5.3A MESOSCALE MODEL SIMULATIONS IN QUASI-FORECAST MODE OF THE GREAT WESTERN STORM OF 16-20 MARCH 2003

Douglas A. Wesley [1*], Gregory Poulos[2], John Snook[4], Ed Szoke[5], Michael Meyers[3], Greg Byrd[1], Robert Rozumalski[3], and Heather McIntyre[1]

[1]UCAR/COMET®, Boulder CO [2]NCAR/ATD [3]NOAA/NWS [4]ATMET [5]NOAA/FSL/CIRA

1. INTRODUCTION

A massive snowstorm crippled large portions of the central Rockies and adjacent plains during the period 16-20 March 2003. Snowfall accumulation in the foothills and mountains exceeded four feet in relatively large regions, while on the plains amounts above two feet were common (Fig. 1; also see Poulos et al. 2003). The large impacts of this historic storm are well documented. This paper examines experimental meso-γ scale model simulations of the event, utilizing larger-scale model-generated boundary conditions, from a forecasting standpoint.

Public forecasts of this event were generally accurate up to several days before the storm hit. NCEP model guidance provided initial alarms (in the form of ensemble forecasts) up to one week prior to the storm (Szoke et al. 2004). As the potential event approached, Eta model forecasts were trending towards a large precipitation event, and by about two days before the onset of snowfall along Colorado's Front Range very large precipitation totals (five or more inches) were output by this model for portions of the region during the period of 17-20 March. Accuracy of these forecasts was perhaps unprecedented in the area, for such a large event, primarily because the orographic forcing was so strong. The Eta forecasts clearly provided a crucial asset towards forecast operations prior to the storm. The model, however, did show some shortcomings regarding the precipitation type distribution, and of course was limited by its relatively large grid spacing, a required feature given the domain size of that model.

Corresponding author address:
Douglas A. Wesley, UCAR/COMET, PO Box 3000, Boulder CO 80307; e-mail <wesley@comet.ucar.edu>

The crippling nature of the subsequent storm period, in terms of disrupting transportation and other day-to-day activities, has shown that even if a very large snowfall potential is emphasized in, say, a 2-4 day forecast, society is still vulnerable to this type of storm. Insurance claims and a paralyzed international airport attest to this fact. Importantly, the current challenge is to increase the resolution and details of the forecast to minimize this vulnerability, as much as currently possible.

Close examination of snowfall totals revealed extremely sharp gradients in snowfall, on the order of several feet within a horizontal distance of 15 miles or less. Many of these sharp gradient regions coincided with strong gradients in elevation; however some did not. For example, an area on the plains/foothills interface just north of Denver accumulated only 3-6 inches of wet snowfall, while 15-25 miles to the south, 24-36 inches fell, and areas another 20 miles to the south recorded nearly four feet. Meanwhile, 20-30 miles *north* of the aforementioned area of snowfall minimum, 24-36 inches fell. *All of these locations are at the same approximate elevation*. The current configuration of NWS forecast zones along the urban corridor is not designed to handle these types of gradients, nor is the current configuration of the Eta model. As NWS forecasts evolve towards gridded forecast fields, this issue will be addressed to some degree.

The purpose of this study is to closely examine the causes of extreme snowfall and wind variations in this storm from a mesoscale modeling standpoint in order to better predict them in the future. The MM5 was run in quasi-forecast mode (with Eta forecasts initialized at 00 UTC 17 Mar.) utilizing non-hydrostatic and multiple-grid configurations, with the smallest grid exhibiting 1-2 km horizontal grid spacing. The primary reason for utilizing such a small grid spacing is the presence of steep and variable topography throughout the foothills and higher terrain of the Front Range. The "workstation" Eta was run (non-hydrostatically) utilizing Eta analyses *and* 3-hr. forecasts at the boundaries. The smallest grid contained 2 km grid spacing.

