A CLOSER LOOK AT THE 22 MAY 2008 TORNADIC SEVERE WEATHER OUTBREAK AND FLASH FLOODING IN SOUTHERN CALIFORNIA

Ivory J. Small, Ted Mackechnie, and Steven Vanderburg
NOAA/NWS, San Diego CA

1. INTRODUCTION

On 22 May 2008 a late season, upper level low pressure system dropped south over Nevada (Fig. 1 and Fig. 2). The 5460 meter height contour extended westward into central and southern California, placing the center of the low near the Nevada/Utah border. By afternoon the upper level low center was along the California/Nevada border. The upper low had enough dynamics to generate supercells over southern California. There was flash flooding and accumulating large hail during the late morning. Very strong afternoon convection resulted in flash flooding, accumulating large hail, and 4 tornadoes. Strong vorticity was largely responsible for the strength of this storm system. The envelope of vorticity bounded by a $24 \times 10^{-5}\ s^{-1}$ contour stretched over 750 miles.

The intent of this paper is to give a more detailed mesoscale account of the factors surrounding the severe weather and flash flood events of 22 May 2008 than was given in Small et al., 2009. Further inspection indicates that this scenario had some resemblance to a Midwestern tornado outbreak, and will be discussed. [Also, it should be noted that at the time of this event, severe hail was considered to be ¾ inches in diameter or greater. This may be officially changed to 1 inch in diameter or greater in the near future]. The challenges of rainfall patterns and amounts will be discussed as well.

2. SYNOPTIC SCALE SETUP

During the morning of 22 May 2008 the 500 mb heights and vorticity graphics (Fig. 2) showed a $24 \times 10^{-5}\ s^{-1}$ vorticity contour in excess of 750 miles in length. This was long enough to be considered a “Tropospheric Vortex River” (TVR) as shown in Small et al., 2009. The TVR is defined as the region enclosed by the $24 \times 10^{-5}\ s^{-1}$ vorticity contour and around 750 miles long or longer. Contours of this magnitude and length, for example in this case, are accompanied by strong positive vorticity advection at its leading edge for strong lift. There are strong winds that increase in the vertical behind the leading edge as well. Combined with low level, terrain-following flow, there can be areas of strong wind shear in both the horizontal and in the vertical. This is a prime setup for organizing and strengthening the convection, possibly into supercells with severe weather. Also, behind the leading edge there can be additional vorticity centers embedded in the TVR that can supply additional vertical motion on top of the already significant shear profiles. Only the vorticity above 24 x 10^{-5} s^{-1} has been shaded to highlight areas of strong vorticity in the figures.

The upper left panel of figure 2 is the NAM80 500 mb heights (green, contour interval 60 meters) and vorticity (orange contours, intervals of 4 x 10^{-5} s^{-1} and shaded) at 1200 UTC 22 May 2008. A 29 x 10^{-5} s^{-1} vorticity core can be seen moving through southern California. It was followed by a powerful 36 x 10^{-5} s^{-1} closed vorticity contour with a peak of 38 x 10^{-5} s^{-1} that was over central California just east of the KOAK sounding at 1200 UTC 22 May 2008. This 38 x 10^{-5} s^{-1} peak was heading for southern California and would arrive during the period of strong midday heating. The strong temperature gradient on a constant pressure surface defining the baroclinic zone ensured the potential for storm strengthening along with wind shear for supercell development. The cold pool can be seen entering central California along the Nevada border on its way to southern California.

3. MESOSCALE ASPECTS OF 22 MAY 2008

The late morning to midday severe weather and flash flooding seemed to be largely due to the upper level features moving through, whereas the afternoon tornadoes were more related to the enhancement of the storms by the Elsinore Convergence Zone (Figs 3 and 4). The Elsinore Convergence Zone has been noted as a severe weather producer in the past (Small et al, 2000), and its characteristics are favorable for producing very strong thunderstorms and tornadoes (Fig. 5). Profiler data can give a good idea of the flow surrounding the Elsinore Convergence Zone (ECZ).

The Moreno Valley profiler, in the air mass southeast of the Elsinore Convergence Zone near KRIV, is shown in the upper panel of figure 6. The vertical wind profile at 1600 UTC began as light southerly at the surface, veers westerly at about 4000 feet MSL, then northwesterly above 4000 feet MSL. By 2300 UTC the surface wind had intensified to 20 knots. This is due to the sea breeze as well as a thunderstorm outflow from the south. An upper level feature appears to move through at about 2200 UTC, with the winds above 10000 feet MSL responding to become northerly. After a brief return to northwesterly at about 2300 UTC, the winds aloft shifted to northerly again by 0100 UTC 23 May 2008.

On the opposing side, northwest of the Elsinore Convergence Zone, the Ontario profiler is shown in the bottom panel of figure 6. The surface wind is initially from the southeast. By 1900 UTC the surface wind shifted to become northeasterly. The shift to northeast was halted by the developing westerly sea breeze and general onshore flow by 2200 UTC. These westerly winds peaked at about 2200 UTC at around 20 knots, then the wind weakens at about 0200 UTC 23 May 2008, which continued until southeast winds developed after 0300 UTC. Aloft, there was northwest flow that turned northerly at around 2000 UTC as an upper level feature went through. Then the wind went northeasterly above about 8000 feet MSL with a backing cold advection profile above until the tornadoes ended.

Sounding data from KNKX are shown in figure 7. Both the 1200 UTC 22 May 2008 (upper panel) and 0000 UTC 23 May 2008 (lower panel) soundings show southerly surface winds with northwest winds above. The 0000 UTC 23 May sounding is the most similar to a Midwest severe weather sounding. It has the low level moisture, some Helicity (albeit very minimal for the Midwest, but substantial for here) along with a drier atmosphere aloft with a "less stable lapse rate" (minimal instability at best). The 1200 UTC 22 May 2008 1 km and 3 km Helicity values from the KNKX sounding only reached 49 m^2/s^2 and 114 m^2/s^2 respectively. The 0000 UTC 23 May 2008 1 km and 3 km Helicity from the KNKX sounding only reached -9 m^2/s^2 and 93 m^2/s^2 respectively. In the Midwest, the "loaded gun" sounding typically has much stronger low level winds, higher shear (Helicity) and a much steeper mid level lapse rate.

4. THE WAVE THAT SET OFF THE MURRIETA STORM AND ASSOCIATED FLASH FLOODING AND SEVERE WEATHER

Waves of energy rotating around the back side of the upper low played a very important role in the development of the day's severe thunderstorms beginning at around 1910 UTC 22 May 2008. [In many places in the country, the severe tornadic weather is mainly in the southeast to southwest flow ahead of a cold front during the transition season. On the west coast, especially in the southwest, waves in the cold, unstable air following a cold front can be prolific producers of strong squalls with hail, and potentially severe weather. It is more common than in the warm sector ahead of the front. Typically thunderstorm activity is delayed until the cold air filters in behind the leading edge of the storm. (It should be mentioned that one type of event that does produce thunderstorms ahead of the low consists of mainly high based convection in diffluent flow aloft, little low level moisture, and sometimes unusually efficient lightning production. These events may be identifiable by a line of high based convection ahead of the low, and a gap in convection behind the line, which is followed later by convection in the center of the low. Dry lightning can be a problem with these events)]. Two waves in particular were notable during the 22 May 2008 event. The waves that swept through the Inland Empire can be seen via a wind shift aloft on the profiler data, with the wind shifting to become northerly behind each wave. One wave went through around 1900-2000 UTC 22 May 2008, and the other swept through between 2300 UTC 22 May 2008 and 0100 UTC 23 May 2008. This section will concentrate on the first wave.

At 1910 UTC a severe thunderstorm produced ¾ inch diameter hail in Murrieta that accumulated a few inches deep. (Hail accumulation is rather common on days when severe hail develops, especially during the cool season. The accumulating hail can clog drains, and flooding can become a problem). Fig. 8 is the 1911 UTC KNKX composite reflectivity, storm relative velocity, VIL, and Echo top, all overlaid with the 1900 UTC METAR surface observation data. There was a 40 knot difference in velocity across the storm showing an obvious mesocyclone. The Composite Reflectivity showed values exceeding 60 dBZ. The VIL peaks at 25-30 g/m^3 with a corresponding echo top of 20-25 thousand feet MSL. It seems that when the VIL is one category or more higher than the echo top, along with an organized storm, severe weather is highly probable in southern California. In this case, severe weather did indeed develop. The storms continued to drift south into the mountains of San Diego County just south of the Inland Empire, causing flooding on highway 76 about 2 hours later. The equilibrium level of 447.2 mb was around 20,700 feet msl. The echo top exceeding the equilibrium level was a signature of strong convection and flash flooding. The outflow from the storm moved northward, (as shown in the satellite imagery in figure 9), and left an outflow boundary in the Inland Empire. The outflow boundary extends southwest to northeast near KRIV. This outflow boundary, combined with the Elsinore Convergence Zone, set the stage for tornadoes later in the afternoon.

5. THE WAVE THAT SET OFF THE MODJESKA CANYON STORM AND ASSOCIATED FLASH FLOODING

On the same wave as the Murrieta storm (but further northwest), very strong convection developed in the Santa Ana Mountains, west of the Inland Empire, by around 1920 UTC. Fig. 10 is the 1858 UTC KNKX Composite Reflectivity, VIL, Echo Top and One-Hour Precipitation. There was very heavy rain indicated by the 60 dBZ echo over the foothills of Orange County in the Modjeska and Santiago Canyons areas. The One-Hour Precipitation based on the KNKX radar was over 1 inch. Based on the 60 dBZ composite reflectivity the amount was likely to be good (except for some possible hail contamination). This is near the 1 inch per hour threshold common for flash flooding in vulnerable coastal and mountain areas, (such as poorly drained urban areas as well as many creeks and streams in steep terrain) in southern California. This is especially true in areas with low water crossings. The rain may have fallen in only ½ an hour, making it that much more extreme. Floodwaters up to 4 feet deep were reported. Summer time storms can deliver approximately ¼ inch per scan when the echo is a wide 50 dBZ echo, as a baseline. This may also be the case with cool season storms on severe weather days.

