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Forecasting Lee-Side Precipitation in the Central and Northern Sierra Nevada
Part I: Instability and Wind

Jim Wallmann and Rhett Milne
Weather Forecast Office Reno, NV

1. Introduction

Forecasting lee side precipitation (hereafter 'spillover') east of the Sierra Nevada due to land falling Pacific extratropical systems is a major forecast challenge. The difficulty lies in forecasting the 'rain shadow effect' where winds normal to a mountain range result in enhanced precipitation amounts on the windward side of the range with drastically reduced precipitation amounts on the leeward side. The Sierra Nevada mountain range in eastern California provides an excellent example of the rain shadow effect where precipitation on the windward slopes averages 50 to 75 inches per year. In contrast, the Reno metropolitan area, in the lee of the Sierra, only averages 7 to 14 inches per year. However, there are cases where the rain shadow effect is minimized and brief but heavy periods of precipitation occur in western Nevada. Forecasting if and when these bursts of spillover precipitation will occur is not well documented in the literature, or understood. While many papers mention that unstable conditions (high Froude number) result in a minimally blocked flow and flow over the mountain range, the focus is on the wind field and not precipitation spillover. Recently, Colle (2004) conducted a modeling study which illustrates how weaker stability will result in more precipitation spillover. Many studies focus on windward precipitation (Houze and Medina 2005, among others), but few focus on lee-side precipitation, although lee-side convergence has been well-documented (Ferber and Mass 1990). However, lee-side convergence does not function well in the immediate lee of a long but relatively narrow mountain range such as the Sierra Nevada. There are some studies that have looked at model quantitative precipitation forecasts across the Sierra (Galewsky and Sobel, 2005 and Grubišić et al, 2005, among others). While few studies have looked specifically at lee-side precipitation, most lee-side research has focused on high winds in the lee of major mountain barriers including the Sierra Nevada. For example, Milne (2003) conducted a climatology of downslope wind events in the lee of the Sierra Nevada.

With the lack of recent research on spillover precipitation, many forecasters have come up with their own conceptual models which may or may not be accurate for predicting spillover precipitation. A few of these conceptual models (taken from National Weather Service Forecast Discussions) include: 'South winds across the Sierra Nevada will limit the rain-shadow effect and result in more precipitation for Reno;' 'moisture depth will be sufficient for precipitation to spill over into western Nevada;' 'strong southwest winds will result in a strong rain shadow effect.' All these conceptual models obtained from Area Forecast Discussions may be based on the forecaster's experience and/or a lack of understanding of mountain waves and the dynamics required for precipitation to spill over the Sierra. However, these conceptual models do not explain spillover sufficiently as exceptions occur too often or these conceptual models are inherently flawed. In addition, if forecasters are inexperienced and/or do not feel confident in their understanding of mountain meteorology, they will often rely on model forecasts for spillover precipitation. Even mesoscale model forecasts are inconsistent with their depiction of spillover precipitation which may be either too dry or wet depending on the storm in question. For example, Colle and Mass (1999) show a distinct dry bias for lee side precipitation in the MM5 for the winter season in the Pacific Northwest during the late 1990s. More recently, many cases have been documented where the model forecasts have been too wet for the immediate lee of the mountains (Garvert et al 2005). In addition, it has been shown that model QPF skill is lower in the lee of the Sierra Nevada than on the windward side (Grubišić et al. 2005). Therefore, determining whether the model is accurately portraying spillover precipitation is called into question.

With all the difficulty in forecasting spillover, a relatively simple conceptual model for spillover precipitation, based on instability and wind speed and direction, will be presented in this paper. Section 2 will profile the ingredients important to spillover. Section 3 will describe some forecast tools that can be used to forecast spillover. Section 4 will briefly describe lee side precipitation events that are not well forecast by instability. Section 5 will present a summary and conclusion.

2. Meteorological Ingredients Important to Spillover

a) Stable profile with mountain-top inversion

Several studies have and continue to investigate winds in the lee of major mountain ranges including the Sierra Nevada (Milne 2003). Many of these studies have shown a stability profile (Fig. 1a) where the atmosphere is weakly to neutrally stable below mountain top level, topped by a layer of strong stability, such as an inversion, followed by weaker stability at higher levels. In Fig. 1a, the Reno sounding shows a well-mixed layer between the surface and 750 mb. Above this well-mixed layer is a very stable isothermal layer to 675 mb, followed by a much less stable layer from 675 mb through 300 mb. Colson (1954) showed that this stability profile was present for strong downslope winds in the lee of the Sierra Nevada. Interestingly, Locatelli et al (2005) show the development of this thermodynamic profile with a split cold front as it approaches the Washington and Oregon coasts (Locatelli et al Figure 1.) As the upper front passed through, it was associated with a wide cold-frontal rainband which is also observed in the northern and central Sierra Nevada. However, little if any precipitation from the wide cold-frontal rainband makes it into the lee-side valleys due to the stability profile. Though there is large-scale forcing present, the mountain waves dominate the lee-side valleys with high winds and rotor clouds often present. The mountain wave results in strong downward vertical motion which results in drying and a lack of precipitation. A radar reflectivity image in Figure 1b shows a typical precipitation distribution for precipitation shadowing in the lee of the Sierra typical of the sounding in Figure 1a.

b) Neutrally stable to unstable profile

A moist adiabatic temperature profile is shown in Fig. 2 with the corresponding radar reflectivity image. Here, moist parcels that ascend the Sierra Nevada continue to rise until they reach a stable layer above 500 mb, as the KREV sounding in Fig. 2a is neutrally stable for a moist environment. As these moist parcels continue to rise, hydrometeors will continue to be produced and fall out further downstream of the Sierra Crest. Therefore, precipitation will fall much further downstream of the Sierra Crest in this thermodynamic environment than in the environment described in Section 2a. It is important to note that the unstable profile should extend through a significant depth, observations suggest at least beyond 600 mb, for the instability method to work. A stable layer too close to mountain top level will result in parcels returning to the surface not far downstream from the Sierra Crest. In addition, the resulting adiabatic warming and drying will limit precipitation. The instability mechanism alone is often not enough for significant precipitation to reach the lee-side valleys of western Nevada. Therefore, relying on only upslope triggering alone is often not sufficient to explain the large amounts of precipitation that can fall in the lee-side valleys during some storms. However, with sufficient dynamics precipitation rates in the lee side valleys can approach those in the higher elevations of the Sierra. In Western Region Technical Attachment 07-02, Milne and Wallmann (2007) describe how the narrow cold-frontal rain band can be used to trace when spillover will occur. It is often along this band that the most extensive lee-side precipitation occurs, and it is a region of strong low-level frontogenesis.

c) Wind direction

Wind direction also plays a significant role in the amount of spillover into the lee-side valleys. While wind direction alone will not determine whether or not spillover will occur, it does dictate the amounts and which locations are most favored to receive the greatest amounts of precipitation. To illustrate the idea, two cases were analyzed which where both warm and wet systems with high snow levels. The first is the New' Year's Eve flood of 2005, and the second is a similar event from February 28, 2006. For ease of illustration, both events showcased a 24 hour period of near moist adiabatic and saturated thermodynamic profiles (not shown).

In the 2005 case, a strong jet stream was pointed at the Sierra (Fig. 3a) with strong 700 mb west to southwest winds, approximately at 250 degrees (Fig. 3c). This wind direction is ideal for orographically forced precipitation in the Sierra as it is almost exactly normal to the Sierra Crest. The 2005 precipitation shield extended a large distance from the Sierra Crest during the peak of the event. Early in the event, the precipitation shield extended through the Reno area, but not much beyond (Fig. 3b). During the peak of the event, the precipitation extended even further downstream across much of western Nevada (Fig. 3d).

For the 2006 case, the wind direction was more southerly between 180 and 200 degrees (Fig 4a and c). While orographic forcing in this situation was sufficient to produce some heavy rain on the windward slopes, the forcing was not as strong as it would have been with a more normal wind direction. The resulting precipitation shield is not as widespread both initially, and later on in the event (Fig. 4b and d). In addition, the precipitation does not extend as far to the east of the Sierra Crest as in the 2005 case. Table 1 shows the precipitation amounts from these cases, as well as spillover duration and precipitation totals for KBLU (Nyack, CA) and KRNO (Reno, NV) for ten additional spillover events.

