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24-25 September 2001 Event in the Sacramento Valley

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1. Introduction

Most thunderstorms in California are rooted in the boundary layer and are dependent on surface or near-surface conditions. During the summer months moist convection is usually not seen in the Central Valley because there is limited moisture and a high-based level of free convection (LFC). Inversion layers can also further stabilize the air mass (i.e., cap) and inhibit moist convection. This often limits thunderstorms during the summer to the higher terrain of California where an air parcel can more easily reach the LFC. Recent research on elevated thunderstorms in northern California (Tardy 2001, 2002) has shown that this type of moist convection tends to occur most often during the warm season. This kind of thunderstorm has been observed to occur across all areas of northern California and is not dependent on terrain or surface diabatic effects. The thunderstorms showed similar intensity when they occurred over the ocean water, in the valleys or across the mountains.

This and prior studies in this series have focused on the exception to the terrain-induced thunderstorm, the elevated thunderstorm. The purpose of this research has been to develop a general model of the environment in which these thunderstorms develop and establish forecasting applications. The consequences of these events can often have major implications on fire danger, humans and agriculture. Despite thunderstorms being rather uncommon in the Central Valley during the summer, given the proper ingredients of mid-level moisture, lift and instability, thunderstorms can occur. This study will focus on the Sacramento Valley of California which is the northern half of the Central Valley. During the early afternoon hours on 24 September 2001 scattered thunderstorms developed in the Sacramento Valley. Later in the afternoon and during the evening hours the thunderstorms became more numerous and organized. Between the hours of 2200 UTC 24 September and 1300 UTC 25 September the National Lightning Detection Network (NLDN) recorded more than 5000 cloud to ground lightning strikes from the San Francisco Bay to the Central Valley. These thunderstorms also produced a period of heavy rainfall.

2. Prior Studies Overview and General Model

Each part of the elevated thunderstorm study illustrated how important moisture advection trends on satellite imagery are to the short term recognition of an elevated thunderstorm environment (Tardy 2001). The southwestern United States summer monsoon can advect mid-level moisture over California around upper-level high pressure as it shifts northward or when an upper-level low pressure develops just off the southern California coast. This pattern can result in daily terrain-driven thunderstorms for up to several days. However, elevated thunderstorms can develop in other patterns as well. When the dynamics associated with an upper-level area of lower pressure in the eastern Pacific, interacts with a source of mid-level subtropical moisture, the result can be significant moist convection. In order to properly identify this type of pre-thunderstorm environment the research has shown it is important to recognize the moisture advection and mid-level synoptic lifting that is evident on the water vapor imagery loops prior to condensation. This is often visible as subtle changes to a layer of the atmosphere where the interaction of increasing dynamics meets the precipitable water plume. The brightest (coldest) colors usually will not depict these changes since they are typically satellite characteristics of thunderstorms already occurring or those that have dissipated (i.e., anvil cirrus debris). Considering that the water vapor imagery is most sensitive to moisture around 400 mb, it is not surprising that the mid-level moisture does not often show up as a significant enhancement. The most effective way to verify the presence of deeper moisture is to view the available upper-air data, satellite microwave imagery and soundings, and model-derived soundings as shown in Part 1 (Tardy 2001).

Prior research on elevated thunderstorms (Colman, 1990), showed that the presence of elevated convective available potential energy (CAPE) was minimal. The thunderstorms in the study were similar in that they were isolated from surface diabatic effects, and were organized by larger scale dynamics. However, the thunderstorms of interest in this study developed in an environment with significant elevated CAPE. The Colman study further found the elevated thunderstorms to be associated with distinct surface warm fronts that produced a low-level inversion. In this research the frontal structure was often not well defined. The synoptic pattern usually exhibited a relatively dry closed upper low that moved across the eastern Pacific and interacted with a moist air mass that was present or advected into California (Fig. 1). This has been identified as a typical weather pattern for elevated thunderstorms in California.

The Oakland (KOAK) observed sounding in Figure 2 depicted a typical profile associated with elevated thunderstorms and monsoonal patterns in California during the summer. The KOAK sounding is conditionally unstable above 800 mb and extremely stable below this level. This sounding indicated that the greatest moisture was confined between 700 and 500 mb. If the low-level moist (marine air) inversion was removed, this would resemble an inverted-V sounding, or the Beebe Type IV (Bluestein 1993). This type of sounding is typically thought to produce high-based thunderstorms with generally little rain and possibly strong wind gusts. The time of the sounding corresponded well with the increase in thunderstorms and the subsequent moistening of the lower and mid-levels of the troposphere (see Fig. 2).

3. Observations on 24-25 September

On 24-25 September 2001 the synoptic pattern was very similar to those in prior elevated thunderstorm studies in this series (Tardy 2001), with an extensive mid-tropospheric closed low pressure approaching the coast of California (see Fig. 1). Ahead of this system upward vertical motion was being generated by differential positive vorticity and warm air advection processes. An upper-level jet stream maximum had moved directly over central California, east of the upper low. The southerly mid-level geostrophic flow ahead of the storm was drawing subtropical moisture (higher precipitable water values) northward into California. On the east-northeast side of this trough, the greatest low-level speed convergence and upper-level divergence produced large scale vertical ascent of the air mass. This is the prime location for thunderstorm development. This finding is similar to a study by Colman (1990) which illustrated that the maximum frequency of elevated thunderstorms was near the inflection point. The inflection point is where the great divergence can occur on the east side of a trough due to strong ageostrophic compensation of the wind flow. The 0000 UTC 25 September sounding from Oakland (KOAK) indicated a large quantity of elevated instability (Fig. 2). In addition, the dry air above 400-mb (see Fig. 2) would increase the environmental instability due to evaporative and adiabatic cooling as the upper-level air mass is lifted at the dry adiabatic lapse rate (faster rate of cooling). However, a surface analysis of CAPE at 2000 UTC indicated that there was no surface-based CAPE in the Central Valley, but there was over the higher terrain (Fig. 3). A Rapid Update Cycle (RUC) sounding for 2100 UTC, at the Sacramento grid point, also indicated a conditionally unstable environment (Fig. 4). However, surface-based convection was not supported because of the strong convective inhibition (CIN) in the boundary layer. The thunderstorms were not rooted in this stable layer. The marine layer observed at KOAK was not present over the Central Valley when the first thunderstorms developed, but instead a subsidence inversion (i.e., cap) existed which is common during the summer months and significantly contributes to poor air quality. It is crucial to recognize that the instability (nearly dry adiabatic) is elevated over the inversion layers depicted in Figures 2 and 4. It was suggested by Colman (1990) that the decoupling could act to decrease the drag on the overriding air and could allow for more efficient convective overturning. This study supports this theory since elevated thunderstorms in California have been observed when boundary layer conditions were dominated by marine, radiational, and subsidence inversions. However, the inversion layer is not a prerequisite to elevated thunderstorms but rather an inhibitor of surface-based mixing into the mid-troposphere.

