NOAA Technical Memorandum NWS WR-229

THE 10 FEBRUARY 1994 OROVILLE TORNADO
A CASE STUDY

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TABLE OF CONTENTS

TABLE OF FIGURES

THE 10 FEBRUARY 1994 OROVILLE TORNADO: A CASE STUDY

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ABSTRACT

An F2 tornado touched down in the northern portion of the Sacramento Valley on 10 February 1994 causing significant damage in Oroville, California. This study documents the event and explores the possibility that the storm had supercellular structures including a mesocyclone. A collision of mesoscale boundaries interacting in a low buoyancy environment acted as the focus for the development of the thunderstorm. A strong barrier jet along the west side of the Sierra Nevada acted to create strong storm-relative helicity in this environment. Dry air rotating around the base of an upper-level trough acted to destabilize the atmosphere allowing for an enhancement of the convection. The orientation of the Sacramento Valley is such that strong storm-relative helicity can be created, under certain synoptic conditions, which is sufficient to develop rotation in developing thunderstorms. Rotation was detected in the mid levels of this storm and was likely responsible for the development of the damaging F2 tornado.

I. INTRODUCTION

On 10 February 1994, strong thunderstorms developed in the northern Sacramento Valley. At approximately 2230 UTC, an F2 tornado (damage survey by Weather Serice Office (WSO) Redding) touched down near Oroville, California (see Fig. 1 for locations). This tornado was associated with a small complex of thunderstorms which developed explosively around 2200 UTC after a cold frontal passage aloft. Due to the unique topography found in the Sacramento Valley, these thunderstorms encountered an environment supportive of supercellular development with strong low-level wind shear. Although the instability was not extreme, this wind shear was sufficient to develop an F2 tornado which damaged 37 homes and injured one person in the town of Oroville. Remarkably, the tornado was estimated to have only spent between 40 to 60 seconds on the ground with a path width of 10 to 20 yards.

Most northern and central California tornadoes occur after a strong, cold frontal passage aloft. Thus, the environment of storm genesis is located in the cold sector of the storm, characterized by low buoyancy. Most California tornadoes were thought to be mainly touchdowns of cold air funnels, but recent studies have shown that some of the larger tornadoes which have occurred in California may have been mesocyclone induced (Braun and Monteverdi 1991; Monteverdi and Quadros 1994). McCaul (1990, 1991) has shown that supercellular convection can even occur in low-buoyancy environments from internally generated pressure perturbations associated with tropical storms with significant low-level wind shear. Thus, if a favorable ambient wind shear profile is present, mesocyclone-induced tornadogenesis can occur even in a low buoyancy environment such as the cold sector of a synoptic-scale storm. Hales (1985) has shown that topography can create a shear profile favorable for supercellular convection in the Los Angeles Basin. Braun and Monteverdi (1991) have shown that channeling effects in the Sacramento Valley can produce wind shear profiles favorable for supercellular convection.

When the location of California tornado occurrence is investigated, a few areas of the Central Valley appear more favorable to tornadic development. Figure 2, which shows tornado touchdowns between 1961 and 1991, illustrates that the northern Sacramento Valley clearly has a localized maximum of tornado touchdowns over southern Tehama County and Butte and Glenn Counties. South of this region in the southern Sacramento Valley, only a few touchdowns have been recorded. Much of the San Joaquin Valley has had tornado touchdowns, however no discernable spacial pattern is evident.

Over the last 10 years, many technological advancements have been made in the National Weather Service software programs which diagnose the current atmospheric patterns, giving forecasters a better estimate of what to expect in the short term. This has greatly improved the ability of forecasters to determine severe weather potential and to forecast areas which are likely to see damaging thunderstorms. This paper will examine two of the new advancements, the Skew-T/Hodograph Analysis and Research Program, or SHARP (Hart and Korotky 1991), and the usefulness of PC-GRIDDS in manipulating gridded data. These programs will be used to diagnose the conditions that led to the Oroville tornado. All of these topics will be investigated further in this study. Primarily, this study will illustrate the conditions which led to the development of the Oroville tornado. The usefulness of both PC-GRIDDS and the SHARP Workstation in determining areas of severe weather potential and forecasting the likely character of severe weather for this case will also be examined. This study will compare the environment of the Oroville tornado with the results from other studies of California tornadoes in order to add to the sparse body of literature on severe thunderstorms in California. Finally, the apparent tornado maximum in the northern Sacramento Valley will be investigated further.

II. ANTECEDENT CONDITIONS OF THE OROVILLE TORNADO

By 1200 UTC 10 February 1994, an environment supportive of severe thunderstorms was developing over the northern portion of the Sacramento Valley. A moderately strong mid- and upper-level cold front was located to the west of California. This system had moved southward from the Gulf of Alaska, a track typical of "high latitude" cyclones (Weaver 1962). There was very little surface reflection to this system. This is typical of frontal systems which are in their later stages of evolution. This type of frontal structure is common in the western United States, western Europe, and the United Kingdom and usually consists of a sharp moisture discontinuity aloft with little surface reflection (Browning and Monk 1982). Located behind this upper-level cold front were open-celled cumulus indicating the cold pool aloft and the instability of the airmass behind the front. This cumulus field showed greatest enhancement under the left front quadrant of an advancing jet streak aloft.

Due to the topography of the Sacramento Valley, the general overall synoptic pattern, and a strong ageostrophic secondary circulation around an upper-level jet streak, a southerly low-level barrier jet was likely present. The low-level barrier jet in the Sacramento Valley has been researched by Parish (1982) and was found to occur between 1200-4500 feet above ground level when a cold front and/or upper-level trough approached the mountains from the west (Fig. 3). The cross-mountain flow which develops over the Sacramento Valley is initially statically stable and becomes dammed against the east side of the valley creating the low-level barrier jet. On 10 February 1994, the barrier jet was likely enhanced significantly by the secondary circulations of the strong jet streak aloft. Unfortunately, wind profiler data was not available for this day, but the barrier jet has been seen on other days when similar conditions have prevailed (Fig. 4). Below the radiation inversion, surface winds were generally southeasterly at around 10-15 mph but were forecast to increase through the day as the upper system moved onshore and tightened the surface pressure gradient.

In the mid and upper levels, strong positive vorticity advection (PVA) increasing in height was occurring over northern California (Fig. 5). This PVA was expected to increase through the afternoon. A 20 X 10^{-6} s^{-1} unit absolute vorticity center, at the 500 mb level, was located about 200 miles west of the California coast and was forecast to be over northern California by 0000 UTC 11 February (Fig. 6). Isentropic and orographic lift were also strengthening through the day as seen in the time cross-section for the Oroville region (Fig. 7). Synoptic-scale lifting generally acts to destabilize the atmosphere, by lowering the level of free convection. This increases the environmental lapse rate which increases the positive buoyancy of a parcel.

Strong cold air advection was occurring into the base of the trough indicating that the trough would deepen as it moved eastward (Fig. 8). 500 mb temperatures of less than -30.0°C were located in the base of the trough. In advance of the trough at lower levels, weak warm air advection was occurring over California with 850 mb temperatures greater than +5.0°C. Since this area of very cold temperatures aloft was forecast to propagate over northern California, becoming vertically collocated with the area of warm air advection at the lower levels, a sharp decrease in stability was expected to occur.

Due to the baroclinicity with this system, strong winds were located at all levels, but were especially concentrated west of the trough axis. A speed maximum was forecast to rotate through the base of the trough and propagate over central California by 0000 UTC. This would create a large area of synoptic lift in the mid-troposphere over most of northern California. At 1200 UTC, wind speeds of greater than 100 knots at 300 mb (Fig. 9) and greater than 40 knots at 850 mb (Fig. 10) emphasized the strength of this system.

The vertical wind profile plays an important role in determining what type of severe weather may occur. However, it is not something quickly or easily calculated from a glance at a Skew-T/log-P diagram. An examination of an observed or modified hodograph will indicate in which kind of environment a storm will develop. Weisman and Klemp (1982), among others, have shown that a low-level wind veering and increasing with height is a necessary criteria for the development of long-lived rotating thunderstorms. The low-level wind shear vectors, particularly in the lowest 3 km, should appear curved in a clockwise sense (i.e., veer with height) on the hodograph. In these situations, the tilting of horizontal vorticity into the vertical is maximized and high values of helicity are produced. Davies-Jones et al. (1990) found that a 0-3 km storm-relative helicity value approaching 150 m^2/s^{-2} generally supported mesocyclone development. A value of 151-299 m^2/s^{-2} supported weak tornadoes; while a value of 300-499 m^2/s^{-2} supported strong tornado development. These should not be taken as rigid boundaries, but rather very general guidelines to tornadic activity. If the hodograph is a straight line, multicellular development is likely. As previously stated, it has been shown that marginal instabilities, as estimated by CAPE, or Convective Available Potential Energy, may be associated with strong to severe tornadoes if they are coincident with high values of storm-relative helicity.

Weisman and Klemp (1982, 1984) have also shown that much of the relationship between storm type, wind shear, and buoyancy can be represented in the form of a Bulk Richardson Number, R, defined to be

$$R = \frac{B}{1/2\ U^2}$$

where B is the buoyant energy in the storm's environment (or CAPE) and U is a measure of the vertical wind shear. U is calculated by taking the difference between the density-weighted mean wind over the lowest 6 km and a representative surface layer wind (500 m mean wind). The numerical modeling results of Weisman and Klemp (1982, 1984) and calculations of R for a series of documented storms both suggest that unsteady, multicellular growth occurs most readily for $R > 30$ and that supercellular growth is confined to magnitudes of R between 10 and 40. However, while ratios of buoyancy to shear might suggest that rotation is possible within a storm, tornadic potential can be realized only for those cases where the synoptic and mesoscale environments are supportive for the development of thunderstorms for a long enough period of time.

The Oakland, CA (OAK) sounding from 1200 UTC indicated a thick, moist layer extending from the surface to 825 mb (Fig. 11). This was capped by a dry, more stable layer between 825 mb and 800 mb. From 800 mb to 575 mb, the lapse rate approached moist adiabatic, with dry air located above 575 mb. The low levels of the OAK sounding were similar to the Sacramento low-level sounding, thus it provided a good proximity sounding for the Sacramento Valley. The Lifted Index at 500 mb was +6.0°C, but was +2.0°C at 700 mb, indicating that most of the buoyant energy available for storm development would be located below 500 mb. The wind profile in the OAK sounding was missing for the lowest 3000 feet, but likely indicated some veering with height since the wind was light southeasterly at the surface but southwesterly above 900 mb. However, in the valley, due to the barrier jet, significant veering with height was occurring in the vertical wind profile.

The Medford, OR (MFR) sounding for the same time period indicated a much thicker moist layer extending up to 700 mb before encountering the remnants of the dry and warm layer (Fig. 12). The fact that this dry layer has been lifted significantly higher at MFR indicated that the moist layer increased in depth towards the north, and that stronger, more persistent, synoptic lift along with dynamic destabilization was occurring at MFR. The wind profile for MFR showed some turning of the wind, but nothing of any significance.

III. ANALYSIS AND STORM EVOLUTION

Gridded data from the 1200 UTC Eta model run indicated that strong PVA was to move over the region throughout the day, as the cold core system moved onshore. Of more importance for the severe weather threat, however, was the dry air intrusion which was shown to be advecting into the region over the next 12 hours (Figs. 13-14). This area of low equivalent potential temperature air was also apparent in the water vapor imagery, as a dry slot on the west side of the trough. A PC-GRIDDS-derived Q-vector field of the 850-400 mb layer indicated a large area of implied ascent in the mid-troposphere over northern California (Fig. 15). This thermal imbalance and its associated ascent, would lead to destabilization over this region.

The six-hour forecasted gridded data field valid at 1800 UTC indicated that parts of California were becoming very conducive to the development of thunderstorms. The 280K isentropic surface indicated an area of strong isentropic rising motion from northeastern California to southeastern California (Fig. 16). When the 286K-306K atmospheric column was investigated, an area of weak static stability was found from southwestern Idaho across northern California to south of San Francisco (Fig. 17). When adiabatic moisture flux convergence was investigated, an area of dynamic destabilization could be seen over northern and eastern California as well (Fig. 18). This area was destabilizing as warm moist air forced isentropes apart due to convergence of mass. Pressure advection at the 282K isentropic level indicated the upward velocities were occurring over northern and eastern California (Fig. 19). This broad area of rising motion in the lowest levels contributed to increasing the lapse rate over this region and destabilizing the airmass further. Although the strongest areas of pressure advection and adiabatic moisture flux convergence were occurring south of the Oroville area at 1800 UTC, it is likely that much of this unstable airmass in the lower atmosphere was being advected northward due to the barrier jet on the east side of the valley.

Satellite imagery at this time (not shown) indicated that the cold front was propagating across northern California. The frontal band of cloudiness associated with the front was pushing southward across central California ahead of the advancing front. This was allowing insolation to occur over northern California causing destabilization to occur. Although the topography was destroying the baroclinicity of the front in the lower levels, the upper-level front remained strong.

A normalized cross-section from 48°N 128°W to 30°N 117°W at 1800 UTC indicated that strong secondary circulations were located underneath the jet streak aloft over the area of concern (Fig. 20). Strong southeasterly flow was occurring at the surface likely contributing to the strong south to southeasterly barrier jet. Thus, isallobaric contributions from the rapidly deepening surface low and strong secondary circulations due to the jet streak aloft were both enhancing the southerly flow in the Sacramento Valley ahead of the approaching system.

At 1900 UTC, the sub-synoptic analysis indicated that a weak pressure trough extended northward through the middle of the Sacramento Valley (Fig. 21). This pressure trough in the valley had been documented in other case studies as well (Weaver 1962; Braun and Monteverdi 1991; Monteverdi 1993). Of significant note were the strong southeasterly winds on the eastern side of the valley. Sustained winds of greater than 20 mph with gusts approaching 30 mph indicated that momentum from the barrier jet was mixing down to the surface. Additional accelerations were being forced by the isallobaric component of the wind. Dewpoints in this region were rapidly approaching 50°F or more, further decreasing the convective stability over this area.

South of Redding, a strong windshift/moisture discontinuity could be identified. This feature was moving toward the southeast and was probably forced by terrain channeling of the geostrophic upper-level winds. Whiteman and Doran (1993) have investigated the relationship between valley and ridgetop wind directions and identified four different mechanisms for their relationship. Of the four, terrain channeling was likely the most important parameter in terms of the development of this windshift/moisture discontinuity. In their study, Whiteman and Doran (1993) found that in certain situations a small wind shift aloft can lead to a 180 degree wind shift at the valley floor due to terrain channeling. Since this channeling forces the low-level wind in a valley to take on the component of the upper-level wind that is parallel to the valley, the strong southwesterly flow ahead of the cold front was producing strong southerly flow in the valley. However, west to northwest flow was located behind the cold front. Thus, as the front propagated over California, a strong windshift line developed at the north end of the valley and propagated southward with the upper-level front. Due to downslope flow and subsidence, this northerly wind was also very dry, with dewpoint temperatures in the 30s. Thus, a moisture discontinuity was created as well as a windshift line.

The 2000 UTC analysis indicated that the windshift/moisture discontinuity had moved farther south, pushing through the Red Bluff area (Fig. 22). Thunderstorms were forming at the triple point between the surface windshift line and the valley pressure trough near Red Bluff. The dewpoint temperature at Chico (CIC) was now 54°F with winds gusting to 20 mph from the southeast while Red Bluff had a dewpoint temperature of 49°F and falling, with winds from the west at 10 mph. Stronger surface winds were developing as the surface pressure gradient became stronger across the southern portion of the Sacramento Valley. Thus, significant moisture convergence was occurring along this windshift line as it moved into the more unstable airmass to the south.

At 2005 UTC, a funnel cloud was reported over Tehama County. This funnel cloud was very short-lived, and was likely a cold-air funnel developing as the cold equivalent potential temperature minimum air aloft continued to destabilize the atmosphere. At this time, satellite imagery indicated significant clearing occurring across the northern Sacramento Valley as the upper-level front continued to propagate southeastward over California.

By 2100 UTC, water vapor satellite imagery clearly indicated the dry slot advecting around the base of the trough and pushing over the triple point at the surface (Fig. 23). This was the dry air that was evident in the 1200 UTC MFR sounding. Visible satellite imagery (Fig. 24) indicated that significant clearing had occurred allowing for solar insolation to continue to rapidly destabilize the airmass over the northern Sacramento Valley. Although hard to see in this image, a thin line was beginning to form along the windshift line as thunderstorms rapidly developed from northeast to southwest. The surface analysis at this time indicated strong southeasterly flow into the region of the triple point which represented increasing moisture convergence and strong baroclinic surface vorticity at that location (Fig. 25). Oroville had a dewpoint temperature of 51°F with 25 mph sustained winds from the southeast. The pressure gradient continued to strengthen over this area as solar insolation decreased the pressure over the northern portion of the valley, and cloud cover remained over the southern portion. A secondary push of drier air had formed on the west side of the valley and was now propagating northeastward as evident from the wind shift from southerly to westerly and the dewpoint drop of 2°F at Brooks (BSS).

By 2200 UTC, a large anvil was covering the northern Sacramento Valley as a large thunderstorm rapidly developed along the triple point. As will be seen later, this storm was now in a region of significant low-level shear with a Bulk Richardson Number less than 15. Chico (CIC) reported a windshift at the time of observation as the windshift line, or possibly the gust front, began to move through the city (Fig. 26). Towering cumulus were being reported north through southeast as thunderstorms began to develop southward along the Sierra Nevada foothills. However, the thunderstorm to the north of CIC was dominating the local environment as many of the other thunderstorms began to weaken due to the upper-level subsidence forced by this rapidly growing thunderstorm. As the near-surface air was lifted by the gust front, it likely began rotating in the high helicity environment near CIC, ultimately developing into a mesocyclone.

At 2228 UTC, the Redding WSO received a phone call from the California Department of Forestry (CDF) Headquarters in Oroville reporting that they were "looking at a tornado out their window". The National Weather Service at Sacramento was called for radar confirmation, but the WSR-57 radar only indicated VIP level 2 in the vicinity of Oroville (Fig. 27). Of greater importance however, was the WSR-88D Doppler radar which indicated a weak circulation in the mid and upper levels of the storm likely indicative of a developing mesocyclone. This rotation was seen by meteorologists working at WSO Sacramento (SAC) that afternoon. Unfortunately, only one velocity image was archived, as testing of the radar was occurring at the same time. This 2.4° scan of velocity indicated strong storm top divergence occurring with this storm (Fig. 28). Since the storm was about 60 miles away, the beam of the radar was slicing through the storm at the 18,500 foot level which was close to the storm top of 22,000 feet. Satellite imagery (not shown) indicated a "V-notch" signature which also remarks on the strength of the storm and the upper-level divergence.

