A C-Band, Dual-Polarimetric Radar Analysis of a Tornadic Mesoscale Convective System: The 25 May 2011 Northern Illinois and Indiana Tornado Event

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ABSTRACT

During the morning hours of 25 May 2011, at least six tornadoes struck a narrow corridor of Northeast Illinois and Northwest Indiana. Two tornadoes were rated EF0, three EF1, and one EF2. These tornadoes occurred in conjunction with a mesoscale convective system (MCS) that traveled northeast across the region during the early to mid-morning hours, between 1200 UTC and 1500 UTC. The tornadoes occurred at least 65 km away from the nearest NEXRAD WSR-88D radar site. The confirmed tornadoes from this event occurred without severe thunderstorm or tornado warnings likely due to the fact that, (1) the squall-line was oriented parallel to the radar beam, (2) there were minimal real-time spotter reports, (3) embedded circulations were shallow, and (4) the tornado producing storms did not exhibit classic radar signatures at the nearest NEXRAD locations. The tornadoes occurred approximately 50-75 km from the C-band dual-polarimetric radar located on the campus of Valparaiso University in Valparaiso, IN.

In this presentation, we examine the data gathered from the C-band, dual-polarimetric radar at Valparaiso University. We review the data in order to reveal methods that could have better detected the tornadoes produced during this event.

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1. Introduction

Valparaiso University operates a 5-cm wavelength, simultaneous dual-polarimetric radar (VU-SIDPOL) located on the university campus in Porter County, Indiana, approximately 65 km southeast of Chicago. Built in 2007, the radar is primarily used in conjunction with radiosonde data gathered by university students for the Massachusetts Institute of Technology's Lincoln Laboratory (MIT-LL), through a joint project with the Federal Aviation Administration (FAA) to study icing hazards for commercial aircraft and aid in the development of an icing algorithm for the National Weather Service (NWS).

Additionally, the VU-SIDPOL radar is useful in the detection of storm-scale circulations. Past research has included the detection of an EF1-rated tornado that occurred on 26 October 2010 approximately 15 km from the radar (Evaristo et al. 2011). In the 2010 case, the VU-SIDPOL radar was useful in detecting a tornado debris signature (TDS) in the cross-correlation coefficient (ρ_{hv}) moment, with a minimum ρ_{hv} of 0.48 observed in association with the tornadic mesovortex.

Another opportunity for studying tornadic circulations with the VU-SIDPOL radar occurred on 25 May 2011. In this case, a remnant quasi-linear convective system (QLCS) from a tornado outbreak in the southern plains on 24 May 2011 moved northeast across central Illinois and into northwestern Indiana, producing at least eight tornadoes, six of which occurred in northeast Illinois or northwest Indiana. These tornadoes ranged in intensity from EF0 to EF2 intensity and caused isolated but locally significant damage. This tornado event was not well-anticipated, as most of the focus was on the potential for a more widespread tornado outbreak in the afternoon and evening hours. National Weather Service records from the Lincoln (ILX), Chicago/Romeoville (LOT),

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and Northern Indiana (IWX) weather forecast offices (WFO) indicate that none of the eight tornadoes confirmed during the morning hours of 25 May were located within tornado warning polygons.

This paper will focus on four tornadoes that occurred within 50-70 km of the VU-SIDPOL radar in Newton and Jasper Counties in northwestern Indiana on 25 May 2011. An in-depth analysis of corrected intensity (reflectivity, Z), storm-relative velocity (SRV), and cross-correlation coefficient (ρ_{hv}) data from the VU-SIDPOL radar is used to look for identifying features that could have potentially aided in the warning process for this tornadic event.

2. Synoptic and Mesoscale Overview

A classic late-spring severe weather pattern dominated the central United States from 20-25 May 2011. A closed low progressed very slowly eastward across the western and central United States, sparking several days of moderate to major severe weather events, including the Joplin, Missouri EF5 tornado on 22 May. Another round of devastating tornadoes occurred on 24 May across Oklahoma and Arkansas.

