WESTERN REGION TECHNICAL ATTACHMENT
NO. 01-09
July10, 2001

Forecasting Applications for Elevated Thunderstorms in California Part 1: The 8 September 1999 Outbreak

Alexander Tardy - Meteorologist - Weather Forecast Office - Sacramento, CA

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

Introduction

On 8 September 1999, California appeared to be experiencing a typical late summer afternoon with warm temperatures across the inland Central Valley and a deck of stratus clouds covering the Pacific Ocean. For most of the day this was the case as Sacramento's temperature warmed up to 96°F and an afternoon sea breeze developed on the central coast. The first thunderstorms of the day developed near 2200 UTC over the eastern Pacific Ocean, southwest of Monterey. By 0100 UTC 9 September, a line of thunderstorms was forming just offshore. This line of thunderstorms continued to intensify through the evening and before midnight, moved through the Monterey and San Francisco Bays. Thunderstorms continued in this general area through 1200 UTC 9 September, and then moved into the Central Valley of California by 1900 UTC 9 September. The thunderstorms were at their peak intensity while they moved through the Bay Area and the coastal hills of central California.

During this thunderstorm outbreak, thousands of cloud-to-ground lightning strikes were observed by the National Lightning Detection Network (NLDN). Shortly after this event, attention turned to a forest fire that had been ignited by the lightning strikes in a remote region near Big Sur, located in the Santa Lucia mountain range. Despite measurable rain, which was reported to be heavy at times, this lightning outbreak was so intense it produced a wildfire that burned for several weeks. According to local residents of the Bay Area, a lightning event of this magnitude had not occurred since 1984. This is significant since it has been shown that compared to the rest of the United States, the West Coast experiences the fewest number of cloud-to-ground lightning flashes annually [(100 flashes) Changnon 1992].

This paper will present Geostationary Environmental Satellite (GOES-10) data, observed upper air profiles, Weather Surveillance Radar-1988 Doppler (WSR-88D) images, and numerical model charts. The study will then show satellite and numerical model data that would have been helpful to predict the initiation and duration of the thunderstorms. Finally, numerical model charts. The study will then show satellite and numerical model data that would have been helpful to predict the initiation and duration of the thunderstorms. Finally, this paper will suggest that synoptic scale forcing may be sufficient to indirectly generate deep moist convection when an upper air low pressure system interacts with subtropical moisture.

Upper Air and Surface Observations

The basic synoptic pattern for this event was dominated by an upper level area of lower pressure situated in the eastern Pacific Ocean (Fig. 1). Figure 2 depicts a disorganized line of strong thunderstorms that developed ahead of the upper low and extended from just south of Monterey Bay northward to the San Francisco Bay. Thunderstorms persistently developed south of Monterey Bay, over the Pacific Ocean, and then moved north over land. The thunderstorms weakened as they veered into the San Francisco Bay, eventually dissipating over the open waters northwest of San Francisco. Surface observations and the NLDN showed that the thunderstorms produced heavy rain and frequent cloud-to-ground lightning for several hours in major populated areas such as San Jose.

The upper air sounding at Oakland (KOAK) for 0000 UTC 9 September was observed just prior to the main thunderstorm outbreak (Fig. 3). The sounding clearly shows an elevated layer of instability above the stable marine boundary layer. Typically, thunderstorm updrafts are rooted in the boundary layer, but this study will document one common exception for northern California. The 900- to 600-mb lapse rate on the KOAK sounding is approaching dry adiabatic (10 $C°km^{-1}$) which would indicate extreme potential instability. The sounding shows that the moisture source for potential deep moist convection was in a layer between 650- and 500-mb and is similar to the so called "inverted V" sounding (Bluestein 1993). This classic type of sounding has been documented as the Beebe "Type IV" (Bluestein 1993; Beebe 1955). Often this is not the level in the atmosphere that a meteorologist would expect intense rain-producing thunderstorms to form, but rather high-based thunderstorms producing virga or light precipitation. The KOAK sounding also resembles the Miller "Type I" sounding since the boundary layer shows a stable layer below the region of low static stability (Bluestein 1993; Miller 1972). This sounding shows capping of the moist boundary layer and convective inhibition. However, this study will show that the boundary layer did not play a role in the formation of thunderstorms.

The findings in this study will show that for northern California thunderstorms, the existence of significant subtropical moisture in the 650- to 400-mb layer is crucial. As an initial comparison to how well the numerical models forecast this event, Fig. 4 shows a forecast sounding at the same time as the observed KOAK profile (Fig. 5). The Eta sounding at KOAK, viewed in the Buffalo Toolkit, or BUFKIT (Mahoney and Niziol 1997), reveals that this 24-h forecast very closely resembled the observed sounding shown in Fig. 5.

New National Weather Service (NWS) software called the Advanced Weather Interactive Processing System (AWIPS) makes it possible for a forecaster to view an upper air profile at any location each hour. Such a profile was produced using the Rapid Update Cycle (RUC) model (Fig. 6). The point selected for this sounding was at a location near San Jose (KSJC). This sounding shows a profile very similar to the KOAK sounding in Fig. 5. This sounding indicated most unstable (MU) convective available potential energy (CAPE) values of 1331 Jkg^{-1} and a 500-mb lifted index (LI) of -6.5. Above the marine layer, this sounding clearly depicts a potentially very unstable atmosphere conducive to strong thunderstorms if sufficient moisture and lift are also available. At 1200 UTC 9 September, the KOAK sounding (Fig. 5) remarkably shows that there is little change to the general temperature and moisture profiles that were observed at 0000 UTC. Precipitable water amounts had increased to almost 1 inch, while the 24-h change profile showed noticeable cooling above 600-mb. A deep dry layer was still present between the top of the marine inversion and 650-mb. Observed lapse rates were nearly dry adiabatic (10 $C°Km^{-1}$) from 900- to 600-mb. Wind profiles continued to show a layer of southeasterly flow between 700- and 500-mb (suggestive of a closed circulation), while there was an onshore flow (west) below 800-mb. The veering wind direction with height between 800- and 700-mb is a possible indication of warm air advection. This would result in additional air mass lifting within this layer.

Satellite Data

Water vapor imagery has always been a valuable tool for a weather forecaster and this study shows just how crucial these images are in identifying pre-elevated thunderstorm environments. Surface data will often reveal few clues as to the potential for elevated thunderstorms since the moist convection can be initiated over cold water, valleys, or high terrain, and has no dependence on surface or boundary layer conditions.

Figure 7 is a GOES-10 water vapor image taken at 2200 UTC 8 September, which is near the time thunderstorms were first evident. This image clearly shows a circulation in the mid-troposphere which is approaching the West Coast. Very dry air had been advected into the upper low, but closely examining the image shows that slightly more moist air is being drawn to the northwest (within the southeast flow) ahead of the mid-level circulation. Figure 8 shows the air mass becoming saturated as depicted by the darkening in the water vapor image (darker coloring is greater than -20°C versus the orange-brown color which is warmer). Once the dynamics associated with the upper low interacted with the subtropical moisture surge, explosive deep moist convection developed (Fig. 8). The individual thunderstorms weakened as they were carried northward into unfavorable dynamics and subsidence on the north side of the upper low. Several hours later, Fig. 9 shows a water vapor image which depicts a weaker upper air system with a large area of anvil cirrus associated with the thunderstorms. Notice that the line of thunderstorms that was seen in the composite reflectivity image from Fig. 2 remains intact and has moved inland, but persists over the San Francisco and Monterey Bays. This figure also shows the importance of the dry air intrusion that took place during this event. The dry air, observed at 0000 UTC 9 September between 550- and 400-mb above a moist layer around 600-mb (Fig. 3), allowed for steeper environmental lapse rates since the dry air will cool faster when it was synoptically lifted. The cooling, or steepening, lapse rates are evident on the 24-h temperature change scale on the right side of Fig. 5. This cooling can also be attributed to cold air advection associated with a colder pool of air in the mid-tropospheric circulation.