Analyzing Table 1 for the 2005 and 2006 cases, it is apparent that a more normal wind direction is favorable for spillover precipitation into the lee side valleys. The likely reasons for this are two-fold: 1) the orographic lift for a normal wind direction is stronger which propagates downstream in an unstable environment and; 2) the lee-side valleys are effectively further downstream from the Sierra Crest when the wind direction is not normal to the crest. Figure 5 shows the location of Reno relative to the crest for a 180 and 250 degree wind direction. Notice that the distance between Reno and the Sierra Crest is 50 km for a 250 degree wind, but 112 km for a 180 degree wind. When the atmosphere is only weakly stable, instead of unstable, the south wind direction may end up putting Reno in an area of downward motion from mountain wave development.

d) Wind speed

Wind speed is a factor in the extent of spillover precipitation, with stronger winds favoring more spillover into the lee side valleys through further downstream advection of the hydrometeors. The wind speed is more important when the atmosphere is slightly stable versus unstable. Given the same wind speed, hydrometeors will fall further downstream in a more unstable airmass. Lighter winds will result in the hydrometeors falling closer to the crest of the Sierra as they fall, while a stronger wind will push the same hydrometeors further downstream, assuming all other factors, including fall speed, remain the same. An excellent description of how wind speed modulates the extent of spillover in a slightly stable environment with no forcing can be found in the idealized modeling study done by Colle (2004).

e) Precipitation rates associated with spillover

It was mentioned earlier that in some cases precipitation rates in the Reno-Carson City area can approach those seen on the west slope of the Sierra. Table 1 shows a comparison of precipitation totals during the spillover period for twelve different events. An average precipitation rate during spillover is shown at the bottom of the table and illustrates that, on average, precipitation rates in Reno (KRNO) are about one-third those seen at Blue Canyon/Nyack Airport (KBLU), or a 3 to 1 ratio from KBLU to KRNO. This is in contrast to the average yearly precipitation ratio of 10 to 1 between KBLU and KRNO (70 inches to 7+ inches). If the forecaster is confident spillover will occur, and also confident in the model QPF forecast for KBLU, the 3 to 1 ratio can be used as a first guess for KRNO. Alternately, the 0.06 inch/hr average rate for Reno during a spillover event can be used as a first guess.

Investigating precipitation rates further, it is apparent that there is a range of ratios that occur (Table 1). Some events, such as the 30-31 Dec 2004 Reno snow storm (Table 2), had a smaller KBLU-KRNO precipitation ratio. Others, such as the 18 Oct 2004 (Table 3) and 1 Dec 2005 events will have larger ratios. Events that are colder with lower snow levels have smaller KBLU-KRNO ratios while the warmer events with higher snow levels have larger ratios. The microphysical processes described in both Colle (2004) and Garvert et al (2005) describe the difference in ratio between warm and cold events. The main difference being warm rain processes dominate warm events with more precipitation falling out on the west slopes. In addition, raindrops have higher terminal velocities than snowflakes. This permits snowflakes to travel further downstream than raindrops if the wind speeds were to remain the same.

3. Tools to assess instability for spillover precipitation

c) Model forecast soundings

Model forecast soundings are one useful tool to assess the potential for spillover into the lee side valleys. As in Section 2b, the profile to look for is one that is nearly moist adiabatic and near saturation, especially near and just above mountain top level. An illustration of what to look for is shown in Figure 6. On the upper left hand side, the 18 hour NAM forecast sounding (Fig. 6a) shows a sounding typical of downslope winds in the lee of the Sierra Nevada. This sounding is dry and stable in the mid levels. The corresponding KRGX reflectivity (Fig. 6b) shows significant shadowing of the precipitation not far downstream of the Sierra Crest. However, nine hours later, on the 27 hr NAM forecast sounding (Fig. 6c), the temperature profile is nearly moist adiabatic from the surface through 500 mb. This profile is much more favorable for spillover. Fig 6d shows precipitation extending well downstream of the Sierra Crest with the neutrally stable profile.

b) Time-heights

Another useful tool to assess instability is a time-height of contoured saturated equivalent potential temperature (θ_e*) and relative humidity for a particular location. An example is shown for Reno, NV in Figure 7 using the Eta40 model initialized at 12 UTC 17 Oct 2004. At the initial time (far right), there is some shallow moisture and instability present below 700 mb, but this shallow layer is capped by a more stable layer between 700 and 600 mb. This profile is unfavorable for spillover, and for comparison, the 12 UTC KREV upper air observation is shown in Figure 8a. The 12 UTC KREV temperature profile is very similar to the blocked sounding depicted in Figure 1. As the time-height progresses, however, this stable layer gradually weakens and by 00 UTC it has diminished as evidenced by the KREV sounding (Fig. 8b). While precipitation is only very light in Reno at the time (Fig. 9), a band of moderate rainfall is beginning to pass over the crest near Susanville, CA (KSVE). Between 00 UTC and approximately 06 UTC, the θ_e* contours become nearly vertical indicating a near moist-adiabatic profile that extends through 600 mb, to approximately 550 mb. The heaviest rainfall occurred during this time.

c) Cross-sections

Cross-sections are another useful tool to diagnose instability and can be constructed using ideas based on conditional symmetric instability from Schultz and Schumacher (1999). As described in Schultz and Schumacher, the cross-section is taken normal to the thermal wind in a layer where CSI may be present. A cross section near the Sierra is displayed in Fig. 10 and shows saturated equivalent potential temperature (θ_{es}) along with an image of the saturated geostophic equivalent potential vorticity (MPV*) where negative values of MPV* are shaded. In a neighboring panel, an image of relative humidity is shown with values close to saturation shaded. (For a complete description of a method to diagnose CSI and straight conditional instability, see Schultz and Schumacher.)

When using the cross-sections, the first step is to look for instability, which is shown by the shaded regions of MPV* (Fig. 10a – the arrow depicts Reno). The cross-section extends from near Mt. Shasta City, CA south and east to Tonopah, NV. The type of instability can be discerned from the contours. For example, the 312 K isentrope slopes to the right, then folds back on itself to the left hand side of the image, indicating an area of conditional instability. Contrast this with the 324 K isentrope, which is in the shaded region near 500 mb and shows an area of CSI. Spillover will occur with conditional instability or CSI provided the condition of saturation is met. The right panel (Fig. 10b) shows the relative humidity shaded greater than 80% which would meet the condition of saturation. Humidity is greater than 80% across much of the path of the 312 K isentrope, satisfying the condition. However, in the area of CSI along the 324 K isentrope, the atmosphere is not near saturation and the instability will not be released. At this point, spillover is likely to occur to the northwest of Reno based on the presence of conditional instability in a moist environment. It is important to note that as described in Schultz and Schumacher and Section 2, the instability alone is not sufficient for spillover. A lifting mechanism such as low-level frontogenesis or upper level divergence must be present to release the instability (not shown). Three hours later (Figs. 10c and 10d), a large area of instability is present over Reno with spillover precipitation likely.

Cross-sections are a useful supplement to forecast soundings since forecast soundings only reveal the thermodynamic environment at a point. The cross-sections mentioned in the above section will show parts of the thermodynamic environment in two-dimensions. There are two benefits to these two-dimensional images: 1) CSI can be diagnosed in the cross-sections, but not on forecast soundings; 2) the cross-sections can help the forecaster locate points where forecast soundings will be most affected by the degree of conditional instability.

4. Lee side precipitation events where instability has limited use

a) Strong warm air advection

While the instability method works well for the majority of lee-side precipitation events, there are small subsets that are not captured well by using instability alone. The first is strong warm air advection where the atmospheric profile is stable at all levels. One example of this type of event is shown in Figure 11 where significant snowfall fell across much of Western Nevada on November 27, 2004 (Fischer et al 2005). Snowfall began across Reno around 1130 UTC, and the Eta12 forecast sounding for 12 UTC NOV 27 shows a stable profile near and below mountain top level (Fig. 11a). A few hours later at 15 UTC, widespread snow was falling across Western Nevada (Fig. 11b).

A potential explanation for the spillover in warm air advection events lies in the fact that the low-level airmass remains very stable and resistant to vertical motion. The extreme stability limits the vertical development of the low-level mountain wave and on the lee side; any air from the mountain wave has difficulty penetrating the valley. The isentropic lift from the synoptic scale motion is then dominant and light rain and/or snow will fall in the lee.

b) 'Inside sliders'

Inside sliders are different in the fact that they have a north to south trajectory and pass over or just to the east of the Sierra Crest (Figure 12). The low-level winds with inside sliders are generally out of the north to northeast which places the Reno area on the windward side of the Sierra. As a result, using lee-side precipitation ideas to forecast an event on the windward side is not valid. Instability remains important with inside sliders (Wallmann, 2006), but it is more useful to use instability to forecast precipitation rates rather than the determination between a precipitation/no precipitation forecast. More detail describing the dynamics of inside sliders can be found in Wallmann, 2006.

