atmosphere

A Numerical Simulation Study of Secondary Ice Productions in a Squall Line Case

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Introduction

This supporting information provides the detailed descriptions about parameterizations of primary ice processes and formation of freezing drops in Text S1 and Text S2, and the figures supplement the analysis.

Text S1.

Following is the descriptions about the parameterizations of primary ice prosses in the Morrison scheme.

The primary ice processes are all simulated using the schemes in the original Morrison scheme. We do not make any changes to the primary ice processes in this study.

Homogeneous freezing occurs when temperature is below -38°C. The cloud droplets below -38°C all homogeneously freeze to ice crystals instantly, while raindrop below -38°C all homogeneously freeze to graupels instantly. Heterogeneous nucleation includes immersion freezing, contact freezing, and deposition and condensation freezing nucleation processes.

The immersion freezing of cloud droplets and raindrops adopts the parameterization of Bigg (1953). The Bigg parameterization provides immersion freezing rates for the temperature range of T<−4°C. Its formulation is a function of temperature and liquid droplet mass and number, and independent with ice-nucleating particles (INP). The immersion freezing of raindrops and cloud droplets use the same method. The immersion freezing rate of raindrops is parametrized as follows:

$$\left.\frac{\partial n_{ice}}{\partial t}\right|_{immersion} = B[\exp\{A(T_0 - T)\} - 1]\frac{\rho q_r^2}{\rho_w n_r} \quad \text{(S1)},$$

where $\left.\frac{\partial n_{ice}}{\partial t}\right|_{immersion}$ is the production rate of ice crystal number concentration through immersion freezing of rain, A = 0.66 K^{-1}, B = 100 $m^{-3}s^{-1}$, ρ_w = 1000 kg m^{-3} is the density of water, ρ is the air density, T_0=273.15 K, T is the temperature, n_r is the number concentration of raindrops, and q_r is the mass concentration of raindrops. Note that the immersion freezing of cloud droplets in the Morrison scheme adopts the same formulation as Equation S1, but with number and mass concentration of raindrops replaced with number and mass concentration of cloud droplets.

The contact freezing is parameterized based on a flux of contact INPs to the drops due to Brownian motion, diffusiophoresis, and thermophoresis. This process is active below -4°C, and has a format as:

$$\left.\frac{\partial n_{ice}}{\partial t}\right|_{contact} = 2\pi D\frac{n_c\Gamma(p_c+2)}{\lambda_c\Gamma(p_c+1)}\left.\frac{\partial n_{INPs}}{\partial t}\right|_{contact} \quad \text{(S2)},$$

where $\frac{\partial n_{ice}}{\partial t}\Big|_{contact}$ is the production rate of ice crystal number concentration through contact freezing of cloud droplets, D is an effective diffusion coefficient given by Young (1974), n_c is the number concentration of cloud droplets, λ_c is the slope parameters of the Marshal-Palmer clod droplet size distribution, p_c is the spectral shape parameter for cloud droplets. $\frac{\partial n_{INPs}}{\partial t}\Big|_{contact}$ is the number of contact INPs per time, and is calculated based on Meyers et al. (1992) as follows:

$$\frac{\partial n_{INPs}}{\partial t}\Big|_{contact} = \exp\{a + b(T_0 - T)\} \quad \text{(S3)},$$

where a = -2.8, $b = 0.262$, $T_0 = 273.15$ K, and T is the temperature.

The deposition and condensation freezing nucleation is parameterized based on Cooper (1986). This process occurs in conditions when the water vapor is supersaturated to liquid and the temperature is below -8°C, or when the water vapor supersaturation relative to ice is higher than 8%. This process rate depends on temperature as follows:

$$\frac{\partial n_{ice}}{\partial t}\Big|_{dep\&cond} = a[\exp\{b(T_0 - T)\}] \quad \text{(S4)},$$

where $\frac{\partial n_{freeze}}{\partial t}\Big|_{dep\&cond}$ is the nucleation rate of deposition and condensation freezing, a = 0.005, $b = 0.304$, $T_0 = 273.15$ K, and T is the temperature.

Text S2.

Following is the descriptions about the parameterizations of the formation of freezing drops in the Morrison scheme.

