DOCUMENTATION OF AN EF1 TORNADO IN THE SIERRA NEVADA FOOTHILLS OF NORTHERN CALIFORNIA

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1. Introduction

Ample research has been accomplished on tornadic thunderstorm development, structure, and climatology in California, including the interior Central Valley of California (Lipari and Monteverdi 2000, Monteverdi et al. 1994a, 1994b, 1996, 2000a, 2000b, 2001, 2003, and Blier and Batten 1994.) Northern California tornadoes typically occur in a favorable meteorological environment as shown in Figure 1.

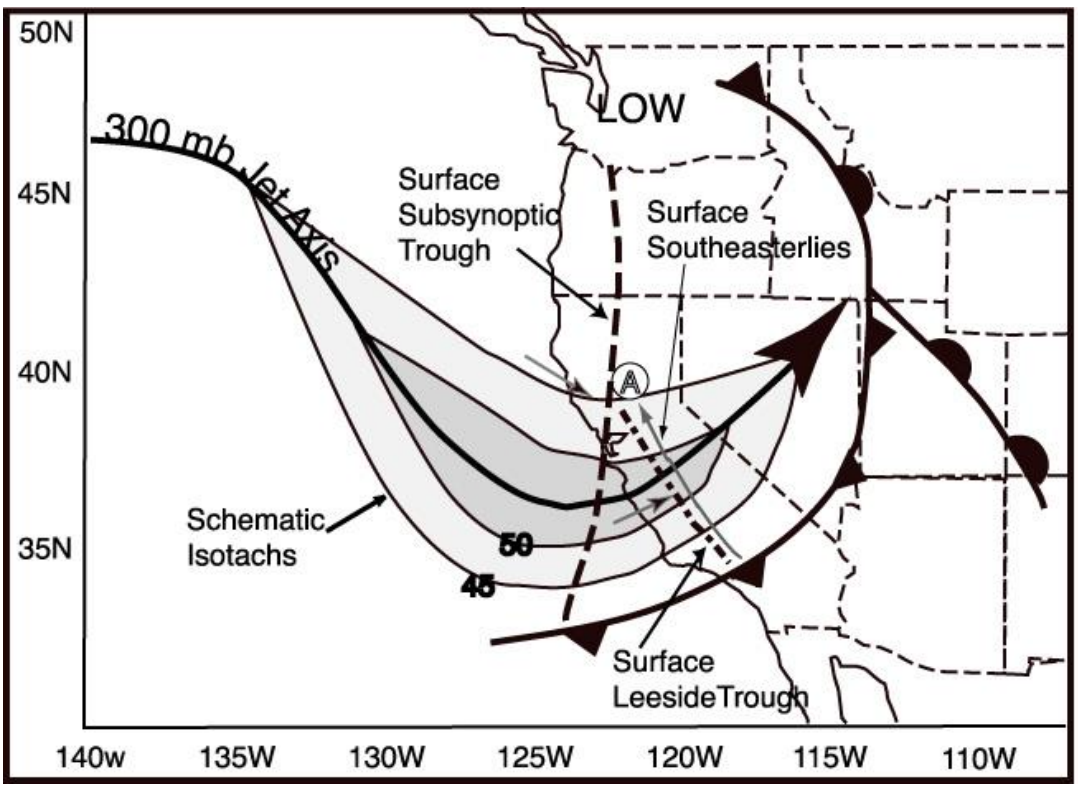

Figure 1. Schematic chart showing location of major features associated with tornado events in California's Central Valley. Schematic isotachs are labeled in meters per second. Location of subsident flow west of leeside trough and surface southeasterlies in central and eastern Central Valley shown by light gray arrows. The letter "A" shows area of major focus for supercell thunderstorm formation (Monteverdi et al. 2000a, 2003).

The synoptic scale pattern, environmental conditions, and radar signatures associated with northern California tornadoes have been fairly well established. However, the weaker, short-lived tornadoes typical in northern California still present a challenge in warning decision making. According to Snow et al. (2007), "…75 percent of the time, a tornado forecast (warning) is a false alarm." Comparatively, since 2007, two out of three (66.7%) of WFO Sacramento's (STO) tornado warnings were unverified according to statistical data from NWS Performance Management (**https://verification.nws.noaa.gov/**).

One significant factor is that northern California tornadoes have a lower Probability of Detection (POD) than other parts of the country. For example, the POD in the Weather Forecast Office Sacramento, CA (WFO STO) County Warning Area (CWA) is 0.271 since the inception of storm-based warnings in 2007, compared to 0.767 for the Norman, OK (OUN) CWA. (See Appendix for STO tornado statistics from NWS Performance Management.)

This study documents a typical northern California tornado event, which occurred on 23 November 2010, and matches the findings of previous research regarding Central Valley tornadoes. In addition, a section on how lightning data could have aided the warning process is included in Part 3. Although lightning data and lightning polarity reversal prior to and during tornadic events has been well studied in other parts of the United States, very little research has been conducted on lightning and lightning polarity reversal prior to and during tornadoes in northern California.

On 23 November 2010, the location of the middle and upper-level trough, jet stream axis, and the surface features were similar to the synoptic features associated with tornadoes in the Central Valley of California (Fig. 2). This study focuses on the supercell thunderstorm that produced an EF1 tornado in the Sierra Nevada foothills near Latrobe, CA in El Dorado County (Figs. 3-5).

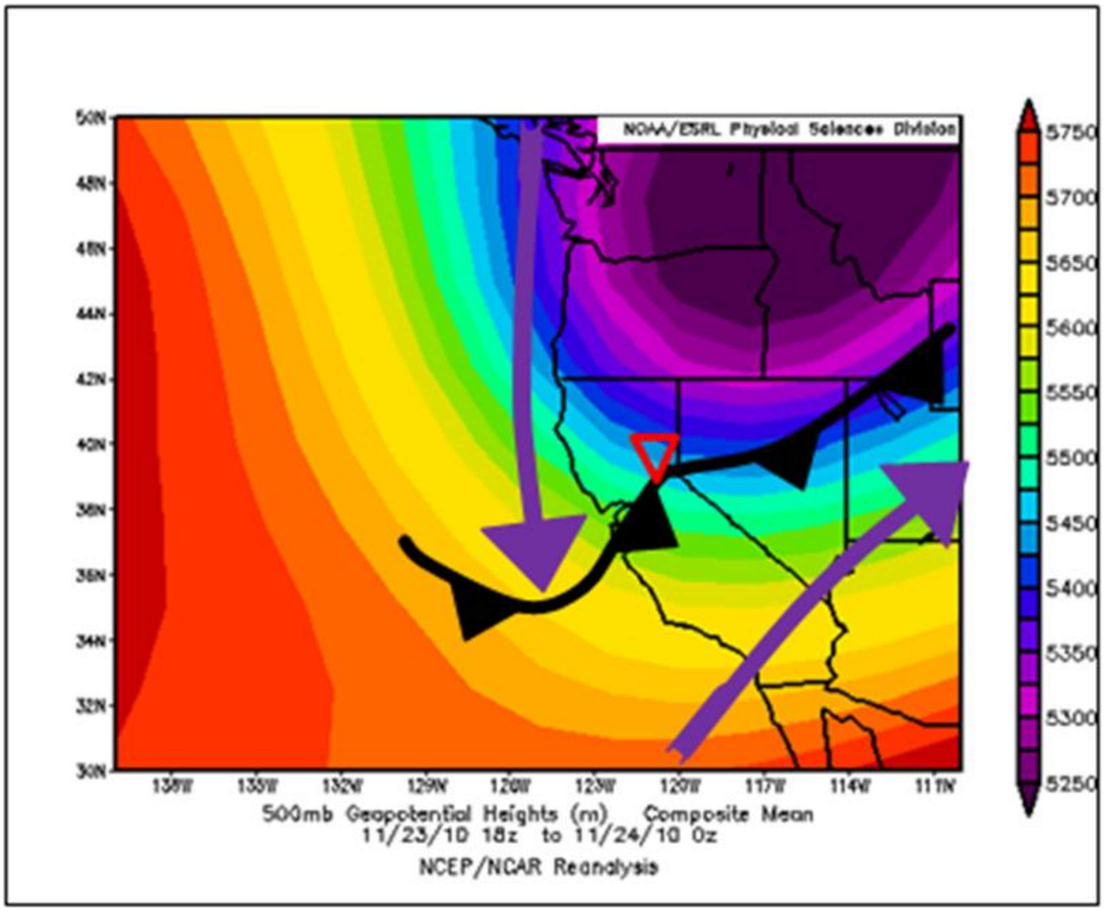

Figure 2. Schematic chart showing major synoptic features on 23 November 2010. NCEP/NCAR Reanalysis 500mb Geopotential Heights Composite Mean 11/23/2010 1800 UTC to 11/24/2010 0000 UTC (m, color shaded), 300mb jet axis (purple lines with arrows) and surface front at 2100 UTC (black). Red inverted triangle (▽) shows relative location of Latrobe, CA tornado

Figure 3 . Funnel cloud/tornado near Latrobe, CA, in El Dorado County, on 23 November 2010. From KCRA News.   Approximately 2117 UTC (1:17 PM LT).

Figure 4. Aerial view of tornado location near Latrobe, CA on 23 November 2010. Tornado tracked from west to east crossing Wetsel-Oviatt Rd and Latrobe Rd denoted by red inverted triangles and red dashed line.

Figure 5. Close-up aerial view of tornado track near Latrobe, CA on 23 November 2010. Tornado track denoted by red dashed line. Building damage denoted by red number 1, water tank dislodged denoted by red number 2, and tree damage denoted by red number 3.

