Doppler Radar Observations of Dust Devils in Texas

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ABSTRACT
Analyses of a dust-devil dataset collected in northwest Texas are presented. The data were collected just above the ground at close range with a mobile, W-band (3-mm wavelength) Doppler radar having an azimuthal (radial) resolution of 3–5 m (30 m) at the range of the dust devils. Most dust devils appeared as quasi-circular rings of relatively high radar reflectivity. Four dust-devil vortices were probed, three of which were cyclonic and one anticyclonic. Documentation was obtained of a pair of adjacent cyclonic vortices rotating cyclonically around each other.

Approximate radial profiles of azimuthal and radial wind components and of radar reflectivity are detailed and discussed. The diameters of the core of the dust devils ranged from 30 to 130 m; the latter diameters are much wider than that of typical dust devils in a homogeneous environment. The widest vortex was cyclonic and exhibited evidence of a two-cell structure (i.e., sinking motion near the center and rising motion just outside the radius of maximum wind), a broad, calm eye, and an annulus of maximum vorticity just inside the radius of maximum wind. As the vortex widened, it developed an asymmetry, and some evidence was found that two waves propagated cyclonically around it. The narrowest dust devil had the structure of a Rankine combined vortex, that is, a central core of constant vorticity surrounded by potential flow.

1. Introduction

a. Kinematics and dynamics of dust devils

Dust devils are columnar, ground-based vortices associated with dry, daytime boundary layer convection when surface heating produces lapse rates that are highly superadiabatic. The results of experiments with laboratory and numerical models suggest that dust devil–like vortices can have a “one cell” (upward motion at the center, downward outside of the center) or “two cell” (downward motion at the center, upward motion away from the center, and downward motion far from the center) (Smith and Leslie 1976; Mullen and Maxworthy 1977). The latter showed that when the surface wind is weak (moderate), vortices are one (two) celled; when the wind is strong, no vortex forms. However, Hess and Spillane (1990) have argued that it is the wind fluctuations that are important in determining whether or not dust devils form, not the mean wind: A dust devil can form even if the mean wind is calm. Possible sources of vorticity in dust devils are ambient horizontal shear (Barcilon and Drazin 1972), horizontal shear related to flow around obstacles (Williams 1948; Hallett and Hoffer 1971), horizontal shear associated with convective-cell circulations (Carroll and Ryan 1970), horizontal shear produced by the action of convection on background vorticity (Julien et al. 1996), tilting of ambient horizontal vorticity (vertical shear) (Maxworthy 1973), and tilting of horizontal vorticity (vertical shear) associated with convective-cell circulations (Kanak et al. 2000). The maximum possible wind speed in a dust devil has been shown to be a function of the product of thermodynamic efficiencies associated with the ver-
tical and horizontal temperature gradients (Renno et al. 1998). There is some suggestion that dust devils are much wider when they occur along the edge of a density current (Hess and Spillane 1990) and in this case may be a result of the rolling up of a vortex sheet (Barcilon and Drazin 1972).

b. Observations of dust devils

What we know about the observed structure of dust devils comes mainly from in situ measurements made as early as half a century ago. Ives (1947) reported attempts to measure the horizontal and vertical components of the wind, temperature, and pressure by chasing dust devils in a jeep in the Salt Lake Desert in Utah and then inserting instruments into them. [His efforts preceded by over 30 years the first attempts to make similar in situ measurements in tornadoes (Bluestein 1983).] In perhaps the most unusual attempt to estimate the vertical velocity in any atmospheric vortex, Ives measured the terminal fall velocity of kangaroo rats ("by dropping several of them from the top of the control tower and timing the last 20 feet of fall"), the largest objects that were observed to drop out of a dust devil. Williams (1948) reported on a visual study in the Mojave Desert of California, though one in situ measurement of winds with a handheld anemometer was made in a dust devil.

Systematic field experiments for the observational study of dust devils, including in situ measurements, were first conducted in 1960–63 using handheld instrument packages, ground-based, mobile in situ sensors, and an instrumented sailplane in the desert near Tucson, Arizona (Sinclair 1964, 1969, 1973). Kaimal and Businger (1970) conducted a boundary layer experiment in Kansas in 1967 in which an instrumented tower at a fixed site recorded measurements in a dust devil. Ryan and Carroll (1970) and Carroll and Ryan (1970) conducted field studies in the Mojave Desert of California in which they, among other things, made measurements in 80 dust devils with instruments mounted on a penetrating aircraft. In 1971, Fitzjarrald (1973) conducted an observational field program, using ground-based instruments at a fixed site, at the same Mojave Desert location used by Ryan and Carroll (1970). Hess and Spillane (1990) have reported on dust-devil observations in Australia.

