Convective and Rotational Parameters Associated with Three Tornado Episodes in Northern and Central California

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ABSTRACT

An overview of the synoptic and subsynoptic controls on three tornado episodes (seven tornadoes) in northern and central California during December 1992 is presented and compared to the "prototype" documented for the 24 September 1986 mesocyclone-induced F2 event in the Sacramento Valley. Convective and rotational parameters calculated interactively on the Skew T/Hodograph Analysis and Research Programs supported anecdotal evidence that the tornadoes considered in this study were mesocyclone induced. The study indicates that careful subsynoptic analyses and evaluation of buoyancy and shear parameters can establish a mesoscale focus for supercellular development in California "cold sector," low buoyancy–moderate shear thunderstorm environments.

1. Introduction

Twelve verified tornadoes occurred in northern and central California during December 1992 (USDC 1992). National Weather Service (NWS) field damage surveys undertaken for the tornadoes of 2 December in the Santa Rosa (STS) area, of 6 December in the Monterey (MRY) area, and of 17 December in the Oroville–Marysville (MYV) areas indicated that each event was characterized by multiple touchdowns of F1 tornadoes (Table 1). Other reports of funnel clouds, large hail, and unconfirmed tornadoes or waterspouts also occurred on these days. The locations of these and other associated severe weather events discussed in the text are shown in Fig. 1.

Most California tornadoes occur in a cold sector, low buoyancy environment that, until recently, had been thought to be characterized only by nonrotating thunderstorms (see, e.g., Cooley 1978; Hales 1985; and others). McCaul (1990, 1991) has shown that supercellular convection can occur in the very low buoyancy environments associated with tropical storms when low-level shear is great. Buoyancy values used in his modeling studies (McCaul 1990) and found in tropical storm environments (McCaul 1991) were as small as those observed for wintertime cold sector tornado events in California. In the context of tornadic thunderstorms in California, Hales (1985) first pointed out that the interaction of topographic factors in the Los Angeles Basin with flow patterns in certain cold sector weather types might create a shear environment favorable for supercellular convection. Braun and Monteverdi (1991) documented a mesocyclone-induced F2 tornado in the Sacramento Valley that occurred in a cold sector, moderate buoyancy environment in which a favorable low-level shear profile was created by topographic channeling of the boundary-layer flow and by favorable midlevel winds.

Most strong and violent tornado events in the United States are associated with supercell thunderstorms (Davies-Jones 1986; Johns and Doswell 1992; and many others). There is some debate, however, on the precise definition of the term "supercell." The authors have adopted the definition used by Johns and Doswell (1992)—namely, that supercells are convective storms with deep and persistent mesocyclones. Tornadoes associated with such storms are mesocyclone induced and tend to be long lived.

Many studies have shown that the synoptic and mesoscale factors that create a favorable buoyancy and shear environment for supercellular convection can be diagnosed operationally (Doswell 1985; Doswell 1987; Johns and Doswell 1992; and many others). The key elements in operational anticipation of such tornado-producing thunderstorms are (i) awareness of the potential for certain weather patterns to be associated with a synoptic-scale environment favorable for penetrative convection; (ii) assessment of the combined roles of

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buoyancy and shear in inducing storm rotation; and (iii) isolation of mesoscale factors that localize or focus the threat based upon subsynoptic analyses of surface data.

The recent spate of tornadoes in California underscores the fact that tornado forecasting is also an important part of the operational problem in certain California weather patterns (Blier and Batten 1994). Although the determination of a focus for the “typical” cold sector funnel cloud and very weak (F0) tornado events may not be possible operationally, many of the stronger (F1 and F2) events in California are probably associated with mesocyclones and can be anticipated using the techniques described above.

Forecastsers using desktop computers are now not only able to diagnose the current thermodynamic and wind shear profile but also are able to interactively estimate afternoon conditions on the basis of thoughtful alteration of the 1200 UTC information. The development of interactive workstations or computer programs, as described by Doswell (1992), have made such “desktop” stability and hodograph analyses easy to accomplish. In the present study, the usefulness of the Skew T/Hodograph Analysis and Research Programs (SHARP) (Hart and Korotky 1991) in assessing the thermodynamic and wind shear conditions for each of the December 1992 cases will be illustrated. Convective and rotational parameters calculated for the December events will be compared to those summarized for the 24 September 1986 F2 tornado–producing thunderstorm in the Sacramento Valley.

Operational diagnosis of local-scale “focusing” mechanisms falls into that branch of local-scale forecasting termed “nowcasting.” As observed by Doswell (1985) and Johns and Doswell (1992), there is no substitute for subsynoptic analyses of hourly surface data in determination of the mechanisms (i.e., fronts, trough lines, outflow boundaries, etc.) that can localize the convective threat. Such analyses also may indicate small-scale areas in which the wind shear profile and/or buoyancy is most favorable for convective development. Such a procedure established the Sacramento Valley as the likely focus for thunderstorm development in the pattern associated with the 1986 Vina tornadic thunderstorm (Braun and Monteverdi 1991). In the present study, two of the events occurred in regions

