THE SIMULATION OF PRECIPITATION IN CONVECTIVELY STABLE ENVIRONMENTS

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1. Introduction

The formation of clouds and precipitation within convectively stable environments is an important process to capture accurately in mesoscale models, since it constitutes the majority of precipitation in the mid-latitude cold season. In addition, the primary dynamical mechanisms by which such precipitation is formed (i.e., baroclinically forced upward motion, in conjunction with orographic enhancement in some locations), are inherently both more predictable, and more amenable to in situ observational study, than convective precipitation. Thus, precipitation within convectively stable environments is not only a necessary subject of study, but offers an opportunity for successful field observation and verification of the representation of this process in bulk microphysical parameterizations (BMPs) that are used in mesoscale and cloud-scale numerical models. This was the motivation for the IMPROVE field project (Stoelinga et al. 2003), carried out in 2001 in the Pacific Northwest, in which stable precipitation environments were studied with and without orographic forcing.

Initial analysis and MM5 model simulations of IMPROVE case studies has yielded promising results and identified concrete areas of potential improvement in the single-moment, mixed phase (including graupel) BMP that is currently used in the MM5 [the "Reisner-2" scheme, described in Reisner et al. (1998) and Thompson et al. (2004)]. At the same time, these investigations have also illustrated the vast complexity and enigmatic behavior of BMPs, and the challenging task of verifying the many interacting processes represented therein. This talk will present examples of both the "promising results" and "enigmatic behavior". It will also present a few examples of other important and interesting precipitation-related phenomena that have emerged from analysis of the rich observational data set gathered during IMPROVE. All of the results presented here will soon be published by the cited authors in a special issue of the *Journal of the Atmospheric Sciences* devoted to IMPROVE.

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2. BMPs: complexities and contradictions

One consistent problem that is emerging is the inability of the BMP to hold relative humidity near ice saturation in middle to upper tropospheric regions where upward vertical velocities are moderate (~10s of cm s^{-1}). Locatelli et al. (2004) discuss such a situation in the case of an offshore upper cold-frontal rainband on 1-2 February 2001. Ahead of the upper front, in the region of strongest updraft, which is only ~30 cm s^{-1} in this coarse-grid (36-km) simulation, the model maintains near-water-saturated conditions at temperatures as cold as -25 °C (Fig. 1), even though ice particles are plentiful. The model also produces liquid water cloud in this same region, which is contradicted by observations. Several recent studies (Lin et al. 2002; Ström et al. 2003)

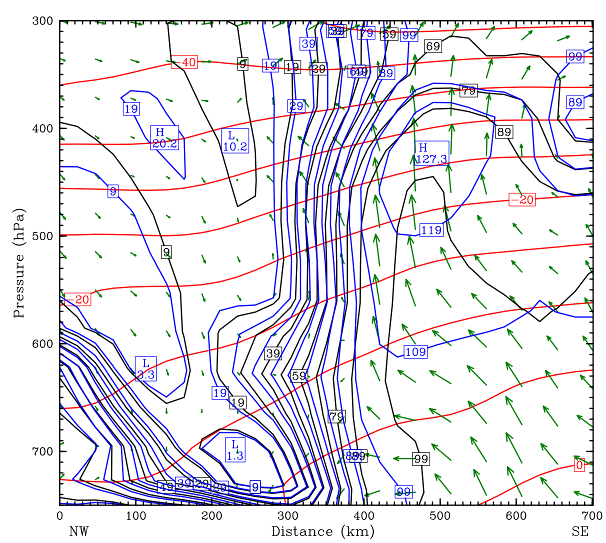

Figure 1. Vertical cross section through model-simulated upper cold front and rainband at 0800 UTC 1 February 2001, showing temperature (red contours), RH w.r.t. liquid water (black contours), RH w.r.t. ice (blue contours), and front-relative circulation (green vectors, maximum upward motion = 30 cm s^{-1}). From Locatelli et al. (2004).

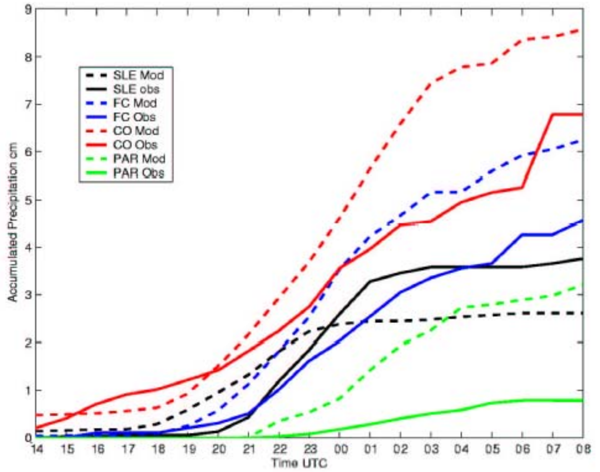

Figure 2. Accumulated precipitation at various sites from both observations (solid lines) and a 1.3-km model simulation (dashed lines), starting at 1400 UTC 13 December 2001. SLE: Salem, OR (upstream of Cascades); FC: Falls Creek, OR (windward slope); CO: Corbett, Oregon (immediate lee of crest); PAR: near Sisters, OR (lee side). From Garvert et al. (2004).

