14.2A EXCEPTIONAL MESOSCALE FEATURES OF THE GREAT WESTERN STORM OF MARCH 16-20, 2003

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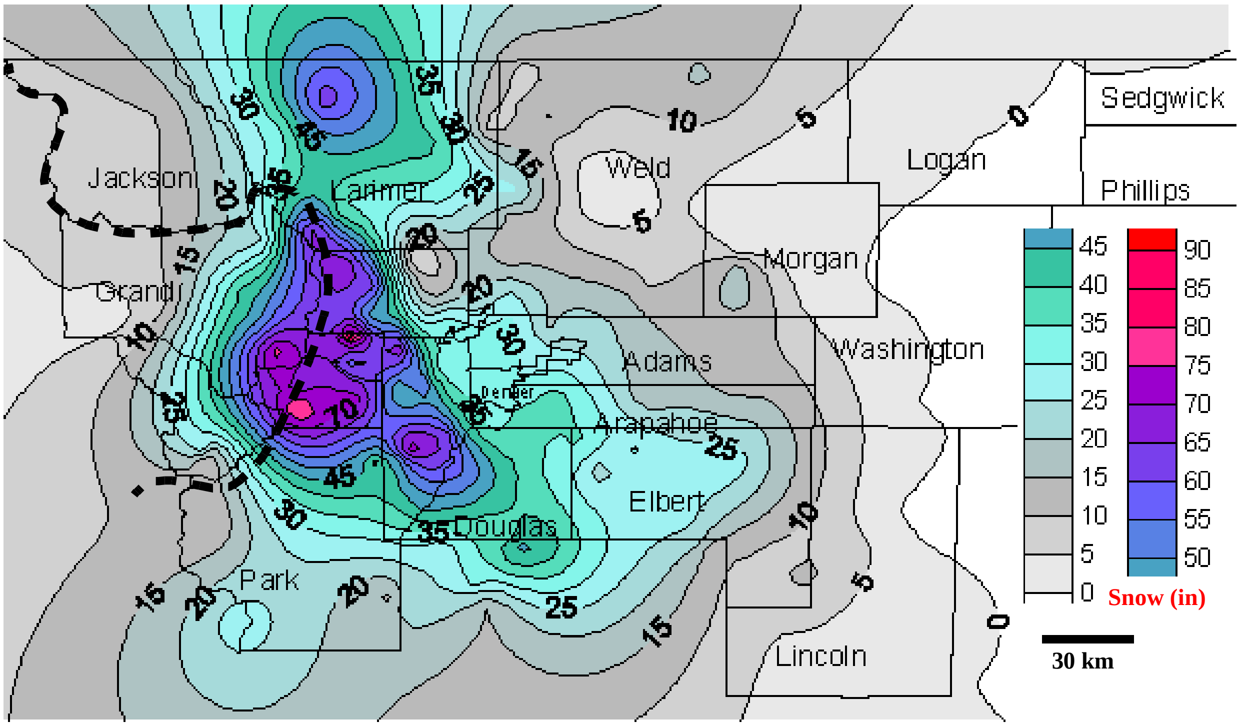

Figure 1. The snowfall distribution (in) in NE Colorado during the period March 17-20, 2003. Courtesy Denver National Weather Service. The thick dashed line denotes the Continental Divide.

1. INTRODUCTION

This winter storm, as it progressed across the southern and central Rocky Mountains during 16-20 March 2003, was characterized by tremendous forcing both synoptically and orographically. The official Denver snowfall fell into the 1-in-50 year statistics for total snowfall (with foothill locations exceeding 85”, Figures 1 and 2).The total volume of precipitation is believed to occur only once per 100 years. As for public impacts, this storm generated the most economic damage in Colorado history of any winter storm, mostly due to falling limbs and roofs (> $100 million - more than 10 times that of the October 1997 blizzard, Poulos et al. 2002, Meyers et al. 2003). In addition to these superlatives, the system was marked by three unusual, persistent, mesoscale features.

