A WES SIMULATION OF THE INTERACTION BETWEEN A TROUGH IN THE WESTERLIES AND MONSOON FLOW LEADING TO FLASH FLOODING IN SOUTHERN CALIFORNIA

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I. Introduction

On 15-16 July 2002 flash flooding occurred in southern California (fig. 1). This flooding was mainly the result of gradual moistening of the airmass up to nearly 1.50 inches of precipitable water (150 % of normal). Along with daytime heating, this moisture then interacted with weak troughs in the westerlies. The monsoonal moisture, descending from aloft, created vertical moisture profiles consistent with producing sprinkles in southern California during the morning of 15 July, and producing flash floods during the afternoons of 15 July and 16 July. Also 500 mb winds falling below 15 knots created slow moving convection and an increased potential for flooding. The intent of this WES case study is to analyze the moisture and dynamics that characterized this event.

II. Case Study

During the evening of 14 July 2002 the airmass over southern California was generally dry and stable. At the same time a huge mesoscale convective system over Arizona created an outflow boundary that propagated westward across the deserts into southern California. The outflow boundary was moistening the low levels over southern California, and the ambient south to southeast monsoonal flow was moistening the mid and upper levels. The outflow boundary can be seen in the 0830 UTC 15 July 2002 infrared satellite imagery overlaid by the 0900 UTC 15 July 2002 surface observations (fig. 2). The 1145 UTC 15 July 2002 infrared satellite imagery overlaid by the 1200 UTC 15 July 2002 surface observations (fig. 3) shows the outflow boundary reaching the coastal mountains of Baja California that extend north into San Diego County (the “Spine”). The flow hitting the spine changes the characteristics from the downdraft of one storm to a “topographical updraft” feeding another thunderstorm developing over the spine. This convection weakens as it moves off the mountains, but still brings light rain to the city of San Diego before it dissipates. (This is because clouds generally produce at least light rain when the 50 % relative humidity contour dips down to at least the 650 to 700 mb range. This is especially true over higher terrain where the drops can more readily reach the ground before evaporating). The marine layer clouds, much thinner than the 2000-3500 foot thick layer that can occasionally produce up to a few measurable amounts, did not even reach the 1500 - 2000 foot thick range generally found for trace events, thus there was little possibility that the trace of rain in San Diego was from the marine layer. However, the moist low levels could help the droplets from the higher clouds reach the ground. Morning convection such as this over southern California is usually an indicator of a very unstable airmass, potentially a convective trigger in place to drive afternoon convection, and possibly flash flooding or severe weather when diurnal heating is added.

The convection during the afternoon of 15 July 2002 over southern California was triggered by not only surface heating, but also by an upper level trough approaching from the west. The approaching upper level trough can be seen just off the west coast in the 500 mb heights, vorticity, and water vapor imagery during the morning at 1200 UTC 15 July 2002 (fig.4). The 1200 UTC 15 July 2002 250 mb heights and winds overlaid with the 1200 UTC 15 July 2002 water vapor imagery (fig. 5) also shows the trough just off the coast. A 50 knot jet behind the trough is easily seen at the location of strongest downward motion, indicated by the orange area of mid-level drying behind the trough line. Ahead of that area of drying is the moisture associated with the trough. Immediately forward of this is the 50 knot jet ahead of the trough, seen as a drier area stretching from just off the southern California coast northeast through KEDW. Ahead of this is the monsoonal moisture. The airmass is still rather wet over southern California in the path of the monsoonal moisture, and the morning thunderstorm set off by the interaction between the MCS outflow boundary and the spine can be seen near KNKX. Instability in the form of surface based CAPE and LI values not only supported thunderstorms (over 200 and below 2) they supported strong thunderstorms in southern California (fig. 6). CAPE values of 300-600 joules in the mountains and 500-1000 joules in the deserts are seen via the ETA model at 0000 UTC 16 July 2002. This is supported by ETA surface lifted indices dipping to just below -2 over the eastern desert portion of the WFO San Diego CWFA. For comparison, the higher resolution MesoETA model at 0000 UTC 16 July 2002 showed the usual increase in detail and more “extreme” values, with peak contours in the CAPE/LI of about 1200/-4 (fig. 7) compared to the peaks in the ETA model of 1000/-2 in the desert portion of the WFO San Diego CWFA.

The vertical moisture profile can be seen in the 1200 UTC 15 July 2002 KNKX sounding (fig. 8). The precipitable water, K index, and Total Totals indices are rather low at 1.23 inches, 24, and 44 respectively. [It should be mentioned that the KI and TT indices (and to an extent the precipitable water) can be severely reduced in value by the sea breeze, yet still produce flooding and severe weather, however this topic will be explored in a future TA]. Since the mean summer precipitable water is about an inch, then the precipitable water is about 123 % of normal. The wet bulb zero, at 14,227 feet above sea level is within the realm of large hail for southern California. (The wet bulb zero becomes less favorable for large hail on the afternoon sounding, which will be discussed later). The winds have turned south (a sign of thunderstorm potential) and are almost unidirectional, which would make one wonder about the potential for flash flooding due to echo training. A well developed monsoonal jet can be seen at around 600 mb. The 14 knot wind at 500 mb is in the “light wind” category (10-14 knots) as far as flooding is concerned, so the resulting slow movement of the cells also indicates the potential for flash flooding.

The 0000 UTC 16 July 2002 KNKX sounding (fig. 9) shows a more moist and unstable profile than the earlier sounding. The precipitable water has increased to near 1.50 inches (nearly 150 % of normal). The precipitable water is about 1.5 standard deviations above the normal PW value of 1 inch, since the standard deviation is about 0.34. The K index and Total Totals indices are a respectable 31 and 49. The wet bulb zero has increased to over 15,000 feet, which reduces the potential for large hail. The 500 mb winds of 9 knots has fallen into the “very light” (less than 10 knots) category. The 500 mb wind speed of 9 knots is about 0.50 standard deviations below the summer mean of about 18 knots since the standard deviation is about 11.5 knots. (The percentage of normal and standard deviations from normal are very useful for determining how “extreme” these values are.) The single digit 500 mb winds combined with precipitable water values near 150 % of normal makes this case a strong candidate for flash flooding in southern California. The drying of the upper levels also helps to allow a more dry adiabatic lapse rate aloft.

Oftentimes easterly waves propagating westward in the monsoonal jet are the features that enhance the heating-related convection in southern California. In this case, the 0000 UTC 16 July 2002 water vapor imagery (fig. 10) actually shows the upper level trough in the westerlies as a trigger, reaching the mountains of southern California at the time of peak heating. The trough added upward motion while interacting with the very unstable monsoonal moisture already over the area. Also, troughs during this type of pattern (when the tail end of the trough just skirts the edge of the monsoonal moisture boundary) have a tendency to dry out the airmass aloft as the jet moves in. The southwest flow aloft associated with the jet can initiate a "top- down drying trend" in the upper levels (above about 550 mb), which decreases any high clouds that can inhibit heating related convection. This can leave the moist lower and mid levels uncapped by high clouds and generate a dry adiabatic lapse rate above the moisture, resulting in explosive convection.

The 2339 UTC 15 July 2002 KNKX composite reflectivity, VIL, and echo top products are shown in figure 11a-c. The 2339 UTC 15 July 2002 KNKX composite reflectivity in figure 11a shows the "infamous pink pixel" (6 pixels in fact) of at least 65 dBZ, with a maximum of 67 dBZ, so either severe weather or flash flooding is possible simply based on composite reflectivity. The 2339 UTC 15 July 2002 KNKX VIL (vertically integrated liquid) product in figure 11b shows a peak value of 56 kg/m2. The 2339 UTC 15 July 2002 KNKX echo top product in figure 11c shows a top of about 48 thousand feet. The VIL density is 3.8.