2. Case Study

Northern California tornadoes usually occur in the late fall, winter and spring, are post-frontal, and often associated with low-topped (shallow) thunderstorms involving cold core mid-level lows (Monteverdi and Quadros, 1994a, 1994b, Davies, 2006). On 23 November 2010, the atmosphere exhibited similar instability and shear parameters described by Lipari et al. (2000), Monteverdi et al. (2000a, 2003) and Thompson et al. (2003).

Figure 6 shows the NAM model sounding near Latrobe, CA modified to the 23 November 2010 2100 UTC surface observation at Sacramento Executive Airport (KSAC). The modified Convective Available Positive Energy (CAPE) value nearly doubled from 398 J/Kg to 772 J/Kg.

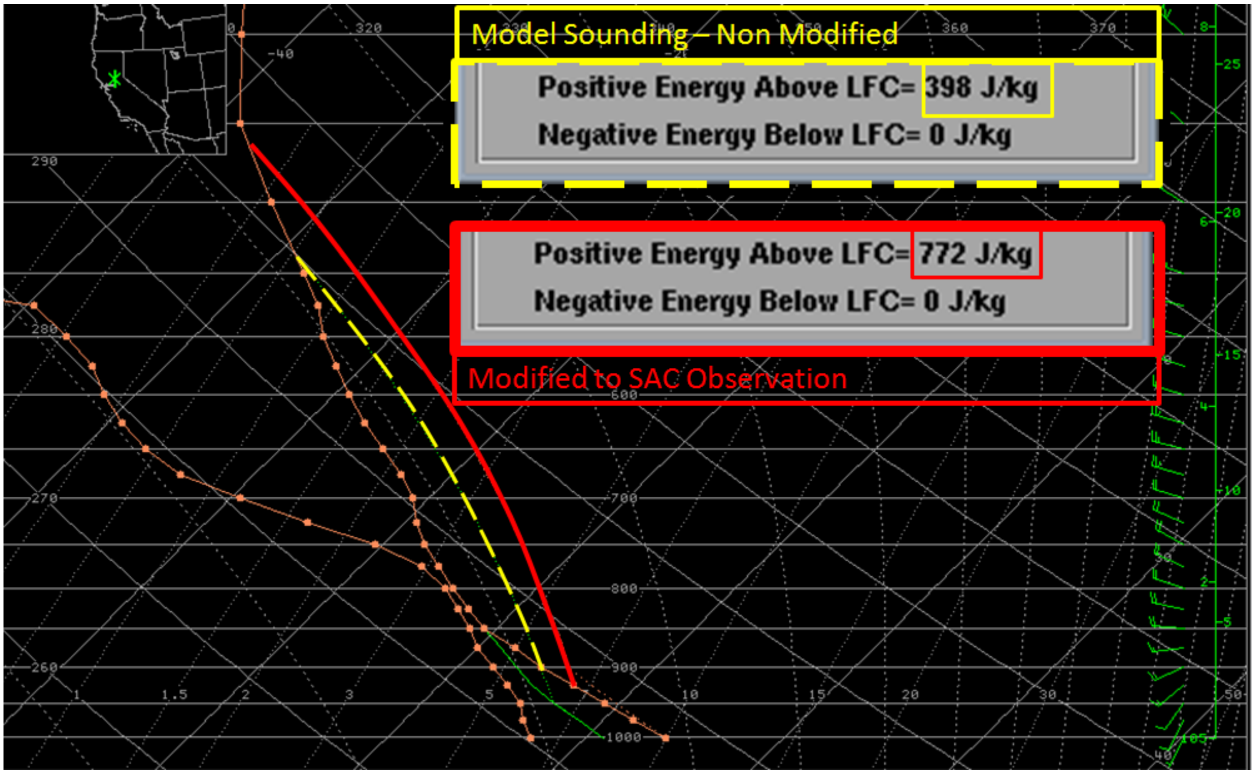

Figure 6. Modified NAM model sounding to Sacramento Executive Airport 11/23/2010 2100 UTC Observation. Notice almost doubling of the Positive Energy above the LFC (Level of Free Convection) value.

The 0-1 kilometers (km) Total Shear value of 14 ms^{-1} and the 0-6 km Total Shear value of 42 ms^{-1} were plotted on a Total Shear Chart (Fig. 7). These Total Shear values fell within a very favorable range for F1 and F2 tornadoes described by Monteverdi (2000a, 2003). It should be noted that the original F-scale was updated to the Enhanced F (EF) Scale by a team of meteorologists and wind engineers in the United States on 1 February 2007 (Table 1, see Appendix).

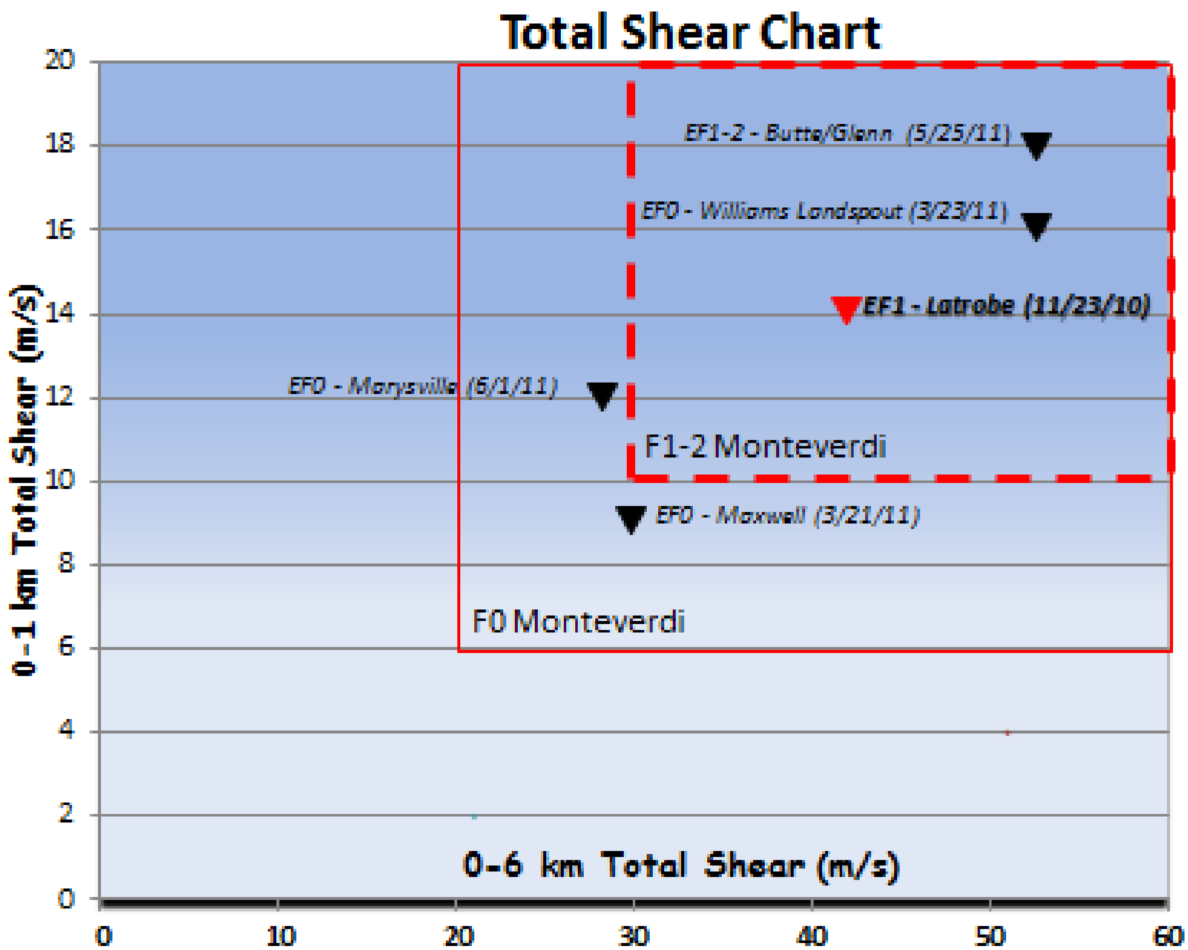

Figure 7. 0-1 km (vertical axis) and 0-6 km (horizontal axis) Total Shear Chart for 2010-2011 northern California tornadoes adapted from Monteverdi et al. (2000a, 2003). Note the shear parameters for the Latrobe, CA tornado (inverted red triangle, upper right) fell within the EF1-2 portion of the chart. Solid red (dashed red) box denotes F0 (F1-2) values found by Monteverdi. Black inverted triangles denote chart vales of four other northern California tornadoes found during the study period.

At 2117 UTC (1:17 PM LT), two thunderstorms with hook echoes developed in the strong convergence zone in the proximity of a cold front moving eastward into the Sierra Nevada foothills, and by topographic channeling of the winds east of the lee-side trough (Fig. 8). This synoptic pattern (Fig. 2) can contribute to favorable shear profiles and instability for the development of low-topped or miniature supercell thundestorms (Monteverdi and Quadros, 1994).

