PICTURE OF THE MONTH

An Analysis of the 7 July 2004 Rockwell Pass, California, Tornado: Highest-Elevation Tornado Documented in the United States

JOHN P. MONTEVERDI
San Francisco State University, San Francisco, California

ROGER EDWARDS
Storm Prediction Center, Norman, Oklahoma

GREGORY J. STUMPF
Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, Oklahoma, and Meteorological Development Laboratory, NOAA/NWS, Office of Science and Technology, Silver Spring, Maryland

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ABSTRACT

This manuscript documents the tornado in the Rockwell Pass area of Sequoia National Park, California, that occurred on 7 July 2004. Since the elevation of the tornado’s ground circulation was approximately 3705 m (12156 ft) MSL, this is the highest-elevation tornado documented in the United States. The investigation of the storm’s convective mode was performed mostly inferentially on the basis of an analysis of the radar imagery from Edwards Air Force Base (which was in clear-air mode on this day), objectively produced soundings and/or CAPE estimates from two mesoscale models, an objectively produced proximity sounding and hodograph, and analyses of satellite imagery. The nearest Weather Surveillance Radar-1988 Doppler (WSR-88D) in Hanford, California, could not be used to observe this storm because of terrain blockage by the Sierra Nevada, and the nearest sounding sites were too distant and in a different meteorological environment on this day. The near-storm environment may have been favorable briefly for a supercell in the upper portion of the Kern River Canyon. The limitations of the radar data precluded the authors from making a definitive conclusion on the convective mode of the storm but do not rule out the possibility that the storm briefly might have been a supercell. There was insufficient evidence, however, to support the notion that the tornado itself was mesocyclone induced. High LCL heights in the proximity sounding also suggest that the tornado was formed by processes not associated with a mesocyclone (popularly known as a “landspout”), but do not allow us to dismiss the possibility that the tornado was mesocyclone induced.

1. Introduction

At 2332 UTC (1632 PDT) 7 July 2004, a backpacker, Scott Newton, hiking near Rockwell Pass in Sequoia National Park (west of Mount Williamson in the southern Sierra Nevada) observed cloud-base rotation and an associated funnel cloud (Fig. 1). The parent thunderstorm (Fig. 2) had formed west of Rockwell Pass over the upper sections of the steeply walled Kern River Canyon (Figs. 3 and 4). Mr. Newton was hiking southward toward the Wrights Lake basin and was nearing the pass itself (Fig. 5).

By 2337 UTC a condensation funnel had extended downward to the east of the ridgeline just south of Rockwell Pass about 1 km from Mr. Newton’s location (Figs. 5 and 6). Although Mr. Newton did not see the portion of the tornado in contact with the ground, debris is clearly seen on this photo southwest of his location, and at a higher altitude. Other hikers in the area also noted the tornado and lofted debris, though there are no...
other photographs. Thus, the tornadic circulation was at ground level at that time.

Mr. Newton reported the elevation of the location from which he took the pictures as approximately 3620 m (~11 880 ft).\(^1\) Based upon his descriptions and his location map (Fig. 5), the tornado’s ground position was just east of the ridge that extends initially southward and then southward from Rockwell Pass, whose elevation is 3687 m (~12 095 ft). Mr. Newton reported that the tornado was about 1 km from his location, but also estimated that it may have been as close as 0.5 km (~0.3 mi) or as far as 1.3 km (~1.0 mi) from him. Based upon his plot as summarized in Fig. 5, the tornado’s elevation was probably between 3680 m (12 073 ft) and 3730 m (12 238 ft). The average of this range is 3705 m (~12 256 ft). Thus, we believe this to be the highest-elevation tornado photographed and documented in the United States.\(^2\)

Mr. Newton estimated that hail with diameters 1.9–2.5 cm (0.75–1 in.) (Fig. 7) accompanied the Rockwell Pass storm and covered the ground in places. Falling hail can be seen as white streaks in the photographs shown in Figs. 1 and 6.

Although tornadoes are not rare in California (e.g., Monteverdi et al. 2003), documentation on tornadoes in the mountainous areas of California and other states is sparse. By coincidence, a tornado that occurred in the same general geographic area was observed and documented in the late 1970s (Bluestein 1979).

