

15.6 ANOMALOUSLY LARGE SNOWFALL VARIATIONS ACROSS SMALL SPATIAL SCALES IN THE ROCKY MOUNTAIN FRONT RANGE: THE ROLES OF BLOCKING, SURFACE WINDS, AND THE ASSOCIATED THERMODYNAMIC STRUCTURE

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1. INTRODUCTION

During the period 17-20 March 2003, a major snowstorm (and blizzard in some locations) paralyzed the Front Range of the Rocky Mountains from east central Wyoming southward to northeastern Mexico. Snowfall maxima in northern Colorado likely represented a 1-in-25/50 year event statistically. In addition, extremely large snowfall variations occurred on spatial scales of 10 km or less, and in many areas the snowfall accumulation was not directly correlated with elevation. In fact, some intriguing snowfall minima occurred at elevations comparable to those that received very deep snows (see Fig. 1). Details on the snowfall west of the Continental Divide, where some very impressive totals were observed, are found in Poulos et.al., 2004. Also, more information on synoptic-scale aspects of the event can be found in Szoke et.al., 2004, Poulos et.al., 2003, and Wesley et.al., 2004. Meyers et.al. (2004) presented an analysis of the event for the CO west slope.

The mesoscale dynamics and thermodynamics of this storm will be investigated to infer the primary causes of the meso- γ -scale variations. The snowfall accumulations along the urban corridor were strongly influenced by the thermodynamic structure during the storm. Surface temperatures at or very close to freezing permeated elevations of 4500 to 6000 feet in some of the hardest hit regions, and snow depths were thus critically dependent on local thermodynamics; some degree of melting was occurring during the early portions of the storm in all areas at or below 6000 feet in elevation. The melting/cooling influence enabled areas of heavy snowfall to occur where perhaps, synoptically, rain should have occurred.

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In addition, observed wind and temperature fields, along with mesoscale model simulations, have revealed a complex surface temperature field during the storm. The pattern was not intuitively obvious based on conventional explanations utilizing local terrain features, including those located immediately upstream of the anomalies. Local influences of the terrain on the barrier jet in some areas were primary determining factors for surface temperature and thus snowfall accumulation. Related factors such as low- and mid-level stability appeared to play important roles.

An understanding of how the local variations in surface temperature developed during such a relatively warm winter storm (in the Rocky Mountain urban corridor) is critical to improving snow depth predictions in this region. The following factors will be examined, on the local scale, in the context of how temperature anomalies, and the associated snowfall distribution, evolved in this storm:

1. blocking and the barrier jet, and their influences on local temperature advection patterns
2. upslope/downslope flow
3. melting

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 played a role in the cause of the snow minima discussed above. These factors will be examined via both observational data and mesoscale model simulations.

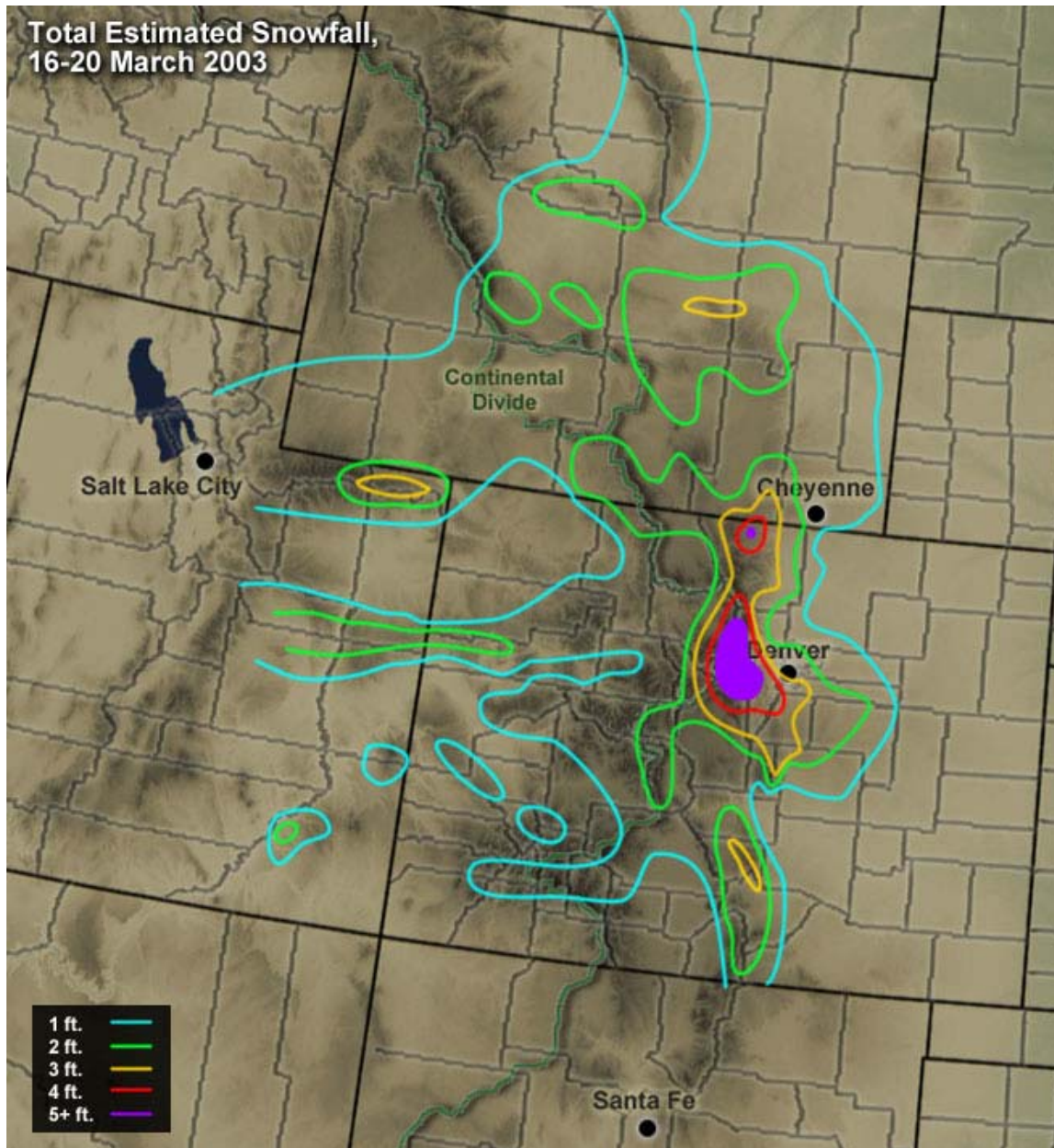


Figure 1 Snow depth increases (in feet) for the Front Range and surrounding regions for 16-20 March 2003.