<table>
<thead>
<tr>
<th>Location of tornado</th>
<th>Date of tornado</th>
<th>Tornado intensity</th>
<th>Pathlength (km)</th>
<th>Other unconfirmed tornado, funnel, or waterspout in area</th>
<th>Hail and/or wind reports</th>
<th>Photo or observation of tornado</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vina</td>
<td>24 September 1986</td>
<td>F2</td>
<td>23</td>
<td>Two tornadoes</td>
<td>Golf ball</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Many funnels</td>
<td>60 mph</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wall cloud</td>
<td>1/2&quot; hail</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>None</td>
<td>None</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Wall cloud</td>
<td>None</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Waterspout</td>
<td>None</td>
<td>Yes</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Funnel clouds</td>
<td>None</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F0 tornado OAK</td>
<td>None</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Funnel clouds</td>
<td>Golf ball</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sebastopol 1</td>
<td>2 December 1992</td>
<td>F1</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sebastopol 2</td>
<td>2 December 1992</td>
<td>F1</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windsor</td>
<td>2 December 1992</td>
<td>F1</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carmel</td>
<td>6 December 1992</td>
<td>F1</td>
<td>12</td>
<td></td>
<td></td>
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<tr>
<td>Monterey</td>
<td>6 December 1992</td>
<td>F1</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oroville</td>
<td>17 December 1992</td>
<td>F1</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loma Rica</td>
<td>17 December 1992</td>
<td>F1</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Location map with topographic contours at 300-m (approximately 1000 ft) intervals. CIC (Chico), STS (Santa Rosa), MRY (Monterey), and MYV (Marysville) indicate the closest observations to tornado episodes discussed in text. Locations of other severe weather events, including F0 tornado at Oakland (OAK) and Oroville (ORO), are indicated.
with a sufficient coverage of hourly reporting weather stations to allow assessment of a subsynoptic focus.

The primary purpose for this report is to enlarge the rather small literature on mesocyclone-induced tornadoes that occur in "cold sector" environments. In particular, two aspects of the short-term operational problem will be discussed for those December 1992 tornado events that occurred "synoptically near" the Oakland (OAK) radiosonde site: (i) the evaluation of the convective potential, both in terms of the role of instability in thunderstorm development and of the relationship of wind shear to storm structure, and (ii) the isolation of low-level focusing mechanisms that pointed toward the locations for storm initiation in each of the cases.

2. Northern and central California tornado "prototype"

a. Synoptic and subsynoptic pattern

Two "weather types" associated with cold sector tornadoes in California have been documented. Reed and Bier (1986) and Hales (1985) have discussed cases in which tornadoes in central and southern California occurred in association with cutoff middle- and upper-tropospheric troughs. Northern California tornadoes can occur in similar patterns but more frequently occur in progressive situations similar to that shown schematically in Fig. 2.

In a typical sequence, a moderate to strong surface disturbance passes through northern and central California. This disturbance is typically associated with a middle- and upper-tropospheric short-wave trough moving southeastward along the upstream side of a long-wave trough. The short-wave trough is often negatively tilted and associated with moderate to strong midtropospheric cyclonic vorticity advection (CVA), significant upper-tropospheric divergence, and midtropospheric upward motion.

Foresters who rely merely on examination of CVA patterns at 500 mb to infer regions of midtropospheric upward vertical motion (and, thus, upper-tropospheric divergence) should keep in mind that the CVA pattern accounts for only a portion of the synoptic-scale forcing for such motion. As pointed out by Doswell (1987), the essence of the synoptic-scale control on vertical motion is expressed by the diagnostic quasigeostrophic \( \omega \) equation. Diagnosis of the \( \omega \) field is important because synoptic-scale layer lifting generally destabilizes the atmosphere and changes environmental lapse rates in such a manner that the level of free convection (LFC) is lowered, effectively increasing the positive buoyancy of lifted parcels.

Quasigeostrophic forcing (i.e., from terms proportional to the differential vorticity advection and the shape of the temperature advection field) for midtropospheric upward vertical motion is generally associated with upper-tropospheric divergence (Bluestein 1993, pp. 338–341). If the assumption is made that vorticity advection is minimal in lower layers, then midtropospheric CVA approximates only the first quasigeostrophic forcing function for vertical motion (and upper-tropospheric divergence), namely, differential cyclonic (in this case) vorticity advection.

Operational forecasters can assess the combined effects of both the \( \omega \)-forcing functions by examining CVA by the thermal wind (termed "cyclonic isothermal vorticity advection" (CIVA)) as determined by an overlay of the 500-mb vorticity field on the 700–300-mb thickness pattern. Such a procedure can be used to determine the sign and relative magnitude of the vertical velocity at the 500-mb level. More accurate assessment of the quasigeostrophic forcing for vertical motion can be obtained by examining the Q-vector divergence field, as computed and displayed by the PCGRIDS or by the "UA" programs (Foster 1988) resident on PC workstations at most National Weather Service Forecast Offices (WSFOS).

The pattern depicted in Fig. 2 also is often associated with moderate to strong cold advection in the lower and middle troposphere. The cold advection near the surface is mitigated by sensible heating of southeastward-moving airstreams initially by the Pacific and, finally, by diurnal heating over the continent. The net effect of these processes is to destabilize the air mass over California in the lowest two-thirds of the troposphere. The low static stabilities associated with such patterns increase the efficiency of the quasigeostrophic forcing described above.

