DEVELOPMENT AND PROPAGATION OF A NARROW COLD FRONTAL RAIN BAND IN THE SIERRA NEVADA OF NORTHERN CALIFORNIA

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1. ABSTRACT

On January 4, 2008, the Northern Sierra Nevada and Northern Nevada region experienced a significant precipitation event with the passage of a surface cold front and upper level trough. Both the Lake Tahoe region and Truckee Meadows area received rain which turned to heavy snow over the day. Although the forecast by the National Weather Service predicted a change from rain to snow on this day, it missed the timing of the precipitation change by nearly six hours. The precipitation change from rain to snow during this storm was likely due to a narrow cold frontal rain band (NCFR) which formed in the left exit region of an upper level jet streak. This paper will explore the dynamics of this event as it moved across Northern California and into Northwestern Nevada using both observational and model generated data to determine what phenomena occurred at both the synoptic and meso-scales.

The Weather Research and Forecasting Model (WRF) was employed to enhance the observational data of the NCFR event (Michalakes, 1999). A number of sensitivity studies were run to determine how to best capture the observed features. The WRF was only able to correctly diagnose the frontal wind shift late in the day when it was initialized approximately three hours before the arrival of the NCFR at Truckee, California. This result showed the model's lack of ability to capture the mesoscale dynamics of the event when initialized earlier, the difficulty of forecasting the event, and the model's sensitivity to initial conditions.

Both observations and WRF model results support the conclusion that ahead of the cold front a NCFR developed in conjunction with a subsynoptic low pressure center that brought intense precipitation to a very narrow region on the upslope of the Sierra Nevada. Additionally, the change from rain to snow was slowed by warm air advection due to a strong, narrow southerly low-level jet which transported a latent heating-fortified warm air surge from near Mammoth Lakes and Bishop, California, keeping the melting level high and preventing formation of snow. As the winds turned from out of the south to southwesterly effectively cutting off the source of warm air, both the NOAA profiler observations and the model show a change from rain to snow and the progression of the cold front into the Truckee and Reno areas.

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2. INTRODUCTION

On January 4, 2008, the Northern Sierra Nevada and Northern Nevada region experienced a precipitation event with the passage of a surface cold front and upper level trough. Both the Lake Tahoe region and Reno area received rain which turned to snow over the day. Although the forecast by the National Weather Service predicted a change from rain to snow on this day, it missed the timing of the precipitation change by hours. This paper will explore the dynamics of this event as it moved across Northern California and into Northwestern Nevada to determine what dynamical, thermodynamical, and microphysical phenomena occurred at both the synoptic and meso-scales.

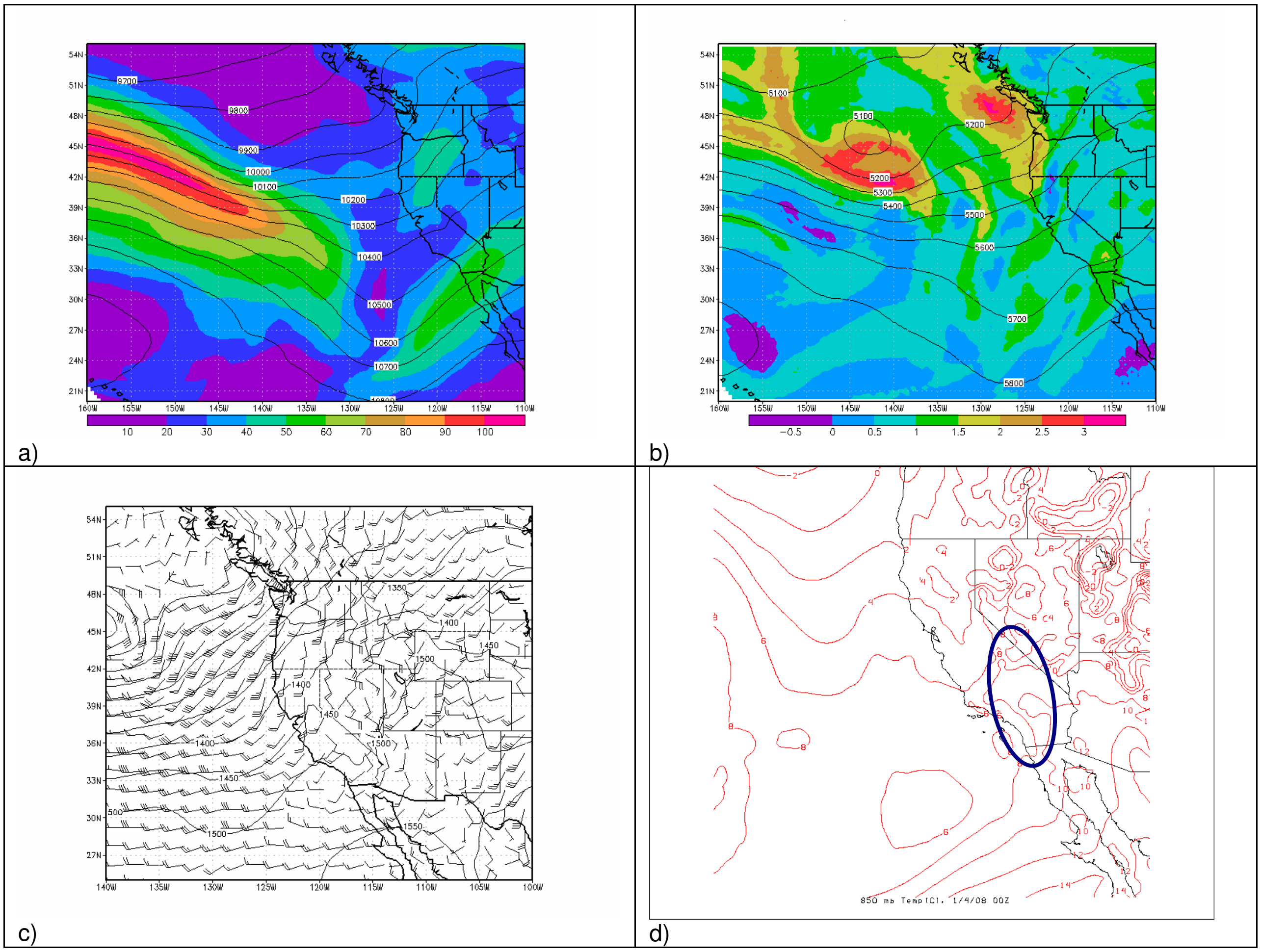


Figure 1: NARR analysis for 1/4/2008 at 00 GMT for a) 250 mb geopotential heights, wind speed, b) 500 mb heights, absolute vorticity, c) 850 mb heights, wind barbs (knots), and d) 850 mb temperatures (℃), blue oval shows region of warm advection by the most southeasterly low level ageostrophic circulation.

As a cold front passes, there may be development of a narrow band of heavy rain, called a narrow cold frontal rain band (NCFR) (Browning, 1994).

These rain bands often have large updrafts and high precipitation rates associated with them, and are generally embedded within a larger scale area with light rain due to lifting over a cold front (Browning, 1994). The NCFR usually occurs just ahead of the cold front due to a build up of mass behind the cold front (Koch and Kocin, 1991). NCFRs are generally characterized by strong cross-frontal gradients over a small spatial area (1 km or less), shallow, strong updrafts at the leading edge of a cold front even though the warm air ahead of the front is convectively stable or neutral, and heavy precipitation in a line along the front (Parsons, 1992).