In situ measurements in dust devils have provided views of one-dimensional slices through dust devils. An X-band, continuous wave (CW) Doppler radar collected Doppler wind spectra in a dust devil in 1959 in Wichita Falls, Texas (Smith and Holmes 1961). To get two-dimensional slices, which can be used to yield a much more detailed look at their structure, a scanning, pulsed Doppler radar can be used. In 1995 a mobile, X-band Doppler radar probed a 1.5-km-wide vortex near Denver, Colorado, that appeared to be associated with a smaller, but not resolved, dust devil (Kanak et al. 2000).

c. Motivation for this study

Both dust devils and tornadoes are small-scale vortices in contact with the ground and driven by convective processes. In the case of the former, the convection is dry and a result of daytime heating of the bottom of the boundary layer; in the case of the latter, the convection is moist and driven by latent-heat release. It is instructive to observe dust-devil behavior on finer space and time scales, and more completely than hitherto possible, by using a mobile, high-resolution Doppler radar, which has been used to probe tornadoes. In doing so, what we know about both dust devils and tornadoes may be enhanced, especially since it is much easier to make measurements in dust devils, which occur much more frequently and are much less dangerous to intercept. In 1999, a group from the School of Meteorology at the University of Oklahoma, in collaboration with a group from the University of Massachusetts–Amherst, made serendipitous measurements in dust devils using a mobile, W-band (3-mm wavelength) Doppler radar while on the way to intercept a potentially tornado-bearing supercell in northwest Texas (Bluestein and Pazmany 2000). The purpose of this paper is to discuss the results of analyses of this dataset, with the main aim of providing a more refined look at the structure of dust devils than possible in the past. The nature of the radar data collected and the techniques used to process and analyze the data are given in section 2. The analyses are detailed in section 3, followed by a summary and discussion of the analyses in section 4.

2. Radar data and analysis techniques

Data were collected on 25 May 1999 in a series of dust devils (Fig. 1) that formed a few kilometers east of Tell, Texas, which is located in northwest Texas, just to the southwest of Childress. The dust devils formed repeatedly in the same general area and moved approximately to the southeast along with the surface flow [cf. the surface wind at Amarillo, Texas, to the northwest (Fig. 2); our wind observations were estimates and were not made with instruments]. The truck-mounted radar was parked on an east-west-oriented road and probed dust devils to the south of the road (Fig. 1). The sky consisted of approximately uniformly spaced cumulus clouds; it is not known whether or not the dust-devil circulations extended up to any of the clouds. Surface winds were relatively weak (approximately 5 m s⁻¹ or less) (Fig. 2), which appears to be one of the necessary conditions for dust-devil formation (Ives 1947; Sinclair 1969; Mullen and Maxworthy 1977). The dust devils were apparently located behind a decaying outflow boundary from an earlier mesoscale region of thunderstorms in Kansas and Oklahoma that had sagged southward through the Texas panhandle during the morning (Fig. 3). Sector scans at as low an elevation angle as possible without having significant ground-clutter con-
The antenna of the University of Massachusetts W-band radar, which is mounted on a pickup truck, is seen scanning the dust devil, which is moving away from the radar. The yellow structure mounted just to the right of the antenna is the boresighted video camera. Note the scattered cumulus clouds above the dust devil. (Photograph copyright H. Bluestein)

tamination were made approximately every 5–13 s, depending on how wide the scans were. The width of the scans was chosen so that the radar beam swept across the entire visible dust column while including some sectors both to the right and left of the dust column. A boresighted video camera (discussed subsequently) was used to aim the antenna.

The radar was operated with a pulse length of 30 m to enhance its sensitivity in the clear-air boundary layer (i.e., in the absence of precipitation); when probing tornadoes, the pulse length is usually set to 15 m, owing to the abundance of scatterers (Bluestein and Pazmany 2000). The W-band radar, when operated with 30-m pulses, is usually sensitive enough to detect clear-air return in the boundary layer at ranges out to 1.5 km in the southern plains. The return signal, however, was sampled every 15 m, so that adjacent sample volumes overlapped. It is thought that the radar can detect backscatter from the dust/dirt particles suspended in the circulation of a dust devil, while clear-air return is mainly from insects (Wilson et al. 1994; Martin 2003, section 3.8.3). Since the wavelength of the radar is 3 mm, the backscattered radiation from insects and dirt is probably in the Mie range; no reasonable estimate of the radar reflectivity can be made, mainly owing to attenuation. However, coherent patterns in radar reflectivity collocated with dust devils could reasonably be thought to be from the dust/dirt lofted and distinguishable from the background field of insects unless the insect concentration was higher in the dust devils than outside. The half-power beamwidth of the radar antenna is 0.18°, which allows an azimuthal resolution ranging from 3 m at 900-m range to 5 m around 1.5-km range. The “effective” beamwidth, however, is slightly wider because the antenna is scanning in azimuth while data are being collected (Doviak and Zrnic 1993; Wood et al. 2001). So, the approximate radar volumes near dust devils, which varied from 870 m to 1.55 km in range, were about 3–5 m by 3–5 m in the plane normal to the radar beam and 30 m along the beam.

The data were processed at the Microwave Remote Sensing Laboratory, and universal format files were produced. Doppler velocities were estimated using the simple pulse-pair technique because the range of the dust devils was at or under 1.5 km (Bluestein and Pazmany 2000). The radar was operated at a pulse repetition frequency such that the Nyquist interval was ±8 m s⁻¹. For some dust devils, the velocity data were aliased and
Fig. 2. Surface plots of weather at stations surrounding (Texas, New Mexico, Oklahoma, southeastern Colorado, and southern Kansas) the location of the dust devils observed on 25 May 1999, at 1500 CDT, the observations having been taken approximately 30 min prior to radar data collection. Half (whole) wind barbs denote 2.5 (5) m s⁻¹ wind speeds; temperature and dewpoint are given in °C; sea level pressure is given in tens of mb, with the leading “10” omitted. Approximate location of the dust devils is noted by the arrow. Dashed line represents a wind shift line associated with outflow from earlier and ongoing convective storms to the north and northeast.

were corrected using the National Center for Atmospheric Research’s SOLO software (Oye et al. 1995). The SOLO software was used also to display data and extract data at selected points.

