J7.4 EVALUATION OF HIGH RESOLUTION MODEL QPF PERFORMANCE IN THE COMPLEX TERRAIN OF THE GREAT BASIN AS PART OF THE DTC WINTER FORECAST EXPERIMENT

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1. INTRODUCTION

Precipitation forecasting in the Great Basin of the western United States is challenging for weather forecasters and numerical models, primarily because of the region's complex terrain (Fig. 1). Dynamics (e.g., vertical motion) play a significant role in precipitation formation and evolution – similar to any region – but the interaction of these precipitation patterns in the Great Basin are significantly enhanced or diminished as weather systems move across the terrain. In addition, northern Utah topography near the Great Salt Lake (GSL), and abrupt valley and mountain slopes, create significant mesoscale weather effects. The two most documented weather phenomena in northern Utah are the lake effect snow bands (Steenburgh et al. 2000) and the orographic enhancement precipitation in the Wasatch Range (Shultz et al. 2002). Transportation interests, mountain recreation and avalanche control, as well as the over 1 million people that live and travel along the Wasatch Front rely heavily on accurate weather forecasts derived from numerical weather prediction.

Recently, improved numerical models have been developed to help address the forecasting challenges in the Great Basin. However, improving model horizontal grid spacing and vertical resolution has produced mixed results (Eckel 2005, Hou 2002, Mass 2002). The National Weather Service (NWS) is now operating a version of the Weather Research and Forecasting Model (WRF) at the National Center for Environment Prediction (NCEP), using the 8-km High Resolution Window (HRW) version (Chuang et al. 2004, Janjic et al. 2005). Achieving the goal of the WRF has been a collaborative effort to have a similar software structure that can accommodate different dynamical cores and physics from other high resolution models in order to produce the best and most consistent output (Skamarock et al. 2001). The University of Utah's NOAA Cooperative Institute for Regional Prediction (CIRP), among many others, have also operated experimental versions of the WRF model (Cheng and Steenburgh 2005). Extensive testing must be completed before a version of the WRF can become operational (Wegiel 2005).

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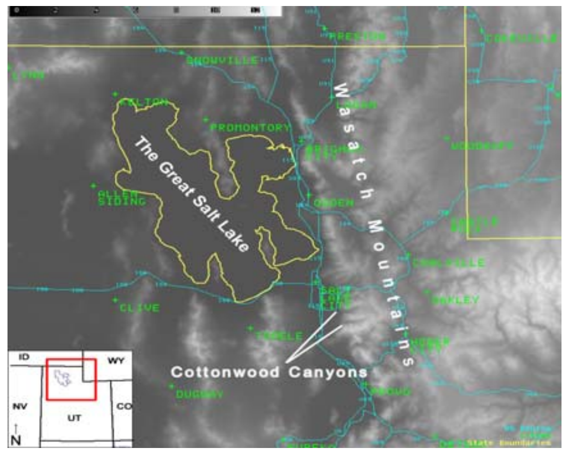

Fig. 1. Topography of northern Utah. Grey scale ranging from 4,200 ft to 13,500 ft MSL.

2. WRF EVALUATION PROJECT

The NWS Weather Forecast Office (WFO) in Salt Lake City, Utah, participated in the Developmental Testbed Center (DTC) Winter Forecasting Experiment (DWFE), held during the 2005 winter season (Nance et al. 2005, Koch et al. 2005). A similar experiment was conducted during the summer convective season of 2004 (Weiss et al. 2004). The recent winter experiment involved running two configurations of the WRF model at 5-km resolution at 0000 UTC and out to 48 hours over a large domain (CONUS). To evaluate high-resolution model performance in complex terrain of the Great Basin, WRF numerical model output from the NCAR Advanced Research WRF (ARW), and FSL Non-hydrostatic Mesoscale Model (NMM) 5-km versions (Bernardet et al. 2005, Skamarock and Dempsey 2005), and the NCEP 8-km HRW WRF were viewed at the Salt Lake City WFO using the FX-Net display software (Wang et al. 2002 and website reference). WRF performance was evaluated in an operational WFO setting with emphasis on model quantitative precipitation forecast (QPF) areal coverage, and their amounts and intensities in the complex terrain of Utah. It is important to note that once a day model data was typically not available until 6 to 8 hours after 0000 UTC. WRF output was also compared to NAM (formerly Eta) and GFS data during real-time and post-mortem settings.