The enhancements (-40°C or colder) seen in the far lower right side, and far upper portions of Figs. 8 and 9, proved not to be relevant to this case. Since water vapor imagery is most sensitive to moisture near 400-mb, these enhancements are more by-products of deep moist convection or cyclogenesis, rather than indications of moisture advection below 500-mb. In other words, the important moisture source between 700- and 500-mb can be overlooked on the water vapor imagery, while the enhanced areas could be given too much consideration. This case shows that careful examination of water vapor imagery does reveal the moisture advection between 600- and 500-mb (Figs. 7 and 8).

Finally, Fig. 10 is a GOES-10 infrared (10.7 µm) image at 0530 UTC 9 September, which corresponds to the mosaic composite reflectivity previously seen in Fig. 2. This 10.7 µm image vividly shows the cold cloud top temperatures (red denotes -40°C or colder) that were associated with the intense line of thunderstorms. Despite the fact that the thunderstorms were at their peak intensity over the land during the night, nocturnal cloud top radiational cooling did not appear to be a significant factor since strong thunderstorms had already developed offshore prior to sunset. Also evident in Fig. 10, to the southwest of Monterey Bay over the Pacific Ocean, is a low level circulation in the stratus clouds which is caused by a surface area of lower pressure, or a weak cyclone. This cyclone is a reflection of the mid-tropospheric disturbance seen in the water vapor imagery.

Numerical Model Data and Forecasting Applications

It will be shown in this paper how well the numerical models predicted the atmospheric conditions that produced the elevated thunderstorm event. It must be pointed out that this does not mean the numerical model quantitative precipitation forecast (QPF) verified, as the QPF's did not indicate any convective or stratiform rainfall. In addition, the models did not produce CAPE over the region of interest, however model-derived CAPE is usually surface-based. In this case, the CAPE was entirely elevated in the "inverted V" type soundings, and often the forecaster needs to calculate the CAPE using the most unstable parcel (see Figs. 3 and 4). Figure 11 shows a 36-h Aviation (AVN) model forecast output of 500-mb relative humidity, omega (upward vertical motion), and geopotential heights valid at 1200 UTC 9 September. Notice the maximum area of relative humidity and omega was placed over central California at this time. The model was slightly too far east with its placement (eastern California), and this was a reflection of the timing being too fast. Typically, numerical models will have difficulty in precisely timing and tracking the movement of closed mid-tropospheric systems. The reason the 500-mb level was selected is based on the findings previously discussed in regards to the water vapor imagery and the observed upper air soundings. In this case, numerical model guidance showed limited moisture below the 600-mb level (less than 50 percent) which was an accurate depiction of the atmosphere during this event (see Figs. 3 and 5).

The Eta analysis and forecast in Figs. 12 and 13, respectively, show how important the synoptic scale dynamics were in this event since the region of strongest PVA (implied differential PVA) and possible warm air advection (not shown) coincided with the area of thunderstorm development. Figure 12 shows a 0000 UTC 9 September 500-mb analysis of geopotential heights and vorticity. Comparing this image with the GOES-10 water vapor picture in Fig. 8, shows that the thunderstorms were developing on the axis of greatest synoptic scale upward motion, or the region of maximum positive vorticity advection (PVA). This region also corresponds to the best area of 700- to 500-mb layer Q-Vector convergence (not shown). Q-vector convergence has proven to be useful as well, because it combines both differential PVA and the LaPlacian of warm air advection for a defined layer. Both of these synoptic mechanisms were acting to lift and destabilize the atmosphere. Notice that the upper low is still a closed system as defined by the geopotential height contours (Fig. 12). The significance of a closed system for northern California summer thunderstorms, as opposed to an open system, is that it results in veering mid-level winds (southeast versus southwest) that are more supportive of drawing subtropical moisture northward. In addition, a closed system will produce better upper level divergence on the northeast side of the upper low which will enhance the thunderstorms.

The Eta model performed well as Fig. 13 depicts 500-mb geopotential heights, relative humidity, and omega with a 24-h forecast valid at 1200 UTC 9 September. The placement of the maximum relative humidity and negative omega (4 $\mu bars^{-1}$) was shifted slightly to the west (compared to the AVN forecast) and more in line with the actual line of thunderstorms that developed. This magnitude of synoptic scale lift (omega) further destabilized a layer of the air mass, thus effectively lowering the LFC. Therefore, the random upward and downward motions in the atmosphere that are common at all times are more likely to allow an air parcel to obtain its LFC (see Fig. 8). Figure 13 and 14 also depict that closer to the event the Eta was accurately slowing the progression of the upper level circulation. The Eta accurately forecast the movement and weakening of the 500-mb low with the 1200 UTC 8 September run, as a strong short wave approached the Pacific Northwest acting to pull the low inland (Fig. 14).

It appears that the upward motion associated with these slow moving systems, though significantly less than that found in convective updrafts, is sufficient over time to allow an air parcel to reach its LFC. Once a parcel obtains its LFC, a mature thunderstorm can develop if there are sufficient moisture and continued buoyancy (i.e., CAPE). A study by Crook et al. (1988) showed that large scale convergence lifts the air mass to saturation over a wide region so that once convection begins the air entering the system requires little further lifting. The large scale speed convergence at the lower levels of the atmosphere in this case was occurring above the boundary layer and in a dry unstable air mass. Therefore, once the moisture was available a layer of the air mass became saturated due to synoptic scale ascent which then can lead to the commencement of moist convection. If there is upper level divergence (500- to 200-mb) above the thunderstorm (Fig. 15), the result can be explosive thunderstorm development. Figure 16 shows that the 1200 UTC 8 September Eta model cycle verified its 18-h forecast placement of the 250-mb jet maximum, since the observed jet was just moving onshore at 0000 UTC 9 September (Fig. 15). The maximum divergence was observed to be located over the San Francisco and Monterey Bays. Comparing the radar image in Fig. 2 and the observed divergence in Fig. 15, with Fig. 16, shows that the Eta model 18-h forecast of 250-mb divergence was too far south. However, Figs. 13 and 14 showed that a divergent wind flow and speed convergence was forecast at 500-mb. This upper level divergence was very important toward sustaining and enhancing the deep moist convection.

Conclusions

This paper explored a case of elevated thunderstorms which exhibited exceptional duration, extent and intensity. However, elevated thunderstorms are fairly common to central California during the summer, and should be considered when a similar pattern to the one discussed in this study evolves. A significant finding in this study was that the numerical models did well forecasting the location of the maximum upward vertical motion and moisture.

This study suggests that the use of basic numerical model output such as 500-mb geopotential heights, vorticity, omega, and relative humidity can aid the forecaster in identifying regions that are most supportive of elevated thunderstorms. During the summer when the upper level areas of lower pressure are usually dry, the interaction of dry air with subtropical moisture is necessary to further destabilize the air mass and commence deep moist convection. The moisture was observed to be in a layer between 600- and 400-mb which is consistent with the Beebe "Type IV" sounding. This profile and the KOAK sounding in this study are likely the keys to understanding, and potentially forecasting, elevated thunderstorms.

The water vapor imagery will often have the first clues to the advection of subtropical moisture and the eventual saturation of the air mass. In order to draw the subtropical moisture into the mid-tropospheric circulation over northern California, a closed system is the most effective at inducing a southeast mid-level wind. A closed system also produces the best upper divergence over the northeast side of the upper low which enhances the thunderstorms.

The interaction of subtropical moisture, with the synoptic scale speed convergence, and upward motions (i.e., PVA and warm air advection) generated over a long duration by a slow moving upper level area of low pressure will lead to saturation of the air mass and aid in obtaining (effectively lowering) the LFC's of the air parcels. This will often result in the formation of deep moist convection as shown in this study. Therefore, it is crucial to identify short waves within the circulation of the mid-tropospheric disturbance or in this case the main vorticity maximum. Additionally, warm air advection in the lower levels of the atmosphere, above the boundary or marine layer, coupled with cold air advection in the middle and upper levels of the troposphere, would further destabilize a layer of the air mass. When the air parcels reach their LFC, explosive thunderstorm development can occur if there is sufficient middle to upper tropospheric divergence and elevated instability (e.g., CAPE).

