Western Region Technical Attachment

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Forecasting Lee-Side Precipitation in the Central and Northern Sierra
Part II: Narrow Cold Frontal Rainbands

Rhett Milne and James Wallmann

Weather Forecast Office Reno NV

Section I: Introduction

Forecasting precipitation in the lee of the Sierra-Nevada mountain range (hereafter Sierra) from storms moving inland off the Pacific Ocean can be a major forecast challenge. This is primarily due to the rain shadow effect caused by the extreme elevation change between California's Sacramento Valley, which lies at an elevation of less than 500 feet msl, and the central Sierra, which has mountain tops of nearly 11,000 feet msl. Meteorologists have generally perceived southwesterly to westerly flow, normal to the Sierra, to result in the rain shadow effect, as most of the precipitation falls on the windward side with little or no precipitation observed on the leeward side. With the rain shadow effect, which could also include snowfall, locations in the Sierra often receive several feet of snow or several inches of rain while lee side valley locations only receive a few flurries or sprinkles. In part I of this investigation, it was shown wind direction did help determine how much precipitation "spills" over into western Nevada valleys, but stability was the most important factor. Predicting when precipitation will make it over the Sierra and affect the lee side valleys has been mere speculation by forecasters with no proven techniques used. Numerical models, both low and high resolution, do a very poor job forecasting when precipitation will overcome the barrier due in part to minimized or exaggerated blocking effects imposed by the Sierra.

Wallmann and Milne (2007) showed stability to be the main underlying factor in determining whether precipitation spills over the Sierra into western Nevada from Pacific storms. Stability was analyzed from numerical model output and could be used as guidance to when the atmospheric state would favor lee side precipitation spillover. This TA focuses on evaluating when spillover will occur based on real time radar and satellite signatures of the Narrow Cold Frontal Rainband (NCFR). The NCFR was found to be a significant feature which marked the transition from a stable atmosphere to an unstable one and could be tracked in real time to aid in determining when "spillover" should be expected.

The Narrow Cold Frontal Rainband (NCFR) has been the focus of numerous investigations in land falling mid-latitude cyclones along the coast of the western United States (Braun 1997, Jorgensen 2003, Yu 2006). Many of these studies evaluated and documented the structure and precipitation rates of the NCFR prior to and just after making landfall. Unfortunately, there has been little or no research evaluating the NCFR as it reorganizes and strengthens over the Sacramento Valley prior to moving into the Sierra. In this investigation we focused on the NCFR as it moves into the Sierra and found it to be a significant feature which leads to the transition from precipitation shadowing in the Sierra's lee to precipitation spilling over. What makes this investigation significant are the operational benefits realized by determining exactly where the NCFR is located and timing if and when precipitation will spill over into western Nevada. The discovery has profound impacts in improving short-term forecast accuracy and providing timely warnings to the public of rapidly changing weather conditions. We believe this technique can be applied to other relatively narrow north-south oriented mountain ranges such as the Cascades.

Another benefit to identifying the NCFR and whether it will cross the Sierra into western Nevada is the effects it has on atmospheric stability and the direct relationship in producing downslope wind storms. Stability is extremely important in providing a favorable environment for producing downslope windstorms. A stable layer, also known as a "critical layer, near the ridgetops are necessary for the phenomenon to occur. Once the passage of the NCFR over the Sierra transpires, stability markedly decreases by the erosion of the "critical level", ending downslope wind events. Milne (2003) analyzed conditions favorable for downslope wind storms in the lee of the Sierra and found wind direction, wind speed, and stability to be essential in producing lee side wind storms. Determining when a downslope wind event would end was a significant forecast problem and is now better understood by realizing the transition to an unstable atmospheric state occurs with the passage of the NCFR.

The goal of this paper is to show how the NCFR can be used to determine when precipitation will spillover into the lee of the Sierra. In section 2, the structure of the NCFR is reviewed. Defining what is considered lee side precipitation shadowing versus spillover is presented in section 3. Identifying the NCFR in WSR-88D radar imagery is presented in section 4 while satellite identification of the NCFR is discussed in section 5. Summary and conclusions are presented in section 6.

Section 2: Review of the Narrow Cold Frontal Rainband

The NCFR is a cold front only a few kilometers wide and is a common occurrence within the Warm Conveyer Belt (hereafter WCB) in relatively strong mid-latitude Pacific cyclones. The structure of the NCFR determined from reflectivity data from a NOAA P-3 aircraft used during the Pacific Jets Experiment (PACJET) is presented in figure 1 and was taken from Jorgensen et al. (2003). The NCFR is not a straight evenly aligned cold front but rather has breaks or gaps with areas of pronounced bowing in the direction of propagation. Regions of bowing often produce strong gusty surface which can exceed 50 mph. Gap regions are devoid of strong updrafts and are associated with much weaker surface winds. The NCFR is usually found at the position of the surface cold front and has strong but relatively shallow updrafts of around 20 ms-1 (Jorgensen 2003) with lightning occasionally associated with it. This convective band is not considered deep as echo tops are typically only 4-5 km above the surface. However, portions of the NCFR can be severe with large hail, strong winds, and even weak tornadoes. The high reflectivity ribbon of the NCFR can extend over 300 km long with maximum reflectivities in the core regions of over 55 dBZ. The entire band is characterized as having reflectivities of greater than 45 dBZ, although this is often underestimated or altogether missed by WSR-88D radar due to poor sampling of high elevation radar sites and the relatively shallow nature of the convective rainbands.

Cross sections through the leading edges of the NCFR often reveal gravity-current like structures similar to mid-latitude, continental squall lines (Jorgensen 2003). Cross sections taken through the NCFR along lines A-A' and B-B' from figure 1 shows the structure of the rainband and the strong convergence and updraft associated with it (figure 2). The gravity currents are fed by low level cold air advection and evaporative cooling from intense precipitation within the NCFR, which helps maintain updrafts. During PACJET, NCFR's were found to exist in an environment of low conditional and or convective instability and high shear. PACJET prefrontal soundings at the leading edge of the NCFR from Jorgensen et al. (2003) revealed only 22 J/kg of Convective Available Potential Energy with surface winds backing from southerly at 30 mph to southwesterly at 50 mph at 700 mb. Finally, bookend vortices can occur within the NCFR and is the location where rotation and weak tornadoes are most likely to be observed.

Section 3: Lee side Precipitation Shadowing vs. Non-Shadowing (Spillover)

To better understand what defines the rain shadow effect in the lee of the Sierra, Wallmann and Milne (2006) used stability indices to show if precipitation will move unabated across the Sierra. When the Sierra shadows out precipitation, most of it will be confined along the western slopes of the Sierra to just east of the crest. That is not to say that some precipitation won't get into lee side valleys. During typical shadowing, the amount of precipitation that does fall may accumulate from 0.01-0.15" in a 6-hour period and typically occurs in bands propagating up to 25 miles east of the Sierra crest before dissipating. These individual pulses are usually short lived, lasting generally less than 1 hour. An example of the rain shadow effect during a winter storm as observed from the KRGX 88D radar, located 20 miles northeast of Reno, is shown in figure 3. There is a marked transition from reflectivities of 20-40 dBZ to zero just east of the California/Nevada border, representing the location of where precipitation shadowing is occurring. When stability is favorable for precipitation to cross the Sierra unabated, precipitation will stream into western Nevada and be seen in the reflectivity data as if there were no mountain barrier impeding the bands of precipitation. An example of precipitation "spilling" over into western Nevada valleys is shown in figure 4.