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

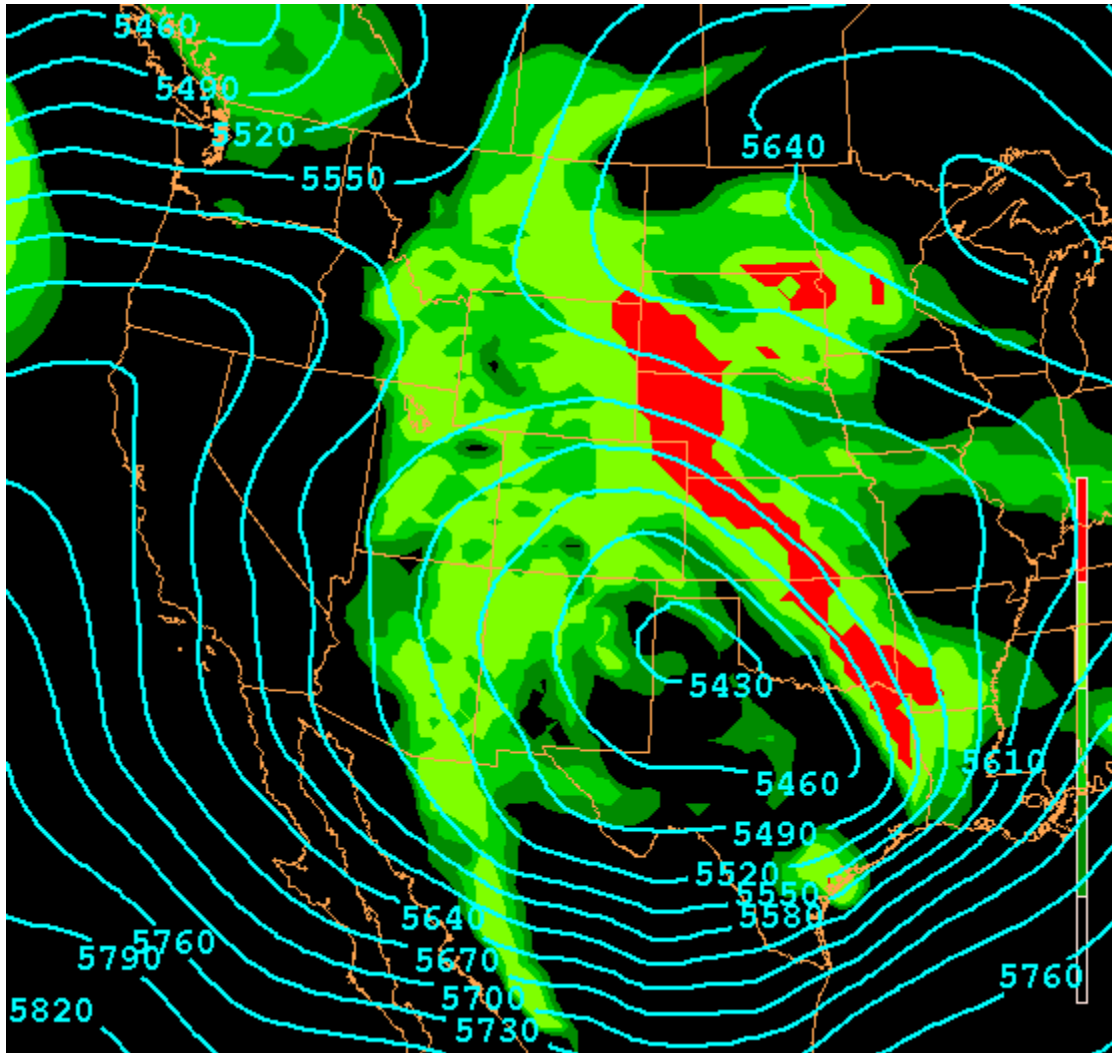


Figure 2 500 mb heights and 700 mb RH, analyzed at 00 UTC 19 Mar. 2003. Red regions correspond to saturated conditions at 700 mb.

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

The mesoscale features of this mega-storm along the Rocky Mountain Front Range were of critical importance to the resulting precipitation distribution. Observationally, the role of the blocking-induced 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 convergence, a feature documented in previous heavy springtime snowfalls in the urban corridor (Marwitz and Toth 1993 and others).

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 were:

- (a) The region of low-level northerlies was sloped upwards to the west, essentially modifying the terrain encountered by upslope (easterly) flow and leading to mesoscale uplift in a saturated air mass over and just east of the Front Range (Fig. 3).

