An Analysis of a Mesocyclone-Induced Tornado Occurrence in Northern California

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ABSTRACT

One documented F2 tornado and several other unconfirmed tornadoes were reported in California’s Sacramento Valley on 24 September 1986. The synoptic pattern which occurred that day was one long-recognized by California operational meteorologists as being associated with severe weather in the state. The present study documents this event and shows that the parent thunderstorm had supercellular characteristics and that the tornado was mesocyclone-induced. As is the case elsewhere when severe thunderstorms are observed, the mesoscale environment established a focus for late morning and early afternoon deep convection. A quasi-stationary leeside trough acted in concert with local channeling effects to promote the advection of relatively moist air to the northern portions of the Valley. This channeled flow contributed to low-level shear which was much stronger than that evident in the Oakland hodograph and one which was comparable to that found with supercell and mesocyclone development elsewhere in the United States. The large scale environment acted as a destabilizing agent and provided a vertical motion field which encouraged the convection. Although CAPE estimates based upon an evaluation of Oakland sounding data were low, estimates of bulk Richardson number in the Valley were within the range observed with supercell storms elsewhere in the country. The thunderstorm initially developed when the vertical motion field associated with an advancing synoptic scale cold front interacted with the moist and destabilizing air moving northward in the Valley. Diurnal heating and layer lifting probably contributed to the destabilization. Photographs show that the F2 tornado was characterized by multiple vortices, had formed from a wall-cloud on the south portion of the right-moving supercell, and was accompanied by a rear flank downdraft. Forecasters familiar with severe weather parameters could have anticipated the potential for supercellular development in California with the aid of computerized analysis and diagnostic routines now available in real-time throughout much of the operational community.

1. Introduction

On 24 September 1986 numerous strong thunderstorms developed in California’s Sacramento and San Joaquin Valleys. At approximately 2015 UTC an F2 tornado (USDC 1986) touched down near Vina, California (all locations shown in Fig. 1). This tornado was associated with a thunderstorm which rapidly developed west of Redding (RDD) (hereafter referred to as “the Redding storm”) at around 1830 UTC and then moved southeastward. There were additional unconfirmed reports of tornado touchdowns at Cottonwood, just southeast of RDD at 1945 UTC, and again east of Chico (CIC) at 2100 UTC. Intense thunderstorms, funnel clouds, and unconfirmed tornadoes also were observed near Stockton (SCK) at around 0000 UTC 25 September.

Previous studies in the literature have examined the general synoptic and thermodynamic conditions as-

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The approach outlined by Doswell (1987) is utilized in presenting the meteorological scenario associated with this thunderstorm. The synoptic scale pattern contributes to a regional threat of severe thunderstorms by creating an upward vertical motion field which favors air mass destabilization. This study investigates how such fields (often termed the “dynamics”) on 24 September 1986 provided an environment favorable for deep convection over northern California.

Doswell (1987) also points out that smaller scale factors can augment the thermodynamics locally and can provide mesoscale lifting mechanisms which initiate the convection. This investigation will show how such factors acted to focus the threat to the northern portion of the Sacramento Valley. A central point in this study is the effect of the local topography in establishing a low-level wind shear profile favorable for supercell and mesocyclone development. Such a profile is distinct from that usually observed with non-supercell cold sector tornadoes along the West Coast.

This paper includes six major sections. The climatology of tornadoes in the state and in the West Coast is presented as background information in section 2. In section 3, the nature of the large-scale forcing and its role in contributing to an environment favorable for the Redding thunderstorm is discussed. Aspects of the surface flow pattern which contributed to the evolution of the parent supercell thunderstorm and a comparison of this storm’s characteristics with those typical of supercell thunderstorms elsewhere in the country are summarized in section 4. The discussions of low level wind shear and the thermodynamic environment in section 5 will compare the local environment of the Redding storm to that of other tornadic thunderstorms in North America. The conclusions of the study are discussed in section 6.

2. Tornadoes in California

a. General overview

Historically, tornadoes have not been considered significant features of the climatology of California. An examination of climatological statistics seems to bear this out. Data extracted from the National Severe Storms Forecast Center (NSSFC) records for the period 1950–1988 indicate an average frequency of approximately four tornadoes per year in California (about 0.3 tornadoes per 26 000 km² per year). This is much smaller than the mean annual frequency for most of the southern Great Plains of 12 to 16 per 26 000 km² (Court 1974).

The use of such averages in estimating “tornado risk” in California can lead to misinterpretations, particularly in regions of complex terrain. Hales (1985), for example, points out that tornado frequencies for the Los Angeles Basin differ markedly from the statewide average and are comparable to those observed in the central United States. Hales' results also show that the San Francisco Bay region experiences relatively frequent tornado occurrences.

The high tornado frequencies reported for urban regions in California might not be indicative of any special meteorological circumstances which make these areas more prone to tornado occurrence. As pointed out by Doswell (1980), tornado frequencies are often high in populated regions and along major highways because of the relatively great numbers of potential observers in these areas. Although this is undoubtedly a factor in California tornado observation patterns, it is also true that forecasters in the state know that the meteorological factors associated with specific synoptic patterns interact with the topography in certain regions (e.g., the Los Angeles area) to enhance the likelihood of severe weather activity (see, e.g., Hales 1985).

Hales' findings, confirmed by the authors in an analysis of a data set which extends through 1988, also identify the Sacramento and San Joaquin Valleys as areas particularly prone to tornado occurrence. The relatively high frequencies observed in the northern and central Sacramento Valley occur in a rural region characterized by low population densities and cannot be entirely attributed to a great number of potential observers. These statistics substantiate the forecasting experience of operational meteorologists who are accustomed to seeing radar and satellite evidence of strong thunderstorm development in the northern Valley in certain spring and fall synoptic patterns.

Although most California tornadoes are weak, strong (F2) to severe tornadoes (F3) occasionally occur (Fig. 2). Smith (1971) estimates the upper limit for tangential wind speeds for California tornadoes to be 87.5 m
gradually warmer ocean or land surfaces destabilizes the air masses so that convection becomes more likely later in the life cycle of these disturbances. The air masses may also destabilize under the influence of strong cold advection in the middle and upper troposphere over California.

