P1.15 A NOCTURNAL COLD SEASON MOUNTAIN WAVE HEAVY PRECIPITATION EVENT OVER THE LEE SLOPES OF THE WIND RIVER MOUNTAINS OF WYOMING

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1. INTRODUCTION

Widespread precipitation occurred across the western mountains of Wyoming on 02 December 2005 between 0000 UTC and 1800 UTC in moist warm southwest flow ahead of a Pacific low pressure trough, depicted in Figure 1. During the event, a dry, cold, shallow continental polar air mass was trapped in the Wind River Basin, east of the Continental Divide and the Wind River Mountains. Cold pools in the Wind River Basin are found to be similar in nature to those in the Columbia Basin, described by Whiteman et al. (2001), and in the Colorado Plateau Basin [Whiteman et al. (1999)].

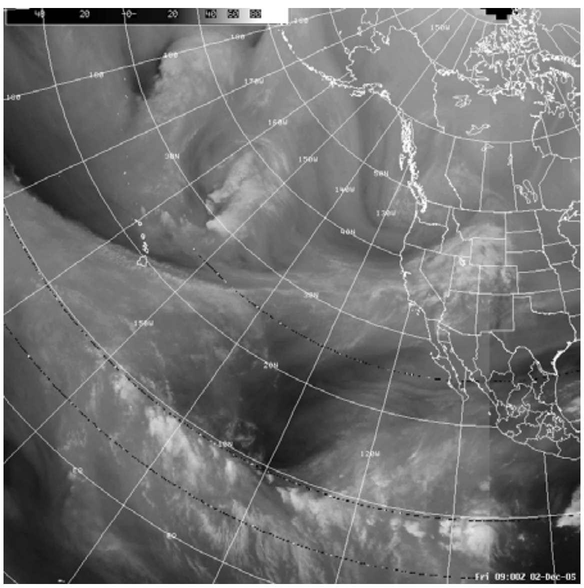

Figure 1. GOES West water vapor image at 0900 UTC, 02 December 2005.

The majority of the precipitation that occurred across western Wyoming during the 02 December 2005 event was distributed orographically increasing with elevation, with the highest precipitation amounts observed on south and west facing slopes and along mountain ridges, along and west of the Continental Divide. This distribution of precipitation generally followed the distribution of precipitation in mountainous areas predicted by Alpert (1986), Daley et al. (1994), and Clark and Slater (2006). The distribution of precipitation also closely followed observed precipitation in mountainous areas of northern Utah described by Shafer et al. (2006), in mountainous areas of northern Arizona by Bruintjes et al. (1994), in the Cascade Mountains of western Oregon and the European Alps by Medina et al. (2005), also in the Cascade mountains of western Oregon by Houze and Medina (2005), and in northeast Pennsylvania by Brady and Waldstreicher (2001).

The precipitation occurred in the warm sector east of the approaching cold front and upper level trough. This conforms to the above mentioned observations from other regions, but is opposite of the precipitation distribution observed in the mountain/basin environment of the Mackenzie River Basin of western Canada where Lackmann et al. (1998) observed the heaviest precipitation to the north of the jet axis in the cold air.

The majority of precipitation amounts over 20 mm occurred at elevations above 2400 meters. However, the heaviest precipitation (40 to 50 mm) and the greatest precipitation intensity (5 to 7 mm per hour) was observed in the extreme southern end of the Wind River Mountains east of the Continental Divide from Deer Park (2957 m) to South Pass (2755 m) between 0500 UTC and 1800 UTC 02 December 2005, depicted in Figure 2. The nocturnal nature of the heavy precipitation event (sunset 2341 UTC and sunrise 1428 UTC, from U.S. Naval Observatory) follows the findings of Riley et al. (1987) for cold season events in western Wyoming. The eastern edge of the heavier precipitation extended to the foot of the Wind River Mountains in Red Canyon, between South Pass and the city of Lander, down to 1700 meters elevation. The precipitation ended along the edge of the warmer, moist maritime air mass and the colder, dry continental polar air mass in the Wind River Basin. The mechanism for the

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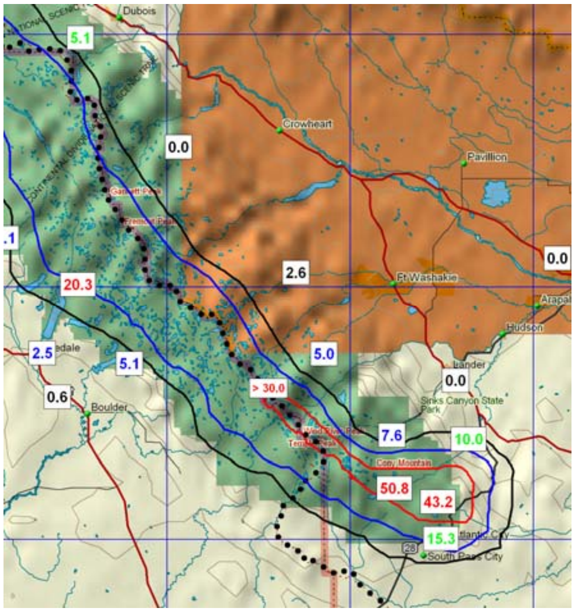

Figure 2. Observed liquid water equivalent precipitation over the Wind River Mountains 0000 UTC through 1800 UTC, 02 December 2005.

shift of the heaviest precipitation from the windward slope to the lee slope was a breaking vertically propagating mountain wave.

The majority of the precipitation that fell across western Wyoming during this event was in the form of snow. However, in Red Canyon, between South Pass and Lander, the snow transitioned to rain, with a narrow strip (2-3 km wide) of freezing rain, with clear ice accumulation of 10 mm along the border between the two air masses. The freezing rain occurred with strong downslope winds of 10 to 15 m/s and gusts as high as 25 m/s. Figure 3 displays the locations of interest that received the heaviest snowfall, and the location of the freezing rain.

One of the earliest descriptions of significant precipitation on a lee mountain slope during a period of strong downslope wind was made by Beckingham (1907) where he used the term “Wet Chinook” to describe conditions observed in western Washington. Much of the early research into downslope wind and mountain wave theory focused on dry wind events along and near the lee slopes. Kessler (1963) discusses the importance of wind-water relationships which forms a foundation for associating a mountain wave wind storm with heavy snowfall and freezing rain. Beran (1967) describes “A major chinook region in western North America extends along a strip 200-300 mi

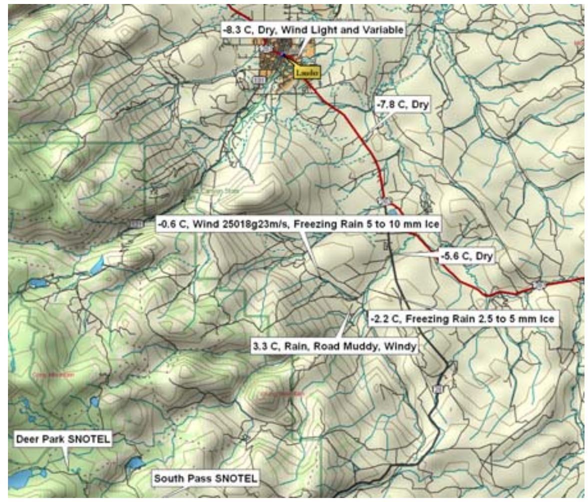

Figure 3. SNOTEL locations for Deer Park and South Pass and observations taken in the foothills and the edge of the Wind River Basin showing areas of freezing rain, rain and dry conditions, as well as surface air temperature and wind.

in width from Alberta, Canada, southward to northeastern New Mexico.” He proposed “The hypothesis that large amplitude lee waves could be a possible driving mechanism for Chinook winds” which has been thoroughly proven in extensive research by Smith (1977), Clark and Peltier (1977, 1984), Laprise and Peltier (1989), Peltier and Scinocca (1990), and Miller and Durran (1991). Note that this paper is not designed to be a thorough review of mountain wave theory.

