10.3A PERFORMANCE OF VARIOUS OPERATIONAL AND EXPERIMENTAL NUMERICAL FORECASTS FOR THE MARCH 2003 COLORADO SNOWSTORM

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1. INTRODUCTION

The massive winter storm that hit Colorado from 17-20 March 2003 was an impressive event, producing extraordinary snowfall amounts both in the mountains/ foothills and up and down the Front Range (Fig. 1). Snowfall totals in the foothills were particularly impressive as were some of the photos of the event (Fig. 2), with some foothill areas approaching 80 in snowfall totals. Remarkable also was the amount of liquid equivalent in the snow, with ratios approaching a very moist 10:1 for even some of the higher elevations resulting in over 6 in of liquid equivalent covering a widespread area. With the high moisture and the fact that the storm was so large and extensive, this single event brought the (at least temporary) end to a several year drought, totally or nearly totally filling resevoirs with the spring melt that in some cases had been drawn down to well under 50 percent capacity.

Along the Front Range the storm crippled transportation for days, including closing the Denver International Airport (DIA) from the afternoon of Tuesday 18 March well into Thursday 20 March. The heavy snow had even higher moisture content at the lower

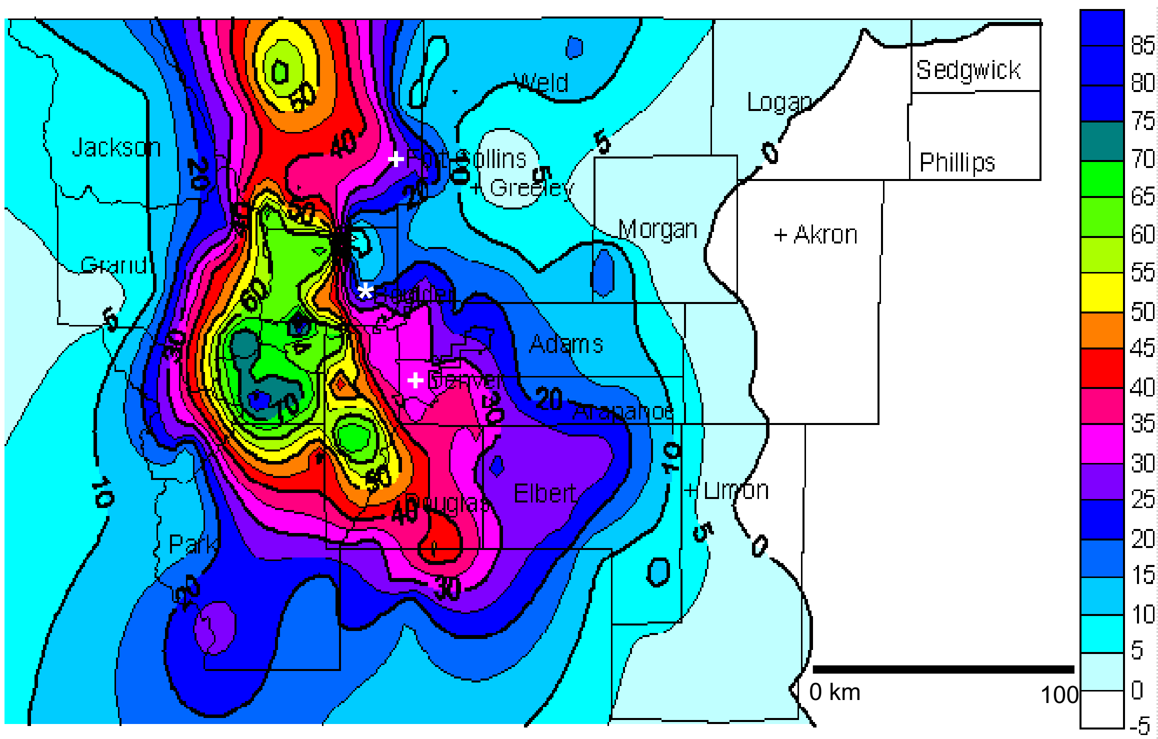

Figure 1. Storm totals (inches). County boundaries are shown on the map, with some selected cities (plus signs). Asterisk is location of Boulder. Distance scale, in km, is shown at bottom right.

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Figure 2. Deep snow in the foothills! Photo courtesy of George Grell, his house at an elevation of about 9000 ft in Coal Creek Canyon, located southwest of Boulder in the foothills.

elevations, resulting in numerous instances of collapsing roofs and downed tree limbs and power lines.

There are many fascinating aspects of this storm, as one might expect, ranging from its predictability in the longer range (beyond 2 days), down to very small-scale issues that resulted in some unusual snowfall totals amid the overall massive snowfall along the Front Range. For example, the very small minimum of snowfall near the foothills in Fig. 1 in northern Boulder County, with snowfall of only a few inches despite accumulated precipitation amounts exceeding 2.50", was apparently a result of the interaction of low-level north-northwest flow with a very localized terrain feature (Wesley et al., 2004). The low-level northerly flow was a result of a well-defined cold air damming structure that developed early in the storm and persisted for over 36 h. This feature was pretty well forecast by both the operational and experimental (local) models. In general, once the storm was within a couple of days of occurrence, the operational models made excellent forecasts, giving forecasters at the Boulder National Weather Service (NWS) Weather Forecast Office (WFO) enough confidence to forecast snow amounts of up to eight feet in the foothills, and over two feet along the Front Range. Although a rare event in terms of the widespread amount of heavy snowfall, the magnitude was still well forecast.

Despite the success of the models and the confidence of the forecasters in the event, there were still, of course, important forecast details. One in particular was when the precipitation would change to snow at lower elevations. Deep foothill snows were as close to a sure thing as one can get, but along the Front Range, where most of the population lives, the precipitation began as rain during the daytime hours of Monday 17 March. In fact, by the afternoon, thunderstorms with hail and some heavy rains developed, even prompting a tornado warning late in the afternoon that included DIA. There was much debate, especially among the meteorologists at the Forecast Systems Laboratory (FSL), about when the changeover would occur. It was noted that some model solutions, such as those from the RUC (Benjamin et al., 2003) and the local model run at the Boulder WFO, MM5 (at a 10 km horizontal grid resolution; Shaw et al., 2001) on 17 March were not changing the rain over to snow below elevations of around 6000 ft. On the other hand, the snowfall algorithm from the Eta model, initialized at 1200 UTC on 17 March, was predicting heavy snowfall to elevations of around 5300 ft. However, examination of the Eta surface temperatures revealed forecast readings well above freezing (even in the 40's ^{o}F) through the period of the first 24 h of forecast snow, in fact even warming the temperatures in the forecast for 18 March. The Eta snowfall algorithm is relatively simple, based on 1000-500 mb thickness values without the use surface temperature, explaining the inconsistency in the two forecasts.

Further inspection of the Eta forecast showed that the initial (0 h) surface temperature field was too warm compared to observations. Given that the locally run MM5 model used analyses from the Local Analysis and Prediction System (LAPS, McGinley et al., 1991) we wondered whether the MM5 might have an improved analysis and at least short-range forecast. As it turned out, the MM5 forecast that was initialized at 0000 UTC on 18 March did not actually use the LAPS initialization as it normally would, due to a problem accessing certain files that evening, and instead used the backup analysis, which was the Eta analysis. Since the actual LAPS analysis was quite good for 0000 UTC on 18 March, we felt it would be useful to examine model runs of the MM5 using the LAPS analysis.