Most important, it must be understood that these thunderstorms are not surface-based, and the traditional techniques, such as using surface-based CAPE, for forecasting deep moist convection often do not apply. The forecaster must combine available numerical model data with water vapor imagery in order to accurately predict elevated thunderstorms. The most unstable parcel must be considered with the soundings observed in this study. Additional cases of elevated thunderstorms will show similar findings to those seen in this event. Further studies on elevated thunderstorms may help to quantify the upward vertical motion from upper level low pressure systems that is necessary to produce thunderstorms. Because of potential wildfire complications and other dangers associated with lightning it is very important that these elevated thunderstorm events are accurately forecast.

Acknowledgment

The author wishes to thank Scott Cunningham and John Monteverdi for their input, advice, and review of this manuscript.

References

Beebe, R. G., 1955: Types of Air Masses in Which Tornadoes Occur. *Bull. Amer. Meteor. Soc.*, 36, 349-350.

Bluestein, H. B., 1993: Synoptic-Dynamic Meteorology in Midlatitudes Vol. II Observations and Theory of Weather Systems. Oxford University Press, 2, 444-455.

Changnon, S. A., 1992: Relationship Between Thunderstorms and Cloud-to-Ground Lightning in the United States. *Journal of Applied Meteorology*, 32, 88-105.

Crook, N. A., and M. W. Moncrieff, 1988: The Effect of Large-Scale Convergence on the Generation and Maintenance of Deep Moist Convection. *Journal of the Atmospheric Science*, 45, 3606-3624.

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

Mahoney, E. A., and T. A. Niziol, 1997: BUFKIT: A software application toolkit for predicting lake-effect snow. Preprints *13th Intl. Conf. on Interactive Information and Processing Systems for Meteorology, Oceanography, and Hydrology*, Long Beach, CA, Amer. Meteor. Soc., 388-391.

Miller, R. C, 1972: Notes on Analysis and Severe Storms Forecasting Procedures of the Air Force Global Weather Central. Tech. Rep. 200 (Rev. 1975). U.S. Air Force, Air Weather Service

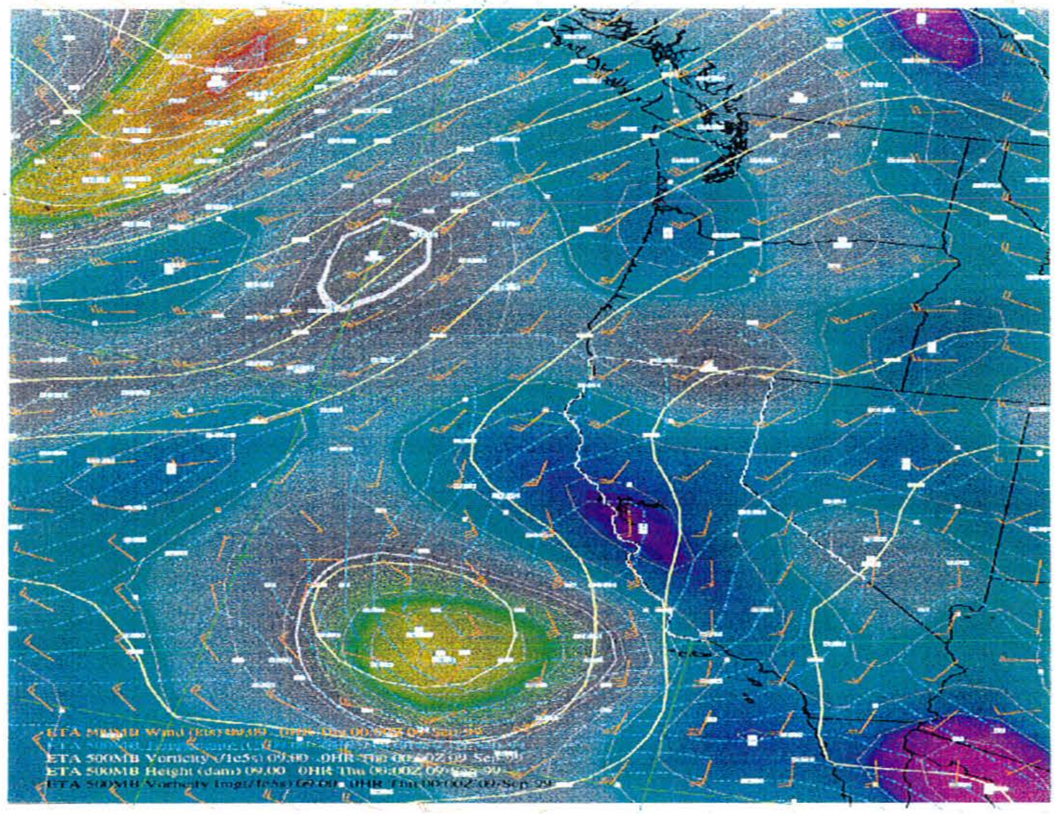

Figure 1. Eta 500-mb geopotential height analysis at 0000 UTC 9 September 1999. Yellow lines are height lines contoured every 30-dm.

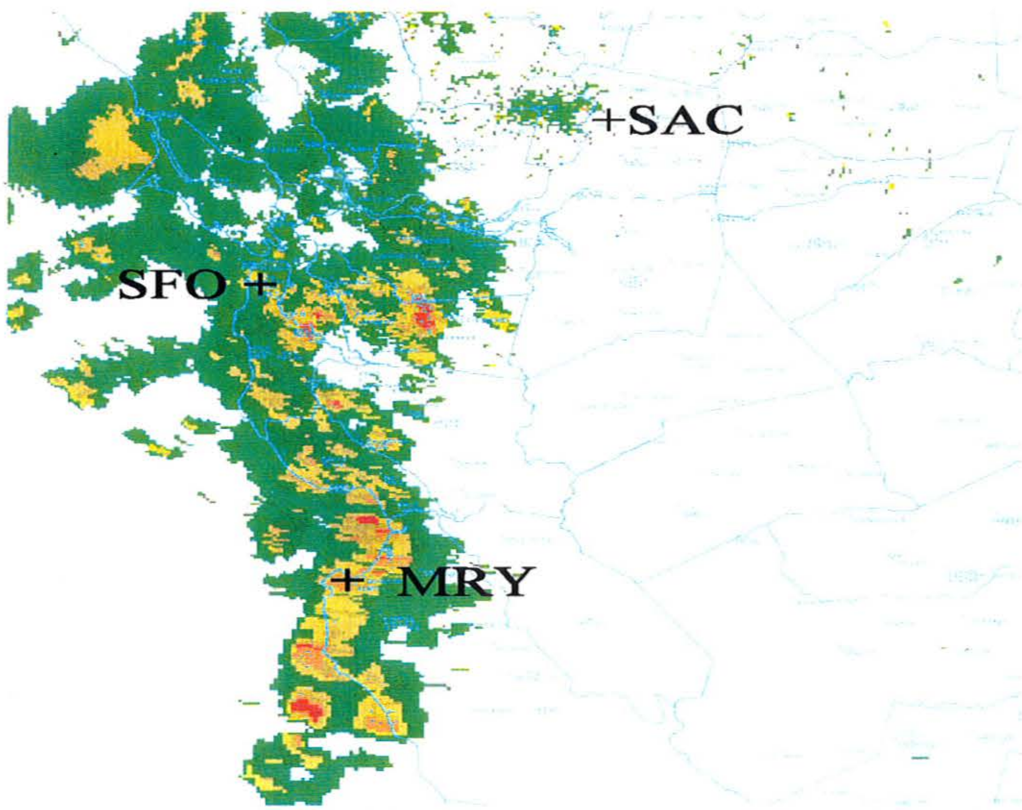

Figure 2. Composite reflectivity at 0530 UTC 9 September 1999. A line of thunderstorms developed over the Pacific Ocean at 0000 UTC and slowly moved inland while intensifying. Sacramento (SAC), San Francisco (SFO) and Monterey (MRY) are labeled for reference.

