J4J.2 CHILL, PARTICLE ID AND MM5: THE ROLE OF THE BARRIER JET IN MESO-γ-SCALE PRECIPITATION DISTRIBUTION IN AN EXTREME SNOWSTORM

Gregory S. Poulos [1], Douglas A. Wesley [2], Patrick C. Kennedy[3] and Steven A. Rutledge[3]

[1] NCAR, Earth Observing Laboratory, Boulder, Colorado, USA
[2] UCAR, COMET, Boulder, Colorado, USA
[3]Colorado State University, Department of Atmospheric Science, Fort Collins, Colorado, USA

1. INTRODUCTION

In this work we study the specific role of the barrier jet on the distribution of precipitation, during the period 16-20 March 2003, when a major synoptic system inundated the central and southern Rocky Mountain and High Plains regions of the western and central US. The official Denver snowfall showed this to be a 1-in-50 year event and the total volume of precipitation is believed to occur only once per 100 years (Doesken 2004, personal communication, see Figure 1). Increases in snow water equivalent of the South Platte River Valley exceeded 25% of the annual maximum accumulation. In addition to surface and other observations, we utilize data from the CHILL radar (see companion paper P9R.15 by Kennedy et al., which includes CHILL operating parameters and additional barrier jet observations) and high-resolution ($\Delta x = \Delta y = 1$ km over the region of interest) MM5 simulations.

We find that strong barrier jet periods are associated with maximum snowfall rates further upwind east of the barrier (over the plains) and immediately in the lee of the barrier, lower snow density, greater variation in meso-γ-scale precipitation differences, and coincident changes to hydrometeor type as identified using particle identification (PID) algorithms in CHILL.

Weaker barrier jet periods are found to correspond to higher snowfall rates immediately upwind of the barrier, less variability in snowfall at constant elevation and a more traditional decrease in snowfall in barrier lee. Since the barrier jet is a routine feature of extratropical cyclones in the vicinity of barriers, and in this region in particular, understanding this phenomena contributes to knowledge of the influences on local climate and, through the intersection of barrier jet dynamics with microphysics, on weather forecasting.

Figure 1 shows the total snow depth increases that occurred in this region during this storm, based on official and public reports. Up to 2.2 meters of snowfall accumulated over the Front Range of north central Colorado, 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. We will not provide a synoptic overview and weather analysis herein, but we refer the reader to Poulos et al. and Wesley et al. (2005) for this information.

Corresponding author address: Gregory S. Poulos, gsp@ucar.edu, NCAR, P.O. Box 3000, Boulder. CO. 80307

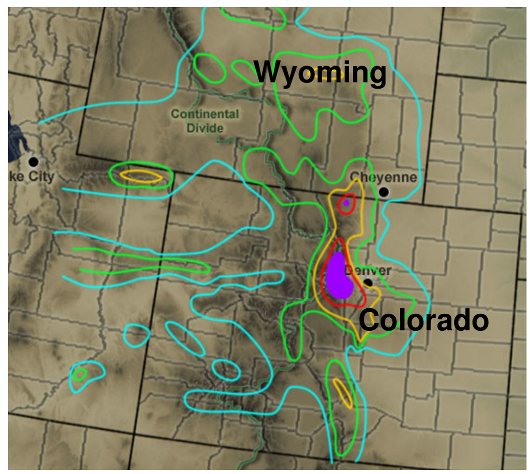

Figure 1. Regional storm total snowfall in 30 cm (1 foot) intervals. Snowfall exceeds 150 cm in the shaded area, and reached 220 cm at the observed maximum (see also Figure 2).

2. THE BARRIER JET

Figure 2 shows the Doppler velocity pattern, obtained from the CHILL radar, which shows the existance of the barrier jet for both RHI and PPI scans early on 19 Mar 2003. Figure 2a shows a N-NNW barrier jet at low-levels of over 20 m s-1 backing to easterly flow at upper levels of near 25 m s-1. This type of PPI persisted for most of the storm creating conditions where warmer, more moist easterly flow was forced to ascend over the stable barrier jet throughout the storm. As a result, rather than unadulterated terrain interception causing vertical motion, rising, cooling and the resultant hydrometeor distribution, the barrier jet forced ascent to the east of the main upslope area while it existed. This is more clearly shown in Figure 2b where a clearly sloping barrier jet creates a virtual barrier that one can readily imagine would enhance vertical motion to the east of the barrier (note ground clutter on the east side of Figure 2b).

