Western Region Technical Attachment
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Microphysical Processes and the Reno Snow Storm of March 1st, 2003

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1. Introduction

An upper low dropped southward along the Oregon and northern California coasts on March 1st, 2003. This pattern is known as an "Inside Slider" (Wallmann, 2005), where short wave energy tracks southward over California and Nevada. This pattern can produce heavy snow amounts over western Nevada if paired with a northeasterly surface flow and sufficient low level moisture. A weak frontal boundary passing through western Nevada turned the surface flow to the northeast as the strong dynamics passed overhead. The combination of these elements along with a deep layer of moisture produced a favorable environment for microphysical processes, resulting in extreme snowfall rates as high as 3.5 inches per hour in the Reno area. Model guidance from 00z March 1st suggested a heavy precipitation event would occur over western Nevada, but uncertainty remained in the severity, location and the snow levels. This paper will look at why quantitative precipitation forecasts (QPF) were underestimated by the models and forecasters, and how cloud microphysical processes assisted in generating the extreme snowfall rates.

2. Synoptic and Model Analysis

The upper low along the Oregon Coast at 15z March 1st (figure 1) was forecast to move south into northern California by 00z March 2nd (figure 2). The track of the low placed western Nevada under the favorable northeast quadrant of the upper low where divergence aloft will assist in producing large scale ascent. This is shown in figure 3, note the strong convergent/divergent couplet over western Nevada and eastern California, where values are between -6 and -12.

With the upper level lift in place, low level convergence and moisture are necessary to provide a trigger for the heavy precipitation event. The pressure pattern in figure 4 is similar to the thermal troughs that occur over western Nevada during the summer and are favorable for developing areas of low level convergence. A time series (figure 5) for Reno depicts the correlation between the strong vertical motion, convergence-divergence couplet and deep layer moisture near 21z. Strong vertical motion and sufficient moisture are important ingredients for microphysical processes.

The surface forecast for 03z March 2^{nd} (figure 6) shows the thermal trough is pushed to the south in response to the digging low over central California (figure 7). This will allow a north to northeast flow to develop behind the passing cold front, yielding an upslope enhancement for the Sierra Nevada Mountains. A time series for Reno (figure 8) shows the increasing depth of the post frontal northeasterly winds between 00z and 06z March 2^{nd}. This prolonged upslope enhancement will provide an additional boost to the vertical motion.

The Eta40 12 hour QPF forecast ending 06z March 2^{nd} (figure 9) reflects the location of the frontal boundary over western Nevada. The heavy snow criterion for the western Nevada valleys is 4 inches in 12 hours. Assuming a 10 to 1 snow to water ratio, the QPF suggests a heavy snow event for many western Nevada valleys, if the snow levels are at the valley floors. With previous Inside Slider events, models underestimated the QPF (Wallmann 2005) and with the strong vertical motion present in the model data, this QPF is likely underestimated.

Forecasters at NWS Reno use several snow level algorithms empirically derived (unpublished work) from temperature and thickness data to forecast snow levels. For this event algorithms for 700 mb temperature and 850 mb to 500 mb thickness were used to forecast snow level. At 12z March 1^{st} the snow levels from the 700 mb and the 850-500 thickness algorithms were 5500 feet and 5300 feet, respectively. These values were close to the freezing level, 5800 feet, and the wet bulb zero, 5000 feet, from the 12z Reno sounding. By 00z, the model snow levels were forecast to drop to 4400 feet, the field elevation of the Reno Airport.

Another tool available to forecasters was the profiler data from the Pacific Jets Experiment (PACJET, NOAA/ETL, 2003). The profiler data produces the height of the snow level based on radar reflectivity and Doppler vertical velocity of hydrometeors (White et al., 2002). Data from the Chico profiler was used to examine the snow level as precipitation band passed over the northern Sacramento Valley between 04z and 10z March 1^{st} (figure 10). As the precipitation began at approximately 430z, the initial snow level was 5000 feet. When the precipitation intensity increased, higher fall speeds (red color below the black dots) between 06z and 08z March 1^{st}, the snow level quickly dropped to 4200 feet. This provided confidence to the forecasters that, as the strong vertical motion moved over the Reno area, moderate to heavy precipitation would occur and snow levels would drop to the valley floor.

Based on the strong vertical motion, abundant moisture and upslope enhancement, the forecasters concluded microphysical processes, discussed in section 4, would be favorable and the model QPF was underestimated. Snow levels were also expected to lower to valley floors and a heavy snow event would result. A Heavy Snow Warning was issued for the Reno area in the early morning of March 1^{st} with storm total accumulations of 3 to 6 inches on the valley floor and 4 to 8 inches above 5000 feet.

3. The Snow Storm

The upper low moved over northwest California by 21z March 1st with a well defined cloud shield over western Nevada (figure 11). Light rain began at the Reno Airport just before 21z with snow levels near 6500 feet. By 00z, the upper low took a track parallel to the California coast with the jet digging to near the southern California coast. This continued to leave western Nevada under the strong vertical ascent in the northeast quadrant of the upper low. Moderate to heavy precipitation was falling in the Reno area and over the northern Sierra Nevada Mountains, with snow levels near 5000 feet, in response to the strong vertical motion. An east-west surface frontal boundary began to develop around this time as seen in the 00z LAPS surface analysis (figure 12). The pressure pattern shows an inverted surface trough extending from Bishop, CA (KBIH), to Lovelock, NV (KLOL) with southerly winds reported at KBIH and Tonopah, NV (KTPH) and northerly winds from KLOL and Fallon Naval Air Station (KNFL). The boundary set up nearly along the Highway 50 corridor from South Lake Tahoe (KTVL) to KNFL and matched well with the Eta40 forecast (figure9). This boundary would be the focus for moderate to heavy precipitation, 0.40 and 0.60 inches was measured, south and east of the Reno area for the next 6 hours.

At 01z, a weak cold frontal boundary that extended from Reno northeastward to north of Lovelock NV was moving southeast. The 0.5 velocity image from the Reno WSR-88D (KRGX, figure 13), shows the front as weak outbound return extending from KRGX to Reno. This front created a northeast flow between 5 and 10 knots at Reno and began the upslope enhancement in the foothills southwest of Reno. The KRGX 0.5 base reflectivity (figure 14) shows two bands of precipitation southwest of Reno (center of the image reporting moderate rain and 35 degrees).

The echoes continued to bank up along the Carson Range southwest of Reno by 02z March 2nd with 30-35 dbz returns. A wet snow began to fall at the Reno Airport by 0130z. With the upslope lift and dynamic lift from the upper low coupled, the strong vertical motion helped to drive the snow levels to the valley floor and allowed several microphysical processes to produce extreme snowfall rates. Between 03z and 05z snowfall rates of 3 to 3.5 inches per hour were reported by spotters in the foothills of southwest Reno, with liquid precipitation rates of 0.20 to 0.25 inches per hour at the airport. The velocity and reflectivity patterns southwest of Reno shown in figures 13 and 14 continued until 05z when the northeast winds at Reno became calm and the upper low moved over San Francisco Bay. This decoupled the upslope lift and upper dynamics and decreased the snow fall rates to less than one inch per hour. Light snow continued to fall at the Reno Airport for another 5 hours with minor accumulations.

4. Application of Microphysical Processes to the Snow Storm

Past Technical Attachments (Cylke, 1999 and Staudenmaier, 1999) explain how microphysical processes affect snowfall amounts and highlight the importance of diagnosing microphysical processes during winter storms. Since models do not account for microphysics or have the scale to properly resolve most microphysical processes forecasters must adjust the model data. Analyzing forecast soundings and time height plots can provide clues to determine if strong lift, moisture and favorable temperatures ranges (discussed in next section) coincide. If they do, then model QPF will likely be underestimated.

For this event, the twelve hour liquid precipitation total at the Reno Airport ending 06z March 2nd was 1.13 inches, with 6 to 8 inches of snow on the valley floor. In the higher elevations of southwest Reno, 8 to 12 inches of snow was observed. The highest snowfall total from this event was 14 inches in Galena Creek, about 10 miles south of Reno at an elevation of 5000 feet. Areas only a few miles north of Reno, an away from the upslope enhancement, received only 1 to 3 inches of snow. The forecasted snow amounts for this event were higher than what the model QPF suggested, but still several inches below the observed values.

Looking back at figure 9, the QPF for the Reno area was 0.40 to 0.50 inches, an underestimation of over 100% for this event. Wallmann (2005) discusses model biases with inside slider systems, but this was an event where microphysical processes assisted in extreme snowfall rates. The next three sections will discuss microphysical processes and how forecasters can use model data to enhance model QPF.

Nucleation and Multiplication

The first process in snow development is the freezing of supercooled liquid water drops in a cloud, which is dependant on the temperature of the cloud and the number of condensation nuclei present. A good rule of thumb to use is if cloud temperatures are below -10 C, then water drops are likely to freeze. From Schultz et. al. (2002), cloud top temperature measured from soundings is a clue for ice nucleation. If cloud top temperatures are below -20 C, then ice nucleation is nearly certain to occur.
In the March 1st case the infrared satellite image (figure 15), shows the cloud top temperatures are near -40 C in the Reno area. This also shows up on the 00z March 2nd Reno sounding (figure 16), note the -40 C temperatures occur near 400 mb.

The concentration of ice nuclei is also important. Higher concentrations of ice nuclei will allow more liquid drops to freeze, yielding more ice crystals and higher precipitation rates. Ice multiplication is a process where ice particles collide and shatter to create more ice nuclei. This greatly impacts the precipitation rates and occurs in the presence of strong vertical motion (Steenburgh, 2004).

Figure 17 shows high relative humidity, strong omega and cold temperatures aloft coincide around 21z. Nucleation and multiplication can be inferred by the combination of strong omega, cold temperatures (-20 C to -40 C), and humidity values greater than 70% between 550 mb and 400 mb.

Deposition

Deposition, the first process in crystal growth, is caused by the difference in saturation vapor pressures of ice and water. In this process, ice crystals grow when they collect evaporated water droplets and is maximized at temperatures near -15 C. Using time height plots and model soundings, forecasters can account for deposition.

The red band in figure 17 indicates the -10 C to -17 C temperature range. This layer coincides with abundant moisture and is below the region of ice nucleation near 21z. This is a "Seeder-Feeder" process (Steenburgh, 2004) where small ice particles fall from one cloud layer into another and provide a boost to ice crystal growth.

