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COMBINING NUMERICAL MODEL AND OBSERVED SOUNDINGS WITH VIL DENSITY TO FORECAST SEVERE THUNDERSTORMS IN THE SIERRA NEVADA

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[Note: Because of the large number of figures, only the text will be published in hard copy. The figures can be accessed on the Web version at http://www.wrh.noaa.gov under Technical Attachments.

Introduction

Thunderstorms are rather common over the California Sierra Nevada during the summer months as subtropical moisture is advected into this area by the summer monsoon. These thunderstorms are usually moderately high-topped and the short-lived pulse type, which produce heavy rain and hail, but they seldom reach severe limits. On 24 May 1999, strong to severe thunderstorms developed along and east of the Sierra Nevada crest during the afternoon. These storms were not related to the monsoon, but rather, an upper level area of lower pressure which wrapped moisture into the northern Sierra Nevada. However, the thunderstorms did show characteristics similar to the monsoon type and were unusually intense.

On the afternoon of May 24, a severe thunderstorm was observed to produce 4-cm (1.5 inch), or walnut-size, hail at the University of California Central Sierra Snow Laboratory (CSSL) in Norden, California. The CSSL is located just west of Donner Summit and the Sierra Nevada crest at an elevation of 2,103-m (6,900-ft) mean sea level (MSL). Hail stones with a diameter this large are thought to be rare in the northern Sierra Nevada. This may be partly due to the lack of reports in such a sparsely populated region. Despite this area having a small population, it is a very popular location for outdoor recreation and is near the Donner Summit mountain pass traversed by Interstate 80. This paper will examine the thunderstorms that occurred on May 24 and evaluate the Weather Surveillance Radar-1988 Doppler (WSR-88D) Hail Detection Algorithm's (HDA) performance.

Methodology

This paper will review three separate thunderstorms that occurred on 24 May 1999. For each case, the WSR-88D HDA output was evaluated to demonstrate some possible weaknesses associated with a near-sea-level WSR-88D, located in Sacramento, California, detecting thunderstorms over the high elevations of the Sierra Nevada. The Davis (KDAX) radar used by the NWS office in Sacramento is located at 44-m (144-ft) MSL and the Sierra Nevada terrain ranges from 900-m to 3,000-m MSL (3,000-ft to 10,000-ft). Studies have been done which showed that the HDA for radars located over high terrain often overestimate severe hail probability for areas located in lower elevations relative to the radar (Graham et al., 1998). This paper will show that the HDA may underestimate hail size and probability for terrain that is much higher than a WSR-88D located near sea level.

The purpose of the study is show how the use of numerical model observed and forecast soundings, and the consideration of vertically integrated liquid (VIL) denisty can help the forecaster better anticipate and evaluate possible severe thunderstorms. The first approach will focus on using numerical model data to gain a perspective of the convective potential prior to the thunderstorm outbreak. Then the paper will show how the forecaster can combine model data, surface analyses, simple equations, and hail nomograms to compliment the real-time warning decision-making process. It is well understood how challenging the accurate and timely detection of hail can be because of radar limitations, and the complex nature of thunderstorms. Furthermore, verifying a severe thunderstorm warning for hail in the Sierra Nevada is difficult alone, because of minor population densities and the small spacial nature of thunderstorm hail shafts. Complicating this is the paper's theory that a near-sea-level radar may be significantly underestimating the hail potential across the Sierra Nevada. Despite these factors, this paper will attempt to give additional confidence to the forecaster through results and applications.

Synoptic Overview

A complex weather pattern had developed over the Western United States between 22-24 May 1999. A closed upper low pressure system had moved from Southern California into Southern Nevada and Northwest Arizona over the course the three days (Fig. 1). At the same time, a strong upper ridge of higher pressure was over the Pacific Northwest and most of far Northern California. The interaction of these two features created a deformation zone (implied divergence) over extreme Northern California. Divergence aloft will enhance vertical motions that develop in the lower levels of the troposphere.

High surface pressure over the Pacific Northwest created a strong north-to-south pressure gradient over Northern California on Saturday and Sunday. This downslope wind flow brought hot weather to much of the region. A record high temperature of 100°F occurred at Redding, California, along with other records in Oregon on 23 May 1999. Also on that day, scattered thunderstorms developed over the Southern Sierra Nevada and proceeded to drift westward into the foothills. In the Sacramento area, a strong onshore flow (known as the Delta Breeze) formed and held temperatures in the 80's on the 23rd and 24th.

Figure 1 shows that by 24 May, mid-level moisture (600 to 500-mb) had advected over the Sierra Nevada in the easterly flow associated with the closed upper low in Southern Nevada. This moisture combined with significant instability and orographic lift (diurnal upslope flow) to generate strong thunderstorms over the mountains that afternoon. Additional thunderstorms developed each afternoon through 26 May 1999. The thunderstorms were only observed to be severe on May 24th and this paper will concentrate on this day.

Local Applications and Observations

The recent installation of an Advanced Weather Interactive and Processing System (AWIPS) has enabled forecasters to quickly obtain an accurate analysis of surface parameters using the Local Analysis and Prediction System (LAPS). On 24 May 1999, these analyses gave strong clues regarding the convective potential. At 2300 UTC, the LAPS products depicted an axis of high Convective Available Potential Energy (CAPE) values (1000 to 1200 Jkg^{-1}) along the Sierra Nevada (Fig. 2). Overlayed LAPS surface moisture divergence also showed an area of maximum surface moisture convergence along the Sierra Nevada with divergence in the Sacramento Valley (Fig. 2). The combination of these two parameters alone is an indication of convective potential provided there is a lifting mechanism. Over the mountains, diurnal upslope effects often will provide the needed lift and focus for convective activity. In this case, surface winds on the east side of the Sierra Nevada, near Reno, were light east to southeast, while on the west side, near Blue Canyon, winds were light southwest to west. This low-level convergence along and near the Sierra Nevada crest can lift an air parcel to its level of free convection (LFC). This can lead to intense thunderstorm updrafts provided there is sufficient CAPE.

Model Data and Soundings

Nearing the main thunderstorm outbreak on 24 May 1999, the Eta model hourly sounding forecasts were analyzed using archived data from the Buffalo toolkit software called BUFKIT (Mahoney and Niziol 1997). Model soundings are the best method for examining kinematic and thermodynamic profiles which may show characteristics of potential severe thunderstorms. The Eta forecast for KBLU (Blue Canyon) is used since it is closest to the location of the event (Fig. 3). It is important to note that the Eta model terrain is fairly representative of the actual terrain height at Blue Canyon which is 5,200-ft MSL. The 0000 UTC 24 May forecast run valid at 2200 UTC indicates mean surface based CAPE values of 461 Jkg^{-1} (Fig. 3). Lifted Indices (LI) for this time were forecast to be -2. The Eta model sounding for KBLU shows a LFC at 10,000-ft AGL, with an EL reaching to 30,000-ft AGL. In this particular case, both CAPE and LI indicated a strong threat for thunderstorms. However, LI's can be misleading because they are dependent on 500-mb temperatures, while CAPE is an integrated value of the atmosphere.

