NOAA Technical Memorandum NWS WR-222

CONVECTIVE AND ROTATIONAL PARAMETERS ASSOCIATED WITH THREE TORNADO EPISODES IN NORTHERN AND CENTRAL CALIFORNIA

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September 1993

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

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National Weather Service
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This publication has been reviewed
and is approved for publication by
Scientific Services Division,
Western Region

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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 SHARP Workstation verified anecdotal evidence that two of the three December episodes were mesocyclone-induced. The study indicates that careful consideration of subsynoptic analyses and buoyancy and shear parameters can indicate a mesoscale focus for supercellular development in California "cold sector" thunderstorm environments.

I. INTRODUCTION

Twelve verified tornado events occurred in northern and central California during December 1992 (personal communication, Mr. Jack Hales, Lead Forecaster, National Severe Storms Forecast Center (NSSFC)). National Weather Service (NWS) field damage surveys, undertaken for the tornadoes of 2 December in the Santa Rosa area, of 6 December in the Monterey area, and of 17 December in the Oroville-Marysville areas, indicated that each event was characterized by multiple touchdowns of F1 (moderate) 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 environment which, until recently, had been thought to be characterized only by non-rotating thunderstorms (see, e.g., Cooley, 1978 and Halvorson, 1971). Hales (1985) first suggested that the interaction of topographic factors in the Los Angeles Basin with flow patterns in certain cold sector weather types might create an environment favorable for supercellular convection. Braun and Monteverdi (1991) documented a mesocyclone-induced F2 tornado in the Sacramento Valley which occurred in a cold sector environment in which a favorable shear profile was created by topographic channelling of the low-level flow.

It is clear that the foci for the "typical" cold sector funnel cloud and very weak (F0) tornado events may be difficult to isolate operationally. It is equally clear that many, perhaps most, of the stronger (F1 and F2) events in California are mesocyclone-induced and associated with synoptic and subsynoptic focusing mechanisms, which may be resolved in an operational setting.

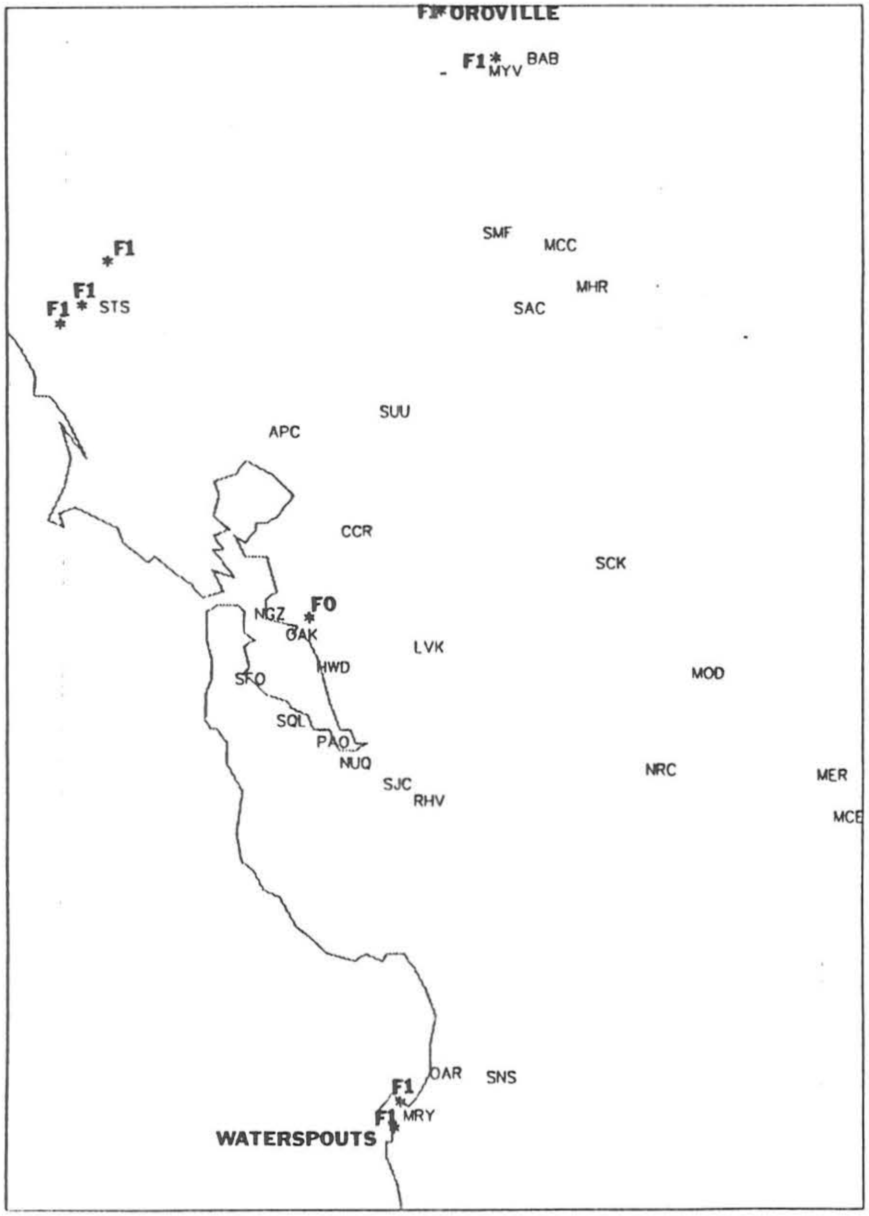


Figure 1 Locations of stations used in subsynoptic analyses and of 1992 tornadoes discussed in text. map. STS (Santa Rosa), MRY (Monterey), and Oroville-Marysville (MYV) indicate the closest observation sites to three tornado episodes.

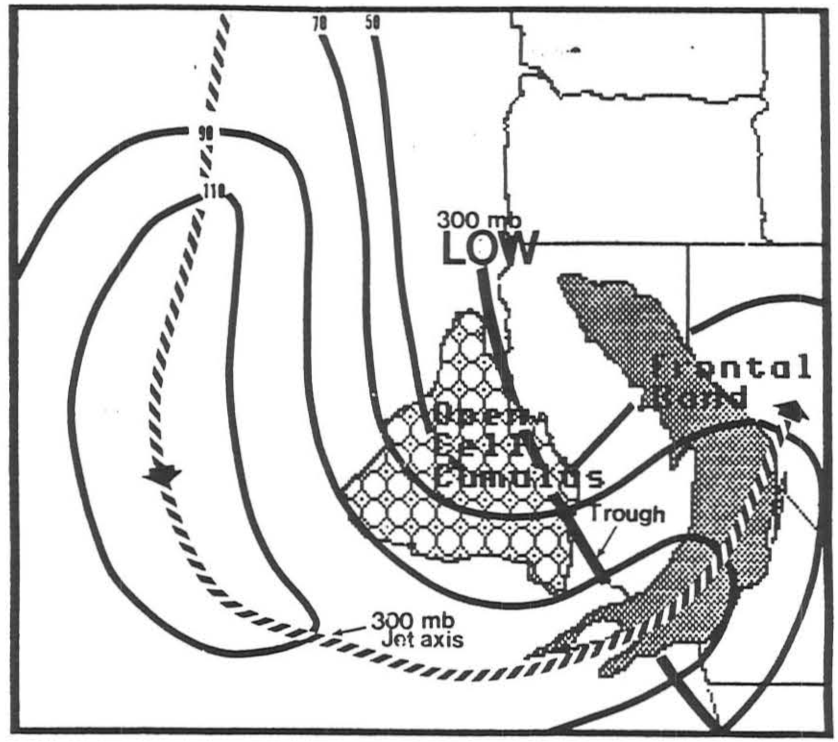


Figure 2 Schematic diagram showing location of features for synoptic "type" often associated with intense "cold sector" thunderstorms in California (after Monteverdi et al., 1988).

Location of Tornado	Date of Tornado	Tornado Intensity	Path Length (miles)	Other Unconfirmed Tornado, Funnel or Waterspout in Area	Hail and/or Wind Reports	Photo or Observation of Tornado
Vina	9/24/86	F2	15	2 Tornadoes, Many Funnel	Golf ball, 60 mph	Yes
Sebastopol 1	12/2/92	F1	7.5	Wall cloud	1/2" hail	Yes
Sebastopol 2	12/2/92	F1	3	None	None	No
Windsor	12/2/92	F1	1	Wall cloud	None	No
Carmel	12/6/92	F1	7	Waterspout	None	Yes
				Funnel clouds	None	
Monterey	12/6/92	F1	1	None	None	No
Oroville	12/17/92	F1	4	Funnel Clouds	Golf ball	No
				F0 Tornado OAK		Yes
Loma Rica	12/17/92	F1	5	Funnel Clouds		Yes

Table 1. Summary of severe weather reports associated with tornado cases discussed in text.

(Sources: USDC Storm Data; John Quadros, Warning Preparedness Meteorologist, WSFO, San Francisco; Chris Fontana, WSO, Redding)

Location of Bogus Sounding	Date of Tornado	Location of Tornado(es)	Tornado Intensity	Meso-cyclone Induced?	500 mb LI (C)	700 mb LI (C)	B+ (J/kg)	Positive Shear (0-2 km) (X 10-3 s-1)	Storm Relative Helicity (m/s)2	Energy Helicity Index	Bulk Richard-son Number
Redding	9/24/86	Vina, Chico	F2	Yes	-3	-5	1806	9.7	342	3.2	15
Santa Rosa	12/2/92	Sebastopol, Windsor	F1,F1,F1	Yes	-2	-3	546	9.4	284	0.98	7
Monterey	12/6/92	Carmel, Monterey	F1,F1	No	-1	-3	446	8.6	254	0.6	5
Marysville	12/17/92	Oroville, Loma Rica	F1,F1	Yes	3	-3.5	552	12.5	454	1.17	3

Table 2. Convective and Rotational Parameters Obtained from Analyses of Bogus Soundings for Four Tornado Occurrences in North-Central California

The same general techniques in use by severe weather forecasters in other parts of the country may be utilized in California to establish the threat of strong to severe thunderstorms and tornadoes, and to determine the factors which would localize the threat subsynoptically.