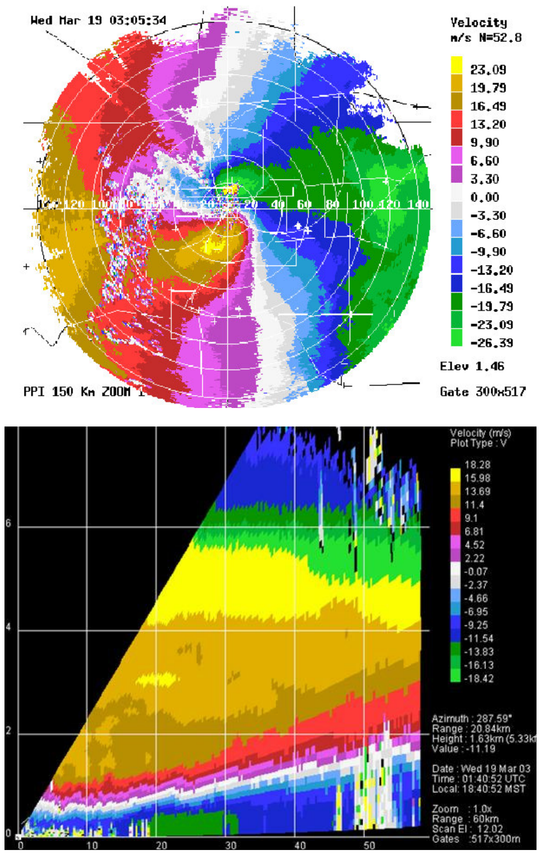

Figure 2. a) CHILL Doppler velocity PPI at 1.46° elevation at 0305 UTC Wed Mar 19, and b) CHILL Doppler velocity RHI at 0141 UTC Wed Mar 19 at 288° azimuth.

The persistent nature of the barrier jet in this storm is elucidatedin Figure 3, which shows the Platteville radar profiler winds during the majority of the precipitating part of the storm. Note that underlying very strong and deep synoptic easterly flow the barrier jet persisted for the 'center' 36 hours. For the first 6 hours shown the barrier jet was weaker and inconsistently measured (perhaps its formative stages) and in the latter 6 hours synoptic northerly flow developed as the low pressure system moved to the east. Note that some data are missing at the lowest levels during the two times shown in Figure 2. Interpolating between measured data however, the wind speeds (~ 20 m s-1 or 40 kts from the N and NNW) and depth (~ 1 km) of the barrier jet are consistent with those shown in Figure 2. Thus, we conclude that during this storm the barrier jet was a persistant feature that for at least 36 hours (06 UTC 18 Mar – 18 UTC 19 Mar) maintained an upward slope toward the west with a maximum observed depth of approximately 2 km above ground (~ 3.5 km or 11500 ft MSL) near the barrier.

3. SOME PRECIPITATION FEATURES OF NOTE

A more detailed snow analysis (Figure 4a) was made possible through utilization of CoCoRaHS (www.cocorahs.org), the National Weather Service cooperative network, and other unofficial reports. A complementary satellite photo, Figure 4b, emphasizes the interesting and apparently unusual features of the precipitation distribution that were produced during this storm,

