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THUNDERSNOW IN THE SIERRA NEVADA

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Introduction

Heavy snowfall is common over the Sierra Nevada, but it is usually associated with a well-developed surface cold frontal system. Snowfall rates of 5 to 7.5 cm (2 to 3 in) per hour are typically observed with the pre-frontal band of precipitation. Strong frontogenetic processes, mid-tropospheric differential positive vorticity, jet stream dynamics and upslope flow provide forcing which produces this heavy snowfall. Post-frontal precipitation is usually not significant unless it is associated with a strong mid-tropospheric short wave trough, persistent upslope flow, or unusually moist onshore flow. Furthermore, lightning is usually not associated with even the strongest bands of precipitation over the Sierra Nevada because of limited instability, sub-freezing surface temperatures and relatively low precipitable water values (Schultz 1999). Thunderstorms are much more common in this region during the summer months. Recent research on wintertime thunderstorms has focused on lake effect thundersnow, slantwise convection typically associated with strong warm fronts and elevated instability (Hunter et al. 2001; Schultz 1999; Bradshaw 1994; Colman 1990a). However, during the night hours of 9-10 November 2000, an atypical event occurred when scattered heavy snow showers and thundersnow developed over the west slopes of the Sierra Nevada, and northward into the southern Cascades. This moist convection appeared to be surface-based. Maximum snowfall amounts of 14 to 20 cm (6 to 9 in) were observed with these thunderstorms in the towns of Pollock Pines and Burney. These locations are at relatively low elevations between 3,000 and 4,000 ft MSL where significant snowfall in November is not common. The unexpected snow squalls resulted in car accidents and closure to Interstate 80. This paper will explore this case and attempt to develop forecasting applications that might better enable a forecaster to predict heavy snow squalls in a post-frontal environment.

Synoptic Overview and Satellite Images

On 9 November 2000, geostationary operational environmental satellite (GOES-10) water vapor imagery depicted a strong short wave approaching the central coast of California (Fig. 1). A 500-mb geopotential height analysis prior to the event illustrated that the upper-level trough was moderately strong and cold with a short wave moving into the base of the mean trough (Fig. 2). The 1200 UTC 10 November 500-mb analysis (Fig. 3) detected this moderately strong vorticity maximum over the Sacramento Valley, which resulted in significant differential positive vorticity advection (DPVA) over the region of interest. The trajectory of this system (from the north) was not favorable to interact with a higher precipitable water plume since this moisture was displaced southward in the Pacific Ocean. In addition, this type of system would have spent insufficient time over the ocean which is necessary to entrain low-level moisture. However, abundant low-level post-frontal moisture was already present over the region of interest (Fig. 4).

Thunderstorms were first detected across the east side of the Sacramento Valley (Fig. 4). Figure 5 illustrates that the thunderstorms became more intense when they encountered higher terrain. At 0500 UTC 10 November, well-developed thunderstorms were occurring near Pollock Pines and Burney and the National Lightning Detection Network (NLDN) depicted several lightning strikes (1 positive, 2 negative) associated with the cold cloud tops (Fig. 5). The author observed cloud-to-ground lightning with the thunderstorms that moved from the Sacramento Valley foothills into the Sierra Nevada near Pollock Pines. The thunderstorms continued with similar intensities during the night hours as illustrated in Figure 6.

Discussion and Model Data

The Eta Model forecast wind profiles appeared to underestimate upslope flow in the Sierra Nevada ahead of the short wave. An Eta profile at Blue Canyon (KBLU), elevation 5,000 ft MSL, observed at 0000 UTC 10 November indicated southwest to westerly winds at 9 to 12 kt (4 to 6 ms^{-1}) and moisture in the lowest levels (Fig. 7). However, just prior to the passage of the short wave trough, at 1200 UTC 10 November, the low-level winds were observed on the Eta analysis (Fig. 8) to have backed to the southwest and increased to 12 to 17 kt (6 to 8 ms^{-1}). Model forecast soundings from the 1200 UTC 9 November Eta run did not show this type of wind profile, but instead, predicted westerly wind under 5 kt [(3 ms^{-1}) (not shown)]. This is significant since a stronger southwest low-level wind would increase surface moisture convergence and result in upslope flow across the western slopes of the Sierra Nevada. Since thundersnow also occurred over the lower elevations of the southern Cascades (Burney Basin), where upslope flow is often less of a factor in precipitation enhancement, it is likely that the orographic effect was not the main contributor to thundersnow. However, the elevated terrain in the southern Cascades would help to destabilize the air mass since it would be closer to the Level of Free Convection (LFC).