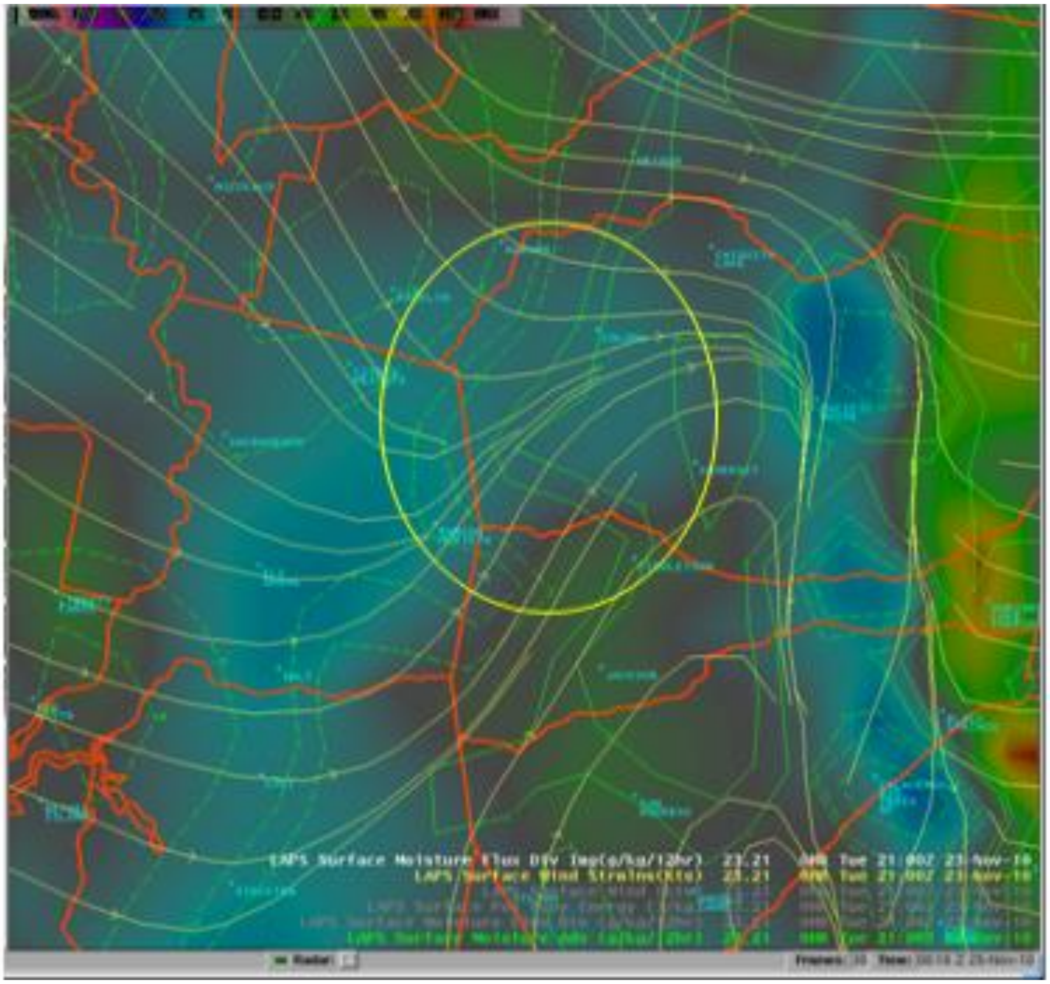

Figure 8. LAPS 2100 UTC 23 November 2010 Surface Moisture Flux Divergence and Surface Wind Streamlines. Strong moisture convergence (blue shade) and wind convergence (yellow streamlines) noted within the yellow circle in the Sierra Nevada foothills.

Radar imagery from the KDAX WSR-88D (Weather Surveillance Radar, 1988 Doppler, Sacramento-Davis, CA) showed strong supercellular characteristics. In addition to the hook echo, the northernmost storm exhibited a tight reflectivity gradient on the inflow or south side of the thunderstorm, a BWER (Bounded Weak Echo Region), V-notch, and a cyclonically-rotating inflow/outflow couplet (Figs. 9 and 10). These are the essential radar signatures of a supercell thunderstorm (Falk, 1997).

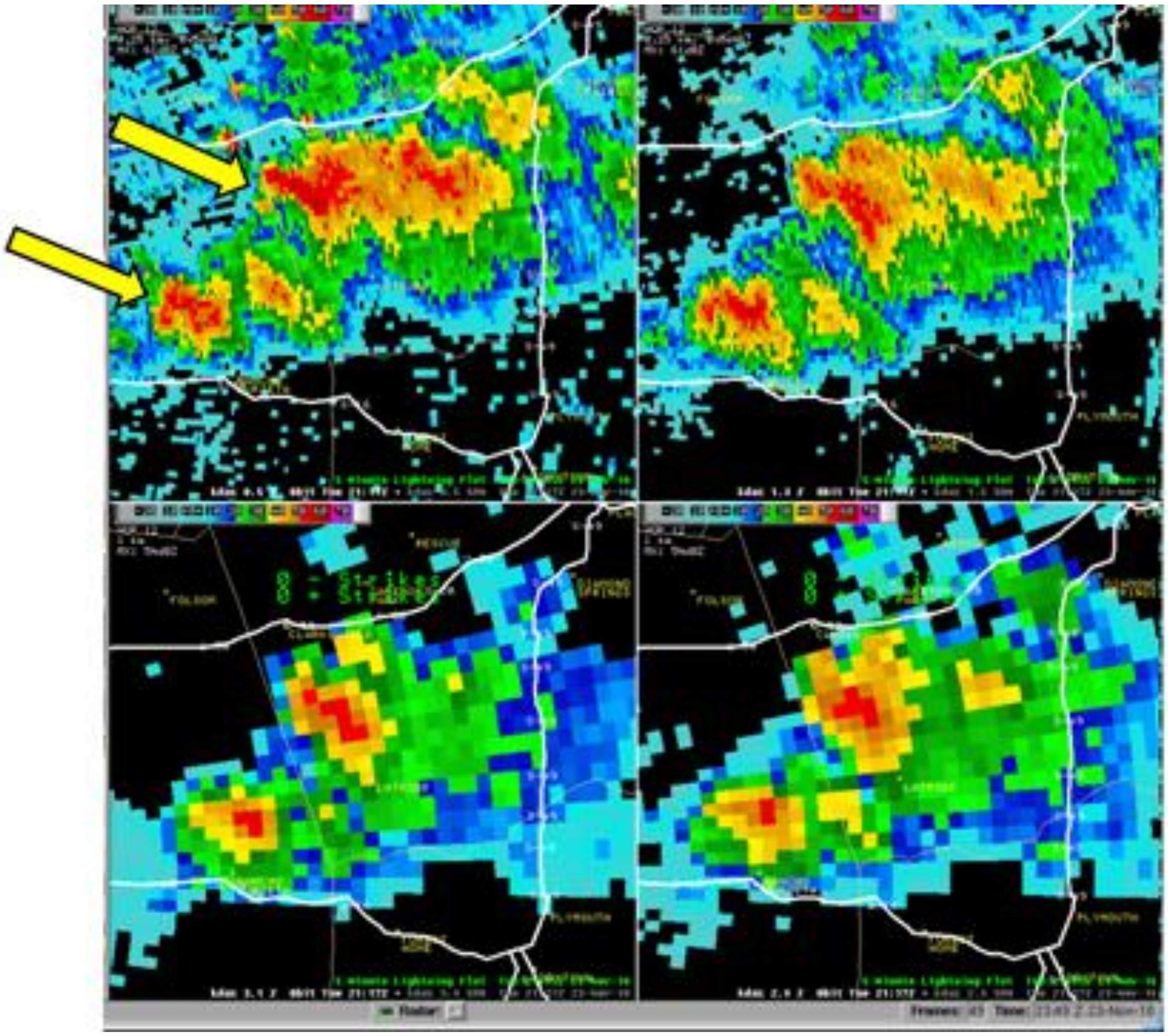

Figure 9. KDAX 2117 UTC 23 November 2010 Reflectivity four-panel, 0.5 degree elevation (upper left), 1.3 degree elevation (upper right), 2.4 degree elevation (lower right), 3.1 degree elevation (lower left). Yellow arrows denote hook echoes.

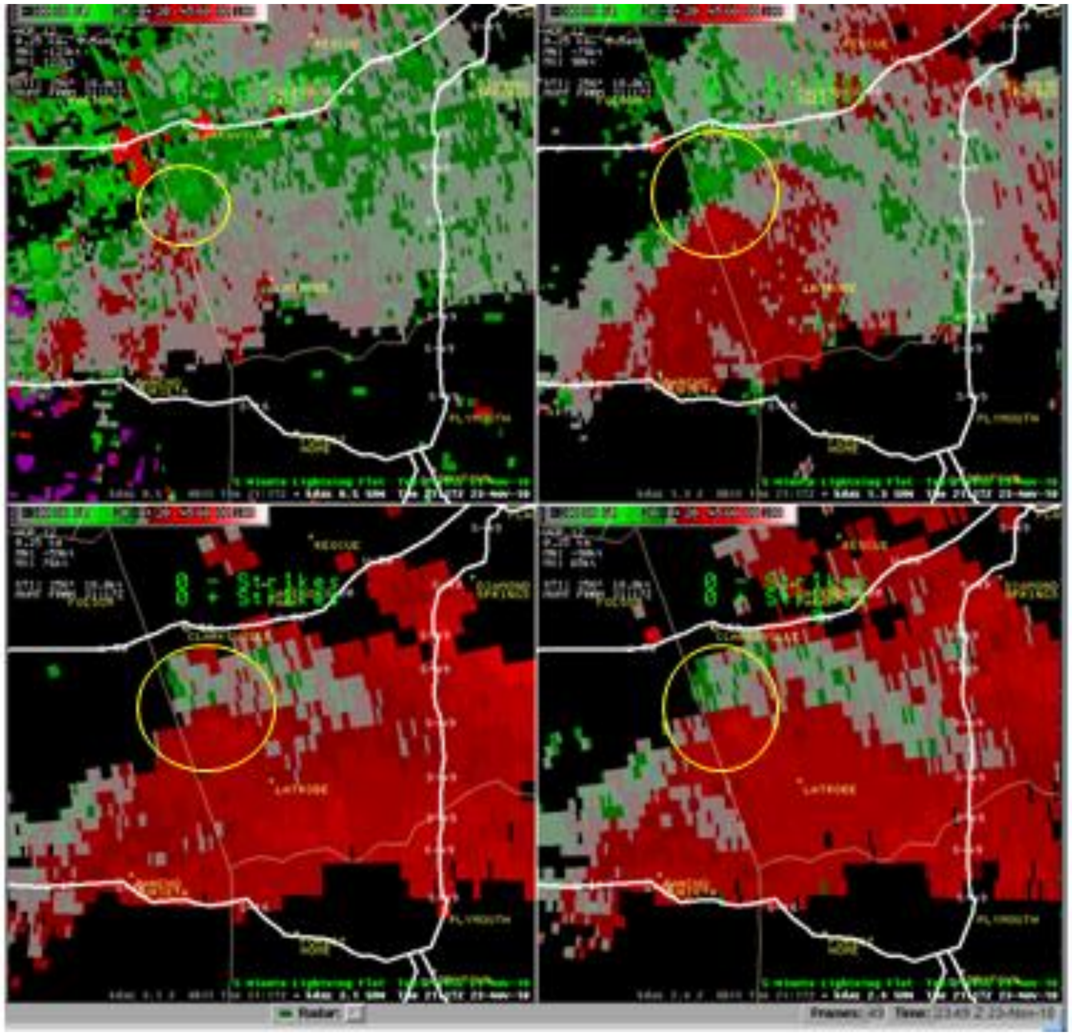

Figure 10. KDAX 2117 UTC 23 November 2010 Storm Relative Motion (SRM) four-panel, 0.5 degree elevation (upper left), 1.3 degree elevation (upper right), 2.4 degree elevation (lower right), 3.1 degree elevation (lower left). Yellow circles denote inbound/outbound couplet and the tornadic circulation.