Riming

Riming occurs when snow flakes come into contact with water drops. The drops then freeze and add to the mass of the snow flake. This process occurs in clouds at temperatures between 0 C to -10 C. Strong vertical motion suspends larger snow flakes for a longer period of time, allowing them more time to collect water drops. Higher precipitation rates and higher snow to water ratios result due to the collection of water drops that will not precipitate from clouds under normal conditions.

The time height plot in figure 17 shows a moist layer with 0 C to -10 C temperatures passing through an area of strong vertical motion from 18z March 1st to 03z March 2nd. The Reno sounding from 00z (figure 16), shows the 0 C to -10 C layer is near saturation and extends from the surface to above 700 mb. This layer, approximately 6000 feet deep, provided favorable environmental conditions for riming and is the main cause of the very high, 7 to 1, snow to liquid water ratio.

5. Summary

Strong vertical motion and abundant moisture provided a favorable environment for microphysical processes to assist in producing extreme snow fall amounts in the Reno area on March 1st, 2003. Numerical models, which do not account for microphysical processes, underestimated the precipitation amounts by 100% or more. This does not mean the model forecast was a bust. Models did handle the synoptic and mesoscale pattern quite well. The official snowfall forecast was underestimated by 6 inches in the foothills southwest of Reno. Forecasters need to be aware of microphysical processes and how they affect precipitation amounts then apply this knowledge to adjust QPFs and add value to the model solutions. Time height plots and model soundings are excellent tools to use in microphysical analysis.

6. References:

Cylke, T. 1999: The Effects of Vertical Motion and Microphysical Processes on Precipitation Type during a Western Nevada Snow Storm. Western Regional Technical Attachment No. 99-13.

NOAA, Environmental Technology Laboratory Pacific Jets Experiment, 2003: http://www.etl.noaa.gov/programs/2003/pacjet/

Schultz, D. M., and J. V. Cortinas, Jr., 2002: Comments on "An operational ingredients-based methodology for forecasting midlatitude winter season precipitation." *Wea. Forecasting*, **17**, 160-167.

Staudenmaier, M. 1999: The Importance of Microphysics in Snowfall: A Practical Example. Western Region Technical Attachment No. 99-12.

Steenburgh, W. J. 2004: Dynamics and Microphysics of Cool-Season Orographic Storms COMET Program Webcast.

Wallmann, J. 2005: Inside Sliders. Part I: Their Features, and Their Effects on the Sierra Front of Western Nevada. WR Technical Attachment No. 06-02.

Wallmann, J. 2005: Inside Sliders. Part II: Model Forecasts for Inside Sliders and Their Biases. WR Technical Attachment No. 06-03.

White, A. B., D. J. Gottas, E. T. Strem, F. M. Ralph, and P. J. Neiman, 2002: An Automated Brightband Height Detection Algorithm for Use with Doppler Radar Spectral Moments, *Atmos. Oceanic Technol.*, **19**, 687-697.

7. Figures:

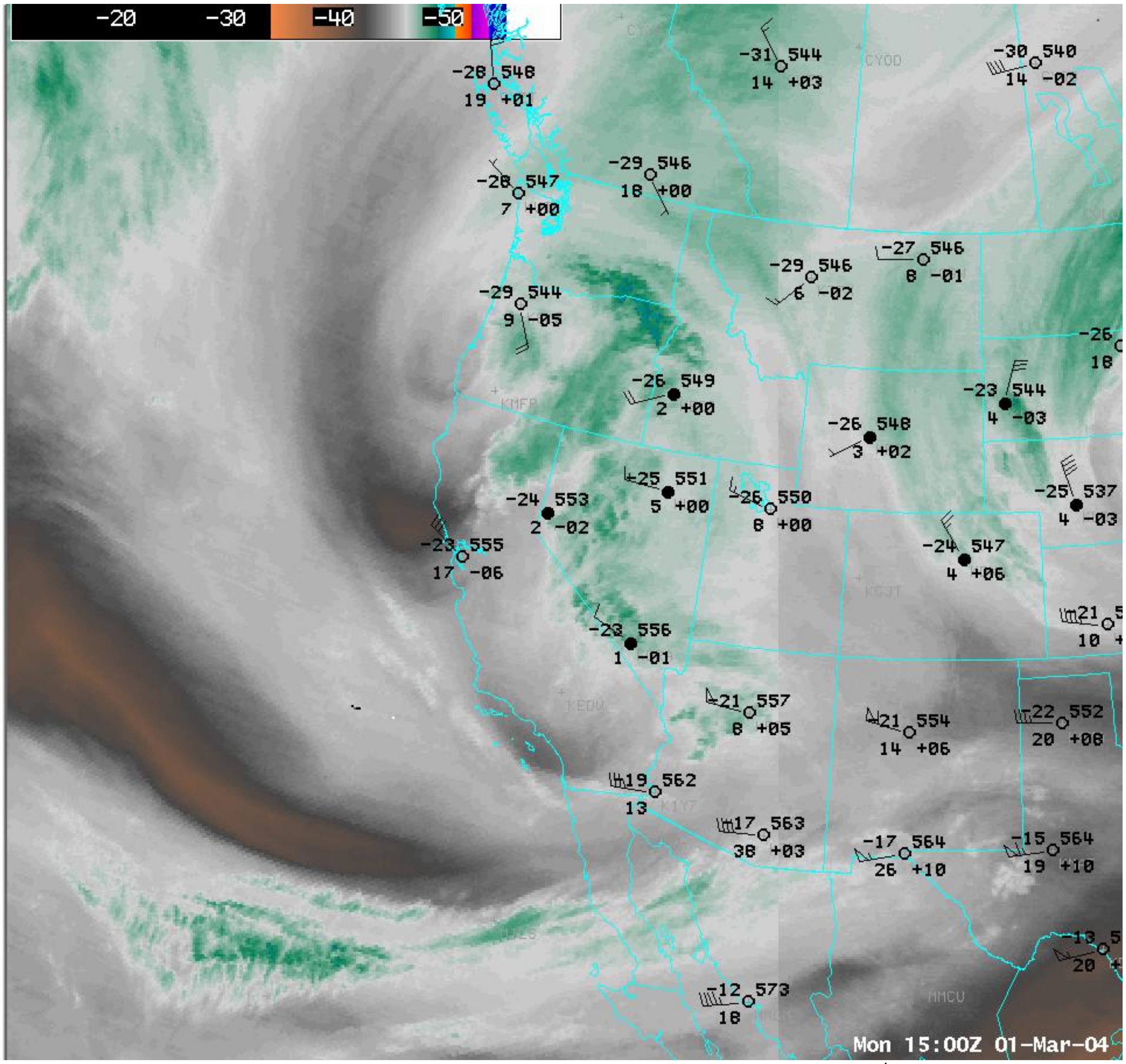


Figure 1: Water Vapor Image 15z and 500mb Sounding Plot 12z from March 1st 2004.

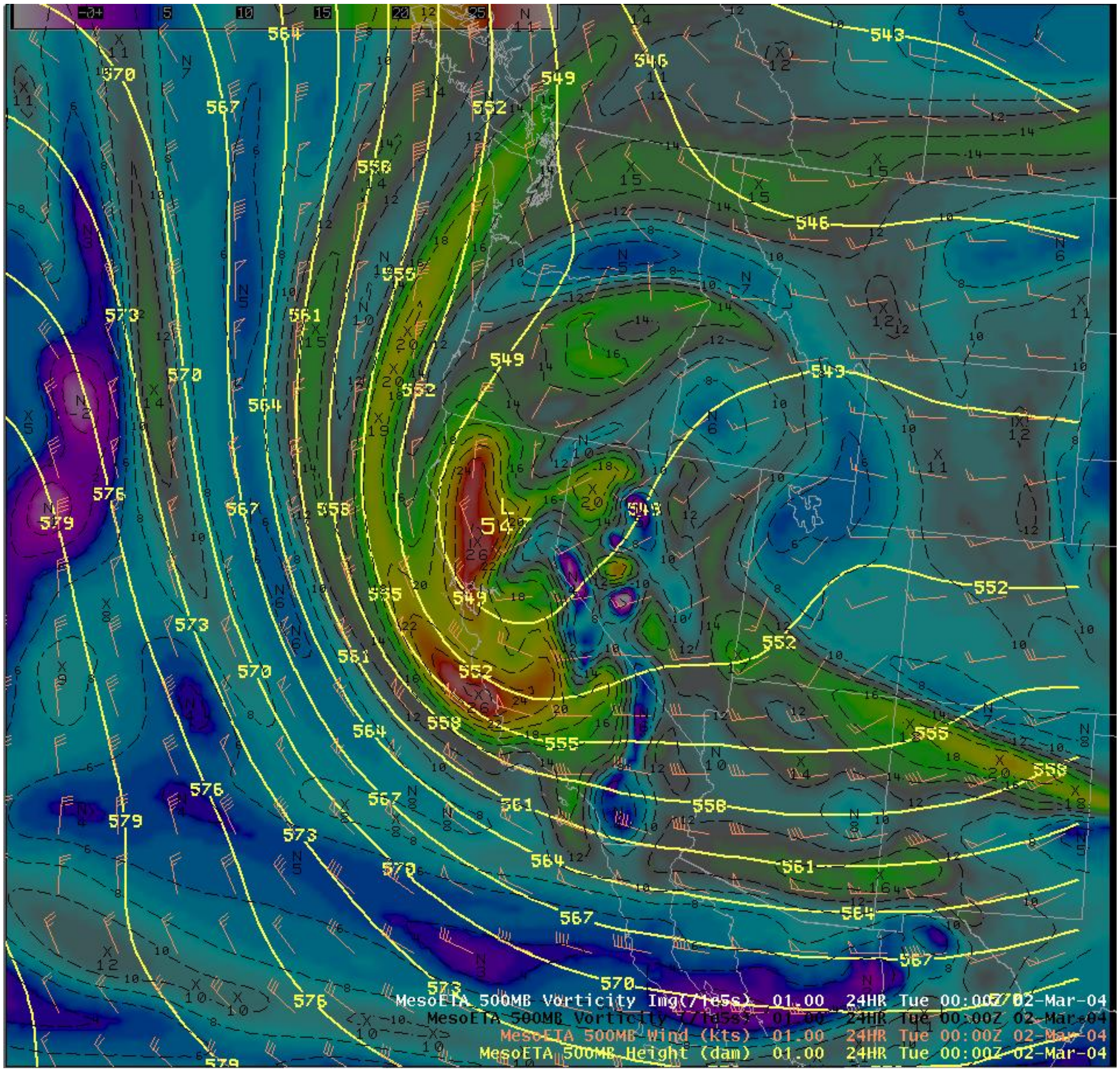


Figure 2: Eta40 24hr forecast of 500mb heights (yellow), winds(orange) and vorticity (image) valid 00z March 2nd 2004.