Besides providing a favorable thermodynamic environment, these high latitude type storms are generally associated with upper tropospheric divergence diagnosed by moderate to strong midtropospheric cyclonic vorticity advection (Reed and Blier 1986) and vertical motions induced by upper tropospheric jet streaks located over, or northwest of the state (Hales 1985; Reed and Blier 1986; Monteverdi et al. 1988). Moderate thunderstorms often take place when such dynamic forcing occurs in combination with low level diurnal heating or other destabilizing factors.

In the typical sequence, an approaching mass of postfrontal open-cellular cumulus in the Pacific would alert forecasters to the threat of thunderstorms in California. The strongest lowland development of such storms frequently takes place in the Central Valley, a phenomenon which is often attributed to greater diurnal heating effects there (e.g., Weaver 1962). Intense thunderstorms with funnel clouds and hail are commonly observed in association with this pattern when favorable dynamic forcing exists. A familiar scenario is one in which the formation of such storms is augmented by the transverse circulations associated with an upper tropospheric jet streak. The relationship of cloud features to the left front portion of such a streak is illustrated schematically by Fig. 3, which depicts the pattern at 1200 UTC on 21 March 1987, about five hours be-

![Fig. 2. Tornado distribution by F-scale intensity for all tornadoes reported in California during the period 1950–1986. (MSG = missing; indicates that no F-scale designation was indicated).](image)

\( v = (175 \text{ mph}) \) with a translational speed of 7 to 13 m \( s^{-1} \) (15 to 25 mph). NSSFC data for the period 1950–1988 indicate that the mean path length for tornadoes in the state is 1.4 km (0.91 mile) and the mean path area is 0.13 km\(^2\) (0.05 mi\(^2\)).

\( b. \) Cold sector tornadoes

Tornadoes in California most often form in the cool, conditionally unstable maritime air mass behind a cold front (Fawbush and Miller 1954; Hales 1985) and, as a result, are referred to as cold sector tornadoes. Cold sector tornadoes occur most often with wave cyclones of the “high latitude type”, as defined by Weaver (1962). These surface disturbances are usually associated with upper tropospheric short wave troughs moving southeastward on the western side of an amplifying longwave trough (Reed and Blier 1986). Smith (1971) and Reed and Blier (1986) suggest that the southeastward movement of the storm systems over the area can extend for several days and that the storms associated with this type of flow have more damaging potential than those of the “midlatitude type”.

![Fig. 3. Schematic diagram showing the location of features for the cold sector thunderstorm pattern of 21 March 1987 in which intense thunderstorms with funnel clouds occurred in California (after Monteverdi et al. 1988).](image)
fore funnel clouds and large hail occurred in the San Joaquin Valley (Monteverdi et al. 1988).

In the Great Plains, tornadoes are most often produced by supercell thunderstorms which develop in an environment characterized by warm, moist low level air capped by potentially cooler, much drier air aloft, often in the warm sector ahead of a cold front (Carlson et al. 1983; Browning 1986). Cold sector tornadoes tend to form in an area of scattered showers and isolated thundershowers (Fawbush and Miller 1954; Cooley 1978) where convective cloud patterns in the area of development may show considerable enhancement and may organize into a nonfrontal comma cloud (Monteverdi 1976; Reed 1979; Mullen 1979; Reed and Blier 1986). While strong potential instability is an important feature of tornado events east of the Rockies, cold sector thunderstorms tend to develop in modified maritime polar air masses characterized by relatively low mixing ratios and less marked potential instability (Monteverdi et al. 1988). In addition, since greatest cold sector parcel buoyancy in these patterns is often found at or below the 700-mb level, the usefulness of traditional indices (such as the Lifted Index (LI)) in estimating the potential for severe weather is reduced (Halvorson 1971; Cooley 1978).

Once formed, cold sector tornadoes are generally weak in nature (F0 or F1 intensity) and are characterized by a slender, ropelike appearance, a short and narrow path, and a very short lifespan (Fawbush and Miller 1954). The occurrence of such funnels and tornadoes has been documented in California by Halvorson (1971), Hales (1985), Monteverdi et al. (1988), and others. Cold sector tornadoes have also been observed in much of the United States (Cooley 1978; Holmes 1984; Goetsch 1988; and others) and in England (Lacy 1968).

3. Large-scale influences on the Redding thunderstorm

a. Synoptic setting

The NMC synoptic scale surface analysis at 1800 UTC (Fig. 4) shows a cold front located over central California, well to the south of the area where the Redding storm was in the process of developing. Earlier analyses (not shown here) indicate that this front was part of an occluded frontal system which extended from a low pressure area west of Vancouver Island. The low pressure center associated with the frontal system had moved southeastward from the northern Gulf of Alaska to the Washington coastline, a track typical of “high latitude” type storms.

At 1801 UTC, the frontal cloud band, indicated by the letter “A” on the corresponding infrared satellite image (Fig. 5), extends across south-central California. The cloud band located west of the Washington and Oregon coastlines, indicated by the letter “B” on Fig. 5, apparently is associated with a post-frontal trough which extends southwestward off the coast of Oregon (Fig. 4). This cloud mass meets the criteria discussed by Businger and Reed (1989) for “cold-type” polar lows which are characterized by deep convection and which are indicative of substantial cold sector instability. A third cloud band (indicated by arrows on Fig. 5) stretches from eastern Washington southwestward through Oregon and northwestern California suggesting that some feature responsible for such organization was passing through the area. This feature is not apparent at the surface (Fig. 4), where only ridging is indicated in the area of the cloud band.

The pattern in the upper troposphere at 1200 UTC (Fig. 6) is one which operational forecasters in California will recognize as favoring severe weather in the Central Valley. A strong, negatively-tilted trough extends from the eastern Gulf of Alaska southeastward across the western United States. The axis of this trough...
has already passed through the western portions of northern and central California by this time.