TIME (UTC)	MAXIMUM VIL (kg/m^2)	MAXIMUM ECHO TOP (kft)	VIL DENSITY (kg/m^3)	ECHO TOP RANGE (kft)	VIL DENSITY RANGE (kg/m^3)
15/2339	56	48	3.8	45-50	3.7 - 4.1

Table1. Values during the peak in VIL density at 2339 UTC 15 July 2002. VIL density is calculated using VIL Density = (VIL / echo top) x 3.281.

Based on the KNKX WSR-88D echo top graphic and the Vertically Integrated Liquid water (VIL) graphic from the WES, the VIL density, at 3.8 was just over the severe hail threshold of 3.5 (Amburn and Wolf, 1996). The upper end of the VIL density range based on VIL and the echo top range is below the "near 100 percent probability threshold for severe hail" value of 4.5 (Small et al., 1998), pointing toward a reduced potential for severe hail. Finally, the wet bulb zero in excess of 15,000 feet reduces the potential for large hail, along with the very high freezing level (also above 15,000 feet). There was no hail reported with the flash flood event during the afternoon of 15 July 2002.

As for flooding, there were at least 5 consecutive composite reflectivity volume scans above 50 dBZ in the same location under this thunderstorm. Past events have shown that about 0.05 inches per minute, which is about 1/4 inch of rain per volume scan, is a good rough estimate of rainfall from a 50 dBZ cell in a southern California warm season thunderstorm. This would indicate up to about 1/4 inch for the first scan reaching 50 dBZ, with 1/4 inch for each scan thereafter. This would add up to nearly 1.25 inches of rain in about 5 scans of 50 dBZ in one location. About 1.25 inches of rain or more occurring in an hour or less usually proves to be a good first guess for flash flooding in southern California. Since this cell was above 65 dBZ for a while, this would indicate flooding in less than 5 volume scans. This type of estimate works well under wide cells, where 50 dBZ or more is consistently over one area for multiple scans before the cell moves away. For the storm on the afternoon of the 15 July 2002 about 1.60 inches of rain fell in one hour, with flash flooding.

It has been noted that when there is a day of flooding in southern California, and there is little change in ambient conditions (or conditions change to become more conducive to flooding by the following afternoon), there is usually flooding on the following day as well. Hence, there may be a significant "persistence" characteristic (maybe there are some dynamic forcings, temperature and moisture characteristics, etc..., that may remain in the area, that kicks off the strong convection and flooding again on the following day). This case was no exception. Another round of flooding occurred on the 16th. The soundings for 0000 UTC 16 July 2002 and 0000 UTC 17 July 2002 (fig. 12) show a more moist and unstable airmass on day 2 than on day1. In this case, the traditional indices along with the precipitable water would point toward a more stable environment on day 2 since these indices depend heavily on low level (at or near 850 mb) moisture. This is contrary to reality, as the environment was actually becoming more unstable. Figure 12 shows the lifting of the most unstable parcel on each sounding and the level from which the lifting takes place is shown in red. These levels were above the marine layer and hence more representative of the environment in the non-coastal areas of southern California. Due to the increased moisture at 750 mb on the 0000 UTC 17 July sounding, the significantly higher CAPE (which is greater at 0000 UTC 17 July 2002 than on the other soundings) indicates that the parcel more unstable to lifting is found on the 0000 UTC 17 July 2002 sounding. The moisture changes based on the traditional indices results in an artificially more "stable" airmass even though the sounding is in fact more unstable. Although the 700-500 mb lapse rate actually decreased slightly from day 1 to day 2, the low level moisture increased, resulting in a more unstable environment. Therefore, much care should be used when evaluating soundings based on indices, as they may show a trend in the opposite direction of what is really happening. Thus, a "modified persistence" (or "adjusted persistence") forecast in this case is a good forecast.

A key feature of the 0000 UTC 17 July 2002 sounding (fig. 13) is that it is approaching the "loaded gun" type of profile for southern California. [The southern California "loaded gun" sounding has a layer on it that, in fact, does sometimes resemble the barrel of a gun. This nearly ideal profile consists of a moist layer of approximately 2-6 degree dew point depression (about 65-90 % relative humidity) down to at least 750 mb, associated with a lapse rate in the layer between the moist and dry adiabatic lapse rates (conditionally unstable), capped by a drier layer above about 550 mb, with winds near 500 mb of less than 10 knots]. This profile appears to provide an environment for lifted parcels to flow upward through a region of the atmosphere where it is not too wet/cloudy to inhibit heating related convection, but at the same time not too dry (so parcels do not dry out too rapidly). This explosive mid level profile has proven in the past to accompany many flooding events, as well as those with large hail and/or microburst winds. The 0000 UTC 17 July 2002 sounding is reasonably close to this profile. This "elevated conditionally unstable layer" usually lengthens in a "top-down" fashion as the monsoon episode matures. Also, the character of the flooding (isolated or widespread) can sometimes be predicted in advance. Based on past events, there seems to be a bi-modal flooding pattern as the 500 mb winds transition from double digit to single digit. Convection seems to organize into an isolated flooding event in only one zone with 10 -15 knot 500 mb winds, (most likely due to the shear organizing only 1 or 2 localized areas into Mesoscale Convective Systems while many of the other cells with weaker updrafts are "sheared apart"). The convection seems to generate widespread (multi-zone) flooding more often with 500 mb winds less than 10 knots (mainly due to the slow movement of many cells), and especially if the winds are very light and variable (less than 10 knots) to the surface. Winds that become too strong (above about 15-20 knots at 500 mb) shear apart the cells, with precipitation developing on and training downwind of only the highest terrain. It is difficult to determine the character of this 15-16 July 2002 event as winds are near 10 knots at 500 mb. The vertical profile mentioned above will be discussed in more detail in a later TA.

III. Discussion and Conclusion

Monsoonal moisture initially sets up the airmass in this case. Precipitable water values were just under 1.50 inches (150 percent of normal). This value was combined with 500 mb winds in the upper single digits (about 66 % of normal) to produce flooding in this case. (The percentage of normal is very useful for determining how “extreme” these values are.) The result was a very moist airmass with slow cell movement and flash flooding. This points toward precipitable water near or exceeding these values, along with 500 mb winds near or lighter than these values (1.50 inches/10 knots) as being good candidates for flooding. Also upper level disturbances in the westerlies were shown to interact with these heating - generated, slow moving thunderstorms and enhanced the strength of the storm. Under these conditions, amounts can easily reach the 0.50 to 1 inch per hour amounts commonly associated with what can generally be called “moderate” urban and small stream flooding, and often exceed 1 to 1.25 inch amounts generally associated with more widespread “high end urban/small stream events” to “low end flash flood events” in southern California. With amounts above 1.25, urbanized areas, along with washes and canyons will usually experience flash flooding. The cell that produced flash flooding on the 15th easily delivered the 1/4 inches of rain per volume scan (5 minutes) common for wide 50 dBZ composite reflectivity cores during the warm season, since returns were as high as 67 dBZ. A conditionally unstable layer with a profile closer to ideal for southern California evolved by 0000 UTC 17 July 2002. This layer is wet enough to keep parcel entrainment from drying the parcel out too much, but the layer is dry enough so that there is not too much cloud around to reduce solar heating as the parcels rise. Also, based on previous events, persistence seems to play a part in whether or not flash flooding will occur, and should be considered as an additive factor (making flooding more favorable) on the day following a flood event.