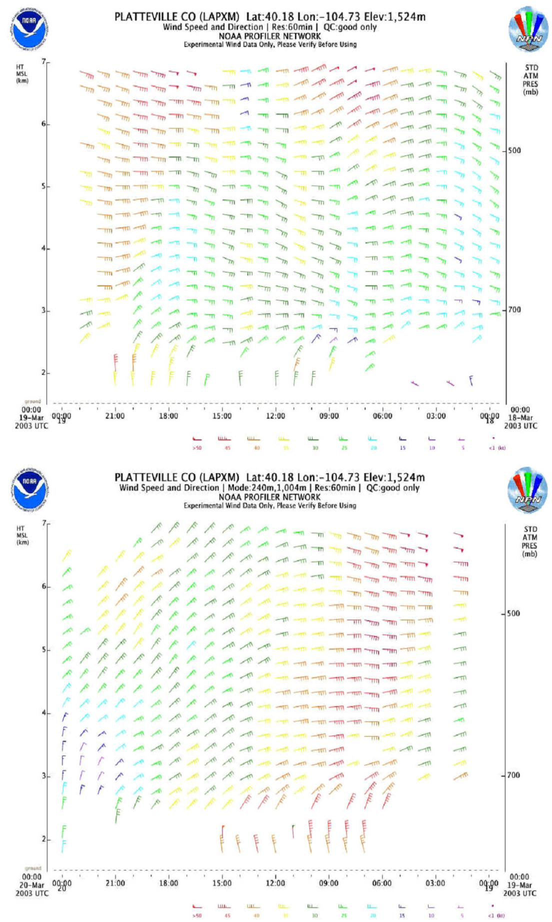

Figure 3. Winds as measured by the Platteville, CO profiler for a 48 hour period during peak precipitation in the Front Range of Colorado. This wind profiler is located ~40 km north of Denver (see Figure 4).

a) The Lyons Minimum and Other Minima

Figure 4a shows that a few local minima occurred along the Front Range, the most impressive and notable of which is found in the vicinity of Lyons, Colorado. 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 locally unaffected having received only 5 cm of snowfall and experiencing only wet driving conditions.

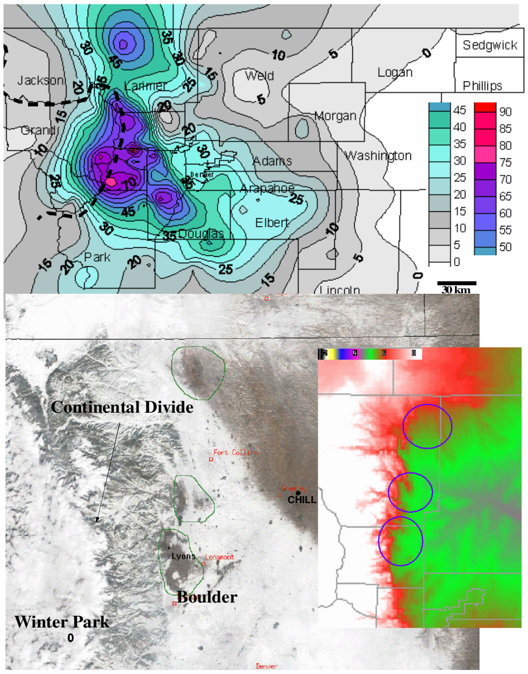

Figure 4. a) The NE Colorado snowfall distribution in 5” (12.7 cm) intervals (courtesy Denver NWS). The thick dashed line denotes the barrier crest and the Continental Divide. b) A MODIS image, and an accompanying map of the relief emphasizing terrain detail in the vicinity of snow minima, of snowcover approximately 36 hours after the end of the storm (some melting has occurred, courtesy Scott Bachmeier, U. Wisconsin/CIMSS).

b) Lee-side/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 4a, 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 40% of the upwind maximum.

4. NUMERICAL SIMULATIONS: MM5 @ 1km

In order to study the influence of the barrier jet on the overall precipitation distribution and the unusual features described above, we have completed two numerical simulations using horizontal grid spacing of 1 km with MM5. 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. A control run uses realistic terrain, whereas a sensitivity test artificially removes a small terrain feature to the north of Lyons (not shown) to investigate if northerly barrier jet flow over the local terrain feature could be a causal mechanism.

