NOAA Technical Memorandum NWS WR-219

A CASE STUDY OF THE OPERATIONAL USEFULNESS OF THE SHARP WORKSTATION IN FORECASTING A MESOCYCLONE-INDUCED COLD SECTOR TORNADO EVENT IN CALIFORNIA

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A Case Study of the Operational Usefulness of the SHARP Workstation in Forecasting a Mesocyclone-induced Cold Sector Tornado Event in California

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ABSTRACT

An illustration of the operational usefulness of the SHARP Workstation in providing supplementary guidance to forecasters in a situation in which two tornadoes occurred in California's Sacramento Valley is presented. Use of the SHARP Workstation in analyzing the initial hodograph and in producing a bogus afternoon sounding and hodograph for the Sacramento Valley indicated that buoyancy and shear were in the correct range for moderate to strong mesocyclone-induced tornadoes. Conventional wisdom would have suggested that weak funnel clouds and small hail were the chief threats in this weather pattern. However, forecasters, aware of the role of shear in inducing storm rotation and of the potential for this weather pattern to be associated with favorable buoyancy and shear parameters in certain regions of California, would have been alert to the possibility of damaging and potentially life-threatening tornadoes.

I. INTRODUCTION

Between 2200 and 2345 UTC 17 December 1992, two tornadoes occurred in the southern Sacramento Valley near Oroville (Butte County) and another at the town of Loma Rica near Marysville (Yuba County), California (see Fig. 1 for locations). Damage surveys have established that both tornadoes were of moderate intensity (F1) (personal communication, Mr. John Quadros, Warning Preparedness Meteorologist, National Weather Service Forecast Office (WSFO), Redwood City). Although the Marysville tornado occurred in a relatively unpopulated area, the Oroville tornado passed near the center of town, causing significant property damage (personal communication, Mr. Chris Fontana, Meteorologist-in-Charge (MIC), Weather Service Office (WSO) Redding).

An earlier tornado, rated as F0, in the Oakland-San Leandro area (1725 UTC) also had been verified. Other funnel clouds were observed in the Sacramento Valley and in the San Francisco Bay

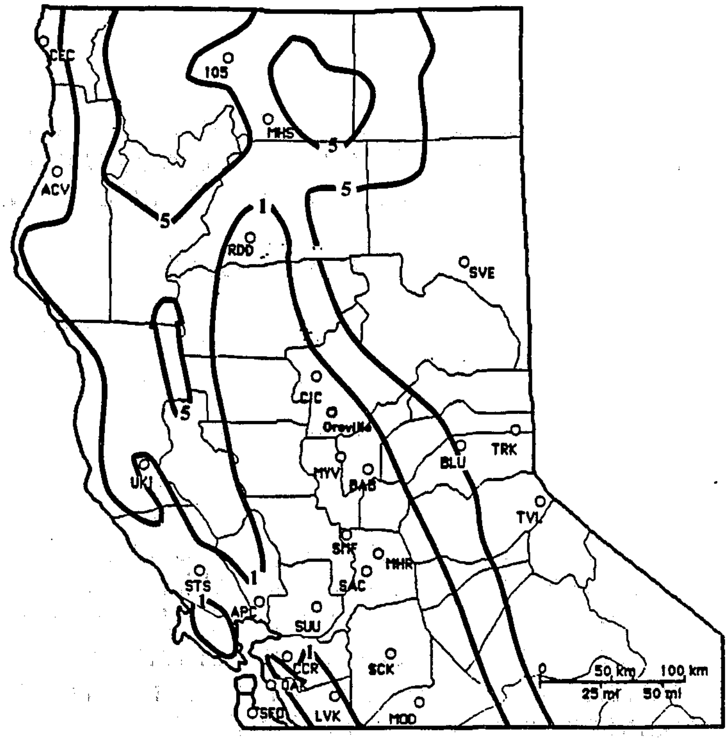

Figure 1. Station location map. Contour labeling: 1 corresponds to 1000 ft (315 m) and 5 corresponds to 5000 ft (1575 m). MYV is designator for Marysville.

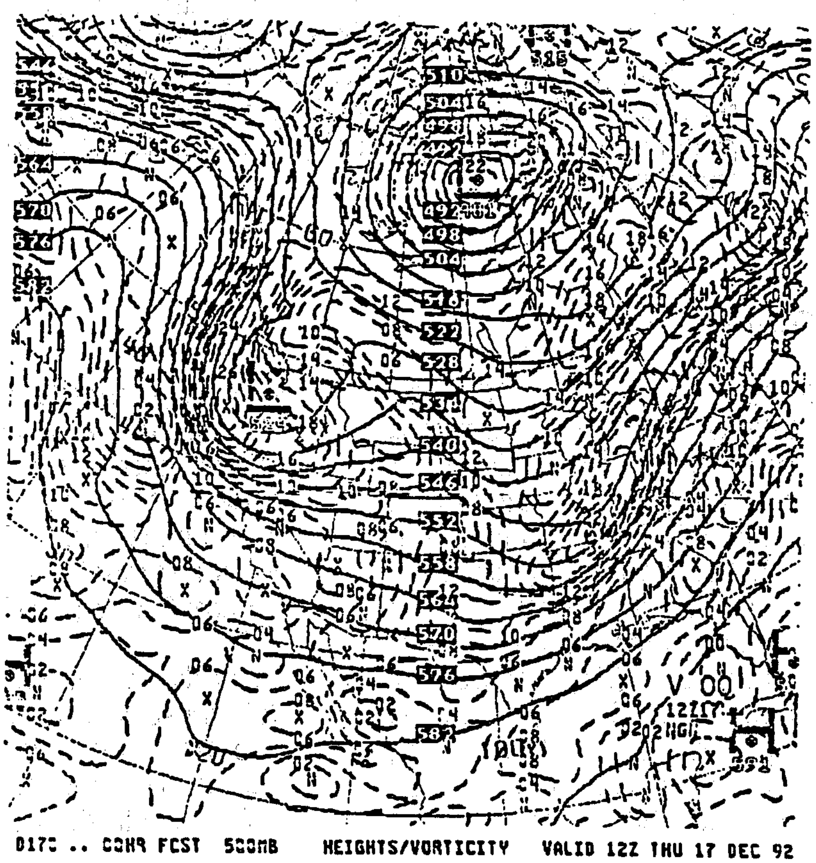

Figure 2. NGM analysis of 500 mb heights (dam) and absolute vorticity ($10^{-5}s^{-1}$) for 1200 UTC 17 December 1992..

region on this day. These tornadoes and funnel clouds occurred in the midst of a month-long period in which at least twelve tornadoes took place in northern and central California (personal communication, Mr. Jack Hales, Lead Forecaster, National Severe Storms Forecast Center (NSSFC) Kansas City, Missouri).

The primary purpose of this report is to illustrate the extent to which subsidiary guidance, available to operational forecasters, would have provided invaluable "forewarning" of the tornadic activity in a weather pattern in which conventional wisdom dictated that weak funnel clouds and small hail were the chief "severe" weather threats. "Subsidiary guidance" is defined here as personal computer or AFOS-resident programs which augment the usual synoptic-scale guidance and thermodynamic diagnoses available to operational meteorologists. The reader is referred to Doswell (1987) for a thorough overview of the synoptic and thermodynamic controls on convective events and Doswell (1992) for a review of the role of interactive workstations in the modernized National Weather Service.

The weather pattern which occurred on 17 December 1992 had been identified in two previous published studies (Monteverdi et al. 1988; Braun and Monteverdi, 1991) as one associated with strong to severe thunderstorms producing funnel clouds and occasional tornadoes in northern and central California. Those studies illustrated the usefulness of quasi-geostrophic diagnostics (e.g., those produced by the "ua-program" developed by Foster (1988)) in highlighting that portion of California most likely to experience dynamics contributing to strong convection.

The importance of destabilization and wind shear in the development of California storms with supercellular characteristics was discussed by Braun and Monteverdi (1991). While the pattern recognition alluded to above would have already directed the attention of the forecaster to the probability of strong thunderstorms over the general area, the present preliminary study indicates that analyses of the 1200 UTC Oakland (OAK) sounding, produced interactively by the **S**kew-T/**H**odograph **A**nalysis and **R**esearch **P**rograms (SHARP) Workstation (Hart and Korotky, 1991) and the forecaster, would have provided "quantitative" evidence that the wind shear was favorable for strong storm rotation. In this case, the usefulness of the SHARP Workstation as a "nowcasting" tool is verified.

