PICTURE OF THE MONTH

First WSR-88D Documentation of an Anticyclonic Supercell with Anticyclonic Tornadoes: The Sunnyvale–Los Altos, California, Tornadoes of 4 May 1998

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Abstract

On 4 May 1998, a pair of tornadoes occurred in the San Francisco Bay Area in the cities of Sunnyvale (F2 on the Fujita scale) and Los Altos (F1). The parent thunderstorm was anticyclonically rotating and produced tornadoes that were documented photographically to be anticyclonic as well, making for an extremely rare event. The tornadic thunderstorm was one of several “pulse type” thunderstorms that developed on outflow boundaries on the left flank of an earlier-occurring thunderstorm east of San Jose. Satellite imagery showed that the tornadic storm moved northwestward along a sea-breeze boundary and ahead of the outflow boundary associated with the prior thunderstorms. The shear environment into which the storm propagated was characterized by a straight hodograph with some cyclonic curvature, and by shear and buoyancy profiles that were favorable for anticyclonically rotating updrafts. Mesoanticyclones were detected in the Monterey (KMUX) radar data in association with each tornado by the National Severe Storm Laboratory’s (NSSL) new Mesocyclone Detection Algorithm (MDA) making this the only documented case of a tornadic mesoanticyclone in the United States that has been captured with WSR-88D level-II data. Analysis of the radar data indicates that the initial (Sunnyvale) tornado was not associated with a mesoanticyclone. The satellite evidence suggests that this tornado may have occurred as the storm ingested, tilted, and stretched solenoidally induced vorticity associated with a sea-breeze boundary, giving the initial tornado nonsupercellular characteristics, even though the parent thunderstorm itself was an anticyclonic supercell. The radar-depicted evolution of the second (Los Altos) tornado suggests that it was associated with a mesoanticyclone, although the role of the sea-breeze boundary in the tornado genesis cannot be discounted.

1. Introduction

On 4 May 1998, a pair of tornadoes occurred in the San Francisco Bay Area in the cities of Sunnyvale (F2) (2331 UTC) and Los Altos (F1) (2355 UTC) (see Fig. 1 for locations). There was an additional unverified report of a third funnel or possible tornado near the city of East Palo Alto. This represents the first instance of a tornadic thunderstorm in the San Francisco Bay region to be within close range (~30 km) of the Monterey (KMUX) Weather Surveillance Radar-1988 Doppler (WSR-88D) site in the Santa Cruz Mountains.

The Sunnyvale tornado was well documented with both video and still images. An analysis of videotape imagery (Fig. 2) shows that this tornado was anticyclonic. Remarkable still images (e.g., Fig. 3) also reveal...
that it both was anticyclonic and had entrained considerable debris during its 12-min life cycle. Witness reports suggest that the tornado was multiple vortex and damage surveys determined that its pathlength was about 2 km. Video and radar evidence of the Los Altos tornado show that this was the second anticyclonic tornado produced by the same parent thunderstorm. This tornado had a pathlength of around 1 km and produced an injury as it moved through the campus of Los Altos High School.

The National Severe Storms Laboratory’s (NSSL) Mesocyclone Detection Algorithm (MDA; Stumpf et al. 1998) detected mesoanticyclones several times during the life cycle of the parent storm (hereafter referred to as the Sunnyvale storm) that had formed on the left flank of an earlier thunderstorm. The motion of the Sunnyvale storm to the left of the hodograph brought it into a shear environment favorable for the development of an anticyclonically rotating updraft.

The radar evidence suggests that the Sunnyvale F2 tornado did not originate from the traditional “supercell cascade” process (as outlined in Wicker and Wilhelm-son 1993). We speculate that the first tornado was non-supercellular and related to the interaction of the thunderstorm with a surface boundary [see Markowski et al. (1998) for a discussion of tornadogenesis in supercells intercepting surface boundaries during the Verification of Rotation in Tornadoes Experiment]. However, the evolution of the radar signatures associated with the Los Altos tornado suggests that it may have been supercellular.