Supercell thunderstorms have been shown to be associated with the majority of moderate, strong, and severe tornado events in the United States (Davies-Jones, 1986 and many others). Many studies have shown that the synoptic and mesoscale factors creating 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 element in anticipation of such tornado-producing thunderstorms is forecaster awareness of the role of shear in inducing storm rotation and of the potential for certain weather patterns to be associated with favorable buoyancy and shear parameters. The recent spate of tornadoes in California underscores that tornado forecasting is also an important part of the operational problem in certain California weather patterns.

A previous report (Monteverdi, 1993) described the operational usefulness of the **S**kew T/**H**odograph **A**nalysis and **R**esearch **P**rograms (SHARP) Workstation (Hart and Korotky, 1991) in assessing the thermodynamic and wind shear conditions in the Sacramento Valley conducive to supercellular-type convection for the 17 December 1992 event in the Oroville area. The study indicated that a focus for the tornadic activity could have been judged by forecasters: (i) alert to the severe weather potential of the synoptic pattern on that day; and, (ii) able to evaluate information available from interactive sounding and hodograph analyses performed with the SHARP Workstation program.

The purpose for this report is to provide general documentation for those December tornado events in north-central California which occurred in a region best represented by the Oakland (OAK) radiosonde site. Convective and rotational parameters calculated for the December events will be compared to those summarized for the 24 September 1986 F2-tornado-producing thunderstorm (Braun and Monteverdi, 1991) in the Sacramento Valley. Finally, a brief discussion of the subsynoptic or local factors which focused the threat will be discussed for each case.

II. NORTHERN AND CENTRAL CALIFORNIA TORNADO "PROTOTYPE"

Two "weather types" associated with "cold sector" tornadoes in California have been documented. Reed and Blier (1986) and Hales (1985) have discussed cases in which tornadoes in central and southern California occurred in association with cutoff mid- and upper-tropospheric troughs. Northern California tornadoes can occur in similar patterns, but most frequently occur in progressive situations similar 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 mid- 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 mid-tropospheric cyclonic vorticity advection (CVA) and strong mid-tropospheric cold advection. As pointed out by Doswell (1987), mid-tropospheric CVA (often termed "dynamics") diagnoses upper-tropospheric divergence and an upward vertical motion field which encourages convection. Such synoptic-scale lifting of a layer destablizes the atmosphere and changes environmental lapse rates such that the Level of Free Convection (LFC) is lowered, effectively increasing the positive buoyancy of lifted parcels.

It is important to remember, however, that differential vorticity advection approximated by CVA patterns comprises only a portion of the quasi-geostrophic forcing for vertical motions. The shape and sign of the temperature advection field also contributes to vertical motion. As a first approximation, operational forecasters can assess the combined effects of both terms by examining CVA by the thermal wind as determined by an overlay of the 700 mb vorticity field on the 1000-500 mb thickness pattern (to determine the sign and relative magnitude of the vertical velocity at the 700 mb level). More accurate assessment of the quasi-geostrophic forcing for vertical motion can be obtained by examining the Q-vector divergence field, as computed and displayed by the PCGRIDS (Petersen, 1992) or by the "UA" programs (Foster, 1988) resident on PC-workstations at most Weather Service Forecast Offices (WSFOs).

California operational forecasters know that the pattern depicted in Fig. 2 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 air streams by the Pacific and 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. Because of this, the 700 mb Lifted Index (LI) is a better "indicator" of buoyancy than the 500 mb LI. In addition, cold sector thunderstorms are often associated with relatively low tropopauses and equilibrium levels even though the lower atmosphere may be quite unstable. The very strong mid-tropospheric cooling (Fig. 3), which occurred in the hours preceding the Vina tornado (Braun and Monteverdi, 1991), is representative of the marked destabilization which occurs in these patterns.

Another important feature common to many of the recent California tornado and funnel cloud episodes (e.g., Monteverdi et al., 1988; Braun and Monteverdi, 1991; and Monteverdi, 1993) is the presence of a jet streak on the southwestern periphery of the advancing short-wave trough. The upward mid-tropospheric vertical 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 (as documented by Uccellini and Kocin, 1988; Meier, 1993; and others). Rapid destabilization is often evident in those portions of California which lay north of the jet axis and east of the main mid-tropospheric trough 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. Recent case studies (Braun and Monteverdi, 1991; and Monteverdi, 1993) have shown that post-frontal mesoscale troughs, or low pressure areas, often develop in the Central Valley of California behind the surface cold front under the area of synoptically-forced vertical motion associated with the main mid- and upper-tropospheric trough. The eastern portions of such surface features are characterized by southerly or southeasterly upvalley flow and can be a focus for significant moisture flux convergence. It is not certain that jet streak-induced circulations have a role in the production of such surface troughs. However, the intersection of the left front quadrant of the jet streak with the surface trough line was the site for thunderstorm initiation in the 1986 F2 Vina Tornado case (Braun and Monteverdi, 1991).

The prestorm sounding (Fig. 4a) and hodograph (Fig. 4b) for the mesocyclone-induced tornado of 24 September 1986 at Vina can be considered as a "prototype" sounding and hodograph for the purposes of this study. The sounding was constructed on the SHARP Workstation 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 the wind veered smoothly between the surface and the top of the coastal mountains at 1500 m (5000 ft)].

Important buoyancy and rotational parameters for the sounding/hodograph (Figs. 4a and 4b) are summarized in Table 2. Similar information for the December 1992 events considered in this study is also provided and will be discussed in this Technical Memorandum. The reader is referred to Weisman and Klemp (1982) for a

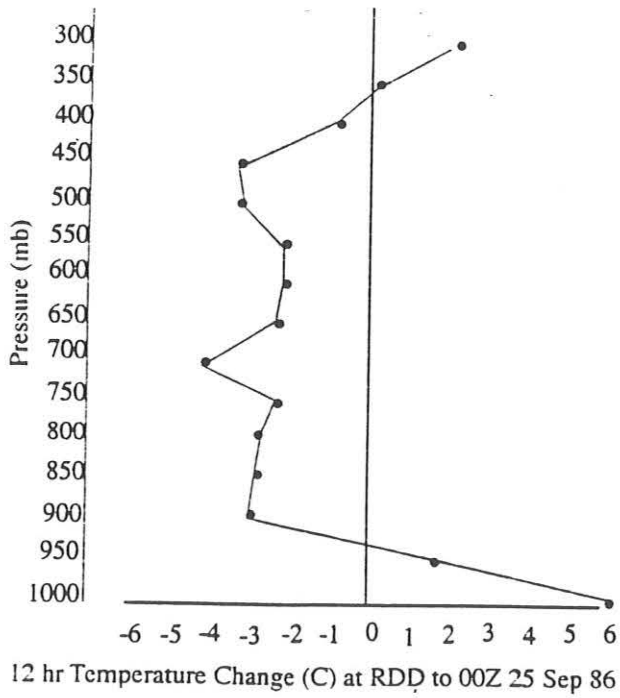


Figure 3 Layer temperature change (°C) at RDD for the 12 hours ending 0000 UTC 25 September 1986.

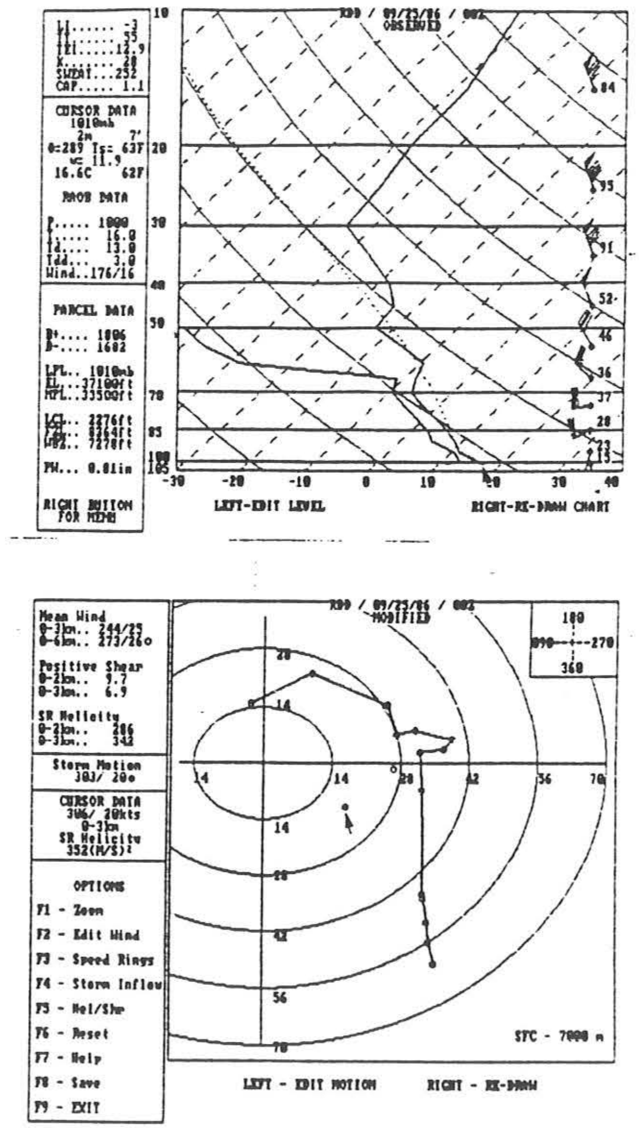


Figure 4 (a) Bogus RDD sounding, 0000 UTC 24 September 1986. Dashed line shows surface lifted parcel. Surface conditions indicated by arrow.

(b) Bogus RDD hodograph, 0000 UTC 24 September 1986. Arrow indicates true storm motion as determined from SAC weather radar.

discussion of the Bulk Richardson Number (BRN), Davies-Jones et al. (1990) 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 to storm rotation (positive shear), and Hart and Korotky (1991) for a brief discussion of the significance of all of the various parameters (including the Energy/Helicity Index -- EHI) displayed in the SHARP Workstation output.

