CAUSES OF SIMULTANEOUS LEE AND UPWIND RECORD SNOWFALL AND EXTRAORDINARY SNOWFALL VARIATION IN A ROCKY MOUNTAIN BLIZZARD

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Abstract: We describe our investigation of an extreme snowfall event in the Colorado Rocky Mountains during Mar 2003. This event was characterized by extraordinary micro-scale snowfall variability and record snowfall both upwind and in the lee of the 3000 m north-south oriented barrier. We utilize observational analysis and numerical sensitivity tests with the MM5 mesoscale model to test our hypotheses. Stunning micro-scale snowfall variability observed *in-situ* and visualized by satellite is found to be a consequence of local terrain-induced warming and reduced microphysical efficiency and the amplified influence of this effect due to the relatively warm temperatures accompanying this storm. Record snowfall (2 m) downwind of the barrier simultaneous with record snowfall (2.2 m) upwind is very rare climatologically, and is found to be caused, in effect, by the exceptional synoptic dimensions of this storm. A rare combination of, 1) moist, deep inflow, 2) a reversal of the mid-latitude westerlies to the tropopause overlying a well-developed barrier jet for an extended period and, 3) static stability favoring cross-barrier microphysical production and hydrometeor transport rather than drying, are implicated.

Keywords – *Precipitation, Mountain, Variability, Snowfall,*

1. INTRODUCTION

During the period 16-20 March 2003, a major snowstorm inundated the central and southern Rocky Mountain and High Plains regions of the western and central US. The official Denver snowfall fell into the 1-in-50 year statistics for total snowfall and total volume of precipitation is believed to occur only once per 100 years (Doesken 2004, personal communication). As for public impacts, this storm generated the most economic damage in Colorado history of any winter storm, but also reduced the threat of ongoing drought. Increases in snow water equivalent exceeded 25% of the annual accumulation.

Fig. 1 displays graphically the general total snow depth increases that occurred in this region during this storm, based on official and public reports. As shown, up to 2.2 meters of snowfall buried the Front Range of north central Colorado, generally over and just east of the Continental Divide. The heaviest snowfall was concentrated in the foothills east of the Continental Divide at elevations of 7000 feet and upwards; this was obviously the upslope side of the Divide in this storm. A more detailed snow analysis (Fig 1b) was made possible through utilization of Cocorahs* (a volunteer precipitation observation network organized and maintained by Colorado State University), the National Weather Service cooperative network, and other unofficial reports.

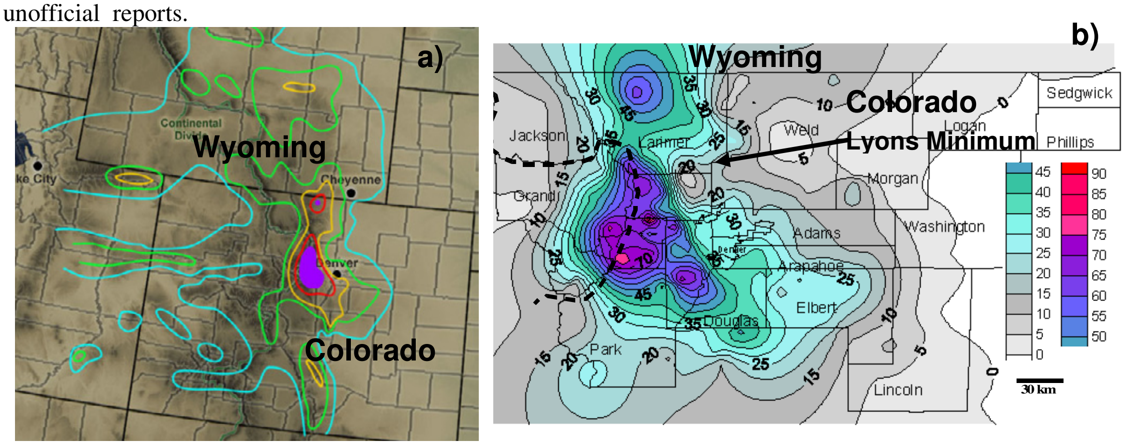

Figure 1. a) Regional storm total snowfall in 30 cm (1 foot) intervals. Snowfall exceeds 150 cm in the shaded area, and reached 220 cm at the observed maximum, and b) the snowfall distribution in 5” (12.7 cm) intervals in NE Colorado during the period March 17-20, 2003 (courtesy Denver National Weather Service). The thick dashed line denotes the barrier crest and the Continental Divide of the Rocky Mountains.