The first development of convective clouds, altocumulus castellanus, was depicted in Geostationary Operational Environmental Satellite (GOES-10) visible (.39 μ) images at

1800 UTC (Fig. 5). The significance of these clouds is that they have been found to be precursors to elevated thunderstorms and indicate mid-level moisture and instability. At 2000 UTC infrared (IR) imagery indicated the thunderstorms had developed further north in the southern Sacramento Valley (Fig. 6). The GOES-10 water vapor image at 2130 UTC gave subtle indications of significant moisture advection southeast of the mid-tropospheric low pressure area and brightening due to synoptic layer lifting east of the system (Fig. 7). Although the cold frontal rain band was clearly visible in Figures 6 and 7, the moisture advection was most apparent on the Special Sensor Microwave/Imager (SSM/I) data which indicated the significant moisture plume having origins from the subtropics (Fig. 8). This rapid influx of moisture into the initially dry region was vital to the destabilization of the air mass as evident by the change in the KOAK sounding. At 1200 UTC 24 September the observed precipitable water value at KOAK was only 0.35 in (Fig. 9). The sounding twelve hours later showed a remarkable increase in moisture with a precipitable water value reaching 1.21 in by 0000 UTC 25 September (see Fig. 2).

The GOES-10 IR imagery also illustrated the location of an upper-level jet streak moving toward central California (see Fig. 6). North to south oriented enhanced cloudiness (cold cloud tops) perpendicular to this jet streak depicted the region of strongest mid to upper-level vertical motion on the east side of the mid-tropospheric system. In this region, an organized and intense area of thunderstorms developed just offshore and advected into the Sacramento Valley (Fig. 10). The NLDN detected more than 500 cloud to ground strikes in the Central Valley and coastal hills between 0400 and 0500 UTC (Fig. 11). Over 200 lightning strikes per hour were detected from 2200 UTC 24 September through 1100 UTC 25 September from the coast to the Sierra Nevada. The peak hour of lightning activity was from 0200 to 0300 UTC when 702 strikes were recorded (mostly along the coast). The IR image at 0715 UTC 25 September depicted a large area of intense thunderstorms over the Central Valley and a well-defined upper-level diffluent pattern (Fig. 12). Corresponding water vapor images clearly showed the upper-level circulation that was producing the thunderstorms (Figs. 13 and 14). This, and other elevated thunderstorm studies, have illustrated that despite the dry air on the KOAK sounding noted below 700 mb (see Figs. 2 and 4), thunderstorms can become strong enough to bring the low-levels of the atmosphere closer to saturation and produce significant rainfall despite this very dry sub-cloud layer. The event on 24-25 September was slightly more intense than the other case studies, but all events in this series had thunderstorms with heavy rain. In this case, the Sacramento Valley received amounts ranging from 0.25 to 0.50 in within a 1 to 2-h period, while across the higher terrain rainfall amounts locally exceeded 1.00 in. This amount of rainfall in such a short period is unusual for northern California in September.

4. Applications of Synoptic Scale Data and Discussions

For elevated thunderstorms to develop there needs to be sufficient moisture above the boundary layer. Secondly, the atmosphere must be sufficiently unstable and dynamics need to be adequate to effectively lower the LFC (destabilization). One way to assess the magnitude of the dynamics is to examine geopotential height fields with omega and differential positive vorticity advection at the 500-mb level or in a defined layer encompassing this pressure level. The 500 and 600-mb levels were found to be useful in diagnosing the moisture and vertical velocity maximums (omega) that lead to the thunderstorm development in this study. This is because the elevated moisture and instability were greatest in this layer. Warm air advection between the 850 and 700-mb level will also contribute to the upward motion. The majority of the elevated thunderstorm cases studied by Colman (1990) showed significant warm air advection at 850 mb. Upper-level low pressure areas and short wave troughs associated with these mid-tropospheric systems can often be viewed on water vapor images (see Figs. 13 and 14) and have been found to be forecast reasonably well by numerical models. In addition to the requirement of mid-level vertical motions, upper level divergence played an important role in the location and strength of the most organized thunderstorms. The importance of upper divergence for thunderstorm development is not a new finding, but it does demonstrate how significant jet dynamics can be when subtropical moisture, elevated instability and synoptic scale lift interact over California. The contribution from dynamics has proven to produce elevated thunderstorms with the intensity, duration and areal coverage as those more commonly associated with surface-based deep moist convection. It is not suggested that the dynamics associated with short waves produce thunderstorms, but rather the environment experiences saturation and destabilization through synoptic motions which then allow random air parcels to realize the potential instability on the mesoscale.

An Eta 30-h forecast of total precipitable water (Fig. 15) illustrated how well the model forecast the moisture plume when compared to the SSM/I data in Figure 8. Water vapor imagery will also show important moisture advection patterns and air mass layer lifting prior to condensation (cooling signatures). The most effective way to verify the presence of deep moisture and instability is to view the available upper-air data, satellite microwave imagery and soundings, and model-derived soundings. An example of a model sounding that accurately predicted the elevated instability and moisture is demonstrated using the BUFKIT software (Mahoney and Niziol 2000) in Figure 16. The use of model soundings has proven to be very useful in forecasting elevated thunderstorms.

5. General Conclusions

It has been shown in this study, and in the entire series (Tardy 2001), that the synoptic scale vertical motion in a rapidly moistening and destabilizing air mass ahead of upper-level low pressure systems, and individual short wave troughs can result in explosive thunderstorm development. Elevated thunderstorms have been observed along the coastal areas, over the Pacific ocean, in the Central Valley, and across the mountains of California with all showing similar characteristics to those in this study. Elevated thunderstorms can bring heavy rain to parts of California, which typically have very little rainfall during the summer months. More significantly, these thunderstorms can produce large numbers of cloud to ground lightning strikes that can start forest fires in areas of severe dry ground conditions which are common in the summer months.

The synoptic scale vertical motion saturates the air mass and effectively lowers the LFC (destabilization) thus allowing random air parcels to become buoyant and develop into thunderstorms. The profile and rapid modification of the air mass, like those illustrated in Figures 2 and 4, are not rare for California, and elevated thunderstorms need to be considered in this type of environment. There is some evidence from other cases that pre-existing mid-tropospheric outflow boundaries from prior diurnal thunderstorms can enhance or focus the thunderstorms (not shown). However satellite and radar data in this part of the study suggests that this is not a prerequisite. The location of initial thunderstorm development can be random, with no dependence on terrain or boundary layer conditions. In this case, the first thunderstorms developed in a region of synoptic scale vertical motion and upper-level divergence that had interacted with a significant subtropical moisture surge. The most organized thunderstorms, and thus the heaviest rainfall, occurred in the region of strongest dynamics and greatest mid-level vertical motions.

Examination of water vapor imagery is important to detect the layer lifting and subsequent moistening of the air mass prior to cloud and thunderstorm development. Then the IR and visible channels can be very useful for detecting altocumulus castellanus (mid-level moisture and instability) which is often a precursor to elevated thunderstorms. Focusing on the enhanced cold cloud tops on the water vapor will often be misleading since this is typically the product of existing or prior thunderstorm anvils. Model, satellite derived, and observed soundings can indicate elevated instability and moisture that are present or forecast to occur. It is hoped that the findings from this series (along with other cases not included) will help the understanding and ability of forecasters to better predict elevated thunderstorm events that are often unexpected.

REFERENCES

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Colman, B. R., 1990: Thunderstorms above Frontal Surfaces in Environments without Positive CAPE. Part II: Organization and Instability Mechanisms. *Mon. Wea. Rev.*,118, 1123-1144.

Mahoney, E. A., cited 2000: BUFKIT Documentation [Available on-line from http://www.nws.noaa.gov/er/buf/bufkit/bufkitdocs.html.]