According to eyewitnesses, a tornado occurred with the northernmost supercell at approximately 2117 UTC (1:17 PM LT), although it is uncertain where and when the photo in Figure 3 was taken. The damage survey conducted by WFO Sacramento, CA, concluded an EF1 tornado occurred with maximum winds up to 45 ms^{-1} (100 MPH). The Local Storm Report (LSR) and other photos of tornado damage can be seen in the Appendix section. Although the duration of the tornado is uncertain, radar indicated storm rotation began as early as 2108 UTC (1:08 PM LT) and persisted through 2142 UTC (1:42 PM LT).

Comparing the Storm Relative Mean Radial Velocity (SRM) from the 2117 UTC, 2121 UTC, and 2125 UTC volume scans revealed the maximum rotational velocity V($_r$), occurred at the 2121 UTC (1:21 PM LT) volume scan, a few minutes after the tornado was sighted by eyewitnesses. Using the following equation for rotational velocity (V_r) (Andra, 1997) where V_i and V_0 are the maximum inbound and outbound winds:

$$Vr = \frac{|Vi| + |Vo|}{2}$$

the rotational velocity was approximately 19.5 knots at the 0.5 elevation angle (Fig. 11), and 23.5 knots at the 1.3 elevation angle (Fig. 12), at a distance of 31 nautical miles (nm) from the KDAX radar.

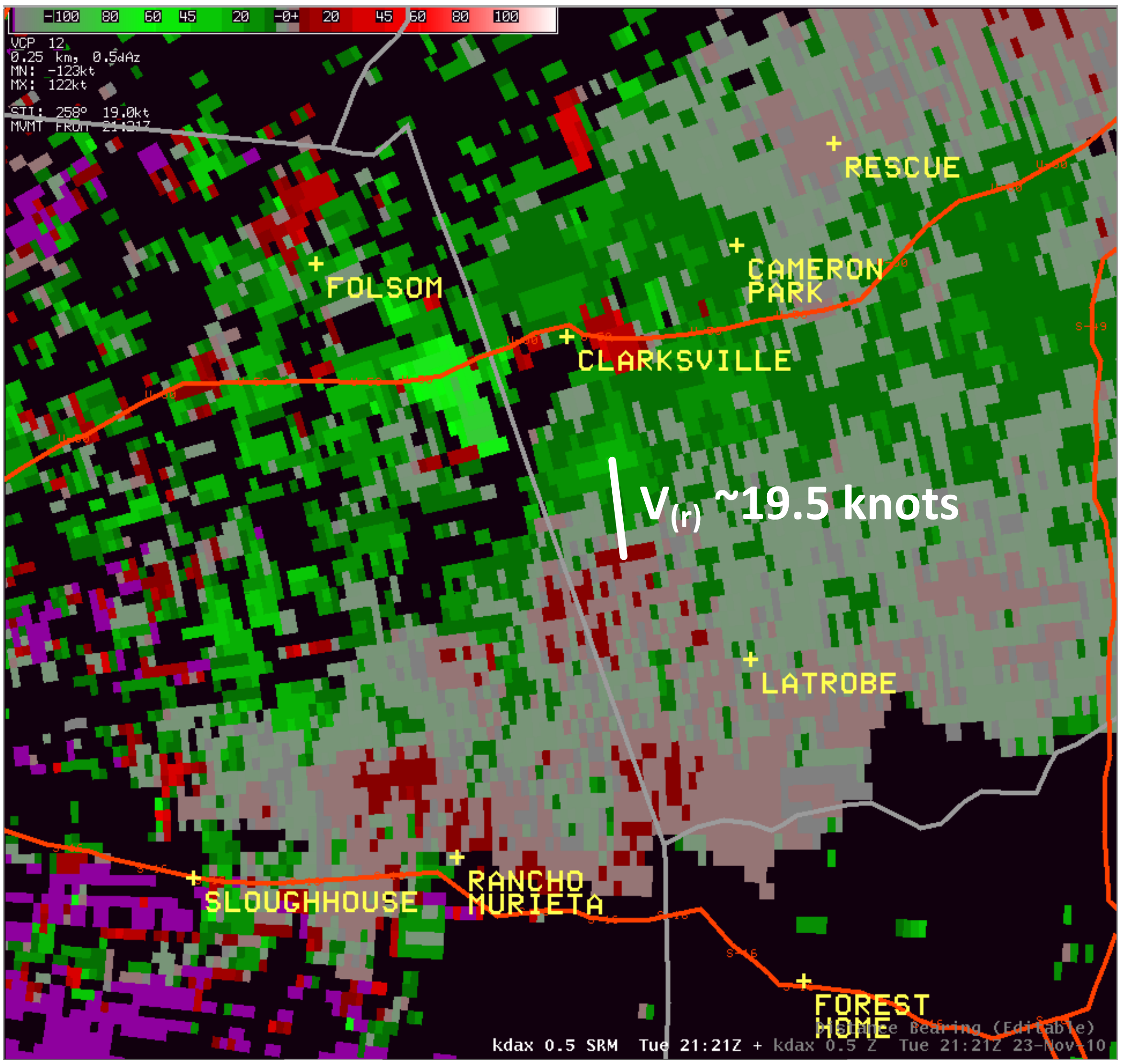

Figure 11. KDAX 2121 UTC 23 November 2010 Storm Relative Motion (SRM), 0.5 degree elevation annotated with $V_{(r)}$ value.

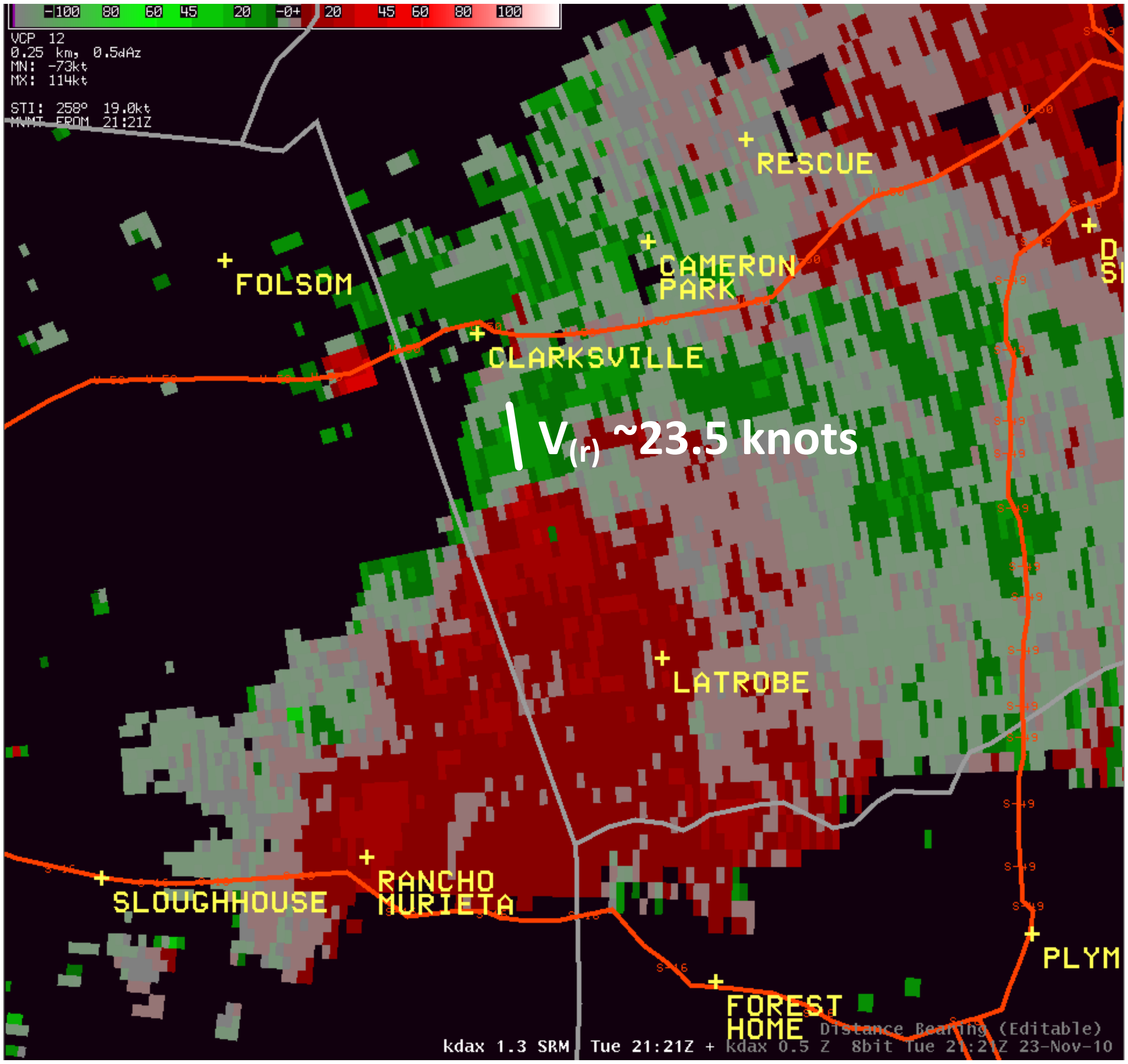

Figure 12. KDAX 2121 UTC 23 November 2010 Storm Relative Motion (SRM), 1.3 degree elevation annotated with $V_{(r)}$ value.

