storm of the day (from a radar perspective) produced a tornado in Eaton County, Michigan (Fig. 1) at approximately 1815 UTC. This cell was a long-lived mini-supercell with the initial rotation appearing in the lowest two slices (4000 to 9000 feet AGL) approximately an hour prior to the tornado.

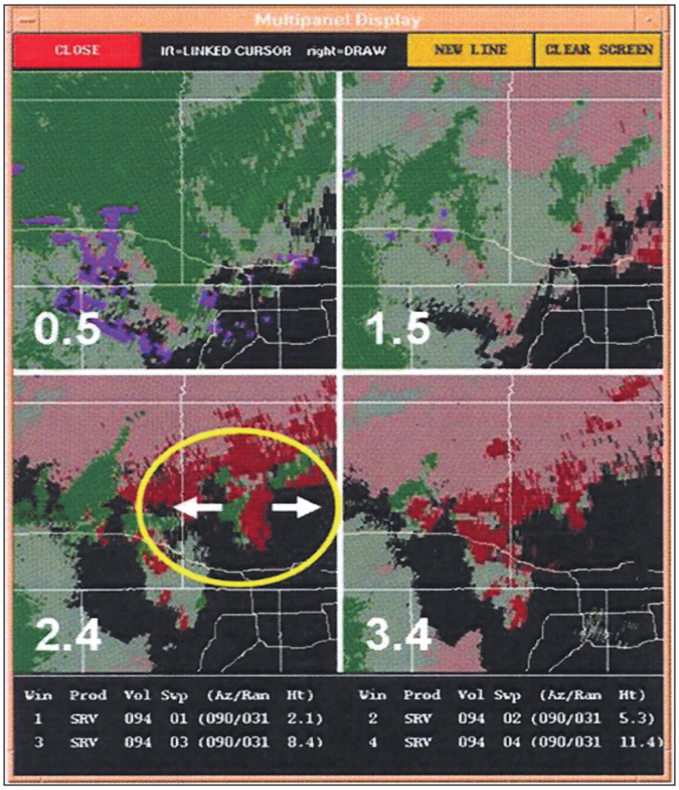

Fig. 16. Same as Figure 12, except for the Riley storm at 1844 UTC 21 May 2001. Note the storm top divergence (white arrows) at roughly 8500 feet AGL in the lower left quadrant. RDA is to the left (west) of the image.

This cell was a little deeper than the Grandville storm (see 3a above) that produced the first tornado in Kent County (15,000-20,000 feet and 12,000-15,000 feet, respectively). The circulation was typically 7,000-9,000 feet deep during the hour leading up to the tornado. In addition, this cell initially exhibited more classical reflectivity structures. At 1739 UTC (~ 35 minutes before the tornado), the cell exhibited a kidney bean shape and a substantial weak echo region (Fig. 11). However, as the circulation strengthened, the storm's appearance in the reflectivity data became less impressive as the mesocyclone was wrapped with high reflectivity which obscured the more classic reflectivity structure noted in prior elevation scans. Still the circulation with this cell was by far the most impressive of the day with 40 m s^{-1} (81 knots) of rotational velocity (Fig. 12) in the mesocyclone noted at roughly 3000 feet AGL at approximately 15 minutes (1759 UTC) prior to the tornado. This was the strongest radar identified circulation of the day and was atypical of the tornado producing storms on 21 May 2001. The tornado with this cell was an F0 that tracked six miles, knocked down numerous trees, and flipped a small airplane northwest of Charlotte, Michigan.

c. Yankee Springs storm

Another storm exhibiting interesting radar characteristics produced a tornado near Yankee Springs, Michigan (Fig. 1) in Barry County around 1850 UTC. The circulation in this cell was first noted in the lowest two elevation slices at 1739 UTC (not shown). At 1745 UTC the circulation intensified in the 1.5 degree scan which intersected the circulation at roughly 5500 feet AGL. The mesocyclone in this cell appeared to be cyclic as it intensified and weakened a couple of times during the next hour. At 1820 UTC, a cross section through the cell (Fig. 13) shows a shallow bounded weak echo region (BWER). The shallowness of the feature is rather dramatic with the vault in the BWER extending to around 6000 feet AGL. At 1824 UTC little circulation was noted in the 0.5 degree scan while the 1.5 degree scan indicated a developing mesocyclone at roughly 4000 feet AGL. This circulation then descended into the lowest elevation slice with an F0 tornado touching down around 1850 UTC. Storm top (height of the 30 dBZ echo) was typically around 15,000 feet during this cell's life cycle. This cell exhibited a descending mesocyclone and a bounded weak echo region prior to tornado touchdown.