This paper will discuss local results of the DWFE during the winter of 2005. Discussion of events will focus on lake effect snow, synoptic scale banded precipitation and terrain enhancement, and convective orographic induced snowfall.

3. PRECIPITATION EVENTS AND RESULTS

Several precipitation events were studied during the DWFE period. Overall, the WRF models had a tendency to over-forecast QPF when conditions were moist and unstable similar to findings by Davis et al. (2004), and when the mean flow was conducive to orographic enhancement. In general, the model performance was too often dependent on the NAM boundary layer conditions which limited its usefulness if the NAM model did poorly. However, the models did successively capture significant banded, lake effect, and orographic precipitation events across northern Utah. This section will discuss several particular events, giving a brief synoptic overview to accompany the model evaluation.

3.1 Great Salt Lake Snow Band Event on 30 March 2005

During the evening of 30 March 2005 a strong cold front moved through the Wasatch Front in northern Utah. A narrow band of heavy snow occurred along this boundary, but accumulations were generally less than 8 cm (3 in). Lake enhanced snow showers developed by 0500 UTC (2200 MST) 30 March with the first lake effect band evident by 0640 UTC (Fig. 2). As colder air continued to advect across the GSL, a strong low-level convergence zone was established near the middle of the lake. After 1200 UTC an organized single band of snow extended from the GSL downwind across the southern Wasatch Front (Fig. 3). Snowfall rates after 1400 UTC increased to 5 to 7 cm (2 to 3 in) per hour. The northwest flow in the boundary layer interacted with the southern Wasatch Range – specifically the Cottonwood canyon areas – to enhance these precipitation rates. The persistent lake band continued until about 2000 UTC 30 March before it dissipated to weaker convective cells across most of northern Utah. Snowfall totals from this event ranged from 12 to 28 cm (5 to 11 in) in the lower elevations downwind of the GSL. In the mountains, impressive snowfall totals accumulated as high as 64 cm (25 in) in a 12-h period and 97 cm (38 in) within 24 hours. Water equivalent for this snowfall was 35 mm (1.40 in) and 56 mm (2.20 in) respectively at the Alta Collins station located at a 9600 ft elevation in the Little Cottonwood Canyon of the Wasatch Range.

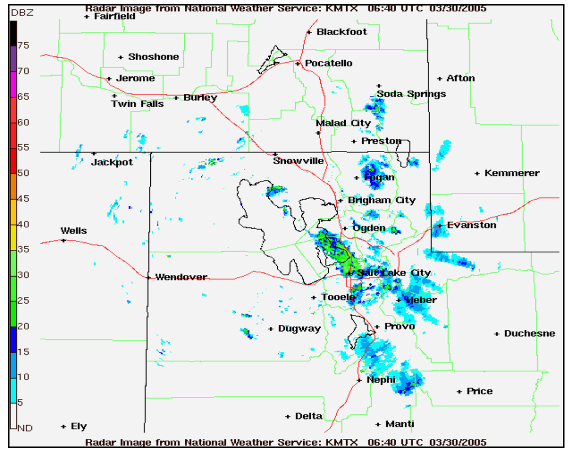

Fig. 2. KMTX WSR-88D composite reflectivity at 0640 UTC 30 March 2005.