Although Figure 1 focusses on Northeastern Colorado, major snowfall occurred further south along the Front Range to the New Mexico border and north into central eastern Wyoming, primarily in upslope prone areas. Although Figure 2 shows little snow remaining in Colorado Springs (1.7” snow) or Pueblo, over 36” of snow fell north of Colorado Springs. Further south 36” to 72” of snow fell in the Wet Mountains southwest of Pueblo. Nearly 24” of snow fell in parts of Wyoming (e.g. Laramie, Casper).

The anomalous depth of the new snow that fell had a major impact on snowpack and therefore in reducing the threat of ongoing drought. SNOTEL sites in the affected area saw increases in snow water equivalent amounting to over 25% of the annual snowpack accumulation. Figure 3 shows that the average increase in snow water equivalent across the South Platte River Basin was over 4” as compared with the average annual snowpack maximum accumulation of just under 15”. Somewhat less impressive increases occurred in the Arkansas River Basin to the south and the Colorado River Basin to the west of the Continental Divide in Colorado.

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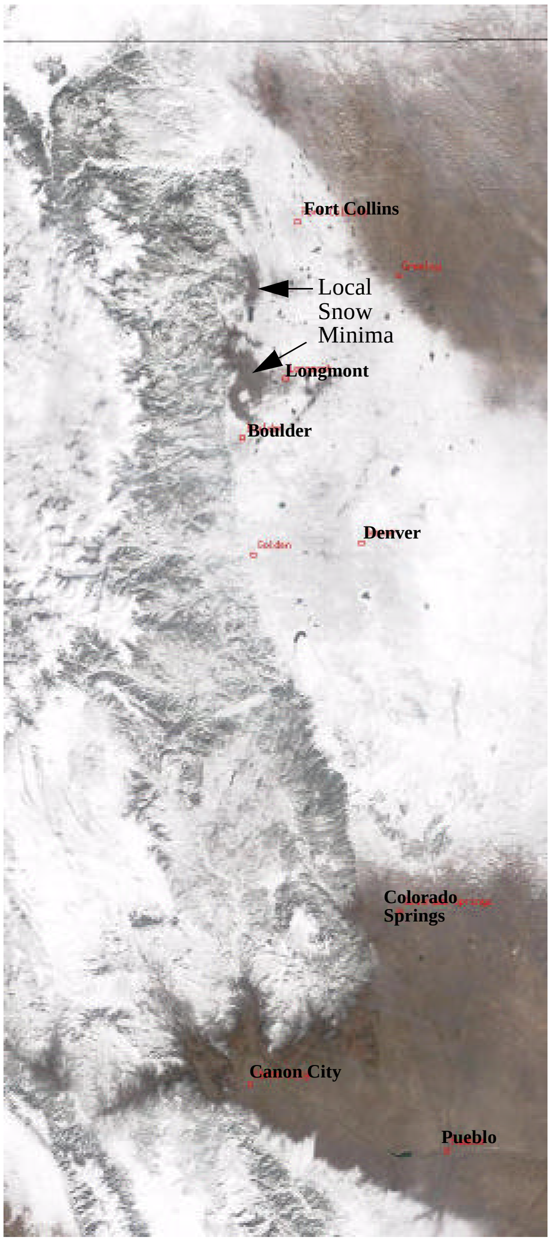

Figure 2. A visible satellite (MODIS) image from the morning of 22 Mar, approximately 24 hours after the snowfall ended and after some melting. This image clearly shows the snowfall minimum that persisted throughout the storm. Provided courtesy Scott Bachmeier, University of Wisconsin, Madison/ SSEC/CIMSS.