The left front quadrant of a southeastward-advancing jet streak can be seen extending over northern California. A split in the flow is indicated over northern and central California, with westerly winds dominant over the northern third of the state and northwesterly flow indicated over the southern two thirds. This split, and the influence associated with it, is also evident on the 0000 UTC 25 September analysis (not shown), but had shifted southeastward out of the state.

b. Quasi-geostrophic forcing

It is well-known that vertical motion forced by synoptic scale circulation can be understood on the basis of quasi-geostrophic (QG) theory (Holton 1979: pp. 119–126). Although QG theory cannot account for forcing, operating at the mesoscale, it can provide clues that the larger-scale environment either encourages (or, at least, does not discourage) ascent in the region of the convective event. Further, it has been shown that the QG diagnosed fields of vertical velocity can be superior to the vertical motion fields produced by the numerical guidance for warm season convective events (see, e.g., Barnes 1985; 1986; Doswell 1987). The QG omega equation is often used to diagnose such fields because it includes both the forcing due to differential vorticity advection and that due to the shape of the temperature advection pattern (Holton 1979 pp. 119–126; Durr and Snellman 1987). Hoskins et al. (1978) shows that the omega field forcing is proportional to the divergence of the \( \mathbf{Q} \)-vector field.

The 700-mb \( \mathbf{Q} \)-vector divergence field for 1200 UTC (0400 LST) 24 September 1986 (Fig. 7) shows that synoptic scale forcing for upward motion extends from southwestern Oregon through the northern one-third of California. This mid-tropospheric forcing helped contribute to an environment favorable for convection in northern California. The area of maximum forcing, centered just west of the northern Sacramento Valley at 1200 UTC, progresses southeastward through the state during the day. At 0000 UTC 25 September, the \( \mathbf{Q} \)-vector divergence field (not shown) indicates that the greatest forcing for upward motion has shifted to west-central Nevada. One may assume that some intensification of this field would have taken place during its transit across the northern portion of California. Values for the static stability parameter used in the computations were obtained from analysis of the radiosonde data for Oakland (OAK) and Medford (MFR). Stability at these two sites was relatively high at 1200 UTC. Since substantial destabilization occurred over the northern third of California through the early afternoon hours (about 2000 UTC) (discussed in section 5), there is justification for assuming that the static
stability parameter over the area would have decreased during this time frame, and that QG-forced vertical motions would have been greater than suggested by the patterns given in Fig. 7.

An examination of the 300-mb pattern (Fig. 6) suggests that the QG-forced upward motion over northern California on 24 September (Fig. 7) is likely related to two significant features. The major short wave trough centered just east of the coastline, and the strong jet streak located just offshore are both in the proper position to induce upward motion over northern California. The forcing associated with the trough is probably adequately diagnosed because mid and upper tropospheric flow patterns, even in the vicinity of troughs and ridges, are in a state of near geostrophic balance.

The accuracy of QG-diagnostics diminishes in the region of marked baroclinity and strong accelerations which characterize jet streaks (Bluestein 1986). However, many studies have shown that QG theory can account for the QUALITATIVE aspects (i.e., the shape) of the vertical motion patterns associated with jet streaks (Barnes 1985; Bluestein 1986). QG-theory accounts best for the vertical motion fields associated with dynamically-straight jet streaks and may not even be qualitatively correct for intense jet streaks where sharp curvature occurs in the trajectories (Bluestein and Thomas 1984). Obviously, the vertical motion field suggested by the QG forcing over northern California should be viewed with caution, given the suggestion of moderately curved trajectories (Fig. 6) in the portion of the jet streak over that area.

Some qualitative aspects of the vertical motion field associated with the jet streak considered in this study can be estimated by an examination of the 1200 UTC 700–300-mb thickness and 500-mb absolute vorticity patterns (Fig. 8). The vorticity maximum seen west of the Oregon coastline is located in the region of strong cyclonic wind shear associated with the mid-tropospheric expression of the wind speed maximum. The reader may recall that QG-forced omega is proportional to the cyclonic vorticity advection (CVA) by the thermal wind (Trenberth 1978; Barnes 1985; Durran and Snellman 1987 and many others). Since most of the CVA evident on Fig. 8 is west of the trough axis, it is clear that most of the omega forcing at 1200 UTC 24 September over northern California is associated with the jet streak rather than with the trough further east.

By 0000 UTC 25 September the 700–300-mb thickness and 500-mb absolute vorticity fields (not shown) indicate that the portion of the pattern characterized by CVA had moved southeastward out of the state. Although it is not the purpose of this study to prove diagnostically that jet-streak induced circulations triggered the Redding thunderstorm, it should be pointed out that the subsynoptic scale region of maximum CVA by the thermal wind associated with the left front portion of the streak must have passed southeastward across the northern Sacramento Valley roughly at the time of development of the Redding storm.

The 300-mb divergence was calculated kinematically (see Holton 1979 p. 73) for the jet streak exit region located over the area of storm genesis at 1200 UTC. The procedure yielded a value of $3.12 \times 10^{-2} \text{ sec}^{-1}$ over the Redding area. Such a value is consistent with estimates of divergence for the left front quadrant sections of jet streaks (Kocin et al. 1986; and Uccellini et al. 1984) and for regions where the left front quadrants of jet streaks have progressed to the eastern side of upper level troughs (Uccellini and Kocin 1987). However, it does represent a value which is rather high when compared to divergence estimates for tornado events elsewhere in the country (McNulty 1978).

4. Surface influences on thunderstorm evolution

a. The pre-storm environment

The surface controls on the Redding storm will be assessed on the basis of subsynoptic scale analyses of hourly altimeter setting and dewpoint temperature information. The authors chose not to contour station pressure data because of the greater numbers of stations which report altimeter settings (Doswell 1982). Hourly aviation observations from all locations shown in Fig. 1 (except Cottonwood and Vina) were included in the analyses. The altimeter settings at Mount Shasta (MHS) were ignored because they were not consistent with those in the vicinity.