Section 4: Real Time Identification of the NCFR with WSR-88D

The passage of the NCFR brings a transition from a stable atmosphere to an unstable one and promotes precipitation spillover into the lee of the Sierra. Forecasters can therefore analyze the location of the NCFR upstream and track the progression eastward in determining when the transition from shadowing to spillover will occur. NCFR's are more easily identified with WSR-88D radars in California than in Oregon, Washington, or Nevada due to the beam of the high elevation radar sites overshooting the core convective elements within the NCFR, even when employing the lowest elevation scan. The radar site near Reno (KRGX) sits atop Virginia Peak at an elevation of 8,200 feet while the NWS Medford 88-D radar is at 7,500 feet. This is significantly higher than the 88D radar from Sacramento which sits below 500 feet. Using a composite map of operational WSR-88D's in northern California, the NCFR can easily be identified in Pacific storms if present. By tracking the NCFR and comparing it to model data, meteorologists can evaluate model performance and make necessary adjustments to the forecast.

An example of an NCFR as it moves through the Sacramento Valley of California and through the Sierra is shown in a sequence of images in figures 3, 5, and 6. Figure 3 shows western Nevada being shadowed out from precipitation, figure 5 shows the NCFR as it moves into western Nevada, and figure 6 shows precipitation spilling into western Nevada after the NCFR passage. The NCFR is more difficult to identify with just the KRGX radar, but there is a higher reflectivity band that extends into northern Washoe County and represents the location of the NCFR, even though reflectivities are never greater than 30-35 dBz (figure 7). The elevation of lowest radar beam samples the NCFR at an elevation of around 13,000-15,000 feet MSL as it crosses the Sierra and is likely just above the elevation of the core reflectivity maximum. This highlights the importance of identifying this feature and the training required to interpret what the radar is detecting. Once this higher reflectivity band moves into western Nevada, precipitation immediately spills over.

Of greater significance than just determining when and if the NCFR will cross the Sierra, is determining how extensive the precipitation shield will be behind it. In some cases, there is very little precipitation behind the NCFR passage and results in only minor additional accumulations (figure 8). A prolonged precipitation event will occur when an extensive precipitation shield remains after passage of the NCFR. Figure 6 shows a larger precipitation shield behind the NCFR which led to a longer duration rain and snow event which caused significant travel disruptions in western Nevada.

The location of the NCFR within the WCB also has significant impacts on accumulation totals. The NCFR can be near the leading edge of the precipitation shield, near the end, or somewhere in between. Figure 9 is an example of the NCFR at the leading edge of the precipitation shield which led to significant precipitation totals after the NCFR passage.

It should be noted the NCFR typically has no problem crossing the Sierra into western Nevada with strong jet driven progressive systems. However, systems that drop south along the California coast are much trickier in predicting whether the NCFR makes it over the Sierra as the band often stalls out on the west side of the crest before dissipating.

Section 5: Using Satellite imagery to identify the NCFR

Identification of the NCFR from WSR-88D is not always possible due to the shallow convective nature of the rain band, especially as it moves into the Sierra. In these situations, the location of the NCFR can be estimated from infrared and visible satellite imagery.

The approximate location of the NCFR can be determined by identifying where transverse banding is occurring within the WCB. The region of the WCB to focus on is the location where cloud top temperatures transition from around -25ºC to near -50ºC in the jet driven WCB seen in infrared satellite imagery (figure 10). Cloud top temperatures can be colder just north of this region, although it doesn't necessarily mean the NCFR will extend that far north due to weaker dynamics. The northern extent of where the NCFR is dynamically supported can be inferred from where the transverse banding ends and where the WCB cloud shield breaks up in figure 10. Of importance is the area in northwestern Nevada where the transverse banding transitions to areas with gaps of significantly warmer cloud top temperatures. It should be noted transverse banding isn't always present, and in these cases, identifying the NCFR is more difficult if it even exists.

With visible satellite imagery, the NCFR can be identified in the WCB by noting where overshooting tops are occurring within the general area of transverse banding seen in the IR imagery. The IR imagery gives the general region where the NCFR should be found and the visible imagery is used to pinpoint the location. Figure 11 shows an example of where convective overshooting tops are occurring within the NCFR. In summary, if the NCFR cannot be identified in WSR-88D imagery due to the radar beam overshooting the NCFR, or if the rainband hasn't moved close enough to land off the ocean, use the IR imagery to locate the region where the NCFR is likely to be found. In daylight hours, the visible satellite imagery can be used to further pinpoint the location of the NCFR.

Summary and Conclusions

Stability was the primary meteorological factor in determining if precipitation will spill over the Sierra and into lee side valleys. The NCFR was found to be a significant feature which leads to the transition from a stable atmospheric state to an unstable one and promotes precipitation spilling over a mountain barrier, such as the Sierra. By tracking the NCFR, forecasters can determine when precipitation will no longer be blocked by a mountain range and how much additional precipitation might be expected after NCFR passage. In addition, downslope windstorms often end after the passage of the NCFR , due to increased instability, leading to improved timing of when strong winds will cease. Due to the shallow nature of the NCFR which can be missed by high elevation WSR-88D's, satellite imagery can be useful in pinpointing locations where the NCFR is likely to be found if present. The key is to focus on transverse banding along the WCB in both IR and WV satellite imagery to find the approximate location of where an NCFR would exist. During the day, visible satellite imagery can further pinpoint the NCFR by focusing on overshooting convective tops within the WCB juxtaposed with transverse banding seen in either IR or WV imagery. It should be noted NCFR's can move into the Sierra when the atmospheric state is already unstable. In these rare cases, precipitation will automatically spill over the Sierra prior to the NCFR passage and often occurs when weather systems immediately follows one another in a short period of time, usually 36 hours or less.

References

Braun et al., 1997. Airborne Dual-Doppler Observations of an Intense Frontal System Approaching the Pacific Northwest Coast. *Mon. Wea. Rev.*, 125, 3131–3156.

Jorgensen et al., 2003: Variations Associated with Cores and Gaps of a Pacific Narrow Cold Frontal Rainband. *Mon. Wea. Rev*., 2705-2729.