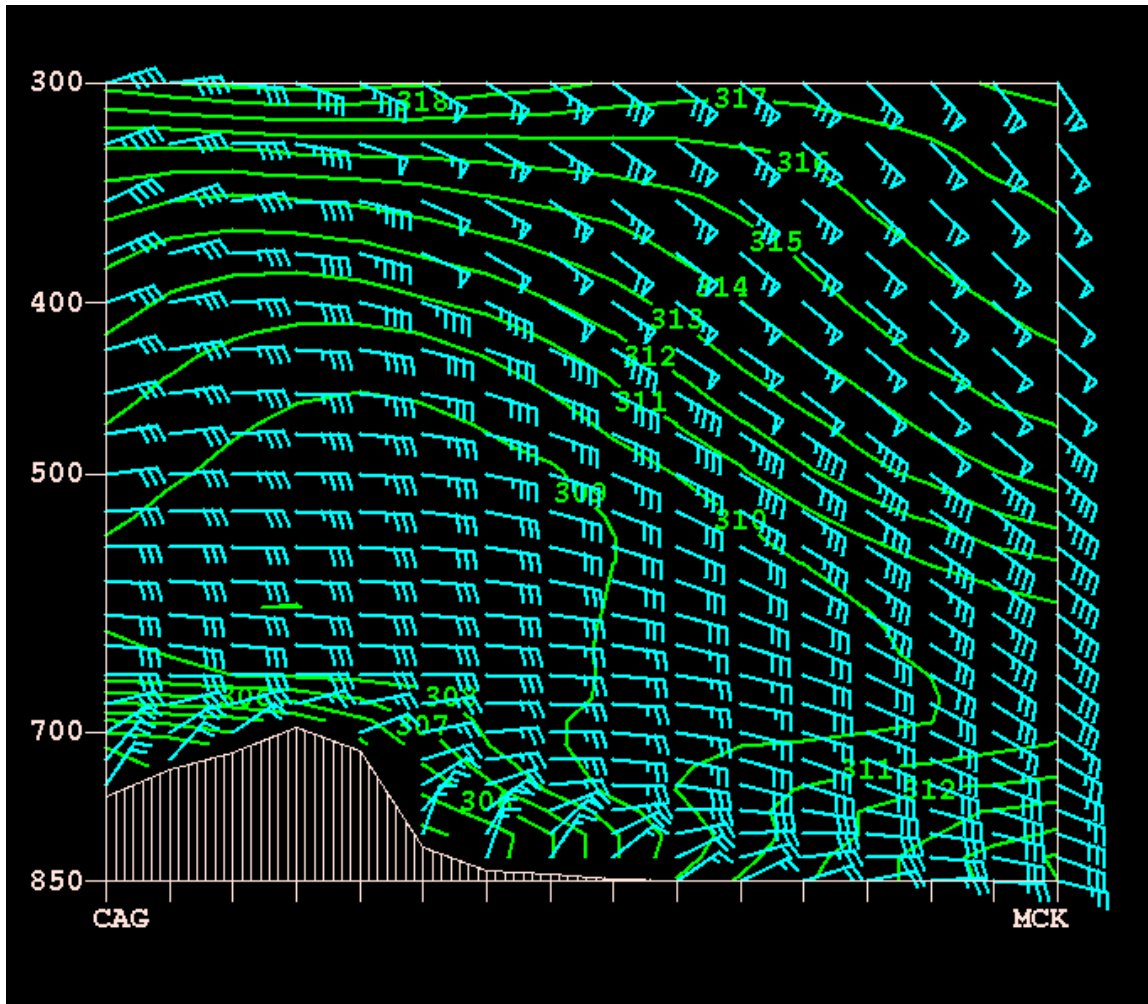


Figure 3 Vertical cross section showing equiv. potential temp. (K) and winds (knots), 6-hr. forecast from the Eta model initialized at 18 UTC 18 Mar.

- (b) large amounts of melting in the low-levels on the east side of the barrier jet provided latent cooling, thus enhancing the thermal gradient and the blocked 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 Front Range.

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. Also, convectively unstable conditions are noted over portions of the plains in Fig. 3.

3. LOCAL SNOWFALL VARIATIONS

One of the biggest predictive challenges in this storm was determining the areas of local maxima and minima in snowfall. At first guess, on the large scale, much of the general snowfall was generated directly by deep ENEly upslope flow (Fig. 1). Closer examination, however, revealed extreme variations not directly explainable by large-scale terrain features (see also Wesley et al., 2004). A key source after the storm for determining details in the snowfall distribution was high-resolution MODIS imagery (Figs. 4 and 5) a couple of days after the storm, under sunny skies. Especially notable:

1. snow-free zone just northwest of the Boulder/Longmont region (Lyons).

2. NW/SE-oriented gradient in snow accumulation over the plains stretching from near the WY border north of Fort Collins to northeast of Denver.
3. smaller snow-free zone near the foothills directly west of Greeley.

The gradients in snowfall next to the snow-free areas are especially intense, considering that areas in and near the foothills adjacent to the snow-free zones

received 2 feet+ of snow (Fig. 6). In fact 3 feet+ was common in the lower foothills in these regions. Note also that the snow-free zones (1) and (3) are evidence of light snow accumulation that has melted, not areas that received no snowfall. Also, for the Lyons minimum, local residents observed generally light surface winds during the event. This is an important observation that will be discussed later.

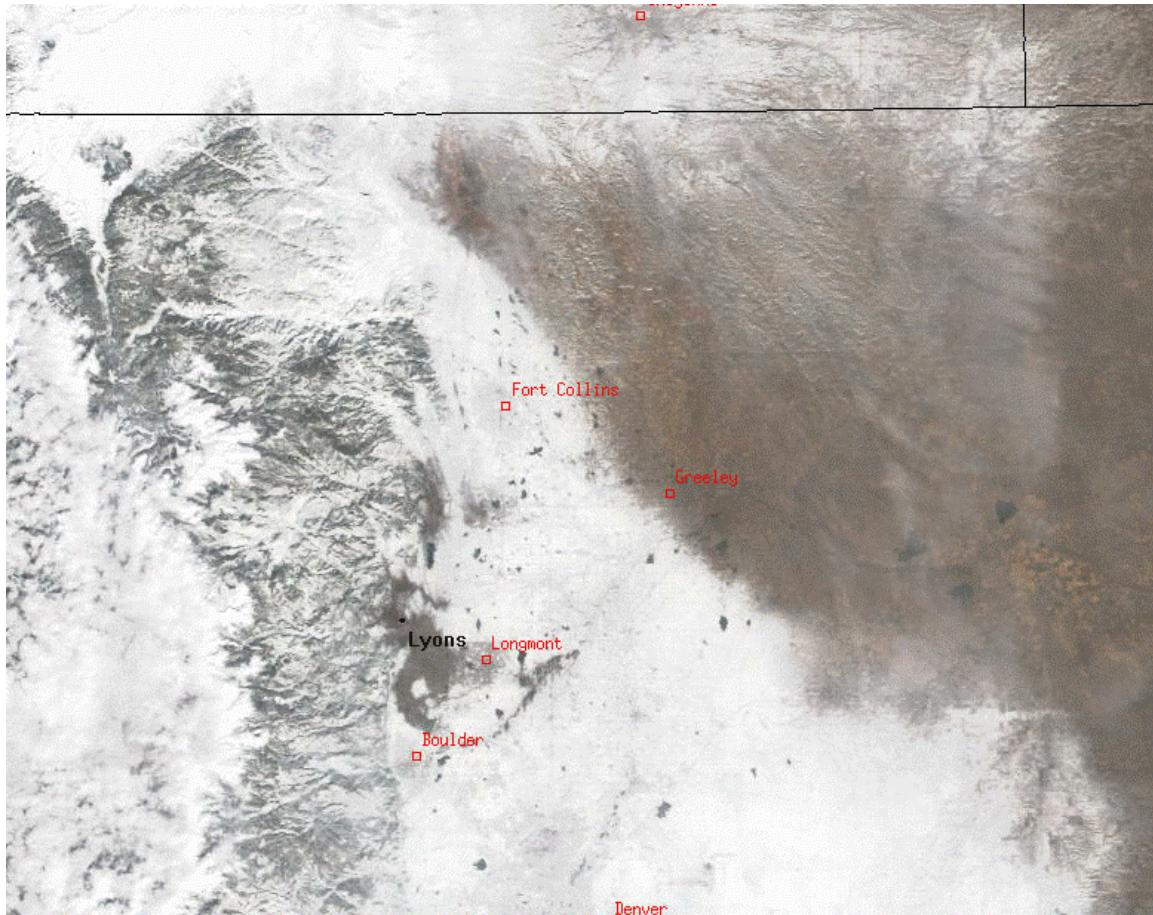


Figure 4 High-resolution image (MODIS 3-channel true color composite) on 22 Mar.. Complex patterns on the west side are timbered and canyon areas. Darker areas just south of the WY state line, southwest of Fort Collins and west of Longmont are areas where much less snow accumulation was observed (source: NASA and Scott Bachmeier of CIMSS).