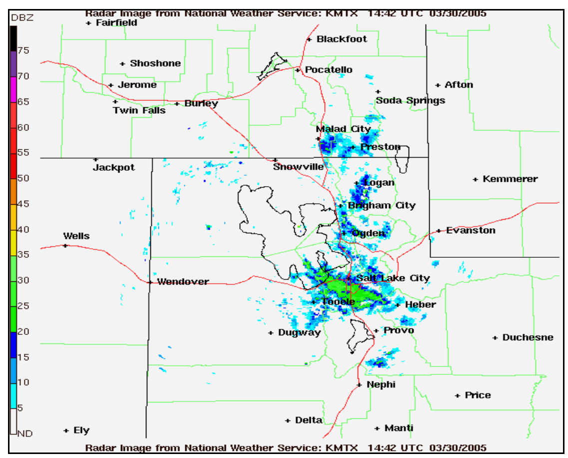

Fig. 3. KMTX WSR-88D composite reflectivity at 1442 UTC 30 March 2005.

A review of WRF model output indicated that the various models predicted some type of post-frontal lake effect event. Specifically, the NMM depicted a banded structure in its QPF field downwind of the GSL, and orographic enhancement along the west facing slopes of the Wasatch Range (Fig. 4). However, placement of the maximum QPF in the lower elevations was poor. The NCEP HRW version produced an excellent depiction of the precipitation band as evident in Figure 5. This model also depicted the orographic enhancement that is experienced during a moist northwest boundary layer flow across the southern Wasatch Range (e.g. Cottonwoods).

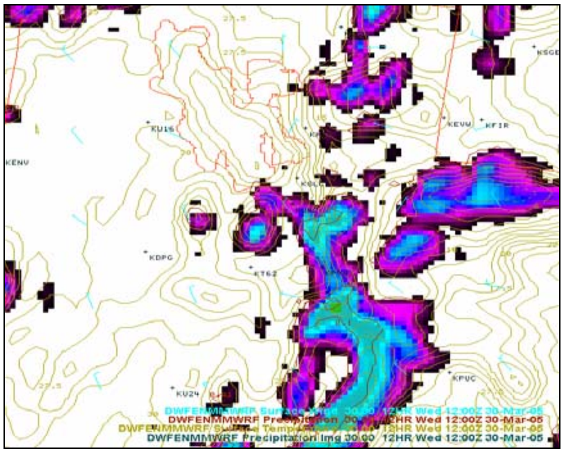

Fig 4. 0000 UTC 30 March 2005 NMM WRF 6-h precipitation forecast (QPF) ending 1200 UTC 30 March 2005. Note the banded precipitation downwind of the Great Salt Lake. Red QPF contours are 0.01, 0.10 and 0.25 in. Surface temperature contours every 0.5˚C are depicted by yellow lines. Surface wind barbs every 2.5 ms^{-1}.

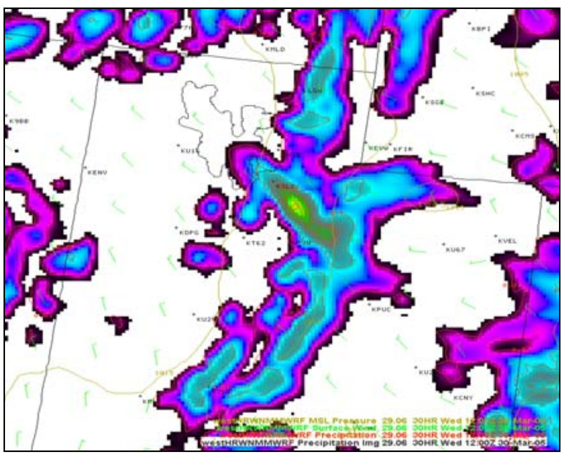

Fig. 5. 0600 UTC 29 March 2005 HRW NMM WRF model 6-h precipitation forecast ending 1200 30 March 2005. Note the banded precipitation downwind of the GSL. Red contours are QPF every 0.25 in with a maximum near 1.00 in. Surface wind barbs are every 2.5 ms^{-1}.

