Observations of Tornadoes and Other Convective Phenomena with a Mobile, 3-mm Wavelength, Doppler Radar: The Spring 1999 Field Experiment

Howard B. Bluestein* and Andrew L. Pazmany+

ABSTRACT

In the spring of 1999 a field experiment was conducted in the Southern Plains of the United States, during which a mobile, millimeter-wavelength pulsed Doppler radar from the University of Massachusetts, Amherst, was used by a storm-intercept team from the University of Oklahoma to collect data in tornadoes and developing tornadoes. With a 0.18° beam antenna, resolution as high as 5–10 m in the azimuthal direction was attained in a tornado on 3 May. Data collected in three supercell tornadoes are described. Features such as eyes, spiral bands, and multiple vortices/wavelike asymmetries along the edge of the eyewall are discussed. Winds approaching 80 m s⁻¹ were resolved without folding using the polarization diversity pulse pair technique. Two tornadoes formed at an inflection point in reflectivity where the hook echo and apparent rear-flank downdraft intersected. Finescale transverse bands of reflectivity were evident in one hook echo. Data in a dust devil are also described. Numerous other datasets collected in mesocyclones are also noted. A plan for future data analysis is suggested and a plan for future experiments and upgrades to the radar are proposed.

1. Introduction

Portable ground-based (Bluestein and Unruh 1989, 1993; Bluestein et al. 1993, 1997b), mobile ground-based (Bluestein et al. 1995; Wurman et al. 1996, 1997; Bluestein et al. 1997a), and airborne (Wakimoto et al. 1996; Wakimoto and Atkins 1996; Wakimoto et al. 1998; Wakimoto and Liu 1998) Doppler radars have been used in the past decade to study the behavior of tornadoes and their parent storms. The advantage of Doppler radars mounted on mobile platforms is that they can be brought relatively close to tornadic storms so that the spatial resolution in the storms is increased, the wind field near the ground can be mapped, the development of the tornadic storms can be monitored more completely over their entire lifetime, the number of cases can be increased, the sensitivity to weak scatterers can be increased, and simultaneous visual documentation can be obtained.

The first portable, ground-based Doppler radar system, which was developed at the Los Alamos National Laboratory, was a 3-cm wavelength (X band), CW/FM–CW system mounted inside a van. Used from 1986 to 1994, its antenna had a half-power beamwidth of 5°; its range resolution in the FM–CW mode was 78 m (Bluestein and Unruh 1989, 1993). The first mobile, pulsed, extremely high frequency (95 GHz-W band) Doppler radar system was developed at the University of Massachusetts, Amherst (the “UMass radar”) and mounted in a van. First used in 1993, its antenna had a half-power beamwidth of 0.7°. The first mobile, pulsed, 3-cm wavelength system, named the “Doppler on Wheels” (DOW), was developed by the University of Oklahoma (OU), the National Severe
Storms Laboratory (NSSL), and the National Center for Atmospheric Research (NCAR) and mounted in a truck and first used during Verification of the Origins of Rotation in Tornadoes Experiment in 1995 (Rasmussen et al. 1994; Wurman et al. 1996; Wurman et al. 1997); its antenna’s beamwidth was 1°.

The following basic scientific questions have been addressed by field programs conducted in the plains of the United States, which have made use of mobile Doppler radars.

1) What are the wind speeds near the ground in tornados and how do they correlate with damage and theoretical thermodynamic expectations?
2) What is the three-dimensional wind field in a tornado?
3) Why do tornados form and dissipate?
4) Why do some convective storms (supercells in particular) produce tornadoes, while others do not?

Wind speeds as high as F5 intensity (117—142 m s\(^{-1}\)) have been measured near the ground (Bluestein et al. 1993) in a tornado. Strong wind speeds have been found even during the rope stage of a tornado (Bluestein et al. 1993), as had been inferred in earlier years from damage surveys (Davies-Jones et al. 1978). The thermodynamic speed limit, when it can be estimated from nearby soundings, is almost always exceeded (Fiedler and Rotunno 1986; Bluestein et al. 1993) and damage is generally commensurate with the radar-indicated wind speed. Evidence has been found of subsidence in the center of a tornado (Wurman et al. 1996).