Using a sounding analyzed by the Rapid Update Cycle (RUC) at 0000 UTC 25 May (Fig. 4) shows an unstable air mass (CAPE value of 1273 Jkg^{-1}) for a point location chosen near Truckee, California. The RUC model can be very helpful in short-term forecasting since its analysis is generated every hour. In addition, the model will use all available surface observations, upper air data, and aircraft reports for its initialization.

Radar Data and VIL Density

Storm 1

A review of WSR-88D HDA data for 24 May showed thunderstorms with a high potential of forecast severe hail ($\geq$0.75-in). At 2139 UTC, composite reflectivity data showed a thunderstorm with a maximum reflectivity of 59 dBZ east of Pine Grove (Fig. 5). Output from the WSR-88D hail algorithms cell trends indicated a 100 percent probability of hail (POH), a 40 percent probability of severe hail (POSH), and a maximum estimated hail size (MESH) of one inch (Table 1). Maximum grid VIL values reached 54 kgm^{-2} (cell-based VIL was 51 kgm^{-2}) with Echo Tops of 37,000-ft MSL. When using NWS in-house VIL density charts to determine the hail potential, a value of approximately 4.8 gm^{-3} was obtained. VIL density is a normalization of the VIL, and it is independent of air mass characteristics. It is determined by the following equation.

Equation:

VIL density (gm^{-3}) = VIL (kgm^{-2}) x 1000 (gkg^{-1})/ echo top (feet) x 3.28 ftm^{-1} (1)

A study by Amburn and Wolf in 1997 used over 200 cases from the Midwest which showed that about 90 percent of the thunderstorms that produced severe hail occurred with VIL densities of 3.5 gm^{-3} or greater. Values over 4.5 gm^{-3} indicated a 100 percent probability of severe hail. Therefore, in this case, the 4.8 gm^{-3} value indicates that large hail has a very high probability of occurring. Small et al. (1998) showed cases in which these VIL density thresholds were applicable in the Western States. Their study also gave an equation (2) for determining the VIL by using an estimation of the echo top from an observed sounding. The resulting VIL value is approximately the critical value that the VIL must meet or exceed in order to reach a VIL density of 4.5 gm^{-3} for that particular echo top. Knowing the echo top and the VIL, the forecaster could then estimate the VIL density, hence the potential for severe hail.

Equation:

Echo top (kft) + (1/3 of the echo top) = approximately the "near 100% probability VIL threshold for severe hail" for that echo top value (2)

This could be taken one step further by using numerical model soundings. Using BUFKIT to display hourly forecast soundings (Fig. 3), a forecaster could determine an approximate echo top for anticipated thunderstorms. Computing the potential VIL using equation (2) from Small et al., followed by the VIL density calculations, would yield a forecast probability of severe hail. For example, using the sounding in Fig. 3, it is reasonable to estimate a forecast echo top of 35,000-ft MSL. Using equation 2 gives a VIL value of approximately 47 kgm^{-2}. Table 1 confirms that this value was more than sufficient to produce severe hail at 2242 UTC 24 May 1999.

Given the nature of these pulsing storms, this value could have been higher and may have occurred between volume scans. Another useful radar product is the Layer Composite Reflectivity Maximum (LRM) at middle or high levels. In this case, the LRM middle (24,000-33,000-ft MSL) showed a maximum of 57 dBZ in this layer. It has been long known that high reflectivities aloft (mid-level cores) are a good indication of strong or severe thunderstorms.

Storm 2

The KDAX composite reflectivity at 2300 UTC showed a maximum reflectivity value of 57 dBZ in a thunderstorm just southwest of Truckee (Fig. 6). The HDA data showed a POH value of 100 percent and a POSH of 50 percent with MESH of 1 inch. A peak grid VIL value of 47 kgm^{-2} was observed at 2254 UTC with Echo Tops at 40,000-ft MSL (Table 1). Using the same method as equation 1 for calculating VIL density indicated a likelihood of severe hail, with a value of 3.85 gm^{-3}. This value was observed by the KDAX radar at 2254 UTC (Table 1). At 2250 UTC, the NWS received a report of 4-cm diameter (1.5 inch) sized hail at the CSSL in Norden. The observer noted that hail swath was up to 20-cm (8 inches) deep and occurred between 2230 and 2250 UTC. According to radar data there was a peak in the storms' intensity at 2242 UTC when a grid VIL of 44 kgm^{-2} and a VIL density of 3.44 gm^{-3} was noted. Reviewing the cell trends data for this storm revealed that this thunderstorm was at its maximum intensity between 2250 and 2300 UTC, suggesting the storm may have produced even larger-sized hail at a later time (Fig. 7 and Table 1). A study of 400 hail events by Edwards et al. in 1997, highly discourages the use of individual parameters for forecasting thunderstorms or for identifying severe hail. This paper does not suggest to use one parameter or threshold value, but rather, encourages using a combination.

It is interesting to note on the cell trends display that at the time of the large hail report, the height of the maximum reflectivity had fallen below the height of the storm centroid (Fig. 7). The author has previously observed this cell trend pattern with collapsing downdrafts and hail occurrence in a variety of terrain. It would appear that the thunderstorm is "loaded" when the maximum reflectivity height is elevated well above the centroid height, as seen in the cell trends display in this case (Fig. 7). The term "loaded" would imply that the thunderstorm had an elevated core of high reflectivity (large hail stones) which would eventually become too heavy to be supported by the updraft. At this time, the hail core would descend to the surface with the thunderstorm downdraft. The corresponding VIL values for this thunderstorm would then be observed to decrease. At 2242 UTC, the time when 4-cm hail was observed, this type of cell trend pattern was observed and corresponded well with an increase then decrease of VIL, VIL density and POSH (Fig. 7

and Table 1). The same pattern was repeated at 2300 UTC, but the thunderstorm was over an unpopulated area. Shortly after this, the values rapidly decreased which likely indicates that more large hail had fallen from the storm.

Storm 3

At 0045 UTC (545 pm PDT), a third intense thunderstorm approached the Sierra Nevada crest. At 0038 UTC, maximum reflectivity associated with this thunderstorm reached 60 dBZ northwest of Truckee (Fig. 8), with VIL values (grid and cell-based) peaking at 53 kgm^{-2} at 0043 UTC and echo tops of 48,000-ft MSL (Table 1). Using these values produces a VIL density near 3.50 gm^{-3} which indicates that severe hail is likely, but this value was lower than Storms 1 and 2. Similar features in the cell trends data were seen in this case, with a POSH of 50 percent while the maximum reflectivity was elevated over the storm centroid by almost 6,000-ft (not shown). This was the highest POSH seen that day, however as mentioned earlier and pointed out by Vasiloff et al. (1997), the HDA is more sensitive to the height of the high reflectivity rather than the storm structure. Since this thunderstorm had a greater echo top (48,000-ft) the higher reflectivities were likely more elevated above the -20°C isotherm which would yield a higher POSH. The higher echo top would produce a lower VIL density since the grid VIL value was similar to Storm 1.