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Tardy, A. O., 2001: Persistent Nocturnal Thunderstorms over Central California in August, Part
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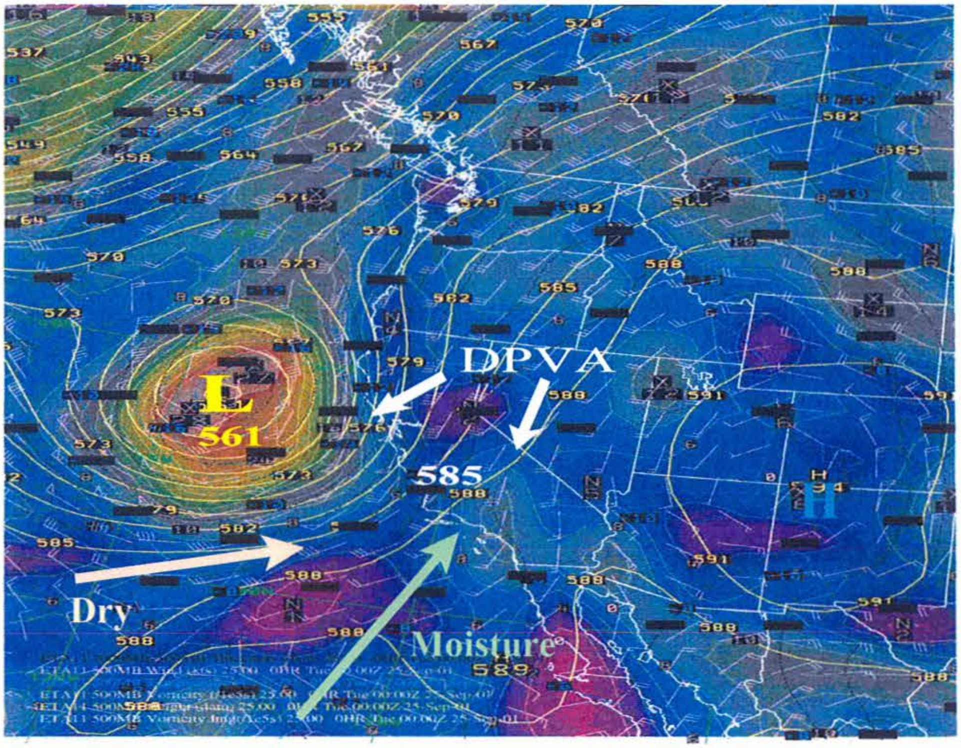


Figure 1. Eta 500-mb geopotential height and vorticity analysis at 0000 UTC 25 September. Height lines are every 30 m and vorticity is every 2 1e5s^{-1}. The 585-dm height line is labeled for reference.

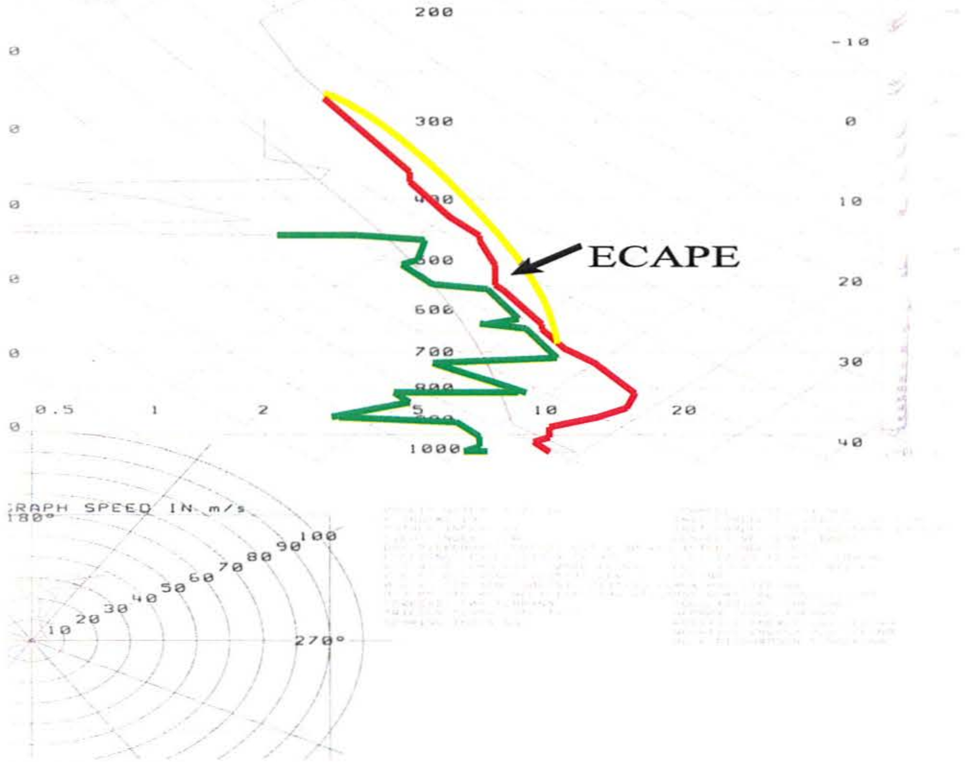
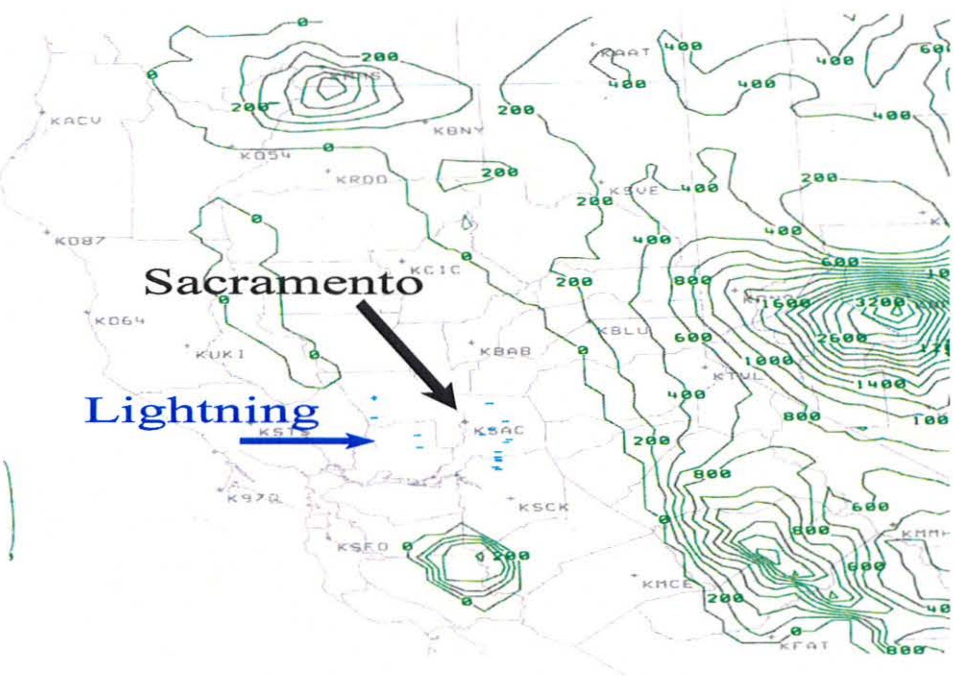
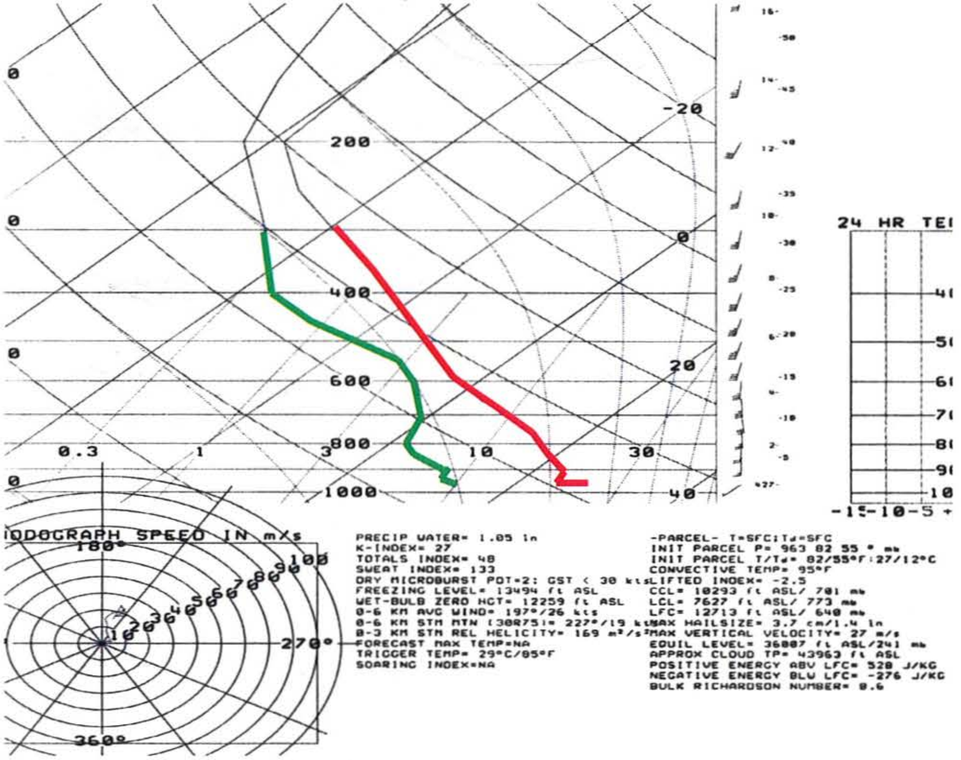