Examination of these major snowfall minima revealed some commonality in the details of the terrain near these regions. Note that all are associated with east-west oriented intrusions of terrain features onto the eastern plains of CO (Fig. 7).

In fact, these are the only significant intrusions of their kind over the northeastern quarter of the state. This immediately begs the question of the dynamical role of the three intrusions. For example, did they create a local downslope effect?

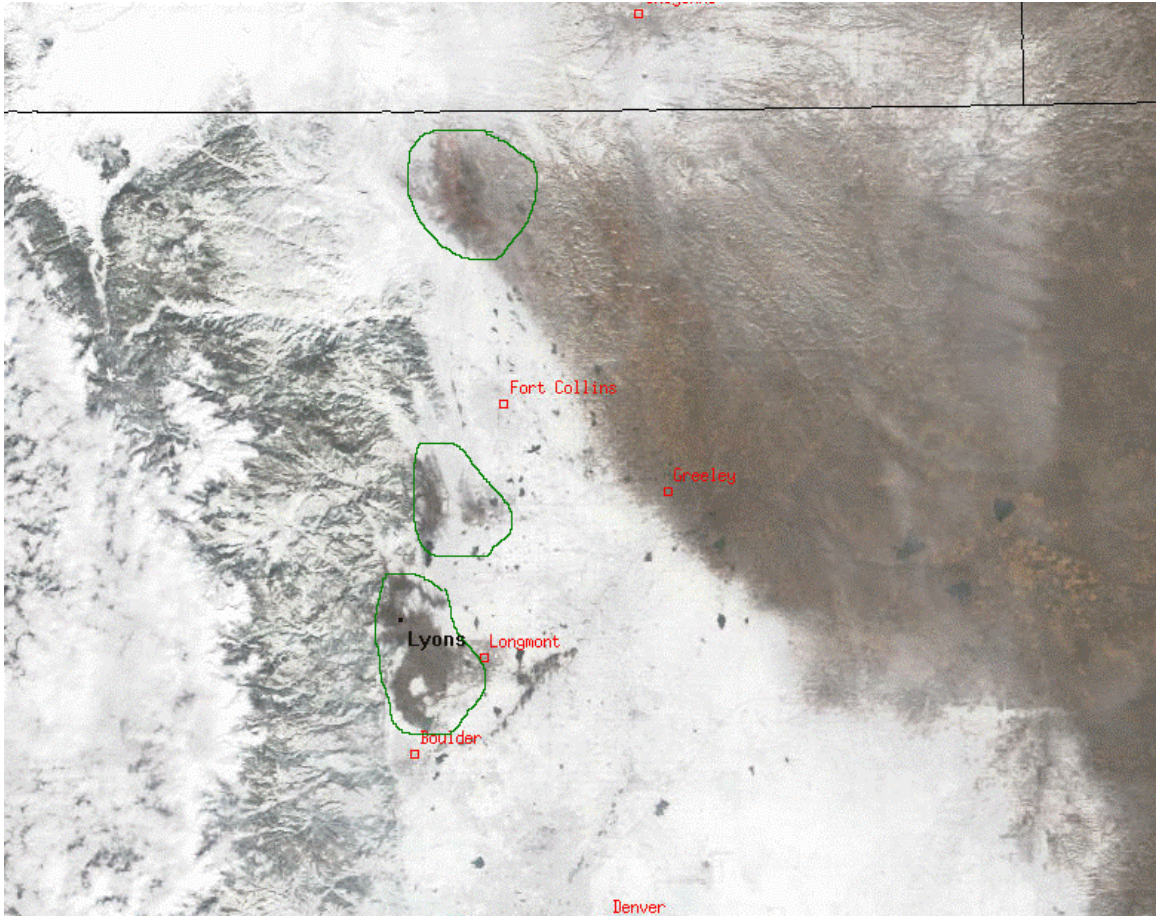


Figure 5 Annotated image with 3 regions of observed snow accumulation minima, relative to adjacent areas of similar elevation.