By 2300 UTC, the surface analysis showed that the outflow boundary was propagating to the east-southeast (Fig. 29). While the storm was moving to the southeast, the actual tornado path was to the northeast. This possibly occurred during the meso-occlusion stage of the mesocyclone. As the storm reached the Sierra Nevada foothills, it took a more eastward track, as did the dissipating tornado (as witnessed by an observer located east of Oroville). The tornado dissipated soon afterward.

Another interesting occurrence between 2200 and 2300 UTC was a polarity switch in cloud-to-ground lightning reported by the BLM Lightning Detection Network. Before 2200 UTC, only negative strikes were occurring, however between 2230 and 2300 UTC, only one positive strike occurred (and no negative strikes). After 2300 UTC, more negative strikes were reported. This polarity switch in tornadic storms has been documented in other cases as well (Branick and Doswell 1992; Curran and Rust 1992).

A sounding representing the local environment of the Oroville tornado was created by using the gridded model data from the 1200 UTC Eta model run and interpolating the temperature and dewpoint data for the mandatory levels with the 12 hour forecast for 0000 UTC 11 February (Fig. 30). This was to simulate what was available to forecasters that morning. These data were entered into the SHARP Workstation and the surface was modified to represent the surface pressure of Oroville, adjusting for the temperature and dewpoint which was expected to occur. The winds were also adjusted to represent the southerly low-level barrier jet in the valley and the strong west to northwesterly winds located aloft.

This sounding clearly indicated that the environment was conducive to the development of supercellular type storms. A Bulk Richardson Number of 11 combined with a 0-3 km storm-relative helicity value of 355 m^2/s^{-2}, using the storm motion vector from 321° at 19 kts, suggest that developing storms could have complex structures with supercellular characteristics (Weisman and Klemp 1982; Davies-Jones 1990). The CAPE was calculated to be near 750 J/kg which was not highly unstable, but as previously stated, with high helicity values, large instability is not needed for tornadogenesis (McCaul 1990). Storm-relative inflow in this environment was from the southeast at 40-45 knots, which verifies the strong convergence which was assumed from the sub-synoptic analyses. The Lifted Index at the 500 mb level at this time was -3.0°C, but at 700 mb was -4.0°C. The hodograph was indicative of a veering of the wind with height in the lower troposphere with northwest winds above this (Fig. 31).

Gridded data at 0000 UTC indicated that at the 250 mb level, a large area of cyclonic vorticity advection was occurring over northern California juxtaposed with an area of warm air advection (Fig. 32). This was leading to strong height falls at the surface and a rapid deepening of the surface low from 1020 mb at 1200 UTC to 1008 mb at 0000 UTC. This rapid deepening created strong southerly isallobaric winds across most of eastern California. Associated with this strong area of warm air advection and cyclonic vorticity advection was a tropopause fold in the upper troposphere. This tropopause fold can be seen in a equivalent potential temperature temporal cross-section as 362K stratospheric air replaces 340K tropospheric air (Fig. 33). Strong rising motion ahead of this tropopause fold suggests the strength of this upper system. As discussed by Hirschberg and Fritsch (1991, 1993), thermal advections in the vicinity of tropopause undulations can be quite large and will have a great effect on height tendency in the lower atmosphere and its associated vertical velocity. Of additional note was the stable layer present at 1200 UTC between 800 mb and 500 mb which was forced upward to a position between 600 mb and 400 mb by 0000 UTC by these vertical motions. This was the dry, stable layer which was present in the OAK and MFR soundings from 1200 UTC and at 0000 UTC. Under this dry stable layer was a moist unstable area, and as the dry stable layer was lifted, dynamic destabilization in the lower levels increased the depth of the moist unstable layer. The dry air intrusion could be seen occurring from 09 hours (2100 UTC) to 30 hours as low equivalent potential temperature air advected into the region. This air was not much cooler than the air it was replacing, thus the decrease in equivalent potential temperature was due mainly to a lack of moisture. This feature was the upper-level front discussed earlier.

A cross-section from 36°N 132°W to 40°N 112°W at 0000 UTC indicated that the strong rising motions in the secondary circulations had decreased (Fig. 34). A strong outflow from the upper-level jet could be seen at the 200-300 mb layer near the jet streak and tropopause fold. The strong secondary circulations seen in the near-surface layer earlier had weakened significantly. Although the airmass behind the cold front was unstable, as seen in the low values of equivalent potential temperature by 0000 UTC, there was a very strong cap between 700 and 500 mb which was prohibiting any convective instability from being realized.

IV. TORNADO OCCURRENCE IN THE NORTHERN SACRAMENTO VALLEY

As previously stated, it appears that certain areas of the northern Sacramento Valley are more prone to thunderstorms which may take on supercellular structures. These storms are responsible for a maximum of tornadic activity over areas of southern Tehama County and Butte and Glenn Counties. South of this region there are relatively few recorded tornado touchdowns. A possible explanation for this is a lack of population centers between Red Bluff, in Tehama County, and Sacramento. However, the relative flatness of the land and the abundance of agriculture in the Sacramento Valley would suggest that tornadoes should have a good chance of detection by agricultural workers. Damage would likely be noticed by them after the storm was over, even if the tornado was not seen. Also, many small communities have developed across this region over the last ten years adding to the potential for tornado sightings.

More likely, however, is that the maximum in tornado occurrence over the northern Sacramento Valley is due to meteorological forcing, such as the existence of a barrier jet developing along the east side of the valley and a maximum of convergence between the valley trough and southeastward moving windshift lines, often associated with upper-level fronts. Additional convergence is likely over the northeastern portion of the Sacramento Valley as the Sierra Nevada Mountains extend further westward and Sutter Buttes rise out of the valley floor.

Parish (1982) has found that low-level mountain parallel jets are a common wintertime and early springtime feature along the western slope of the Sierra Nevada Range. He proposes that the development of the barrier jet occurs whenever a large-scale component of wind is directed towards a mountain chain causing the air to be forced to rise over the barrier. If the air has a high static stability, the forced ascent is resisted and appreciable deceleration occurs. This leads to the damming of stable air against the mountains and consequently an increase in pressure along the windward slopes. The resulting damming leads to a pressure gradient force strikingly dissimilar to the large-scale conditions, being directed away from the mountains. If such conditions persist for periods of time exceeding a few hours, Coriolis effects become important. The local pressure field will then support southerly geostrophic-type motion parallel to the mountains. Of course, friction and diabatic effects must also be considered, but their combined effect is not as easily calculated. It was found that the strongest winds were located 600-1500 m above ground level, with a horizontal extent of at least 100 km, reaching down into the California Valley. He found that much weaker winds existed at the surface below the radiative inversion. Occasionally, a valley trough formed with westerly winds located on the west side, in striking contrast with the surface pressure gradient.

Another reason for a preferred area of thunderstorm development over the northern Sacramento Valley is the climatological location of the triple point formed between the valley trough and a southeastward moving windshift line associated with terrain channeling of the ridgetop winds. As this windshift line moves southeastward, a collision between it and the valley trough will occur over the northern portion of the Sacramento Valley. It has been shown that the collision between two boundaries is a preferred region for the development of strong to severe thunderstorms (Doswell 1985). This was likely the genesis mechanism for the Oroville thunderstorm. The near-surface moist flow was vertically stretched as it accelerated upward and began rotating in the high helicity environment in the lower levels which likely caused the Oroville thunderstorm to develop into a severe storm.

The orientation of the valley leads to a gradient of Bulk Richardson Number across the valley. Bulk Richardson Numbers will decrease from west to east due to the increasing shear found on the east side arising from the barrier jet (assuming storm motion from a northerly direction). The shear is likely increased through compression on the east side of Sutter Buttes and the merging of the valley walls at the north end of the valley. All of this leads to the lowest Bulk Richardson Numbers on the east side of the valley, likely within the values supportive of supercellular development as defined by Weisman and Klemp (1982).

All of these factors lead to an area in the northern Sacramento Valley which appears to be more prone to storms which may take on supercellular structures. Due to the finite width of the valley, many of these storms will likely develop rotation briefly, if at all, and quickly return to a multicellular structure when the foothills are reached. Also, due to the post frontal environment, storm tops are usually below 30,000 feet, thus limiting the extent to which they can be examined by Doppler radar. Thus, these storms take on characteristics similar to the early stages of supercells in the Midwest, but never have enough time or instability to develop into the much more powerful supercells which plague that region.

V. DISCUSSION AND CONCLUSION

The northern Sacramento Valley is an area where interactions between a valley-induced pressure trough and a strong windshift line climatologically occur. General convergence occurs here, as well, due to a confluence of the valley walls. A high occurrence of thunderstorm echoes over this region, which are likely due to this phenomena, can be seen in the WSR-57 radar data archive (WSO-SAC).

A strong southerly barrier jet which develops along the east side of the Sacramento Valley during the winter causes strong moisture convergence to occur as well. Previous studies of California tornadoes (Hales 1985; Braun and Monteverdi 1991; Monteverdi and Quadros 1994) support the theory that shear profiles favorable for storm rotation can be created by topography in California. In the Oroville case study, this strong southerly flow transported high moisture values northward along the east side of the valley-induced pressure trough. This moist flow impinged on the southeastward moving windshift line and was forced upward. Strong thunderstorms developed as a midlevel dry push advected over the area adding to the destabilization. This occurred in an environment which was being destabilized by solar insolation due to the midlevel dry push behind the upper-level front. The near-surface moist flow was vertically stretched as it accelerated upward and began rotating in the high helicity environment in the lower levels which likely caused the Oroville thunderstorm to develop into a severe storm.

This study has explored the uses of the SHARP Workstation and PC-GRIDDS in determining the area of severe weather potential on 10 February 1994. The Oroville tornado was a good example of how certain storms may behave under optimum conditions over the northern Sacramento Valley. The Oroville storm appeared to contain brief supercellular structures. These structures, including mesocyclones and moderately strong tornadoes, can develop due to high values of valley-induced storm-relative helicity which can support tornadogenesis even within the post-frontal, low buoyancy environment. This study shows how important it is for forecasters to be aware of the mesoscale processes which occur in their forecast area and to realize when the interaction between the mesoscale and the synoptic scale can lead to the development of severe thunderstorms and tornadoes. With the implementation of the WSR-88D Doppler radar in Sacramento, it is likely that this type of thunderstorm will be detected and investigated more closely in the future.

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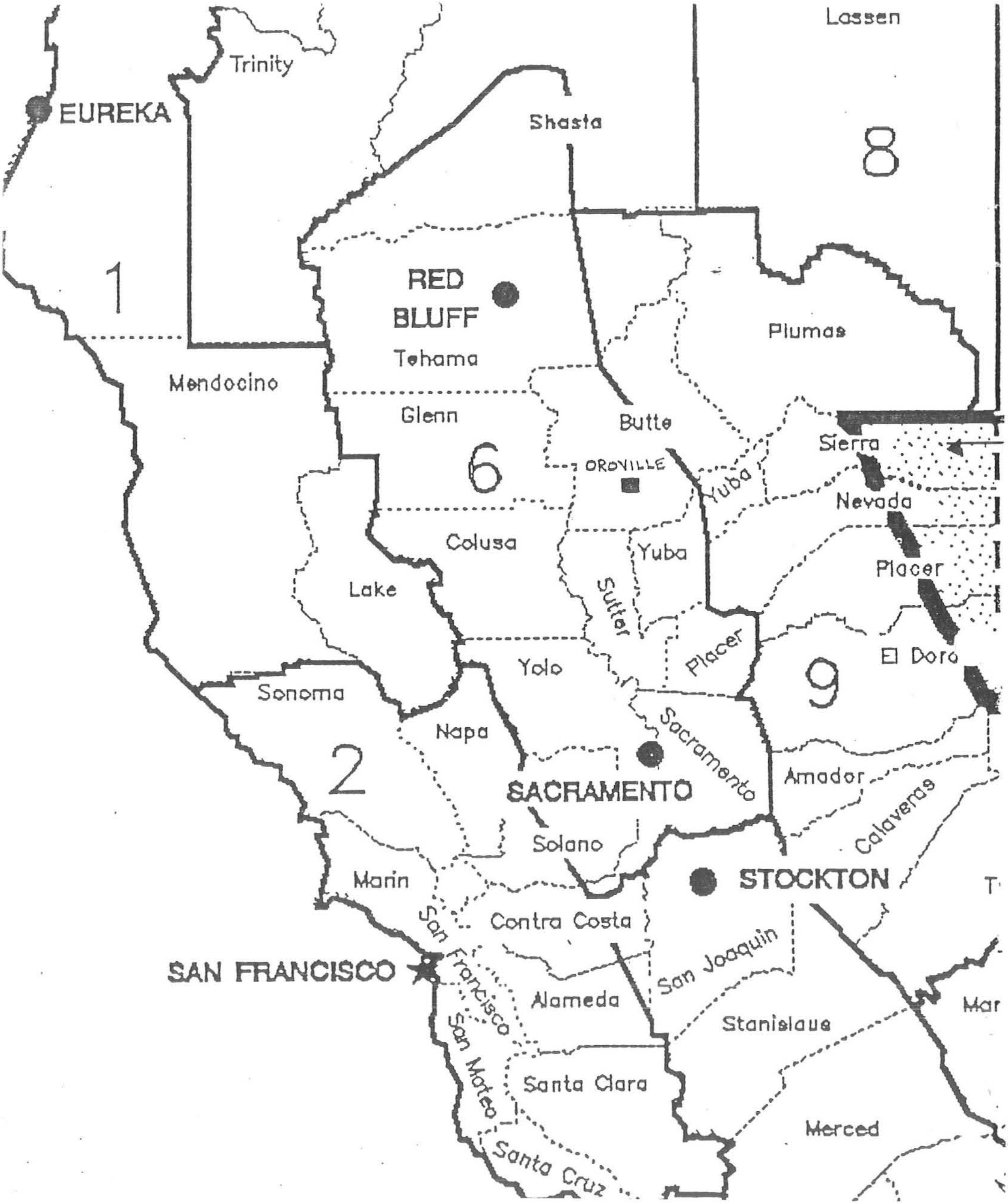


Figure 1 Map of northern California showing locations of major cities and Counties. The city of Oroville is indicated by the square in Butte County.

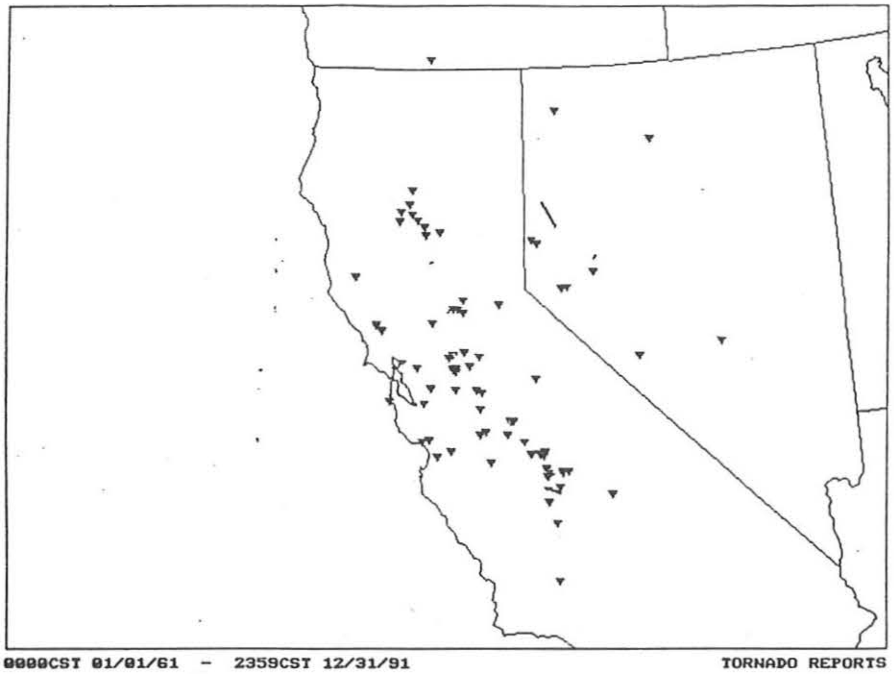


Figure 2 Tornado occurrence in northern and central California from 1961-1991. (Compiled by Storm Data)

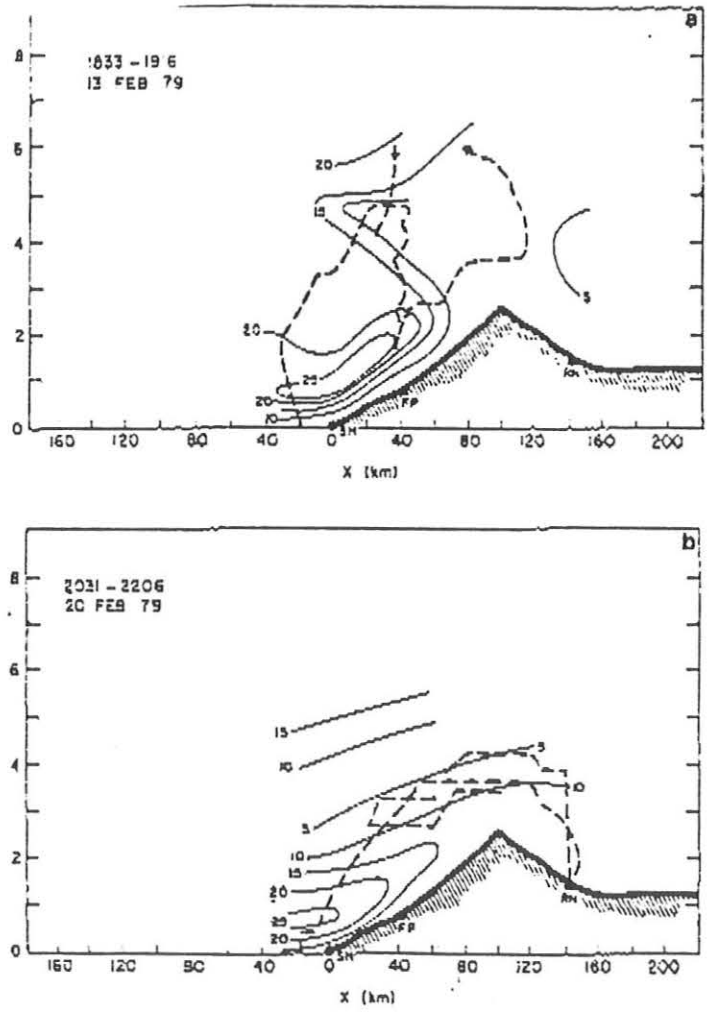


Figure 3 Mountain-parallel motion components (m s^{-1}) derived from rawinsonde and K/A data for 13 and 21 February 1979. Flight track shown by dashed line; flight time listed at top. (From Parish, 1982)