d. Riley storm

Another cell of interest produced a tornado near Riley, Michigan (Fig. 1) in Clinton County at 1855 UTC. A circulation was originally noted in this cell in the 0.5 degree slice at approximately 3000 feet AGL at 1824 UTC which was approximately 30 minutes before the tornado occurrence. In the 1829 UTC volume scan, the circulation deepened and was visible from approximately 3000 feet AGL to 7000 feet AGL. The storm top at this time was around 14,000 feet AGL. By 1844 UTC, the circulation was visible primarily in the 1.5 degree elevation slice (~5300 feet AGL) with no substantial circulation noted in the 0.5 degree slice. A four panel of reflectivity at this time indicated a subtle weak echo region was co-located with this mid-level circulation. A cross section (Fig. 14) at this time shows the very shallow weak echo region with this cell. The circulation then descended into the 0.5 degree slice during the next ten minutes and by 1854 UTC, near the time of the reported tornado, the circulation exhibited roughly 22 m s^{-1} (44 knots) of rotational velocity in the lowest slice (Fig. 15). To highlight the shallowness of the storms, note that a 4-panel of SRM at 1844 UTC (Fig. 16) clearly indicates a storm summit divergence signature at only 8500 feet AGL. This cell produced a F1 tornado with a four and a half mile track length. Two sheds were destroyed and a barn was damaged. Also, a shop at an archery range was destroyed with the insulation carried three miles to the north. The shallowness of this cell, in particular, is remarkable.

6. Discussion

On 21 May 2001 a record-breaking outbreak of tornadoes occurred across southern Lower Michigan. Between 1730 UTC and 2130 UTC, 15 tornadoes occurred across the twenty-three counties that comprise the CWA of the National Weather Service Office in Grand Rapids, Michigan. Of particular note in this case was the surface based instability north of the warm front that coincided with enhanced 0-1 km storm-relative helicity. Frequently in the transition and cool seasons, a relatively deep layer of stable air is found just north of a warm front. However, during the summer in the Great Lakes Region, it is not entirely uncommon to have surface-based instability or only a very shallow stable layer just north of a warm front as was the case on 21 May 2001. This was an important consideration for this event because as storms crossed the warm front during the afternoon, they did not become elevated. The storms remained surface-based. It is hypothesized that the low-level vorticity found in the vicinity of the warm front was able to be tilted and stretched, aiding in low-level mesocyclogenesis. In addition to favorable surface-based instability north of the warm front, low-level winds backed sharply in a narrow corridor north of the boundary increasing the low-level storm-relative helicity. Also, the environment exhibited favorable low LFC heights and the potential for rapid parcel acceleration near cloud base which likely aided in the development of numerous tornadoes.

This event demonstrates the utility of a variety of traditional and recently documented tornado precursors such as significant low-level parcel acceleration, low LFC heights, and significant 0-1 km storm-relative helicity. The outbreak provides insight into the potential usefulness of these parameters with respect to anticipating tornadoes in a low-topped supercell environment. Further studies may examine the consistency with which these parameters are useful in anticipating rare low-topped tornado outbreaks, such as the one that occurred on 21 May 2001, as well as the frequency of false alarms when similar conditions are in place. Given the evolution of the low-level environment, this event reinforces the need for diligent near storm environment analysis and is an example of how recent research advances can lead to improved anticipation of rare events.

Many of the tornadic storms on 21 May 2001 did exhibit the signs of classic supercells such as BWERs, inflow notches, and long-lived mesocyclones. Examination of radar data associated with this event demonstrated that these radar signatures are not only identifiable, but can serve as vital precursors to tornadogenesis in low-topped supercell events. However, the scale on which the storms occurred with some as small as 2-3 nm across and storm tops, in some cases, below 12,000 feet AGL made storm interrogation particularly challenging. The diminutive nature of the storms in this event highlights potential complications from a radar analysis perspective. Moreover, if the cells were a substantial distance from the radar, then these precursors may not be readily identifiable or, in some cases, not even sampled at all. The concerns associated with sampling issues with respect to the identification of significant tornado precursors in low-topped supercells may be mitigated by lower radar elevation angles. This would then allow for a more thorough interrogation of these shallow, yet potentially significant events.

Acknowledgments

The author wishes to thank the staff at the NWS WFO in Grand Rapids, Michigan for their insightful discussions during the preparation of this manuscript. Also, special thanks go to Dolores Kiessling, COMET, for her assistance in obtaining data sets utilized in this study. Radar images were created utilizing WATADS 10.2 radar display software developed by NSSL. The surface background maps (Fig. 3 and Fig.7) were generated utilizing the Digital Atmosphere software. The hodograph (Fig. 9) was created utilizing an application developed by Matt Bunkers, the Science Operations Officer for the NWS WFO in Rapid City, SD. The author especially appreciates the input and recommendations provided through the peer review process from Dennis Rodgers, Research Scientist at the Global Systems Division of the Earth System Research Laboratory; Ray Wolf, the Science Operations Officer at the NWS WFO in Davenport, Iowa; and Dr Anthony R. Lupo, Professor of Atmospheric Science in the Department of Soil, Environmental, and Atmospheric Sciences at the University of Missouri at Columbia. Their insightful comments and suggestions led to improvements in both the content and appearance of the final manuscript.