Boresighted video images of the dust devils were also archived. However, in 1999 a boresighted video camera was used for the first time and exact calibration marks were not available because the camera shifted slightly in its mount. The precise viewing window of the radar with respect to the dust devil is therefore not known. Since the elevation angle was chosen by raising the elevation angle to the approximate point that ground targets disappeared, it is likely that the elevation angle permitted viewing as low as 5–10 m above the ground in some scans. Another problem with the 1999 dataset is that the computer time was not exactly the same as the videotape time. Consequently, the accuracy of the time is not better than a few seconds.

3. Analyses of the radar data

The characteristics and evolution of the radar reflectivity and Doppler velocity fields associated with the dust devils are first described in a qualitative way. The characteristics of two dust-devil vortices are then detailed in a quantitative fashion.

a. Qualitative description of the reflectivity and Doppler wind field in the dust devils

A summary of the data collected and the gross characteristics of two of the dust devils are given in Tables 1 and 2 for the reader’s convenience and should be referred to in the following discussion. Four dust devils (A–D) were scanned; the properties of two of them (A and B) are the focus of this paper. We stopped collecting data after the dust column from dust devil B disappeared, even though more dust devils formed, so we could continue onto the supercell we had initially targeted. From 1515:25 to 1516:12 central daylight time (CDT; all times hereafter in local time, CDT), a relatively narrow, cyclonic dust devil [the distance between the Doppler velocity maximum and minimum composing the couplet of the vortex signature (Brown and Wood 1991, hereafter referred to as BW) was approximately
FIG. 3. GOES-8 visible satellite image corresponding approximately to the area covered by the weather map in Fig. 2, on 25 May 1999, at 1515 CDT, during the time of radar data collection. Note the mostly overcast skies in the northeastern half of Oklahoma, the Oklahoma panhandle, and southwest Kansas, which was associated with the remnants of earlier convective storms and with ongoing storms.

30–40 m] was scanned nine times at a range of just under 890 m. Highest ground-relative wind speeds in this dust devil (A) ranged from 6.6–7.7 m s⁻¹. The radar reflectivity signature of the dust devil was frequently a quasi-circular ring of enhanced backscatter surrounding a weaker-echo eye (Fig. 4a), similar to the reflectivity structure of tornadoes (e.g., Wurman et al. 1996; Bluestein and Pazmany 2000; Wurman and Gill 2000; Bluestein et al. 2003; Wurman 2002); the associated Doppler velocity pattern was that of a cyclonic vortex signature (Fig. 4b). The center of each dust devil was located from the center of each reflectivity ring and the midpoint between each member of the associated couplet in Doppler velocity extrema.

From 1517:43 to 1521:52, a relatively wide, long-lived cyclonic dust devil (the distance between velocity extrema increased with time from approximately 60–70 m to around 150 m) was scanned 25 times at a range that varied from 930 m initially to 1550 m at the end of the scan sequence. Highest ground-relative wind speeds in the dust devil (B) ranged from 10.1–13.6 m s⁻¹. The maximum highest ground-relative wind speeds were greatest early on in the scan and leveled off at around 10–11 m s⁻¹ after 1518:32. When the dust devil had the strongest wind speeds (1518:01), the reflectivity and Doppler velocity fields (Fig. 5) looked similar to those of the other dust devil (cf. Fig. 4).

It is seen (Tables 1 and 2) that while the ranges of the two primary dust devils (A and B) increased monotonically with time, as would be expected for dust devils having a major component of motion in the direction away from the radar, the azimuths (as measured clockwise from the right side of the truck; see Fig. 1, which

<table>
<thead>
<tr>
<th>Time</th>
<th>Ør (°/km)</th>
<th>Δα (+/-)</th>
<th>Maximum Doppler velocity (m s⁻¹)</th>
<th>ΔV (m s⁻¹)</th>
<th>D (m)</th>
<th>2ΔV/D (s⁻¹)</th>
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<td>-</td>
<td>7.0</td>
<td>11.1</td>
<td>33</td>
<td>0.67</td>
</tr>
<tr>
<td>:33</td>
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<td>10.6</td>
<td>40</td>
<td>0.53</td>
</tr>
<tr>
<td>:38</td>
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<td>-</td>
<td>7.2</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>:45</td>
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<td>12.8</td>
<td>40</td>
<td>0.64</td>
</tr>
<tr>
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<td>-</td>
<td>7.6</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>:56</td>
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<td>7.4</td>
<td>11.2</td>
<td>40</td>
<td>0.56</td>
</tr>
<tr>
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<td>123/0.87</td>
<td>-</td>
<td>7.7</td>
<td>12.3</td>
<td>40</td>
<td>0.62</td>
</tr>
<tr>
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<td>6.9</td>
<td>12.0</td>
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<td>0.60</td>
</tr>
<tr>
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<td>6.6</td>
<td>10.2</td>
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<td>0.76</td>
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Table 2. As in Table 1, but for dust devil B.

