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ON THE REPRESENTATION OF SNOW IN BULK MICROPHYSICAL PARAMETERIZATION SCHEMES

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1. Introduction

Of the various hydrometeor species represented in bulk microphysical schemes used in mesoscale models, snow is perhaps the most important in cold-season precipitation events, since virtually all precipitation that reaches the ground in any form derives either directly or indirectly from snow particles. Unfortunately, snow has arguably the most complex array of interactions with other hydrometeor types, and is also the least straightforward particle to represent with simple assumptions about shape, density, and size distribution. Thus the challenge to represent snow particles properly in bulk microphysical schemes is acute.

For these reasons, we have focused our attention on assessing the fidelity of the assumptions about snow particles in a typical bulk parameterization scheme (the Reisner-2 scheme developed for the MM5 model), and on testing the sensitivity of that scheme to refinements in the representation of snow. This paper will discuss current typical assumptions about snow in bulk schemes, and discuss the model sensitivity to reasonable changes in those assumptions. Based on our findings we will argue for the potential benefits of including at least a rudimentary prognostic or diagnostic determination of dominant snow particle habit in a bulk scheme.

2. Snow particles in current bulk schemes

The characterization of snow particles in bulk schemes is typically highly simplified. The bulk scheme that is commonly used in the MM5 Mesoscale Model (and is now available in WRF) is the single-moment, mixed-phase scheme described by Reisner et al. (1998) and Thompson et al. (2004). The assumptions about snow particles in this scheme derive heavily from the Rutledge and Hobbs (1984) bulk scheme, and are typical of the assumptions in many schemes that are currently used in research and operational models.

As a single-moment scheme, the Reisner-Thompson (R-T) scheme predicts only the mixing ratios of the various hydrometeor species (q_s, for snow). Snow particles are assumed to be spheres of constant density, and their size distribution is assumed to follow an exponential form:

$$\hat{N}(D) = N_{0s}\exp(-\lambda_s D), \qquad (1)$$

where $\hat{N}$ is the number of particles per unit volume per unit size range and D is the maximum dimension of a particle. In earlier incarnations of the R-T scheme, the intercept parameter (N_{0s}) was held constant, but is now diagnosed from other prognostic variables in the model. Once the intercept is known, the slope parameter (λ_s) is uniquely determined by combining (1) with the assumption of constant-density spheres and integrating over all sizes to obtain the total mass concentration. This yields an expression for the slope parameter:

$$\lambda_s = \left(\frac{\pi N_{0s}\rho_{\text{snow}}}{\rho_{\text{air}} q_s}\right)^{1/4} \qquad (2)$$

where ρ_{snow} and ρ_{air} are the densities of snow particles and dry air, respectively. More sophisticated "double-moment" schemes predict the total number concentration of snow particles, which then uniquely determines both the intercept and slope parameters. However, the issues discussed here are still relevant.

Both N_{0s} and λ_s are extremely important quantities for the microphysical scheme, because they enter into nearly every production term involving snow. Furthermore, the expression for λ_s is directly dependent on the assumption of spherical particles of constant density. Therefore, it is reasonable to anticipate potential benefits of adding a modest level of sophistication to the highly simplified assumptions about snow particles. Even if one were to stick with an assumption that all snow particles are the same shape and density, an important initial question is whether the current assumption (snow particles as spheres of density, $\rho_{\text{snow}} = 100\ \text{kg m}^{-3}$) represents a reasonable "mean" for true snow particles. Beyond that question, it is of interest to ascertain the sensitivity of microphysical growth processes to different choices for snow particle shapes and densities that are indicated by observations of natural snow particles.

3. Mass-diameter relationships

Numerous observational studies of snow particles have yielded power-law relationships between the mass of snow crystals and their diameter (Mitchell 1996), of the form

$$m = a_m D^{b_m}. \qquad (3)$$

The empirically derived constants a_m and b_m differ significantly for different snow crystal habits. Table 1 shows the values of these constants for a few different commonly occurring snow crystal habits, as determined from the Locatelli and Hobbs (1974) observational study.

Habit	a_m (mg mm^{-bm})	b_m
Dendrites	0.0141	2.19
Cold-type	0.0370	1.90
Needles	0.0092	2.01
Columns	0.0450	3.00
Model spheres	0.0520	3.00

Table 1. Constants in the mass-diameter power-law relationships for different particle habits, as reported by Locatelli and Hobbs (1974) (except for "model spheres"). Note, relationships were derived from samples that included both single crystals and aggregates of the indicated habit.