Figure 2. KOAK sounding at 0000 UTC 25 September 2001. The precipitable water was 1.21 in and the LI was 6.3. The sounding clearly shows the elevated instability (ECAPE) above the stable low levels (marine layer capped by subsidence dry layer). Notice the much drier air below 700 mb and above 450 mb.



1 Hour Lightning Plot Mon 20:00Z 24-Sep-01
LAPS Surface Pos Buoy Energy (J/kg) 24 20 0HR Mon 20:00Z 24-Sep-01

Figure 3. LAPS surface-based CAPE (contoured every 200 Jkg^{-1}) analysis at 2000 UTC at the time of the first hour of lightning strikes (dashed blue). Notice the CAPE is confined to the high terrain and CAPE is zero in the Sacramento Valley.



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PRECIP WATER= 1.05 in
K-INDEX= 27
TOTALS INDEX= 48
SWEAT INDEX= 133
DRY MICROBURST POT=2: GST < 30 kts
FREEZING LEVEL= 13494 ft ASL
WET-BULB ZERO HGT= 12259 ft ASL
0-6 KM AVG WIND= 197°/26 kts
0-6 KM STM MTN (30R75)= 227°/19 kt
0-3 KM STM REL HELICITY= 169 m²/s²
FORECAST MAX TEMP=NA
TRIGGER TEMP= 29°C/85°F
SOARING INDEX=NA
```

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-PARCEL- T=SFC:Td=SFC
INIT PARCEL P= 963 82 55 ° mb
INIT PARCEL T/Td= 82/55°F:27/12°C
CONVECTIVE TEMP= 95°F
LIFTED INDEX= -2.5
CCL= 10293 ft ASL/ 701 mb
LCL= 7627 ft ASL/ 773 mb
LFC= 12713 ft ASL/ 640 mb
MAX HAILSIZE= 3.7 cm/1.4 in
MAX VERTICAL VELOCITY= 27 m/s
EQUIL LEVEL= 36807 ft ASL/241 mb
APPROX CLOUD TP= 43963 ft ASL
POSITIVE ENERGY ABV LFC= 528 J/KG
NEGATIVE ENERGY BLW LFC= -276 J/KG
BULK RICHARDSON NUMBER= 8.6
```

Figure 4. RUC sounding for Sacramento at 2100 UTC 24 September. The sounding is similar to Figure 2 except there is a low-level subsidence inversion. The precipitable water value is 1.05 in. CAPE, using the most unstable parcel, was calculated at 528 Jkg^{-1}. The negative area, or CINS, on the sounding was 276 Jkg^{-1}.

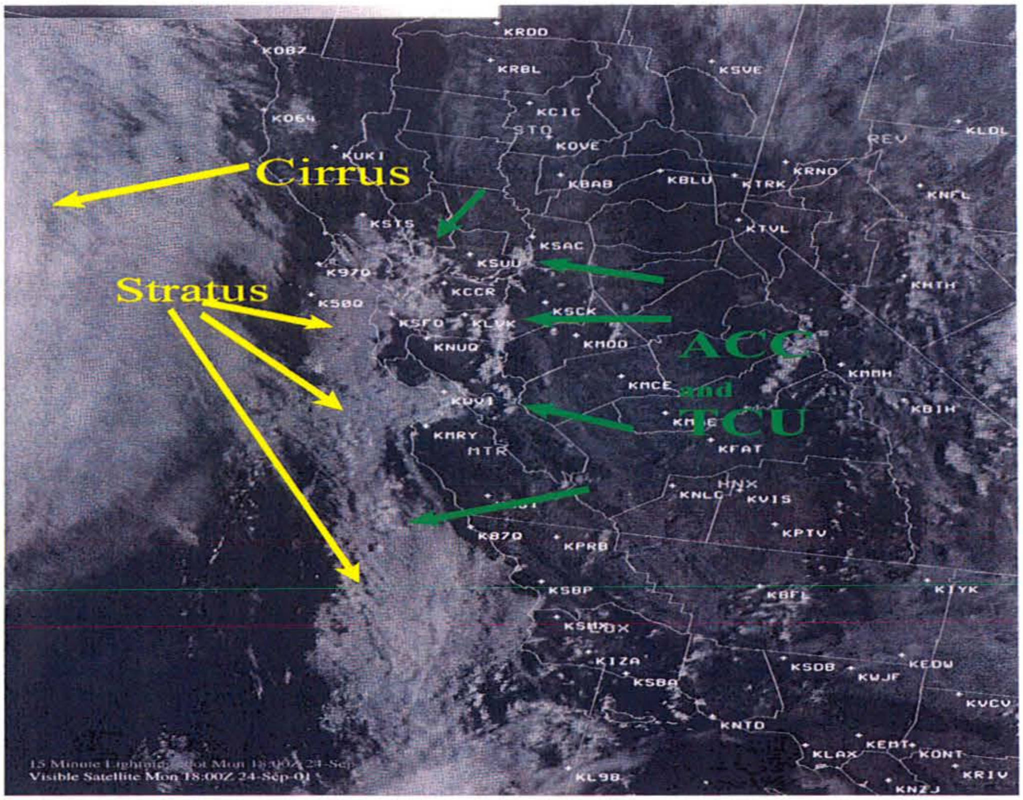


Figure 5. GOES-10 .39μ image at 1800 UTC 24 September showing the earliest stages of the thunderstorm development. Green arrows point to altocumulus castellanus (ACC) and towering cumulus (TCU).