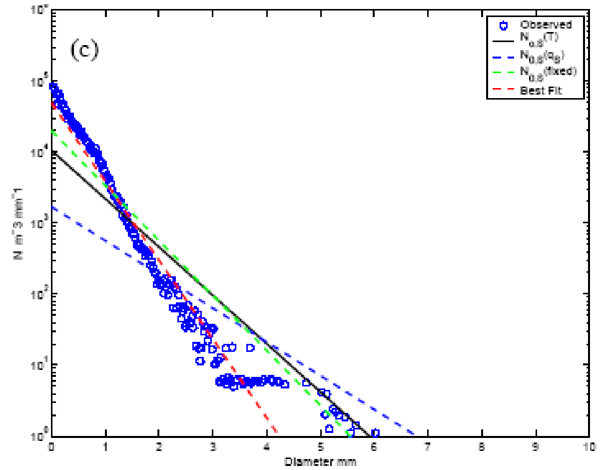

Figure 3. Snow particle size distribution measured by the Convair-580 research aircraft along an ~80 km flight leg over the Oregon Cascades on 13 December 2001 (from Woods et al. 2004). Red dashed line shows best fit, whereas other lines show model-predicted size distributions for different experiments in which the formulation for the intercept parameter N_0, varied. From Colle et al. 2004.

have also shown that upper-tropospheric clouds with moderate ascent are able to lower relative humidity to ice saturation shortly after ice is initiated.

Such a behavior in the BMP might arise from an underprediction of vapor deposition, and thus might be accompanied by an underprediction of snow aloft (assuming a correct vertical velocity field). However, in another IMPROVE case in which an upper-level frontal band passed over the Oregon Cascade range on 13-14 December 2001, the same behavior of overpredicted relative humidities in the upper troposphere occurred, but were accompanied by an *overprediction* of snow mass concentration in that region (Garvert et al. 2004). This suggests that the model may have been overpredicting the large-scale vertical velocities aloft, one of the most challenging aspects of a model to verify.

Another contradictory result from the 13-14 December case is the distribution of simulated precipitation across the barrier. Previous studies of MM5 model behavior in the Cascade Range have consistently showed a tendency for the model to overforecast windward-side precipitation and underforecast lee-side precipitation (Colle and Mass 2000; Colle et al. 2000). Colle and Mass (2000) explored the potential benefits of using a slower snow fall speed for reducing this bias. However, in the 13-14 December case, while the model did overpredict the windward-side precipitation, it overpredicted the lee-side precipitation by an even greater amount (Fig. 2). Application of a slower fall speed (Colle 2004) did not eliminate the windward overprediction, and exacerbated the lee-side overprediction.

3. Room for IMPROVEment

In spite of the complexities discussed above, IMPROVE research thus far has been successful in narrowing the focus of the search for the most significant problems in the MM5's BMP. For example, measured size distributions of snow particles within the cold, upper portion of the precipitating cloud in the 13-14 December case appear to follow an approximately exponential size distribution (e.g., Fig. 3) at multiple vertical levels within the storm (Woods et al. 2004), lending confidence to the BMP's assumed exponential size distribution. Where there is need for improvement is in the specification of the slope and intercept parameters of the size distribution. For example, the temperature-dependent intercept parameter used in the BMP excessively broadens the size distribution at colder temperatures, in effect, over-simulating the effects of aggregation (Colle et al. 2004).

A useful tool that has emerged from IMPROVE-related work is the microphysical budget approach employed by Colle and Zeng (2004) and Colle et al (2004). With this approach, the net affect of each microphysical mass transfer process is averaged over a finite time period and model subdomain, yielding a budget that clearly indicates the most important processes (Fig. 4) of precipitation growth within the specified orographic upslope region. Note that of the 23 different processes included in the BMP, only 10

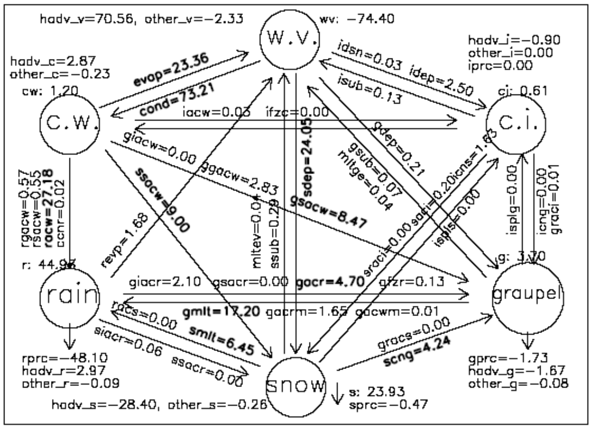

Figure 4. Total mass transfers among the various hydrometeor species via the 23 microphysical processes during a simulation of the 13-14 December 2001 event. Values are averaged over the a subdomain in the upslope zone, and are normalized by the total water vapor loss in that subdomain. From Colle et al. (2004).