The most famous and well-documented supercell tornado in high mountains (see Table 1 for a listing of the five highest-elevation tornadoes in the United States) was the F4-rated Yellowstone/Teton Wilderness tornado of 1987 (Fujita 1989). This tornado and parent thunderstorm formed in an area with topography as rugged as that in the southern Sierra Nevada, although elevations in the Rockwell Pass area are much higher. Nuss (1986) observed another very high-elevation tornado near Longs Peak, Colorado. A high-elevation [2700 m (8858 ft) MSL] mesocyclone-induced tornado occurred in rugged terrain near Divide, Colorado, in 1996 and was documented by Bluestein (2000). Two other high-elevation tornadoes

\(^1\) All elevations determined by authors and Mr. Newton using Google Earth.

\(^2\) This tornado is being considered for inclusion in the Guinness World Records as the highest-elevation world tornado.
(Table 1) observed near Mount Evans, Colorado, in 2012 and in the Ashley National Forest, Utah, in 1993 have not yet been documented in the refereed literature, and the authors have accepted the elevations as listed in National Weather Service (2014) and (National Climatic Data Center) NCDC (1993), respectively.

The purpose of this paper is to present photographic documentation and an examination of the synoptic and thermodynamic controls of this event. An interesting issue was the convective mode of the parent thunderstorm. Because of this we focused on establishing the shear setting, to the degree it was possible, and on examining the evidence for convective mode on the basis of the available radar information.

2. Data sources

a. Surface data

The location of this event (Figs. 3 and 4) presented a challenge in documenting the Rockwell Pass storm meteorologically. Although there were several surface observation sites nearby, they were located in the Owens Valley to the east, at a much lower elevation, and in a desert environment.

Fortunately, there were data available for the Remote Automated Weather Station (RAWS) at Rattlesnake, a surface observational platform located in the Kern River Canyon about 15 km south of Rockwell Pass (Figs. 3 and 4). The temperature, dewpoint, and wind for the afternoon hours between 1900 and 2300 UTC 7 July 2004 (see Table 2) from Rattlesnake (at 2621 m MSL) indicated an abruptly strengthening upvalley (southerly) flow with gradually increasing temperatures and dewpoints. This is important because the tornadic thunderstorm developed west of Rockwell Pass in the headwaters area of the Kern River northwest of Rattlesnake.

b. Radar data

Although the Weather Surveillance Radar-1988 Doppler (WSR-88D) at Hanford, California (KHNX) (see Fig. 3), was located fairly close to the event, the eastern portion of Sequoia National Park is topographically blocked from the radar’s field of view. The Department of Defense’s Doppler radar at Edwards Air...
Force Base (KEYX; Fig. 3) observed the Rockwell Pass thunderstorm, though from a great distance (Table 3). Since the level-II data for KEYX were not archived, the lower-resolution level III data had to be used instead. Unfortunately, since the KEYX radar was in clear-air mode on the day of the Rockwell Pass tornado, the highest reflectivity archived in this mode was 28 dBZ.

c. Sounding data

The tornado location was between National Weather Service (NWS) radiosonde sites (see Fig. 3) at Reno, Nevada (KRNO); Desert Rock, Nevada (KDRA); Elko, Nevada (KEKO); and Vandenberg Air Force Base, California (KVBG). All of these were distant enough from the tornadic storm or at distinctly different elevations to preclude the direct use of their data for establishing its proximity thermodynamic and shear environment. An objectively produced sounding and hodograph interpolated from the available radiosonde data and numerical model soundings and plots were examined instead (section 3a).

d. Satellite imagery

Fortunately, the catalog of satellite imagery from the Geostationary Operational Environmental Satellite (GOES) for 7 and 8 July 2004 is extensive. The authors obtained 1-km resolution satellite visible imagery from

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FIG. 3. Outline map showing location of Rockwell Pass, the Rattlesnake RAWS site, the Kern River Gorge, and Kings Canyon/Sequoia National Parks (inset) in relation to sounding and radar sites utilized in sounding and hodograph reconstructions and radar analyses, as explained in text. (Background outline map: Terry Dorschied, Arizona Geographic Alliance.)
the National Oceanic and Atmospheric Administration’s (NOAA) Comprehensive Large Array-Data Stewardship System (CLASS). This allowed a complete documentation of the visual aspects of the evolution of the thunderstorms in that portion of California for those two days.

e. Synoptic charts

The authors obtained synoptic charts and plots from NOAA’s National Operational Model Archive and Distribution System (NOMADS) and the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR; Kalnay et al. 1996). The current version of the NARR runs at a resolution of 32 km, allowing the authors to reconstruct many of the standard fields used in synoptic interpretation. The authors were also able to retrieve output from the 12-km mesoscale version of the hydrostatic Eta Model (hereafter Meso-Eta) (Black 1994) to reconstruct some of the fields with greater resolution.