The NWS was unable to obtain any ground truth from storms 1 and 3, most likely due to the very sparse population in this area of the Sierra Nevada range. All the thunderstorms appeared to be developing in the same general area and propagated southwest at 10 to 15 knots. It is important to consider that due to the high terrain of these regions, ranging from 5,000 to 8,000-ft MSL, large hail stones are more likely to reach the ground because of considerably less melting. In eastern parts of the country, studies conducted on low-elevation radar sites have shown that the radar reasonably estimates hail size and occurrence (Barjenbruch and Laplante 1997). However, in the high terrain, like the Sierra Nevada, it is possible that the KDAX radar, which is located near sea level, may be underestimating MESH and POSH. This may be partially due to high (too warm) -20°C isotherm inputs in the HDA which are not representative of the atmosphere over the higher terrain. Klimowski et al. (1997) eluded to the fact that errors of up to 3000-ft for the -20°C height can lead to POSH variations up to 40 percent. The KDAX radar location would be opposite to the study by Vasiloff et al. (1997) which showed that radars located over higher terrain tend to overestimate hail output for the lower elevation were the thunderstorms occurred . It is also important to note that the 0.5 deg radar beam center-line at a range of 120 to130-km from the WSR-88D would be at an elevation near 8,000-ft once it reached the Sierra Nevada. Therefore, since thunderstorm bases in this region are often 8,000-ft MSL or higher, it would be safe to assume the radar sampling quality is very good. However, some of the radar beam's energy may be lost due to ground clutter interference from side lobe returns between the RDA and the Sierra Nevada. It is not believed, however, that this accounts for the HDA underestimating the hail size.

Conclusions

Despite the problems numerical modeling has in resolving actual terrain, and the radar beam blockage or side lobe interference that occurs in mountainous terrain, there are forecasting applications that exist when a combination of model and radar data is used. Knowing the effect of increased mid-level moisture and instability over the Sierra Nevada, and considering the time of year, would suggest a strong possibility of thunderstorms in this case.

This study showed that using derived model output, such as CAPE and NCAPE, displayed in software like BUFKIT, one can get a good assessment of the thunderstorm potential for the next 48 hours by analyzing the model soundings. Of course, caution and other considerations should be taken whenever using any numerical model output of convective parameters. Therefore, a parameter such as CAPE should never be used individually to predict hail, but ideally, thermodynamic and kinematic information should be analyzed on all forecast or observed soundings and this should be combined with radar data (e.g. VIL density) to achieve the best results. Model soundings can be used to approximate the possible echo top height of a thunderstorm. Using simple equations developed by the NWS, such as equation 2, the forecaster can estimate the VIL and VIL density that can be expected. This information will give a good assessment of the severe hail potential for a particular forecast period. With the addition of AWIPS, it is now possible to quickly and accurately gain an understanding of how unstable the atmosphere is by using near real-time meso scale surface analyses such as LAPS, or cycled model analyses from the RUC. Prior to an event, the available model output (e.g. soundings), LAPS data, and the knowledge of potential VIL density values should give the forecaster a better understanding of the thunderstorm potential, which should improve the warning decision-making process when examining real-time WSR-88D data.

In real-time convective outbreaks when it is most important to monitor WSR-88D output, it is possible to combine the model-generated perspective of the atmosphere with that seen on the radar scope. For example, this study showed that on May 24, using the Eta soundings displayed in BUFKIT and equation 2, there was a potential for thunderstorms having VIL density values as high as 3.85 gm^{-3}. Knowing this and recognizing the unstable atmosphere that was displayed on LAPS, surface analysis should heighten the forecasters' situational awareness. In this case, the HDA proved to be very useful guidance when the forecaster also considered VIL density. Using additional charts, such as a VIL density nomogram, for guidance enables the forecaster to determine how significant the severe threat may be. It is reasonable to assume that the strong thunderstorms that developed on May 24 all had the potential to produce severe hail despite only having one report of large hail. It is important to consider the elevation of where the storms are occurring since higher terrain (i.e., 7,000-ft MSL) will likely experience less melting before the hail reaches the surface. Therefore, this study showed that the HDA may be underestimating the severe hail potential and size across the higher terrain. However, more case studies and verification will be needed to further prove this theory. As often is the case with pulsing short-lived thunderstorms, there may only be one or two radar volumes scans that meet the criteria for severe thunderstorms and waiting until after the thunderstorm peaks in intensity may often be too late.

Finally, the forecaster must not lose confidence in his or her judgment of thunderstorm severity just because there is little or no ground truth. This is just one of several challenges to forecasting weather and issuing short-term warnings for sparsely populated areas. Using an understanding of meteorology (such as convective processes), along with nomograms, as well as real-time observed data, such as radar, surface analyses and spotter reports, are the best tools that will produce the most success. This study does not offer a magical number for identifying severe thunderstorms by using WSR-88D observed VIL, POSH, MESH or calculated observed VIL density, and is based on a limited data set. Instead, it suggests applying a more normalized derived method which uses pre-estimated VIL densities from forecast soundings viewed in BUFKIT to compliment the prediction of severe hail over the Sierra Nevada.

References

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Table 1. This table shows the volume scans when the three thunderstorms were the strongest on 24 May 1999. Near the 2242 UTC volume scan 4-cm (1.5 inch) sized hail was observed.

Storm #	Time UTC	MESH Inch	Cell VIL Kgm^{-2}	Grid VIL Kgm^{-2}	Max dBZ	EchoTop Kft	POSH Percent	VIL gm^{-3} Density
1	2133	0.75	33	41	56	37	30	3.63
	2139	1.00	51	54	59	37	40	4.79
	2145	0.75	44	45	59	38	30	3.88
	2150	<0.50	31	33	59	37	0	2.93
2	2242	0.75	43	44	57	42	30	3.44
	2248	0.50	35	39	56	40	20	3.20
	2254	0.75	42	47	56	40	30	3.85
	2300	1.00	45	42	57	39	50	3.53
3	0038	1.25	53	49	60	48	50	3.35
	0043	1.00	53	53	60	44	50	3.95
	0048	0.75	50	49	61	44	40	3.65
	0053	0.75	42	41	57	43	30	3.13