To facilitate interpretation of the Table 2 and the soundings and hodographs provided in this study, the reader is reminded that supercell thunderstorms have been observed for BRNs between 2 and 45. However, the forecaster must keep in mind that the BRN is a "bulk" measure (i.e., based upon absolute value of shear and not whether it has the right characteristic). A BRN in the correct range of values for rotating thunderstorms and associated with favorable s-r helicities is a necessary, but not sufficient, condition for supercell development. Davies-Jones et al. (1990) advise that 0-3 km s-r helicities approaching 150 m^2 s^{-2} support mesocyclone development, 151-299 m^2 s^{-2} support weak tornadoes, 300-449 m^2 s^{-2} support strong tornadoes, and greater than 450 m^2 s^{-2} support 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 m^2 s^{-2} certainly would suggest a threat for strong (F2 or F3) tornadoes.

Johns et al. (1990) have shown that low-level shear, associated with a wind veering and increasing with height (positive shear), in the 0-2 km layer is a parameter most highly correlated with tornado occurrence. Particularly their results indicate values between 6 x 10^{-3} s^{-1} to 25 x 10^{-3} s^{-1} encompassed all of the tornado events. Finally, the EHI is another measure of the ratio of the buoyancy and shear, using the 0-2 km s-r helicity rather than the absolute value of the shear (as does the BRN). 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 x 10^{-3} s^{-1} for the hodograph strongly suggests potential for rotating thunderstorms when combined with the buoyancy (B+) of 1806 J kg^{-1}. In fact, Johns et al. (1990) show that such shear can be associated with F2 and F3 tornadoes with a B+ of only around 500 J kg^{-1}. The EHI of 3.2 is also suggestive of high risk for strong and violent tornadoes.

III. SELECTED TORNADO EVENTS OF DECEMBER 1992 IN NORTHERN AND CENTRAL CALIFORNIA

A. General Overview

The tornado events of 2 December, 6 December, 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 Medford and Winnemucca radiosonde observations. The authors make the assumption that the OAK radiosonde data, modified for the low-level temperature and wind conditions at the stations nearest the tornado occurrences, are representative.

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 (personal communication, Mr. Roger Williams, Deputy Meteorologist in Charge, WSFO, San Francisco). The Oroville tornado was investigated by a team from the Redding Weather Service Office (WSO) and the Loma Rica (near Marysville--MYV) 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. For example, it is interesting to note that NSSFC data for the period 1950-1988 indicate the mean path length

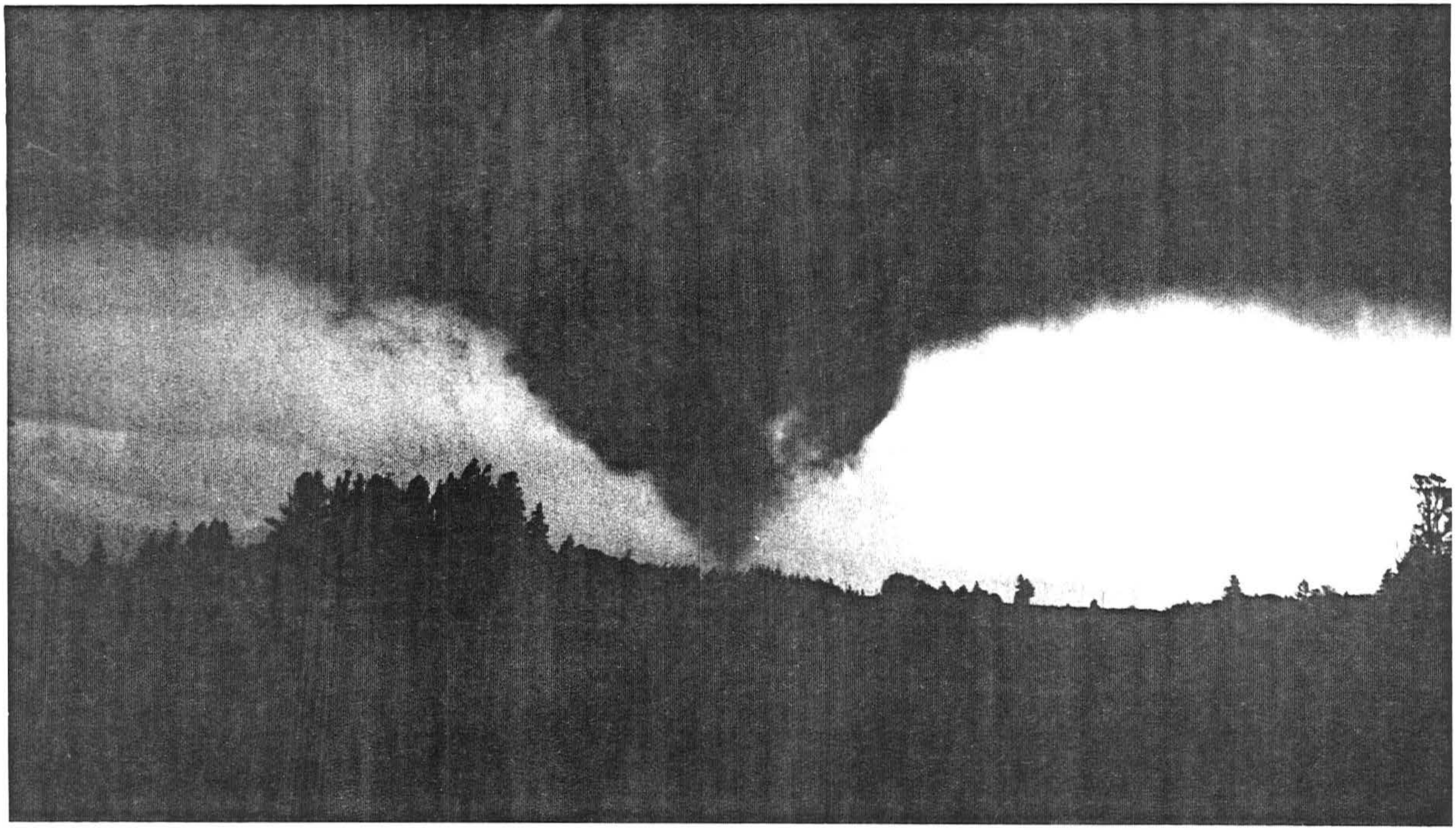


Figure 5 Photograph of first Sebastopol tornado taken from Santa Rosa, approximately 8 km away, looking west-southwest. Note two vortices. Photo courtesy of Kent Porter, Santa Rosa Press Democrat.

for tornadoes in California during that period to have been about 1 mile. The mean path length for the tornadoes considered in this study was about 4 miles with two verified tracks of 7 miles or greater. This suggests that California tornadoes have path lengths which are on average about the same as those observed in other parts of the country.

Post-event 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 concluded that the damage associated with the first Sebastopol tornado suggested winds approaching (but not quite the same as) those observed with F2 tornadoes. These observations contradict the conventional wisdom that cold sector funnels most often only touch down briefly, singly, and are very weak.

B. Sebastopol/Windsor Tornadoes of 2 December 1992

i. Description

On 2 December 1992, a number of tornadoes were reported in the Santa Rosa (STS) area (see Fig. 1 and Table 1). Witness reports of a quasi-stationary lowered base were verified by a number of photographs and video images, which substantiated the lowering was a wall-cloud that remained stationary for around one-half hour. It is interesting to note that other thunderstorms in northern California moved northeastward at 20 to 25 knots at the time of the tornado sightings and quasi-stationary wall-cloud observations in the Santa Rosa area.

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

The tornado (Fig. 5) was the first of three in the area and was documented with a path length of 7.5 miles. As it moved slowly north-northeastward, it dissipated to be replaced by a second tornado with a track slightly east of the first. This tornado had a path length of 3 miles before dissipating. At this time, video images of the wall cloud were captured by television cameramen. It slowly moved northeastward towards Windsor, at which time the third and final tornado in this sequence descended.

Damage surveys and reports indicated that the parent thunderstorm moved northeastward at 9 knots while other thunderstorms in the region were moving 20 to 25 knots. This slow movement is consistent with the quasi-stationary and quasi-steady nature of supercell thunderstorms.

ii. Synoptic and Subsynoptic-scale Controls

The 500 mb height and absolute vorticity patterns for 0000 UTC 3 December (Fig. 6) show that the mid-tropospheric trough affecting northern California was closed, 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 given) indicated that it had progressed around the north side of the long-wave ridge in the Gulf of Alaska and approached California from the northwest, as also occurred for the prototype discussed above. At the time of Fig. 6, moderate to strong mid-tropospheric CVA in southwesterly flow characterized the middle third of California.

A series of subsynoptic surface analyses indicated that a post-frontal 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 meso-low in the area between Ukiah and STS. Unlike the prototype discussed above, winds at OAK had not yet veered to the northwest, undoubtedly because the mid- and upper-tropospheric short-wave was located farther off the coast in this case. Thus, all of the coastal valleys, including those in the San Francisco Bay region and the Central Valley, were situated to

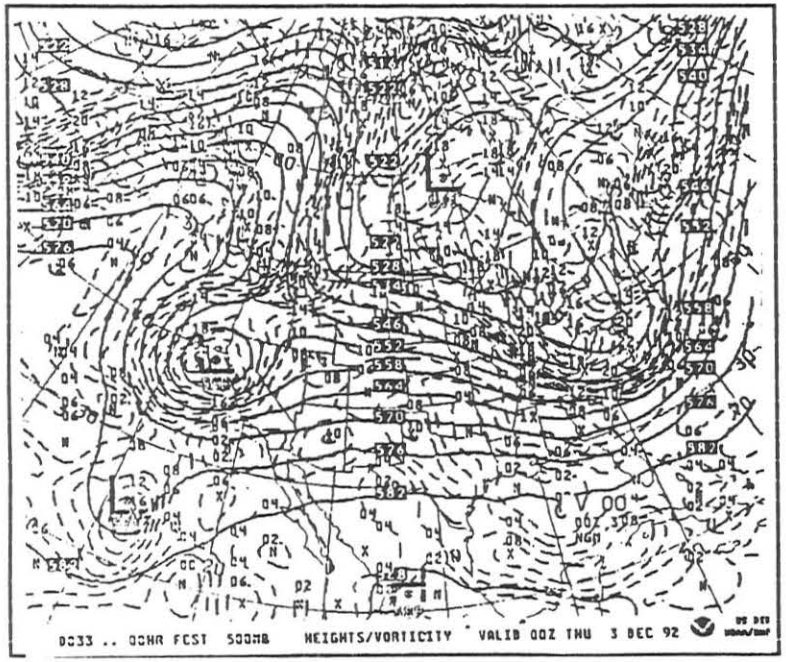


Figure 6 NGM analysis of 500 mb heights (dam) and absolute vorticity ($10^{-5}s^{-1}$) for 0000 UTC 3 December 1992.