Moisture relationships with mountain waves and the distribution of clouds and precipitation have been advanced by Durran and Klemp (1982, 1983) and Reinking et al. (2000). Colle (2004) and Chen and Lin (2005) have successfully modeled mountain waves, that, due to several factors including instability, Froude number, moisture, CAPE, wind speed and shear, height of the freezing level and mountain shape, to name a few, shift the precipitation to the mountain crest and over onto the lee slope of the mountain barrier, as was observed in this event.

While documented observations of precipitation/snowfall over complex terrain frequently discuss the occurrence of mountain waves/gravity waves [Medina et al. (2005), Lackmann et al. (1998), Houze and Medina (2005), Brady and Waldstreicher (2001), Bruintjes et al. (1994) and Shafer et al. (2006)], the main theme has been the distribution of precipitation on the windward slope to near the mountain crest, with a minima occurring on the lee slope. None of the above references observed a significant shift to the lee slope, or freezing rain at the base of the lee slope.

The occurrence of freezing rain and drizzle in Wyoming, especially east of the Continental Divide has been documented as a rare event. Cortinas et al. (2004) found that from 1976-1990 the area where freezing rain occurred in this event received less than 5 hours of freezing precipitation annually, this being the lowest category presented. The most common synoptic and mesoscale patterns associated with the occurrence of freezing rain across North America have been documented by Stewart and King (1987), Bernstein (2000), and Robbins and Cortinas (2002). Strong downslope winds with a breaking vertically propagating mountain wave were not included in the list. Whiteman (2001) describes freezing rain in the Columbia Basin, an environment similar to the Wind River Basin, as an overrunning event where warm moist air aloft overruns the basin cold pool. In this event, the freezing rain occurred in the strong downslope wind zone, near the edge of the cold pool air mass but in the warm air. A warm layer existed just above ground level where surface temperatures were 0 C to -3 C (Figure 3).

Analysis of KRIW WSR-88D reflectivity products (Figure 4) and velocity products (Figure 5) indicated that shallow convective cells formed along and downwind of the Continental Divide in the southern Wind River Mountains. The convective cells formed as part of a quasi-stationary saturated vertically propagating mountain wave. Precipitation intensities and accumulations observed under the strongest convective cell centered over Deer Park and South Pass; these Natural Recourses Conservation Service (NRCS) SNOTEL observation platforms were nearly double that of the widespread orographic snowfall observed over the rest of western Wyoming (Figure 6). Deer Park received 59% of the average December snowfall during the event, and the snowfall was the second heaviest 24-hour snowfall of the snow year at this site (Figure 7).

The mountain wave was significant as a mechanism to distribute the heaviest precipitation onto the lee slopes of the Wind River Mountains east of the Continental Divide, as well as a mechanism for producing significant freezing rain at the base of the lee slope of the mountains, in a region where freezing rain from any atmospheric pattern is extremely rare. This research is designed to document the details of

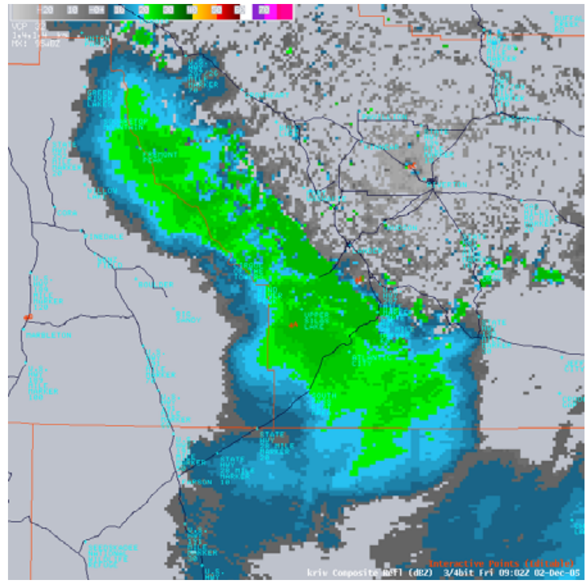

Figure 4. Composite Reflectivity from the KRIW WSR-88D depicting an elongated area of convective cells over the east slopes of the Wind River Mountains at 0902 UTC, 02 December 2005.

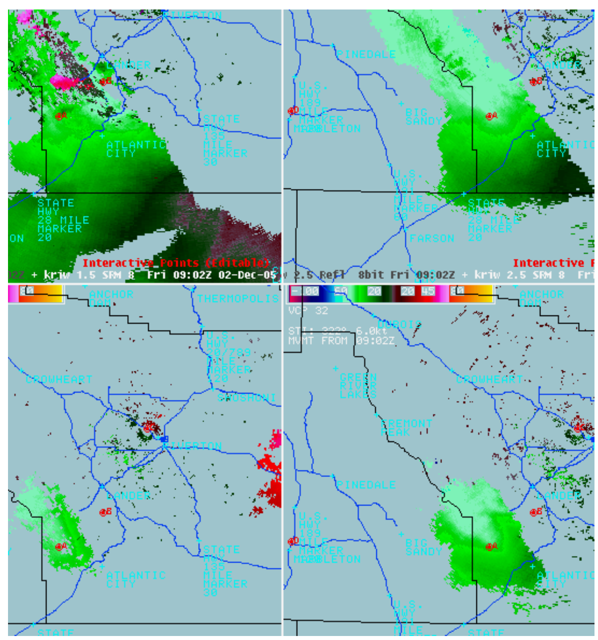

Figure 5. Storm Relative Motion (SRM) from the KRIW WSR-88D 1.5, 2.5, 3.5 and 4.5 degree angles depicting inbound velocities (kts). Wind speeds convert to 25 to 43 m/s in convective cells over the east slopes of the Wind River Mountains at 0902 UTC, 02 December 2005.

the mountain wave event, and to investigate the ability of operational mesoscale numerical models run operationally at the NWS National Centers for Environmental Prediction (NCEP)

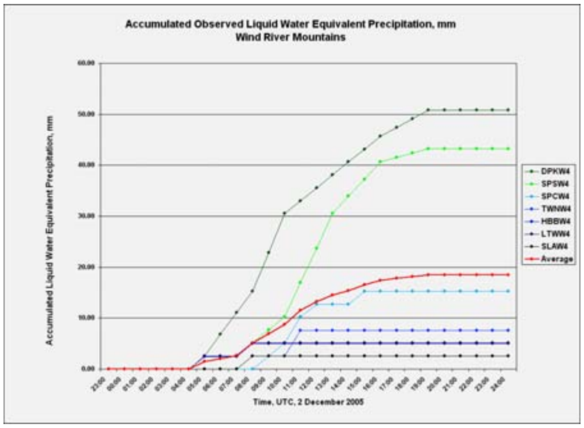

Figure 6. Hourly averaged precipitation observed by NRCS SNOTEL observing platforms from 0000 UTC to 2300 UTC 02 December 2005 for Wind River Mountains.