3. Proximity sounding and hodograph

a. Sounding

A difficult task was establishing the thermodynamic and shear setting for the development of the tornadic thunderstorm. On 7 July 2004, a weak closed low was present off the coast of Southern California at all levels from 850 hPa through the upper troposphere. For example, at 300 hPa, this feature was present all day, with a weak closed circulation approaching the coast by 2100 UTC 7 July 2004 (see Figs. 8 and 9). The southern Sierra Nevada experienced persistent southerly or southwesterly flow from 850 hPa to the upper troposphere during the day.

Since thunderstorms developed in the Sierra Nevada from Sequoia National Park northward to Yosemite National Park and into west-central Nevada in the late afternoon, it was clear to the authors that some CAPE had to be present in that portion of the mountains. This was supported by plots of mixed-layer CAPE (MLCAPE) from the Meso-Eta (that for 0000 UTC 8 July 2004 is given in Fig. 9). The value of MLCAPE in the Rockwell Pass area in Fig. 8 is ≈200 J kg⁻¹.

Since the convective mode of the parent thunderstorm and the evidence that the convection was surface based were issues needing some clarification, the authors first attempted to construct an inferred sounding (not shown) based upon sounding information from KVBG at 0000 UTC 8 July 2004 (Fig. 3), located southwest of the Rockwell Pass area. The sounding had essentially no CAPE, unless a surface-based parcel was assumed.

Next the authors retrieved soundings from the 40-km Rapid Update Cycle model (RUC-40; Benjamin et al. 2004). We were able to obtain a sounding for the Kern River Canyon area near Rattlesnake (discussed below), but the wind information was missing.

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Unauthenticated | Downloaded 04/09/22 09:38 PM UTC
We also used the program raob (Shewchuk 2014) to construct a sounding for Rattlesnake. This was created objectively by the software along a cross section based upon the 0000 UTC 8 July radiosonde data for KBVG, KRNO, KDRA, and KEKO. The resulting sounding at the distance of the cross section from the actual tornado location had an elevation base that was too low. The program then allowed that sounding to be layer lifted to the elevation of the Rattlesnake RAWS. We assumed that the inflow into the thunderstorm came upvalley through the Kern River Canyon (discussed below), and that the surface conditions at Rattlesnake (see Table 2) were representative of the boundary layer of the sounding in the inflow air at a location about 15 km from the thunderstorm.

This objectively obtained sounding was then modified by insertion of the temperature, dewpoint, and wind information from the 2300 UTC observation at Rattlesnake, as shown in Table 2. The program then averaged the temperatures in the superadiabatic layer in the lowest part of the sounding resulting in a dry adiabatic lapse rate in the lowest part of the sounding (Fig. 10). The sounding was similar to the sounding available from the RUC-40 at a nearby location (Fig. 11). The location of the RUC-40 sounding was ≈10 km due east of Rattlesnake on the east side of the Kern River Canyon, at 36.5°N, 118.3°W at a slightly higher elevation of 2891 m (≈9500 ft). The RUC-40 sounding also had a marked superadiabatic layer that we did not eliminate. The 50-mb (1 mb = 1 hPa) MLCAPE for the Rattlesnake sounding is 494 J kg⁻¹ and that for the RUC-40 sounding 117 J kg⁻¹.

Next we created the estimated sounding for the Rockwell Pass area at 2300 UTC 7 July 2004 by having raob lift the 792–600-mb layer upward 92 mb, taking the bottom of the sounding from the elevation of Rattlesnake roughly to the elevation of Rockwell Pass (Fig. 12). Since the Rattlesnake sounding had a deep dry adiabatic layer, this process lifted the bottom of the sounding along an isentrope while the dewpoint field in the boundary layer changed along mixing ratio lines. We estimated the wind profile for the Rattlesnake sounding’s lower portion (see winds plotted on right side of Fig. 11) by assuming the surface wind was that observed at Rattlesnake at 2300 UTC (Table 2) and then smoothly varying the wind direction and wind speed geometrically from the ground to the top of the Kern River.
Canyon locally, about 1000 m above Rattlesnake. To estimate the wind profile at Rockwell Pass, the program eliminated the winds from the ground to 700 mb in the process and simply inserted the surface wind information from Rattlesnake for the surface wind information.