This report provides a preliminary assessment of the meteorological controls on the Butte/Yuba County events. A more complete case study of these and other northern and central California tornadoes in December 1992 will be submitted as a possible separate Technical Attachment or Memorandum.

II. FORECASTER AWARENESS OF ROTATIONAL POTENTIAL OF CALIFORNIA THUNDERSTORMS

A. Measures of Buoyancy

Operational forecasters have been utilizing various indices evaluated from sounding data to judge thunderstorm potential. As observed by Doswell (1985) and alluded to by Braun and Monteverdi (1991), unquestioning acceptance of the thunderstorm probability and severity thresholds defined on the bases of these indices without the application of sound meteorological reasoning can lead the forecaster to bad judgments. This is especially true in the case of California cold sector convective situations which are characterized by quite different thermodynamic characteristics than those observed in the Great Plains or Midwest severe thunderstorm patterns for which such thresholds were defined.

One such index, often misused in California, is the 500 mb Lifted Index (LI), which is essentially a measure of the buoyancy as a function of the temperature deficit (excess) of the environment at 500 mb compared to that of a parcel lifted to 500 mb. In convective situations east of California, the 500 mb LI (or, even, that at 300 mb) often qualitatively "describes" the buoyancy at the level at which the convectively-driven vertical acceleration is maximum. As pointed out in Monteverdi et al. (1988) and Braun and Monteverdi (1991), a LI based upon 700 mb temperature information is more appropriate for convective situations typical of the cool season in California. Such indices may be strongly negative (unstable) while those at 500 mb are positive, possibly leading a forecaster to underestimate convective potential.

The 500 mb LI, as a measure of potential instability in California convective situations, is a very poor quantitative estimator of total buoyancy, since the index computed for other levels often has very little relation to that computed at 500 mb. On the other hand, the Convective Available Potential Energy (CAPE), or Positive Buoyancy (B+), provides a measure of instability which is vertically integrated and not biased by the arbitrary level at which the calculation is performed. CAPE can be qualitatively estimated from an examination of the "positive" area on a sounding plotted on a Skew-T/Log P diagram. Moreover, graphics available on AFOS and output from the SHARP Workstation programs can provide the forecaster with a quantitative estimate of CAPE.

Finally, **a common pitfall for forecasters is to estimate rotational potential based upon any of the measures of sounding instability** mentioned above. As pointed out by Weisman and Klemp (1982), Lazarus and Droegemeier (1990), and many others, rotational potential for a storm depends upon a favorable shear profile superimposed on an unstable environment. Marginal instabilities, as estimated by CAPE, may be associated with strong to severe tornadoes if winds veer with height and, more importantly, if the 0-3 km shear vector veers with height. Thus, as observed in the documentation for the SHARP Workstation, tornadoes have been observed for B+ values as low as 200 J kg^{-1} with appropriate shear values. Thus, while estimations of the potential for large hail may be based solely upon some sort of LI or B+, **it is not possible to judge the rotational potential of a storm without consideration of the storm-relative shear environment.**

B. Measures of Favorable Shear

The question arises of how an operational meteorologist is to judge the degree to which the shear environment is "favorable" for the development of rotating thunderstorms. It is not something quickly or easily calculated from a glance at the mandatory and significant level winds plotted on the right of the sounding on AFOS. However, with practice, forecasters can become adept at estimating "rotation potential" from a visual examination of the observed or modified hodograph.

Many studies have shown that rotational potential of thunderstorms is a function of the degree to which horizontal vorticity may be tilted into the vertical by the updraft of the convective cell. For example, a low-level wind at nearly right angles to the wind aloft will be characterized by strong shear vorticity, which may be converted to vertical vorticity as this horizontal air stream is tilted upward in the updraft core. This vorticity (which you cannot "see") may be converted to mesoscale circulation (which you can "see") if the thunderstorm is moving in a manner favorable for the generation of rotation (discussed below).

Weisman and Klemp (1982), and many others, have shown that a low-level wind veering and increasing with height is a necessary but not a sufficient characteristic of the hodograph in situations in which rotating thunderstorms develop. The low-level wind, particularly in the layer between 0 and 2 to 3 km, must vary in such a manner that the hodograph appears "curved" in a clockwise sense. Only for situations characterized by curved hodographs is the production of horizontal vorticity maximized. Once generated, such vorticity may be converted to storm-relative rotation in the manner conceptually described above. A quantitative measure of this storm-relative rotation is the so-called storm-relative helicity (s-r helicity).

Davies-Jones et al. (1990) have shown that s-r helicity values of around 150 m^2s^2 are often found for thunderstorms with forming mesocyclones. (Such storms, then, are classified as "rotating thunderstorms"; i.e., supercells.) Thus, while ratios of buoyancy to shear (e.g., the Bulk Richardson Number (BRN)) might suggest rotation in thunderstorms, **storms will show precursor rotation to tornado development only in those cases in which this ratio is in the proper range (discussed below) AND s-r helicity indicates that the shear is favorable for rotation.** (It is important to note s-r helicity values only give an indication of tornado potential. Once a storm begins to rotate (i.e., becomes supercellular), the forward and rear flank downdrafts then interact to contribute to tornado formation.)

C. Judging Buoyancy and Shear in the Central Valley from Oakland Sounding

It is well known to operational forecasters that the convective risk in the Central Valley of California is not often directly indicated by an evaluation of the OAK sounding. The same thing may be true for estimating thunderstorm risk for other large valleys in the Coast Range, particularly those which have a topographic configuration similar to that of the Sacramento Valley (e.g., the so-called "Santa Rosa Plain"). The SHARP Workstation programs allow the forecaster to quickly modify the 1200 UTC sounding for observed low-level conditions in the valley or to alter temperature and wind information to estimate changes which might occur synoptically and subsynoptically by the time of peak convective risk. Since the Sacramento Valley (and, to a lesser extent, the San Joaquin Valley) have been identified as regions particularly prone to tornado occurrence (e.g., Hales, 1985 and Braun and Monteverdi, 1991), it is especially important for forecasters to be cognizant of those mesoscale conditions which might enhance the threat for severe weather in the Central Valley when pattern recognition has already indicated a likelihood of strong convection region-wide.

Monteverdi et al. (1988) and Braun and Monteverdi (1991) document two cases in which a weather pattern, similar to the one which occurred on 17 December 1992 (discussed below), was associated with a number of tornadoes (including an F2) and funnel clouds in the Sacramento and San Joaquin Valleys. This pattern is associated with an enhanced risk of small-to-moderate hail and cold sector funnels across northern and central California. In the case of the 24 September 1986 tornadoes near Redding and Chico (documented in Braun and Monteverdi, 1991), manual alterations of the OAK sounding and hodograph produced buoyancy and wind shear profiles for the valley well within the ranges expected for right-moving, rotating (supercell) thunderstorms and with mesocyclone-related tornadoes. The SHARP Workstation programs allow the forecaster familiar with the operation of the software to perform these alterations in approximately five to ten minutes.

D. The Role of Pattern Recognition in Estimating Rotation Potential

It is important for the forecaster to recognize those synoptic patterns associated with severe weather in the Central Valley. There are dangers, however, in reliance on mere pattern recognition to direct the forecaster's attention to the severe weather threat. Rotating thunderstorms can occur in any situation in which buoyancy and shear are in favorable ranges. While certain patterns (as is the case of the one described in this study) are most prone to be characterized by the proper buoyancy to shear ratios, California tornadoes and severe thunderstorms have been observed in other synoptic configurations (e.g., Reed and Blier, 1986 and Hales, 1985). **Forecasters who understand the cooperative role of buoyancy and shear will be able to anticipate tornado potential when any pattern produces favorable wind and instability profiles.**

Moreover, mere reliance on pattern recognition cannot provide the forecaster with the guidance necessary to judge where the mesoscale focus of severe convection is likely to occur. Outmoded notions in California, that once this pattern occurs, tornadic convection "is random" and cannot be anticipated, must be discarded. There is ample evidence in the literature that this is as much NOT the case in California as it is NOT the case in portions of the country where operational meteorologists are accustomed to evaluating severe weather potential.