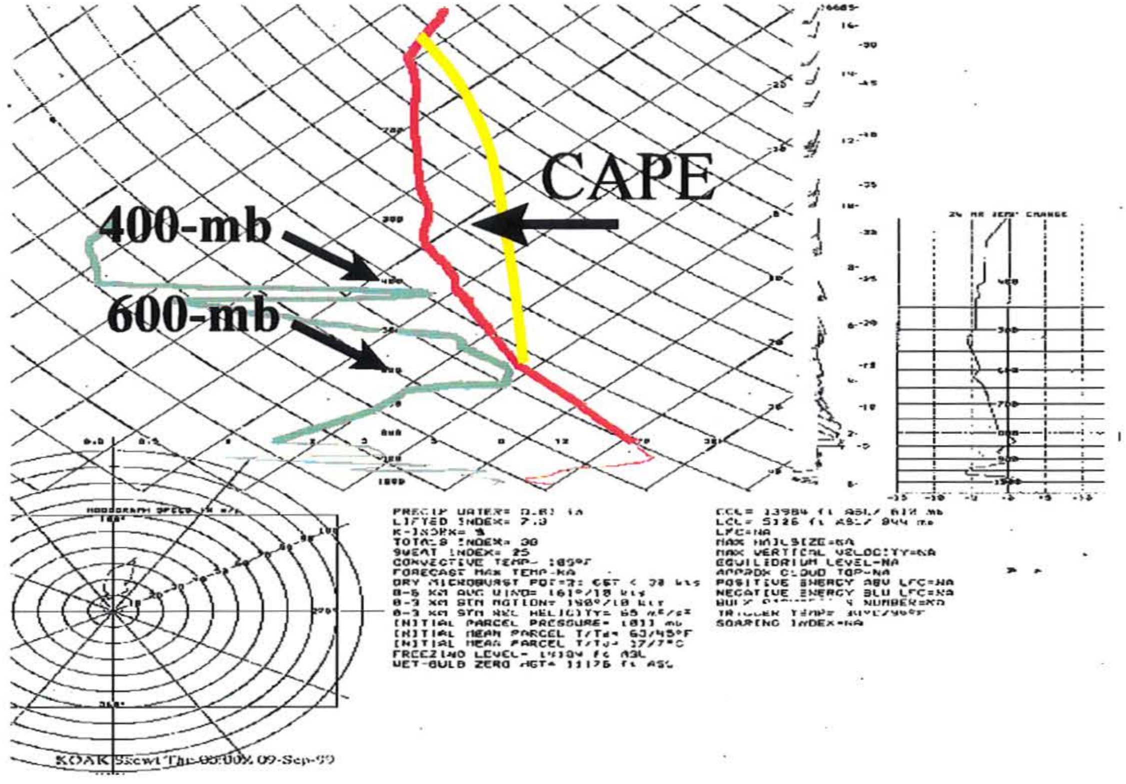

Figure 3. KOAK sounding at 0000 UTC 9 September 1999. Notice the steep lapse rates above 900-mb and the moisture between 650 and 500-mb. Lifted Index was 7.3 and precipitable water was 0.81-in. The marine layer inversion is shown up to 950-mb. A vertical profile of 24-h temperature change is shown to the right. The yellow line shows the path of an air parcel that reaches its LFC from an elevated level.

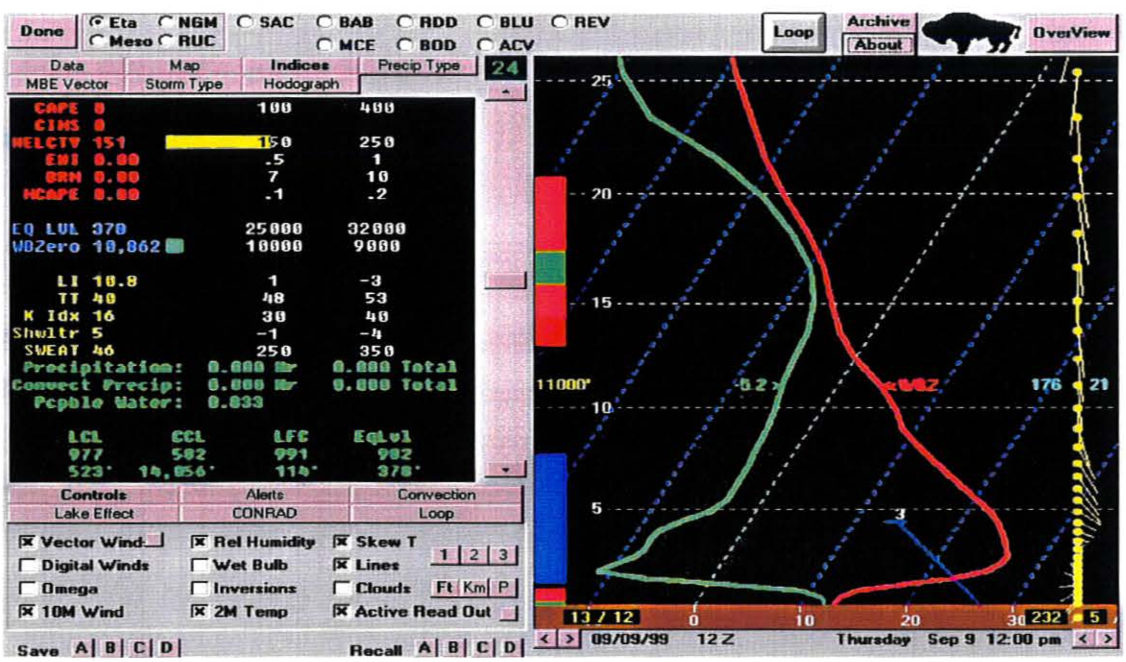

Figure 4. KOAK BUFKIT Eta 24-h forecast sounding valid at 1200 UTC 9 September from the 1200 UTC 8 September model run. Deepest moisture is between 13,000 to 20,000-ft. Notice the precipitable water forecast was 0.83-in which is close to the observed 0.99-in. Later soundings showed an increase to 0.93-in by 1800 UTC. Note the CAPE was zero and the LI was 10.8. All indices are shown on the left side (Mahoney 2000).

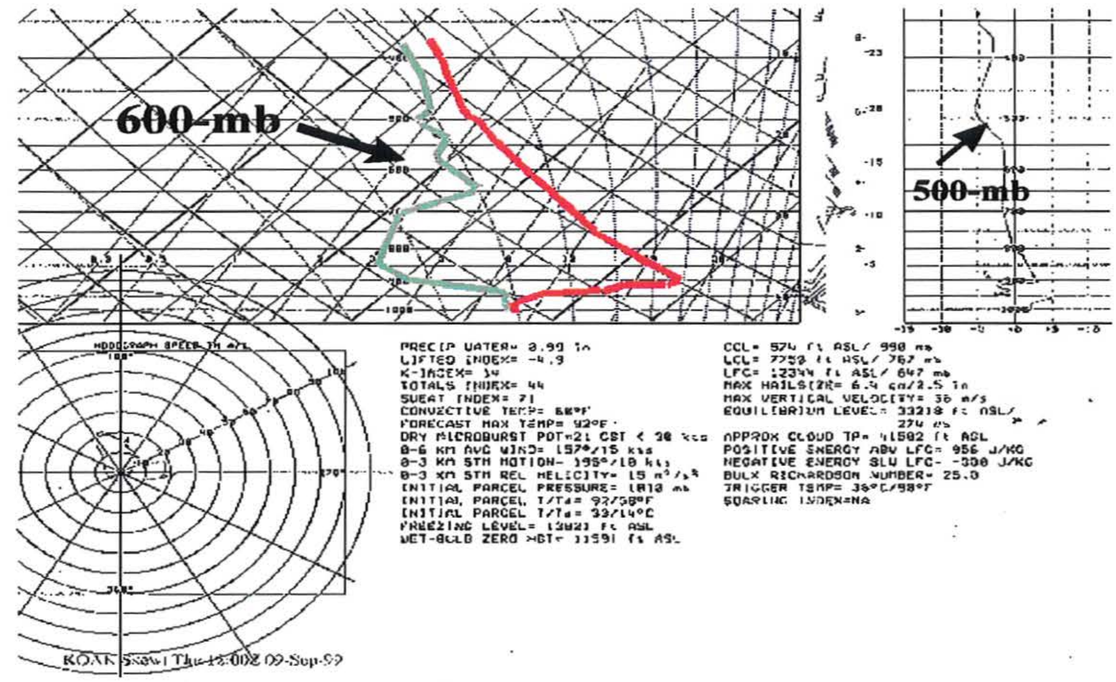

Figure 5. KOAK observed sounding at 1200 UTC 9 September 1999. CAPE values were 956 Jkg^{-1} and the LI was -4.9. Precipitable water had increased to 0.99-in. Additional cooling was seen at 500-mb level. The marine layer remains around 950-mb. Notice the moisture is confined above 650-mb which is typical in an "inverted V" type sounding. A vertical profile of 24-h temperature change is shown to the right