By 1200 UTC on 25 May, the low was vertically-stacked and located over northern Kansas (Fig. 1). The supercell activity that had developed across Kansas and Oklahoma on 24 May had coalesced into a QLCS and reached central Illinois. At 1200 UTC a warm front was located from the surface low in Kansas across northern Missouri, central Illinois, and central Indiana. Surface temperatures immediately north of the warm front were generally near 20°C with dewpoints in the 16-18°C range (Fig. 1).

At 850 hPa, warm air advection (WAA) was evident on the east side of the low across Illinois and Indiana (Fig. 2). The airmass at 850 hPa was very humid, with mixing ratios of 12-16 g kg^{-1} across the region. A 30 m s^{-1} low-level jet (LLJ) is noted on the 1200 UTC central Illinois (KILX) observation, aiding in the warm air advection east of the low (Fig. 2).

The 1200 UTC 500-hPa analysis (Fig. 3) shows a jet streak rounding the base of the closed low, with the axis of the jet streak roughly from eastern New Mexico to the Ozarks and a peak intensity of about 40 m s^{-1}. Temperatures at 500 hPa across Illinois and Indiana were -12 to -13°C, indicative of good mid-level lapse rates (Fig. 3).

The 1200 UTC ILX sounding (Fig. 4) shows a weakly stable layer from the surface to above 850 hPa, with 7.5°C km^{-1} lapse rates between 700 and 500 hPa. The QLCS was impacting the Lincoln site at this time. The 1200 UTC Detroit/Pontiac, MI sounding (Fig. 5) indicates weaker mid-level lapse rates and a much stronger surface-based inversion, as it was north of the warm front and ahead of the QLCS.

The morning tornadoes of 25 May 2011 occurred just north of the warm front, where, presumably, there would have been minimal surface-based instability but strong low-level wind shear. Additionally, these tornadoes occurred at a time of day that is climatologically rare for tornadoes across the event region (Trapp et al. 2005). Trapp et al. (2005) showed that an overall minimum in QLCS tornado activity is often observed during the 8:00 AM LST hour, the precise hour in which the four tornadoes thoroughly studied in this paper occurred. Thus, the immediate cause of the tornadoes is unclear and is further investigated in the proceeding sections of this paper.

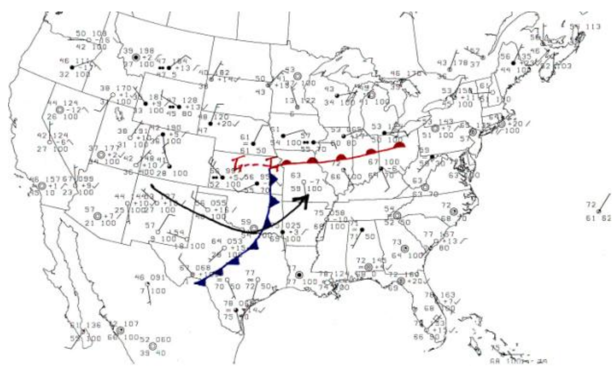

Fig. 1 Surface plot with fronts and pressure centers for 1200 UTC 25 May 2011. The black line and arrow indicate the approximate location of the 500-hPa jet axis at this time. Analysis by lead author.

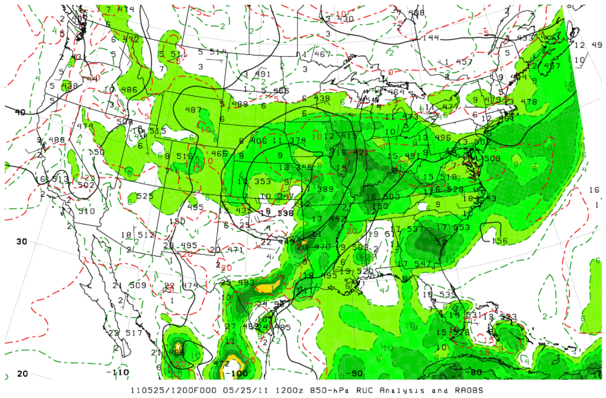

Fig. 2 850-hPa analysis for 1200 UTC 25 May 2011. Height lines are solid black, mixing ratio values are shaded green and dashed green lines, isotherms are dashed red.