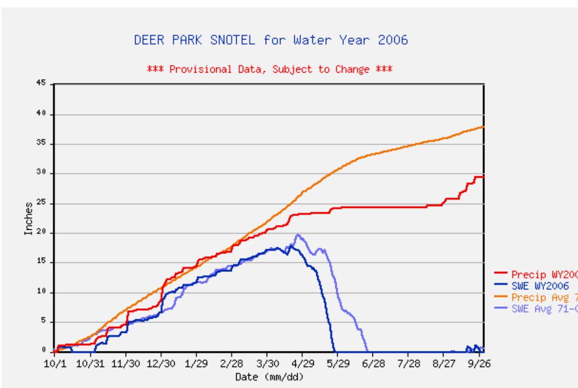

Figure 7. Deer Park NRCS SNOTEL liquid water equivalent precipitation for the 2005-2006 snow year.

and locally at the Weather Forecast Office in Riverton, WY to forecast such events. This research also aims to improve local high resolution (2.5 km) gridded forecasts currently being produced.

The Wind River Mountains extend along a significant portion of the Continental Divide in western Wyoming. The mountain range is rather straight and narrow, with several peaks between 3000 m to 4000 m in a line along the mountain crest. The highest point is Gannett Peak at 4208 m, the highest point in Wyoming. On the west slopes of the Wind River Mountains are found the headwaters for the Green River and Big Sandy River which make up part of the upper Colorado River drainage. The southern tip of the mountain range is the headwaters of the Sweetwater River which flows into the North Platte River near Alcova. The east slope of the

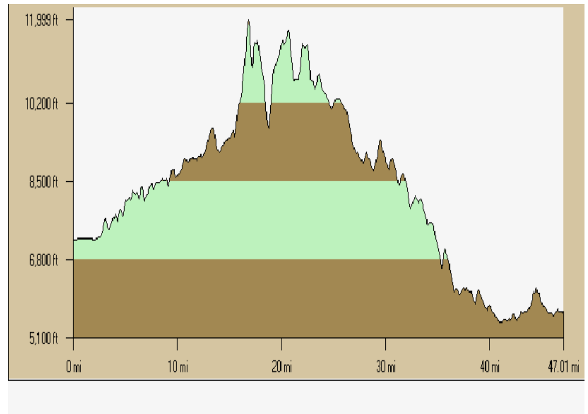

Figure 8. West to east cross section profile across the southern end of the Wind River Mountains in the area of interest.

range is the head waters for the Wind, Little Wind, North Fork of the Popo Agie, Middle Fork of the Popo Agie, and the Little Popo Agie Rivers. They flow into Boysen Reservoir and through the Wind River Canyon. At the mouth of the canyon, the Wind River becomes the Big Horn River at what is known as the Wedding of the Waters. The Big Horn River is a major tributary to the Missouri River. With water from the Wind River Mountains snowmelt flowing into three major river systems in the western United States, the distribution and accumulation of snowfall in the Wind River Mountains is significant. The Wyoming State Legislature has funded a 5 year, 8 million dollar cloud seeding project that includes the Wind River Mountains, as discussed by Goering et al. (2007). Enhancing snowfall on both the west and east slopes of this mountain range will likely be advanced by better understanding the flow patterns which provide significant snowfall. In this case, west-southwest flow provided significant snowfall to the lee slope.

Figure 8 provides a cross section profile of the Wind River Mountains running perpendicular through the area most affected by the mountain wave and associated convective cell. The Upper Green River Basin located to the west of the Wind River Mountains has elevations generally from 2000 to 2200 m, while the Wind River Basin to the east is lower with elevations from 1700 to 1500 m. This provides some asymmetry to the mountain range as discussed by Miller and Durran (1991). They found that such asymmetry was not significant in the development of a breaking vertically propagating mountain wave, especially if the lee slopes were

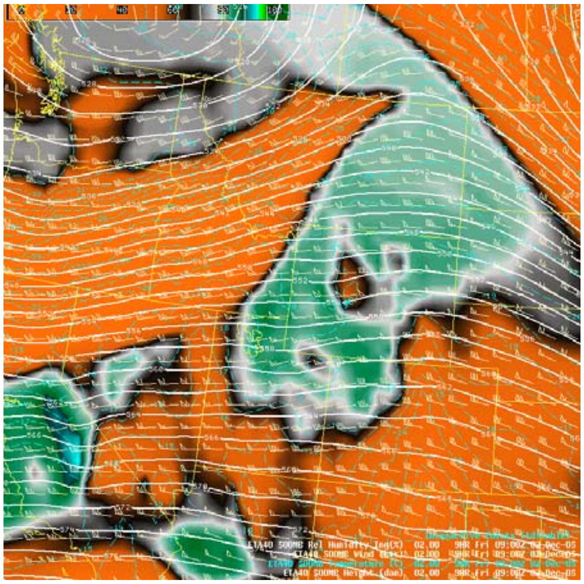

Figure 9. NAM (Eta) 40km 9-hour 500 hPa forecast of height (m), RH (%), temperature (C), and wind (kts) valid 0900 UTC 02 December 2005.

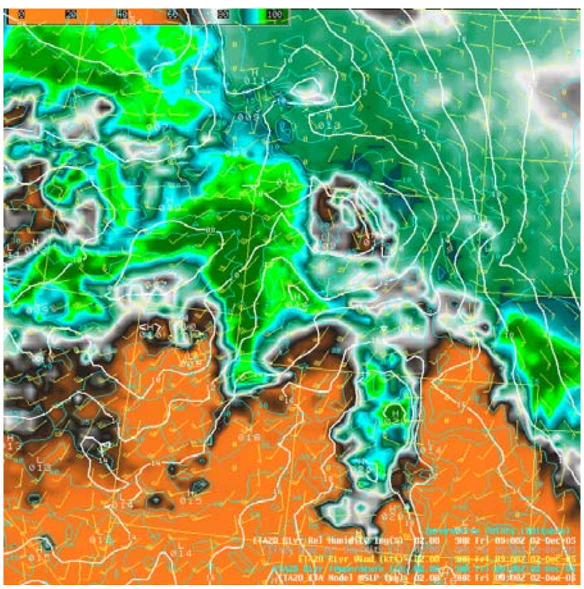

Figure 10. Same as Fig. 9, except for NAM (Eta) 20km surface mean sea level pressure (mb), RH (%) temperature (C), and wind (kts)

steep, which is the case with the Wind River Mountains.

2. SYNOPTIC PATTERN

A 500 hPa upper-level low pressure center was centered over southern British Columbia between 0000 UTC and 1500 UTC on 02 December 2005, with a long wave trough

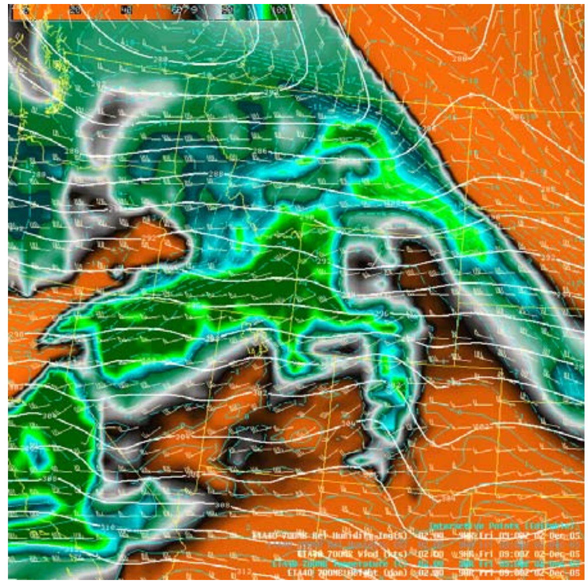

Figure 11. Same as Fig. 9, except for 700 hPa height (m), RH (%), temperature (C), and wind (kts).