In this paper, then, we will concentrate on one aspect of the storm; model forecasts initialized at 0000 UTC on 18 March, examining whether the models were able to capture the cooler air that evolved along the Front Range that evening and did in fact change the rain over to snow (by 0600 to 0700 UTC in the Boulder area), with a significant snowstorm in progress by the next morning (1200 UTC or 5 AM MST). Several experimental runs of the MM5 model were made using the LAPS analysis, and these will be discussed here and compared to the real-time model forecasts and to observations.

2. OVERVIEW OF CONDITIONS

In this section we review conditions around the 18 March 0000 UTC period in Figs. 4 to 6. The Eta 500 mb analysis along with a 500 hPa plot and IR satellite image is shown in Fig. 3. A broad upper-level low is approaching the Four-Corners region with two distinct waves rotating around it, one on the eastern side and the other extending south across Arizona. A surface pressure analysis from 1800 UTC on 17 March is shown in Fig. 4. In response to the shortwave trough rotating around the

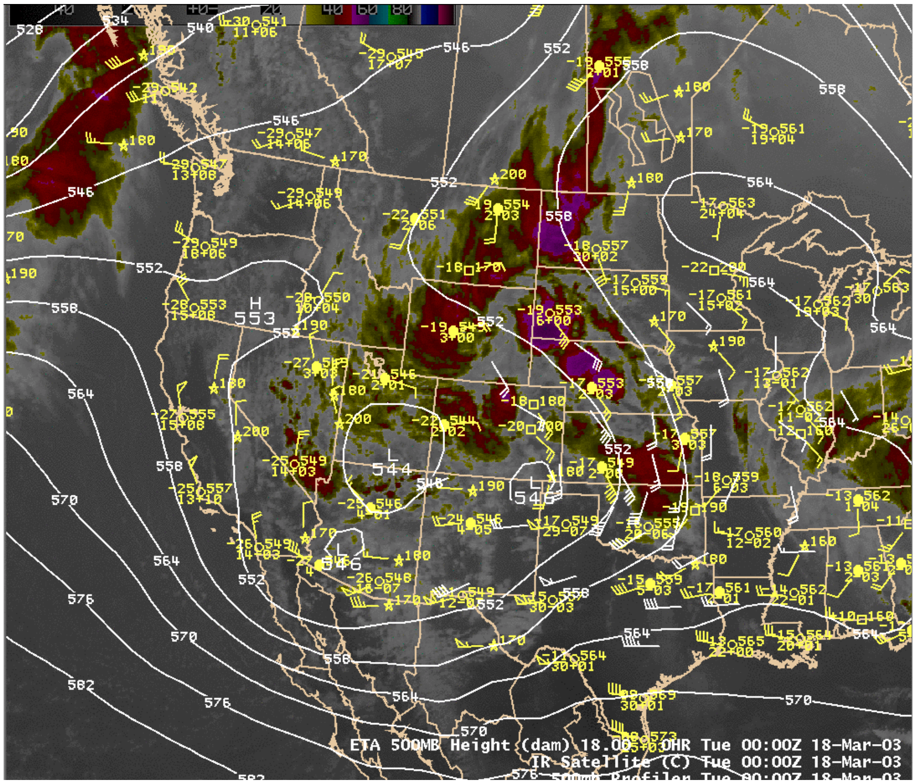

Figure 3. 500 hPa analysis from the Eta model along with observations and an IR image for 0000 UTC.

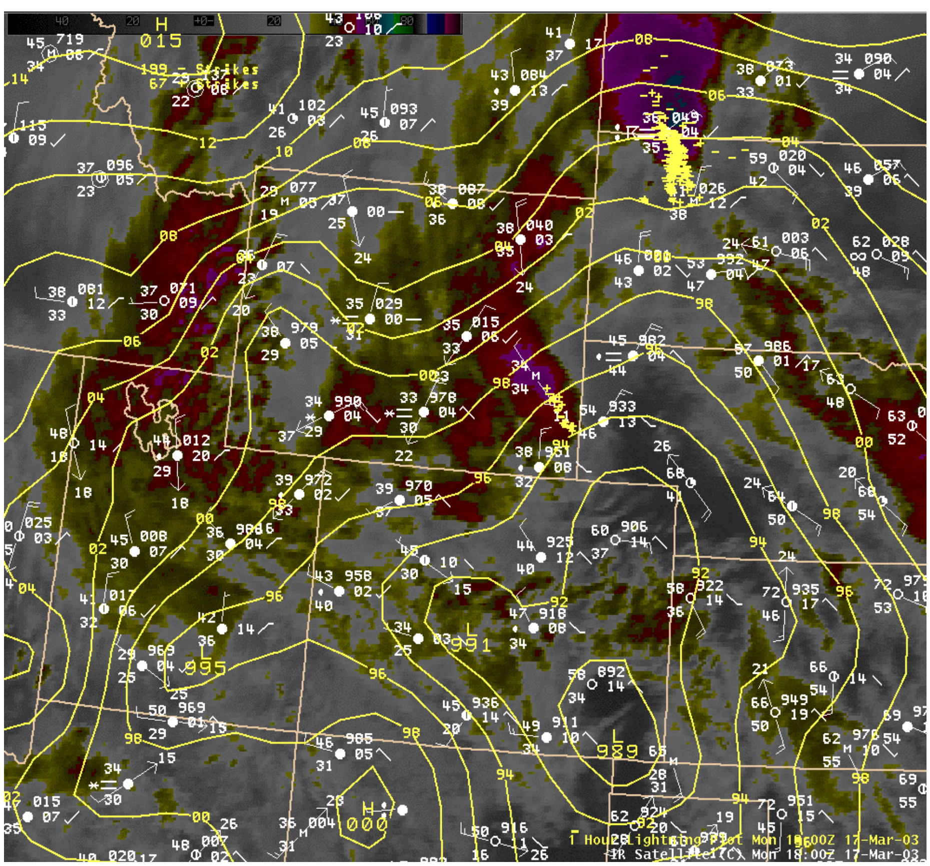

Figure 4. Surface pressure analysis with observations, 1-h lightning plot, and IR image for 1800 UTC on 17 March.