6. OVERVIEW OF THE CONVECTIVE ACTIVITY ASSOCIATED WITH THE FIRST 3 TORNADOES

Figs. 11-15 show the collision of the 2 storms that ultimately created the EF-2 “Moreno Valley Tornado” and associated supercell storm. The mesocyclone associated with the main cell was about 2-3 kilometers in diameter during the life of the storm. The difference in speed between the inbound and outbound velocities in the mesocyclone was about 35 knots through about 0004 UTC 23 May 2008, near the end of the 2nd tornado. (It should be noted that the velocity difference across the mesocyclone peaked at about 50 knots just before the 4th tornado, which will be discussed later). The sequence of tornadoes (EF-0, EF-2, EF-0, and EF-0) occurred at 2330-2336 UTC, 2342-0003 UTC, 2350-2358 UTC and 0040-0045 UTC on 22-23 May 2008 respectively, covering a period exceeding 1 hour.

Fig 13 shows the convection about 10 minutes before the severe hail was reported (but most likely was also occurring at 2245 UTC, especially under the 3 pixels of 65 dBZ radar return).

7. THE 1ST TORNADO

The first tornado of the day was indicated on the 2330 UTC 22 May 2008 METAR surface observation at March Air Reserve Base (KRIV).

SPECI KRIV 222330Z 36007KT 10SM +FC TS FEW025 BKN037CB OVC100 16/08 A2945 RMK AO2A TORNADO B30 4SE MOV S TS OHD MOV S

SPECI KRIV 222338Z 03008KT 360V060 10SM -TSRA SCT030 OVC039CB 16/08 A2946 RMK AO2A TORNADO E36 MOV S OCNL LTGICCG TS OHD MOV S

The tornado developed at 2330 UTC and dissipated at 2336 UTC. There is little signature on the 2329 UTC KSOX Base Reflectivity 4-panels and associated Storm Relative Velocity as seen in Figure 16. The 2333 UTC KSOX Storm Relative Velocity 4-panel shows a signature likely to be the first tornado. It is best seen at 1.3 degrees.

8. THE EVIDENCE OF SIMULTANEOUS TORNADOES AND THE CROSSING OF THE 215 FREEWAY BY THE EF-2 TORNADO

Fig. 16 and Fig. 17 show the sequence of radar imagery leading up to the simultaneous tornadoes (The 2nd and 3rd tornadoes) and the 2nd tornado (the EF-2 “Moreno Valley Tornado’) crossing the 215 freeway.

SPECI KRIV 222344Z 10010G14KT 10SM +FC TSRAGS SCT025 OVC038CB 16/09 A2946 RMK AO2A TORNADO B42 ON FLD SW MOV S OCNL LTGICCG TS OHD MOV S

SPECI KRIV 222350Z 11026G31KT 10SM +FC TSRAGR SCT025 OVC035CB 16/09 A2945 RMK AO2A TORNADO ON FLD SW STNRY PK WND 12031/2347 OCNL LTGICCG TS OHD MOV SW GR 1/2

METAR KRIV 222355Z COR 10020G31KT 10SM +FC -TSRA BKN033 15/10 A2946 RMK AO2A TORNADO SW MOV SW PK WND 12031/2347 RAB38GRB50E55 TSB30 OCNL LTGIC OHD TS OHD-SW MOV SW GR 1/2 SLP980 P0000 60000 T01500095 10194 20137 53000 COR 0004

SPECI KRIV 230003Z 11012KT 7SM -TSRA FEW020 BKN030CB 13/10 A2947 RMK AO2A TORNADO DSIPTD SW OCNL LTGICCG TS OHD-S-SW MOV SW

The imagery is the 4 - panel Base Reflectivity and the 4 – panel Storm Relative Velocity for the KSOX radar. The panels are (clockwise from the upper left) 0.5, 1.3, 2.4, and 3.1 degree slices. Fig. 16 is the 2329 UTC, 2333 UTC, and 2338 UTC 22 May 2008 KSOX Composite Reflectivity and Storm Relative Motion 4-panels, along with 2300 UTC METAR observations. Fig 17 is the 2342 UTC, 2346 UTC, and 2351 UTC May 2008 KSOX Base Reflectivity and Storm Relative Velocity 4 - panels. The 2nd and 3rd tornadoes (the simultaneous tornadoes) are seen on the 2342 UTC panel. At 2351 UTC the 2nd tornado is seen crossing the 215 freeway. A blow-up of the 2342 UTC and 2351 UTC SRM from the KSOX radar shows the 2nd and 3rd tornadoes just east of the 215 freeway, and at least 1 tornado (the 2nd tornado) crossing the freeway, respectively (Fig. 18). As it crossed the freeway, it lifted a tractor trailer rig briefly into the air and injured the driver. It also blew 9 rail cars of a train off their track. Many people saw the tornadoes since they occurred during rush hour traffic.

9. THE 4TH TORNADO

There was a temporary drop in the composite reflectivity values of the Moreno Valley supercell storm after the 3rd tornado. The storm did not produce a 65 dBZ echo for 3 consecutive scans for either the KSOX or KNKX radar. Figure 19 shows the KSOX radar 4-panel Composite Reflectivity and Storm Relative Velocity (1.3, 4.0, 6.4 and 10.0 degree slices) at 0026 UTC 23 May 2008, about an hour after the first tornado was reported. The storm still showed an inbound/outbound velocity couplet, which points toward a continued tornadic threat for the storm since it had a prior history of tornadoes

Even though the storm did not produce a 65 dBZ echo for 3 consecutive scans for either the KSOX or KNKX radar, suddenly, at 0030 UTC 23 May 2008 there was explosive development, as 4 pixels of 65 dBZ developed based on the KSOX radar Composite Reflectivity (not shown). This increase in intensity at the KSOX radar was supported by the appearance of 7 pixels of 65 dBZ developing on the more distant KNKX radar (not shown). This strengthening occurred about an hour after the first tornado was reported and just before the 4th tornado developed. The continuation of the storm alone points toward a continued tornadic threat for the storm since it had a prior history of tornadoes. This is enhanced even more by the explosion in strength as seen by both radars. It produced the 4th tornado of the day about 10 minutes later (0040 - 0045 UTC 23 May 2008), which is about 1 hour after the 1st tornado of the day. This hammers home the fact that storms can re-strengthen and produce additional tornadoes if the storm does not completely disappear. Interestingly, the storm relative motion data was less useful for the 4th tornado, with little radar return showing up on the SRM product for either radar during the time that the 4th tornado was on the ground. It produced the 4th tornado of the day about 14 minutes after the figure 19 time of 0026 UTC 23 May 2008, and about 10 minutes after the 0030 UTC 23 May 2008 time of the explosion in convective strength. The 4th tornado was reported by a trained spotter.

10. PARALLELS TO A MIDWEST SEVERE WEATHER OUTBREAK

There are some parallels between this case and Midwest tornado outbreak cases. In a classic Midwest tornado case, aloft there is southwest to westerly flow coming off the Rocky Mountains into the middle of the country. This airmass has a steep lapse rate. At the surface there is a moist southeast to south flow from the moist Gulf of Mexico.

In the 22 May 2008 case there was a cold, unstable northerly flow off the mountains to the north flowing over the Inland Empire. Undercutting this air mass was the southerly sea breeze, an outflow from the convection to the south, and general onshore flow in the southeast portion of the valley, as well as the opposing moist westerly flow from the Ontario area (also undercutting the cold, unstable northerly flow). Although not as volatile as a Midwest scenario, the basic setup was comparable.

May is the peak of tornado season in the Midwest, so it is not too surprising that this southern California severe weather event occurred in May. In May there is an excellent mix of late season cold outbreaks to combine with good heating in the May sun. This creates moderate to strong thermal potential through the convective condensation level (CCL) in the low level convergent flow that can develop in southern California. It does seem that the thermals in the boundary layer help precondition the air mass to enable explosive growth supplemented by features such as synoptic scale lift, Tropospheric Vortex Rivers, etc.

11. CHALLENGES INVOLVING THE LOCATION AND INTENSITY OF THE HEAVIEST RAINFALL AND THE STRONGEST STORMS

Upper level lows such as these also bring some interesting problems, such as highly variable rainfall (and snowfall) amounts due to the convective nature of such events. The convective nature of the precipitation makes forecasting the probability of precipitation (PoP) and accumulation of precipitation (QPE) difficult at times.