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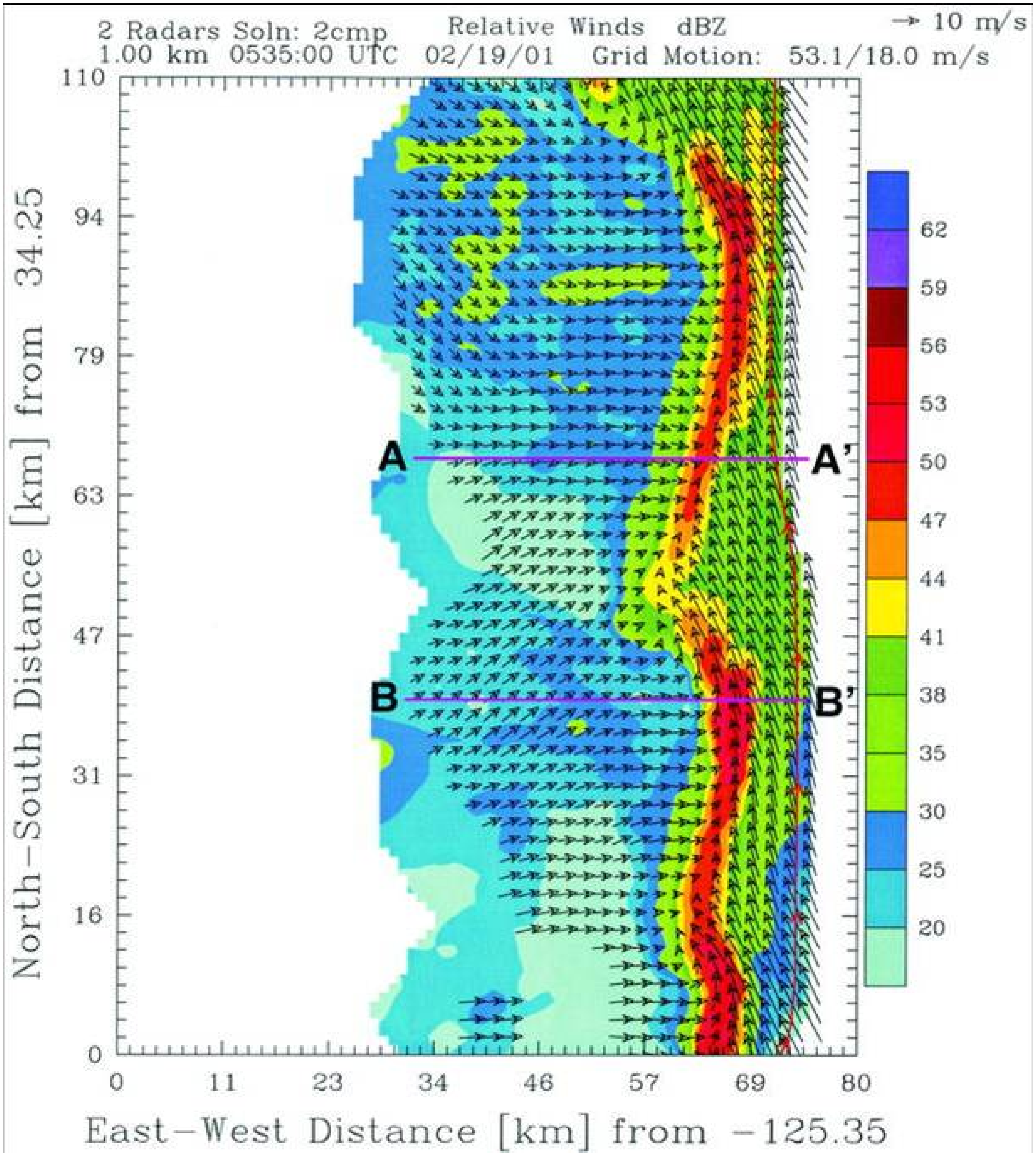

Figure 1. Radar reflectivity composite from the NOAA P-3 aircraft during the Pacific Jets Experiment. The P-3 flight track is shown as the thin red line running approximately south to north near the right-hand side. Lines A-A' and B-B' indicate the locations of vertical cross sections. Image taken from Jorgensen et al. 2003.

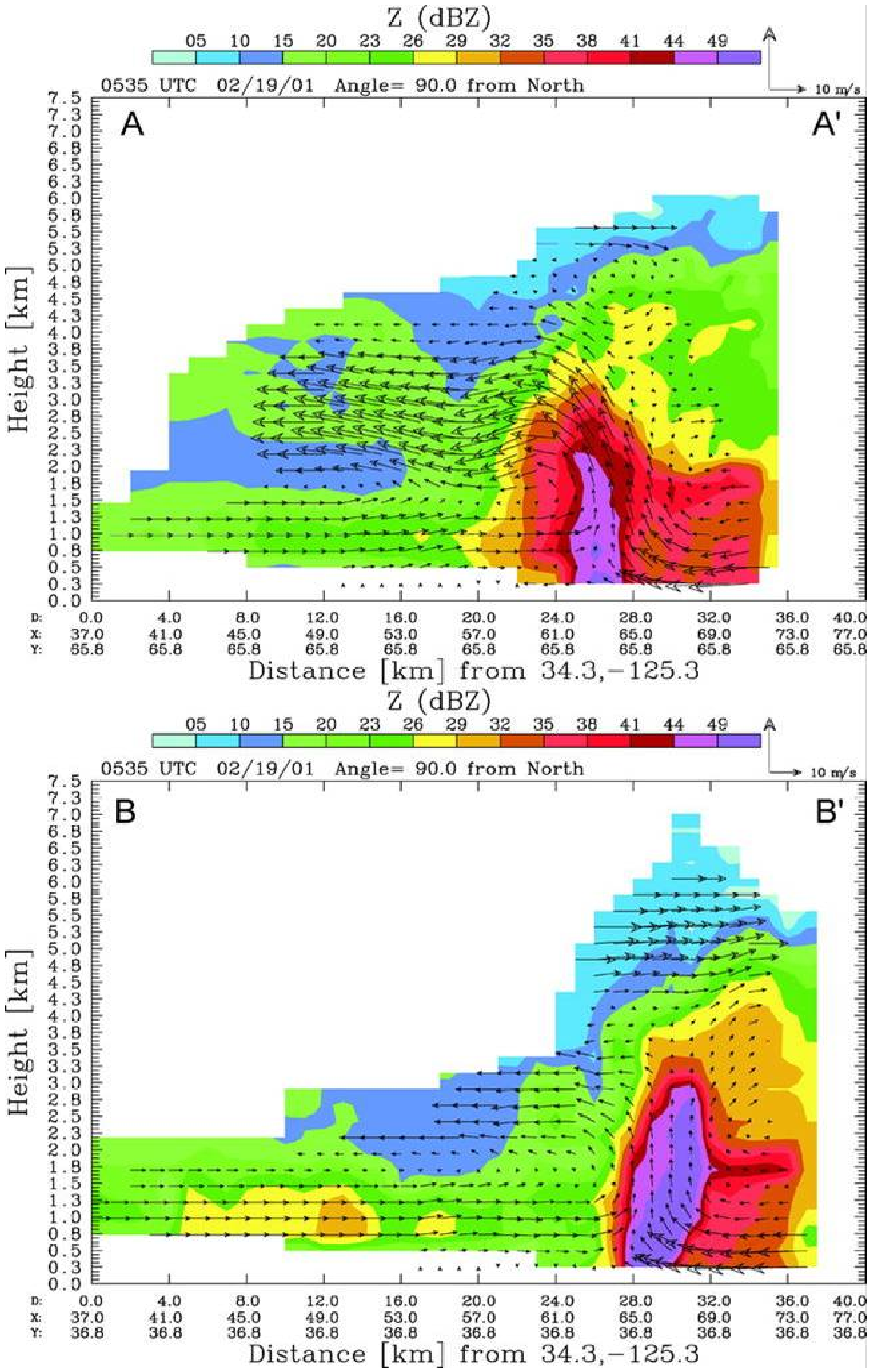

Figure 2. Vertical cross section of radar reflectivity and system-relative winds in the plane of the cross section. Cross sections A-A' and B-B' are shown in figure 1 and the data is from NOAA P-3 aircraft used during the Pacific Jets Experiment.