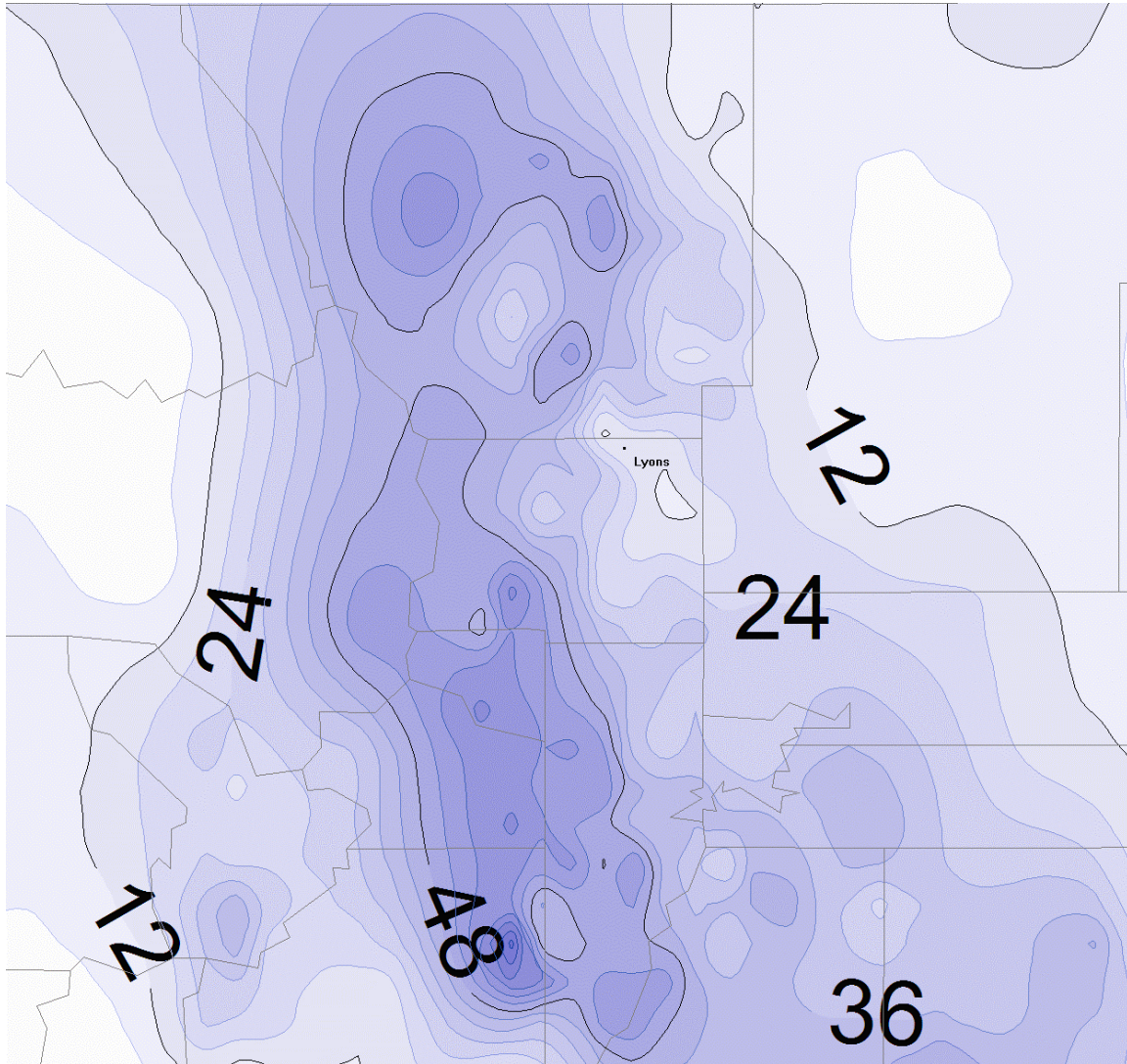


Figure 6 Approximate total snowfall observations (inches) for the region centered on the foothills west of Denver, 16-20 Mar. 2003. County boundaries are shown in Colorado. Contour interval is 6 inches. The 12" contour is darkened.

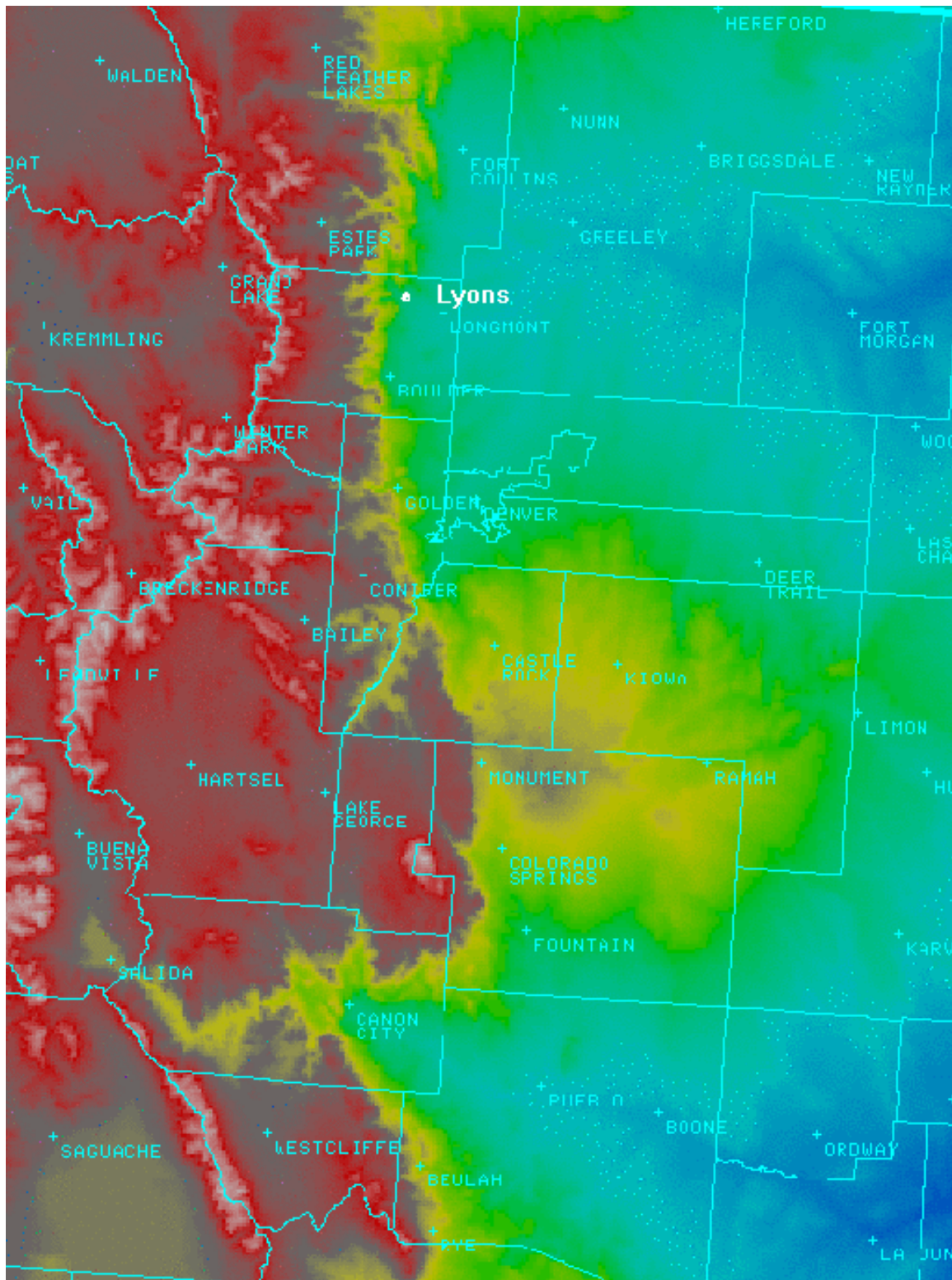


Figure 7 High-resolution terrain image from the NOAA/NWS/AWIPS system.

4. MESOSCALE MODEL SIMULATIONS

The MM5 was set up quasi-operationally, with a 5-grid nested configuration, the smallest domain (grid 5) centered on north-central CO and exhibiting a 1.0 km grid spacing. Eta operational forecasts from the run initialized at 00 UTC 17 Mar. served as large-scale boundary conditions. Fig. 8 shows the model terrain for the inner portion of grid 5.