Model forecast and observed soundings for the period of heaviest snowfall did not show any CAPE (mean surface to 100 mb layer parcel). Researchers have found that surface-based CAPE is not useful for thundersnow (Hunter et al. 2001; Schultz 1999). However, steep lower troposphere environmental lapse rates were forecast by the 1200 UTC 10 November Eta run for KBLU (Fig. 9). The steep lapse rates of near 8°Ckm^{-1} were forecast to occur through a rather deep layer of the lower troposphere (surface to 500 mb). Hunter et al. (2001) found that using a defined layer for temperature difference was more applicable than CAPE to assess instability (i.e., 850 to 700 mb lapse rate) in sub-freezing surface temperatures. The model sounding also depicted a deep layer of low-level moisture as evident by the small dew point depressions (Fig. 9). It was evident in satellite imagery that the synoptic scale short wave trough (see Figs. 1-5) provided the necessary lift and destabilization as it encountered the moisture over the foothills of the Sierra Nevada. The elevated terrain of the Sierra Nevada and the southern Cascades likely provided local surface moisture convergence regions that were necessary to initiate and sustain thunderstorms. Considering that the activity occurred and intensified at night, there were no contributions from solar insolation. The cold core nature of this mid-tropospheric short wave, time of day, and additional diabatic cooling effects from the convection allowed for snowfall to occur at relatively low elevations. It was also noteworthy that the sounding indicated temperature and moisture conditions that support maximum snow crystal growth (see Fig. 9). Studies have shown that snow dendritic formation (i.e., large snow flakes) through deposition and aggregation is most effective when temperatures in the lower clouds are -10 to -22°C (Staudenmaier 1999). Therefore, snowfall accumulation was likely enhanced in this event due to increased deposition and aggregation effects. In addition, since the moist convection moved into an area with abundant low-level moisture, there was likely "seeder-feeder" processes that occurred (Houze 1993). Hunter et al. (2001) found this mechanism to be important for enhancing frozen precipitation.

Storm electrification usually occurs in the mixed-phase region of the cloud. In this region, strong vertical motions supply sufficient water vapor for supersaturation. The interaction of riming ice particles and non-rimed ice particles create separate electric charges (Zipser 1994). This occurs most efficiently near the -10°C isotherm in a cloud layer since there will be a mixture of ice particles and supercooled droplets (Schultz 1999). This theory supports the finding of lightning most often occurring near the surface 0°C isotherm and usually does not extend far into the cold side, since this environment would not be conducive to electrification (Holle and Cortinas 1998). This is also consistent with observations of moist convection that develops in the Central Valley of California and advects into the Sierra Nevada. However, in this case the combinations of strong upward vertical motion, steep low-level lapse rates, sufficient water vapor, proper cloud microphysics and near freezing surface temperatures allowed thunderstorms to persist in a colder environment that could support heavy snow. Figure 10 is an Eta Model forecast time-height section that illustrates how the significant low-level moisture was situated in a temperature profile and upward vertical motion (omega) conducive to maximum snow crystal growth and storm electrification. Finally, research on lightning associated with frozen or freezing precipitation has shown there is often a high percentage of positive flashes, but no direct correlation existed for Hunter et al. (2001). In this case, the total number of flashes was small but the percentage of positive strikes was high (see Figs. 4-6).

Conclusions

Despite the difficulty with forecasting moist convection, there was sufficient data in this case that could indicate a potential for locally heavy snow and rain showers. Recognizing the strength of the mid-tropospheric short wave by using model and satellite data is crucial to predicting unusual weather events. Sufficient low-level moisture was evident on satellite and model data. The synoptic scale forcing (i.e., DPVA) associated with the short wave trough provided synoptic lift which further destabilized an air mass with steep environmental lapse rates. In this case, the significant snowfall amounts were attributed to post-frontal thundersnow which has not been observed to be a common phenomenon in the Sierra Nevada. However, the terrain provides for localized surface moisture convergence, upslope enhancement, and given sufficient moisture and instability, can support locally intense moist convection. This case study documents that significant snow showers, with or without lightning, can occur over higher terrain which are not associated with primary synoptic scale surface fronts, and can be used for future forecast considerations.

The use of land surface-based CAPE is not recommended for assessing instability in most lightning events that produce freezing or frozen precipitation. However, the recognition of steep low-level lapse rates in sufficient water vapor, and monitoring lightning and satellite data are the best tools for short-term forecasting of these not so typical events. When thunderstorms advect or develop in near or subfreezing surface temperatures, it is important to consider the cloud microphysics and possible "seeder-feeder" processes that might contribute to unusually heavy snow squalls. The detection of cold cloud tops (e.g., -40 °C) and lightning flashes could indicate the potential for intense snow bursts downwind in colder surface air.

Acknowledgment

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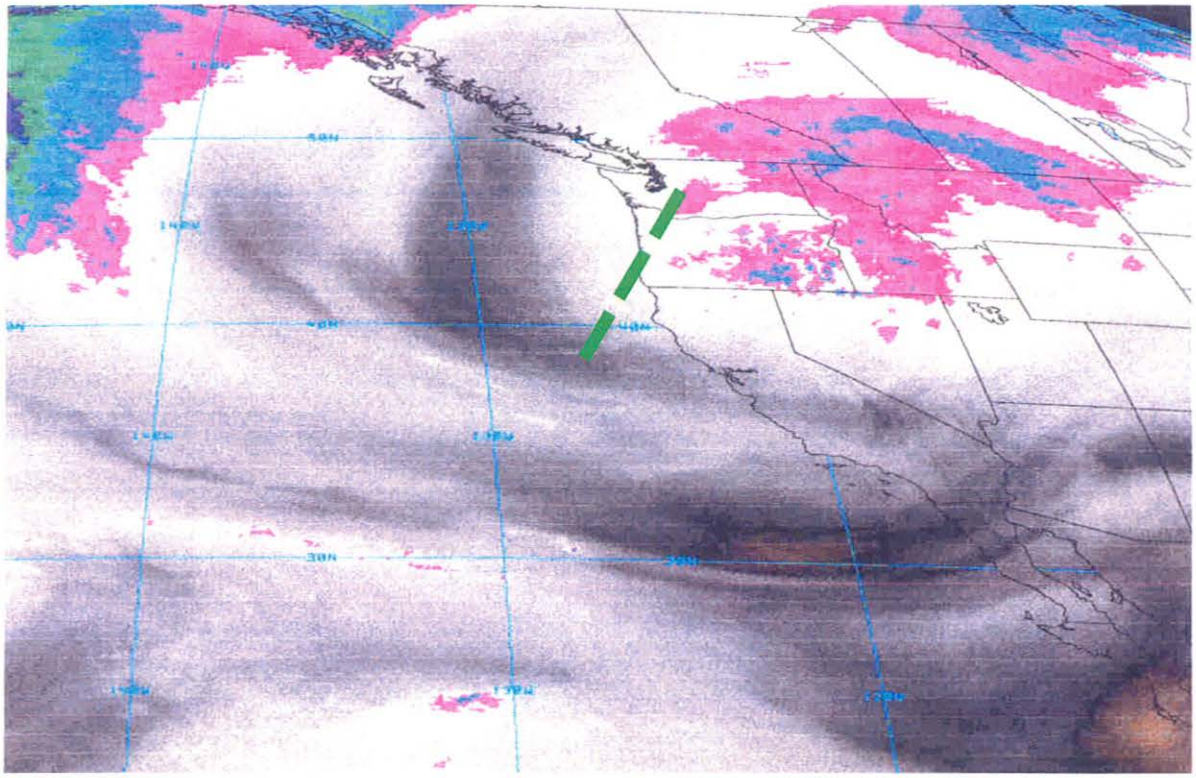