In order to better understand the dynamics and thermodynamics occurring during this event, both observational and model generated data will be used. Observational data from the North American Regional Reanalysis (NARR) (Mesinger, 2006), the Plymouth State Weather Center analysis, NEXRAD, the Total Ozone Mapping Spectrometer (TOMS), rawinsonde data, station observations, satellite imagery, and wind profiling radar will be used in this study. The simulation employed the operational version of the Weather Researching and Forecast Model (WRF) and used North American Mesoscale Model (NAM) analysis data from 00:00, 12:00, and 18:00 GMT on January 4, 2008 to initialize the model. Data from both a 9 kilometer and a 3 kilometer grid size run will be used to enhance the observational data and further interpret this event because it is significantly more detailed than the observational data.

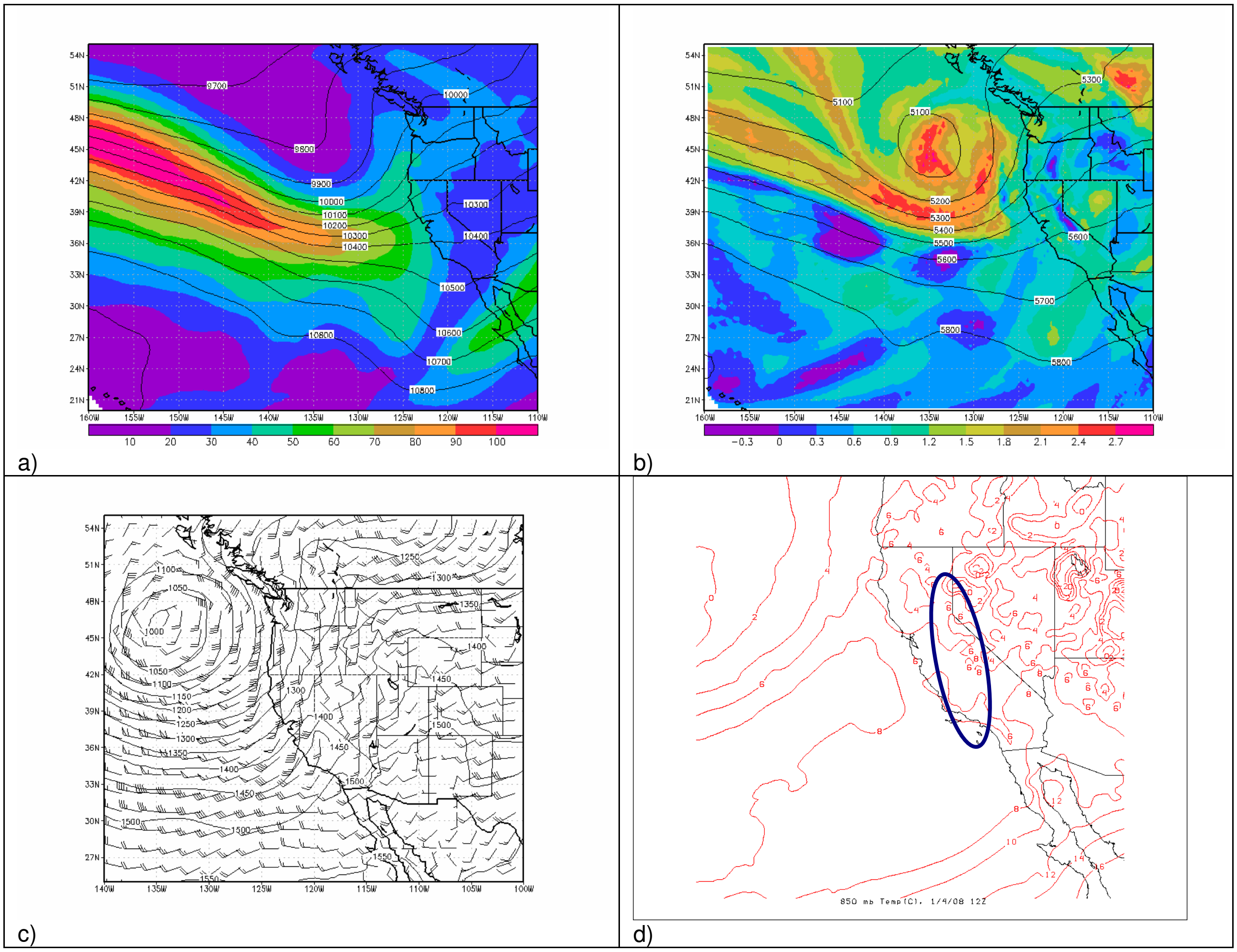


Figure 2: NARR analysis for 1/4/2008 at 12 GMT for a) 250 mb geopotential heights, wind speed, b) 500 mb heights, absolute vorticity, c) 850 mb heights, wind barbs (knots), and (d) 850 mb temperatures (℃), blue oval shows region of warm advection by the most southeasterly low level ageostrophic circulation.

3. OBSERVATIONS

3.1 *Jet and Synoptic Scale Dynamics*

At the large scale, the January 4 event is characterized by an approaching low pressure system, jet streak, and cold front as shown in Figure 1. Over the time period from January 3 through January 5, an upper level trough and jet streak approach the Northern California and Nevada area placing the region in the left exit region of the jet and bringing very cold air over the region.

The 250 mb NARR analysis for 00 GMT on January 4, shown in Figure 1, shows that the Northern California and Nevada region is under the influence of an upper level trough and a powerful polar jet (PJ) is approaching the west coast of the United States. To the southeast, a subtropical jet (STJ) is located over Baja California and Southern California and extends to the northeast over Arizona. It is likely that the right exit region of the PJ is interacting with the left entrance region of the STJ to the west of Baja California based on their collocation. At 500 mb, the upper level trough is approaching the west coast and has relatively high levels of absolute vorticity associated with the base of the trough. At 850 mb, a trough to the west of British Columbia and the Pacific Northwest, associated with the upper level low pressure system, is advecting a large amount of cold air into the area with a cold core low off the British Columbia coast. There is also a short wave, subsynoptic ridge evident in the 850 mb analysis over Southern California and a southwest to southerly flow over California's Central Valley is advecting warm air towards Northern California. This results in two plumes of low-level ageostrophic warm air advection with a strong one to the northwest and a weak one to the southeast.

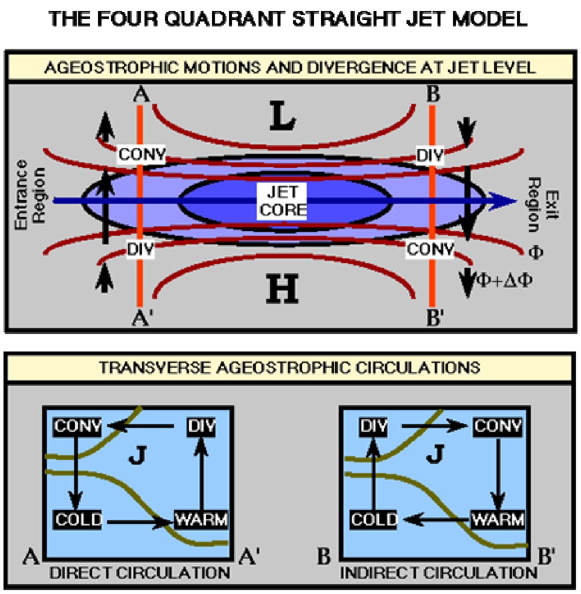


Figure 3: The four quadrant straight jet model (Uccellini, 1987).

By 12 GMT on January 4, shown in Figure 2, the PJ has moved to the east and Northern California and Nevada are located in the left exit region of the jet, Southern California and the region to its south is located in the right exit region of the jet. Both the PJ and the STJ appear to be straight jet streaks and we would expect them to act as the model of a four-quadrant jet streak (Uccellini, 1987). Therefore, the left exit region of each jet should be characterized by divergence aloft leading to rising motion, convergence at the surface and lower levels, and a thermally indirect ageostrophic circulation transverse to the jet as shown in Figure 3. This circulation should set up a low level jet from the south in the jet exit region over California and Nevada.