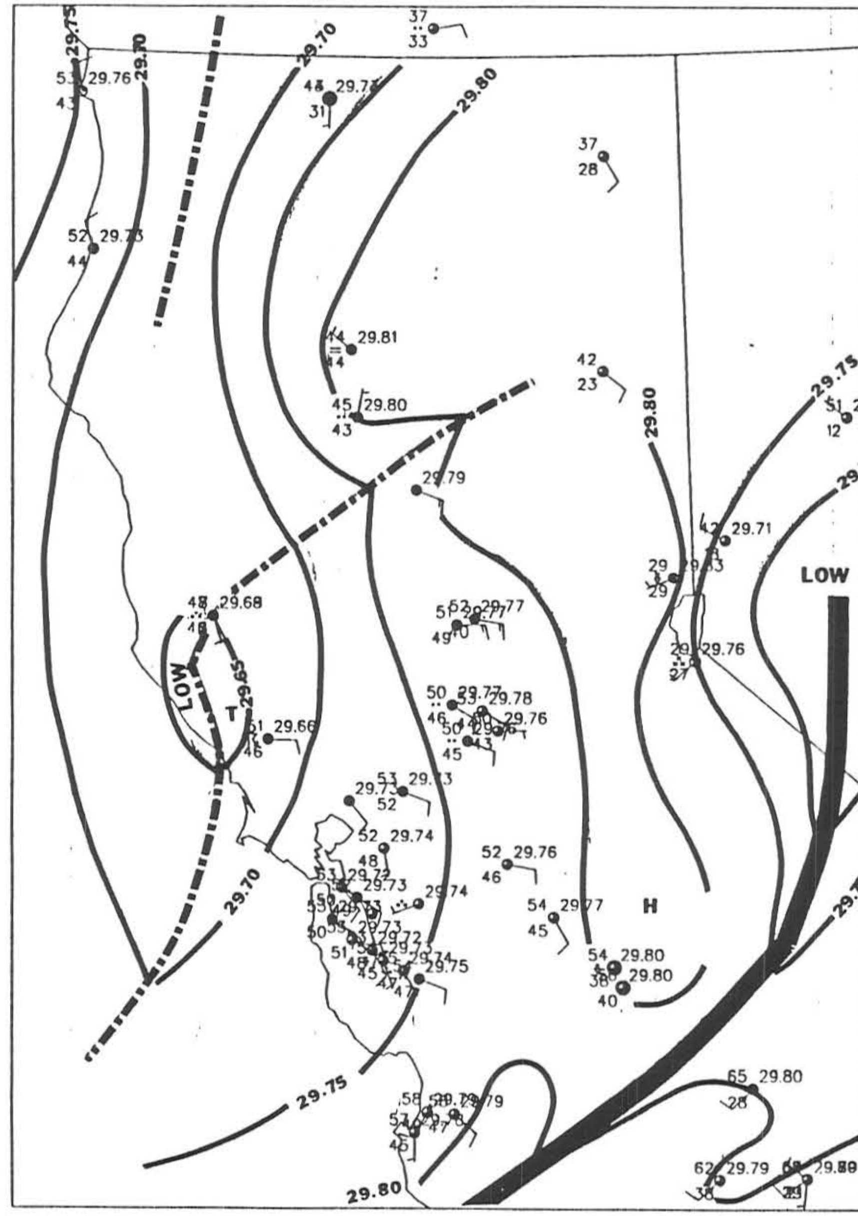


Figure 7 **Subsynoptic analysis of altimeter settings for 0000 UTC 3 December 1992. Broad solid line is main cold front, light dashed line is post-frontal trough. Approximate location of tornadic thunderstorm at this ti[illegible] indicated by "T".**

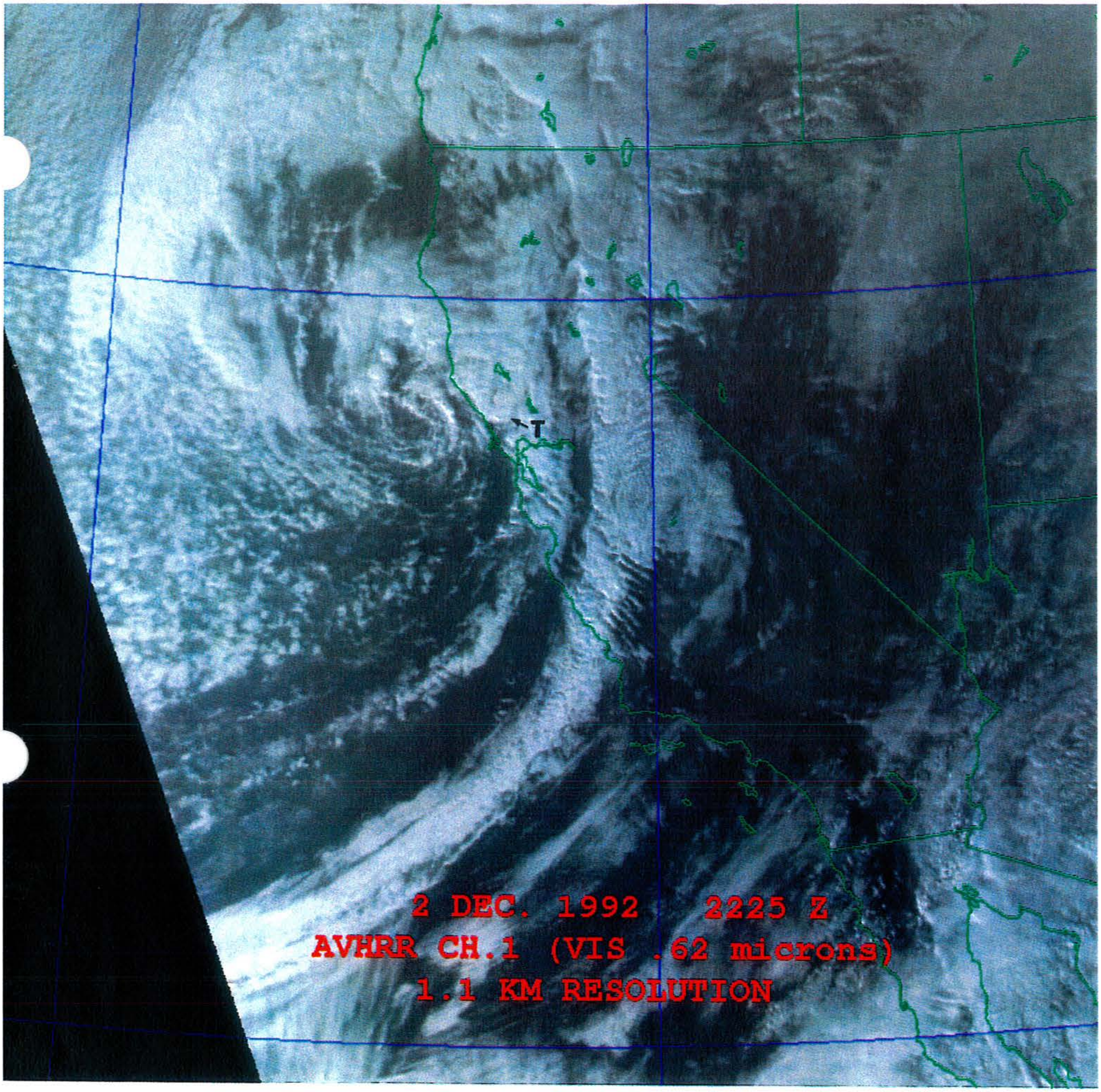


Figure 8 Advanced Very High Resolution Radiometer (AVHRR) visible image for 2225 UTC 2 December 1992. Note suggestion of mesoscale vortex in the cloud mass (indicated by "T"). First tornado occurred under the southernmost portion of the vortex.

channel low-level flow to a southeasterly direction. The meso-low acted as a local focus in the vicinity of STS, which at the time of Fig. 7 was reporting an east wind. The "T" on Fig. 7 gives the approximate position of the second tornado at the time of the chart.

The enhanced 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 mid- and upper-tropospheric circulation center west of Point Arena. The initial development in the Santa Rosa area was the southern-most in a complex of thunderstorms which extended northward and then northwestward across Cape Mendocino. A mesoscale circulation, possibly related to the meso-low near STS, is indicated by the tight, comma shaped spiral indicated by the letter "T".

iii. Buoyancy and Wind Shear Parameters

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

The bogus STS sounding (Fig. 10a) was obtained on the SHARP Workstation by insertion of the 2300 UTC STS temperature and wind information into the OAK 0000 UTC sounding. 2300 UTC was chosen because this was the time closest to initial tornado development. The bogus hodograph (Fig. 10b) was constructed by insertion of the surface wind for STS at 2300 UTC and by assuming that the narrow valley in which STS lays would prevent any directional shear until the crest at 5000 m (1500 ft). Storm motion was determined from tornado track information as summarized above.