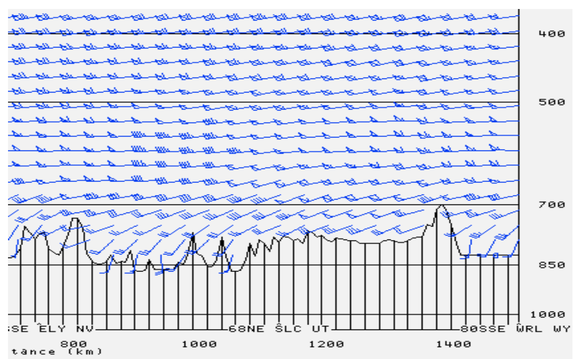

Figure 12. Same as Fig. 9, except for wind aloft (kts) cross section from near Ely, Nevada to near Riverton, Wyoming.

extending south-southwest across western Oregon into northwest California and into the eastern Pacific. A flat high pressure ridge extended north across eastern Colorado and eastern Wyoming through eastern Montana into southern Saskatchewan, east of the low pressure center (Figure 9). An upper level jet extended from south of the Hawaiian Islands, to northeast across western Wyoming with a moisture plume in the southwest flow aloft perpendicular to the southeast to northwest oriented Wind River Mountains (Figure 1).

A surface cold front extended from northern Nevada across central Idaho with an occluded cold front extending north-northwest to the surface low pressure center over southern British Columbia. A warm front extended across northern Wyoming into southwest Montana to the point of occlusion (Figure 10).

A series of weak short wave troughs were in the west-southwest flow with a strong temperature gradient displaced slightly to the west of the surface front at 700 hPa (Figure 11). The flow aloft from 700 hPa to 500 hPa showed little directional shear with a slight increase in speed with height with a mean flow of 20 to 25 m/s (Figure 12).

3. MESOSCALE FEATURES

A weak surface high pressure center was over the Upper Green River Basin with a lee side surface low pressure trough over the Big Horn Basin, extending southwest across the Wind River Basin. The boundary layer was at or near saturation across southwest Wyoming extending over the Wind River Mountains. Drying of the boundary layer was evident east of the Wind River Mountains throughout the lee side trough. Boundary layer winds averaged 20 m/s down the lee slopes of the Wind River Mountains (Figure 10). Numerous weak short wave troughs were embedded in the west-southwest flow at 700 hPa with wind speeds of 20 to 27 m/s (Figure 11). On GOES West water vapor and IR animations from 0300 UTC through 1800 UTC 02 December 2005 (not shown), it appears that a series of trapped gravity waves were forming off the Sierra Nevada Mountains and propagating through the west-southwest flow into southwest Wyoming.

Over the Wind River Mountains, cloud top temperatures cooled to -62 C over the convective cell (Figure 13). The convective cell is evident in the radar reflectivity in Figure 14. The 4.5 degree elevation reflectivity (not shown) showed the cell top over the 3.5 degree elevation reflectivity with an estimated cell top around 8300 m. The radar was operating in clear air mode so elevations above 4.5 degrees were not available. The 4.5 degree SRM showed inbound velocities of 43 m/s in the cell top reflectivity (Figure 5). The drying east of the Wind River Mountains is apparent in Figure 13, and was also evident on water vapor in Figure 1.

The radar, water vapor, and IR animations from 0300 UTC through 1800 UTC 02 December 2005 (not shown) showed oscillations in the strength of the mountain wave (evident in radar reflectivity increases and decreases and in cooling and warming of cloud top temperatures which seem to be in phase with each other, and with the passage of weak propagating gravity waves forming off the Sierra Nevada Mountains).

It should be noted that a significant gap occurs in the mountains of western Wyoming and northern Utah, between the southern end of the parallel Wyoming and Salt River Ranges and the northern slopes of the Uinta Mountains. The southwest flow above ~2400 m is unobstructed for ~600 km from eastern Nevada to the southern half of the Wind River Mountains. This is evident in the terrain cross section in Figure 12. Flow above ~2740 m is unobstructed from the Sierra Nevada Mountains to the Wind River Mountains. The northern half of the Wind River Mountains has flow obstructed by the Wyoming and Salt River Ranges. This allows a more laminar flow to reach the southern half of the Wind River Mountains, which is a condition more favorable for lee-vortex formation in a breaking vertically propagating mountain wave as discussed by Epifanio and Duran (2002).

Another aspect of the southern end of the Wind River Mountains that is important is South Pass. The lower elevations (~2285 m) allow low-level flow that is blocked to the west by the higher elevations to divert around the southern tip of the mountains. This forms a low-level convergence zone which also produces moisture convergence. Low-level cyclogenesis is predicted in the area from South Pass north to around Lander along the lee slopes of the mountains by the findings of Schar (1990), Sun and Chern (1994), and Olafsson and Bougeault (1996). However, a closed cyclonic circulation was not evident on the surface data available, and the radar velocities show inbound velocities throughout the convective cell. There is however a large area without reflectivity returns to produce velocity data down wind of the convective cell, between the cell and the radar (Figures 4 and 5).

As mentioned previously, a cold pool of dry continental polar air was trapped in the Wind River Basin prior to the onset of the west-southwest flow. This cold air was present in the foothills the night before with surface air temperatures around -6 C in the area where the freezing rain would occur. This cold pool only retreated east a few km to a line along Highways 287 and 28 from Beaver Rim near South Pass, northwest to Lander. The observations taken at 1300 UTC 02 December 2005 in the area with freezing rain showed wind speeds of 18 m/s with gusts to 23 m/s. Along Highways 287 and 28, from the Little Popo Agie River bridge to Lander,

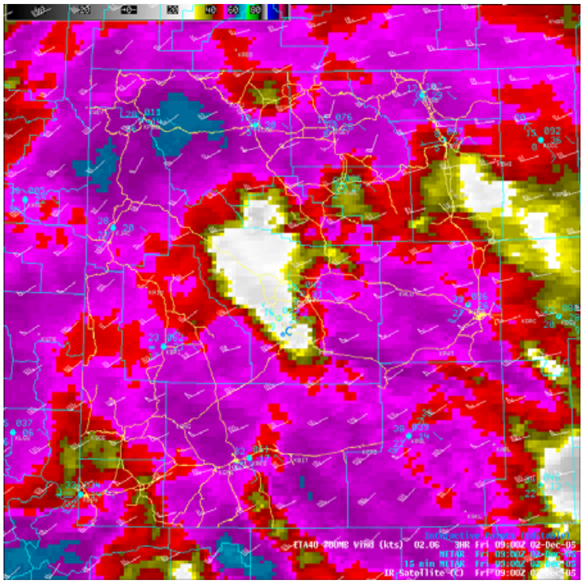

Figure 13. GOES West IR image at 0900 UTC, 02 December 2005 with NAM (Eta) 40km 9 hour 700 hPa forecast of wind (kts) valid 0900 UTC.

