Revisiting Cloud Particle Size Distribution: Insights from a Statistical Theory and a Particle Based Model

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The form of cloud particle size distributions (PSDs) is a crucial fundamental assumption for both numerical bulk microphysical parameterization schemes and remote sensing retrievals. In-situ observations collected from various locations and meteorological scenarios show a similar shape of cloud PSDs, based on which various probability distribution functions have been proposed empirically to represent cloud PSDs, including exponential, gamma, lognormal, and Weibull distributions. Theoretical investigations have also been used to determine the form of cloud PSDs by solving the equation governing the change of PSDs. However, the integro-differential equation is too complex to have analytical solutions except for cases with very simple kernels. Therefore, other approaches are needed to explain the observed cloud PSD. Instead of solving the equation analytically, the use of the principle of maximum entropy (MaxEnt) for determining the analytical form of PSDs from a system perspective is examined here. First, the issue of inconsistency under coordinate transformation that arises using the Gibbs/Shannon definition of entropy is identified, and the use of the concept of relative entropy to avoid this problem is discussed. Focusing on cloud physics, the four-parameter generalized gamma distribution is proposed as the analytical form of a PSD using the principle of maximum (relative) entropy with assumptions on power law relations between state variables, scale invariance and a constraint on the expectation of one state variable (e.g. bulk water mass).

To examine the theory, a particle-based model is developed to explore the analytical form of cloud PSDs. The model directly simulates millions of cloud particles under various warm rain microphysical processes, such as diffusional growth, evaporation, stochastic collision-coalescence, spontaneous breakup, and collision-induced breakup. Each model setup is simulated for many realizations to get both mean and fluctuations of cloud properties. To evaluate the performance of the model, numerical simulations are compared against the analytical solutions for a constant kernel and the commonly used Golovin kernel. Furthermore, the simulations using a realistic geometric collection kernel are compared with previous studies using bin microphysical models. The model shows good agreement with the analytical solutions and has better mass conservation compared to previous bin microphysical simulations using a geometric collection kernel. By combing different microphysical processes, the form of the equilibrium PSD found in previous numerical modeling studies of warm rain is then explored with the model by incorporating related microphysical processes.

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