Upper level lows that are mostly "convective", without large rain bands that sweep through the entire area, can result in huge variations in PoP and QPE. The models can do a better job with the more "frontal" types of systems that sweep through (albeit with a dry bias), but upper low events that are highly convective require local tools and knowledge in order to deal with them. Extreme rainfall accumulations and accumulating hail can occur in the areas of "forcing", while almost no precipitation occurs in areas that receive little or no forcing. Upper lows, especially those with trajectories that bring the system from the interior toward the coast, can have huge variations in the amount of rainfall that they can generate. This was definitely the case with this storm. There was flash flooding in the Santa Ana Mountains on 22 May. Meanwhile, about 40 miles to the southwest at Newport Beach (near Laguna Niguel) no measurable rainfall was recorded on 22 May. Similarly, with flash flooding in northern San Diego County, downtown San Diego received no measurable rainfall until noon of the following day. This is partially because unlike many of their moisture rich counterparts from the west, there is a reduction in moisture typically associated with lows of this type of inland trajectory. [It should also be noted that "moisture starved" storms from the west can also occur, and mimic the characteristics of storms with a trajectory from the interior. If a low drops into a location offshore, and its arrival is delayed, it can become modified and lose most of it dynamics and deep moisture before moving in. This can result in much lower precipitation than was originally expected. In addition, "ridging" ahead of the low may generate an offshore surface pressure gradient that extends to near the coast or even out over the coastal waters to a surface trough (possibly even a thermal trough). This easily creates a drying, downslope offshore flow with afternoon high temperatures well above MOS guidance that oftentimes lasts longer than that indicated by MOS. (This is especially true over the coastal plain, where it can easily be 5 to 10 degrees above MOS for a day or so before and/or after the period of the warm-up/heatwave indicated by MOS. At the same time, along with the drying in the low levels, PoPs and rainfall amounts generated when the low finally moves in can be well below MOS)]. As for QPE, whether the system trajectory is from inland areas or from the west, convection can result in a highly variable rainfall totals (quantitative precipitation estimates, or QPEs). This is the result of the locations of the strongest convection being highly variable as well. In areas without terrain forcing, the amounts are at the mercy of the surface heating or synoptic scale lift near the core of the low. Isolated to widely scattered activity is generally the rule in those locations. In other areas, terrain forced, banded features such as convergence zones forced by the islands or mountains, as well as "topographic updrafts" (flow up the mountainside) can develop and increase the local PoP and QPE. This was likely the case in the San Diego County Mountains as the storm drifted south from the Murrieta area. Often it is the terrain forced features that deliver the heaviest precipitation. Areas that do not get terrain forced convection, adequate heating, or synoptic scale lift (for example, Newport Beach or Downtown San Diego) may not get much rain. One of the challenges is trying to determine what type of forcing is associated with the expected low pressure system, and then to determine whether or not (as well as where) the above forcing mechanisms place the heaviest precipitation and potentially severe weather. The activity in the Santa Ana Mountains appeared to be both terrain related and related to an area of lift associated with the synoptic scale system itself.

Sometimes, even higher terrain areas may not produce the highest amounts. Big Bear Lake, at almost 7000 feet MSL managed only 0.12 inches for the entire 3 day event. This was only about 1/2 of the 0.21 that finally fell in Downtown San Diego at KSAN (Lindbergh Field) at the coast. During these convective events, the QPE becomes more mesoscale (or "storm based"), somewhat more useful than the typical 6 hour block generally used for large, synoptic scale cool season pacific "frontal passage type" systems. This is because QPE projections can rapidly deteriorate during convective scenarios. This also must be kept in mind when looking at QPEs in the post-frontal convection of large cool season pacific frontal systems.

Lastly, the time of day can help determine the convective strength, and in this case, it was a strong factor. The storms followed a strengthening pattern that is somewhat expected. Storms generally become stronger and stronger until late afternoon. Individual storms colliding with other individual storms were a strengthening factor. Terrain forced boundaries colliding with other terrain forced boundaries or with thunderstorm outflows are yet another. This can create stronger storms than either of the original storms or features that were involved in the initial collision. After the first severe thunderstorm of the day develops, it is not going too far out on a limb to expect later storms (especially those involving collisions) to be at least as strong as or even stronger than the features interacting to create it as the late afternoon period approaches. (In many cases it will be stronger than the strongest storms that occurred earlier in the day). Although sometimes there can be a shield of high clouds following strong to severe convection to temporarily slow additional convection, it may not take long during a brief clearing period for a storm to "go severe", and a second pulse of severe weather to occur. This is especially true on boundaries such as the Elsinore Convergence Zone, where a storm can go severe in 3 or 4 scans of the radar (or about 10-15 minutes).

12. DISCUSSION AND CONCLUSION

The 22 May 2008 Moreno Valley supercell tornado developed in a scenario not too different than a Midwestern case, but significantly different than the typical southern California cool season tornado case. In the winter, the expected scenario has been a low offshore, with the maximum energy moving into the coastal area from the west. In this case, the upper level low was well inland, with the maximum energy moving into the valley areas from the north. This probably shifted the tornado and severe weather events from the typical coastal plain setting to one targeting the valley areas. The culprit in this case was an initial outflow boundary from convection in the south combined with the Elsinore Convergence Zone (or otherwise known as a "Modified Elsinore Convergence Zone). The velocity difference across the mesocyclones was typically around 30 to 45 knots (except near 50 knots in the 4th tornado). Although not very strong compared to the values seen in some parts of the country, these lower values can result in severe, even tornadic weather in southern California. Forecasters need to consider this as the values approach this 30-45 range, and possibly as low as the mid 20s (especially when terrain forced confluence/convergence features and rapidly growing cells are involved).

The flash flooding in the Santa Ana Mountains seemed to be related to the slow moving upper level feature moving south into the area. As the wave was moving southwest down the coastal side of the Santa Ana Mountains, there was additional lift generated as the southwesterly, upslope flow converged with the convection of the wave moved in from the northeast. The accumulation of large hail in the southern Inland Empire was also tracking along with the upper level feature, and there was strong southerly onshore flow which assisted the upward motion. The flash flooding in the mountains of San Diego County had a similar formation mechanism as the Santa Ana Mountains flooding (again, an upper level feature which drifted into higher terrain). Due to the system being an upper low from the interior, there was much variation in the QPE, and a more targeted approach to rainfall estimates was needed.

On a final note, apparently, property damage associated with Tropospheric Vortex River Phenomena is not limited to only supercells. Recently, widespread wind damage has occurred with strong non-thunderstorm winds during Tropospheric Vortex River Events. This topic will be explored in more detail in later studies.

13. REFERENCES

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http://ams.confex.com/ams/pdfpapers/144420.pdf

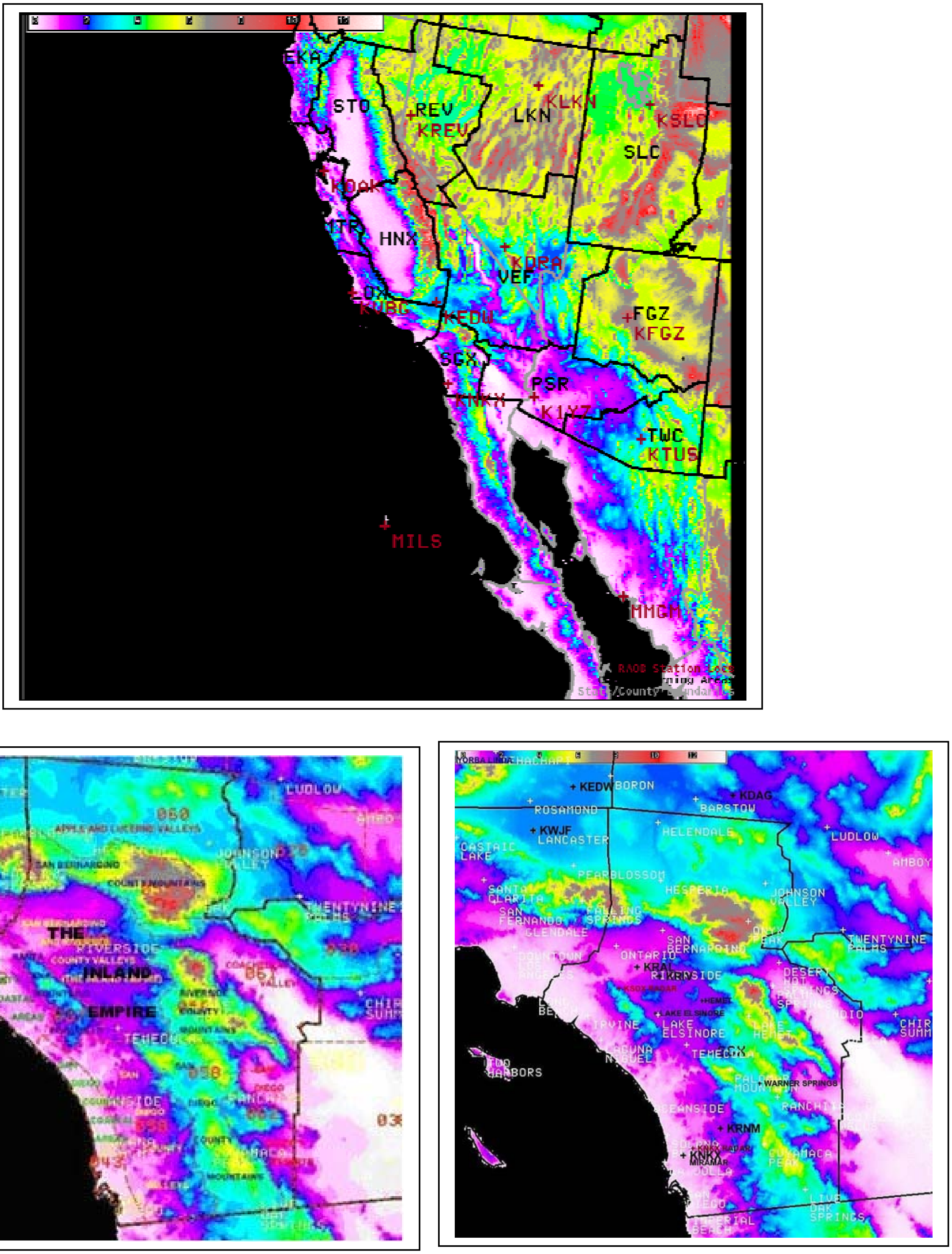

Fig. 1. Terrain map of the WFO SGX CWFA. Color coding in the legend is in thousands of feet MSL. The sounding sites are indicated in red on the upper panel. The San Bernardino and Riverside County Valleys (the "Inland Empire") is indicated in the center of the lower left panel.