Both the right exit region and the left entrance region of a straight jet tend to have subsidence and build regions of high pressure. In this case, the right exit region of the PJ and the left entrance region of the STJ overlap which creates a zone of convergence, amplifying the subsidence, increasing the transverse ageostrophic circulation (e.g., southerly winds over central and northern California at 850 mb), and building a ridge which can be seen over Southern California. This ridge is likely a high frequency adjustment due to the phasing of the PJ and the STJ. The low level southerly winds advect a secondary region of warm air from the south into the region of the central Sierra Nevada Mountains, as shown in Figure 2(d) as a warm tongue extending from Southern California to the Lake Tahoe region.

We would expect surface and low level winds out of the south over most of Northern California and Nevada due to the transverse ageostrophic circulation and frontogenesis in this area due to rising of cold air in the left exit region and sinking of warm air in the right exit region thus intensifying the north/south temperature gradient. In Miller's Frontogenesis Equation (Shapiro, 1981), this will cause a positive forcing (frontal development) through the tilting terms of the equation:

$$F \propto \frac{1}{\nabla\theta}\left(-\frac{\partial\theta}{\partial y} * \frac{\partial w}{\partial y}\frac{\partial\theta}{\partial z}\right)$$

$$\frac{\partial\theta}{\partial y} < 0, \frac{\partial w}{\partial y} > 0, \frac{\partial\theta}{\partial z} > 0,$$

$$\textit{therefore}$$

$$F > 0.$$

As expected from the four quadrant jet model, the 850 mb (lower level) wind field is from the south and strengthens over the day; the low level jet moves from off the California coast to over northwestern Nevada over the period from 00 GMT on January 4 through 00 GMT on January 5. This southerly wind will act to advect warm air from the south into the area, keeping the precipitation at Truckee and Reno in the form of rain, not snow until the wind changes.

As Figure 4 shows, at 18 GMT on January 4, the Northern Nevada and California areas continue to be located in the left jet exit region. Northern California is in an area of positive vorticity advection, which should lead to rising motions through the quasi-geostrophic omega equation. Both Northern California and Northern Nevada are experiencing strong southerly flow at 850 mb, probably as a result of the transverse

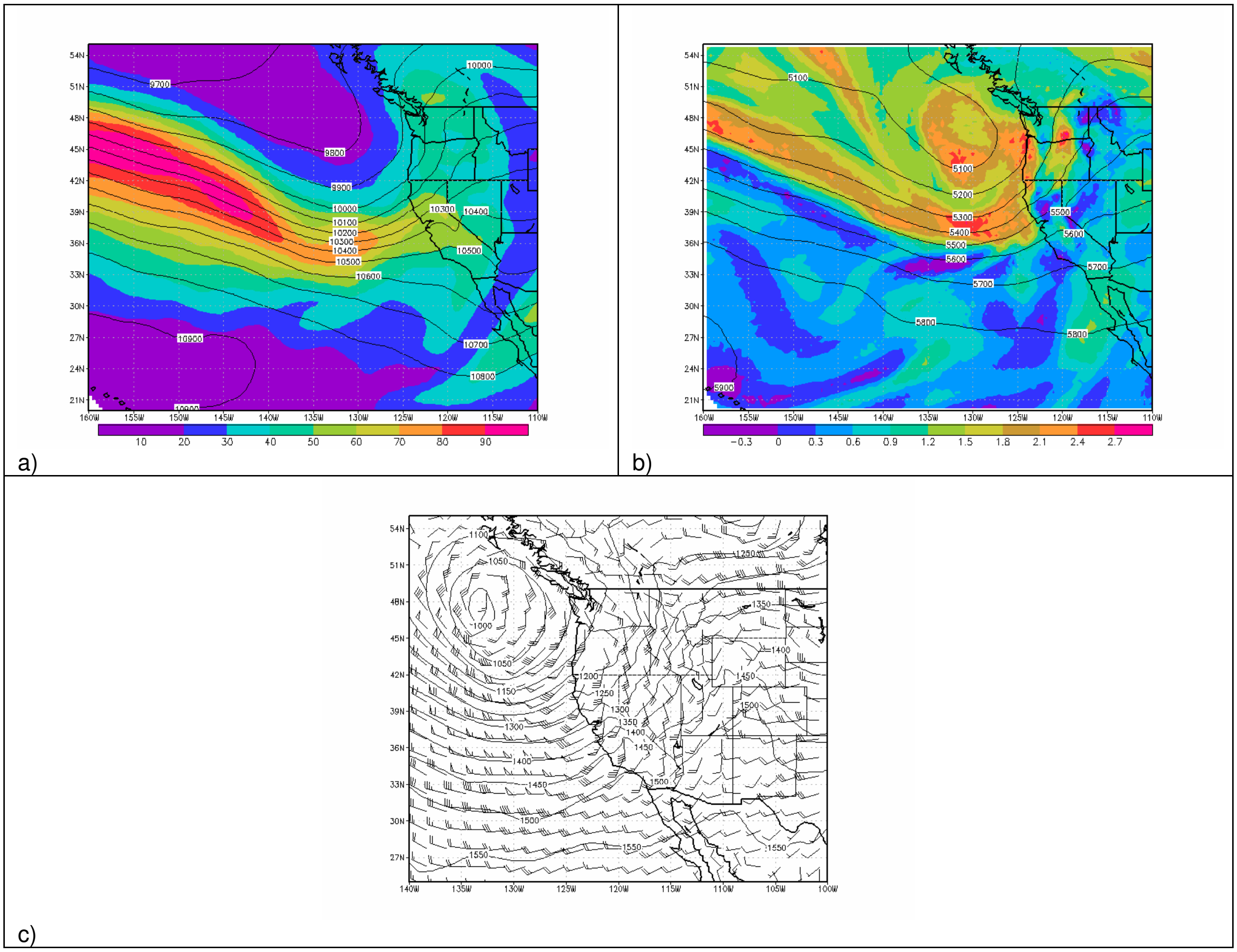


Figure 4: NARR analysis for 1/4/2008 at 18 GMT for a) 250 mb geopotential heights, wind speed, b) 500 mb heights, absolute vorticity, and c) 850 mb heights, wind barbs (m/s).