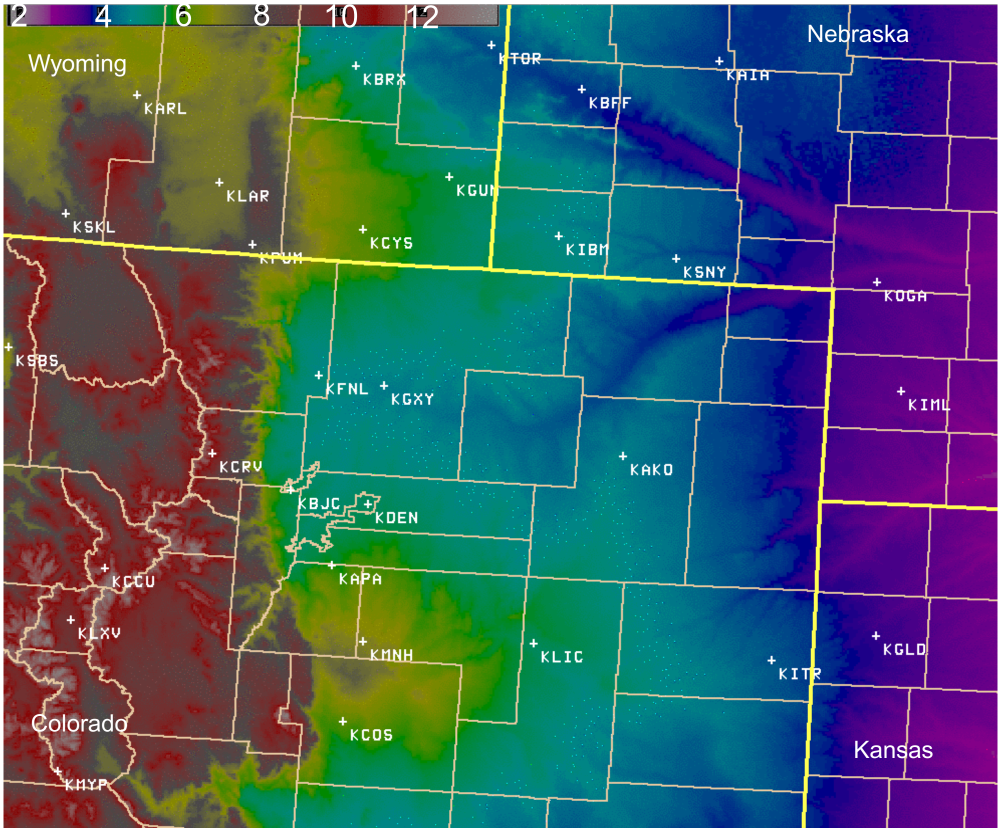

Figure 5. Terrain image, in thousands of feet, along with METAR sites and county boundaries, as in other figures.

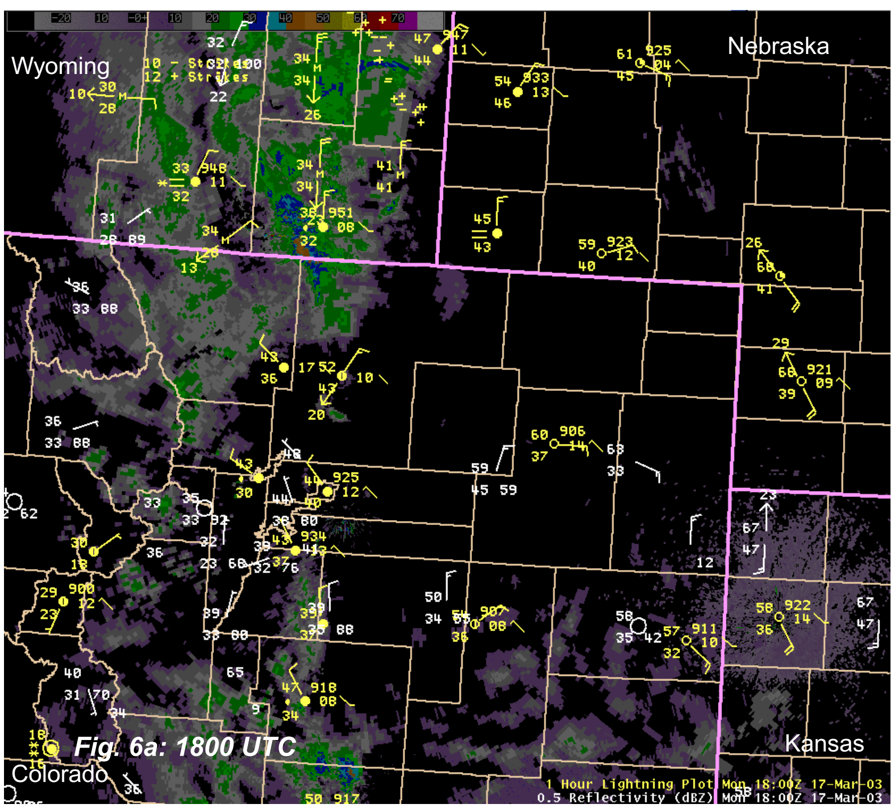

Figure 6 a-d. Composite low-level reflectivity images with observations and 1 h lightning plot.