The assumption of constant-density spheres in the bulk scheme also implies a mass-diameter power-law relationship, of the form $m = \rho_{\text{snow}}(\pi/6)D^3$. The implied values of a_m and b_m for this assumption are also shown in Table 1. The value of a_m is high compared to the range of values for the naturally occurring habits. Perhaps more importantly, while the spherical assumption implies $b_m = 3$, most of the actual crystal habits have b_m much closer to 2. This means that natural crystals (and aggregates thereof) tend to grow much more two-dimensionally than three-dimensionally. In other words, they increase their maximum dimension more rapidly for a given mass growth rate, compared to the fictitious spherical particles. This has important implications for all growth processes involving snow.

Using the general form of the mass-diameter relationship (rather than the assumption of constant-density spheres), a more general form of (2) can be derived:

$$\lambda_s = \left(\frac{a_m N_{0s} \Gamma\left(b_m + 1\right)}{\rho_{\text{air}} q_s} \right)^{1/(b_m+1)} . \qquad (4)$$

Since λ_s depends on both a_m and b_m, it is of interest to investigate the sensitivity of λ_s (and ultimately the entire microphysical scheme) to the various values of a_m and b_m listed in Table 1. A starting point is to plot the size distributions implied by these different mass-diameter relationships, assuming the same total mass concentration of snow and intercept parameter (Fig. 1). It is clear that the assumption of constant-density spheres yields a slope that is steeper than any of the empirically derived mass-diameter relationships for various commonly occurring classes of particle habit. Thus, from this perspective, the assumption of constant-density spheres does not represent a proper "mean" characteristic of snow particles.

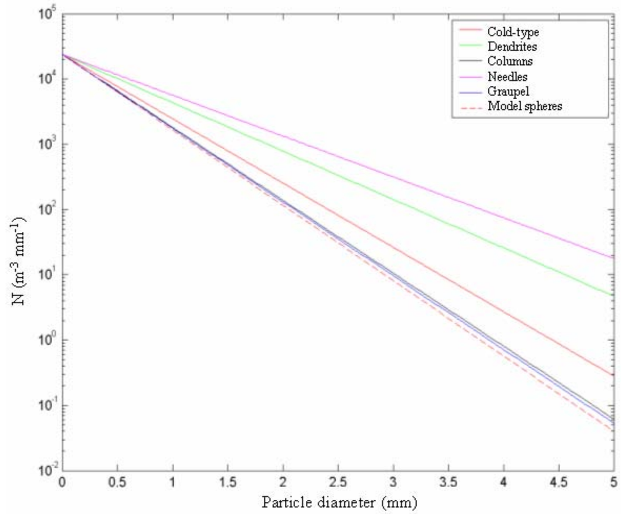

Figure 1. Exponential size distributions for various empirically derived mass diameter relationships, using the same values of intercept and mixing ratio.

4. Fallspeed-diameter relationships

Another important aspect of the bulk scheme is that it assigns to each class of hydrometeors a single terminal fallspeed, namely, the mass-weighted terminal fallspeed, $\bar{V}$. The value of $\bar{V}$ affects not only the fallout of snow, but also collection and depositional growth terms. Calculation of the mass-weighted mean terminal fallspeed requires both a mass-diameter relationship and a fallspeed-diameter relationship. Similar to the mass-diameter relationship, observational studies have yielded fallspeed-diameter relationships of the form

$$V = a_v D^{b_v} , \qquad (5)$$

where different particle habits are associated with different values of the constants a_v, and b_v. The general mass-weighted mean fallspeed is obtained by multiplying (1) by the diameter-dependent expressions for mass and fallspeed [(3) and (5)] and integrating over all sizes. The resulting expression for mass-weighted fallspeed is

$$\bar{V} = \frac{a_{\text{v}} \Gamma\left(b_{\text{m}} + b_{\text{v}} + 1\right)}{\lambda_s^{b_{\text{v}}} \Gamma\left(b_{\text{m}} + 1\right)} \qquad (6)$$

Note that $\bar{V}$ depends on all four constants, a_m, b_m, a_v, and b_v. Thus, the mean fallspeed is sensitive not only to the habit-specific fallspeed relationship chosen,

