# A novel approach for representing ice microphysics in models

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## Motivation

Most schemes used today include the traditional logic of "cloud ice-snow-graupel/hail" to represent ice processes.

Such a logic follows approaches proposed 20+ years ago (Rutledge and Hobbs, Lin et al.) that transplanted ideas from warm-rain microphysics into ice physics. Does it make sense? Not really!

For warm rain, clear separation does exist between cloud water and drizzle/rain; for ice, the boundaries are not obvious and usually gradual transitions from one category to another take place. For warm rain, cloud water grows by diffusion of water vapor, drizzle/rain forms through collision/coalescence. For ice, both diffusional and accretional growth contribute to the growth.

The ice scheme should produce various types of ice (cloud ice, snow, graupel) just by the physics of particle growth; partitioning ice particles a priori into separate categories introduces unphysical "conversion rates" and involves "threshold behavior" for various parameters (e.g., sedimentation velocity).

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## Description of the New Scheme

The new two-moment three-variable ice scheme:

**Number concentration of ice crystals, $N$**

$$\frac{\partial N}{\partial t} + \frac{1}{\rho_a}\nabla \cdot [\rho_a(\mathbf{u} - V_N \mathbf{k})N] = \mathcal{F}_N$$

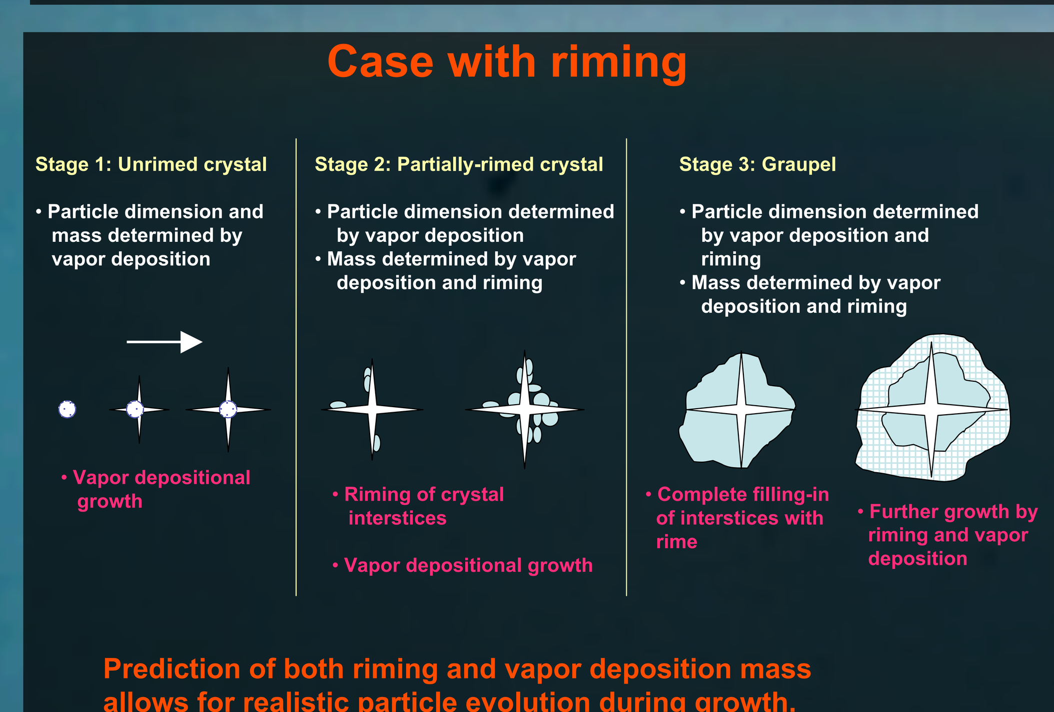
**Mixing ratio of ice mass grown by diffusion of water vapor, $q_{dep}$**

$$\frac{\partial q_{dep}}{\partial t} + \frac{1}{\rho_a}\nabla \cdot [\rho_a(\mathbf{u} - V_q \mathbf{k})q_{dep}] = \mathcal{F}_{q_{dep}}$$

