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EXAMPLES OF USING PRECIPITABLE WATER AND SOUNDINGS TO FORECAST THUNDERSTORMS

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Introduction

There are three main parameters that forecasters evaluate in order to predict warm season thunderstorm potential. This includes sufficient moisture and instability along with a way to lift the air parcels to their level of free convection (LFC). The use of convective available potential energy (CAPE) or lifted indices (LI) are considered acceptable ways to assess instability. The use of CAPE is preferred because it measures an integrated layer of the atmosphere. Determining if there is adequate lift is usually accomplished by diagnosing surface boundaries, considering surface heating (convective temperature), and locating areas of synoptic vertical motion or terrain that could effectively bring an air parcel closer to the LFC. However, determining whether there is sufficient available moisture appears to be the most challenging task, especially in the West. The purpose of this paper is to discuss the merits of using precipitable water over the traditional methods, and to illustrate that there are severe limitations when using relative humidity to assess available moisture in the atmosphere. By definition precipitable water is the total column of moisture (i.e., mixing ratio) in a defined layer of the atmosphere that if completely condensed would be expressed in terms of a height of standing water. The units of precipitable water (inches) are easily understood and applied, which make it a useful tool. This paper will use examples demonstrating that to most accurately determine how much moisture might be available to develop thunderstorms, the forecaster should examine observed and forecast precipitable water values.

Methods of Assessing Moisture

Observed or forecast surface dew points are often good indicators of available moisture when diagnosing the potential for surface-based moist convection. However, during the warm season in northern California the thunderstorms that occur are usually high-based, and therefore surface dew points can be unrepresentative. CAPE can indicate sufficient available moisture as well, because in order to have an LFC (obtain CAPE) there must be sufficient moisture in a layer of the atmosphere. Therefore, an increase in moisture results in destabilization when environmental temperature lapse rates are conditionally unstable. Vertical time-sections or spatial displays of equivalent potential temperature can also be a good method to diagnose both instability and moisture availability.

A less desirable method of determining moisture in a convective environment is the use of relative humidity for a particular level or in a defined layer. One such limitation is more noticeable during the warmer months when relative humidity values are typically low. In a warm air mass the same relative humidity value when compared to a colder atmosphere will actually contain more moisture. Therefore, relative humidity is dependent on temperature where as precipitable water is an absolute measurement. In addition, with the same amount of moisture, it will take less vertical lift to increase relative humidity in a cool air mass versus a warmer one. Therefore, the same threshold value such as 60 percent for one level, or in a layer, cannot be applied in the same manner during every season and may not correctly indicate the available moisture or trends. Changes in relative humidity during the warm season often appear more subtle, but those changes can have significant effects on the development of moist convection.

If a forecaster only considers relative humidity, the air mass may then appear to be too dry for thunderstorm development. However, examination of precipitable water data can be more useful for these situations. This is often observed over northern California when a mid-level ridge of higher pressure dominates during the warm season. The easiest way to determine precipitable water amounts is by using observed upper-air soundings, model forecast soundings and plan view model precipitable water. Weather satellites have the ability to measure precipitable water and this near real-time data is available from the Special Sensor Microwave/Imager (SSM/I), Advanced Microwave Sounding Unit (AMSU), and Geostationary Environmental Operational Satellite (GOES) sounder derived imagery (DPI). This information is successfully used in the initialization of numerical models, is comparable to radiosonde data, and is very important in data sparse oceanic regions (Dostalek and Schmit 2001; Xiao, Zou and Kuo 1998; Filiberiti, Eymard and Urban 1993).

Supporting Events

Event one: Coastal mountain thunderstorms on 20 March 2001

On 20 March 2001, strong to possibly severe thunderstorms developed over the coastal mountains of northern California in Lake County (Fig. 1). The elevation of the terrain in this region ranges from 1,000 to 4,000 ft MSL. This elevated terrain appeared to be very important to the initiation of these thunderstorms. The synoptic pattern consisted of a weak mid-level ridge of high pressure and prevailing southwesterly flow (Fig. 2). The Eta forecast BUFR data viewed in BUFKIT (Mahoney 2000; Mahoney and Niziol 1997) at Sacramento (KSAC) was very unstable depicting a CAPE value of 1773 Jkg^{-1} (Fig. 3), however significant relative humidity (>60 %) was confined to between 16,000 and 26,000 ft MSL. The sounding at KSAC (25 ft MSL) predicted a significant precipitable water value of 0.90 inches. A sounding at Santa Rosa (KSTS), elevation 208 ft MSL, indicated less instability but depicted a slightly more moist layer in the lower to middle levels (Fig. 4). The precipitable water value was forecast to exceed one inch at KSTS, which is a significant amount of moisture during any season. It is also significant to note that the LFC at KSTS was forecast to be much higher than KSAC because of less moisture in the lower levels, however the convective inhibition (CIN) was similar. Therefore, based on the height of the LFC, and without terrain considerations, it is reasonable to expect a greater chance of surface-based moist convection for KSAC than at KSTS. The forecast for KSAC suggested that a limiting factor for thunderstorms in the Sacramento Valley would be the large CIN in the low-levels of the atmosphere. This is common during the warm season because of a relatively dry boundary layer capped by warmer air. It would take either a short wave trough to effectively lower the LFC, or an increase in low-level moisture to develop thunderstorms. Neither of these was forecast to occur at this location under the prevailing upper-level ridge of high pressure. The area of interest in Lake County for this case is located between these two sites, and therefore the most representative forecast sounding for this location was likely a blend of these two available Eta soundings (Figs. 3 and 4). The elevated terrain over Lake County was closer to the LFC and not subject to strong boundary layer inversions. The terrain also allowed for increased moisture convergence (Fig. 5) and instability once solar insolation was sufficient. An area of low pressure depicted in Figure 5 was likely induced by the heating of the terrain which provided local convergence, and this allowed air parcels to reach the higher-based LFC and initiated thunderstorm development. Short wave energy in the southwesterly flow may have provided additional destabilization (see Fig. 2). A visible satellite image supports the existence of a capped environment in the Sacramento Valley where only a few scattered cumulus were detected and no thunderstorms (Fig. 6), however satellite and radar images show that persistent intense thunderstorms continued over Lake County for several hours (Figs. 7 and 8). In this case, the forecaster considered a significant portion of the air mass to be too dry for thunderstorm development since most of the forecast relative humidity was confined to the middle and upper levels. However, the use of precipitable water would indicate that total available moisture was not a limiting factor for deep moist convection.

