A new unified mixed-phase particle fall speed in bulk microphysics parameterizations

Jimy Dudhia, Song-You Hong*, and Kyo-Sun Lim*

Mesoscale and Microscale Meteorology Division/National Center for Atmospheric Research, Boulder, Colorado, USA
*Department of Atmospheric Sciences, Yonsei University, Seoul, Korea

1. Introduction

Bulk microphysical parameterizations that represent mixed-phase processes divide particles into categories such as snow and graupel or hail. The distinction between these is in the primary habit of the particles, where snow is assumed to be unrimed ice crystals or aggregates of crystals that have predominantly grown by deposition of ice, while graupel and hail have grown mostly by collection of water droplets, and are therefore denser and rounder than the snow category.

This distinction is important in numerical models because the density of the particles affects process rates, and particularly the fall speed of the particles that in turn affects cloud structure and precipitation intensity.

In reality, of course, there is no such clear distinction between snow and graupel in clouds, and there are many degrees of riming between these extremes. By labeling particles as either snow or graupel, bulk schemes are unable to represent this continuum of habits, and, due to the assumptions about these habits there is a partitioning in behavior that is not likely to be so well defined in nature. Probably the most extreme difference would be due to the factor of two or three in the assumed fall speeds for a given mass content as graupel has a much greater density (further enhanced for hail). This difference in turn leads to a separation of trajectories of snow and graupel within the same modeled cloud, even when they have the same origin.

In this paper, we introduce a simple method to alleviate the problem of species separation by revising the paradigm that a particle is either graupel or snow, particularly in the treatment of its fall speed, and hence trajectory, thus preventing a false separation and enhanced accretion due to their relative sedimentation rates.

2. Modifications to the WSM6 scheme

The underlying new assumption introduced in this paper is that graupel and snow that inhabit the same grid box have the fall properties of an intermediate (partially rimed) particle that is weighted by the snow and graupel contents of the grid box. The basis of this assumption is that riming does not affect select snow particles in a grid box, turning just those into graupel and leaving other snow particles unaffected. Instead riming affects all snow particles equally, and it is therefore unrealistic to treat any affected particles as pure snow (likewise pure graupel), but more realistic to treat all particles equally, and as rimed to the same degree, at least in terms of the mass-weighted fall speed applied. We treat all the particles as hybrid lightly-rimed particles with a single weighted fall speed, which we regard as more realistic given the common histories of these particles.

Fig. 1. Mass weighted terminal velocity (ms⁻¹) as a function of graupel and snow amount with the assumption of the temperature at -10 °C

Given this assumption, the mass-weighted velocity for both species can be expressed as
where the subscripts \( s \) and \( g \) denote snow and graupel. The new velocity as a function of graupel and snow amount is seen in Fig. 1.

The modified scheme proposed here therefore has two major components, (i) a new mass-weighted fall speed, and (ii) modified accretion rates including elimination of snow-graupel accretion.

The benefit of such a scheme is that as riming begins, the snow/graupel weight is more towards snow, and the fall speed is more like snow, but as riming completes, the mixture transitions towards a graupel fall speed. This is perceived as giving a more realistic evolution of the bulk properties of the cloud than the bimodal fall speed distribution and consequent gravitational species separation inherent in current bulk schemes.

### 3. Numerical experimental setup

Two sets of experiments were carried out using an idealized 2D thunderstorm case, a 3D real-data simulation for a heavy rainfall (snowfall) event over Korea. The model used in this study is the Advanced Research WRF (ARW; Skamarock et al. 2005) version 2.1.2, which was released in January 2006.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp1</td>
<td>WSM6 microphysics (current option in version 2.2)</td>
</tr>
<tr>
<td>Exp2</td>
<td>Replacing the sedimentation velocities for snow and graupel to new ones</td>
</tr>
<tr>
<td>Exp3</td>
<td>Replacing the accretion terms by using the new velocities for snow and graupel</td>
</tr>
<tr>
<td>Exp4</td>
<td>Combined effect of the sedimentation and accretions (Exp2 + Exp3)</td>
</tr>
</tbody>
</table>

Four experiments are designed as summarized in Table 1 for each set. Exp1 is the current WSM6 scheme in WRF. Exp2 replaces the sedimentation velocities of snow and graupel with the new ones from Eq. (1). Exp3 alters only accretion terms with the new velocities. The accretion of snow by graupel (Pgacs) is also taken out in Exp3. Exp4 considers both effects from Exp2 and Exp3.