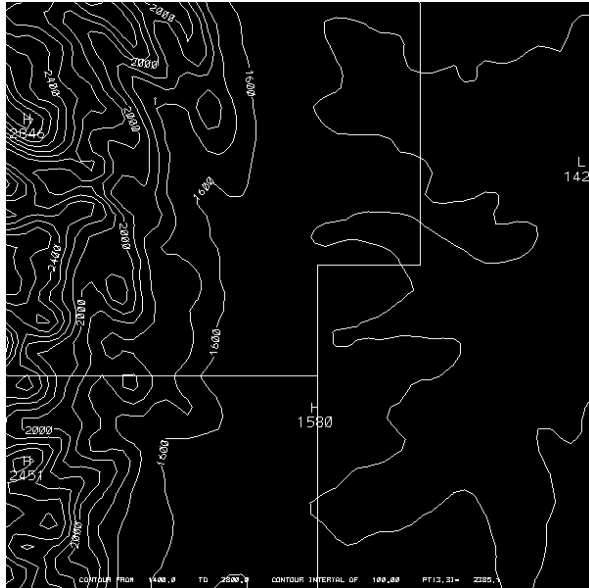


Figure 8 Model terrain elevation (m) for a portion of grid 5.

Immediately evident are two of the aforementioned east-west oriented intrusions of terrain along the

plains/foothills interface, first in the Lyons vicinity (northeastern Boulder Co.) and, second, southwest of Fort Collins (southeastern Larimer Co.).

Fig. 9 shows the total precipitation (mm) (liquid equivalent) 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). These regions correlate well (qualitatively) with observed snowfall maxima shown in Fig. 1.

Interestingly, three relative minima over the plains/foothills interface are also present (Fig. 10):

1. northeastern Boulder Co. (less than 50 mm)
2. southeastern Larimer Co. (43.4 mm)
3. northeastern Larimer Co. (27.1 mm)

As shown earlier on the high-resolution satellite image after the storm, all 3 of these regions experienced snow minima compared to observed snowfall in immediately surrounding regions of similar elevations (Fig. 6). For all of the minima, snowfall within 5-10 km to the west was very heavy; for the first and second minima, snowfall just to the *east* (at slightly *lower* elevation) was also heavier. Note also in particular that the exact location in the Lyons minima is predicted to be just north of the Boulder/Larimer Co. line, as is the objectively-analyzed minima based on surface observations (Fig. 6).

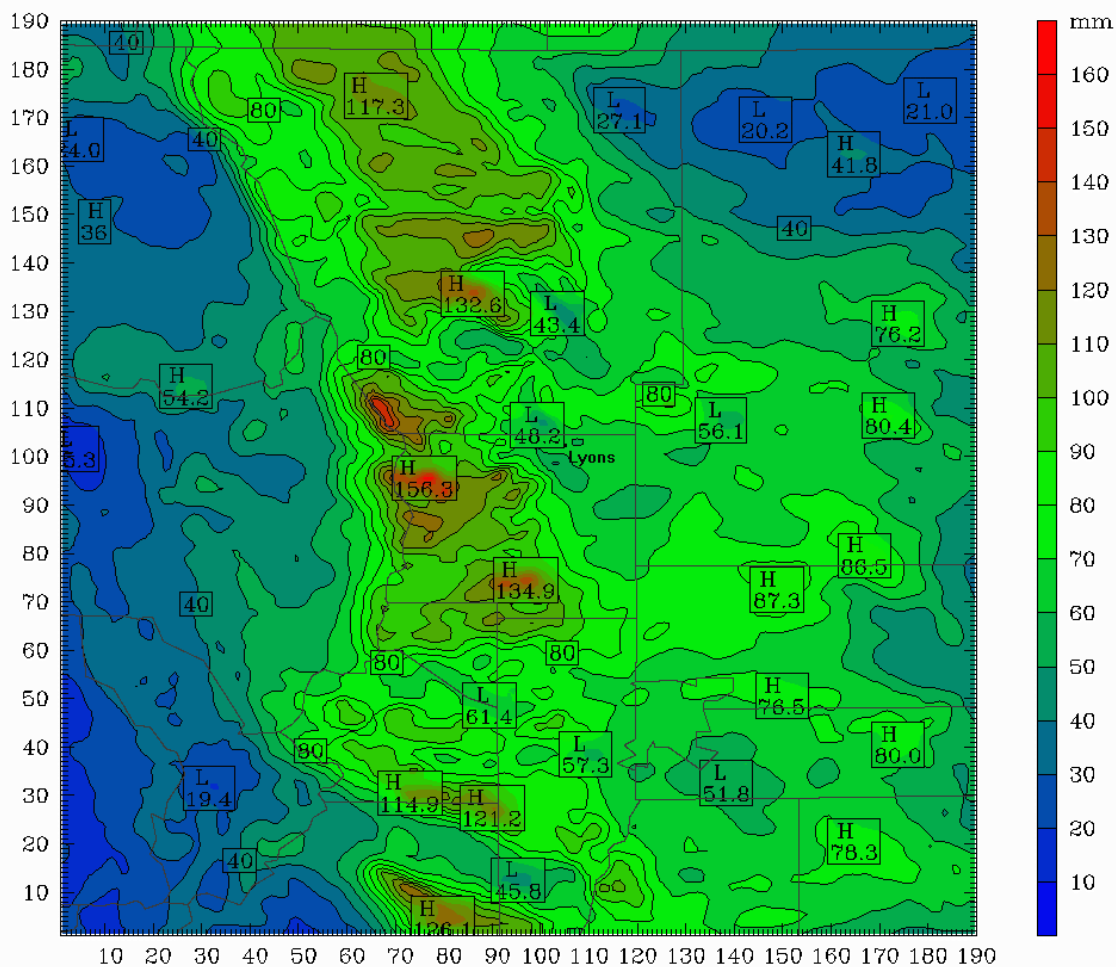


Figure 9 MM5-predicted total precipitation (mm, grid 5) for 84 hours of simulation ending at 12 UTC 20 Mar.. County boundaries for this portion of north-central Colorado are shown.