Cold sector thunderstorms are often associated with very low tropopauses and equilibrium levels even though the lower atmosphere may be quite unstable. Because of this, a lifted index (LI) obtained for the
700-mb level is a better “indicator” of buoyancy for such cold sector events than is the commonly used 500-mb L. The very strong midtropospheric cooling that occurred in the hours preceding the Vina tornado (Braun and Monteverdi 1991), depicted in Fig. 3, is representative of the marked destabilization that occurs in these patterns.

Another important feature common to many of the recently studied California tornado and funnel cloud episodes (e.g., Reed and Blier 1986; Monteverdi et al. 1988; Braun and Monteverdi 1991) is the presence of a jet streak on the southwestern periphery of the advancing short-wave trough. The midtropospheric upward motion found east of synoptic-scale troughs tends to be augmented when the divergent front left quadrant of an advancing upper-tropospheric jet streak approaches and passes to the east of the trough axis (Uccellini and Kocin 1987; Meier 1993; and others). Rapid destabilization is often evident over those portions of California that lie north of the jet axis and east of the main midtropospheric axis in patterns similar to that shown in Fig. 2.

Tornadic convection occurs most often in the “cold” air north or northwest of the main cold front and, occasionally, along the cold front itself. This cold air is often marked by “open cellular” cumulus on satellite images in the Pacific before making landfall. Terrain-induced quasi-stationary mesoscale troughs or low pressure areas develop in California’s Central Valley behind the surface cold front under the area of synoptically forced upward motion associated with the main midtropospheric and upper-tropospheric trough when there is a significant cross-mountain flow in the middle and lower troposphere. The eastern portions of such surface features are characterized by southerly or southeasterly flow that can contribute to significant moisture flux convergence in portions of the Sacramento Valley. Such a trough established a focus for the development of the thunderstorm that produced the 1986 F2 Vina tornado (Braun and Monteverdi 1991).

Low-level “jet streams” are common in the Sacramento and San Joaquin Valleys in the weather patterns associated with northern and central California tornadoes. Parish (1982) has documented several instances of mountain-parallel jet streams averaging 100 km in width and extending through the 600–1500-m layer above ground level (AGL) in the eastern Sacramento Valley. This low-level jetlike feature is associated with speeds between 15 and 30 m s⁻¹ and develops when synoptic-scale troughs approach the coastline. The cross-mountain flow of initially statically stable air is topographically “dammed” with the resulting production of a barrier jet in the Sacramento Valley. It is probable that such features contributed to even greater low-level shear in the Vina tornado and in the Oroville–Loma Rica tornado events than assumed in

Braun and Monteverdi (1991) and in the analyses summarized herein.

b. Buoyancy and shear parameters

As will be shown below, although buoyancy parameters for the December 1992 cases differed considerably from those of the Vina case, the synoptic and subsynoptic patterns were quite similar and corresponded to the familiar California severe weather type described above. Hence, the prestorm sounding and hodograph for the mesocyclone-induced tornado of 24 September 1986 at Vina, given in Figs. 4a,b, will be considered as a “prototype” sounding and hodograph for the purposes of this study. It is important to keep in mind, however, that the Vina event occurred in the warm season. Cold sector thunderstorms occurring in the warm season occur in an environment characterized by higher boundary-layer dewpoints and temperatures and greater buoyancy than their cold season counterparts.

The sounding was constructed quickly and easily on the SHARP by insertion of the Redding (RDD) surface temperature and wind information into the OAK 0000 UTC [approximate time of thunderstorm initiation as explained in Braun and Monteverdi (1991)] radiosonde data and by assuming that the wind veered smoothly between the surface and the top of the coastal mountains at 1500 m (5000 ft). Forecasters under the pressure of time can make such first-guess alterations of sounding information in less than 5 min. Additional alternations, including estimation of mandatory and
significant level temperatures at the thunderstorm initiation site by interpolation of OAK, Medford (MFR), and Winnemucca (WMC) radiosonde information may take much longer to accomplish. Since the authors endeavored to check SHARP output as an aid to real operations, such alterations were not made for the purposes of this study. In addition, the soundings and hodographs produced by SHARP are included in this study to illustrate the nature of the output available to operational forecasters.¹

Important buoyancy and rotational parameters for the sounding/hodograph given in Figs. 4a,b are summarized in Table 2. Similar information for the December 1992 events considered in this study is also provided and will be discussed below. The reader is referred to Weisman and Klemp (1982) for a discussion of the bulk Richardson number (BRN), Davies-Jones et al. (1990) and Johns and Doswell (1992) for an overview of the significance of the storm-relative helicity (s-r helicity) in the development of thunderstorm rotation, Johns et al. (1990) for discussion of the relationship of the curvature of the low-level hodograph (positive shear) to storm rotation, Johns et al. (1993) for a discussion of variations in combinations of wind and instability parameters associated with strong and violent tornadoes, and Hart and Korotky (1991) for a brief but thorough discussion of the significance of all of the various parameters (including the energy/helicity index—EHI) displayed in the SHARP output.