The MLCAPE for this estimated Rockwell Pass sounding was 502 J kg$^{-1}$ with an MLCIN of $-13$ J kg$^{-1}$. The MLCAPE value obtained from the 12-km resolution Meso-Eta (Fig. 10) of $\approx 200$ J kg$^{-1}$ is considerably smaller than the MLCAPE value obtained from the sounding shown in Fig. 12. We do point out that the Meso-Eta uses a 180-mb mixed parcel to determine MLCAPE. Hence, its estimate of MLCAPE values should be smaller given the structure of the sounding.

A key feature in both the RUC-40 sounding (Fig. 11) and the Rockwell Pass sounding (Fig. 12) was a shallow low-level moist layer. To verify that this moist layer was physically realistic the authors examined plots of specific humidity and heights for various levels from about the elevation of Rattlesnake through the lower midtroposphere, roughly the elevation of the crest of the Sierra Nevada. This moist layer, no matter how deep, was key in creating soundings supportive of deep moist convection.

As an example, the specific humidity plot for the 700-hPa level, roughly the pressure elevation of Rockwell Pass and the base elevation of the sounding at 0000 UTC 8 July 2004, is presented in Fig. 13. Over the course of the day, the specific humidity field evolved similarly at this elevation through the lower elevations (not shown). One area of high specific humidity appeared to develop locally as the afternoon progressed, probably related to evapotranspiration effects. But another area of high specific humidity appears to have advected over the area from the south, embedded in the aforementioned southwesterly or southerly flow in the middle and upper troposphere.

**Table 1.** Ranking of five highest-ground-elevation U.S. tornadoes known to the authors, as of this writing. Greatest along-path elevation is used if a track was recorded. Mapping in Fig. 1 of Fujita (1989) indicates some Rocky Mountain tornadoes that may qualify for this list; but their ground elevation is not specified. The elevations of the Mt. Evans and Ashley National Forest tornadoes are estimates not subjected to peer review.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Elev It (m)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Jul 2004</td>
<td>Rockwell Pass, CA</td>
<td>12 156 (3705)</td>
<td>This study</td>
</tr>
<tr>
<td>17 Aug 1984</td>
<td>Longs Peak, CO</td>
<td>11 400 (3475)</td>
<td>Nusse (1986)</td>
</tr>
</tbody>
</table>

**Fig. 7.** Hail estimated as 1.9–2.5 cm (0.75–1 in.) collected by the photographer during the thunderstorm associated with the Rockwell Pass tornado. (Photo by Scott Newton.)
Table 2. Hourly observations from Rattlesnake RAWS (see Figs. 2 and 3 for location) from 1600 UTC 7 Jul to 0300 UTC 8 Jul 2004. “Sustained” wind speeds are the average of all the wind speeds for the 10 min before the hour ending the time indicated. “Gust” speeds represent the peak wind speed value observed during 60 min ending at the time indicated.

<table>
<thead>
<tr>
<th>Hour of day ending at UTC</th>
<th>Wind</th>
<th>Temperature</th>
<th>Dewpoint</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Sustained</td>
<td>Gust</td>
<td>°F</td>
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<tr>
<td></td>
<td>mph</td>
<td>m s⁻¹</td>
<td>mph</td>
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<tr>
<td>1600</td>
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<td>2.2</td>
<td>4</td>
</tr>
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<td>10</td>
<td>4.5</td>
<td>11</td>
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<td>18</td>
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<tr>
<td>0200</td>
<td>6</td>
<td>2.7</td>
<td>20</td>
</tr>
<tr>
<td>0300</td>
<td>4</td>
<td>1.8</td>
<td>13</td>
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</table>

By late afternoon a large area of specific humidities >7 g kg⁻¹ was evident at the 800-hPa level (roughly the pressure elevation of Rattlesnake) over the entire southern Sierra Nevada (not shown). At the 700-hPa level (roughly the pressure elevation of Rockwell Pass) by 0000 UTC 8 July 2004, specific humidities ≈5 g kg⁻¹ (Fig. 13) had overspread the area. The value of around 4.5 g kg⁻¹ for the area around Rockwell Pass was consistent with the 5 g kg⁻¹ on the interpolated Rockwell Pass sounding (Fig. 12). We infer that the characteristics of the lower portion of the soundings favorable for deep moist convection were mostly related to the evapotranspiration effects that are common over forested regions (Anderson et al. 2012) modified by moisture advection from the south associated with the synoptic pattern.