Figure 1. GOES-10 water vapor image at 2100 UTC 9 November 2000 depicted a short wave trough (dashed green line) approaching northern California.

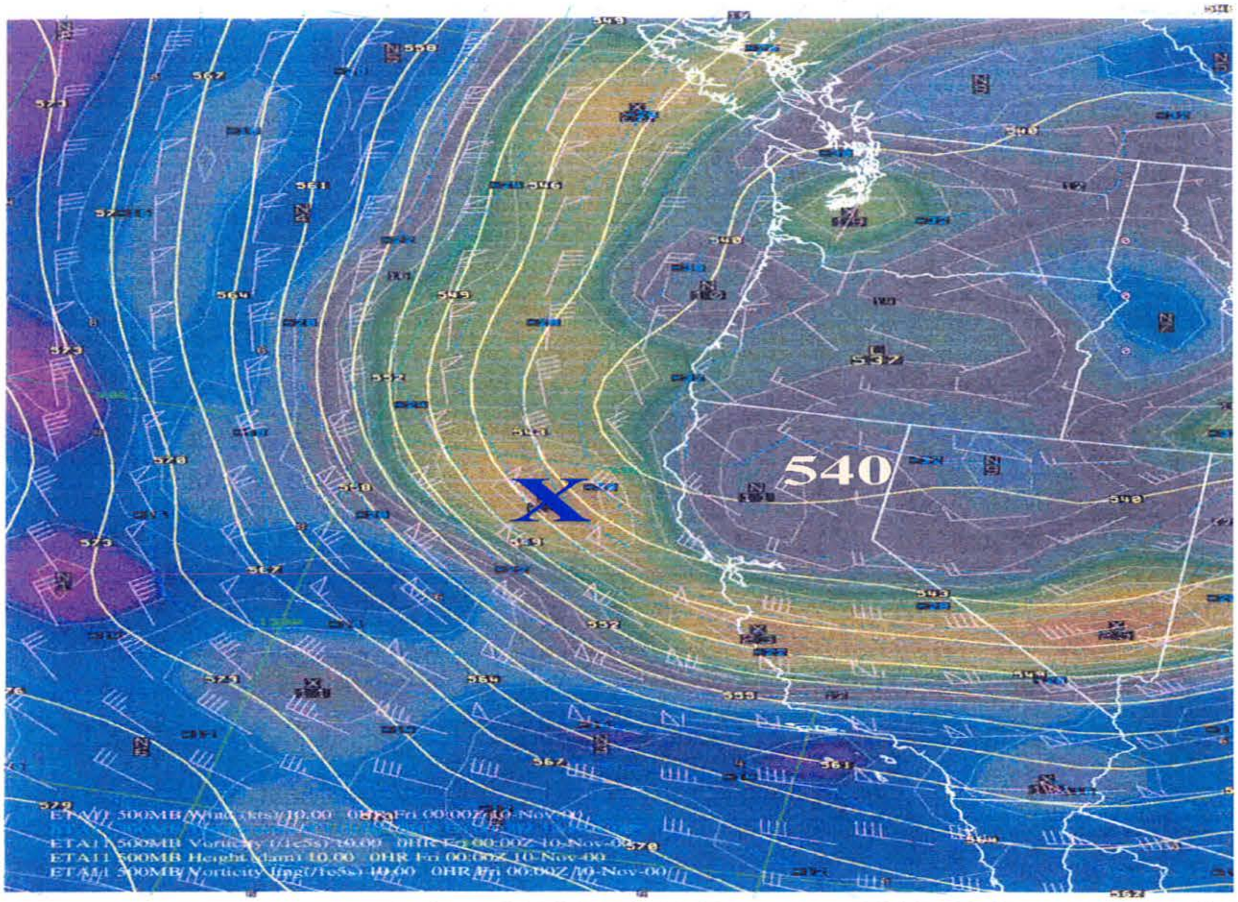


Figure 2. Eta 500-mb analysis at 0000 UTC 10 November 2000. Yellow geopotential height lines are contoured every 30 m and vorticity is every 2 e5s^{-1}. The 23 unit vorticity maximum is labeled with the blue X. The 540-dm height line is labeled for reference.