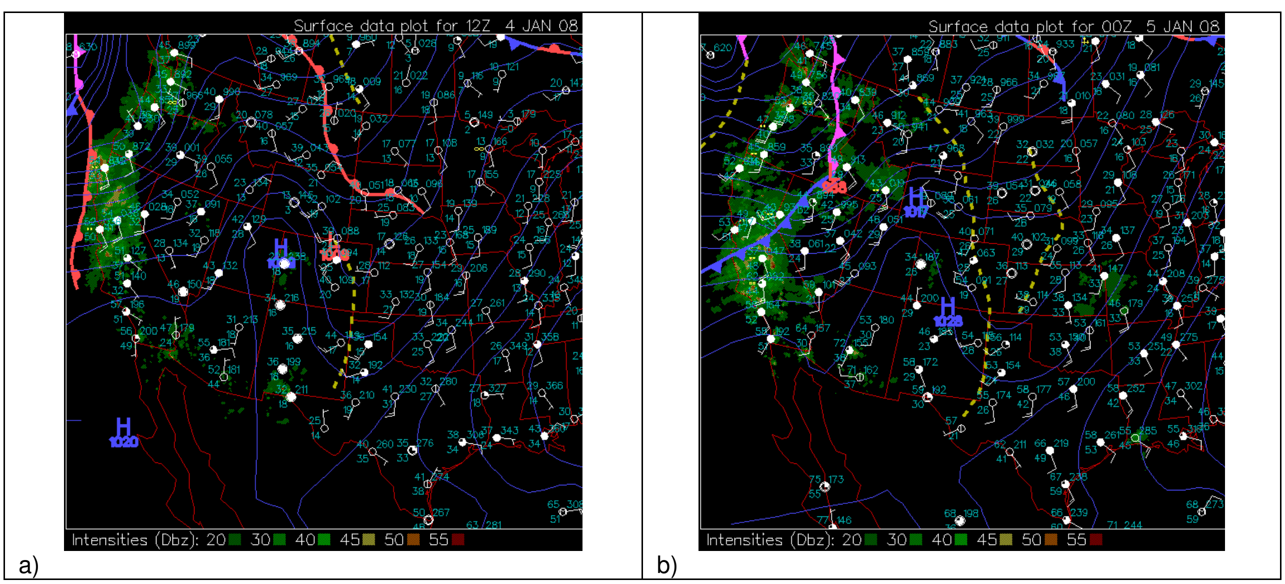
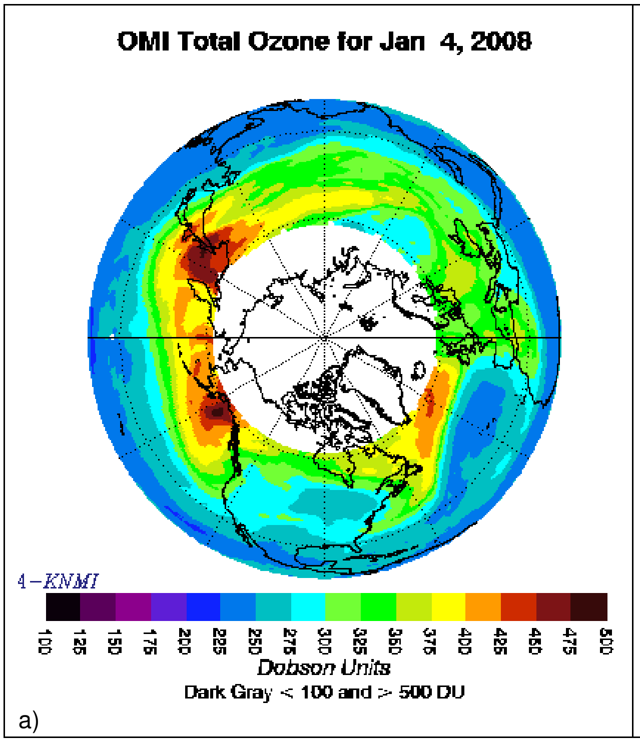


Figure 5: Surface data from a) 12 GMT on January 4, 2008 and b) 00 GMT on January 5, 2008.



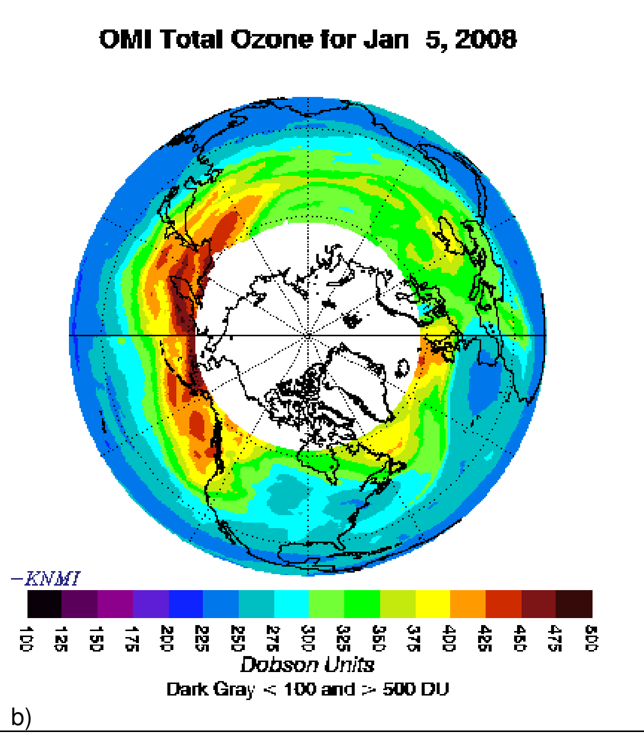


Figure 6: Northern Hemispheric view of TOMS satellite data showing total ozone for a) January 4, 2008 and b) January 5, 2008.

ageostrophic circulation driven by the jet exit region.

Looking at the surface maps on both January 4 at 12 GMT and January 5 at 00 GMT in Figure 5, an occluded surface low pressure system is approaching the west coast of the United States and Canada. At 12 GMT, there is cloudiness ahead of the warm front and mostly southerly flow over California and Nevada. At 00 GMT on the 5th, the cold front has moved to the southeast across Northern California and into Northern Nevada. The surface winds at Reno are now turned to west-southwesterly, whereas the winds ahead of the front are from the south. The low pressure center is now over the Oregon/Idaho border and surface temperatures have dropped behind the front.

This large scale upper level trough also causes an injection of stratospheric air into the troposphere on the backside of the trough. We can see this stratospheric injection using the TOMS satellite data of total ozone. Figure 6 shows the OMI total ozone for January 4 and 5, 2008. There is a large pool of high ozone air over the western part of North America at both times, illustrating the injection of stratospheric air into the troposphere. The high ozone air moves to the southwest over the period, following the upper level trough. This air likely carries high potential vorticity with it, increasing the probability of cyclone development in the area.

3.2 *Mesoscale Dynamics*

The January 4, 2008 system was characterized by an incoming upper level trough, associated cold pool, jet exit region dynamics, and positive vorticity advection at the synoptic scale. This system also has strong dynamical features in the mesoscale. This section will discuss some of those features and how they contributed to the precipitation development over Truckee and Reno.

Looking at the mean sea level pressure and surface temperature fields from 21 GMT on January 4 though 00 GMT on January 5, we see a cold pool of air associated with a mesolow just to the northwest of Truckee, CA. The cold pool at 21 GMT is centered over the area where California, Oregon, and Nevada join and a tongue of cold air is pushing south to almost Reno. The mesolow is centered over the Susanville area at 21 GMT. As time progresses,