Model run total precipitation proved to be a useful field in this experiment since it was not as sensitive to slight timing differences, thus clearly depicting orographic and banded signatures. The 0000 UTC 30 March NMM run precipitation total ending at 0300 UTC 31 March had a maximum of 32 to 38 mm (1.25 to 1.50 in), which under-forecast precipitation (Fig. 6) when compared to actual observations. However, the prior NMM run at 0000 UTC 29 March run total (Fig. 7) was near 64 mm (2.50 in) and the ARW version (Fig. 8) was slightly less but still close to 50 mm (2.00 in). These results are encouraging since they encompassed the observed amount at the Alta Collins station.

This difference from run to run is a good example of the model's dependence on the initial boundary layer conditions set by the NAM model, and demonstrates the importance of viewing all model runs prior to an event in order to consider run-to-run consistency. The 0000 UTC 30 March NAM run prior to the event also decreased QPF by 25-50 percent. A forecaster may have only used the most current model run and subsequently decreased the precipitation forecast if a conceptual model was not also considered.

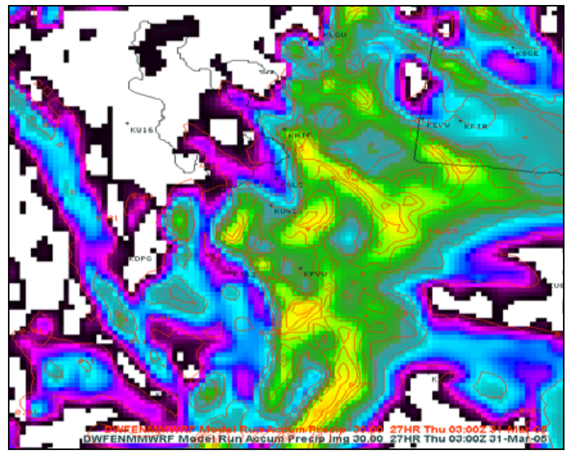

Fig. 6. 0000 UTC 30 March 2005 NMM WRF model run total precipitation ending 0300 UTC 31 March. The model is depicting banded and orographic precipitation downwind of the GSL. Red lines are QPF contours of 0.01, 0.10, 0.25, 0.50 and 0.75 in. Maximum QPF is 1.25 to 1.50 in.

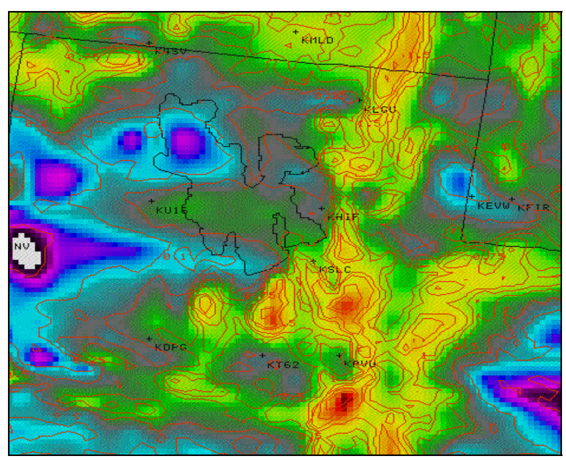

Fig. 7. 0000 UTC 29 March 2005 NMM WRF model run total precipitation ending 0000 UTC 30 March 2005. Red contours are labeled for 0.01, 0.10, 0.25, 0.50 , 0.75, 1.00, and 1.50 in with a maximum area of near 2.50 in over the southern Wasatch Range.

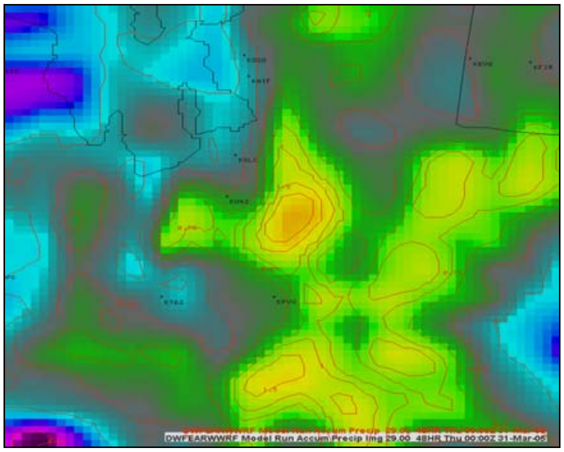

Fig. 8. 0000 UTC 29 March 2005 ARW WRF model run total precipitation ending 0000 UTC 31 March 2005. Red labeled contours are labeled 0.10, 0.75 and 1.50 in with a maximum of 2.00 in over the Cottonwoods.