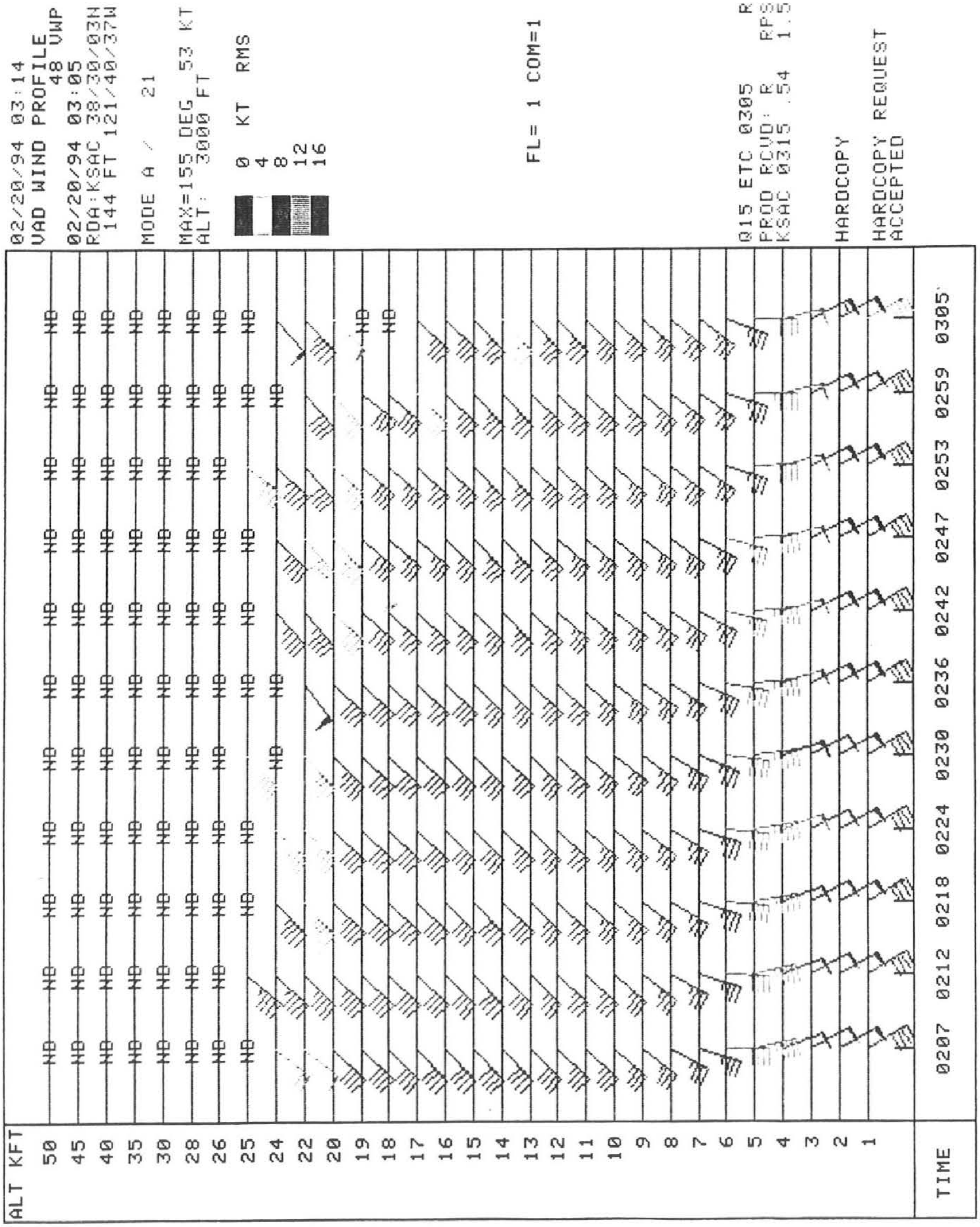


Figure 4 VAD wind profiler data from Sacramento WSR-88D for 20 February 1994. Note strong winds in the lowest 3000 feet.

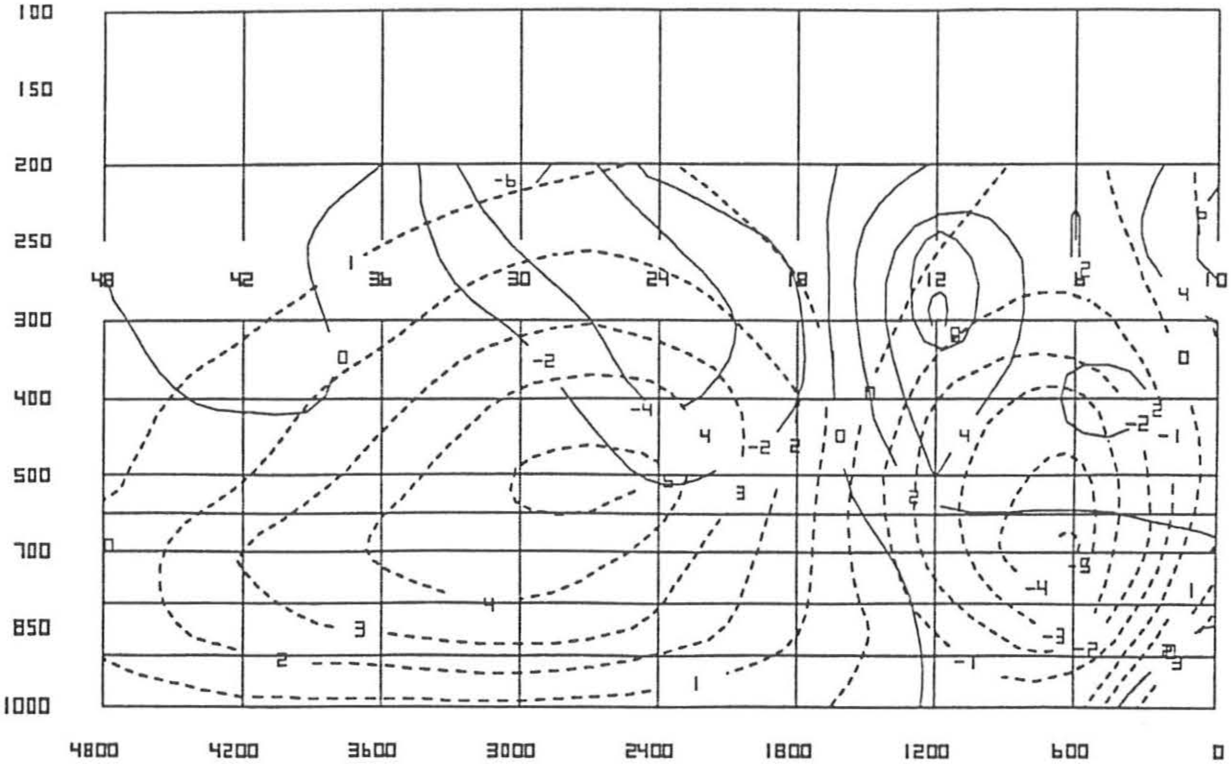


Figure 5 Time-height cross-section of vorticity advection contoured every $1x10^{-10}s^{-2}$ (solid) and vertical velocity contoured every contoured every $1\mu b\ s^{-1}$ (dashed) for 40° N 122° W.

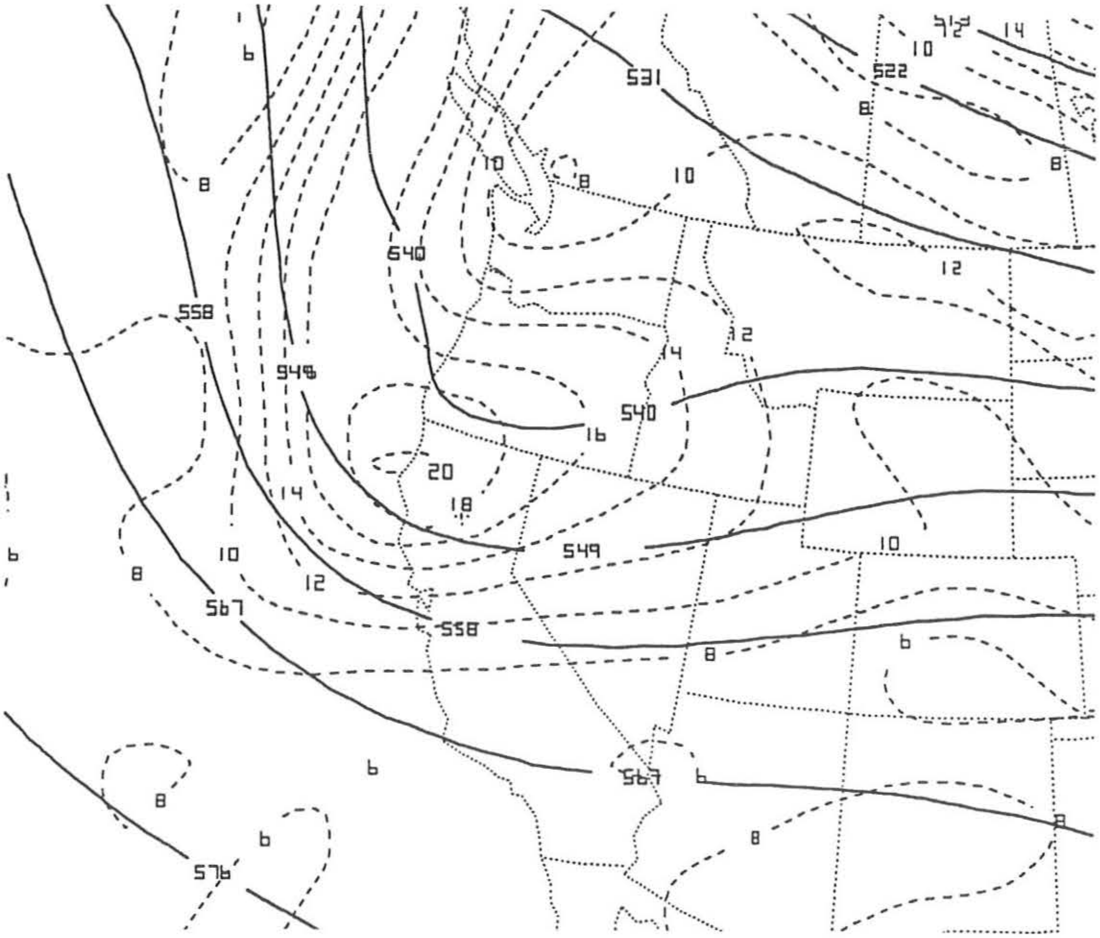


Figure 6 Height contoured every 6 dam (solid) and vorticity contoured every $2x10^{-5}\ s^{-1}$ (dashed) at 500 mb valid 0000 UTC 11 February 1994.

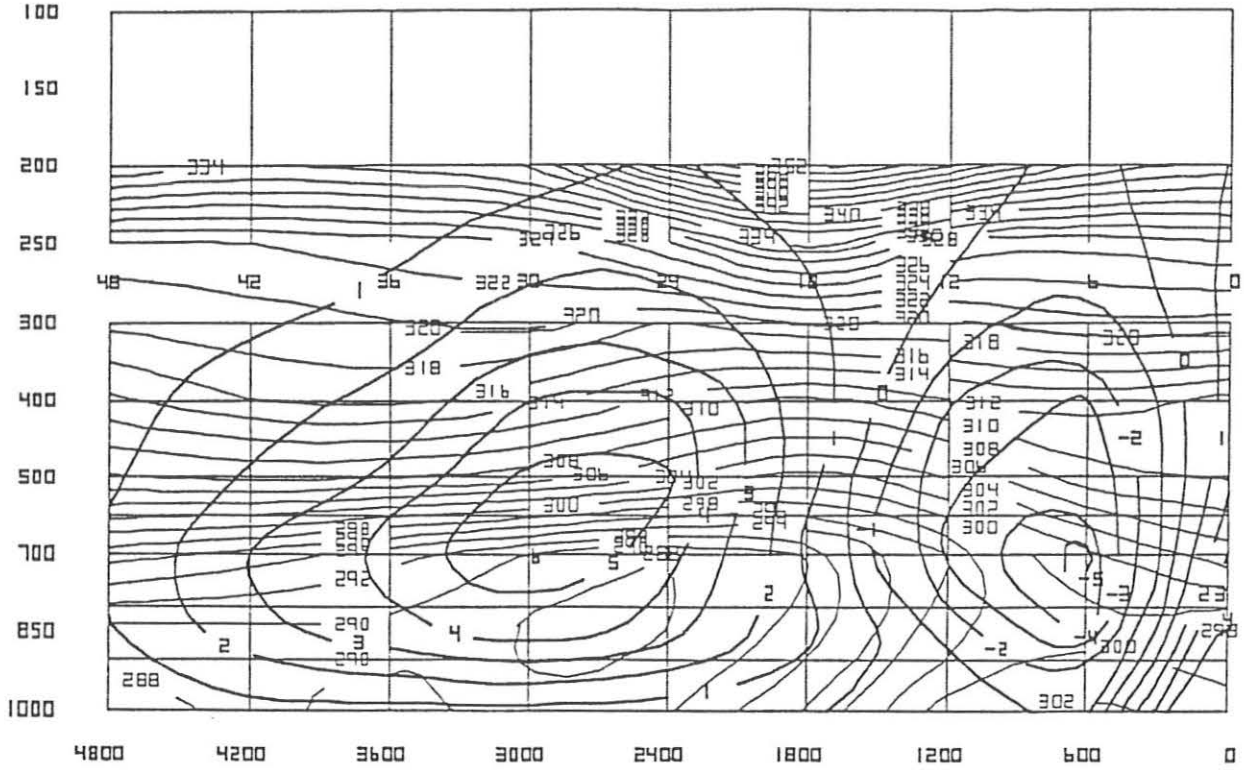


Figure 7 Time-height cross-section of equivalent potential temperature (K) (solid) and vertical velocity contoured every 1μb s^{-1}.

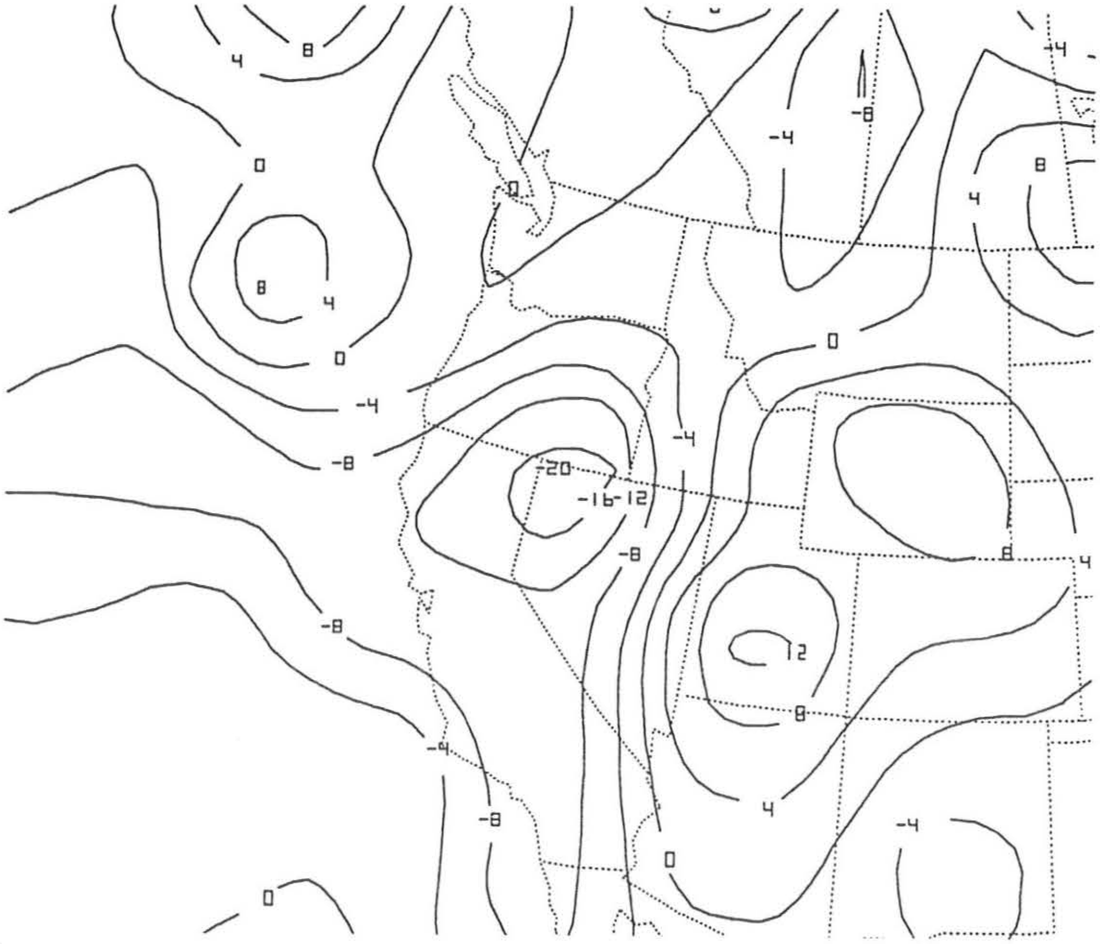


Figure 8 Temperature advection contoured every 2x10^{-4} °C s^{-1} in the 1000-500 mb layer valid 0000 UTC 11 February 1994.