To facilitate interpretation of Table 2 and the soundings and hodographs provided in this study, the reader is reminded that classic supercell thunderstorms have been observed in moderate buoyancy–moderate shear cases for BRNs between 15 and 45 as isolated storms and within complex convective structures (i.e., clusters of multicellular thunderstorms with some cells having persistent mesocyclones) in low buoyancy–high shear cases for BRNs between 2 and 14 (Johns and Doswell 1992). However, the forecaster must keep in mind that the BRN is a bulk measure (i.e., based upon the absolute value of shear and not whether it has characteristics favorable for generating streamwise vorticity and low-level s-r helicity). Thus, a BRN in the correct range of values for rotating thunderstorms must also be associated with favorable s-r helicities for supercell development.

BRN does correlate well with storm type, because the ambient environmental shear of which it is partially composed is sampled across the 0–6-km layer. Winds in the upper part of the range are in the midtroposphere and are important in removing the precipitation from the updraft. This is consistent with Doswell’s (1991) observations that the potential for supercellular development is indicated when midtropospheric (i.e., 700–500 mb) winds are in excess of 11 m s⁻¹ (20 kt).

In the case of very low buoyancy convective available potential energy [(CAPE) < 500 J kg⁻¹] environments, McCaul (1990) has shown that low-level directional shear can be several times more important than the buoyancy in controlling updraft strength. Shear-induced pressure forces (Rotunno and Klemp 1982)

¹ Note that hodograph speed rings are distorted in the SHARP output.
augment the updraft in situations in which the shear vector veers with height from the lower to middle troposphere. McCaul's results suggest that in circumstances in which very low buoyancies are combined with a critical value of low-level directional shear, a rotating convective column can be sustained in a very low BRN environment.

The s–r helicity can be used as a measure of the degree to which the low-level shear is favorable for the development of a rotating updraft. Davies-Jones et al. (1990) advise that 0–3-km s–r helicities approaching 150 \((\text{m s}^{-1})^2\) support mesocyclone development, 151–299 \((\text{m s}^{-1})^2\) weak tornadoes, 300–449 \((\text{m s}^{-1})^2\) strong tornadoes, and greater than 450 \((\text{m s}^{-1})^2\) violent tornadoes. In the case of the information for the Vina tornado given in Table 2, the BRN of 15 combined with the s–r helicity of 342 \((\text{m s}^{-1})^2\) is consistent with the occurrence of a supercellular F2 tornado.

Johns et al. (1993) have shown that low-level shear associated with wind veering and increasing with height (positive shear) in the 0–2-km layer and the 0–2-km s–r helicities are parameters most highly correlated with strong and violent tornado occurrence. Finally, the EHI, another measure of the influence of the cooperative influences of buoyancy and shear, focuses on the role of the low-level shear by incorporating the 0–2-km s–r helicity. This index is still undergoing operational testing; however, values of the EHI of around 1 indicate a tendency for rotation to support strong (F2 and F3) tornadoes.

The positive shear value of 9.7 \(\times 10^{-3} \text{s}^{-1}\) for the Vina hodograph strongly suggests potential for rotating thunderstorms when combined with the buoyancy (B+) of 1806 J kg\(^{-1}\). Johns et al. (1993) show that such a shear can be associated with F2 and F3 tornadoes with a B+ of around 1500 J kg\(^{-1}\). The 0–3-km s–r helicity of 342 \((\text{m s}^{-1})^2\) and EHI of 3.2 are also consistent with the development of an F2 tornado.

3. Selected tornado events of December 1992 in northern and central California

a. Overview

The tornado events of 2, 6, and 17 December 1992 in northern and central California occurred synoptically near the OAK radiosonde site. “Synoptically near” is defined here as less than half the distance to the neighboring MFR and WMC radiosonde observations. The authors made the assumption that the OAK radiosonde data, modified for the low-level temperature and wind conditions at the stations nearest the tornado occurrences, were representative. Storm motion vectors were obtained from Sacramento WSR-57 radar information.

A summary of the severe weather reports for each of the tornadoes observed in the events, and for the 1986 Vina tornado, is given in Table 1. Although damage survey teams have investigated tornado sites in
California before, the information for the Santa Rosa and Monterey tornadoes was obtained from the first two intensive ground surveys ever undertaken from the San Francisco WSFO (R. Williams 1993, personal communication). The Oroville tornado was investigated by a team from the Redding Weather Service Office (WSO) and the Loma Rica (near Marysville) tornado by a team from the Sacramento WSO.

The authors believe that heightened awareness to the risk of severe weather in California on the part of the WSFOs and WSOs will lead to more complete damage surveys in the future. Postevent examinations of the data suggest that each event was associated with multiple touchdowns of tornadoes from the same thunderstorm. In addition, although all of the tornadoes were classified as F1, the authors, who served as the field survey team for the Santa Rosa area tornadoes, concluded that the damage associated with the first Sebastopol tornado suggested winds approaching (but not quite as great as) those observed with F2 tornadoes. Two of the tornadoes (one each in the Santa Rosa and Monterey events) had pathlengths of 13 km (7.5 miles). The postevent surveys indicated that at least three of the December 1992 tornadoes did not match the conventional paradigm—namely, that cold sector tornadoes most often are very weak (F0), touch down briefly and singly, and, thus, do not constitute a significant threat to the public (see, e.g., Cooley 1978; Davies-Jones 1986).