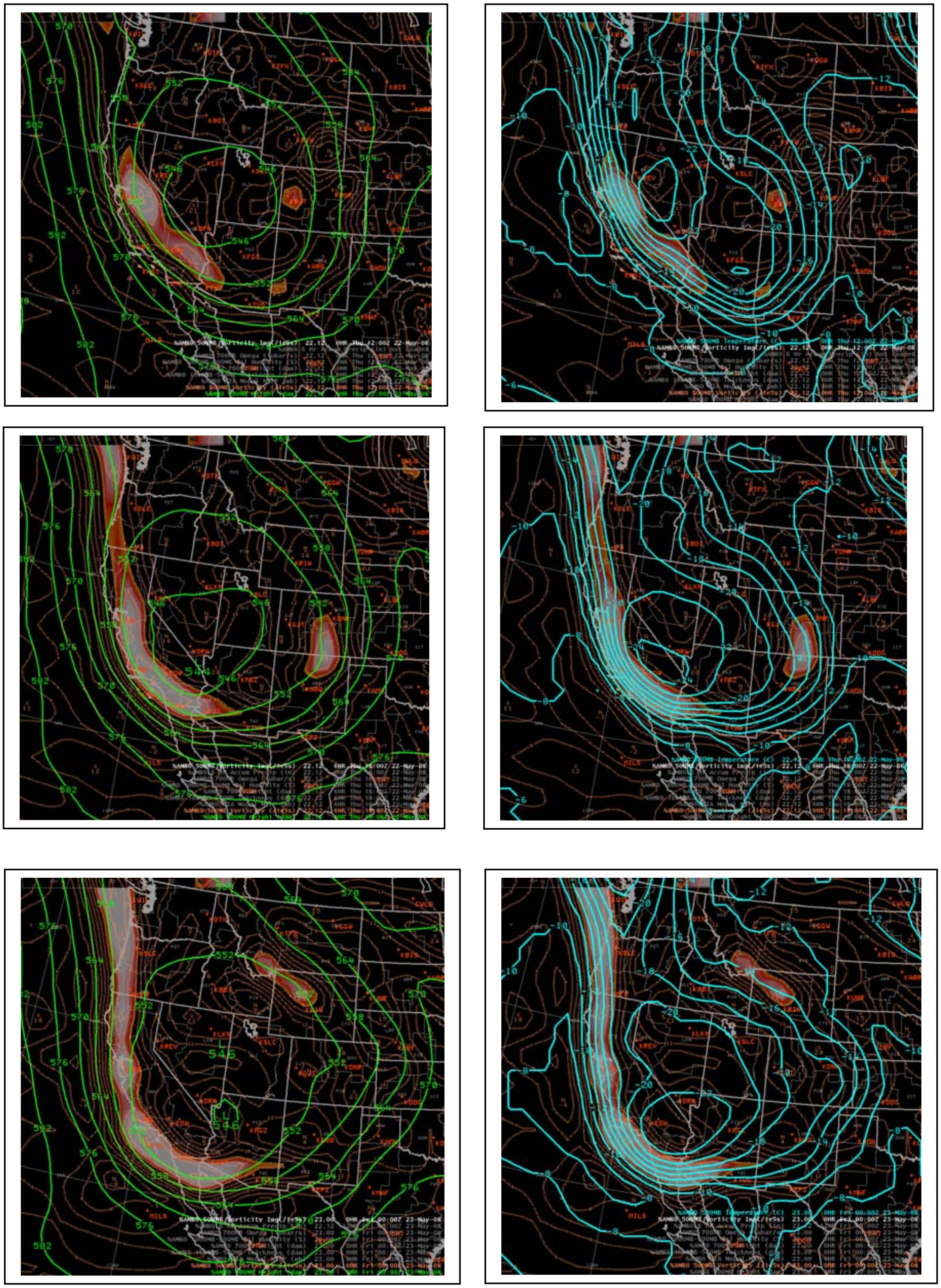

Fig.2. The left column is the NAM80 500 mb heights (green, contour interval 60 meters) and vorticity (orange contours, intervals of 4 x 10^{-5} s^{-1} and shaded) at 1200 UTC 22 May 2008, along with the forecasts valid at 1800 UTC 22 May 2008 and 0000 UTC 23 May 2008. The right column is the NAM80 500 mb temperatures (cyan, intervals of 2 degrees C) and vorticity (orange contours, intervals of 4 x 10^{-5} s^{-1} and shaded) at 1200 UTC 22 May 2008, along with the forecasts valid at 1800 UTC 22 May 2008 and 0000 UTC 23 May 2008. Only the vorticity values of 24 x 10^{-5} s^{-1} and larger are shaded, to indicate the “Tropospheric Vortex River”.

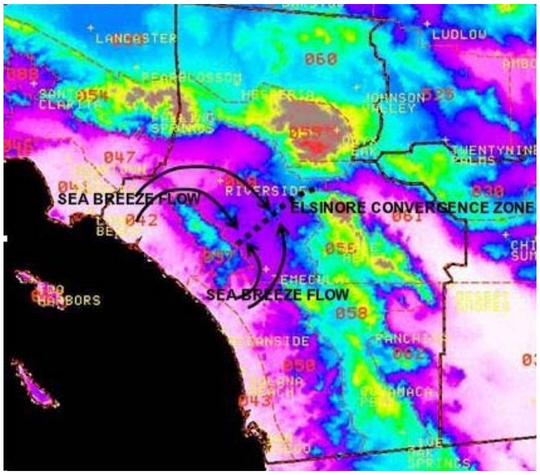

Fig. 3. Example of a typical Elsinore Convergence Zone and the associated wind flow commonly found (after Small et al., 2009).

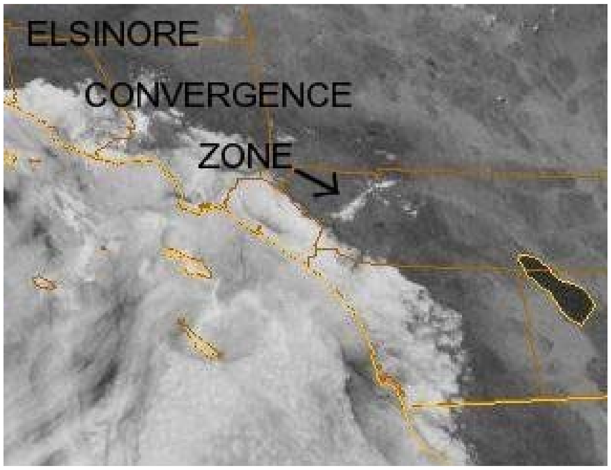

Fig. 4. Example of a cloud band developing on the Elsinore Convergence Zone under benign conditions at 2230 UTC 2 April 2009.

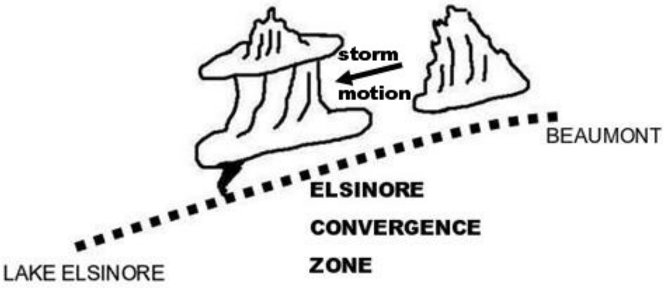

Fig. 5. Conceptual model of an “Elsinore Storm” with a tornado. The tornado may be the result of stretching on the leading edge of a gust front, stretching of circulations along the Elsinore Convergence Zone, a mesocyclone induced tornado, or some combination of the three (after Small et al., 2009).