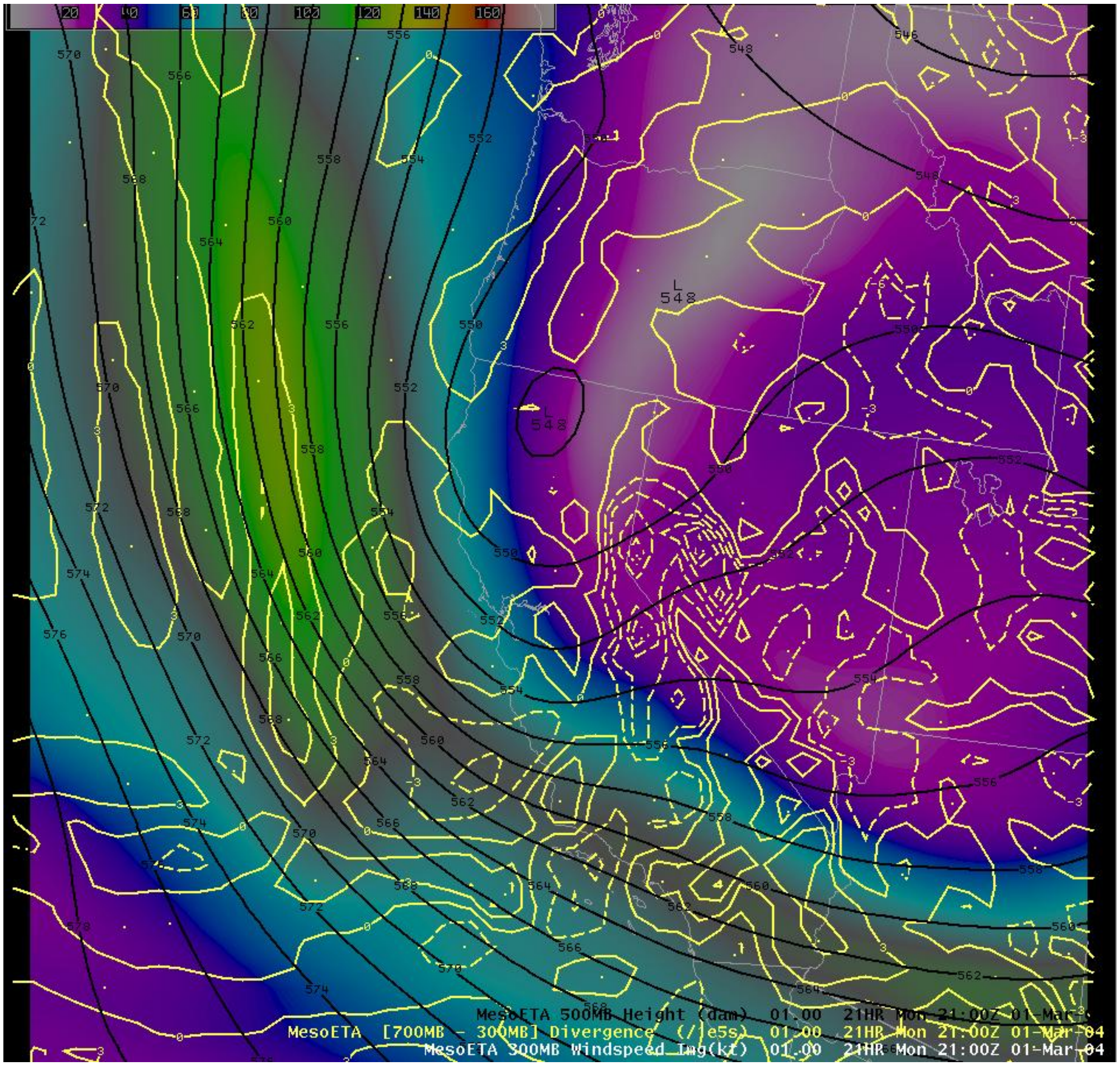


Figure 3: Eta40 21hr forecast of 500mb heights (black), 300mb divergence subtracted from the 700mb divergence (yellow) valid 21z March 1st 2004. Dashed yellow lines are negative values and represent a 700mb convergence 300 mb divergence couplet.

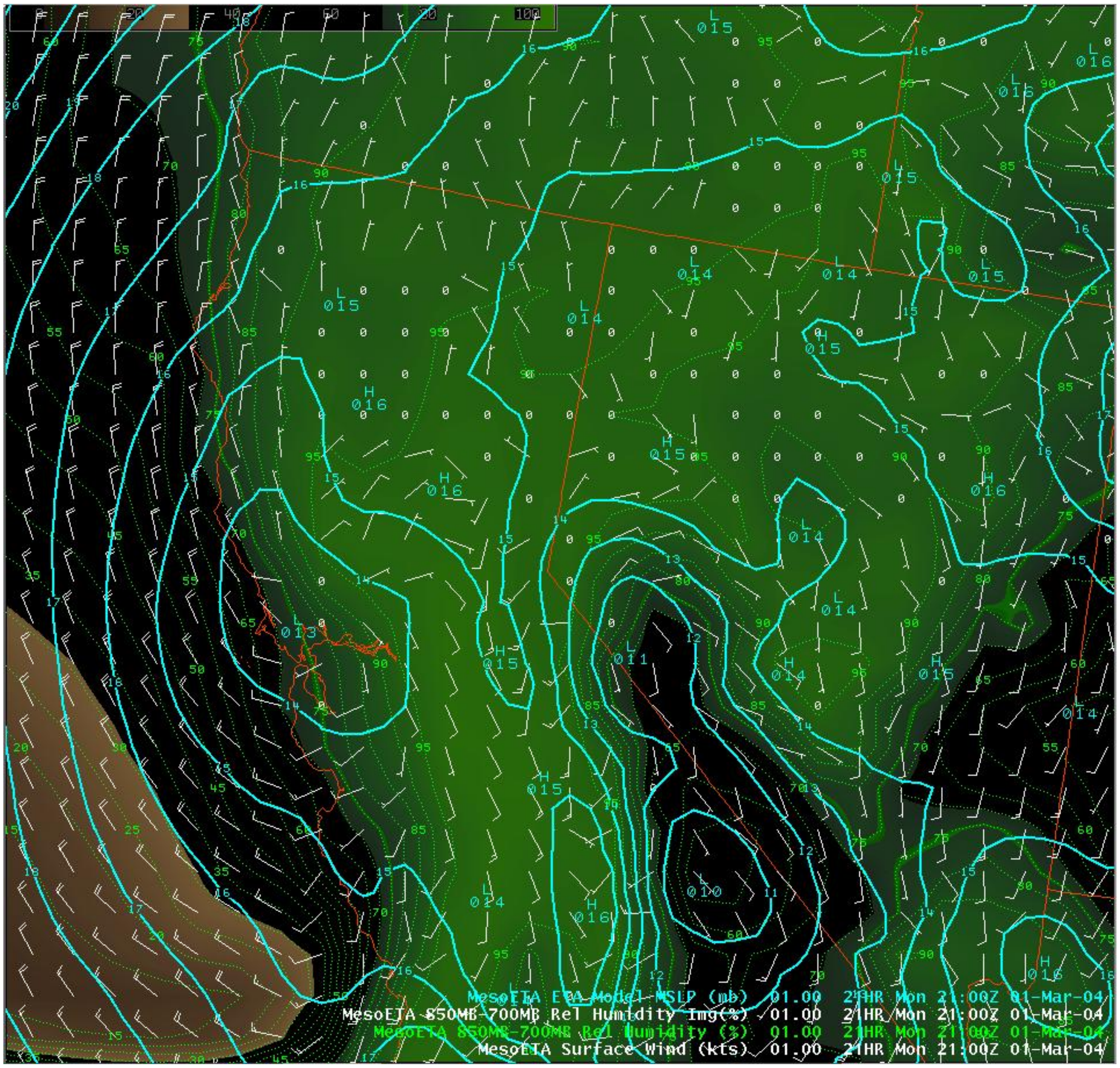


Figure 4: Eta40 21hr forecast for MSLP(blue), Surface Winds and 850mb to 700mb layer moisture (green shade is RH >70%) valid 21z March 1st 2004.