Additional examination of the model fields reveals some interesting characteristics regarding thermal structure. Figure 11 shows the lowest-level temperature at 12Z 18 March, during the initial portion of the snowstorm. First, a large portion of northeastern Boulder Co. is relatively warm in comparison with other areas of similar elevation. Additionally, the correlation between the warmest locations in northeastern Boulder Co. and southeastern Larimer Co. with 2 of the aforementioned regions of much lighter snow accumulation is striking. Temperatures in these regions are in the 0.5-1.5C range, while surrounding (but still east of the foothills) temperatures are about 1C cooler. So, it appears (at first guess) that both warmer temperatures and lighter precipitation overall contributed to the snowfall minima shown in Fig. 6. These simulations immediately generate questions about the exact cause of the warm pockets: local downslope flow, or perhaps diversion/blocking of the lowest levels of the barrier jet so that the effect of cold advection is reduced? The latter situation is not readily evident in the low-level wind fields plotted in Fig. 11.

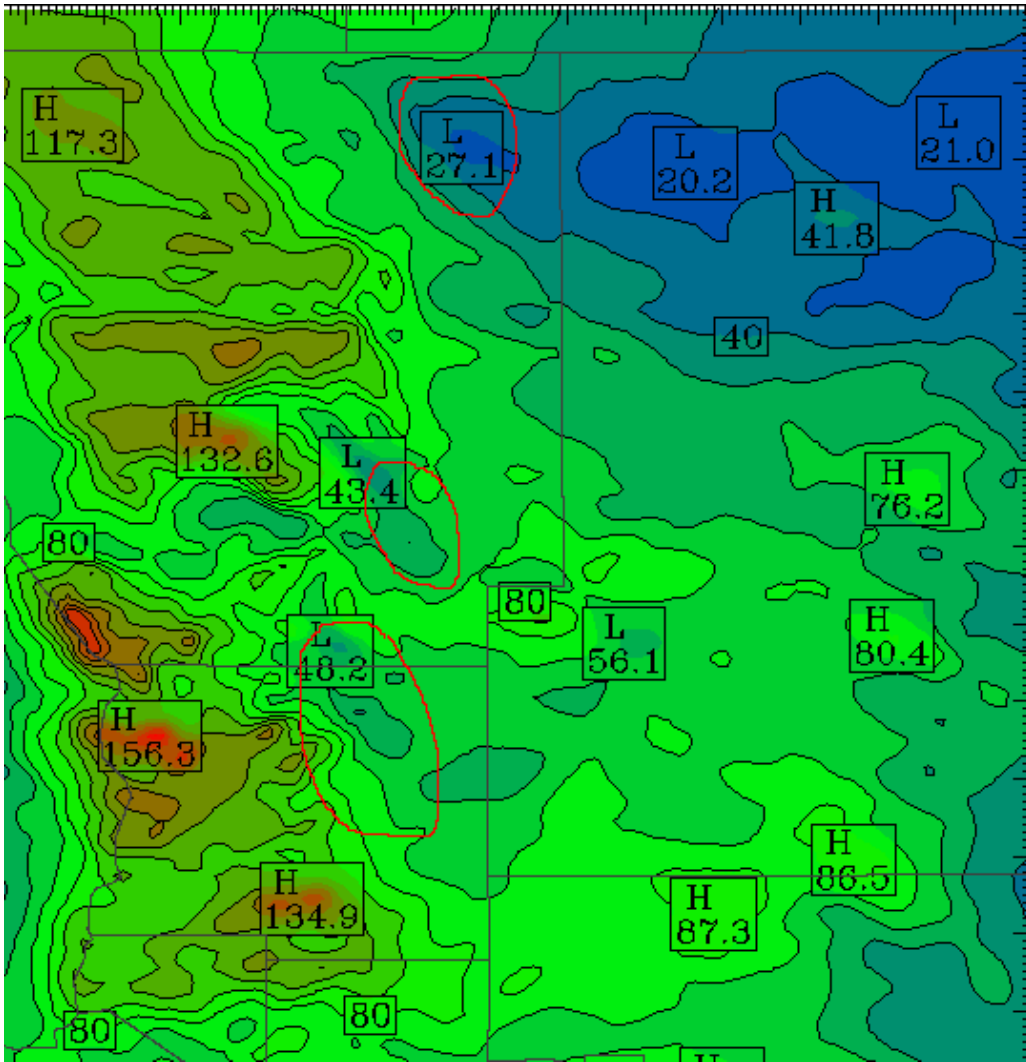


Figure 10 Same as Fig. 9 with annotated locations of snow depth minima shown by satellite data.

Springtime snowstorms in these regions tend to be a combination of rain and snow events in the urban corridor, especially during the late springtime; the barrier jet setup is conducive to a rain/snow boundary located on the eastern side of the barrier jet, east of the foothills. Typical observations are that snow accumulation is highly sensitive to surface temperatures, especially on this eastern portion of the barrier jet. It appears from both observations of the 16-20 March snow accumulation and these high-resolution simulations that local terrain influences are generating slightly warmer regions over certain portions of the plains/foothills interface. Even slightly warmer surface temperatures would dramatically increase the melting of snow as it fell, in this situation, and this was commonly observed during the early portions of the storm, and through the event in the locally warmer areas. Additionally, note that the model-predicted liquid equivalent precipitation is reduced in the meso- γ -scale warmer area.