**Mixing ratio of ice mass grown by riming, $q_{rim}$**

$$\frac{\partial q_{rim}}{\partial t} + \frac{1}{\rho_a}\nabla \cdot [\rho_a(\mathbf{u} - V_q \mathbf{k})q_{rim}] = \mathcal{F}_{q_{rim}}$$

Conceptual models of ice particle growth:


$$N(D) = N_o D^{\mu} e^{-\lambda D}$$

**Ice particles assumed to follow gamma distribution**

**(3 parameters: $N_o$, $\mu$, $\lambda$)**

$$N = \int_0^{\infty} N(D)\, dD$$

$$q_{dep} + q_{rim} \equiv q = \int_0^{\infty} m(D)\, N(D)\, dD$$

$$\mu = 0.076\lambda^{0.8} - 2\,; \quad 0 \le \mu \le 6$$

**Diagnostic relationship based on observations (Heymsfield 2003)**

All ice processes are calculated in terms of the particle mass-dimension (m-D) and projected area-dimension (A-D) relationships. m-D and A-D evolve during the simulation as a function of the rimed mass fraction (derived locally from prognostic $q_{dep}$ and $q_{rim}$). Partitioning of the size distribution as shown below allows smooth transition of m-D during particle growth.

Transition of mass-dimension relationship for crystals/snowflakes grown by aggregation and diffusion of water vapor:

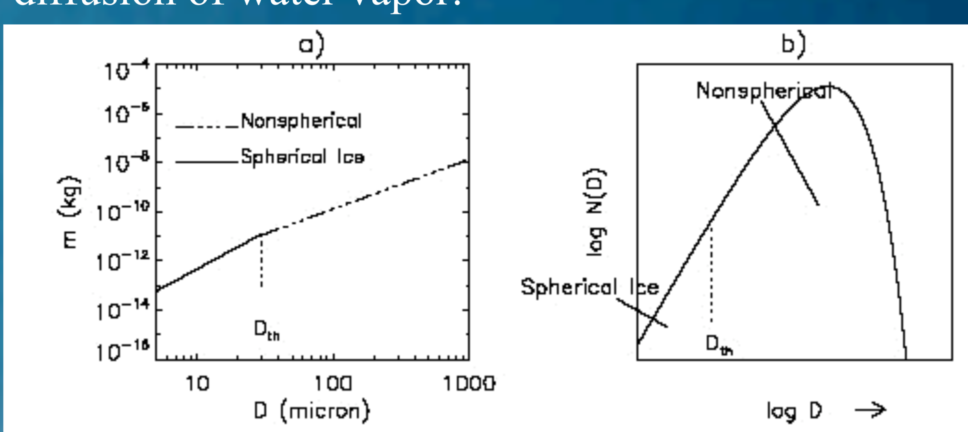


Figure 1: a) Mass ($m$)-dimension ($D$) relationships in unrimed conditions for solid spherical ice and unrimed nonspherical ice using parameters in Table 1, and critical particle dimension $D_{th}$. b) Schematic diagram of the gamma particle size distribution $N(D)$ divided into two regions based on $D_{th}$.

Transition in mass-dimension relationship for ice particles grown by diffusion, aggregation, and riming:

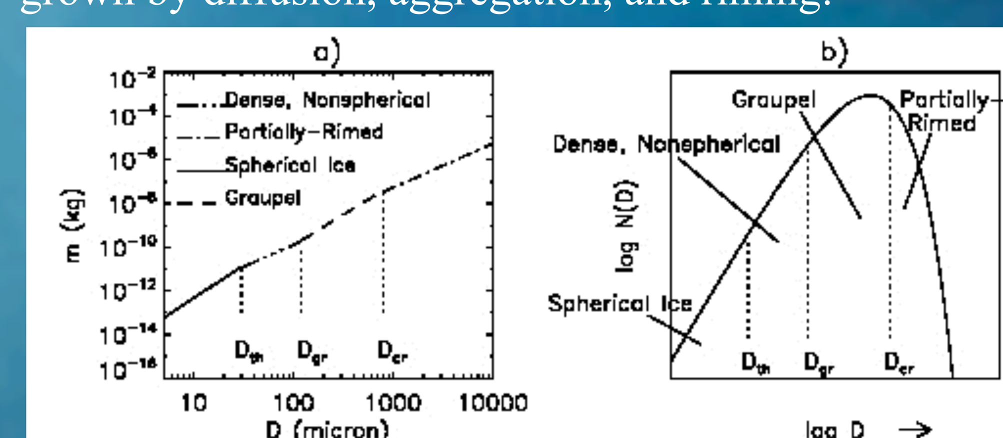


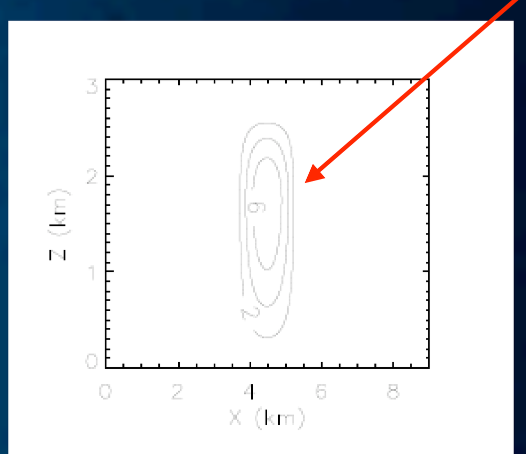
Figure 2: a) Mass ($m$)-dimension ($D$) relationships in rimed conditions for solid spherical ice, graupel, dense nonspherical ice, and partially-rimed ice using parameters in Table 1, and critical dimensions $D_{th}$, $D_{gr}$, and $D_{cr}$. The m-D relationship shown in this example is calculated using a rimed mass fraction of 0.75. b) Schematic diagram of the gamma particle size distribution $N(D)$ divided into four regions based on $D_{th}$, $D_{gr}$, and $D_{cr}$.

## Results

New scheme is tested in a kinematic framework mimicking a shallow mixed-phase cumulus.

Version of scheme based on traditional approach with separate variables for ice/snow and graupel (following Rutledge and Hobbs 1984) is also tested.

2D (x-z) prescribed-flow framework (low-level convergence, upper-level divergence, evolving-in-time updraft, with weak vertical shear)



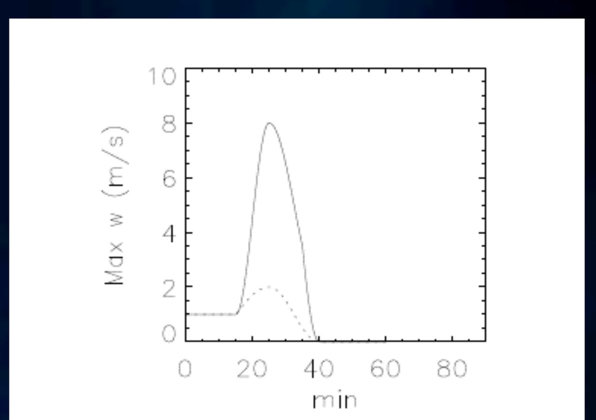
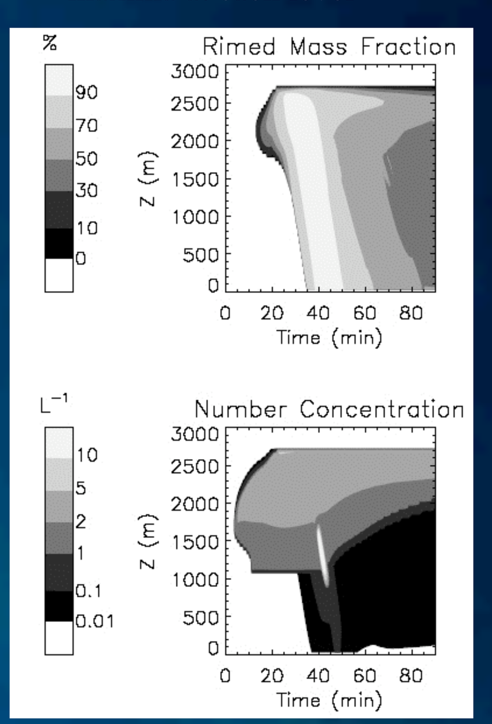


Figure 4: Maximum updraft velocity $w$ in the X-Z plane as a function of time for peak updraft strength of 8 m/s (solid) and 2 m/s (dotted).