Event two: **Sierra Nevada thunderstorms on 9 July 2001**

The next event was chosen in order to demonstrate the applicability of precipitable water in the middle of the summer when the lower troposphere over interior northern California is typically very dry. On 9 July 2001 there was southerly mid-level flow, an upper-level ridge of high pressure over the Inter-mountain West and a trough of low pressure off of the California coast. This is a common summer pattern for that time of year and sometimes occurs with a recent monsoonal flow. Beginning on 9 July, deeper moisture, with precipitable water values near one inch were advected into northern California within the southerly flow between the areas of upper-level low and high pressure. This resulted in explosive thunderstorm development across the Sierra Nevada during the afternoon on 9 July (Fig. 9). Large hail (> 0.75 in) was reported with the strongest activity.

The satellite image in Figure 9 shows that most of the cloud development was confined to the Sierra Nevada crest on 9 July. The sounding at Reno (KREV) that corresponded to near this time illustrated significant moisture indicated by the precipitable water value of 0.63 in (Fig. 10). The precipitable water value at KOAK at 0000 UTC 10 July (not shown) was almost doubled (1.22 in). This amount of moisture for both sites is climatologically high. It appears that moisture was not a limiting factor across all of northern California, however the thunderstorm development was mainly confined to the Sierra Nevada (see Fig. 9). An Eta forecast sounding at Blue Canyon (KBLU), near 5000 ft MSL, demonstrated how well the model forecast the instability, precipitable water value and high-based LFC, but it is significant to note that the forecast relative humidity was minimal (<60 percent) at any level (Fig. 11). Similar to event one, a mental adjustment of the forecast sounding to higher terrain (above 5,000 ft MSL) was required by the forecaster in order for this forecast sounding to overcome the low-level CIN. Diurnal heating and elevated terrain were needed to effectively reach the LFC and develop thunderstorms. In this case, the lower troposphere in the Sierra Nevada was dry and thus the LFC was higher. Therefore, it took elevated terrain (above 5000 ft MSL) and surface convergence near the crest of the Sierra Nevada to "trigger" the thunderstorms.

Event three: Elevated nocturnal thunderstorms in the northern Sacramento Valley on 10 and 11 July 2001; Afternoon thunderstorms over the northern mountains of California on 10 July 2001

The significance of the high amount of moisture that was present over northern California in event two became even more apparent during the night hours of 10 July 2001. Event three will focus on the elevated nocturnal thunderstorms that occurred on 10 and 11 July. As the short wave trough (Fig. 12) interacted with the available moisture (Fig. 13), under an area of upper-level divergence, thunderstorms developed over the northern Sacramento Valley around 1200 UTC 10 July (not shown). The short wave trough lowered the LFC (destabilization) which allowed air parcels to realize the abundant elevated CAPE and mid-level moisture. In this case, the moist convection was not surface-based but rather it was elevated, similar to other events in northern California that have been documented by Tardy (2001). An Eta sounding for Red Bluff (KRBL) in Figure 14 illustrated that the elevated instability and high precipitable water values were accurately forecast by the model based on the thunderstorm development during the more typically stable boundary layer conditions observed at night. This sounding is similar to the classic inverted-V type profile (Bluestein 1993, Tardy 2001). The higher relative humidity (greater than 60 percent) was limited to a layer between 550 and 450 mb. The use of model relative humidity to diagnose moisture could have again misled the forecaster to consider the air mass as too dry for deep moist convection. However, the forecast precipitable water indicated that sufficient moisture was available, and the sounding predicted significant elevated instability. In this case, the recognition of the short wave trough (see Fig. 12) interacting with the moisture and elevated instability could have indicated the potential for moist convection.

This pattern repeated itself on 10 July 2001 with strong to severe thunderstorms developing over the mountains of northern California during the afternoon hours which were followed by additional nocturnal elevated thunderstorms over the northern Sacramento Valley on 11 July (Fig. 15). Numerous lightning strikes were detected by the National Lightning Detection Network (NLDN) during the entire period.

Conclusion

This paper has shown that the proper way to diagnose the moisture content of the atmosphere is to use an absolute measurement of atmospheric moisture, such as precipitable water, rather than relative humidity. Often when relative humidity is the only parameter used, the atmosphere may be incorrectly considered too dry for moist convection, but the precipitable water value might indicate sufficient moisture. This study demonstrated that the forecaster can obtain a spatial perspective by using graphical model output and satellite precipitable water products to locate areas of higher moisture or to monitor advection and trends. It is not suggested that using model relative humidity should be completely avoided, since very high values are often associated with clouds and precipitation.

Using observed and model soundings to view CAPE (surface-based and elevated) along with precipitable water is a useful tool to depict the regions of most favorable moisture and instability for forecasting thunderstorms. In addition, plan view depictions of these parameters can indicate small spatial or temporal changes that can lead to thunderstorm development. Model relative humidity should only be used in conjunction with this, and never as a single parameter to determine available moisture.

Acknowledgments

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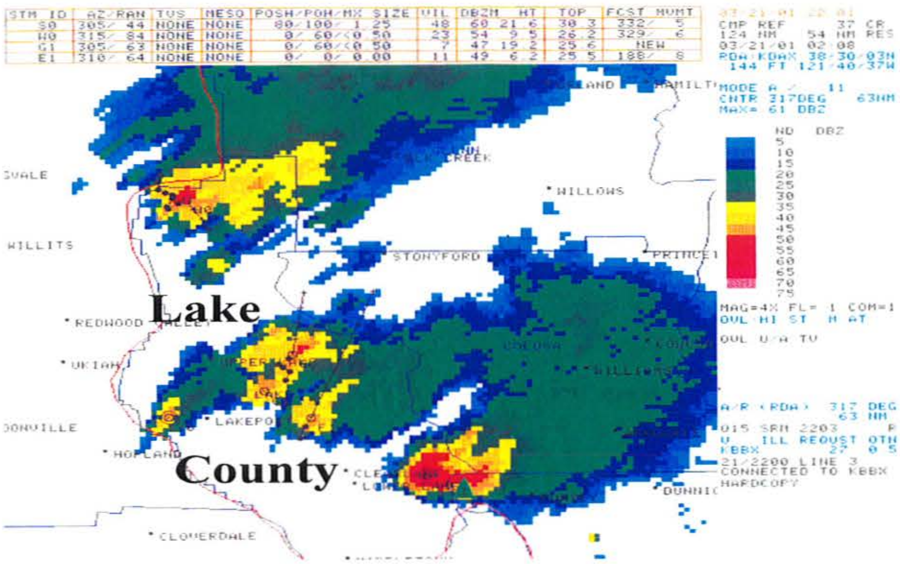

Figure 1. KDAX composite reflectivity at 0208 UTC 21 March 2001 detected intense thunderstorms in Lake County. Notice the enhanced V-notch signature on the southern storm.