<table>
<thead>
<tr>
<th>Time (CDT)</th>
<th>( \theta r (\degree /\text{km}) )</th>
<th>( \Delta \alpha (\degree /+) )</th>
<th>Maximum Doppler velocity (m s(^{-1}))</th>
<th>( \Delta V ) (m s(^{-1}))</th>
<th>( D ) (m)</th>
<th>( 2\Delta V/D ) (s(^{-1}))</th>
</tr>
</thead>
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<td>1517:43</td>
<td>136.4/0.93</td>
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<td>12.7</td>
<td>14.1</td>
<td>67</td>
<td>0.42</td>
</tr>
<tr>
<td>18:01</td>
<td>134.9/0.96</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>21:01</td>
<td>134.9/0.97</td>
<td>+</td>
<td>13.6</td>
<td>18.6</td>
<td>80</td>
<td>0.47</td>
</tr>
<tr>
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<td>131.4/1.01</td>
<td>-</td>
<td>12.6</td>
<td>16.7</td>
<td>73</td>
<td>0.46</td>
</tr>
<tr>
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<td>12.9</td>
<td>16.8</td>
<td>67</td>
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</tr>
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<td>19.1</td>
<td>60</td>
<td>0.64</td>
</tr>
<tr>
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<td>+</td>
<td>12.9</td>
<td>16.7</td>
<td>53</td>
<td>0.56</td>
</tr>
<tr>
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<td>-</td>
<td>11.3</td>
<td>18.1</td>
<td>80</td>
<td>0.45</td>
</tr>
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<td>+</td>
<td>10.1</td>
<td>17.8</td>
<td>73</td>
<td>0.49</td>
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<td>+</td>
<td>11.9</td>
<td>17.6</td>
<td>87</td>
<td>0.40</td>
</tr>
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<td>15.3</td>
<td>100</td>
<td>0.31</td>
</tr>
<tr>
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<td>+</td>
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<td>18.3</td>
<td>93</td>
<td>0.39</td>
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<tr>
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<td>X</td>
<td>X</td>
<td>X</td>
</tr>
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<td>16.2</td>
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</tr>
<tr>
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<td>10.5</td>
<td>15.3</td>
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<tr>
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<td>9.8</td>
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</tr>
<tr>
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<td>10.9</td>
<td>14.5</td>
<td>127</td>
<td>0.23</td>
</tr>
<tr>
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<td>15.3</td>
<td>133</td>
<td>0.23</td>
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<tr>
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<td>17.9</td>
<td>107</td>
<td>0.33</td>
</tr>
<tr>
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<td>-</td>
<td>11.1</td>
<td>15.3</td>
<td>107</td>
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<td>16.1</td>
<td>107</td>
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<tr>
<td>23:52</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

shows the truck pointed to the right (to the west); the dust devils were located southeast of the truck, or between 90° and 180° in azimuth] of the dust devils oscillated back and forth with each successive scan; the azimuth increased on the average 1.9° between counterclockwise and successive clockwise scans and decreased on the average 2.6° between clockwise and successive counterclockwise scans. Thus, the centers of the dust devils drifted to the left of the field of view (toward lower azimuth angle), which is consistent with the northwest wind experienced at the truck. The azimuth of the dust devils therefore oscillated back and forth approximately 0.7° on each successive scan. This oscillation rate corresponds to an oscillation in distance normal to the line of sight of the radar of about 11–18 m, which is about 10%–25% of the diameter of the core of the dust devils. Ives (1947; Fig. 2) has documented oscillations in other dust-devil trajectories. However, in the 25 May 1999 case the period of the oscillations coincided with the scanning period, and the azimuths of the dust-devil centers exhibited systematic biases with respect to the direction of scanning; hence, it is strongly suspected that the oscillations were an artifact due to an error in the positioning system. Such an oscillation was not detected in tornado data collected with the same radar in 1999 (Bluestein et al. 2003). However, the tornadoes were at longer ranges, had a larger component of motion in the cross-beam direction, and were in general wider than dust devils. It therefore would have been more difficult to detect such an oscillation if it indeed had existed.

The changes in azimuth and range for the first dust devil (A) scanned were not great enough over the 47-s period it was scanned to estimate a motion accurately. For the second major dust devil (B), it was possible to estimate an average motion: the motion averaged over a 227-s period was 2.7 m s\(^{-1}\) away from the radar in the along-beam direction and 1.1 m s\(^{-1}\) perpendicular and to the left of the beam. Since the truck was oriented parallel to the road and the road was oriented approximately in the east–west direction, then the dust devil moved from the northwest (338°) at 2.9 m s\(^{-1}\). This
estimate of dust-devil motion is consistent with the wind speed and direction at Amarillo (Fig. 2); this estimate will also be considered again later and rechecked using another independent method.