The surface environment a little over one hour before the development of the Redding thunderstorm is illustrated in Fig. 9. Several important features can be discerned on this analysis which do not appear on the NMC synoptic chart (Fig. 4). A pressure trough extends from near RDD southward through the western portions of the Sacramento and San Joaquin Valleys. Operational meteorologists in California have long known that the process of “leeside troughing” can produce a mesoscale low pressure area in the Central Val-

![Figure 8](image_url)
ley when a surface disturbance is approaching the state, and when flow nearly perpendicular to the Coastal Range characterizes the lower and mid-troposphere (see, e.g., Weaver 1962). Winds east of the quasi-stationary trough axis will be southerly in the Central Valley and often can result in advection of moisture and warmer temperatures into the northern Sacramento Valley. Weaver (1962) reports that such a favorable advection pattern combined with upper tropospheric divergence, associated with an approaching disturbance produced a violent flash flood-producing thunderstorm near RDD on 19 September 1960.

In the present case, the analyses show that the leeside trough remained quasi-stationary until late afternoon and was responsible for the lack of the pronounced wind veer to northwesterly which usually accompanies a frontal passage in California. Note that all the stations in the Sacramento Valley are reporting upvalley (southerly) winds at 1700 UTC. In addition, the isothermo-isosobar analysis shows that air with high dew points is being advected northward through the valley.

The hatched line depicted over extreme northwestern California on Fig. 9 corresponds to the position of the subsynoptic scale cloud band indicated by arrows on Fig. 5. A surface expression for this feature is neither evident on the NMC analysis, where surface ridging characterizes the region, nor on the subsynoptic plots of hourly surface data. Cross-sections of potential temperature (not shown) indicate that this cloud band is associated with a baroclinic zone found in the middle and upper troposphere. At 700 mb, this zone corresponds to a subsynoptic scale area of baroclinity (labeled "A" on Figs. 10a and 10b) which passes through northern California as the day progresses. The passage of the cloud band southeastward across the state can be traced on hourly satellite imagery and seems to be related to a similar advance of the midlevel baroclinic zone.

The subsynoptic cloud band is moving into an area in which the large scale vertical motion field is already favorable for convective growth. The subsynoptic scale forcing associated with this cloud band can be viewed as a mechanism which augmented the existing vertical motion field and stimulated the destabilization over northern California.

b. Initial development of the Redding storm

By 1800 UTC (Fig. 11), it can be seen that the leeside trough is acting as a "focusing mechanism" by setting up a low-level flow pattern that is advecting air with higher dewpoints into the northern Sacramento Valley. The moistening effects of this low-level flow are quite apparent at RDD with dewpoint temperatures there rising 3°C (5°F) during the 1-h period ending at 1800 UTC.

Previous studies of thunderstorm-related flash flooding in the Valley (e.g., Weaver 1962) point to the importance of blocking by the local physiography (i.e., the Sierra Nevada and Coastal Ranges) in inducing moist southeasterly flow in the Valley. An examination of the topography of the area (see Fig. 1) suggests that some confluence would take place in the Valley in the layer beneath 1.5 km (5000 ft) MSL due to channelling of the low-level southerly flow. A surface streamline analysis for 1800 UTC (not shown) qualitatively shows that confluence is characteristic over the entire Sacramento Valley. It is probable that this confluence is associated with the topographical effects described above and also with the leeside trough discussed earlier. Although station spacing in the northern section of the Valley complicates interpretation of the streamline analyses, the generally featureless (i.e., flat) aspect of the Valley floor justifies the suggestion of marked subsynoptic scale confluence there in this case. In addition, the relative lack of wind speed differences across this area suggests that actual surface convergence is occurring in the Valley.

Since the low-level wind field is favoring both convergence in the Valley and the advection of moisture into the northern portion, it can be concluded that the subsynoptic environment is acting to focus a maximum of moisture flux convergence in the northern Sacramento Valley. Significant low-level moisture flux convergence contributes to destabilization and is recognized as one of the precursors to severe convection elsewhere in the country (e.g., see Doswell 1985).
Several other mechanisms for destabilization can be identified in this case. Low-level southeasterly flow in the Sacramento Valley experiences gentle lifting in most of its passage northward through the Valley and more abrupt lifting at the northern end where the Cascade and Coastal Range converge. Weaver (1962) reports that such orographic effects destabilize the northward moving flow. Also, diurnal heating is more significant at the northern end of the Valley because the southward-facing slopes there are subject to more intense solar radiation than the more flat-lying terrain elsewhere in the region. It is probable that most if not all of these factors were acting in concert in this case, establishing the northern Sacramento Valley as a locus for intense convection in much the same way that the Caprock formation in the Texas Panhandle is a preferred location for severe thunderstorm development (Doswell 1985).

Thunderstorm activity commenced in the Redding area at 1840 UTC. This roughly corresponds to the time at which the southeastward-moving subsynoptic cloud band would have advanced into the northern Sacramento Valley. In fact, the superposition of the vertical motion field and midlevel baroclinic zone associated with the cloud band with the favorable low-level wind field east of the leeside trough was simultaneous with the development of the deep convection. The advancing cloud band thus can be viewed as a "trigger" in the Redding storm's development.

By 1900 UTC (Fig. 12), an outflow boundary from the developing thunderstorm apparently has passed RDD as winds have veered there from SSE to SSW with gusts to 30 kt and temperatures have fallen about
3°C (5°F) from the previous observation. As it moved southward through the Valley, this boundary would act as an additional mechanism for thunderstorm development.

c. Evolution of the Redding storm and tornado development

The first echoes associated with the Redding storm appeared on the plan position indicator (PPI) of the WSR-57 radar in Sacramento by 1828 UTC (Fig. 13), roughly one-half hour before the time of the subsynoptic analysis given in Fig. 12. At this time, thunderstorms in northern California are oriented roughly parallel to and ahead of the advancing subsynoptic cloud line with the Redding storm located just southwest of RDD. By 1927 UTC (Fig. 14), the cell has shifted southeastward and the associated video integrator processor (VIP) derived precipitation intensity has increased from level 3 (moderate) to 5 (intense). The 12 200 m (40 000 ft) precipitation echo top had overshot the tropopause, which was near the 275-mb level at 10 972 m (36 000 ft). The apparent tornado which occurred at Cottonwood around 1915 UTC was roughly simultaneous with the appearance of the overshot of the overshooting echo top.