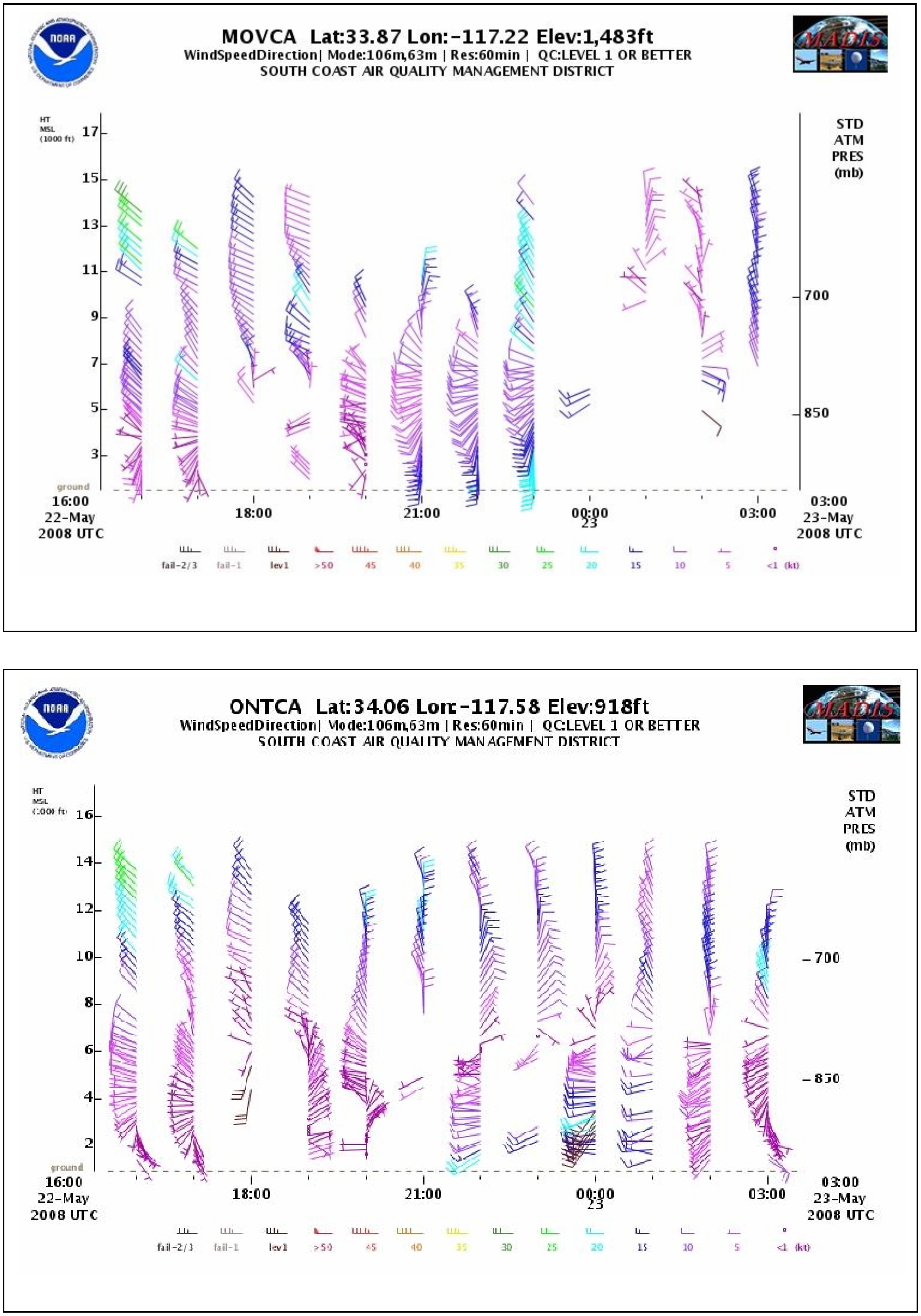

Fig. 6. Profiler data from southeast of the Elsinore Convergence Zone (Moreno Valley Profiler, near KRIV) is in the upper panel, and northwest of the Elsinore Convergence Zone (Ontario Profiler near KONT) is in the lower panel.

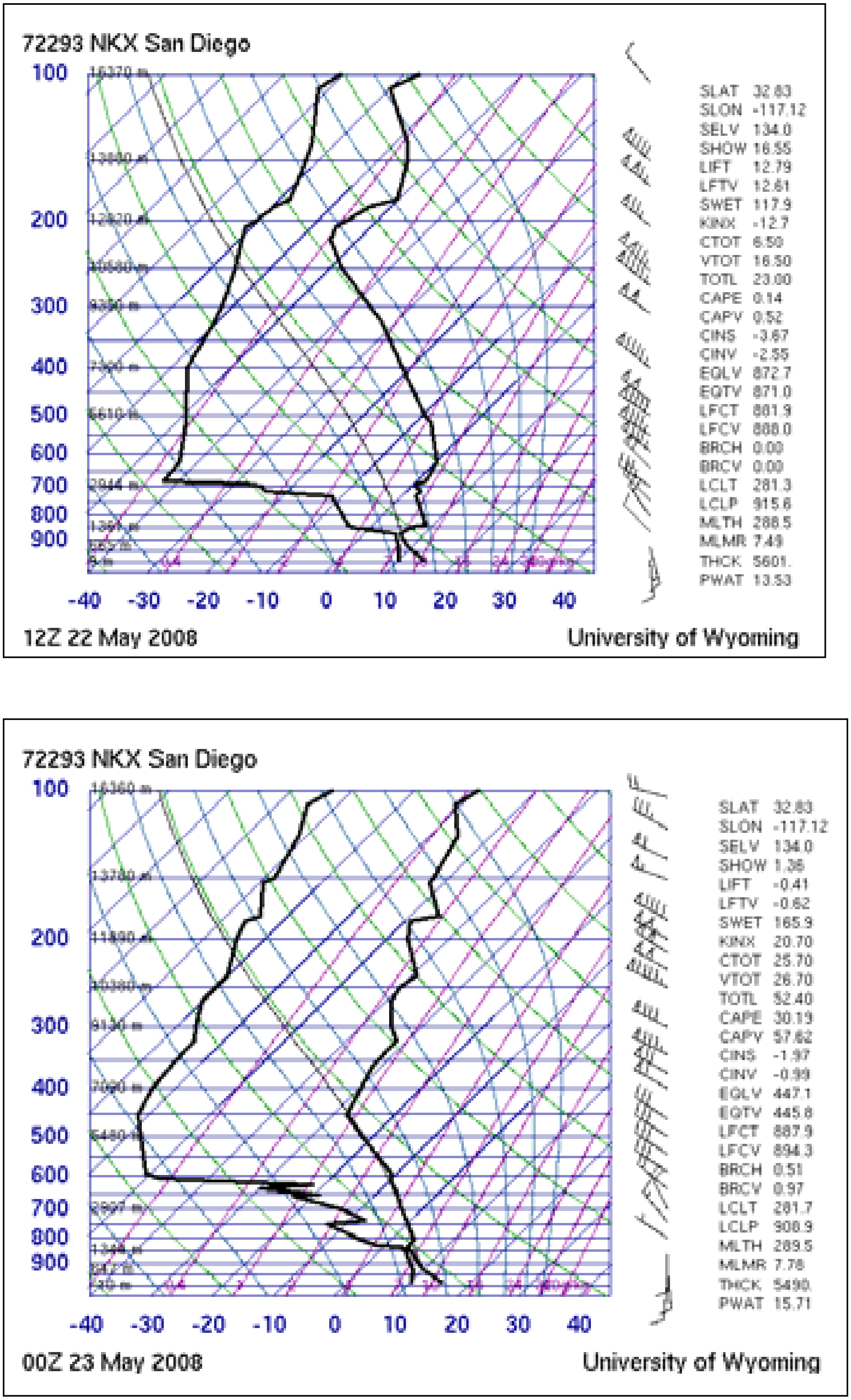

Fig. 7. The 1200 UTC 22 May 2008 KNKX sounding (top) and the 0000 UTC 23 May 2008 KNKX sounding (bottom).

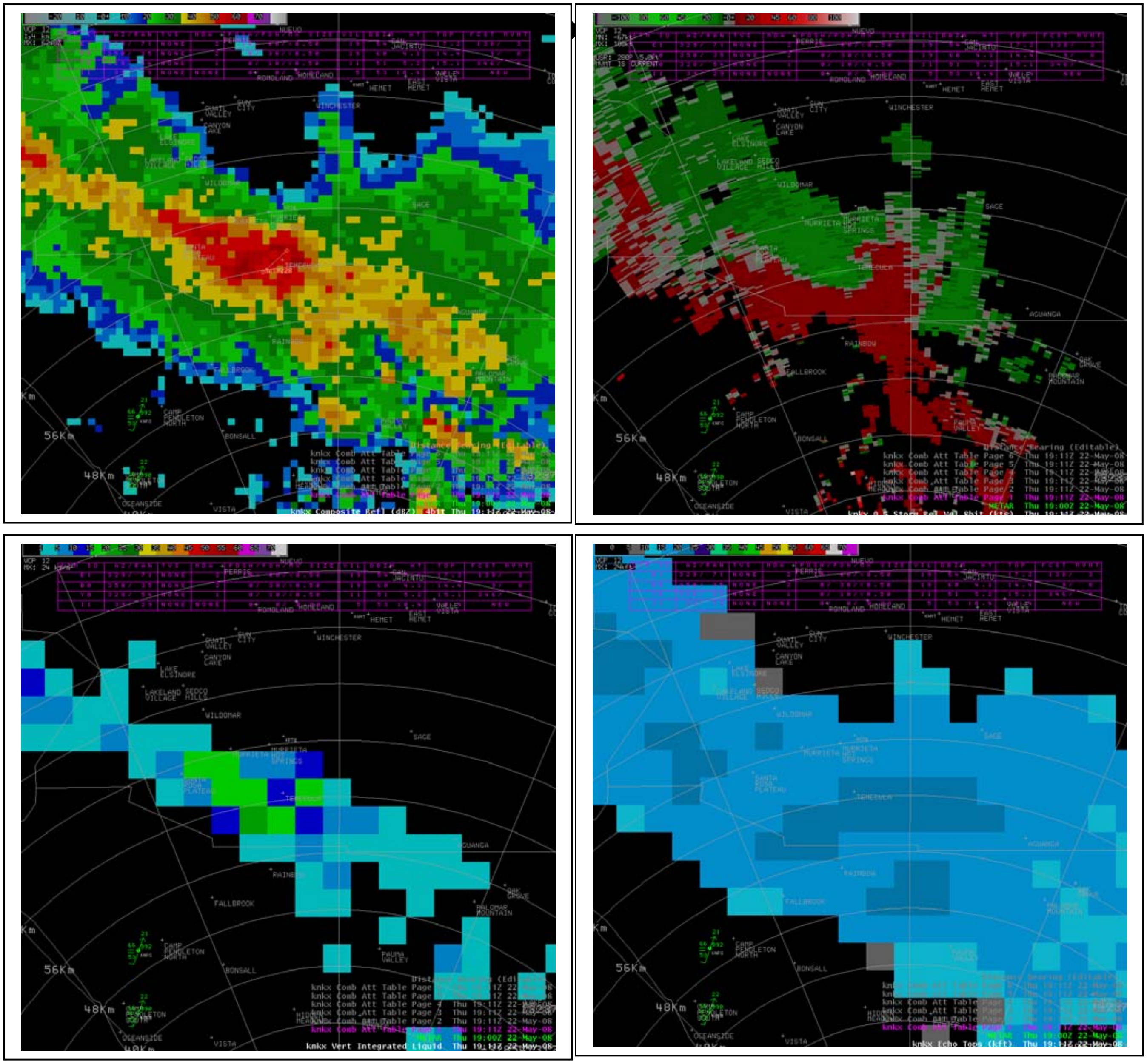

Fig. 8. 1911 UTC KNKX composite reflectivity (upper left), storm relative velocity (upper right), VIL (lower left), and echo top (lower right), as well as the 1900 UTC METAR observation data. There are 22 knots of inbound and 18 knots of outbound velocities with the storm showing an obvious mesocyclone. The VIL peaks at 25-30 g/m^3 with a corresponding echo top of 20-25 thousand feet MSL.