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. 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.

a) Results: Barrier Jet and Lee-side Snowfall

Figure 5 shows a sequence of east-west cross-sections through the approximate location of the snowfall maximum on the lee-side (Winter Park, CO). During the first half of the storm the simulation produced a robust, sloping barrier jet (Figure 5a) at and through 12 UTC 18 Mar. Our analysis of the simulation indicates that during this time, the snowfall rate in Winter Park matched the observed snowfall rate (recorded hourly). At the mid-point of the storm evolution, when Platteville wind profiler data (Figure 3) and CHILL data (Figure 2) continue to show a strong, deep barrier jet, the simulation (Figure 5b) instead shows a weakening barrier jet by 21 UTC 18 Mar. The barrier jet is simulated to be weak thereon, while the profiler shows a strong barrier jet through 15 UTC 19 Mar.

The weakened simulated barrier jet coincides with a 50-60% decrease in simulated snowfall rate at the Winter Park location, and a total precipitation estimate that therefore is ~ 60% of the observed (58 mm vs. 102 mm actual). This, we believe, indicates that a robust barrier jet was a crucial element (combined with strong, moist cross-barrier flow) in allowing heavy snowfall in the lee. Note also the downward vertical motion that develops in the lee when the barrier jet weakens in the simulations. Additional x-z sections (not shown) indicate that during the period of robust barrier jet that the static stability was positive in the lee, allowing for continued upglide and favorable conditions for microphysical growth in the lee. 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.

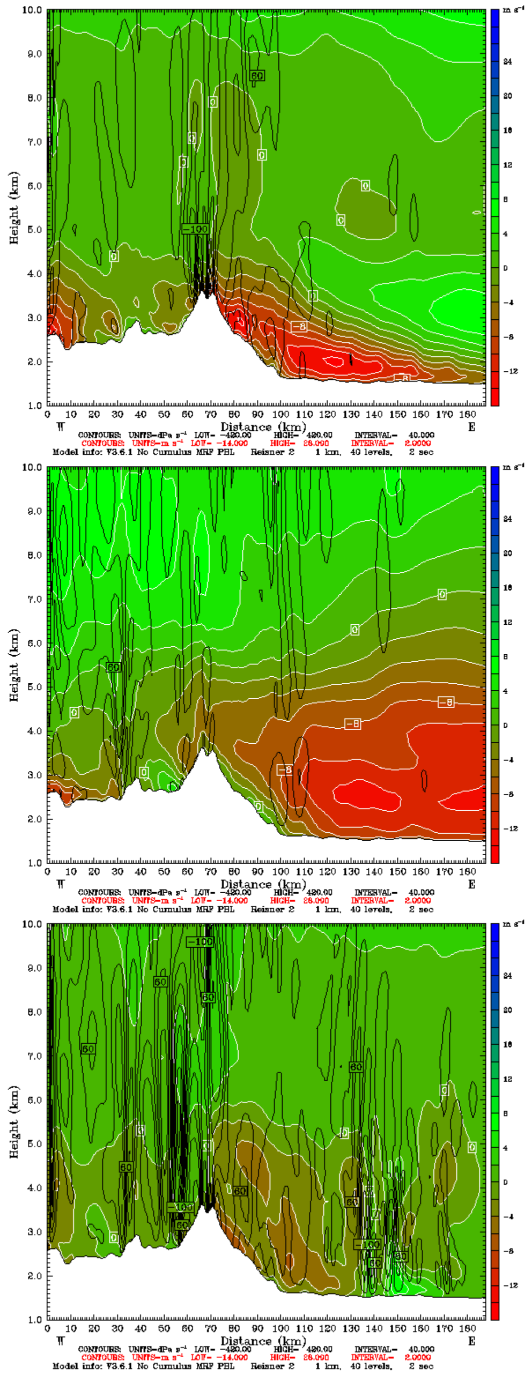

Figure 5. East-west (x-z) cross-sections showing the v-component winds and vertical motion through the approximate latitudinal location of Boulder and Winter Park for a) 12 UTC 18 Mar, b) 21 UTC 18 Mar and c) 21 UTC 19 Mar.

b) Results: Snow Minima

Our simulations confirm that the small terrain feature north of Lyons is a plausible source for the localized snow minimum. Comparing Figure 6a (real terrain) to Figure 6b (small terrain feature removed), 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 surprisingly reminiscent of the snowfall contours and satellite photography in Figure 2. A review of the simulation through its entirety shows that the anomalous warm pattern varies considerably, but is generally present when the northerly (or NNW) barrier jet exists. 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 there.