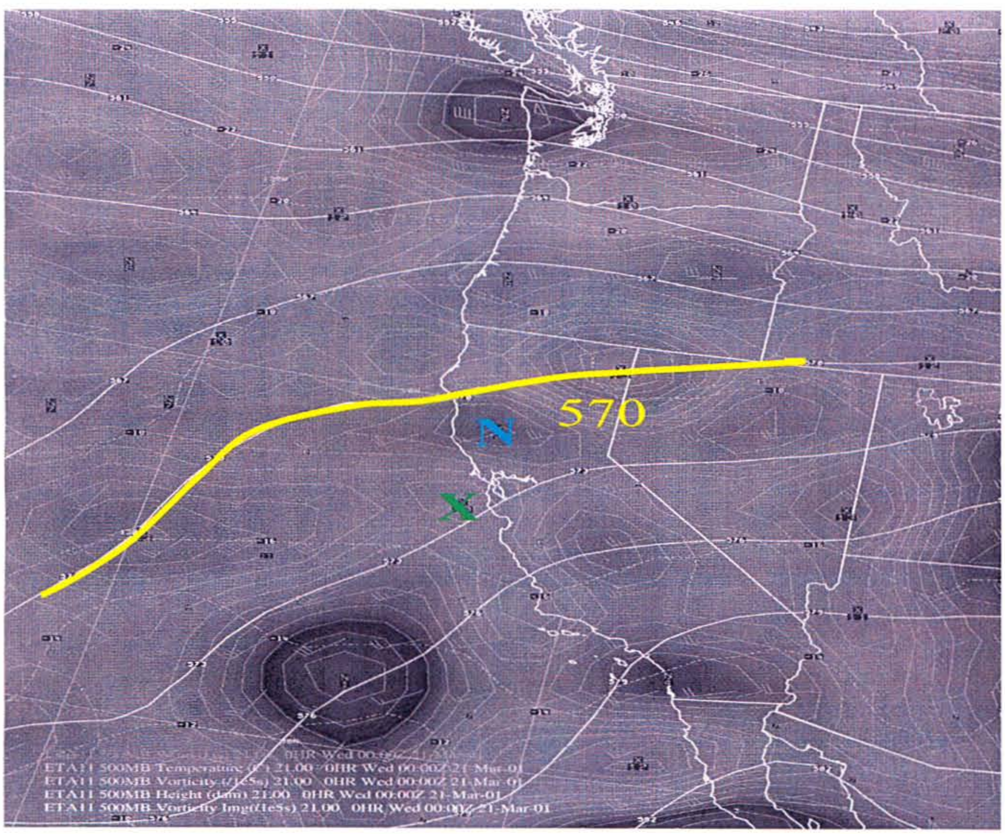

Figure 2. 500-mb geopotential height analysis at 0000 UTC 21 March depicted a weak vorticity maximum that was moving into northern California. Thick lines are geopotential height lines every 30 m and vorticity is every 1 e5s^{-1}. 570 height line and a 10 unit vorticity maximum (X) labeled for reference.

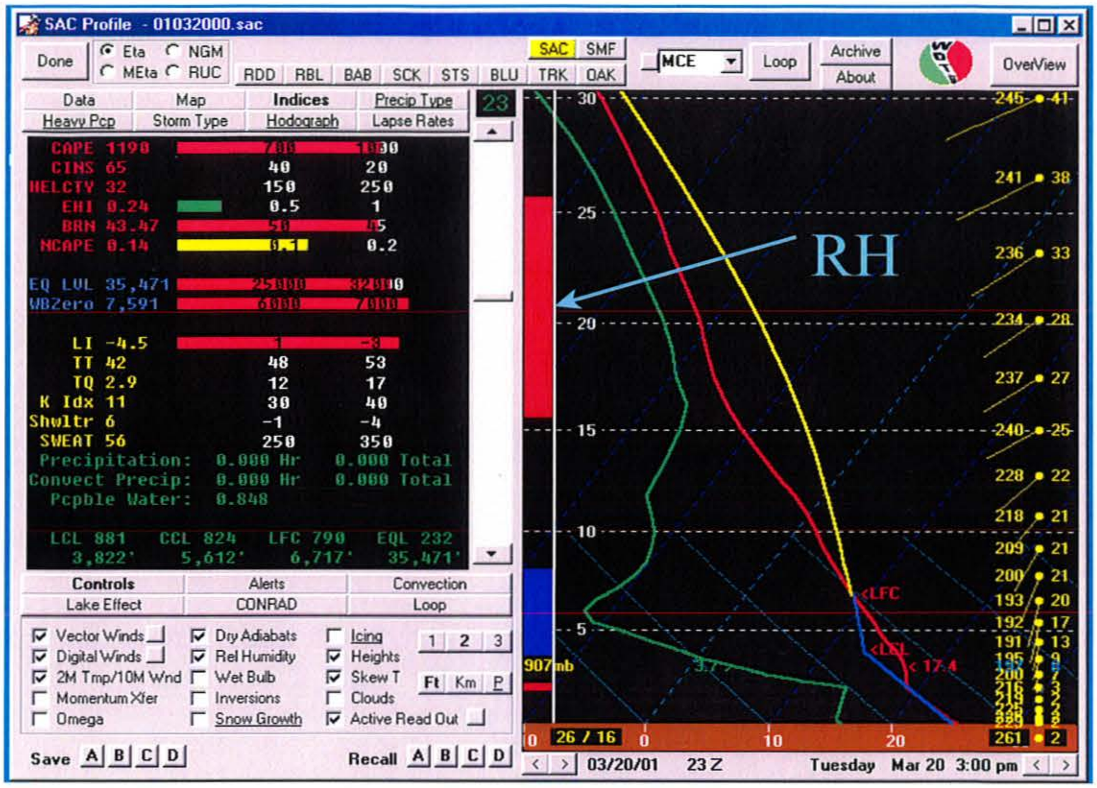

Figure 3. BUFKIT sounding for KSAC at 2300 UTC 20 March 2001 from the 0000 UTC 20 March Eta run. NCAPE was 0.14 ms^{-2}, LI was -4.5, CAPE was 1190 Jkg^{-1} and precipitable water was 0.85 in. Notice the large dry area on the sounding up to 15,000 ft and the low level CIN (blue line).