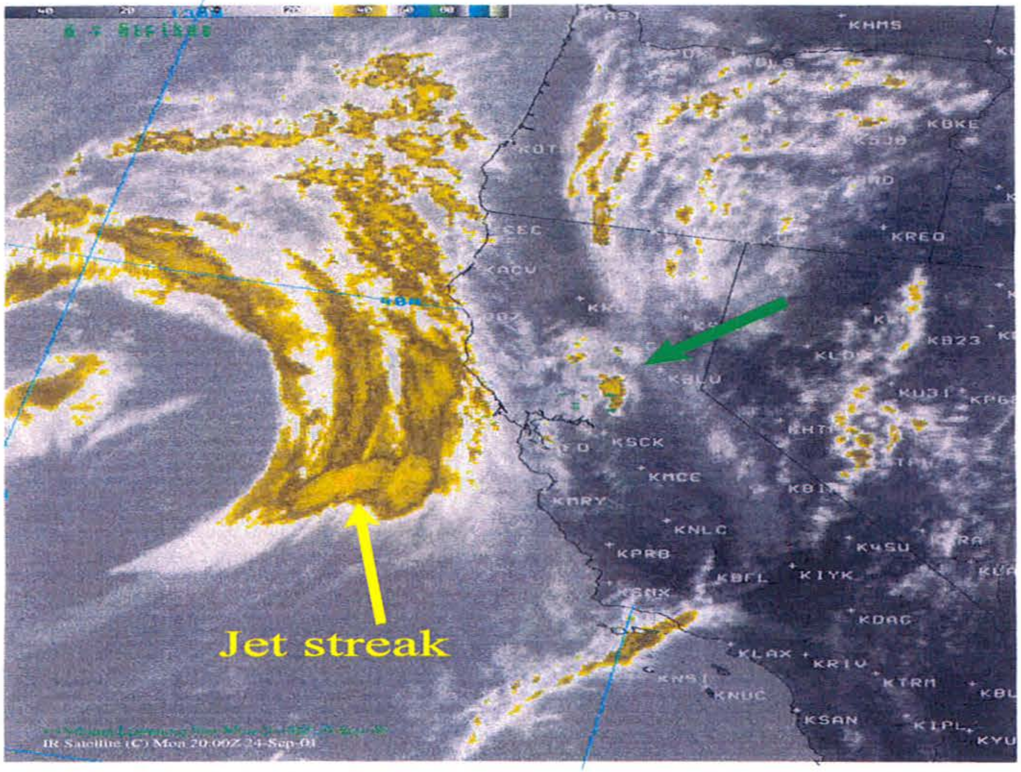


Figure 6. GOES-10 10.7 μ image at 2000 UTC 24 September showing the first area of thunderstorm development well out ahead of the main shield of enhanced clouds. Green dashes are 15 min cloud to ground lightning strikes.

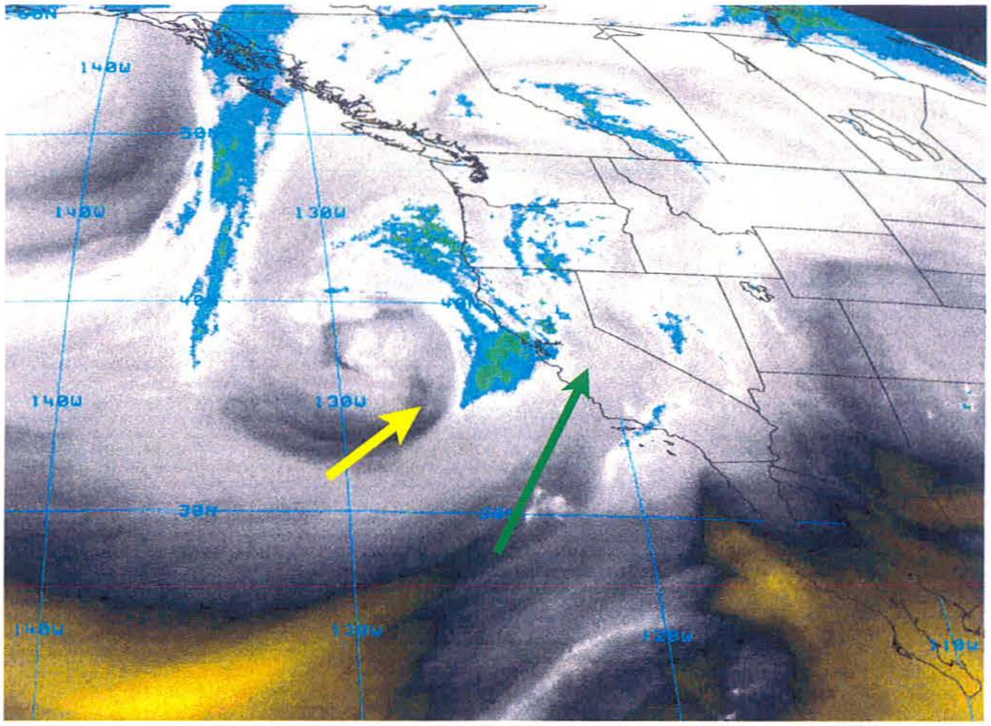


Figure 7. GOES-10 water vapor image at 2130 UTC 24 September showing the early stages of thunderstorm development. The strongest moisture advection is indicated by the arrow not the enhanced cold tops.