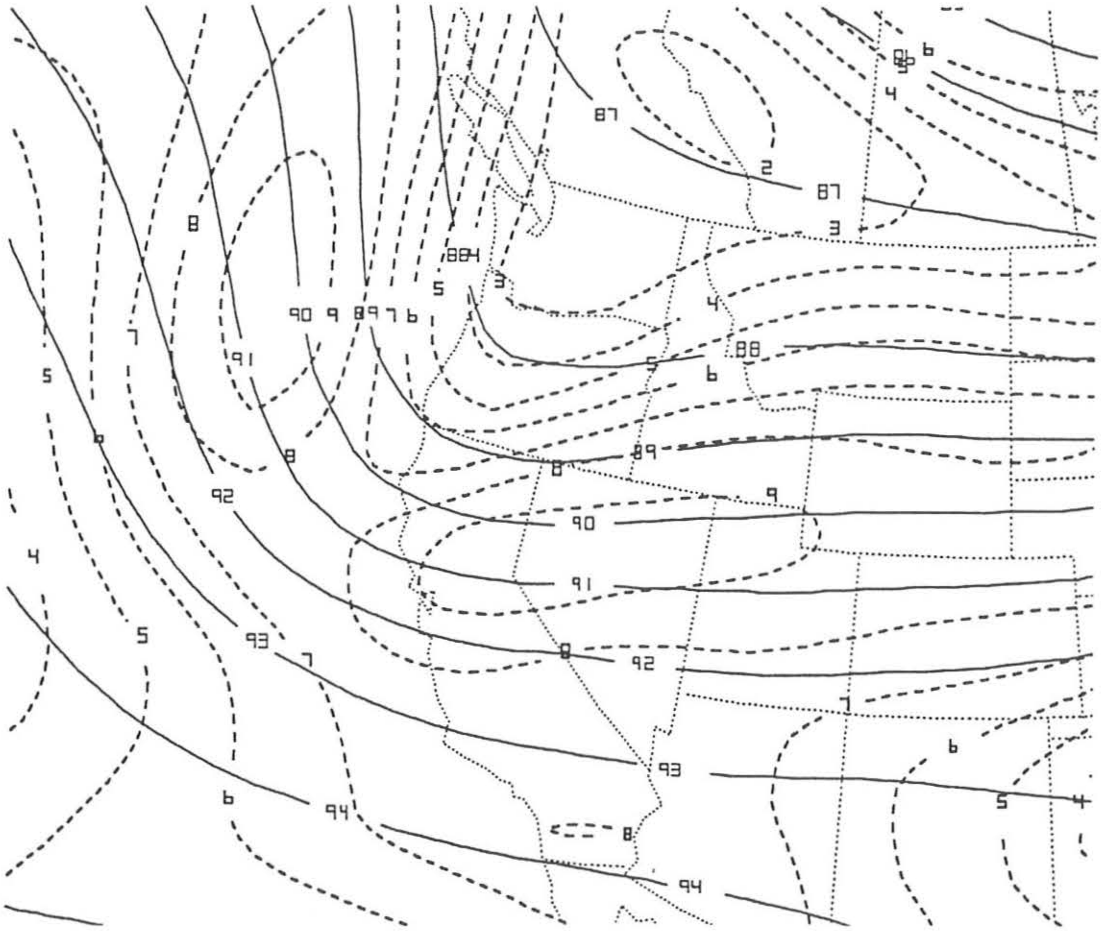


Figure 9 Height (solid) contoured every 12 dam and wind speed contoured every 10 knots (dashed) at 300 mb valid 1200 UTC 10 February 1994.

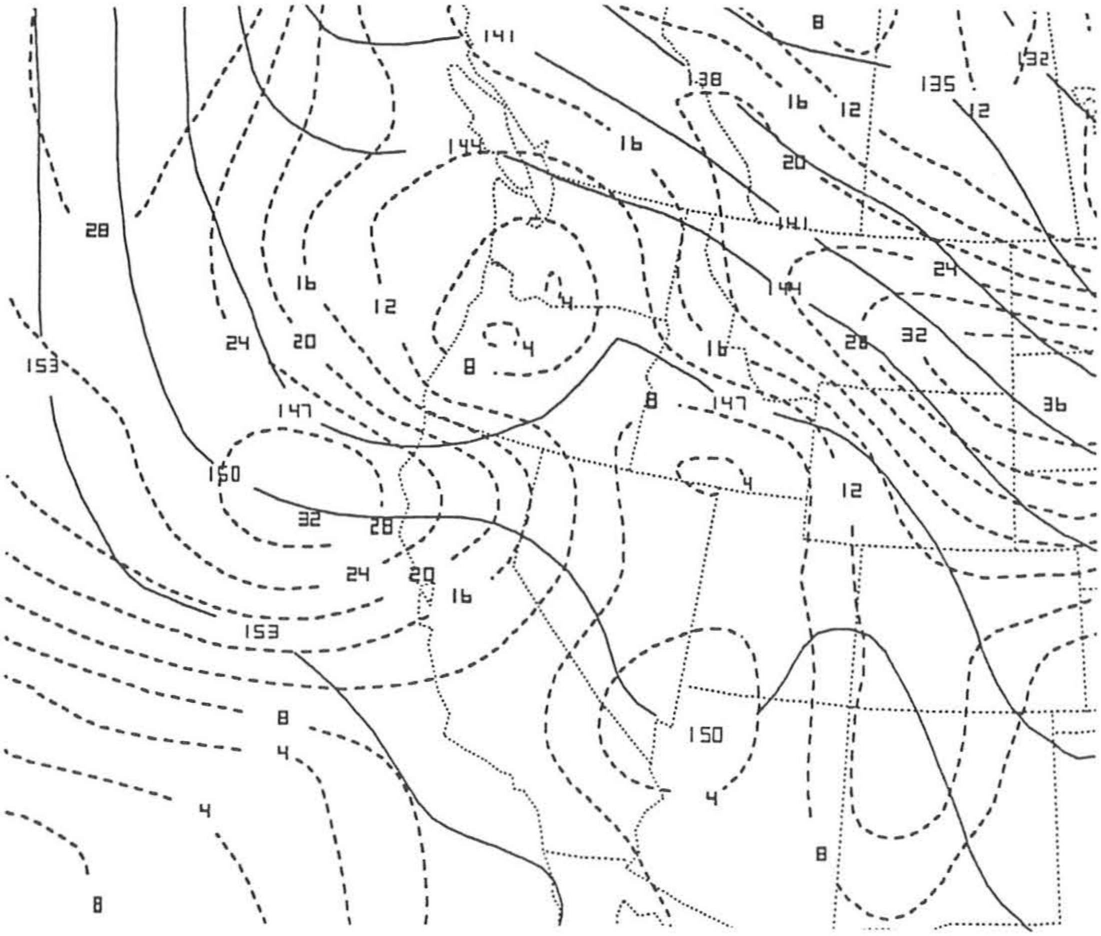


Figure 10 Height (solid) contoured every 3 dam and wind speed contoured every 10 knots (dashed) at 850 mb valid 0000 UTC 10 February 1994.

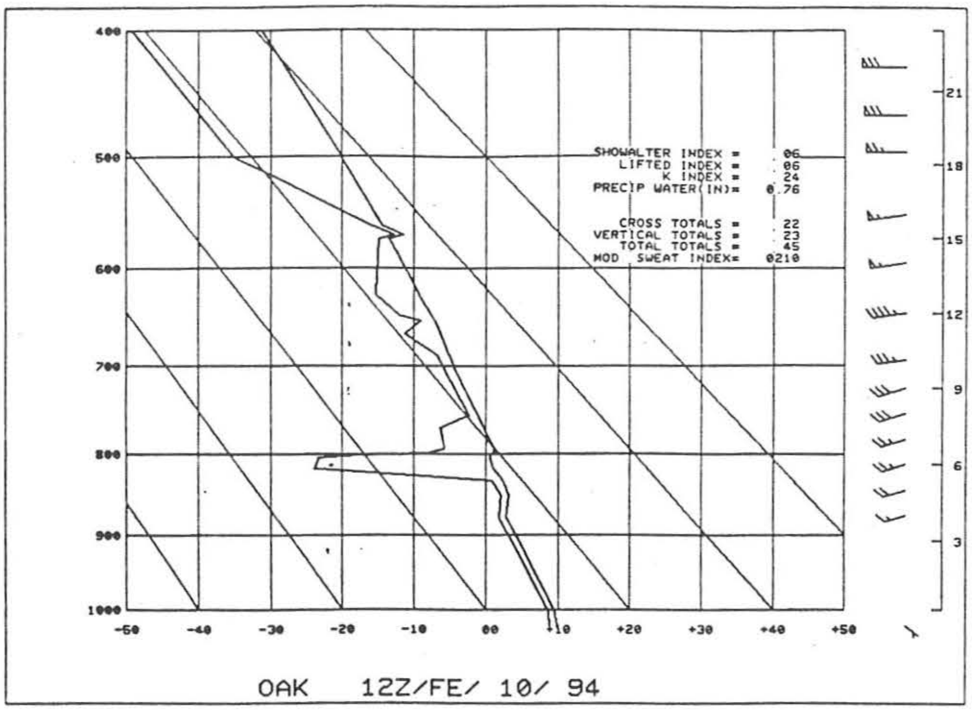


Figure 11 The Oakland (OAK) sounding for 1200 UTC 10 February 1994.

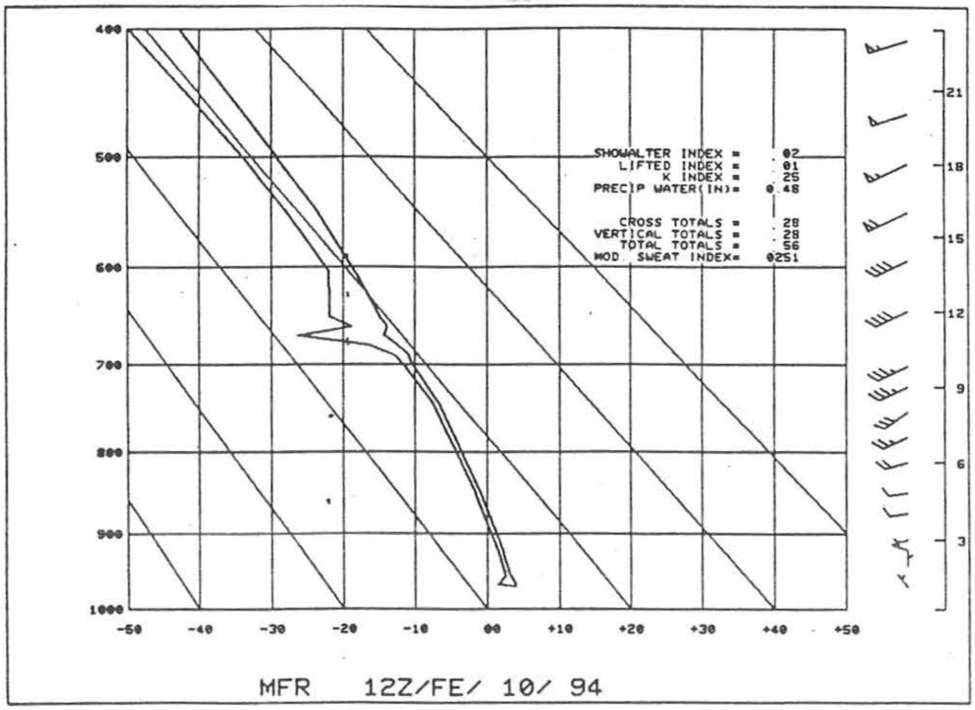


Figure 12 The Medford (MFR) sounding for 1200 UTC 10 February 1994.

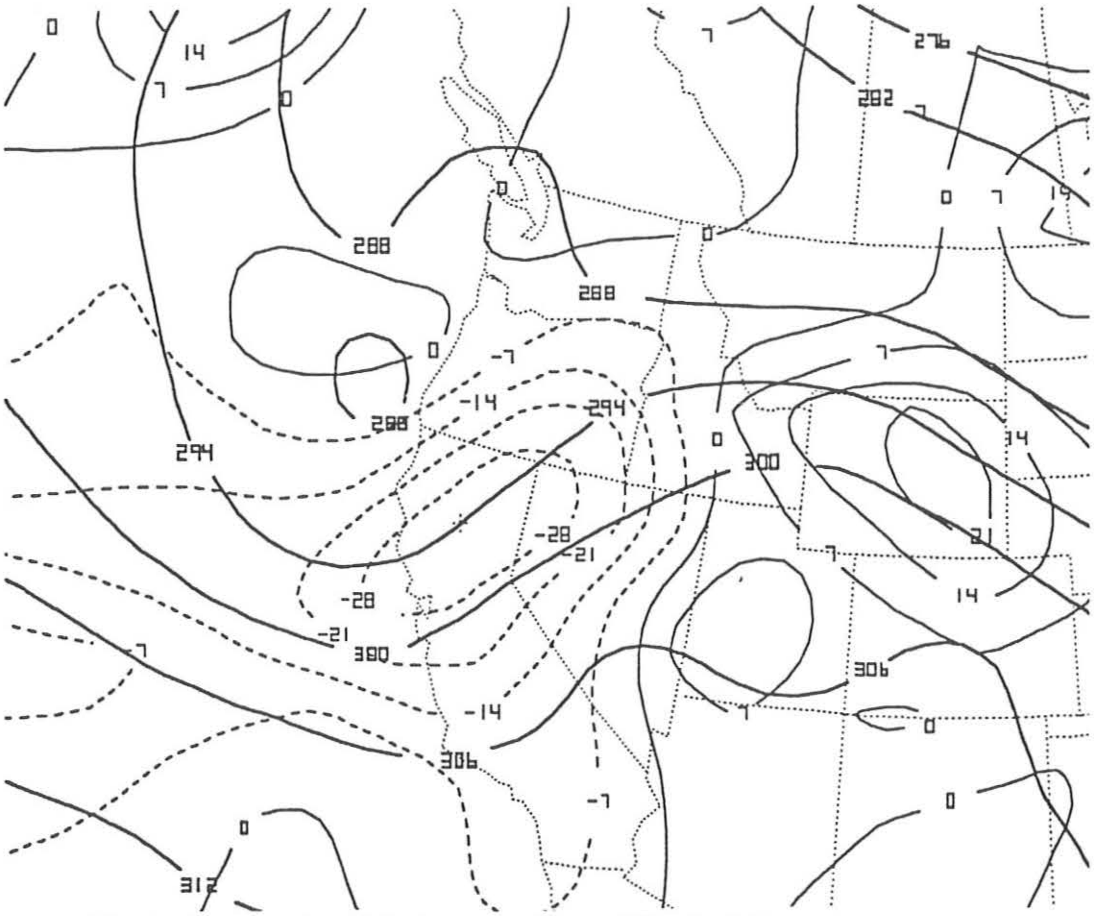


Figure 13 Equivalent potential temperature (K) (solid) and equivalent potential temperature (K) advection contoured every 0.7 K s^{-1} (dashed) at 700 mb valid 0000 UTC 11 February 1994.

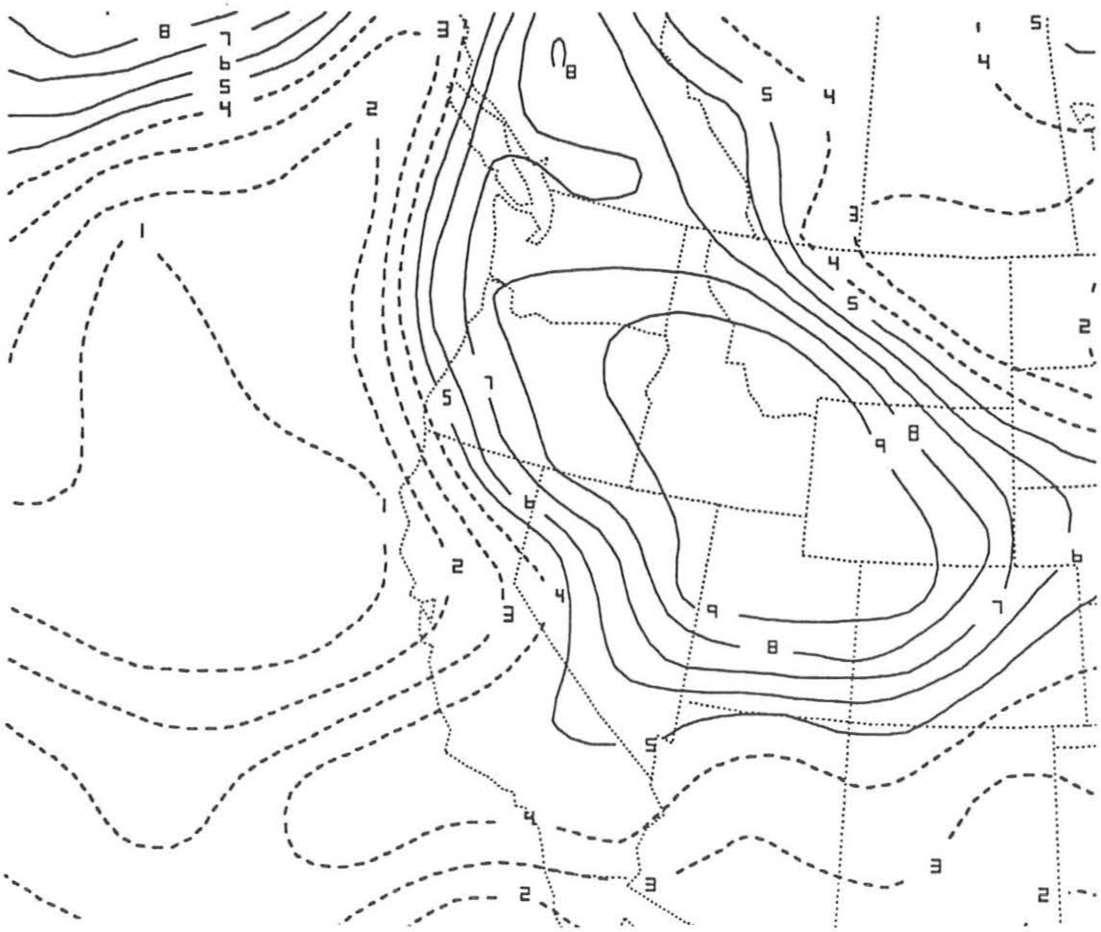


Figure 14 Relative humidity (in 10 percent intervals) at 500 mb valid 0000 UTC 11 February 1994.