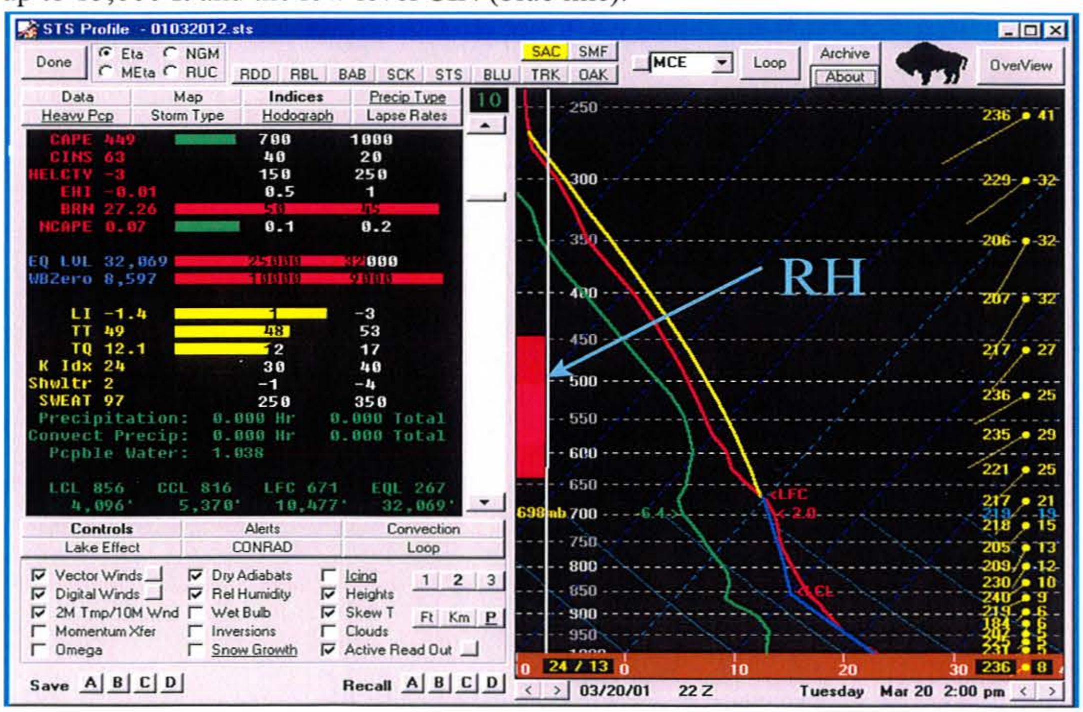

Figure 4. BUFKIT profile for KSTS from the 1200 UTC 20 March 2001 Eta run valid at 2200 UTC 20 March. The NCAPE was 0.07 ms^{-2} and the precipitable water was 1.04 in. Notice the relative humidity is forecast to be less than 60 percent from the surface to 650 mb on this profile.

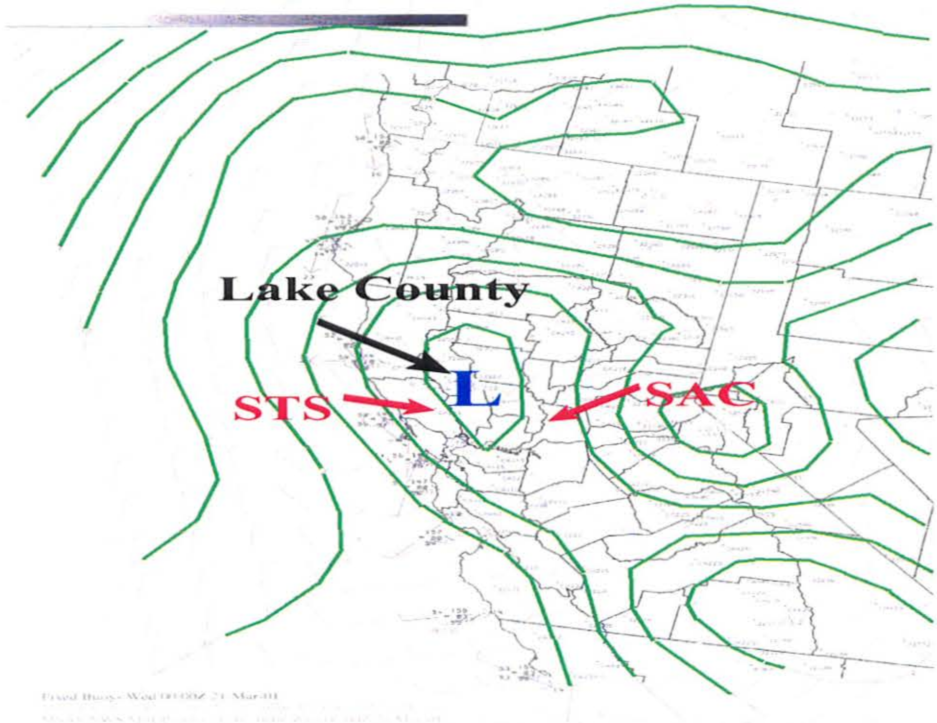

Figure 5. MSAS surface analysis at 0000 UTC 21 March 2001. Solid lines are MSL pressure contoured every 1 mb. Notice the low pressure over Lake County where there is surface convergence.