5. Summary

Forecasting precipitation in the lee of the Sierra Nevada can be improved by focusing on the stability of the air mass and wind direction and speed. If the atmosphere is unstable, precipitation is more likely to occur assuming there is a lifting mechanism present to release the instability. Wind direction also plays a role, with winds more normal to the Sierra Nevada favoring greater spillover into the lee side valleys. Wind speed influences spillover in weakly stable environments, where stronger winds will promote more distant spillover. Using instability to forecast in this matter will help forecasters improve on the models, which have more difficulty forecasting precipitation on the lee side than the windward side (Grubisic et al 2005).

This study primarily looked at spillover due to instability and wind from an observational perspective. In the future, it would be helpful to look at spillover from a modeling perspective to analyze the sensitivity to the type of lifting mechanism. Those studies could also investigate the sensitivity of spillover to the location of the low-level front, jet streaks, latent heat release, etc.

6. References

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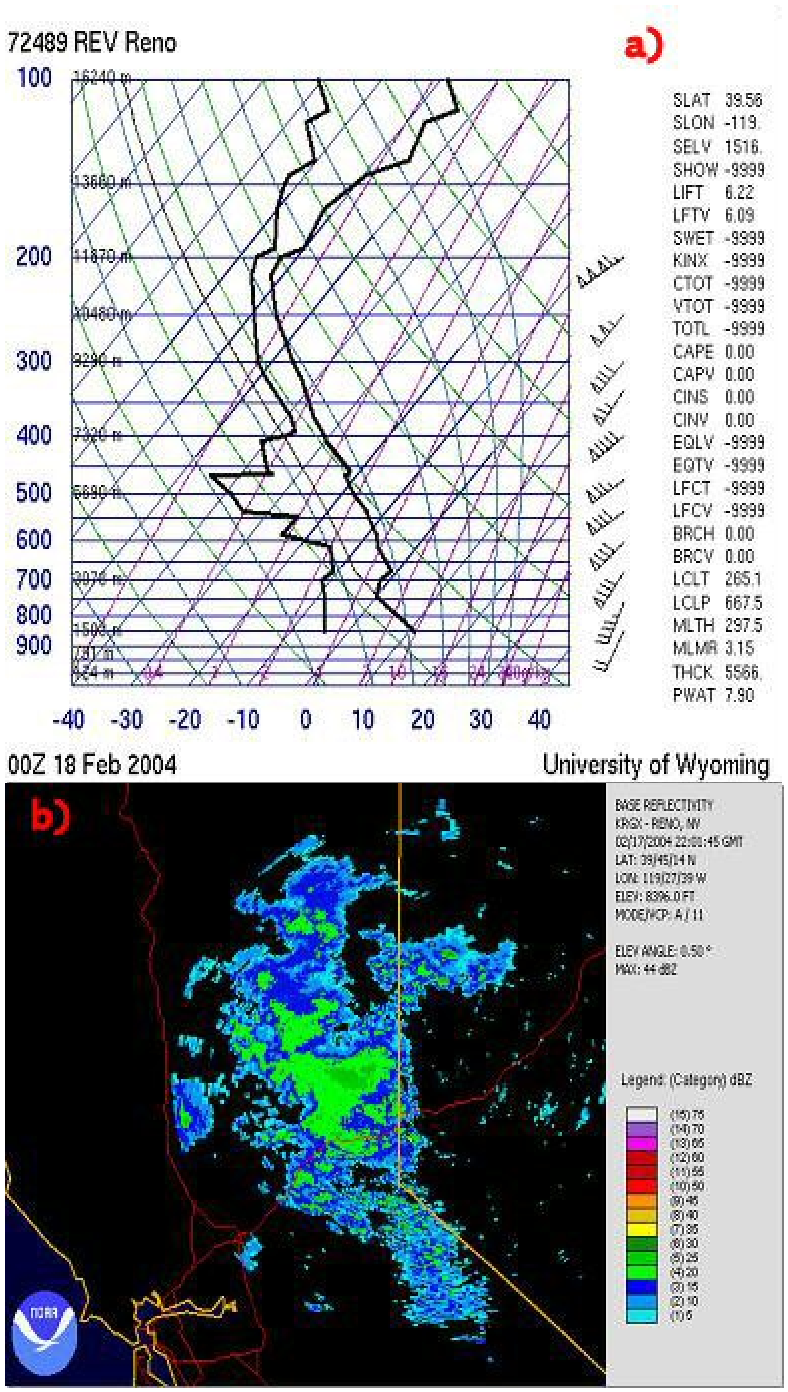

Figure 1. 18 Feb 2004 00 UTC KREV upper air observation (top – courtesy University of Wyoming), and 22 UTC KRGX 0.5 degree reflectivity (bottom). The east slopes of the Sierra Nevada are approximately around the California-Nevada border.

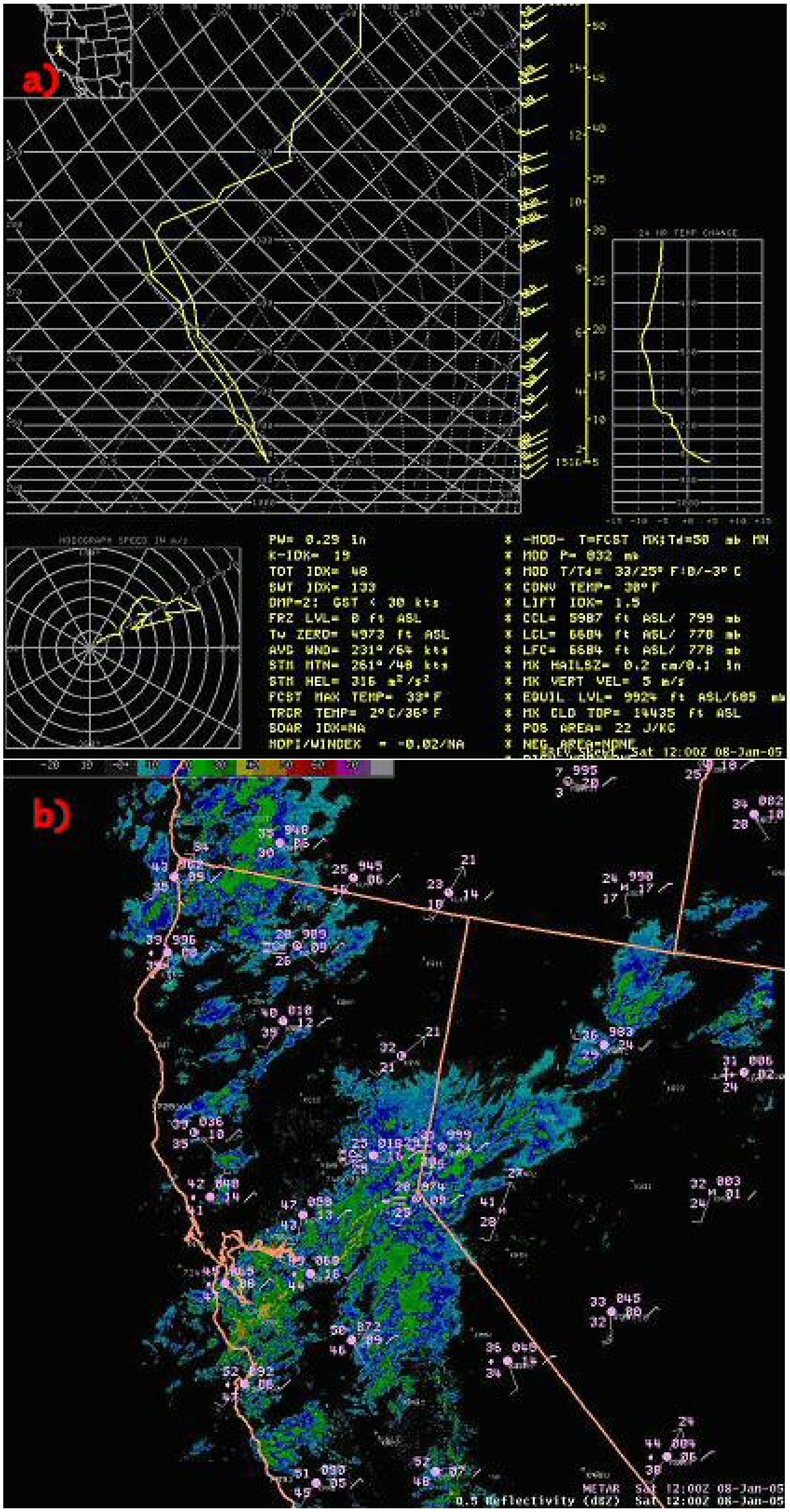

Figure 2. 08 Jan 2005 12 UTC KREV upper air observation (top), and 08 Jan 2005 12 UTC Sierra Nevada 0.5 degree reflectivity mosaic (bottom).