Answers to the latter two questions, however, have remained elusive. Although hypotheses for tornado formation have been presented (Wakimoto and Atkins 1996; Wakimoto et al. 1998; Wakimoto and Liu 1998), it is still not known why some supercells produce tornados and others do not (Trapp 1999; Wakimoto and Cai 1999). Lack of datasets containing adequate spatial and temporal resolution of the three-dimensional wind field and of the temperature field at very low levels are probably in large part responsible for our lack of understanding.

During the spring storm season (1 April–15 June) of 1999 we used an updated and improved version of the UMass radar to make measurements of wind speeds in tornados and other convective features in the Plains region of the United States. This field experiment, unlike most others, did not have an acronym for its title. However, it was conducted in loose collaboration with others who called their respective experiments Verification of the Origins of Rotation in Tornadoes Experiment—1999 (VORTEX99) and Radar Observations of Tornadoes and Thunderstorms Experiment (ROTATE). During VORTEX99 a mobile mesonet (Straka et al. 1996) was deployed to make in situ thermodynamic measurements at the surface near tornados and in mesocyclones (P. M. Markowski and J. M. Straka 1999, personal communication). In ROTATE, two DOWs were used to collect dual-Doppler and single-Doppler data in tornadoes and tornadic storms (J. Wurman 1999, personal communication).

Prior to the spring of 1999, data from tornados had not been collected by the UMass radar. The purposes of this paper are to present an overview of the 1999 experiment using the UMass radar, describe the nature of the datasets collected, note some preliminary significant findings, outline a plan for analyzing the datasets collected, and suggest modifications for future experiments. The mobile radar system is described briefly in section 2. The methodology of the field experiment is discussed in section 3. A list of datasets collected is detailed in section 4. Section 5 contains a summary of the field experiment and plans for future data analysis and future field programs.

### 2. Description of the mobile radar system

The UMass 3-mm wavelength, mobile, Doppler radar system (Bluestein et al. 1995), which was previously mounted in a van, was remounted in a new Ford 350 Crewcab pickup truck (Fig. 1) so that a larger antenna could be used effectively. A 1.2-m (4 ft) Cassegrain dish antenna was added to the radar in place of the previous 0.3-m (1 ft) lens antenna to improve spatial resolution and sensitivity. With the new antenna, which has a half-power beamwidth of 0.18°, it is possible to achieve azimuthal resolution of just under 10 m at 3-km range with a relatively small structure. The radial resolution is 15 m at all ranges. The antenna is housed in an enclosure and is quickly slid on rails rearward when fully deployed. A video camera is mounted on the antenna so that boresighted video of the radar’s field of view can be determined. The generator is mounted at the rear of the truck.

The radar transmitter was redesigned and rebuilt with a multiplier chain to eliminate a previously used, unreliable W-band (3-mm wavelength) preamplifier. An all Hewlett-Packard (HP) VXI data system with new software was added to the radar, which increased...
the rate of data acquisition over 20 times and thus increased the scan rate, improved the sensitivity, increased the spatial resolution, and increased the number of range gates sampled. The transmitter, power supply, computers, a video recorder, and video monitors were mounted inside the cab of the pickup truck. The radar operator was seated in back of the cab. A driver and team leader were seated in the front.

A hybrid transmit pulse train was developed to combine the high maximum unambiguous Doppler velocity and range of polarization diversity pulse pairs (PDPP) with the precision of conventional pulse pairs (Doviak and Sirmans 1973; Bluestein et al. 1995; Pazmany et al. 1999). Since the PDPP technique is noisier than the conventional pulse-pair technique, the PDPP data are used to unfold the conventional pulse-pair data whenever possible. A drawback of the PDPP method is that it does not work at very close range (within about 1.5 km), owing to the finite polarization isolation of the switch network and antenna. To operate the radar at a safe distance from tornadoes, however, we tried to avoid collecting data at ranges closer than about 1.5 km. Detailed specifications of the radar system are found in Table 1. In the interest of brevity, the reader is referred to the aforementioned papers for details on how PDPP works.