There is a pervasive attitude among operational meteorologists that since F0 and F1 tornadoes are classed as "weak", they do not compare with the type of tornadoes that forecasters must anticipate east of the Rockies. Such reasoning often leads to a minimization of the risk associated with such tornadoes. The fact is that most tornado events in Kansas, Oklahoma, and Texas are in the F0 to F1 range, with most Tornado Warnings issued for F0, F1, and F2 events. Moderate (F1) and even strong (F2) tornadoes occur with some frequency in California (e.g., Hales, 1985 and Braun and Monteverdi, 1991). Furthermore, even a weak (F0) tornado can cause significant damage and hazard to life. **The forecaster must be aware that despite the lower frequencies of tornado events in California (compared to those observed in the Great Plains), similar risks are associated with their occurrence.**

III. CASE STUDY: SOUTHERN SACRAMENTO VALLEY TORNADOES OF DECEMBER 17, 1992

A. Pattern Recognition

1. Synoptic-scale Controls

The synoptic pattern which occurred on December 17, 1992 is illustrated in Fig. 2, the NGM analysis of 500 mb heights/absolute vorticity for 1200 UTC. This pattern was similar to that described in Monteverdi et al. (1988), associated with funnel clouds and large hail in the San Joaquin Valley on 21 March 1987, and in Braun and Monteverdi (1991), associated with a number of tornadoes, including an F2, in the Sacramento Valley on 24 September 1986. In each of these three cases, cyclonic vorticity advection associated with an advancing jet streak seemed to play an important role in diagnosing a vertical motion field which enhanced thunderstorm development and contributed to destabilization. For the present case, the jet streak was evident (Fig. 2) by the vorticity dipole centered at 43°N, 130°W.

Satellite imagery (Fig. 3) indicated open cellular cumulus with greatest enhancement under the left front quadrant of the advancing jet streak. This pattern was quite similar to the schematic "type" associated with strong to severe convection in northern and central California, as illustrated by Fig. 4. Armed with this knowledge, a forecaster would certainly anticipate thunderstorm activity in California which might approach severe limits and which probably would be associated with funnel clouds.

2. Sounding

The 1200 UTC 17 December 1992 OAK sounding is given in Fig. 5a. A glance at the sounding indicates fairly stable initial conditions at OAK. In fact, the initial LI was +6, indicative of a stable atmosphere. Moreover, since heating effects are minimized during the winter season, it could be expected that very little destabilization due to diurnal effects would occur and that the low-level characteristics of the sounding during the day, even in the Sacramento Valley, would remain unaltered.

The fact that strong cold advection in the middle and lower troposphere, in association with the trough (Fig. 2) advancing southeastward, would destabilize the sounding profoundly can be considered part of the "pattern recognition" portion of the forecasting decision. Figure 5b, the 0000 UTC 18 December 1992 OAK sounding, indicates that such destabilization did occur and was associated with between a 5°C to a 10°C cooling for every level from the top of the mixed layer at (920 mb) to about the 550 mb. It is interesting to note that a similar initial sounding configuration and destabilization occurred in association with cold advection during the 24 September 1986 tornado case documented for the same general area (Braun and Monteverdi, 1991).

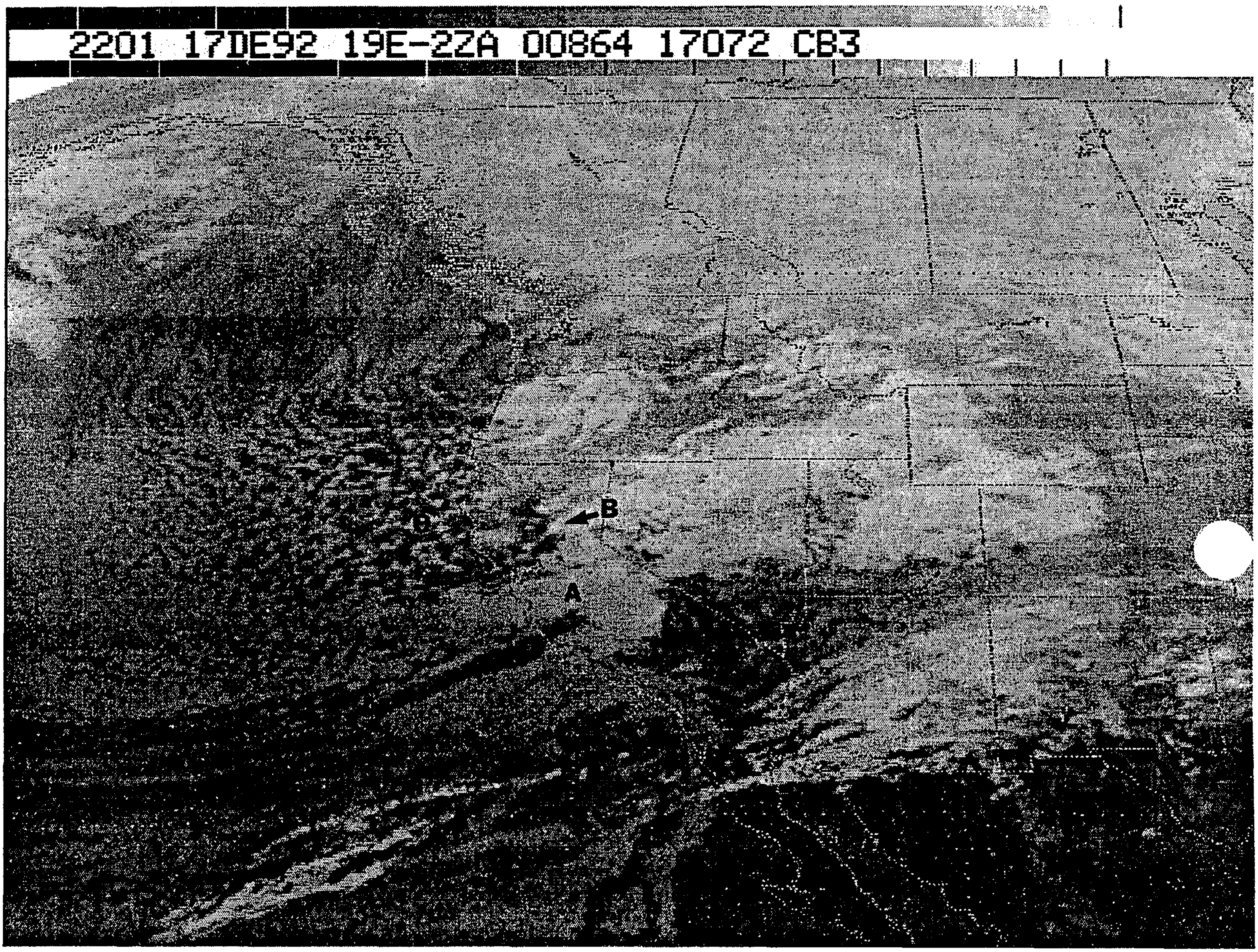

Figure 3. Infrared satellite image for 2201 UTC (1401 LST) 17 December 1992. "O" indicates enhanced open cellular cumulus. Letters "A" and "B" refer to cloud features discussed in the text.