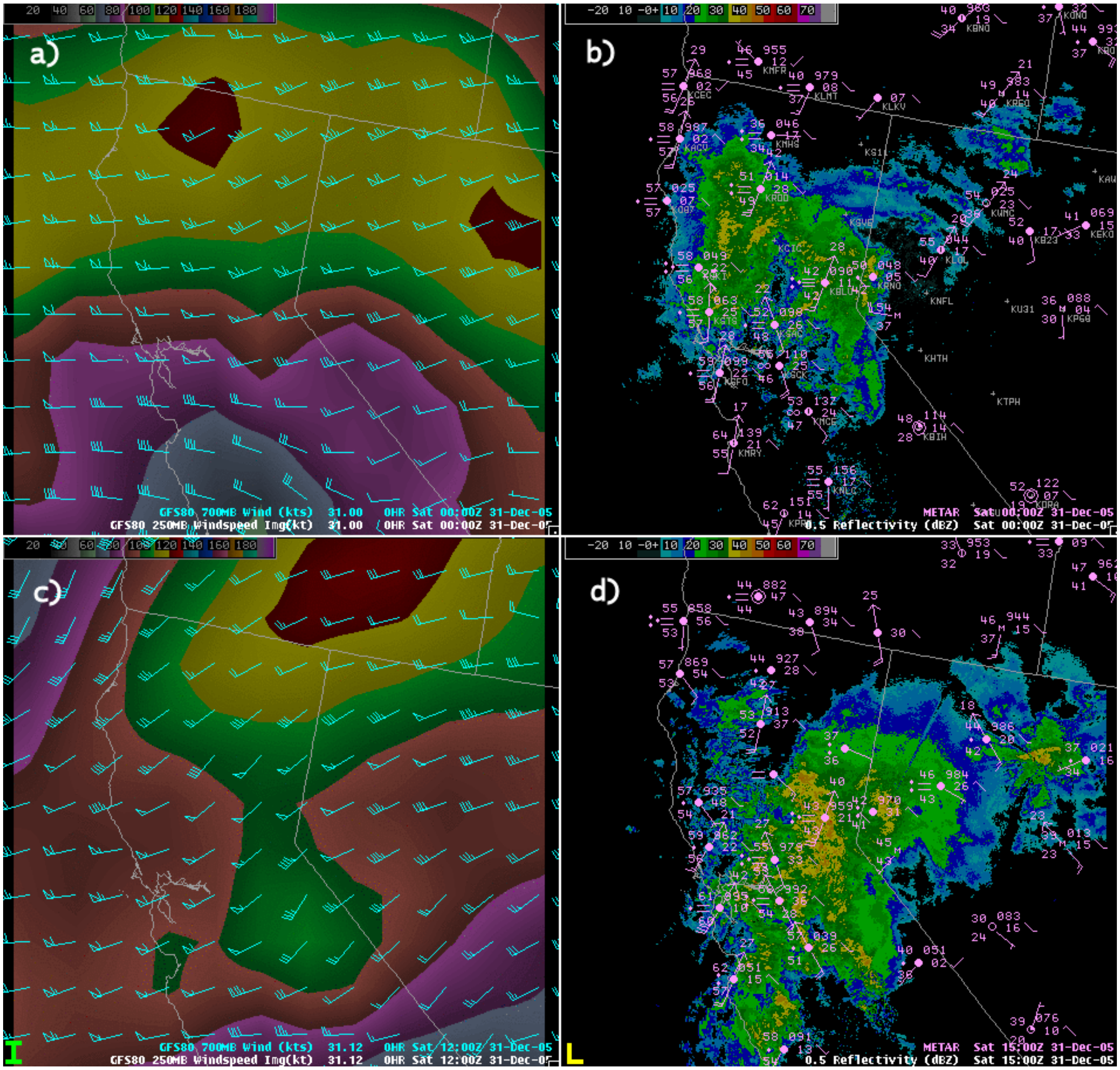

Figure 3. a) GFS analysis of 250 mb wind speed (shaded every 10 kts for with green shading indicating values between 100 and 110 kts) and 700 mb winds (barbs in kts) for 00 UTC 31 Dec 2005. b) 0.5 degree California-Nevada reflectivity mosaic and METAR plot at 00 UTC 31 Dec. c) Same as a) except the 12 UTC analysis. d) same as b) except at 15 UTC.

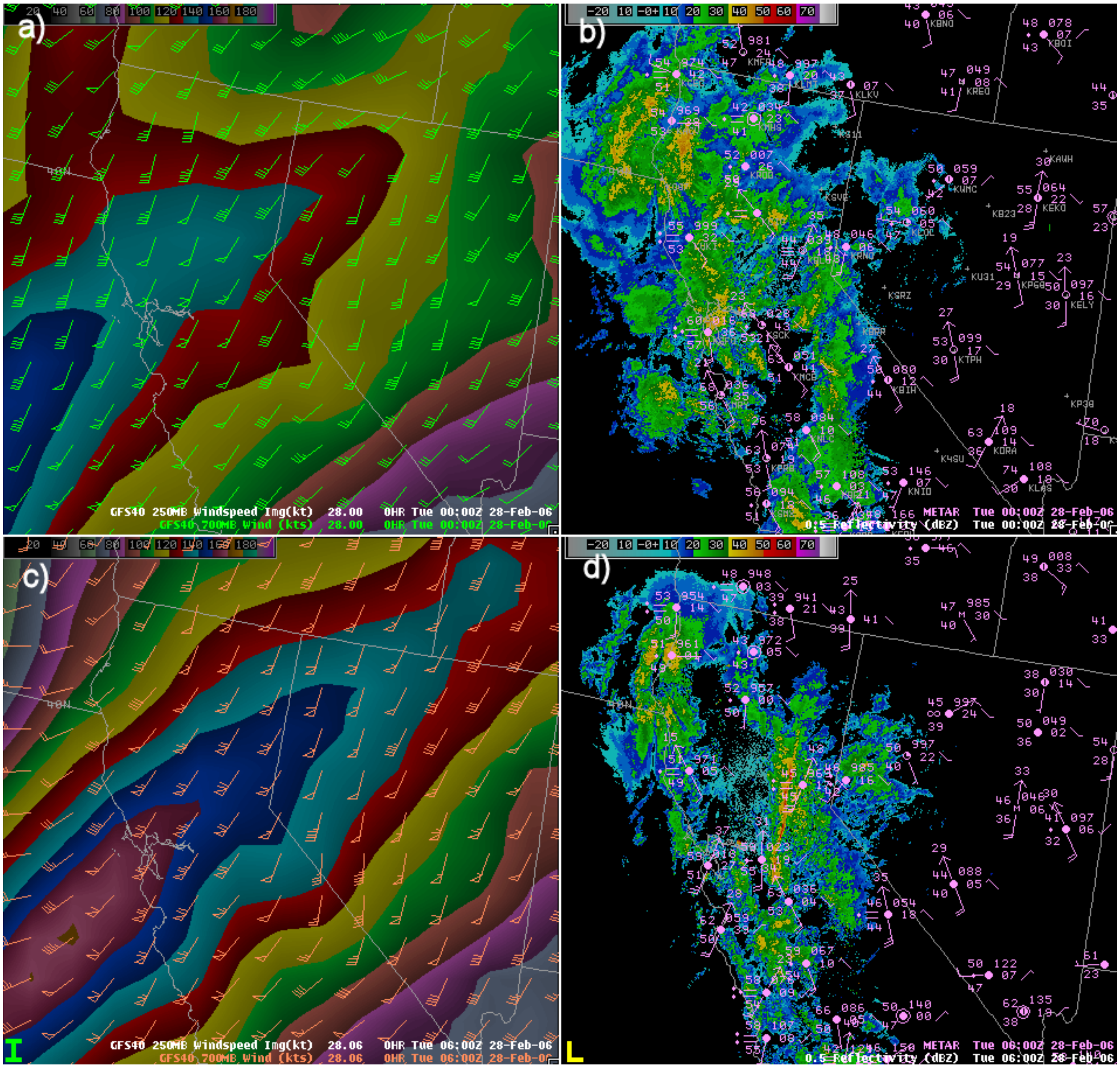

Figure 4. a) GFS analysis of 250 mb wind speed (shaded every 10 kts for with green shading indicating values between 100 and 110 kts) and 700 mb winds (barbs in kts) for 00 UTC 28 Feb 2005. b) 0.5 degree California-Nevada reflectivity mosaic and METAR plot at 00 UTC 28 Feb. c) Same as a) except the 06 UTC analysis. d) same as b) except at 06 UTC.