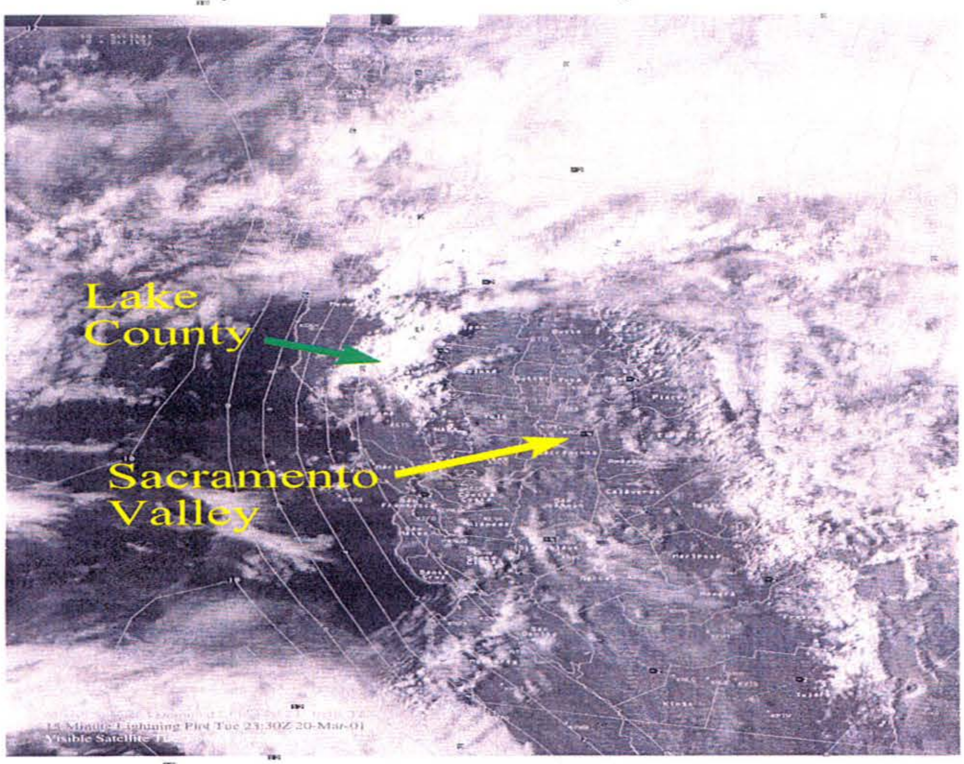

Figure 6. GOES-10 visible (.65 μ) images at 2330 UTC 20 March 2001 depicted the thunderstorm complex. Notice that there are few clouds over the Sacramento Valley.

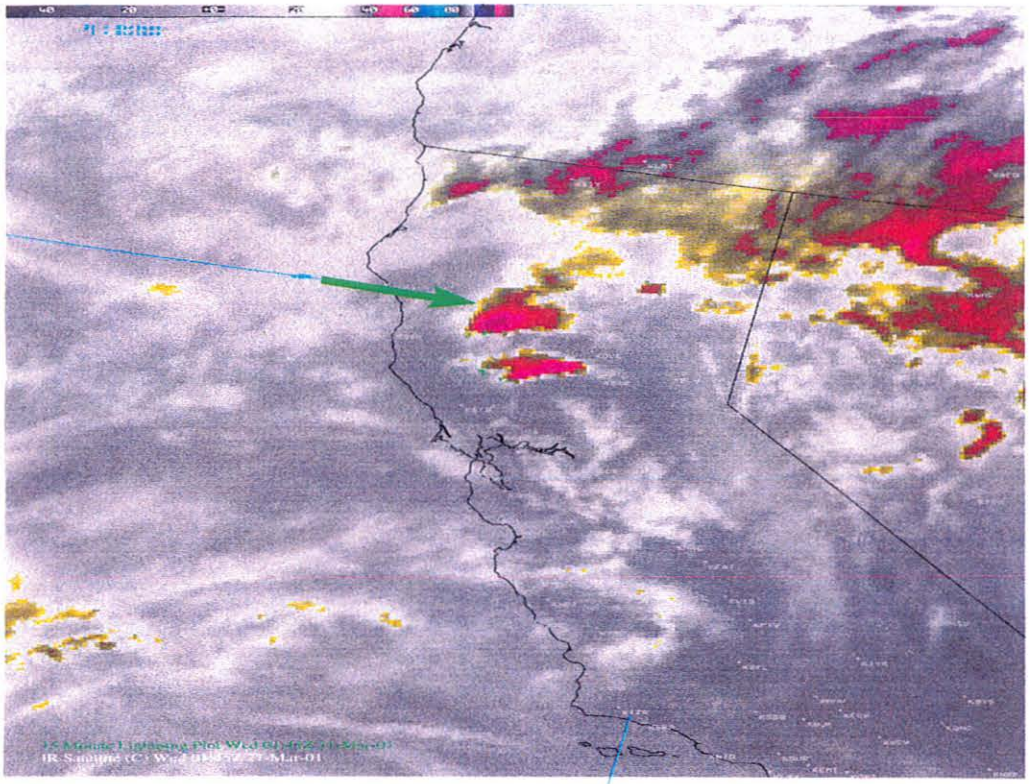

Figure 7. GOES-10 IR image at 0145 UTC 21 March detected cold cloud tops (-50 to -55 °C) associated with the thunderstorm. Notice the v-notch feature on the northern thunderstorm indicating a vigorous updraft. The direction of the anvils shows the southwesterly flow in the mid and upper-levels of the atmosphere.

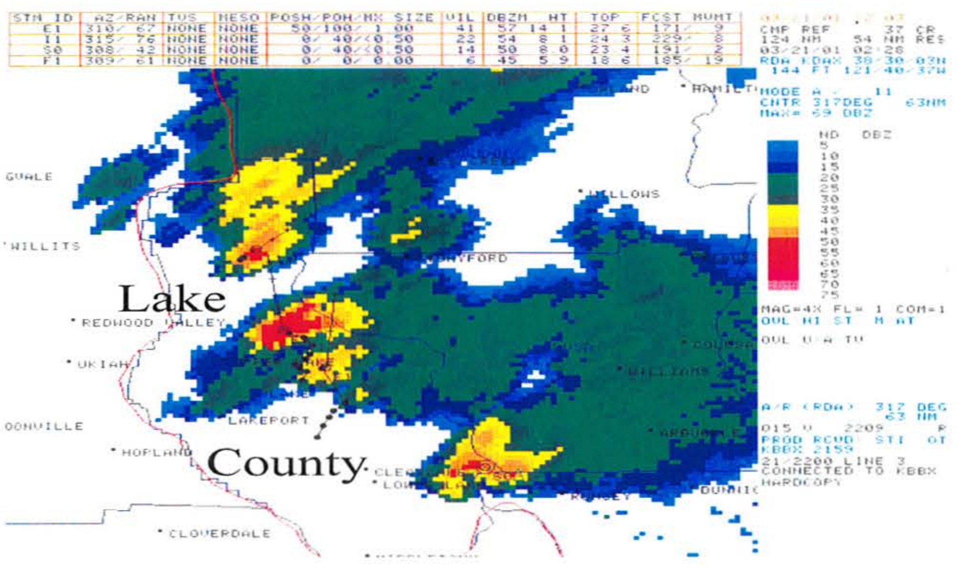

Figure 8. KDAX composite reflectivity at 0228 UTC 21 March 2001. Several intense thunderstorms are depicted by the high reflectivity values over Lake County.