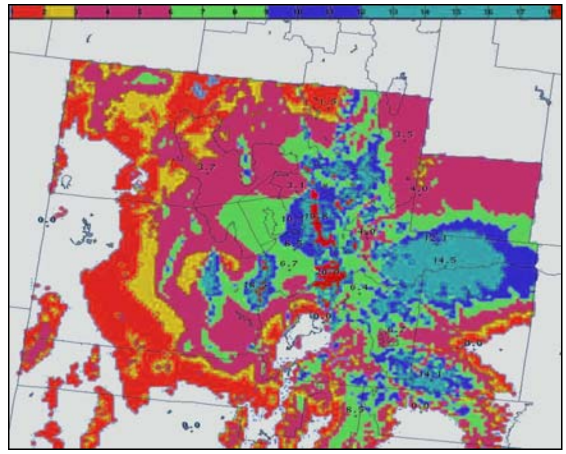

Fig. 9. Snowfall totals for 7 February 2005 banded precipitation event across northern Utah. Colored shaded areas range from 1.0 to 20.0 in.

3.2 Wasatch Front Banded Snow Event on 7 February 2005

A common forecast challenge in northern Utah is the formation of post-frontal bands of heavy precipitation. These are most challenging when a cold front moves through northern Utah and initially produces little precipitation, then an organized band of precipitation develops across northwest Utah and becomes enhanced over and near the Wasatch Front. This is primarily the result of mid and upper-level dynamics enhancing a midlevel (i.e., 700 mb) boundary and terrain enhancement due to back building against the Wasatch Range. A similar banded precipitation event developed on the evening of 7 February 2005 along a midlevel baroclinic zone in northern Utah. Precipitation progressed eastward and produced significant snowfall across the Wasatch Front and Range. Heavy snowfall spilled across the Wasatch Plateau and into the Uinta Mountains. Snowfall amounts ranged from 5 to 25 cm (2 to 10 in) in the lower terrain and up to 60 cm (24 in) in the Wasatch Range (Fig. 9).

WRF numerical model output depicted reasonable model skill in capturing this event. The ARW precipitation forecasts displayed accurate movement of the intense snowfall band as it progressed across the northwest deserts and into the Wasatch Front (Figs. 10 and 11).

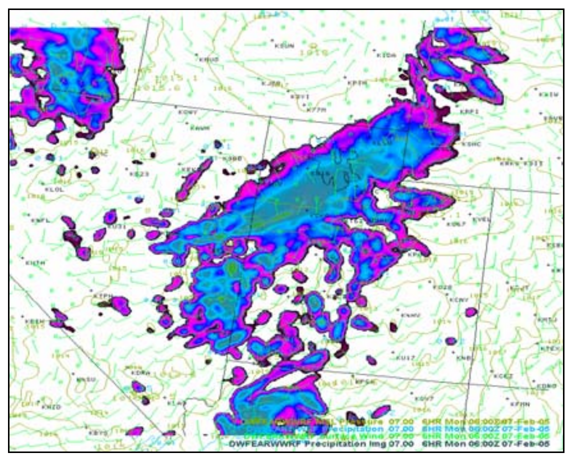

Fig. 10. 0000 UTC 7 February 2005 ARW WRF precipitation ending 0600 UTC 7 February 2005. QPF contours are 0.01, 0.10 and 0.25 in. Light green contours are MSL pressure every 1-mb and darker green wind barbs are every 2.5 ms $^{-1}$.