Two adjacent cyclonic dust devils were noted rotating cyclonically around each other during a 32-s interval (Fig. 6). The boresighted videotape was not of high enough resolution to resolve visually the individual vortices. At 1518:07 the main (second) dust devil (B) was probed, while a segment from another dust devil as denoted by a separate reflectivity ring (C) appeared serendipitously along the edge of the scan. The radar operator was focusing on the main dust devil, and the scan was not initially wide enough to capture the beginning of the process of vortex-pair interaction. Over the next four scans, however, vortex interaction could be documented as a line joining the centers of the two vortices, as evidenced by the centers of the reflectivity rings and the Doppler vortex signatures (i.e., velocity couplets), changed orientation consistent with a counterclockwise rotation of each vortex about each other (i.e., about a central axis). The Doppler shear in the main vortex (B) was greater than that of the second vortex of the pair (C). The second vortex of the pair (C) passed out from the scan sector, and attention again was focused on the main dust devil (B) at 1519:48. The way vortices B and C interacted is an example of the Fujiwhara (1923, 1931) effect, which is sometimes observed when tropical cyclones get close enough to interact with each other (Dong and Neumann 1983) so that the vorticity from each one is advected by the wind field from the other (Chang 1983).

The second, main dust devil (B) then widened with time (Table 2). The reflectivity ring associated with vortex B from 1520:26 until the last full scan at 1521:30 was elliptically shaped (Fig. 7). The major axis of the ellipse rotated cyclonically about the center one full revolution in approximately 60 s. The major axis was oriented in the azimuthal direction at 1520:26, in the radial direction at 1520:52, and back in the azimuthal direction at 1521:20. At 1520:38 the major axis was skewed from the radial direction one away and to the other at 1521:10.

Evidence of smaller-scale (a few meters across) vortices embedded within the larger dust-devil vortex can be seen in the Doppler velocity fields (Fig. 8). The reader is referred to Figs. 12 and 13 in BW for the correspondence between an idealized flow pattern of a pair of adjacent cyclonic vortices for three orientations of the line connecting the vortex pair and the Doppler velocity pattern: two cyclones aligned along the radar beam, skewed with respect to the radar beam, and normal to the radar beam. The reader is referred also to Figs. 7 and 8 in BW for the correspondence between an idealized flow pattern of convergent and divergent cyclonic and anticyclonic vortices. The reader also may find it helpful to compare the panels showing the reflectivity structure in Fig. 7 with the corresponding panels showing the Doppler velocity patterns in Fig. 8.

The overall Doppler velocity pattern at 1520:26 is that of a slightly convergent cyclone (cf. Fig. 8a in BW). Embedded within the dust devil–scale (i.e., ~100 m) cyclone is the signature of a cyclonic vortex on its near (with respect to the radar) side (Fig. 8a; cf. Fig. 13f in BW). At 1520:38, the Doppler velocity pattern could be interpreted either as a slightly divergent cyclonic vortex (Fig. 8b; cf. Fig. 8c in BW) or as a skewed vortex pair (Fig. 13b in BW). At 1520:52, the Doppler velocity pattern resembles a cyclone pair skewed slightly (Fig. 8c; cf. Figs. 13h and 13a in BW). At 1521:01, the Doppler velocity pattern could be interpreted either as a slightly convergent cyclonic vortex or a skewed vortex (Fig. 8d; cf. Figs. 8a and 8h in BW). At 1521:10, the Doppler velocity pattern is that of either a highly convergent cyclonic vortex or a skewed vortex pair (Fig. 8e; cf. in BW Figs. 8a and 13b rotated by 90°). At 1521:20 and 1521:30, the Doppler velocity patterns resemble those at 1520:26 (Figs. 8e and 8f; cf. Figs. 8a and 13f in BW). The Doppler velocity patterns seen in Fig. 8 therefore support somewhat the inferences based on the rotation of the elliptically shaped reflectivity ring seen...
in Fig. 7 that there were two vortices rotating cyclonically around a common axis.

While earlier two cyclonic dust devils were observed in close proximity, between 1520:04 and 1520:38, two widely separated dust-devil reflectivity rings and vortex signatures are apparent in each scan, but did not appear to interact. The most prominent signatures were seen at 1520:38 (Fig. 8b); while the main dust devil (B) was cyclonic, the other weaker and narrower vortex signature was anticyclonic. In subsequent scans the anticyclonic dust devil (D) was either outside the sector scanned and/or had dissipated.
b. Profiles of reflectivity, Doppler velocity, vorticity, and divergence through the dust devils

In this section, the relationship among radar reflectivity, the azimuthal wind component, the radial wind component, vertical vorticity, and horizontal divergence in the two major dust devils (A and B) at selected times is discussed. To estimate the wind components and the quantities derived from them, it was necessary to assume that the dust-devil vortices were circularly symmetric. To a first approximation this was deemed reasonable, since most of the reflectivity rings were approximately circular (Figs. 4-7); while some rings were less circular than others, at and after 1520:26, the rings...
were mainly elliptically shaped. The radial profiles of the azimuthal wind component were estimated from the Doppler velocities at the ranges of the centers of the dust devils as a function of azimuth. The radial profiles of the radial wind component were estimated from the Doppler velocities at the azimuths of the centers of the dust devils as a function of range. The Doppler wind data at adjacent ranges and azimuths were also inspected subjectively to make sure that the centers of the dust-devil vortices were correctly located. If adjacent ranges or azimuths had been selected, the results to be discussed would still be valid both qualitatively and quantitatively. Vorticity (divergence) was estimated in polar coordinates from the azimuthal (radial) wind component profiles.