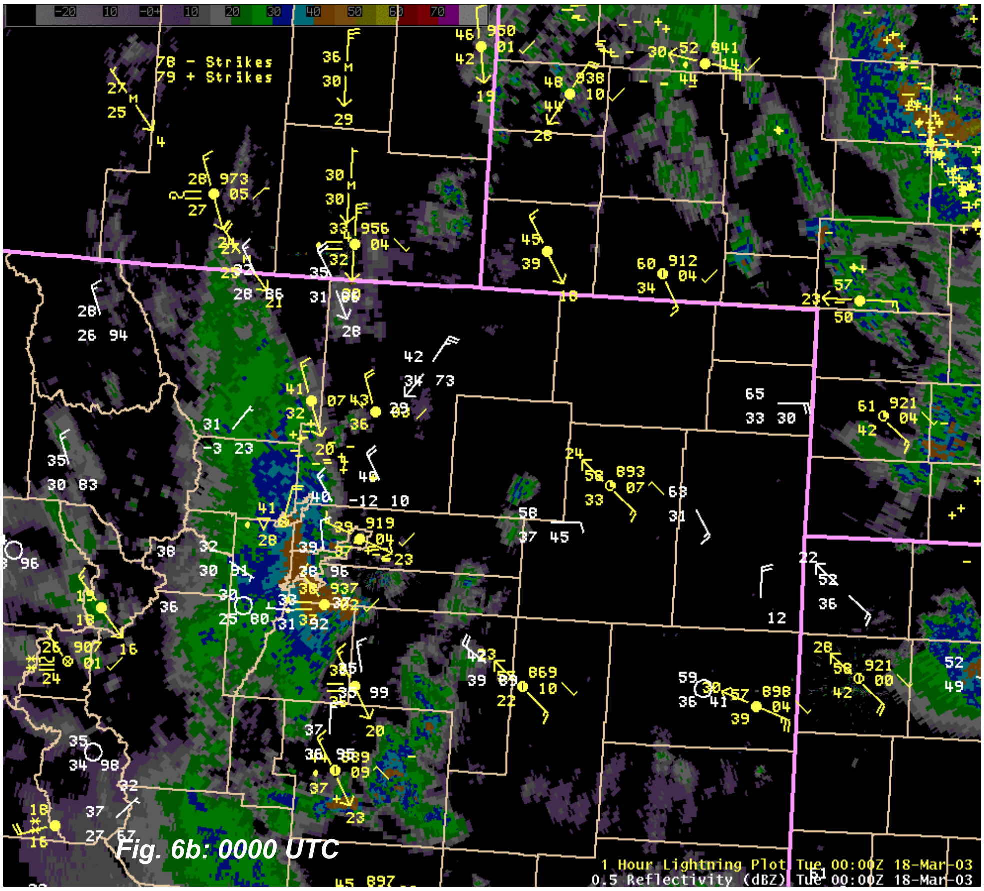

Fig. 6b: 0000 UTC

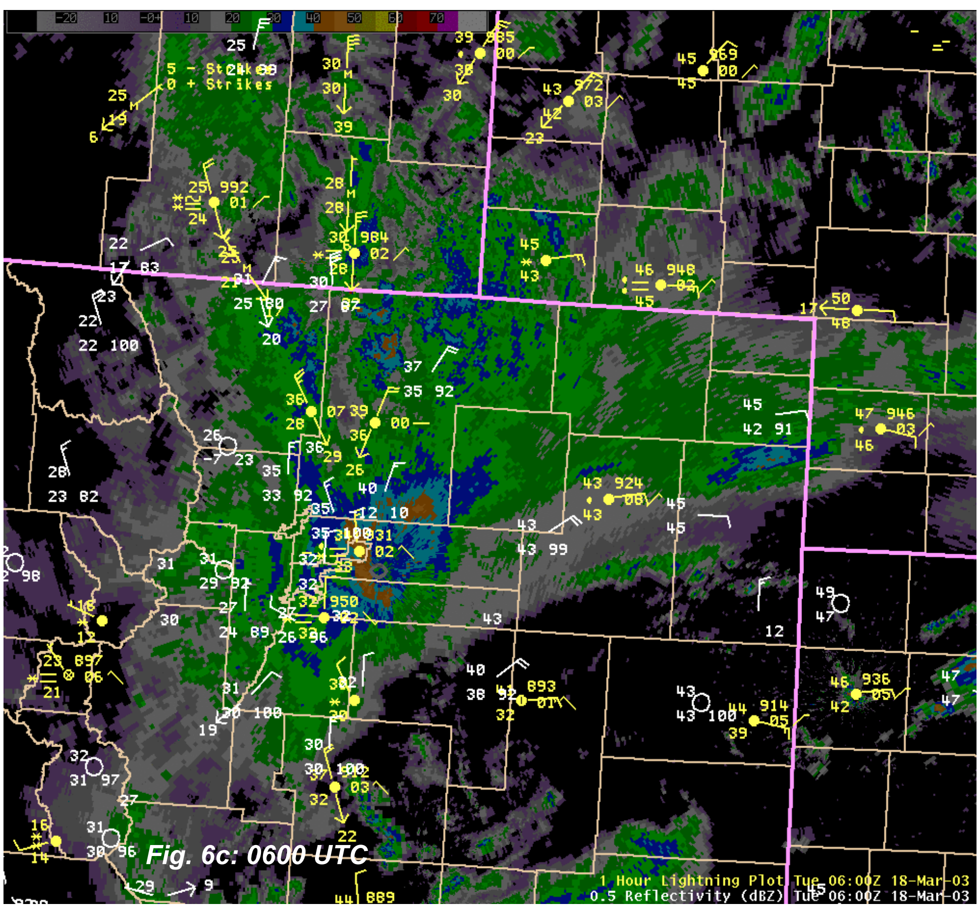

Fig. 6c: 0600 UTC

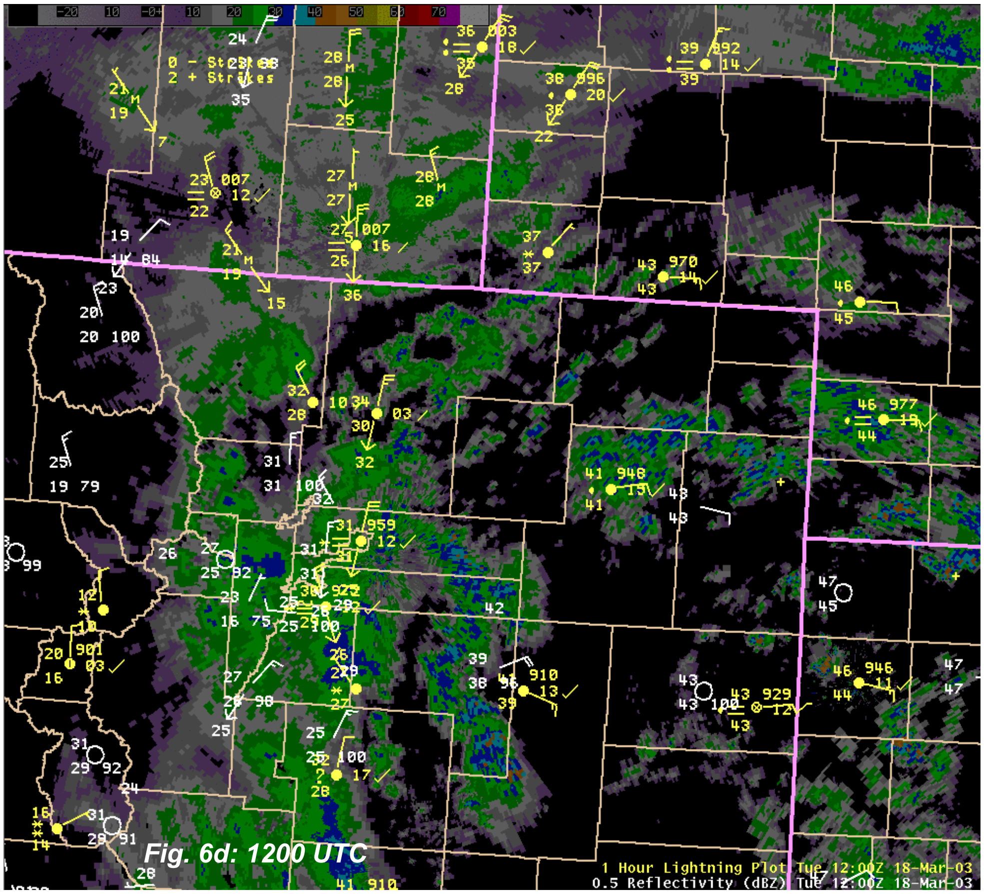

Fig. 6d: 1200 UTC

main upper level low, a surface low gradually deepened over southeastern Colorado during this period. Most of the precipitation during the daytime hours, at least until early afternoon, was found over Wyoming and northward. Synoptically driven high pressure was building to the northwest over Idaho, but over Wyoming cooling beneath the precipitation area enabled a secondary pressure maximum to develop during the day. Over eastern Colorado, the surface low that developed was elongated north-south to the east of Denver, with cooler northerly flow closer to the foothills and extending onto the plains for about 50 km, while more than 20^{o}F warmer air and southeast flow was to the east of the inverted trough. Normally an inverted trough is not a favorable feature for snows along the Front Range, as low-level winds tend to have a downslope component with the main precipitation farther east. In this case, the storm was in its early stages, and the sharpness of the inverted trough would collapse over the next 12-24 h.

A barrier jet was an important and long-lived feature of this storm, and this aspect of the storm was well forecast by the Eta and other models. For example, Fig. 7 displays a 12 h forecast of an Eta cross-section from the 0000 UTC run on 18 March, valid at 1200 UTC on 18 March. The barrier jet is well established by 1200 UTC, with the colder air within the low-level northerly flow clearly shown in Fig. 7. Not only was the cold air with this northerly flow critical to changing the rain to snow, but as seen in Fig. 7, the easterly flow, with abundant moisture, was forced upward as it encountered the cold dome of air. In many ways this is equivalent to moving the foothills eastward, and resulted in shifting the eastern edge of the heavier snowfall to the east. In weaker events the presence of a barrier jet can decrease the snowfall in the nearby mountains to the west because the low-level air is lifted farther to the east then would be the case without a barrier jet, but for this event the moisture was both plentiful and very deep, as well as being driven westward by strong and deep east flow, so there was no shortage of snowfall well back into the mountains. Indeed, one noteworthy aspect of this storm was the extent of heavy precipitation, including very heavy snows falling at least 50 km west of the Continental Divide.