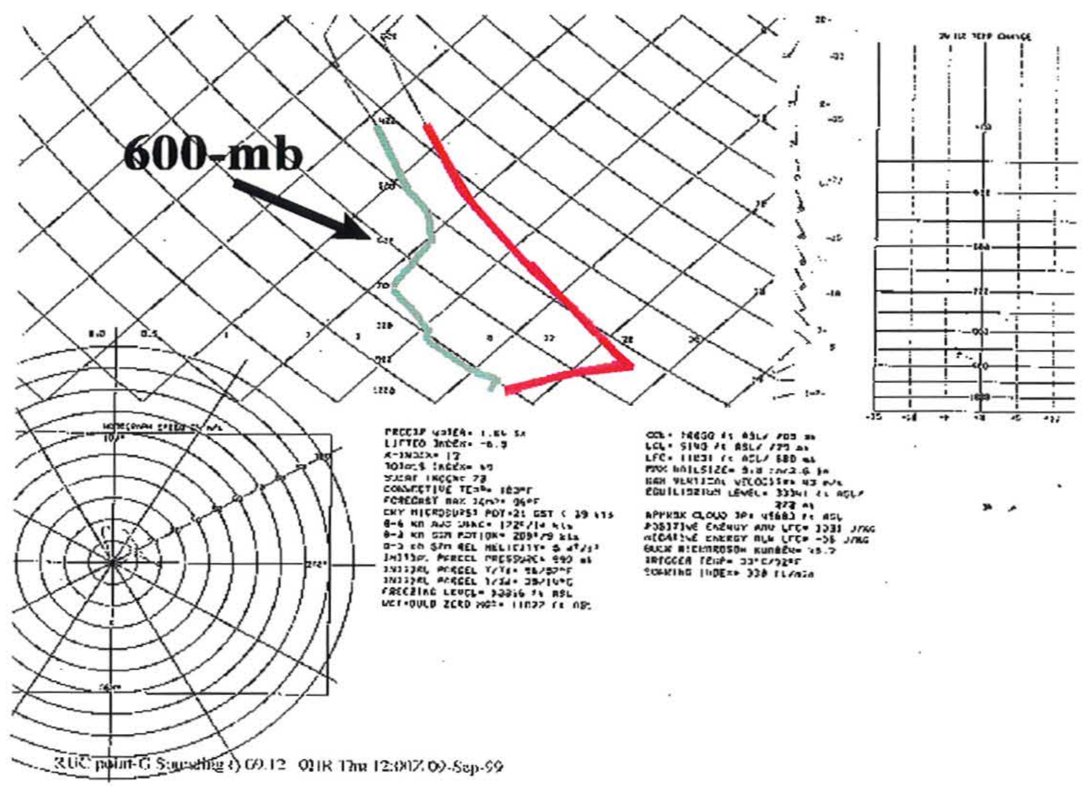

Figure 6. RUC analyzed sounding at 1200 UTC 9 September 1999 over a defined location near San Jose. CAPE values were 1331 Jkg^{-1} and the LI was -6.5 with precipitable water at 1.04-in.

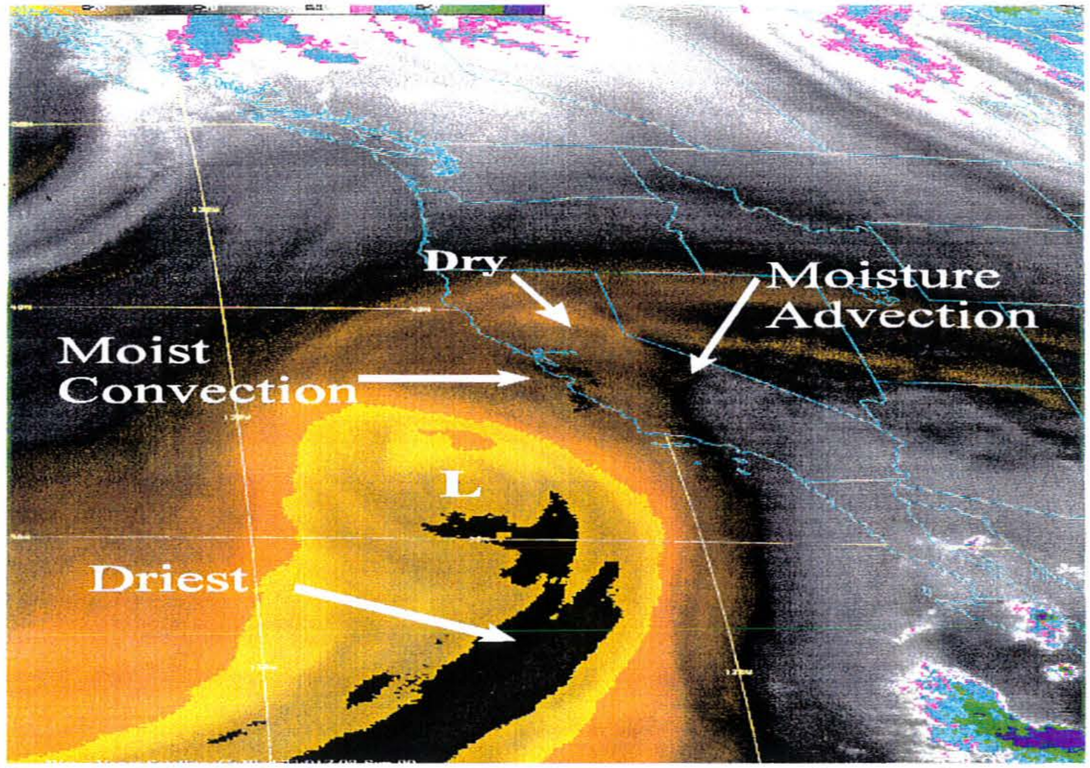

Figure 7. 2200 UTC 8 September 1999 GOES-10 water vapor image. The upper circulation is clearly visible approaching the California coast. Dark area inside the yellow denotes the driest air on this image. Note the color scale on the upper left. Arrows note the subtropical moisture surging northward and the early stages of the moist convection developing near Monterey Bay.