Radars operating at 3-mm wavelengths are subject to extreme attenuation in heavy precipitation. We hoped that the radar would be sensitive enough to collect high quality data at ranges of 3–5 km even in the presence of heavy precipitation. Any clear-air return is probably from insects in the boundary layer. We hoped also that the radar would be sensitive enough to collect high quality data in clear air out to 3 km or so.

3. Methodology

We conducted field operations much as they have been for over 20 years (Bluestein 1999). Our base of operations was the School of Meteorology at OU. Decisions were made in the morning whether to conduct field operations and if so, what location to target. Our forecasts were made based on surface data, soundings, satellite imagery, profiler data, both operational and experimental mesoscale model output available via computer over the Web, and on forecast discussions issued by the Storm Prediction Center. We discussed our strategies and forecasts with Josh Wurman and his DOW group based at OU, and with Erik Rasmussen (NSSL/NCAR) and Jerry Straka (OU) and their mobile-mesonet group, based at NSSL. We shared information with all units in the field via cell phone. We also made use of information from National Oceanic and Atmospheric Administration Weather Radio broadcasts, local radio station programming, and local television station broadcasts.

In our group the team of six occupied two vehicles: the UMass radar truck, which holds three participants, and a “follow” car, a station wagon rented from OU, which holds three or four (if there was a visitor). The radar truck was in constant communication with the follow car via FM radio. Our group eschewed using
<table>
<thead>
<tr>
<th>Specifications of the UMass mobile radar system.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmitter</strong></td>
</tr>
<tr>
<td>Operating frequency</td>
</tr>
<tr>
<td>Transmitter power</td>
</tr>
<tr>
<td>Transmit pulse length</td>
</tr>
<tr>
<td>Polarization</td>
</tr>
<tr>
<td><strong>Receiver</strong></td>
</tr>
<tr>
<td>Noise figure</td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>Dynamic range</td>
</tr>
<tr>
<td>Sampling resolution</td>
</tr>
<tr>
<td>Range window</td>
</tr>
<tr>
<td>Max. range</td>
</tr>
<tr>
<td>Radar parameters</td>
</tr>
<tr>
<td>Max. unambiguous velocity</td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>Beamwidth (3dB)</td>
</tr>
<tr>
<td>Scan rate</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
</tr>
<tr>
<td>Averaging</td>
</tr>
<tr>
<td>Single pulse, 0 dB SNR</td>
</tr>
</tbody>
</table>

either FM or cell phone communication while collecting data, owing to the potential for contamination of the recorded data by the communication signals. This communication silence made it difficult to coordinate operations with other units, including our own, when tornadoes were being probed.

4. Description of cases

The 1999 tornado season turned out to be one of the most active in recent years in the Southern Plains. We collected data on nearly all of the days on which we had field operations and tornadoes or funnel clouds were observed on six of those days. The most useful data were recorded in tornadoes on 3 May, 15 May, and 5 June (Table 2). Other significant (i.e., extensive and well documented) datasets were collected in dust devils (25 May) and in nontornadic mesocyclones (16 May, 20 May, 25 May, 31 May, and 4 June).

a. 3 May 1999

The second day of field operations was during a major tornado outbreak on 3 May. The first tornado dataset we collected was south and east of Verden, Oklahoma. The circulation from this tornado eventually produced the highly destructive and publicized tornado that moved through parts of Oklahoma City and Moore. The tornado formed as a number of multiple vortices (Fig. 2) to our south and southeast, and consolidated into a single condensation funnel to our east (Fig. 3). It was decided that since we first needed to demonstrate that a millimeter-wavelength radar could probe tornadoes successfully, we focused on simple sector scans at the lowest elevation angle possible, to map the reflectivity and Doppler velocities as close to the ground as we could. We repeated scans at this one elevation angle only to minimize the time between scans; scans were taken every 15–20 s. We also collected data while holding the beam fixed, so that the entire tornado passed through the beam.