It may be that some of the northerly flow developing during the afternoon of 17 March was the initial stages of the barrier jet, although the better low-level easterly flow that can create a barrier jet was still in Wyoming. Whatever the cause of this initial northerly flow, the persistence of low-cloudiness in the area of the northerlies as opposed to broken clouds with more solar radiation farther east helped to enhance the temperature gradient between the two air masses. This is better shown by the series of radar images from KFTG (located near DIA) overlaid with observations (Fig. 6, for reference local terrain is shown with the observations sites in Fig. 5). The

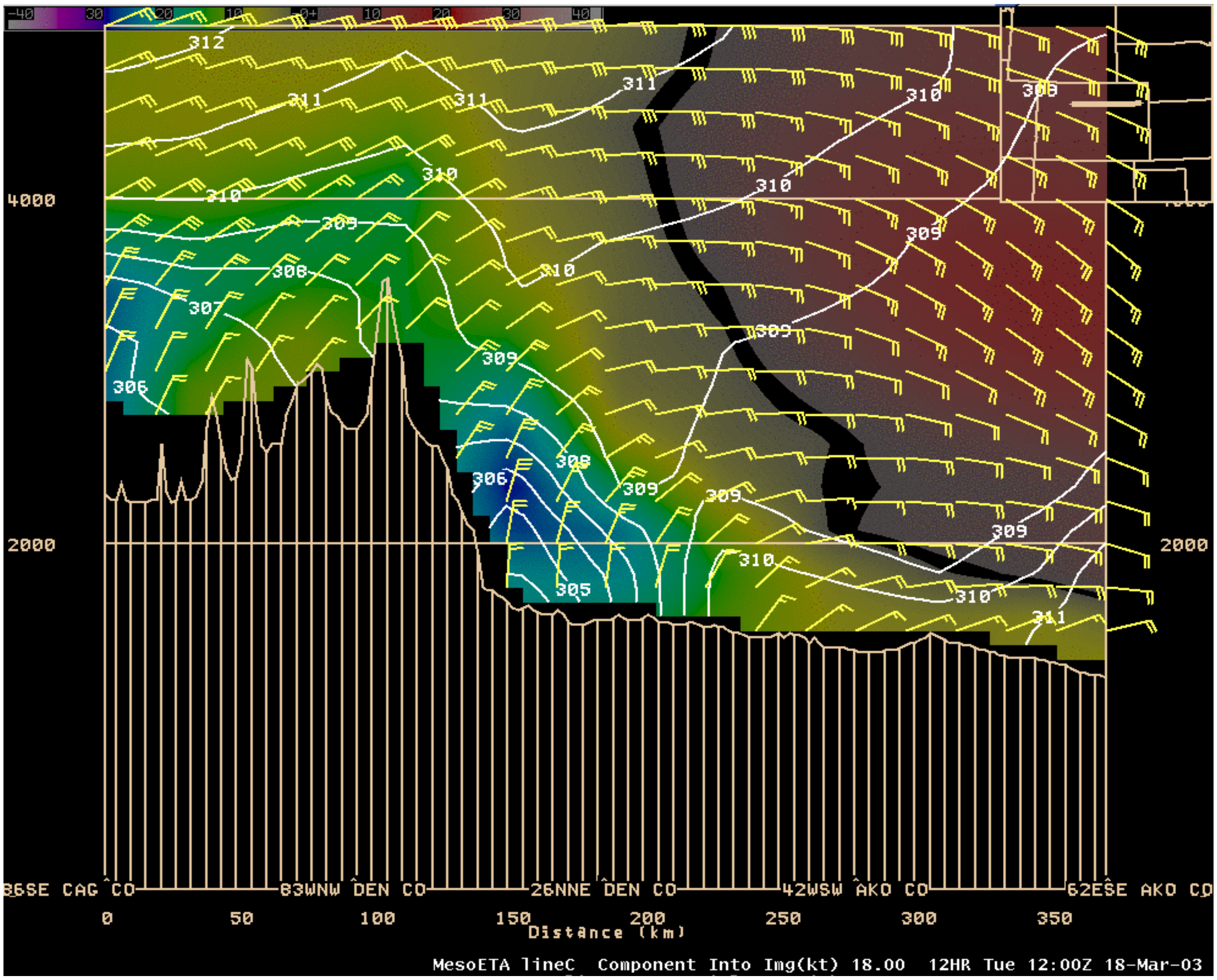

Figure 7. Cross-section east-west through Boulder (see inset in upper right), of total wind (barbs), equivalent potential temperature (white contours), and wind component into the cross-section (knots, image, black band denotes zero-line. The vertical scale is in m (top is at 5000 m MSL), while the horizontal scale is in km.

observations shown are a collection of METARS with numerous local observations that are ingested by the Boulder WFO AWIPS, and whose source includes automated observations from schoolnets, the Colorado Highways Department, the United States Forest Service, and other sources.

At 1800 UTC (Fig. 6a) precipitation was largely confined to Wyoming where temperatures were dropping towards freezing, but most of the precipitation (at lower elevations) was still rain. By 2100 UTC, a line of thunderstorms had developed east of Denver, the first of several lines of convection that would develop along the convergence zone marking the boundary between the east-southeast flow and the northerly flow. By 0000 UTC the line of storms had moved into the western suburbs of Denver and into the foothills. We will return to the conditions at 0000 UTC in the next section, but a perusal of the observations in Fig. 6b indicates temperatures in the northerly flow regime were in the upper 30s to lower 40s (^{o}F), while farther east they ranged from the mid 50s to mid 60s.

After 0000 UTC echo coverage along the Front Range gradually increased, as did the low-level northerly flow, with the combination of local cooling associated with the precipitation and advection of colder air that had accumulated in Wyoming allowing the rain to convert to snow around 0600 UTC (Fig. 6c). By 1200 UTC on 18 March, several inches of snow were on the ground on the plains from south of Denver north along the Front Range well into Wyoming, with deepening snow in the foothills (Fig. 6d). A strong barrier jet was in place at 1200 UTC, and was being overrun by deep easterly flow (Fig. 7). An impressive plume of moisture stretched around the upper level low and wrapped back into northeastern Colorado, and then over the barrier jet and into the mountains. One can see the reflectivity echoes within this plume in the radar image in Fig. 6d extending from northeastern Colorado back into Kansas.

In the next section, we will return to the conditions at 0000 UTC on 18 March and the main issue, which is how well the actual conditions were initialized in the operational Eta model and in our local MM5 model.

3. MODEL ANALYSES AT 0000 UTC/18 MARCH

At 0000 UTC 18 March the storm was developing as expected with snows increasing in the mountains and foothills, and rain and embedded thunderstorms becoming more widespread on the plains. The main area of remaining uncertainty was forecasting if and when the rain would change to snow through the Front Range cities. The afternoon forecast package issued by the Boulder WFO at 2230 UTC on 17 March included a Winter Storm Warning for the Front Range cities with a change over to snow occurring around midnight. As stated earlier, numerical model solutions were not actually indicating such a change to snow, as the model forecast surface temperatures remained well above freezing through the entire night, with some model solutions indicating that the air might not be cold enough for snow until Tuesday night, or 24 h later then in the NWS forecast. One of the reasons forecasters tended to discount these warmer solutions was their experience with such storms, where enough cooling (from mechanisms such as adiabatic cooling and advection not modelled correctly enough) to produce a change-over typically occurs in most all storms occurring at the elevation of the Front Range cities when it is still mid-March. Of course, temperatures were indeed quite warm just to the east, and there was strong and deep flow from that direction, so model solutions indicating warmer then freezing temperatures were also believable, adding to the difficulty for the operational forecasters.