The three mesoscale features that we describe herein are: 1) the persistent narrow band of moist inflow, 2) the unusually deep snowfall in the lee of the barrier, and 3) a local snow minima of unknown origin. For convenience, we use the fact that these three features fall individually into the three horizontal sub-scales that define the mesoscale; α - 200 - 2000 km, β - 20 - 200 km and γ - 2 - 20 km respectively, to organize the discussion. Our research on these topics should be considered preliminary. First, we present synoptic context and discuss operational numerical weather prediction of this major event.

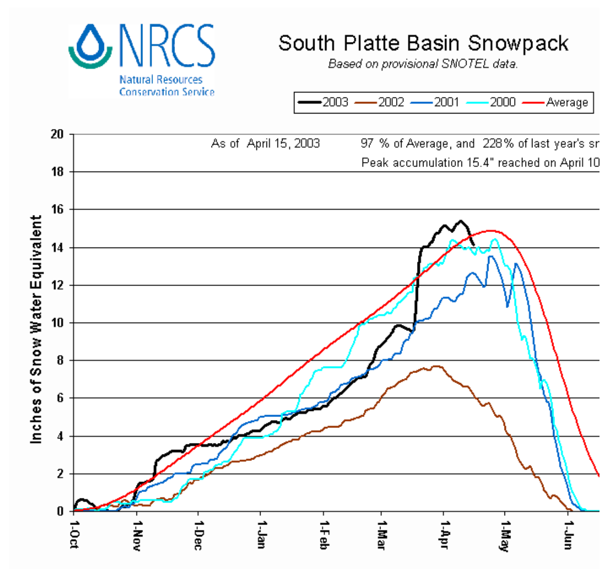

Figure 3. South Platte River Basin snow water equivalent (inches) in snowpack based on an average of many SNOTEL sites. National Resource Conservation Service. The black line is the current water year.

2. SYNOPTIC OVERVIEW

Overall, this megastorm was forced on the large scale by the development of a very strong cutoff low over the southwestern US (Figure 5). This deep cutoff low pressure system developed late on 16 March and persisted over the region until early on 20 March, progressing slowly eastward. Such a configuration will produce strong Front Range upslope flow over Colorado and Wyoming (e.g. Marwitz and Toth 1993, Poulos et al. 2002). In the low levels, the easterly component of wind was particularly strong (Figure 6), and the signature of a strong barrier jet (from the north) was readily evident even on the synoptic scale analyses and predictions. This barrier jet was critical in the production of sufficient diabatic cooling to aid in the production of snowfall despite the relative warmth of the inflow (Marwitz and Toth 1993).

A critical aspect of the synoptic, deep easterly flow was its fetch nearly directly out of the Gulf region, leading to large-scale transport of copious amounts of moisture into an upslope region. This region also was an area of strong synoptic uplift as the storm evolved.

Another key component of the synoptic evolution was the presence of moderately-strong ridging over the northern Rockies and plains, which aided both the low-level upslope component over the Front Range and contributed to low-level cold air supporting the barrier jet and snowfall.

