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Development of NTU triple-moment ice-phase microphysics scheme with consideration of particle shape and density variation

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Introduction

A new multi-moment microphysics scheme developed in-house by the Cloud and Aerosol Research Laboratory at the National Taiwan University. The first version of the NTU scheme (NTU-v1) contains a two-moment bulk warm cloud scheme, which explicitly predicting the mass and the drop number of cloud drops and raindrops. The warm cloud scheme is based on the scheme of Chen and Liu (2004) which applied a multi-component bin microphysical model and then statistically fit the simulation results into bulk formulas. The 2-moment mixed-phase parameterization is based on Reisner et al. (1998) with some modifications (Cheng et al. 2010). In the second version of NTU scheme (NTU-v2), the mixed-phase parameterization is written to reduce model uncertainties and errors associated with mathematical and physical representations. Furthermore, the NTU-v2 scheme is one of the first bulk parameterization to consider the ice crystal growth habit (shape) effects by adopting the parameterization method of Chen and Tsai (2016). Also, density is allowed to vary for several hydrometeor categories, and the effects of shape and density on fall speed are explicitly calculated.

Method

The NTU-v2 scheme applied somewhat different definition of hydrometeors. The "cloud ice" category commonly used in bulkwater schemes is redefined as "pristine cloud ice" which grows only by vapor diffusion; the aggregation of pristine cloud yields "snow aggregate", whereas riming produces "rimed ice" (or graupel). Using this physical process-based definition, we eliminated the artificial process of autoconversioin between cloud ice and snow that is based on a specified size threshold. So, in our scheme, ice-phase particles have no upper and lower size limits. This eliminated the problem in mathematics associated with incomplete integration of size distribution due to the artificial cutoff.

Ice particle size spectrum is represented with a 3-parameter gamma distribution in the form of $n(D) = N_0 D^{\alpha} e^{-\lambda D}$. The parameters N_0, α, and λ can be retrieved by knowing 3 moments of the size distribution, which are defined as $M_k = \int_0^{\infty} r^k n(r) dr$, where k = 0, 2 or 3, representing the concentrations of total number, surface area, or volume (red symbols in Fig. 1), respectively. For pristine cloud ice and snow aggregate, two extra properties, aspect ratio and mass, are tracked to allow representation of particle shape and density variations. Graupel and hail particles are assumed to be spherical, while hail is further assumed to have a fixed density.

The rate change of moments (i.e., dM_k/dt) are solved by placing the growth kernel into the moment equation, and solve the integral analytically with as little simplification as possible using the kernel transformation or integral transformation methods of Chen et al. (2013).