A LAPS analysis with observations superimposed is shown in Fig. 8. Inspection of the temperature analysis reveals that it closely follows the observed temperatures. For clarity, we only include the METAR observations in Fig. 8, although it should be noted that the LAPS analysis package uses most available observations, which would include all or most of those depicted in Fig. 6. The LAPS analysis will be used as a basis for comparison with the analyses from other models. The initial analyses of temperature and wind at the surface from the Eta is shown in Fig. 9a, while the same from the MM5 that was run on 18 March is in Fig. 9b. However, as noted earlier, a data problem forced the MM5 run to begin with an analysis from the Eta model instead of the LAPS analysis. We reran the MM5 model using LAPS as it would have run in real-time, and in the next section we will contrast these forecasts. The analysis from this

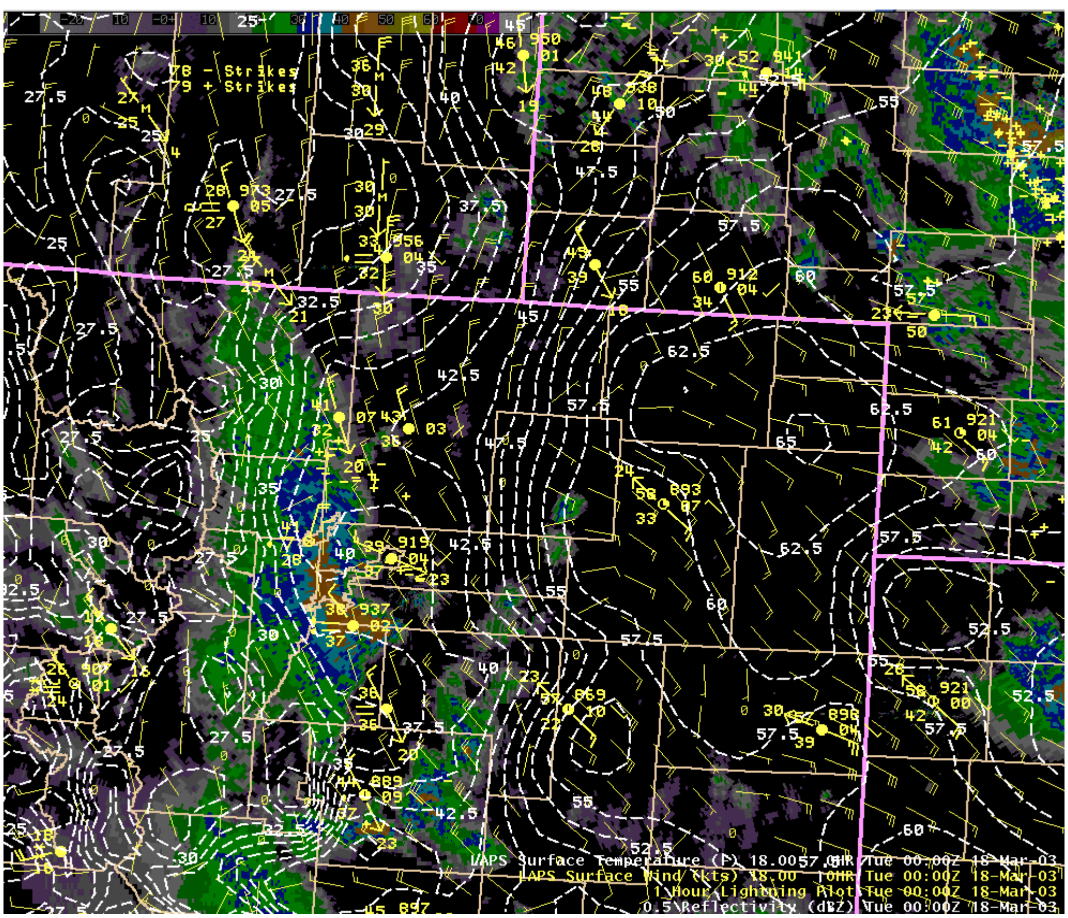

Figure 8. LAPS analyses of surface wind and temperature with METAR observations and radar for 0000 UTC.

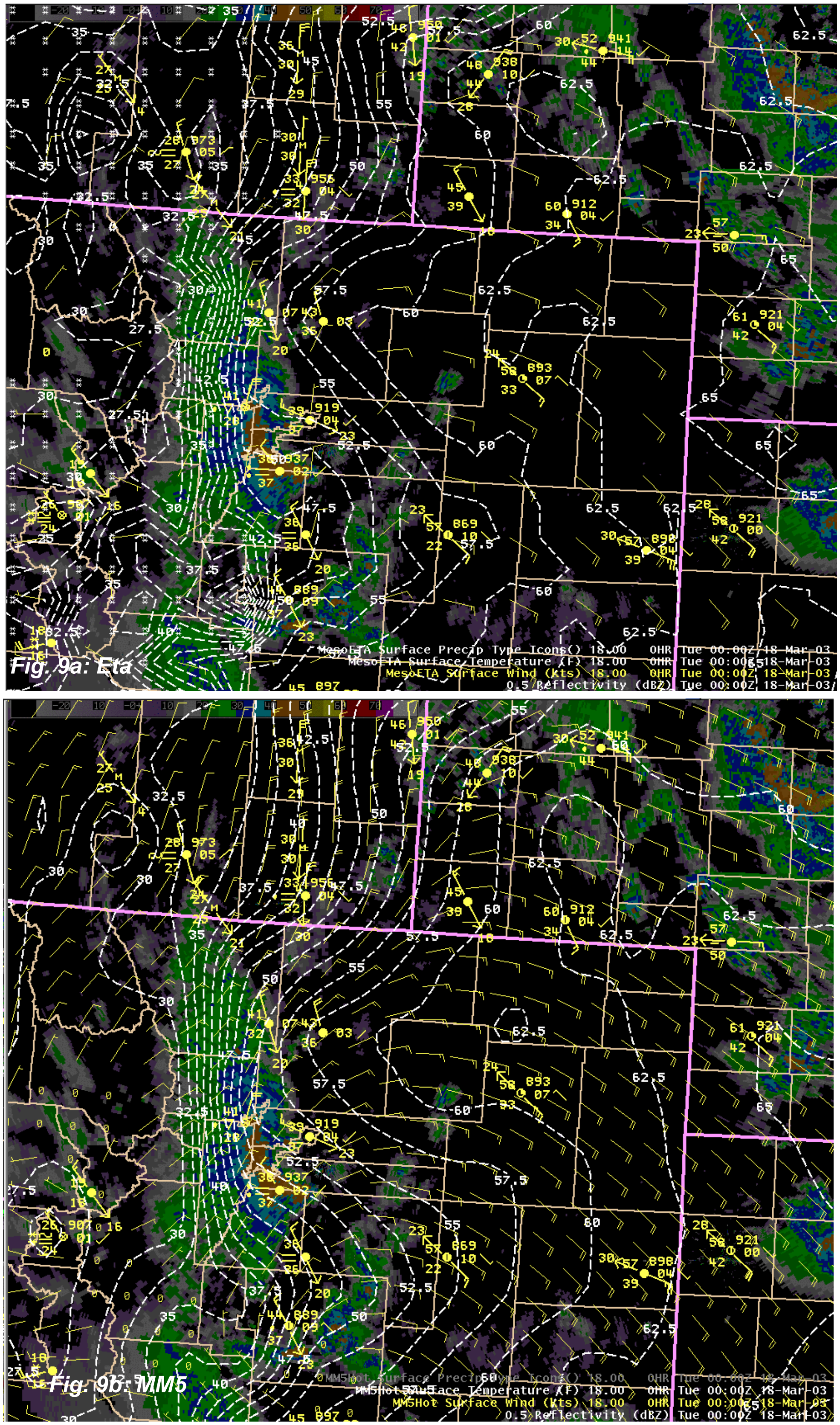

Figure 9 a-c. 0000 UTC 18 March analyses from the Eta, MM5, and MM5 rerun, of temperature and wind. METAR observations and a low-level reflectivity image are shown with Figs. 9 a and b.