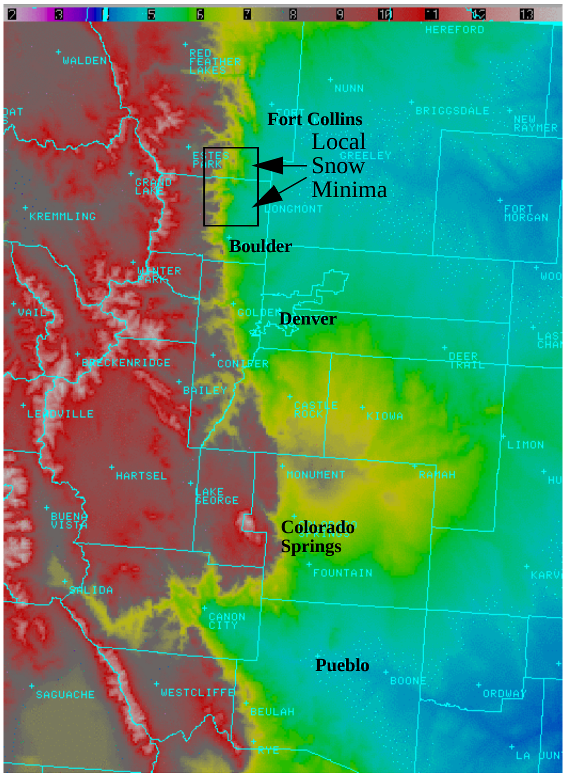

Figure 4. The topography of the study area with towns and county borders. Since the scale is difficult to read, note that blue represents ~ 4000 ft, yellow ~ 7000 ft and red ~ 11000 ft, with the highest values over 13500 ft.

3. OPERATIONAL MODELS

3.1 > 7 day range

In advance of this major storm an upper level ridge was positioned firmly over the Western U.S. and temperatures reached over 20 C across the Front Range of Colorado. However, even the very long range forecasts (> 10 days ahead) from the NCEP GFS (formerly the Aviation and MRF models) indicated a major change in jet stream amplitude was coming, with a significant trough predicted to move into the Rockies. This fact was corroborated by 15-20 day ensemble predictions by Foresight Weather (a local private forecasting outfit) of a transition to high amplitude ridge-trough state with the jet stream being positioned south of Utah and Colorado. This change and confidence that it might occur was further bolstered by the observation of a very strong and extensive zonal jet (near and above 300 mb) emerging from Asia into the western Pacific almost two weeks before the storm.

3.2 3-7 day range

As the timing of the event came into the forecast period of other models there was far better then average consensus on the potential for a significant storm in the 3 to 7 day range. Of course details such as how the actual trough would set up, if and where a closed upper level low might develop, and where the surface storm might track varied amongst the model forecasts until closer to the event.

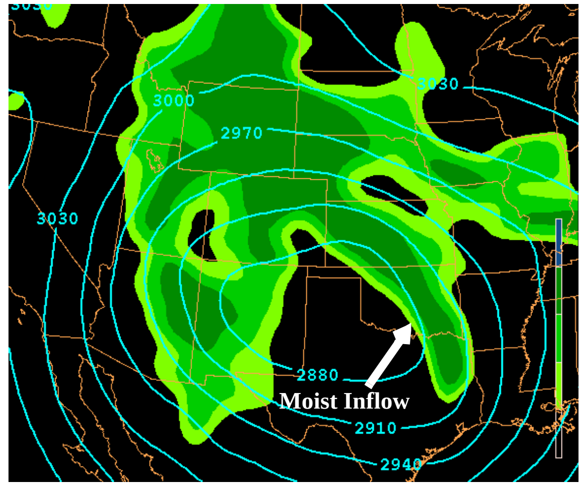

Figure 5. The Eta 12 hour forecast valid 00Z 19 Mar of 700 mb heights (30 m increments) and relative humidity (green shading at 70%, 80% and 90%) showing the moisture source emanating from the Gulf of Mexico.

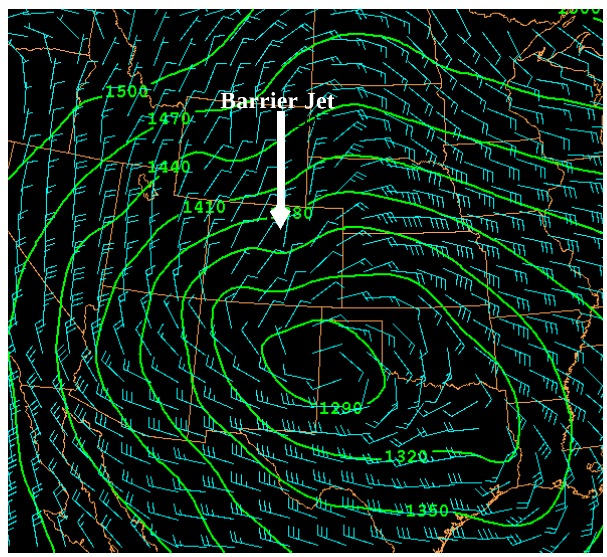

Figure 6. As in Figure 5 but for 850 mb heights and winds (kts).