b. Sebastopol/windsor tornadoes of 2 December 1992

1) DESCRIPTION

On 2 December 1992, a number of tornadoes were reported in the Santa Rosa area (see Fig. 1 and Table 1). Witness reports of a tornado forming from a quasi-stationary lowered base were verified by a number of photographs, which substantiated that the lowering was a wall cloud and that the first tornado developed from it. It is interesting to note that witness reports indicate a northeastward motion of this wall cloud of about 5 m s⁻¹ (9 kt). At the same time, the observer at STS reported (not shown here) a southeastward thunderstorm motion. Meanwhile, SAC WSR-57 radar observations indicated that other thunderstorms in northern California moved northeastward at 12.5–15.0 m s⁻¹ (20–25 kt) at the time of the tornado sitings and wall-cloud observations in the Santa Rosa area.² The apparent discrepancies between these observations can be explained if the motion of the STS storm was "deviate," that is, slower than and to the right of the mean motion of other storms in the area.

² The authors used a storm motion of 12 m s⁻¹ at 245°, obtained from SAC WSR-57 radar, in the calculations for s-r helicity below.

At approximately 2300 UTC, a large cone-shaped tornado descended from the lowered base. The photograph shown in Fig. 5 was taken from Santa Rosa looking southwest when the forming tornado was around 8 km (5 miles) distant. There were no other thunderstorms in the vicinity and the region southwest of the descending tornado was in sunlight.

The tornado shown in Fig. 5 was the first of three in the area and was documented with a pathlength of 13 km (7.5 miles), suggesting that the parent mesocyclone, if present, was persistent. As this tornado moved slowly north-northeastward, it either dissipated to be replaced by a second or redeveloped, with a track slightly east. This tornado had a pathlength of 1.5 km (1 mile) before dissipating. At this time, video images of the wall cloud were captured by television cameramen. It moved slowly northeastward toward Windsor, at which time the third and final tornado with a pathlength of 5 km (3 miles) descended.

2) SYNOPTIC- AND SUBSYNOPTIC-SCALE CONTROLS

The 500-mb height and absolute vorticity pattern for 0000 UTC 3 December is given as Fig. 6. The midtropospheric trough affecting northern California had a closed circulation, suggesting that the pattern was similar to that documented by Hales (1985) for central and southern California. The history of the short-wave trough (not shown) indicated that the disturbance had progressed around the north side of the long-wave ridge in the Gulf of Alaska and approached California from the northwest, similar to the prototype discussed above. At the time of Fig. 6, moderate to strong midtropospheric CIVA in southwesterly flow characterized the middle third of California (not shown).

A series of subsynoptic surface analyses indicated that a postfrontal trough had developed in the region of California northwest of the major cold front. A wave had developed on this surface trough by 0000 UTC (Fig. 7) with a mesolow in the area between Ukiah and STS. Unlike the situation for the prototype discussed above, winds at OAK had not yet veered to the northwest, undoubtedly because the middle- and upper-tropospheric wave was located farther off the coast in this case. The mesolow acted as a local focus in the vicinity of STS, which at the time of Fig. 7 was reporting an east wind. The "T" in Fig. 7 gives the approximate position of the first tornado at the time of the chart.

The Advanced Very High Resolution Radiometer (AVHRR) visible satellite image for 2225 UTC (Fig. 8), about the time of the first tornado touchdown, shows numerous showers and thundershowers arrayed around the midtropospheric and upper-tropospheric circulation center west of Point Arena. The initial development in the Santa Rosa area was the southernmost in a complex of thunderstorms that extended northward and then
northwestward across Cape Mendocino. The first tornado (approximate location indicated by the letter “T”) developed on the south end of the tight cloud spiral located just west of STS in Fig. 8.

3) BUOYANCY AND WIND SHEAR PARAMETERS

As in the case of the prototype, strong cold advection produced profound changes in the sounding from 1200 to 0000 UTC. The temperature changes in the midtroposphere shown in Fig. 9 were even greater than those for the prototype (Fig. 3).

The bogus STS sounding given in Fig. 10a was obtained on the SHARP by insertion of the 2100 UTC STS temperature and wind information into the OAK 0000 UTC sounding; 2100 UTC was chosen because this was approximately 1 h before the tornadic thunderstorm developed and conditions at that time probably reflected the prestorm environment. The bogus hodograph (Fig. 10b) was constructed by insertion of the surface wind for STS at 2100 UTC and by assumption that the valley in which STS lies would prevent large directional shear until the crest at 1500 ft (500 m).

Of the parameters given for the modified sounding and hodograph in Table 2, only the s-r helicity values [i.e., 0–2-km s-r helicity of 286 (m s⁻¹)² and 0–3-km s-r helicity of 284 (m s⁻¹)²] unambiguously support ground observations of storm rotation. The rather meager buoyancy of 393 J kg⁻¹ would need to be associated with positive shear values of at least \(15 \times 10^{-3} \text{ s}^{-1}\) (Johns and Doswell 1992) to support strong or violent mesocyclone-induced tornadoes. However, the 0–2-km s-r helicity is indicative of a low-level shear favorable for mesocyclone development despite the rather low buoyancy. Johns et al. (1993) show that for such a buoyancy, 0–2-km s-r helicities on the order of 250 (m s⁻¹)² or greater could be associated with the development of strong mesocyclone-induced tornadoes. Such a value of low-level s-r helicity suggests that the low-level shear was adequate to augment the updraft in the manner documented experimentally by McCaul (1990) for situations with comparable buoyancies associated with tornadoes in tropical cyclone environments.