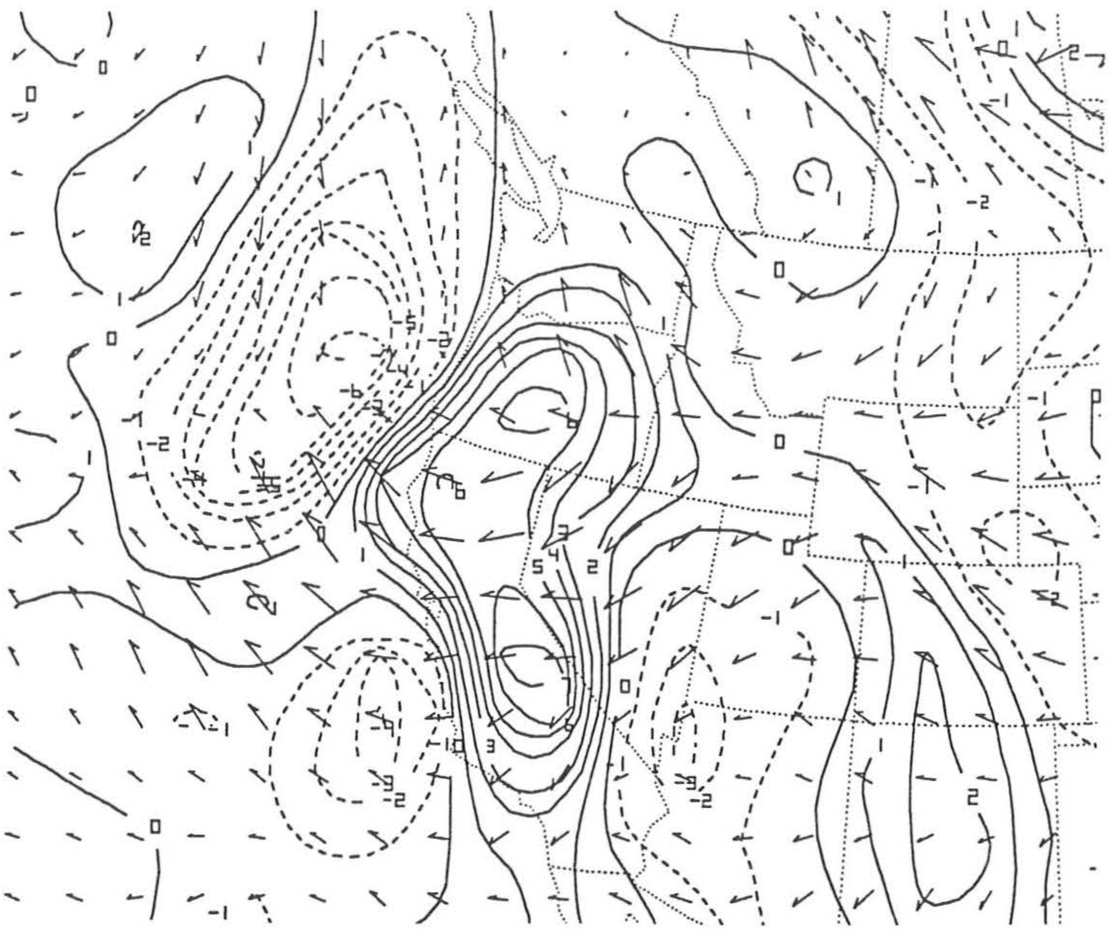


Figure 15 Q-vectors and Q-vector convergence (solid) in the 850-400 mb layer valid 0000 UTC 11 February 1994.

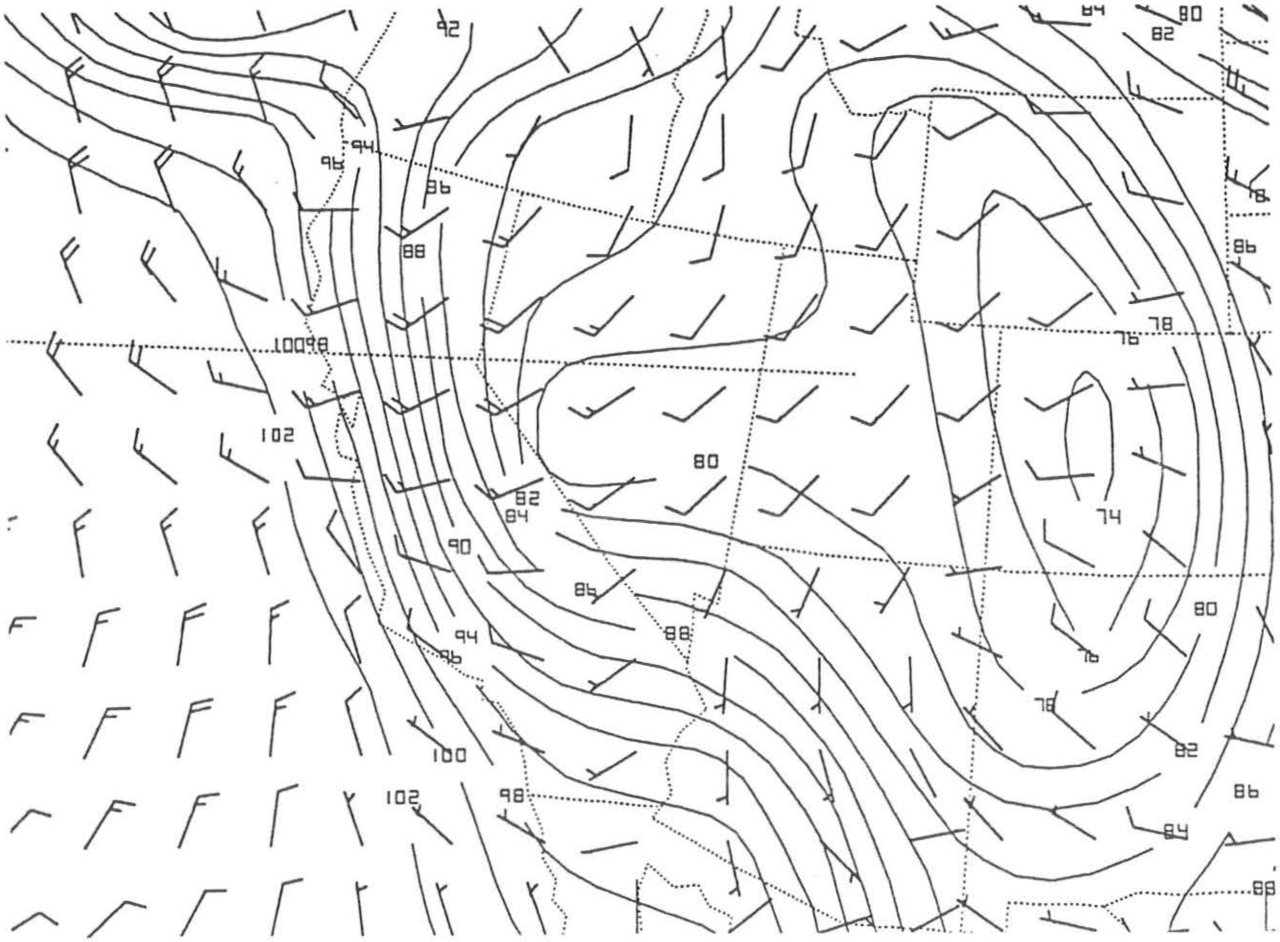


Figure 16 280K isentropic surface with pressure, contoured every 20 mb, (solid) and wind barbs valid 1800 UTC 10 February 1994.

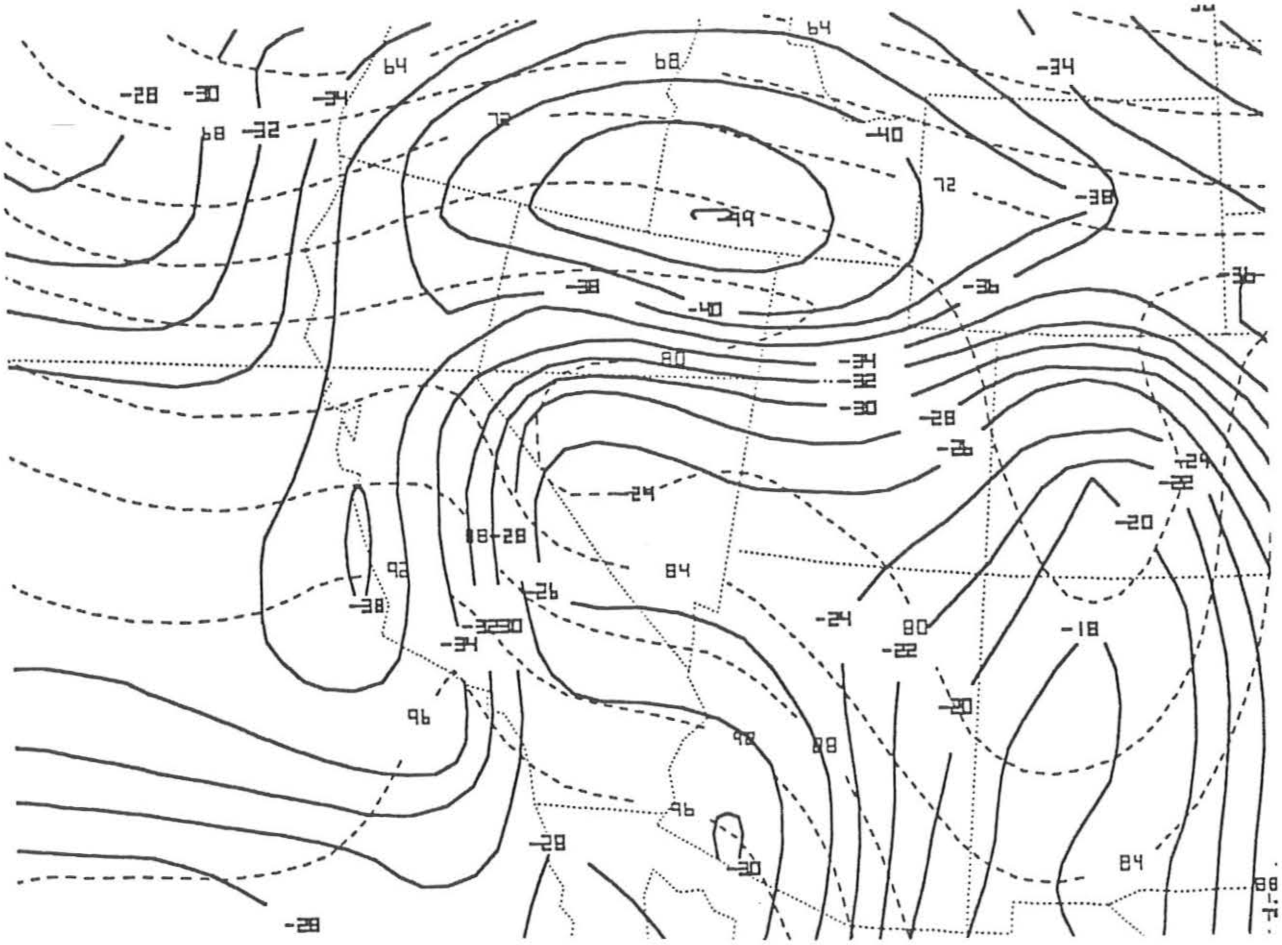


Figure 17 286-306K isentropic layer with stability (dark solid) and pressure at 306K (dashed) valid 1800 UTC 10 February 1994.

Figure 18 Adiabatic moisture flux convergence (solid) with wind vectors valid 1800 UTC 10 February 1994.

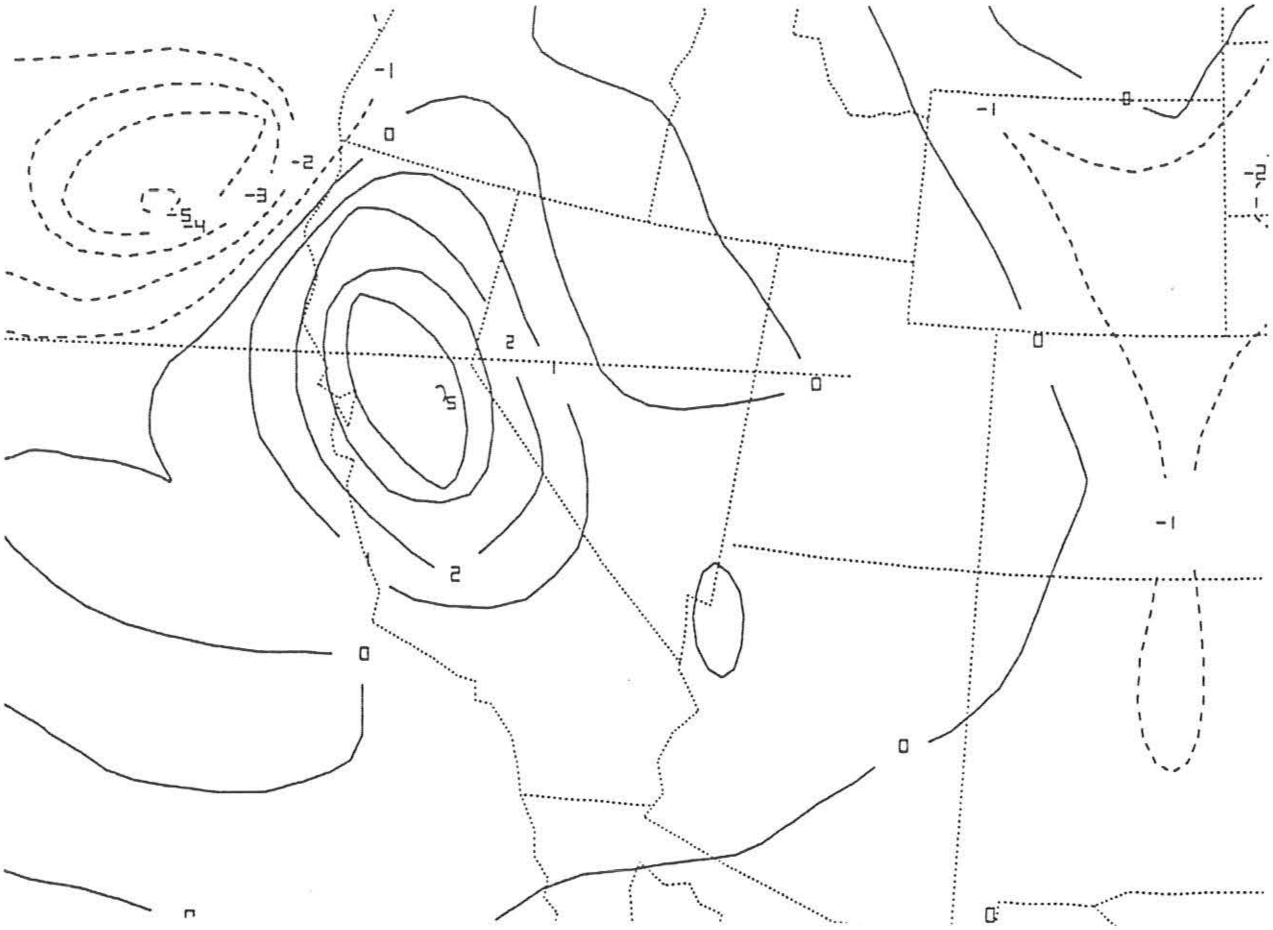


Figure 19 Vertical velocity contoured every 1μb s^{-1} due to pressure advection in the 286-306K isentropic layer valid 1800 UTC 10 February 1994.

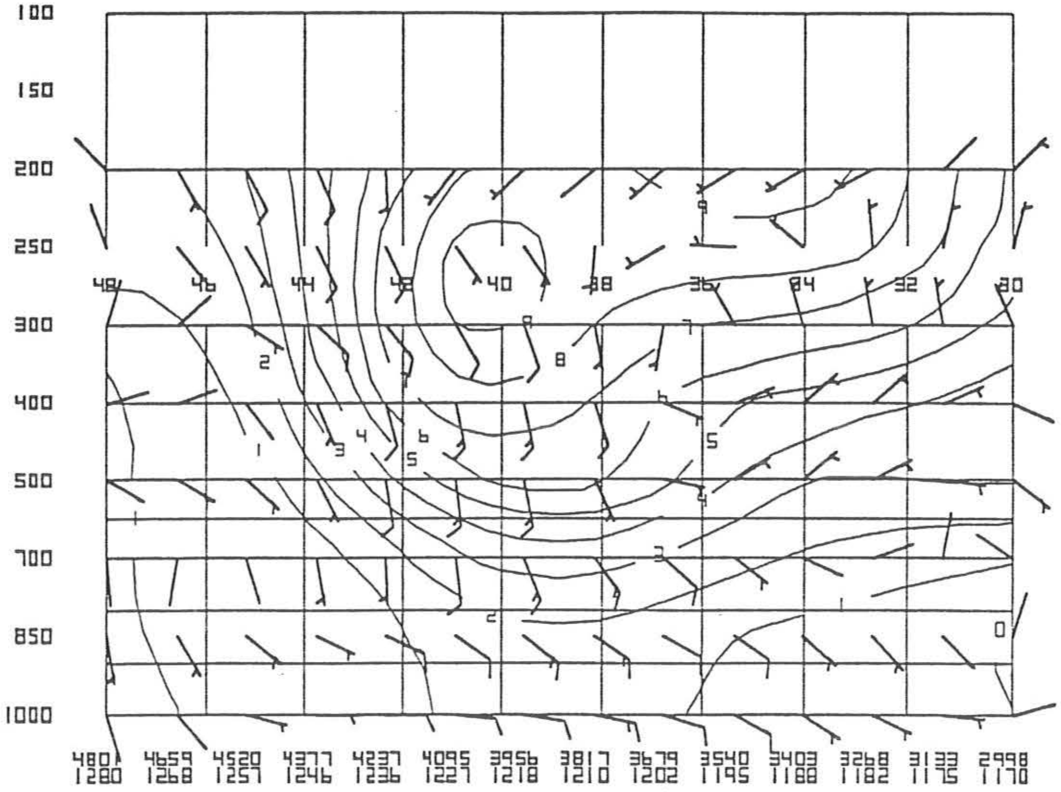


Figure 20 Cross-section from 48° N 128° W to 30° N 117° W with ageostropic wind (barbs) and normalized wind speed contoured every 10 knots (solid) valid 1800 UTC 10 February 1994.