In previous studies, California supercell tornadoes have been documented with the more typical right-moving cyclonically rotating storms (e.g., Monteverdi and Quadros 1994; Braun and Monteverdi 1991) although nonsupercell tornadoes are probably the most common in the state (Blier and Batten 1994). Although radar signatures have been documented for California storms (see, e.g., Carbone 1983; Monteverdi and Johnson 1996), the hooks seen thus far were cyclonic. There are published cases of both anticyclonic tornadoes and anticyclonic supercells in the refereed literature. Fujita (1977) provided the first documentation

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1 The “supercell cascade” leading to tornadogenesis is a conceptual model that starts with the development of the midlevel mesocyclone, advection of precipitation by the mesocyclone around the updraft area, development of a rear-flank downdraft (RFD) simultaneous with the development of the mesocyclone at lower levels, and interaction of the RFD with the low-level shear to produce the low-level tornado cyclone and, eventually, the tornado.
of anticyclonic tornadoes but did not postulate a relation of the tornadoes to the storm-scale rotation. Fujita and Grandoso (1968) first hypothesized that leftward-propagating, anticyclonic thunderstorms occur as part of storm splitting. This was verified in modeling studies by Wilhelmson and Klemp (1978) and Weisman and Klemp (1982), who showed that storms propagating to the left of the hodograph rotate anticyclonically. However, no case study of an anticyclonic tornado in association with an anticyclonic supercell has yet appeared in the reviewed literature.

The purpose of the present manuscript is to document what was a remarkable event. This is the first study that provides Doppler radar documentation of the rare combination of an anticyclonic tornado associated with an anticyclonic supercell. The fact that this unusual tornadic storm was photographed and also occurred in a region in which tornadoes and supercells are themselves relatively infrequent further establishes the uniqueness of this case.

2. Storm environment

a. Synoptic overview

The synoptic-scale environment associated with this tornadic event was characterized by weak cyclonic flow through the depth of the troposphere, significantly cooler than normal temperatures aloft, and relatively abundant moisture. At 1200 UTC 4 May 1998, a 500-hPa low was centered about 1100 km west-southwest of San Francisco, with a central height of approximately 549 dm; a very weak upper trough extended from the low center through north-central California (Fig. 4). The system had an equivalent barotropic structure, with analyses of sea level pressure and 850-hPa height (not shown) appearing qualitatively similar to the 500-hPa-height analysis. Over the ensuing 12 h, the system moved eastward but, at 0000 UTC 5 May (not shown), still lay well to the west of the coast, with only very minor enhancement of the cyclonic flow over California having occurred. Although the very weak synoptic-scale flow throughout the troposphere would suggest minimal, if any, contributory quasigeostrophic (QG) forcing, comprehensive Eta and Aviation (AVN) Model based QG analyses were constructed and examined (not shown). In all cases, and at both the model initialization time of 1200 UTC 4 May and the approximate time of the tornadic event (0000 UTC 5 May), this forcing was found to be quite weak throughout the region of interest.

b. Buoyancy and shear

A rare thermodynamic environment occurred in the San Francisco Bay Area on 4 May 1998. The Oakland (KOAK) 0000 UTC 5 May 1998 sounding (not shown) showed a great departure from the typical warm season thermal and moisture structure in the San Francisco Bay region. The usually seen marine inversion was absent, due to the influence of the offshore cold upper-level low. The relatively moist nature of the surface air was evidenced by atypically high surface dewpoints of nearly 16°C. The superposition of relatively cold middle- and upper-tropospheric temperatures over an uncharacteristically warm and moist marine intrusion created stratification, which, for California, was highly unstable. Surface-based convective available potential energy (CAPE) for the observed KOAK sounding of 2137 J kg⁻¹ underscored the potential for strong-to-severe convection on this day.

The shear environment on the afternoon of 4 May 1998 was not remarkable. The KOAK 0000 UTC 5 May 1998 hodograph (not shown) was straight and of relatively short length. Both deep-layer shear and that in the lowest layers were weak and unremarkable. The buoyancy and shear combination at KOAK, as estimated by the bulk Richardson number (BRN) of 173, was favorable for multicellular or pulse-type convection.

The evolution of the afternoon subsynoptic environment in the southern portion of the San Francisco Bay area was dominated by a surge of marine air into the region from the northwest, due to the typical thermally induced onshore pressure gradient in the boundary layer (with lowest surface pressures in the Central Valley in the afternoon; not shown). This was evidenced by a wind shift and a decrease in temperature (Fig. 5) at Moffett Field (KNUQ; see Fig. 1). Virtual temperatures were 2.2 K colder north of this sea-breeze boundary.

The marine surge advected air with atypically high dewpoints (undoubtedly related to unusual warm sea surface temperatures offshore) southward into the northern Santa Clara valley. Thus, this channeled flow was associated with an unstable stratification since it brought air with relatively high equivalent potential temperatures underneath lower midtropospheric flow characterized by cold advection.