One of the more consistent differences in the model forecasts was the tendency for the operational version of the GFS to forecast a more northern track to the system than other models, and hence a far less significant potential storm for the area that eventually ended up most impacted. Interestingly, the northern bias for the GFS runs was not true of all the ensemble members nor for the Foresight Weather ensemble mean, with approximately one third of the GFS members forecasting a closed upper level low in the right location more than three days in advance, even when the operational version suggested the storm would transition to the north and east before closing off.

3.3 < 3 day range

The difference between the operational GFS and Eta models was seen as soon as the Eta model forecast was available into the storm period. An 84 h (the farthest out in time the Eta model is run) surface forecast from the Eta run initialized at 1200 UTC on 14 March (Figure 7, valid for 0000 UTC on 18 Mar) shows a surface low set up in southeastern Colorado with precipitation wrapping back into the Front Range and already showing an extension back to the Gulf of Mexico. Although the operational version of the GFS model was considerably farther north with the upper level and surface low for this same forecast, other models (Navy NOGAPS, Foresight Weather mesoscale and ensemble, Environment Canada spectral model, and ECMWF spectral model) were similar to the Eta forecast.

Overall the use of either ensemble forecasts from a single model or forecasts from different models available to forecasters on the web and out beyond the 3-day period, were very useful in adding more than an average amount of confidence to a forecast of a potential significant storm well in advance. That said, it is also true that because the operational version of the GFS did not forecast a big storm for the Front Range region, actual forecasts did not reflect as much conviction in a potential significant storm as they might otherwise have in the longer range, or as was predicted by other models. It is not clear whether these differences are related to initialization techniques used in ensemble forecasts, the fact that the terrain resolved by the GFS is considerably less detailed than that of the Eta model or simply difference their dynamical cores and physics packages.

Within a couple of days of the event even the GFS model came into agreement with the Eta and other models, and Winter Storm Watches for Monday night (17 March) and beyond were issued as early as Sunday afternoon, 16 March. As the models continued to predict a slower evolving system one issue that began to arise was whether precipitation on the Plains of eastern Colorado would fall as rain instead of snow, and/or when the rain might change over to snow. Specifically, since a stalled system would advect in warm air at low levels on strong east-southeast flow at and above the surface across eastern Colorado with a trajectory back towards the eastern Texas/Louisiana Gulf, the possibility existed of a good portion of the Plains well above freezing. Of course this same flow would allow for the potential for extraordinary snowfall where conditions would be cold enough. The resulting snowfall distribution (Figures 1 and 2) was highly dependent on this issue. The deep easterly flow also created the likelihood of a barrier jet from Wyoming south across Colorado near the Front Range, which would not only provide a lifting zone extending out onto the Plains, but also allow for colder air that might gather in Wyoming to advect southward and help make conditions cold enough for snow along the Front Range.