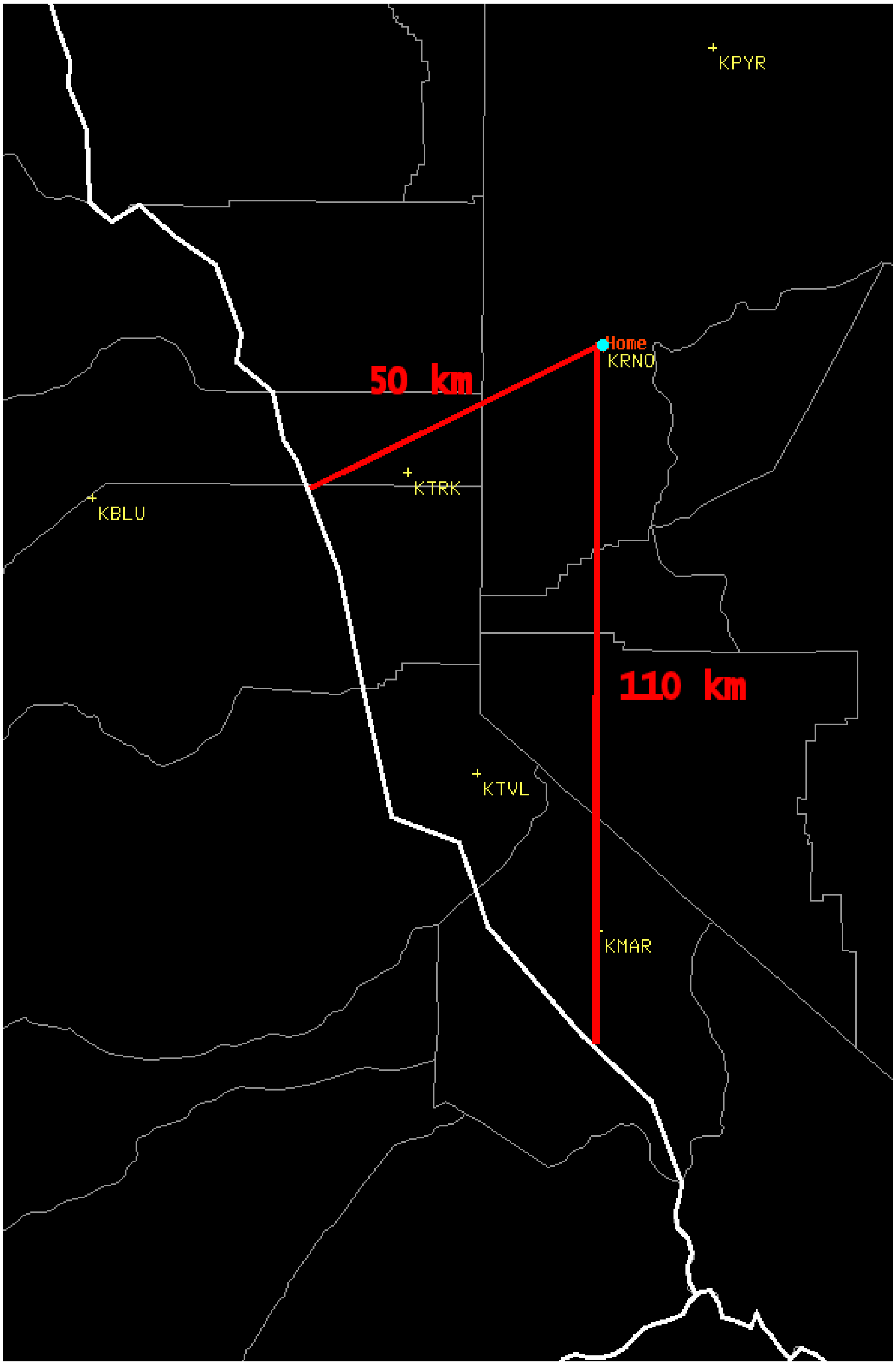

Figure 5. Diagram showing the distance from the Reno Airport (blue dot, KRNO) to the Sierra Crest for a 250 and 180 degree wind. The top distance is for the 250 degree wind and the bottom is for the 180 degree wind.

Date	Duration	Type	Wind Dir.	KBLU Total	KBLU Rate	KRNO Total	KRNO Rate	Ratio
4-13-2003	6	C	WSW	0.74”	0.12”/hr	0.42”	0.07”/hr	1.75:1
12-14-03	4	C	WSW	0.53”	0.13”/hr	0.42”	0.11”/hr	1.26:1
2-2-2004	2	C	SSW	0.24”	0.12”/hr	0.09”	0.05”/hr	2.67:1
10-18-04	4	W	WSW	0.73”	0.18”/hr	0.17”	0.04”/hr	4.29:1
10-19-04	6	H	WSW	0.91”	0.15”/hr	0.43”	0.07”/hr	2.12:1
10-20-04	9	C	WSW	0.73”	0.08”/hr	0.51”	0.06”/hr	1.43:1
12-30-04	12	C	WSW	0.74”	0.06”/hr	0.42”	0.035”/hr	1.75:1
12-31-04	15	C	WSW	1.62”	0.11”/hr	1.05”	0.07”/hr	1.52:1
1-8-2005	8	C	WSW	0.35”	0.04”/hr	0.39”	0.05”/hr	1:1.14
12-1-05	4	W	WSW	1.44”	0.36”/hr	0.37”	0.09”/hr	3.89:1
12-30/31-2005	23	W	WSW	6.76”	0.29”/hr	1.68”	0.07”/hr	4.02:1
2-26/27-2006	30	W	SSW	3.71”	0.12”/hr	0.69”	0.02”/hr	5.38:1
Average Rate					**0.153”/hr**		**0.055”/hr**	**2.78:1**
Cold Events					**0.098”/hr**		**0.062”/hr**	**1.57:1**
Warm Events					**0.202”/hr**		**0.050”/hr**	**4:1**

Table 1. Table showing the comparison of precipitation amounts and average hourly precipitation rates during spillover events for KBLU (Blue Canyon/Nyack, CA) and KRNO (Reno, NV). For type of event, ‘C’ is a cold event with snow level below 6000 feet, ‘H’ is a hybrid event with snow level between 6000 and 7000 feet, and ‘W’ is a warm event with snow level above 7000 feet. The predominant 700 mb wind direction during the unstable portion of the event is also shown, either WSW or SSW.

Hour	KBLU	KRNO
0000	0.04	0.04
0100	0.06	0.05
0200	0.09	0.04
0300	0.09	0.03
0400	0.11	0.10
0500	0.11	0.11
0600	0.15	0.13
0700	0.10	0.12
0800	0.14	0.09
0900	0.17	0.08
1000	0.07	0.05
1100	0.10	0.02
1200	0.03	0.03
1300	0.18	0.09
1400	0.18	0.08
TOTAL	1.62”	1.05”
Avg. Hourly	0.11”	0.07”

Table 2. Table showing the comparison of precipitation amounts and hourly precipitation rates during the 30-31 Dec. 2004 snowstorm. Table is observations ending at 00 UTC through 14 UTC 31 Dec during the unstable portion of the event. This is an example from a “cold” event with strong 700 mb west to southwest winds.

Hour	KBLU	KRNO
0100	0.35	0.01
0200	0.35	0.07
0300	0.03	0.07
0400	0	0.02
TOTAL	0.73”	0.17”
Avg. Hourly	0.18” (0.24”)	0.04”

Table 3. Table showing the comparison of precipitation amounts and hourly precipitation rates during the 17 Oct. 2004 spillover event. Table is observations ending at 01 UTC through 04 UTC 18 Oct during the unstable portion of the event. This is also an example of a “warm” event with strong west to southwest 700 mb winds.