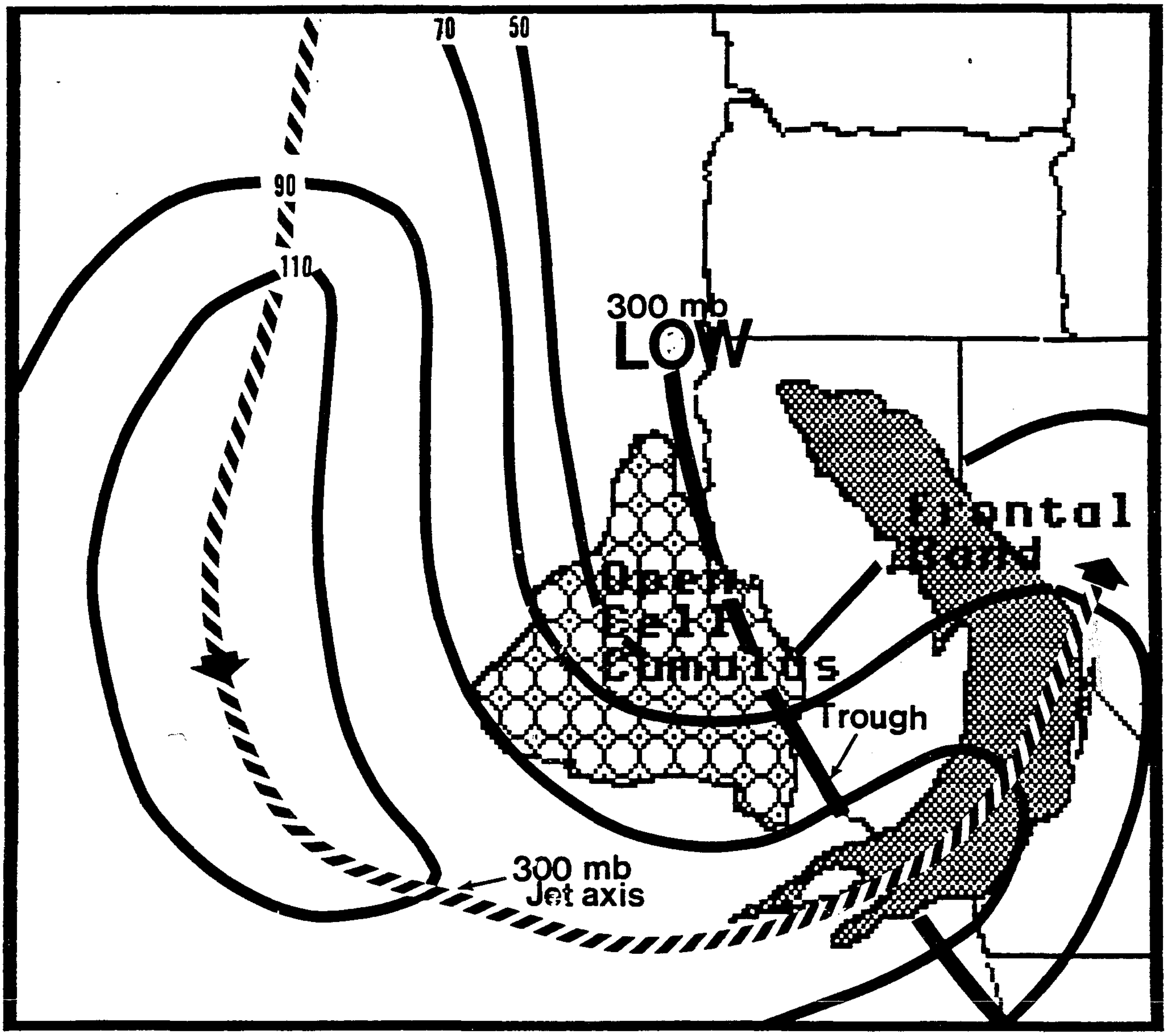

Figure 4. Schematic diagram showing location of features for synoptic "type" often associated with intense "cold sector" thunderstorms in California (after Monteverdi et. al. 1988).

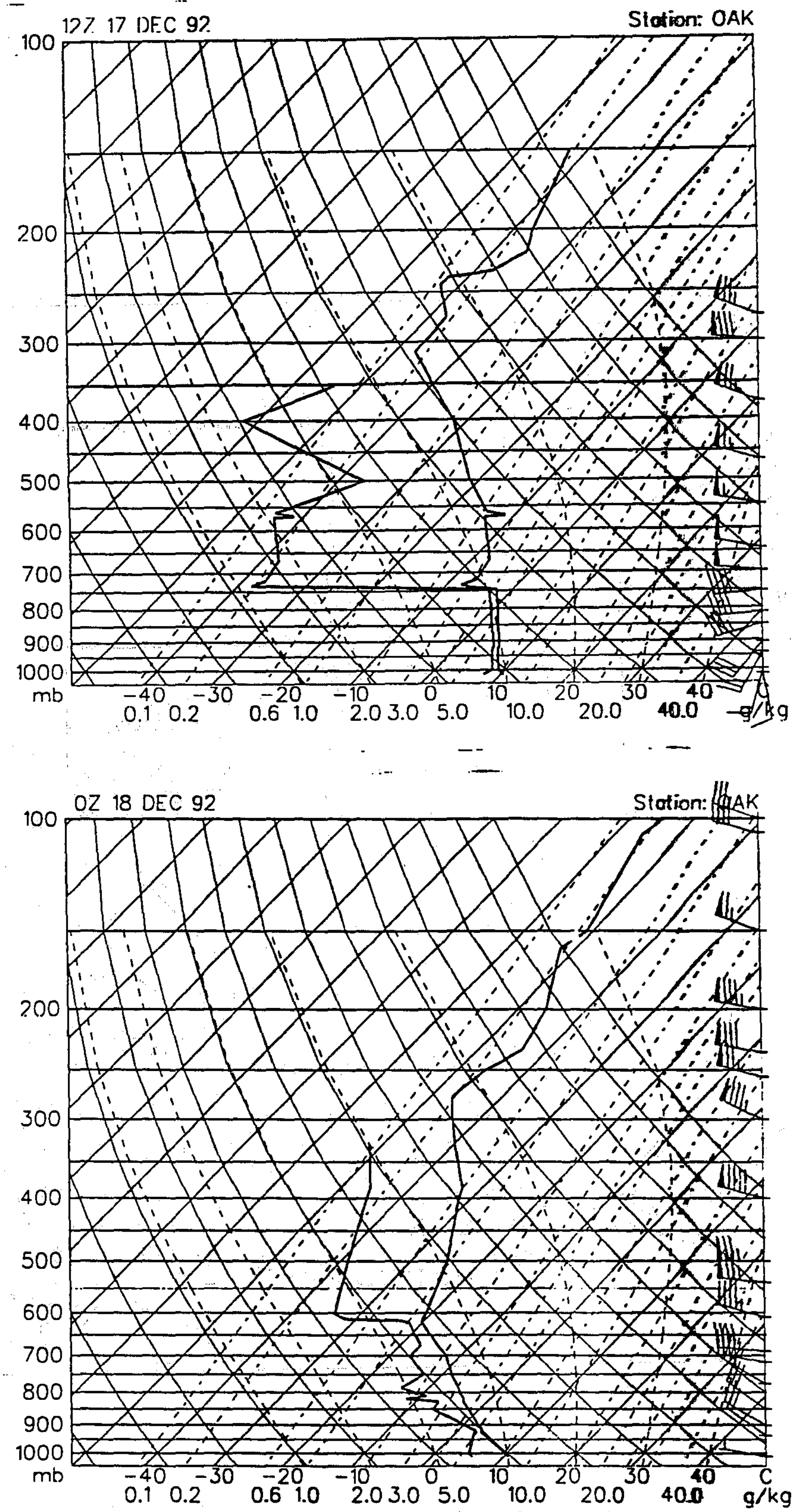

Figure 5. OAK sounding and plotted mandatory and significant level winds.
(a) 1200 UTC (0400 LST) 17 December 1992.
(b) 0000 UTC (1600 LST) 18 December 1992.

3. Wind Shear Profile

The mandatory and significant level winds, plotted on the right side of Fig. 5a, show a wind veering and increasing in strength with height. As described above, such a wind profile QUALITATIVELY may indicate the proper shear for thunderstorm rotation, if the hodograph of this wind information is curved in a clockwise sense.

The forecaster would first need to decide if the favorable wind profile was likely to persist until the cold advection and vertical motion fields described above would destabilize the atmosphere enough for thunderstorms to form. A consideration of the probable destabilization of 1200 UTC sounding and the favorable wind shear combined with recognition of the synoptic pattern would have already directed the forecaster's attention to the risk of funnel clouds and strong thunderstorms in the forecast area.

Pattern recognition might also lead the forecaster to seek a focus for the threat in the Sacramento Valley. As described in Braun and Monteverdi (1991), this type of synoptic pattern is often associated with mesoscale, perhaps leeside, troughs situated in the Central Valley. In such a pattern, low-level winds at OAK will shift to northwesterly but will remain southeasterly in the Central Valley. When this occurs, the OAK hodograph will indicate unfavorable shear profile for rotation (see winds plotted on right of Fig. 5b) even when the shear profile in the Central Valley continues to be favorable for rotating thunderstorms. When such a shear profile in the Central Valley is combined with other destabilizing influences, possible development of supercell thunderstorms should be anticipated.

B. Interactive Analysis of Sounding and Hodograph by SHARP Workstation and Forecaster

1. Unaltered Sounding and Hodograph

The SHARP Workstation can provide additional insight to the forecaster even without alteration of the original sounding and hodograph. For this particular case, the indicators of rotation potential suggested by the SHARP Workstation analyses will be stressed. The forecaster should realize that the programs may also be used to provide information on hail and strong (downburst) wind forecasts.