The Sounding Hodograph Analysis Research Program (Hart and Korotky 1991) was used to construct a
proximity sounding and hodograph by insertion of the 2300 UTC observation from KNUQ into the 0000 UTC 5 May 1998 KOAK radiosonde observation. CAPE was calculated on the basis of a lifted surface parcel. In this case, insertion of the surface temperature and dewpoint temperatures at KNUQ into the KOAK sounding resulted in a lowering of the CAPE from its initial 2137 J kg$^{-1}$ to 1730 J kg$^{-1}$ (Fig. 6).

The shear environment into which the Sunnyvale storm moved was much different than that which was observed at KOAK (as described above). The strong northwest wind associated with the sea breeze created a basically unidirectional shear profile for KNUQ (Fig. 7) but with some cyclonic curvature. However, the surface wind at KNUQ contributed to large negative shear in the 0–0.5- and 0–1-km layers and a deep-layer shear magnitude marginally favorable for supercells as indicated by the BRN of 50 (contrasted to that for KOAK of 173).

The shear evident in the KNUQ hodograph (Table 1) for the 0–0.5- and 0–1-km layers was only marginally consistent with the values associated with tornadic storms in California. For example, Monteverdi et al. (2000) have shown that tornadic events in California typically are associated with very strong shear ($\geq 15 \times 10^{-3}$ s$^{-1}$) in the 0–1-km layer. However, the 0–6-km negative shear of $-3.0 \times 10^{-3}$ s$^{-1}$, although weak to moderate, was sufficient for supercells (Weisman and Klemp 1982).

The parameters calculated on the basis of the modified KOAK hodograph indicated that the environment in the northern Santa Clara valley into which the Sunnyvale storm moved was characterized by shear that would favor both anticyclonic rotation in the updraft and the continued deviate motion of the storm to the left of the hodograph. The deviate motion then would contribute to negative storm relative helicity in the 0–3-km layer indicating the potential for at least the development of a weak mesoanticyclone.

The relatively minimal cyclonic curvature evident in the KNUQ hodograph was consistent with the marginal values of low level negative shear seen in Table I. This also suggests that the supercell would not be tornadic.

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2 The term negative shear refers to shear that creates streamwise negative relative vorticity that can be converted into negative relative vertical vorticity by the updraft.
or, at least, that the traditional “supercell cascade” to tornadogenesis would not be expected to occur for this case, since the strongest mesocyclones and mesoanticyclones tend to occur with curved hodographs (Bluestein 1993, p. 475). This is verified by the relatively small storm-relative environmental helicity (SREH) values (e.g., \(-111 \text{ m}^2 \text{s}^{-2}\) in the 0–3-km “inflow” layer).

3. Satellite imagery

An examination of satellite imagery and surface observations shows that the Sunnyvale storm interacted with a sea-breeze boundary that had passed through KNUQ earlier in the afternoon. The motion of the sea-breeze front past KNUQ could be noted in the hourly observations (Fig. 5), and was marked by a wind shift from southerly to northerly, a decrease in temperature, and an increase in dewpoint between 2000 and 2100 UTC [1300–1400 Pacific daylight time (PDT)].

The sea-breeze front was marked by a discontinuous arc of cumulus that extended from west to east across the northern Santa Clara valley by 2200 UTC (Fig. 8a), where it intersected a developing thunderstorm east of San Jose (Figs. 8a–c). This thunderstorm (labeled 1 in Fig. 8) was the first to form in the afternoon hours. Another thunderstorm (labeled 2 in Fig. 8) developed on the outflow boundary extending out from the left flank of the initial storm (Fig. 8c) and then propagated west-northwestward. The Sunnyvale storm (labeled 3 in Fig. 8) can be seen both on radar (not shown) and on the satellite imagery (Fig. 8d) to be an apparently independent development on the sea-breeze boundary.

The passage of the outflow boundary associated with storm 2 through the San Jose area could also be noted in the hourly observations at San Jose International Airport (KSJC) (Fig. 9). This was marked at around 2200 UTC (1400 PDT) by a wind shift from northerly to easterly, temperature and dewpoint temperature falls, and observations of rain, hail, and lightning passing from southeast to northwest. The progression of the outflow boundary was clearly noted in the satellite imagery (Figs. 8b–f) and the composite radar imagery (not shown) and intersected the Sunnyvale storm at about the time of the first tornado.

