Investigation of a Severe Downburst Storm near Phoenix, Arizona, as Seen by a Mobile Doppler Radar and the KIWA WSR-88D

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ABSTRACT

A Shared Mobile Atmospheric Research and Teaching Radar (SMART-R) was deployed near Phoenix, Arizona, during the summer of 2004. The goal was to capture a severe microburst at close range to understand the low-altitude wind structure and evolution. During the evening of 27 July, a severe storm formed along the Estrella Mountains south of Phoenix and moved south of the SMART-R as well as the National Weather Service’s (NWS) Weather Surveillance Radar-1988 Doppler (WSR-88D) in Phoenix (KIWA). Several microburst–downburst pulses were observed by radar and a surface wind gust of 67 mi h\(^{-1}\) was reported. The radar data illustrate the finescale structure of the microburst pulses, with the SMART-R’s higher-resolution data showing Doppler velocities 3–4 m s\(^{-1}\) greater than the KIWA radar. SMART-R wind shear values were 2–3 times greater with the finer resolution of the SMART-R revealing smaller features in the surface outflow wind structure. Asymmetric outflow may have been a factor as well in the different divergence values. The evolution of the outflow was very rapid with the 5-min KIWA scan intervals being too coarse to sample the detailed evolution. The SMART-R scans were at 3–5-min intervals and also had difficulty resolving the event. The storm environment displayed characteristics of both moderate-to-high-reflectivity microbursts, typical of the high plains of Colorado.

1. Introduction

During the past 10 yr, the frequency of damaging winds from downbursts occurring in the Phoenix, Arizona, metropolitan area and surrounding suburbs has markedly increased, presumably due to population growth and better reporting (SPC 2007). Within the southwestern U.S. Sonoran Desert, downbursts from severe storms frequently produce strong outflows that entrain dust and reduce visibility to dangerous levels, particularly hazardous to traffic along the Interstate Highway System in southern Arizona (e.g., Maddox et al. 1995). The peak period for these storms is the summer monsoon season (e.g., Maddox et al. 1995). Long-lived dust storms accompanying thunderstorm outflows are referred to as “haboobs” (Idso et al. 1972; Fig. 1). Severe winds also pose a threat to aviation and disrupt electrical service by damaging overhead electrical transmission lines.

The severity of wind damage to electrical power transmission lines from an engineering perspective has resulted in speculation of an especially violent class of downbursts that result in velocities and shear exceeding what has been typically observed or documented in the formal literature. In an effort to better understand and document the occurrence of Sonoran downbursts and their background environments, the National Severe Storms Laboratory (NSSL) deployed a Shared Mobile Atmospheric Research and Teaching Radar [SMART-R1 (SR1); Biggerstaff et al. 2005] near Phoenix (PHX) during the summer of 2004. On 27–28 July, a series of severe downbursts occurred south of PHX and were observed at close range by the SR1 and the National Weather Service (NWS) Weather Surveillance Radar-1988 Doppler (WSR-88D; KIWA). (Figure 2 shows a photograph taken during the time of peak surface winds associated with one of the downbursts.) The observations facilitate a unique examination of the scales of motion and the life cycle structure of a series of severe downburst pulses as observed by two radars having different spatial and temporal resolutions as well as viewing perspectives.