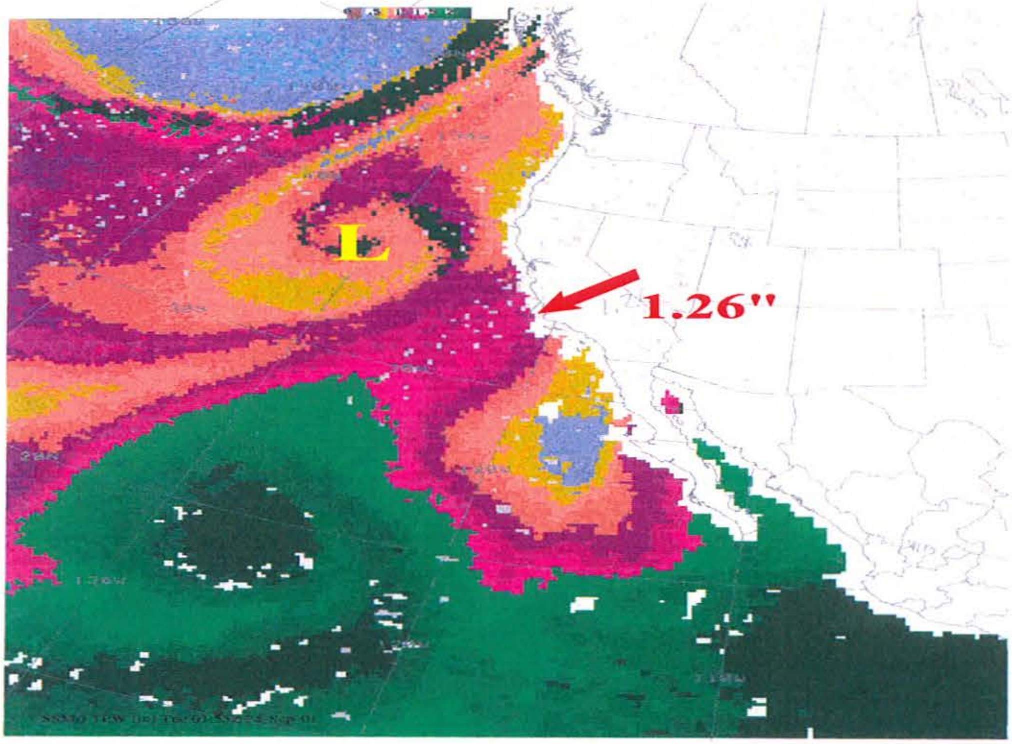
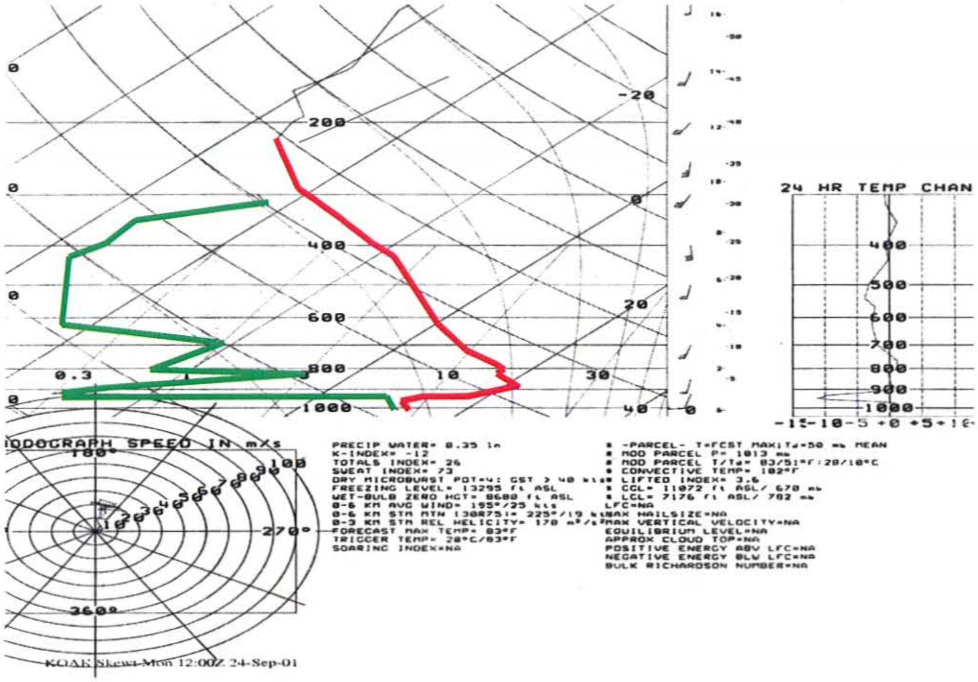


Figure 8. SSM/I total precipitable water at 0155 UTC 25 September. Purple shaded area are values 1 in to 1.45 in, and green shade is 1.5 in or greater.



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PRECIP WATER= 0.35 in                        * -PARCEL- T=FCST MAX;Td=50 mb MEAN
K-INDEX= -12                                 * MOD PARCEL P= 1013 mb
TOTALS INDEX= 26                             * MOD PARCEL T/Td= 83/51°F:28/10°C
SWEAT INDEX= 73                              * CONVECTIVE TEMP= 102°F
DRY MICROBURST POT=4: GST > 40 kts           * LIFTED INDEX= 3.6
FREEZING LEVEL= 13295 ft ASL                 * CCL= 11072 ft ASL/ 670 mb
WET-BULB ZERO HGT= 8680 ft ASL               * LCL= 7176 ft ASL/ 782 mb
0-6 KM AVG WIND= 195°/25 kts                 LFC=NA
0-6 KM STM MTN (30R75)= 225°/19 kts          MAX HAILSIZE=NA
0-3 KM STM REL HELICITY= 170 m²/s²           MAX VERTICAL VELOCITY=NA
FORECAST MAX TEMP= 83°F                      EQUILIBRIUM LEVEL=NA
TRIGGER TEMP= 28°C/83°F                      APPROX CLOUD TOP=NA
SOARING INDEX=NA                             POSITIVE ENERGY ABV LFC=NA
                                             NEGATIVE ENERGY BLW LFC=NA
                                             BULK RICHARDSON NUMBER=NA
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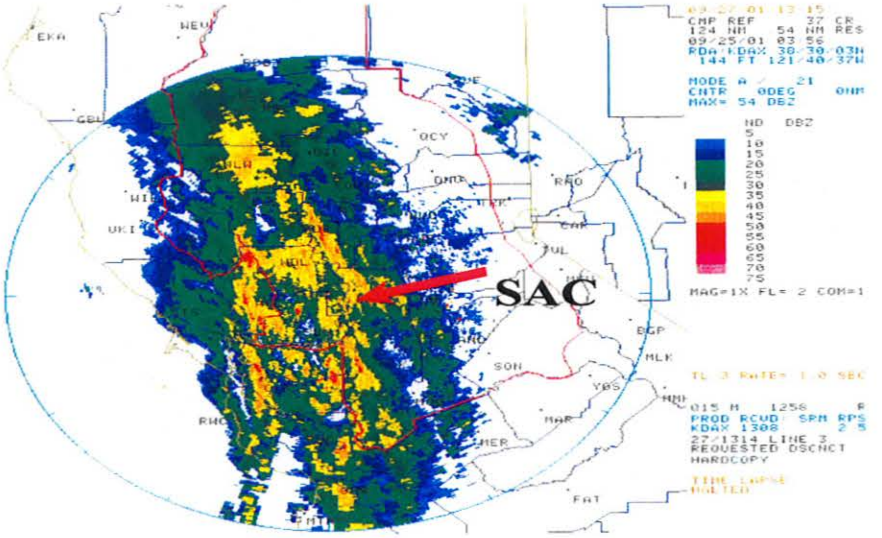
Figure 9. KOAK sounding at 1200 UTC 24 September. The precipitable water was 0.35 in which is indicative of the very dry air over the marine layer. The 24-h temperature change (right side) showed cooling from 700 to 500 mb. The cooling at 950 mb is from a deepening stratus (marine) layer.



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09/27/01 13:15
CMP REF          37 CR
124 NM     54 NM RES
09/25/01 03:56
RDA:KDAX 38/30/03N
 144 FT 121/40/37W

MODE A /    21
CNTR   0DEG      0NM
MAX= 54 DBZ

MAG=1X FL= 2 COM=1

TL 3 RATE= 1.0 SEC

015 M    1256      R
PROD RCVD  SPM RPS
KDAX 1308       2 5
27/1314 LINE 3
REQUESTED DSCNCT
HARDCOPY

TIME LAPSE
HALTED
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Figure 10. KDAX composite reflectivity at 0356 UTC 25 September showing a widespread thunderstorm outbreak. Maximum reflectivity is 54 dBZ.