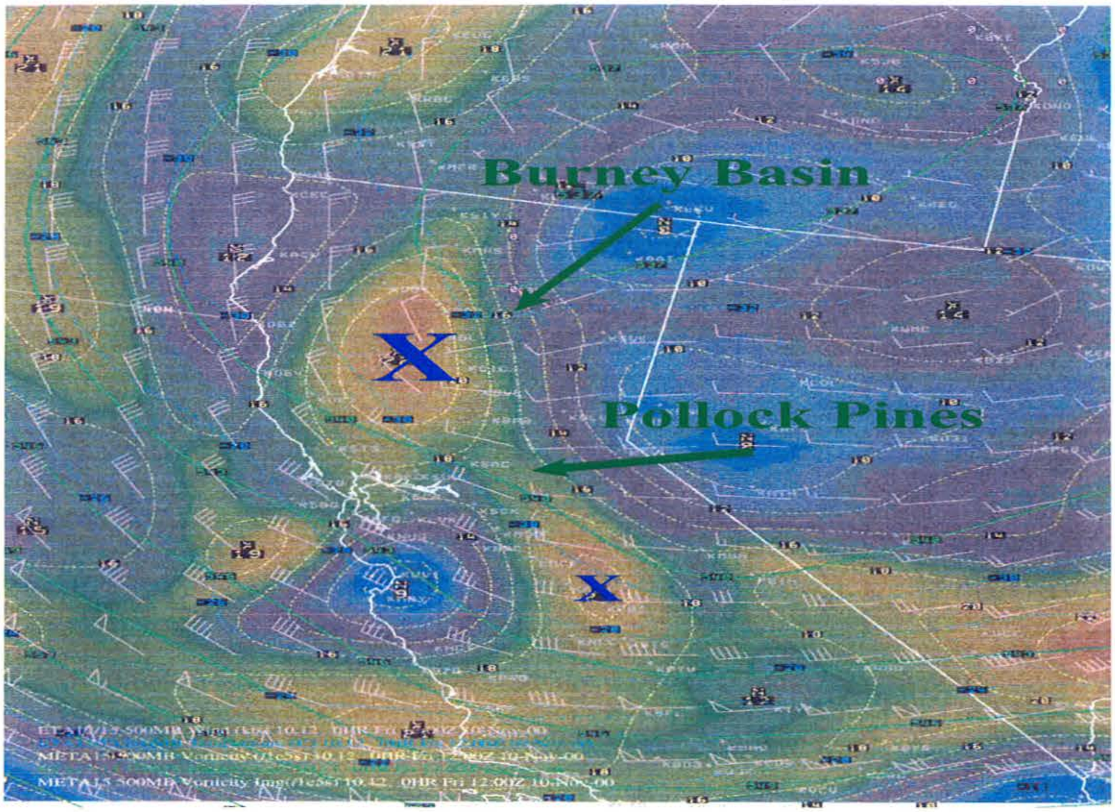


Figure 3. Eta 500-mb geopotential height and vorticity analysis at 1200 UTC 10 November. Units the same as Fig. 2. Large X is a 23 unit vorticity maximum.

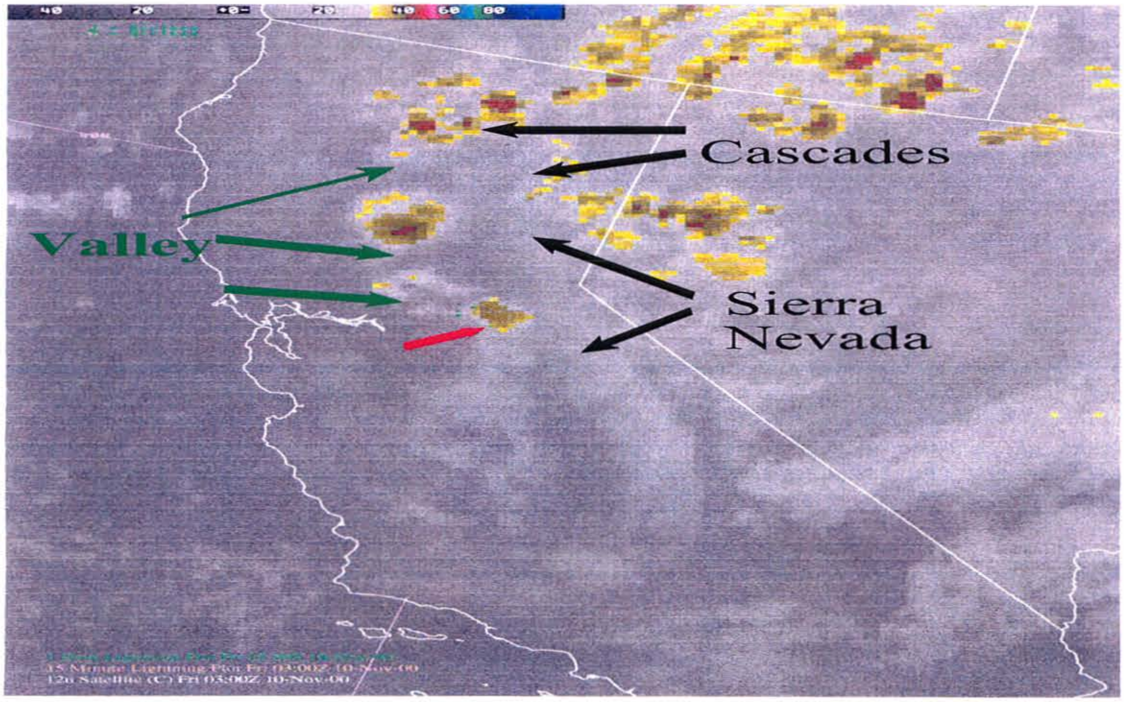


Figure 4. GOES-10 IR image captured the early stages of thunderstorm development in the Sacramento Valley and foothills of the southern Cascades and northern Sierra Nevada at 0300 UTC 10 November. Low-level clouds are depicted covering the Sierra Nevada. Red small arrow points to cloud to ground lightning strikes. Two negative and two positive strikes detected from 0200 to 0300 UTC.