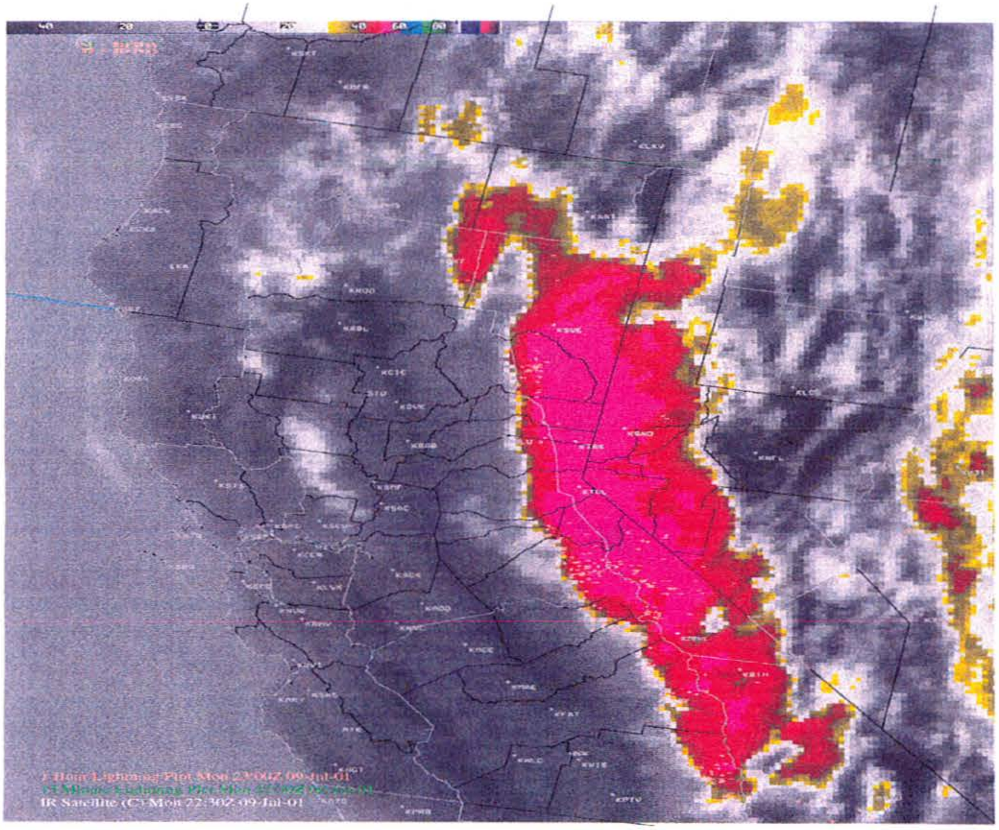

Figure 9. GOES-10 IR image at 2230 UTC 9 July 2001. Cloud top temperatures are -50 to -55°C. Numerous lightning strikes are detected by the NLDN across the Sierra Nevada and shown as small orange dashes (negative) and pluses (positive). Only a few clouds are seen elsewhere in California.

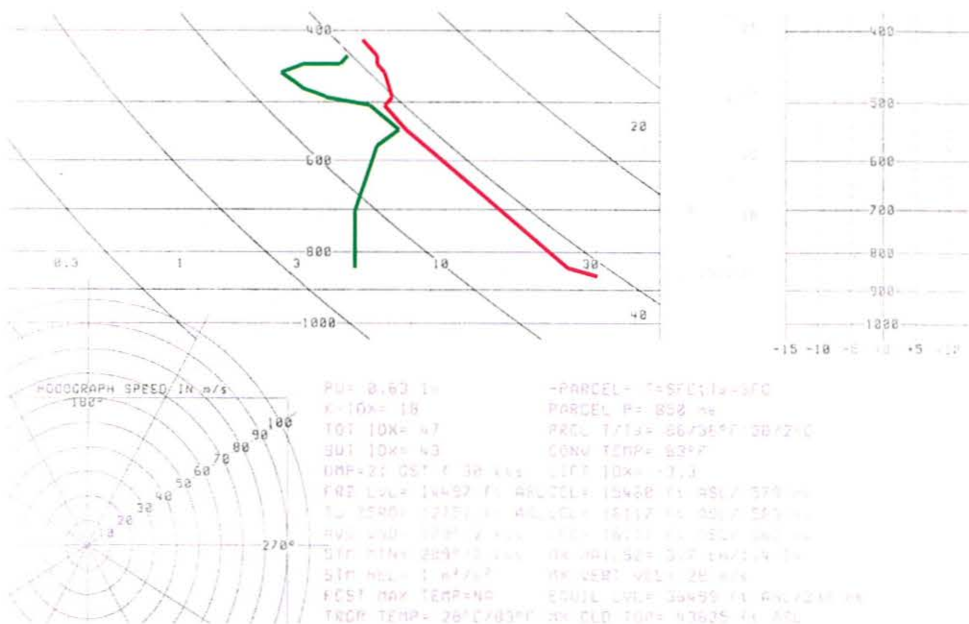

Figure 10. KREV sounding at 0000 UTC 10 July 2001. Precipitable water was observed at 0.63 in and CAPE was 552 Jkg^{-1}.