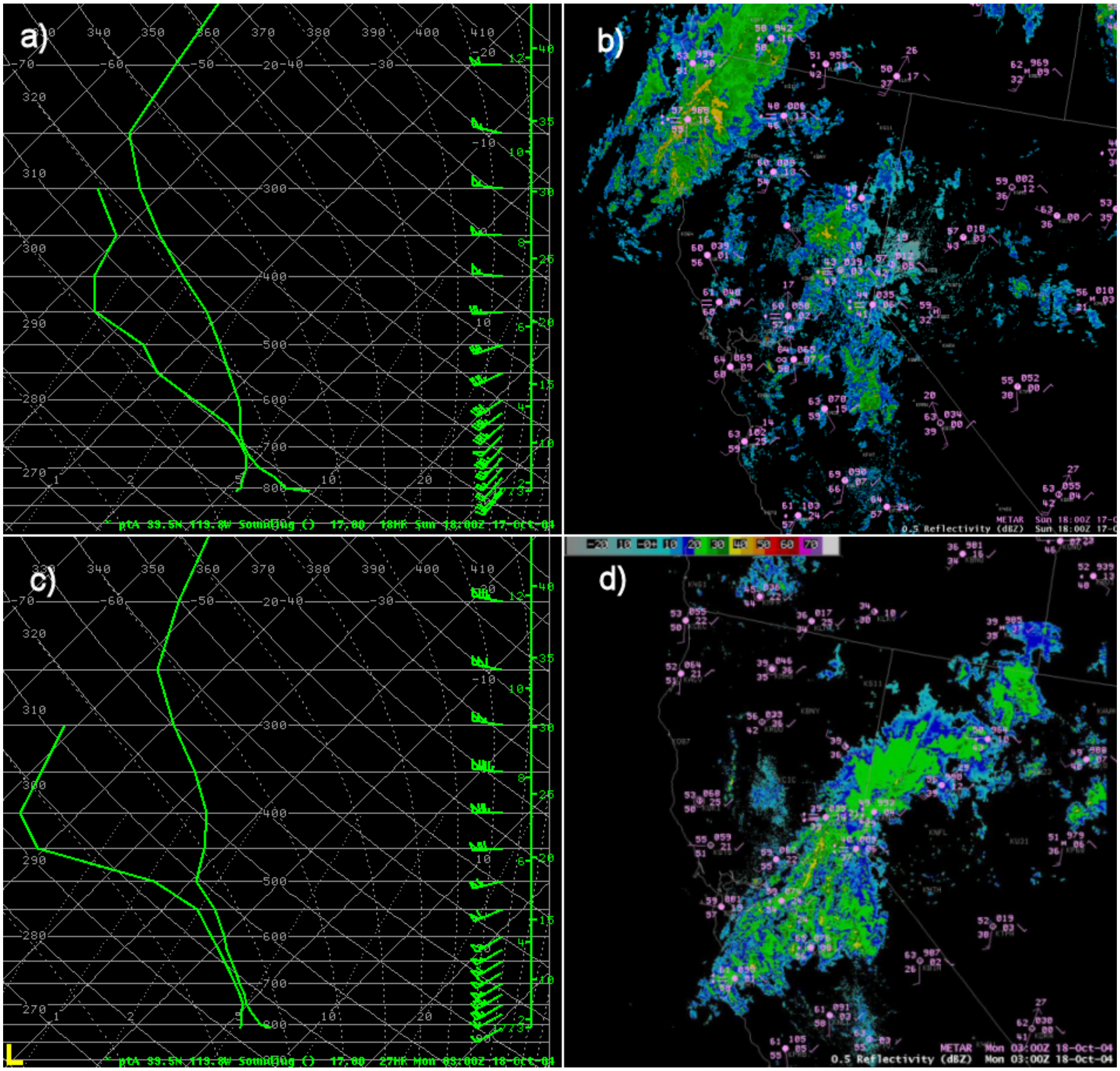

Figure 6. 00 UTC 17 OCT 2004 Eta40 forecast sounding for KREV valid at (a) 18 hrs (18 UTC 17 OCT) and (c) 27 hrs (03 UTC 18 OCT). Sierra Nevada Reflectivity composite for 18 UTC 17 OCT (b) and 03 UTC 18 OCT (d).

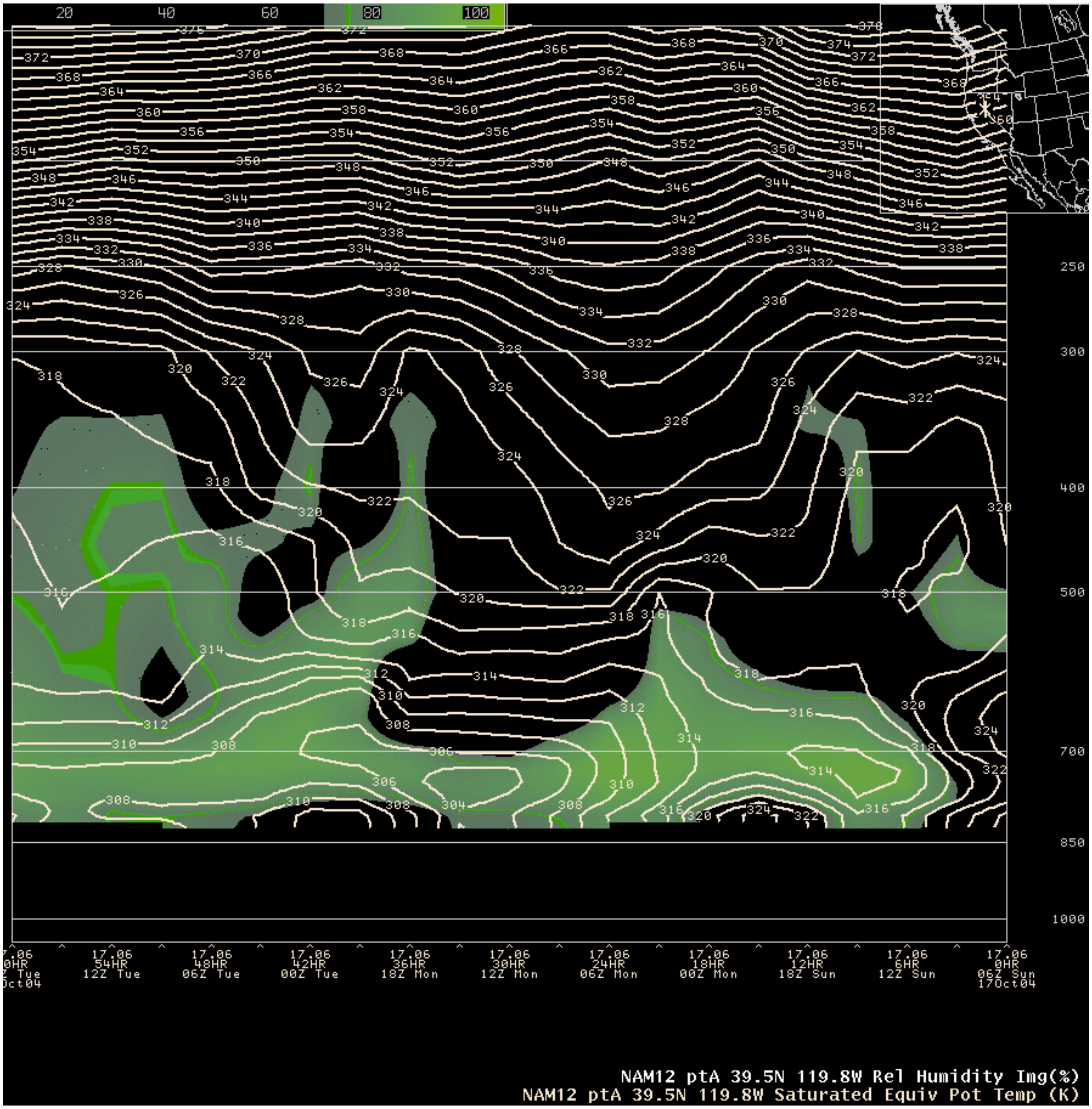

Figure 7. 06 UTC 17 Oct 2004 Eta12 forecast time-height for KREV. Beige contours are θ_e* and relative humidity greater than 70% is shaded.