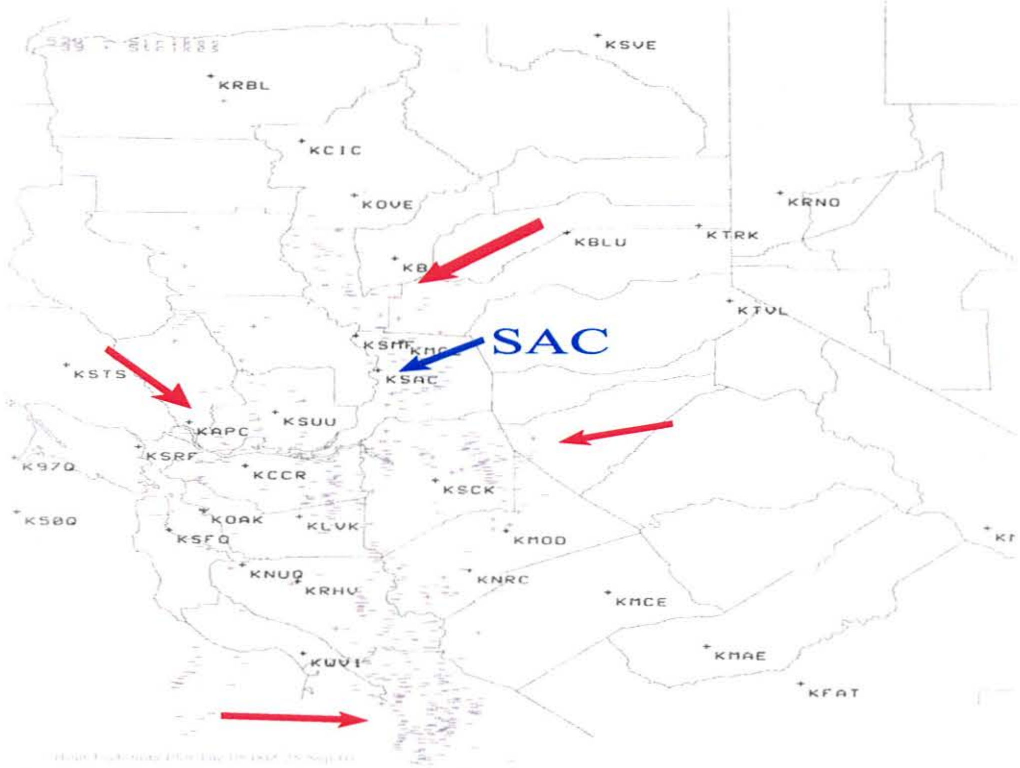

Figure 11. NLDN showing 563 strikes between 0400 and 0500 UTC 25 September 2001. 39 strikes were positive.

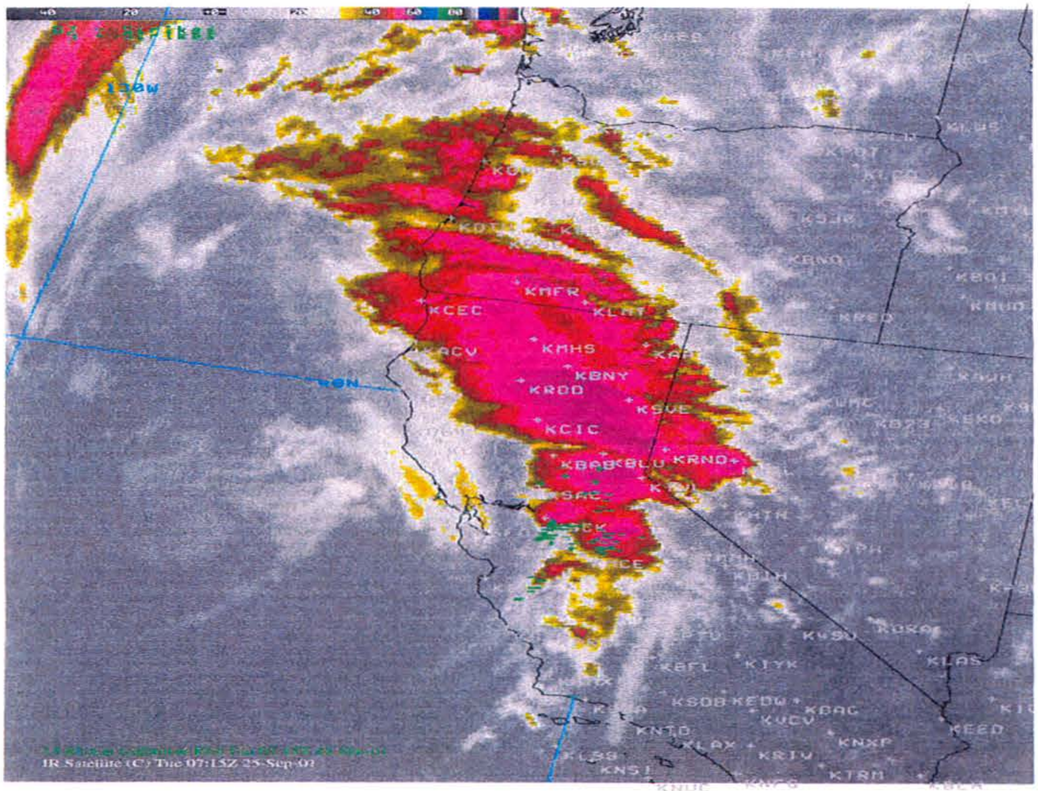

Figure 12. GOES-10 10.7 μ image at 0715 UTC 25 September. Coldest cloud top temperatures are -50 to -55°C. Green dashes are 15 min lightning strikes.

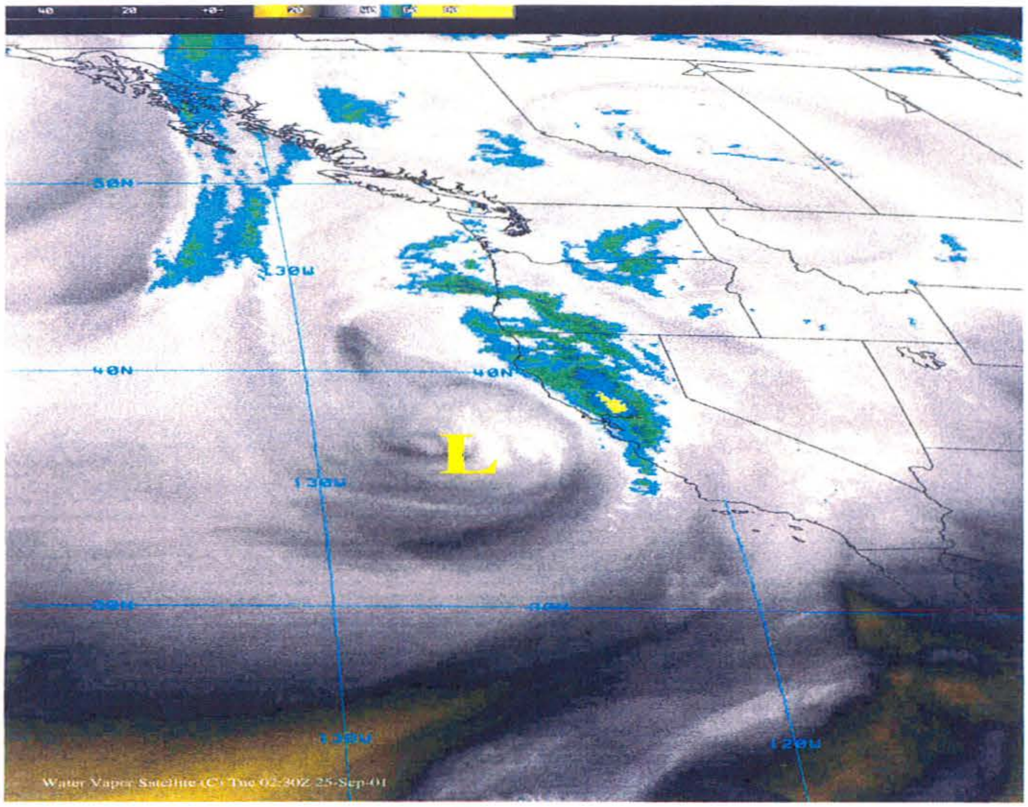

Figure 13. GOES-10 water vapor imagery at 0230 UTC 25 September showing the explosive thunderstorm development on the east side of the upper low.