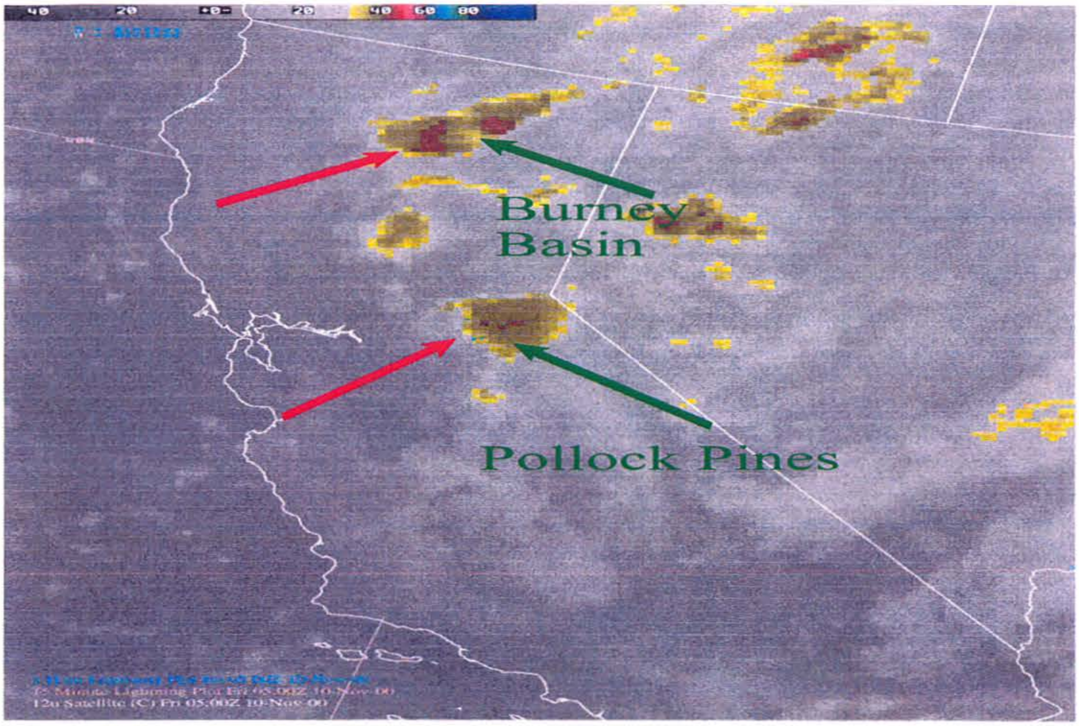


Figure 5. GOES-10 IR image at 0500 UTC 10 November. Arrows point to the cold cloud tops (-40°C) that produced heavy snow. Cloud to ground lightning was detected with the southern enhancement (bottom red arrow). One positive and two negative strikes detected between 0400 and 0500 UTC.