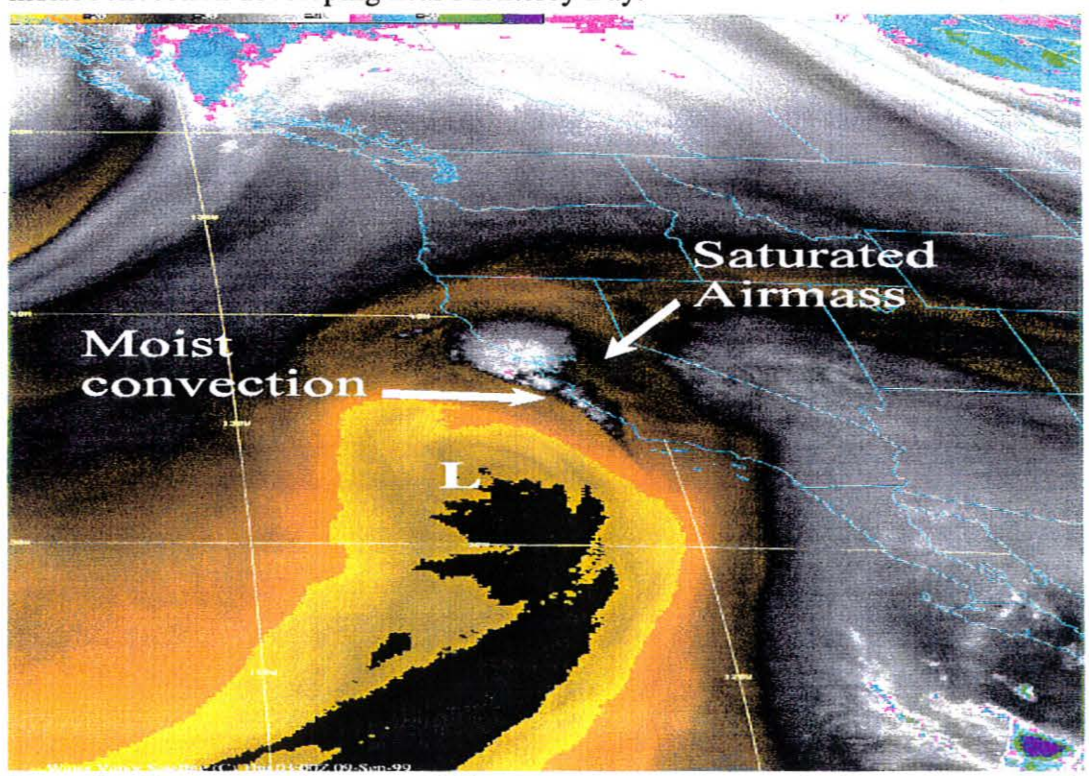

Figure 8. Water vapor image at 0300 UTC 9 September. Explosive moist convection is seen just offshore ahead of the upper low. The air mass is becoming saturated over central California.

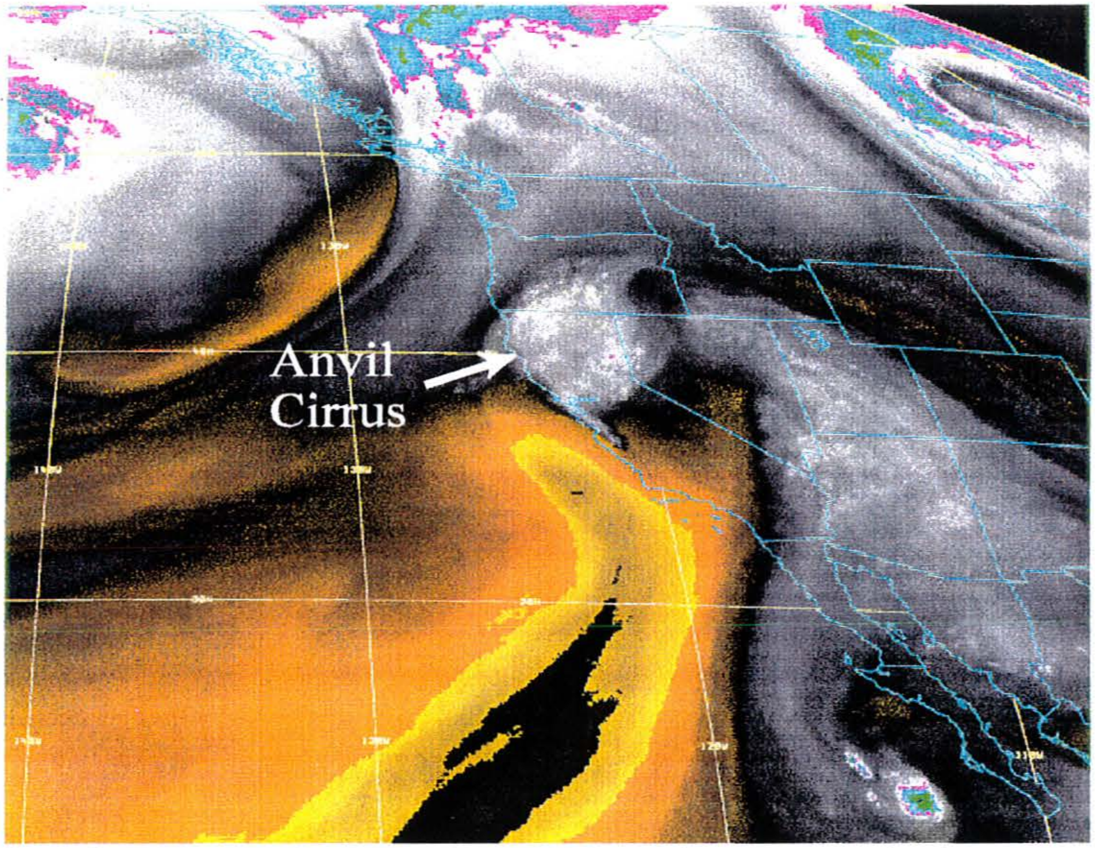

Figure 9. Water vapor image at 1200 UTC 9 September. The upper low is not as well defined, however a line of thunderstorms has moved further inland. Notice the large circular area of high level moisture covering northern California that resulted from thunderstorm anvil blow off.

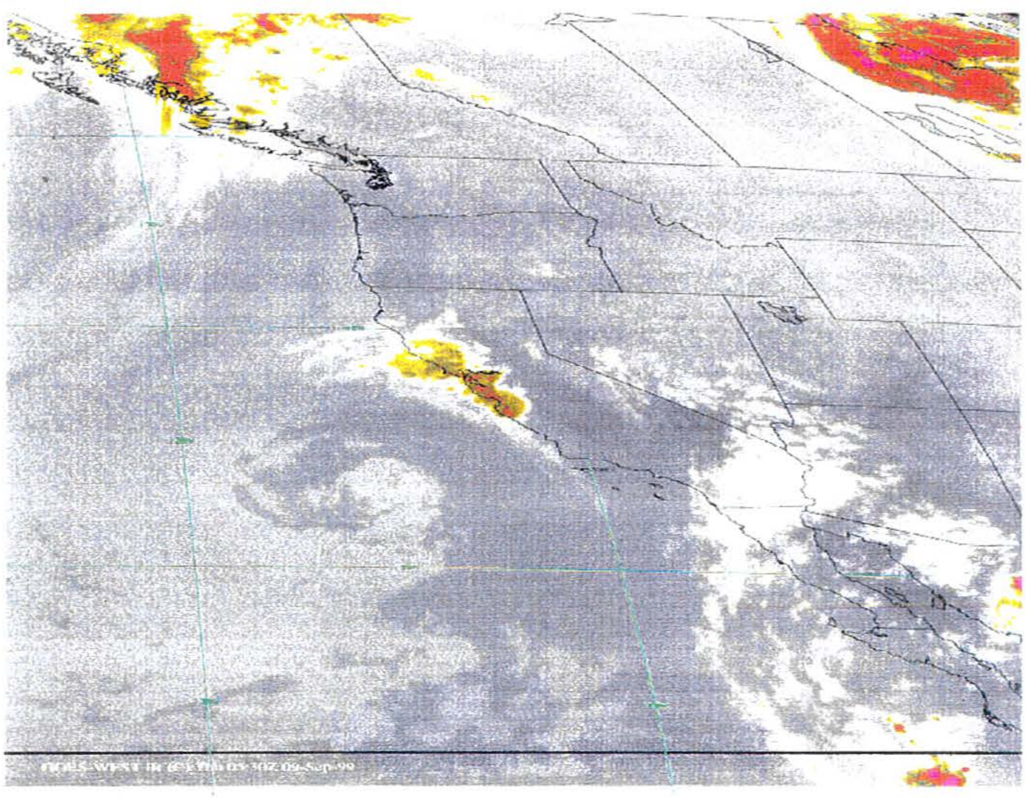

Figure 10. GOES-10 10.7 µm satellite image at 0530 UTC 9 September. This image is the same time as the radar in Figure 2.