The experiments for a heavy rainfall were carried out for 24 h, from 0000 UTC July 14 to 0000 UTC July 15, 2001. The experimental setup for snowfall is the same as that in the summer case, except for the simulation time of 36 h starting at 00 UTC March 4, 2005.

### 4. Results and discussion

a. **Idealized experiments**

The general structure of the thunderstorm, such as the cloud droplets and ice particles near the storm center, is well simulated. Cloud condensate reaches a maximum in the middle troposphere in the area of the updraft for both experiments. Apparently, these basic features of the simulated storm are unchanged from Exp1 to Exp4, but it is seen that in Exp4 the amount of cloud ice is reduced, as compared to that in Exp1 (Figure 2).

![Fig. 2. Isolines of the condensation fields for cloud particles (first low), cloud ice (\( q_i \); shaded), cloud water (\( q_c \); solid), and for precipitable particles (second row), rain (\( q_r \); shaded), snow (\( q_s \); short dashed) and graupel (\( q_g \); long dashed), from (a) Exp1, and (b) Exp4 experiments. Contour lines are at 0.01, 0.02, 0.04, 0.08, 0.16, 1.28, 2.56, 5.12, and 10.24 g kg\(^{-1}\).](image)

The vertical profiles of differences of Exp2, Exp3, and Exp4, from Exp1, in the time-domain-averaged condensates are plotted in Fig. 3. It is seen that replacing the sedimentation velocity for snow and graupel decreases (increases) the amount of snow (graupel) in the middle-upper atmosphere from 6 km to 13 km, where both species coexist (Fig. 3a). The reduction (increase) of snow (graupel) is due to the enhanced (reduced)
sedimentation rate due to the newly combined terminal velocity for snow and graupel, as compared to the profiles with the conventional fall speeds. A more distinct impact is found by the changes in the accretion terms due to the new combined velocity (Fig. 3b). The increase of snow and decrease of graupel are pronounced. Among the changed microphysics terms, the removal of snow-graupel accretion (pgacs) was found to be a major factor in accounting for the changes in hydrometeors. Reduction of graupel at the melting level brings about a reduced rainfall conversion from graupel, which leads to the decrease of surface rainfall during this phase of the convective system. Both sedimentation and accretion processes due to a new combined terminal velocity tend to offset, but the latter effect is more pronounced (Fig. 3c).

**b. Heavy rainfall (snowfall) event**

Figure 4 shows the results of the simulated precipitation obtained from the heavy rainfall and snowfall experiments. We can see that the results from the Exp1 and Exp4 do not show significant differences in the distribution of precipitation. For the wintertime snowfall case, the distribution of snowfall covering the Korean Peninsula is well reproduced by both experiments. The pattern correlation coefficients are similar for Exp 1-4 (not shown). The resulting impacts of the changes in sedimentation and accretion processes on the simulated precipitation comply with the behaviors analyzed in the 2D thunderstorm case. For example, the changes in sedimentation do not affect the resulting precipitation, but the amount of precipitation is decreased by the modified accretion processes with the new terminal velocity, which is closer to what was observed.

![Figure 3](image1.png)

**Fig. 3.** Vertical distribution of the differences in the domain-averaged water species from Exp1 during the 60 min integration period, (a) Exp2 minus Exp1, (b) Exp3 minus Exp1, and (c) Exp4 minus Exp1 experiments. Units are gkg⁻¹ for rain, snow, and graupel, and 10gkg⁻¹ for cloud ice and cloud water.