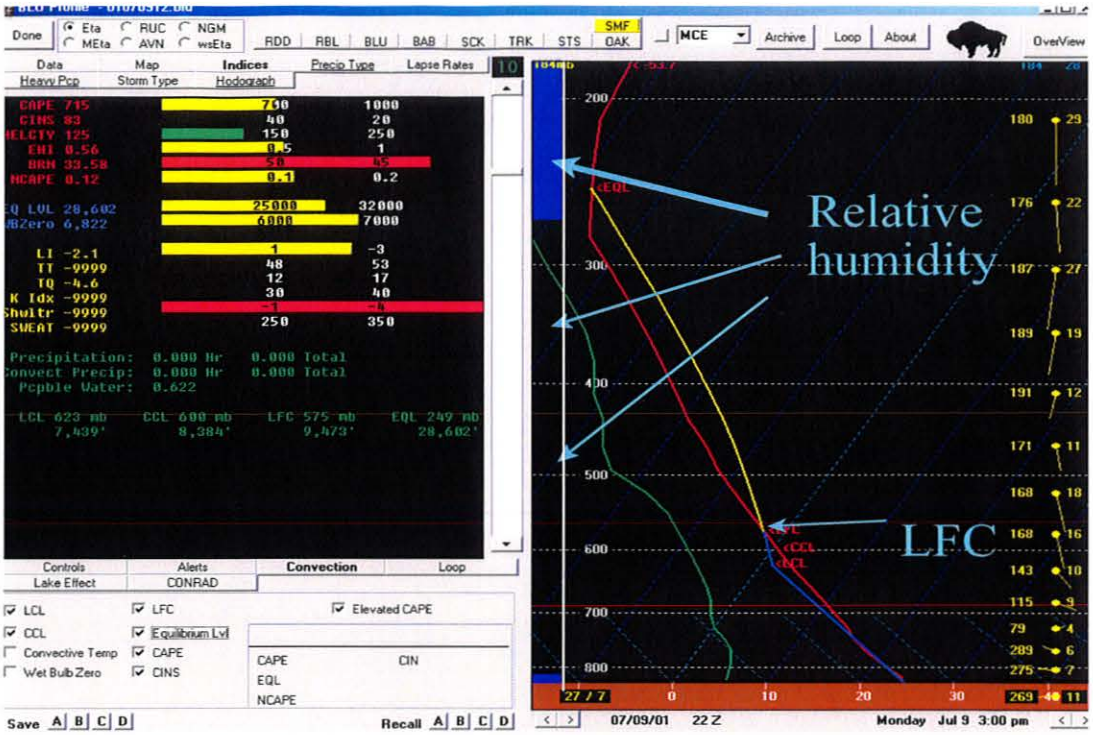

Figure 11. KBLU at 2200 UTC 9 July from the 1200 UTC Eta run. Note the forecast relative humidity was less than 60 percent (black area) through the entire troposphere, however the CAPE was 715 Jkg^{-1} and the precipitable water value was 0.62 in. It is also significant to note the high LFC at 580 mb which produced a CIN of 83 Jkg^{-1}.

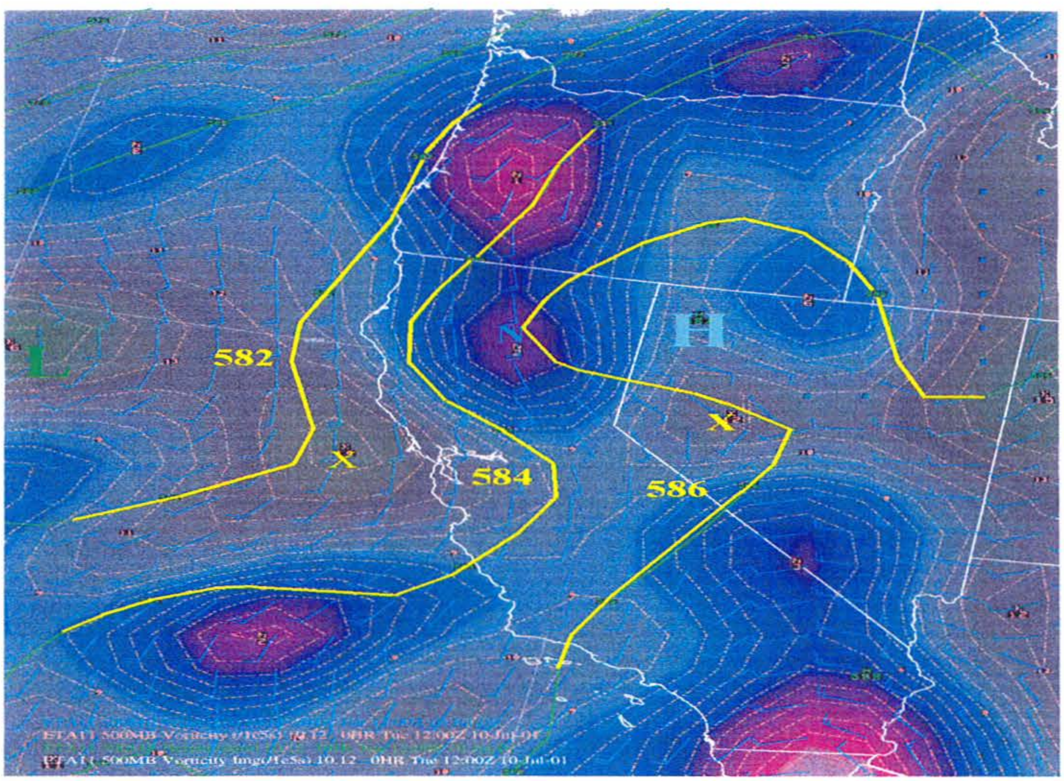

Figure 12. Eta 500-mb geopotential height analysis at 1200 UTC 10 July 2001. Wind barbs are every 2.5 ms^{-1}. Vorticity is every 1 $e5s^{-1}$.