5. PARTICLE ID: THE BARRIER JET IN E-W PRECIPITATION DISTRIBUTION

Figures 7 and 8 show CHILL PID, reflectivity and radial velocity for 05 UTC, 18 Mar and 23 UTC LT 18 Mar, respectively. In Figure 7c, in the lower right hand side of the plot we find that the barrier jet has partially formed, showing inbound velocities in the range 28 – 45 km. Correspondingly, the aggregated snow category persists aloft in Figure 7a at the same range, and the total extent of frozen precipitation is limited. The barrier jet extent corresponds with the rain-snow or wet-frozen line. Note also in Figure 7b that the reflectivity is largest starting ~ 25 km from CHILL to the west.

Figure 8, from 18 hours later, shows a barrier jet (Figure 8c) that has strengthened and expanded in east-west extent, such that it envelopes CHILL. The barrier jet development to the east coincides with the eastward and vertical expansion of frozen precipitation identification and aggregated snow. Radar reflectivity values have increased as well, indicating that significant snowfall rates have moved eastward.

6. CONCLUSIONS

In this study we have found that the barrier jet had a profound influence on three features of the mesoscale precipitation distribution for the March 2003 Front Range Blizzard, 1) the development of extreme local minima, 2) the heavy snow production (record snowfall) in the lee of the barrier during an upslope storm, and

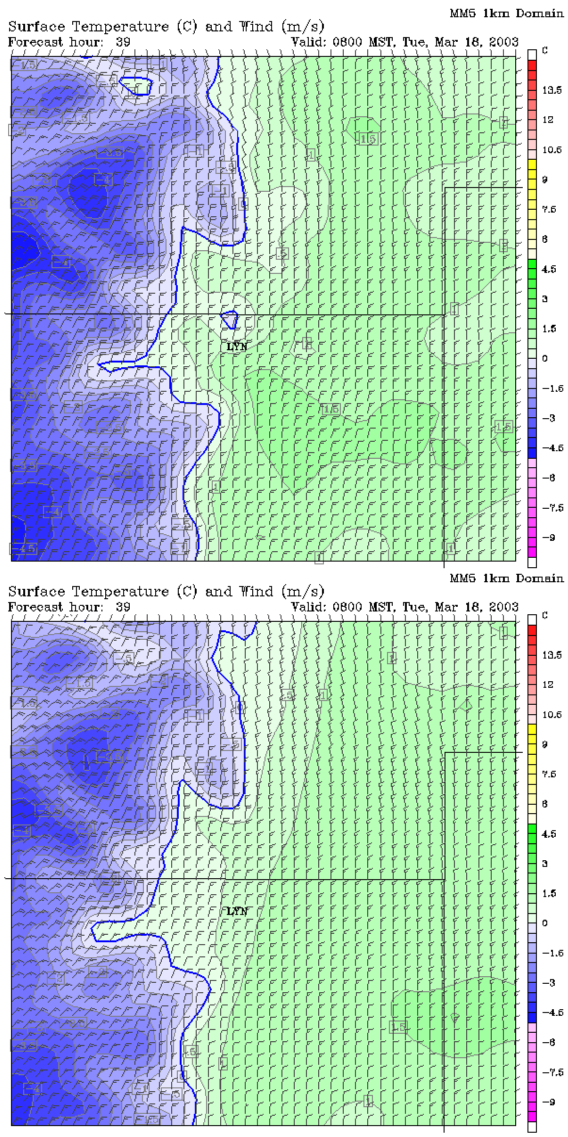

Figure 6. Temperature and winds from a) the control run with realistic terrain and, b) from the sensitivity test with terrain modified slightly to the north of Lyons (LYN). Note the warm temperature anomaly to the south-south east of Lyons in a) that is not present in b).

3) the east-west extent of snowfall (the rain-snow line).