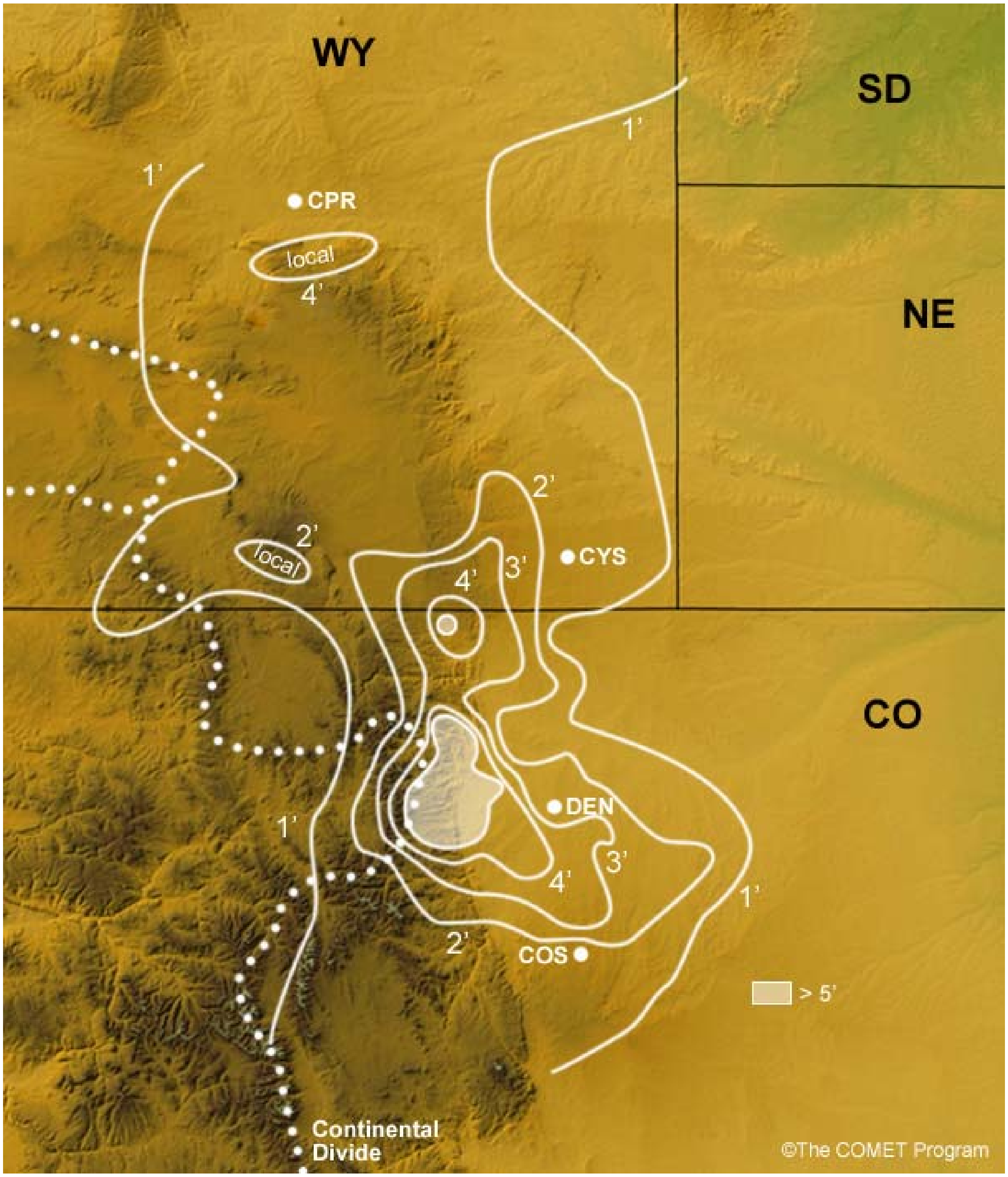


Fig. 1 Snowfall totals (in feet) for a portion of the Front Range region for 17-20 March 2003. Significant snows fell in other regions of the Rocky Mountains to the west of this area (see Meyers et al., 2004).

Preliminary indications are that both mesoscale models produce generally accurate precipitation distributions, and both produce cooler (but still above freezing) low-level conditions along the urban corridor for much of the storm evolution when compared to the operational Eta forecasts. The MM5 forecasts appear to capture better detail in the precipitation distributions, as expected, and exhibit low-level temperatures closer to freezing in critical areas near the rain/snow line. Comparisons with operational profiler winds show some problems with the strength of the mid-level upslope, a critical component of the storm, and one perhaps related to the relatively warm low-level conditions along the urban corridor. This component is likely a primary factor in determining precipitation rates, in the sense of the warm conveyor belt running up and over the barrier jet, and thus a critical determinant of surface precipitation type. It appears that an accurate initial analysis and subsequent prediction of the depth of the barrier jet is a crucial requirement to an accurate precipitation forecast. Another important feature of the mid-level easterly flow is its strong variation through the 3-4 day period as synoptic waves passed through the region, and these variations will be compared to the barrier jet depth and distributions of precipitation rates in the near future.

Initially it also appears that relatively subtle terrain features along the plains/foothills interface interacted with the barrier jet to contribute significantly to low-level vertical motion fields, and likely play a role in the cause of the snow minima discussed above.

2. STORM DYNAMICS OVERVIEW

During the period 15-17 March, significant troughing built into the central and southern Rockies and the Great Basin as intense mid- and upper-level jet energy impacted the California coast from the west-northwest. The amplification of the pattern increased rapidly as ridging built over the upper Midwest and mid-Atlantic regions. By 00 UTC 19 March, a strong, deep cutoff low pressure system was established over the southern Rockies and central/southern plains (Fig. 2). For a period of about 48 hours, a classic warm conveyor belt out in front of the cutoff set up and transported large amounts of moisture directly from the Gulf of Mexico northwestward into