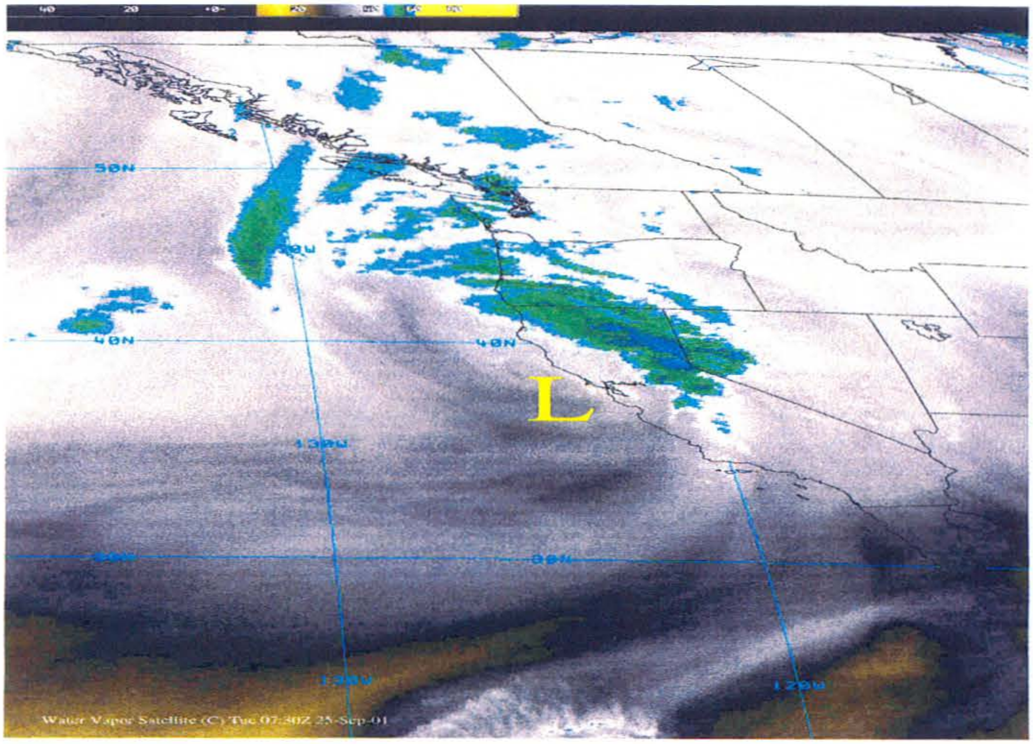

Figure 14. Water vapor image at 0730 UTC.

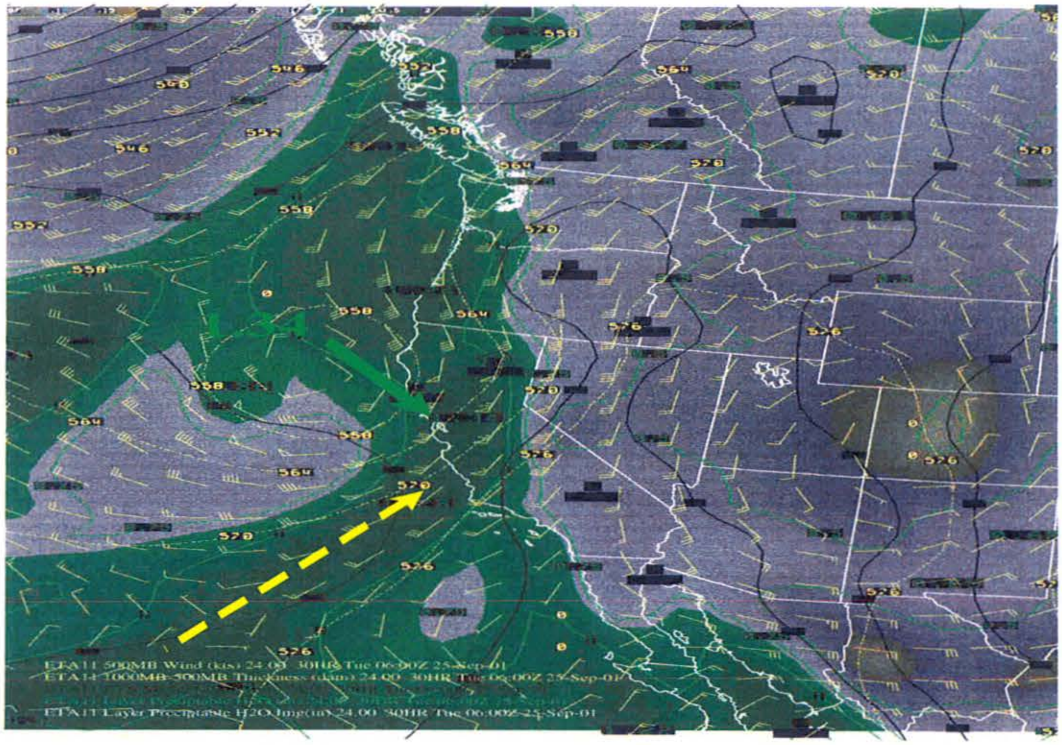

Figure 15. Eta precipitable water (in) 30-h forecast at 0600 UTC 25 September from the 0000 UTC 24 September run. Compare to Figure 8. Broken arrow indicates the high precipitable water plume axis and movement.

```
CAPE 0                 700     1000
CINS 0
HELCTY 437             150     250
EHI 0.00               0.5     1
BRN 0.00               7       10
NCAPE 0.00             0.1     0.2

EQ LVL 158             25000   32000
WBZero 12,345          10000   9000

LI 6.7                 1       -3
TT 40                  48      53
TQ 6.3                 12      17
K Idx 25               30      40
Shultr 7               -1      -4
SWEAT 110              250     350

Precipitation:  0.000 Hr   0.000 Total
Convect Precip: 0.000 Hr   0.000 Total
Pcpble Water:   1.263

LCL 836 mb    CCL 675 mb    LFC1012 mb    EQL1008 mb
   5,214'        10,802'          46'          158'
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573 mb      -3.6 C   -4.1 C
CAPE     508 J/kg    CIN      0 J/kg
EQL   36293 ft
NCAPE     8 cm/s²
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Figure 16. BUFKIT profile at KSMF at 0400 UTC 25 September from the 1200 UTC Eta on 24 September 2001. Using surface-based CAPE the sounding showed zero instability, however the elevated CAPE (ECAPE) was 508 Jkg^{-1}. The precipitable water for this sounding was 1.26 in.