The parameters given for the modified sounding and hodograph in Table 2 verify ground observations of storm rotation. Buoyancy and shear were in the correct range for the development of supercells and mesocyclone-induced tornadoes. The EHI value of slightly less than 1 combined with a s-r helicity of 284 J kg^{-1} were consistent with the development of tornadoes in the F1 to F2 range.

C. Monterey Tornadoes of 6 December 1992

i. 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 shingle loss to roofs. There were several reports of waterspouts and funnel clouds off the Carmel coast. Observations of the Carmel tornado suggested that it occurred from the flat base of the parent thunderstorm and no observations of wall-clouds or lowered bases reported. Damage surveys indicated that the path length of the Carmel tornado was 7 miles and that of the second tornado in Monterey was 1 mile. These surveys also indicated that the tornadoes moved along with the thunderstorm motion, as observed on SAC weather radar.

ii. Synoptic and Sub-synoptic Controls

The 500 mb analysis for 0000 UTC 7 December 1992 (Fig. 11) shows a negatively-tilted trough extended from the Gulf of Alaska southeastward over California. The trough was associated with strong mid-tropospheric CVA (not shown). The axis of the upper-tropospheric jet stream intersected the California coast near Vandenberg Air Force Base. The mid-tropospheric expression of a jet streak is evident 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 in the process of advancing through the north-central portions of California. AVHRR infrared imagery for 2317 UTC (Fig. 12), about 45 minutes before the first tornado report, indicated that considerable enhancement of the frontal cloud band had occurred east of the main mid-tropospheric trough axis in the vicinity of the left front quadrant of the advancing jet streak. Strong thunderstorm development was

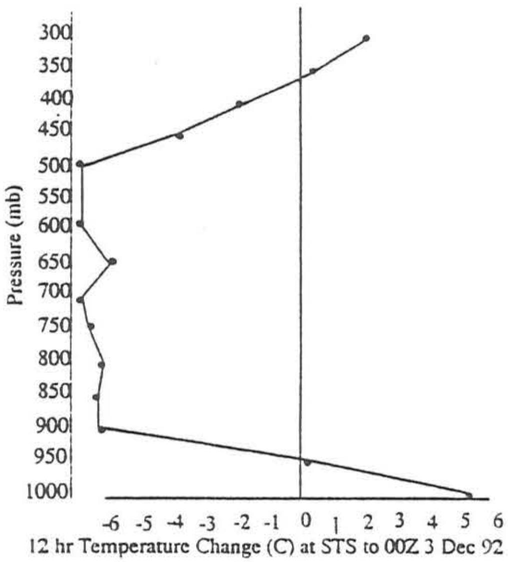
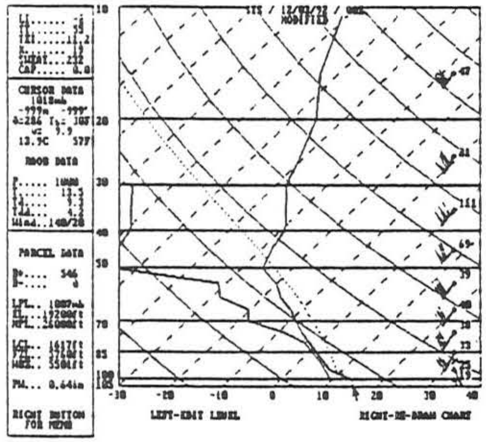


Figure 9 Layer temperature change (°C) at STS for the 12 hours ending 0000 UTC 3 December 1992.



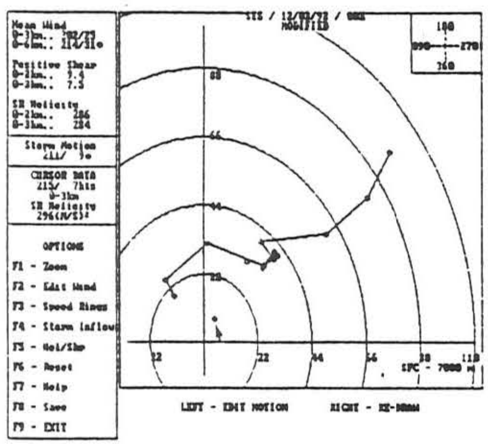


Figure 10 (a) Bogus STS sounding, 0000 UTC 3 December 1992. Dashed line shows surface lifted parcel. Surface conditions indicated by arrow.

(b) Bogus STS hodograph, 0000 UTC 3 December 1992. Arrow indicates true storm motion as determined from tornado tracks.

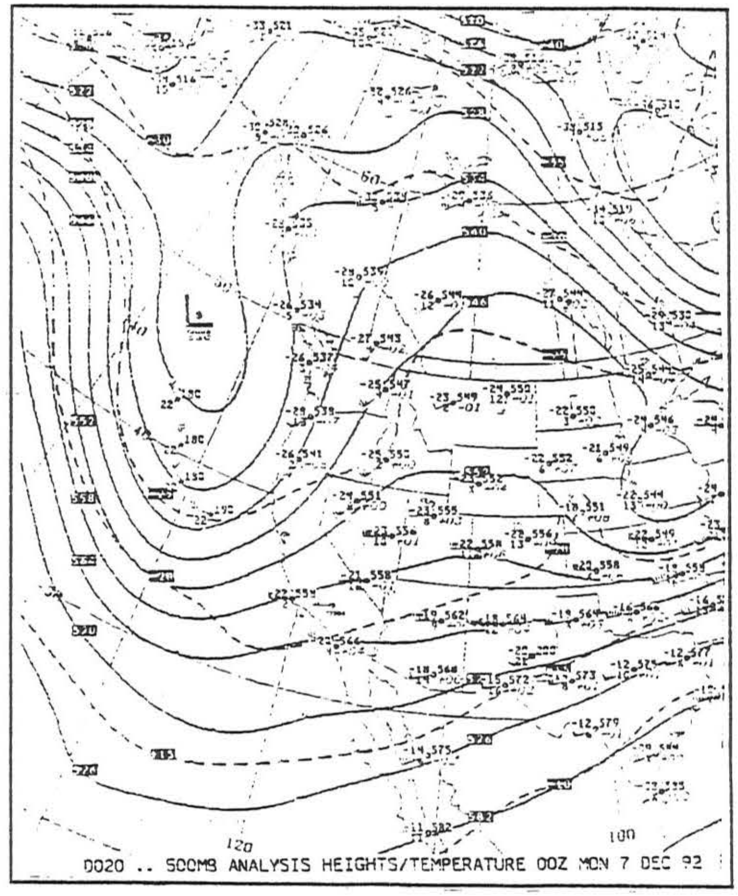


Figure 11 Analysis of 500 mb heights (dam) and temperatures (°C) for 0000 UTC 7 December 1992.

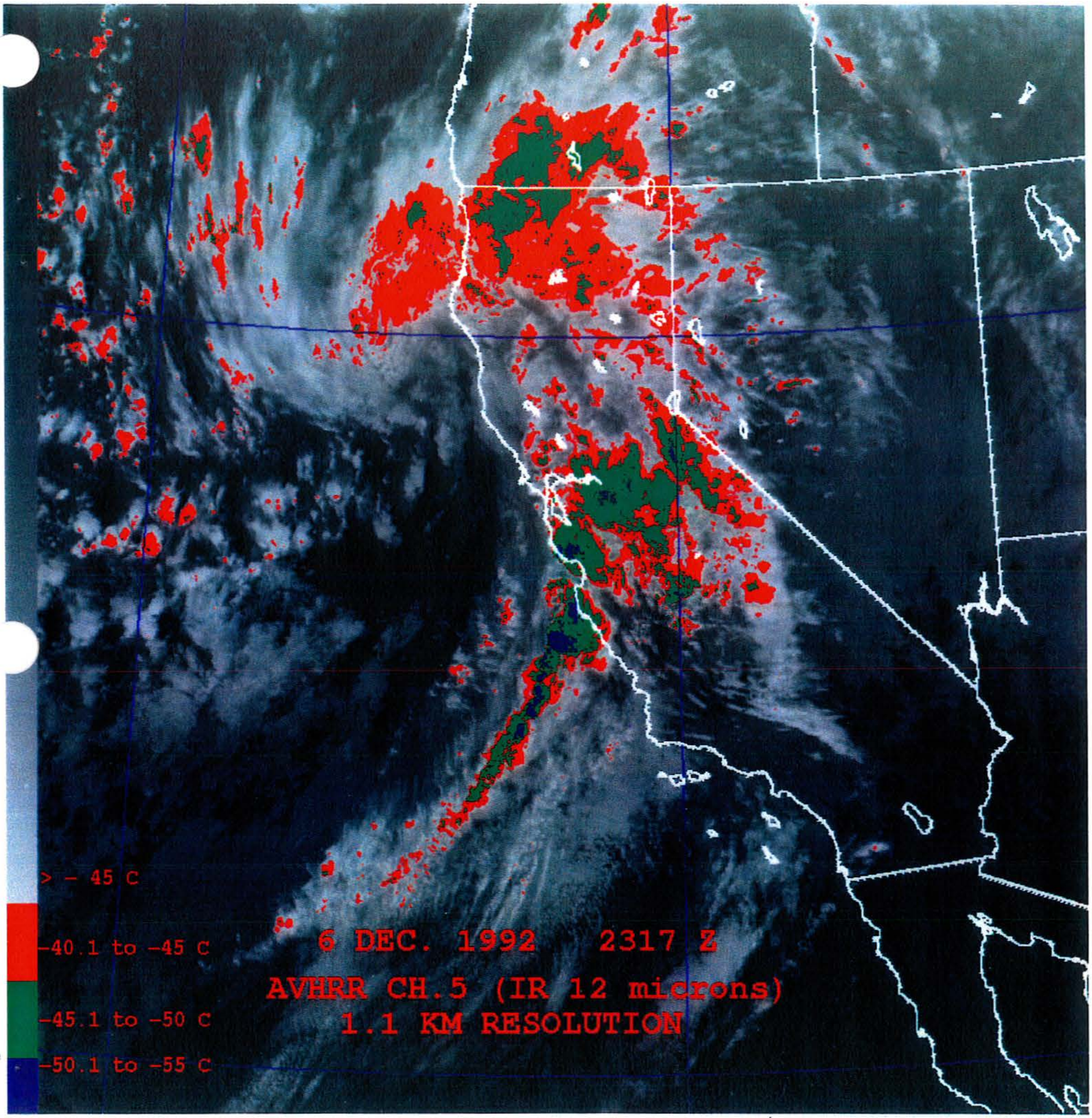


Figure 12 AVHRR infrared image for 2317 UTC 6 December 1992. Thunderstorm cells southwest of Monterey peninsula produced waterspouts and tornadoes about 45 minutes after image time.

evident from just east of San Francisco southwestward across the coastline near Monterey.