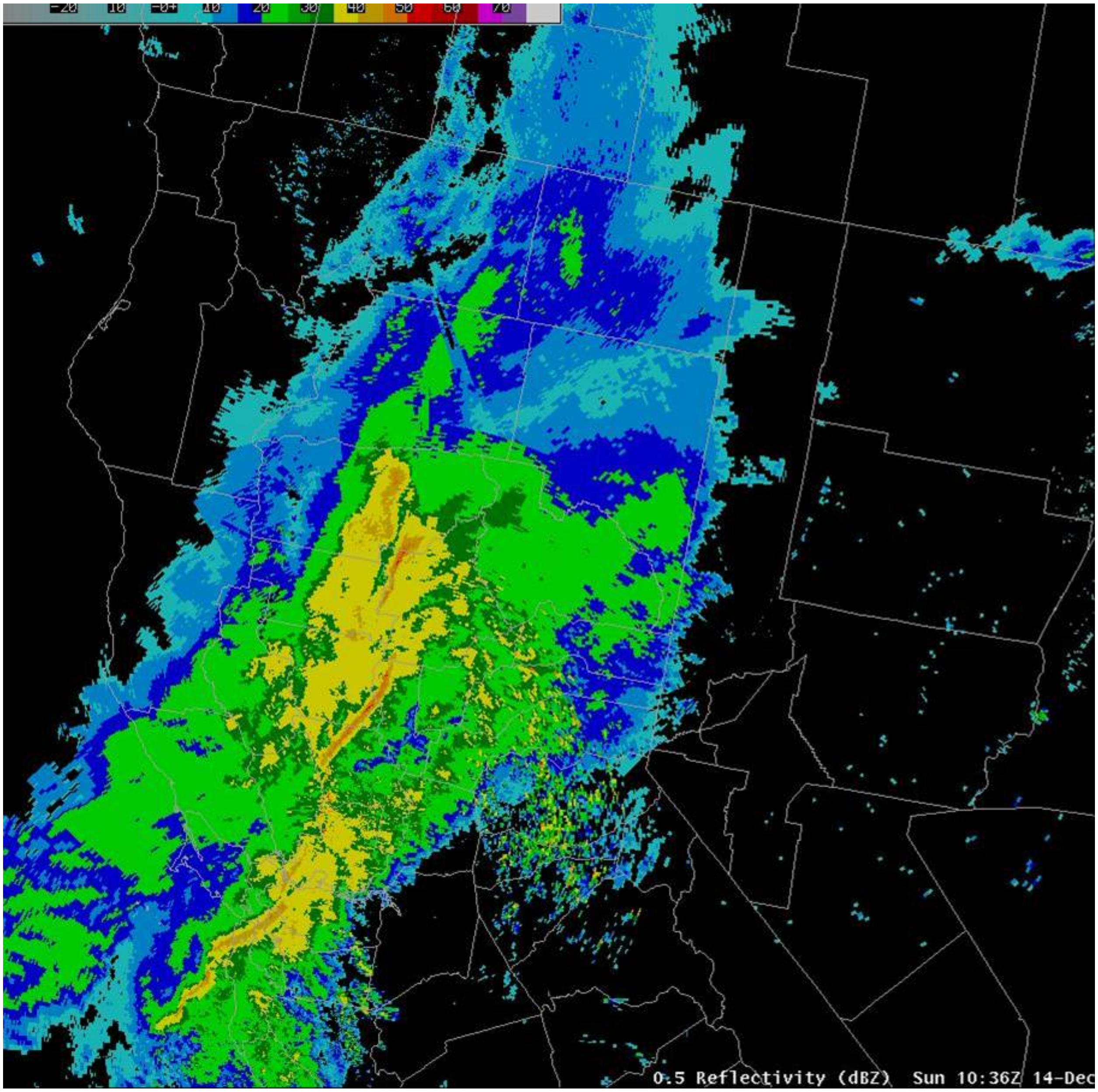

Figure 3. Reflectivity composite image from 10:36 UTC on December 14th, 2003. Strong precipitation shadowing is occurring immediately east to the Sierra along the California-Nevada border.

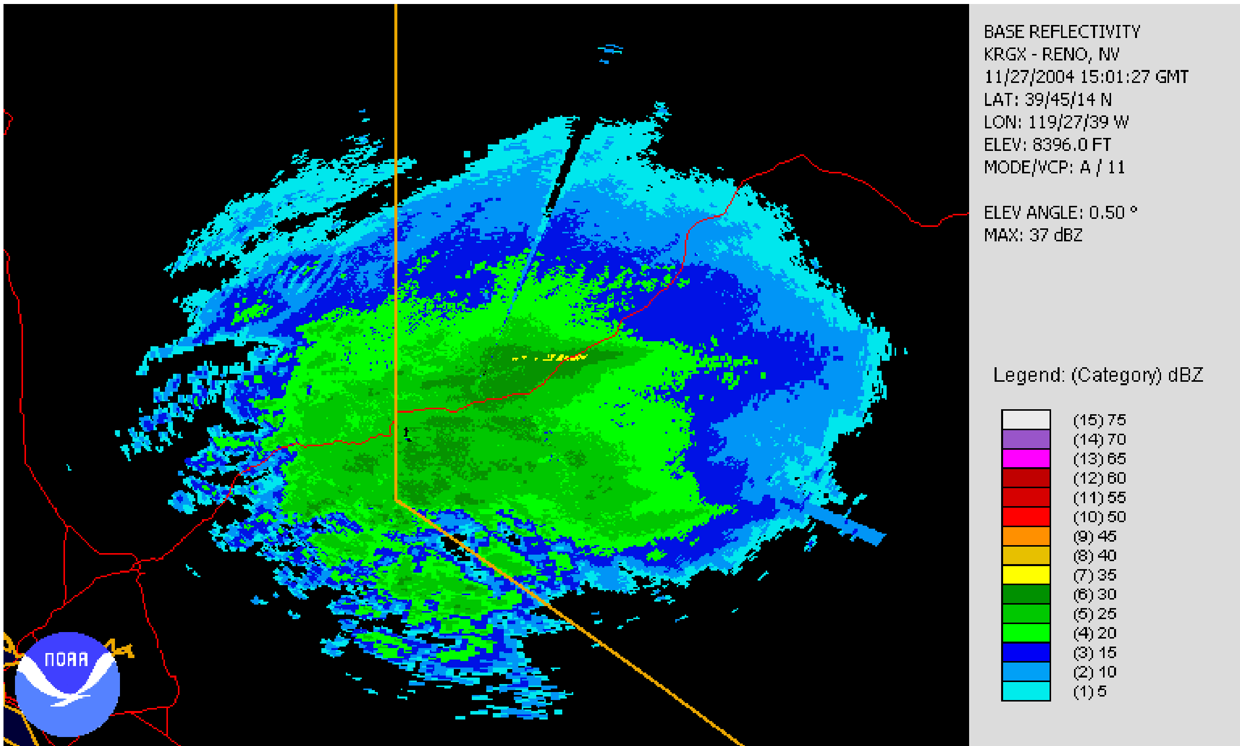

Figure 4. Reflectivity image from KRGX at 1501 UTC on Nov 27th 2004 showing precipitation spilling over the Sierra into western Nevada.