Another important feature of all the soundings shown in Figs. 11 and 12 was a very high LCL. For the actual proximity sounding, this was 1953 m AGL. This value is an indication that the tornado itself was not mesocyclone induced. Thompson et al. (2003) examined various parameters for 413 cases and found that the mean LCL heights for the mesocyclone-induced tornado cases were <1250 m. They also found that for tornadoes not resulting from mesocyclone-induced processes, the mean LCL height was 1919 m. This is consistent with Davies (2006) who found in his study of 123 nonmesocyclone tornadoes³ that 43 occurred with low storm-relative helicity (SRH; discussed in the next section) and LCL heights >1300 m AGL. Davies (2006) pointed out that nonmesocyclone-induced tornadoes can occur with supercells due to formation processes that are unrelated to the mesocyclone. Davies (2006) also underscored the fact that high LCLs do not completely rule out the formation of a mesocyclone-induced tornado.

The authors believe that the LCL height of 1953 m (Table 4; Fig. 12) is inconsistent with the cloud-base height AGL one would estimate visually from Figs. 1 and 6. The cloud base does not appear to be nearly 2000 m (=6000 ft) AGL in these photos. We realize we cannot infer much about LCL from a visual inspection of two-dimensional photographs. However, it could be that the layer thickness of 50 mb in the averaging process to obtain MLCAPE was too large and that the actual LCL was somewhere between that calculated for the MLCAPE and surface-based CAPE (not shown).

b. Hodograph

The proximity hodograph obtained on the basis of the wind information plotted on the right margin of Fig. 12 is shown in Fig. 14. The authors imported radar files into Google Earth to obtain the average storm motion for the time when the storm was at the upper portion of the

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³Tornadoes forming from processes unrelated to the mesocyclone are sometimes referred to as misocyclic tornadoes or, popularly, as “landspouts.”

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<table>
<thead>
<tr>
<th>Height of radar beam (m)</th>
<th>Elev angle</th>
<th>Above sea level</th>
<th>Above radar elev</th>
<th>Above Rockwell Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5°</td>
<td>4859</td>
<td>3719</td>
<td>1053</td>
<td></td>
</tr>
<tr>
<td>1.5°</td>
<td>7881</td>
<td>7010</td>
<td>4345</td>
<td></td>
</tr>
<tr>
<td>2.4°</td>
<td>11142</td>
<td>10272</td>
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</tr>
<tr>
<td>3.3°</td>
<td>14464</td>
<td>13594</td>
<td>10929</td>
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</table>
Kern River Canyon between 2231 and 0000 UTC. During that time the storm moved first south-southwest 3 km and then east-northeast 2 km or so but, on average, moved very little during that 89-min period. Thus, we used a storm motion of zero in the shear calculations (and rendering the radar-base velocity equivalent to a storm-relative framework, as discussed in section 4). The discussions below relate to the storm at the time it produced the tornado, and not later on when both the parent storm and the right-flank development had moved southeast of the Kern River Canyon into the area east of the Sierra Nevada.

The results of the sounding and hodograph calculations are summarized in Table 4. The total length of the hodograph from 0–6 km is relatively short, suggesting that the storm was either a single cell or multicell. The bulk 0–6-km and 0–1-km shear values of $1.6 \times 10^{-3}$ s$^{-1}$ and $3.7 \times 10^{-3}$ s$^{-1}$, respectively, were not within the range that modeling and observational results suggest are consistent with a supercell convective mode (Weisman and Klemp 1982; Thompson et al. 2003). However, the 0–6-km positive shear value $2.8 \times 10^{-3}$ s$^{-1}$; see Johns and Doswell (1992) for a discussion of the value of positive versus bulk shear calculations in determining rotational potential of the environmental shear is nearly within the range of $3.0 \times 10^{-3}$–$5.0 \times 10^{-3}$ s$^{-1}$ in which the environmental shear commonly supports increasing tendency for thunderstorm organization and supercell characteristics (Weisman and Klemp 1982). The bulk Richardson number (BRN) value of 18 was within the range observed for supercell storms. These parameter values suggest that the parent storm might have been a single or multicell that showed organization to a storm with supercellular characteristics in its passage over the favorable shear and moisture environment of the upper Kern River gorge.