Acknowledgements: *We acknowledge those who have graciously supplied figures for this manuscript (as noted in the captions), CoCoRAHS and the Winter Park Ski Patrol for access to its historical data. The radar data processing and display software used in these analyses were developed at and supplied by UCAR/NCAR which are supported by the National Science Foundation. The CSU-CHILL radar facility is supported by ATM-0118021.*

7. BIBLIOGRAPHY

Bell, G. D. and L. F. Bosart. 1988: Appalachian Cold-Air Damming. *Monthly Weather Review*: Vol. 116, No. 1, pp. 137–161.

Dunn, L.B.,1992: Evidence of Ascent in a Sloped Barrier Jet and an Associated Heavy-Snow Band. *Monthly Weather Review*: Vol. 120, No. 6, pp. 914–924.

Dunn, L.B., 1987: Cold Air Damming by the Front Range of the Colorado Rockies and its Relationship to Locally Heavy Snows. *Weather and Forecasting*: Vol. 2, No. 3, pp. 177–189.

Marwitz, J., and J. Toth. 1993: The Front Range Blizzard of 1990. Part I: Synoptic and Mesoscale Structure. *Monthly Weather Review*: Vol. 121, No. 2, pp. 402–415.

Meyers, M.P., J. Snook, D. Wesley and G. Poulos. 2003: A Rocky Mountain Storm. Part II: The Forest Blowdown over the West Slope of the Northern Colorado Mountains—Observations, Analysis, and Modeling. *Weather and Forecasting*: Vol. 18, No. 4, pp. 662–674.

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.

Poulos, G. S., D. A. Wesley, M. P. Meyers, E. Szoke and J. S. Snook, 2003: Exceptional mesoscale features of the Great Western Storm of March 16-20, 2003. American Meteorological Society - 10th Conference on Mesoscale Processes, Portland, Oregon, 23-27 June, paper 14.2A (available in the online permanent archive of the AMS).

Wesley, D.A., R. Rasmussen, and B. Bernstein. 1995: Snowfall Associated with a Terrain-Generated Convergence Zone during the Winter Icing and Storm Project. *Monthly Weather Review*: Vol. 123, No. 10, pp. 2957–2977.

Wesley, D. A., G. S. Poulos J. S. Snook and P. Kennedy, 2005: Mechanisms for extreme snowfall in the Front Range heavy snowstorm of 17-20 March 2003. *Wea. Fore. (to be submitted*