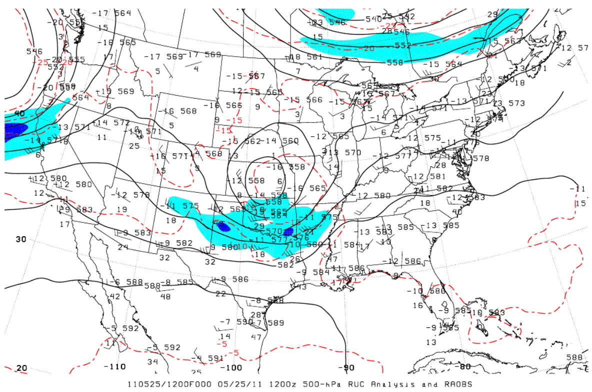

Fig. 3 500-hPa analysis for 1200 UTC 25 May 2011. Height lines are solid black, isotachs are shaded blue, and isotherms are dashed red.

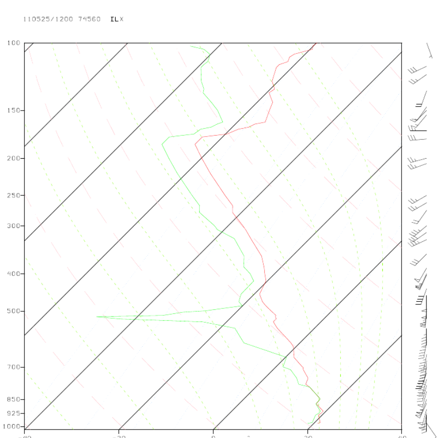

Fig. 4 Central Illinois (ILX) sounding for 1200 UTC 25 May 2011.

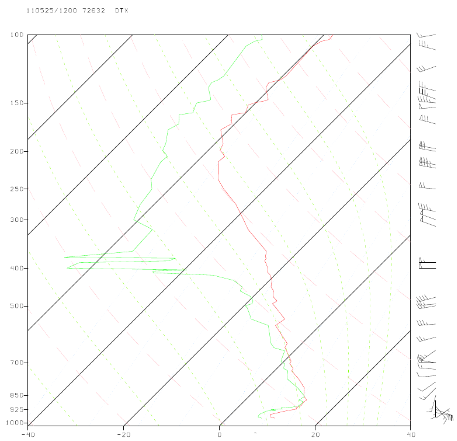

Fig. 5 Detroit/Pontiac, MI (DTX) sounding for 1200 UTC 25 May 2011.

3. The VU-SIDPOL Radar

The Valparaiso University Simultaneous Dual-Polarization (VU-SIDPOL) radar was constructed in 2007 by Enterprise Electronics Corporation of Enterprise, AL. The radar operates with a wavelength of 0.053 m and a PRF of 1014s^{-1}. The radar has a maximum range of 300 km and a Nyquist velocity of 26 kt. Each PPI volume scan consisted of 14 elevations that took approximately 6.5 minutes to complete.

4. Experimental design

Three 0.5° scans of the VU-SIDPOL radar were analyzed from the morning of 25 May 2011. These scans were at 1416, 1423, and 1430 UTC. Corrected intensity (Z) and cross-correlation coefficient (ρ_{hv}) were analyzed for all times, while storm-relative velocity was only analyzed at 1416 and 1423 UTC. These images were used to elucidate clues to tornado formation along the leading edge of the QLCS. The study focused on four tornadoes across Newton and Jasper Counties in Indiana. Of the four tornadoes, one was EF0, two were EF1, and one was EF2. The EF0 occurred near the town of Morocco, IN in Newton County. The two EF1 tornadoes occurred in or near the town of Rensselaer, IN in Jasper County, with one striking just northwest of town and one striking the southeast side of town. The EF2 tornado struck areas southeast of the town of Mt. Ayr, IN in Newton County, near the Newton/Jasper county line. These tornadoes were surveyed and confirmed on the afternoon of 25 May by the lead author, along with another EF1 tornado in Kankakee County, IL, that was too far from the VU-SIDPOL radar for adequate observation. Additionally, the National Weather Service Office in Northern Indiana confirmed a sixth tornado, rated EF0, in Pulaski County, IN. The maximum path length of the five surveyed tornadoes was over 10 km, with a maximum path width of 275 m observed in the EF2 tornado (Figure 6).