The clockwise loop in the lower part of the hodograph does suggest a wind profile that would support rotating convection. The hodograph geometry itself suggests initially splitting storms and resembles a combination of those shown in Figs. 6a,b of Klemp (1987). However, the 0–3-SRH value of 54 m$^2$ s$^{-2}$ is not supportive of mesocyclone development (Davies-Jones et al. 1990). Similarly, the 0–1-km shear value of $3.6 \times 10^{-3}$ s$^{-1}$ is much smaller than the usual lower bound given for such shear values for tornadic supercells. Favorable low-level shear could have occurred as the thunderstorm inflow intercepted the strongly channeled flow in the Kern River Canyon and, for a short time, was in an environment characterized by a strongly curved hodograph with adequate values. We realize this is predicated on the low-level portion of a proximity hodograph that is speculative. Hence, we conclude that we can make no judgment that the tornado itself was mesocyclone induced even if the parent storm might have been a supercell.

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4 Supercell supporting storm-relative 0–6-km AGL shear values typically $>4.2 \times 10^{-3}$ s$^{-1}$ (25 m s$^{-1}$ over 6 km), 0–1-km AGL shear values $>15.0 \times 10^{-3}$ s$^{-1}$ (~8 m s$^{-1}$ over 1 km), and BRN values 10–45 (Weisman and Klemp 1982; Thompson et al. 2003).

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FIG. 8. NCEP reanalysis at 1200 UTC 7 Jul 2004 showing 300-hPa heights (dam) and wind barbs. A nonstandard contour interval was used to emphasize the position of the closed low.
The parameters based upon the proximity sounding and hodograph we developed for this study are not conclusive. The shear and buoyancy parameters as well as the shape of the hodograph suggest that the convective mode might have been supercellular but only for a short time when surface flow was southeasterly and shear vectors, though short, veered with height through the boundary layer. During most of the initial and subsequent life cycle of the storm the data seem to support a dominant multicellular mode.

The environment for the Rockwell Pass storm was different than that documented by Bluestein (1979) for the nonmesocyclone tornado he observed in association with a monsoonal thunderstorm. However, as pointed out above, tornadoes not related to processes associated with mesocyclone evolution also occur with supercells. Thus, it is possible that the Rockwell Pass tornado was a nonmesocyclone tornado even if the parent thunderstorm briefly was a supercell. In fact, Davies (2006) points out that supercell storms with high LCL heights and marginal or weak SRH may present favorable environments for tornadoes that form from nonmesocyclone processes particularly when a low-level shear source (such as topographic channeling) is present.

4. Satellite and radar evidence for storm development and evolution

In the early-morning hours of 7 July 2004, the Rockwell Pass area lay very close to the neutral point in the deformation zone on the northeast side of the 300-hPa trough shown in Fig. 8. The axis of dilatation for this feature appeared to be the northern limit of the boundary layer specific humidity field previously discussed and it moved northward during the day (Fig. 9).

a. Storm initiation and initial evolution

A low-level cumulus field developed by the early afternoon hours of 7 July. Examination of the visible
satellite imagery from GOES-10 (Fig. 15) shows that the Rockwell Pass storm developed first in the high-elevation areas west of the upper portions of the Kern River Canyon at around 2130 UTC. By 2230 UTC, the initial cloud feature had drifted over the northern portion of the Kern River Canyon and appeared to develop rapidly during its transit over that area.

Since the WSR-88D site at KEYX (Fig. 3) was so distant from the storm (about 190 km), the storm’s radar echo was only observable on the lowest three elevation angles (0.5°, 1.5°, and 2.5°). This presents some challenges in the radar diagnosis of the event. The approximate height of the centerline of the radar beam at those three elevation angles is provided in Table 3. Also, at this range, the 1° radar beam is wide (about 3200 m), and the radar data are more or less averaged in a volume that is centered on the elevations shown in Table 3. These height values also assume standard atmospheric propagation.

The first indication of a radar echo observed from KEYX is at 2152 UTC 7 July 2004 at the 1.5° elevation scan, about 105 min prior to the time of the tornado (not shown). The echo continued to expand and develop. For the next two hours or so it remained mostly over the high terrain, moving slowly first south-southwestward and then northeastward at about 1 m s$^{-1}$ or less (average ground relative storm motion from 2230 to 0000 UTC nearly zero).