It has been noted that unless the VIL density is very huge (The top of the VIL density range based on the VIL and the echo top range reaches about 4.5), large hail is usually not reported in the sparsely populated eastern slopes of the mountains and in the deserts of the San Diego CWFA. To an extent, this is also true west of the mountains when there are huge lapse rates due to well above normal surface temperatures, very high wet bulb zeros, and very high freezing levels that approximate desert conditions. In these cases the wet bulb zero and freezing level may be at or above about 15,000 feet, and the huge, hot lapse rates melt the hail down to non-severe sizes. Even though very moist, low level gulf surges can cool the deserts (down to about 105 degrees F or so) , the low levels are usually hot enough to seemingly melt large hail, but then microbursts become the main problem. These moist, cooling desert surges can decrease the ocean to desert thermal gradient, weaken the sea breeze, and allow hotter conditions in the coastal and mountain areas, which may also serve to melt hail. On the other hand, these hotter conditions allow storms to remain stronger, (and last longer than they normally would) near the coast because of the lack of cool, stabilizing marine air during such hot conditions. All these things should be considered in locations such as southern California which has marine, mountain, and desert environments that affect the potential for severe thunderstorms and flash flooding.

IV. References

Amburn, S. A., and P. L. Wolf, 1996: VIL Density as a Hail Indicator. *Wea. Forecasting*, **12,** 473-478

Small, I. J., D. V. Atkin, and T. E Evans III, 1988: Severe Hail Detection Using VIL Density and its Application in the Western States. Western Region Technical Attachment No. 98-37, 8 pp. www.wrh.noaa.gov/media/wrh/online_publications/TAs/ta9837.pdf

Figure 1

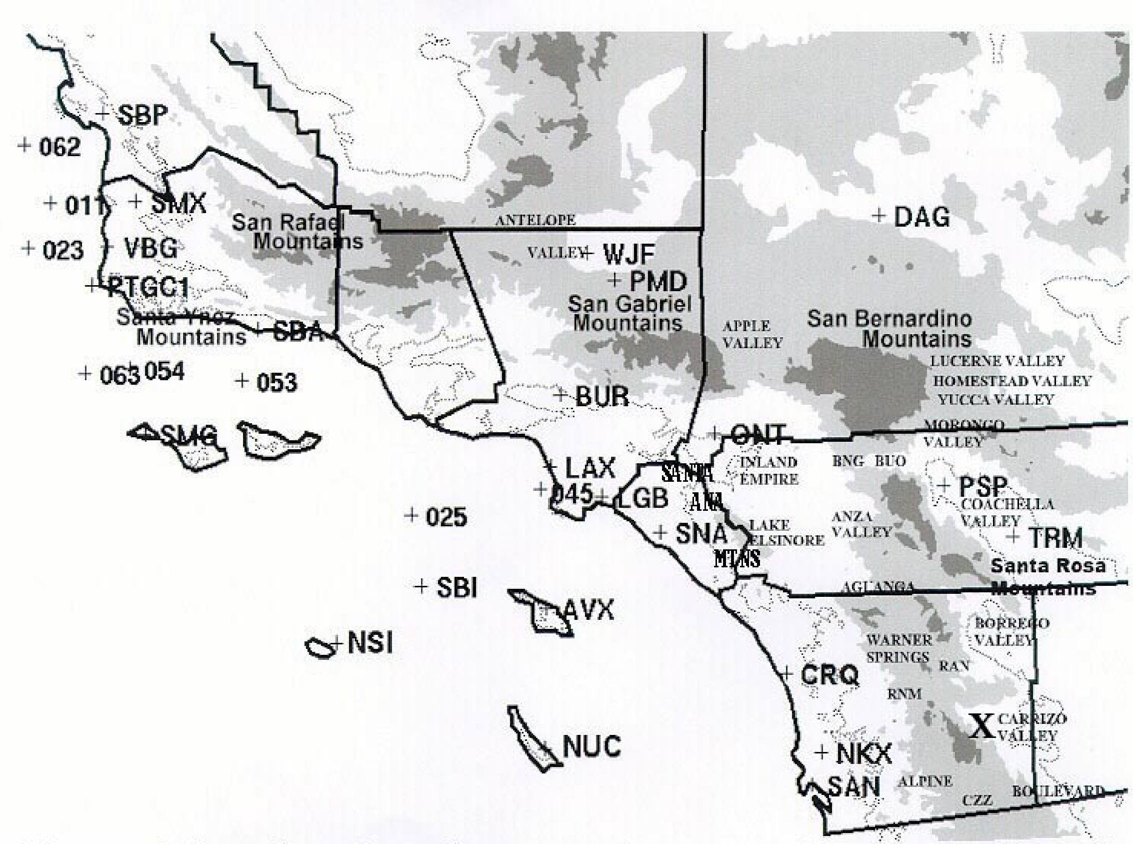


Fig. 1. Map showing the rugged mountainous terrain of southern California. The "X" shows the location of the 0000 UTC 16 July 2002 flash flood.

Figure 2

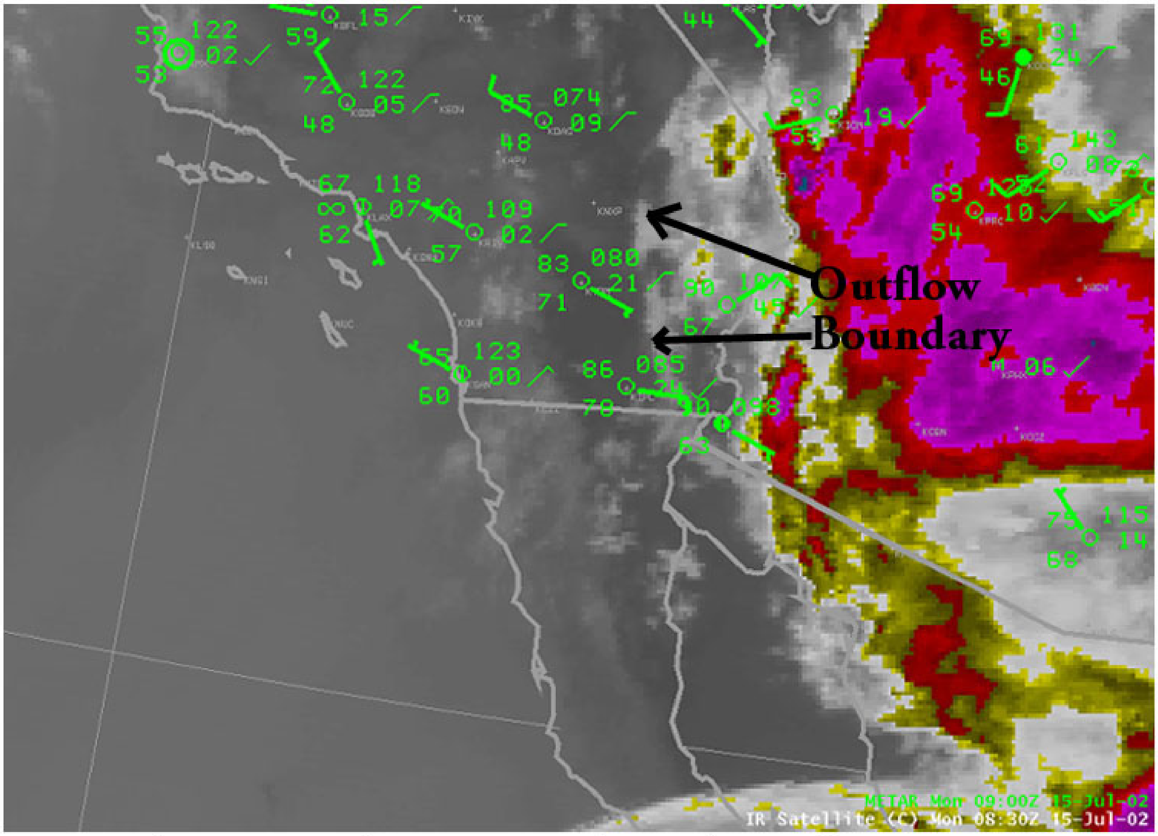


Fig. 2. 0830 UTC 15 July 2002 infrared satellite imagery and 0900 UTC 15 July 2002 surface observations. Outflow boundary from Arizona MCS has moved west across the California border.