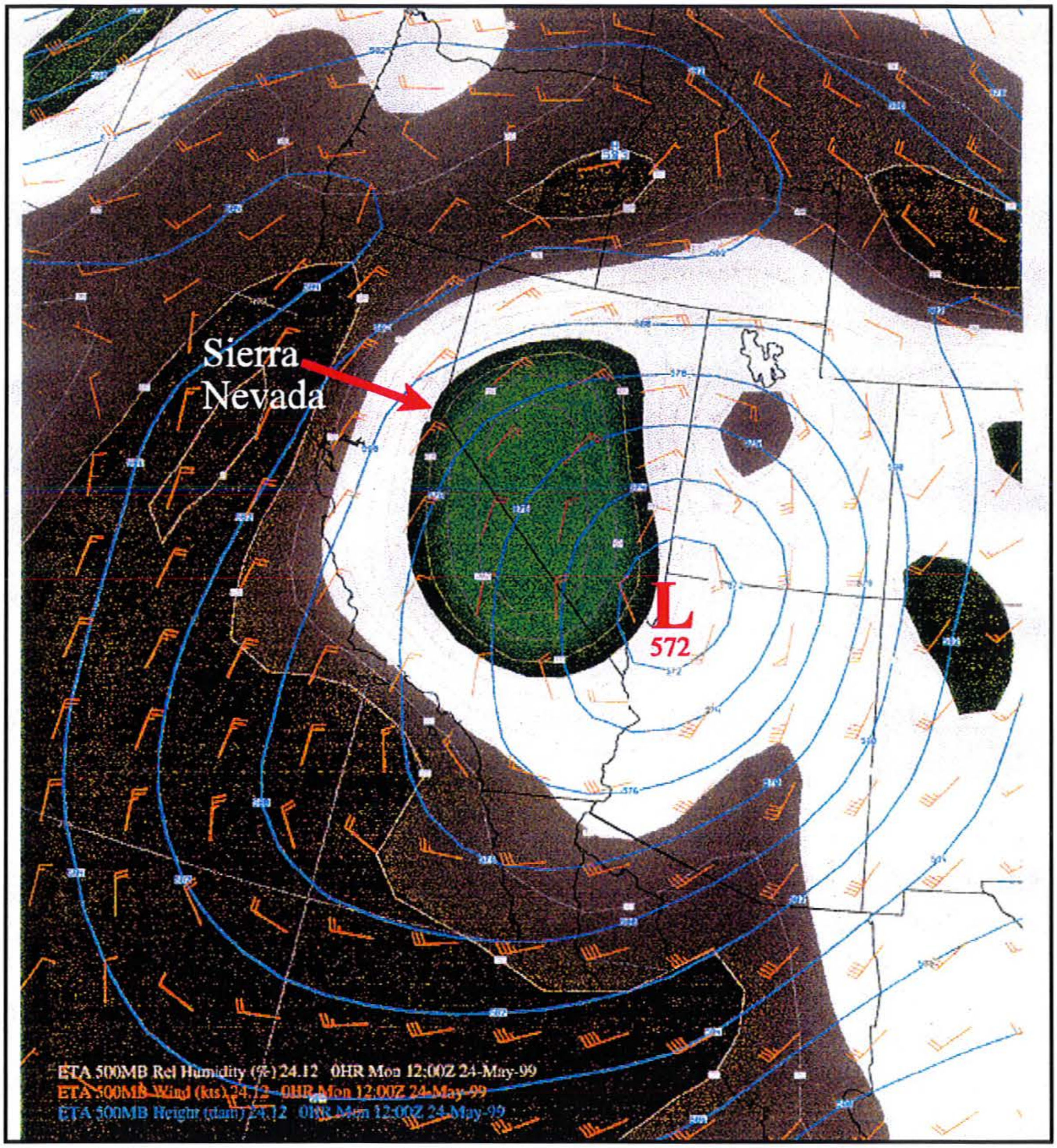

Figure 1. Eta 500-mb analysis at 1200 UTC 24 May 1999. 500-mb relative humidity is colored filled with green beginning at 70 percent. Geopotential height contours are every 20-m starting with 572-dm. Wind bards are every 2.5 ms^{-2}. Not shown is the omega field (upward vertical velocity) that was forecast over the northwest portion of the 70 percent or greater relative humidity.

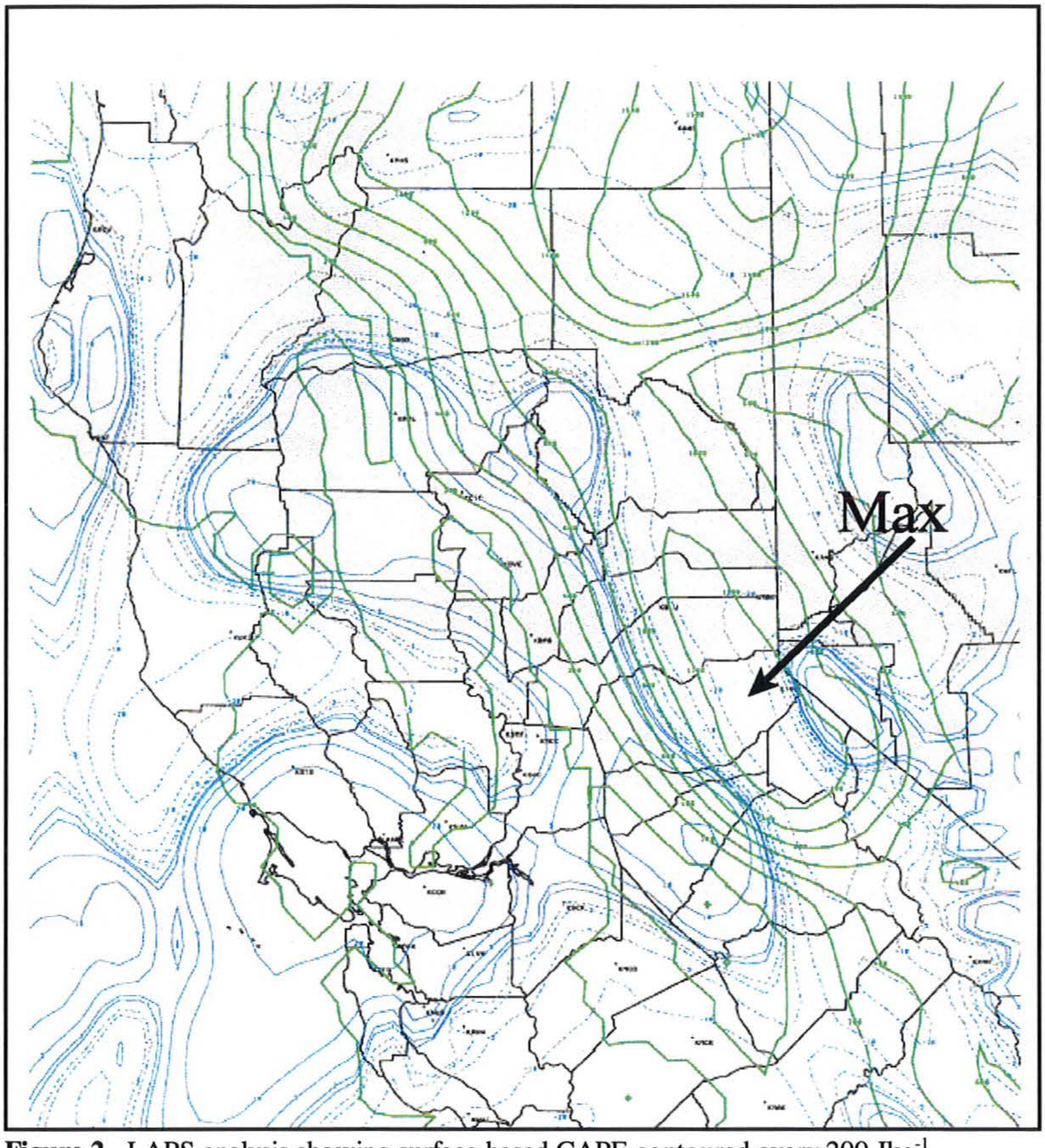

Figure 2. LAPS analysis showing surface based CAPE contoured every 200 Jkg^{-1} (green lines) overlaid on surface moisture flux divergence contoured every 10 $gkg^{-1}12hr^{-1}$ (blue lines) at 2300 UTC 24 May 1999 indicating a strong thunderstorm threat across the Sierra Nevada. The maximum area is 1200 Jkg^{-1} and 50 $gkg^{-1}12hr^{-1}$.