Reflectivity data collected in the tornado look like radar data from a hurricane, since they display spiral bands and an eye (Fig. 4, top), features that have been noted previously in hurricanes and other tornadoes with the DOWs (Wurman et al. 1996). The millimeter-wavelength radar was able to penetrate through the...
tornado with no limiting effects from attenuation. Some attenuation, however, was evident; for example, the radar reflectivity on the side nearest the radar was higher than it was on the far side. An expanded view of the eye shows wavelike structures (Fig. 4, lower left) that are reminiscent of the waves seen in dishpan experiments years ago (Fultz et al. 1959); the wavelike structures might be evidence of multiple vortices. Unfortunately, it was impossible to see if the waves were coherent and propagating around the tornado because even in the relatively short time between scans the waves could have propagated all the way around the tornado.

The Doppler velocity field along the edge of the eyewall shows several smaller-scale couplets in velocity (Fig. 4, lower right) that might be manifestations of subvortices within the tornado. This suggestion is tentative, however, owing to our uncertainty of the wind measurements related to the PDPP technique and to the relatively weak radar backscattering in the eye. However, increasing the threshold for data rejection owing to noise did not remove all the couplets, a few of which exhibit local maxima and minima in Doppler velocity that encompass a number of contiguous pixels (not shown). The multiple-vortex phenomenon has been studied extensively and a number of hypotheses for it have been presented (Snow 1978; Staley and Gall 1979; Gall 1983; Rotunno 1984; Staley and Gall 1984; Schubert et al. 1999). Recently large eddy simulations of tornadoes have reproduced asymmetric structures similar to those seen in Fig. 4 (Lewellen and Lewellen 1997; see their Fig. 8; D. C. Lewellen 2000, personal communication). It is possible that some of the smaller-scale elements of high Doppler velocity inside the eye could be flying debris.

Doppler-velocity data at low elevation angle in the PDPP mode resolve unfolded Doppler velocities in excess of 70 m s$^{-1}$ (Fig. 4, lower right), which is in the F3 range of the Fujita scale (Fujita 1981). Folded velocities beyond 80 m s$^{-1}$ were not evident. The National Weather Service estimate of the damage was also F3 (Fig. 5). At the range of the tornado from the radar (3.4 km) the azimuthal resolution was only about 10 m inside the eye.

A plot of Doppler velocity at a range of 3.4 km (see Fig. 4, top) represents the tangential wind speed as a

---

**Table 2. Significant datasets collected by the UMass mobile Doppler radar system in 1999.**

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 May</td>
<td>Tornado southeast of Verden, OK; low elevation angle sector scans at close range; detailed damage survey done on 6 May; tornadoes observed west of Minco and east of Amber, OK, but data not collected.</td>
</tr>
<tr>
<td>11 May</td>
<td>Vertically pointing data across a front in south-central Oklahoma.</td>
</tr>
<tr>
<td>15 May</td>
<td>Life cycle of a tornado southwest of Stockton, KS; low elevation angle sector scans; VAD about 10 km east of storm 10 min prior to tornado formation; damage survey done on 16 May.</td>
</tr>
<tr>
<td>16 May</td>
<td>Developing supercell near Taloga, OK; low elevation angle sector scans; RHIs (range–height indicator) through updraft tower.</td>
</tr>
<tr>
<td>20 May</td>
<td>High precipitation supercell in the eastern Texas Panhandle; low elevation angle sector scans; two tornadoes observed but data not recorded.</td>
</tr>
<tr>
<td>25 May</td>
<td>Dust devils near Tell, TX; nontornadic supercells in northwest Texas; low elevation angle sector scans.</td>
</tr>
<tr>
<td>26 May</td>
<td>Nontornadic supercells near Carlsbad, NM, and Kermit, TX; low elevation angle sector scans.</td>
</tr>
<tr>
<td>27 May</td>
<td>Cumulimbus mamma in Odessa, TX; RHIs.</td>
</tr>
<tr>
<td>31 May</td>
<td>Supercell near Meade, KS, that produced softball-size hail and a tornado (no data collected); low elevation angle sector scans of storm; RHIs in anvil.</td>
</tr>
<tr>
<td>3 Jun</td>
<td>Storms in Texas panhandle; no data collected.</td>
</tr>
<tr>
<td>4 Jun</td>
<td>Supercell north of Tryon, NE, that produced three tornadoes; low elevation angle sector scans.</td>
</tr>
<tr>
<td>5 Jun</td>
<td>Life cycle of a tornado west of Bassett, NE; low elevation angle sector scans.</td>
</tr>
</tbody>
</table>
function of radius in the tornado (Fig. 6) if the scatterers were moving along with the horizontal components of the wind. The “core” radius of a vortex is the radius at which the tangential wind speed is the highest; the core of the tornado extends from zero radius out to the radius of maximum tangential wind speed (Davies-Jones 1986). The variation of tangential wind speed within the core of the 3 May tornado is approximately linear with respect to radius, that is, the tornadic flow is in solid-body rotation, as in a combined Rankine vortex (Davies-Jones 1986); outside the core it falls off much more slowly, but not as the inverse of the radius, that is, without vorticity, as in a combined Rankine vortex. The diameter of the core of the tornado was 400 m; the diameter of the reflectivity signature was approximately 1600 m. The diameter of the condensation funnel, estimated photogrammetrically, was approximately 450 m at cloud base and narrowed down to 175 m near the ground; the diameter of the visible debris cloud near the ground was 650 m. It thus appears that many of the targets detected by the radar lay outside the condensation funnel. It is likely that many of the scatterers were precipitation particles since the reflectivity image of the tornado was much wider than both the visible debris cloud and the condensation funnel.