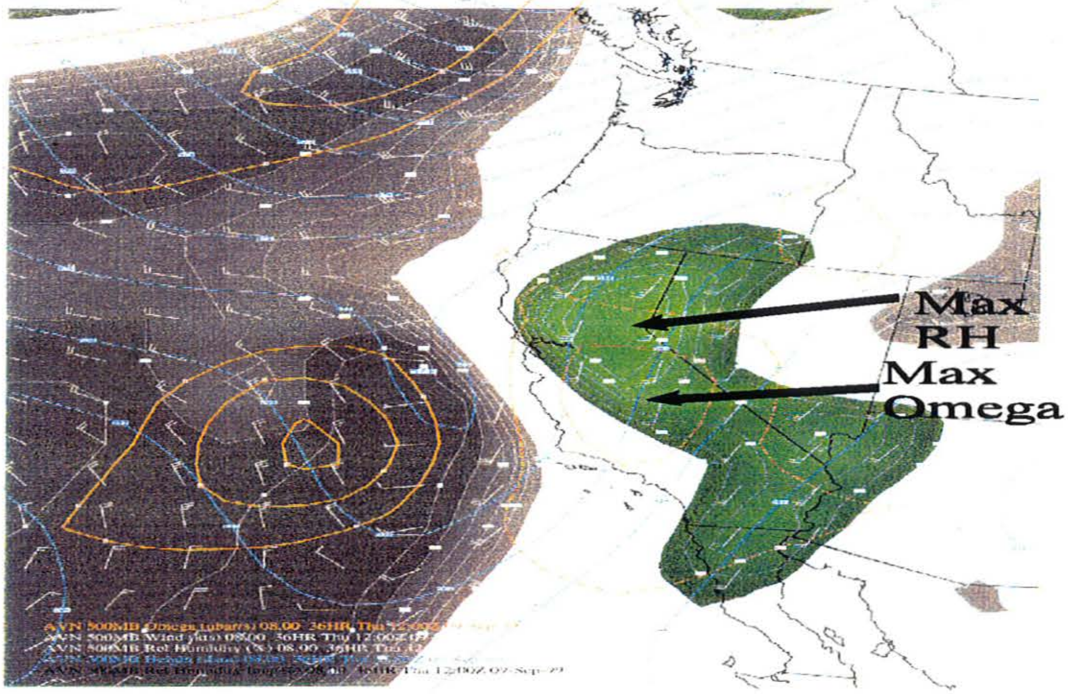

Figure 11. AVN 500-mb relative humidity and geopotential height 36-h forecast from the 0000 UTC 8 September model run. This figure is valid at 1200 UTC 9 September 1999. Green filled area is relative humidity 70 percent or greater. Dashed orange lines are omega contoured every 1 $\mu bars^{-1}$. Maximum relative humidity (90 percent) and omega (2 $\mu bars^{-1}$) are indicated by arrows. Half wind barbs are every 2.5 ms^{-1}.

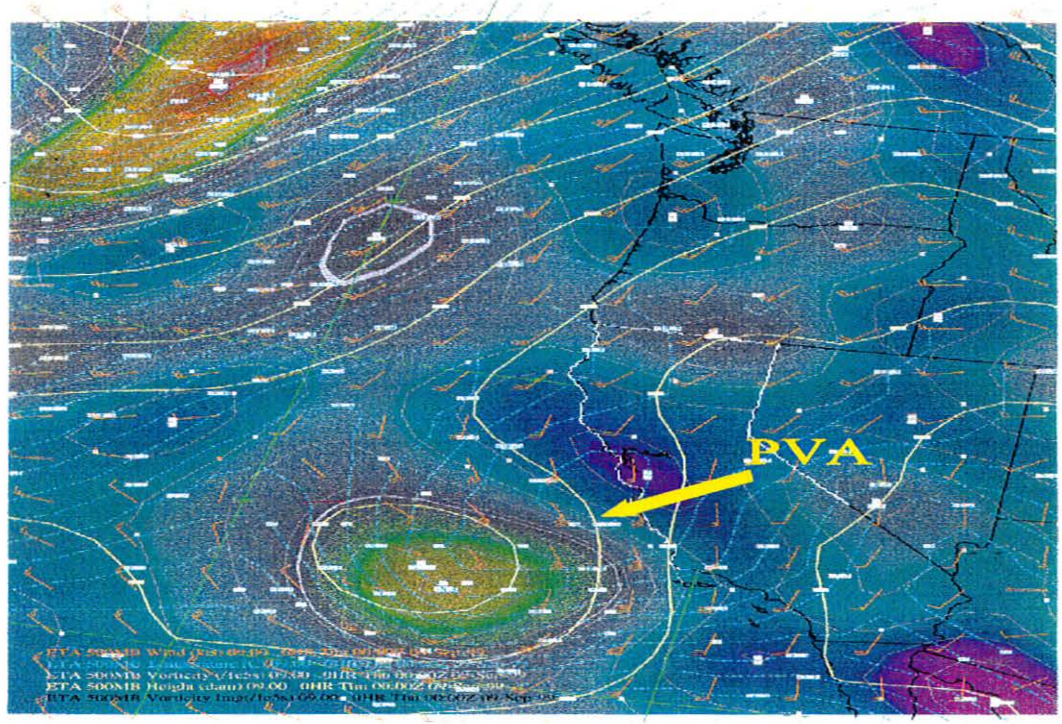

Figure 12. Eta 500-mb analysis at 0000 UTC 9 September 1999. Geopotential height lines are contoured every 30-m and positive absolute vorticity is shaded green in units of 1 $e5s^{-1}$. A -11°C isotherm at 500-mb is contoured over the San Francisco Bay. Half wind barbs are every 2.5 ms^{-1}.

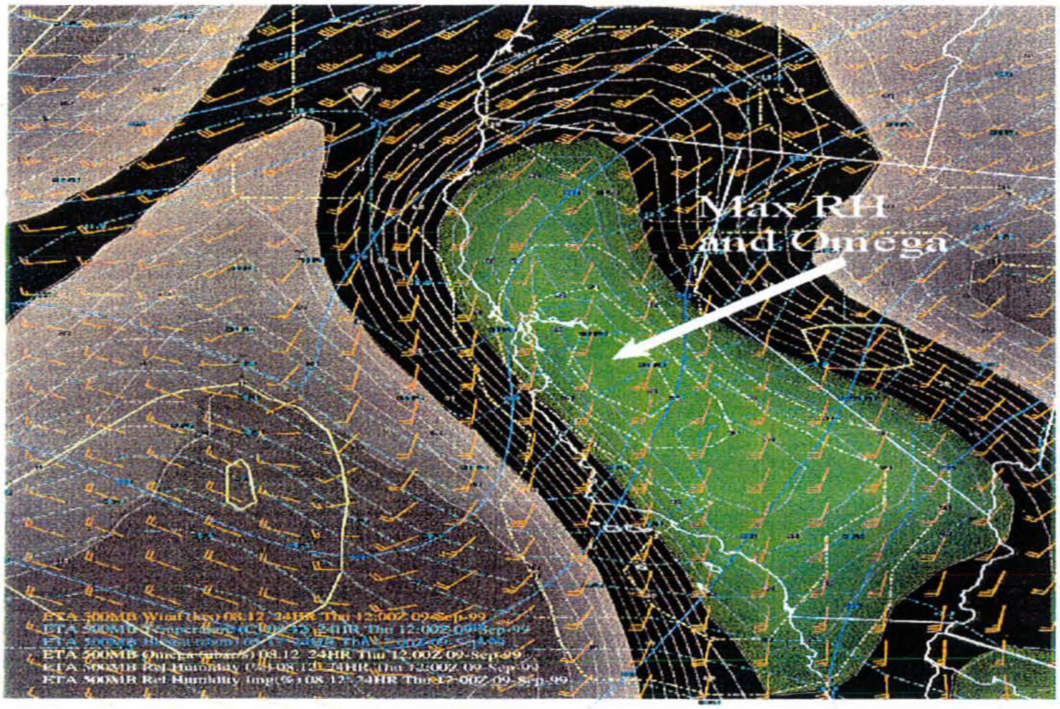

Figure 13. Eta 500-mb geopotential heights and relative humidity 24-h forecast valid at 1200 UTC 9 September 1999 from the 1200 UTC 8 September model run. Dashed yellow lines are omega contoured every 1 μbars^{-1} with a maximum of 4 μbars^{-1} just east of Monterey Bay. Blue height lines are contoured every 20-m. Half wind barbs are every 2.5 ms^{-1}. Light blue dashed blue lines are 500-mb temperature contoured every 1°C starting with -12°C over far northern California.