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 insights to the focus for this case. However, 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 would be discerned from subsynoptic analyses. In addition, since the funnel clouds and waterspouts which preceded the tornadoes were observed over the Pacific, west of Carmel, it is probable that any such focusing mechanisms would have been active west of the coastline and away from any observation sites.

iii. Buoyancy and Wind Shear Parameters

Mid-tropospheric cold advection and low-level diurnal heating produced 12 h temperature changes (Fig. 13) in the Monterey area in the same sense (but of a smaller magnitude) than those observed for the other cases considered. The destabilization for this case was not as marked as that which occurred for the other cases. In fact, the B+ (Table 2) obtained from a bogus 0000 UTC MRY sounding (Fig. 14a), constructed on the SHARP Workstation, is the smallest of the cases discussed in this study.

The bogus hodograph for MRY (Fig. 14b) was constructed by insertion of the 0000 UTC wind observation for MRY and the true storm motion as determined from SAC weather radar. The 0-2 km positive shear and 0-3 km s-r helicity, as estimated from the SHARP Workstation analysis of the bogus hodograph, were also somewhat smaller than those observed for the other cases (Table 2). The curvature of the hodograph between the surface and 2000 m was clockwise and, with the storm motion indicated, produced a s-r helicity of 254 m^2 s^{-2}, a "rotational potential" which can support weak tornadoes, according to Davies-Jones et al. (1990).

Although the BRN obtained from the sounding (Fig. 14a) was in a range which suggested developing thunderstorms might have supercellular characteristics, the buoyancy and shear evident in Table 2 for this case were likely too small for mesocyclone development. This is substantiated by the EHI of 0.6, by far the smallest of such values for the cases considered in this study.

The parameters summarized in Table 2 for this case suggest that the potential for cold sector funnels and weak tornadoes region-wide was high in this case. However, no discernible mesoscale or subsynoptic focus was evident which would have aided forecasters in localizing the threat to the Monterey area. This lack of focus is probably consistent with the fact that both anecdotal evidence and buoyancy/shear parameters indicate that these tornadoes were not mesocyclone-induced.

D. Oroville-Marysville (Loma Rica) Tornadoes of 17 December 1992

i. 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 (personal communication, Mr. Chris Fontana, Meteorologist in Charge, WSO Redding) along its path length of 3/4 mile. A previous report (Monteverdi, 1993) described the usefulness of the SHARP Workstation in providing guidance to forecasters in anticipating this event.

The second tornado occurred at 2330 UTC and passed through an unpopulated area near Loma Rica, which is a small village around 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 the tornado was "cone-shaped" as it traversed its approximately 5 mile path length.

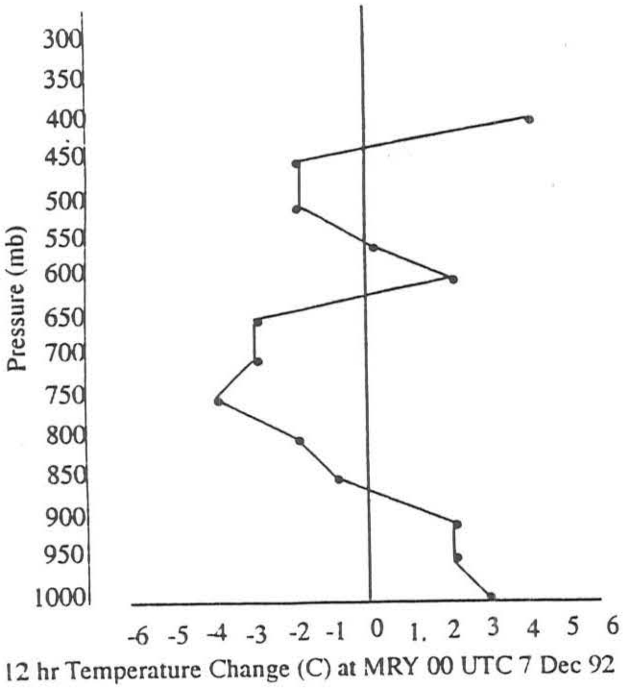


Figure 13 Layer temperature change (°C) at MRY for the 12 hours ending 0000 UTC 7 December 1992.

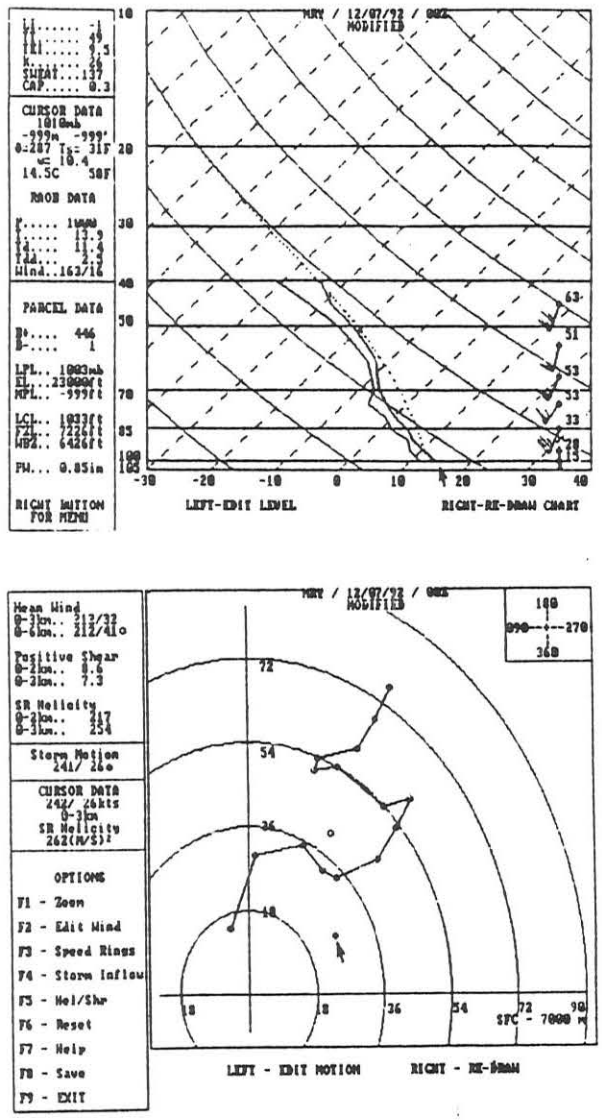


Figure 14 (a) Bogus MRY sounding, 0000 UTC 7 December 1992. Dashed line shows surface lifted parcel. Surface conditions indicated by arrow.

(b) Bogus MRY hodograph, 0000 UTC 7 December 1992. Arrow indicates true storm motion as determined from SAC weather ra

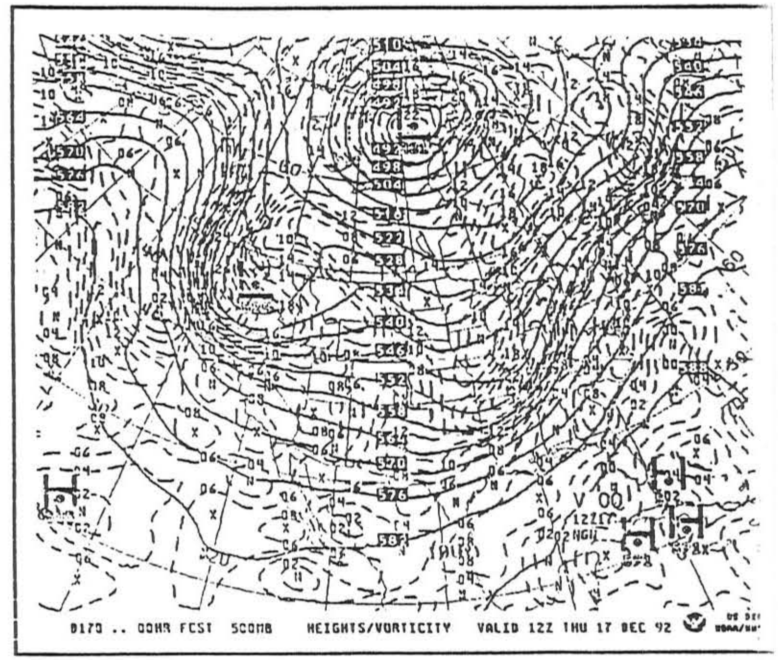


Figure 15 NGM analysis of 500 mb heights (dam) and absolute vorticity ($10^{-5} s^{-1}$) for 1200 UTC 17 December 1992.

Analyses of radar and satellite imagery confirm that both tornadoes were associated with a thunderstorm which 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.

ii. Synoptic and Subsynoptic-scale Controls

The synoptic pattern which occurred on 17 December 1992 (Fig. 15) was the most similar of the other December 1992 cases to the prototype described earlier. CVA associated with an advancing jet streak seemed to play an important role in diagnosing a vertical motion field which 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 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 (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 of a subsynoptic scale trough located in the southern Sacramento Valley even though northwesterly winds characterized the low-level flow in the San Francisco Bay region. Mesoscale or subsynoptic lee-side troughs are common in patterns which closely resemble the prototype surface and mid-tropospheric patterns (Fig. 2), discussed in section 2.