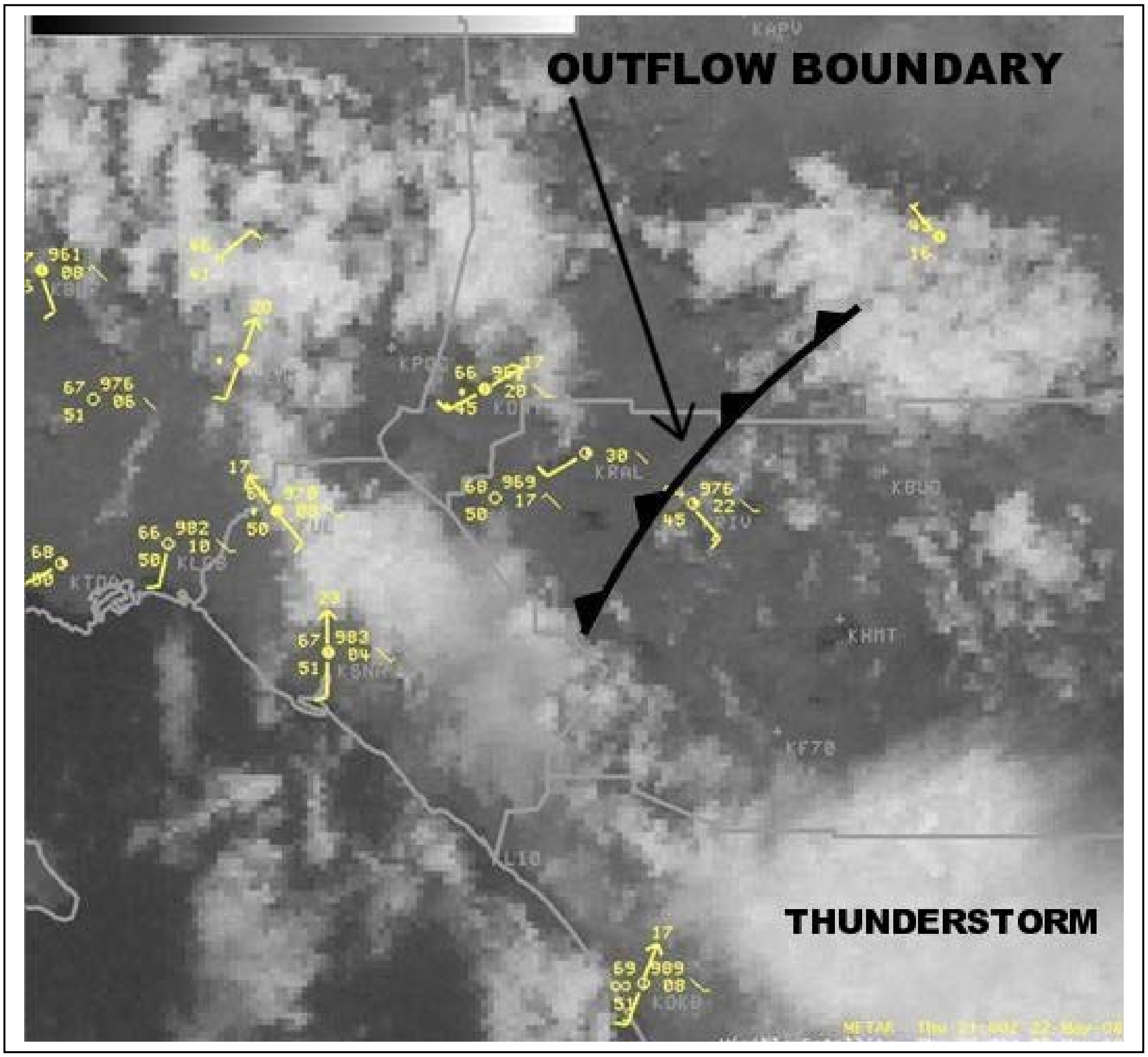

Fig. 9. The 2030 UTC 22 May 2009 visible satellite imagery and 2100 UTC 22 May 2008 METAR surface observation data shows an outflow boundary extending southwest-to-northeast near KRIV, setting the stage for the Modified Elsinore Convergence Zone. The outflow boundary separates the west-southwest flow at KRAL from the strong southeast flow of the outflow boundary noted at KRIV.

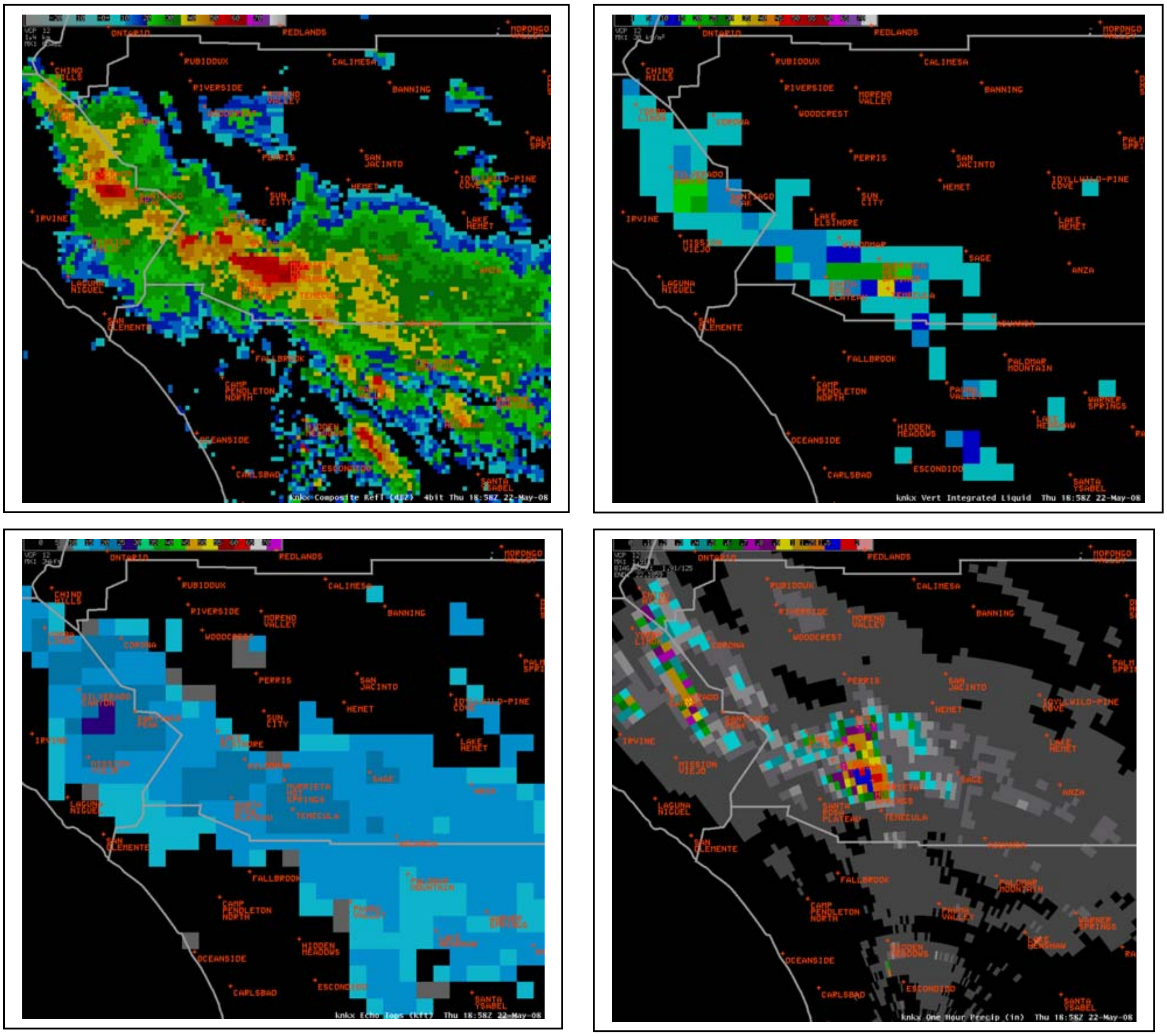

Fig. 10. 1858 UTC KNKX composite reflectivity (upper left), VIL (upper right), echo top (lower left) and one-hour precipitation (lower right). There is very heavy rain indicated by the 60 dBZ echo over the foothills of Orange County in the Modjeska, Silverado, and Santiago Canyon area (near the left edge of the panels). The one hour precipitation based on the KNKX radar was over 1 inch. Based on the 60 dBZ composite reflectivity also the amount was likely to be good (except for some possible hail contamination). This is near the 1 inch per hour threshold common for flash flooding in poorly drained urban areas and steep terrain (especially those with low water crossings) in southern California.