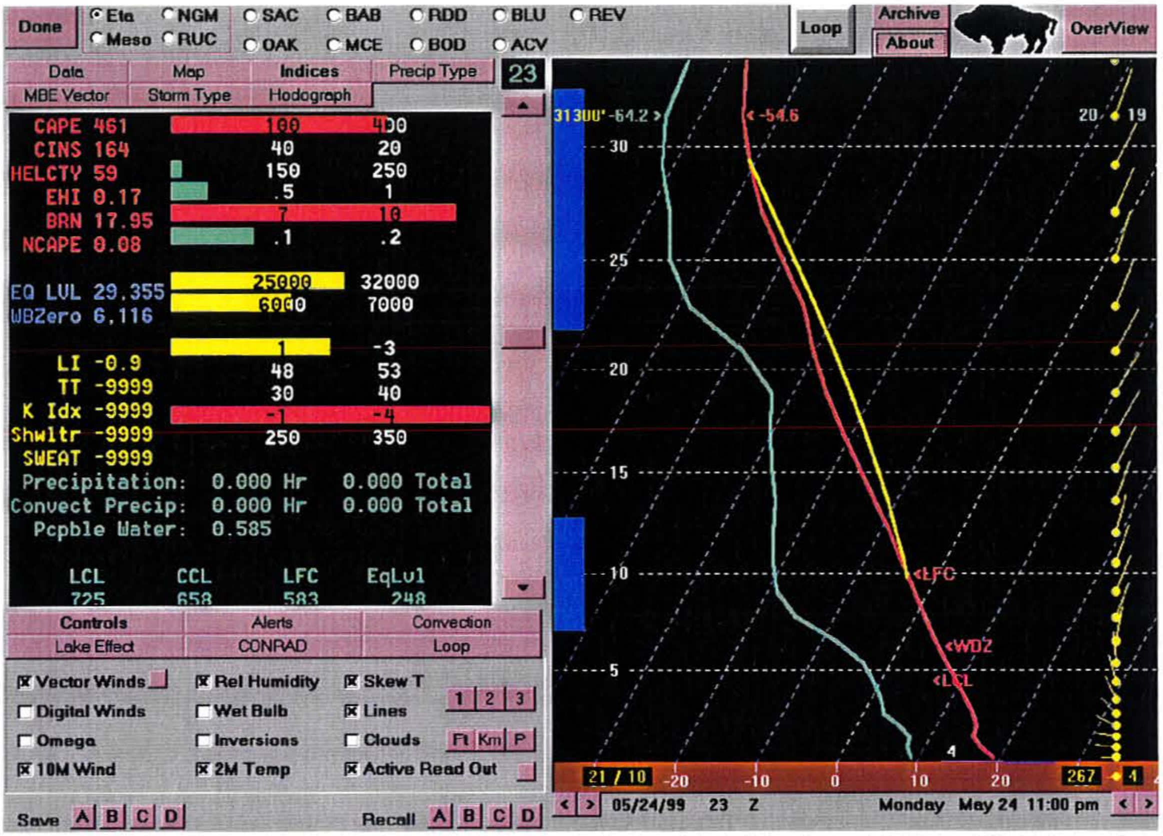

Figure 3. KBLU sounding displayed in BUFKIT at 2300 UTC on 24 May 1999 from the 0000 UTC Eta model run 24 May. The yellow line on the sounding clearly shows the large area of forecast instability (CAPE) with an equilibrium level at 30-kft. The table on the left shows various forecast parameters including CAPE, NCAPE, and LI.