The prestorm moisture flux convergence field over California (Fig. 17) was characterized by two maxima, one associated with the frontal system over central California and another associated with the trough line. Maxima of moisture flux convergence indicate a mesoscale focus for destabilization and/or wind convergence (Doswell, 1985 and many others). The tornadic thunderstorm (indicated by the letter T on Figs. 16 and 18) initially developed in the northern-most area of surface moisture flux convergence ahead of the trough line and north of the main front. Moisture flux convergence occurring in association with post-frontal troughs was also found to be an important feature in the prestorm environment with the 24 September 1986 tornadoes in the Sacramento Valley (Braun and Monteverdi, 1991).

iii. Buoyancy and Wind Shear Characteristics

Strong cold advection in the mid- and lower-troposphere, in association with the trough (Fig. 15) advancing southeastward, caused pronounced destabilization over northern and central California. The cooling in the 900-400 mb layer was very marked, as is evident in Fig. 19, which shows the 12 h layer temperature changes for the period from 1200 UTC 17 December and 0000 UTC 18 December. Figure 19 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 20.

The bogus 2200 UTC MYV sounding (Fig. 20a) was constructed on the SHARP Workstation. The sounding information (Table 2) substantiates the fact that weak positive buoyancy characterized the lower-troposphere even though the 500 mb Lifted Index (LI) indicated negative buoyancy at that level. As pointed out in Braun and Monteverdi (1991) and Monteverdi (1993), the 700 mb LI provides a more accurate indicator of instability in cold sector California events, particularly during the cool season (-3.5 in this case).

The bogus MYV hodograph (Fig. 20b) 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

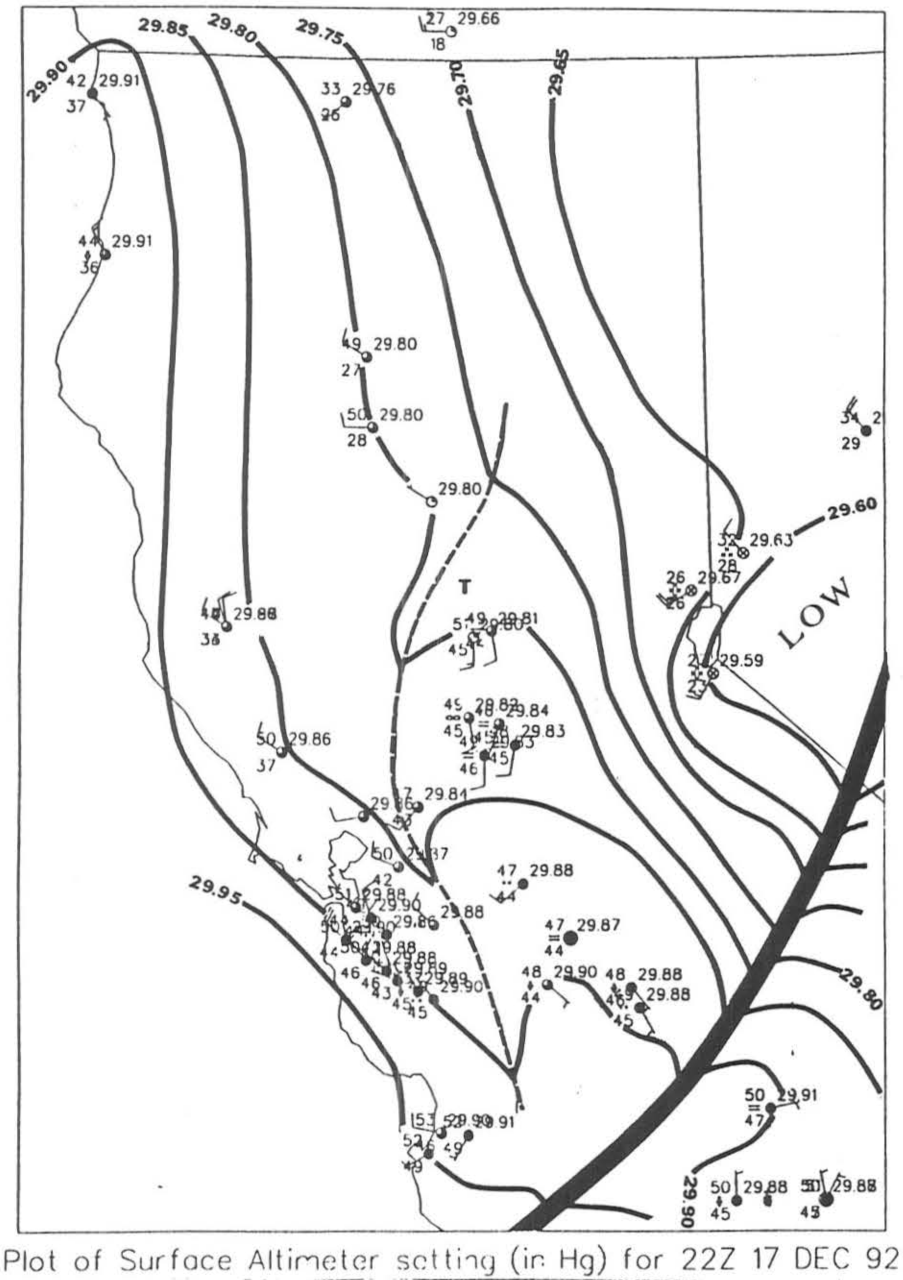


Figure 16 Subsynoptic analysis of altimeter settings for 2200 UTC 17 December 1992. Broad solid line is main cold front, light dashed line is post-frontal trough. Approximate location of tornadic thunderstorm at this time indicated by "T".

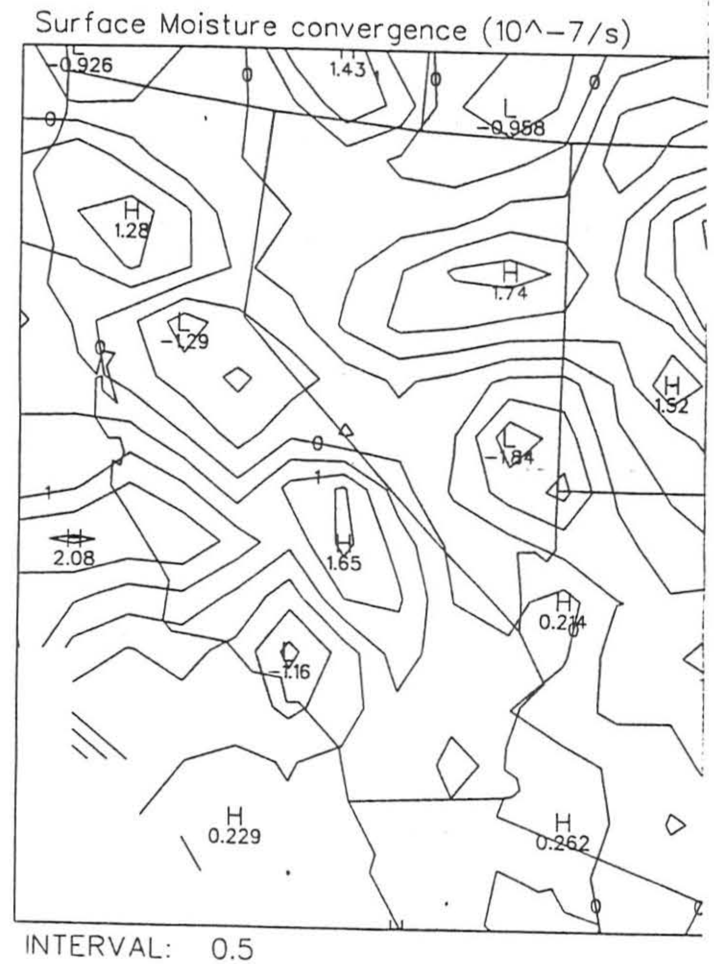


Figure 17 Surface moisture flux convergence field (10^{-7} s^{-1}) for 2100 UTC 17 December 1992. Positive values indicate moisture flux convergence.