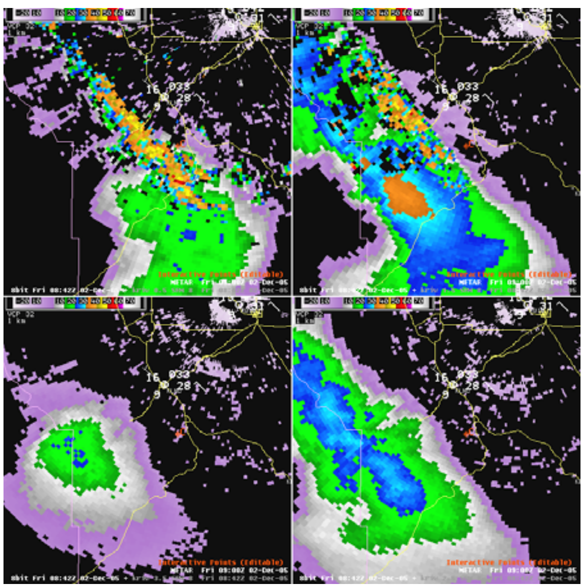

Figure 14. KRIW WSR-88D at 0842 UTC 02 December 2005 of reflectivity at 0.5, 1.5, 2.5 and 3.5 degree elevations showing convective cell over lee slope heavy snow area.

wind speeds were less than 2.5 m/s with temperatures from -5.6 C to -8.3 C (Figure 3). This area shows a rapid decrease in reflectivity at 0.5 and 1.5 degree elevations (Figure 14). The edge of the freezing rain along the cold pool appeared to be the region of hydraulic jump on the lee side of the mountain wave. Modeling performed by Lee et al. (1989) predicts that the cold pool would not be eroded by the mountain

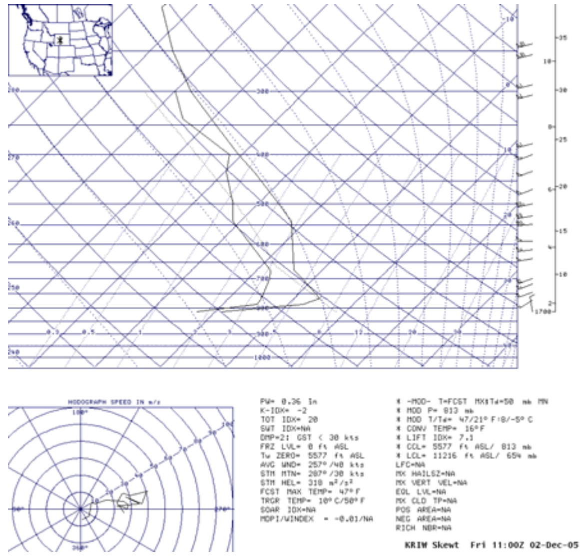

Figure 15. KRIW 1200 UTC 02 December 2005 rawinsonde observation (wind in kts).

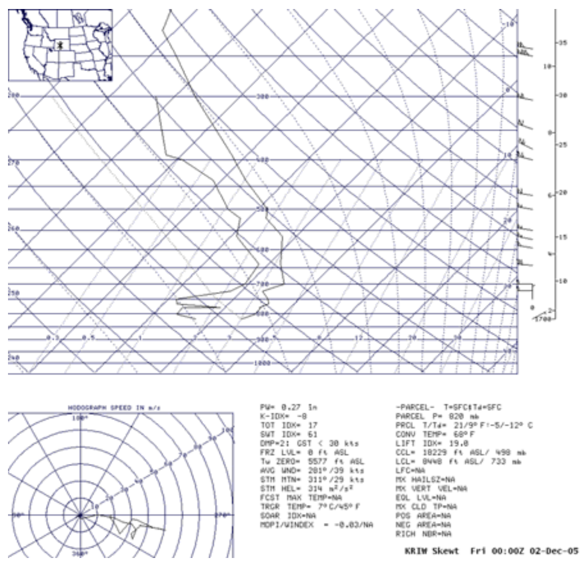

Figure 16. KRIW 0000 UTC 02 December 2005 rawinsonde observation (wind in kts).

wave and the downslope winds would not propagate northeast into the cold pool. This aids in keeping the mountain wave over the lee slope. The stationary aspect of the mountain wave and convective cell allowed for 40 mm to 50 mm of liquid water equivalent to be deposited over the area and also allowed conditions to remain favorable for freezing rain accumulation of 5 mm to 10 mm along a narrow strip 2 to 3 km wide at the base of the lee slope. Figure 15 shows the depth of the cold air over Riverton and also shows the warm layer which provided for the melting of the snowfall to produce freezing rain at the surface. Note that the warm

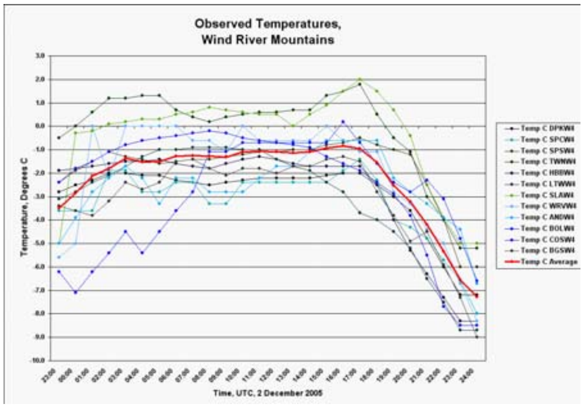

Figure 17. Hourly averaged surface air temperatures observed by NRCS SNOTEL, HADS DCPs, and RAWS observing platforms from 0000 UTC to 2300 UTC 02 December 2005 for the Wind River Mountains and adjacent Gros Ventre Mountains.

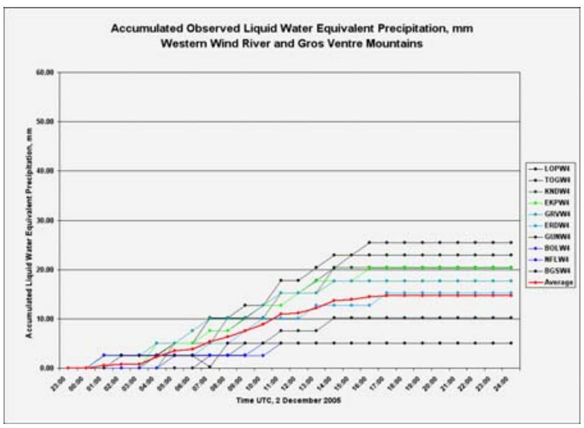

Figure 18. Hourly averaged precipitation observed by NRCS SNOTEL observing platforms from 0000 UTC to 2300 UTC 02 December 2005 for western Wind River Mountains and adjacent Gros Ventre Mountains.

layer did not exist at 0000 UTC (Figure 16) prior to the onset of the strong southwest flow aloft.

As mentioned earlier, a cold front from the surface to 700 hPa was west of the area during the precipitation event. Figure 17 indicates that surface air temperatures over the mountains during the precipitation event were nearly steady. As the cold air with the front moves in around 1500 UTC in the west and 1700 UTC in the east, the precipitation ended across the western mountains (Figures 6 and 18). As the front and trough passed, and the wind shifted to the west-northwest, the moisture plume was shifted east of the area, and the mountain wave rapidly dissipated.