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2. Downburst background

Severe winds from convective storms often begin as downbursts. Fujita (1981) defined a downburst as “a strong downdraft which induces an outburst of damaging winds on or near the ground,” and a microburst as “a small downburst with...damaging winds extending only 4 km (2.5 mi) or less.” The Joint Airport Weather Studies (JAWS) field project in Colorado (e.g., Wilson et al. 1984; Hjelmfelt 1988) was designed to study microbursts and the associated wind shear that can be hazardous to aircraft arriving and departing from an airport. During JAWS, observed microbursts had a median velocity difference ($\Delta v$) of 22 m s$^{-1}$ across an average distance of 3.1 km, with the median time of 5–10 min to reach the maximum $\Delta v$. Most occurred with isolated pulse storms though some occurred in conjunction with multicellular convective lines. The typical local thermodynamic environment for JAWS microbursts is characterized by a deep, dry, well-mixed boundary layer capped by a layer of high relative humidity (RH) with low convective available potential energy (CAPE). This environment supports the development of low-reflectivity microbursts (LRMs) where very little rain reaches the surface and downdrafts are driven primarily by evaporative cooling as small raindrops and graupel fall from a relatively high cloud base into dry subcloud air (Srivastava 1985). Roberts and Wilson (1989) reported on a spectrum of microbursts and their association with various reflectivity values that includes the categories moderate-reflectivity microbursts (MRMs) and high-reflectivity microbursts (HRMs). HRMs have frequently been observed in moist environments, occur in conjunction with heavy rainfall, and are the result of evaporating rain, melting hail, and precipitation loading (e.g., Atkins and Wakimoto 1991; Caracena and Maier 1987). HRMs in Florida, as described in Rinehart et al. (1995), had surface wind characteristics similar to those of JAWS microbursts. Downbursts and microbursts have also been documented in other parts of the country including Oklahoma (Eilts and Doviak 1987) and Utah (Mielke and Carle 1987).

Kessinger et al. (1988) and Roberts and Wilson (1989) discussed factors that result in a variety of Doppler velocity features associated with downbursts that may be used as predictors. Radial velocity convergence, and its location with respect to cloud base, are associated with evaporation, melting, and precipitation drag. Convergence develops in response to the downdraft through the conservation of mass. Rotation (vertical vorticity) near cloud base is associated with vertical pressure gradient forces and can be enhanced via stretching and tilting. Rotation can initially be separate from a...

Fig. 1. Photograph of the SR1 with a haboob in the background. (Courtesy of K. Howard.)
downdraft and become collocated. Hjelmfelt (1988) and Kessinger et al. (1988) discussed how rotors along the leading edge of an outflow are associated with the strongest winds. Descending reflectivity cores and notches in radar echoes caused by the intrusion of dry air are additional radar indicators. These predictors are not always present and when they are, their evolution is very rapid (on the order of a few minutes) making it very difficult to assess with the 5–6-min volume scans performed by the current WDR-88D system (Roberts and Wilson 1989).

3. Storm environment on 27 July 2004

Special soundings were taken from the NWS Weather Forecast Office (WFO) in PHX on 27 July 2004. The 2100 UTC sounding (Fig. 3a) shows that 700–500-hPa steering winds were west-northwesterly with south-westerly surface winds. Moderate CAPE (767 J kg\(^{-1}\)) was present with a 500-hPa lifted index of \(-2.5^\circ\)C. The boundary layer was well mixed with a dry-adiabatic lapse rate from just above the surface to \(\sim 720\) hPa and a small amount of convective inhibition (CI). Three hours later (Fig. 3b), subsidence appears to have occurred in the lower troposphere; warming and a decrease in RH were observed between 700 and 800 hPa and were thus increasing the CI. These soundings deviate from typical LRM soundings that approach 100% RH near the top of the boundary layer. Furthermore, they were not typical Arizona microburst soundings, as this was more of a transitional event with the 500-hPa ridge well south of PHX indicating that a break in the monsoon was imminent (D. Green, NWS Phoenix, 2007, personal communication).

4. Radar data analysis

The representativeness of radar observations depends primarily on the radar beam resolution volume size with respect to the ambient vertical wind shear. Sharp vertical gradients of winds as well as peak wind speeds will be dampened if they occur over a small distance compared to a radar beam volume dimensions. For example, Eilts (1987) used instrumented tower data to show that radar underestimated the vertical shear in gust fronts while overestimating surface winds. Vasiloff (2001) described significant differences between tornado observations as sampled by different resolution volumes.