By 2000 UTC (Fig. 15), winds at CIC have backed and have increased to 25 kt, suggesting the existence of a mesow at the southwestern flank of the Redding storm. Tornado touchdown near Vina (just northwest of CIC) took place at roughly this time. Air with relatively high dew point continues to flow northward through the San Joaquin and Sacramento Valleys towards the developing thunderstorm.

The 2027 radar tracing (Fig. 16) indicates that the elevation of the echo top of the storm has decreased 915 m (3000 ft) in the 1 h since 1927 UTC (Fig. 14). The VIP level 5 echo has moved southeastward to a position just north of Vina. Hodograph analyses (discussed in section 5) show that the storm had moved southeastward at an approximate angle of 30° to the right of the mid and upper tropospheric flow and that the storm-relative wind profile favored "ventilation" typical of supercell thunderstorms (Doswell 1985).

The Vina tornado occurred just after 2000 UTC, a time when the CIC observation suggests that a mesow.


FIG. 14. As in Fig. 13, except at 1927 UTC.
was associated with the Redding thunderstorm. Photographs of the F2 tornado show a number of the features which are diagnostic of mesocyclone-induced tornadoes. For example, at 2015 UTC (Fig. 17) a multiple vortex tornado can be seen extending from a wall cloud which is flanked by relatively clear skies. Photographs of Great Plains' storms often show that tornadoes form beneath the right or rear portion of a low- ered cloud base or wall cloud, and also reveal a "clear slot" to the rear or right rear of the tornado which is indicative of the existence of a rear flank downdraft (RFD) (Lemon andDoswell 1979; Davies-Jones 1986). The RFD is a secondary downdraft which develops upwind of the updraft and often forms simultaneously with mesocyclone-induced tornadoes.

The bright area seen in the left-center (northwest) part of Fig. 17 suggests that an RFD was present and is a feature visible in each of three pictures taken during a 15-min period. The tornado appears to be connected to the lowered cloud base adjacent to the RFD. This is consistent with the observations of Lemon and Dos-
well (1979) and Davies-Jones (1986) who point out that tornadoes are usually positioned in the zone of strong vertical velocity gradient between the updraft and RFD. The tornado tends to develop on the updraft side of the vertical velocity gradient (on the upwind side of the mesolow).

The 2100 UTC (1300 LST) subsynoptic analysis (Fig. 18) corresponds roughly to the time of reports of funnel clouds and an unconfirmed tornado touchdown east of Chico. The wind shift from southeasterly to westsouthwesterly which has occurred at CIC suggests that the mesolow seen in the previous figure has moved east of the city. Rain-cooled air now covers the northern portion of the Valley, and a well-defined gust front continues to move southward behind the mesolow.

The enhanced visible images for 1930 UTC and 2130 UTC (Figs. 19 and 20) encompass the period of time from the first reports of tornado touchdown near Cottonwood to the last reports of funnel clouds east of CIC. The tornadic storm is indicated by the letter “T”

Fig. 19. Enhanced visible satellite image for 1930 UTC. Tornadic storm is indicated by “T”. Dash-dot lines: “A” indicates subsynoptic cloud band as discussed in text; “B” indicates post-frontal trough analyzed on Fig. 4.
and the advancing subsynoptic cloud band is shown by the dash-dot line labeled "A." The relatively clear air immediately northwest of the storm delimits a probable midlevel dry air intrusion that provided support for the RFD. The trough labeled "B" corresponds to the NMC-analyzed post-frontal trough shown in Fig. 4.

An examination of the 0000 UTC infrared satellite image (Fig. 21) shows that the cold front seen in Fig. 5 is now located over extreme southern California. All of the strong thunderstorm development has taken place in the "cold sector" north of this front.

By late afternoon the Redding storm joined with other subsequent storms which formed on its right flank in the southern Sacramento and northern San Joaquin Valleys. The resulting comma-shaped mesoscale convective system (MCS) (indicated by arrow on Fig. 21) extends from just northeast of Marysville, through northwestern Nevada, and into northeastern California. The strongest of these late-developing thunderstorms
may have attained severe limits since funnel clouds and an unconfirmed tornado touchdown were reported near Stockton at 0000 UTC 25 September.

5. Thermodynamic and wind shear characteristics

The importance of the combined effects of thermodynamic instability and vertical wind shear in the development of severe thunderstorms is well documented (Rasmussen and Wilhelmsen 1983; Browning 1986; Weisman and Klemp 1986; Leftwich and Wu 1988; and many others). Thunderstorm growth and intensity are largely dependent upon the ability of air parcels to accelerate vertically (Weisman and Klemp 1986). The form that convection takes, however, is strongly influenced by the vertical wind shear (Doswell 1982, 1985; Weisman and Klemp 1986). The following subsections focus on the development of a thermodynamically unstable environment over northern California on 24 September 1986 and on the influence of the wind shear on storm development and mesocyclone formation.

a. Thermodynamic setting

Stability characterizes the 1200 UTC OAK sounding (Fig. 22). The lifted index (LI) of +4.5 is indicative of minimal convective threat unless significant destabilization were to occur during the day. The moisture profile is similar to that of the typical Oklahoma tornado sounding (Carlson et al. 1983) with moist air found from the surface up to the 720-mb level and a very dry layer above. However, the temperature profile differs from the “loaded gun” sounding in that it lacks the strong capping inversion and is nearly wet adiabatic. A cross-section of equivalent potential temperatures (not shown) indicates that the atmosphere in north-central California at 1200 UTC was characterized by convective instability from the surface to about 700 mb.