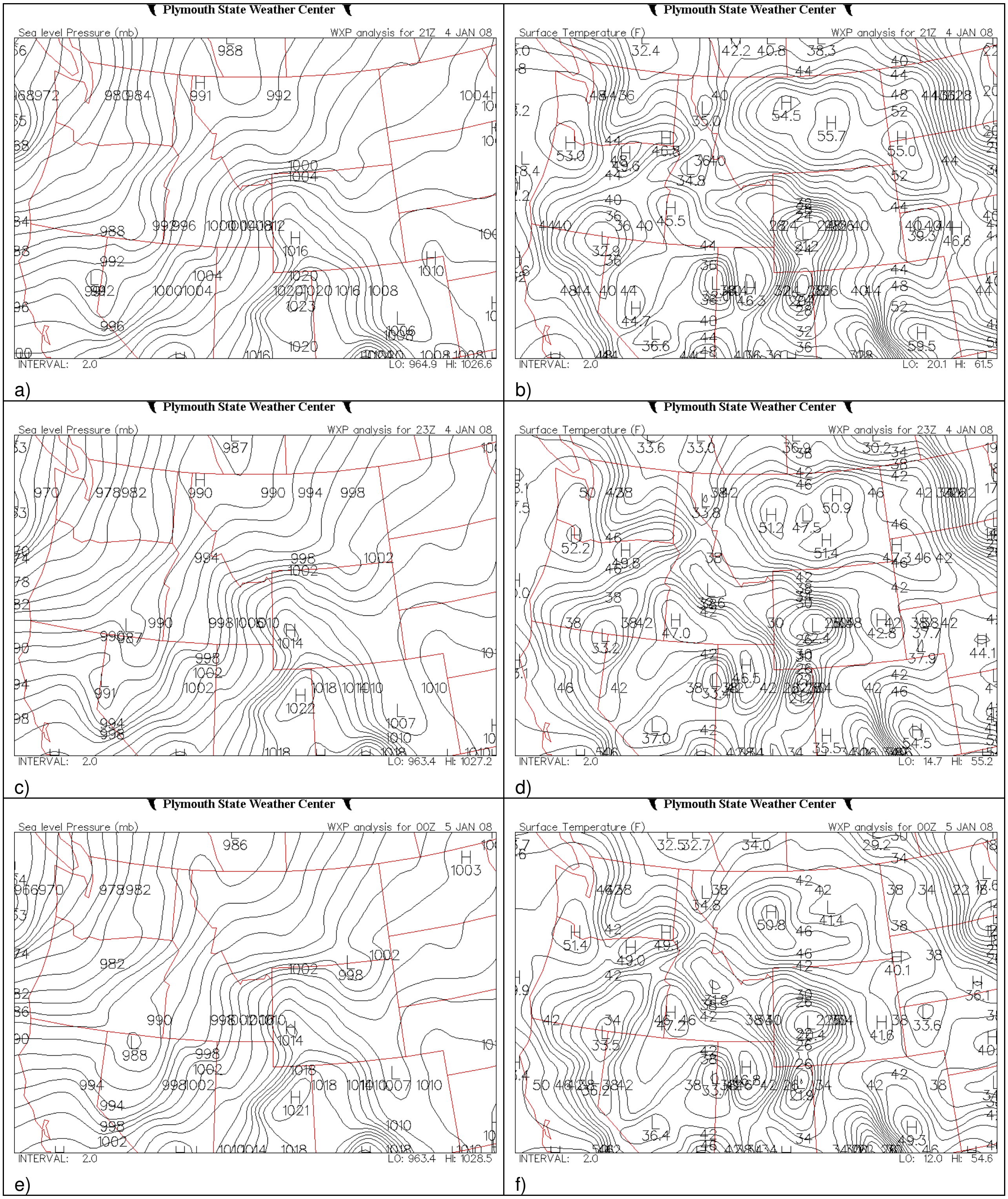


Figure 7: MSLP and surface temperature maps illustrating the cold pool and mesolow associated with the NCFR event on January 4-5 for a), b) 21Z, c), d) 23Z, and e), f) 00Z

the trough axis associated with the mesolow extends southward over the Tahoe region and then moves to the east over Reno and into western Nevada. The cold pool stays centered over the state border junction, but the cold tongue extends to the south to cover the Tahoe region. This progression of the cold pool over Truckee and Reno brings the change from rain to snow.

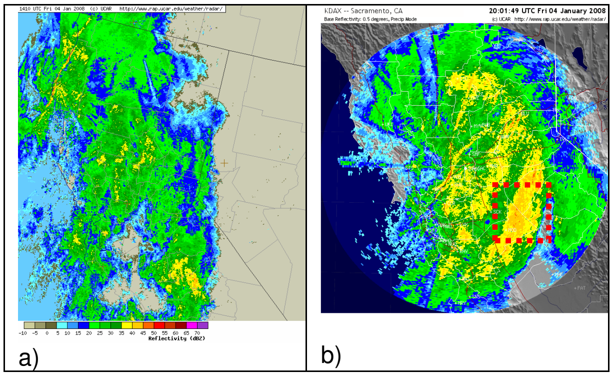
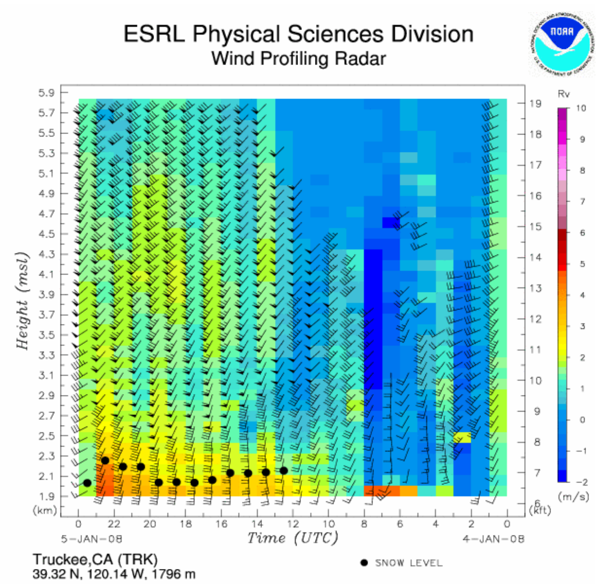


Figure 8: Radar returns from the January 4, 2008 NCFR event: a) composite image at 14:10 GMT showing area of high precipitation and latent heating to the south of Truckee, and b) KDAX (Sacramento) radar base reflectivity for 20:01 GMT 4 January 2008 showing possible NCFR (thin line of red) over Sacramento/Davis area and into the Sierra foothills.



Time (UTC)	2330	2230	2130	2030	1930	1830	1730	1630	1530	1430	1330	1230
Snow Level (m)	2033	2256	2195	2193	2038	2042	2036	2063	2133	2130	2139	2155
Snow Level (ft)	6668	7399	7199	7193	6684	6697	6678	6766	6996	6986	7015	7068
Sfc Temp (C)	0.00	4.26	3.34	3.39	2.31	2.29	2.10	2.89	3.83	2.58	2.34	2.69

Time (UTC)	1130	1030	0930	0830	0730	0630	0530	0430	0330	0230	0130	0030
Snow Level (m)	none	none	none	none	none	none	none	none	none	none	none	none
Snow Level (ft)	none	none	none	none	none	none	none	none	none	none	none	none
Sfc Temp (C)	2.78	1.69	2.53	2.33	1.89	2.36	1.66	1.07	0.67	−0.14	−1.27	−0.48

Figure 9: Wind profiler showing horizontal wind speed and direction and melting level at Truckee, CA for January 4, 2008.

The southward movement of the pool of cold air provided a lifting mechanism in the area which produced precipitation. Radar returns in Figure 8 show that the synoptic system was already causing precipitation in the Sierra Nevada by 14:10 GMT. In particular, the area south of Lake Tahoe, near Bishop and Mammoth Lakes, CA was receiving very high levels of precipitation by 14:00 (see red box highlighting high reflectivity values in Figure 8a). With low level winds coming out of the south, the warming forced by latent heating from condensation of water vapor in this area was likely advected to the north and over the Tahoe area keeping temperatures relatively warm even as the cold pool to the north moved towards Truckee. This advection of warm air from the south probably led to a change from rain to snow later than expected by forecasters.

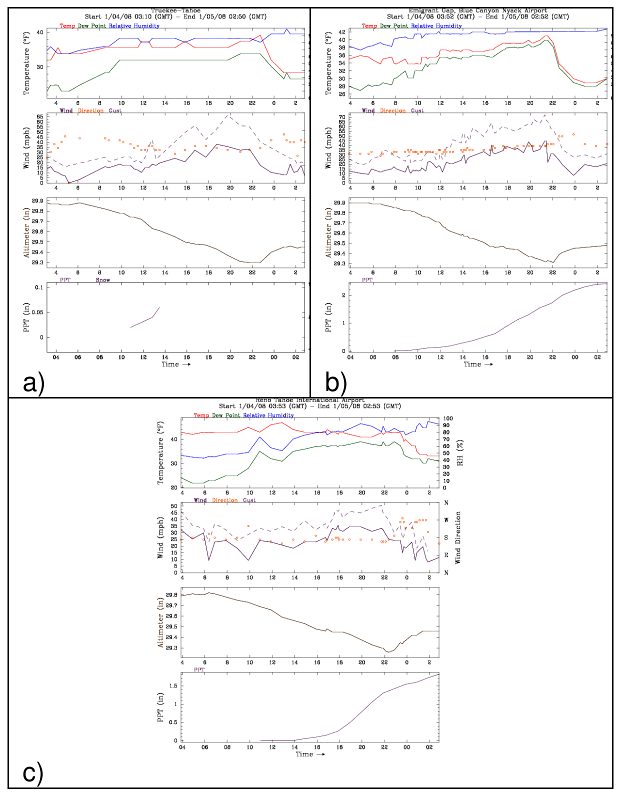


Figure 10: Surface meteograms from a) Truckee (KTRK), b) Blue Canyon/Emigrant Gap, and the c) Reno International Airport (KRNO) for January 4-5, 2008.