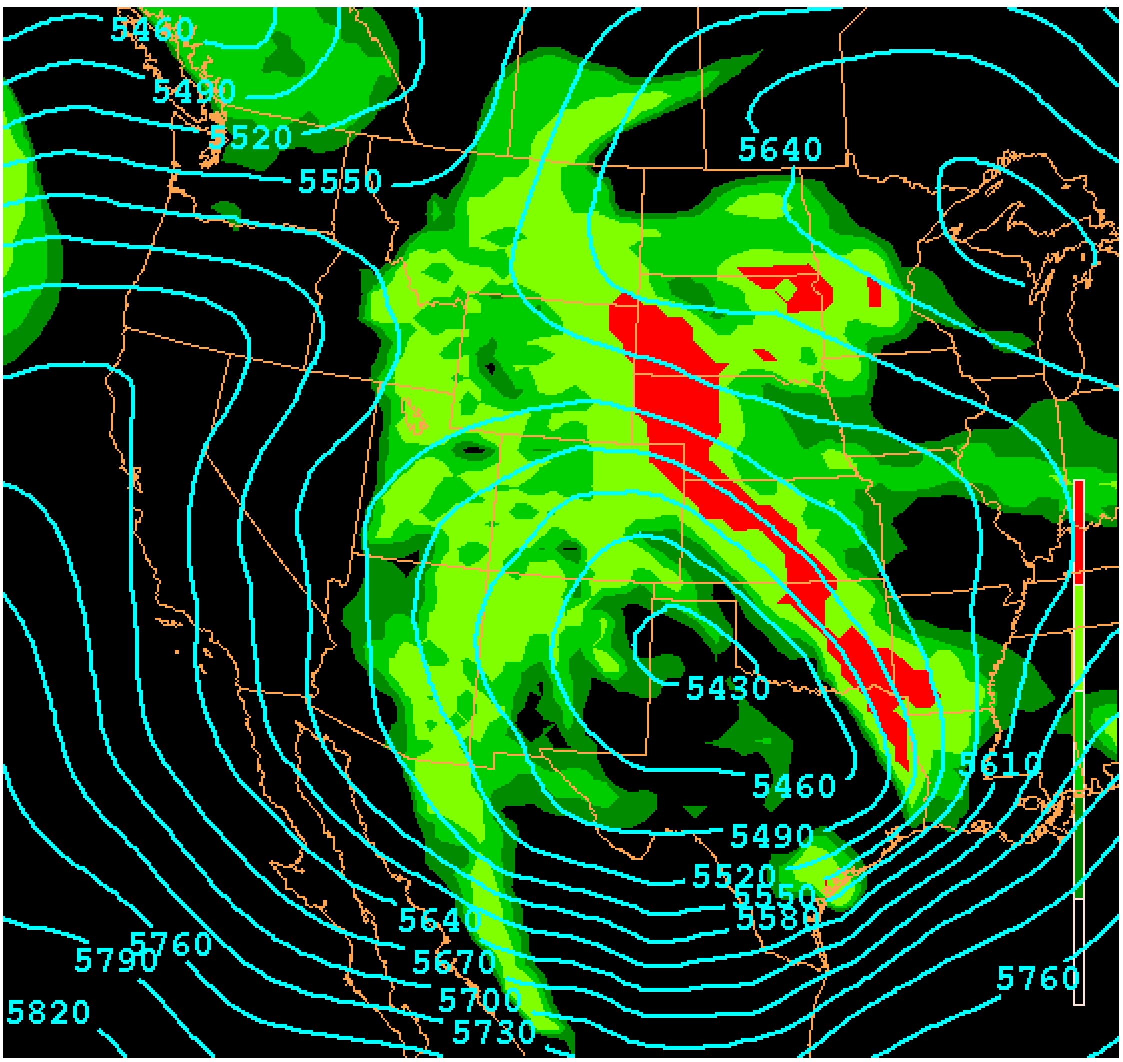


Fig. 2 500 mb heights and 700 mb RH, analyzed at 00 UTC 19 Mar. 2003. Red regions correspond to saturated conditions at 700 mb.

the central Rockies. In the northwestern portion of the cutoff system, a TROWAL-like feature set up as the occlusion matured, and this wraparound feature contributed to heavy precipitation well-removed from the cutoff center off to the southeast.

The mesoscale features of this mega-storm were of critical importance to the resulting precipitation distribution. Observationally, the role of the barrier jet in the storm in producing, first, snow instead of rain in the urban corridor, and, second, uplift strong enough to produce snowfall rates of 1-3 inches per hour for 2-3 days, cannot be overemphasized. Clearly the barrier jet was located on the cold side of a persistent rain/snow boundary that exhibited the classic characteristics of strongly diabatically-forced mesoscale dynamics, a feature documented in previous heavy springtime snowfalls in the urban corridor (Marwitz and Toth 1993). Furthermore, the three-dimensional configuration of this barrier jet is critical to the attempt to explain the astounding snowfall and wind gradients along the urban corridor. A well-developed barrier jet was apparent by 18 March, and persisted through the 19th. Important facets of this low-level northerly flow regime over and next to the foothills:

(a) low-level northerly zone was sloped upwards to the west, essentially modifying the obstacle encountered by upslope (easterly) flow and leading to mesoscale uplift in a saturated air mass over and just east of the jet

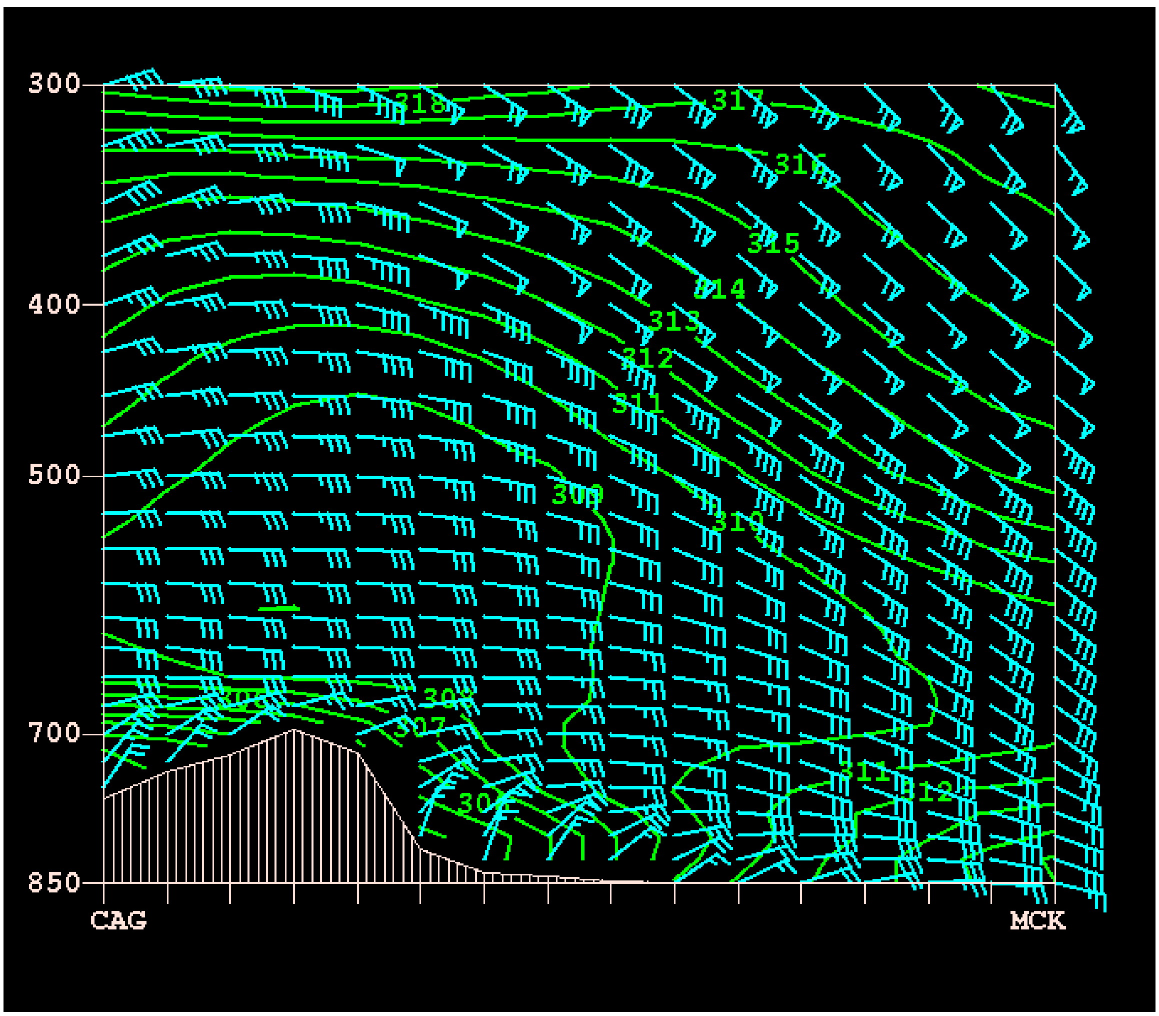


Fig. 3 Vertical cross section showing equiv. potential temp. (K) and winds (knots), 6-hr. forecast from the Eta model initialized at 18 UTC 18 Mar.