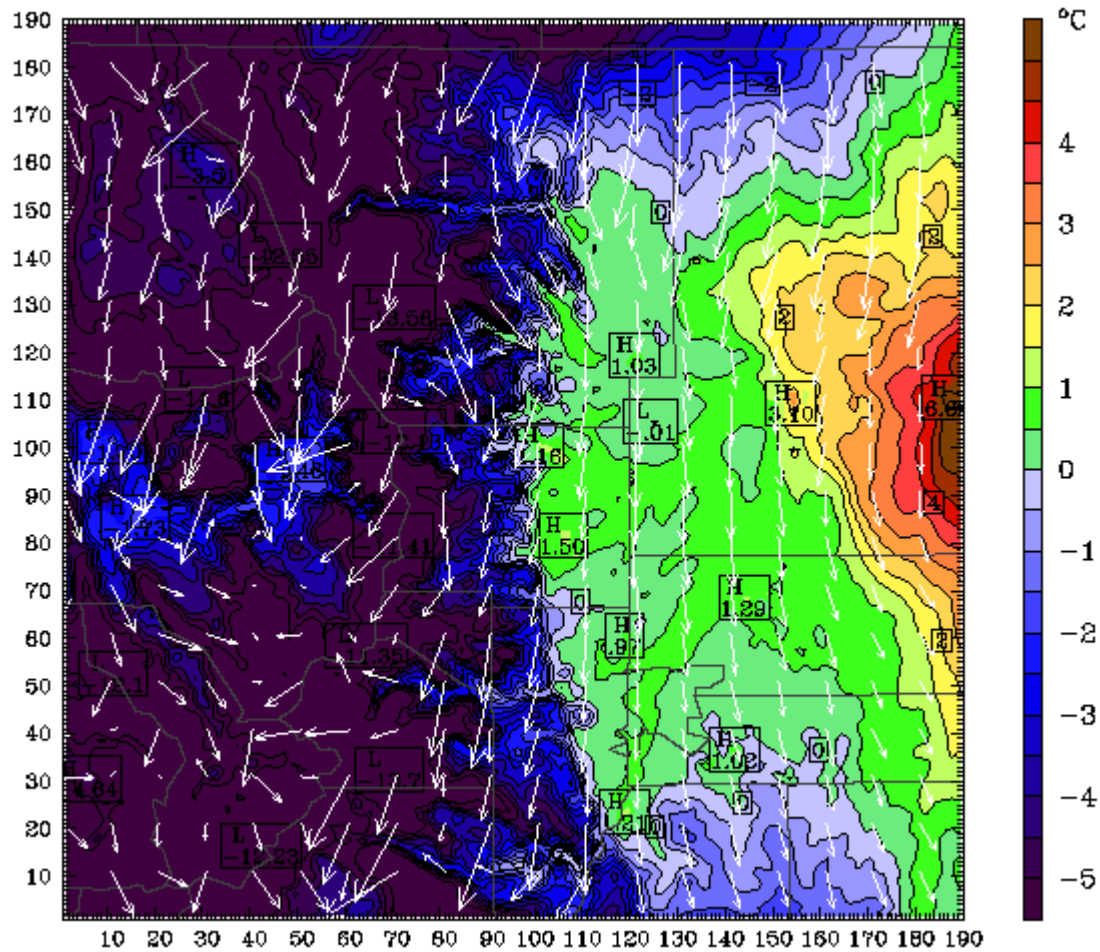


Figure 11 MM5 36-hr. forecast of lowest level temperature (C) and winds (m/s), for 12Z 18 March. Note the relatively warmer areas along the foothills in southeastern Larimer Co. and northeastern Boulder Co.

In the urban corridor region just south of the Cheyenne Ridge, the snow minimum region discussed previously (number 3 in the previous list) appears to be caused by lower precipitation values rather than warmer temperatures (see Wesley et al.,

1995), and attributable to local downslope flow. Note that in Fig. 11 this area is well below freezing at the surface. This

is often observed in storms characterized by strong north winds at the surface in this region.

More results of these MM5 simulations are under investigation, including a sensitivity examination of the areas that experienced warmer surface conditions and less snowfall. Potential mechanisms include local downslope warming, and blocking of the barrier jet-induced cold advection by small-scale terrain features just upstream of these locations. A model experiment being considered is to modify the model terrain as follows:

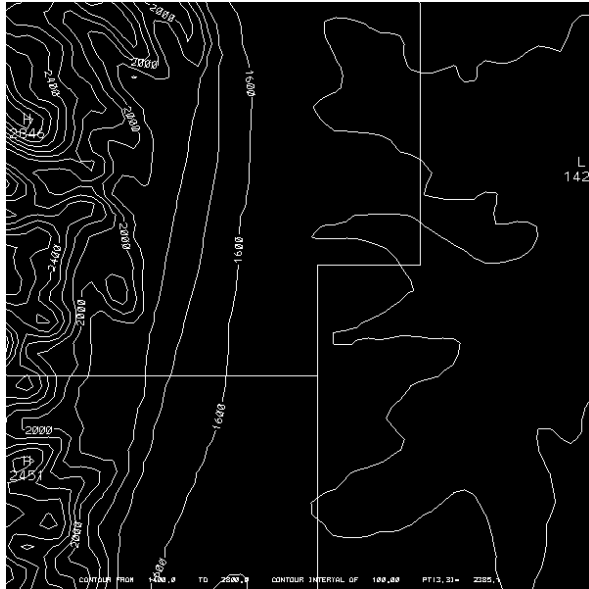


Figure 12 Modified model grid 5 terrain. Compare to Fig. 8 to see how the terrain was altered for experimental simulations.

We have smoothed out the intrusions of terrain features onto the plains in 2 locations, the Lyons area and southeastern Larimer Co. (compare to the original model terrain for this grid shown in Fig. 7). By running this experimental simulation, we hope to isolate the local effects of the terrain in these areas, and determine if in the original simulations local downslope flow in the warmer areas is dominant, or if the cold advection associated with the barrier jet is being blocked or delayed by these terrain features.

More model simulation details will be presented at the conference.

5. MODEL COMPARISONS AND VERIFICATION

The MM5 and Eta models' abilities to capture the depth and strength of the upslope flow are likely important to the ability to predict the barrier jet regime accurately, and thus the low-level temperatures and precipitation types (more details on the 3 km meso-Eta experiments can be found in Wesley et.al. 2004). 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 March, which is 42 to 54 hours into the simulations (and 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.

Ht (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. It is interesting that both mesoscale models' precipitation predictions were qualitatively accurate for the Front Range region. Whether this mid-level upslope problem is related to

the warm bias at the surface in the Eta model is unclear, but at first guess is plausible. Another possibility, of course, is inaccurate boundary conditions at this time (2 to 3 days after model initialization).

6. SUMMARY

This study has begun to address the applications of very high-resolution snowfall observations and mesoscale model forecasts for a major late winter 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-forcing 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. At the same time, accumulations less than 6 inches occurred in a few peculiar locations. In this research we have set up the MM5 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 model. The three-dimensional nature of the barrier jet structure and the temporal dependence of the upslope forcing also represent important aspects of these simulations. On a related note, a verification issue associated with the predicted vertical profiles of the upslope flow is under investigation.

We have focused on snow minima regions along the foothills of eastern Colorado in this study. As revealed by high-resolution satellite data, some areas in the urban corridor next to the foothills received very low snowfall totals, while 5-10 km from these areas, at similar elevations, very heavy accumulations were recorded (1-2 feet +). The snow minima appear to be the result of both warmer surface temperatures and less precipitation overall. Small-scale terrain features are associated with the warm anomalies. The terrain features perhaps caused both local downslope flow and blocking of colder northerly winds. These simulations have potential applications towards both conceptual model development and current operational problems, as continuing computing speed enhancement has allowed unprecedented nesting and grid spacings. It is anticipated that in the future, WRF simulations with grid spacings of 1-5 km will be operational and routine in forecast offices.

7. ACKNOWLEDGEMENTS

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