3.3 Non-forecasted Banded Snow Event on 16 February 2005

The importance of accurately forecasting the placement of snow bands was evident on the morning of 16 February 2005. A band of snow developed along a stalled midlevel boundary and slowly moved across the southern Wasatch Front. Satellite imagery depicted this narrow band of enhanced snowfall (Fig.12).

The significance of this event was that none of the available model data, including WRF (Figs. 13 and 14), NAM, or GFS, produced precipitation this far north. Although snowfall was relatively minor, it did accumulate from 3 to 7 cm (1 to 3 in) in the Salt Lake Valley and southern Wasatch Front.

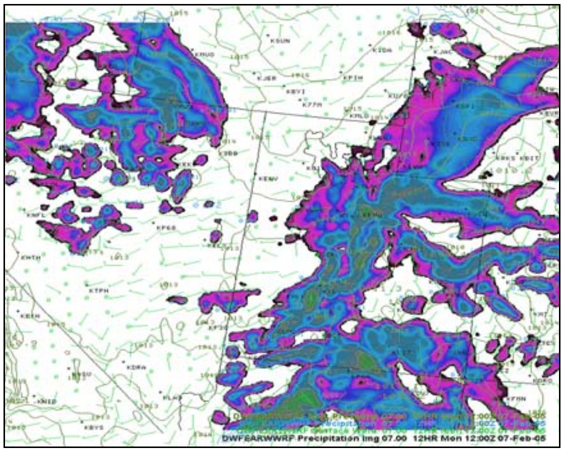

Fig. 11. 0000 UTC 7 February 2005 ARW WRF 6-h precipitation ending 1200 UTC 7 February 2005. QPF contours are 0.01 and 0.10 in. Solid contours are MSL pressure every 1 mb and green wind barbs are every 2.5 ms $^{-1}$.

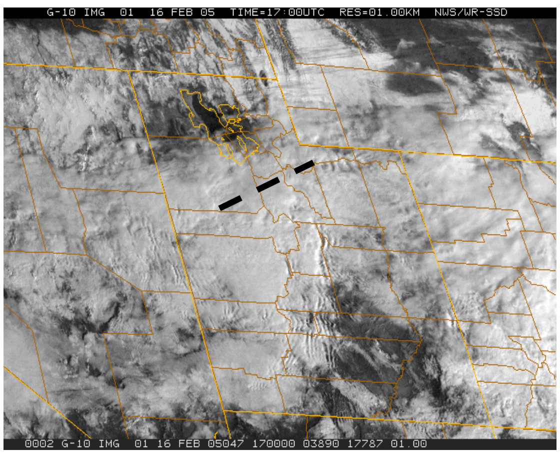

Fig. 12. GOES-10 visible image at 1700 UTC 16 February 2005. Dashed line marks the band of snow.

3.4 Standing Convective Wave Event

One of the most interesting weather events during the winter season occurred on 30 December 2004. It was explained earlier that the WRF models tended to severely over-forecast convective precipitation over higher terrain. However, for this event the NMM WRF attempted to capture a persistent area of snow showers that occurred over the southern Wasatch Range.

The synoptic pattern consisted of moderate southwest flow with a moist and conditionally unstable air mass. Snow showers developed over the Wasatch Range, but rather than advecting downstream in the flow, the precipitation was nearly stationary for up to 24 hours. Snowfall reports showed that as much as 20 cm (8 in) accumulated over the Wasatch crest and just downwind in the Wasatch mountain valleys. This is not considered significant snowfall for this region, but more importantly water equivalent was as much as 38 mm (1.5 in) at the 9000 foot elevation. This was unusually dense snow given 700 mb temperatures between -6 to -8 °C. The WFO Salt Lake City sounding (Fig. 15) indicated the relatively shallow moist and unstable layer capped by a weak inversion. From the radar and satellite imagery (Figs. 16 and 17) it was apparent that a persistent standing wave cloud produced the snowfall.