The rotational velocities (V_r values) would fall within the "Weak Shear" value for the 0.5 elevation angle and "Minimal Mesocyclone" for the 1.3 elevation angle on the 1.0 nm and 2.0 nm Nomogram Chart developed by the Operational Support Facility (OSF) for determining mesocyclone strength in supercell thunderstorms (NSSL and OSF, 1997). It is very common for northern California tornadoes to be associated with "weak shear" or "minimal mesocyclone" rotational velocity values in reference to the 1.0 nm to 2.0 Nomogram Chart (Fig. 13). Often these weaker rotational velocities result in circulations that are challenging for Doppler radars to resolve, hence, there is a reliance on public and/or spotter reports for sightings of funnel clouds and tornadoes.

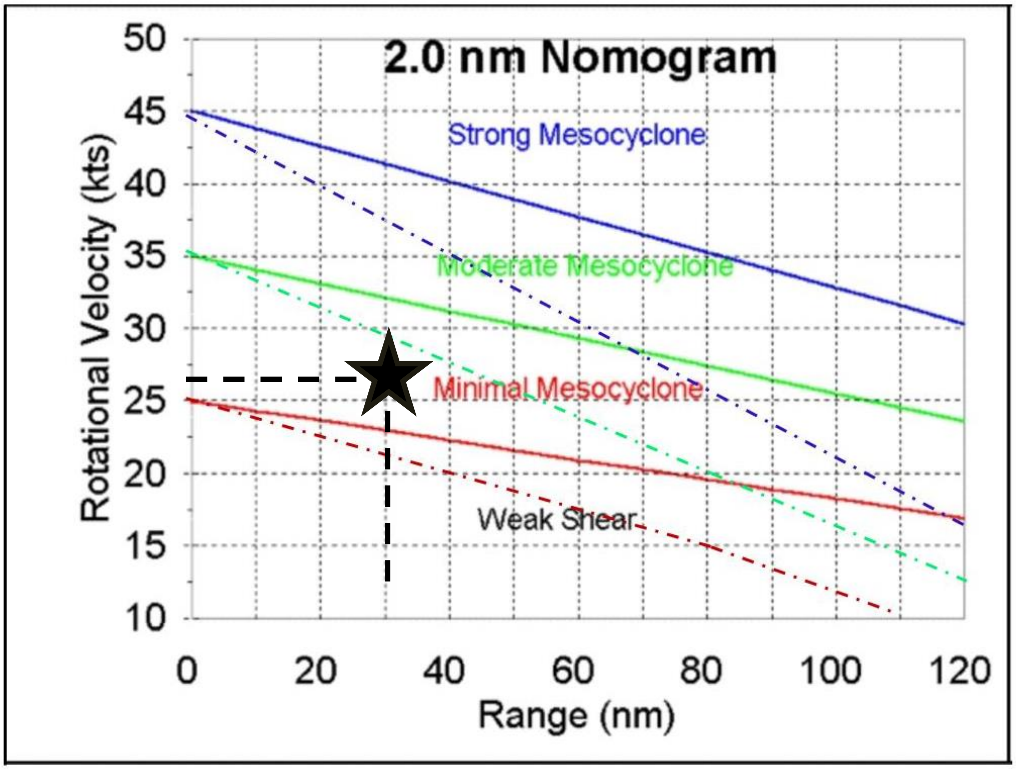

Figure 13. Mesocyclone Recognition Nomogram (Andra, 1997). 2.0 nm Nomogram (solid colored lines), 1.0 nm Nomogram (dotted colored lines). Rotational velocity value plotted for Latrobe, CA tornado (black star). See text for details.

Forecasters in Shreveport, LA developed a rotational shear nomogram which takes into account both the rotational velocity and the diameter of a mesocyclone and is believed to be more applicable to mini supercell thunderstorms with smaller mesocyclone diameters typical for northern California tornadoes. Rotational shear is calculated from the equation:

$$Sr = \frac{2Vr}{D}$$

Where S_r is rotational shear (s^{-1}), V_r is rotational velocity (ms^{-1}), and D is mesocyclone diameter (m) (NSSL, 1997). Using the V_r value in Figure 12, a rotational shear (S_r) value of 0.0065 s^{-1} was calculated for a range of 31 nm. On the Rotational Shear Nomogram developed by Falk and Parker (1998), this value would fall within the “minimal mesocyclone” category (Fig. 14), confirming the result from the Mesocyclone Recognition Nomogram above.

The V_r shear function on the WSR-88D display can also be used to calculate rotational shear (S_r) values on mesocyclones.

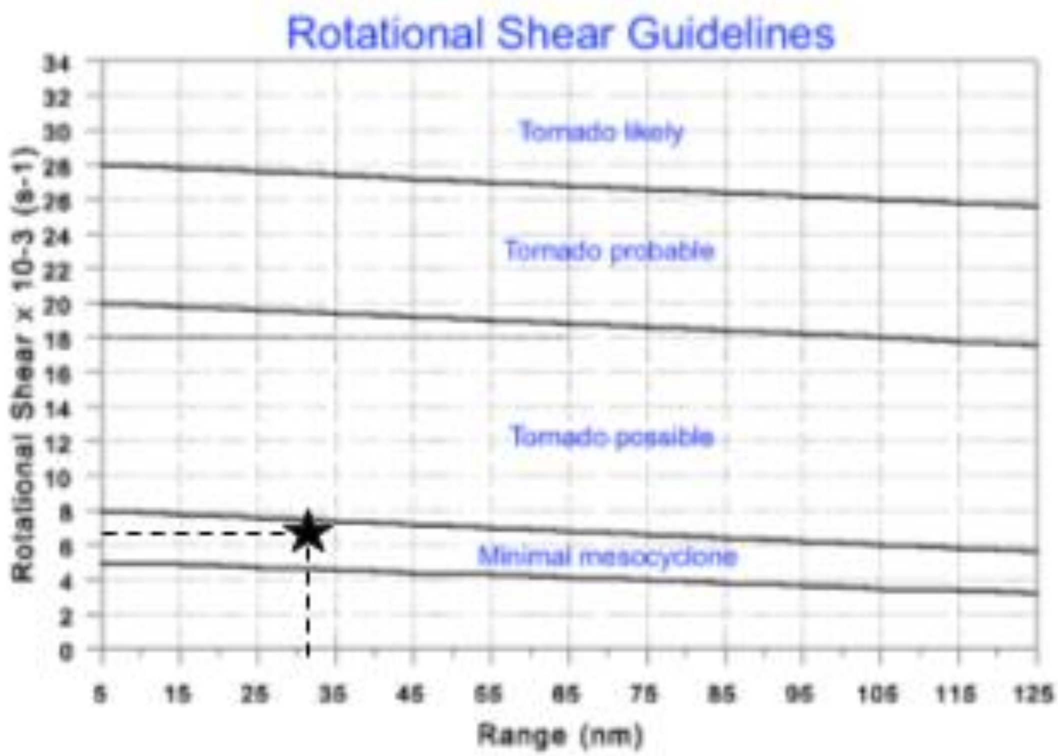

Figure 14. Rotational Shear Nomogram (Falk and Parker, 1998). Rotational Shear value plotted for Latrobe, CA tornado (black star). See text for details.

The Local Area Processing System (LAPS) 2100 UTC sounding from 23 November 2010 showed a veering wind profile from southwest to northwest winds and increasing wind speeds from 2.6 ms^{-1} (5 knots) near the surface to 23 ms^{-1} (about 45 knots) at about 4 km or 13,100 feet (Fig. 15). Because of the low-topped nature of the storm the average wind off the LAPS sounding (275° at 26 knots or 13 ms^{-1}) was a better estimate of the storm motion than the forecast storm motion of 305 degrees at 19 knots (9.8 ms^{-1}) using the 30R75 method, and Bunkers method for the expected storm motion for a right-mover of 305° at 13 ms^{-1} or 26 knots.