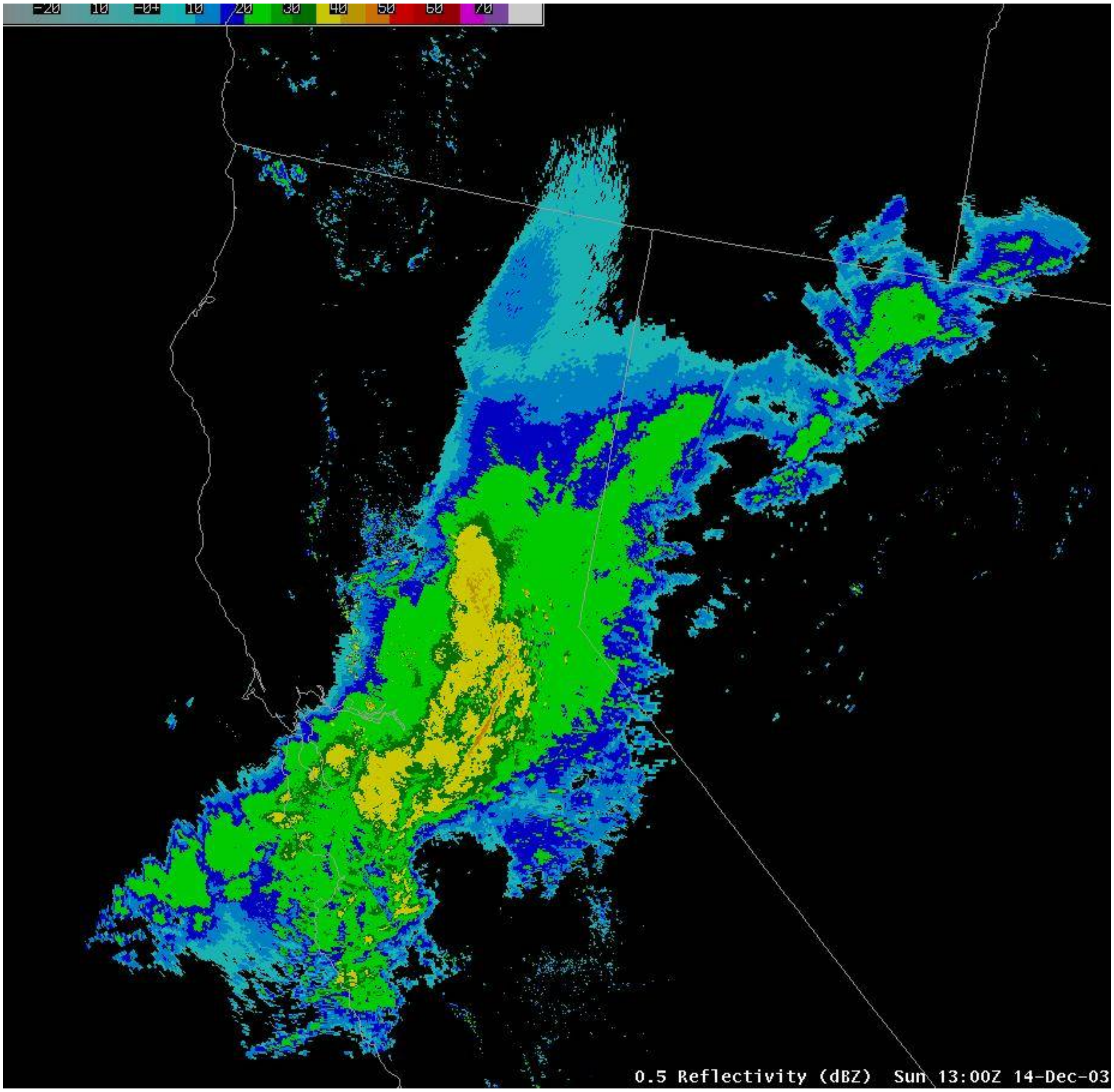

Figure 5. Reflectivity image at 1300 UTC on December 14th, 2003 showing the NCFR crossing the Sierra and moving into western Nevada.

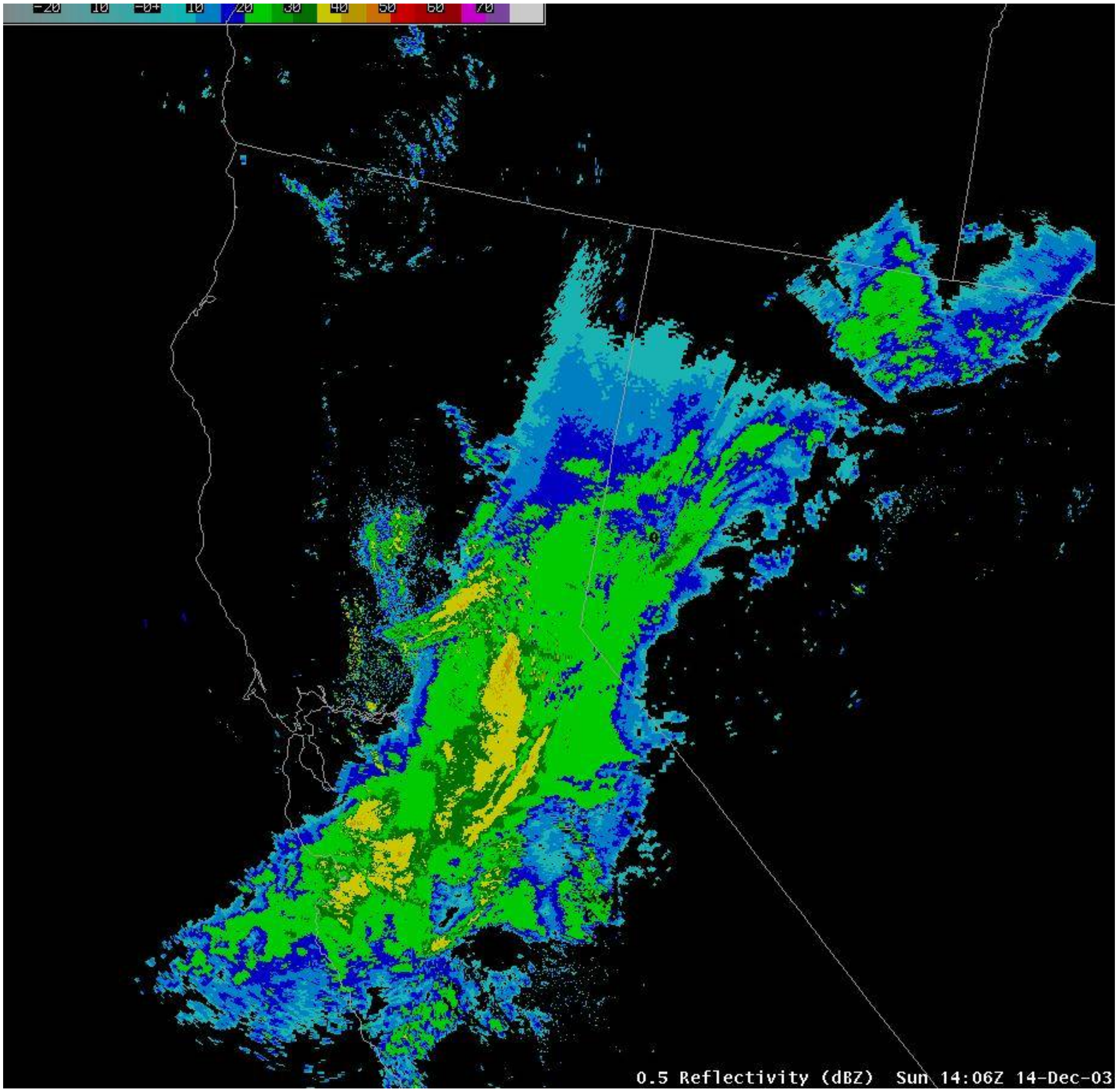

Figure 6. Reflectivity image at 1400 UTC on December 14th, 2003 showing precipitation spilling into western Nevada behind the passage of the NCFR.