b. 15 May 1999

On 15 May 1999 we were fortunate to collect a velocity azimuth display (VAD) (Doviak and Zrnic 1984) in the boundary layer approximately 10 km east-southeast of the updraft base of a supercell that produced a tornado in northwest Kansas, 8 km to the north, just southwest of Stockton, about 10–15 min later. The VAD was computed from approximately 2.5–3 scans at 45° elevation angle, over 3/4 of a cone, over about a 1-min period. The enhanced vertical wind shear in the 740–1060-m above ground level (AGL) layer of the hodograph of this VAD (Fig. 7) is a result of easterly outflow from earlier storms undercutting an environment of southeasterly, southerly, and southwesterly flow. The horizontal vorticity associated with this shear layer, which was directed toward the west, was substantial ($6 \times 10^{-2}\text{ s}^{-1}$) and could have been the source for a strong low-level mesocyclone if it had been tilted onto the vertical by the storm’s updraft, that is, if air parcels had flowed westward in the easterly flow and into the supercell’s updraft near cloud base. Measurements of boundary layer horizontal vorticity in the environment of supercells are rare (e.g., Dowell and Bluestein 1997) but are necessary to verify the source of vorticity in low-level mesocyclones and tornadoes (Davies-Jones and Brooks 1993).

A set of scans was collected at low elevation angle only, beginning just seconds after the tornado appeared and continuing every 12–15 s (Fig. 8) until after the tornado had gone through the rope stage and dissipated. During the early life history of the tornado it appeared as a doughnut in reflectivity, connected to the edge of the hook echo by a thin (100 m or less in width) curtain of precipitation that looked like an umbilical cord, and to an echo we believe marked the leading edge of the rear-flank downdraft (Fig. 9, first panel, lower half). This echo is associated with a surge of about 20 m s$^{-1}$ toward the radar (not shown). Hoskins et al. (1985) have described umbilical cord-like features in the potential vorticity field of cutoff, synoptic-scale extratropical cyclones. It is believed that the dynamics of this “vortex rollup” phenomenon on the
scans at low elevation angle varying from every 40 s when the tornado was farthest away to every 10 s when the tornado was closest (Fig. 10). Well before the tornado formed, the hook echo extended to an inflection point, which probably marks the intersection of the leading edge of the rear-flank downdraft with the hook echo (Fig. 11, upper-left panel, $x = -2, y = 6.7$). That the inflection point marked the leading of the rear-flank downdraft is supported by Doppler velocities of 25–30 m s$^{-1}$ toward the radar (not shown) before the tornado appeared. A small curved band is discernible near the inflection point. Some 100-m-scale transverse bands of reflectivity of unknown origin are visible along much of the 2-km wide hook echo (lower-right portion of upper-left panel). As the inflection point progressed toward the radar, the curved band rolled up (Fig. 11, upper-right panel, $x = -2, y = 5.4$ and lower-left panel, $x = -2, y = 3.3$) and eventually developed into an echo hole (Fig. 11, lower-right panel, $x = -2, y = 2.3$) associated with the tornado. As in tornado scale have not been investigated. R. P. Davies-Jones (2000, personal communication) has recently argued, however, that curtains of precipitation near hook echoes may actually contribute to tornado formation, rather than be a passive response. During the mature stage of the tornado, its radar-reflectivity depiction looks like that of a tropical cyclone, with concentric inner bands and outer spiral bands (Fig. 9, center panel). During the rope stage the circulation was still evident (Fig. 9, right panel) and the scale of the velocity couplet associated with the tornado vortex had contracted (not shown).