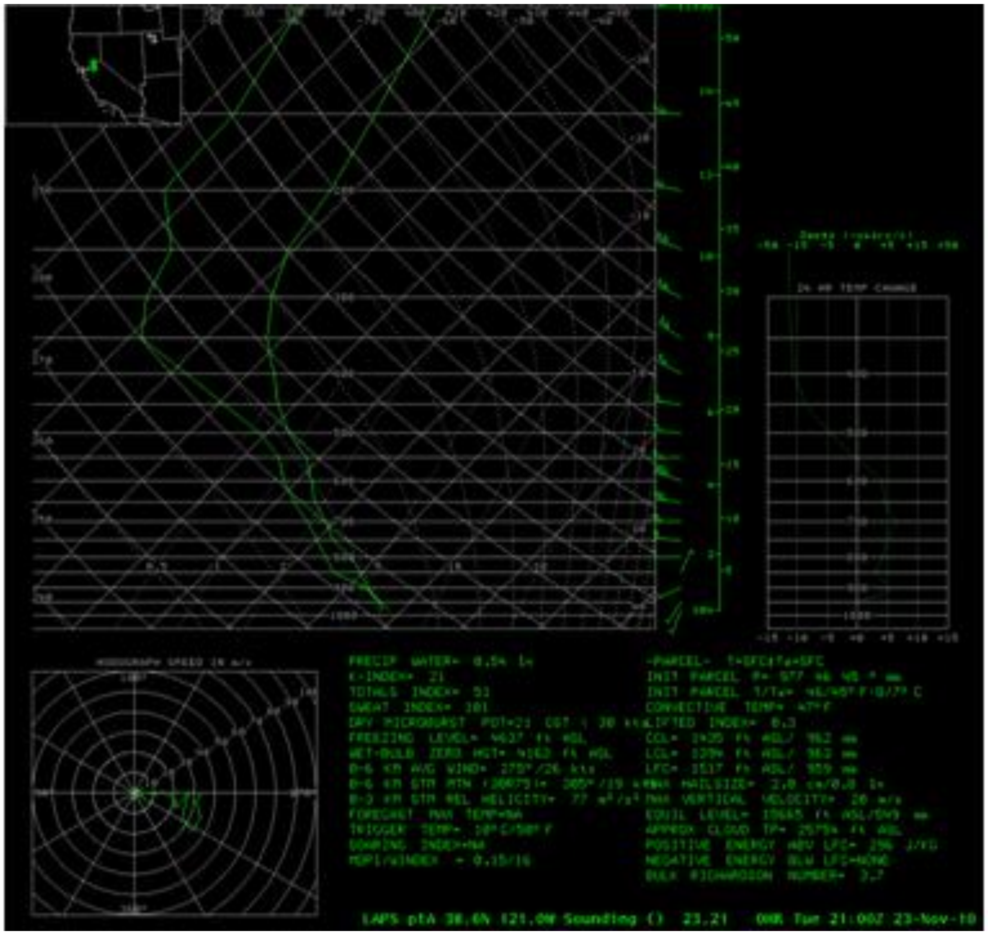

Figure 15. 2100 UTC 23 November 2010 Local Area Processing System (LAPS) proximity sounding near Latrobe, CA (El Dorado County). Hodograph in bottom left portion.

The hodograph supported a storm motion from west to east at 13 ms^{-1} or about 25 knots (Fig. 16). Analysis from the Weather Event Simulator (WES) workstation showed a storm motion from west to east at 14 knots (from 264° at 7.2 ms^{-1}). Northwest flow at 6 km (about 20,000 feet) as indicated by the LAPS sounding and the hodograph explained the northwest to southeast orientation of the radar echoes in the mid to upper-levels, or anvil portion, of the storm.

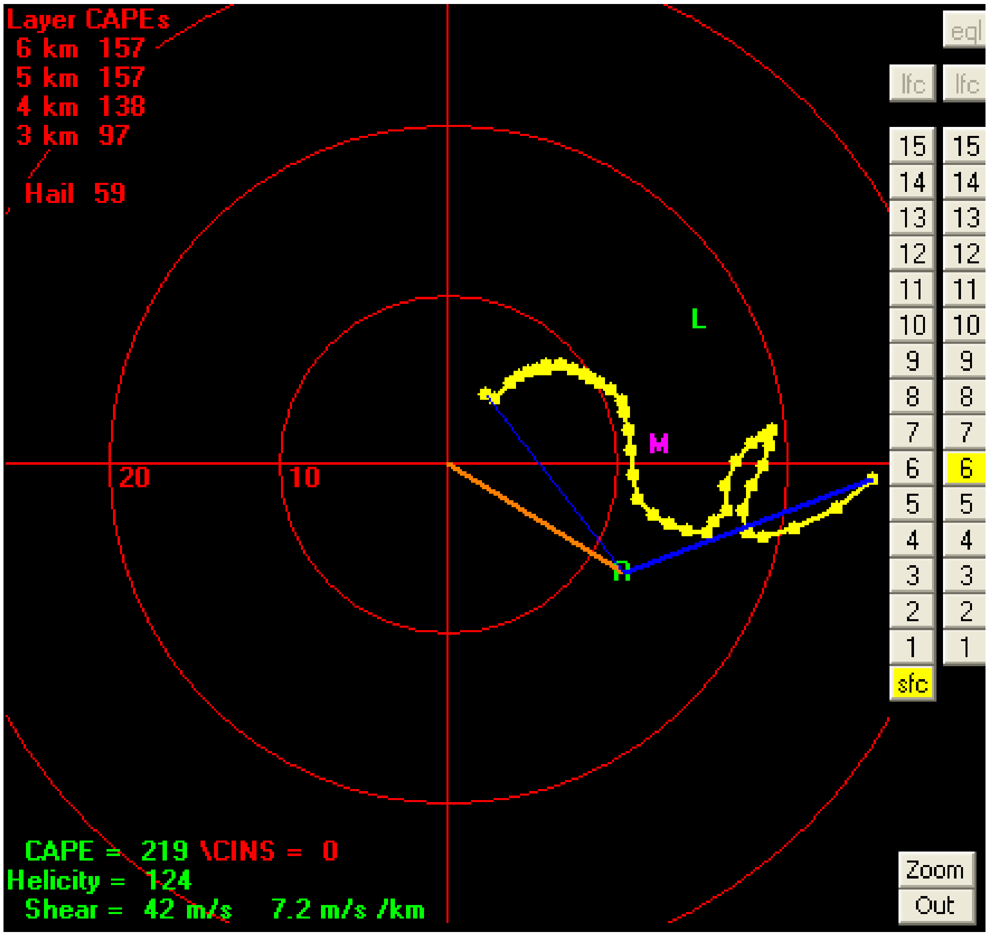

Figure 16. BUFKIT NAM model forecast hodograph for Sacramento, CA 2100 UTC 23 November 2010. "M" forecast storm motion to the east at about 13 ms^{-1}. "R" and "L" indicate right and left-moving storms.

The Echo Tops (ET) product showed a maximum storm top up to 22,000 feet with this storm. Considering the depth of the cyclonic circulation from the 0.5 degree elevation to 3.1 degrees elevation, the cyclonic circulation occurred within 50 to 55 percent of the storm. On an order of scale, this would be equivalent to some Plains tornadoes with a storm top of 60,000 feet and a cyclonic circulation or mesocyclone up to at least 30,000 feet.

Burgess et al. (1995) referred to thunderstorms lower than 30,000 feet that exhibited radar signatures including, hook echoes, well-defined weak echo regions (WER), bounded weak echo regions (BWER) and mesocyclones as mini supercells. Mini supercells are smaller than traditional supercells in both the horizontal and vertical extent but still can produce severe weather.

3. Lightning Data

Another helpful tool to assess the tornadic potential of a thunderstorm is lightning data. Lightning research from other parts of the United States has uncovered several theories on how to apply lightning data and lightning polarity reversal as a tool to enhance the tornado warning decision. This study applies those theories to the Latrobe, CA tornadic supercell.

First, researchers discovered that storms dominated by positive lightning have stronger updrafts. Lang and Rutledge (2002) found that large and strong updrafts, greater than 10 ms^{-1}, produced more rain and hail than other storms, and enhanced the regions of net positive charge. According to Snow et al. (2007) researchers in the International H_2O Project found that strong updrafts changed the electrical charge structure within the storm and produced positive lightning. Notice in Figure 17 the location of the positive lightning strike to the east of a developing low and mid-level cyclonic circulation. The 2110 UTC five-minute lightning data identified the positive strike within 10 minutes of the tornado touchdown.

The occurrence of positive lightning strikes with developing thunderstorms should alert the meteorologist of the potential for stronger updrafts within the storm and the greater potential for severe weather. This information could be very useful with thunderstorms in rural areas, where spotter reports are rare or infrequent, and the storm is approaching an urban area.