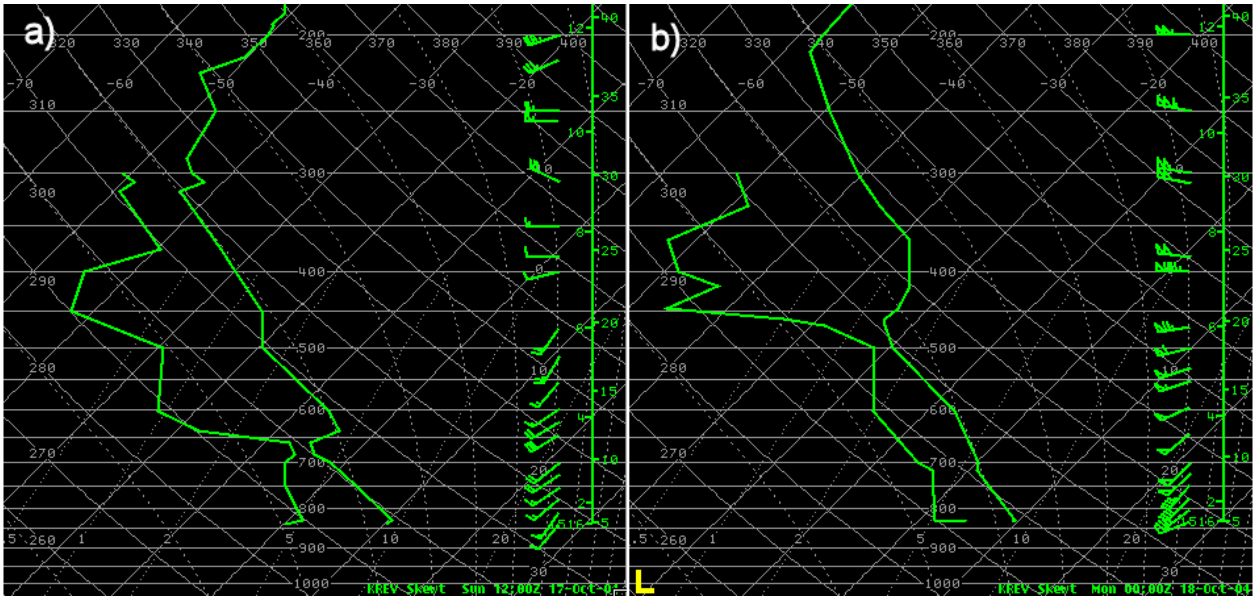

Figure 8. 12 UTC 17 OCT 2004 KREV upper air observation (a) and 00 UTC (b).

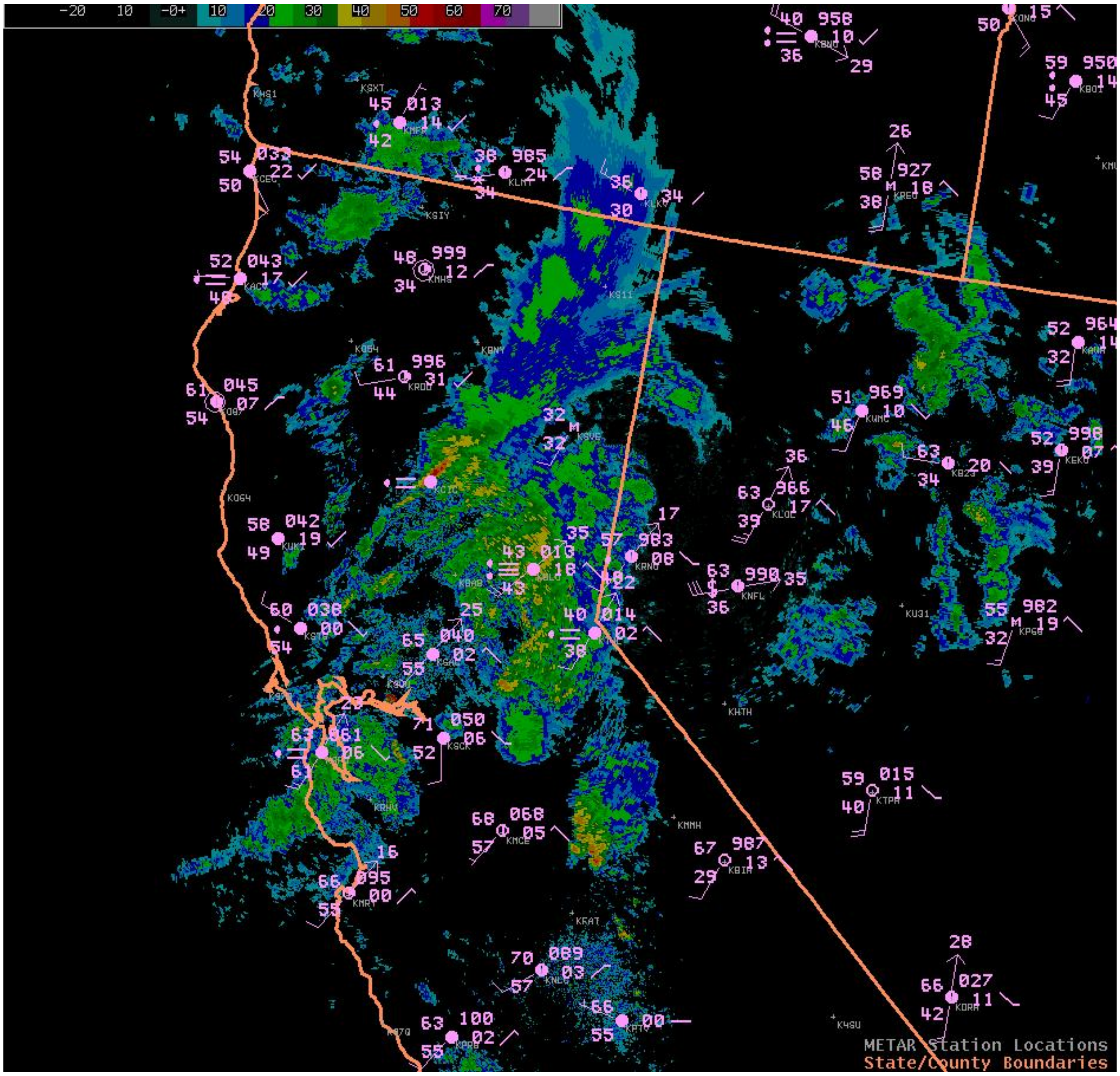

Figure 9. 00 UTC 18 Oct 2004 0.5 degree Sierra Nevada reflectivity mosaic with plotted METAR observations.