2. MICROSCALE VARIATION OF SNOWFALL: THE LYONS CASE

Figure 1b shows that a local minimum occurred in the vicinity of Lyons, Colorado. Figure 2, from MODIS satellite visually emphasizes the impressive nature of this feature (encircled). While nearly the entire local populace (of over 1 million persons) surrounding Denver, Colorado were severely impacted by this storm, including many within 5 km of Lyons – the residents of this small town were essentially unaffected having received only 5 cm of snowfall and good driving conditions in the local area.

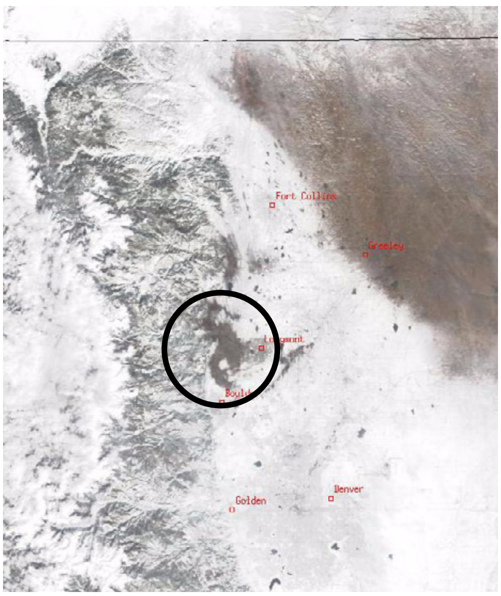

Figure 2. A visible satellite (MODIS) image from the morning of 22 Mar, approximately 24 hours after the snowfall ended and after some melting. This image clearly shows the Lyons snowfall minimum that persisted throughout the storm. Provided courtesy Scott Bachmeier, Wisconsin, Madison/ SSEC/CIMSS.

In order to study this local minimum, we have completed two numerical simulations using horizontal grid spacing of 1 km with MM5. A control run uses realistic terrain, whereas a sensitivity test artificially removes a small terrain feature to the north of Lyons (not shown). These simulations were completed in forecast mode, where initial conditions were obtained from objective observational analyses and the 84 hour forecast was created by using boundary conditions from the operational National Weather Service ETA model. By process of elimination, we hypothesized that this extraordinary feature was caused by a very local terrain feature of less than 100 m in height to the north of Lyons, that would have created a slight downslope flow and minor localized moist adiabatic warming under the influence of the barrier jet observed by the CHILL S-band radar. Because of its very small vertical rise this feature would only be capable, under the right conditions, of creating warming of 0.65C - we were skeptical that such a feature might be capable of the incremental warming required to create the Lyons minimum.

The results of our sensitivity simulations, however, have confirmed that indeed this small terrain feature is a plausible source for the localized snow minimum. As shown in Figure 3, in the control simulation (where realistic terrain was used) we find a local warm anomaly in the vicinity of Lyons. Comparing Figure 3a to Figure 3b, we find that the simulation without the local terrain feature included shows a temperature pattern devoid of the anomaly. While the anomaly is small, the size and shape are indeed reminiscent of the snowfall contours and satellite photography in Figures 1 and 2. A review of the simulation through its entirety shows that the anomalous warm pattern varies considerably, but is generally present when flow is northerly. As a result, and within the near-freezing environment of this storm at the general altitude of Lyons, the cumulative effect of this slight warming was to create an environment where wet snow or rain would fall while surrounding areas experienced snowfall. This is confirmed by using standard precipitation type algorithms which show a greater frequency of rain or mixed precipitation in the Lyons area (not shown).

3. SIMULTANEOUS UPWIND AND DOWNWIND RECORD SNOWFALL

A surprising lee side snowfall maximum (2.0 m), roughly equal to that of the recorded upwind snowfall maximum (2.2 m) was generated by this storm (Figure 1b, note amounts west of the Continental Divide) at a ski area approximately 7000 m to the west of the barrier crest. This snowfall represented the largest storm total recorded in over 50 years of operation at this location. Orographically influenced storms such as the one described herein typically 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 (based on historical observations from the ski area and surrounding areas) as vertical motion typically becomes downward. Operational numerical models, while predicting record snowfall amounts on the upwind side of the barrier, predicted snowfall with a more standard distribution in the lee – approximately 20-40% of the upwind maximum.