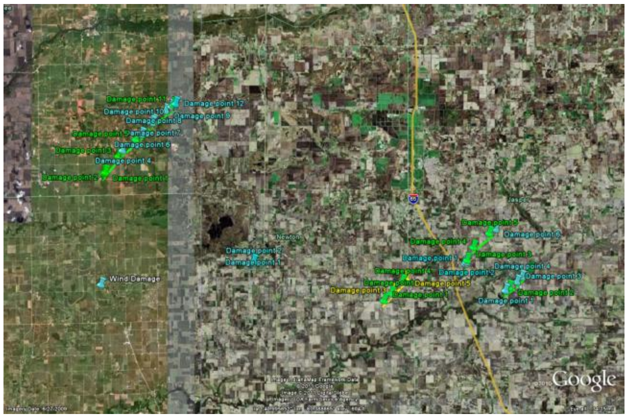

Fig. 6. Damage survey map for 5 of the tornadoes on 25 May 2011. Map created on Google Earth, with survey conducted by lead author.

5. Results

5.1 Corrected Intensity (Reflectivity, Z)

The locations of the touchdown points for the studied tornadoes were superimposed on top of the 0.5° Z data using precise latitude and longitude data gathered from the damage survey. This overlay allowed for simplified comparison of the features observed on the radar with the actual locations of the tornadoes.

Several notable features are prominent on the Z images. First and foremost prominent are the notches in Z along the leading edge of the QLCS. At 1416 UTC, notches are noted just northeast of the EF0 touchdown point, right at the EF2 touchdown point, and just southeast of the EF2 touchdown point. Based on radar data and survey information, the EF0 had just recently occurred, and the EF2 was likely beginning right around this time (Fig. 7). These notches continue to be present at 1423 UTC, although the notch associated with the EF0 tornado is less prominent while the notch associated with the EF2 is more prominent. This is even though survey data indicates that the tornado had lifted by this time. Additionally, the notches southeast of the EF2 tornado are more prominent at 1423 UTC, with both of the Rensselaer EF1 tornadoes likely beginning around this time (Fig. 7). At 1430 UTC the radar clearly shows the notches weakening along the leading edge of the QLCS. By this point, all tornadoes except for the Pulaski County tornado had already occurred (Fig. 7).

In addition, several features were noted in the region surrounding the QLCS. First, a series of east-west oriented bands were evident ahead of and perpendicular to the advancing squall line. Reflectivity loops show these bands as coherent features with a south-north motion, moving parallel to the orientation of the QLCS. These bands acted very similarly to bands observed in Murphy et al. (2011), which were hypothesized to be wave-like features. Additionally, two bulges in reflectivity were apparent on the back side of the QLCS. These bulges also moved from south to north and at a rate similar to the bands ahead of the QLCS. Barker (2006) noted these reflectivity bulges as being potential signs of gravity wave interaction and as precursors to severe wind or tornado activity.

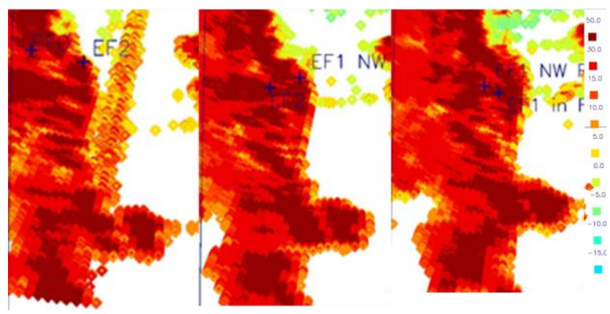

Fig. 7. 0.5° corrected intensity (reflectivity, Z) images from VU-SIDPOL radar on the morning of 25 May 2011. From left to right: 1416 UTC, 1423 UTC, and 1430 UTC.