It is important to note that the B+ and thus the EHI for this case might be underestimated. Cloud-top temperatures in the vicinity of STS, as deduced from infrared AVHRR imagery (not shown), were between \(-30°\) and \(-35°\). Such temperatures are found between the 375- and 350-mb levels on the sounding and would suggest that the elevation of the equilibrium level (shown at the 490-mb level in Fig. 9a) and thus the buoyancy were underestimated.
c. Monterey tornadoes of 6 December 1992

1) Description

Two F1 tornadoes occurred in the Monterey–Carmel area between 2300 UTC 6 December and 0000 UTC 7 December (see Fig. 1 and Table 1). Damage consisted mainly of many uprooted trees and loss of roof shingles. There were several reports of waterspouts and funnel clouds off the Carmel coast. Observations of the first tornado (Carmel) indicated that it occurred from the flat base of the parent thunderstorm and no wall clouds or lowered bases were reported. Damage surveys verified that the pathlength of the Carmel tornado was 12 km (7 miles), and of the second tornado in Monterey 1.5 km (1 mile). These surveys also indicated that the tornadoes moved along with the thunderstorm motion, as observed on SAC weather radar.

2) Synoptic- and subsynoptic-scale controls

The 500-mb analysis for 0000 UTC 7 December 1992 is given as Fig. 11. A negatively tilted trough extended from the Gulf of Alaska southeastward over California. The trough was associated with strong midtropospheric CIVA (not shown). The axis of the upper-tropospheric jet stream intersected the California coast near Vandenberg Air Force Base. The midtropospheric expression of a jet streak is evidenced by the height contour packing on the southern periphery of the trough (Fig. 11).

At the time of the tornado reports, a cold front was advancing through northern and central California. AVHRR infrared imagery for 2317 UTC (Fig. 12), about 45 min before the first tornado report, indicates that considerable enhancement of the frontal cloud band had occurred east of the main midtropospheric trough axis in the vicinity of the front left quadrant of the advancing jet streak. Strong thunderstorm development is evident from just east of San Francisco southwestward across the coastline near Monterey.

Since the funnel clouds and waterspouts that preceded the tornadoes were observed over the Pacific west of Carmel, it is probable that any focusing mechanisms would have been active west of the coastline and away from most observation sites. The development of thunderstorms along the frontal cloud band evident in Fig. 12 suggests that subsynoptic waves along the front may have served as focusing mechanisms for this case. However, since there are few observations in the Monterey area and the front lay over the data-sparse Pacific, subsynoptic analyses could not be used to provide in-

FIG. 7. Subsynoptic analysis of altimeter settings for 0000 UTC 3 December 1992. Broad solid line is main cold front; light dashed line is postfrontal trough. Approximate location of tornadic thunderstorm at this time indicated by “T.”
sights into the focus for this case. Certainly, since the surface winds in the Monterey area, the San Francisco Bay region, the southern Sacramento Valley, and the northern San Joaquin Valley were all southeasterly at this time, it appears that no evidence for a mesoscale focus on the continent could be discerned from sub-synoptic analyses.

3) **Buoyancy and Wind Shear Parameters**

Midtropospheric cold advection and low-level diurnal heating produced 12-h temperature changes (Fig. 13) in the Monterey area in the same sense as those observed for the other cases considered. However, as was the case for the STS event, rather small buoyancy was characteristic. The B+ (Table 2) of 446 J kg\(^{-1}\) was obtained from the bogus 0000 UTC MRY sounding (Fig. 14a) constructed on the SHARP.

The bogus hodograph for MRY (Fig. 14b) was constructed by insertion of the 0000 UTC wind observation for MRY and of the storm motion as determined from SAC weather radar. The 0–2-km positive shear and 0–2- and 0–3-km s-r helicity, as estimated from the SHARP analysis of the bogus hodograph, were consistent with those observed for the STS case (Table 2). The curvature of the hodograph between the surface and 2 km was clockwise and, with the storm motion indicated, produced a 0–2-km s-r helicity of 217 (m s\(^{-1}\))^2 and a 0–3-km s-r helicity of 254 (m s\(^{-1}\))^2. The latter suggests a "rotational potential" that can support weak mesocyclone-induced tornadoes, according to Davies-Jones et al. (1990). Neither the shear buoyancy nor the s-r helicity buoyancy values meet the lower threshold for strong mesocyclone-induced tornadoes, according to Johns et al. (1993).

The BRN of 5 obtained from the buoyancy and shear information and the s-r helicity values suggest that developing convective storms could have complex structure with supercellular characteristics (Johns and Doswell 1992). The relatively low buoyancy and moderate shear combined gave an EHI of 0.6.