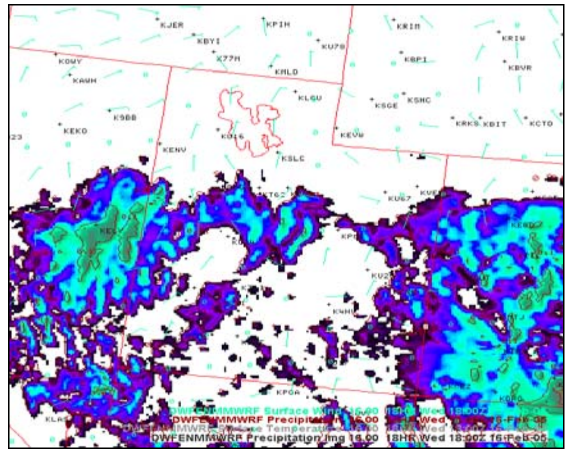

Fig. 13. 0000 UTC 16 February 2005 NMM WRF precipitation ending 1800 UTC 16 February 2005. QPF contours are every 0.01 and 0.10 in. Surface wind barbs are every 2.5 ms $^{-1}$.

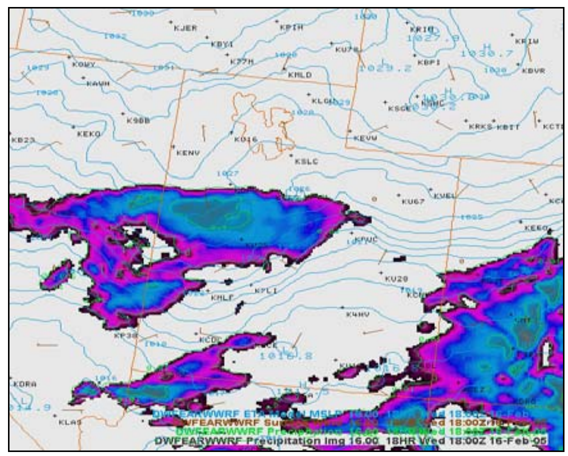

Fig. 14. 0000 UTC 16 February 2005 ARW WRF precipitation ending 1800 UTC 16 February 2005. Surface wind barbs are every 2.5 ms^{-1}. Blue MSL pressure contours are every 1 mb. QPF contours are 0.01 and 0.10 in.

WRF model data was limited for this event since it occurred prior to the official DWFE. However, a model run from the 0000 UTC 30 December NMM displayed persistent 6-h periods of QPF over the same locations for 18 to 24 hours (Fig. 18). The placement of this precipitation was slightly too far upstream and located over the lower elevations west of Timpanogos Peak (11,800 ft).

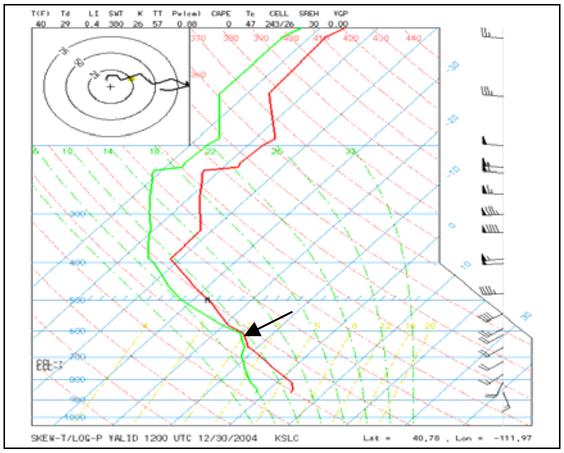

Fig. 15. KSLC sounding at 1200 UTC 30 December 2004. Arrow points to inversion area.