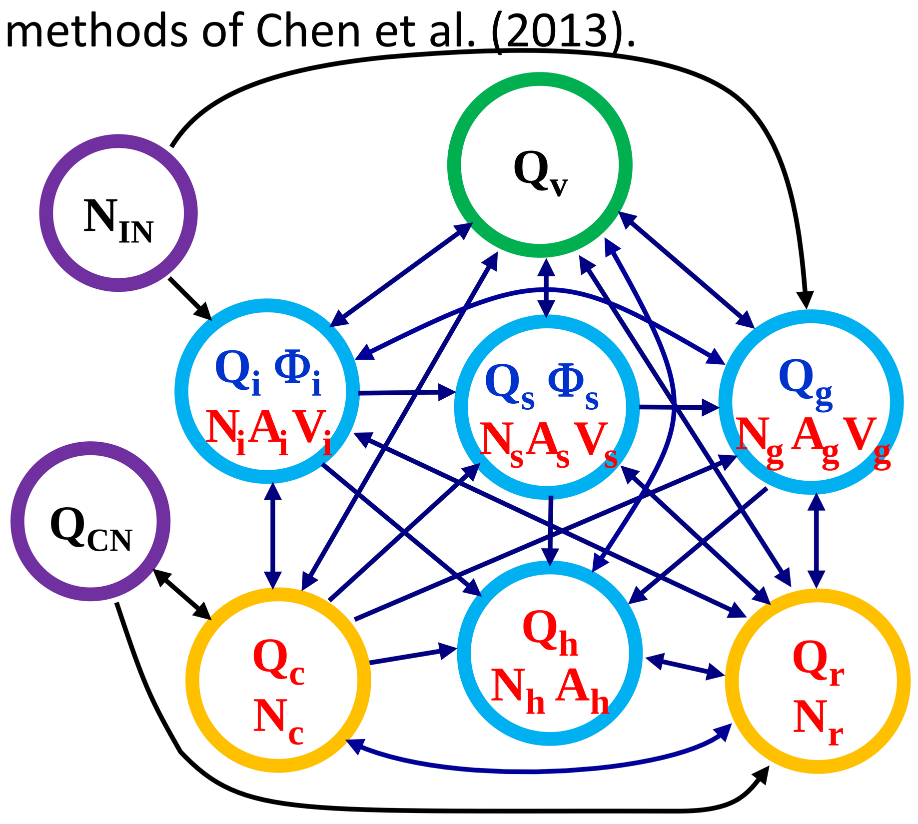

Figure 1: Schematic of the NTU bulk parameterization. Circles indicate hydrometeor/particle categories: water vapor (v), cloud drop (c), raindrop (r), pristine cloud ice (i), snow aggregate (s), rimed ice/graupel (g), hail (h), condensation nuclei (CN) and ice nuclei (IN). Symbols within the circles are major properties of hydrometeors, with N, A, V, Q, for number, area, volume, mass, and shape (volume-weighted aspect ratio), respectively.

Summary of main features in the NTU-v2 scheme:

- Warm cloud
  - Double-moment parameterization from bin-model statistics
  - Supersaturation resolved
  - Explicit collision coalescence and breakup processes
- Cold cloud
  - Triple moment gamma distribution for size spectra
  - Resolved shape (aspect ratio) for cloud ice and snow
  - Resolved particle density for cloud ice, snow, graupel
  - Shape- and density-dependent fall speeds
- Aerosol-cloud interactions
  - CN/GiantCN activation into cloud drop/raindrop following Kohler theory
  - Aerosol recycling
  - Heterogeneous ice nucleation according to classical theory for various IN types

Results

Our scheme has been applied in several cloud systems, showing satisfactory results especially in rainfall and the radar reflectivity analysis. Here we use the MC3E (the Midlatitude Continental Convective Clouds Experiment) case for demonstration of the NTU scheme's performance. This case occurred in the southern Great Plain in 2011, and is viewed as a "Dream Scenario" for cloud model evaluations. Figure 2 presents the precipitation rate during the day, showing that the model roughly captured the major peak in the afternoon particularly for the simulation using more polluted aerosol initial condition. The clean aerosol condition tends to produce much too strong first peak.

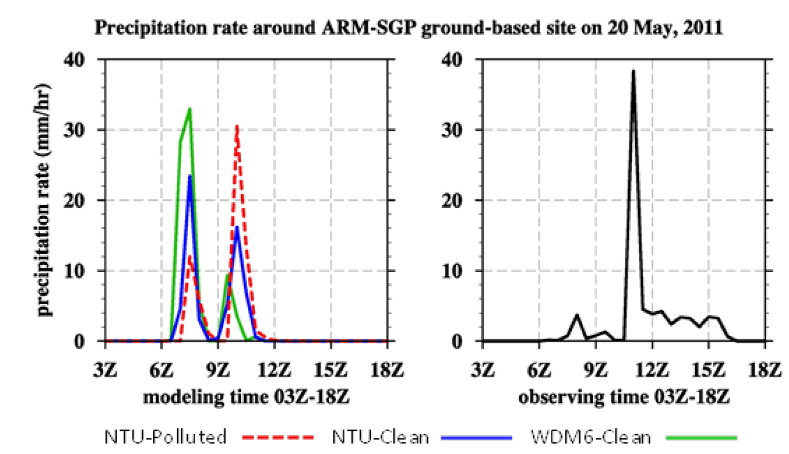

Figure 2: Left: hourly precipitation rates for the MC3E case simulated using the WDM6 scheme with clean aerosol (green), using NTU scheme with clean and polluted aerosols (blue and red, respectively). Right: observed precipitation rate.

The simulations roughly captured the horizontal structure of the squall line (Fig. 3 left), but large discrepancies exist in radar reflectivity in terms of absolute amplitude and vertical structure (Fig. 3 right), indicating uncertainties in the mixed-phase processes. Also, large discrepancies may stem from the assumption of spherical particle shape in microphysical schemes (cf. NTU-sphere vs. NTU-shape). Also, the effects of particle shape and density in the calculation of radar scattering amplitude seem to be crucial.