Although the parameters summarized in Table 2 for this case present a somewhat ambiguous interpretation, there appeared to be enough s-r helicity and low-level shear to generate mesocyclone-induced waterspouts and weak tornadoes. Moreover, the long track of the first tornado suggests that if present, such a mesocy-
clone was persistent. However, no discernible mesoscale or subsynoptic focus was evident that would have aided forecasters in localizing the threat to the Monterey area.

d. Oroville-Marysville (Loma Rica) tornadoes of 17 December 1992

1) DESCRIPTION

Two tornadoes occurred in the southern Sacramento Valley between 2125 and 2330 UTC 17 December 1992 (see Fig. 1 and Table 1). The first tornado passed through the town of Oroville at 2125 UTC and produced substantial damage (C. Fontana 1993, personal communication) along its path length of 1.1 km (0.75 mile). A previous report (Monteverdi 1993) described the usefulness of the SHARP in providing guidance to forecasters in anticipating this event.

The second tornado occurred at 2330 UTC and passed through a sparsely populated area near Loma Rica, which is a small village around 23 km (15 miles) northeast of Marysville. Videotapes and eyewitness reports verified both the presence of a wall cloud and the subsequent touchdown of the tornado outside of Loma Rica. Other reports indicate that a cone-shaped tornado traversed an approximately 8 km (5 mile) path length.

Radar analyses and analyses of satellite imagery confirm that both tornadoes were associated with a thunderstorm that moved southeastward through the Sacramento Valley. There were unconfirmed reports of golf-ball-size hail and other funnel clouds when the storm was between Oroville and Marysville.

2) SYNOPTIC- AND SUBSYNOPTIC-SCALE CONTROLS

The synoptic pattern that occurred on 17 December 1992, illustrated in Fig. 15, the NGM analysis of 500-mb heights/absolute vorticity for 1200 UTC 17 December 1992 was the most similar of the December 1992 cases to the prototype. CVA associated with an advancing jet streak seemed to play an important role in diagnosing a vertical motion field that enhanced thunderstorm development and contributed to destabilization. The jet streak was evident (Fig. 15) by the vorticity dipole centered at 43°N, 130°W.

Satellite imagery during the morning of 17 December (not shown) showed open cellular cumulus west of the coastline in the hours before the initiation of convection in the Sacramento Valley, with greatest enhancement under the left front quadrant of the advancing jet streak. This pattern was quite similar to the schematic “type” associated with strong to severe convection in northern and central California, as illustrated in Fig. 2.

Figure 16 gives the 2200 UTC 17 December subsynoptic analysis for northern and central California. Note that upvalley, southerly flow was occurring ahead.
closely resembled those documented for the tornadic Vina thunderstorm. Both the Vina and Oroville–Loma Rica midtropospheric patterns were similar to those documented by Parish (1982) as being associated with a strong low-level jet in the eastern portion of the Sacramento Valley. Such a jet, if present, would have contributed to even more significant low-level shear than was assumed in the analyses for the Vina tornado and those summarized below for the Oroville–Loma Rica event.

3) Buoyancy and Wind Shear Characteristics

Strong cold advection in the middle and lower troposphere in association with the trough (Fig. 15) advancing southeastward caused pronounced destabilization over northern and central California. The cooling in the 900–500-mb layer was very marked, as is evident in Fig. 17, which shows the 12-h temperature changes from 1200 UTC 17 December to 0000 UTC 18 December. Figure 17 was obtained by substitution of the surface data for MYV into the respective OAK soundings. It is interesting to note that the development of favorable buoyancy for the three mesocyclone-induced tornado cases considered in this study was associated with similar 12-h layer temperature changes, as is evident from a comparison of Figs. 3, 9, and 17.

The bogus 2200 UTC MYV sounding (Fig. 18a) was constructed on the SHARP by substitution of the

Fig. 12. AVHRR infrared image for 2317 UTC 6 December 1992. Thunderstorm cells southwest of Monterey peninsula produced waterspouts and tornadoes about 45 min after image time.

Fig. 13. As in Fig. 3 except for 12 h ending 0000 UTC 7 December 1992 at MRY.
surface data for MYV into the 0000 UTC 18 December radiosonde data. The sounding information (Table 2) substantiates the fact that weak positive buoyancy characterized the lower troposphere even though the 500-mb LI indicated negative buoyancy at that level.

The bogus MYV hodograph (Fig. 18b) was created from the 1200 UTC OAK hodograph by substitution of the 2200 UTC surface wind at MYV and by insertion of the true storm motion obtained from SAC weather radar (indicated by arrow). The modified hodograph shows the sort of low-level curvature that is indicative of high rotational potential, verified by the 0–3-km s-r helicity of 454 (m s⁻¹)². The weak buoyancy of 552 J kg⁻¹ is in the correct range to support strong and violent tornadoes for positive shear values near 10⁻³ s⁻¹ and 0–2-km s-r helicity values of 300 (m s⁻¹)² or greater (Johns et al. 1993). The buoyancy combined with the 0–2-km s-r helicity of 338 (m s⁻¹)² gives an EHI of 1.17, suggesting that storms in the southern Sacramento Valley could have been associated with strong (F2 or F3) tornadoes.