c. 5 June 1999

The tornadogenesis process was captured in far north-central Nebraska west of Bassett on 5 June with

Fig. 5. Damage from the tornado that corresponds approximately to the time of the photograph in Fig. 3 and the data shown in Fig. 4 (6 May 1999; photograph copyright H. Bluestein).

Bulletin of the American Meteorological Society
FIG. 6. Doppler velocity as a function of distance from the center of the tornado vortex at 3.4-km range, from the tornado data shown in Fig. 4. Positive (negative) distances from the center of the tornado are to the right (left) with respect to the view of the radar. The spikes at distances greater than 0.7 km (1 km) to the left (right) of the center of the tornado and near the center of the vortex are probably erroneous, owing to a relatively low signal level.

5. Summary

Based on the results of the field experiment conducted in the spring of 1999 we conclude that the UMass millimeter-wavelength radar is able to probe tornadoes and pretornado structures at distances as remote as almost 10 km and make significant mea-

FIG. 7. Hodograph constructed from VAD data collected by the radar (see the text for details) approximately 1838 CDT 15 May 1999, 6.1 km north of Plainville, KS. Heights shown are in km AGL.

FIG. 8. Tornado southwest of Stockton, KS, being probed by the UMass radar to its west northwest at approximately 1902 CDT 15 May 1999. OU graduate student C. Weiss is seen in motion on the far right (photograph copyright H. Bluestein).
measurements of reflectivity and Doppler velocity. In the three tornadoes we successfully probed, none was affected by attenuation to the extent that the signal was below the noise level. Furthermore, the PDPP technique worked in the face of wind speeds approaching 80 m s\(^{-1}\); prior to the 1999 experiment, we had not recorded wind data representing tornadic wind speeds. The radar was also sensitive enough to allow for the calculation of VADs in the boundary layer.

Even though it is premature to draw significant scientific conclusions from our datasets, pending much more intensive analysis, we briefly highlight some significant preliminary findings. Based on our limited sample of cases and others documented by the DOWs (Wurman et al. 1996; J. Wurman 2000, personal communication), it appears that many tornadoes (and even vortices not intense enough to be classified as tornadoes), have “echo-free eyes” (Fujita 1981). In addition, the radar-reflectivity structure of tornadoes also exhibits spiral bands. High-resolution reflectivity images of tornadoes look very much like those of hurricanes.

Evidence was found of multiple vortices or wave-like asymmetries along the “eyewall” of some tornadoes. The evolution of the tornadoes occurred on minute timescales. In one case in which there was documented damage from the tornado while data were collected, the F-scale inferred wind speeds agreed well with the radar measurements. In both cases for which tornadogenesis was documented, the tornado formed at the inflection point between what appeared to be the radar echo associated with the rear-flank downdraft and the hook echo. In one hook echo, small-scale tranverse bands of unknown cause are evident. In the rope stage of a tornado the maximum winds remained intense (Golden and Purcell 1978a,b; Bluestein et al. 1993), but the spatial scale of the tornado’s vortex signature contracted, as implied by the visually shrinking condensation funnel.