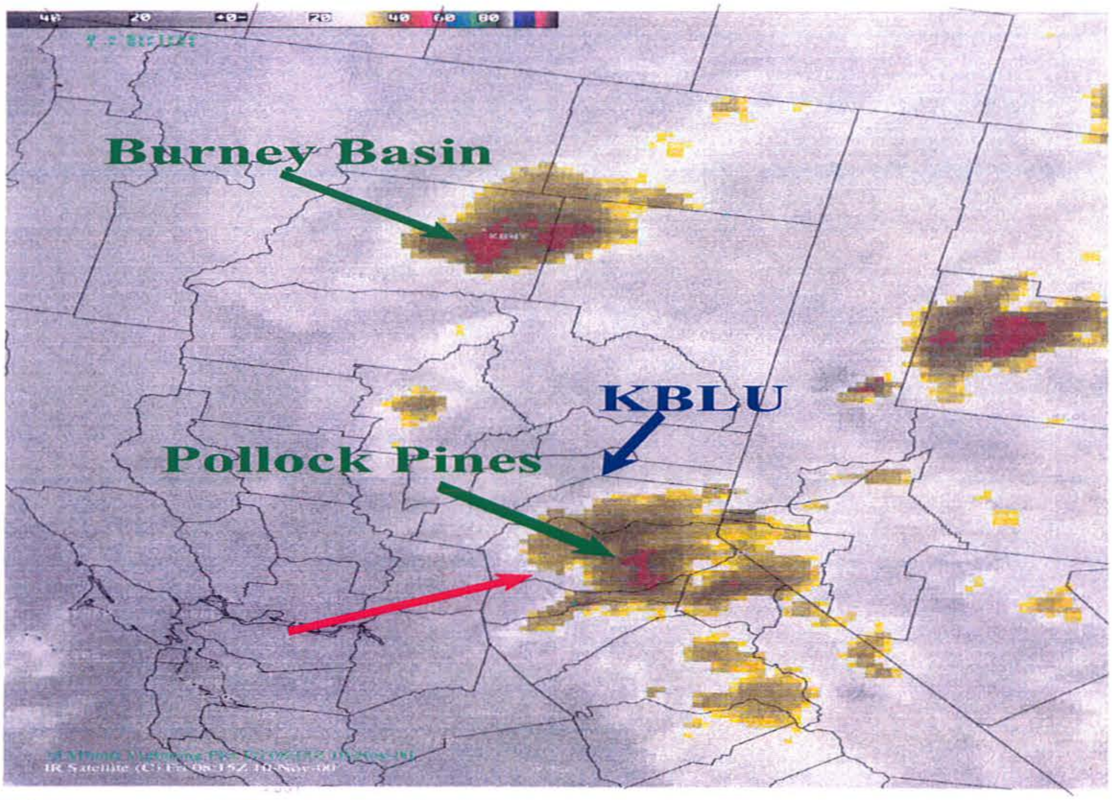


Figure 6. GOES-10 IR picture detected enhanced cold cloud tops (-40°C) at 0815 UTC. Cloud to ground lightning was still detected at the bottom arrow. One positive strike detected within 15 min (red arrow).

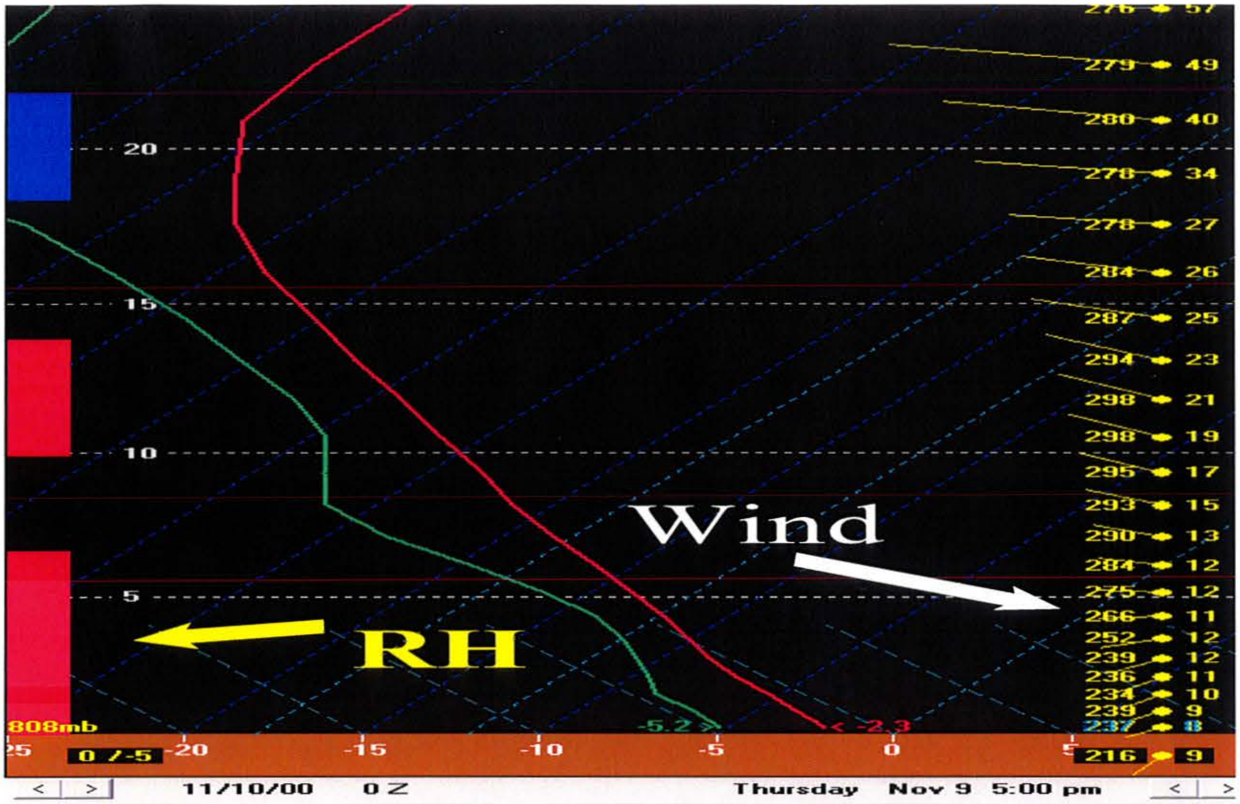


Figure 7. KBLU Eta analysis at 0000 UTC 10 November 2000 viewed in BUFKIT. Right side depicts the wind profile (kt) and the left scale is 1000's ft above ground level. Red layer is relative humidity (RH) greater than 70 percent.