Fig. 11. The 2201 UTC 22 May 2008 KSOX Composite Reflectivity and the 2200 UTC 22 May 2008 METAR observation data

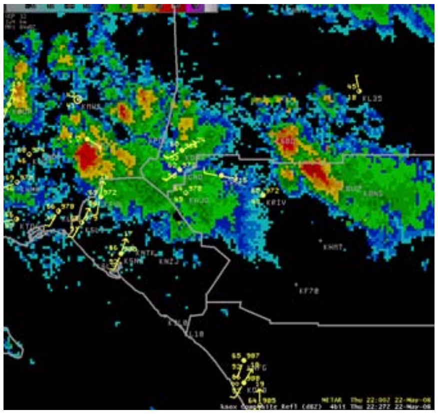

Fig. 12. The 2227 UTC 22 May 2008 KSOX Composite Reflectivity and the 2200 UTC 22 May 2008 METAR observation data

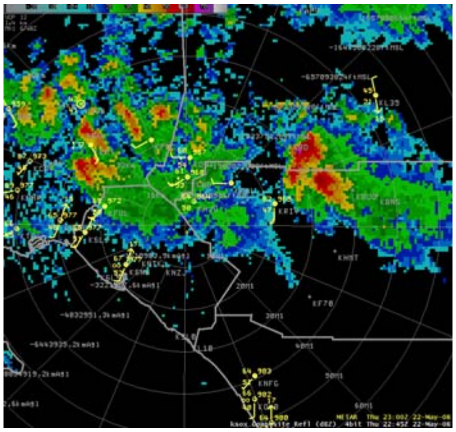

Fig. 13. The 2245 UTC 22 May 2008 KSOX Composite Reflectivity and the 2300 UTC 22 May 2008 METAR observation data

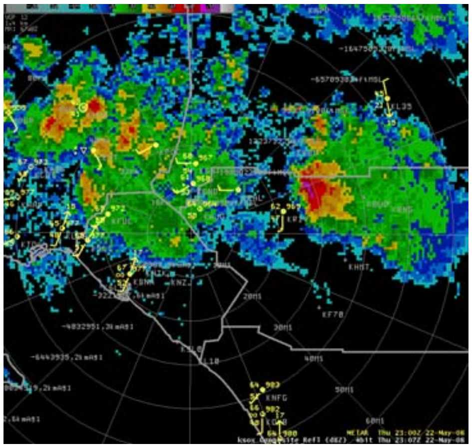

Fig. 14. The 2307 UTC 22 May 2008 KSOX Composite Reflectivity and the 2300 UTC 22 May 2008 METAR observation data

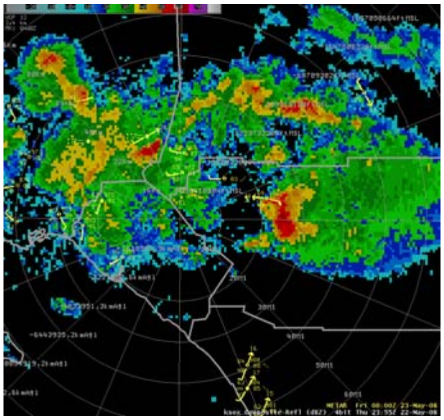

Fig. 15. The 2355 UTC 22 May 2008 KSOX Composite Reflectivity and the 0000 UTC 23 May 2008 METAR observation data during the EF-2 tornado. The storm has a well defined hook and is an excellent example of a storm with bounded weak echo region (BWER), an indicator of a very strong updraft.

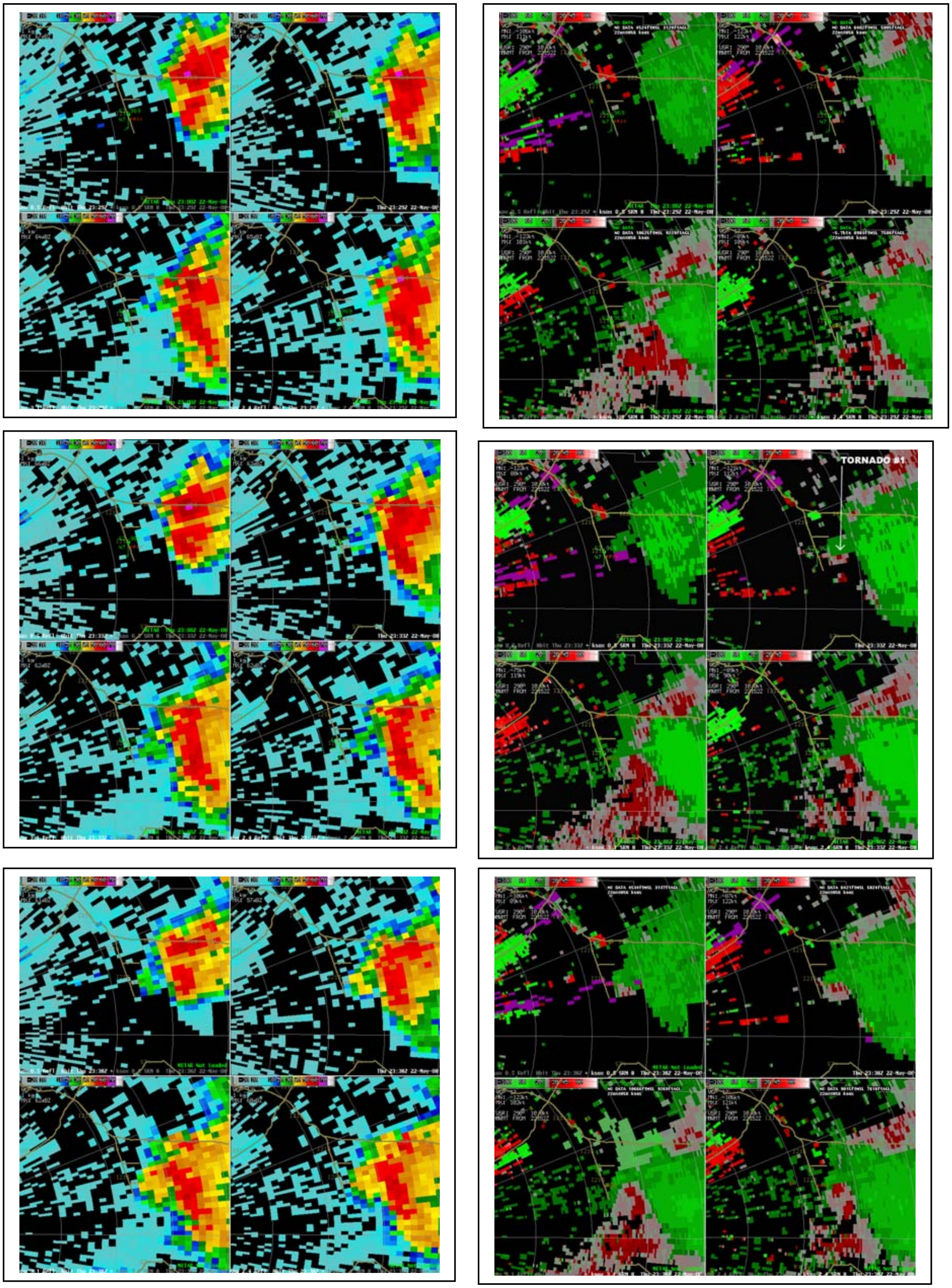

Fig. 16. The left column is the 2329 UTC, 2333 UTC, and 2338 UTC 22 May 2008 4-panel base reflectivity from the KSOX radar at (clockwise from the upper left) 0.5, 1.3, 2.4, and 3.1 degrees. The right column is the 2329 UTC, 2333 UTC, and 2338 UTC May 2008 4-panel SRM from the KSOX radar at (clockwise from the upper left) 0.5, 1.3, 2.4, and 3.1 degrees. Overlaid are the 2300 UTC METAR surface observations.

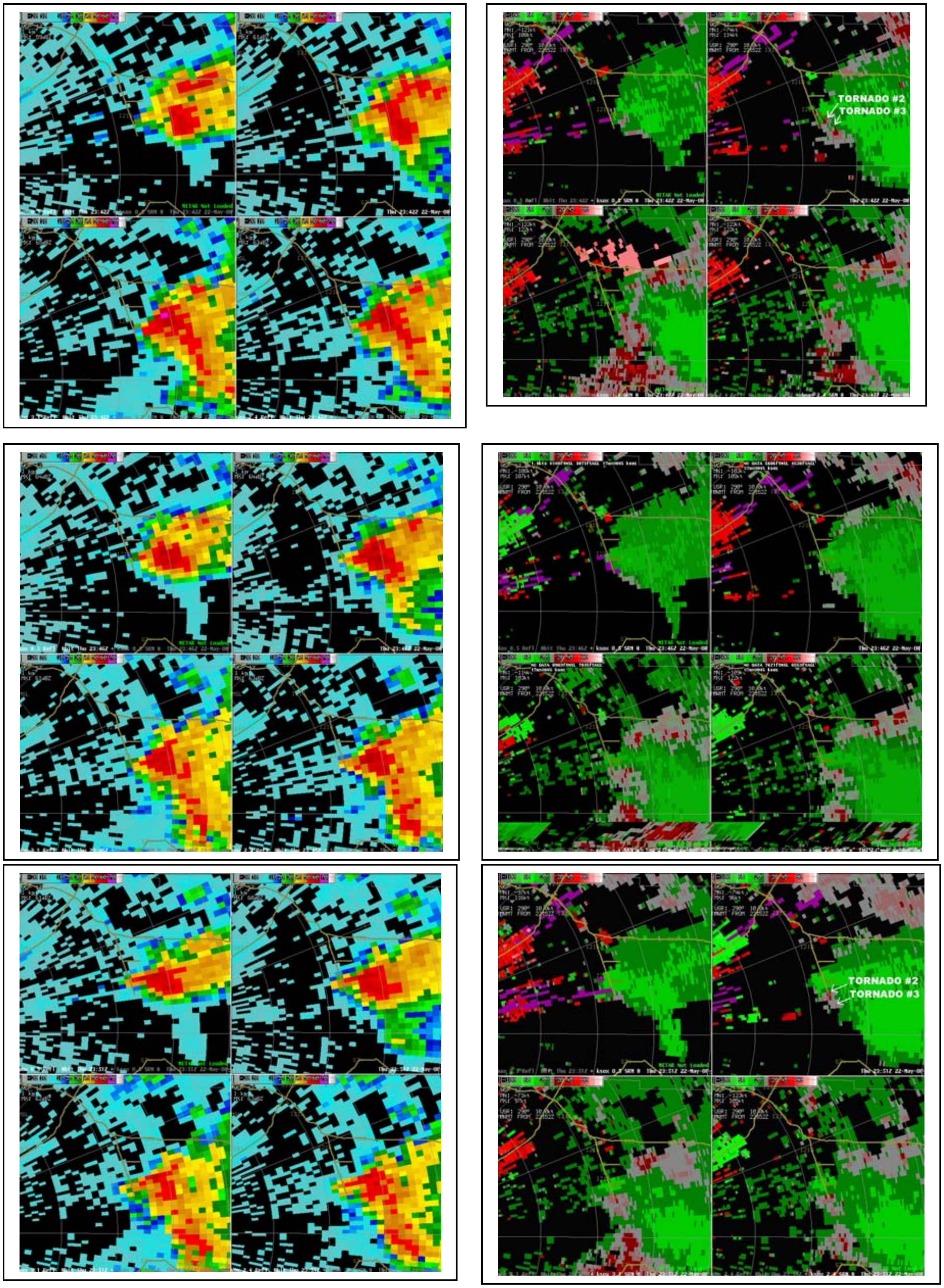

Fig.17. The left column is the 2342 UTC, 2346 UTC, and 2351 UTC 22 May 2008 4-panel base reflectivity from the KSOX radar at (clockwise from the upper left) 0.5, 1.3, 2.4, and 3.1 degrees. The right column is the 2342 UTC, 2346 UTC, and 2351 UTC May 2008 4-panel Storm Relative Velocity (SRM) from the KSOX radar at (clockwise from the upper left) 0.5, 1.3, 2.4, and 3.1 degrees. Simultaneous tornadoes are seen on the 2342 UTC panel. At 2351 UTC a tornado is seen crossing the 215 freeway.