In addition to radar and analysis data, at the time of this storm there was a wind profiler in Truckee, California (Figure 9). The profiler returns show both the wind speed and direction and the melting level. The profiler data shows moderate low level winds (4 m/s) primarily out of

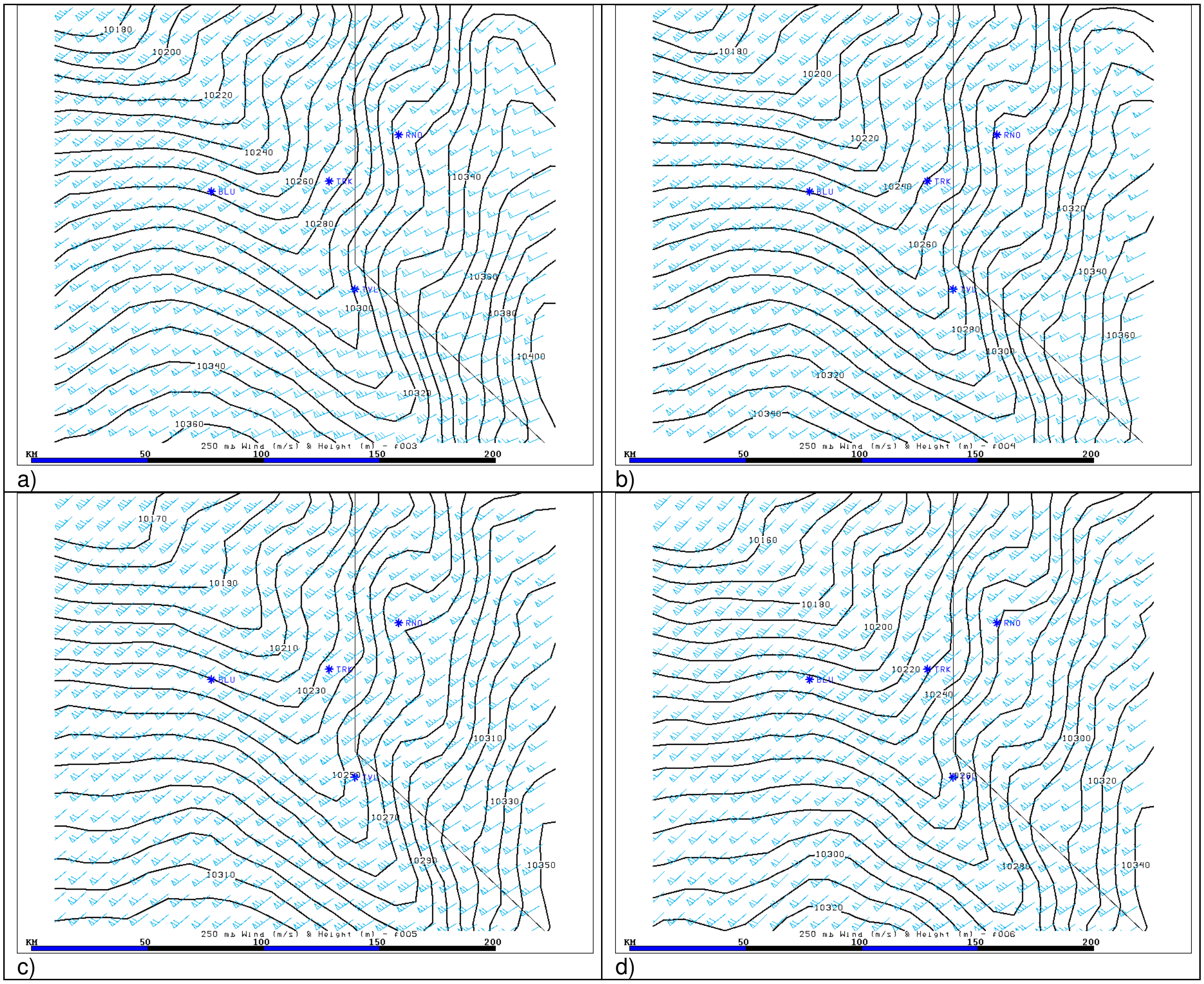


Figure 11: WRF 250 mb geopotential height and wind model analysis fields from the 9 km grid run for a) 21 GMT 1/4/2008, b) 22 GMT, c) 23 GMT, and d) 00 GMT on 1/5. Reno, Truckee, South Lake Tahoe, and Blue Canyon stations are marked with blue stars.

the south for the period from 12 GMT through 23 GMT on January 4 to a height of at least 2.5 kilometers. The vertical profile for these times is veering with height, implying warm advection through the column. At 00 GMT on January 5, the surface wind shifts to southwesterly. Additionally, the melting level from 12-15 GMT is approximately 2.1 kilometers and then drops to about 2 kilometers until 20 GMT when it rises to between 2.2 and 2.3 kilometers. At 00 GMT on the 5th, the melting level drops abruptly to 2 kilometers; this is likely due to the passage of the narrow cold frontal rain band and cold front. The rising of the melting level from 20-23 GMT is likely due to the influx of warm air from the south caused by the latent heating of condensation over the Southern Sierras as described above. When the winds shift from southerly to southwesterly, it is not surprising that the cold air then advances and the melting level drops significantly.

Surface meteograms from both Blue Canyon and Truckee, California in Figure 10 also give an idea of the small and large scale dynamics occurring in the Sierras on January 4, 2008. In both meteograms, we see temperatures above the freezing level until approximately 22 GMT, when there is a sharp decline in temperature due to frontal passage. Over the same time period, the winds begin to turn from southerly to southwesterly and gustiness decreases after

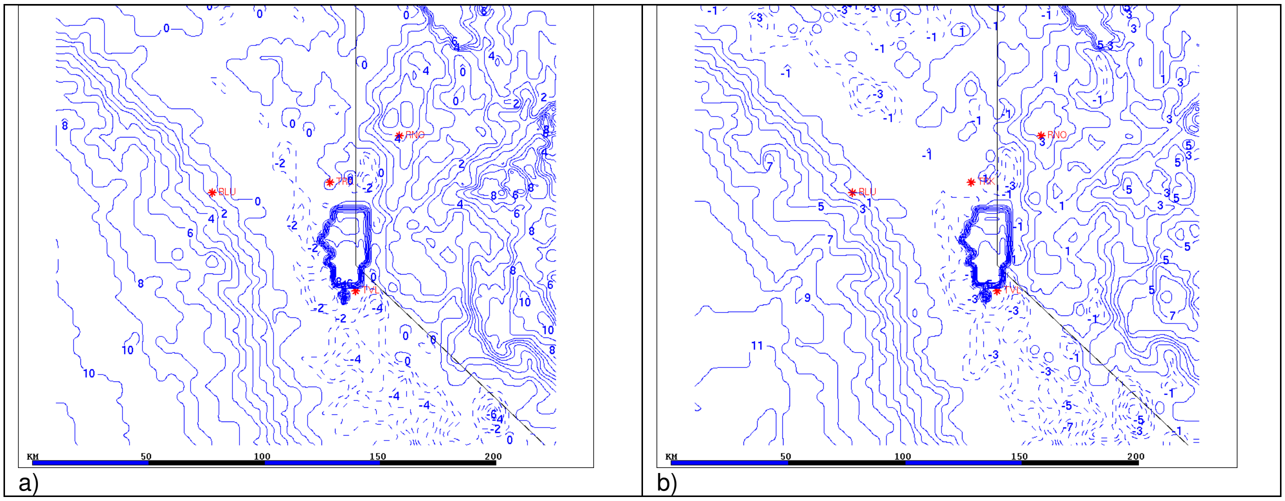


Figure 12: WRF derived surface temperature for the 3 km run at a) 21 GMT 1/4/2008 and 00 GMT on 1/5.

frontal passage. At both Truckee and Blue Canyon pressure is decreasing steadily to a low at 22 GMT, but then jumps up again around 23 GMT. This is due to the mesolow moving east into Nevada. At Blue Canyon, we also see precipitation throughout the day with an increased precipitation rate from 17 through 00 GMT most likely due to the passage of the narrow cold frontal band. The precipitation turns from rain to snow at approximately 23:45 GMT, consistent with the drop in temperature and turning of the winds to westerly.