Figure 6 is an example of the first screen that greets the forecaster on the SHARP Workstation analysis of a sounding and hodograph. On the 1200 UTC OAK sounding, the LI of +6 is consistent with the lack of positive buoyancy (B+ = 0). Other indices, including the Showalter Index, the K-Index, and the Totals-Totals index, also suggest no risk of thunderstorm development. However, each of these indices has been developed to assess the risk of thunderstorms in portions of the country where the roots of the convection are in deep layers of moisture. This is often not the case in California, and forecasters are urged not to use these indices to produce a "cookbook" thunderstorm forecast.

Since positive buoyancy (B+) is zero, the Bulk Richardson Number (BRN) is not defined for the 1200 UTC sounding.

```
                        OAK / 12/17/92 /  12Z
                   OBSERVED SOUNDING PARAMETERS

ZDDDDDDDDDDDDDDDDDDDDDDDDDDDDDCONVECTIVE POTENTIALDDDDDDDDDDDDDDDDDDDDDDDDDDDDDD
3   K-Index............ -4                    B+.............     0 J/Kg
3   Precip Water....... 0.68 in.              B-.............     0 J/Kg
3   Showalter Index.... 5                     Max UVV........     0 m/s
3   LI................. 6                     Cap Strength...   6.1 xC
3   LPL..(PMAX)........ 2572 ft/ 925 mb
3                                             Total Totals...   47
3   Tropopause......... 34600 ft.             Sweat Index....  150
3   Equilibrium Level.. -999 ft.              700-500mb LR...   5.6 xC/km
3   Max Parcel Level... -999 ft.
3   Wet-Bulb Zero...... 6500 ft.              TEI( 750- 700). 11.3 xC
CDDDDDDDDDDDDDDDDDDDDDDDDDDDDDWIND / STORM TYPEDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDD
3   Mean Wind (0-6Km).. 268/ 37 kts     SR Helicity (0-3Km).. 446 (M/S)}
3   Storm Motion....... 297/ 28 kts     Pos Shear   (0-2Km).. 12 (10-3 S-1)
3                                       SR Dir Shr  (0-3km).. 123x
3   BRN................    0
3   BRN Shear.......... 155 (M/S)}      Energy/Helicity Index......  0.00
FMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM
3   (F1)-Print              (F3)-Skew T              (F5)-Next Screen
3   (F2)-Main Menu          (F4)-Hodograph           (F7)-Help
TMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM
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Figure 6. Opening display from SHARP Workstation after analyses of 1200 UTC OAK sounding and hodograph data.

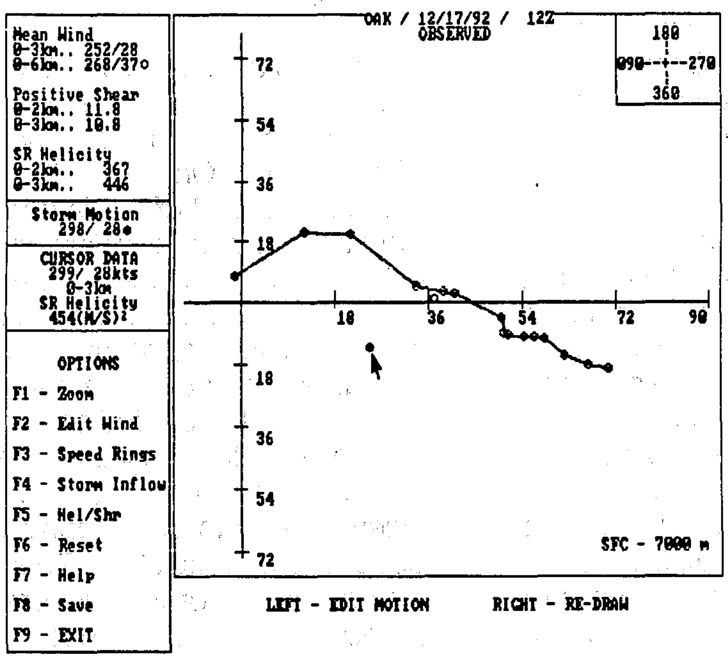

Figure 7. 1200 UTC 17 December 1992 OAK hodograph display from SHARP Workstation. Arrow indicates storm motion inferred by the program from the mean wind information.

However, the forecaster should keep in mind that small BRNs are associated with supercell (rotating) thunderstorms, whereas larger values are associated with multi-cellular convection. BRNs less than about 2 indicate the shear is too great for the buoyancy and thunderstorms tend to "shear out". The higher the BRN the more "upright" the convection. However, too high of a BRN would imply a thunderstorm in which the downdraft would "overwhelm" the updraft; such a thunderstorm could not develop the self-sustaining nature so characteristic of supercells. **Supercells have been observed for BRNs between 2 and 45.** However, the forecaster must keep in mind that the BRN is a "bulk" measure (i.e., based upon absolute value of shear and not whether or not it has the right characteristic). A BRN in the correct range of values for rotating thunderstorms is a necessary but not a sufficient condition for supercell development.

The low-level portion of the 1200 UTC hodograph (Fig. 7), plotted by the SHARP Workstation, is curved in the clockwise sense, indicative of a wind shear conducive to storm rotation. The degree to which the low-level shear profile is favorable for storm rotation can be estimated from the 0-3 km sr-helicity, the 0-2 km positive shear, and the energy/helicity index. The 0-3 km s-r helicity is calculated by the SHARP Workstation assuming storms develop with a storm motion (shown by arrow on the hodographs) dictated by the mean wind. **Davies-Jones et al. (1990) advise that 0-3 km s-r helicities approaching 150 $(m/s)^2$ support mesocyclone development, 151-299 $(m/s)^2$ weak tornadoes, 300-449 $(m/s)^2$ strong tornadoes, and greater than 450 $(m/s)^2$ violent tornadoes.** It is important that the forecaster note that such values should only be used to evaluate rotation potential and never should be used in isolation from other considerations which determine whether or not a storm will become tornadic. In the present case, the 0-3 km s-r helicity of 446 $(m/s)^2$ stands out as an indicator of strong rotation potential IF thunderstorms develop and IF buoyancy achieves values in the proper range (discussed below).

Johns et al. (1990) have shown that low-level shear associated with a wind veering and increasing with height (called positive shear) in the 0-2 km layer is a parameter most highly correlated with tornado occurrence with **values between 6 X 10^{-3} sec^{-1} to 25 X 10^{-3} sec^{-1} encompassing all of the tornado events documented in the study**. The value of 12 X 10^{-3} sec^{-1} for the 1200 UTC sounding also suggests potential for rotating thunderstorms if the shear profile persisted during the time of storm development. In fact, Fig. 8 indicates that if such a shear were associated with a B+ of around 500 J kg^{-1}, strong or violent mesocyclone-induced tornadoes may result.