(b) large amounts of melting in the low-levels on the east side of the barrier jet provided latent cooling, thus enhancing the blocking and barrier jet structure, similar to the March 1990 storm studied by Marwitz and Toth (1993) and others.
(c) significant low-level cold advection from the north/northeast enhanced the stability in the air mass east of the terrain obstacles.

Note in Fig. 3 the cold air stacked up against the Front Range, and the moderate northerly flow within that cold air. Many regions just east of the foothills experienced surface wind gusts in the 30 to 40 knot range, causing extensive blowing and drifting snow. Interestingly, at this point a well-defined convergence line does not exist on the east side of the jet, and this was confirmed in surface observations. Convectively unstable conditions are noted over portions of the plains in Fig. 3.

3. Mesoscale model simulations

The MM5 was set up with a 5-grid nested configuration, the smallest domain (grid 5) centered on north-central CO and exhibiting a 1.5 km grid spacing. Eta operational forecasts from the run initialized at 00 UTC 17 Mar. served as large-scale boundary conditions.

Fig. 4 shows the total precipitation (mm) predicted by the model through 84 hours (ending at 12 UTC 20 Mar.). Notable features are the foothills maxima in the higher terrain (but east of the Continental Divide) of Boulder and Larimer Counties (the Divide runs along the western boundaries of these two counties), with several locations predicted to have over 130 mm (more than 5 inches). Three relative minima are also very interesting:

1. northeastern Boulder Co. (less than 50 mm)
2. southeastern Larimer Co. (43.8 mm)
3. northeastern Larimer Co. (27.5 mm)

All of these regions experienced snow minima compared to observed snowfall in immediately surrounding regions of similar elevations (Fig. 1). This is best shown by examining high-resolution satellite imagery after the storm as the melting process started under sunny skies (Fig. 5).

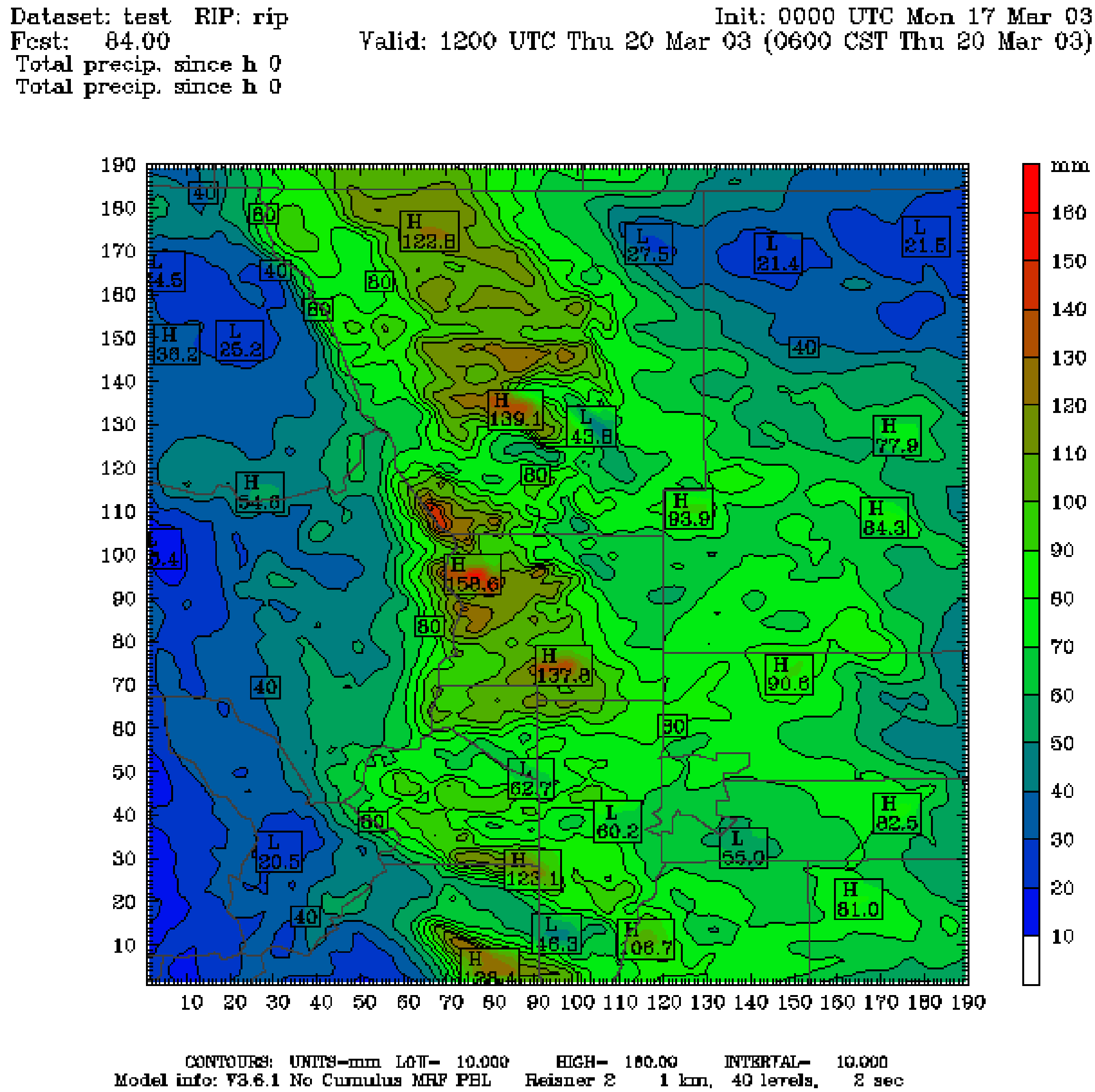


Fig. 4 MM5-predicted precipitation (mm) for 84 hours of simulations ending at 12 UTC 20 Mar..