![Figure 4](image2.png)

**Fig. 4.** 24-hr accumulated precipitation (mm) ending at 0000 UTC 15 July 2001, from (a) Exp1, and (b) Exp4, and 36-hr accumulated precipitation (mm) ending at 1200 UTC 05 March 2004, from (c) Exp1, and (d) Exp4 experiments. Contour lines in (c) and (d) indicate the percentage of precipitation due to snow. Results are obtained with the 5-km grid interval experiments.

Figure 5 compares the vertical profiles of averaged condensates over the heavy precipitation region centered in Korea. The results from Exp1 and Exp4 produce similar profiles for ice, clouds, and rain, but not for snow and graupel, as was also seen in the idealized experiments. In both cases, increased snow and reduced graupel are the dominant differences through the entire atmosphere in Exp4. The new scheme induces a more realistic surface precipitation type, with more snow than graupel contributing to the surface precipitation (cf. Figs. 5c and 5d) in the snowfall case.

Scatter plots of mixing ratios of graupel and snow over the heavy precipitation region are shown in Fig. 6. These show that the graupel and snow change from uncorrelated fields to correlated ones because of their unified fall speeds, and that in both these cases, all snow is affected to some degree by riming, because no significant amounts of pure snow remain. In the summer case, the typical ratio of snow to...
graupel from Fig. 6b is around 1:1, while in the winter case (Fig. 6d) it increases to 3:1, which is a measure of the relative degrees of riming between these cases. The original scheme, on the other hand, had higher average ratios of graupel to snow in both cases, but no well-defined ratio.

Fig. 5. Vertical distribution of water species, obtained from (a) Exp1 and (b) Exp4, averaged over the heavy rainfall region (32.3-41.2 N, 121.5-131.3 E) during the 24-h hrs, the results from the heavy snowfall simulation during the 36-h hrs, (c) Exp1 and (d) Exp4, averaged over the heavy snowfall region (34.0-36.5 N, 125.2-128.4 E). Results are obtained with the 5-km grid interval experiments.

Fig. 6. Scatter plots of $q_g$ versus $q_s$ averaged over the heavy rainfall region (123-129E, 35-38N) during the 24-hr simulation period, obtained from (a) Exp1 and (b) Exp4, and the corresponding results obtained for the snowfall experiments, (c) Exp1 and (d) Exp4, over the heavy snowfall region (125-131E, 35-39.5N) during the 36-hr simulation period. The plotted points in the figures are the values in overlapping layer of $q_g$ and $q_s$ from 600 hPa to 100 hPa for the heavy rainfall, and from 1000 hPa to 400 hPa for the heavy snowfall case. Results are obtained with the 5-km grid interval experiments.

5. Concluding remarks

A new method has been introduced of handling partially rimed species within the framework of an existing simple single-moment bulk microphysical scheme. This scheme is designed to alleviate the effects of the separation of precipitating ice particles into distinct rimed graupel and unrimed snow categories with clearly defined properties and fallspeeds. The method used is to merge the categories by mass-weighting the fallspeeds and modifying accretion rates consistently, which has the effect of treating all the particles in an intermediate way with a dependence on their degree of riming.

The experiments have shown a potential to reduce a previous precipitation high bias in WSM6 due to the reduced production of graupel. Furthermore the surface precipitation type in a winter snowstorm case was more realistically simulated with the new scheme. A systematic underestimation of snow and overestimation of graupel in the WSM6 that was indicated by the previous studies (e.g., Lin et al. 2006, WRF workshop, Tao et al. 2007, in review in Mon. Wea. Rev.) is expected to be alleviated by the introduction of the new falling velocity. Modifications to the hydrometeor distribution in the atmosphere could also be important for comparisons with remote sensing data and for cloud data assimilation.

The content of this paper is based on the study of Dudhia et al. (2008, J. Meteor. Soc. Japan, in press), and the new unified velocity proposed in this study was announced in WRF version 3.0.

Acknowledgements

This research was supported by the Korean Foundation for International Cooperation of Science & Technology (ICOS) through a grant provided by the Korean Ministry of Science & Technology (MOST) in 2007.