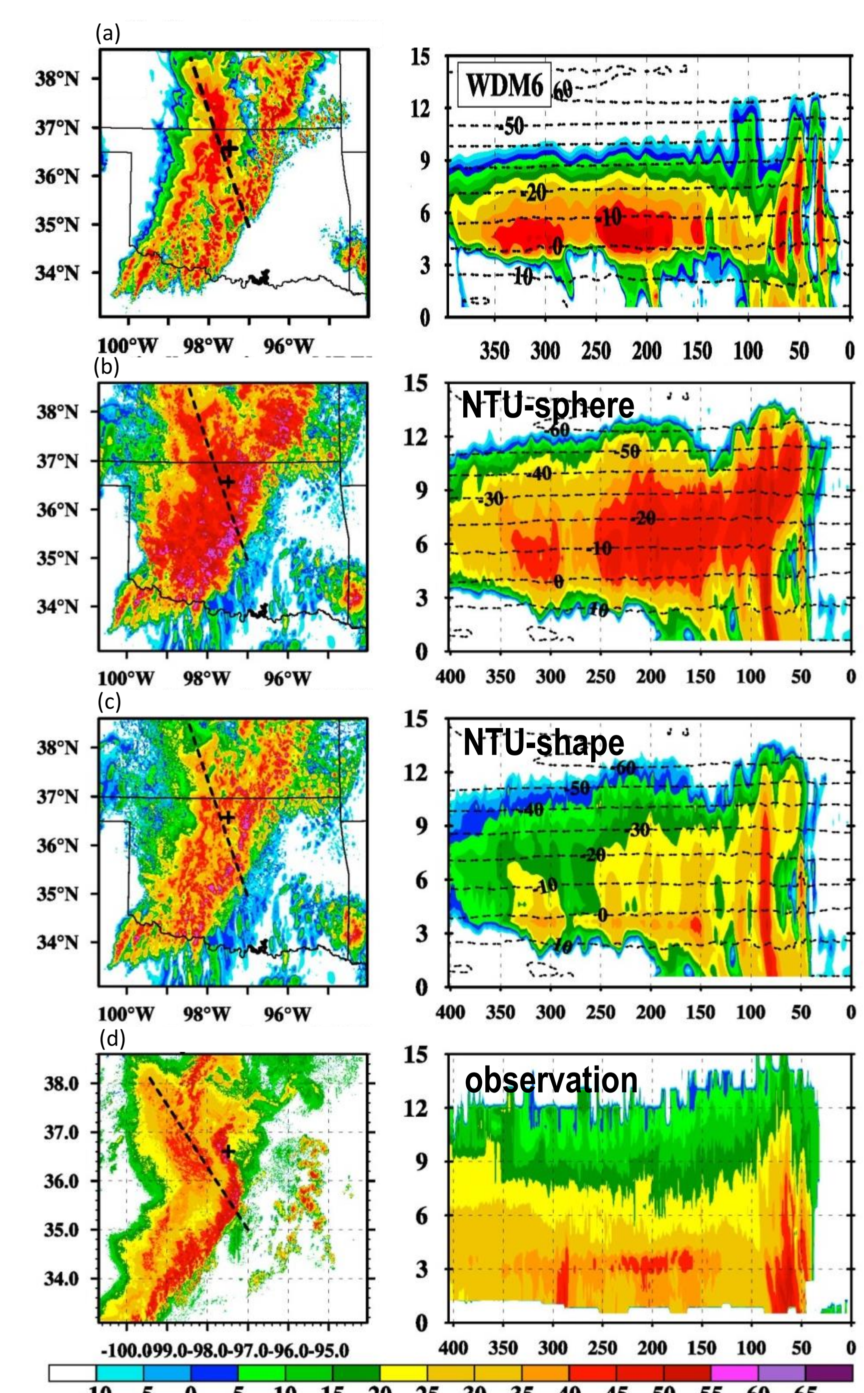

Figure 3: Projected maximum radar reflectivity (left) and vertical scan (right) from WDM6 run (top panel), NTU-C run (middle two panels) and observation (bottom). Radar reflectivity from NTU scheme was calculated by assuming all hydrometeors are spherical (2nd row) or with shape consideration (3rd row).

The radar reflectivity CFAD in Fig. 4 shows that better vertical profiles can be obtained when including the shape/density in microphysical processes (NTU-shape vs. NTU-sphere), and in calculating radar reflectivity (NTU-shape vs. NTU-Zsphere).