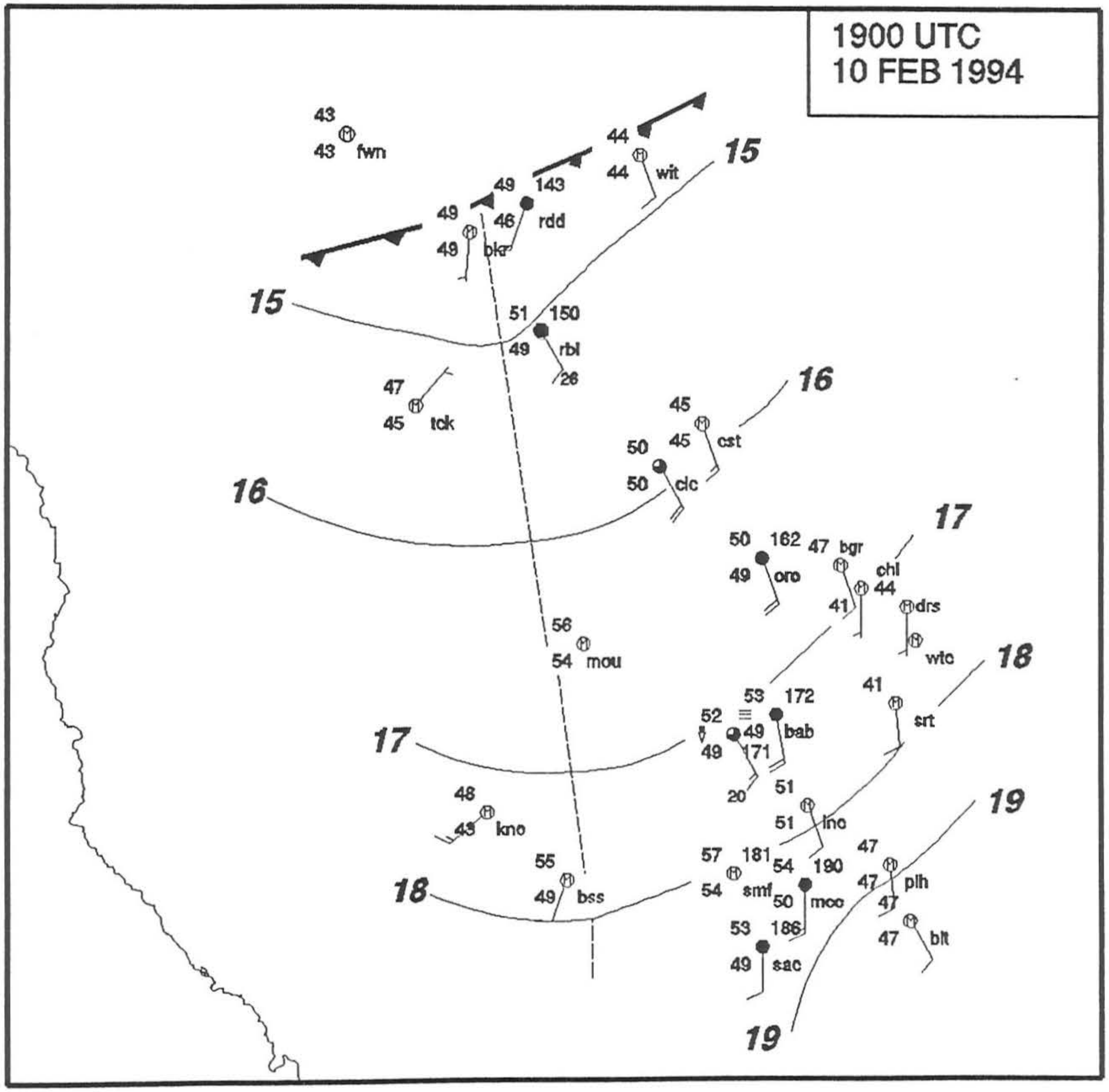


Figure 21 1900 UTC 10 February sub-synoptic pressure analysis (solid lines, every mb) indicating weak pressure trough (dashed line) along with a windshift/moisture discontinuity (solid front with barbs).

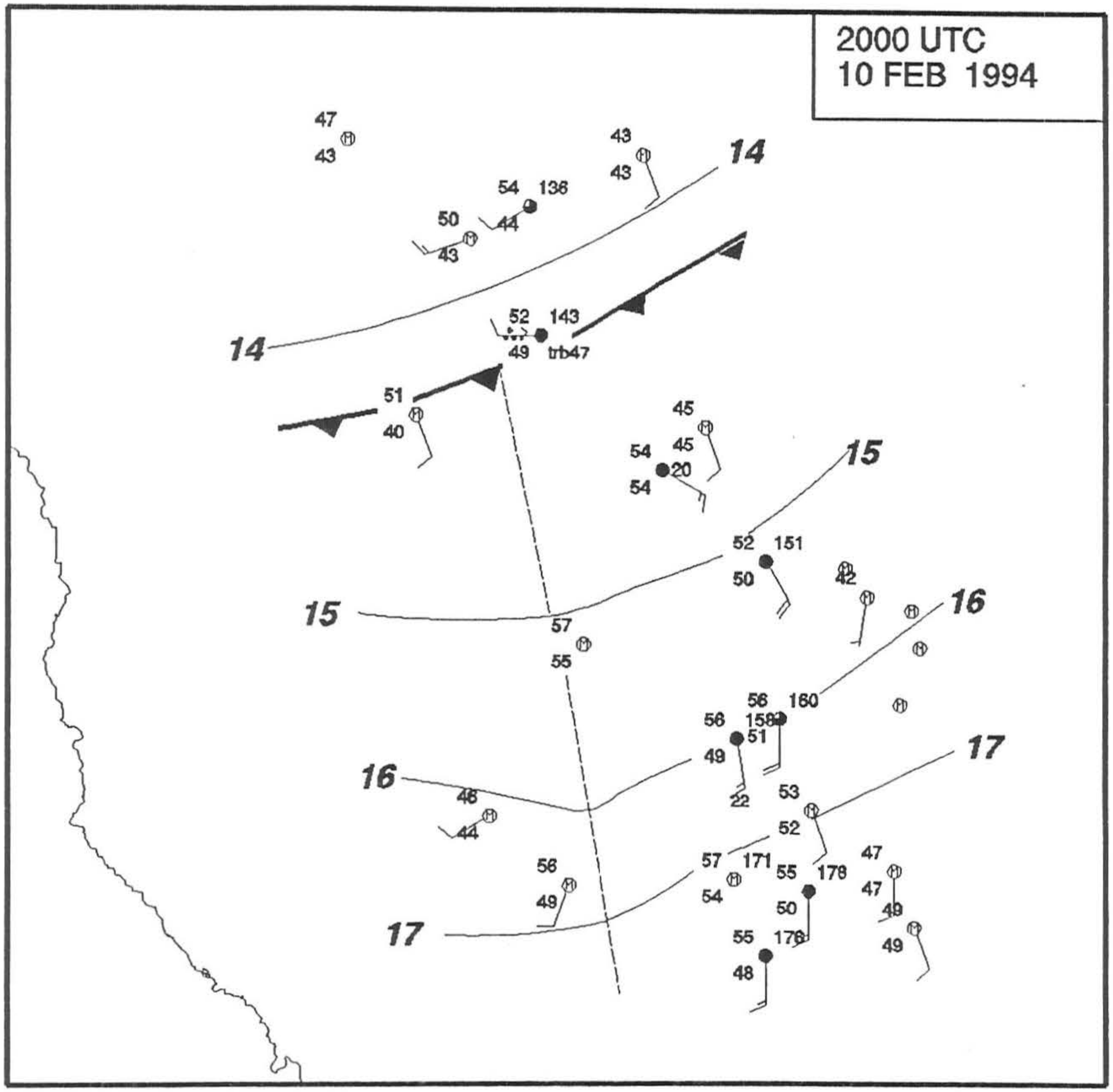


Figure 22 Same as Figure 21 except 2000 UTC 10 February 1994.

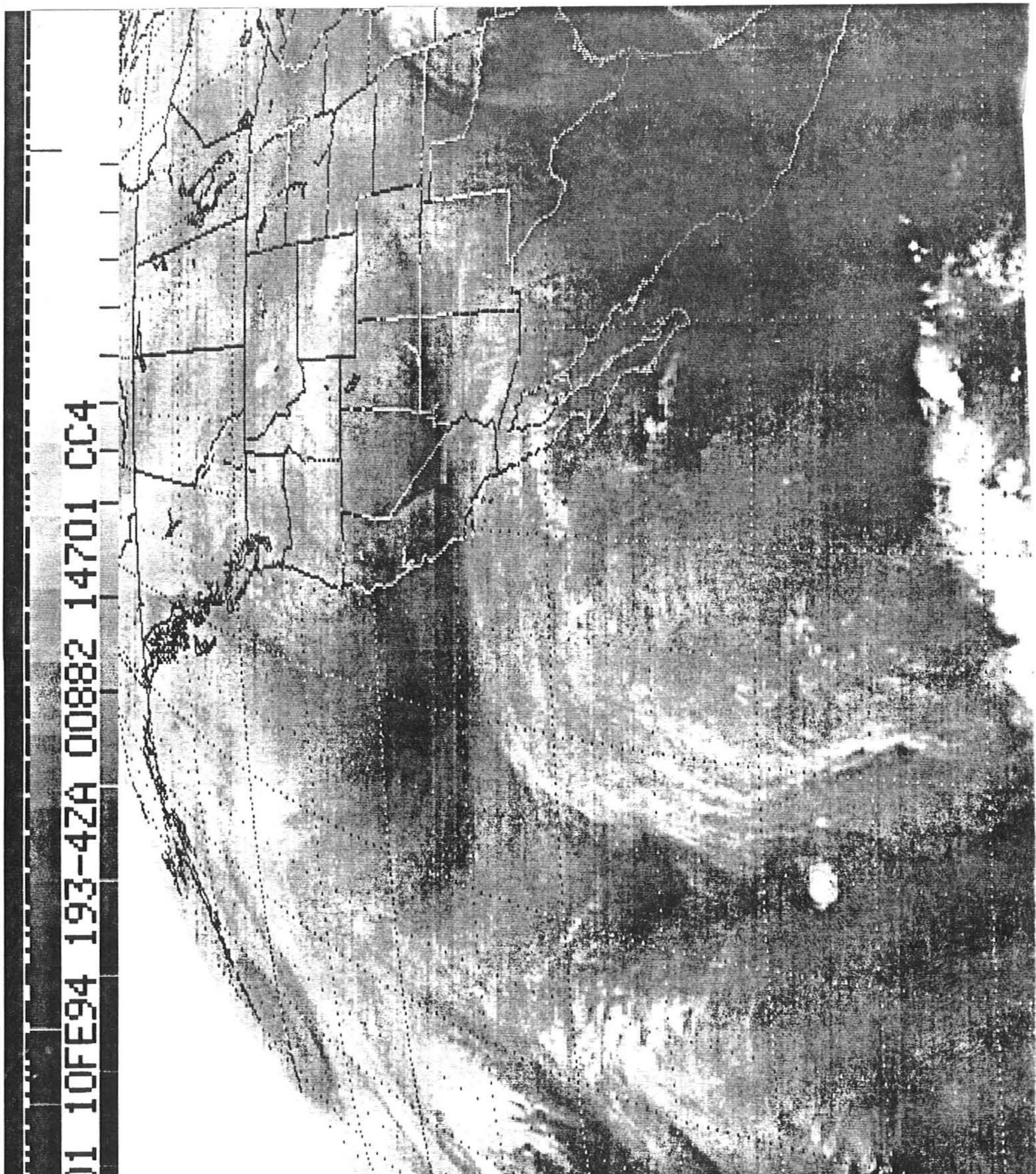


Figure 23 Water vapor imagery for 2100 UTC 10 February 1994.

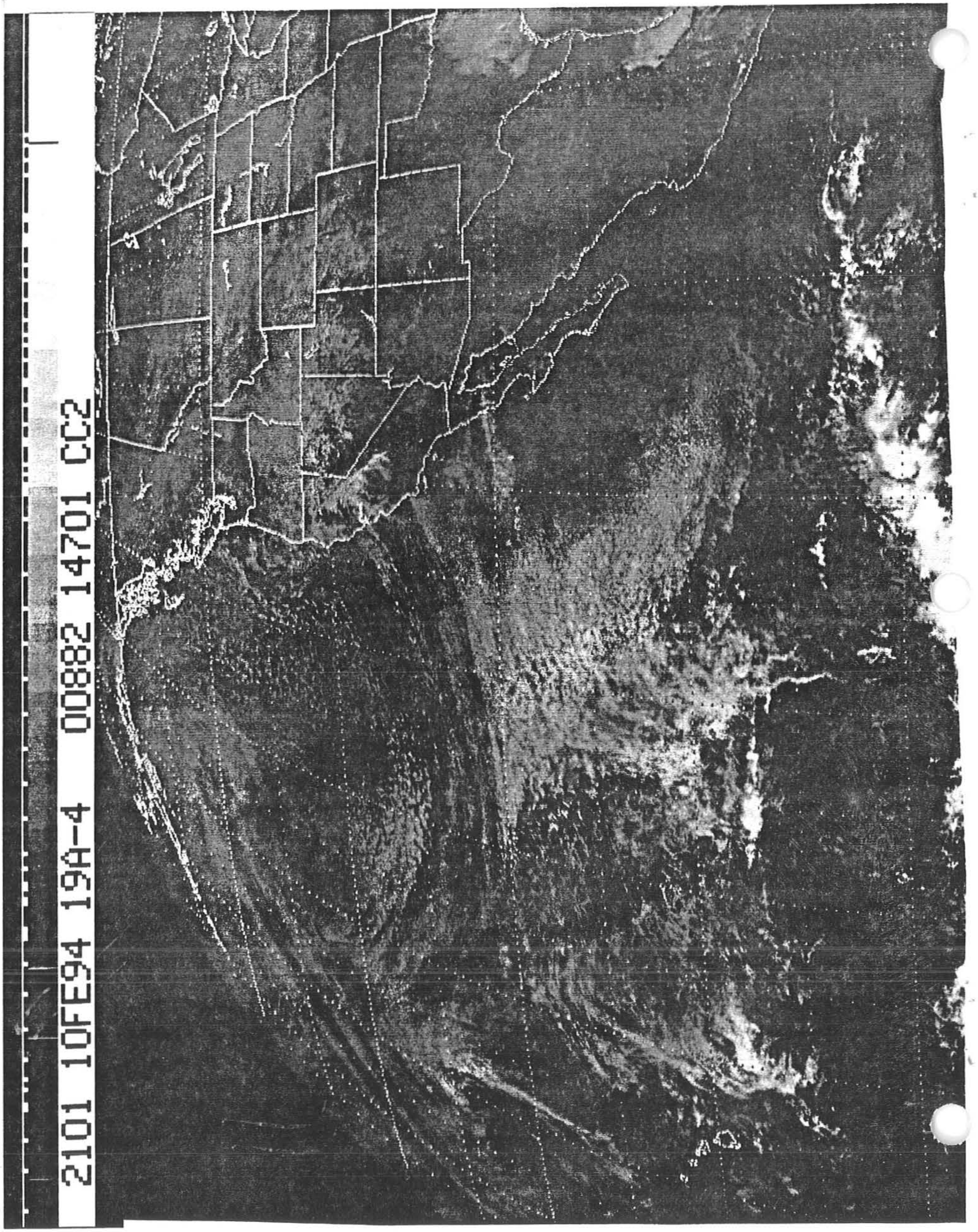


Figure 24 Visible satellite imagery for 2100 UTC 10 February 1994.

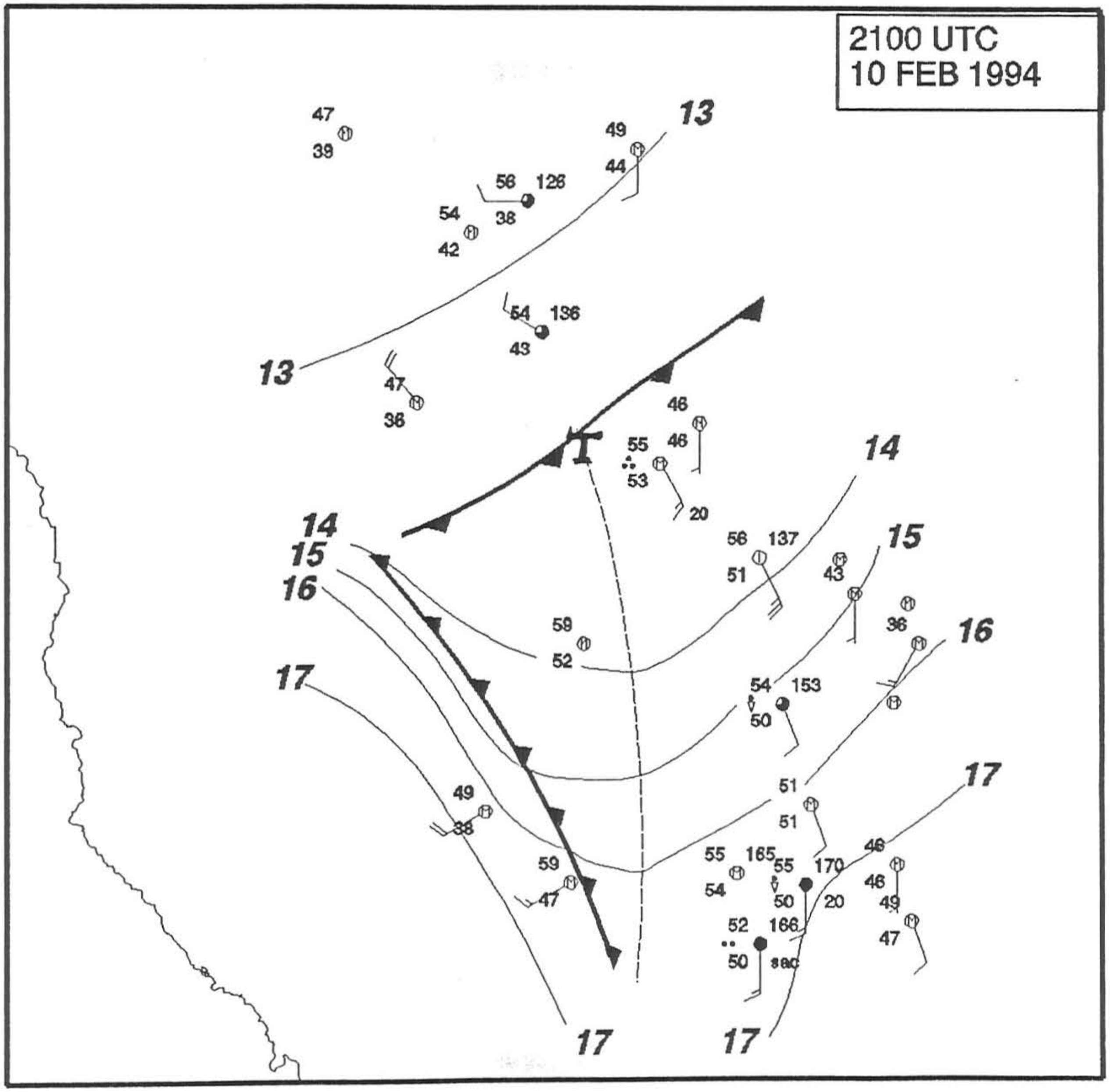


Figure 25 Same as Figure 21 except 2100 UTC 10 February 1994. Triple point indicated by T.