Finally, the Energy/Helicity Index (EHI) is undefined for the 1200 UTC sounding because it is another measure of the ratio between buoyancy and shear. Rather than being a bulk measure (as is the BRN), it uses the 0-2 km s-r helicity rather than the absolute value of the shear. This index is still undergoing operational testing; however, **values of the EHI of around 1 indicate a tendency for rotation to support strong (F2 and F3) tornadoes.**

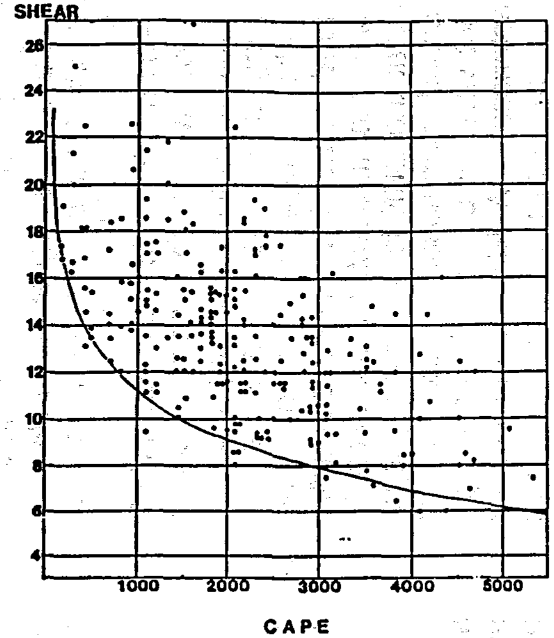

Figure 8. Scatter diagram (from Johns et. al. 1990) showing the relationship between buoyant energy (CAPE or B+) and 0-2 km AGL positive wind shear for 242 strong and violent tornado cases. Solid curved line is their suggested lower bound for the buoyant energy/shear combination associated with strong or violent tornadoes.

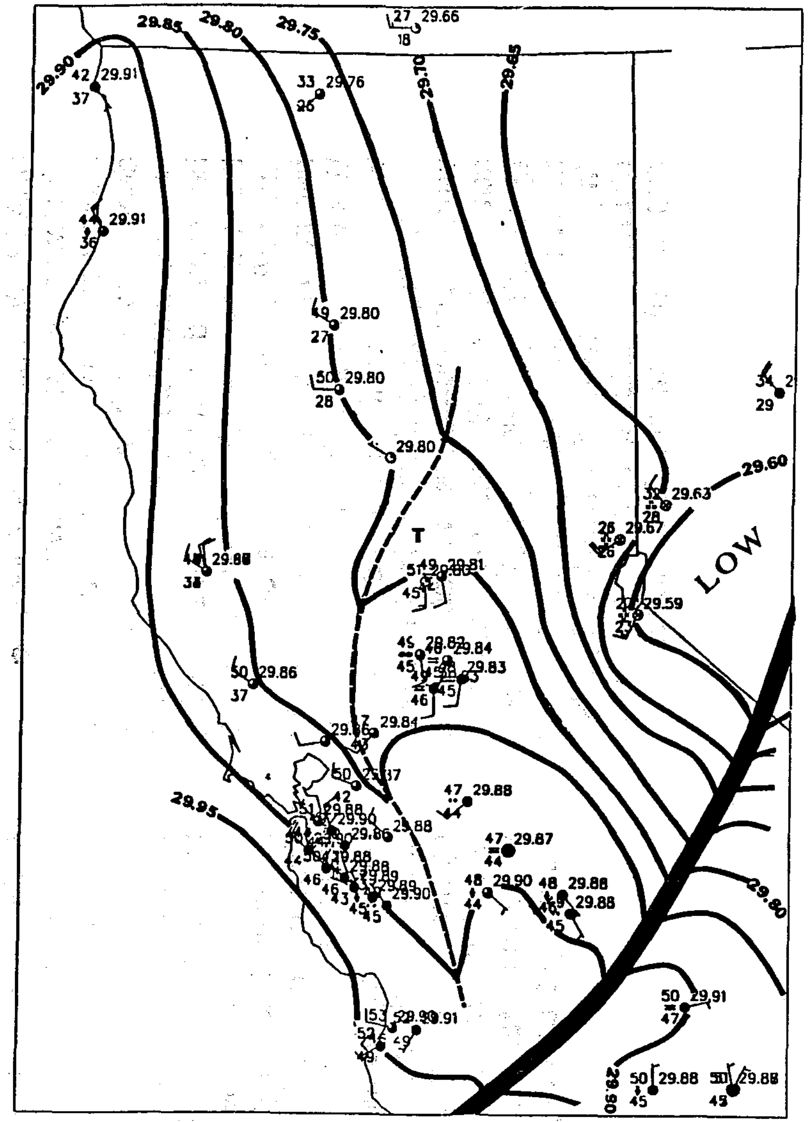

Figure 9. Subsynoptic analysis of altimeter settings for 2200 UTC 17 December 1992. Broad solid line is main cold front, light dashed line is post-frontal trough. Approximate location of tornadic thunderstorm at this time indicated by "T".

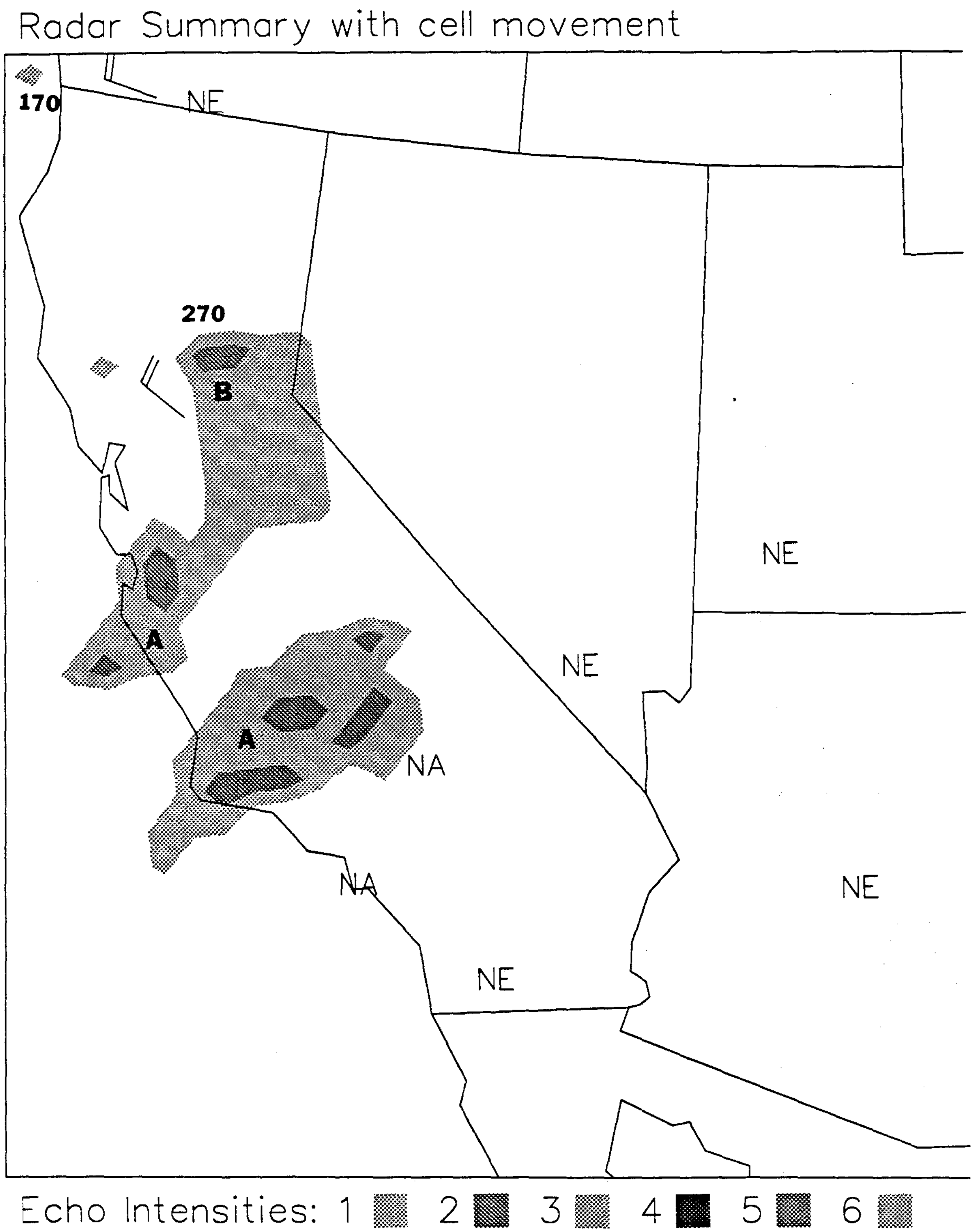

Figure 10. Radar summary for 2335 UTC 17 December 1992. "A" indicates front and "B" the tornadic thunderstorm.

2. Forecaster-altered Sounding and Hodograph

Pattern recognition on the part of the operational forecaster would have already established the regional risk of thunderstorm activity for this case. An evaluation of the initial sounding and hodograph and consideration of the initial s-r helicity obtained from the SHARP Workstation would definitively establish the threat of tornadoes in any portion of the forecasting area in which the hodograph and buoyancy would be favorable. Since the low-level winds often remain southeasterly in the Sacramento Valley for the duration of such a pattern and that diurnal heating effects are often much greater there than along the coast, a first "guess" should establish an enhanced risk of tornadoes for the valley. The forecaster should not dismiss the threat for other interior valleys in the forecast area, however.

Figure 9 gives the 2200 UTC 17 December subsynoptic analysis for northern and central California. Note that up-valley, southerly flow occurred ahead of a subsynoptic scale trough located in the southern Sacramento Valley even though northwesterly winds characterized the low-level flow in the San Francisco Bay region (and in the 0000 UTC OAK hodograph). The main cold front (wide solid line) had already passed through northern California and was evidenced by a rain area on radar (indicated by the letter A on Fig. 10) and a large cloud band on satellite imagery (indicated by the letter A on Fig. 3 and Fig. 11). A large thunderstorm (indicated by the letter B on Figs. 3, 10, and 11) developed in the area of surface moisture flux convergence (Fig. 12) ahead of the trough line and north of the main front. The southeastward motion of the cell is evident from a comparison of Figs. 3, 10, and 11.

Note the prestorm moisture flux convergence field over California was characterized by two maxima, one associated with the frontal system over central California and another associated with the trough line. Maxima of moisture flux convergence indicate a mesoscale focus for destabilization and/or wind convergence (Doswell, 1985 and many others). **Moisture flux convergence occurring in association with post frontal troughs was also found to be an important feature in the pre-storm environment with the 24 September 1986 tornadoes in the Sacramento Valley** (Braun and Monteverdi, 1991). The equivalent of the field of moisture flux convergence given in Fig. 12 may be obtained from the MESOS or ADAP programs resident on AFOS.

Figure 13 gives a "hindcasted" bogus 2200 UTC sounding and Fig. 14 a bogus hodograph for Marysville (MYV) constructed on the SHARP Workstation. The bogus sounding was created by inserting the surface data for MYV at 2200 UTC and altering the temperatures of all levels above the mixed layer by the amount suggested by the 1200 UTC advection patterns (for simplicity in this case study, determined from a comparison of the 1200 UTC and 0000 UTC OAK soundings). The bogus hodograph was created from the 1200 UTC OAK hodograph by substitution of the 2200 UTC surface wind at MYV and by insertion of the true storm motion obtained from Sacramento (SAC) weather radar (indicated by arrow). Figure 15 displays the opening screen from the SHARP Workstation when analyzing the sounding and hodograph information.

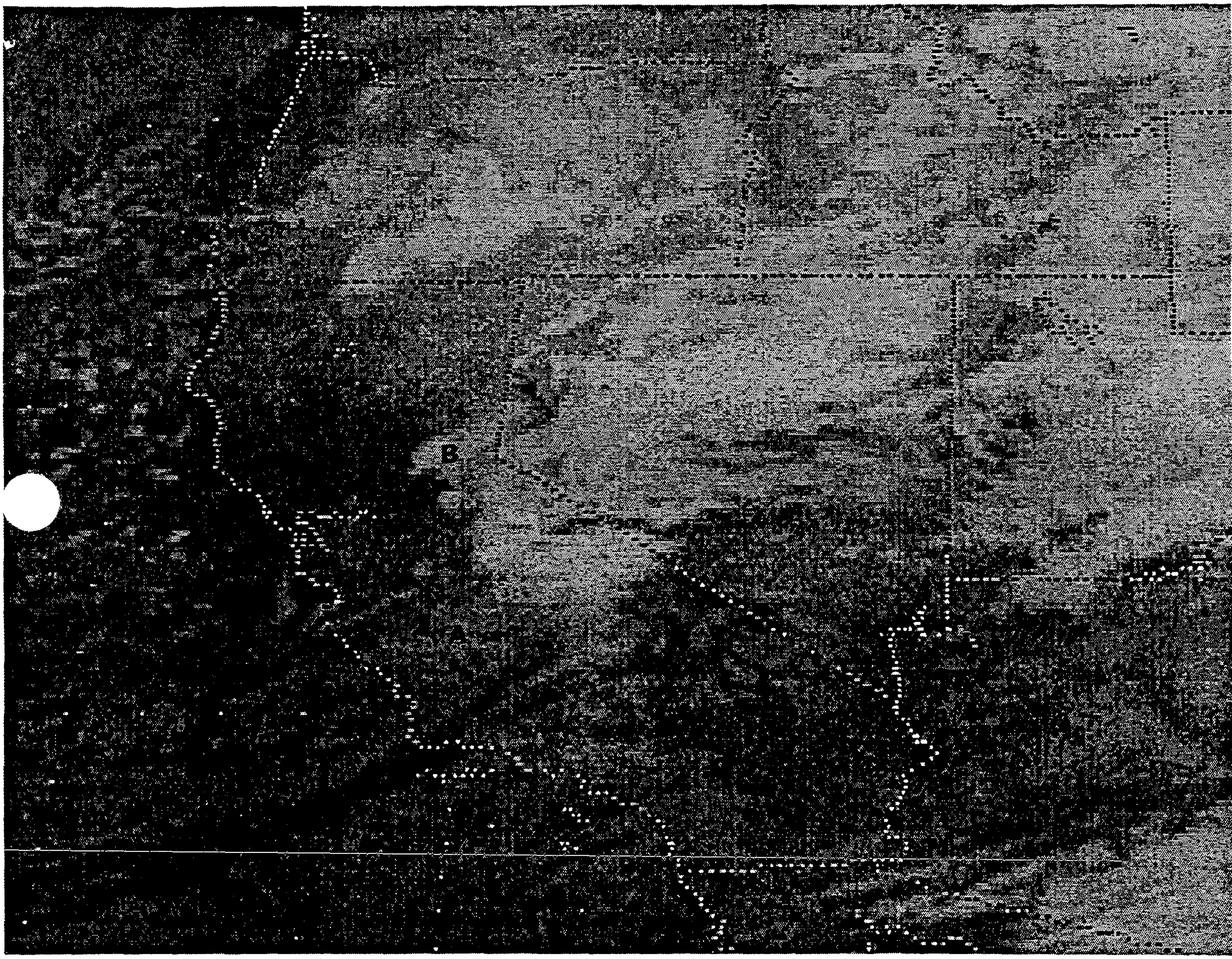

Figure 11. Infrared satellite image for 0101 UTC 18 December 1992. "A" indicates front and "B" the tornadic thunderstorm.

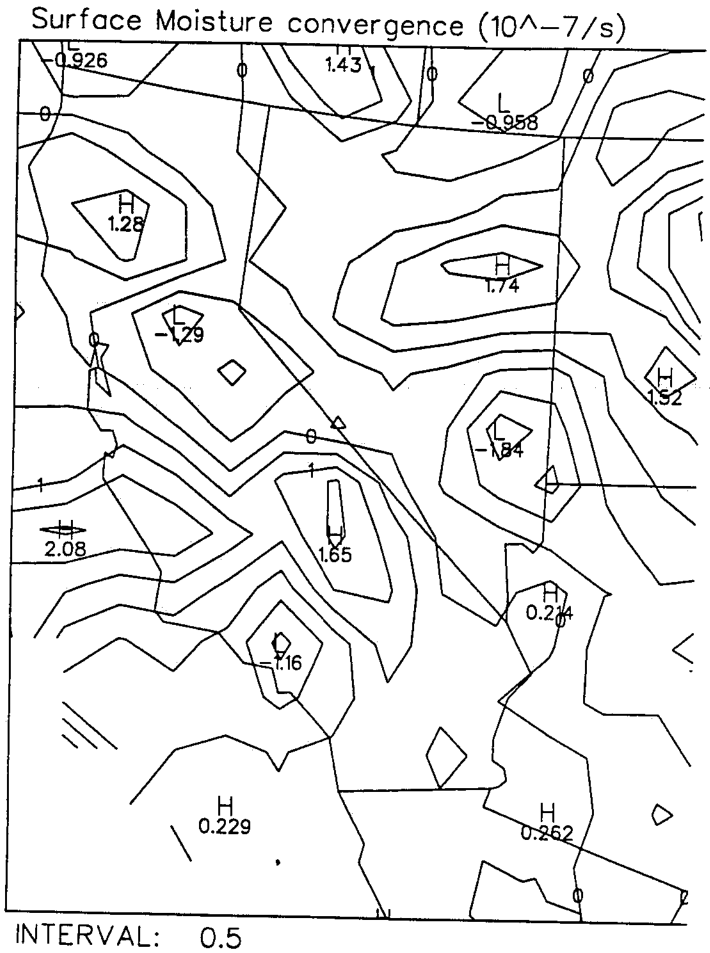

Figure 12. Surface moisture flux convergence field (10^{-7} s^{-1}) for 2100 UTC 17 December 1992.

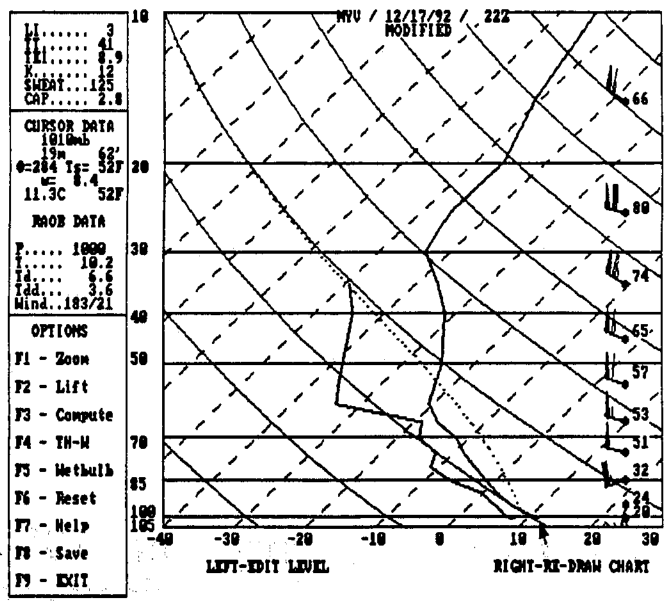

Figure 13. Bogus 2200 UTC sounding for MYV area produced by SHARP Workstation. Dotted line indicates temperature profile of lifted surface parcel.