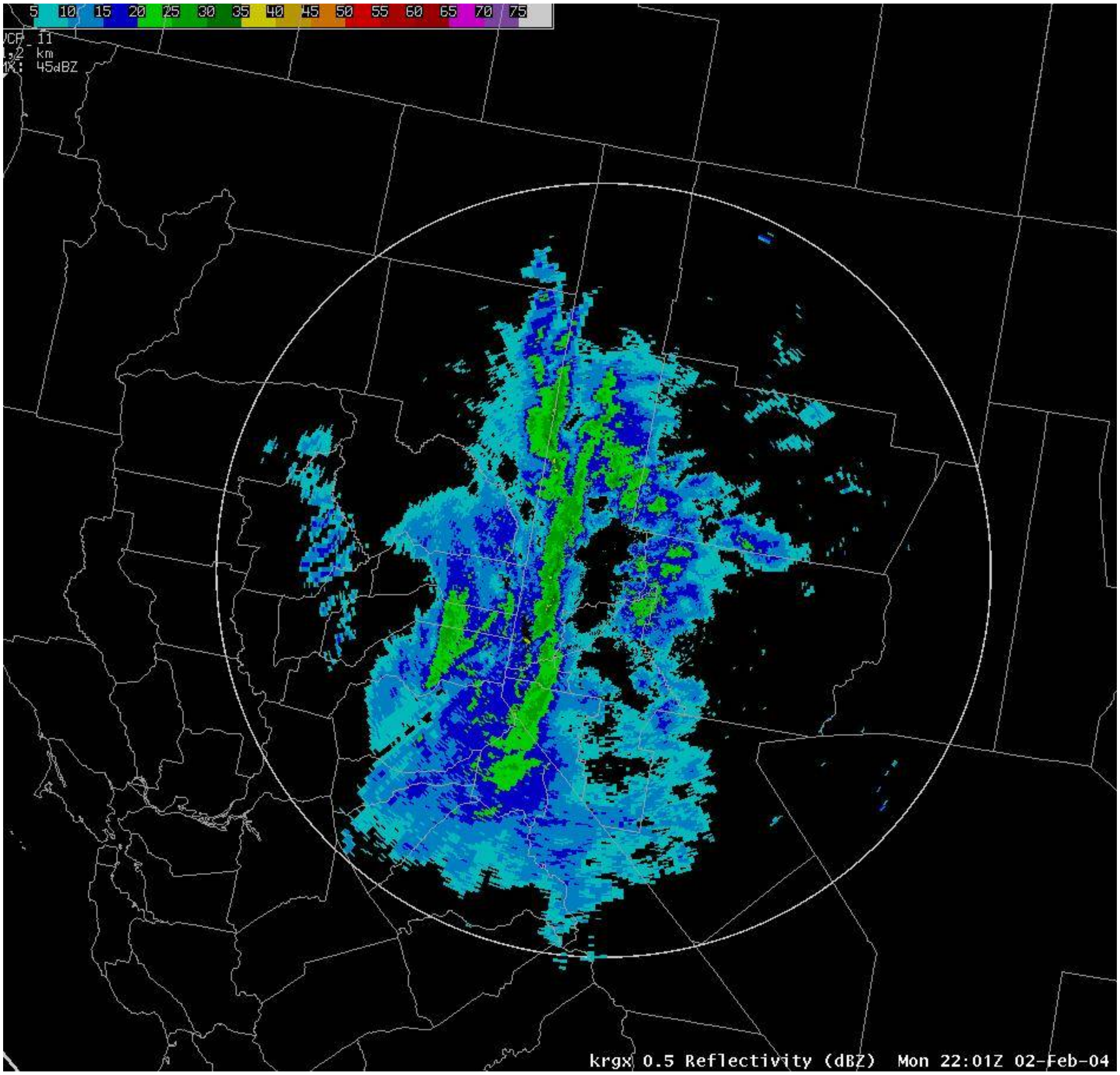

Figure 7. Reflectivity image from KRGX at 2201 UTC on February 2nd, 2004 showing the NCFR exiting the Sierra and moving into western Nevada. Maximum reflectivities within the NCFR are only 30-35 dBZ due to the high elevation KRGX radar.