![Fig. 2. Photograph, looking SW, of the microburst dust cloud just before 0200 UTC on 28 Jun 2004. (Courtesy of S. Sipple, Phoenix WFO.)](image-url)
and scan frequencies by a WSR-88D and a Federal Aviation Administration Terminal Doppler Weather Radar (TDWR) that performs a “microburst” scan every minute. Table 1 lists the resolution and scanning patterns for the SR1 and the KIWA WSR-88D. (A TDWR is close-by but data were not archived for this event.) The range gate resolution for the WSR-88D is 1 km for reflectivity and 250 m for Doppler velocity. KIWA operated in volume coverage pattern 11 (VCP 11), which includes 14 constant-elevation angle sweeps from 0.5° through 19.5°. The SR1 has a considerably finer range gate resolution of 70 m for both reflectivity and velocity while both radars’ azimuthal resolutions are nearly equal. The SR1 VCP is variable and contains several more elevation sweeps, especially at lower altitudes. The KIWA radar completed a VCP in 5 min while the SR1 VCPs varied between 3 and 5 min.

Figure 4 shows a shaded relief image of central Arizona’s terrain and the locations of the radars on 27–28 July 2004. The Mogollon Rim to the north of PHX is a favored area for storm initiation, especially during the summer (Maddox et al. 1995). During the afternoon of 27 July, a line of storms formed along the rim with an associated outflow boundary moving toward PHX (Fig. 5). As seen in Fig. 5, the lowest KIWA tilt is blocked in two sectors to the north and northeast with more substantial blockage to the south of the radar. The blockage to the south affected the radar’s ability to sample the last of the microburst pulses described later. There is also a small amount of blockage on the 1.45° tilt to the northeast and south of KIWA (not shown). Also note that the mesonet data indicate weak east-northeast surface winds ahead of the outflow to the north and a shift to northeast and southwest winds behind the gust front.

Since the SR1 radar was scanning the approaching gust front to the north, the downburst storm’s formation is documented using base data from the KIWA radar. The first cells developed at the SE end of the Estrellas around 0100 UTC (Fig. 5). Storms in the western United States typically form along mountains that serve as an elevated heat source (e.g., Wakimoto 1985). It is hypothesized that the CI present in the sounding discussed in the previous section was overcome by terrain forcing. The northwestern-most cell in the short line was growing rapidly while the other cells decayed as they moved to the east-southeast. Figures 6 and 7 depict the formation of the first downburst pulse. At 0110 UTC, a 50-dBZ reflectivity core had developed aloft. Over the next 20 min, high reflectivity reached the surface and

<table>
<thead>
<tr>
<th>Attribute</th>
<th>SR1</th>
<th>KIWA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (cm)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Azimuthal resolution (°)</td>
<td>1</td>
<td>0.95</td>
</tr>
<tr>
<td>Radial resolution</td>
<td>70-m reflectivity, 1-km reflectivity, and velocity</td>
<td>250-m velocity</td>
</tr>
<tr>
<td>VCP angle (°)</td>
<td>0.5, 0.8, 1.2, 1.6, 2.1, 2.6, 3.4, 4.2, 5.1, 5.9, 6.9, 7.9, 9.1, 10.2, 11.4, 12.9, 14.5, 16.3, 18.5, 20.0, 22.0</td>
<td>VCP 11: 0.5, 1.45, 2.4, 3.35, 4.3, 5.25, 6.2, 7.5, 8.7, 10.0, 12.0, 14.0, 16.7, 19.5</td>
</tr>
<tr>
<td>VCP interval (min)</td>
<td>3–5</td>
<td>5</td>
</tr>
</tbody>
</table>
FIG. 4. Gray-shaded terrain image of PHX and surrounding area. The southeast end of the Estrella Mountains is indicated by the star. SR1 and KIWA locations are shown to the southeast of the PHX metropolitan area.

FIG. 5. Images from the KIWA 0100 UTC volume scan on 28 Jul 2004 showing the storms aligned along the Mogollon Rim of (a) 0.5° reflectivity at 0100:57 UTC and (b) 0.5° velocity at 0101:16 UTC. Arizona surface alert wind data are overlaid. Note the Estrella Mountains and the initial echoes SW of SR1 that will produce the downburst storm. The KIWA and SR1 radar locations are also shown. Blue arrows indicate blockage.
was associated with the outflow signature seen in Fig. 8. Note that there appear to be several very small cells identifiable aloft but only one apparent cell near the surface (Figs. 7b and 7c). The first downburst pulse (P1) peaked at ~0131 UTC and had a radial divergence of 26 m s$^{-1}$ over a distance of 5.6 km ($4.6 \times 10^{-3}$ s$^{-1}$; Figs. 8 and 9). While the dimensions of the outflows in this event conform to downburst definitions, peak divergence values often occurred over a smaller radial distance of less than 4 km. Subsequent attempts to associate individual pulses with individual cells was not possible due to the inability to associate very small cells with larger outflow signatures. Also, it was often difficult to identify separate cells at low altitudes.