Figure 3

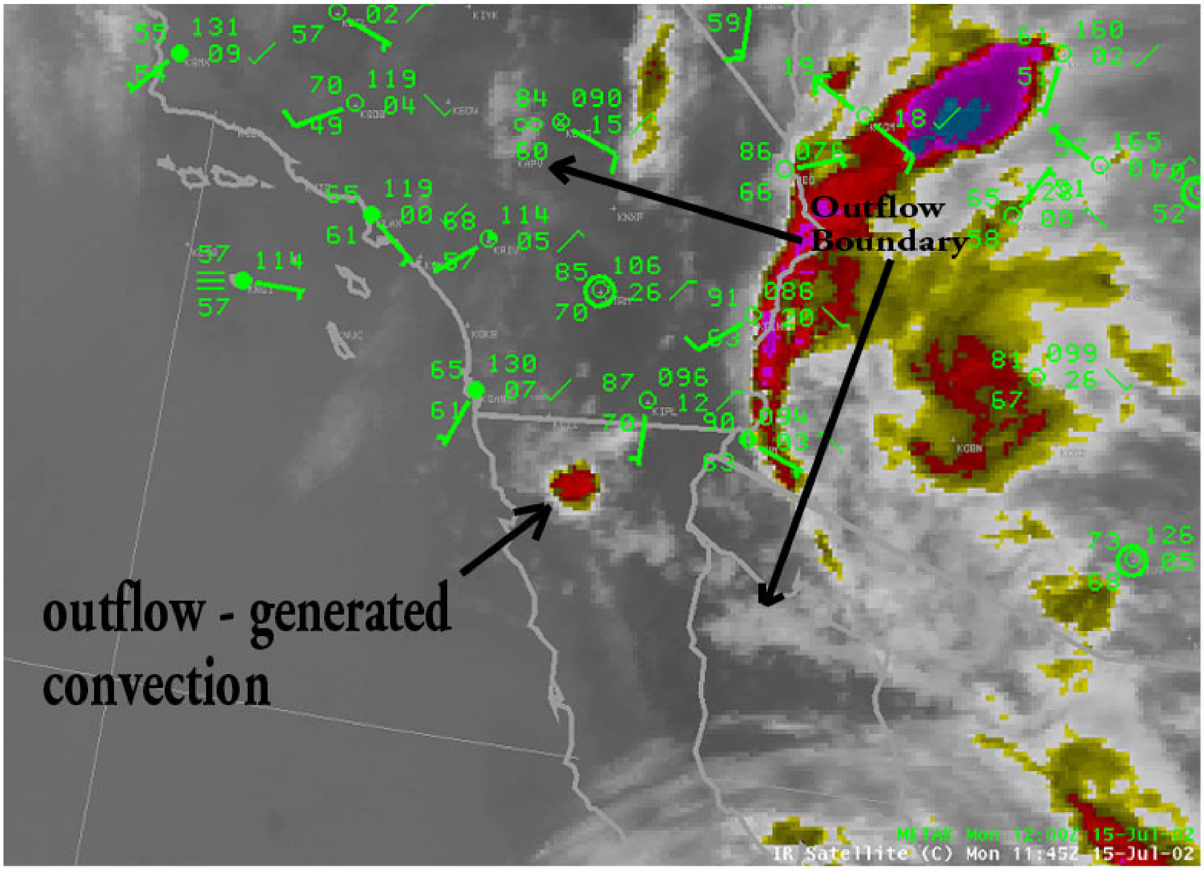


Fig. 3. 1145 UTC 15 July 2002 infrared satellite imagery and 1200 UTC 15 July 2002 surface observations. Outflow boundary has generated convection on the mountains southeast of KSAN.

Figure 4

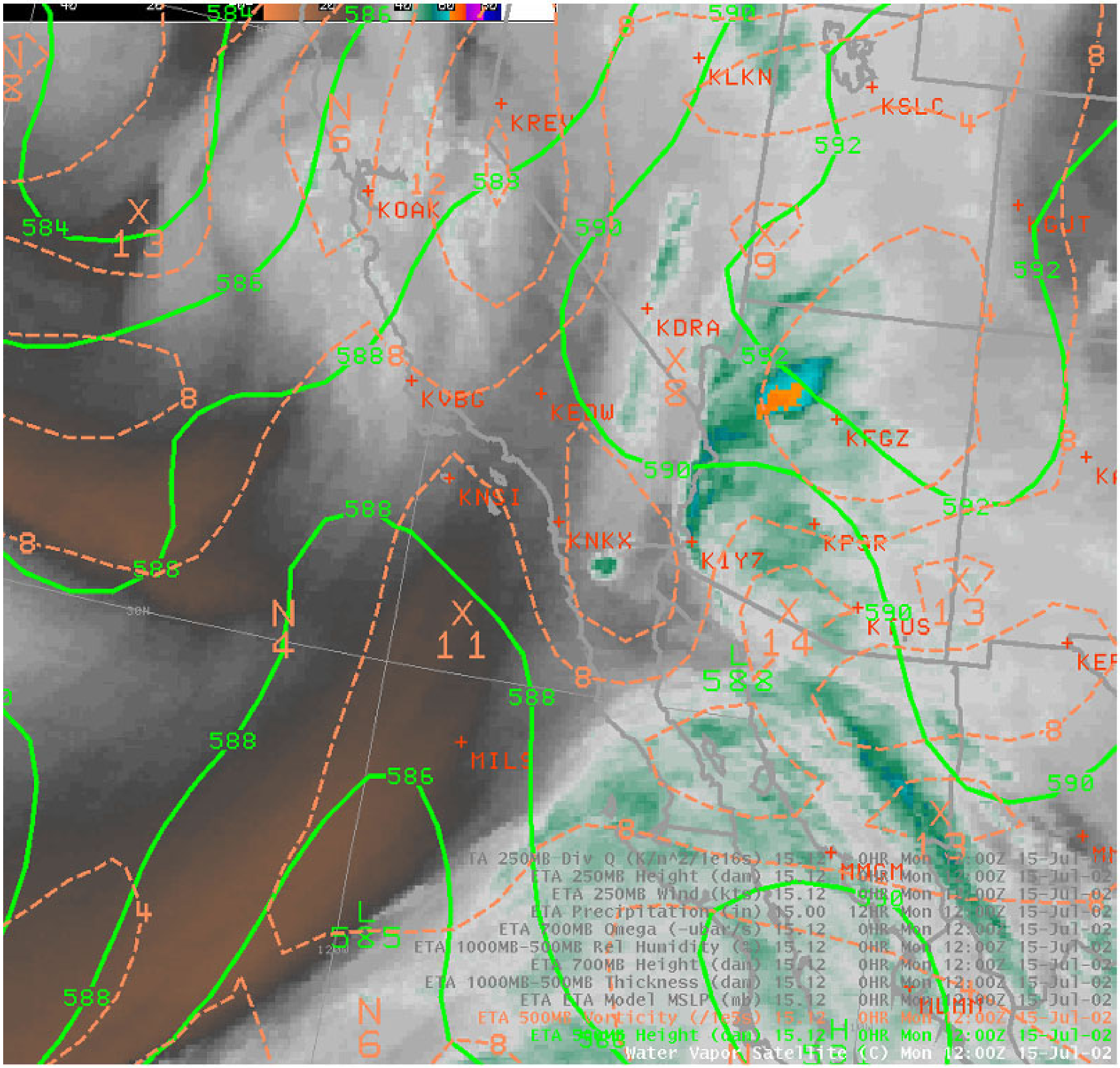


Fig. 4. 1200 UTC 15 July 2002 500 mb heights (in intervals of 2 dekameters), vorticity (in intervals of 4 s-1), and 1145 UTC 15 July 2002 water vapor imagery showing the trough approaching the monsoonal moisture.