Vortex-relative motion was subtracted from the wind field associated with each dust-devil vortex in the following way: Each profile of azimuthal wind was ad-
Fig. 9. Approximate vortex-relative azimuthal wind component $V$ (solid line; m s$^{-1}$), vorticity $\zeta$ (dashed line; $\times10^3$ s$^{-1}$), and relative radar reflectivity $Z_r = (Z - Z_{\text{noise}})/C$, where $Z$ is the reflectivity factor (dBZ), $Z_{\text{noise}}$ (dBZ) is a subjectively determined approximate noise floor, and $C$ is a dimensionless compression factor chosen subjectively so that the range of relative reflectivity remains within the scale of the figure, in dust devil A, at 1515:33 CDT, as a function of distance from the center of the vortex (m). Negative (positive) distances are measured to the left (right) of the vortex center, as viewed by the radar. The vorticity at the center is estimated as the average of the vorticities computed just to the right and left of the center.

adjusted so that the azimuthal wind component at the center was as close to zero as possible and so that the maxima in the azimuthal wind component on the near and far sides of each vortex were approximately equal. It was not always possible to satisfy both of these conditions exactly, most likely because the vortices were not precisely circularly symmetric, especially at and after 1520:26. The estimated motion in the along-beam direction of the main dust devil (B), using the aforementioned technique, ranged from 2.3 to 3.2 m s$^{-1}$, in which range the estimated mean motion from the track of the dust devil (Table 2) of 2.7 m s$^{-1}$ falls. In the following discussions, it must be remembered that the radial profiles presented are based on the assumption of circular symmetry; there could be some quantitative errors if there were any multiple-vortex structure and/or deviations from circular symmetry.

In dust devil A, at 1515:33 (Fig. 4), the radial profile of dust-devil relative azimuthal wind is like that of a Rankine combined vortex (Fig. 9). The vortex core of A has vorticity of around 0.7–1 s$^{-1}$ and approximately solid-body rotation; it is surrounded by potential flow. A ring of maximum radar reflectivity is coincident with the radius of maximum azimuthal wind (RMW), the distance of the highest azimuthal wind speeds from the center, at 15 m. The vorticity $[O(1 \text{ s}^{-1})]$ is as high as it is in some tornadoes (e.g., Wurman and Gill 2000; Bluestein et al. 2003) because relatively small changes in azimuthal wind speed ($\sim5$ m s$^{-1}$) are found at correspondingly small changes in radial distance ($\sim15$ m).

The radial profile of dust-devil relative radial wind velocity is composed of very small wind speeds [O(1 m s$^{-1}$) or less] and is therefore not known very accurately (not shown). A necessary condition for the radial profile of radial velocity being believable is that it is relatively symmetric about the center; even if it is relatively symmetric, there is still no assurance that it is in fact accurate. However, if the same pattern of symmetric velocities is seen over and over again, we can have more confidence in the profiles. The radial distribution of divergence for the 1515:33 dust devil exhibits no symmetry about the center of the dust-devil vortex and therefore cannot be used to infer the vertical-motion pattern.

The structure of dust devil B is markedly different from the structure of dust devil A (Fig. 10). First, the RMW of B is more than twice as wide (~35 m radius rather than 15 m) at 1518:01, when the vortex produced the strongest ground-relative wind speeds of 13.6 m s$^{-1}$ (Table 2). Rather than behaving like a Rankine combined vortex, vortex B exhibited a 10–15-m-wide annulus of strong shear vorticity just inside the RMW. The center of the vortex had an eye of relative calm of approximately 40 m in diameter; outside the annulus of vorticity there was approximate potential flow. The radar reflectivity profile had a broad, weak-echo eye; a ring of high reflectivity was located within the RMW, not coincident with it.

The radial profile of dust-devil relative radial wind velocity (Fig. 11) that corresponds to the azimuthal wind profile seen in Fig. 10 has divergence near the center and bands of convergence at distances from the center of the vortex that are near or just beyond the RMW. However, the degree of radial symmetry is far from perfect. If the divergence/convergence patterns seen in Fig. 11 are qualitatively correct and representative of the layer of air near the surface, then kinematically there must be sinking motion at the center and rising motion
just beyond the RMW, which is characteristic of two-celled vortices. This inference for the profile shown in Fig. 11 is made with some caution because the vortex-relative radial wind velocities were only \( O(1 \text{ m s}^{-1}) \) and the vortex deviated somewhat from circular symmetry.

Several minutes later (1520:17), the dust-devil vortex exhibited the most circular symmetry (Figs. 12 and 13), while the highest ground-relative wind speeds were several meters per second weaker (Table 2). The RMW had nearly doubled to 65 m in just a few minutes. Vorticity was concentrated, owing mainly to strong radial shear of the azimuthal wind component, in an approximately 15-m-wide annulus just inside the RMW. Approximate potential flow was found both outside and inside the annulus. A nearly calm eye 80 m in width was located inside the annulus of vorticity. As before at 1518:01, the maximum in radar reflectivity fell inside the RMW. Caution must still be applied in the interpretation of the wind profile in this, the most circular-looking vortex, because it seen in Fig. 12b that there was evidence of sub-dust-devil-scale vortex signatures despite the circular appearance of the dust devil. Like the sub-tornado-scale multiple vortices in the tornado described by Wurman (2002), the vortex signatures in dust devil B (Fig. 12b) were apparent only on one side of the vortex.