Evaluation of the velocity signatures of the storm was made on the basis of the radial velocity data. Storm-relative velocity scans were available only for the 0.5°
and 1.5° elevation scans and, because of the slow storm motion, did not differ substantially from the radial velocity plots, which were available for all four tilts. The velocity data revealed a storm-top divergence signature, measured as 11 m s\(^{-1}\) (22 kt) radial velocity difference, already apparent at 2212 UTC (not shown) on the 2.5° tilt. Divergence increased to 20 m s\(^{-1}\) (40 kt) by 2241 UTC (not shown), about 1 h before the tornado. Also, weak cyclonic rotation, measured as azimuthal velocity difference between 8 and 11 m s\(^{-1}\) (15–22 kt), exists off and on from 2221 to 2310 UTC at the 0.5° tilt.

b. Storm evolution around time of tornado

By midafternoon, strong, boundary layer, upvalley flow developed in the Kern River Canyon, as estimated from the Rattlesnake RAWS (Table 2) and also seen in the observations for Bishop and other RAWS sites (not shown). The authors believe that the initial cloud development escalated when the storm intercepted the moist low-level flow that was accelerating northward through the valley during the afternoon hours. That acceleration may have been merely due to diurnal mixing, but also thermally driven up-valley flow may have played a role. Also, internal thunderstorm dynamics (i.e., shear-related perturbation vertical pressure gradient forces) could also have contributed to acceleration of the low-level flow northward if the hodograph at least initially supported this.

By 2330 UTC, the storm had an overshooting top and the anvil had grown to over 5 times the area of the original development and extended nearly 60 km to the east-northeast. The initial eyewitness accounts of cloud-base rotation and funnel clouds came around this time, as did reports of large hail. The tornado occurred between the times of the 2330 and 2353 UTC images in Fig. 15.

The radar reflectivity plots at the lowest four elevation angles for the 2340 UTC 7 July 2004 volume scan...
The storm was too distant from KEYX to observe any of the reflectivity characteristics typically associated with supercells, such as a low-altitude hook or pendant echo, or a bounded weak-echo region (Lemon and Doswell 1979). However, there is evidence of an echo overhang and an indication of an intense updraft, particularly for 20 min on either side of the reported time of the tornado (2337 UTC 7 July 2004; not shown).

The Doppler radial velocities at 0.5°, 1.5°, and 2.5° (along with 0.5° reflectivity) from the 2340 UTC 7 July 2004 volume scan (closest to the 2337 UTC tornado time) are presented in Fig. 17. Noteworthy values include

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**TABLE 4.** Parameters calculated by raob on the basis of the 0000 UTC proximity sounding and hodograph for the Rockwell Pass area given in Figs. 12 and 14 and explained in section 3. SRH calculated on basis of average storm motion between 2230 and 0000 UTC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLCAPE</td>
<td>502 J kg⁻¹</td>
</tr>
<tr>
<td>MLCIN</td>
<td>−13.5 J kg⁻¹</td>
</tr>
<tr>
<td>LCL/LFC heights</td>
<td>1963/2152 m AGL</td>
</tr>
<tr>
<td>0–6-km positive shear</td>
<td>2.8 × 10⁻³ s⁻¹</td>
</tr>
<tr>
<td>0–6-km bulk shear</td>
<td>1.6 × 10⁻³ s⁻¹</td>
</tr>
<tr>
<td>0–3-km SRH</td>
<td>54 m² s⁻²</td>
</tr>
<tr>
<td>Actual storm motion</td>
<td>Stationary</td>
</tr>
<tr>
<td>0–1-km shear</td>
<td>3.6 × 10⁻³ s⁻¹</td>
</tr>
<tr>
<td>BRN</td>
<td>18</td>
</tr>
</tbody>
</table>
15 m s\(^{-1}\) (30 kt) convergent cyclonic rotation (azimuthal velocity difference) at 0.5\(^{\circ}\), and 11 m s\(^{-1}\) (22 kt) of symmetric cyclonic rotation at 1.5\(^{\circ}\). These values correspond to a weak-to-moderate mesocyclone using the definitions supplied by Stumpf et al. (1998; “strength rank” of 3 or 4). A divergence signature of 16 m s\(^{-1}\) (33 kt) radial velocity difference near the storm summit indicated a robust storm updraft collocated with the tornado (yellow square). Both the presence of a mesocyclone and the divergence signature are consistent with the notion that the storm might have been a supercell while it was briefly over the upper portion of the Kern River Canyon.