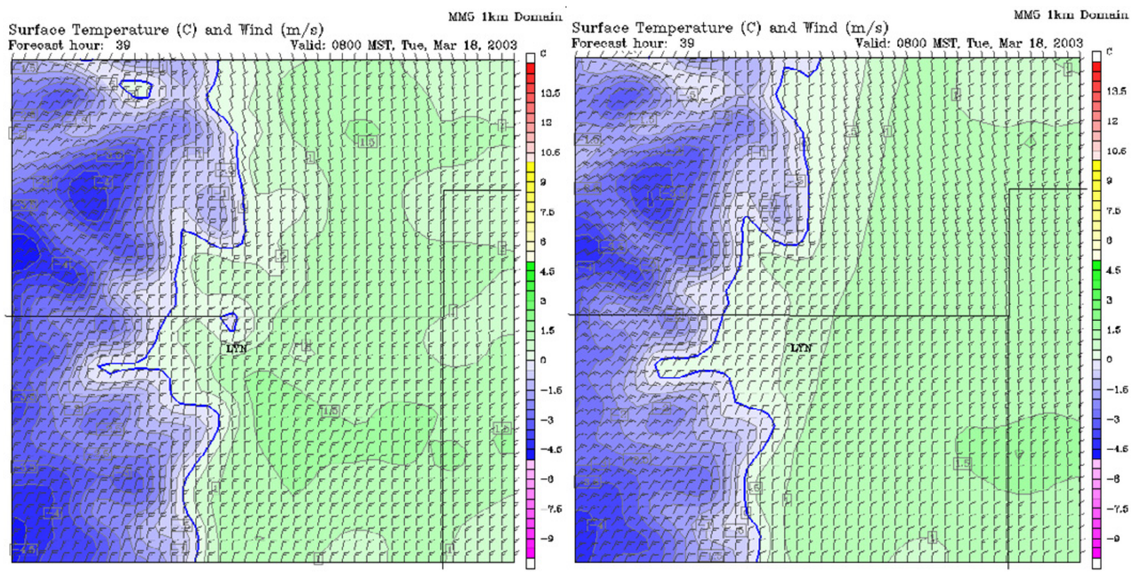

Figure 3. Temperature and winds from a) the control run with realistic terrain and, b) from the sensitivity test with terrain modified slightly to the north of Lyons (LYN). Note the warm temperature anomaly to the south-south east of Lyons in a) that is not present in b).

Our simulations were not able to reproduce the downwind maximum observed, although through analysis of the model output we found that for the first part of the simulation snowfall accumulated in the lee side of the barrier at nearly an equal rate as to the upwind side. Various observational analyses confirm that this storm possessed some unusual features, which give some clues as to possible causes of heavy lee side snowfall; 1) a very strong, slowly progressing cutoff low over the southwestern US (e.g. Marwitz and Toth 1993, Poulos et al. 2002), 2) a deep strong -*U* component, 3) a powerful, consistent northerly barrier jet (CSU CHILL, not shown) and, 4) a moist fetch from the Gulf region, leading to large-scale transport of copious amounts of moisture and westward-propagating convection (NEXRAD national radar composites, not shown). A comparison of our simulation to observations shows that MM5 failed to retain the elements required for heavy lee-side snowfall throughout the simulation period, a) upward sloping isentropes over the barrier crest, b) strong sub-500 hPa easterly flow, c) deep moisture, and d) a large-scale upward sloping barrier jet. Convective activity also appeared to be underrepresented in parts of the simulation relative to observations.

The above combination of conditions would provide not only the environment where hydrometeor growth was enabled, but also that in which snow particles drifting downwind could readily accumulate far in the lee of the barrier. Using a fall speed of 1 m/s, the observed 20 m/s advection and noting the 7000 m distance to the ski area site (~350 m < Divide), hydrometeor drift could be a significant phenomena not represented in the latter half of the simulation.

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