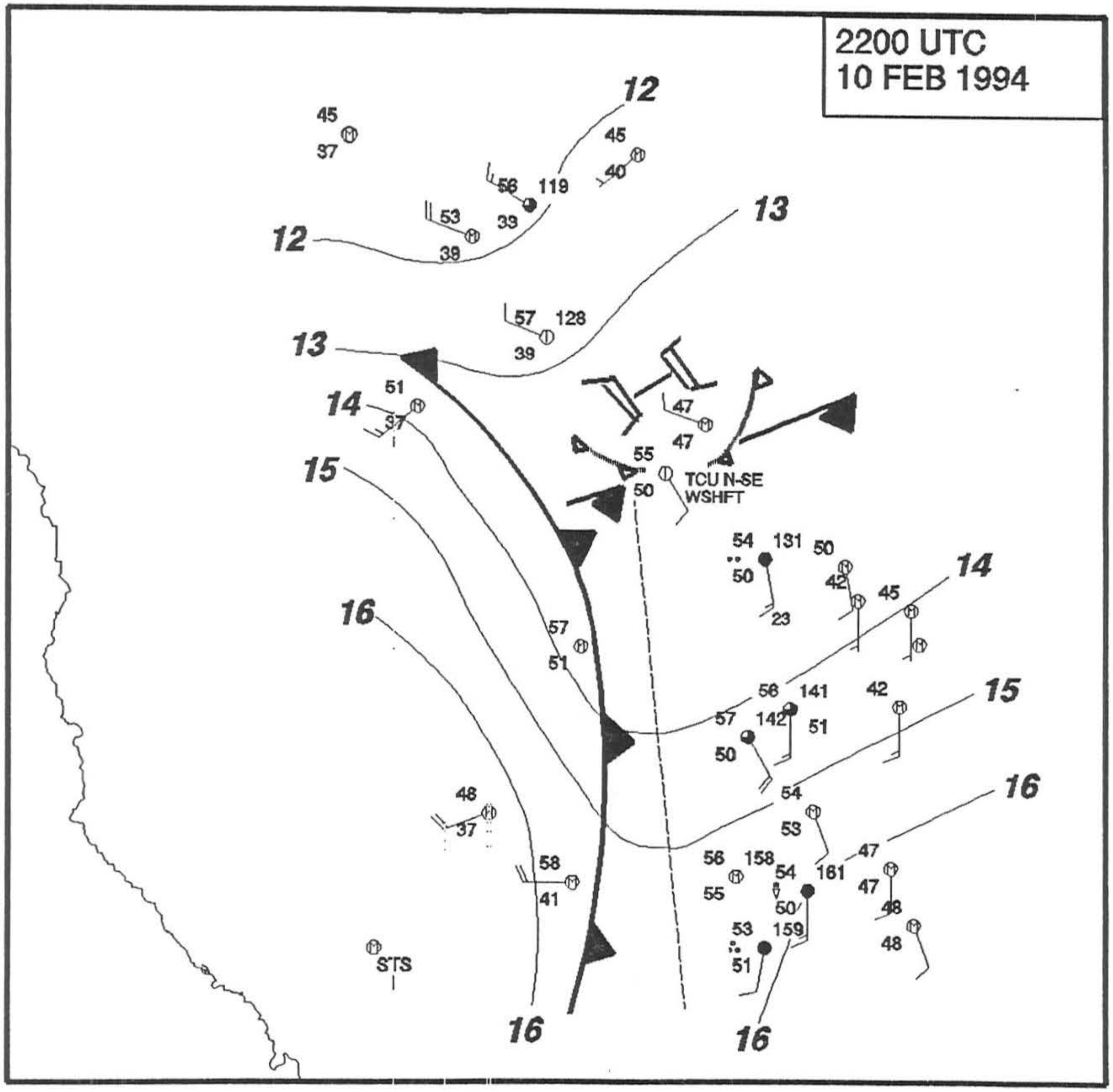


Figure 26 Same as Figure 21 except 2200 UTC 10 February 1994. Mesohigh is represented by H and outflow boundary by hatched frontal boundary.

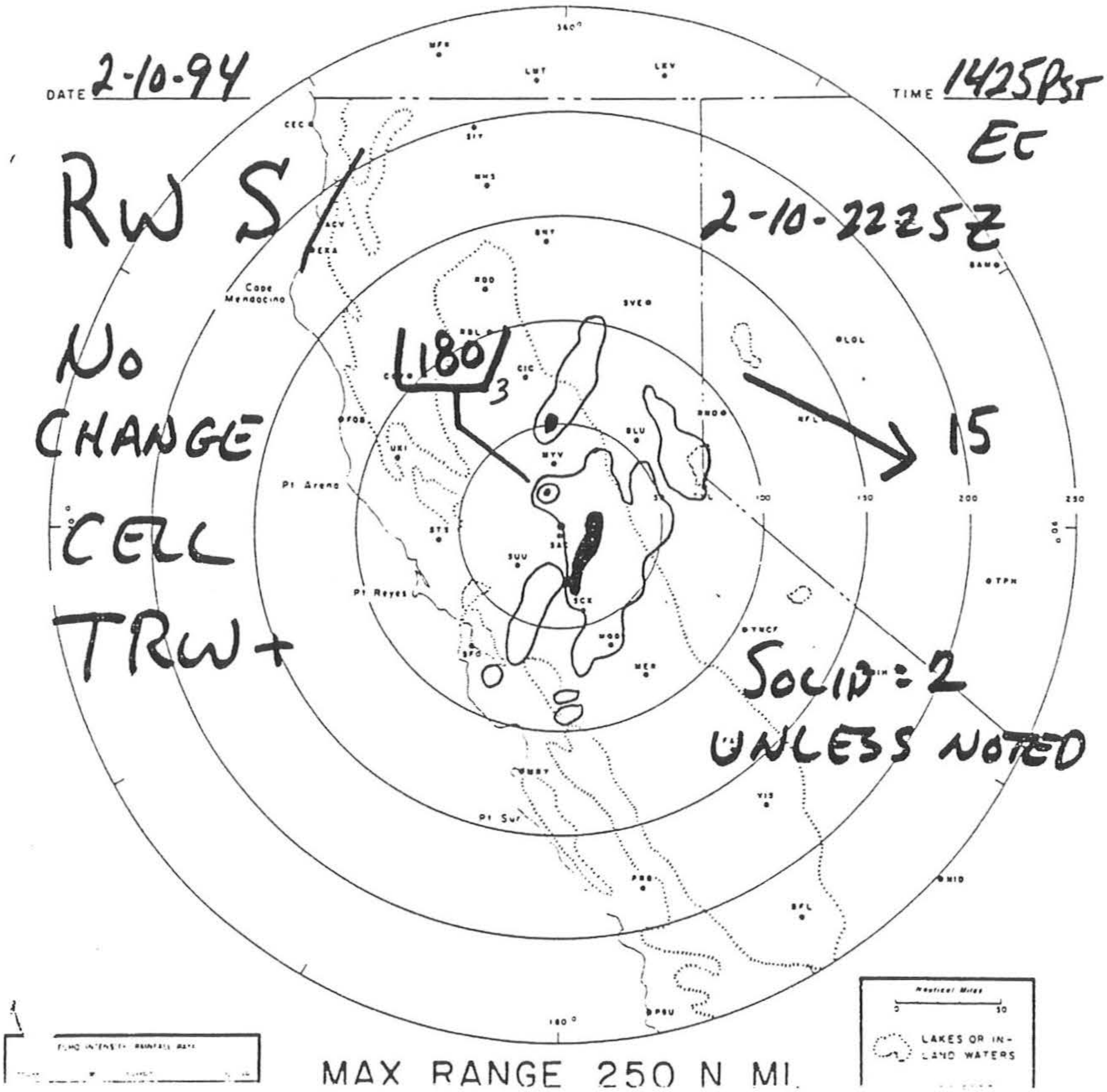


Figure 27 Sacramento WSR-57 radar overlay of precipitation echoes from 2225 UTC 10 February 1994.

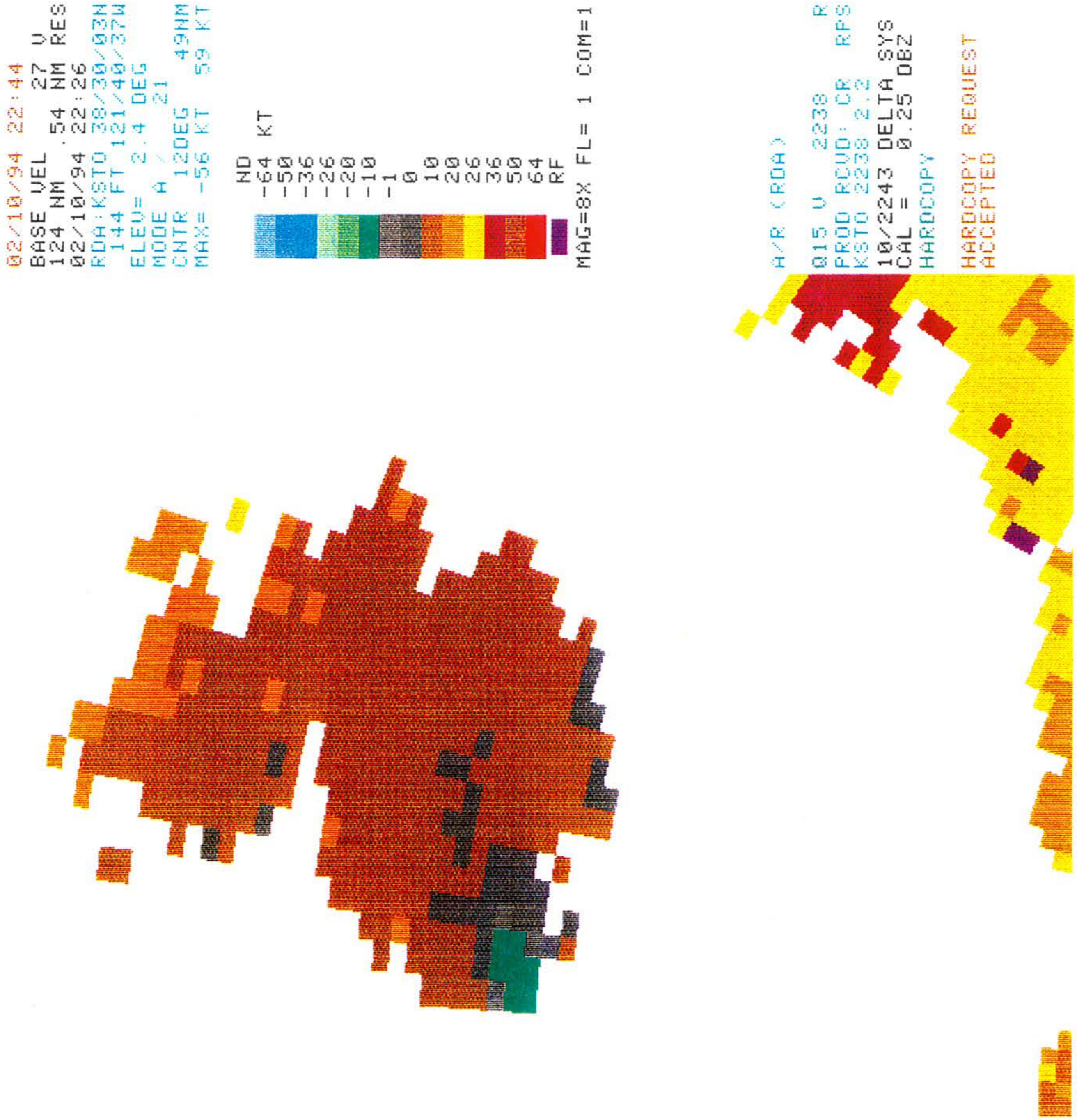


Figure 28 WSR-88D 2.4° base velocity scan at 2244 UTC indicating storm top divergence. Green represents movement towards the radar and brown represents movement away.

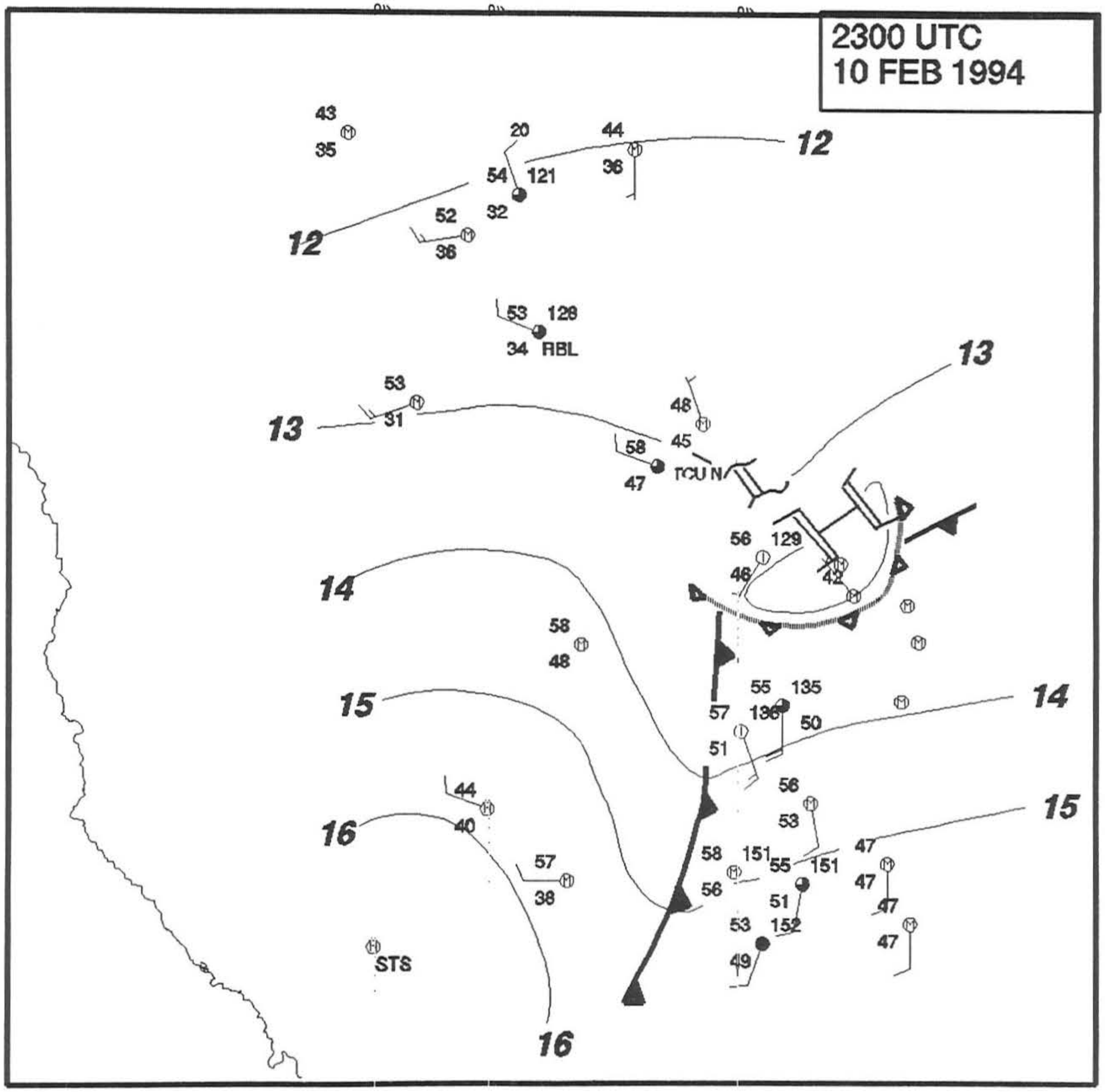
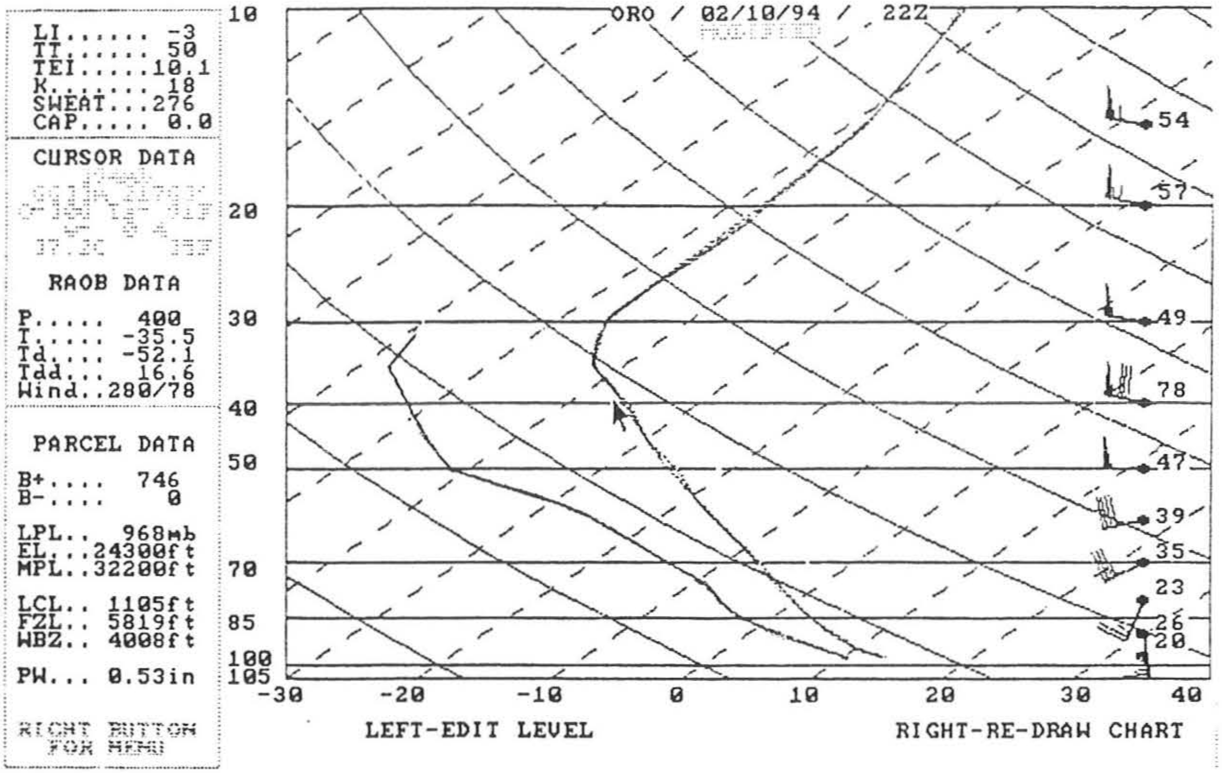
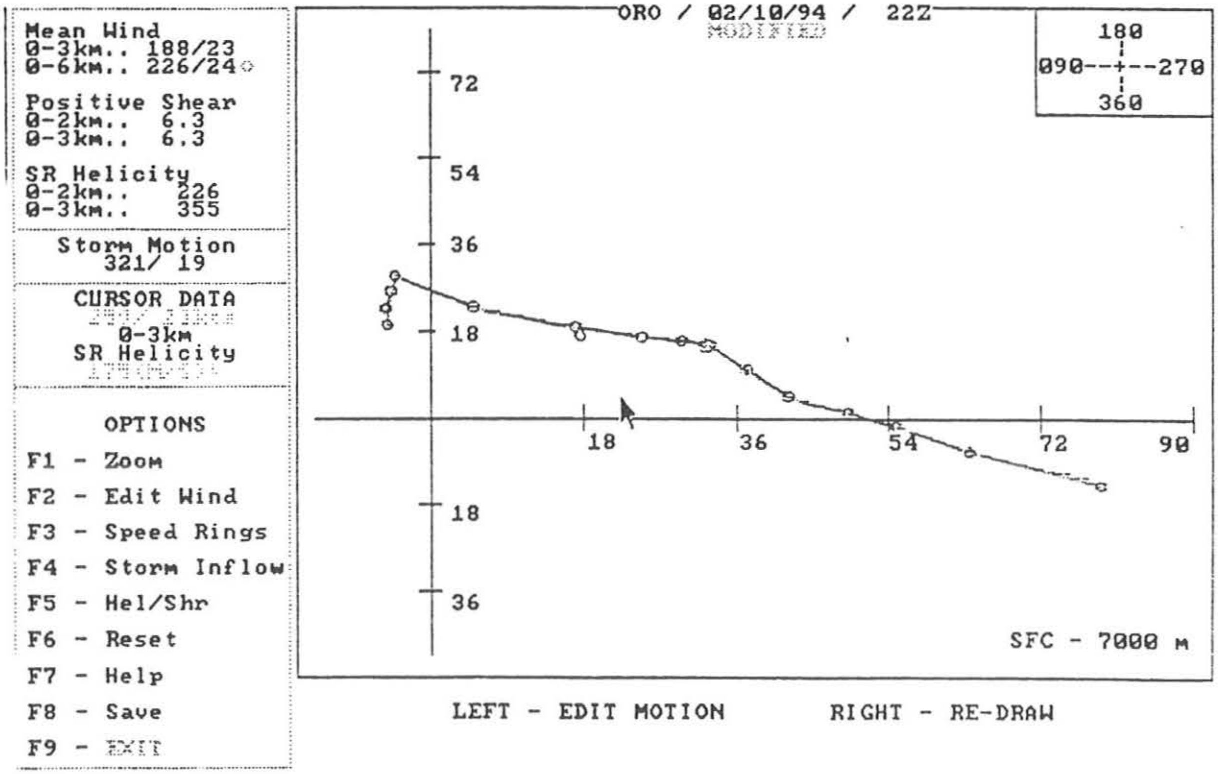