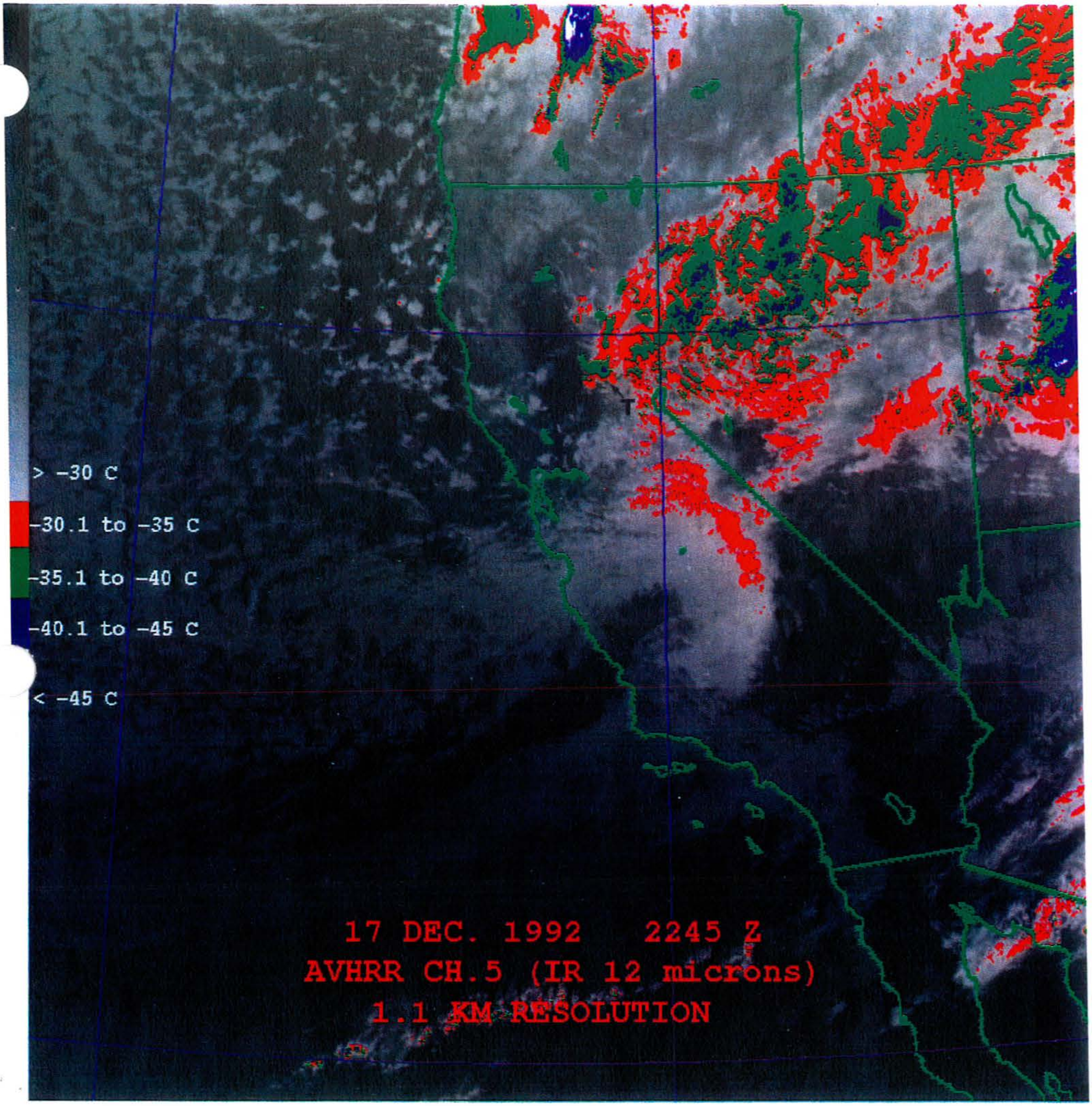


Figure 18 AVHRR infrared image for 2245 UTC 17 December 1992. Tornadic thunderstorm indicated by letter "T".

obtained from SAC weather radar (indicated by arrow). The modified hodograph shows the type of low-level curvature indicative of high rotational potential, verified by the s-r helicity of 454 $m^2 s^{-2}$. The weak buoyancy of 552 J kg^{-1} is in the correct range to support strong and violent tornadoes if the positive shear exceeded 10 x 10^{-3} s^{-1} (Johns et al., 1990). The positive shear of 13 x 10^{-3} s^{-1} combined with the s-r helicity gives an EHI of 1.17, suggesting that storms in the southern Sacramento Valley could be associated with strong (F2 or F3) tornadoes.

IV. DISCUSSION AND CONCLUSIONS

Previous studies (Braun and Monteverdi, 1991; and Monteverdi, 1993) have pointed out that shear profiles which support s-r helicities favorable for storm rotation can be created or augmented locally by most valleys in northern and central California. Since both the Coast Range and the Sierra Nevada trend northwest-to-southeast, most ridges and valleys are oriented in the "proper" direction to channel low-level southwesterly and southerly flow to southeasterly. For the cases considered in this study, this low-level channelling combined with the west-southwest flow in the mid-troposphere, created a situation in which moderate to strong streamwise vorticity was generated in the low-level flow. As a result, in all of the cases considered in this study, s-r helicities achieved values which could support moderate to strong tornadoes.

The southern Sacramento 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. Of the soundings and hodographs considered here, those for 17 December 1992 (Figs. 20a and 20b) most closely resembled those for the Vina tornado (Figs. 4a and 4b). In the Vina event (Braun and Monteverdi, 1991), a post-frontal subsynoptic trough focused the topographically channelled low-level flow. It appears that, in the case of the 17 December 1992 tornadoes, proper phasing of synoptic-scale features also supported the development of a subsynoptic, leeside trough in the Sacramento Valley which, in turn, augmented the channelled flow in the same manner. The s-r helicities for these two events were the greatest of those calculated for all events considered here and actually were in a range which could support strong (24 September 1986) and strong to violent (17 December 1992) tornadoes (Table 2).

Strong and violent tornadoes have been observed for a wide range of buoyancy and shear ratios (Johns et al., 1990). 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 were "cold sector", the Vina tornado occurred in a warm season environment characterized by much higher temperatures and dew points than those that occurred with the December 1992 tornadoes. This study substantiates the conclusions of Johns et al. (1990), and many others, that weak instability can be associated with at least moderate mesocyclone-induced tornadoes if shear values are in favorable ranges. In the case of the events considered here, only the Monterey tornadoes occurred in an environment in which the buoyancy to shear ratios failed to support strong thunderstorm rotation.

Each of the three December events occurred in a synoptic pattern which corresponded to one of the two already discussed in the literature as being associated with cold-sector tornadoes in California (Hales, 1985; Braun and Monteverdi, 1991). The Monterey and southern Sacramento Valley tornadoes were associated with a progressive mid-tropospheric 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 mid-tropospheric trough became closed off west of the coastline. This apparently kept the greatest upper-tropospheric divergence and ascent along the coast.

This study indicates that careful subsynoptic analyses and thoughtful consideration of buoyancy and shear information, obtained interactively on the SHARP Workstation (or any similar analysis system) by the forecaster, can

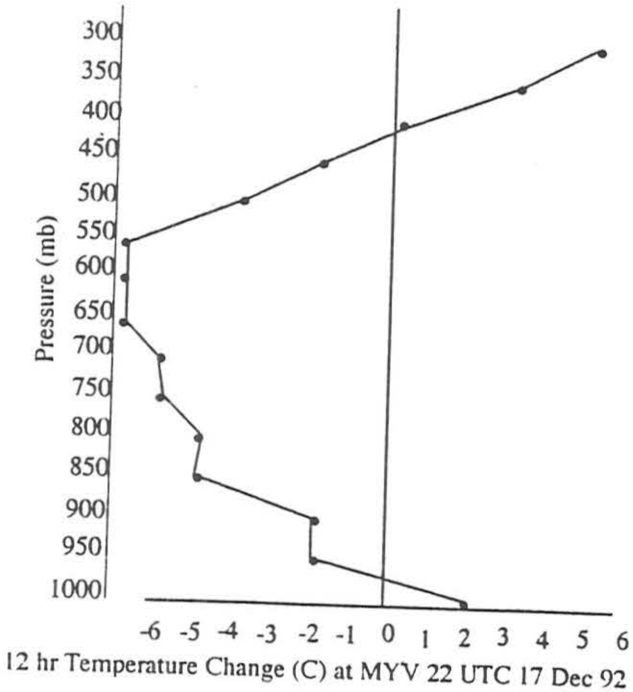


Figure 19 Layer temperature change (°C) at MYV for the 12 hours ending 2200 UTC 17 December 1992.

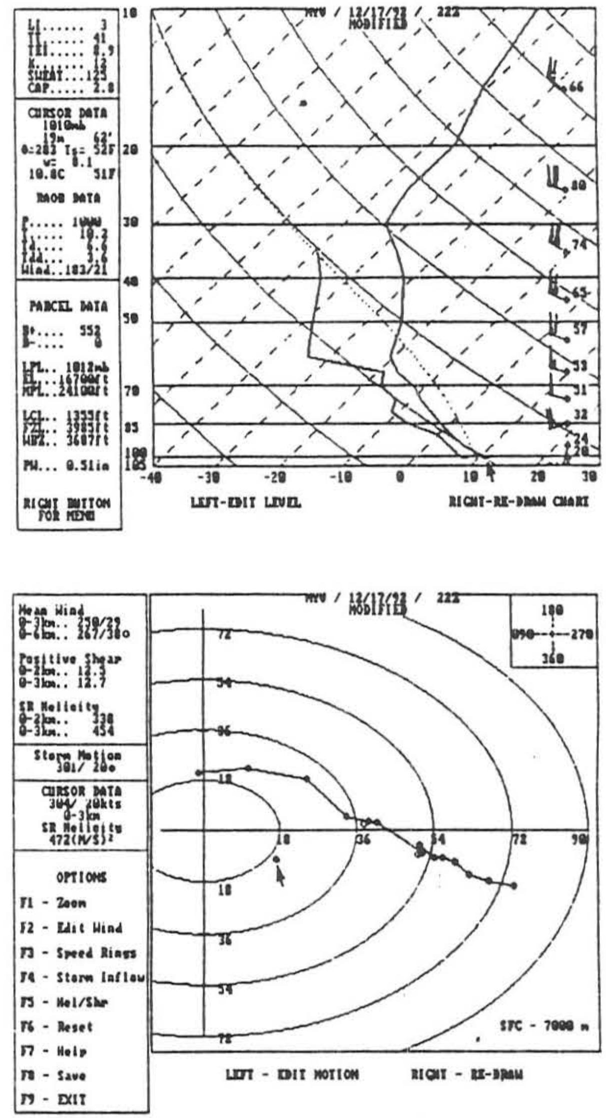


Figure 20 (a) Bogus MYV sounding, 2200 UTC 17 December 1992. Dashed line shows surface lifted parcel. Surface conditions indicated by arrow.

(b) Bogus MYV hodograph, 2200 UTC 17 December 1992. Arrow indicates true storm motion as determined from SAC weathe- radar.

indicate a mesoscale or subsynoptic focus for those tornado events in California which are mesocyclone-induced. On the other hand, determination of such a local focus may not be possible for thunderstorms which do not have supercellular characteristics and those supercellular events which are initiated over the data-sparse Pacific.

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

Acknowledgments.

AVHRR imagery was supplied courtesy of Mr. Steve Hipskind, Earth System Science Division, NASA Ames Research Center and was processed by Ms. Kathy Pagan, Research Technician, SFSU. The subsynoptic plots included in this report were produced by the SDM/WXP programs obtained by the Department of Geosciences from UNIDATA and meticulously installed, customized, and documented by the site manager, Dr. David Dempsey. This research was partially sponsored by COMET grants S9209 and S9236. The authors gratefully acknowledge the support and encouragement from Area Manager Norman Hoffmann, Deputy Meteorologist in Charge Roger Williams, and all the forecasters of the WSFO San Francisco (Redwood City) in the joint interactions with SFSU and the WSFO.

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