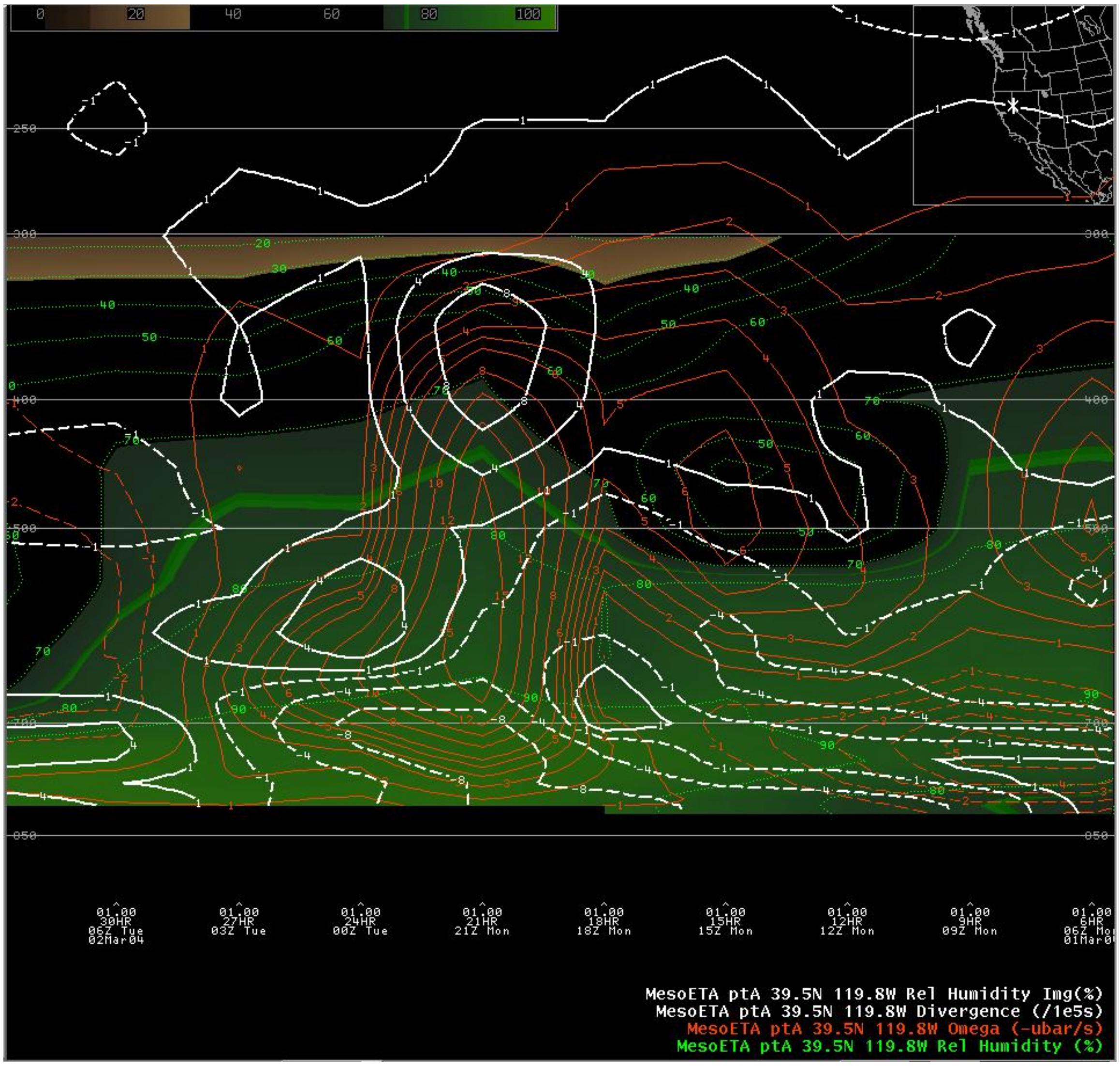


Figure 5: 00z March 1st Eta40 Time Series at Reno from 06z March 1st (right) to 06z March 2nd (left). Omega (red), Divergence (white), Relative Humidity (green shade is RH > 70%).

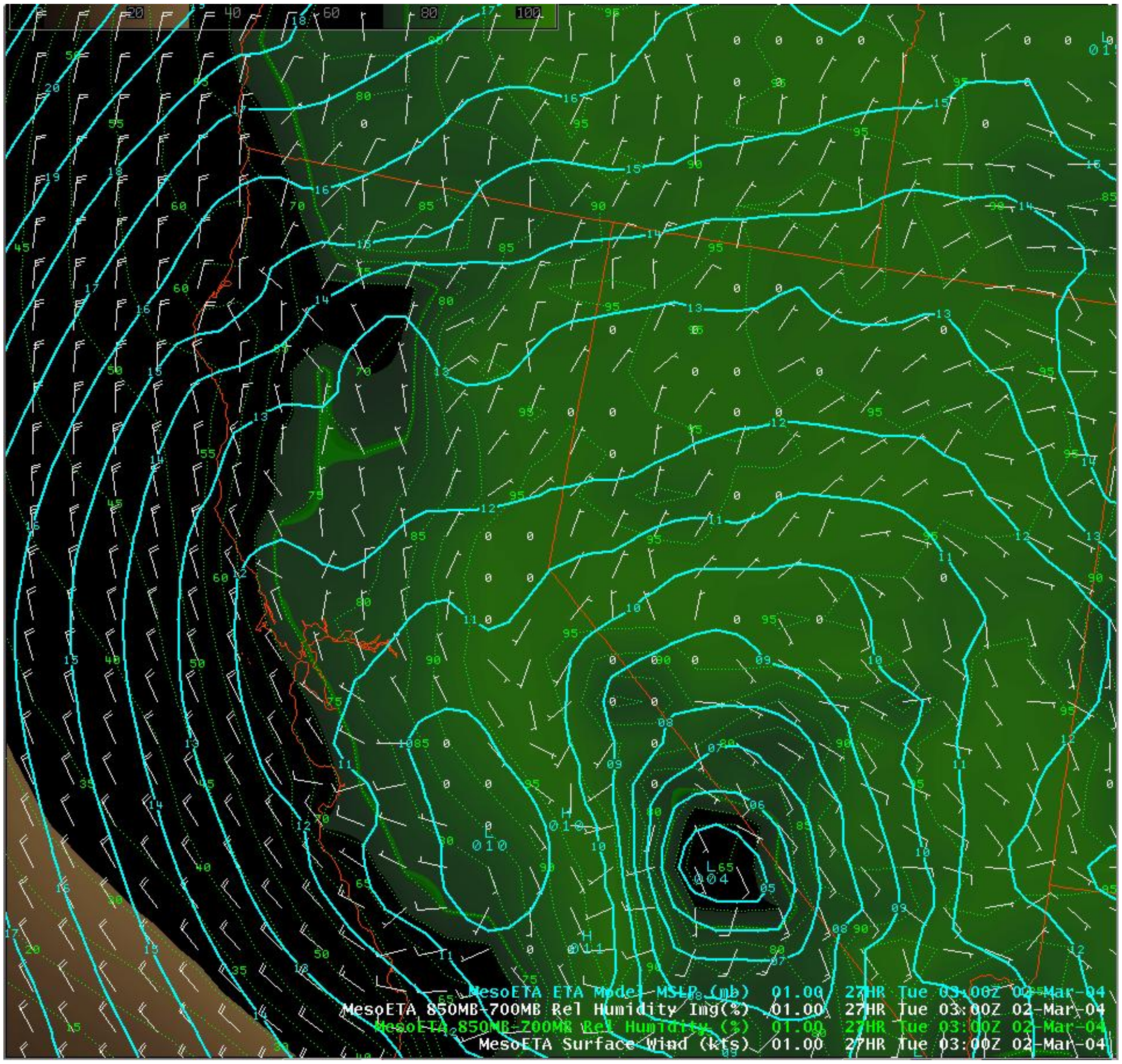


Figure 6: : Eta40 27hr forecast for MSLP(blue), Surface Winds and 850mb to 700mb layer moisture (green shade is RH >70%) valid 03z March 2nd, 2004.

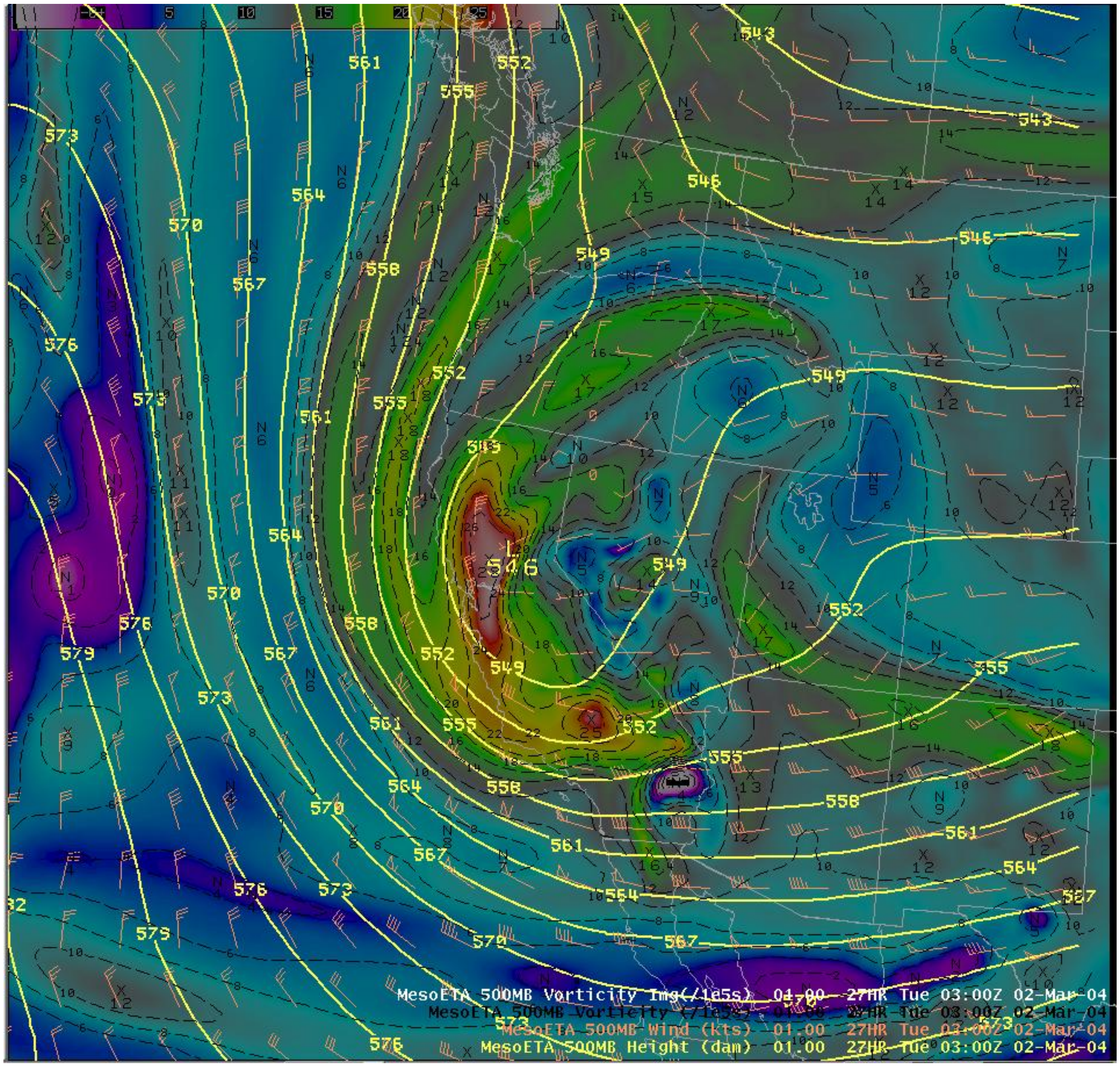


Figure 7: Eta40 27hr forecast of 500mb heights (yellow), winds(orange) and vorticity (image) valid 03z March 2nd, 2004.