The SR1 radar began scanning the storm at 0144:44 UTC as P1 was weakening and P2 was starting. By this time, the storm had assumed a multicellular appearance that was well defined by the high resolution of the SR1. Figure 10 shows the reflectivity and velocity from the SR1 at low, middle, and high altitudes. Initially, there is a cluster of small cells at the southern edge of the ring-shaped outflow boundary from the initial downburst. Because of its higher resolution, there is more detail in the SR1 than in the KIWA data (not shown) with a well-defined reflectivity thin line associated with the outflow boundary and better echo definition. While differences between the two radars' velocity fields can be significant due solely to asymmetry and different viewing angles (see e.g., Hjelmfelt 1988), the SR1 data had stronger gradients along the gust front to the north, now impinging on the downburst outflow, and finer-scale structure in the downburst divergence signature. The $\Delta \nu$ in P2 at 0145:51 UTC for KIWA was 22 m s$^{-1}$ across a distance of 3.7 km ($5.9 \times 10^{-3}$ s$^{-1}$) while the SR1 radar at 1044:44 depicted a $\Delta \nu$ of 31 m s$^{-1}$ across a distance of 2.5 km ($12.4 \times 10^{-3}$ s$^{-1}$). Similar differences between the KIWA and SR1 data were noted aloft. For instance, the
KIWA radar showed very weak midlevel rotation while rotation couplets in the SR1 data were more pronounced with radial velocities 3–5 m s$^{-1}$ stronger. The rotational features were likely the result of the inferred downdraft as noted by Rinehart et al. (1995). Near storm top, both radars depicted small areas of divergence on the western edge of the cell complex, indicating new cell growth. The divergent radial velocities were also stronger in the SR1 radar data.

The initial pulses dissipated rapidly as the complex moved eastward. A third pulse, P3, began just minutes later around 0154:03 UTC in nearly the same location as P1 (Fig. 11a). Over the next 15 min, the sequence of midlevel images from the SR1 7.8° tilts (Figs. 11b, 11d, 11f, and 11h) shows intensification of midlevel rotation and convergence as the surface outflow expanded. For instance, at 0158:30 UTC (Fig. 11b), remnants of the two rotational couplets associated with P2 can be seen south of the SR1. Just above and to the west of P3 there is a broad area of weak convergence and rotation. Within about 7 min (0205:47 UTC; Fig. 11f) the rotation had become well defined and an area of enhanced inbound velocity had developed, increasing the midlevel convergence south of the surface divergence. It is hypothesized that this inflow was directed toward the surface, helping to explain the outflow asymmetry. At the surface, P3 produced a 67 mi h$^{-1}$ gust observed at the Maricopa Cooperative Observer Program (COOP) site between 0155 and 0205 UTC; the peak inbound velocity at 0203:21 UTC from the SR1 was 28 m s$^{-1}$, ~1 km to the east of the COOP site (Fig. 11e). The photo in Fig. 2 was taken at about this time. What appears to be the leading edge of P3 can be seen just north of the COOP station. The maximum radial velocity from the KIWA radar near this time was ~21.5 m s$^{-1}$ at 0200:44 UTC. Hjelmfelt (1988) and Kessinger et al. (1988) pointed out that rotors along the leading edge of a microburst can result in a local enhancement of winds as well as very small-scale convergence–divergence.
couplets. The structure of the outflow winds at 0203:21 UTC supports the presence of one or more rotors in this event; there appear to be at least two convergence–divergence couplets ahead of the main divergence center. There is only a hint of these features at the next 0.5° tilt at 0208:00 UTC (Fig. 11g). While the maximum velocity measured by the SR1 was 31.5 m s⁻¹ at this time, it was well away from the centers of the pulses, further supporting the presence of a rotor. There were a few gates with higher radial velocities but the data were indiscernible and not used.