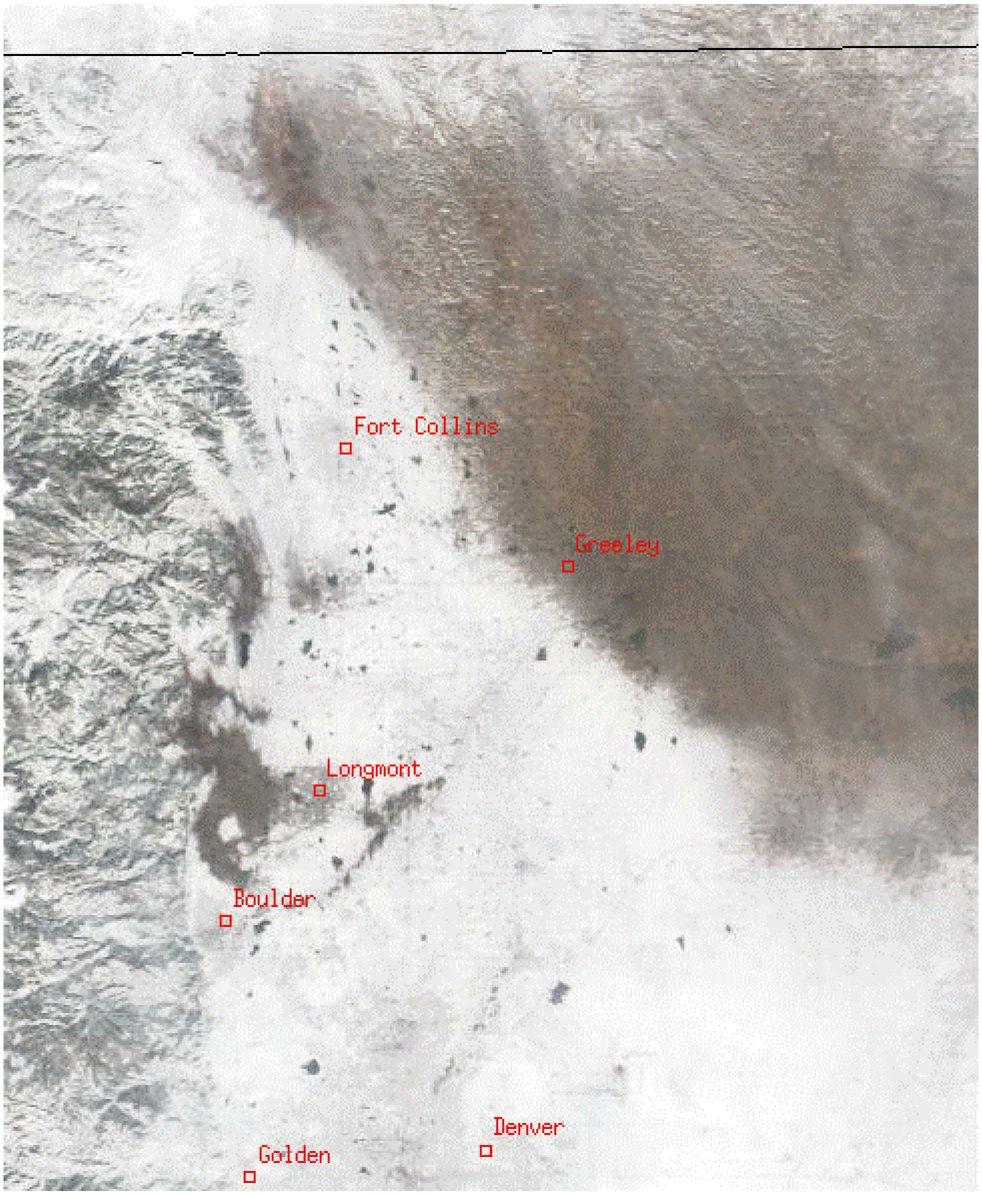


Fig. 5 High-resolution visible image (MODIS) on 22 Mar.. Complex patterns on the west side are timbered and canyon areas. Darker areas just south of the WY state line, southwest of Fort Collins and west of Longmont are areas where much less snow accumulation was observed.