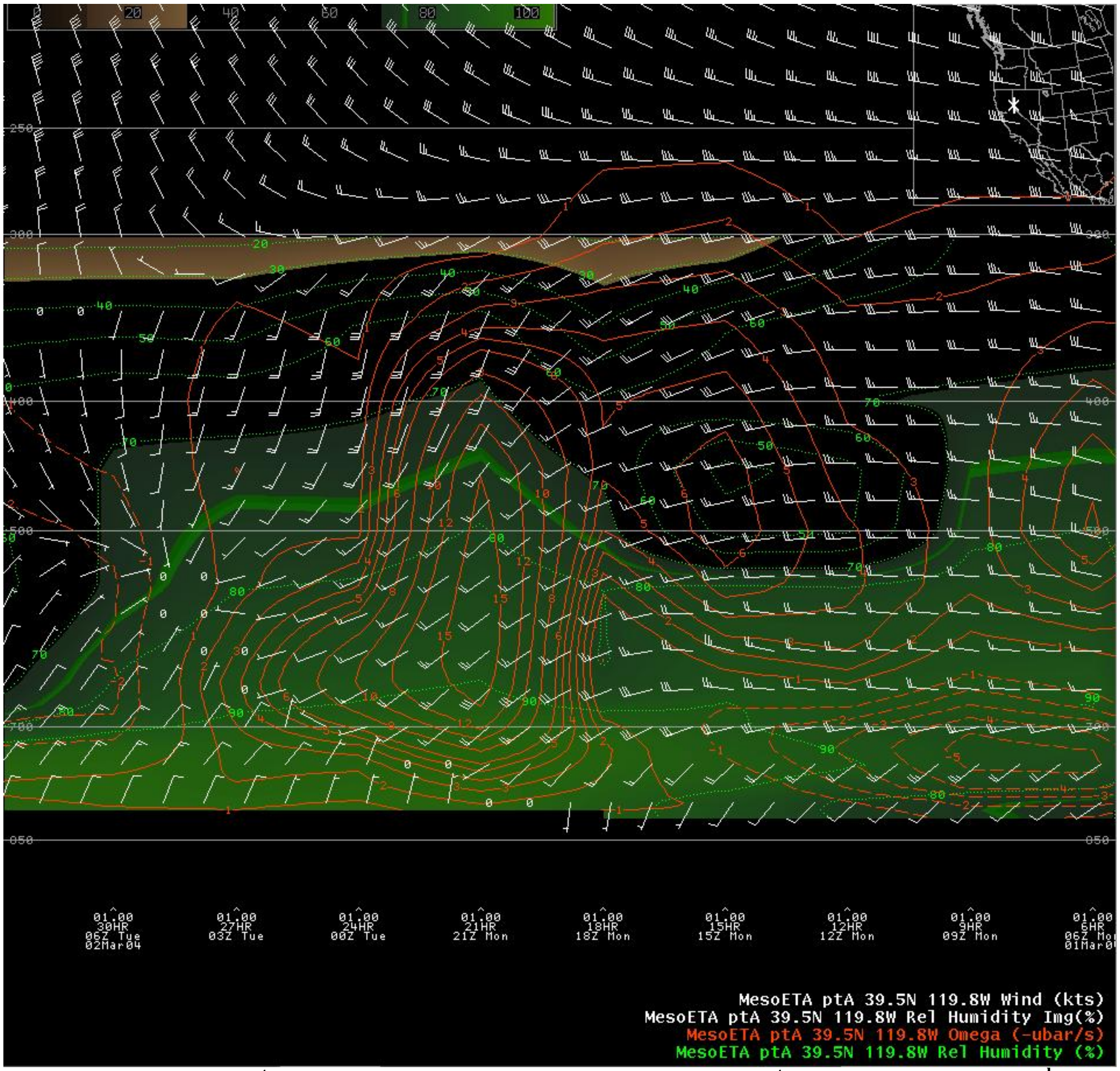


Figure 8: 00z March 1st Eta40 Time Series at Reno from 06z March 1st (right) to 06z March 2nd (left). Omega (red), Winds (white), Relative Humidity (green shade is RH > 70%).

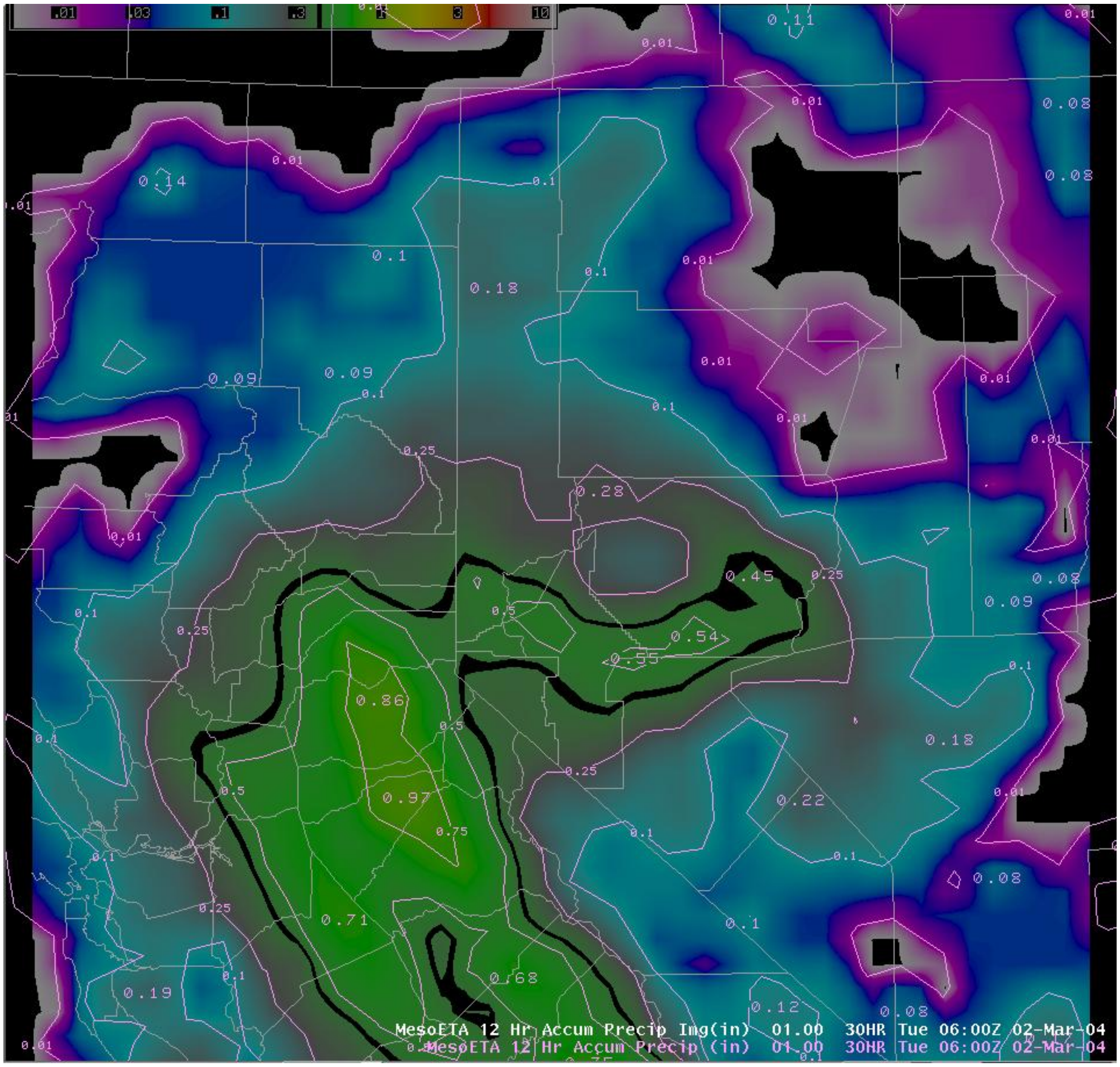
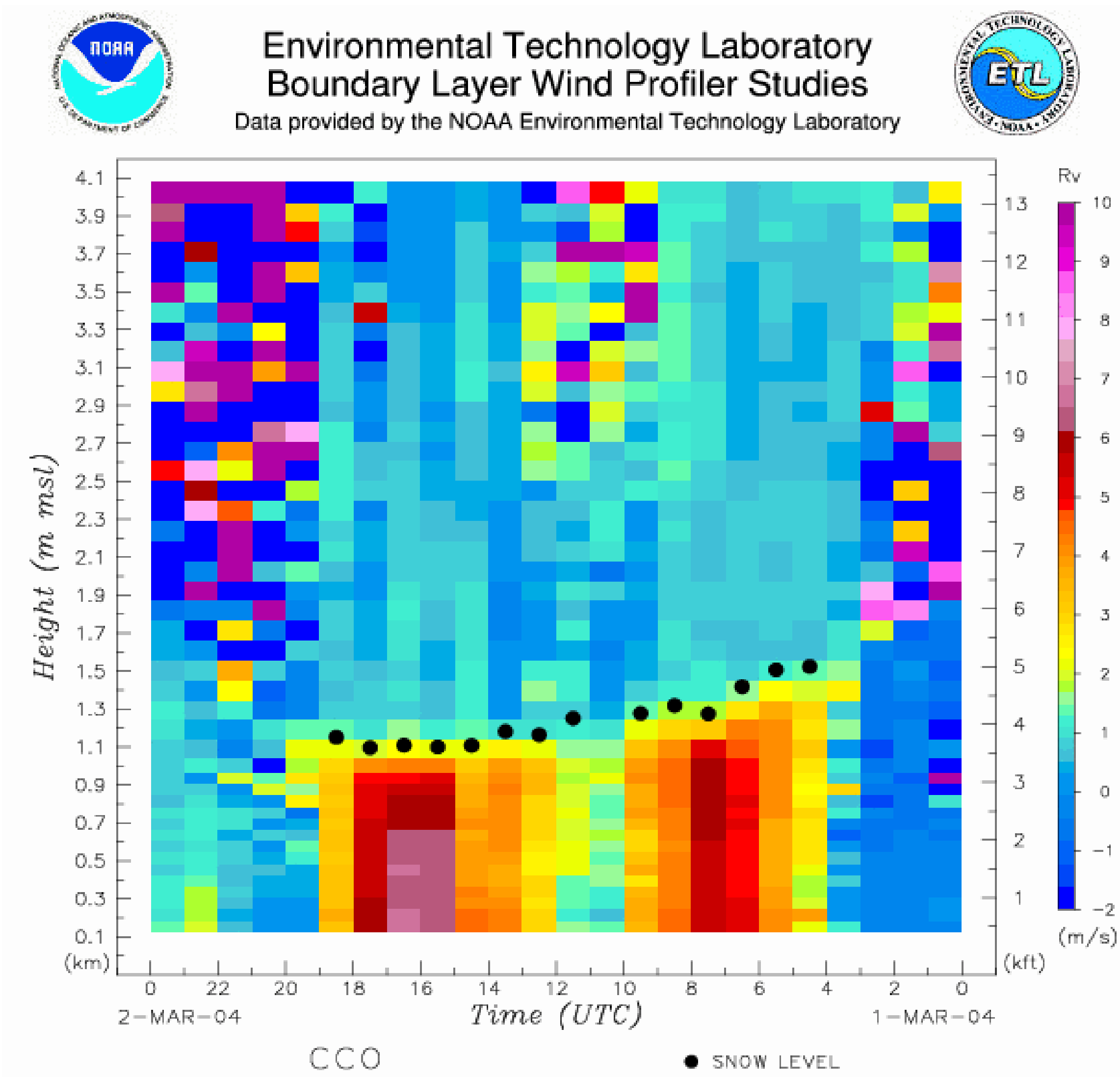