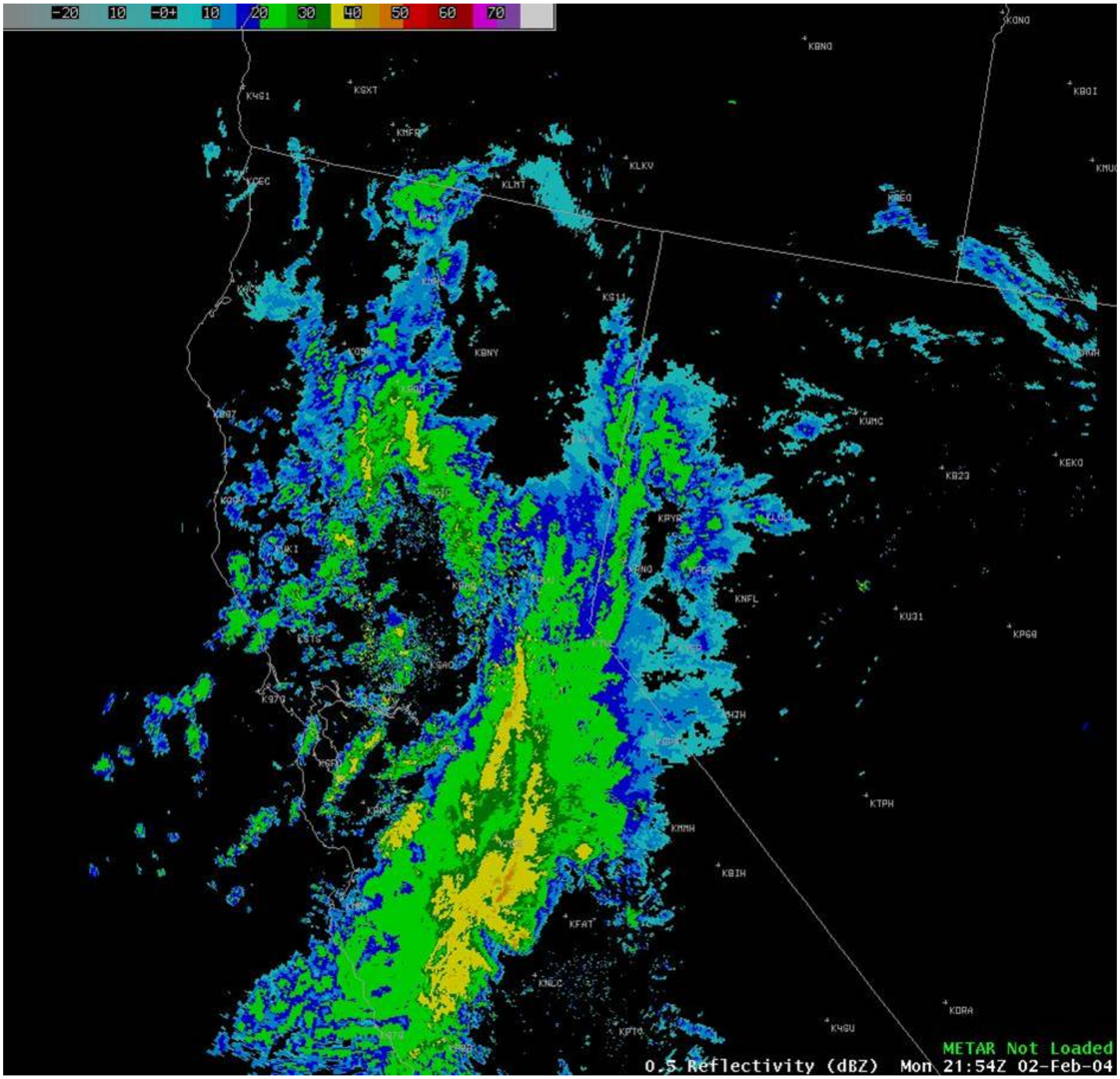

Figure 8. Reflectivity image from 2154 UTC on February 2nd, 2004 showing very little precipitation behind the NCFR.

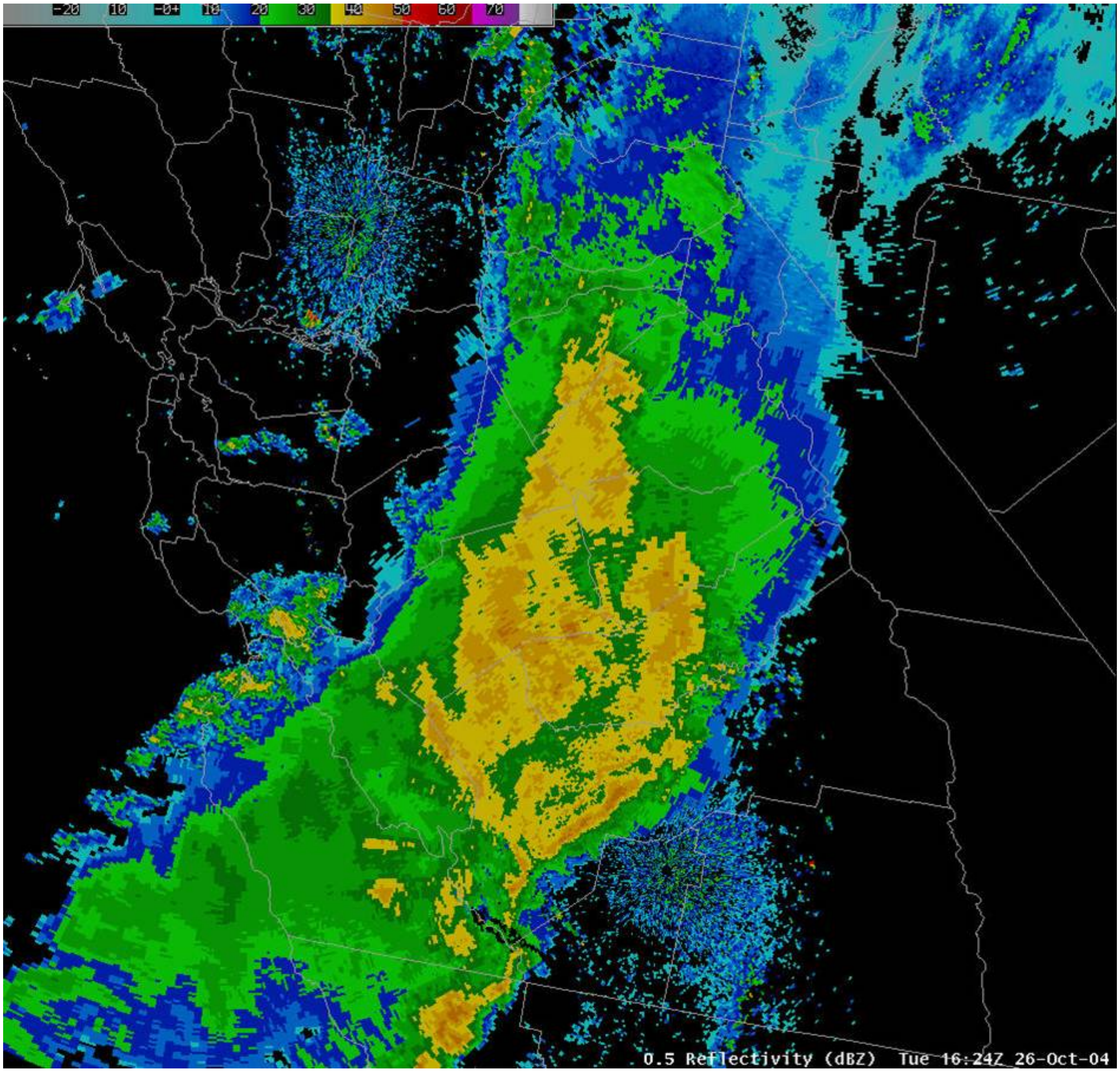

Figure 9. Reflectivity image at 1624 UTC on October 26th, 2004 showing an NCFR at the leading edge of an extensive WCB precipitation shield.