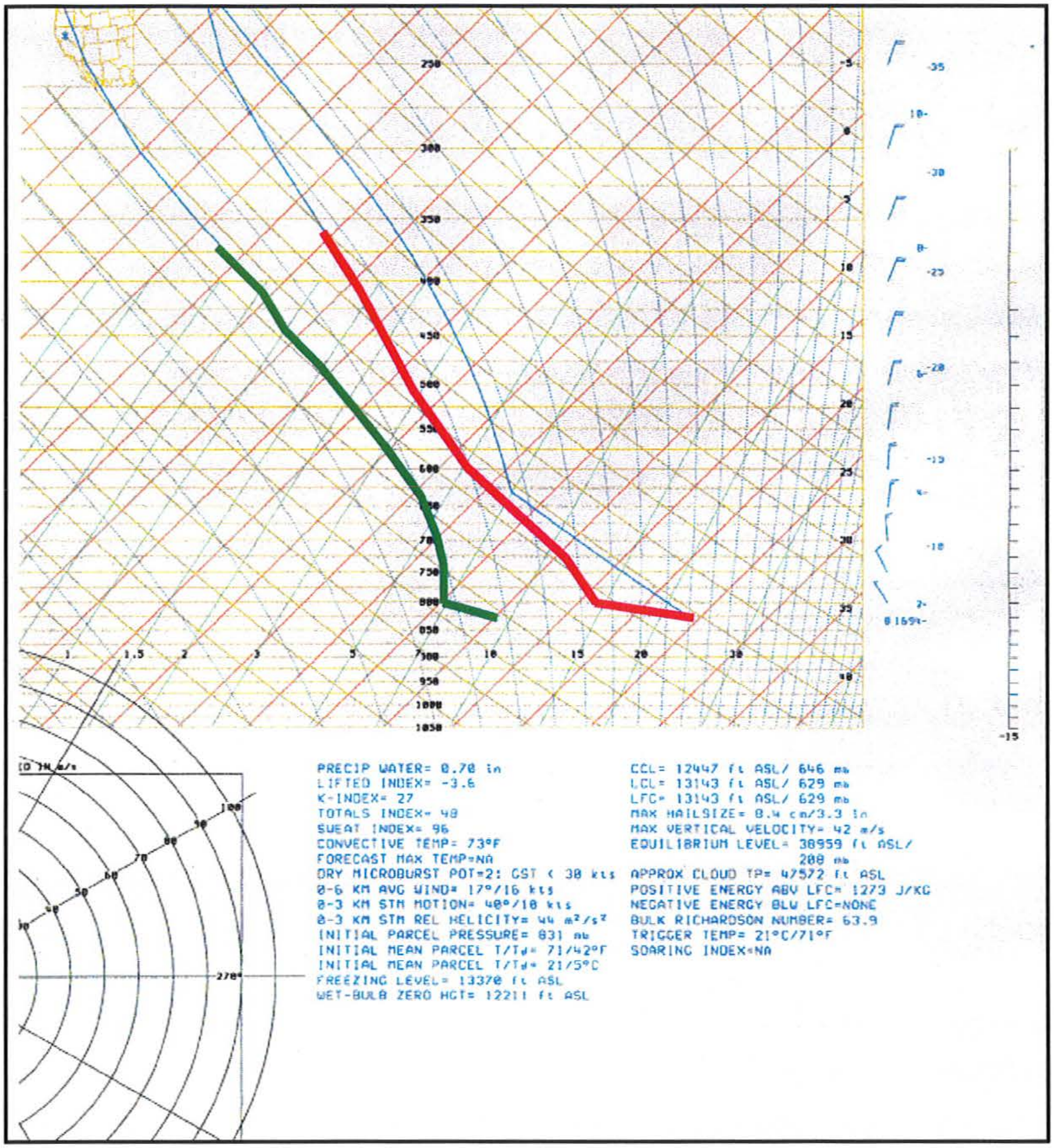

Figure 4. RUC analyzed sounding at a point selected near Truckee, CA at 0000 UTC 25 May 1999. The sounding produces a CAPE value of 1273 Jkg^{-1} and a LI of -3.6. Precipitable water was 0.70-in. Notice the moisture is mainly above 600-mb.

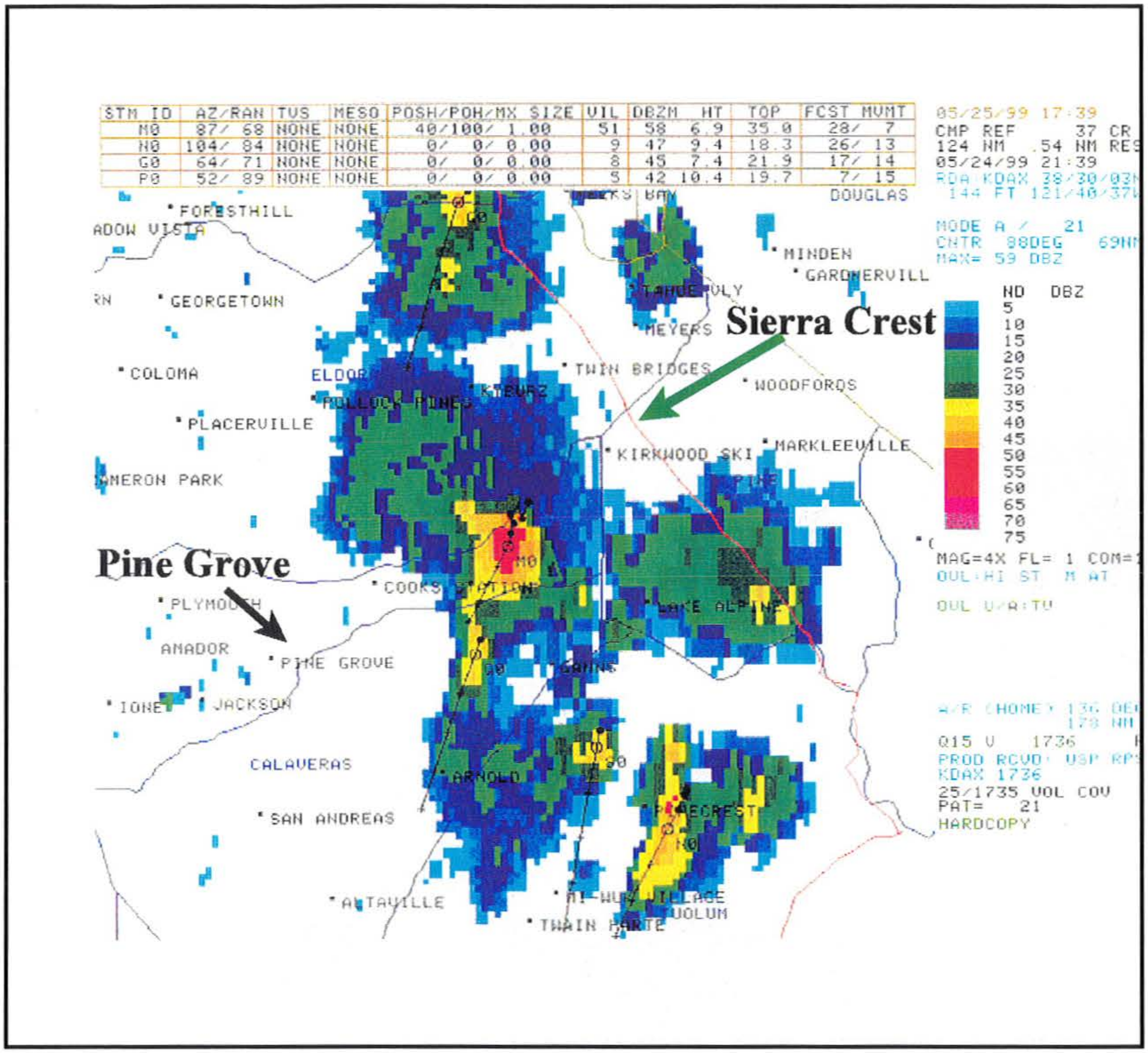

Figure 5. KDAX composite reflectivity at 2139 UTC 24 May 1999. A maximum of 59 dBZ is depicted and a grid based VIL of 51 kgm^{-2}. Also shown is the attribute table displaying the HDA output associated with this thunderstorm. The Sierra Nevada crest is noted by the thin red line.