of those are responsible for a significant transfer of mass between hydrometeor species, and only 4 transfer >20% of the total water vapor loss within the budget domain. This method illustrates that the number of degrees of freedom of the BMP are considerably less than implied by the total number of available processes, and focuses analysis on the few processes that are key.

4. Other interesting phenomena

In addition to providing observations for direct comparison with model output, the rich data set gathered during IMPROVE, which included ground-based and airborne radar observations, has provided insight into unique precipitation-related phenomena. Two examples are shown here.

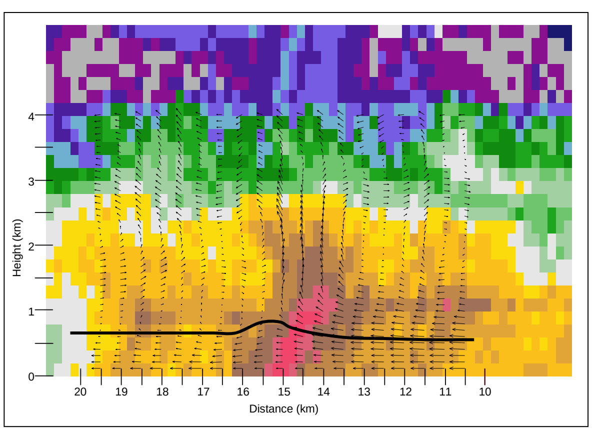

Figure 5. Radar reflectivity from an RHI scan of the NCAR S-Pol radar, and single-Doppler-derived circulation vectors, in a vertical cross section normal to a narrow cold frontal rainband on 2 February 2001. The heavy black line represents a limiting streamline separating incoming air that rises at the front from incoming air that passes beneath the front.

During the 1-2 February offshore case discussed above, a secondary cold front passed through the radar study area, with an associated narrow cold frontal rainband (NCFR, James and Browning 1979; Hobbs and Biswas 1979). A unique aspect of this NCFR, however, was the fact that it was associated with a cold front above the surface. In a single-Doppler wind retrieval from this approximately 2-D feature (Fig. 5), two air streams approaching the front and rainband can be identified, separated by a limiting streamline. An upper airstream approaches the front and then rises rapidly in a precipitation-producing updraft, as in a conventional NCFR. However, a lower airstream also approaches the front, but rises only slightly and then subsides again as it passes underneath the front and continues rearward along the surface. This unique NCFR structure is currently being analyzed further.

In another example, on 28 November 2001, a unique set of polarimetric radar measurements were obtained for a case of multiple melting layers in association with the passage of a warm front in the Willamette Valley, Oregon (Fig. 6). Using the polarimetric measurements, Ikeda et al. (2004) were able to infer characteristics of the hydrometeor habits and behavior in the vicinities of the two melting layers.

5. Conclusions

The unique data set gathered during the IMPROVE field projects in 2001, and associated mesoscale model simulations and tests, has provided insights into key areas in which the MM5 model's bulk microphysical parameterization is not behaving properly in simulations of stable precipitation environments, and has also

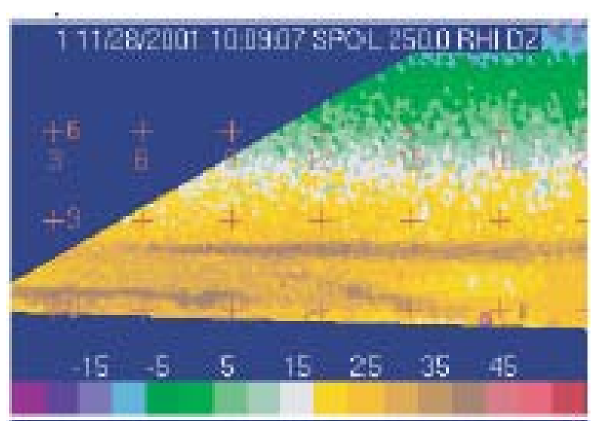

Figure 6. Radar reflectivity from an RHI scan of the NCAR S-Pol radar on 28 November 2001, showing multiple melting bands, at ~0.8 km and ~2.2 km MSL. From Ikeda (2004).

illustrated the complex and enigmatic behavior of these schemes. In addition, the rich data set gathered during IMPROVE has provided opportunities to observe and analyze unique precipitation-related phenomena.

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