Although it would be desirable to use a second mobile Doppler radar to collect dual-Doppler data on tornadoes as suggested by Bluestein et al. (1995), and implemented recently with 3-cm wavelength mobile radars by Wurman and collaborators (J. Wurman 2000, personal communication), millimeter-wavelength radars are too expensive to adopt this strategy at this time, unless existing ones such as that operated by the University of Miami (Albrecht et al. 1999) is modified for mobile operations and for much faster moving targets.

We will be attempting to use some currently available techniques to estimate the horizontal wind field using the single-Doppler wind data we have collected. The tracking radar echoes by correlation (TREC)

---

**FIG. 9.** Radar reflectivity in dBZ of the tornado shown in Fig. 8 (left) during the early stage of its life, (center) during its mature stage, and (right) during its dissipating, rope stage. Color code is indicated at the bottom. Times are shown in CDT.

---

**FIG. 10.** Tornado southwest of Bassett, NE, at approximately 2017 CDT 5 Jun 1999. View is to the south (photograph copyright H. Bluestein).
FIG. 11. Radar reflectivity in dBZ at three times during the life cycle of the tornado shown in Fig. 10 (top left and top right) before the tornado formed, (bottom left) as the tornado was forming, and (bottom right) during the mature stage of the tornado. Color scale is shown below. Times are given in CDT.

method, which makes use of sequences of reflectivity images (Rinehart and Garvey 1978), has been successfully applied to clear-air boundary layer flow (Tuttle and Foote 1990) and tropical cyclones (Tuttle and Gall 1999). Since the tornado data look like scaled-down versions of tropical cyclone data, there is hope that TREC might be successfully applied to tornadoes. However, since the scans of tornadoes in 1999 were collected about every 10–20 s, air parcels within the core of the tornadoes would have moved approximately all the way or a substantial fraction of the way around the tornado vortex. Thus, to apply TREC to data from the UMass radar we would have to reduce the time between scans by an order of magnitude. It may be possible, however, to apply TREC to pretornado conditions under and near the wall cloud when wind speeds are subtornadic.

The ground-based velocity track display (GBVTD) technique developed by Lee et al. (1999) for tropical cyclones is another method that might be applied to the tornado data. This scheme is suitable for use with tornado data since the GBVTD technique is based on the assumption of a circular vortex. The radial profile of tangential and radial wind components and the mean flow can be estimated using it. Finally, techniques for combining either or both of the aforementioned methods along with the raw single-Doppler data via weak constraint variational formulations should be investigated.

If the vertical velocity field in tornadoes is to be computed kinematically, the horizontal wind field is needed at multiple levels. Since in 1999 we chose to scan only at the lowest elevation possible, vertical velocity might be estimated based on our analyses only near the ground. In the future we need to scan through a number of elevation angles so that the vertical structure of tornadoes can be ascertained. To do this we would have to increase the time it takes to complete successive volume scans, so that we would be compromising temporal resolution. The radar antenna could scan mechanically more rapidly than it already does. However, the data cannot be sampled and stored quickly enough to keep up with the rate at which it is being generated. The solution is a faster data acquisition system. Once three-dimensional data are available, dynamically important quantities such as swirl ratio and vortex aspect ratio can be computed (Nolan and Farrell 1999).

An impediment to the analysis of tornado data is that the targets seen by the radar are not exactly following air motion, owing to the centrifuging radially outward of debris and water droplets. Dowell (2000)
has estimated that in a tornado the spurious divergence caused by centrifuging can significantly corrupt the real divergence or convergence of the air. A possible way to solve this problem, at least partially, is to estimate the size of the scatterers, so that the centrifuging component of motion can be removed. Probing the tornado at two different frequencies (e.g., at 3-cm and 3-mm wavelengths) and then comparing the amounts of attenuation at each frequency might provide some information on the size of the scatterers (Wexler and Atlas 1963).

Another problem that needs to be solved is devising a scheme to edit out data that are erroneous. The simplest scheme is to reject data whose returns are below some threshold. However, as a result of the complexity of the PDPP technique, such a strategy may not be entirely successful and other factors will have to be considered.