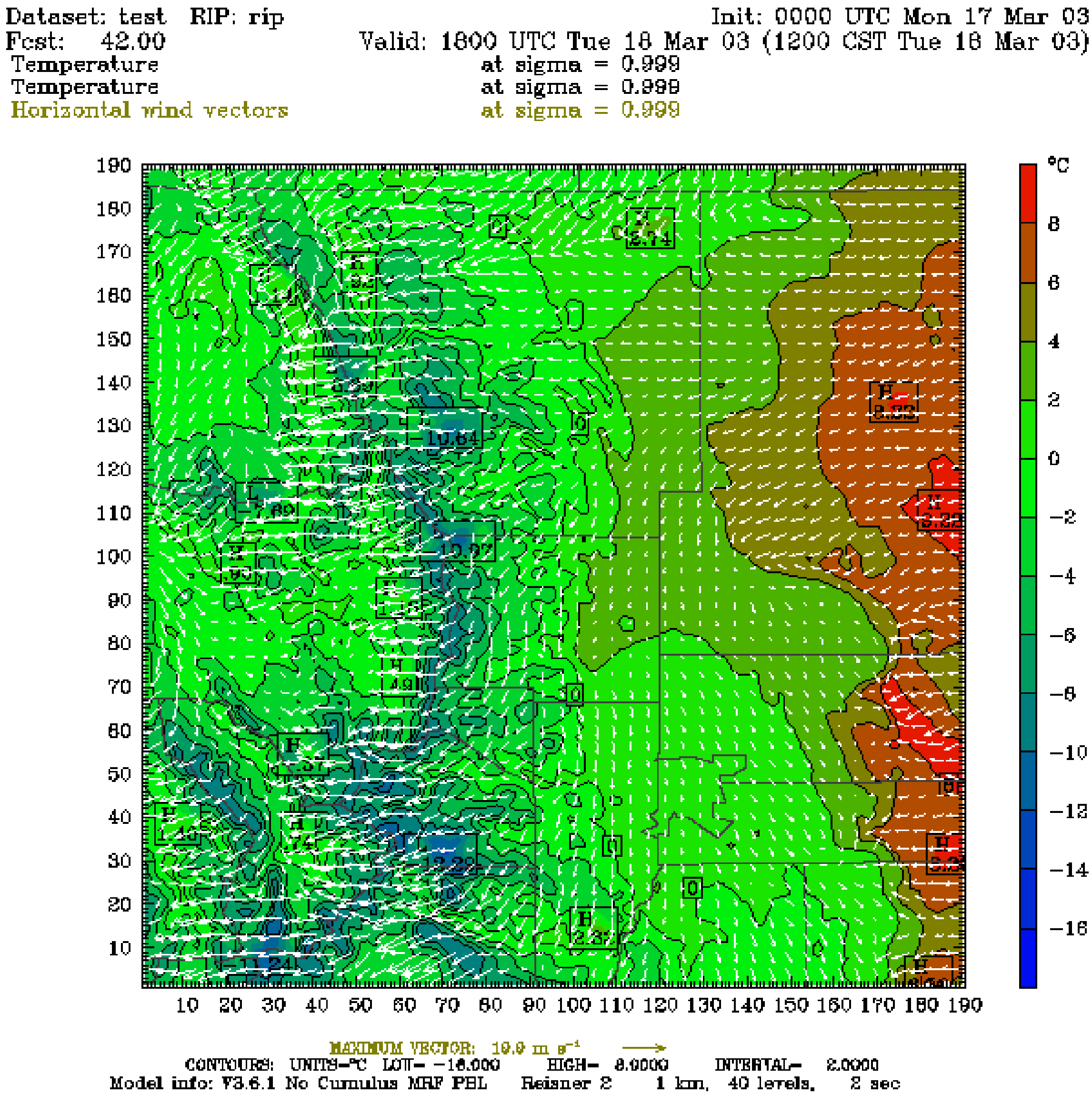
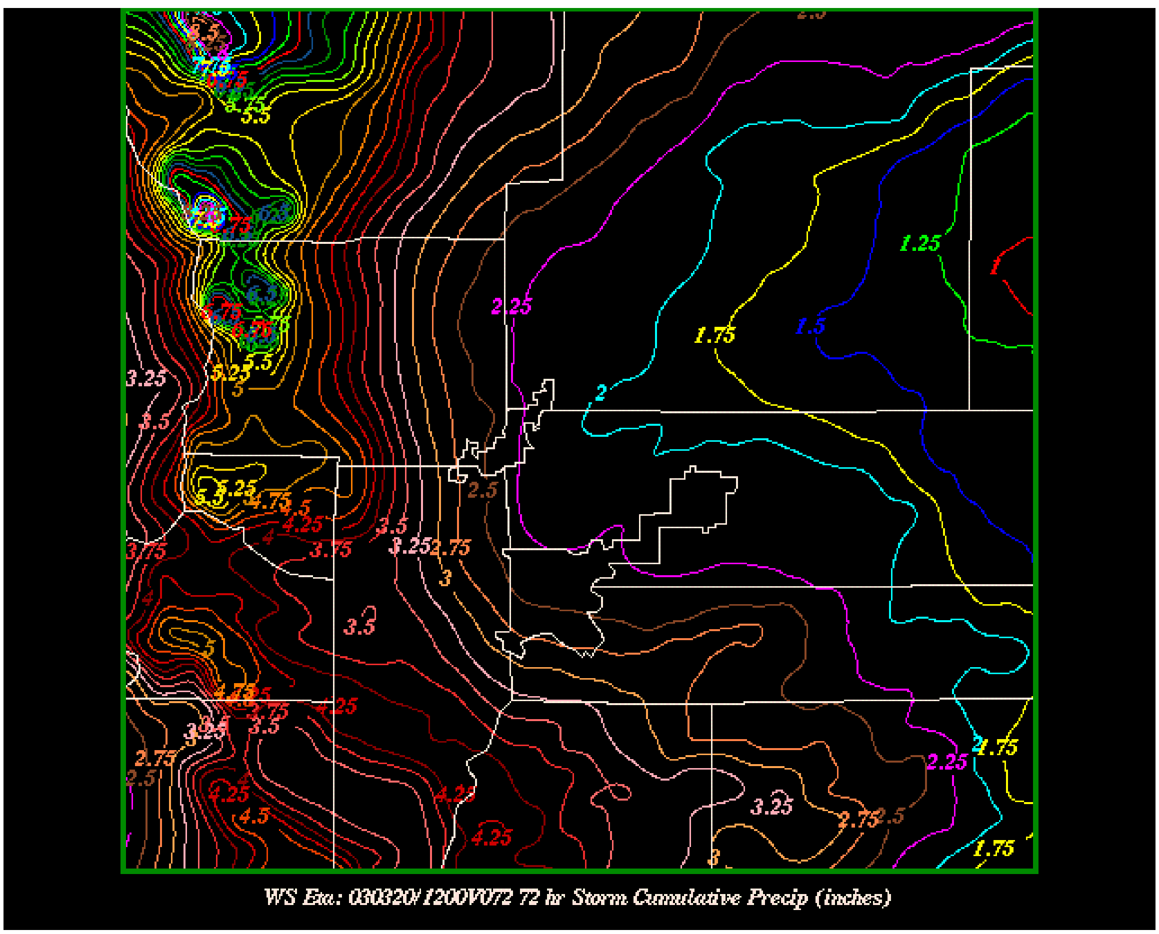


Fig. 6 MM5 42-hr. forecast of lowest level temperature (C) and winds (m/s). Note the relatively warmer areas along the foothills in southeastern Larimer Co. and northeastern Boulder Co.

Fig. 6 demonstrates several interesting aspects of the simulations. Relatively warmer conditions are predicted in general along the eastern portions of Larimer Co. and northeastern Boulder Co., in agreement with observations in two of the snow minima regions. However, in comparison with observations, these areas are predicted to be a few degrees F warmer by the model. In the urban corridor region just south of the Cheyenne Ridge, the snow minimum region discussed previously appears to be caused by lower precipitation values rather than warmer temperatures (see Wesley et al., 1995). This is often observed in storms characterized by strong north winds at the surface in this region. Also note the northerly flow over the foothills, and a strong convergence line oriented nearly E-W along the WY border.

More results of these MM5 simulations are under investigation, including a detailed examination of the areas that experienced warmer surface conditions and less snowfall. Potential mechanisms include blocking of the barrier-jet induced cold advection by small-scale terrain features, and relatively warm air (originating over the canyons to the northwest of these locations) acting as the source region for the surface conditions over these areas.

The “workstation” Eta model was also set up non-hydrostatically, with multiple nested grid configuration and innermost grid spacing set at 2 km. Fig. 7 shows the predicted total precipitation for the 72-hr. period ending at 12 UTC 20 Mar.. Though the details in the plot do not resemble those of the MM5-predicted precipitation, especially over the eastern foothills and plains interface, note the maxima in the high terrain just east of the Continental Divide, with one elevated area in northwestern Larimer Co. exceeding 8.5”. The urban corridor values are generally in the 2.25-3” range, with relatively lower values over eastern Boulder Co.. Overall, these values correlated well with observed values in a general sense, including the magnitudes of the maxima. However, some underprediction of precipitation is noted in the Fort Collins and Golden areas, and along the I-25 zone north of Denver. These issues are under further investigation, including examining the role of the diffusion processes in the Eta results.