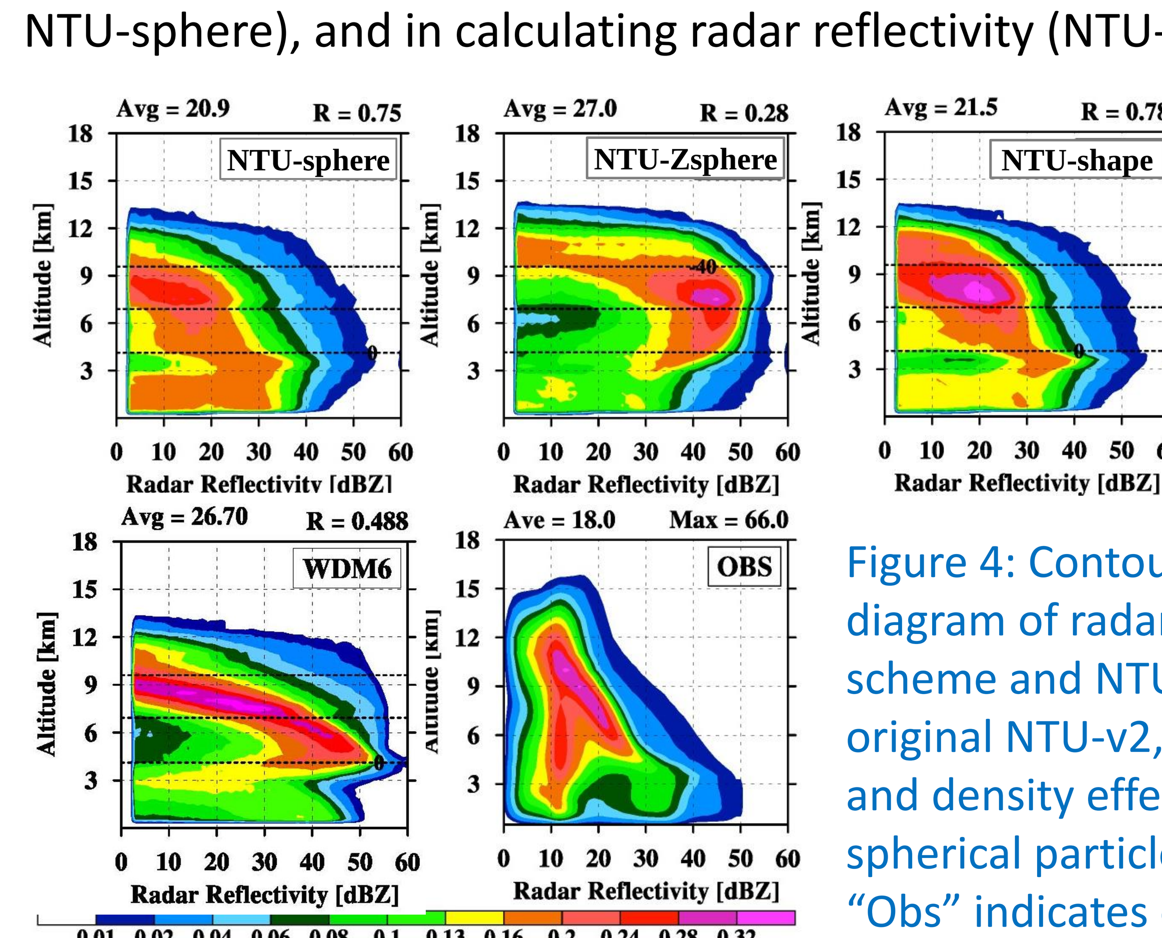

Figure 4: Contoured frequency by altitude diagram of radar reflectivity using the WDM6 scheme and NTU scheme. "NTU-shape" is the original NTU-v2, "NTU-sphere" ignored shape and density effects, "NTU-Zsphere" assumes spherical particle in radar reflectivity calculation. "Obs" indicates observation.

Summary

The NTU-v2 scheme is developed for improving microphysical representation in the WRF model. This scheme used 2 and 3 moments, respectively, for describing liquid and ice-phase hydrometeors. Additional properties are considered for describing the variation of particle shape and density for cloud ice and snow. Preliminary results indicate that the NTU scheme performed fairly well in simulating various cloud systems (e.g., fronts, squall lines, thermal convections, marine stratiform clouds, and snow storms). As computational cost is high, the NTU-v2 scheme is more suitable for research purposes.

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