This Sunnyvale storm also propagated along the sea-breeze front boundary (Figs. 8e and 8f). It is interesting to note that at the time of the Sunnyvale tornado an intersection of the outflow boundary and sea-breeze front was apparently collocated with the updraft area of the storm. Similar intersection of boundaries near the updraft areas of strong supercells were observed by Markowski et al. (1998) for the tornadic storms in the Texas Panhandle on 2 June 1995. They hypothesized that the updraft of these storms tilted and stretched the horizontal vorticity associated with the boundaries upward shortly before tornadoes occurred. In the case of the Sunnyvale storm, the evidence suggests a similar set of circumstances, since the motion of the storm would have had the effect of tilting horizontal anticyclonic vorticity solenoidally generated on the sea-breeze front into the updraft in much the same manner. Thus, this essentially nonsupercellular process could have had an important role in the formation of the first tornado early in the life cycle of the Sunnyvale tornado.

4. WSR-88D radar imagery

To the authors’ knowledge, the WSR-88D images from KMUX presented in this section are the first images of an anticyclonic tornadic supercell ever recorded and analyzed. Analysis of WSR-88D radial velocity data for the storm showed anticyclonic storm-scale vortices with vertical and time continuity. WSR-88D reflectivity data revealed the storm’s supercell structure, but as a mirror image to that of the typical Northern Hemisphere cyclonic supercell. The storm motion was to the left of the mean flow, opposite to that of a classic right moving cyclonic supercell. The supercell, and both tornadoes associated with it, moved from southeast to northwest. These observations are consistent with the nature of the storm as expected from the discussions of the shear environment in section 4b above.

An experimental version of the NSSL MDA,\(^3\) tuned to detect clockwise-rotating storm-scale vortices using WSR-88D radial velocity data, was run on the KMUX level-II data. The level-II archive, which is the highest-resolution data archived from the WSR-88D, began with a volume scan collected at 2331 UTC 4 May 1998, the time of the F2 Sunnyvale tornado. Therefore, using the level-II data alone, it was difficult to ascertain the origins of the vortex that produced this initial tornado. However, the radar velocity characteristics of this first tornado at 2331 UTC were similar to other nonsupercell tornadoes, in that only a very small gate-to-gate shear couplet (albeit anticyclonic) was observed, with no accompanying or surrounding larger mesoanticyclonic vortex (Fig. 10a). In fact, the vortex was too small to be accurately detected by the MDA at this time and, at

\(^3\)At the time of this publication, the NSSL MDA has been recommended for inclusion as an official operational algorithm for the WSR-88D system.
Fig. 8. GOES-9 visible images from 2200 to 2353 UTC showing location of initial thunderstorm development in relation to sea-breeze boundary; development of new storms on outflow boundary; motion of Sunnyvale storm along the sea-breeze boundary; sense of solenoidal circulation along boundary, as explained in text; and locations of Sunnyvale tornado at 2331 UTC (T in 2341 UTC image) and Los Altos tornado (T in 2353 UTC image) in relation to storm. Light contours represent 200-m elevation. Imagery courtesy of U.S. Navy.

this range (31 km), was more typical of a weak tornadic vortex signature (TVS). The subsequent volume scan, at 2337 UTC (not shown), continued to show the anticyclonic Sunnyvale vortex; this was near the time of the tornado’s demise based on visual observations.

Radar reflectivity characteristics at 2331 UTC depicted this “mirror image” supercell (Fig. 10b). For this volume scan at the lowest elevation scan (0.5°), a pendant echo, most likely a degraded view of a hook echo, was apparent on the left flank of the anticyclonic supercell, as opposed to the typical right flank of cyclonic storms. An inflow notch was also apparent on the left side of the reflectivity echo.

The KMUX WSR-88D was sited at an elevation of
1077 m above mean sea level (MSL) to minimize terrain blockage, yet with a trade-off that the radar horizon is much higher than that for flatland radars. At the 30-km range to the tornadic storm, the KMUX radar beam at its lowest elevation angle of 0.5° was intersecting the storm at about 1350 m above ground level (AGL). This height is typically too high to observe any reflectivity fine lines associated with thunderstorm outflow boundaries and sea-breeze boundaries so it was not possible to verify on the radar imagery the location and evolution of the boundaries discussed in section 4.4.

Nonetheless, the WSR-88D data suggest that this first tornado may have formed from the nonsupercell tornadoogenesis mechanisms discussed in previous sections of this paper, even though the overall storm reflectivity structure was beginning to assume supercell characteristics (nonsupercell tornadoes are occasionally observed in conjunction with flanking lines of developing supercells).