Figure 9: Eta40 12hr QPF ending 06z March 2nd, 2004. Black band is approximately 0.40 inches.



Time (UTC)	2330	2230	2130	2030	1930	1830	1730	1630	1530	1430	1330	1230
Snow Level (m)	none	none	none	none	none	1151	1096	1109	1100	1108	1181	1164
Snow Level (ft)	none	none	none	none	none	3775	3594	3637	3607	3634	3873	3817
Sfc Temp (C)	8.50	8.03	8.63	8.00	9.14	8.65	7.98	7.94	7.85	8.20	8.53	8.58

Time (UTC)	1130	1030	0930	0830	0730	0630	0530	0430	0330	0230	0130	0030
Snow Level (m)	1251	none	1277	1319	1275	1418	1507	1524	none	none	none	none
Snow Level (ft)	4103	none	4188	4326	4181	4651	4942	4998	none	none	none	none
Sfc Temp (C)	8.57	8.83	9.02	8.98	9.08	9.76	10.38	11.14	11.60	12.25	13.06	13.34

Figure 10: Snow Level (black dots) data from Chico Profiler between 00z March 1st and 00z March 2nd, 2004.

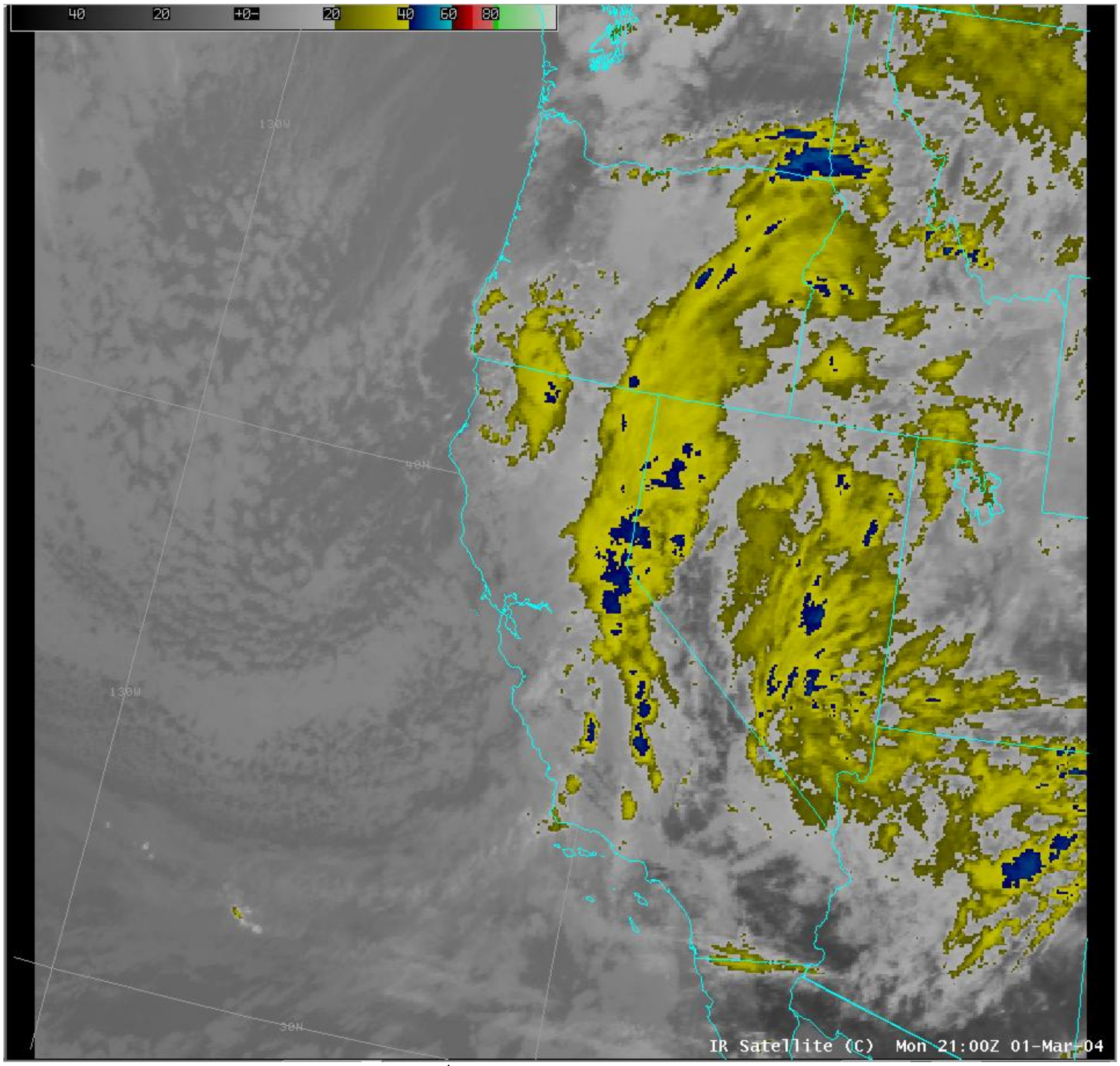


Figure 11: IR Image from 21z March 1st, 2004.

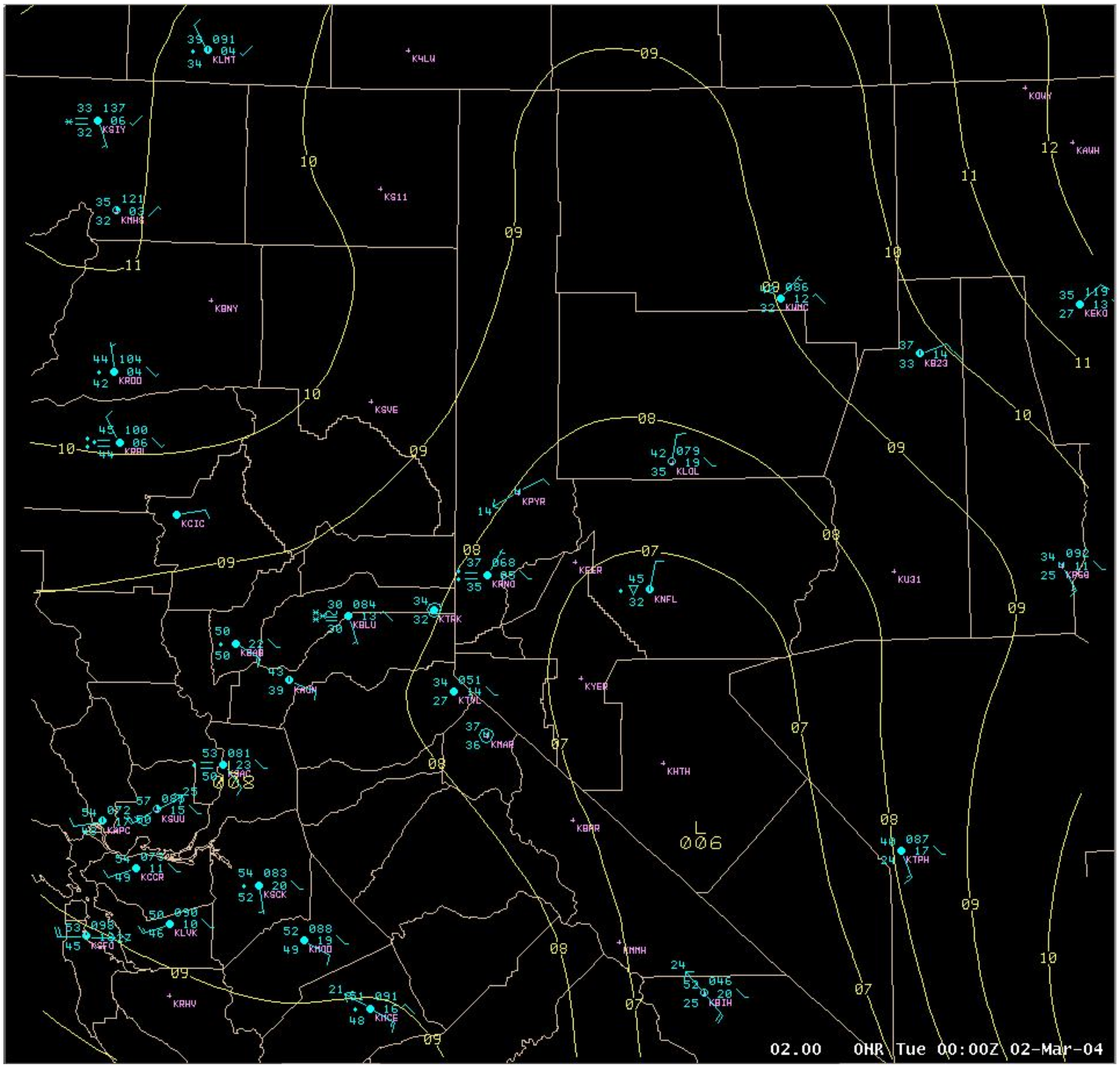


Figure 12: LAPS Mean Sea Level Pressure Analysis and Surface Observations from 00z March 2nd, 2004.