Figure 5

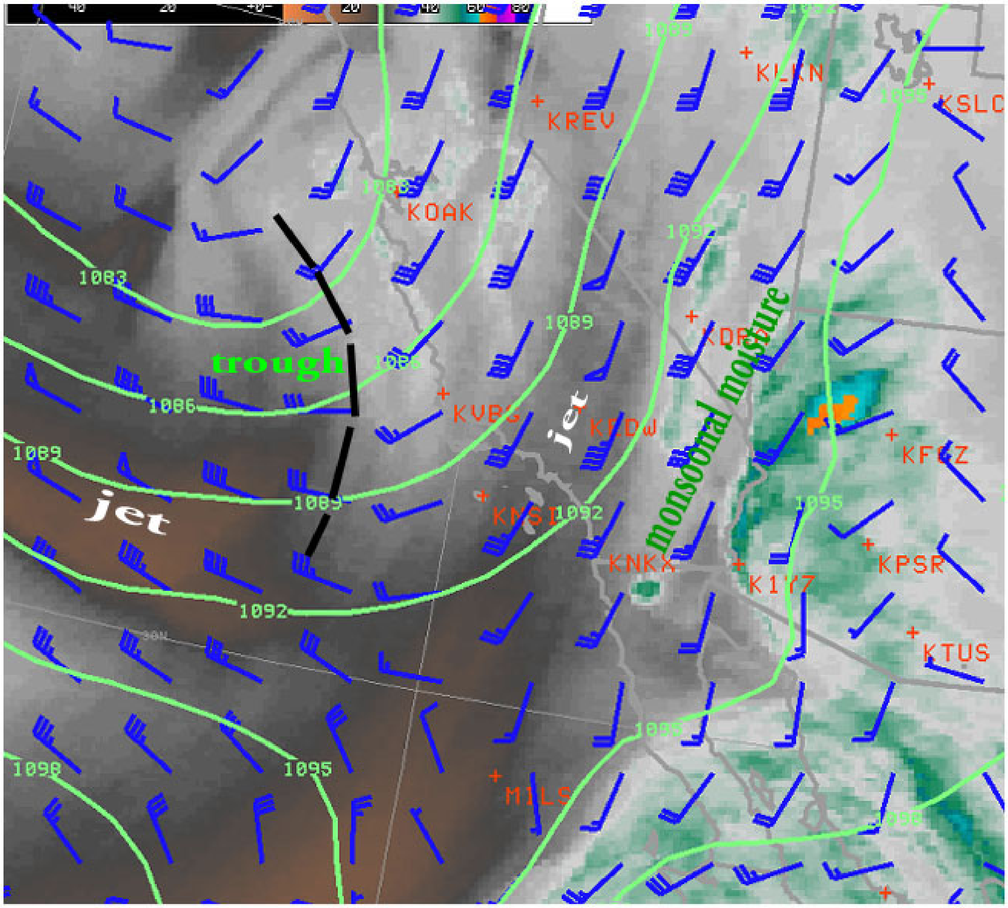


Fig. 5. 1200 UTC 15 July 2002 250 mb heights (in intervals 3 dekameters) and winds (knots) overlaid with the 1145 UTC 15 July 2002 water vapor imagery showing the trough approaching the monsoonal moisture.

Figure 6

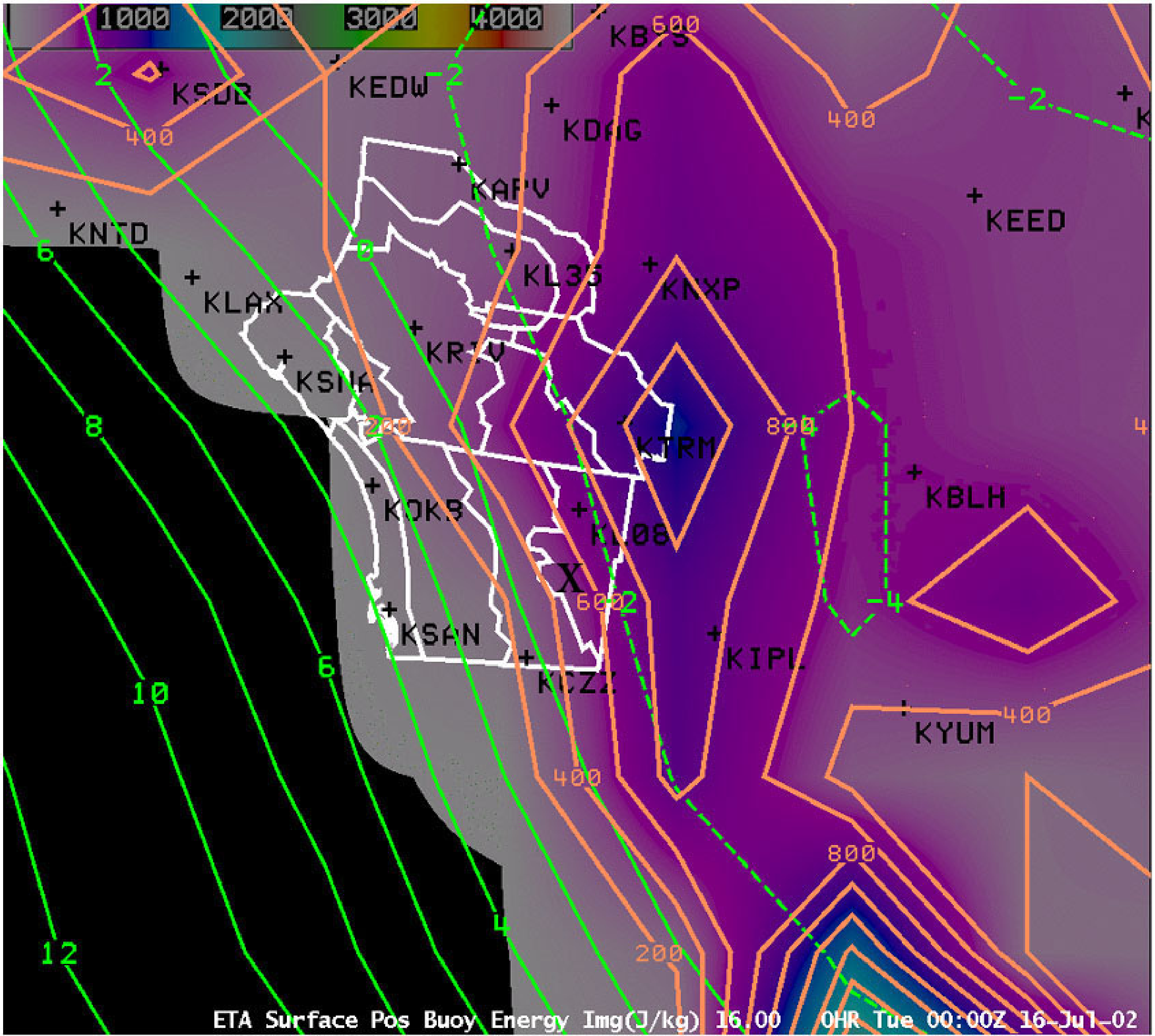


Fig. 6. 0000 UTC 16 July 2002 ETA surface CAPE (solid orange contours in intervals of 200 joules) and surface LI (green, contour intervals of 2 degrees C).