5.2 Cross-Correlation Coefficient (ρ_{hv})

Like Z, 0.5° cross-correlation coefficient (ρ_{hv}) was studied from 1416, 1423, and 1430 UTC volume scans. In addition to also showing the banding features depicted in Z, the ρ_{hv} images held two additional notable features. The first and perhaps most notable and puzzling feature is a weakness in ρ_{hv} located slightly behind the leading edge of the line, as denoted by the arrows in Figure 8. The minimum ρ_{hv} value is 0.69 at 1423 UTC. Ryzhkov et al. (2005) showed that ρ_{hv} below 0.8 is often an indicator of tornado debris. The location of this signature, however, did not correspond to the any location where known tornado damage occurred or with any features that produced torandic damage. Additionally, sizeable hail was not a prevalent feature with the QLCS. This fact is supported by the weakness in Z associated with the weakness in ρ_{hv}. Finally, the weakness is too far away from the location of any of the tornadoes to be directly attributable to tornado debris. Therefore, the source of this ρ_{hv} anomaly is still unknown.

Also of note is the distinct minimum in ρ_{hv} observed along the leading edge of the QLCS at 1423 UTC, northeast of the other ρ_{hv}. This signature appeared in the scan following the lifecycle of the EF2 tornado. Though a TDS is conceivable given that the tornado produced projectiles and had a debris field over 400 m wide, the noise in the data precludes a definitive conclusion as to whether or not the minimum in ρ_{hv} at the leading edge of the line is a TDS (Figure 8).

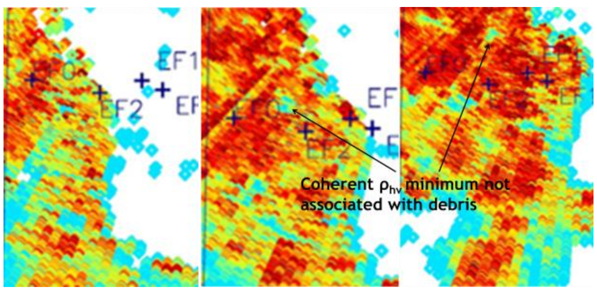

Fig. 8. 0.5° cross-correlation coefficient (ρ_{hv}) images from VU-SIDPOL radar on the morning of 25 May 2011. From left to right: 1416 UTC, 1423 UTC, and 1430 UTC.

5.3 Storm-Relative Velocity (SRV)

The velocity data had to be unfolded several times as velocities reached up to 31m s^{-1}, well above the Nyquist velocity of 13m s^{-1}. The scans show weak rotational signatures along the leading edge of the QLCS (Fig. 9). The strongest circulation is evident at 1423 UTC, associated with the EF1 tornado that occurred northwest of Rensselaer, IN (Fig. 9). Additionally, the banding features show up more prominently on SRV, with additional bands noted. The bands also show up in the main precipitation and in the reflectivity bulges on the back end of the squall line on the SRV images (Fig. 9).

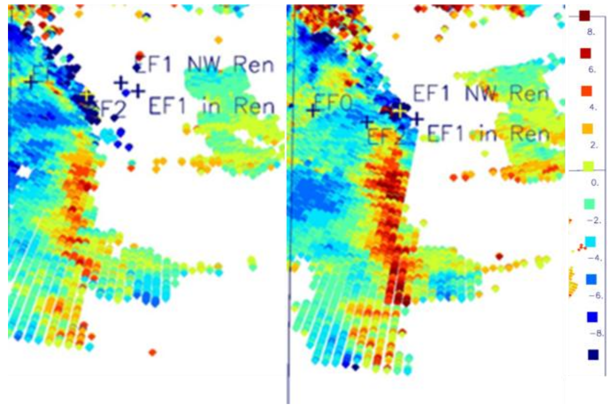

Fig. 9. 0.5° storm-relative velocity (SRV) images from VU-SIDPOL radar on the morning of 25 May 2011. From left to right: 1416 UTC and 1423 UTC.