The dry air evident at midlevels in Fig. 22 was probably important in the evolution of the RFD associated with the Redding storm. It is well known (see, e.g. Lemon and Doswell 1979) that the dry air which reaches the ground in the RFD organizes in a downdraft entrainment region which in most cases is about 3 to 7 km above the ground.

An examination of the 0000 UTC 25 September OAK sounding (Fig. 23) reveals that a marked decrease in stability has taken place at that location by midafternoon. This destabilization is accompanied by a change in the lifted index at OAK from +4.5 in the morning to −0.5 in the afternoon. Fig. 24 shows that, in the 12 h since the morning sounding, moderate temperature decreases occurred in the midtroposphere with the greatest cooling at the 700-mb level. Warming characterizes the layer from the surface to approximately 930 mb.

Caution must be exhibited when assessing the thermodynamic characteristics of the convective threat in the Valley on the basis of an examination of the Oakland sounding. Conditions along the coast are often not completely representative of the thermodynamic environment in the Central Valley, particularly in the lower layers. Diurnal heating and cooling effects often are stronger in the Central Valley (Weaver 1962). In addition, low level southerly flow entering the Sacramento Valley is subject to destabilization as it is forced by topography to converge and rise (Weaver 1962; Hales 1985). In the present case, while diurnal heating most likely accounted for the low-level temperature increase at OAK evident in Fig. 24, cold advection was
were also at maximum. Lifting (see Fig. 7) of dry mid-
level air may also have accounted for the cooling in
the middle troposphere over all of northern California.

The degree to which stability in the Valley differed
from that at OAK in this case was estimated by an
examination of surface based lifted indices (SLI) for
the region. SLI values are calculated from bogus
soundings constructed from hourly surface aviation
temperature and dewpoint reports and interpolated
500-mb temperatures [see Hales and Doswell (1982)
for details]. The 1800 UTC SLI values in northern
California (courtesy Mr. Jack Hales, Lead Forecaster,
NSSFC) provide an overview of the thermodynamic
environment in the Valley at roughly the time of thun-
derstorm genesis near RDD (Fig. 25). SLI values of
−3 to −4, indicative of moderate instability, charac-
terize the entire Sacramento Valley. Such values can
support the development of strong tornadoes when suf-
ficiently strong values of low level wind shear are pre-
sent (Weisman and Klemp 1986; Leftwich and Wu
1988).

Although indices such as the LI, SLI, K-Index, and
others are typically used operationally to diagnose the
degree of instability, a more accurate measure can be
obtained explicitly from the radiosonde data. The con-
vective available potential energy (CAPE) (also known
as potential buoyant energy) may be used as a superior
indication of instability since it is not defined on the
basis of information from only one or a few levels
(Moncrieff and Green 1972). This is particularly im-
portant in California where convectively driven vertical
accelerations are rarely maximum at 500 mb (the level
at which the LI is defined).

The value of the CAPE for the 0000 UTC OAK
sounding is 766 J kg⁻¹. This relatively weak instability

![Fig. 23. As in Fig. 22 except for 0000 UTC 25 September 1986.](image)

![Fig. 24. Layer temperature change (°C) at Oakland from
1200 UTC 24 September to 0000 UTC 25 September.](image)

![Fig. 25. Surface lifted indices for selected locations
at 1800 UTC 24 September 1986.](image)
is due in part to the low EL shown in the 0000 UTC sounding (Fig. 23). For comparison, Weisman and Klemp (1986) find that values between 1500 and 2500 J kg$^{-1}$ are typical for moderately unstable convective days. Although the CAPE value for OAK is relatively low, the work of Leftwich and Wu (1988) suggests that strong and violent tornadoes can occur with CAPE values less than 1500 J kg$^{-1}$ provided that sufficient low level shear is present (discussed in more detail below).

A bogus sounding (not shown) for a location at 40°N, 122°W (just north of CIC) was constructed from the 0000 UTC upper air data. Temperature and dewpoint interpolations were made from objectively analyzed and contoured mandatory level data. Surface temperature and dewpoint were obtained by averaging information from the 1900 UTC hourly observations for the region upwind (southeast) of the Redding thunderstorm. The time was chosen to estimate boundary layer conditions in the Valley at the time of most rapid development of the storm.

The CAPE for the bogus Valley sounding is 1216 J kg$^{-1}$, indicative of moderate instability. This value approaches the range of CAPE values which has been reported for supercell storms elsewhere in the country (Weisman and Klemp 1986) and underscores the fact that the OAK sounding can grossly underestimate the buoyancy and, thus, the convective potential in the Valley. Although mid and upper tropospheric temperatures were considerably colder over the Valley than at OAK (see Figs. 10a and 10b), surface temperatures differed little. Thus, at least in this case, greater diurnal heating in the Valley apparently was not a mechanism for the greater buoyancy in the thunderstorm genesis area.

b. Analysis of lower tropospheric wind fields

Doswell (1982), Barnes and Newton (1986), Browning (1986) and many others describe the importance of strong vertical shear in the generation of severe convection. Generally, a wind strongly veering and increasing with height in an unstable environment favors the development of long-lived thunderstorms. This type of wind distribution ensures that the warm updraft will not be eliminated by the precipitation-cooled downdraft air. In addition, such wind shear leads to the continuous formation of a new updraft on the right flank of the storm (Rotunno and Klemp 1982).

A hodograph for the Central Valley obtained by a modification of wind information taken from the 0000 UTC 25 September OAK sounding is given in Fig. 26. The 0000 UTC sounding was used since it was more representative of the afternoon convective environment in the Central Valley than the 1200 UTC sounding.

To obtain Fig. 26, the OAK hodograph was altered by a replacement of the surface wind information with the 1800 UTC wind speed and direction observed at Redding (170°, 7.7 m s$^{-1}$). The winds AGL at 305 m (1000 feet elevation is indicated by 1 on Fig. 26), 610 m (2000 ft indicated by 2) and 915 m (3000 ft indicated by 3) were obtained by assuming that wind directions smoothly changed from the surface to the top of the coastal mountains at about 1.2 km (4000 ft) AGL.