Figure 7

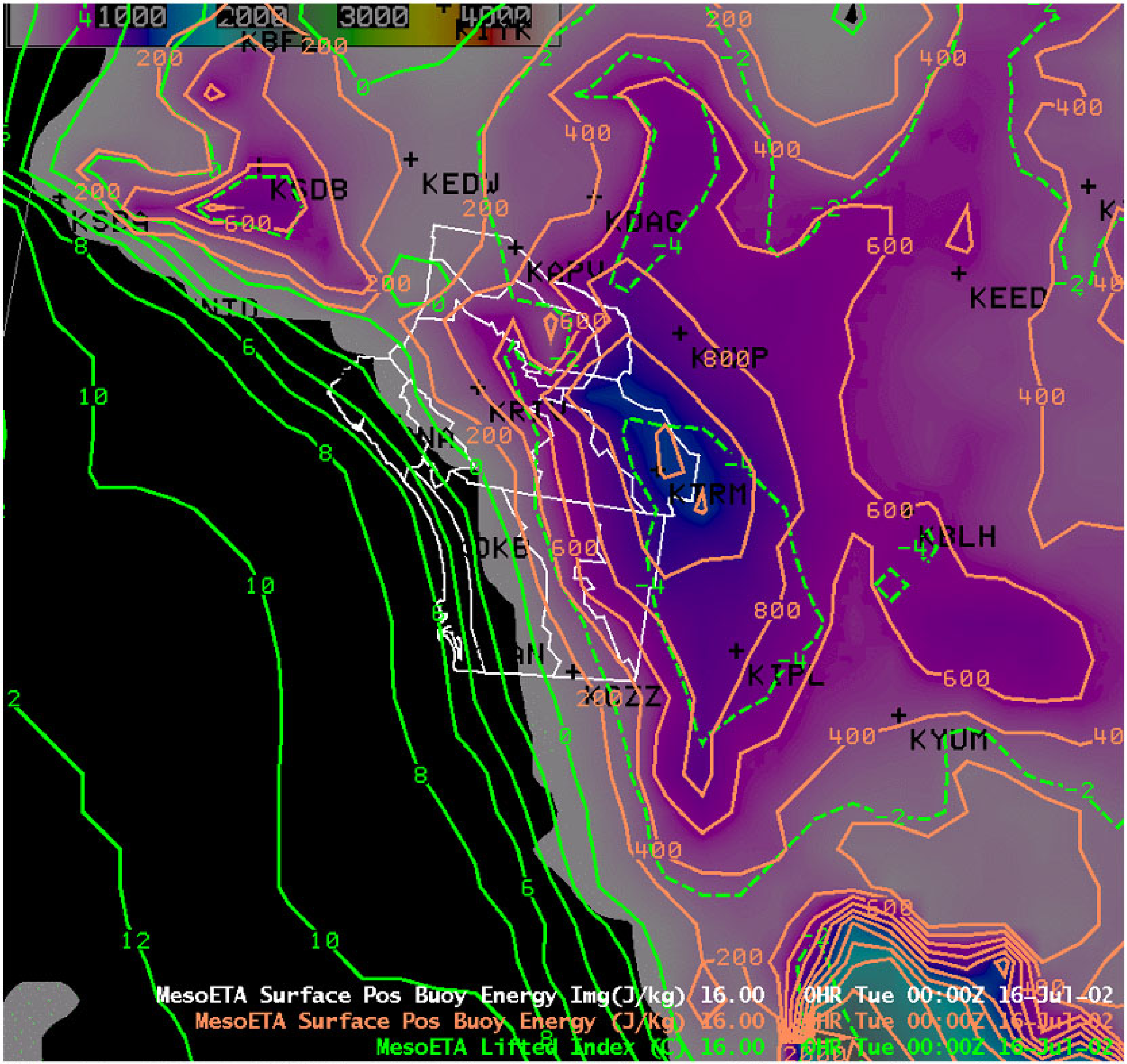
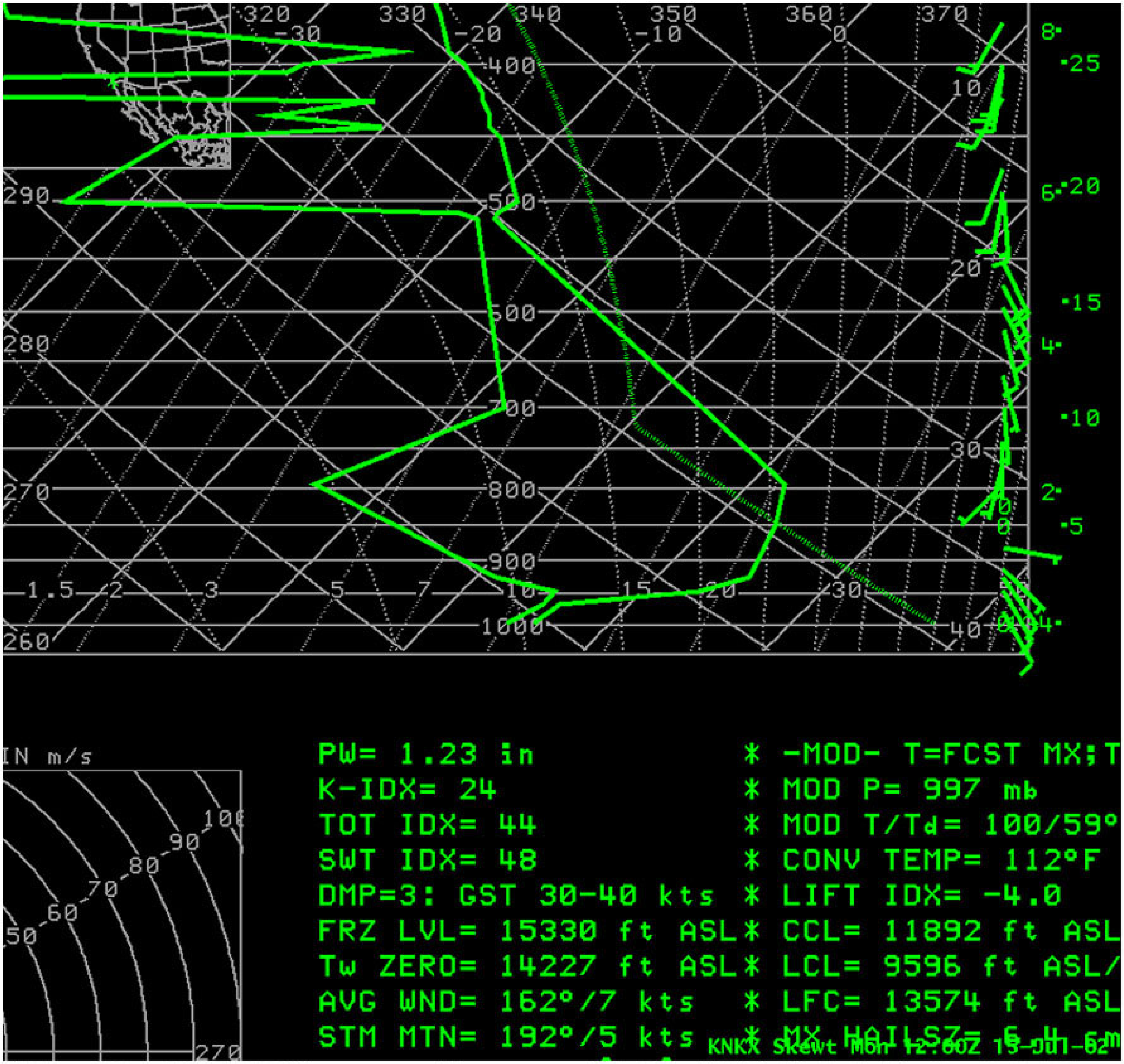


Fig. 7. 0000 UTC 16 July 2002 MesoETA surface CAPE (solid orange contours in intervals of 200 joules) and surface LI (green contours in intervals of 2 degrees C).