As P3 dissipated, the midlevel rotation and convergence continued to increase. At 0212:40 UTC (Fig. 11i), a short-lived “minipulse” (MP) appeared beneath the convergence zone, possible indicating the effect of the convergence aloft noted earlier. The MP with 15.3 × 10⁻³ s⁻¹ divergence was the only outflow signature that was small enough to be classified as a microburst. There

Fig. 10. SR1 images of (a) reflectivity at 0.5° at 0144:44 UTC, (b) velocity at 0.5° at 0144:44 UTC, (c) velocity at 5.5° at 0146:54 UTC, and (d) velocity at 16.3° at 0148:33 UTC. The centers of the images at 0.5°, 5.5°, and 16.3° are 0.23, 3.5, and 7.4 km AGL, respectively. Areas of convergence–rotation discussed in the text are circled. The blue arrows show the 4-km distance scale.
Fig. 11. As in Fig. 10 but for a sequence of images at low and midlevels from the SR1 showing velocities at (a) 0.5° at 0154:03 UTC, (b) 7.8° at 0158:30 UTC, (c) 0.5° at 0158:43 UTC, (d) 7.8° at 0201:08 UTC, (e) 0.5° at 0203:21 UTC, (f) 7.8° at 0205:47 UTC, (g) 0.5° at 0208:00 UTC, (h) 7.8° at 0210:26 UTC, (i) 0.5° at 0212:40 UTC, (j) 7.8° at 0215:08 UTC, (k) 0.4° at 0217:22 UTC, (l) 7.8° at 0218:49 UTC, (m) 0.4° at 0220:06 UTC, (n) 7.8° at 0221:34 UTC, (o) 0.4° at 0222:53 UTC, and (p) 7.8° at 0224:20 UTC.
FIG. 11. (Continued) The centers of the images at 0.5° and 7.8° are approximately 0.41 and 3.5 km AGL, respectively. The COOP wind observation of 67 mi h⁻¹ is shown in (e). The MP in (i) shows the location of the minipulse discussed in the text. An enhanced area of inbound radial velocities is denoted by the “surge.” Divergence−convergence couplets indicating possible rotors are also indicated.
TABLE 2. Microburst type, average velocity difference, average distance between peak velocities, and average time to reach peak divergence for the studies mentioned in the text. N/A indicates that the data were not available from the study. The PHX data are from those used for the shear calculations.

<table>
<thead>
<tr>
<th>Region, No. of samples (reference)</th>
<th>Microburst type</th>
<th>Avg Δv (m s⁻¹)</th>
<th>Avg distance (km)</th>
<th>Avg time to max divergence (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado, 68 (Wilson et al. 1984)</td>
<td>All</td>
<td>22 (median)</td>
<td>3.1</td>
<td>5–10</td>
</tr>
<tr>
<td>Florida 1991, 84 (Rinehart and Borho 1993)</td>
<td>HRM</td>
<td>15.7</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Florida 1992, 908 (Rinehart et al. 1995)</td>
<td>HRM</td>
<td>16.2</td>
<td>2.4</td>
<td>N/A</td>
</tr>
<tr>
<td>Oklahoma, 3 (Eilts and Doviak 1987)</td>
<td>HRM</td>
<td>25</td>
<td>6</td>
<td>N/A</td>
</tr>
<tr>
<td>Utah, 1 (Mielke and Carle 1987)</td>
<td>LRM</td>
<td>41 (anemometer)</td>
<td>1.8</td>
<td>N/A</td>
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<tr>
<td>PHX, 3</td>
<td>HRM</td>
<td>36.6</td>
<td>2.3</td>
<td>3–10</td>
</tr>
</tbody>
</table>

was also a brief rotation signature associated with the MP. As P3 continued to weaken, the rotation tightened into a small vortex resembling a mesocyclone while the convergence began to dissipate (Fig. 11j). During P3, divergence values for KIWA never exceeded \( 7.4 \times 10^{-3} \) s⁻¹ while SR1 divergence values exceeded \( 12 \times 10^{-3} \) s⁻¹ for three consecutive scans. The MP had a divergence of \( 15.4 \times 10^{-3} \) s⁻¹.