Figure 29 Same as Figure 26 except 2300 UTC 10 February 1994.



```
LI...... -3
TT...... 50
TEI.....10.1
K....... 18
SWEAT...276
CAP..... 0.0

CURSOR DATA

RAOB DATA
P..... 400
T..... -35.5
Td.... -52.1
Tdd... 16.6
Wind..280/78

PARCEL DATA
B+.... 746
B-.... 0

LPL.. 968mb
EL...24300ft
MPL..32200ft

LCL.. 1105ft
FZL.. 5819ft
WBZ.. 4008ft

PW... 0.53in

RIGHT BUTTON
FOR MENU
```

Figure 30 Modified sounding for Oroville for 2200 UTC 10 February 1994.



```
Mean Wind
0-3km.. 188/23
0-6km.. 226/24

Positive Shear
0-2km.. 6.3
0-3km.. 6.3

SR Helicity
0-2km..  226
0-3km..  355

Storm Motion
321/ 19

CURSOR DATA
0-3km
SR Helicity
```

Figure 31 Modified hodograph for Oroville for 2200 UTC 10 February 1994.

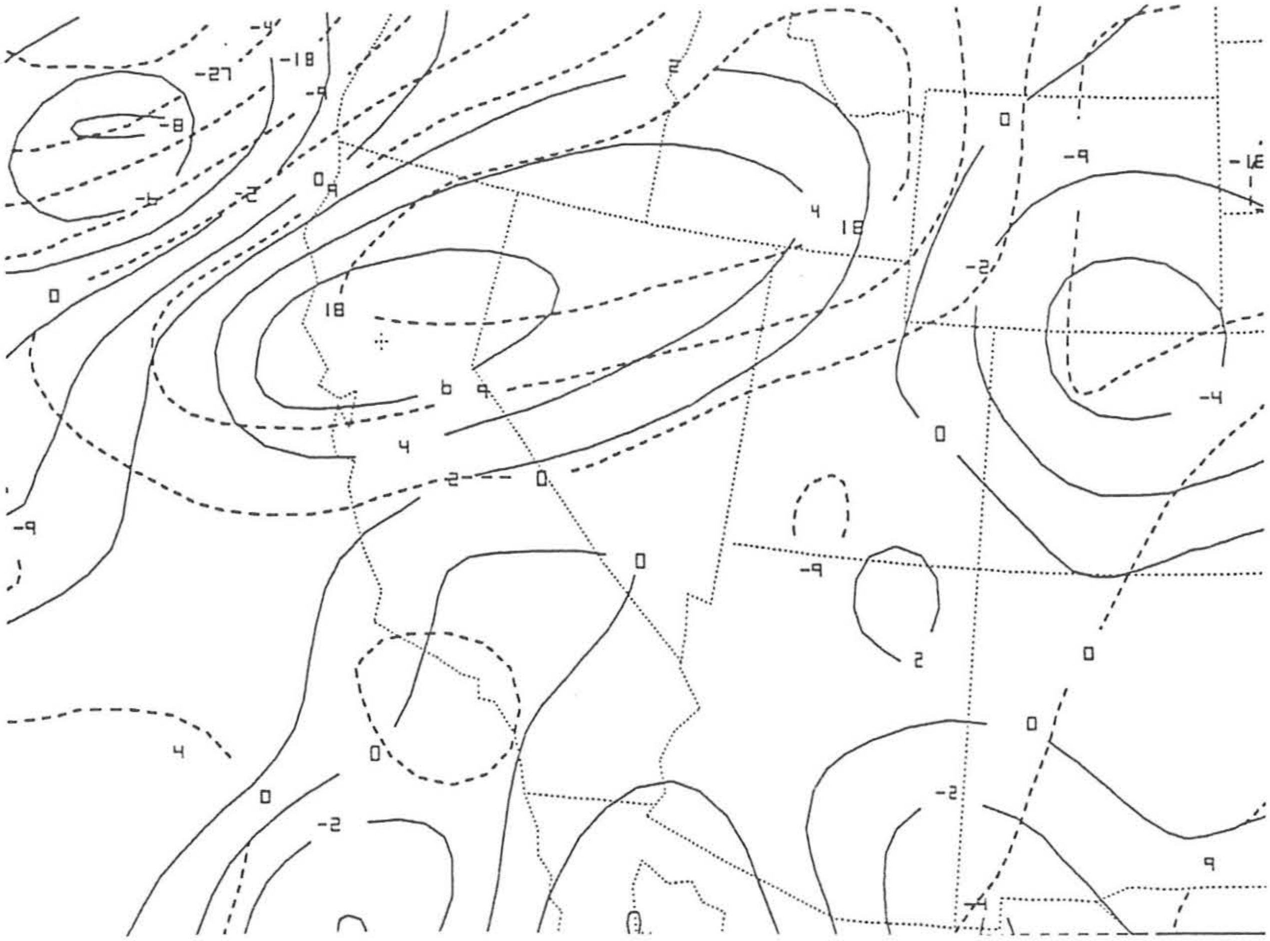


Figure 32 Warm air advection contoured every 1x10^{-4} °C s^{-1} (dashed) with cyclonic vorticity advection contoured every 1x10^{-10} s^{-2} (solid) at 250 mb valid 0000 UTC 11 February 1994.

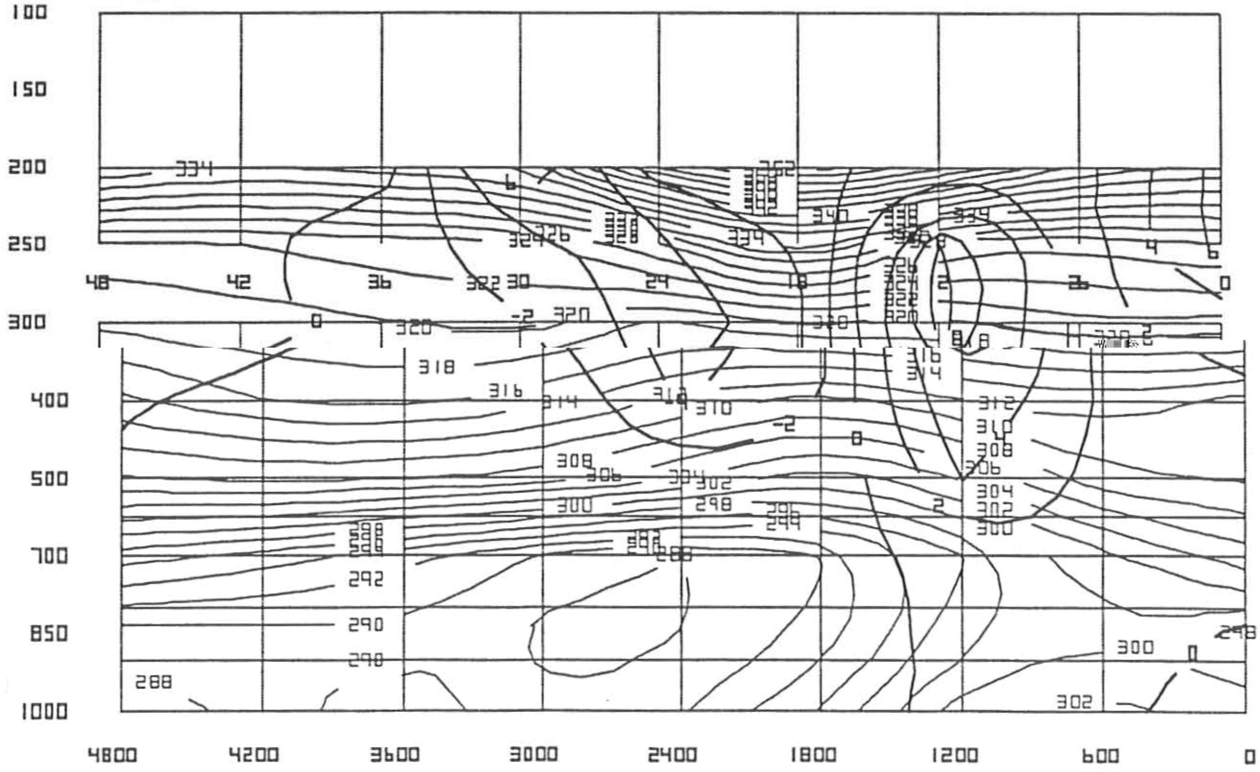


Figure 33 Time-height cross-section at 40°N 122°W with equivalent potential temperature (K) (solid) and vorticity advection (dark solid). Note strong cyclonic vorticity advection contoured every 1x10^{-10} s^{-2} ahead of the tropopause fold.

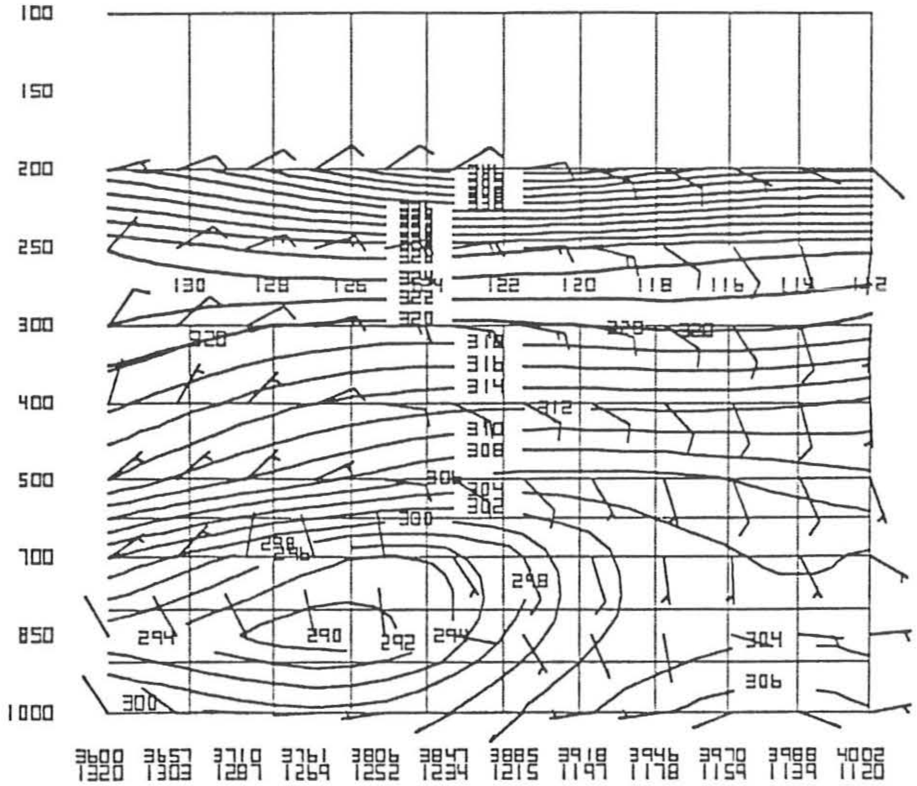
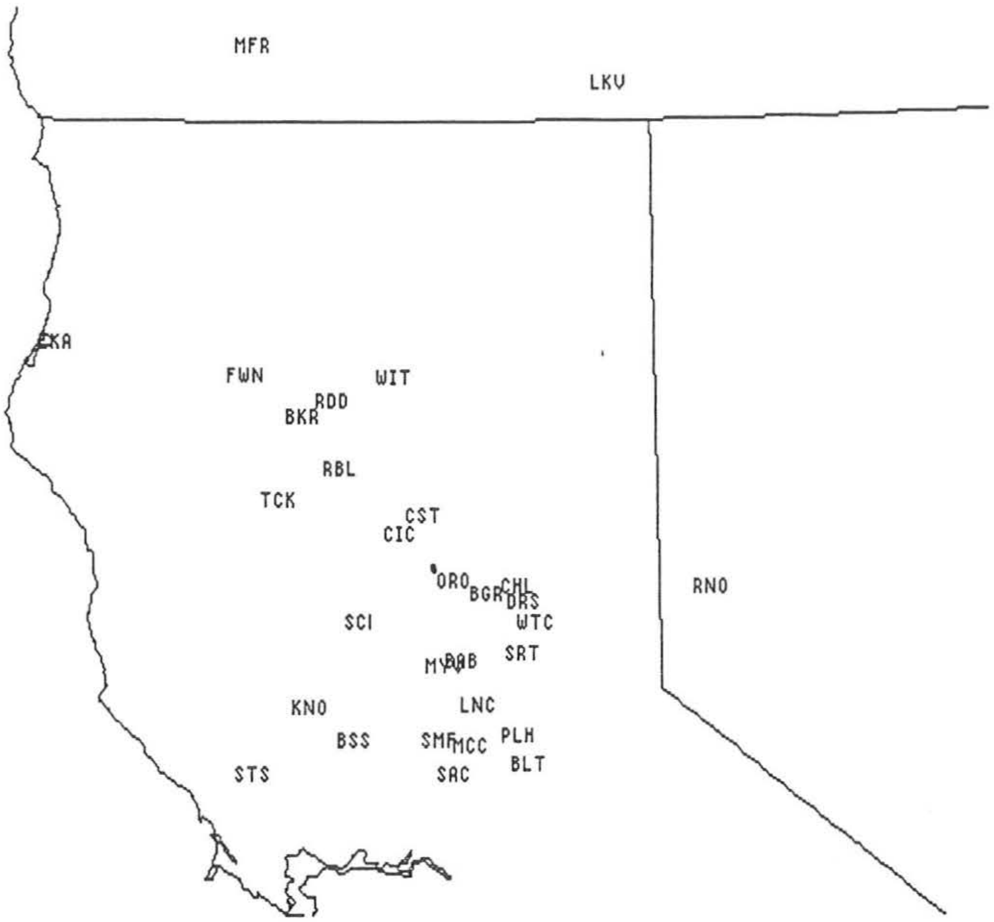


Figure 34 Cross-section from 36° N 132° W to 40° N 112° W with ageostropic circulations (barbs) and equivalent potential temperature (K) (solid) valid 0000 UTC 11 February 1994.



Appendix A Map of northern California with three-letter identifiers. Oroville is ORO.

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