Author

Randy Graham is the Science Operations Officer at the NWS WFO in Salt Lake City, Utah. Mr. Graham has been with the NWS for 13 years. He served as a Meteorologist Intern in Sioux Falls, South Dakota, a General Forecaster in Salt Lake City, Utah, and a Senior Forecaster and Science Operations Officer in Grand Rapids, Michigan prior to his appointment as Science Operations Officer in Salt Lake City. He received his B.S. degree from the University of Nebraska-Lincoln in 1993. Randall.Graham@noaa.gov

References

Bunkers, M. J., B. A. Klimowski, J. W. Zeitler, R. L. Thompson, and M. L. Weisman, 2000: Predicting supercell motion using a new hodograph technique. *Wea. Forecasting*, 15, 61-79.

Burgess, D. W., R.L. Lee, S.S. Parker, S.J. Keighton, and D.L. Floyd, 1995: A study of mini supercells observed by WSR-88D radars. Preprints, *27th Conference on Radar Meteorology*, Vail, CO, Amer. Meteor. Soc., 4-6.

Davies, J. M., 1993: Small tornadic supercells in the central plains. Preprints, *17th Conf on Severe Local Storms*, Saint Louis, MO, Amer. Meteor. Soc., 305-309.

___________, 2004: Estimations of CIN and LFC associated with tornadic and non-tornadic supercells. *Wea. Forecasting*, 19, 714–726.

Edwards, R., and R. L. Thompson, 2000: RUC-2 supercell proximity soundings, Part II: An independent assessment of supercell forecast parameters. Preprints, *20th Conf on*

Severe Local Storms, Orlando, FL, Amer. Meteor. Soc., 435-438.

Foster, M.P., and A.R. Moller, 1995: The rapid evolution of a tornadic small supercell: observations and simulation. Preprints*, 14th Conference on Weather Analysis and Forecasting*, Dallas, TX, Amer. Meteor. Soc., 323-328.

Guerrero, H., and W. Read, 1993: Operational use of the WSR-88D during the November 21, 1992 Southeast Texas tornado outbreak. Preprints, *17th Conf. on Severe Local Storms*, Saint Louis, MO, Amer. Meteor. Soc., 399-402.

Markowski, P. M., E. N. Rasmussen, and J. M. Straka, 1998a: The occurrence of tornadoes in supercells interacting with boundaries during VORTEX-95. *Wea. Forecasting*, 13, 852-859.

_________, J.M. Straka, E. N. Rasmussen, and D.O. Blanchard, 1998b: Variability of storm-relative helicity during VORTEX.-95. *Mon. Wea. Rev.*, 126, 2959-2971.

NCDC, 2001: *Storm Data*. Vol. 43. [Available from National Climatic Data Center, 151 Patton Ave., Asheville, NC 28801-5001].

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, 13, 1148-1164.

________, 2003: Refined supercell and tornado forecast parameters. *Wea. Forecasting,* 18, 530–535.

Thompson, R.L., R. Edwards, and J.A. Hart, 2002: An assessment of supercell and tornado forecast parameters with RUC-2 Model close proximity soundings. Preprints, *21st Conf. on Severe Local Storms*, San Antonio, TX, Amer. Meteor. Soc., 5

_________, _________, _________, K. L. Moore, P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting*, 18, 1243-1261.

Vescio, M. D., K.K. Keeter, G. Dial, and P. Badgett, 1993: A low-top weak reflectivity severe weather episode along a thermal/moisture boundary in eastern North Carolina. Preprints*, 17th Conf, on Severe Local Storms*, Saint Louis, MO, Amer. Meteor. Soc., 628-632.

NSSL, 2000: WSR-88D algorithm testing and display system (WATADS): Reference guide for version 10.2. [Available from Storm Scale Applications Division, National Severe Storms Laboratory, 1313 Halley Circle, Norman, OK 73069].

Wicker, L.J., and L. Cantrell, 1996: The role of vertical buoyancy distributions in miniature supercells. Preprints, *18th Conference on Severe Local Storms*, San Francisco, CA, Amer. Meteor. Soc., 225-229.

Appendix: Lists the web sites and data sources utilized in the 'Data and Methodologies' section.

BUFKIT software from the National Weather Service's Warning Decision Training Branch (WDTB): http://www.wdtb.noaa.gov/tools/BUFKIT/index.html

Cooperative Program for Operational Meteorology, Education and Training (COMET): http://www.comet.ucar.edu/

Digital Atmosphere:
http://www.weathergraphics.com/da/

GEMPAK Analysis and Rendering Program (GARP): http://www.unidata.ucar.edu/software/gempak/tutorial/garp.html

National Climatic Data Center Radar Data: http://www.ncdc.noaa.gov/nexradinv/

Storm Prediction Center Severe Thunderstorm Event Archive: http://www.spc.noaa.gov/exper/archive/events/010521/index.html