Figure 18 presents a comparison of the radial velocity data for the 0.5\(^{\circ}\) tilt and the GOES-10 visible image for 2340 UTC, just a few minutes after the 2337 UTC time of the tornado. One would expect that any mesocyclone-induced tornado would be near the center of the rotational couplet this far away from the observing radar and, for this shear profile, on the southwest side of a supercell. However, the southwest portion of a storm developing in a region with a wind profile favorable for a rotating updraft could also be in a position for that updraft to ingest and amplify the low-level shear occurring in the Kern River Canyon. In this manner, a nonmesocyclone tornado could form as the updraft stretches and amplifies the low-level shear vorticity.

To summarize the analyses of the radar observations of the Rockwell Pass storm, we point out that the KEYX radar data possess numerous limitations, including partial terrain blockage, the availability of only the clear-air mode data, and a storm at far range. The radar evidence does suggest a possibility that the Rockwell Pass storm was a supercell during the 2300–0000 UTC time period but is not robust enough to allow us to state definitively that this was the case.

By about 0030 UTC 8 July 2004, the storm started to weaken and move east before dying. At no time was there any echo observed at the 3.5\(^{\circ}\) elevation or higher, indicating that the storm summit never exceeded a height between 11 142 and 14 464 m (about 36 000–47 000 ft).
FIG. 15. (left) Initial development of Rockwell Pass storm overlain on a topographic map showing locations of Rockwell Pass, Rattlesnake RAWS, and the Kern River Canyon, as explained in the text. GOES-10 visible satellite imagery at 2130, 2230, 2330, and 2353 UTC are provided, with the latter two bracketing the time of the tornado. (right) A regional context to the satellite imagery, with the inset indicating the area shown in (left). Initial storm formed on west side of Kern River Canyon (2130 UTC) and rapidly developed as it moved across the southerly flow coming northward and upslope through the canyon (2230 UTC).
Between 2353 UTC 7 July, roughly the time of the tornado, and 0000 UTC 8 July (Fig. 19), the storm had developed two clearly discernible overshooting tops (indicated by crosses in Fig. 19). This probably was a separate right-flank development and not a split of the initial updraft into two storms between 2353 and 0000 UTC. At some point both storms crossed east of the crest of the Sierra and moved into the desert environment where they probably ingested very dry air and began to dissipate.

5. Conclusions

The authors documented a tornadic thunderstorm that had developed in a remote location, far removed
from upper-air and WSR-88D observation sites. In establishing the thermodynamic and shear setting for the storm, the authors made a number of assumptions to estimate the observations for the lowest 1 km of the thunderstorm’s inflow layer. These were used to modify the objectively obtained estimated sounding and hodograph at Rattlesnake to an estimated proximity sounding and hodograph at Rockwell Pass, as explained in section 3.

Our analyses indicated that the thermodynamic and shear environment might have been briefly supportive of a supercellular convective mode. The shear values were not compelling, though, so the authors realize that this is speculative. The evidence for low-level mesocyclogenesis based upon the proximity sounding and hodograph was weak. Even if organization of the storm to a supercell did occur because of the local shear environment in the Kern River Canyon, the period during which the storm might have been a supercell only spanned the hour or so period when the storm was quasi-stationary in the upper portions of the Kern River Canyon.

The satellite imagery alone suggested that the parent thunderstorm initially intensified in the local environment as it intercepted low-level air moving up valley in the high-elevation portion of the Kern River Canyon. The wind shear environment was probably dominated by topographic channeling in the lowest 1 km or so and so it was possible that it was briefly favorable in this location for the thunderstorm to evolve into a supercell.

The available radar information was also sparse. Radar beams from KHNX, the nearest WSR-88D site, were blocked by terrain. The next closest radar site, KEYX, was in clear-air mode and nearly 200 km from the storm. Yet the available radar information suggests that the Rockwell Pass storm had some of the characteristics of a supercell when it was in the upper part of the Kern River Canyon, including a weak–moderate mesocyclone centered in the updraft area over the area in which the tornado was observed.

The authors believe that the combination of the evidence summarized above suggests that the Rockwell Pass tornado was not only the highest-elevation tornado documented in the United States, but also might have been associated with a thunderstorm that was at least briefly a supercell. None of the evidence allows us to conclude that the tornado itself was mesocyclone induced though we cannot rule out this possibility.

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FIG. 19. Sequence of GOES-10 visible satellite images showing the development of a new overshooting top/updraft that occurred after 2353 UTC. By 0000 UTC, two overshooting tops can be noted, also shown by crosses. Over next four images, the southern storm seemed more dominant until it moved east of the Sierra crest and was probably ingesting much drier air.
REFERENCES