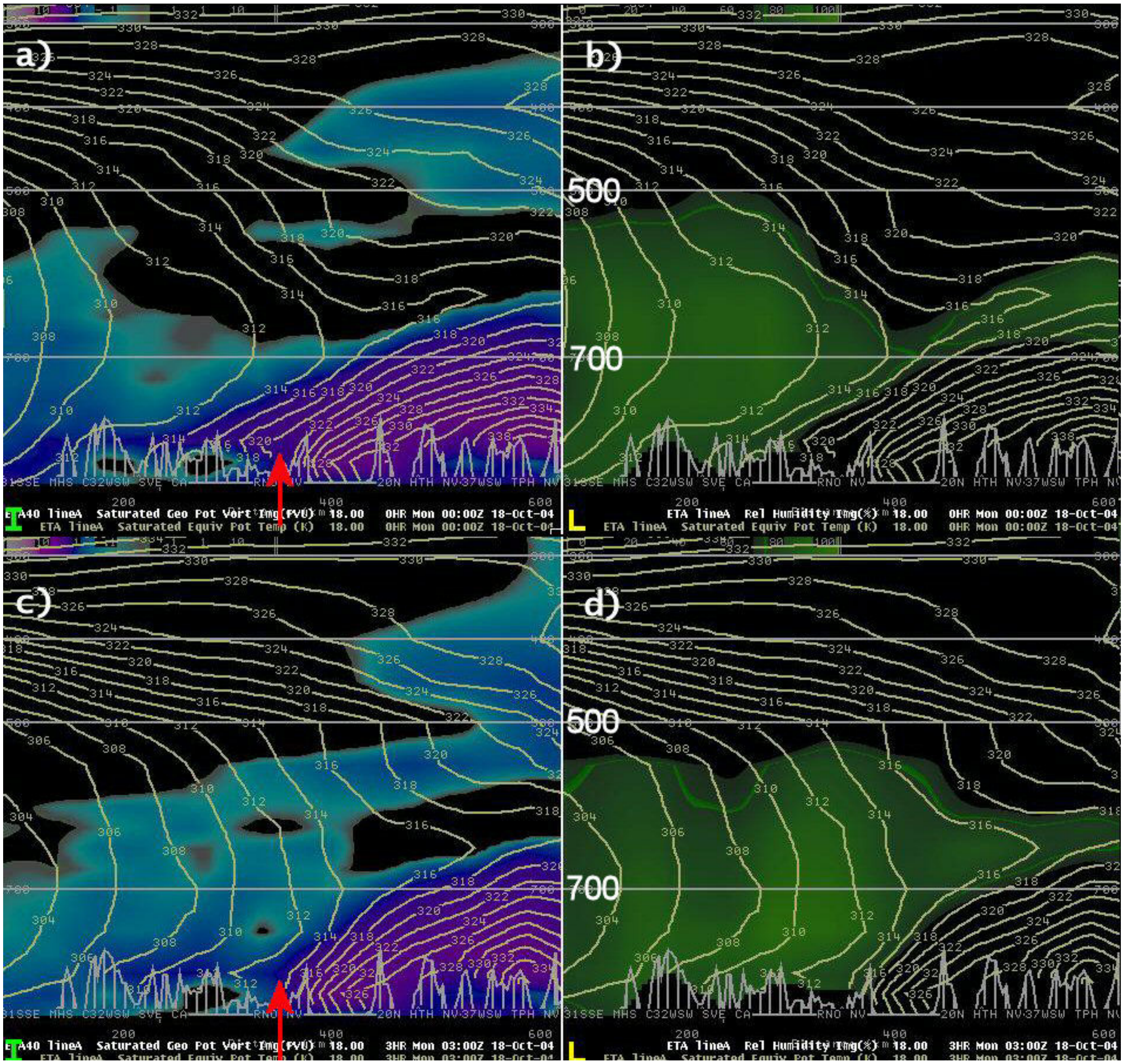

Figure 10. Eta40 cross section of theta, MPV*g *(shaded (a and c) values less than 0 PVU), and relative humidity (shaded (b and d) greater than 70%). 00 UTC 18 Oct 2004 analysis (top, a and b) and 3-hr forecast (bottom, b and d). Red arrow depicts Reno.

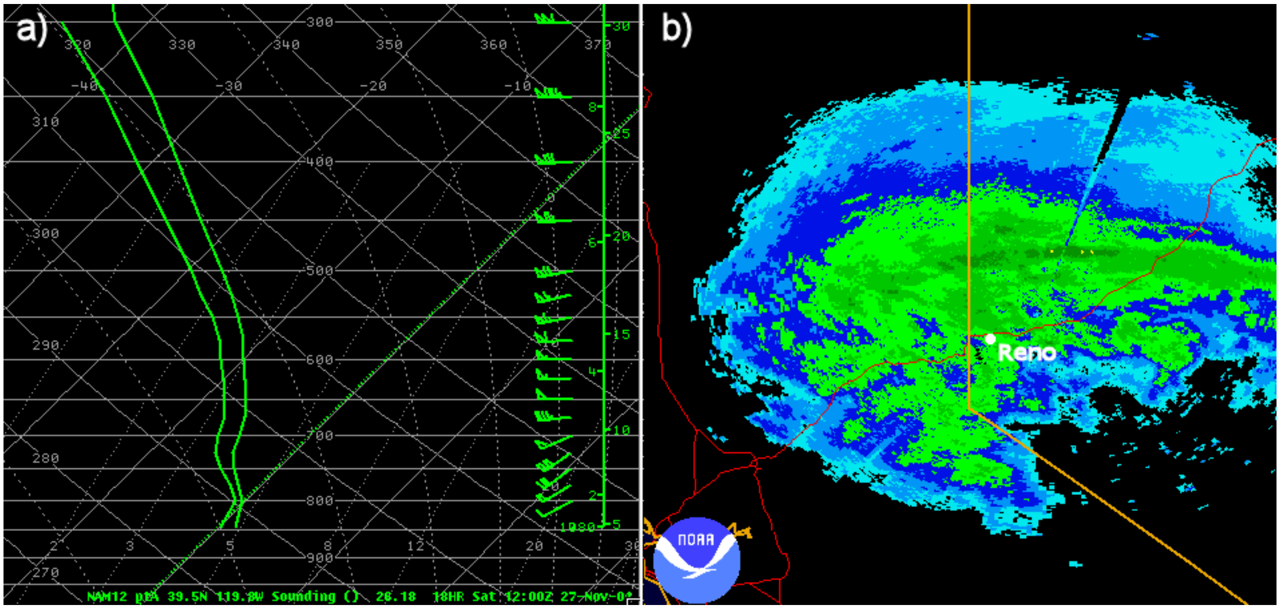

Figure 11. NAM12 18 hour forecast sounding verifying at 12 UTC 27 NOV 2004 (left) and KRGX 0.5 degree reflectivity image at 12 UTC 27 NOV (right).

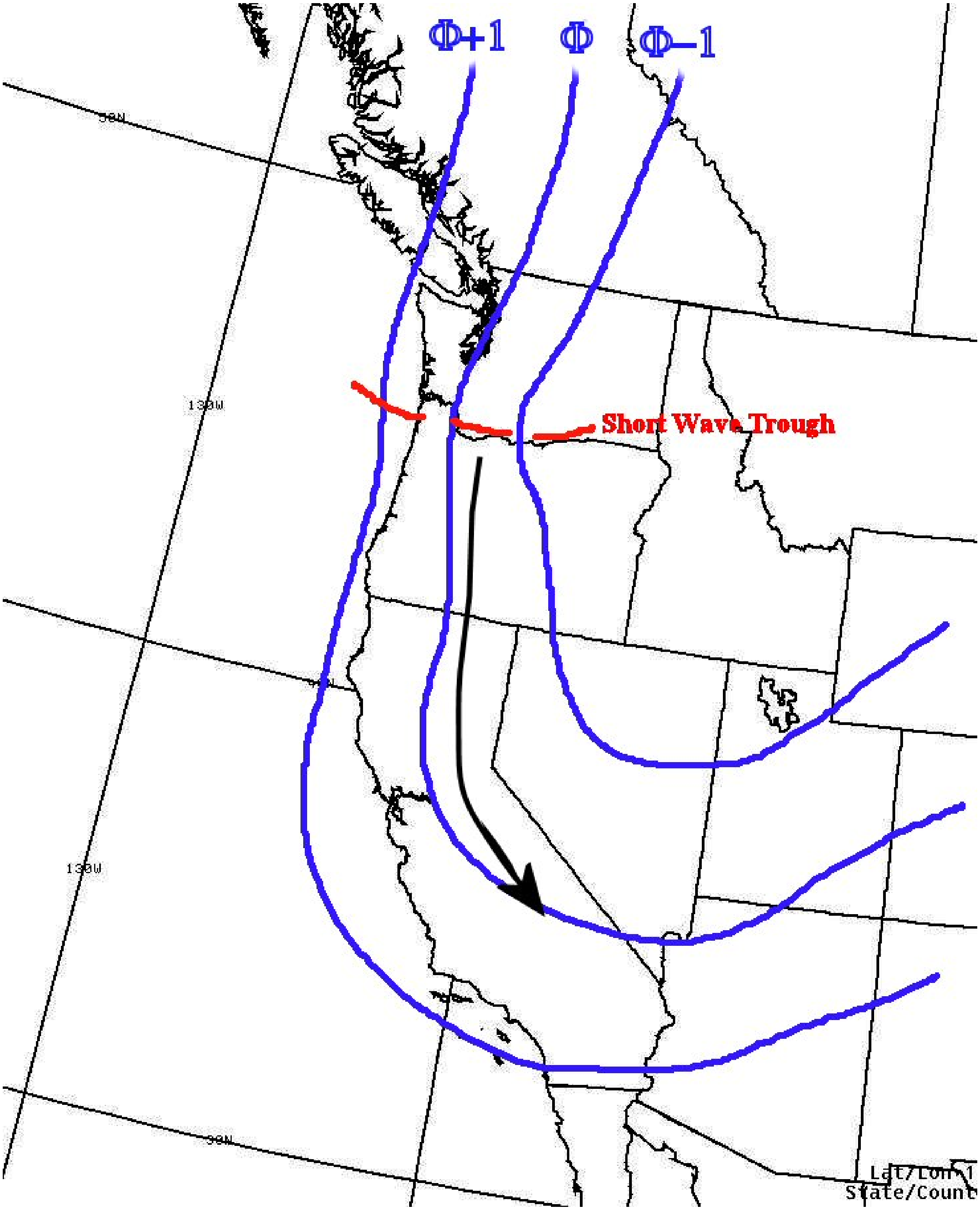

Figure 12. A 500 mb level schematic of the overall long wave trough across the Western United States, and the embedded short wave trough in the north-northwest flow on the upstream side of the long wave trough. Taken from Wallmann (2006).