4. THE NATURE OF THE FREEZING RAIN

The observation of freezing rain accumulation of 10 mm in Red Canyon started the interest into further investigation of this event. Observations were taken with a hand-held Brunton ADC Pro with temperature and wind sensors. The observations were taken from Peaks Road in Red Canyon, along Red Canyon Road, and along Highways 28 and 287 into Lander. These observations are documented in Figure 3. The ice was clear as glass when observed at 1300 UTC and a few large rain drops were still falling. Individual sand grains and blades of grass were clearly visible through the ice. The rain had fallen periodically since around 0700 UTC with strong winds gusting to 23 m/s throughout the night.

On a hill on Peaks Road, the elevation increased enough to move into the warmer air above the surface. On the hill the surface air temperature was 3.3 C and the dirt road was muddy. The wind on the hill top continued to blow strong. Dropping down the hill onto Red Canyon Road along the Little Popo Agie River, the temperature dropped back down to -2.2 C and ice accumulation was again observed on the road.

The ice ended before reaching Highway 28 near the Little Popo Agie River bridge. The surface air temperature fell to -5.6 C, the wind was light, and the paved road was dry. Along Highway 287 into Lander the temperature continued to drop, falling to -8.3 C at the intersection with Highway 789. The flag at the post office on the corner showed no movement. It is not exactly known how far the freezing rain accumulated along the base of the mountains. From the radar reflectivity and the relative uniformity of the terrain in the foothills from Red Canyon to northwest of Lander, it is possible the strip extended 15 to 25 km along the foothills. This area is rather sparsely populated and no other observations were received. Further observations could not be made as time did not permit.

5. THE WARM CONVEYOR BELT

Classic features of cyclones that are frequently associated with the production of heavy snow are well documented. The warm conveyor belt, cold conveyor belt, and dry tongue jet described by Carlson (1980) are widely accepted (Figure 19), with some proposed changes in the details. Snow storms along the east slopes of the mountain ranges in Wyoming that meet this classic pattern produce deep upslope flow on the east slopes with the warm conveyer belt overrunning the cold upslope flow. They are frequently associated with cold air damming on the east slopes. The development of barrier jets does sometimes occur along the east slopes of the mountains of Wyoming, just as Dunn (1987, 1992) documented along the east slopes of the mountains of Colorado.

In a study of 213 snow storms in non-mountainous areas of the contiguous United States, Auer (1982), defined preferred temperature ranges for 700 hPa, 600 hPa, and 500 hPa. These temperature ranges are plotted in Figure 20. The thermodynamic diagram shows that the temperature ranges fall between two wet adiabats. Lifted parcels in the warm conveyor belt are most efficient at snow production in this range due to this being the temperature zone of preferred dendritic crystal growth and super cooled liquid water availability within the storm cloud. By lifting the parcels moist adiabatically in the warm air above the cold pool in Figures 15 and 16, one finds that the temperatures fall in the range plotted in Figure 20.

The moist water vapor plume (Figure 1) provided the needed temperature environment and an ample supply of moisture (the warm conveyor belt) for the mountain wave convection. This deep saturated air mass from mountain top near 700 hPa to above 500 hPa, possibly as high as 8300 m MSL, would be conditionally unstable before encountering the mountain wave. With velocities from 20 m/s increasing to as high as 43 m/s around 8300 m, the mountain wave produced significant lift and a very turbulent environment favorable for large super cooled drops [see Pobanz et al. (1994) for the region of significant dendritic crystal growth].

In this heavy snow/freezing rain event, the mountain wave provided adequate lift from the ridge crest to the middle of the lee slope in an environment without a cold conveyor belt, significant upslope, or significant divergence aloft. Without the warm conveyor belt, the mountain wave would not have sufficient moisture to be an effective producer of snow. Aside from the absence of significant directional shear and significant CAPE which would be favorable for deep long-lived convection (11-13 hours in duration), the mountain wave possessed a long-lasting undisturbed warm

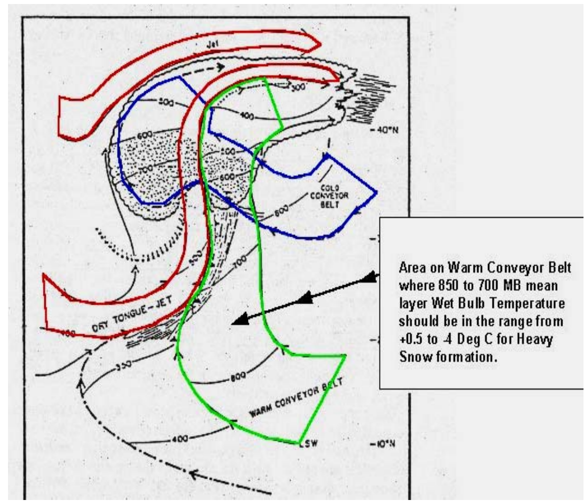

Figure 19. From Carlson (1980) Airflow into mature cyclone associated with heavy snowfall.

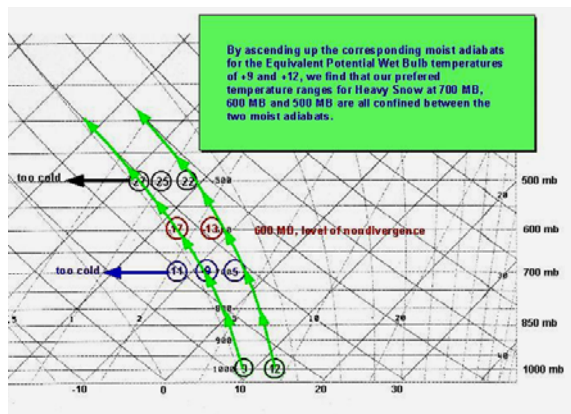

Figure 20. Graphic plot of temperatures favorable for heavy snowfall in Wyoming from Auer (1982).

moist inflow on the windward side of the mountain, and a long-lasting undisturbed moist outflow/downdraft on the lee slope which produced significant snowfall from 0500 UTC to 1800 UTC (13 hours). Without the mountain wave, there was insufficient instability to support deep (for a cold season environment) convection. No precipitation occurred over the cold air pool in the Wind River Basin north and east of the mountains.

6. OPERATIONAL NUMERICAL MODEL PERFORMANCE

At the time of the event, the operational numerical models available to the Weather Forecast Office in Riverton, WY were the GFS at 80km, the RUC at 20km, and the NAM (Eta) at

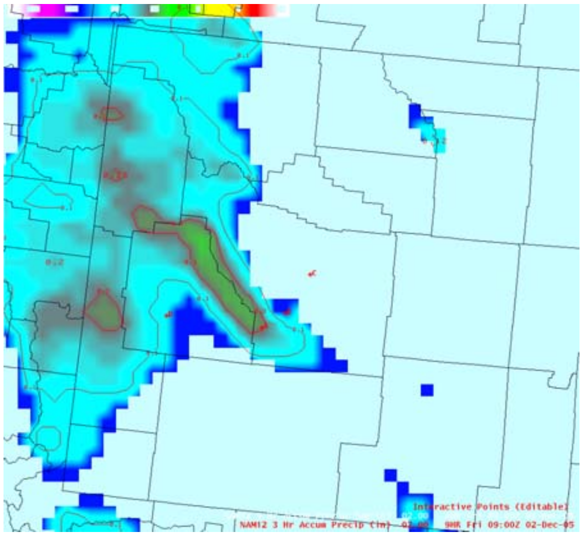

Figure 21. 3-hour accumulated liquid precipitation valid at 0900 UTC 02 December 2005 from the 12km NAM (Eta), in inches.