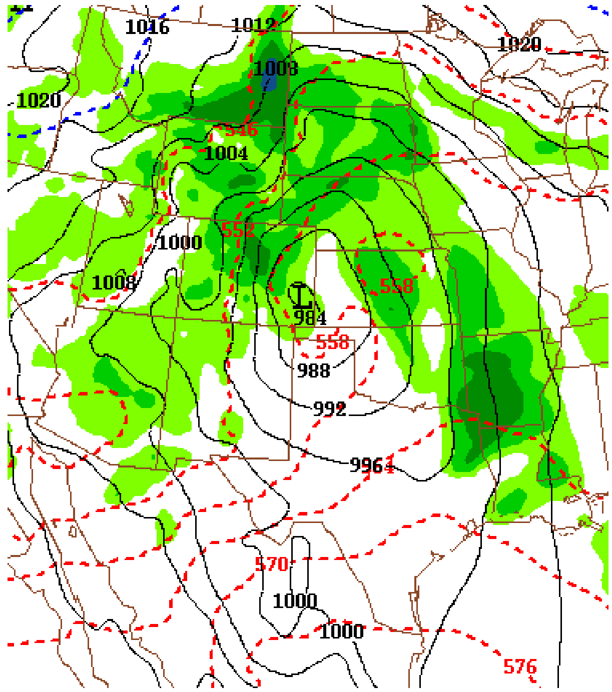

Figure 7. The NCEP ETA 84 hour operational forecast valid 00 UTC18 Mar 2003. Shown are 1) mean sea level pressure (solid contours, 4 hPa increments), 2) 1000 - 500 mb thickness (red dashed, 60 m increments) and 3) 6 h precipitation (color, shading intervals, are 0.01”, 0.10”, 0.25” and every 0.25” thereafter) from the run initialized from 12Z March 14 data.

For the foothills and mountains east of the Continental Divide there was no doubt there would be snow due to their elevation and upwind position (Figure 4), and so confidence increased for very heavy snow amounts. Forecasters at the Boulder WFO mentioned in statements a comparison to the October 1997 storm that dropped over 4 feet of snow in some foothills locations, and amounts that were given in Public Information Statements ranged from 1 to 3 feet for the Front Range cities including the Denver area to more than 6 feet in the foothills (Poulos et al. 2002). The storm total snow forecasts from the Eta model were truly amazing, with individual forecasts producing up to 80”. As it turned out these were fairly accurate, and were ultimately trusted by the forecasters.

The Eta model forecast from the 1200 UTC 17 Mar run has snow accumulation totals exceeding 50” for the foothills from extreme southern Wyoming to southwest of Denver (Figure 8), amounts that while quite impressive were actually not quite as much as forecast by earlier runs. The confidence by the forecasters in enormous amounts of snow for the foothills allowed for such amounts to be forecast in the warnings and other Public statements, even before snow began to fall. These impressive forecast amounts certainly got the attention of the public and public safety officials, which turned out to be a desirable effect given the magnitude of the resulting storm and impact on transportation (many roads into the foothills being impassable due to heavy snowfall as well as avalanches, some at lower elevations than usually occur). It is relatively unusual for an official forecast to predict near-historical snowfall amounts, even when justified, and it is noteworthy that such forecasts were made in this case.

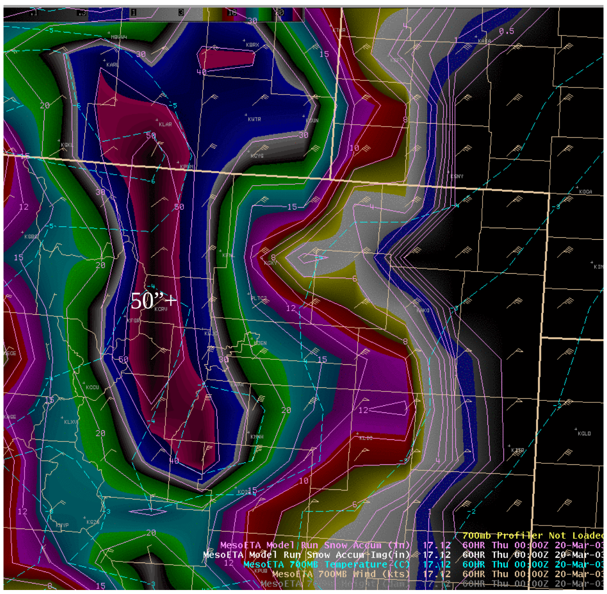

Figure 8. 60 hours storm total snowfall (inches, contours on image up to 50") from the 12 UTC 17 Mar MesoEta valid 00 UTC 20 Mar. Other fields are 700 mb wind barbs and temperature (dashed blue).