Figure 8



```
PW= 1.23 in          * -MOD- T=FCST MX;T
K-IDX= 24            * MOD P= 997 mb
TOT IDX= 44          * MOD T/Td= 100/59°
SWT IDX= 48          * CONV TEMP= 112°F
DMP=3: GST 30-40 kts * LIFT IDX= -4.0
FRZ LVL= 15330 ft ASL* CCL= 11892 ft ASL
Tw ZERO= 14227 ft ASL* LCL= 9596 ft ASL/
AVG WND= 162°/7 kts  * LFC= 13574 ft ASL
STM MTN= 192°/5 kts  * MX HAILSZ= 6.4 cm
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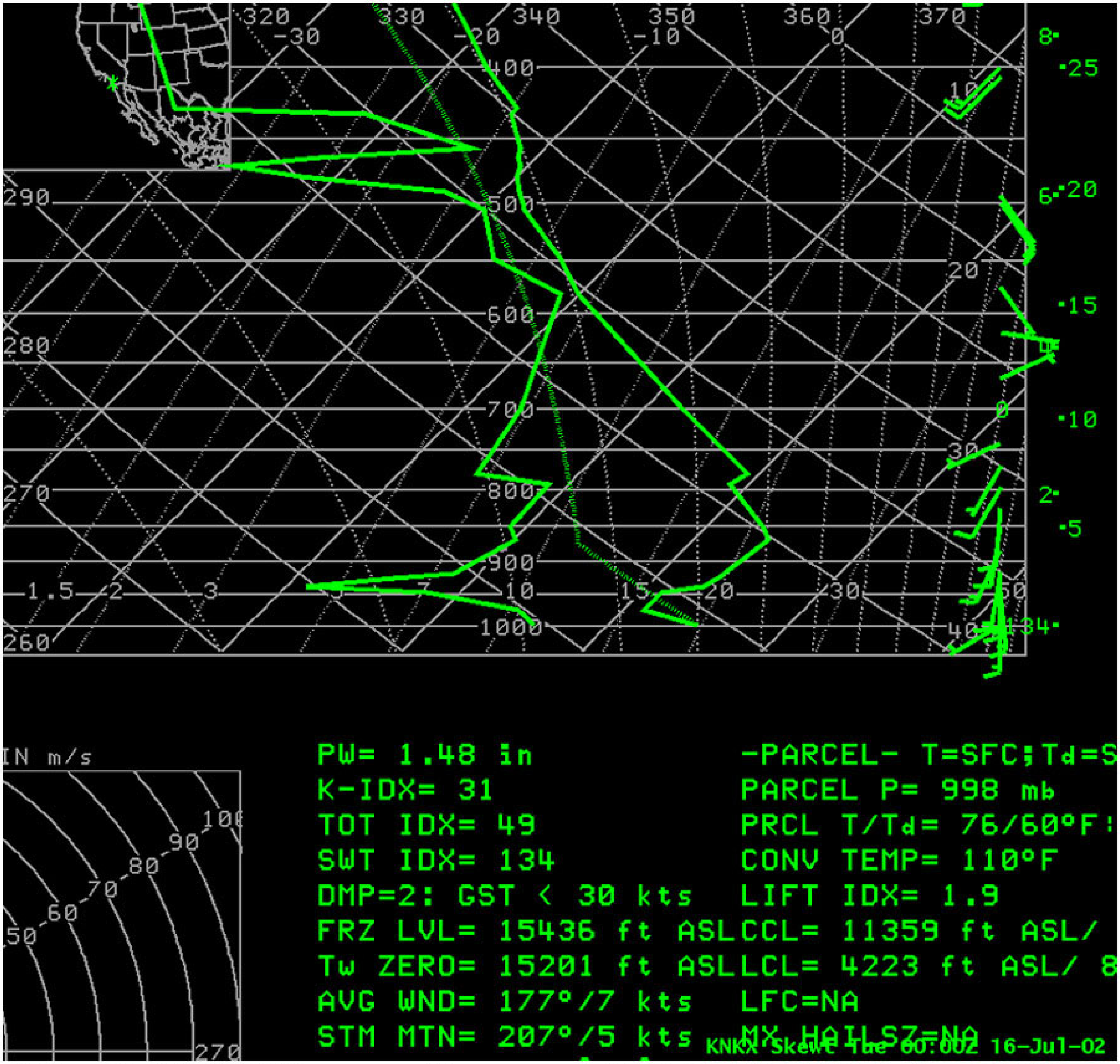
Fig. 8. KNKX sounding at 1200 UTC 15 July 2002.

Figure 9



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K-IDX= 31            PARCEL P= 998 mb
TOT IDX= 49          PRCL T/Td= 76/60°F:
SWT IDX= 134         CONV TEMP= 110°F
DMP=2: GST < 30 kts  LIFT IDX= 1.9
FRZ LVL= 15436 ft ASLCCL= 11359 ft ASL/
Tw ZERO= 15201 ft ASLLCL= 4223 ft ASL/ 8
AVG WND= 177°/7 kts  LFC=NA
STM MTN= 207°/5 kts  MX HAILSZ=NA
KNKX Skewt Tue 00:00Z 16-Jul-02
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Fig. 9. KNKX sounding at 0000 UTC 16 July 2002.