The surface meteogram from the Reno airport shows a similar pattern to those from the North Lake Tahoe area; a temperature drop associated with the turning from southerly to westerly and decreased gustiness of the winds at close to 0 GMT on January 5. The reports list the change in precipitation from rain to snow at about 00:53 GMT on January 5, consistent with the drop in temperature seen on the meteogram.

Overall, at 00 GMT on January 5 the observational data shows an upper level low pressure system associated with a straight jet streak and an associated tropopause fold and intrusion of high potential vorticity stratospheric air approaching the west coast of the United States. The left jet exit region falls over Northern California and Nevada, leading to a transverse low level jet which advects warm air from the south keeping the North Tahoe and Reno areas warm and in rain, rather than snow until the passage of the NCFR and cold front. The passage of the NCFR also caused a turning of the winds from southerly to westerly leading to an end to the warm advection by the southerly winds. This, in conjunction with the passage of the cold front, led to a change to snow in both the North Lake Tahoe and Reno observations.

4. MODEL ANALYSIS

In order to better understand the mesoscale dynamics of the January 4, 2008 storm, the Reno, Nevada NWSFO WRF model was run over the Northern California and Nevada area with grids of 9 and 3 kilometers. The model should fill in gaps in the observations and assist with understanding the smaller scale dynamics of the NCFR passage. This section will analyze the model results from 20 GMT January 4 through 00 GMT January 5 in detail.

The WRF was run with initialization times of 00:00, 12:00, and 18:00 GMT on January 4, 2008 in order to determine the sensitivity of the model to initial conditions. Data from both the NAM and NARR analysis were used to initialize the model runs. Initializing the model at both 00 and 12 GMT with both the NAM and the NARR analysis led to results that did not replicate the physical situation occurring (as described by the NARR analysis). In particular, these runs failed to capture the low level southerly winds that advected warm air into the Truckee/Tahoe region keeping the precipitation in the form of rain. Fields from the NAM analysis at both 00 and 12 GMT show that the NAM failed to build the early morning short wave ridge and related pressure gradient over southern California with the intensity required to capture the southerly low level jet. Only when initializing the model at

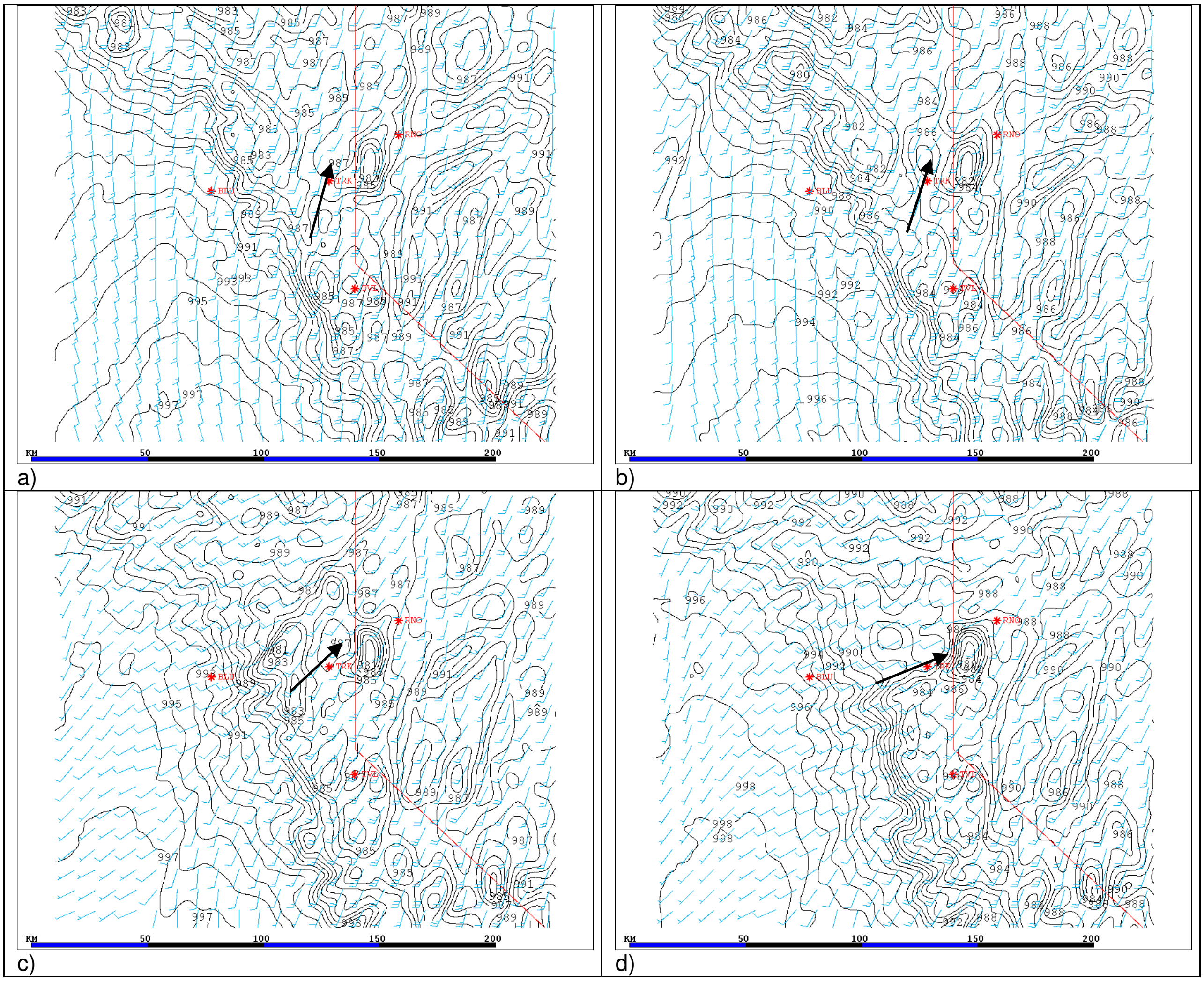


Figure 13: WRF 3 km model run surface winds and mean seal level pressure for a) 21 GMT 1/4/2008, b) 22 GMT on 1/4, c) 00 GMT on 1/5, and d) 00:40 GMT on 1/5. Black arrows represent mean surface wind direction at Truckee, CA.

18 GMT was the WRF able to capture the southerly winds required to advect warm air into the Truckee region keeping the precipitation as rain for as long as the observations. The model analysis below focuses on the run initialized at 18 GMT.

Figure 11 shows the model results for the 250 mb geopotential height and wind fields for 21 GMT through 00 GMT for the run initialized at 18 GMT on January 4 with NAM analysis data, focused on the Sierra Nevada and the I-80 corridor. A shortwave negatively tilted trough is located over the region with the trough axis directly between Blue Canyon and Truckee which deepens over the four hour period. This shortwave trough is consistent with a feature in Figure 4 which shows a shortwave trough over the Tahoe region ahead of the large scale low pressure system at 18 GMT. The winds are out of the southwest and increase in intensity to the northwest.