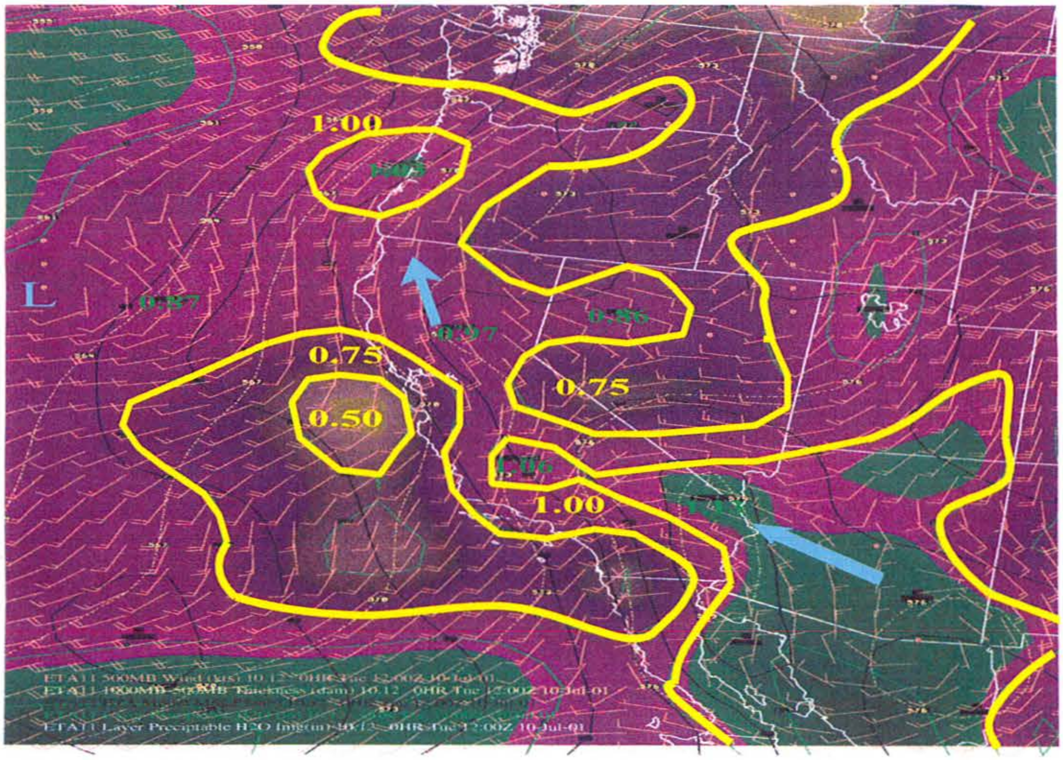

Figure 13. Eta layer precipitable water (inches) analysis at 1200 UTC 10 July 2001. Note the higher precipitable water axis that entered southern California and extended northward into western Oregon (blue arrows). Wind barbs are every 2.5 ms^{-1} at 500 mb.

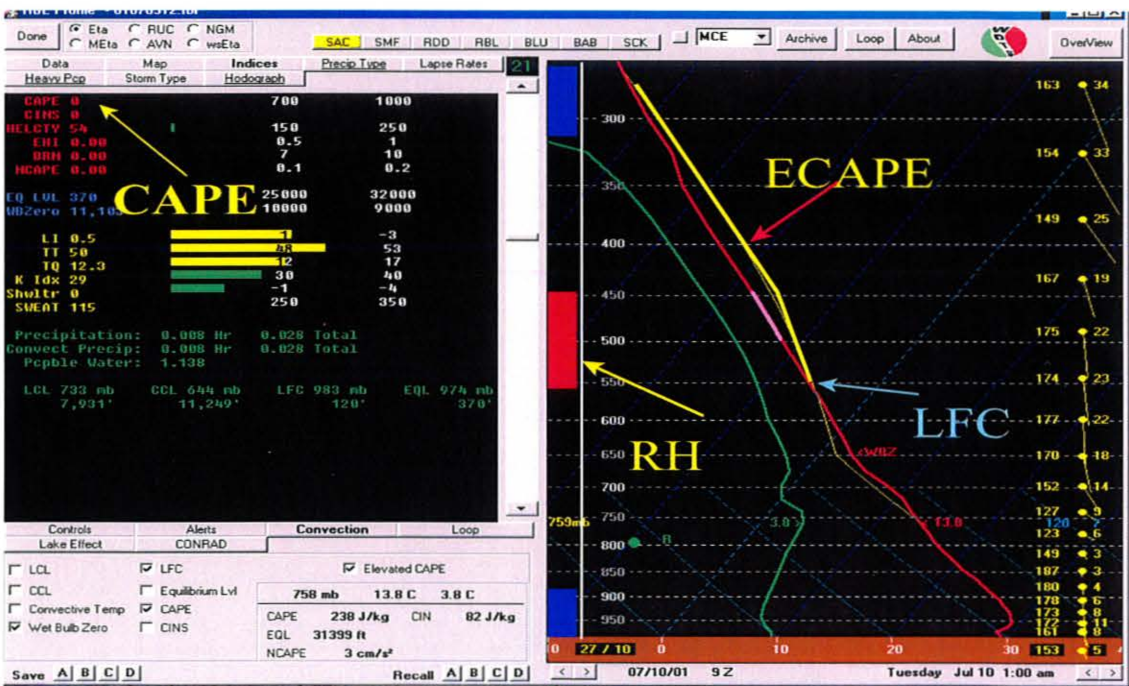

Figure 14. KRBL Eta at 0800 UTC 10 July from the 1200 UTC run. This sounding produced zero surface-based CAPE (lowest 100-mb layer mean), but the elevated CAPE was 281 Jkg^{-1} (yellow line). The only significant relative humidity (between 60 and 80 percent) was forecast between 550 to 450 mb, however the precipitable water was 1.14 in.

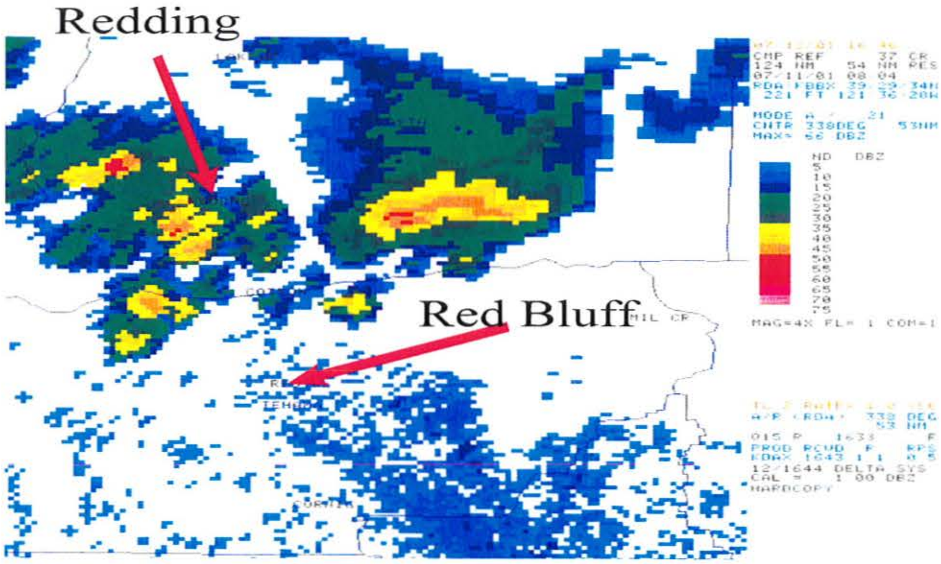

Figure 15. KBBX composite reflectivity at 0804 UTC 11 July 2001.