In order to maximize the usefulness of the data, they should be augmented by data from other radars and sensors. Broader-view scans of the entire storm by the DOWs would allow us to nest the millimeter-wavelength radar data analysis inside the DOW dual-Doppler analysis. Such an undertaking would involve much tighter coordination than we had in 1999. The problem of communication contamination could be solved by having a follow car do most of the transmitting while data are being collected. The problem of having three or four vehicles that travel at different rates of speed could be solved by being more disciplined and designating a coordinator who will use all the information available to him/her to direct all the vehicles. However, as many years of experience show, in the heat of the chase, when a tornado is visible, each vehicle must move independently of the others.

Finally, other techniques that could be exploited in the future are phased-array antennas and/or multiple-beam antennas (J. Wurman 2000, personal communication) for more rapid scanning.

**Fig. 12.** Radar depiction of a dust devil near Tell, TX, at 1520 CDT 25 May 1999. (left) Radar reflectivity in dBZ; (right) Doppler velocity (which folds at 8 m s\(^{-1}\); folding has not been corrected) in m s\(^{-1}\). Color codes are at the right of each panel.

**Acknowledgments.** This project was funded by NSF Grants ATM-9612674 to OU and ATM-9616730 to the University of Massachusetts, Amherst. The author is grateful to the School of Meteorology at the University of Oklahoma for its support and to the Mesoscale Microscale Meteorology (MMM) Division of the National Center for Atmospheric Research (NCAR) for its support during the summer of 1999. NCAR is funded by the National Science Foundation. Andy Pazmany (UMass) operated the UMass radar; Chris Weiss (OU graduate student) was the backup radar operator. Chris Weiss, Greg Lehmliller, and Pete Leptuch (OU graduate students) shared the driving, and rotated their time between the UMass radar truck and the follow car. H. Bluestein (OU) acted as the team leader in the radar truck. David Dowell (OU graduate student) in the follow car provided navigation information and assisted in getting real-time data in the field. Chris Weiss, Greg Lehmliller, and David Dowell assisted with the preliminary processing of the radar data. Erik Rasmussen (NSSL/CIMMS) provided valuable and expert nowcasting from his base in Boulder. Josh Wurman (OU) and Jerry Straka (OU) are acknowledged for sharing timely information during the experiment. Two anonymous reviewers provided useful suggestions.

**References**


With the development of meteorological science and the continual refinement of the technologies used in its practical application, the need to produce a new edition of the *International Meteorological Vocabulary* (IMV) became evident (the original edition was published in 1966). This volume is made up of a multilingual list of over 3500 terms arranged in English alphabetical order, accompanied by definitions in each of the languages (English, French, Russian, and Spanish) and an index for each language. This new edition has been augmented with numerous concepts relating to new meteorological knowledge, techniques, and concerns. It should help to standardize the terminology used in this field, facilitate communication between specialists speaking different languages, and aid translators in their work.

WMO No. 182, 784 pp., softbound, color-coded index, $95 (including postage and handling). Please send prepaid orders to: WMO Publications Center, American Meteorological Society, 45 Beacon St., Boston, MA 02108-3693. (Orders from U.S. and Canada only.)

**International Meteorological Vocabulary**
Mid-Latitude Weather Systems is the first text to make extensive use of conventional weather charts and equations to fully illustrate the behavior and evolution of weather patterns. With the use of well-documented case studies, Pennsylvania State University Professor of Meteorology Toby Carlson has achieved a unique presentation of selected concepts, which facilitate a clear interpretation of this active and challenging area of study.

Presenting a fusion between the mathematical and descriptive fields of meteorology and integrated coverage of synoptic and dynamic approaches, Mid-Latitude Weather Systems provides students with an invaluable course text and reference source to gain an unclouded appreciation of the underlying processes and behavior of mid-latitude weather patterns.

A publication of the American Meteorological Society

Mid-Latitude Weather Systems is available for $42/list, $32/AMS members, or $22/student members, by sending prepaid orders to: Order Department, AMS, 45 Beacon Street, Boston, MA 02108-3693. Please make checks payable to the American Meteorological Society, or call 617-227-2425 to order by phone (Mastercard, VISA, and American Express accepted).