6. Conclusions

The VU-SIDPOL radar data shed light on many interesting features of the 25 May 2011 tornadic QLCS. Reflectivity data found clear notches in reflectivity associated with confirmed tornadoes from that morning. Additionally, reflectivity bands and bulges were noted in association with the QLCS. These features were also noted in the SRV and ρ_{hv} data, with SRV showing especially prominent banding features. Of particular note is that all four tornadoes occurred in regions near where a band intersected the QLCS.

The question remains, then, as to the cause of these bands and reflectivity bulges. Barker (2006) speculated that reflectivity bulges occur in association with gravity waves propagating ahead of a QLCS. Thus, one potential explanation for these features would be ducted gravity waves. Evidence for such potential exists in the large-scale synoptic setup. The pattern across the central United States at 1200 UTC on 25 May 2011 very closely matches the schematic of the synoptic setup described in Koch and O'Handley (1997), with northeastern Illinois and northwestern Indiana in the prime location identified for mesoscale gravity wave formation (Figs. 1, 3, 10). Additionally, 1200 UTC DTX sounding indicates a rather shallow but sharp inversion from about 950 hPa to 900 hPa (Fig. 5), providing a potential ducting layer. The rather shallow depth of the ducting layer would be supportive of higher maximum vorticity in association with ducted gravity waves (Coleman and Knupp 2008). Given the synoptic setup, the location of the tornado event north of the warm front, and the potential ducting layer on the DTX sounding, it appears likely that the banding and reflectivity bulges are depictions of ducted gravity waves.

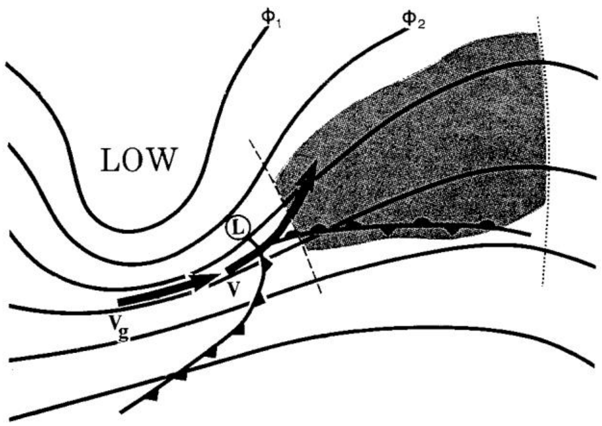

Fig. 10. Schematic of a typical mesoscale gravity wave formation pattern. V is the location of the 300-hPa jet streak, LOW is the center of the 300-hPa low, the solid lines are 300-hPa heights, V_g is the 300-hPa geostrophic wind maximum, the shaded region is the area of gravity wave formation. Surface features are also shown. From Koch and O'Handley (1997).

The SRV data reveal, after much unfolding and cleaning of data, several weak circulations along the leading edge of the line. These circulations last for a couple scans, lingering after the associated tornadoes had dissipated.

Cross-correlation coefficient revealed two features of note. The first is a weakness in ρ_{hv} along the edge of the line at 1423 UTC in association with the notch that had earlier produced the EF2 tornado. The noise associated with the leading edge of the QLCS precludes any conclusion as to whether or not this feature is a TDS. The other feature is another ρ_{hv} weakness within the line, collocated with a Z weakness but not with a tornadic circulation. The source of this anomaly is also unknown, but it remains coherent through the 1423 and 1430 UTC scans.

Overall, the main feature noted in the 25 May 2011 case is the likely gravity wave interactions with the QLCS. These banding and reflectivity bulge features may hold the key to better recognition of tornadogenesis potential in future QLCS events where tornado potential is not immediately clear to the warning forecaster.

7. ACKNOWLEDGMENTS

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