The sounding was not modified for the greater cooling which would have occurred in the middle and lower middle troposphere over the Sacramento Valley. Greatest cold advection at these levels occurred over northern California, as is indicated by the brighter aspect of the cloudiness, which moved over that portion of California in Figs. 3 and 11. The temperature changes above the mixed layer evident in Fig. 13 and Fig. 5b (the unaltered 0000 UTC OAK sounding) from 1200 UTC (Fig. 5a) probably underestimate the degree to which destabilization occurred over the storm development region.

The dotted line (Fig. 13) represents the temperature of a surface lifted parcel in the Marysville area at 2200 UTC. Note that the equilibrium level lies just below 500 mb, resulting in an LI of +3 (Fig. 15). Radar echo tops (in this case, 27,000 feet), were much lower than the types of tops found with tornadic storms in the eastern portion of the United States. **It is important for the forecaster not to bias judgment based upon preconceived notions that severe thunderstorms have radar tops over an arbitrary elevation, such as 40,000 or 50,000 feet.**

The sounding analyses indicate that the atmosphere was buoyant beneath the 500 mb level. The 700 mb LI of -3 is more indicative of the fact that positive buoyancy is quite evident in this sounding. The B+ value of 552 J kg^{-1} is small, but when combined with the nature of the shear, this value may be associated with strong tornadic thunderstorms according to Fig. 8.

The modified hodograph shows the sort of low-level curvature indicative of high rotational potential. As would be expected, **s-r helicity of 454 $(m/s)^2$, positive shear of 13 X 10^{-3} sec^{-1}, and EHI of 1.17 would suggest that storms in the southern Sacramento Valley could be associated with tornadoes and that such tornadoes could be strong (F2 or F3).**

IV. DISCUSSION AND CONCLUSIONS

This study illustrates the advantages and insights that the interactive use of the SHARP Workstation provided on the severe weather threat in California on 17 December 1992. Many of the AFOS products used by forecasters are useful in establishing the synoptic controls on a regional convective event but provide little insight to those factors which might "focus" the threat subsynoptically. An evaluation of such products in this case would lead to the recognition of the pattern as one often associated with severe weather phenomena in the state. Subtle aspects of the pattern include a post frontal subsynoptic or mesoscale low in the Central Valley which remains there until the main upper trough passes. Thus, while low-level winds may veer to northwesterly in the OAK hodograph, southeasterly flow can persist in that portion of the Central Valley east of the surface post frontal trough axis.

Previous studies have shown that such southeasterly flow is subjected to lifting as it moves northward in the Sacramento Valley and is associated with moisture advection and moisture flux convergence. In the present case, cold advection in the middle and lower middle troposphere could have been expected to lower temperatures at those levels over all of northern and central California, with the greatest changes over the northern

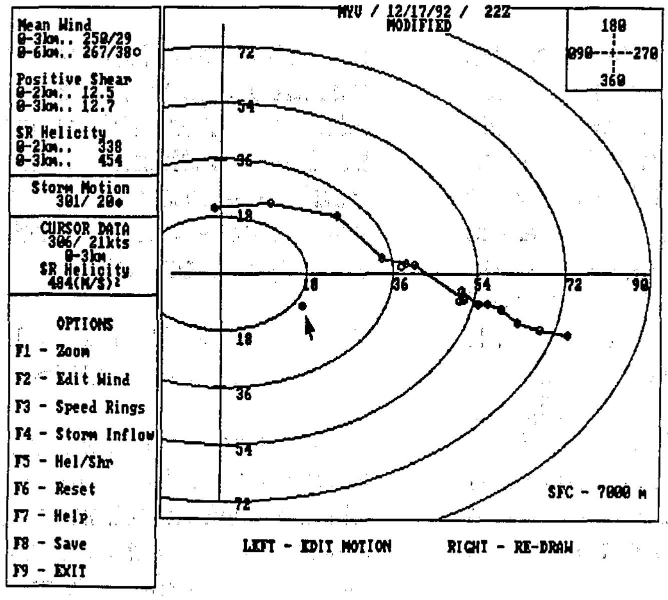

Figure 14. Bogus 2200 UTC hodograph for MYV area produced by SHARP Workstation. Arrow indicates true storm motion as obtained from SAC weather radar.

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                         MYV / 12/17/92 /  22Z
                      MODIFIED SOUNDING PARAMETERS

ZDDDDDDDDDDDDDDDDDDDDDDDDDDDDDCONVECTIVE POTENTIALDDDDDDDDDDDDDDDDDDDDDDDDDDDDDD?
3   K-Index...........  12                     B+.............  552 J/Kg   3
3   Precip Water.......  0.51 in.              B-.............    0 J/Kg   3
3   Showalter Index....  9                     Max UVV........   33 m/s    3
3   LI.................  3                     Cap Strength...  2.8 xC     3
3   LPL..(PMAX)........    0 ft/1012 mb                                    3
3                                              Total Totals...   41        3
3   Tropopause......... -999 ft.               Sweat Index....  125        3
3   Equilibrium Level..  16700 ft.             700-500mb LR...  8.6 xC/km  3
3   Max Parcel Level...  24100 ft.                                         3
3   Wet-Bulb Zero......  3600 ft.              TEI(1012- 600).  8.9 xC     3
CDDDDDDDDDDDDDDDDDDDDDDDDDDDDDWIND / STORM TYPEDDDDDDDDDDDDDDDDDDDDDDDDDDDDDDD4
3   Mean Wind (0-6Km).. 267/ 37 kts      SR Helicity (0-3Km).. 454 (M/S)}   3
3   Storm Motion....... 301/ 20 kts      Pos Shear   (0-2Km).. 13 (10-3 S-1)3
3                                        SR Dir Shr  (0-3km).. 117x          3
3   BRN................   3                                                  3
3   BRN Shear..........  194 (M/S)}      Energy/Helicity Index......  1.17   3
FMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM5
3   (F1)-Print               (F3)-Skew T                (F5)-Next Screen     3
3   (F2)-Main Menu           (F4)-Hodograph             (F7)-Help            3
TMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMMM>
```