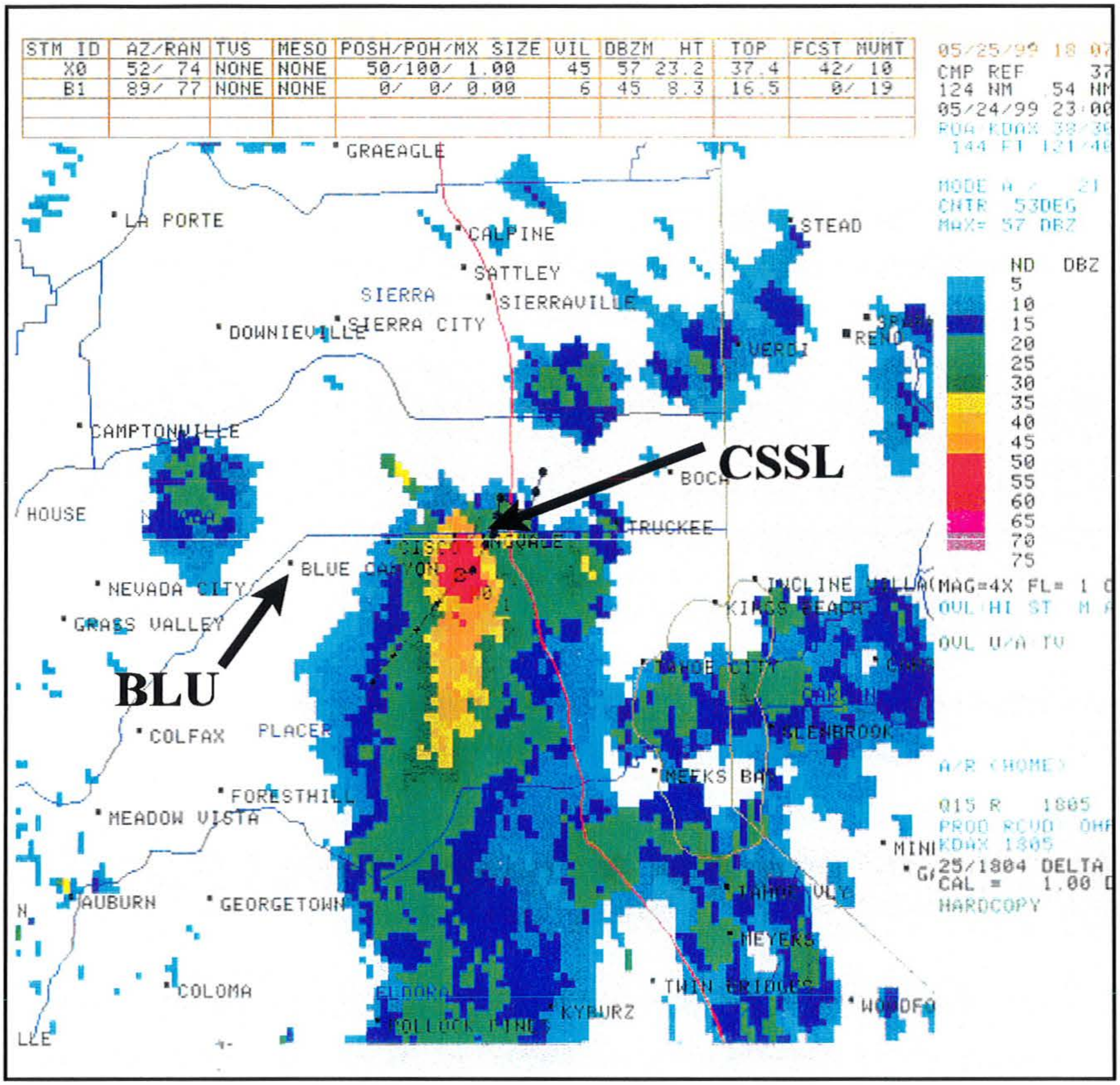

Figure 6. KDAX composite reflectivity at 2300 UTC 24 May 1999 showing a maximum reflectivity of 57 dBZ. The CSSL is located just east of the storm centroid (open circle in red area) and the black dotted line shows that the thunderstorm tracked directly over this site. The attribute table shows the HDA output and echo top associated with this thunderstorm. Thin red line is the Sierra Crest.

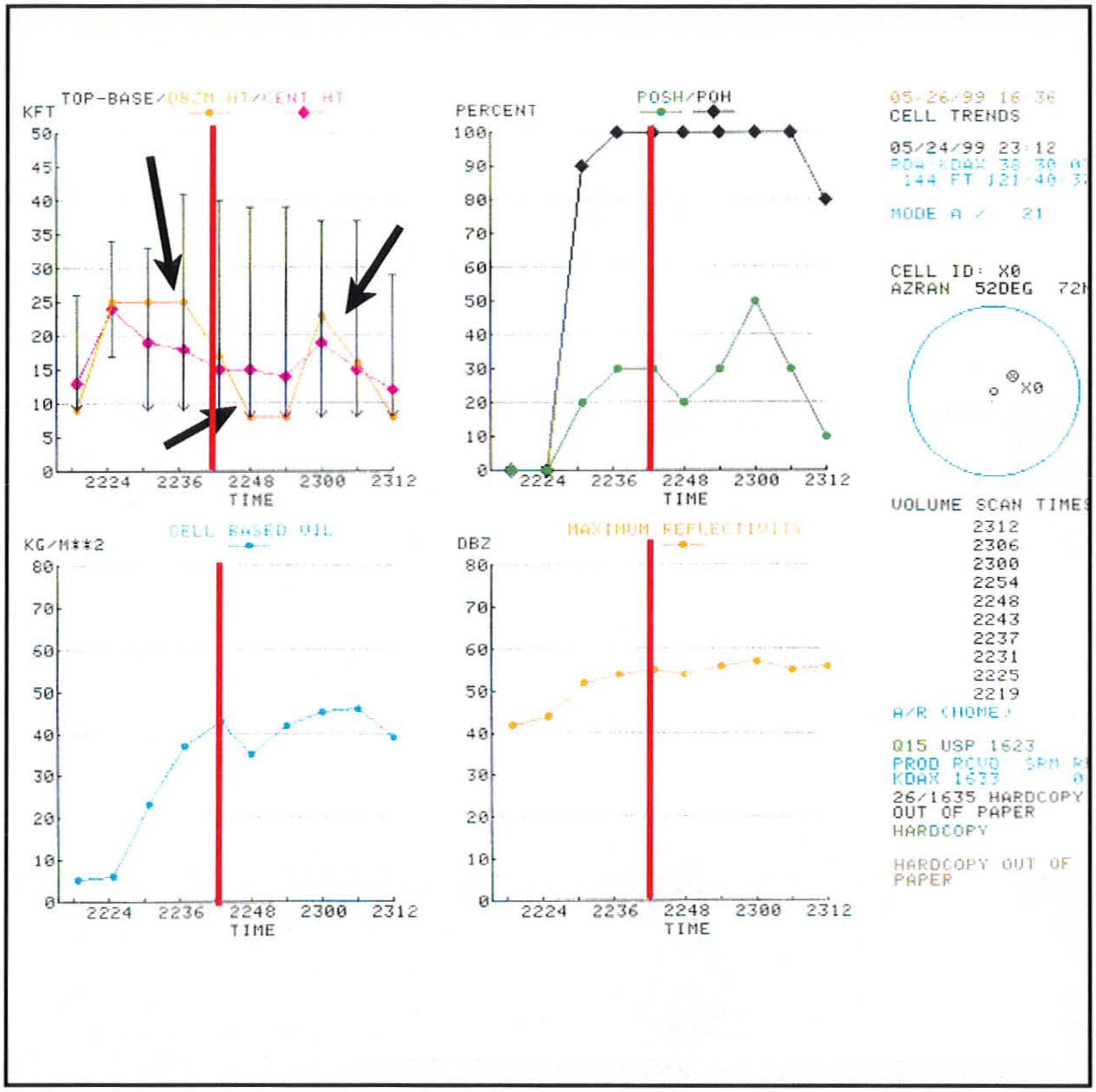

Figure 7. KDAX cell trends data for the period 2218 to 2312 UTC on 24 May 1999. This storm produced 4-cm (1.5 inch) size hail between 2230 and 2250 UTC. The highest POSH was 50 percent which occurred at 2300 UTC. The red line notes 2240 UTC when the hail was reported at the CSSL.