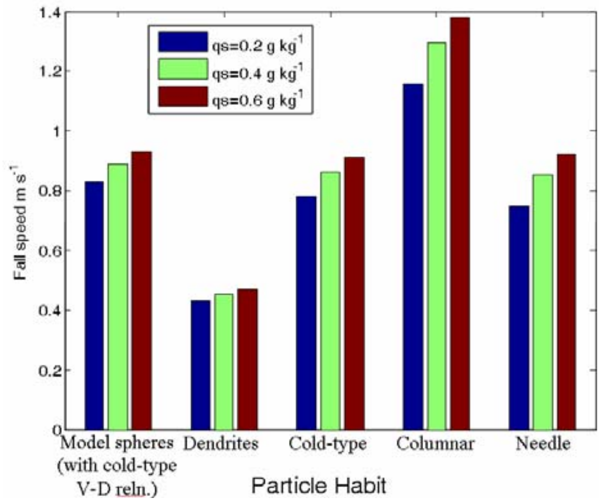

Figure 2. Mass-weighted mean fallspeeds of snow, using the mass-diameter and fallspeed-diameter relationships for the indicated particle habits, for three different values of mixing ratio..

but also the habit-specific mass-diameter relationship chosen. Figure 2 shows, for a constant value of N_{0s}, how $\bar{V}$ varies as a function of particle type and snow mixing ratio. The R-T bulk scheme inconsistently uses the mass-diameter relationship for constant-density spheres but the fallspeed-diameter relationship for cold-type crystals from Locatelli and Hobbs (1974), a common procedure in many bulk schemes. Also shown are the results for fallspeed derived by consistently using both the mass-diameter and fallspeed-diameter relationships for the same snow particle habit, for certain commonly occurring snow habits. While the differences are small between the model assumption and the fully consistent approach for cold-type and needle-type snow particles, the differences become more significant for dendritic snow particles (-50%) and columnar snow particles (+50%). Therefore, it appears that making greater use (and more consistent use) of the empirically derived mass-diameter and fallspeed-diameter relationships in the bulk scheme could lead to significant improvements in the snow microphysics.

5. A case study

We performed a model simulation of a wide cold-frontal rainband that approached the Washington coast on 1-2 Feb 2001 (described in detail by Evans et al. 2005). This storm was chosen for investigation since fairly complete measurements were obtained of the storm's microphysical structure at various levels within the precipitation band. It is a good test case because the microphysical processes were relatively simple, steady state, and well documented by observations. A snapshot of the 12-km control model simulation (using the standard bulk scheme issued with version 3.7 of the MM5 model) is shown in Fig. 3.

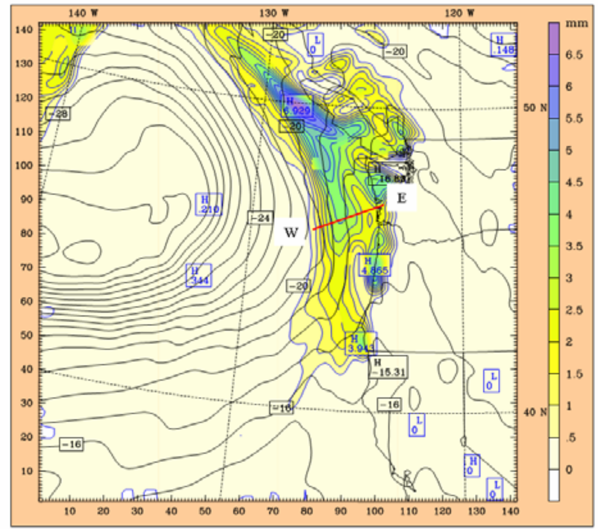

Figure 3. 12-h forecast of 1-h accumulated precipitation (color contours), valid at 00 UTC 2 February 2001.
Black contours are temperature at 600 hPa.