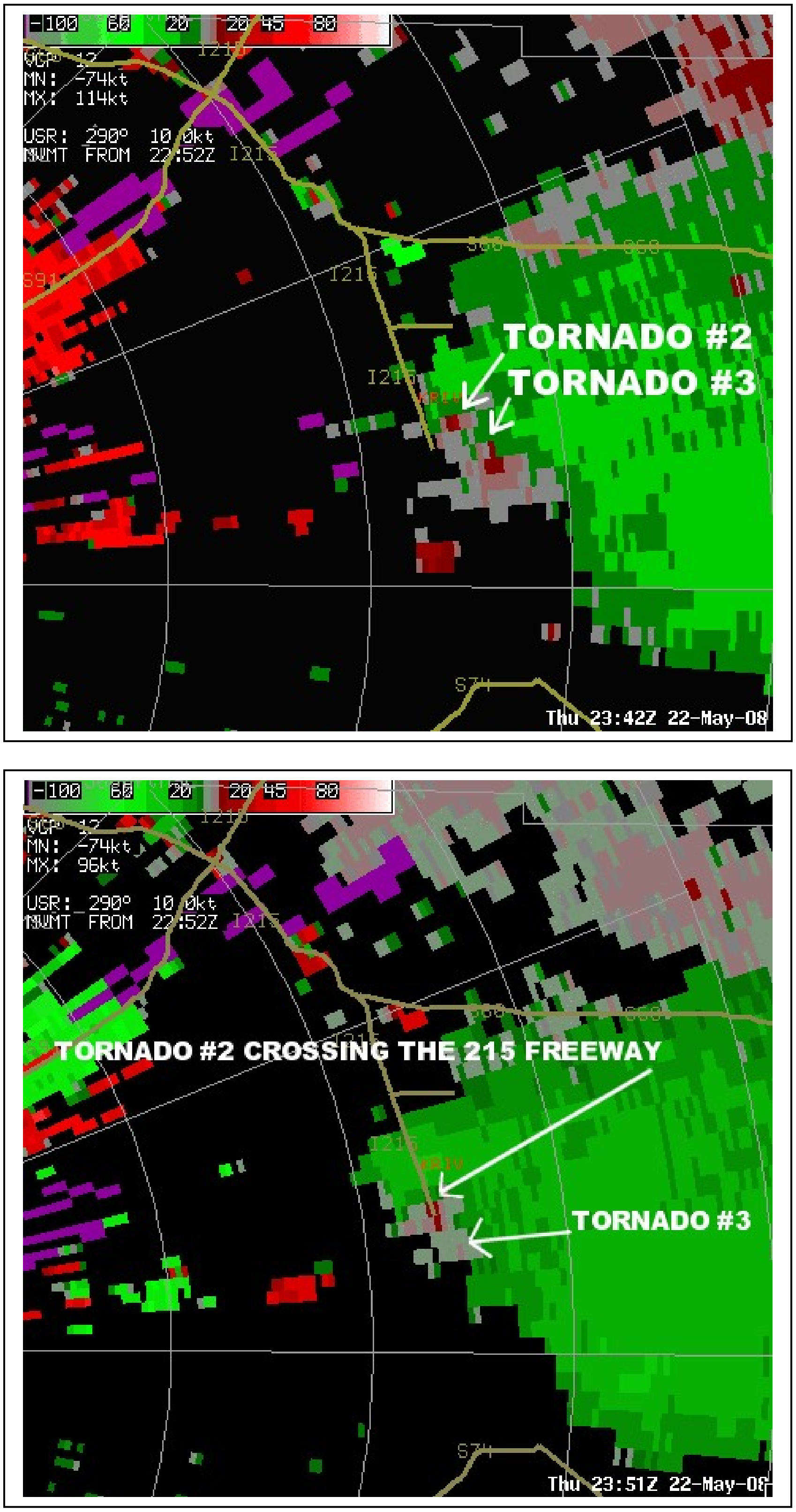

Fig. 18. The above is the 2342 UTC 22 May 2008 (top) and 2351 UTC 22 May 2008 (bottom) SRM (storm relative velocity) from the KSOX radar at 1.3 degrees. Simultaneous tornadoes can be seen. At 2351 UTC a tornado, (most likely the EF-2 tornado), is seen crossing the 215 freeway just south of KRIV.

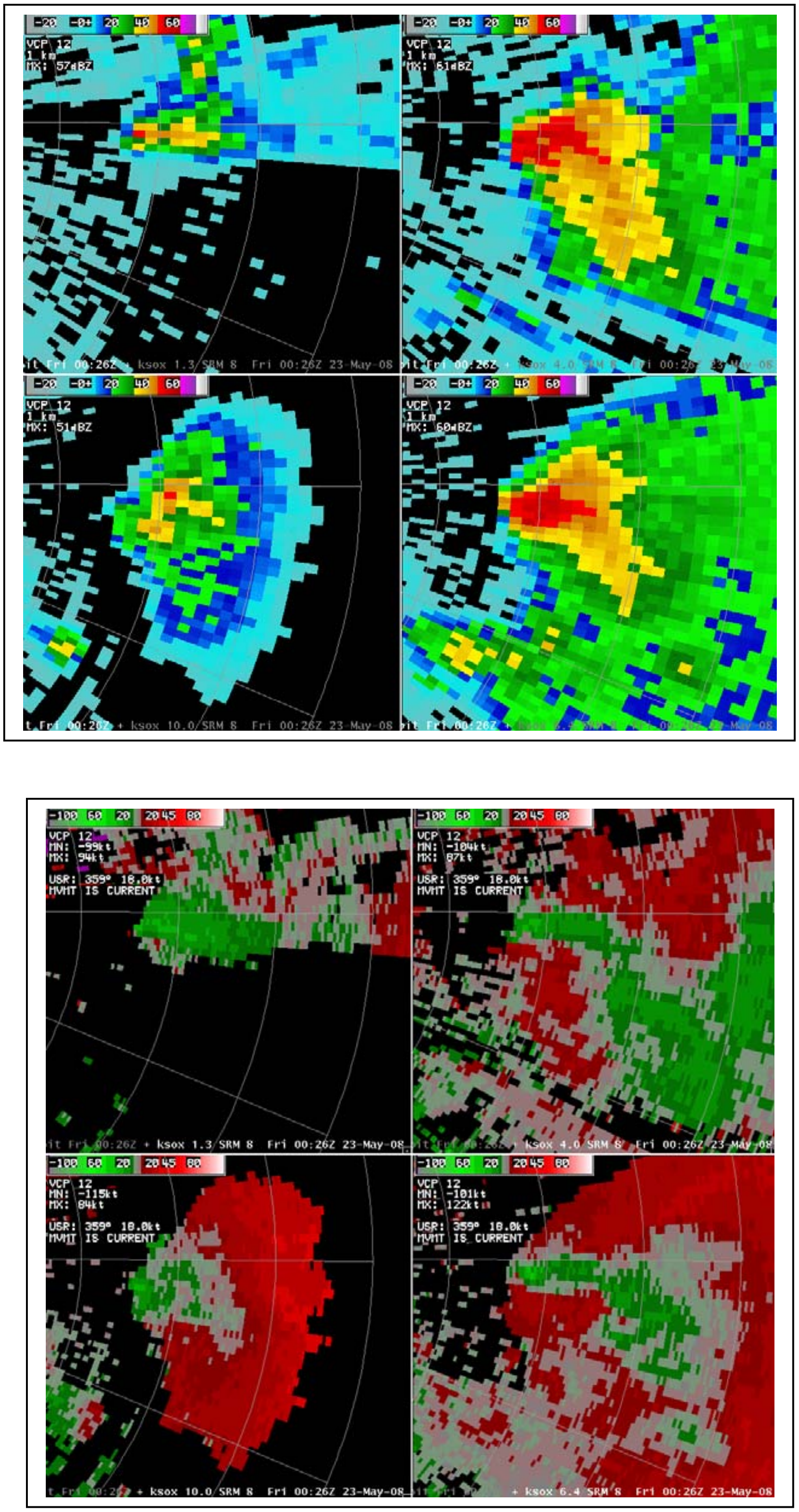

Fig. 19. The top is the 0026 UTC 23 May 2008 4-panel base reflectivity from the KSOX radar at (clockwise from the upper left) 0.5, 1.3, 2.4, and 3.1 degrees. The bottom is the 0026 UTC 23 May 2008 4-panel Storm Relative Velocity (SRM) from the KSOX radar at (clockwise from the upper left) 0.5, 1.3, 2.4, and 3.1 degrees.