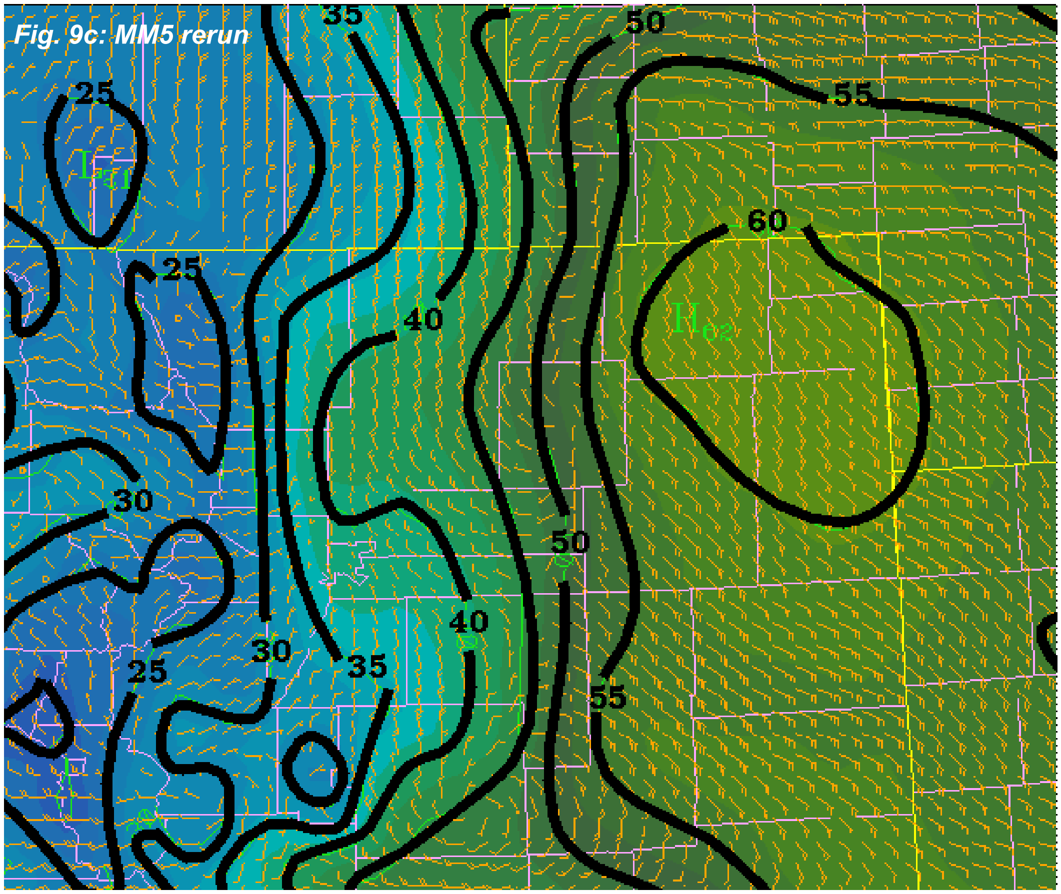

Figure 9c. MM5 rerun analysis for 0000 UTC. Image and contours show temperature (^oF).

rerun is in Fig. 9c. It is apparent that the Eta and MM5/real-time analyses in Fig. 9 fail to capture the strength of the cold air in the northerly flow. Even though these are analyses, the warm air from the east is blended well into the colder air as the southeast flow overruns the shallower northerly flow. By contrast, the analysis from the MM5 rerun, which used LAPS, looks quite reasonable (Fig. 9c, compare to data in the other figures or the LAPS analysis in Fig. 8).

4. MODEL FORECASTS FROM 0000 UTC

The basic question we wanted to address here was whether the MM5 model, run on a regular schedule at the Boulder WFO, would have a better forecast of surface temperature using LAPS to define the 0000 UTC initialization for this case, instead of the default Eta background field. To accomplish this, MM5 was rerun using the analysis shown in Fig. 8. In this section, we will briefly examine some 6-h model forecasts from the initializations shown in Fig. 9.

We also used this opportunity to rerun MM5 with changes to evaporation rate (two experiments), then applied a new version of the Schultz microphysics (Schultz, 1995) with these changes (two more experimental runs), and finally tried a run where the LAPS surface analysis was allowed to influence the lowest five levels of the model instead of the standard two levels. Because of space limitations, only one forecast from the basic MM5 rerun will be compared to the Eta and MM5 runs that were made in real-time. Examination of the five MM5 reruns to this point has indicated that there is little difference in the surface temperature and wind fields between the various reruns. Some differences occur with respect to location of precipitation maxima, but otherwise they are similar.

The three 6-h forecasts from the initializations shown in Fig. 9 and valid at 0600 UTC on 18 March, are shown in Fig. 10. The Eta and MM5/real-time forecasts are similar, and both have too much warm air moving towards the foothills with not enough of the northerly barrier jet flow. Refer to Fig. 6c for more observations at 0600 UTC.

The MM5 rerun 6h forecast in Fig. 10c is cooler then the other two models, by about 5 ^oF in the area of the northerly flow. This is still up to 5 ^oF too warm compared to the observations, with model temperatures in the mid- and upper-30s compared with lower to mid 30s and a change to snow occurring. The MM5 rerun precipitation type was still rain along the Front Range. The solutions at 1200 UTC (not shown here) remained warm in all the

