Improvements to a Commonly Used Cloud Microphysical Bulk Parameterization

BRIAN E. POTTER

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

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1. Introduction

The cloud microphysical bulk parameterization described by Lin et al. (1983) (hereafter, LFO) has found some acceptance as a reliable and accurate model, and a number of other researchers (Rutledge and Hobbs 1984; Marwitz 1987; Fovell and Ogura 1988; Proctor 1988; Dudhia 1989) have implemented it in their own work. While the model has become more complex, the basic structure and assumptions have remained the same.

In using LFO's parameterization in my own work, I have encountered two inconsistencies in the basic assumptions that merit note. They appear to have some effect on model results and should be corrected in the interest of accuracy and consistency.

2. Distribution functions for snow and graupel/hail

LFO cite the findings of Gunn and Marshall (1958) regarding the size distribution of snow particles. The latter represent this distribution in the form:

$$N_x(D_x) = N_{0x} \exp(-\lambda_x D_x) \qquad (1)$$

where x is used to indicate either snow or graupel, $N_x(D_x)$ is the concentration of particles of diameter D_x per unit size interval, N_{0x} the intercept, and λ_x the slope of the particle distribution function. LFO interpret D_x as the dimension of the still frozen ice particle, while Gunn and Marshall (1958) use it to indicate the diameter of the water drop formed when the ice particle melts (i.e., the so-called equivalent drop diameter). Following Gunn and Marshall's terminology, the total mass of the substance x per unit volume of air is

$$\rho q_x = \int_0^\infty N_{0x} \exp(-\lambda_x D_x)(\pi D_x^3 \rho_w/6) dD_x \qquad (2)$$

where ρ is the density of air, q_x the mass mixing ratio of the ice category, and ρ_w the density of water. Note, the density of the particle should be that of water, rather than that of snow or graupel/hail, as was used by LFO.

Assuming N_{0x} is constant (as LFO did), solving the integral in (2) yields:

$$\rho q_x = \pi \rho_w N_{0x} \Gamma(4)/(6\lambda_x^4),$$

or

$$\lambda_x = (\pi \rho_w N_{0x}/\rho q_x)^{1/4}, \qquad (3)$$

where Γ is the gamma function. The form of (3) obviates the need to guess a density for snow, graupel, or hail.

Citing Gunn and Marshall (1958), LFO take N_{0x} to be 3×10^{-2} cm^{-4}. However, Gunn and Marshall provide only a relationship between N_{0x} and the rain rate. The choices of which parameter, N_{0x} or λ_x, to hold constant, and what value to assign these parameters, should be made carefully, with regard to the meteorological situation in question. Cotton and Anthes (1989) discuss in some detail the question of which parameter should remain constant and which should vary.

3. Fallspeeds for snow and graupel/hail

Bearing in mind that D_x represents the melted drop diameter, a problem arises with snow and graupel/hail fallspeeds. The equations used by LFO for the fallspeed of snow, and Rutledge and Hobbs' (1974) equations for the fallspeeds of snow and graupel, are taken from Locatelli and Hobbs (1974), and, unlike the distribution equations, depend on the maximum ice-particle dimension, which is denoted as $\mathbf{D}_x$. The quantities D_x and $\mathbf{D}_x$ can be quite different for a snowflake or graupel particle, and the two should not be confused.

Fortunately, Locatelli and Hobbs provide mass–$\mathbf{D}_x$ [i.e., $M_x(\mathbf{D}_x)$] and velocity–mass [i.e., $V_x(M_x)$] relationships for many types of snow. By relating mass to D_x:

$$M_x = \pi \rho_w D_x^3/6 \qquad (4)$$

and combining this with either $V_x(M_x)$, or $V_x(\mathbf{D}_x)$ and $M_x(\mathbf{D}_x)$, a relationship for $V_x(D_x)$ can be obtained.

For example, Locatelli and Hobbs' relationships for "graupel-like snow of hexagonal type" are (in SI units)

Corresponding author address: Mr. Brian Potter, Department of Atmospheric Sciences, AK-40, University of Washington, Seattle, WA 98195.

$$V_s = 5.15M_s^{0.14} \tag{5}$$

and

$$V_s = 4.84\mathbf{D}_s^{0.25}. \tag{6}$$

[Equation (5) includes correction of a typographical error in the published version of Locatelli and Hobbs.] Combination of (4) and (5) yields

$$V_s = 5.15(\pi\rho_w D_s^3/6)^{0.14} = 12.4D_s^{0.42}. \tag{7}$$

Equations (6) and (7) produce very different results if the same value is used in each (i.e., D_s and $\mathbf{D}_s$ are considered interchangeable). For example, if D_s is 0.5 mm, then (7) gives a fallspeed of 0.51 m s^{-1}; using 0.5 mm in (6) would increase the velocity to 0.72 m s^{-1}. This is a significant difference with potentially important consequences, as demonstrated by Heymsfield and Kajikawa (1987).

One consequence of the nature of D_x in (1) is that the expressions for accretion processes, which depend on the sweep-out volume, and hence on the cross-sectional area of a falling ice particle, can become rather protracted. If D_x is the melt diameter and $\mathbf{D}_x$ is the maximum particle dimension, what dimension should one use to determine this cross-sectional area? I argue that D_x may be employed here. Using $\mathbf{D}_x$ would yield the maximum cross section the particle may present as it falls, and hence the maximum accretion rate. If the particle were spherical this would be reasonable, but few snowflakes are spheres. In general, the melt diameter D_x will represent a diameter somewhere between the maximum and minimum particle dimensions and will provide a reasonable average cross-sectional area. In view of the uncertainties in the fallspeed relations, any extrapolation to derive an ersatz cross-sectional area carries no guarantee of improved realism and may even prove detrimental to the model's performance.