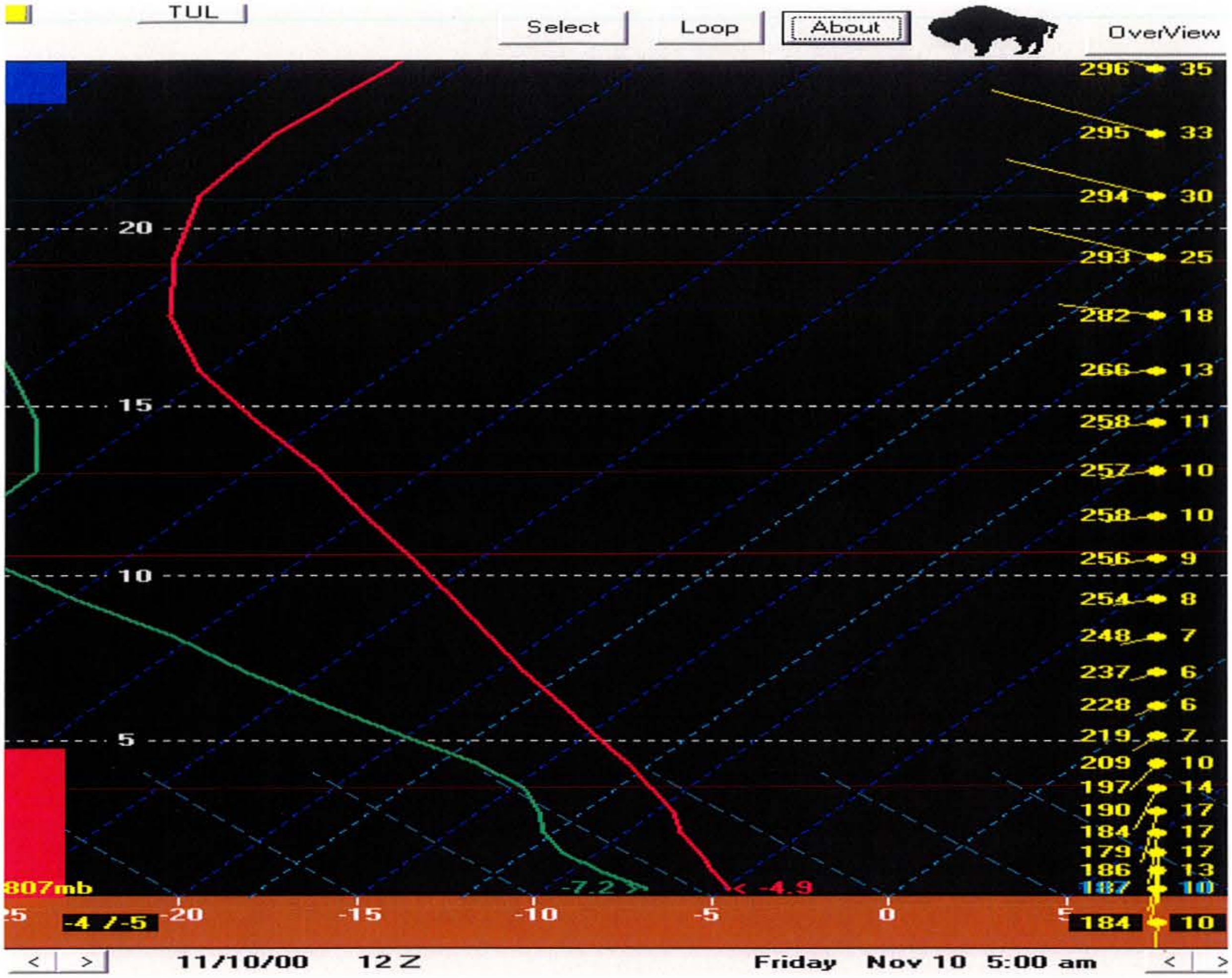
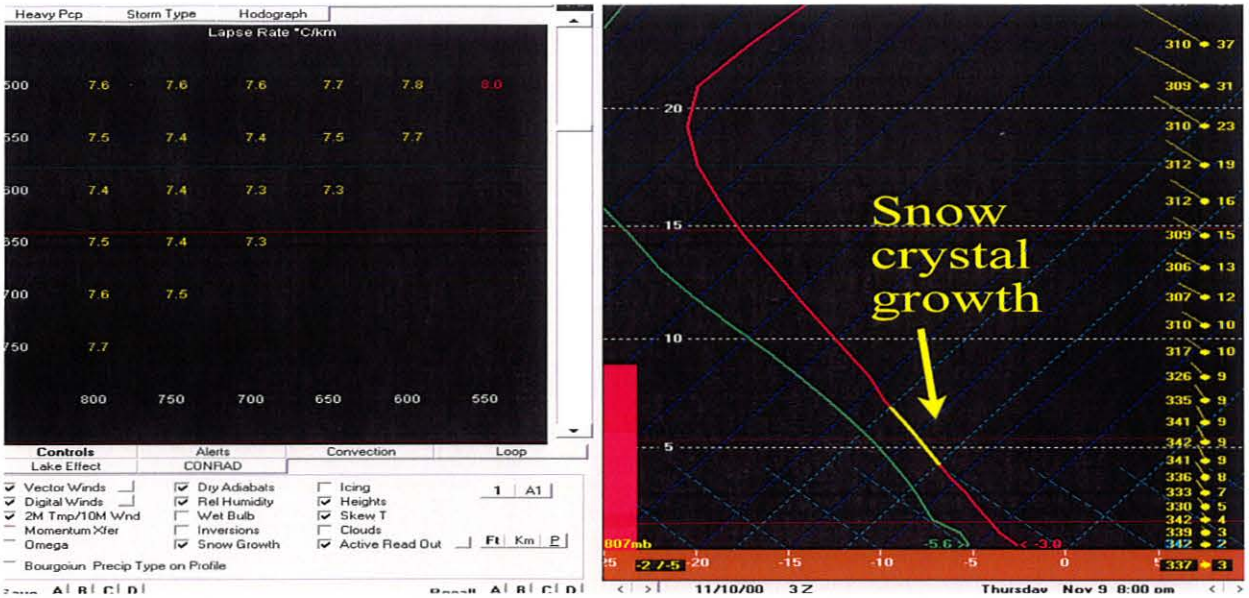


Figure 8. Eta analysis at 1200 UTC 10 November for KBLU. Units same as Fig. 7.