Although the vortex-relative radial wind component was still only \( O(1 \text{ m s}^{-1}) \), its radial profile exhibited a high degree of circular symmetry (Fig. 14). Inside the eye, a 30-m-wide zone of convergence near the center, which was not distributed symmetrically about the origin, was flanked by a ring of divergence out to near the RMW; beyond the RMW, there was a ring of convergence centered around 70–80 m from the center. It
is inferred kinematically then that the broad eye was characterized by sinking motion, and the area near the RMW was characterized by rising motion. Vortex B therefore still had a two-cell structure. At this time, when the highest degree of circular symmetry is seen and the radial profile of radial wind can be accepted with the highest (in a relative sense) degree of confidence, the centers of the regions of convergence are located beyond the RMW. Thus, the width of the dust devil may have been increasing with time because the annulus of vorticity was propagating radially outward: Low-level convergence acting on the outer portion of the annulus would tend to propagate the annulus radially outward. To test the viability of this hypothesis, radial wind profiles for the scans just before and after that at 1520:17 are now considered.

Thirteen seconds earlier, at 1520:04, the radial profile of azimuthal wind was similar, but not as circularly symmetric (Fig. 15). Again, the maximum in reflectivity was located just inside the RMW, which was at 50–60 m from the center. However, the radial wind profile exhibited a stronger signal, owing to higher vortex-relative radial wind speeds (Fig. 16). Again, there was divergence inside the eye and a ring of convergence centered about 70 m from the center, beyond the RMW.

Nine seconds later, at 1520:26, the radial profile of azimuthal wind still exhibited temporal continuity (Fig. 17). However, the ring of maximum reflectivity coincided approximately with the RMW, and the radial wind profile was highly asymmetric about the origin (not shown).

At the time of one of the last scans through B, about 40 s later at 1521:20, the RMW had not increased any more (Fig. 18). While the overall radial profile of azimuthal wind was relatively circularly symmetric, the radial profile inside the eye of the vortex was not symmetric; the eye was nearly calm on one side, while azimuthal wind speeds were a few meters per second on
the interaction of a small-scale vortex with a rigid lower boundary (Davies-Jones et al. 2001) were observed. The dust devils exhibited much of the range of vortex structure found in tornadoes.

The narrowest dust-devil vortex (A) profile was similar to that of a Rankine combined vortex: It had a central core of nearly constant vorticity surrounded by potential flow. The vorticity of the core averaged approximately 0.8 s$^{-1}$, which is comparable to that of some tornadoes. However, the vorticity was as large as that in some tornadoes, in spite of much weaker wind speeds, because the wind speed varied rapidly over very short distances.

The widest dust devil (B), on the other hand, had a relatively broad, calm eye, characterized by an annulus of vorticity just inside the RMW. Evidence was found of a two-cell structure, with sinking motion near the center and rising motion near the RMW. While this dust devil widened, it became asymmetric and there was some evidence in both the reflectivity and Doppler wind patterns that two sub-dust-devil-scale vortices were propagating cyclonically around the center of the vortex. Although the wind profile was not that of a Rankine combined vortex, it is noted that, according to theory, in a Rankine combined vortex, two Rossby-like waves should propagate at the angular phase speed of $\Omega/2$, where $\Omega$ is the solid-body rotation rate of the core, that is, 1/4 the vorticity of the core (Lamb 1945). Thus, consider the evolution of the wide dust devil (B) between 1520:26 and 1521:20: For vorticity $\sim$0.5 s$^{-1}$ (cf. Figs. 17 and 19), the angular rotation rate of each wave should therefore be 7.1° s$^{-1}$; in 54 s, each wave should move about 387°, or a little more than one revolution about the center of the vortex, which is approximately what was observed (cf. Figs. 7 and 8). For a maximum azimuthal wind speed of $\sim$7.5 m s$^{-1}$ at 65 m from the center, the angular rotation rate of air parcels in the solid-body core is 6.3° s$^{-1}$; thus, the Rossby-like waves retrograde with respect to the mean azimuthal flow.

However, it is not clear how much the theory is applicable to this case of a non-Rankine combined vortex. It is noted, however, that Rotunno (1978) considered the stability of a cylindrical vortex sheet having downward motion near the center and rising motion farther out from the center; his stability analysis is more applicable to dust devil B than it is to a Rankine combined vortex. In this case, for relatively large swirl ratio, he found that wavenumber-2 disturbances could be unstable.

In addition to finding evidence of sub-vortex-scale vortices, it was found that two cyclonic vortices interacted with each other in that they rotated around each other. Such behavior is consistent with the Fujiwhara effect. The radar scans were not wide enough, however, to determine how both vortices formed and became close enough to each other to interact. In the field, it was not noticed whether or not two debris clouds were rotating around each other.