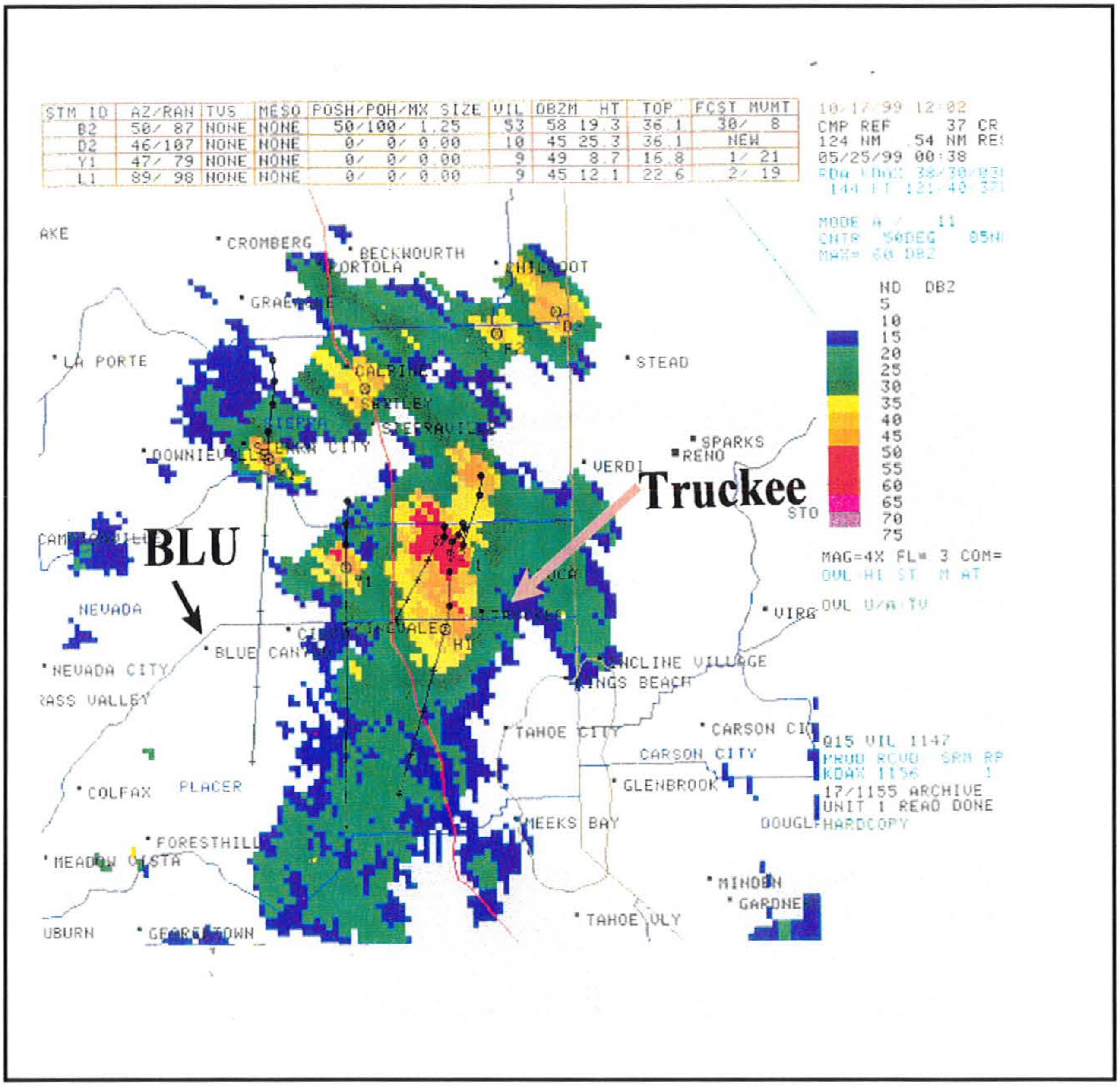

Figure 8. KDAX composite reflectivity at 0038 UTC 24 May 1999. This intense thunderstorm dissipated near the Sierra crest which is noted by the thin red line.

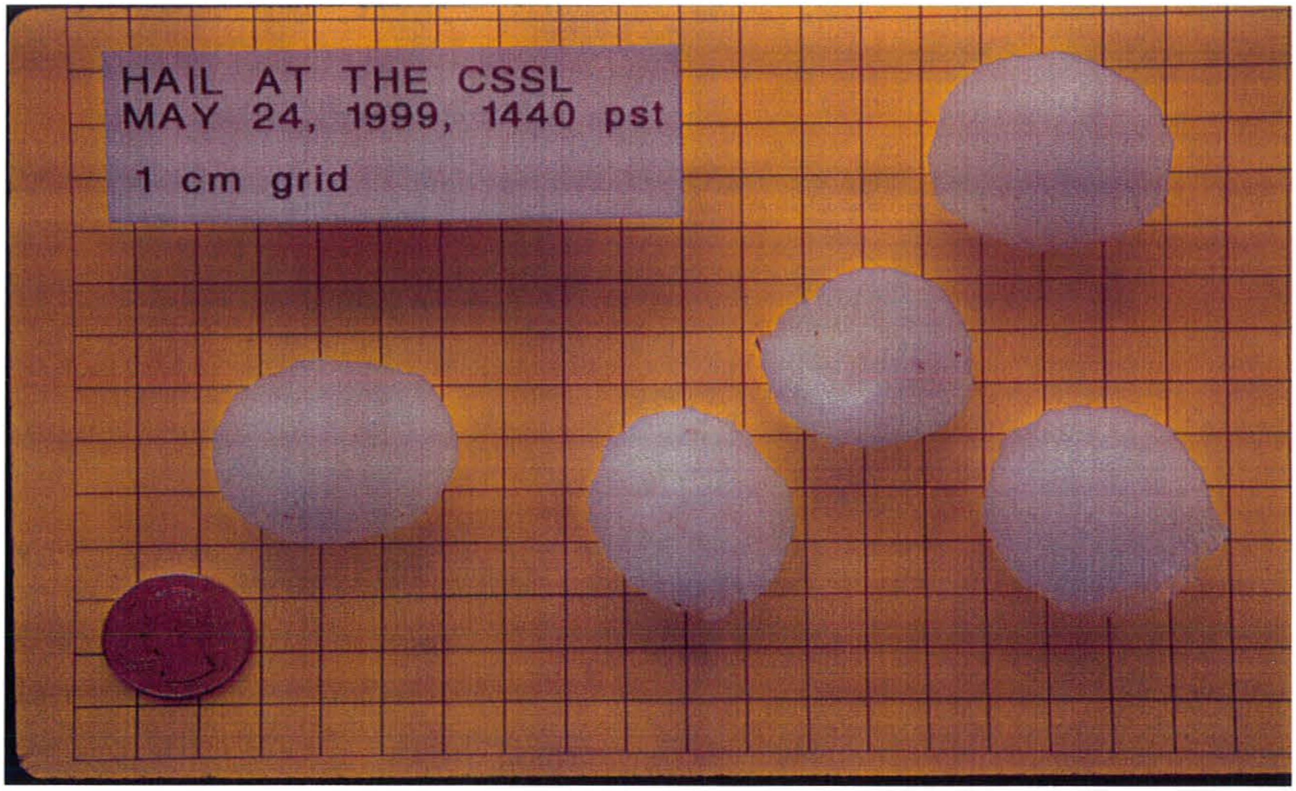

Photo courtesy of Randall Osterhuder of the Central Sierra Snow Lab (CSSL)