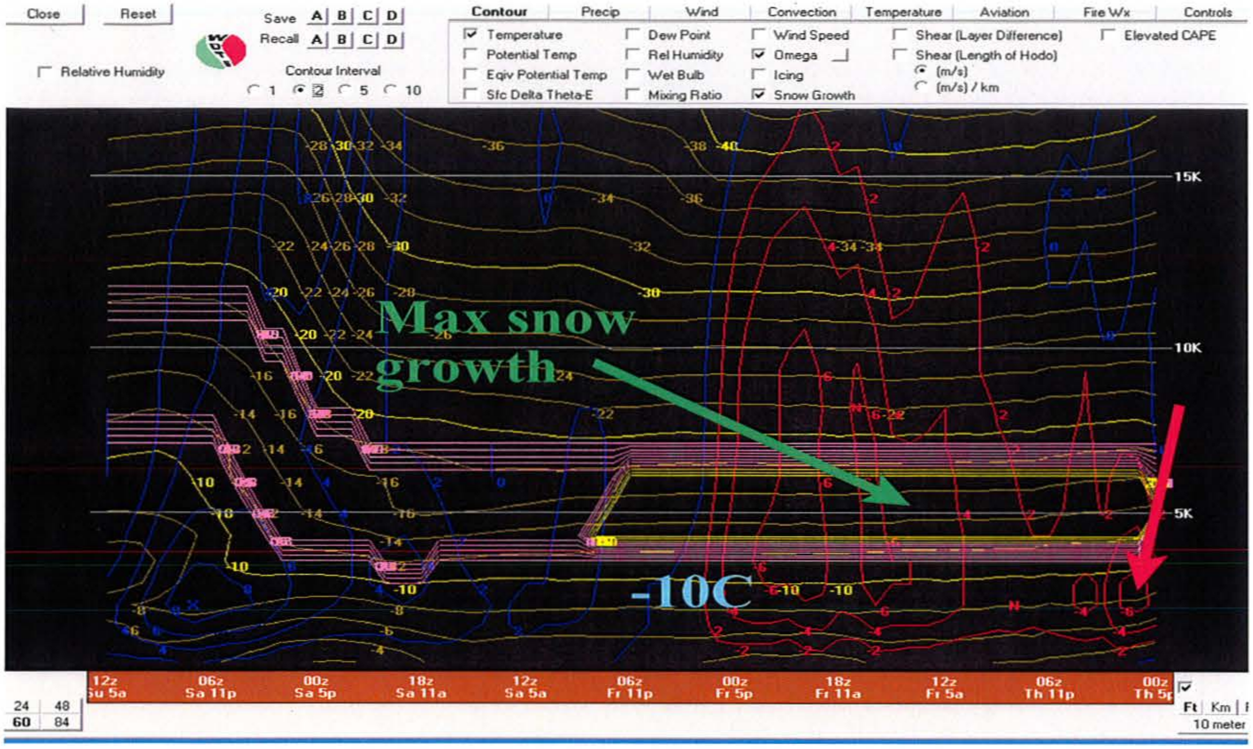


Lapse Rate °C/km

	800	750	700	650	600	550
500	7.6	7.6	7.6	7.7	7.8	8.0
550	7.5	7.4	7.4	7.5	7.7	
600	7.4	7.4	7.3	7.3		
650	7.5	7.4	7.3			
700	7.6	7.5				
750	7.7					

☑ Vector Winds
☑ Digital Winds
☑ 2M Tmp/10M Wnd
☐ Momentum Xfer
☐ Omega
☑ Dry Adiabats
☑ Rel Humidity
☐ Wet Bulb
☐ Inversions
☑ Snow Growth
☐ Icing
☑ Heights
☑ Skew T
☐ Clouds
☑ Active Read Out
☐ Bourgoiun Precip Type on Profile

Figure 9. Model forecast profile for KBLU at 0300 UTC 10 November from the 1200 UTC 9 November Eta run. Notice the steep lapse rates (near 8°Ckm^{-1}) on the profile and indicated on the left side of the display. The snow crystal growth potential was forecast to be maximized (yellow line on temperature profile). BUFKIT highlights in yellow areas on the temperature profile between -12 and -18°C when the relative humidity is greater than 75 percent. The wind forecast was poor when compared to Fig. 7.



☐ Relative Humidity

Contour Interval ○ 1 ● 2 ○ 5 ○ 10

☑ Temperature
☐ Potential Temp
☐ Eqiv Potential Temp
☐ Sfc Delta Theta-E
☐ Dew Point
☐ Rel Humidity
☐ Wet Bulb
☐ Mixing Ratio
☐ Wind Speed
☑ Omega
☐ Icing
☑ Snow Growth
☐ Shear (Layer Difference)
☐ Shear (Length of Hodo)
● (m/s)
○ (m/s) / km
☐ Elevated CAPE

Figure 10. Time-height section of the Eta 0000 UTC 10 November forecast at KBLU. Time increases from right to left (UTC). Yellow horizontal lines are temperatures (°C), red lines are omega (every 1 $\mu bars^{-1}$) and the yellow enclosed area is maximum snow crystal growth potential. Scale on the right is 1000's ft above ground level. The -10°C isotherm is labeled for reference. Red arrow points to maximum omega (6 $\mu bars^{-1}$).