The final pulse of note was P4 and was associated with a large reflectivity core east of the location of the previous pulses with an initial divergence of \( 14.6 \times 10^{-3} \) s⁻¹ at 0217:22 UTC (Fig. 11k). This pulse was also coincident with the rotation aloft that had decreased in size but peaked in intensity at this time with a gate-to-gate velocity difference (at constant range) of 22 m s⁻¹. The next three 0.4° sweeps from the SR1 were only 3 min apart and document the rapid evolution of P4. At 0220:06 UTC the divergence was \( 12.1 \times 10^{-3} \) s⁻¹ and increased to \( 17.1 \times 10^{-3} \) s⁻¹ at 0222:53 UTC. Thus, it appears that this pulse reached its maximum strength in less than 6 min. Three minutes later, the outflow had begun to dissipate with another apparent rotor on the northern leading edge. Midlevel rotation and convergence continued to dissipate with this last pulse. Note that KIWA was blocked to the south and could not observe the later pulses.

Due to the relatively coarse scan frequencies, these pulses may have begun as microbursts yet were not captured in their infant stages. For the three downburst pulses observed by the SR1, the average maximum radial velocity difference was \( 33.5 \) m s⁻¹ across an average distance of 2.3 km. As shown in Table 2, these values are much stronger than those (on average) observed in different parts of the country. However, many of the Colorado events had maximum velocity differences of greater than 30 m s⁻¹. Thus, a larger sample size of Sonoran Desert downburst storms is needed to provide a more meaningful comparison.

Overall, the SR1 velocities were 3–5 m s⁻¹ stronger than those from KIWA. Due to its higher resolution, divergence values computed using the SR1 radar data were 2–3 times greater than values computed from the KIWA radar data. Furthermore, at times the SR1 scanned the lowest elevation at 3-min intervals and still did not fully resolve the evolution of the outflows; that is, peak shears were likely missed. Reasons for the difference in values include resolution, viewing angle, and beam height. Since the velocity differences were small, it is believed that the ability of the SR1 to resolve smaller features was the largest contributor to the greater divergence values as compared to the lower-resolution KIWA radar. These results have practical implications for the interpretation of WSR-88D data. At relatively close distances from the radar, outflow velocities can be underestimated by 10% or more and radial divergence by 2–3 times. Also, the 4–5-min scan frequencies will most likely miss the peak winds in the rapidly evolving outflow since the pulses peaked in intensity in under 10 min. Thus, once a downburst signature has first been identified, there is a small time window of ~5 min in which to issue a warning. Perhaps a special scan strategy could be developed that would increase the frequency of low-elevation scans. Additional warning lead time may result from monitoring descending reflectivity cores and increasing convergence and rotation near cloud base (see, e.g., Roberts and Wilson 1989). Finally, the areas of blockage of the
lowest elevation angles can result in the missed detection of events. Higher angles should be examined for evidence of shear.

It is believed that this paper is the first to document the structure and evolution of a Sonoran Desert downburst storm. Comparisons to downburst storms across the United States support the conclusion that this event was unique in that it was a long-lasting event yet displayed characteristics of both MRMs and HRMs in Colorado described by Roberts and Wilson (1989). A second field deployment of a SMART-R in Arizona will occur during the 2008 monsoon season with the objective toward potentially quantifying the frequency of Southwest downbursts and their associated mesoscale environments.

Acknowledgments. The SMART-R deployment and data collection were facilitated by the Salt River Project. The authors thank Chuck Dempsey and Charlie Ester of the Salt River Project for their continued support and Doug Green of the Phoenix Weather Forecast Office for his helpful review and insight into the environmental data. The authors also thank James Walter for providing the sounding figures and surface data.

REFERENCES