The problem of vortex identification by Doppler radar

4. Summary and conclusions

The behavior of several dust-devil vortices was documented at and within 1.5-km range using a mobile Doppler radar. Four dust devils were noted, three of which were cyclonic and one of which was anticyclonic. The diameter of the vortex cores ranged from 30 to 130 m. The core of the latter [O(100 m)] was much wider than that of typical dust devils in a homogeneous environment [O(10 m)] (in Australia at least) and more like dust devils found on density currents (Hess and Spillane 1990). The width of the dust column of the dust devil seen in Fig. 1 was photogrammetrically analyzed and found to be 45–65 m in diameter. The 20-m uncertainty stems from the variation in range of the dust devils we probed over the time period the photograph was taken. The relationship between the core diameters and width of the visible dust columns is therefore not known. Maximum ground-relative wind speeds ranged from 6.5 to 13.5 m s$^{-1}$; maximum vortex-relative wind speeds were around 9 m s$^{-1}$. A variety of vortex characteristics that are consistent with the dynamics of
is now considered. If the dust devils had been tornadoes detected by a remote radar, then the magnitude of the difference of the Doppler velocity ($\Delta V$) across the vortex signature and the magnitude of the Doppler shear [velocity difference/distance between velocity extrema in the vortex signature ($D$)] would have been considered as parameters used to estimate the likelihood and intensity of a tornado, and subsequently used to aid in tornado warnings (Stumpf et al. 1998; Mitchell et al. 1998). The intensity of the velocity difference ($\Delta V$) and magnitude of the Doppler shear ($\Delta V/D$) converted to vorticity ($2\Delta V/D$) behaved differently (Table 2): The maximum velocity difference was not well correlated with the estimated vorticity. For example, relatively high values of velocity difference were noted at 1520:38 and 1519:23, even though the estimated vorticity was relatively low. Vorticity computed from the estimated azimuthal wind profiles was different in the wide vortex B, because the bulk of the vorticity was concentrated in an annulus about the center of the vortex. Hence, the Doppler estimate of vorticity from $2\Delta V/D$ is not a good one when the wind profile deviates significantly from that of a Rankine combined vortex or when the resolution is not good enough to resolve the vortex structure well. For example, after 1519:48, $2\Delta V/D$ was 0.3 s$^{-1}$ or less, while the actual vorticity was around 0.5 s$^{-1}$ or greater. Even when the dust-devil vortex was like that of a Rankine combined vortex (Table 1), $2\Delta V/D$ was less than the vorticity computed from the wind profile.

There might be instances when the Doppler shear in a tornado is estimated to be relatively low, when in fact it is much higher because it is concentrated on smaller scales. Inferences about changes in tornado intensity based on $2\Delta V/D$ must therefore be made with caution.

Most dust devils were associated with rings of reflectivity. While the maximum in radar reflectivity was sometimes located at the RMW, it more often was located within the RMW. Bluestein et al. (2003) found that in a tornado vortex the maximum in radar reflectivity was also inside the RMW. Snow (1984) demonstrated how particle sheaths form in columnar vortices when the particles are centrifugally ejected. It is assumed that the maximum in radar reflectivity marks the location of either the largest, most reflective particles, or the highest concentration of particles, or both. In the case of the dust devils presented here, one possible mechanism for locating the highest reflectivity within the RMW is that the radar probed the surface layer of the dust devils. In the surface layer, the frictional inflow of air carrying particles that are not heavy enough to fall out are transported inward within the RMW; they then are lofted upward. D. Dowell (2003, personal communication), has shown, using numerical simulations of axisymmetric, one-cell vortices (Dowell et al. 2001), that when relatively small particles of the same size are injected into the vortices, the particles can indeed be concentrated within the RMW. When the particle size is increased, they fall out and never make it into the RMW. Whether or not the results from one-cell vortices can be applied to the two-cell vortices documented herein, however, is not clear.

The effects of centrifuging were also crudely considered. If particles centrifuging radially outward from the dust devils were significant, then the radial air motions in the dust devils that are detected by radar would be contaminated by divergence and therefore kinematic inferences about vertical motions would be in error (Dowell 2000; Wurman and Gill 2000). D. Dowell (2003, personal communication), using his aforementioned model (Dowell et al. 2001), showed that dust particles would have negligible effect on radial velocity. However, for small gravel or large bugs, centrifuging can be significant, accounting in the latter case for as much as 90% of the radial “wind” component. Since the exact sizes and densities of the particles lofted in the dust devils on 25 May 1999 are unknown, it cannot be determined precisely how much centrifuging may have affected our results.

A major lesson learned from the data-collection phase of this study is that scans should sweep past dust devils at much wider angles than is suggested by the visual appearance of the dust clouds alone: Scans should be taken far to the right and left of the edges of dust devils to reveal interactions between the dust devils and their environment, which might contain a larger-scale vortex. It might be revealing to scan the clear-air boundary layer to search for precursor signatures of dust-devil formation. A second lesson learned is that it might be prudent to increase the pulse length when probing tornadoes in order to increase the sensitivity of the radar to the scatterers inside the eye of tornadoes where the reflectivity is relatively weak. In the dust devils, backscattered radiation was detected all the way to the center of the vortices. In the tornado described by Bluestein et al. (2003), there were insufficient detectable scatterers well inside its eye. However, in the tornado study the pulse length was only 15 m rather than 30 m as in this dust-devil study. In other words, it may be necessary to degrade the radial resolution while increasing the sensitivity in order to determine radial profiles all the way to the center, when probing tornadoes.

In late May of 2002, W-band radar data were collected deliberately in dust devils in Arizona. The results of the analyses of this dataset are forthcoming.

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