WSR-88D radial velocity data show the development of a second separate vortex, northwest of the Sunnyvale vortex. The second vortex was associated with the second (Los Altos, F1) tornado. The first indications of the second vortex were observed as early as 2337 UTC (not shown) to the northwest of the dissipating Sunnyvale gate-to-gate shear vortex. This second vortex was composed of a larger region of anticyclonic shear with a diameter of 3–5 km. The second anticyclonic tornado was born from this larger vortex at 2349 UTC. At 2355 UTC (Fig. 10c), the tornado was associated with a more-pronounced vortex signature in the radial velocity field. This radar vortex was detected by the MDA (overlaid in Fig. 10d) and classified as a “low-topped mesoanticyclone,” a vortex detection that is defined as occupying at least 25% of the storm depth, but is less than 3 km tall. The storm depth was about 9 km, which was in the general range of low-topped storms.

Also at 2355 UTC (Fig. 11), the MDA detected two-dimensional anticyclonic vortex features with vertical continuity. The radar data also suggest that this second tornado was characterized by a gate-to-gate shear couplet at the lowest elevation, encompassed by a larger 3–5-km mesoanticyclonic vortex at the higher elevation angles. The time evolution and vertical structure of the radar vortex suggest that the second tornado in Los Altos formed in the traditional supercell cascade process. Since the storm was still interacting with the sea-breeze boundary at that time, the tornado’s formation may have been a hybrid of supercellular and nonsupercellular processes.

5. Conclusions

Temperature and wind patterns in the San Francisco Bay Area on the afternoon of 4 May 1998 contributed to conditions favorable for strong-to-severe pulse-type thunderstorms throughout the area. An unusual wind profile developed in the southern portion of the Bay Area in the midafternoon when a strong sea breeze moved southward into the Santa Clara valley producing a vertical wind profile characterized by backing wind with height and negative deep layer and boundary layer shear.

Several thunderstorms developed on an outflow boundary associated with a thunderstorm near San Jose. This outflow boundary and one of the thunderstorms developing along it moved to the left of the hodograph and intersected the sea-breeze boundary in the northern Santa Clara valley.

The Sunnyvale storm formed on the left flank of this thunderstorm on the intersection of the outflow boundary and the sea-breeze boundary. Analyses of the satellite and radar evidence suggest the storm both moved along the sea-breeze boundary (strongly to the left of the hodograph) and, possibly, tilted the solenoidal vorticity associated with the boundary into the updraft. It is interesting to note that both the deep-layer shear and the solenoidal vorticity associated with the sea-breeze boundary would have produced midlevel and low-level anticyclonic rotation, respectively, in this storm.

The radar evidence corroborates the fact that when the first tornado occurred, its signature resembled a TVS, with an unrelated nascent larger-scale rotation indicative of a mesoanticyclone at midlevels of the storm. Thus, the Sunnyvale tornado was a nonsupercell anticyclonic vortex that did not form in the classical supercell cascade even though the parent storm was an anticyclonic supercell.

The radar evidence suggests that the second clockwise vortex associated with the Los Altos tornado experienced the more conventional progression expected, in
Fig. 10. Radar imagery from KMUX WSR-88D: (a) 2331 UTC 4 May 1998 reflectivity at 0.5° elevation angle showing cyclonically curved pendant, as well as an inflow notch on the west side of the storm, near Mountain View; (b) 2331 UTC 4 May 1998 radial storm relative velocity showing 2.4° elevation angle location of anticyclonic vortex associated with the F2 Sunnyvale tornado (small yellow dot), along with the direction of motion (arrow); (c) 2355 UTC 4 May 1998 reflectivity at 0.5° elevation angle at time of F1 Los Altos tornado with red-in-yellow circle indicating MDA output of a “low-topped mesoanticyclone”; and (d) 2355 UTC 4 May 1998 radial 0.5° elevation angle storm relative velocity with locations of anticyclonic vortex associated with the F2 Sunnyvale and F1 Los Altos tornadoes (small yellow dots), along with the directions of motion (arrow).

In this case, with an anticyclonic supercell. The larger-scale anticyclonic vortex appeared first at midlevels and was followed by the development of a smaller-scale vortex visible at the lower elevation scans. Although the second vortex, therefore, apparently was formed from the traditional supercell cascade, the influence of the tilt of the solenoidal-generated vorticity associated with the sea-breeze boundary cannot be discounted as an important influence as well.

The mesoanticyclones identified by the MDA on the
KMUX data for this case represent the first WSR-88D documentation of anticyclonic mesocirculations in combination with anticyclonic tornadoes. Although this case was very unusual, it also underscores the utility of the latest experimental suite of WSR-88D algorithms (e.g., the NSSL MDA) in detecting both cyclonic and anticyclonic rotation in thunderstorms, even in the more typical low-topped supercells common in the Pacific coast states.

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