Figure 15. Opening display from SHARP Workstation after analyses of bogus 2200 UTC sounding and hodograph data for MYV area.

portions of the state. All of these factors would have acted to destabilize the sounding in the Sacramento Valley by the afternoon of the 17th and transform the sounding from one in which buoyancy was absent into one in which thunderstorms could develop.

Once the likelihood of thunderstorm development in the valley is recognized, monitoring of those rotation-generation factors which might be present must occur. The operational meteorologist would need to become familiar with those "indices" which estimate buoyancy and shear, and become adept at utilizing these indicators in assessing the rotational characteristics of developing thunderstorms. Such indicators include the Bulk Richardson Number, the Positive Shear, the Energy Helicity Index, and, most importantly, the storm-relative helicity.

The present case illustrates that the storm-relative helicity evident in the SHARP Workstation analyses of the 1200 UTC OAK sounding and hodograph, modified for conditions in the valley, was favorable for rotating thunderstorms. This storm-relative helicity was dependent upon low-level winds veering from southeasterly at the surface to west-southwesterly at the 3 km level. The keys to establishing the mesoscale focus for the tornado threat in northern and central California in this case were: (a) understanding of the role of storm-relative helicity in storm rotation; and (b) isolating the portion of the region which would retain low-level southeasterly flow (and, thus, favorable storm-relative helicity) until the main upper trough passed and all aspects of the hodograph became unfavorable.

Finally, California forecasters must remember that tornadoes are an important feature of California climatology in certain weather patterns. Once the operational meteorologist recognizes the risk for such storms, the same techniques used by forecasters in more tornado-prone portions of the country must be applied to establish a focus for the threat.

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