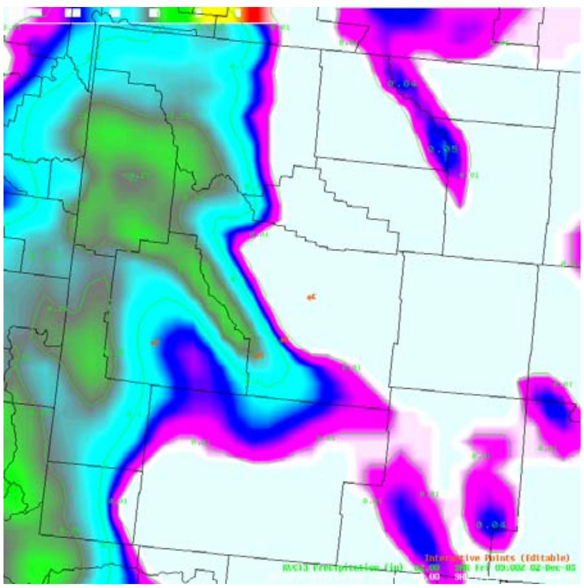

Figure 22. 3-hour accumulated liquid precipitation valid at 0900 UTC 02 December 2005 from the 20km RUC, in inches.

12km, 20km, and 40 km. Not all of the model data were available to analyze for this case study, especially fields for the 12km NAM (Eta) and 20km RUC. Saturated equivalent potential temperatures were not available. Also, LAPS analysis data normally available to the forecaster were not available for this case study.

Numerical models with grid resolution from 12km to 80km cannot resolve mountain wave phenomena with a wave length of 25 to 35 km. Without being able to resolve waves at this scale, the heavier precipitation on the lee slope

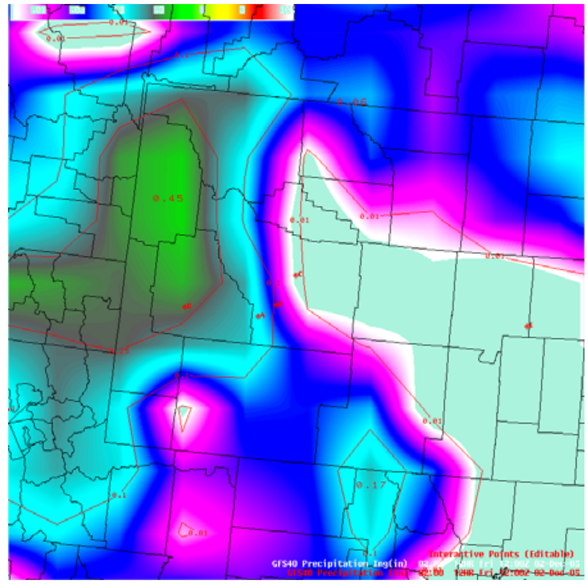

Figure 23. 80km GFS 6-hour accumulated precipitation valid 1200 UTC 02 December 2005, in Inches.

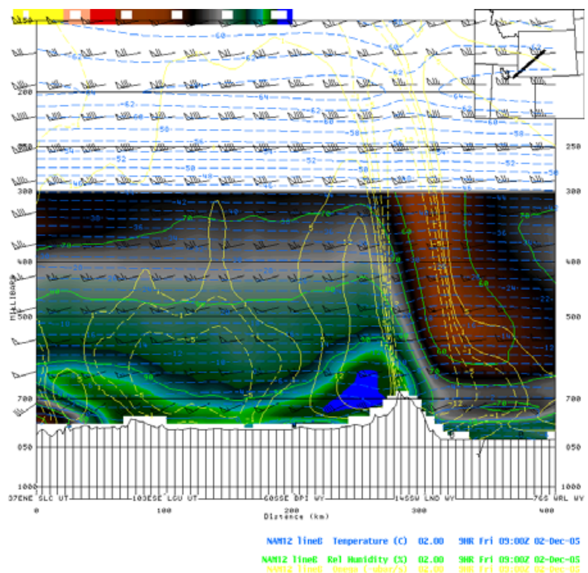

Figure 24. 12km NAM (Eta) cross section from near SLC to near RIW 9-hour forecast of temperature (C), RH (%), wind (kts) and omega (ubar/s)valid at 0900 UTC 02 December 2005.

of the Wind River Mountains was not predicted (Figures 21, 22 and 23).

The 12km NAM (Eta) did produce a mountain wave with a wave length around 80 km (Figure 24). This placed the moisture and upward motion too far south over the foothills on the windward side of the mountain. Too much drying occurred in the downdraft/sinking air from the mountain crest to the base of the lee slopes

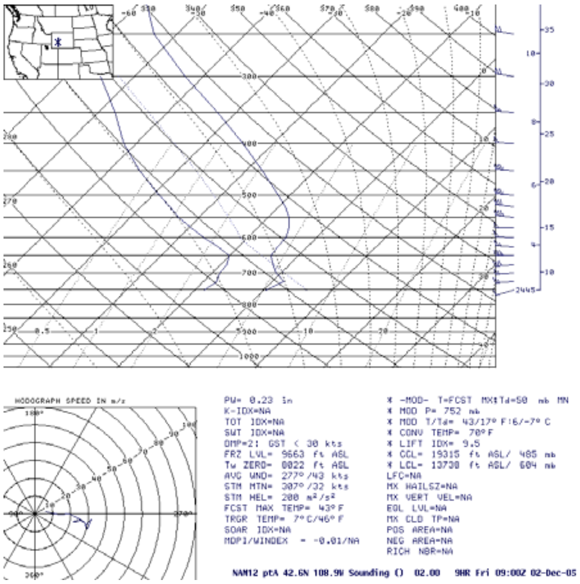

Figure 25. 12km NAM (Eta) 9-hour forecast model sounding of temperature (C), RH (%), and wind (kts), at Deer Park, valid at 0900 UTC 02 December 2005.

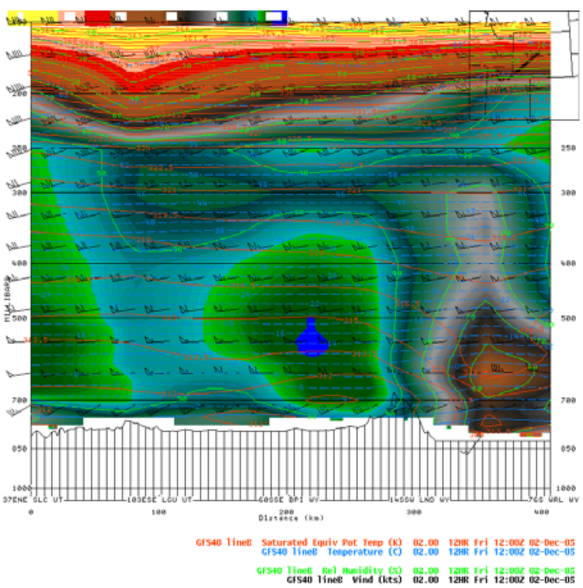

Figure 26. 80km GFS cross section from near SLC to near RIW, 12-hour forecast valid at 1200 UTC 02 December 2005, Temp, RH, Wind kts, and Saturated Equivalent Potential Temperature.

through the area of heavier snowfall and the area of freezing rain. Figure 25 shows the extent of the drying forecast over Deer Park, during the time when the highest convective reflectivity was observed overhead (Figure 14).