This modification resulted in a gradually veering profile (about 25° for each 305 m). Strongest veering characterizes the wind profile in the lowest 1.5 km (5000 ft; the LCL was at about 1 km or 3400 ft). Such shear has been shown to be favorable for severe convection and mesocyclone development elsewhere (Marwitz 1972; Weisman and Klemp 1982; and, Davies 1989). Very little wind shear is evident from 1.5 km to about 3.7 km (12 000 ft) with strong speed shear characteristic above.

Curvature is evident in the hodograph from the surface through 1.2 km (4000 ft). Such curvature indicates a veer of the wind shear vector with height and is consistent with the fact that Redding storm was a right-moving supercell with a mesocyclone. Rotunno and Klemp (1982) show that enhanced vertical non-hydrostatic pressure forces preferentially occur on the right flank of storms developing in an environment characterized by a wind shear vector which veers from the lower to middle troposphere. Updrafts and new development are thus augmented on the right flank of such thunderstorms. Rotunno and Klemp (1982) also show that such a shear profile creates strong relative vorticity around a horizontal axis which is then tilted into the vertical by this enhanced updraft. Doswell and Lemon (1979) and Davies-Jones (1986) calculate that the vertical vorticity which is thus created is of the same order of magnitude as that seen in the mesocyclones which are precursor to many tornadoes.

Doswell (1982) states that it is not entirely clear that supercell thunderstorms are dependent upon a particular type of hodograph, but that the storm-relative flows
Fig. 27. Depiction of flow relative to the Redding storm at selected levels. Wind speeds given in m s⁻¹.

may be more significant. However, it is in the strongly sheared environment that the appropriate relative flow can most easily develop. The flow relative to the Redding storm when it was near CIC is depicted in Fig. 27. The storm relative flow was obtained by subtraction of the storm motion vector (300° at 12.9 m s⁻¹; determined from the radar tracings) from the winds at each level.

Note that the storm-relative flow veers strongly through 12 km, especially in the lowest 1 km. Lower and middle tropospheric relative flow (e.g., 1 km and 8 km) are approximately at right angles to each other. Such a relative flow profile appears to 1) provide the strong low-level inflow needed to sustain the updraft; 2) provide the mid and upper level winds needed to take precipitation away from the updraft; 3) contribute to destabilization by producing differential temperature advection; and, 4) produce strong horizontal vorticity which could be tilted by the updraft to the vertical to produce storm rotation and, possibly, tornadoes (Browning 1986; Davies-Jones 1986; McGinley 1986).

The wind shear evident in Figs. 26 and 27 is quantitatively similar to that observed in the Great Plains with supercell storms. Marwitz (1972) has computed stability and wind shear parameters for various types of severe thunderstorms in the central United States. Table 1 gives a) these parameters averaged for many supercell cases and b) the same parameters computed from the 0000 UTC Oakland sounding. Since, as explained above, the Oakland sounding was not totally representative of the storm environment, we have utilized the SLI for 1800 UTC at Redding and have modified the wind profile as described above. A cloud base at approximately 1 km (3400 ft) was determined from the sounding, and the radar-indicated height of 12 192 m (40 000 ft) was used for the thickness of the cloud layer.

A comparison of these parameters illustrates the similarity between the shear environment for the Redding storm and that for typical supercells elsewhere in North America. Note that the mean subcloud wind, mean surface-10 km wind, and the storm motion are comparable and that the storm motion is to the right of the mean environmental winds in both cases. The cloud layer shear is greater at OAK reflecting the active polar jet stream present in this case.

Leftwich and Wu (1988) find that strong tornadoes can occur even when the air mass displays relatively weak instability if sufficiently strong low level wind shear is present. As a measure of the low level shear environment for the Redding storm, the shear vector (calculated using density-weighted winds from the modified OAK sounding) was summed over the lowest 4 km and then divided by 4 km. The resulting value of 10.6 × 10⁻³ s⁻¹ is consistent with the findings of Lemon and Doswell (1979) and Davies (1989) who show that shear values of 6.0 to 8.0 × 10⁻³ s⁻¹ or greater in the 0–4 km layer are representative of shear associated with strong tornadoes. It is probable that this strong low level shear, due largely to the topographic influences on southerly flow discussed in Section 4, may have compensated for the relatively weak buoyant energy in this situation.

The work of Weisman and Klemp (1982) suggests that supercell thunderstorms occur within a limited range of shear for a given amount of instability. They

<table>
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<tr>
<th>LI (°C)</th>
<th>Veering in subcloud layer (deg)</th>
<th>Mean subcloud wind (deg/m s⁻¹)</th>
<th>Mean Sfc-10 km wind (deg/m s⁻¹)</th>
<th>Storm motion (deg/m s⁻¹)</th>
<th>Cloud layer shear (10⁻³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical supercells (average values)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>−6.2</td>
<td>68</td>
<td>184/12.8</td>
<td>244/21.8</td>
<td>282/11.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Modified Oakland sounding</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>−4.0</td>
<td>75</td>
<td>212/10.6</td>
<td>273/19.1</td>
<td>300/12.9</td>
<td>5.5</td>
</tr>
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</table>
have shown that the relationship between thunderstorm type, buoyancy, and wind shear can be represented in the form of a bulk Richardson number, $R$, defined as

$$ R = \frac{\text{CAPE}}{1/2U^2} \quad (1) $$

where $U$ is the vector difference between the density-weighted mean winds in the lowest 500 m and the lowest 6 km. Their modeling results show that multicellular growth occurs most readily for $R > 30$ and that supercells are typically associated with values of $R$ between 10 and 40.

$R$ values were determined using 1) the 0000 UTC CAPE value at OAK and a $U$ value determined from the OAK hodograph; and, 2) as an estimate of conditions in the Valley, the CAPE value from the bogus afternoon sounding (discussed in the last section) and a $U$ value determined from the OAK hodograph modified for the stronger shear in the Valley. At Oakland, where the shear was relatively weak, the value of $R$ was 88, indicative of multicellular thunderstorm growth. The $R$ calculated on the basis of the information modified for the Valley was approximately 21, a value which suggests that the Valley environment was favorable for the development of quasi-steady supercellular updrafts.