4. MESOSCALE FEATURES

4.1 Meso-α-scale: Narrow band of moist inflow

As shown in forecasts (Figures 5 and 7) and verified by analyses (Figure 9), the synoptic system engendered a meso-α-scale, high humidity (> 80%), inflow. This feature, at times only 100-200 km in width, extended directly from the Gulf of Mexico to central Colorado, with an approximate fetch length of 1500 km. Once developed, it persisted for an unusually long period of time (~ 24 hours). In combination with the orographic-forcing of the Front Range of the Rocky Mountains, this inflow produced a barrier jet that was very strong and critical to the development of the snow distribution.

This particular feature is believed to have formed through the combination of three factors, 1) the NW-SE elongation of the primary cut-off towards the Gulf, generating an unusually long deep fetch of SE winds with synoptic uplift, 2) the cooling associated with gradual orographic uplift moving westward across the plains, and 3) unusually warm, moist pre-cursor conditions. The fact that this was such a high amplitude synoptic system created warm, moist conditions east of the Rocky Mountains. Then, as the system cut-off, and therefore slowed down, this ample moisture aided its intensification and enlargement. The amplifying wave aloft and southward diving jet to the southwest then elongated the trough such that moisture transport to the Front Range of the Rockies could be optimized.

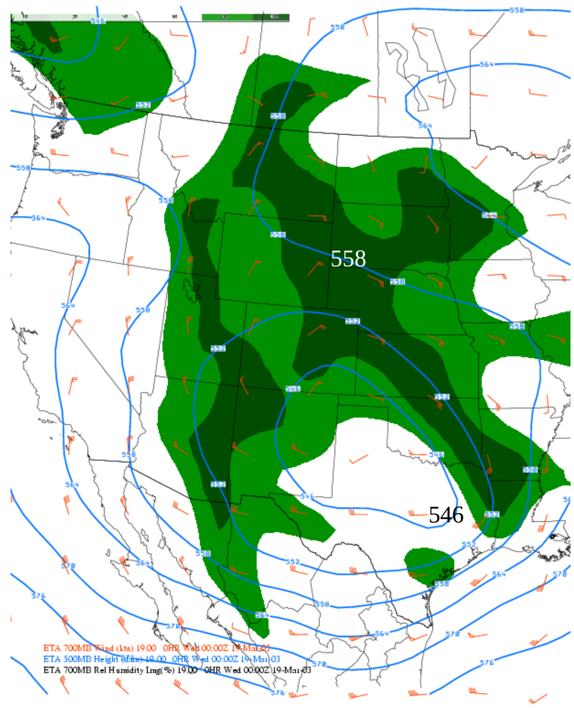

Figure 9. Eta analysis valid at 00Z 19 Mar (compare to Figure 4) showing the moist inflow to the Front Range in the relative humidity field (green shading, 70% and 90%), with wind barbs (kts) and 500 mb height (60 m increments).

4.2 Meso-β-scale: Deep lee side snowfall

A surprising lee side snowfall maximum was generated by this storm (Figure 1, note amounts west of the Continental Divide). Typical so-called upslope snowstorms generate snowfall that is quite heavy on the upwind side of the barrier due to orographic intensification of uplift, but only 20-40% of the upwind-side maximum at most falls downwind as orographic forcing wanes. In Front Range upslope storms there is typically an even greater disparity in snow water equivalent as less dense snow falls in the lee. In this case, while a maximum of ~ 2.2 m of snowfall was reported upwind, 2.0 m or 90% fell in some locations (e.g. Winter Park where record snowfall occurred) on the lee side. Snow density at lower elevations on the Front Range were 10-16%, while snowfall density across the Continental

Divide was ~ 6%. Predicted snowfall from the Eta model (Figure 8) for Winter Park was ~ 1.0 m, or a bit more than typical upslope storm snowfall behavior in this region.