We ran a sensitivity test in which the constant-density sphere assumption was replaced by the mass-diameter relationship for cold-type crystals from Locatelli and Hobbs (1974), so that it is consistent with the fallspeed-diameter relationship used in the scheme. Figures 1 and 2 indicate that this is among the least drastic changes that could have been chosen. One of the primary changes in the modified simulation was the reduction of the relative humidity with respect to ice to values more reasonable for stratiform cold clouds (as discussed by Locatelli et al. 2005), in the region of the primary snow band near 600hPa (Fig. 4). This resulted from more efficient removal of excess water vapor aloft, (i.e., increased depositional growth), most likely from both a reduction in the mass-weighted terminal fallspeed of snow under the new mass-diameter assumption, as well as a decrease in the slope of the mass distribution which acts to enhance depositional growth. The increased efficiency of depositional growth within the primary band also acted to limit the vertical extent of the cloud water field compared to the control run (Fig. 4). This led to a decrease in graupel (though reduction in the riming of snow and collection of cloud water by graupel) immediately below the main snow band, which is more consistent with observations than the control, as there was a lack of observational evidence for graupel in this region (Evans et al. 2005).

6. Continuing studies

Our analysis and modeling of cases observed during the IMPROVE field experiment (Stoelinga et al. 2003) indicate further potential modifications and improvements to the bulk scheme, which we are currently studying.

- The apparent sensitivity of the microphysical scheme to reasonable variations in mass-diameter and fallspeed-diameter relationships (consistent with the variability among natural snow particles) suggests the potential benefit of including at least a rudimentary prediction or diagnosis of particle habit, and then using relationships consistent with the predicted/diagnosed habit.

- Observations indicate that λ_s correlates better with temperature than does N_{0s}. Therefore, it may make more sense to diagnose λ_s from temperature and then calculate N_{0s}, rather than the other way around (as is currently done).
- Our observations from IMPROVE case studies also indicate that ice multiplication processes need to be accounted for not just in the cloud ice field, but in the snow size distribution, whereby an infusion of small particles noticeably steepens observed particle size distributions.

7. Conclusions

There are several assumptions about snow particles in the current Reisner-Thompson bulk microphysical scheme used in the MM5 and WRF models that are either over-simplistic, inconsistent among different aspects of the scheme, and/or not representative of characteristics of naturally occurring snow particles. These assumptions include the treatment of snow particles as spheres of constant density, and the use of a single fallspeed formula that applies to only one particle habit. Improvements in precipitation forecast may be realized if consistent, habit-dependent relationships for the dependence of particle mass and fallspeed are implemented.

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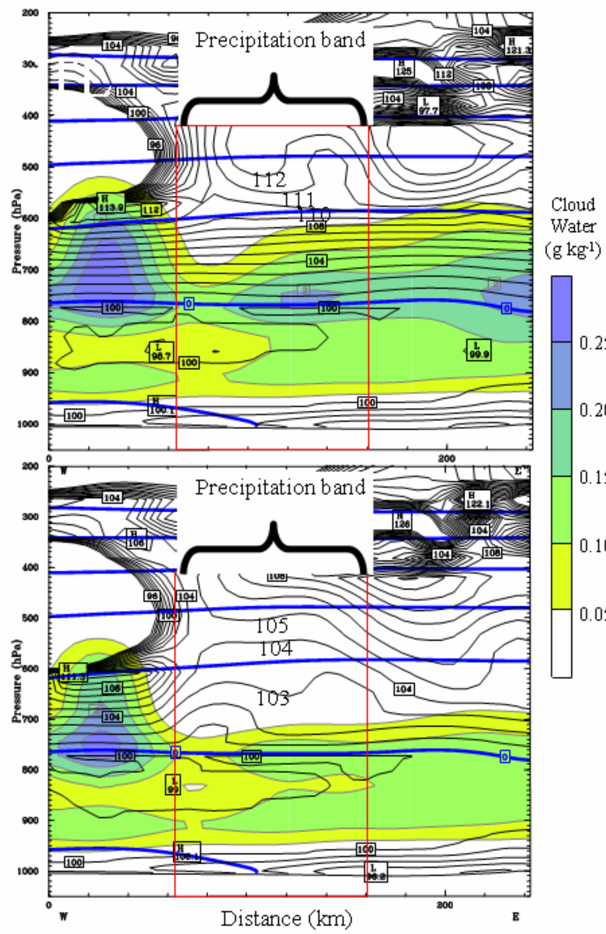

Figure 4. Cross section along line W-E in Fig. 3, of RH w.r.t. ice (black contours) and cloud water (color contours). Top panel is control, bottom panel is test with mass-diameter and fallspeed-diameter relationships for cold-type crystals.

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