WS Eta: 030320/1200V072 72 hr Storm Cumulative Precip (inches)

Fig. 7 High-resolution Eta predicted total precipitation (inches) for the period 12 UTC 17 Mar. through 12 UTC 20 Mar.

In regards to the precipitation type and the low-level temperature fields, the workstation Eta forecast even warmer conditions along the urban corridor than the MM5 during the storm (Fig. 8). The precipitation-type forecasts (Fig. 9) which utilize a partial-thickness approach, exhibited liquid precipitation for extreme eastern Larimer and Boulder Counties at 00 UTC 19 Mar. (at this time these areas were receiving the heaviest snowfall of the event), but do predict snowfall in some foothill/plains interface areas that were above freezing in the model through most of the storm. Note in Fig. 9 that the liquid precipitation area that extends westward over northeastern Boulder Co. has some similarity to the observed snowfall minima shown in Fig. 1. In Fig. 8, this tendency for warmer surface conditions is evident in the locations of the 2C and 3C contours over this area, especially in comparison to these locations in other areas within the urban corridor. Further examination of these thermal fields is currently underway.

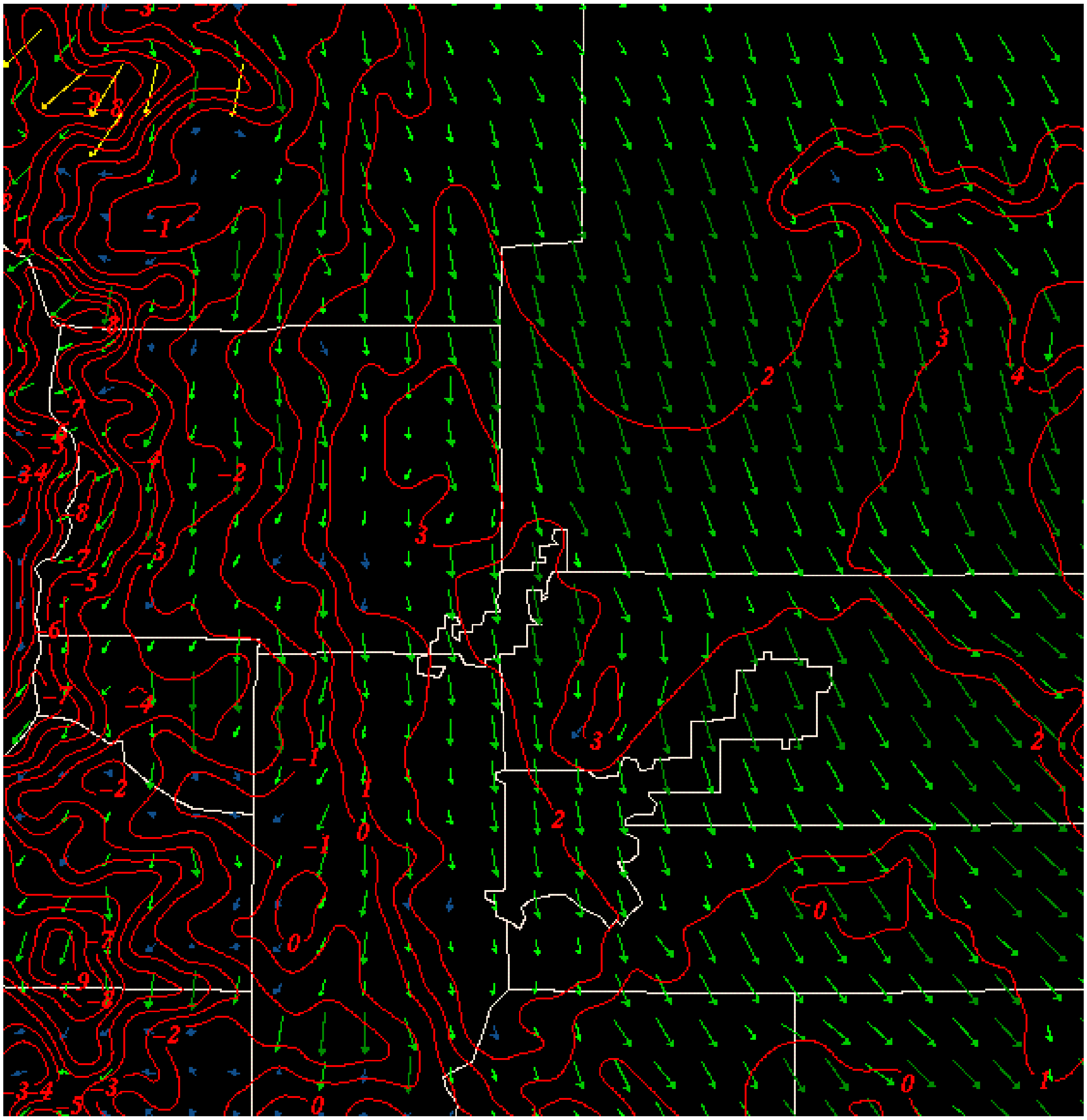


Fig. 8 High-res. Eta-forecast temperatures (C) and winds at 10m, for 00 UTC 19 Mar. The longest vector on the chart corresponds to about 25 knots.