Some of the problems with the Eta model step terrain with flow over steep mountains have been documented by Gallus and Klemp (2000). The NAM (Eta) has been replaced operationally at NCEP by the NAM (WRF), and is still only operationally available at 12km [Black and Michalakes (2004) and Uccellini et al. (2005)]. The Weather Forecast Office at Riverton is running the workstation WRF with NMM core on a small regional area at 4km horizontal resolution.

The 80km GFS created a much longer and flatter wave, which started well south of the Wind River Mountains in the upper Green River Basin and ended well north of the mountains in the Wind River Basin, and placed the highest moisture values well south and west of the lee slopes of the Wind River Mountains over the upper Green River Basin (Figure 26). Because of the poorer model terrain resolution, the 80km GFS did spill precipitation onto the lee slopes of the Wind River Mountains, and farther north and east into the Wind River Basin (Figure 23). The 80km GFS model terrain and horizontal resolution allows for more moisture to advect east of the Continental Divide than occurs in reality. The saturated equivalent potential surfaces in the 80km GFS (Figure 26) show the inability of the model to develop a steep mountain wave over and to the lee of the Wind River Mountains.

7. WRF NMM TESTS

This event provides a significant test for determining the capability of the locally run workstation WRF (NMM core). These tests have not been attempted at the time of this writing. The goal is to run the WRF at the current 4km horizontal resolution, at 2 km, and at 1 km to test the ability of the model to approximate the correct precipitation distribution onto the lee slope of the Wind River Mountains.

Currently at 4 km, the model output is not available until 10 hours after the NCEP model cycle at 0000 UTC and 1200 UTC. Because of the length of time it takes for the model to run, with the current computer resources available at the Weather Forecast Office in Riverton, WY, the 0600 UTC and 1800 UTC cycles are not attempted. Output is made available at 3-hourly forecast intervals. A successful test with hourly output would provide a benchmark for what additional computer resources are required to provide more timely output for each forecast cycle. Running the model for each 6 hour forecast cycle and providing hourly output to better define significant mesoscale phenomena should also be beneficial. With current National Weather Service operations attempting to produce 2.5 km local gridded forecasts and 5 km gridded forecasts on a national level [National Digital Forecast Database, NDFD; see Glahn and Ruth (2003)], much better model output is required to attempt to capture significant mesoscale events in complex terrain.

The documentation provided here clearly shows the complexity of mountain wave phenomena even though only a minimal amount of the available research has been reviewed. It is impractical to believe that forecasters, with the current tools available, can accurately forecast significant events such as this at 2.5 km resolution without first having solid model output to corroborate such a forecast. Even then, at 2.5 km to 5 km, the freezing rain event (2-3 km wide and ~15-25km in length) cannot be accurately depicted in a gridded forecast without significantly exaggerating the extent of the freezing rain, which would be no better than not forecasting the event at all, which is exactly what happened. Accurately forecasting such fine scale phenomena is currently not possible, and display of such phenomena could realistically only occur with a forecast grid down to 0.5 km to 0.25 km. This would provide a freezing rain area forecast with a width of 5 to 10 grid points.

It should be noted that if the freezing rain was shifted a few kilometers north, highways 28 and 287 would have been covered with black ice from the lower elevations of South Pass through Lander, and possibly as far west as Ft. Washakie. This would have had a significant impact on transportation safety along the highways for 15-25 km. Such a shift of only a few kilometers would have also covered the Lander airport with ice.

8. SOME IMPLICATIONS FOR WEATHER MODIFICATION

Significant snowfall on the lee slopes of the Wind River Mountains may come during strong southwest flow, especially if a saturated mountain wave can develop. In these events, seeding from the base of the lee slope of the mountain would not be effective as the particles would not be transported up the lee slope. Airborne seeding operations over the lee slopes in the mountain wave may prove hazardous due to severe to extreme turbulence and icing with significant updrafts and downdrafts.

Seeding from the windward slope may be effective in increasing snowfall over the mountain, but the snowfall increase would likely occur on the windward slope, depleting the significant super-cooled water available to keep the mountain wave saturated, thus decreasing the snowfall on the lee slope. Reinking et al. (2000) found that orographic gravity waves are very effective in significantly increasing the available cloud liquid water (CLW) in the convective precipitation clouds over a mountain, but that conversion to ice consumed and precipitated wave CLW. The periods of gravity wave forcing contributed some 80% or more of the total precipitation. By removing the available CLW upwind of the mountain wave, the distribution of precipitation would be affected. Furthermore, Chen and Lin (2005) found that the nature and location of convection over a mesoscale mountain ridge is partially influenced by CAPE and available atmospheric moisture content. The nature of the mountain wave itself can be altered by removing the moisture alone, and can also be altered by adjusting the CAPE which may occur by drying the inflow into the mountain wave. Deep saturation of the inflow maintains a conditionally unstable environment which is needed for the generation of heavy precipitation in the mountain wave.

Since the rivers flowing from the Wind River Mountains flow into three different major river systems (Colorado, North Platte, and Missouri) and two different oceans, redistributing the precipitation that was destined for the lee slope onto the windward slope could alter the hydrology over a larger area than just the mountain itself. The redistribution of snowfall back onto the windward slope, away from the lee slope, may worsen long term drought conditions in the Wind River Basin, and decrease the water supply along the Big Horn River across the Big Horn Basin and southeast Montana. Further research is needed to define the impact of removing super-cooled water by cloud seeding upwind of a mountain wave. Would this in fact decrease snowfall production by the mountain wave on the lee slope?

9. DISCUSSION

The phenomena of increased snowfall on the lee slope of the Wind River Mountains by a breaking vertically propagating mountain wave has been observed and documented. The development of a convective cell formed in a saturated mountain wave has been identified as the mechanism for these phenomena, as well as the occurrence of freezing rain at the base of the lee slope. It has been pointed out that the redistribution of the precipitation from the windward slope to the mountain crest and over onto the lee slope has been modeled by researchers including Chen and Lin (2005). This event falls within the descriptions provided for the development of moist convection in the breaking vertically propagating mountain wave. It has also been shown that this heavy snow event conformed to conventional temperatures aloft observed in other heavy snow events where a warm conveyor belt provided the moisture and temperature profile needed for significant snow development [Auer (1982)].

Further research is needed to develop a climatology for the occurrence of the distribution of snowfall onto the lee slopes of the Wind River Mountains in strong west-southwest flow by the formation of breaking vertically propagating mountain waves. Knowing the frequency of such events would be beneficial to weather forecasters, as well as those involved in weather modification over the area in question.

The ability to model such events in a research environment is encouraging. Defining the resolution required of a local workstation WRF model is crucial as it would then help define the computer resources needed to run such a model, and provide more timely output, at a higher time step frequency. This should also allow for the local model to be run for the 0600 UTC and 1800 UTC model cycles as well. Providing such data to the operational forecasters should significantly enhance the efforts to produce accurate 2.5 km gridded forecasts in complex terrain.

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