6. Conclusions and discussion

The operational meteorologist in California is often confronted with an interesting set of forecast challenges. However, since tornado-producing thunderstorms are relatively rare in the state and the documentation on those that do occur is sparse, most forecasters would not rank such storms high on a priority list of operational problems. This lack of documentation has had the effect of creating a void in the understanding of which local patterns and parameter values are important in the process of severe thunderstorm and tornado development in the state.

This paper documents the occurrence of a tornadic supercell in a region where conditions are usually thought to be generally unfavorable for such development. Further, this investigation represents the first detailed study of a mesocyclone-induced tornado west of the Rockies and one of the only studies of supercellular-type convection in a "cold sector" environment. This paper demonstrates that the restrictive conditions which favor strong supercellular tornadoes can occur in California and is meant to alert operational meteorologists to the fact that tornadic supercells, while rare, are indeed features of the climatology of the state.

The factors present over northern California's Sacramento Valley on 24 September 1986 were similar to those associated with the development of supercell thunderstorms in the more tornado-prone areas east of the Continental Divide. The formation and subsequent evolution of the Redding storm, therefore, could have been anticipated. In this case, the operational meteorologist needed first to have been aware that the general pattern which occurred on 24 September 1986 was one which had been identified in the literature as being associated with severe weather in California's Central Valley. Once aware of this, the forecaster could consider various aspects of the pattern which would "focus" the severe weather threat to certain areas of the state and which would have provided a "trigger" to initiate the convection. The forecaster would also consider what factors may contribute to the evolution of the threat during the day (e.g., increase or decrease of instability, change in position of focus area or in location of trigger).

The "dynamics", or large-scale forcing, for this case included a favorable synoptic scale vertical motion field, diagnosed quasi-geostrophically. Upward vertical motions were augmented by the subsynoptic scale transverse circulation associated with a strong jet streak approaching the state. The resulting vertical motion field ensured that thunderstorm development over the Sacramento Valley would not be suppressed dynamically and provided a destabilizing influence.

Manual subsynoptic plots of the hourly surface data proved indispensable in establishing the northern Sacramento Valley as a threat area in this case. The presence of mesoscale, quasi-stationary post-frontal leeside troughs in the Central Valley is a relatively common occurrence. These troughs are not easily resolved at the synoptic scale and normally will not appear on the NMC surface chart. In the present case, such a trough facilitated the advection of relatively moist air to the higher northern end of the Sacramento Valley. This phenomenon, together with other topographic effects local to the Valley, resulted in a moisture flux convergence there which could only have been resolved by a subsynoptic analysis. Since 1986, forecasters have had access to a suite of "mesoscale" products which can be run on request on AFOS. AFOS plots of moisture flux convergence could have been used as additional information to substantiate that the northern Sacramento Valley would have been a focus for convection in this case.

Thunderstorm development commenced when the vertical motion field associated with a southeastward-moving subsynoptic scale cloud band interacted with the topographically-augmented low level wind field. The southward-moving outflow boundary from the developing thunderstorm then became the focus for subsequent thunderstorm development as it intercepted the relatively moist air moving northward through the Valley.

The convection rapidly became severe because of a combination of favorable thermodynamic and wind shear factors specific to the Valley environment. Buoyancy and low level shear parameters in the Sacramento Valley were estimated from bogus soundings and hodographs, and were found to be within the range spec-
ified for supercellular convection. In addition, the vertical variation of the wind shear vector in the Valley was favorable for the development of right-moving, cyclonically-rotating supercell thunderstorms. Estimates of buoyancy and low level shear made on the basis of the OAK data alone would not have suggested a threat for supercell or mesocyclone development in the Valley. The results of this study underscore the fact that thermodynamic and wind shear environments in the two locations are often dissimilar.

Operational meteorologists have at their disposal a number of tools which allow them to qualitatively and quantitatively assess the thermodynamic and shear environment in areas away from sounding sites. The low level flow in the Sacramento Valley, as depicted on subsynoptic analyses, would have indicated that the low-level shear there was quite strong and conducive for supercell development. A personal computer based routine could easily have calculated the inferred shear in the Valley. In addition, while there was considerable justification by 1200 UTC that destabilization of the Oakland sounding would take place during the day, the use of operationally-available surface-based lifted index programs, updated hourly on the basis of actual station information and interpolated 500-mb temperatures, would have substantiated that more significant destabilization was ongoing in the Valley. This was particularly true in this case since midtropospheric cold temperature advection was more of a factor over the Sacramento Valley than over Oakland.

One final point about the thermodynamic setting for the Redding thunderstorm should be stressed. There is a danger in estimating buoyancy solely on the basis of indices (including the LI, the Showalter Index, the Totals-total index, etc.). While useful as "rules of thumb," such indices can seriously misrepresent the potential for strong thunderstorms if used without the consideration of other information. It is quite clear that mesocyclone-induced tornadoes do not occur exclusively within strongly unstable environments and that vertical wind shear plays an equally important role in determining whether convection will become self-sustained and severe. Use of indices which include both the vertically-integrated buoyancy and wind shear can provide much more useful information in this regard than the other more conventional indices mentioned above. In the present case, a simple calculation of the bulk Richardson number, as approximated for a Valley location, would have alerted the forecaster to the possibility of supercellular convection somewhere in the Valley.

Although no definitive forecast of thunderstorm type for this case can be made simply on the basis of the OAK hodograph, inferred wind shear parameters in the Valley and the storm-relative flow profile present strong support for supercell-type convection. The combined effects of the topography of the Valley and the lower midtropospheric flow pattern produced a low level shear profile sufficient (given the degree of instability) for supercell and mesocyclone development. These results suggest that local effects in other areas of the West which experience "cold sector" tornadoes may also yield a buoyancy and shear combination which is favorable for mesocyclone formation.

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