4. CONCLUSIONS

We evaluated the high resolution models during the DWFE at the WFO in Salt Lake City and analyzed numerous events during the 2005 winter. This paper included a few events that demonstrated that there is significant skill with running a 5-km WRF across the complex terrain of the Great Basin. In particular, banded, convective, lake effect, and

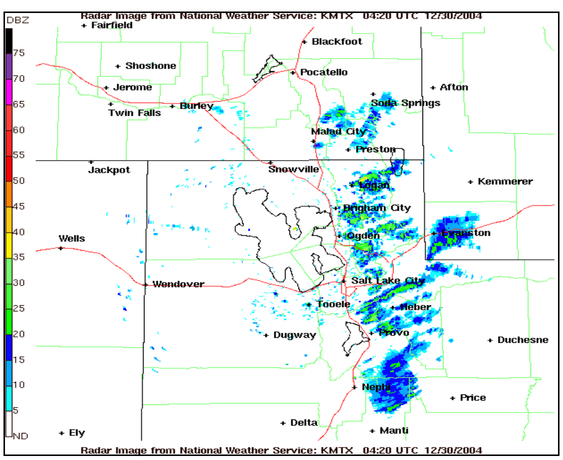

Fig. 16. KMTX WSR-88D composite reflectivity at 0420 UTC 30 December 2004.

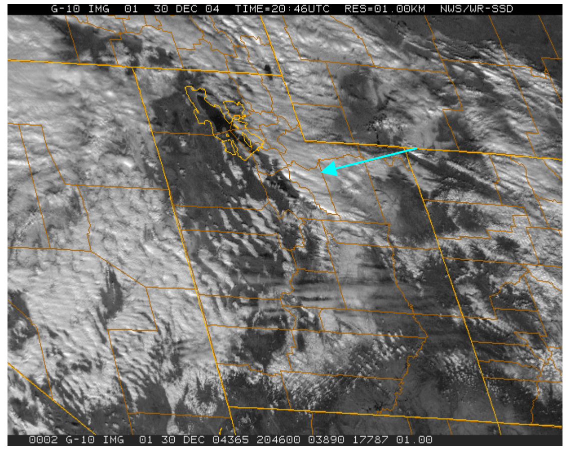

Fig. 17. GOES 10 visible image at 2046 UTC 30 December 2004. Arrow depicts wave cloud and area of persistent snow showers.

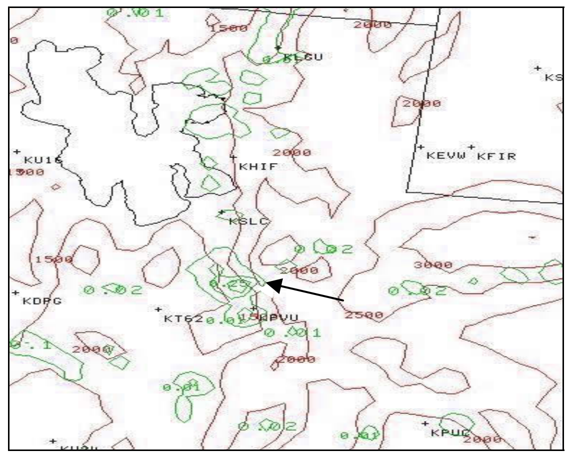

Fig. 18. 0000 UTC 30 December 2004 NMM WRF ending at 1800 UTC 30 December. Green lines depict 6-h QPF (arrow points to maximum 0.25 in) and red lines are topography every 500-m.

orographically enhanced precipitation events present the most challenge to the forecast process and were predicted with relatively good skill by the WRF. However, the models ability to consistently forecast accurately or perform better than current models was not proven.

The experiment this winter also revealed weaknesses with using a high resolution model in operations, most importantly its over dependence on initial boundary layer conditions from another numerical model. Specifically, convective precipitation output was noted to be over-forecast at times. In order to improve this output, the WRF model may need to be run at a higher resolution than 5 km, or a convective parameterization scheme may need to be utilized.

Future plans to run a local version of the WRF model in northern Utah and have an operational version of the NCEP high resolution WRF should prove to be useful guidance to forecasters. These models should also benefit toward a better understanding of mesoscale weather phenomena and orographic enhancement in both populated and remote areas in Utah.

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