4. Discussion and conclusions

This study underscores the fact that anticipation of tornadic thunderstorms is an important part of the forecasting problem in certain California weather patterns (Blier and Batten 1994). Previous studies (Hales 1985; Braun and Monteverdi 1991) have pointed out that shear profiles favorable for storm rotation can be created or augmented by local topography in California. Since both the Coast Ranges and the Sierra Nevada trend northwest to southeast, most ridges and valleys in northern and central California are oriented in a direction favorable for channeling low-level westerly and southerly flow to southeasterly. For the cases considered in this study, such channeling com-

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3 Distortion of hodograph rings on SHARP output creates a hodograph that appears straight but is really curved.
The southern Sacramento Valley tornado events of 17 December 1992 occurred in a synoptic and subsynoptic setting very similar to that associated with the "prototype" 24 September 1986 Vina tornado. In the Vina event, a postfrontal subsynoptic trough focused the topographically channeled low-level flow. The subsynoptic trough in the Sacramento Valley is a common feature in the synoptic pattern depicted in Fig. 2. As shown in Braun and Monteverdi (1991), the trough remains quasi-stationary, while the lower-mid tropospheric winds have a component normal to the Coast Ranges. This occurs when the main midtropospheric and upper-tropospheric trough lags offshore while the surface cold front has already passed through the area. In such a situation, northern and central portions of California pass into the area of lower thickness behind the cold front, and the surface wind veers to northwesterly at Oakland but remains southerly in the Sacramento Valley. This trough does not move but dissipates from the northwest when the cross-mountain flow disappears from the northwest as the midtropospheric trough moves southeastward.

It appears that, in the case of the 17 December 1992 tornadoes, favorable phasing of synoptic-scale features also supported the development of such a subsynoptic trough in the Sacramento Valley, which in turn provided a focus for thunderstorm development. The s-r helicities associated with the Vina and the Oroville–Marysville tornadic thunderstorms were the greatest of those calculated for the events considered here and actually were in a range (Table 2) that did support strong

combined with west-southwest flow in the midtroposphere to create a situation in which moderate to strong streamwise vorticity existed in the low-level flow. In all of the cases considered in this study, storm motion was such that 0–3-km s-r helicities achieved values that could support tornadoes even given rather low buoyancies.

Each of the three December events occurred in a synoptic pattern that corresponded to one of the two already discussed in the literature as being associated with tornadoes in California (Hales 1985; Braun and Monteverdi 1991). The Monterey and southern Sacramento Valley tornadoes were associated with a progressive midtropospheric pattern similar to that of the "prototype" discussed earlier in this study. The Santa Rosa/Sebastopol tornadoes occurred in a similar pattern except that the midtropospheric trough closed off west of the coastline to produce a pattern analogous to the prototype documented by Hales for central and southern California. This apparently kept the greatest upper-tropospheric divergence and upward vertical motion fields along the coast.
study were very low (ranging from 3 to 5) due both to low buoyancy and moderate to high shear. Midlevel winds (i.e., 700 mb) exceeded 19.5 m s\(^{-1}\) (approximately 40 kt) in all of the cases and were greater than 24.5 m s\(^{-1}\) (approximately 50 kt) for the Monterey and Oroville–Marysville events, a factor that contributed to the rather large 0–3-km helicities, particularly for the Oroville–Marysville tornadoes.

While moderate buoyancy was associated with the Vina event (Table 2), only weak instability occurred for the December events. This was partially due to the fact that although all of the events considered here developed in a cold sector environment, the Vina tornado occurred in a warm season environment characterized by much higher temperatures and dewpoints than those that occurred with the December 1992 tornadoes. However, 0–2-km s-r helicity, calculated for each of the cases, was large enough to be associated with rotating updrafts and mesocyclones. This has operational usefulness for short-term forecasts since all of the s-r helicities were obtained using actual hourly surface weather observations and radar-derived storm motions rather than estimates.

This study indicates that careful subsynoptic analyses and thoughtful consideration of buoyancy and shear information obtained interactively on the SHARP or any similar analysis system by the forecaster can indicate a mesoscale or subsynoptic focus for those tornado events in California that are mesocyclone induced. On the other hand, determination of such a local focus using currently available tools may not be possible for thunderstorms that do not have supercellular characteristics and for those supercellular events that are initiated over the data-sparse Pacific. With the siting of the WSR-88D Doppler radar facilities in California, real-time examination of reflectivity and radial velocity data will augment such determinations.

This study also suggests that buoyancy and shear parameters may yield operationally useful guidance in distinguishing between the threat for funnel clouds, and weak and strong tornadoes in California severe thunderstorm events. Research is ongoing at San Francisco State University (SFSU) to determine buoyancy and shear information for all of the tornado events in northern and central California since 1950.

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**Fig. 18.** As in Fig. 4 except for MYV at 0000 UTC 18 December 1992.

(24 September 1986) and might have been able to support strong to violent (17 December 1992) tornadoes.

Strong and violent tornadoes have been observed for a wide range of buoyancy and shear ratios. Most supercellular tornadoes have occurred within a relatively narrow range of BRNs (15–45) (Johns and Doswell 1992) although hurricane–tornadoes associated with mesocyclones have been observed by McCaul (1991) in much lower BRN environments. BRNs calculated for each of the 1992 cases considered in this
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