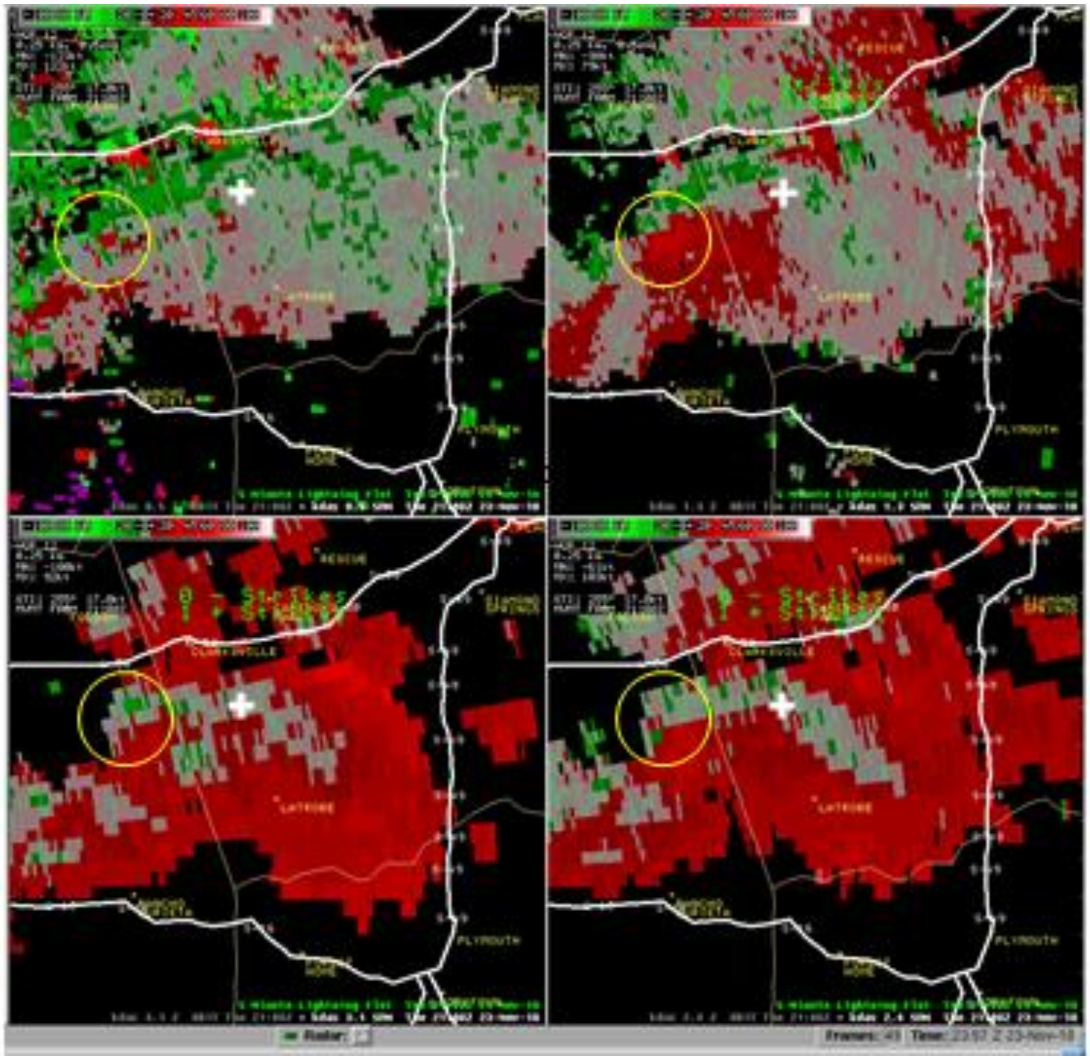

Figure 17. 2108 UTC 23 November 2010 Storm Relative Motion (SRM) four-panel, 0.5 degree elevation (upper left), 1.3 degree elevation (upper right), 2.4 degree elevation (lower right), 3.1 degree elevation (lower left). Notice the location of positive lightning strike east of the developing cyclonic circulation (yellow circle). 2110 UTC 23 November 2010 five-minute lightning plot is overlayed.

Second, Knapp (1994) found that lightning in many storms switched polarity about 10 minutes prior to tornado formation. Although there was a reversal in lightning polarity in the Latrobe, CA tornado event it may not have occurred several minutes prior to tornado formation. Positive lightning strikes were detected on the 2110 UTC and 2120 UTC five-minute lightning plots (Figs. 17 and 18). No lightning strikes were observed on the 2115 UTC five-minute lightning plot. The reversal of lightning polarity to a negative strike within the proximity of the inflow/outflow couplet occurred with the subsequent 2125 UTC five-minute lightning plot (Fig. 19). In this case, the lightning polarity reversal may have occurred a few minutes after the known initial touchdown time at 2117 UTC.

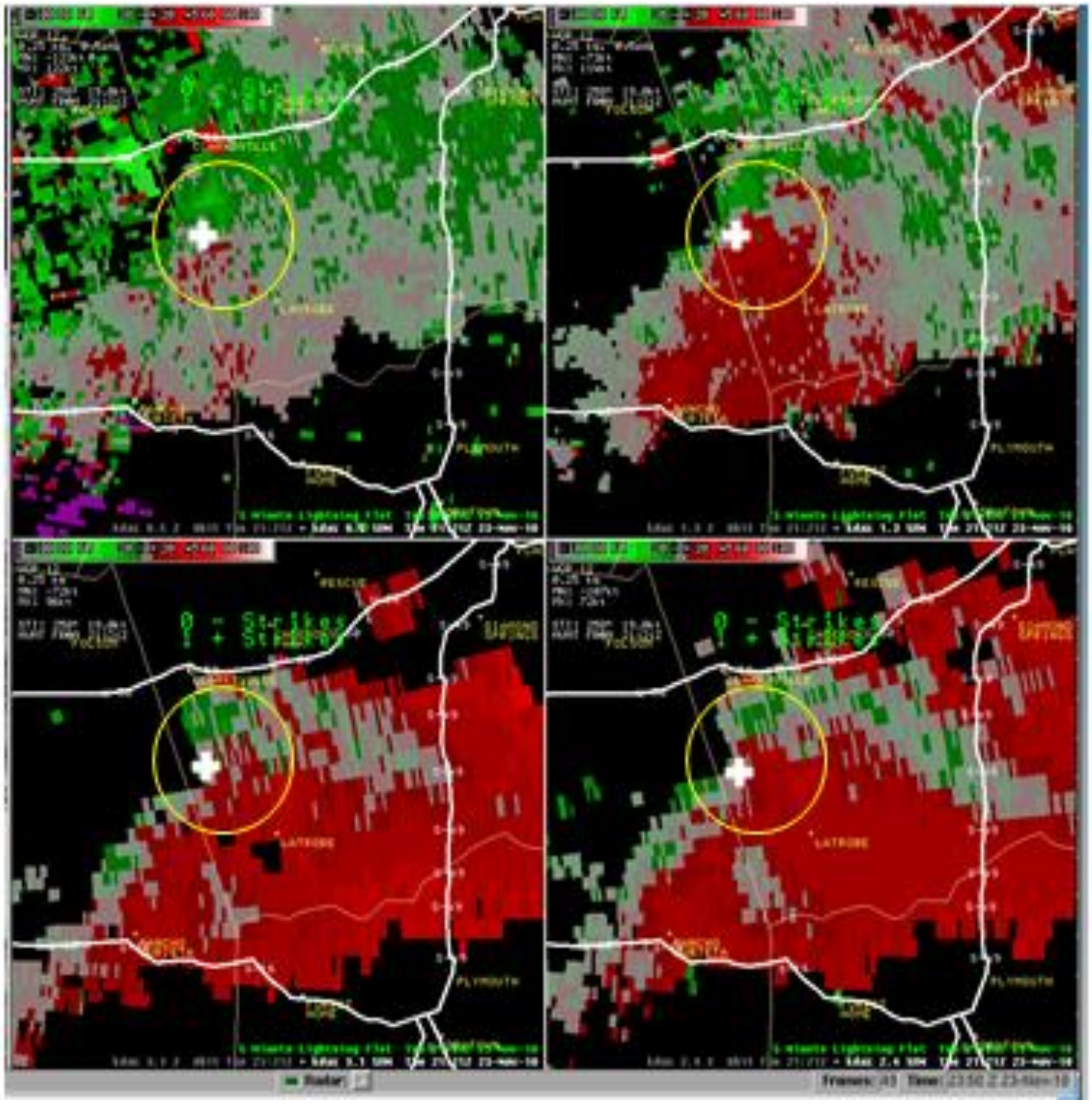

Figure 18. KDAX 2121 UTC 23 November 2010 Storm Relative Motion (SRM) four-panel, 0.5 degree elevation (upper left), 1.3 degree elevation (upper right), 2.4 degree elevation (lower right), 3.1 degree elevation (lower left). Yellow circles denote inbound/outbound couplet and tornadic circulation. Notice the positive lightning strike within the yellow circle from the 2120 UTC 23 November 2010 five-minute lightning plot.

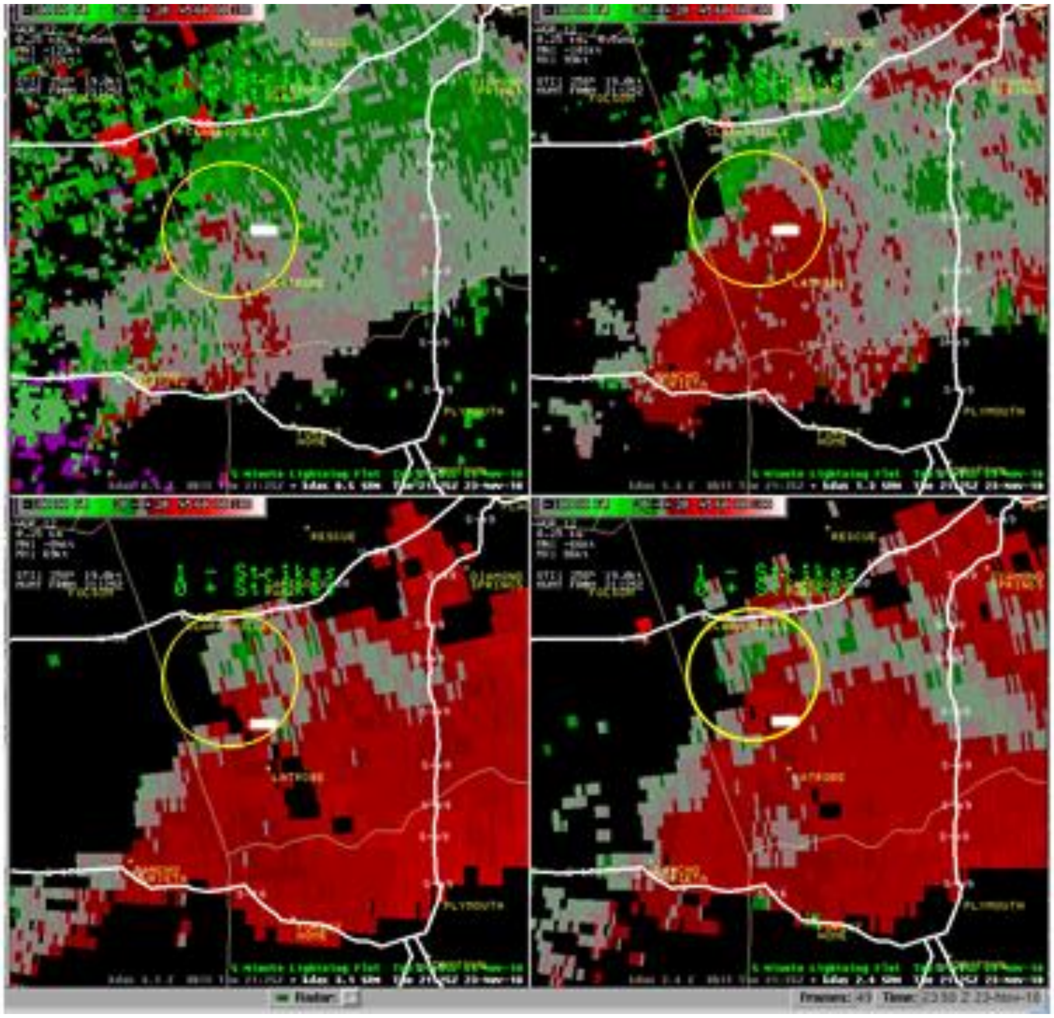

Figure 19. 2125 UTC 23 November 2010 Storm Relative Motion (SRM) four-panel, 0.5 degree elevation (upper left), 1.3 degree elevation (upper right), 2.4 degree elevation (lower right), 3.1 degree elevation (lower left). Notice location and reversal of polarity from positive cloud-to-ground lighting strike in figure 17 to negative cloud-to-ground lightning strike denoted by the white minus sign in relation to the inbound/outbound couplet (within the yellow circle) from the 2125 UTC23 November 2010 five-minute lightning plot.