Figure 10

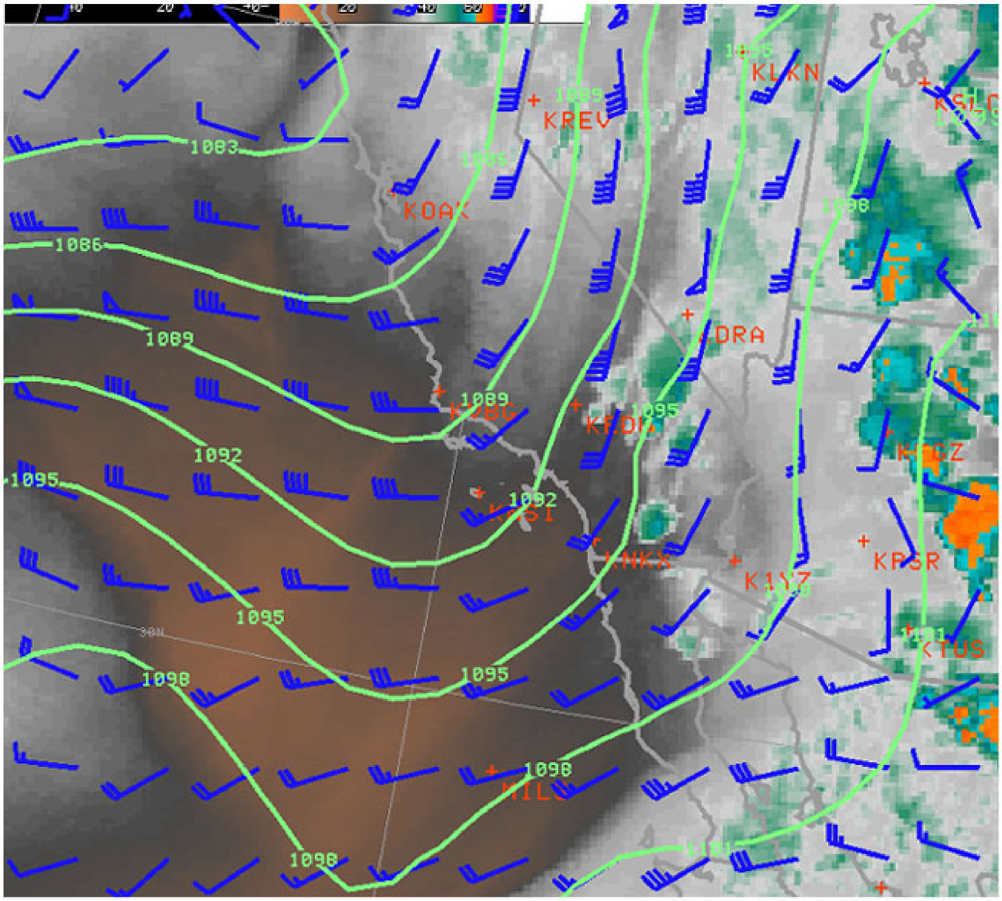


Fig. 10. 0000 UTC 16 July 2002 250 mb heights (green contours, in intervals of 3 dekameters) and winds (knots) overlaid with the 0000 UTC 16 July 2002 water vapor imagery showing the trough enhancing the convection.

Figure 11a-c

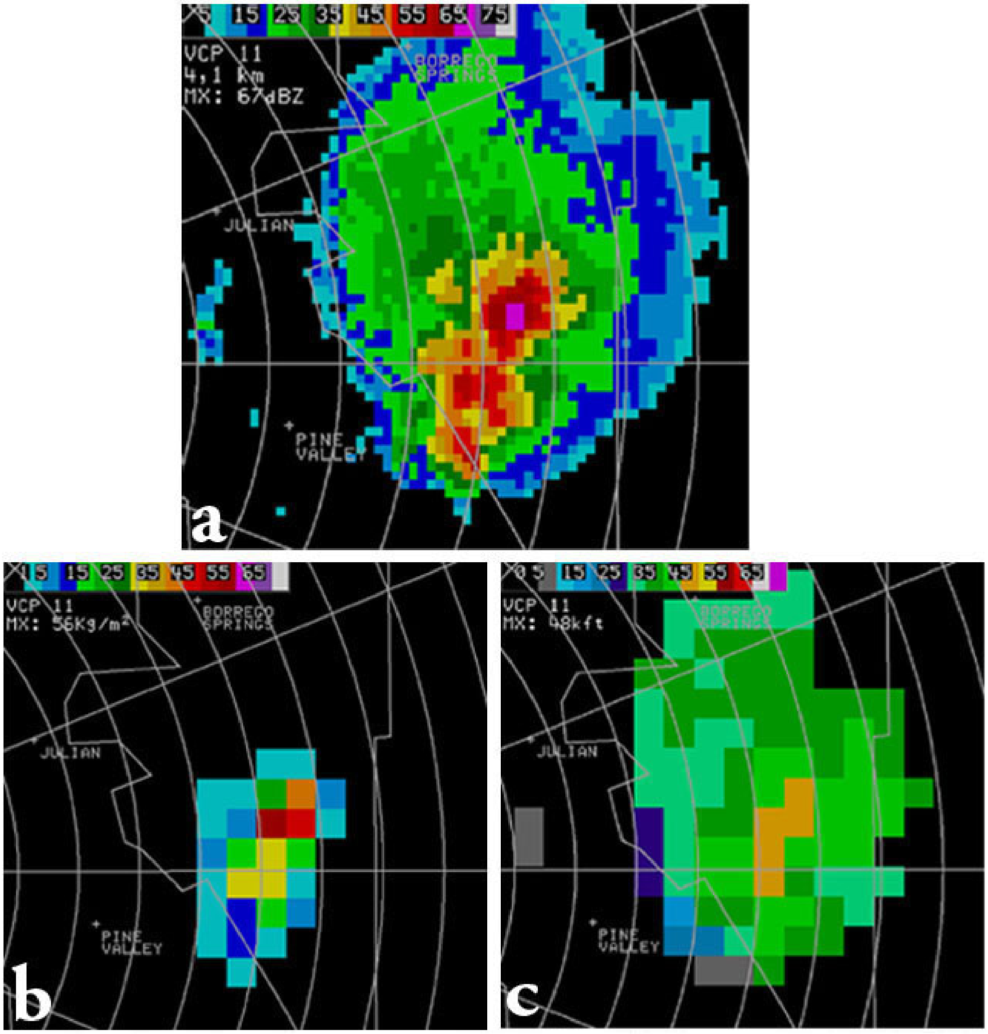
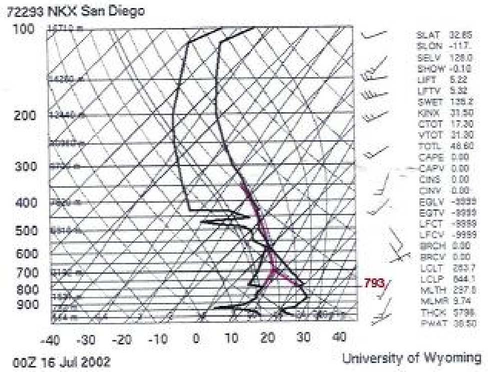


Fig. 11. Radar imagery of the cell from the KNKX WSR-88D radar at 2339 UTC 15 July 2002 showing (a) Composite Reflectivity, (b) VIL, and (c) Echo Top.

Figure 12



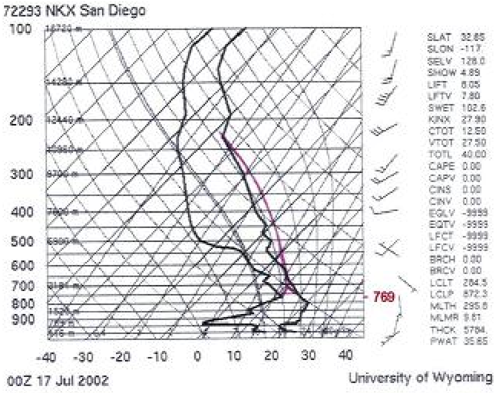


Fig 3.

KNKX soundings showing the most unstable lifted parcel on the soundings. CAPE and instability is highest at 17/00z even though lower traditional indices and a lower precipitable water value point toward a more stable environment.

Figure 13

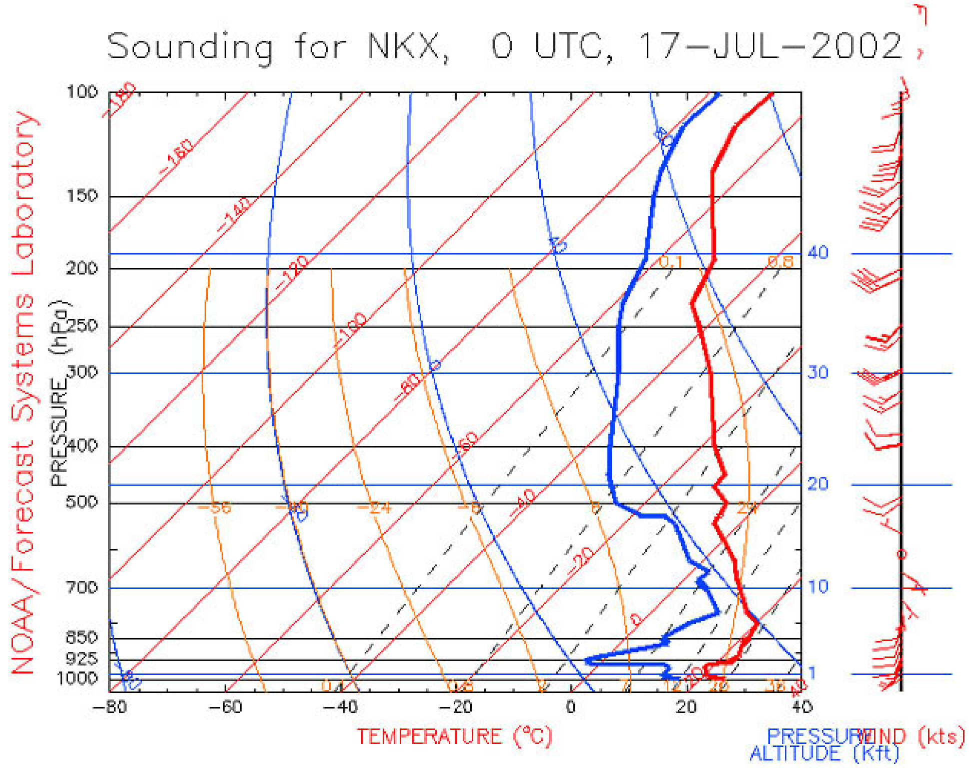


Fig. 13. KNKX sounding at 0000 UTC 17 July 2002.