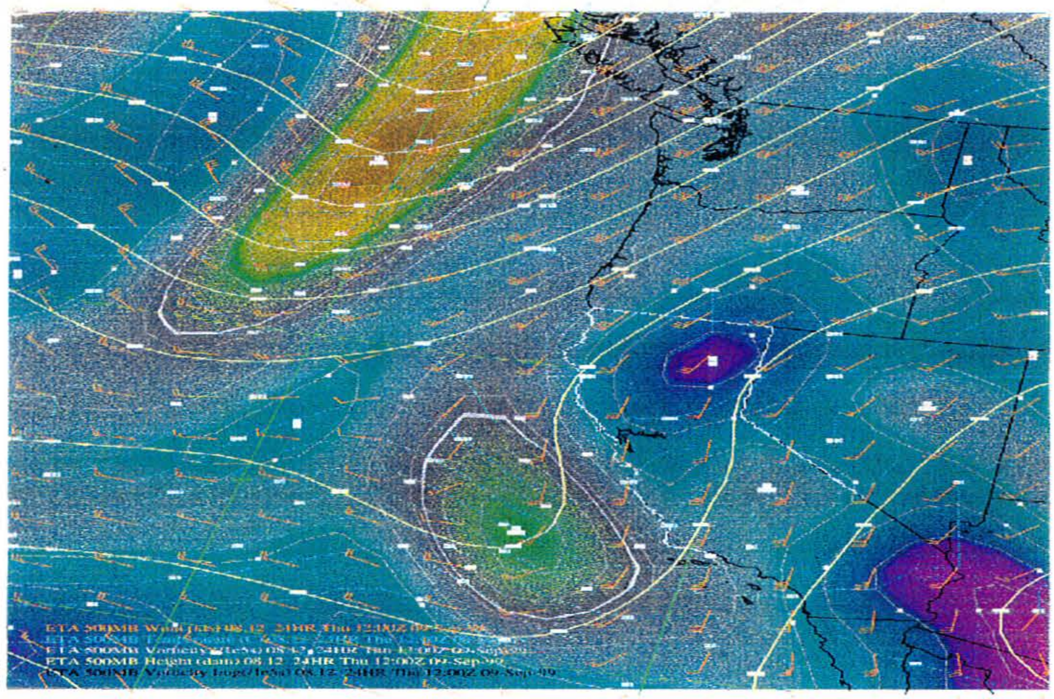

Figure 14. Eta 24-h forecast from the 1200 UTC 8 September model run valid at 1200 UTC 9 September. Units are the same as Figure 12. The upper low was forecast to open and weaken as a short wave approached from the north. Satellite pictures in Figures 8 and 9 confirmed that the system did weaken with time. Half wind barbs are every 2.5 ms^{-1}.

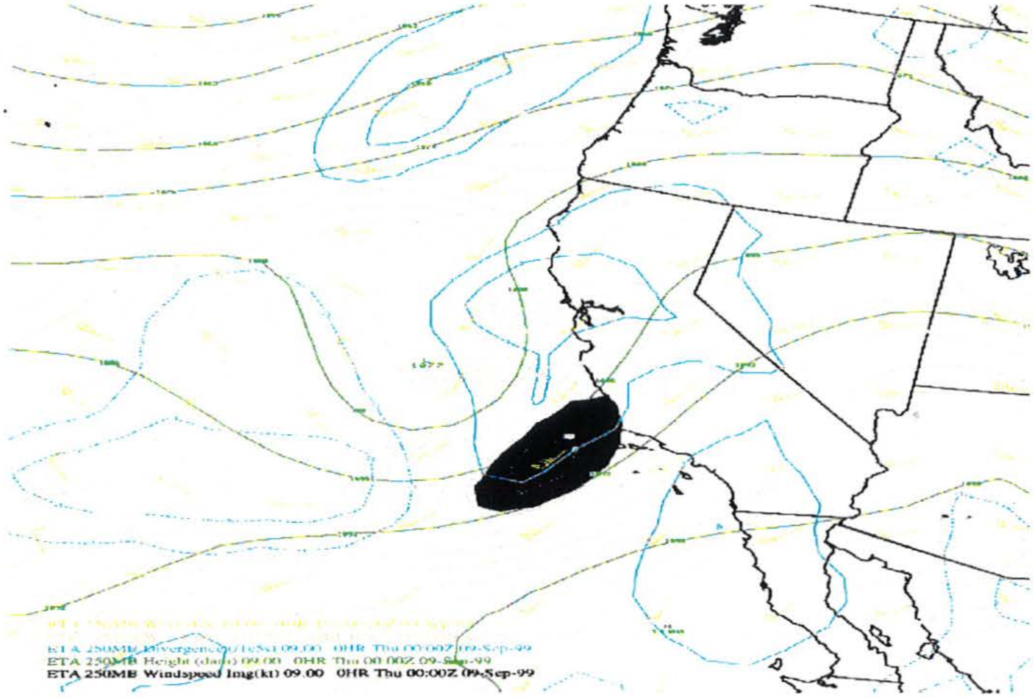

Figure 15. Eta analysis of a 70-kt 250-mb jet maximum (dark shaded area) at 0000 UTC 9 September 1999. Thick blue lines denote divergence contoured every 1 1e5s^{-1}.

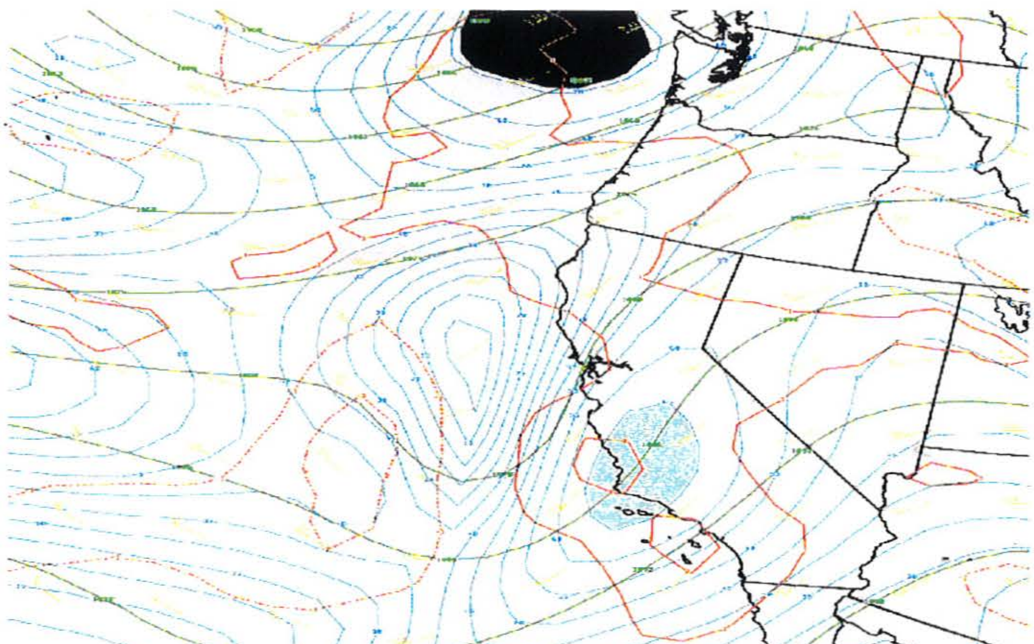

Figure 16. Eta 1200 UTC 8 September 1999 18-h forecast valid at 0600 UTC 9 September showing a 60-kt jet at 250-mb (blue shaded area) moving into central California with upper divergence (thick orange lines) along the coast. Thick orange lines denote divergence contoured every 1 1e5s^{-1}. Wind speed is contoured every 5 ms^{-1}.