Third, Snow et al. (2007) found that the spatial pattern of CG lightning strikes changed prior to the tornado. About 20 to 30 minutes before the tornado there was a concentration of CG lighting strikes near the beginning of the tornado path, the strikes continue to be centered around and ahead of the path of the tornado, and that positive strikes were concentrated near the path of the tornado. In the Latrobe, CA tornado the negative lightning strike occurred near the inflow/outflow couplet, and the positive lightning strike occurred ahead of the track of the couplet and tornado (Figs. 18 and 19).

The research primarily dealt with supercell storms and/or a much larger number of lightning strikes than the Latrobe, CA tornado. However, the detection of positive lightning and location of the few lightning strikes that did occur during the Latrobe, CA tornado followed the findings of Snow et al. (2007). In addition to WSR-88D radar images, spotter reports, and the meteorologist's knowledge of the storm structure, lightning data can be used as an additional tool to assist meteorologists in their tornado warning decision and to more precisely predict or anticipate the location and path of possible tornadoes.

4. Conclusion

The 23 November 2010 Latrobe, CA, El Dorado County, tornado was a typical northern California tornado event, and matched the findings of previous research regarding Central Valley tornadoes. The radar exhibited essential radar signatures of a low-topped tornadic thunderstorm or mini supercell including, a hook echo, a bounded weak echo region (BWER), and a tight reflectivity gradient on the storm's inflow side. However, rotational velocity (Vr) and rotational shear (Sr) values fell within the "weak shear" and "minimal mesocyclone" categories on the Mesocyclone Recognition and Rotational Shear Nomograms.

Sometimes, the warning decision for these storms can be difficult because of the relatively weak storm circulations compared to the stronger tornadoes that typically occur in other areas of the United States. In these cases, lightning data, especially a reversal of lightning polarity, may be another tool to assist meteorologists in their warning decision.

Acknowledgements. The author is very grateful to Mr. Paul Schlatter for his review of the paper and invaluable comments. Special thanks to Ms. Kathryn Hoxsie for conducting the damage survey and providing information on the tornado's path, and to Mr. William Rasch for use of the modified NAM model sounding and Total Shear Chart figures.

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APPENDIX

FUJITA SCALE			DERIVED EF SCALE		OPERATIONAL EF SCALE	
F Number	Fastest 1/4-mile (mph)	3 Second Gust (mph)	EF Number	3 Second Gust (mph)	EF Number	3 Second Gust (mph)
0	40-72	45-78	0	65-85	0	65-85
1	73-112	79-117	1	86-109	1	86-110
2	113-157	118-161	2	110-137	2	111-135
3	158-207	162-209	3	138-167	3	136-165
4	208-260	210-261	4	168-199	4	166-200
5	261-318	262-317	5	200-234	5	Over 200

Table 1. Enhanced F Scale for Tornado Damage. Storm Prediction Center. (http://www.spc.noaa.gov/faq/tornado/ef-scale.html)

Local Storm Report

Time: 2010-11-23 21:17 UTC
Event: 0 TORNADO
Source: public
Remark: An EF1 tornado developed near Latrobe, CA in El Dorado County. Winds are estimated at 100 mph with a damage path of two miles. There was damage to the roof of a commercial building, power lines, a small water tower, and to numerous trees.

Storm Damage Photos from the 11/23/2010 Latrobe, CA tornado

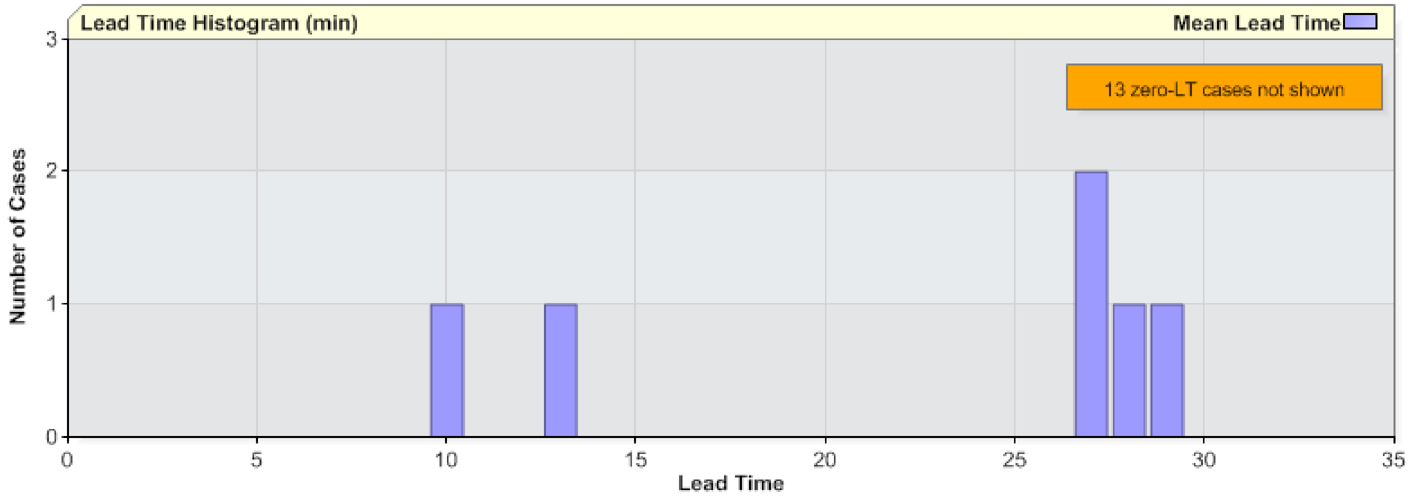

HONDA

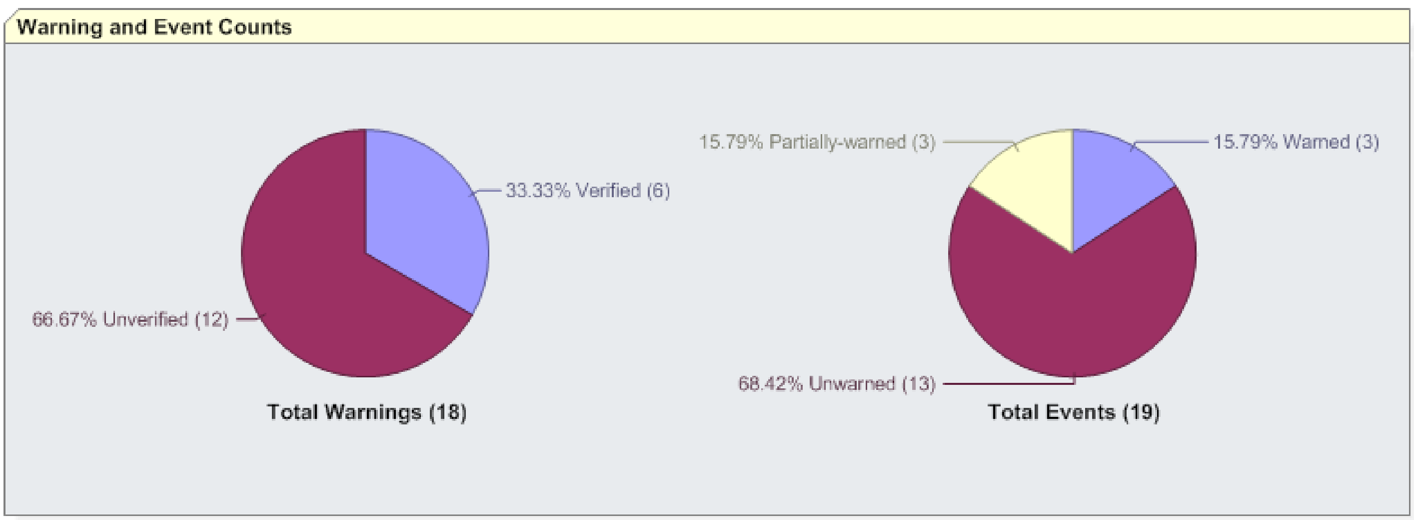
NWS Performance Management - Storm-based Severe Weather Warning Verification

Sacramento, CA (STO)*

Group	Counts						
	Warnings			Events			
	Total	Verif	NOT Verif	Total	Fully Warned	Partially Warned	NOT Warned
STO	18	6	12	19	3	3	13

Statistics							
Scores			Lead Time (min)		Warning Area (sq. mi)		
POD	FAR	CSI	Mean	Initial	Total	Average	County Reduction
0.271	0.667	0.176	7.09	6.84	4308.85	239.38	0.96





*Through 11 June 2013