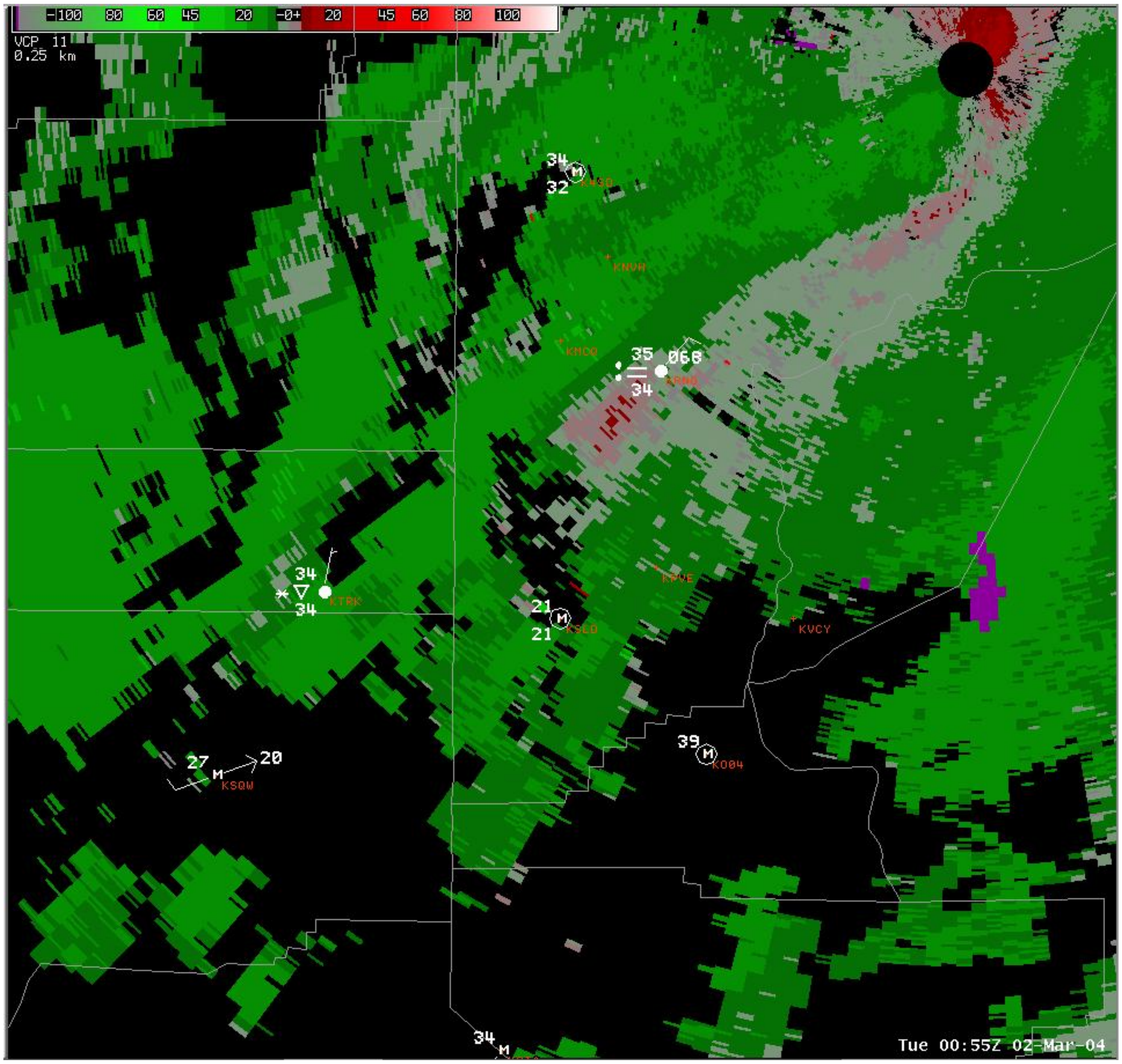


Figure 13: KRGX (black circle upper right) 0.5 velocity and surface observations from 01z March 2nd, 2004.

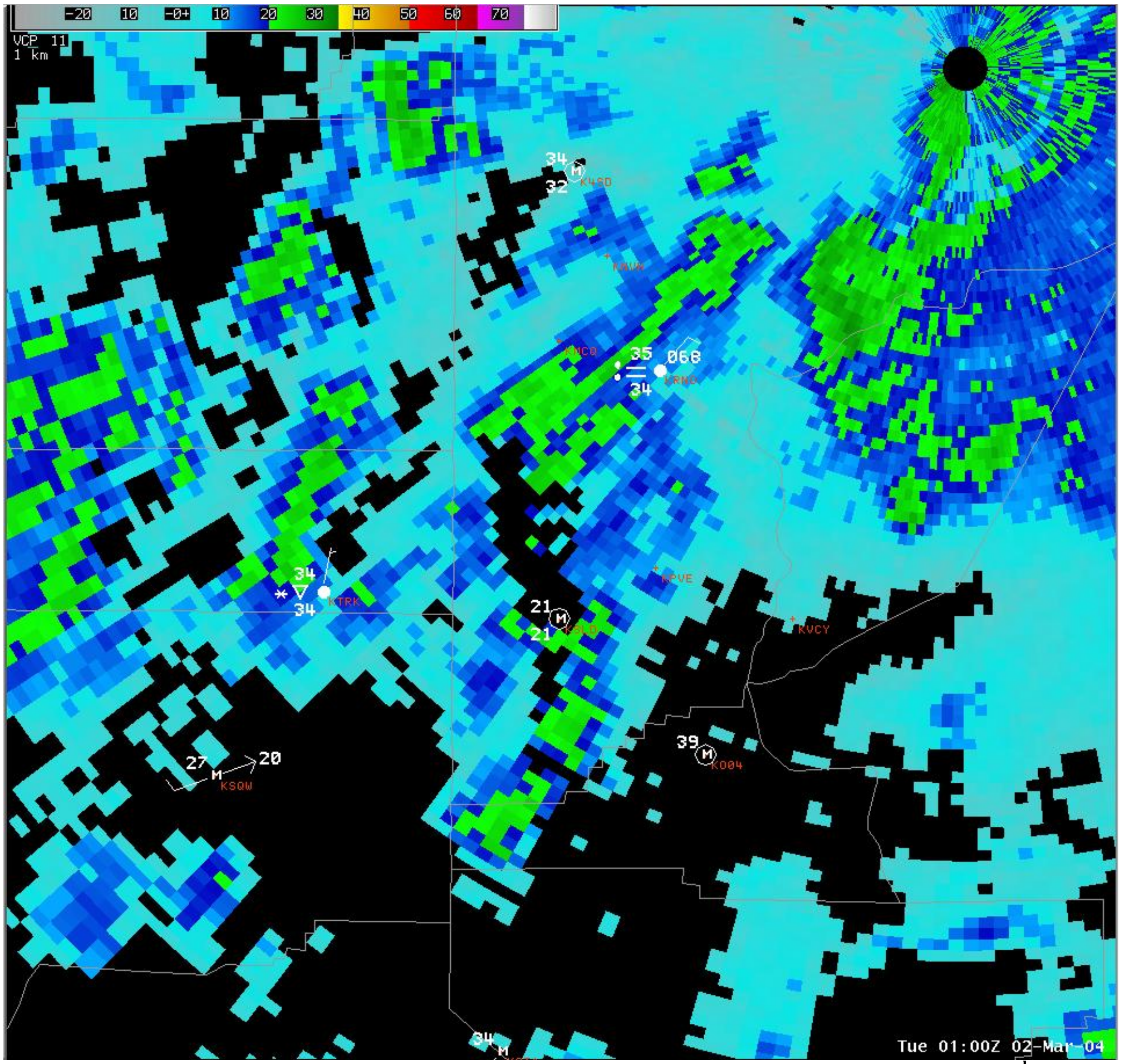


Figure 14: KRGX (upper right) 0.5 reflectivity and surface observations from 01z March 2nd, 2004.