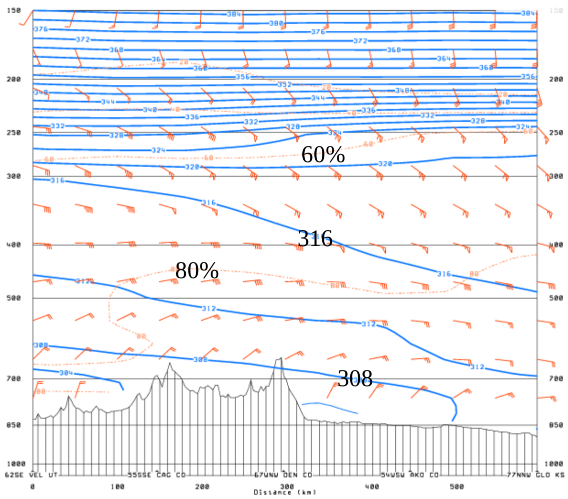

Figure 10. An east-west cross section through the Eta model analysis valid 00Z 19 Mar of winds (kts), θ_e (4K increments, blue lines) and relative humidity (10% increments, light dashed orange lines).

Figure 10 shows an cross-section through the Rocky Mountains near Boulder at a time when heavy snowfall rates (1-3" per hr) were being recorded at the Winter Park Ski Area approximately 7 km in the lee. The figure shows that easterly-component flow existed to above 250 mb and that high relative humidities (80% and above) were present to 450 mb, in the lee. Combined with the upward orientation of the isentropes, conditions for ongoing development of snow are present. What is not clear from the figure is why the rapid fall-off in snowfall occurred further west (Figure 1) and why the snowfall was roughly double that expected from the Eta at Winter Park.

We are investigating the possibility of localized mountain wave effects that may not be well captured by the Eta terrain. Another possibility is that flow around the locally higher terrain east of Winter Park created a convergence zone for an extended period enabling non-typical accumulation. Furthermore, in order to discern whether this heavy snowfall in the lee was prevalent, we will be analyzing additional data from SNOTEL and the CoCoRAHS volunteer network (www.cocorahs.com).

4.3 Meso-γ-scale: Local, imbedded, snow minima

As shown in Figures 1 and 2, a localized snow minima developed along the mountain-plains interface west of Longmont and north of Boulder. In these snow minima, locally 1-2 C warmer temperatures delayed the changeover to snow and, even when that changeover occurred, it was very wet snow that seldom accumulated (and quickly melted). As a result of this local warming, surrounding areas within 10 km that received roughly similar amounts of liquid precipitation but were colder, received snowfall of over 24". Elevation alone does not differentiate these areas of snow minima from surrounding terrain (Figure 4). Eta model forecasts of snowfall (Figure 8) also do not generate a localized region of lower snowfall over these locations.

Because of the prominent role played by the barrier jet in advecting cold air southward along the Front Range, we hypothesize that the locally more east-west oriented ridges north of the snow minima were responsible for physically preventing the rapid cooling experience by other locales (Figure 4). Combined with the local concavity of the foothills in this region it is plausible that temperatures could remain locally elevated by this mechanism. We also speculate that, in the easterly flow, downslope warming induced by local terrain or the deviated position of the cold air dome of the barrier jet may also have contributed. However, the detailed shape of the snow minima in Figure 2 cannot be explained by these concepts. With high resolution mesoscale modeling studies underway we hope to resolve these issues.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Poulos, G. S., D. A. Wesley, J. S. Snook and M. P. Meyers, 2002: A Rocky Mountain storm - Part I: The Blizzard - observations, dynamics and modeling. *Wea. and Forecasting*, **17**, 955-970.

Marwitz, H., 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. S. Snook, D. A. Wesley, and G. S. Poulos, 2002: A Rocky Mountain storm - Part II: The Forest Blowdown - observations, dynamics and modeling. *Wea. and Forecasting* (in press).