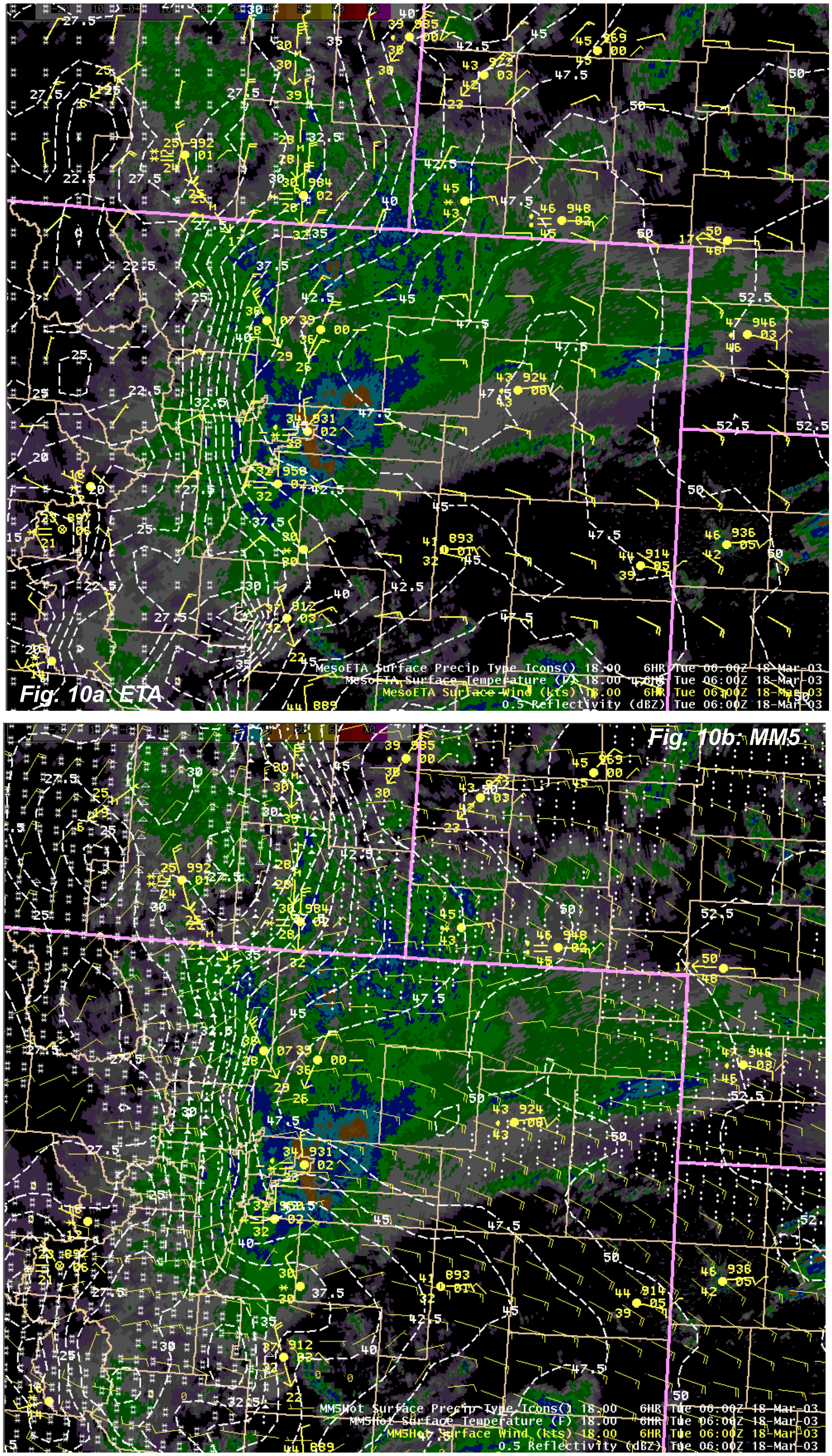

Figure 10a-c. As in Fig. 9, except for 6-h forecasts, with precipitation type icons in 10a and 10b.

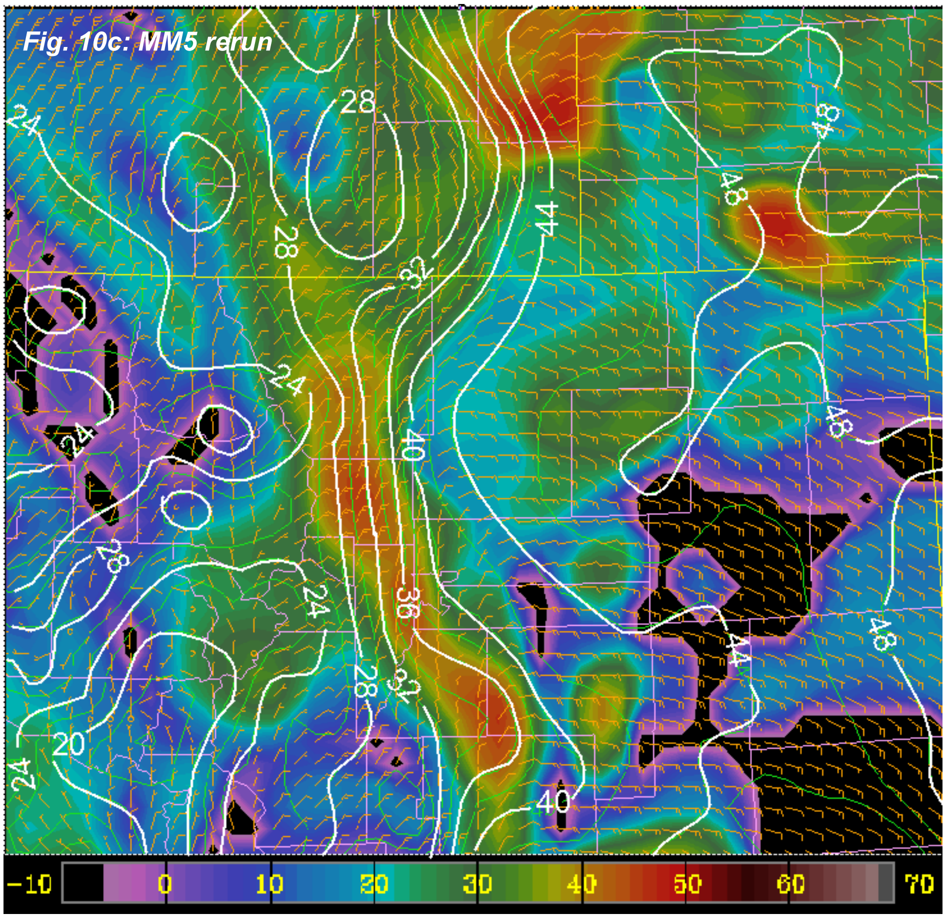

Figure 10c. As in Figs. 10 a and b but for the MM5 rerun 6-h forecast. Surface wind barbs and temperature (contours at 2°F intervals, highlighted in white at 4°F intervals). Also shown is an image of forecast column maximum reflectivity in dBZ, using the scale at the bottom.

runs, and, similar to the 0600 UTC time, the MM5 rerun was an improvement, but not enough to have indicated snow along the Front Range.

We hope to further investigate this case to determine whether there is a better configuration of model parameters and blending of the LAPS surface analysis into the model at the initialization that might yield a better forecast. Although, as noted, the MM5 reruns were similar, there was a slight preference for cooler temperatures for the rerun where the analysis blended the LAPS surface analysis through more of the model's lower levels. These results will be discussed at the conference.

4. SUMMARY

While the forecasts issued by the Boulder WFO for this event were very good and the overall model forecasts accurate in the precipitation amounts, there was inconsistency between the Eta snowfall forecast and the actual temperatures forecast by the model for the near-surface. Close examination of the Eta indicated that indeed, the model did a poor job even in the analysis of a sharp thermal boundary at 0000 UTC on 18 March. The reason that the snowfall forecast from the Eta was accurate for the lower elevations was the use of a simple algorithm based on thickness values and not surface temperatures, which worked well in this case, but does not necessarily perform well at other locations. The LAPS did correctly analyze the sharp gradients, and the MM5 model initialized with this analysis produced a better forecast, but still did not forecast surface temperatures cold enough to have snow along the Front Range. We continue to examine this event and will report on further insights at the conference.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Benjamin, S.G., D. Devenyi, S.S. Weygandt, K.J. Brundage, J.M. Brown, G.A. Grell, D. Kim, B.E. Schwartz, T.G. Smirnova, T.L. Smith, and G.S. Manikin, 2003: An hourly assimilation/forecast cycle: The RUC. Mon. Wea. Rev., 131, in press.

McGinley, J.A., S.C. Albers, and P.A. Stamus, 1991: Validation of a composite convective index as defined by a real-time local analysis system. *Weather and Forecasting,* **6,** 337-356.

Schultz, P., 1995: An explicit cloud physics parameterization for operational numerical weather prediction. *Mon. Wea. Rev.,* **11,** 3332-3343.

Shaw, B.L., E.R. Thaler, and E.J. Szoke, 2001: Operational evaluation of the LAPS-MM5 "Hot Start" local forecast model. *Preprints, 18th Conference on Weather Analysis and Forecasting and 14th Conference on Numerical Weather Prediction,* Ft. Lauderdale, FL, American Meteorological Society, 160-164.

Wesley, G.A., G. Poulos, J. Snook, E. Szoke, M. Meyers, G. Byrd, and R. Rozumulski, 2004: Mesoscale model simulations in quasi-forecast mode of the great western storm of 16-20 March 2003. *Preprints, 20th Conference on Weather Analysis and Forecasting and 16th Conference on Numerical Weather Prediction,* Seattle, WA, American Meteorological Society, Paper 10.3.