Figure 12 is the surface temperature analysis for the 3 kilometer model run from 21GMT through 0 GMT on the 5th. These fields highlight that the model run has the surface too cold compared to the observations at Blue Canyon, Truckee, and Reno. Keeping this error in mind, we can use the model trends to understand how the temperature field evolves over time. At 21 GMT, Truckee is just above 0˚C according to the model (note that the observations show Truckee at 2˚C at this time). By 00 GMT on January 5,

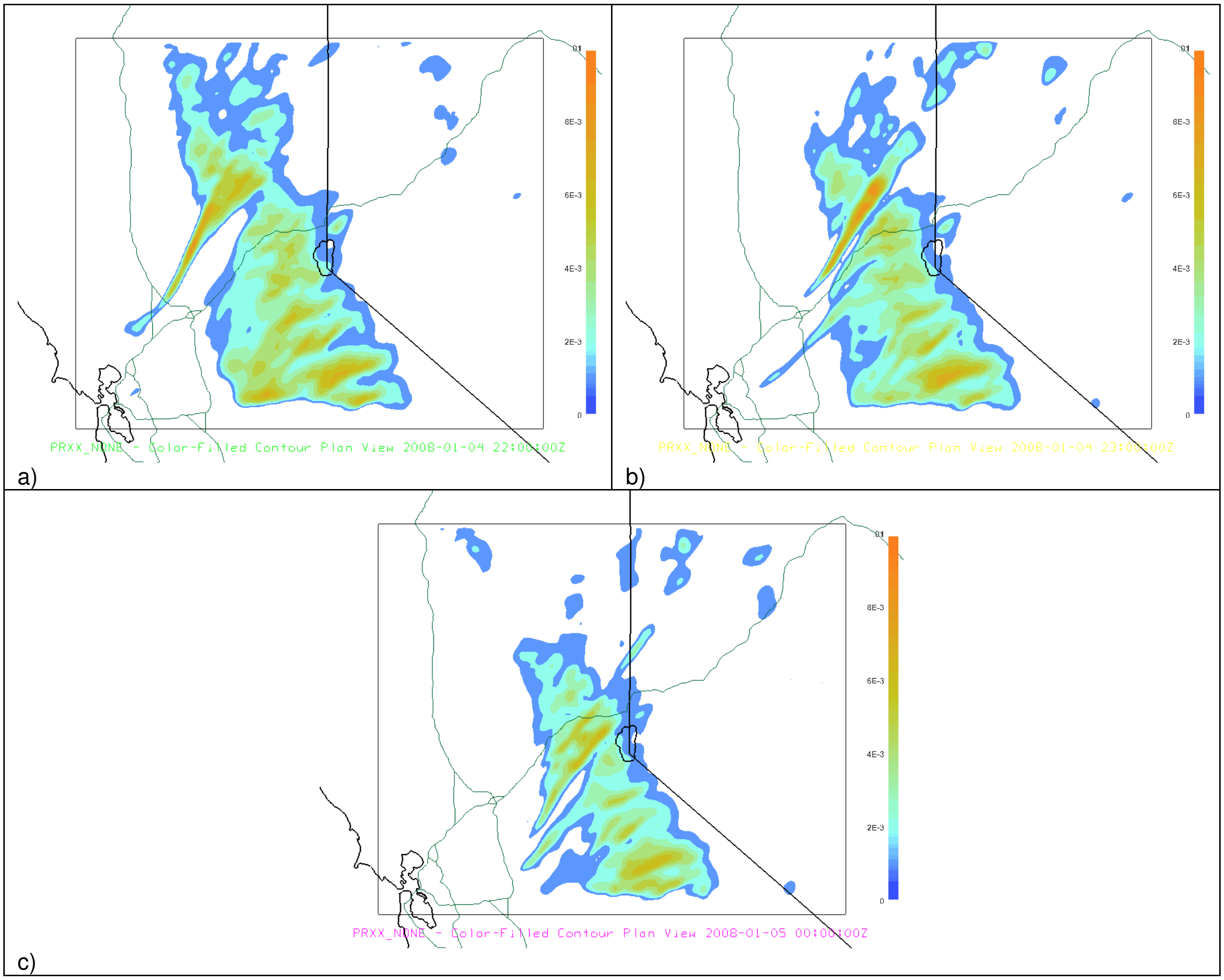


Figure 14: Precipitation accumulated over 20 minute periods ending a) 22Z on 1/4, b) 23Z on 1/4, and c) 00Z on 1/5.

the model surface temperature at Truckee is also near 0˚C. While close, the model initialized at 1800 GMT still did not correctly model either the temperature or the passage of the cold front for Truckee.

Figure 13 shows the model results of mean sea level pressure and surface winds for the 3 kilometer run from 21 GMT on January 4 through 00 GMT on January 5. Here we see the formation and deepening over time of a mesolow just to the east of Truckee, California. There appears to be surface convergence (dv/dy < 0 or stretching deformation) in this area likely leading to vertical motions providing a lifting mechanism and leading to condensation and precipitation. There is also a larger surface low pressure trough over the ridge of the mountains. The flow is out of the south, again supporting the hypothesis that warm advection of air from the south keeps temperatures relatively high and leads to rain, not snow until approximately 00 GMT on January 5. Beginning at 00 GMT and proceeding through 00:40 GMT on January 5, we begin to see the winds turn to the southwest leading to removal of the source of warm air. Not surprisingly, this is the same time period that the rain turns to snow in the Truckee surface observations (and about an hour later for Reno, NV).

Figure 14 illustrates precipitation over 20 minute intervals from the 3 kilometer run for 21 GMT on January 4 through 00 GMT on January 5, 2008. At 21 GMT there is a well defined band of precipitation extending from west of the Sacramento area to northwest of Truckee, California. The high rate of precipitation associated with this band is obvious in the 20 minute precipitation figures; there is a distinct, thin line of high rainfall rate. This band continues and appears to combine with another band of precipitation forming to the south over the next four hours. This band represents the NCFR that developed ahead of the cold front. The observations show that the cold front was further to the north at each of these time periods.

5. CONCLUSION

The January 4, 2008 event that brought rain and then snow to the Lake Tahoe and Reno area was characterized by rainfall for most of the day which turned to snow late in the afternoon. The weather forecast for the area predicted the change from rain to snow much earlier than observed. The precipitation from this storm was likely due to a narrow cold frontal rain band as well as upslope flow which formed in the left exit region of an upper level jet streak. The jet dynamics likely led to intensification of the front and cyclogenesis, but also led to warm air advection from the south, keeping the temperatures above freezing in the Truckee region and delaying the change from rain to snow. Both observations and model results support the conclusion that ahead of the cold front a NCFR developed that brought intense precipitation to a very narrow region. Additionally, the change from rain to snow was slowed by warm advection by a southerly wind which brought warm air from upslope latent heating in the Sierras near Mammoth Lakes and Bishop, California, keeping the melting level high and preventing formation of snow. As the winds turned from out of the south to southwesterly, effectively cutting off the source of warm air, both the observations and the model show a change from rain to snow and the progression of the cold front.

Sensitivity studies using the WRF model illustrate the importance of the initial state on the results of the model run. Different model initialization times illustrate the importance of the initial state capturing the subsynoptic scale convergence and ridge building that occurs over Southern California. This process drives the first wave of warm advection which kept temperatures in the Truckee area above freezing and the melting level above the surface. The WRF incorrectly predicted the strength and duration of southerly winds using both the 00 and 12 GMT initial states from the NARR and NAM analyses. This led to an incorrect forecast of the changeover from rain to snow at Truckee and demonstrated the importance of the initial conditions on model results. This likely was due to an underanalysis of the early southeastward-displaced ageostrophic warm air advection that began over southern California where the polar and subtropical jet were initially juxtaposed.

6. ACKNOWLEDGEMENTS

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