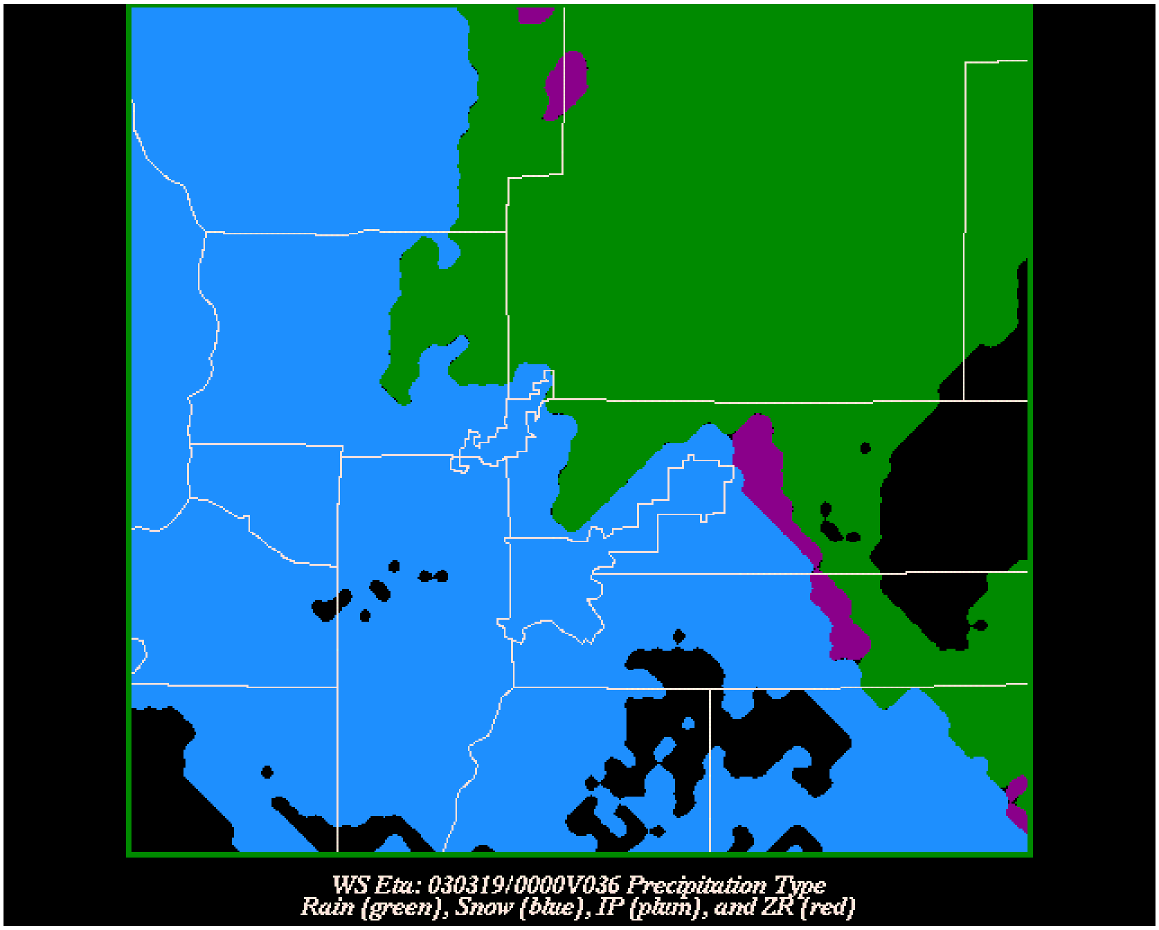


Fig. 9 Eta-forecast precipitation type, for 00 UTC 19 Mar.

The MM5 and Eta models' abilities to capture the depth and strength of the upslope flow are likely critical to the ability to predict the barrier jet regime accurately, and thus the low-level temperatures and precipitation types. This table shows a comparison of observed and predicted vertical wind speed profiles at Platteville, CO (about 25 miles north of Denver) for the u-component at 06 UTC 19 Mar. (during the height of the storm). The "profiler" column is for the winds measured at the site. A value above 0 indicates a westerly direction.

■Height (msl)	profiler	MM5	wEta	Eta
■2km	+8 knots	-2	+3	~0
■3	-30	-10	-4	-8
■4	-33	-20	-22	-15
■5	-31	-32	-27	-25
■6	-40	-40	-41	-30
■7	-49	-44	-42	-40

Obviously, serious issues exist with the ability of the models to predict the upslope component accurately in the 10-15,000 (MSL) foot layer. Whether this is related to the warm biases is unclear, and at first guess is non-intuitive. Another possibility is inaccurate boundary conditions.

4. SUMMARY

This study has begun to address the applications of very high-resolution mesoscale model forecasts for a major wintertime snow event over the high plains and mountains of central/northern CO. This storm represented a situation where very strong synoptic forcing interacted with major terrain-forced processes to create snow accumulations above 40 inches in some urban areas and above 70 inches in many foothill locations during a 3-4 day period. In this research we have set up the MM5 and "workstation"-Eta models in quasi-forecast mode to investigate small-scale mechanisms for snowfall maxima and minima, precipitation type, and wind variations. Clearly the detailed precipitation and surface wind fields generated by the high-resolution models have produced insight into the physical processes involved, including blocking, melting, and barrier-jet induced uplift. Relatively high accuracy characterizes the total precipitation fields generated by the models. The three-dimensional nature of the barrier jet structure and the temporal dependence of the upslope forcing also represent important aspects of these simulations. The problem associated with the predicted vertical profiles of the upslope flow is under investigation. In addition, though the model forecasts seemed to accurately predict surface temperature gradients, the issue of forecast temperatures being too warm (by both models) in critical areas is also under further investigation. This is also the subject of a companion paper on this storm (Szoke et al., 2004).

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Marwitz, J., and J. Toth, 1993: The Front Range Blizzard of 1990: Part I: Synoptic and mesoscale structure. *Mon. Wea. Rev*. **121**, 402-415.

Meyers, M.P., J. Colton, R. McAnelly, W. Cotton, D. Wesley, J. Snook and G. Poulos, 2004: The Operational Implications of Forecasting a Heavy Snow Event over the Central Rockies in an Atypical Flow Regime. *Preprints, 20th Conf. on Weather Analysis and Forecasting,* Seattle, Paper P2.9.

Poulos, G.S., D. Wesley, M. Meyers, E. Szoke, J. Snook, and G. Byrd, 2003: Exceptional Mesoscale Features of the Great Western Storm of 16-20 March 2003. *Preprints, 10th Conf. on Mesoscale Processes*, Portland, Oregon, Paper 6.6A, 6 pp..

Szoke, E. J., B. Shaw and P. Schultz, 2004: Performance of various operational and experimental numerical forecasts for the March 2003 Colorado snowstorm. *Preprints, 20th Conf. on Weather Analysis and Forecasting,* Seattle, Paper 10.3A.

Wesley, D.A., R.M. Rasmussen, and B.C. Bernstein, 1995: Snowfall associated with a terrain-generated convergence zone during the Winter Icing and Storms Project. *Mon. Wea. Rev.,* **123**, 2957-2977.