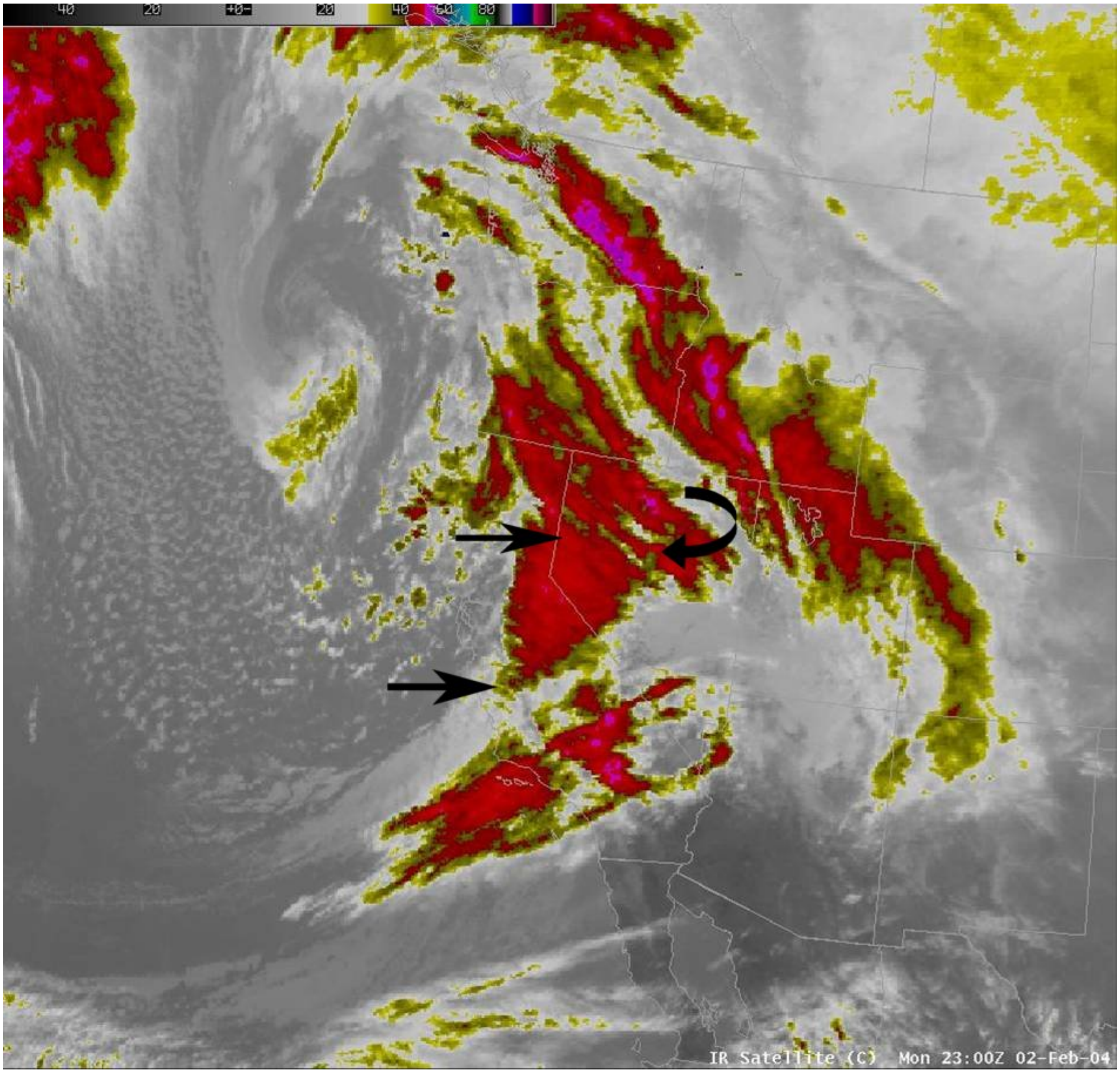

Figure 10. Infrared satellite image at 1445 UTC on December 14th, 2003 showing the transverse banding across the California-Nevada border. The southern most straight arrow points to where the cloud tops reach around -25ºC and the southern extent of where the NCFR would likely be found. The northernmost straight arrow shows where transverse banding ends with cloud tops near -50ºC and the northern extent of where dynamics support the NCFR. The curved arrow shows where cloud top temperatures have gaps with noticeably warmer temperatures indicative of where the NCFR would no longer be expected to exist.

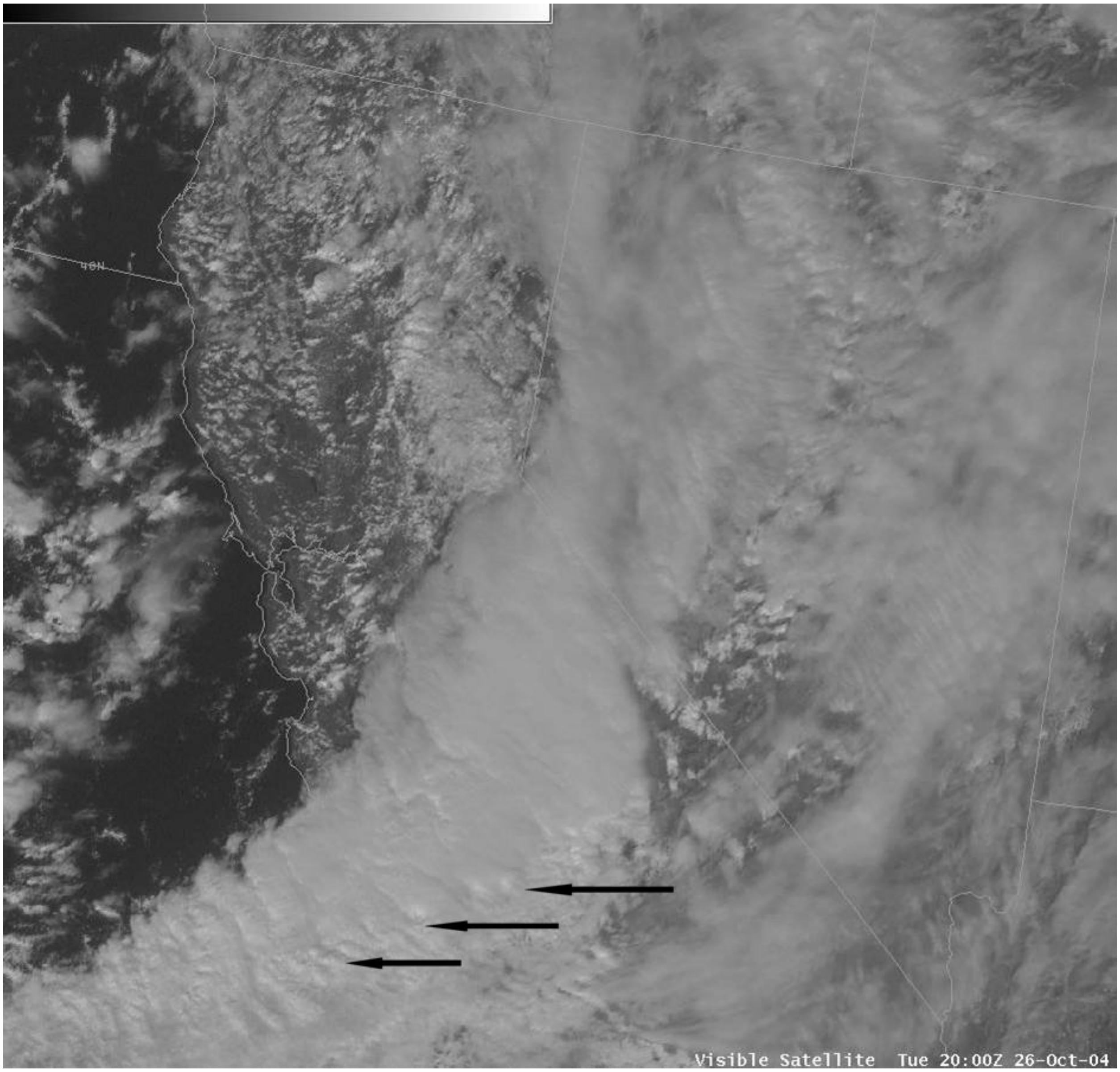

Figure 11. Visible satellite image at 2000 UTC on October 26th, 2004 showing convective elements and overshooting tops, indicated with arrows, at the location of the NCFR.