Time evolutions of horizontal maxima at each level



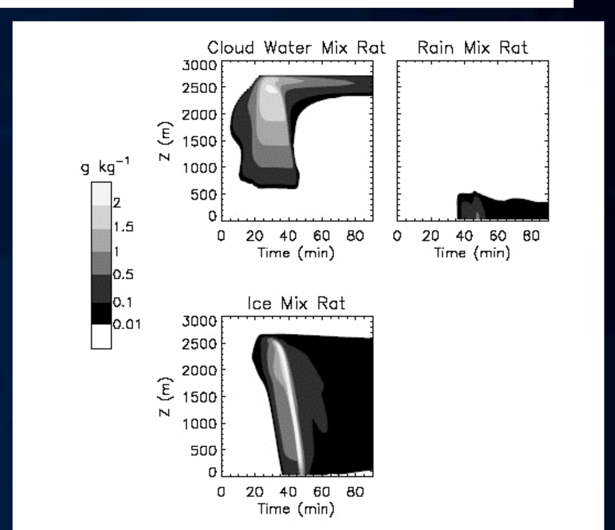


Figure 7: Time evolution of horizontal maxima of cloud water mixing ratio, rain mixing ratio, and ice mixing ratio at each vertical level using the new scheme and maximum updraft speed of 8 m/s.

Results using the traditional approach are highly sensitive to the specified graupel conversion thresholds.

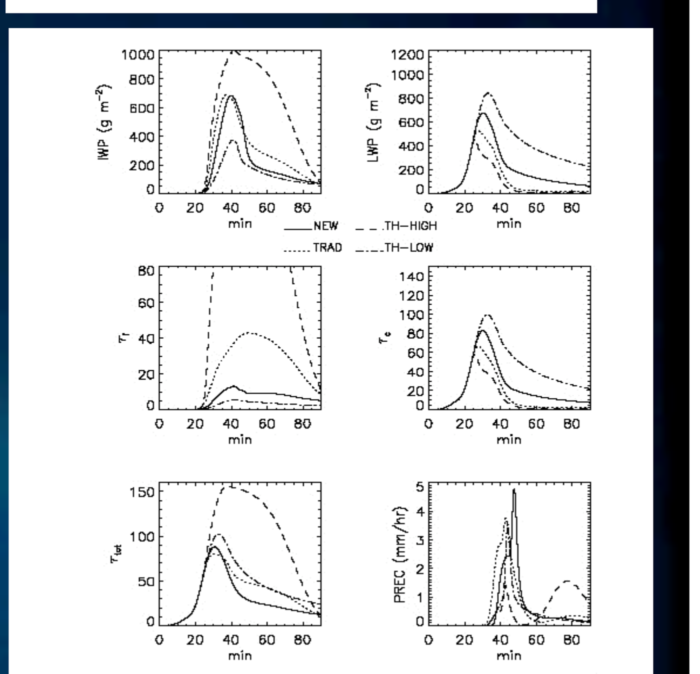


Figure 8: Time evolution of domain-average cloud liquid water path $LWP$ (g m$^{-2}$), ice water path $IWP$ (g m$^{-2}$), droplet optical depth $\tau_c$ (unitless), ice optical depth $\tau_i$ (unitless), total cloud optical depth $\tau_{tot}$ (unitless), and surface precipitation rate $PREC$ (mm/hr), for maximum updraft speed of 8 m/s. "NEW" and "TRAD" refer to simulations using the new and traditional ice microphysics schemes, respectively. "TH-HIGH" and "TH-LOW" refer to sensitivity tests using the traditional scheme but with the threshold ice/snow and droplet mixing ratios for graupel production during droplet collection increased or decreased, respectively.

## Conclusions

The new scheme presents a physically-based approach for treating the transitions between small ice, snow, and graupel during aggregation, deposition, and riming, in contrast to the traditional approach that separates small ice, snow, and graupel into separate categories with arbitrary conversion thresholds and rates. These transitions are treated by locally deriving the particle mass-dimension and projected area-dimension relationships according to the rimed mass fraction. The rimed mass fraction is obtained locally by the prediction of two ice mixing ratio variables: 1) mixing ratio due to riming, and 2) mixing ratio due to vapor deposition.