4. Conclusions

The changes noted previously (i.e., using ρ_w instead of ρ_s or ρ_g; carefully choosing N_{0x} and/or λ_x; converting fallspeed relationships to depend on D_x rather than $\mathbf{D}_x$) have been applied to the LFO parameterization and used in simulations of a squall line similar to the work reported by Fovell and Ogura (1988), using the two-dimensional dynamical model of Durran and Klemp (1983). A thermal bubble near the ground initiated convection, and the model was run to 24 800 s (nearly 7 h). The original LFO scheme (version 1) and the modified scheme (version 2) produce similar results, but with several important differences. In version 1, ice mixing ratios were lower by about 20% and confined to a smaller volume in space. Snow mixing ratios in version 1 were as much as double those in version 2 (see Fig. 1). Version 1 also has a stronger circulation and deeper cold pool beneath the updraft and produced more rain in the region of the updraft. All of these observations are generalizations, and the effects appear to result from the changes in V_s, which is smaller in version 2 than in version 1 for all values of q_s (Fig. 2). Lower fallspeeds result in less accretion, less snow and graupel, and ultimately, less evaporative cooling at low levels. The cold pool is thus weaker, and the overall result is a less vigorous storm.

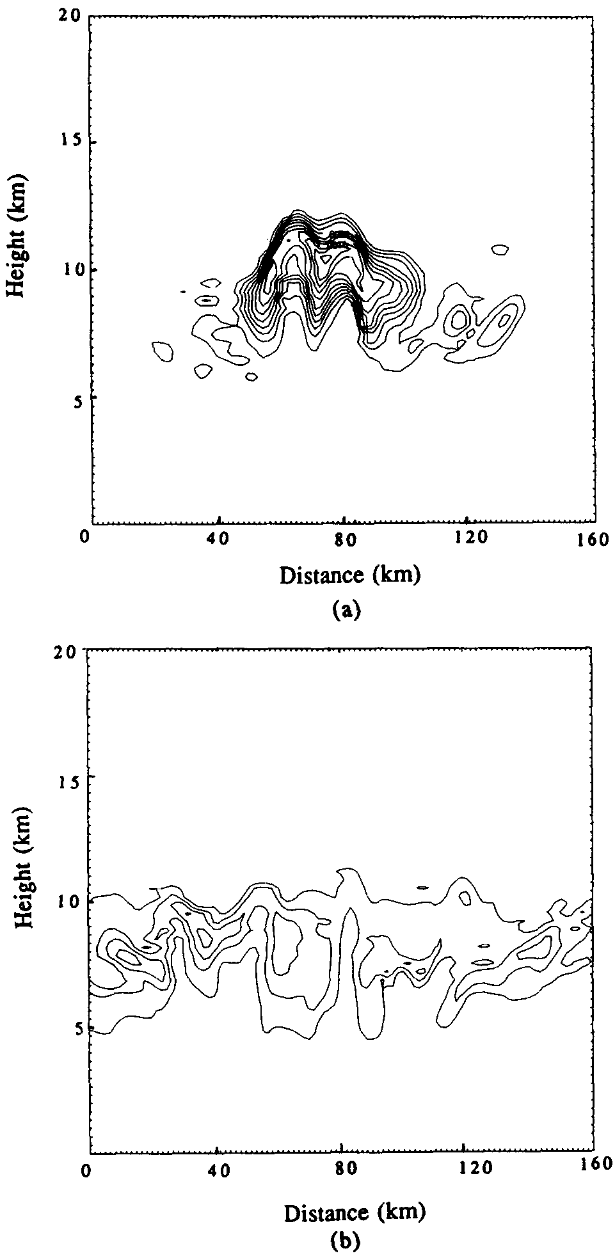

FIG. 1. The mass mixing ratios for snow, q_s, are shown at 5.6 h run time for (a) version 1, and (b) version 2. The domain shown is 160 km wide and 20 km high. (The total domain used for the model is 200 km × 32 km.) Horizontal tick marks are 1.7 km apart, vertical ticks are 0.3 km apart, and the contour interval is 2.0 × 10^{-4} kg kg^{-1}.

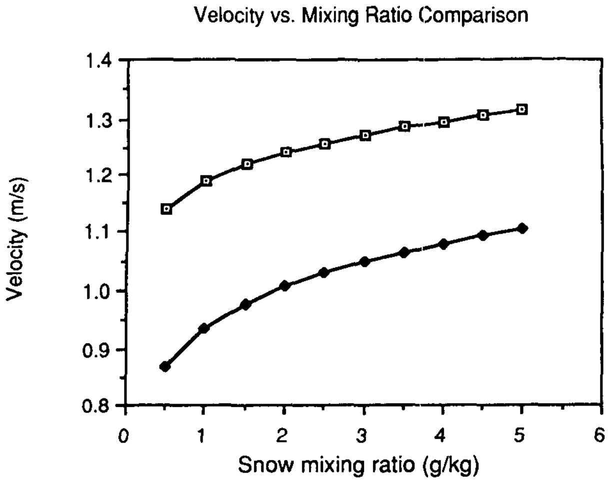

FIG. 2. Snow fallspeed as a function of mixing ratio q_s. Open diamonds correspond to LFO's fallspeed relationship ($V_s = 4.84\ D_s^{0.25}$ in SI units) and $\rho_s = 100$ kg m^{-3}; the solid diamonds show the corrected fallspeed relationship from Locatelli and Hobbs (1974) ($V_s = 12.4\ D_s^{0.42}$, in SI units) and $\rho_s = p_w$.

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