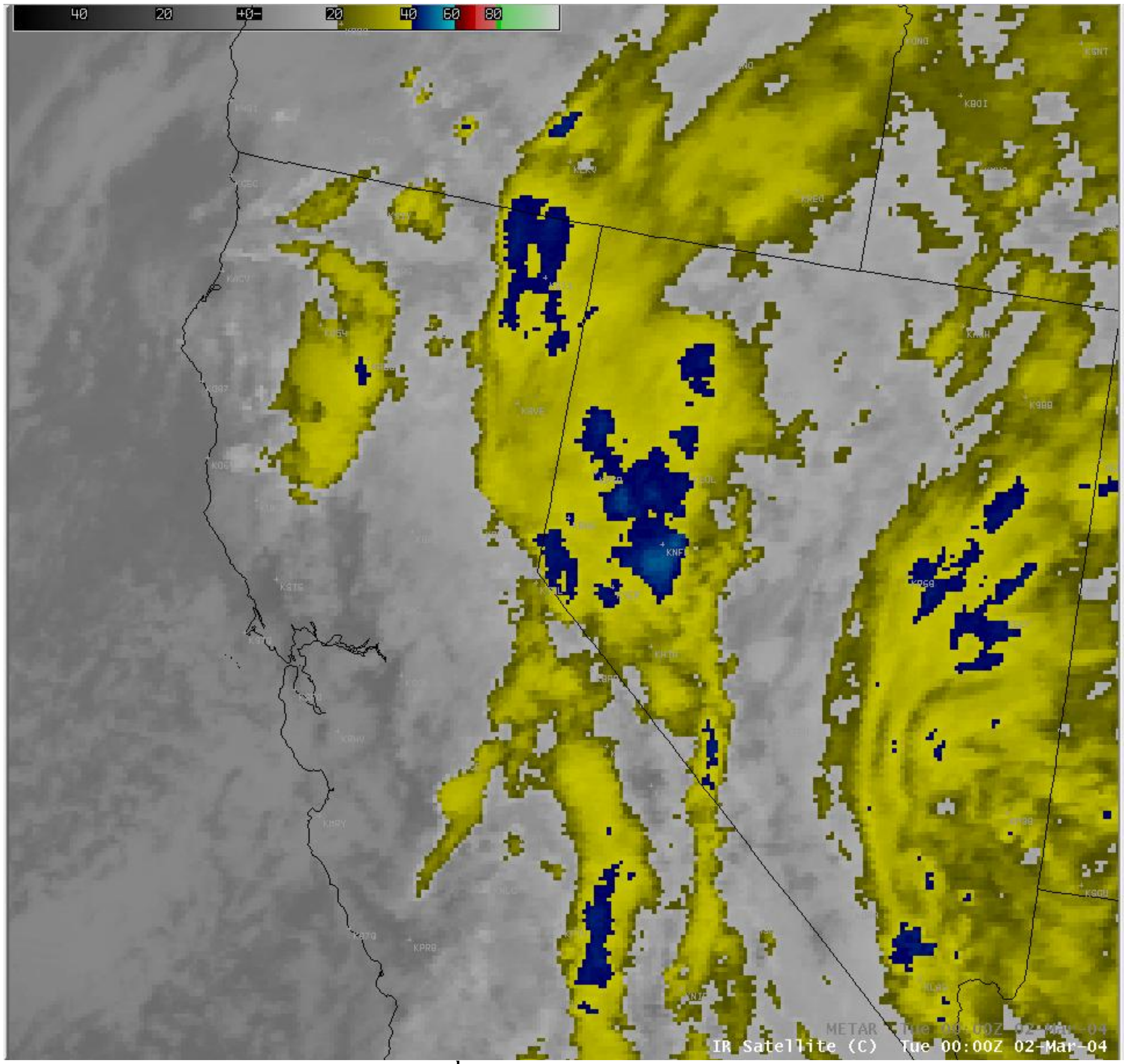


Figure 15: IR Image from 00z March 2nd, 2004. Yellow shade is -20C to -40C, blue is -40C to -60 C.

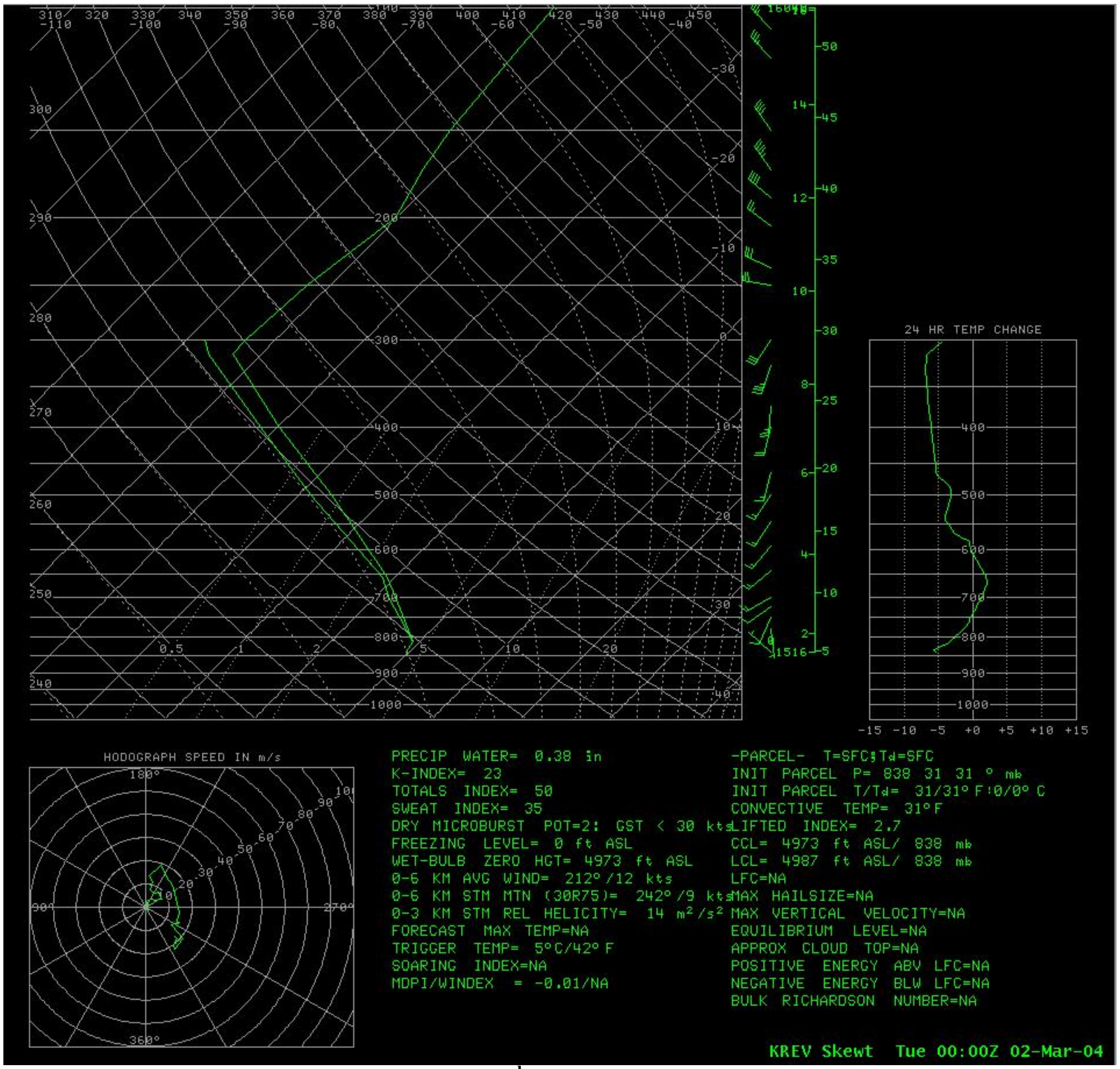


Figure 16: Reno Sounding from 00z March 2nd, 2004.

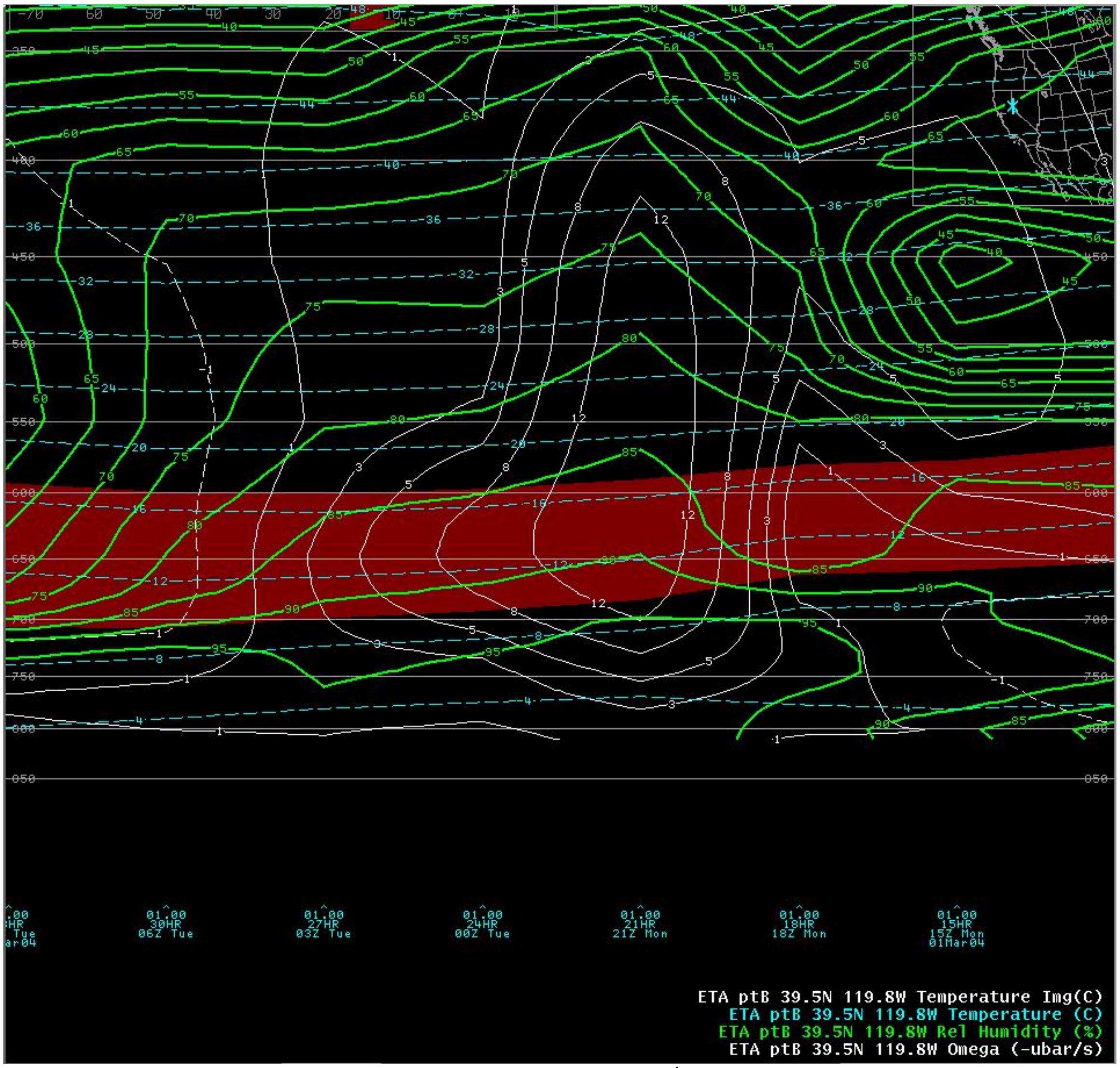


Figure 17: Eta40 Time Series at Reno from the 00z March 1st run. Omega (white), Relative Humidity (green) and -10C to -17C Temperature band (red).