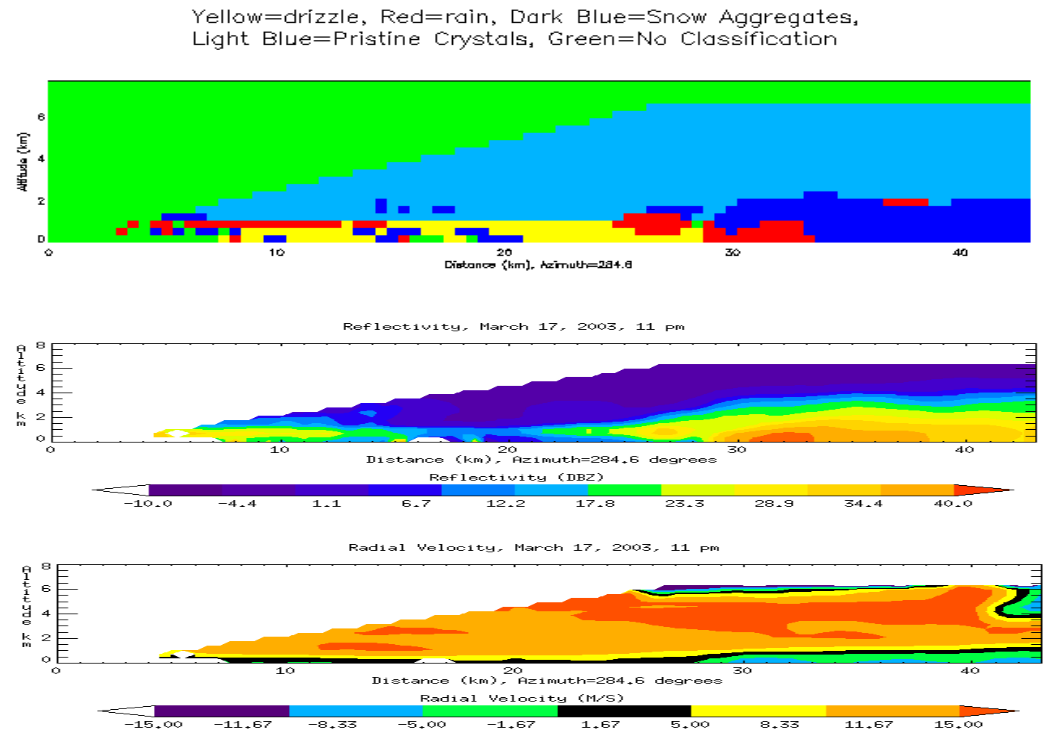

Figure 7. CHILL a) Particle ID, b) reflectivity and c) radial velocity for 05 UTC 18 Mar 2003, showing that aggregated snow extent, frozen precipitation extent, and the strongest reflectivity corresponds to the barrier jet extent (light green in (c)).

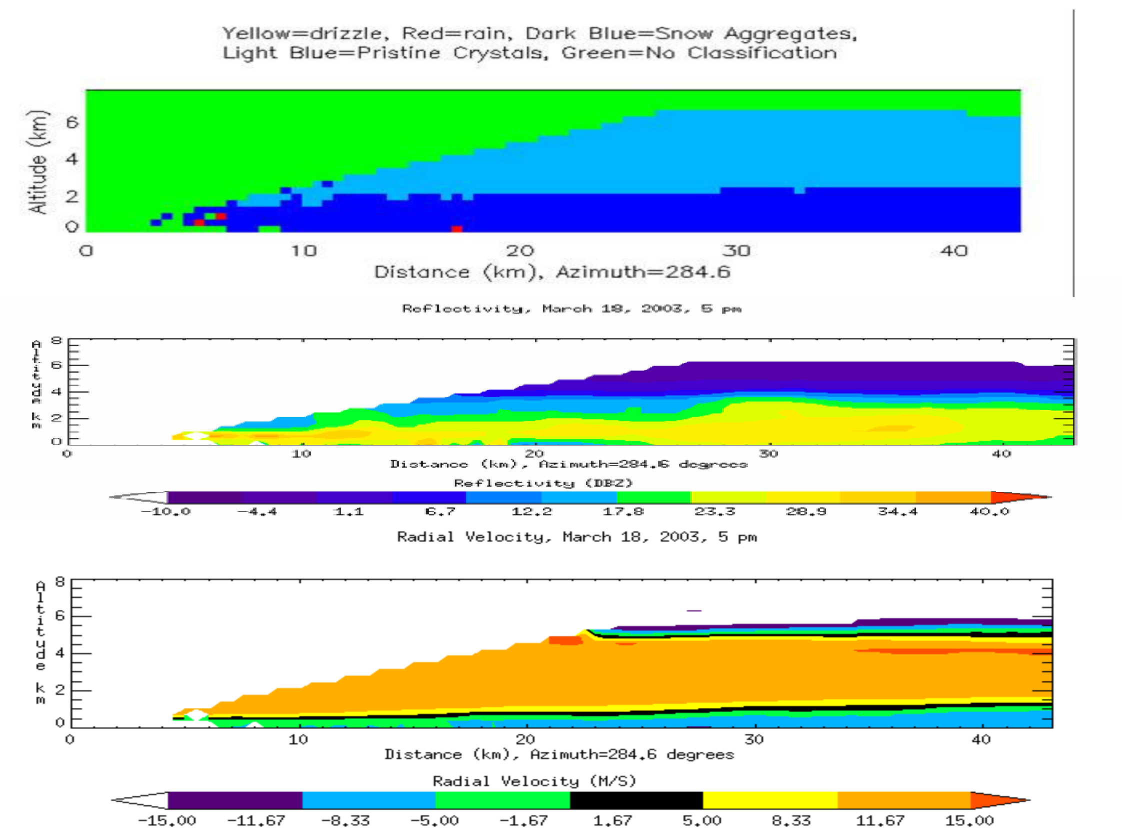

Figure 8. As in Figure 7 but for 23 UTC 18 Mar 2003.