In the Morrison scheme, freezing raindrops are produced by the immersion freezing of raindrops and ice crystal-rain collision processes. The production rate of freezing raindrop number concentration through immersion freezing is calculated as in the Equation (S1). The parameterization of ice crystal - rain collision in the Morrison scheme follows Reisner (1998), assuming that the fall speed and size of ice crystals are much smaller than that of raindrops and that the collision follows the "continuous collection" approach. The freezing rate of rain drops is the ice-rain collection rate:

$$\frac{\partial n_{freeze}}{\partial t}\Big|_{collision} = \frac{\pi}{4}\rho E_{col}\Gamma(b_r + 3)a_r \frac{n_i N_{0r}}{\lambda_r^{(b_r+3)}} \quad \text{(S5)},$$

where $\frac{\partial n_{freeze}}{\partial t}\Big|_{collision}$ is the production rate of freezing raindrop number concentration through collision with ice crystals, ρ is the air density, E_{col}=1 is the collection efficiency between raindrop and ice crystals, a_r and b_r are two constants in the fall speed-diameter relationship for rain drops (Morrison et al., 2005). Γ is the Euler gamma function, N_{0r} and λ_r are the intercept and slope parameters of the Marshal-Palmer rain drop size distribution, and n_i is the number concentration of ice crystals.

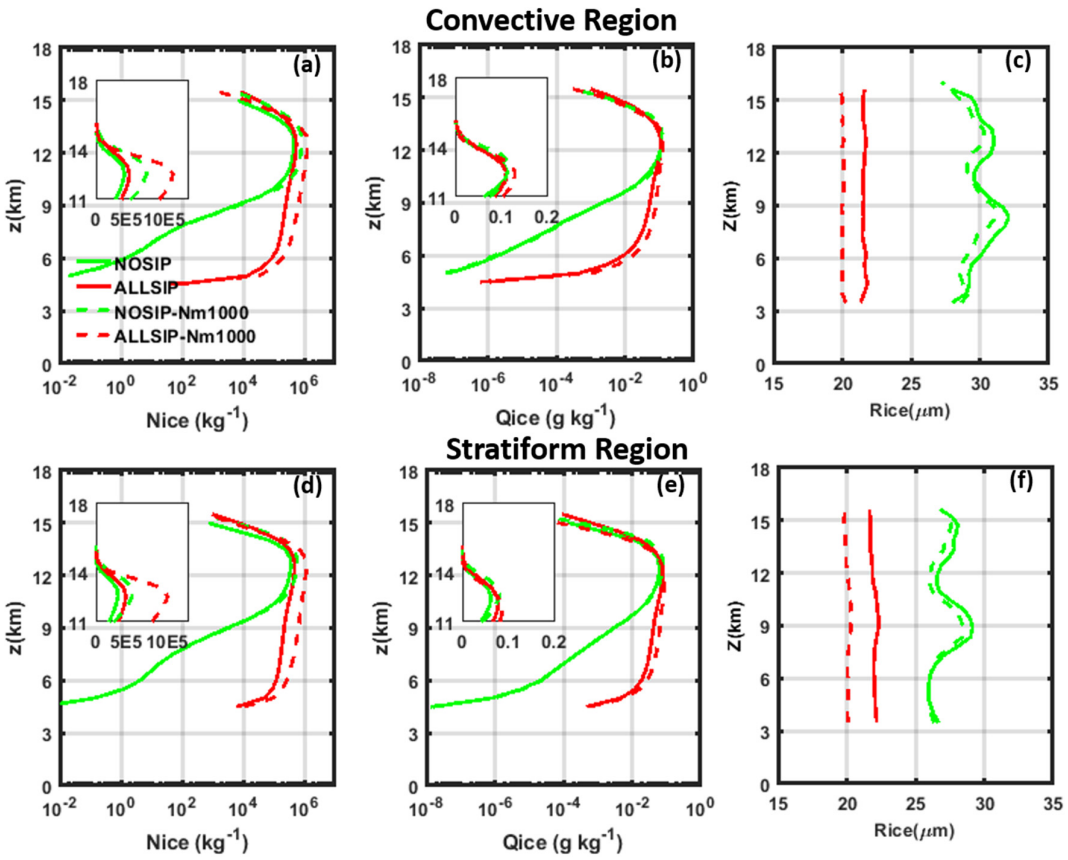


Figure S1. The number concentration (a, d), mass concentration (b, e), and the effective radius of ice crystals (c, f) averaged in the convective region (a, b, c) and stratiform region (d, e, f) during 17:00 to 19:00 BJT for the NOSIP, ALLSIP, NOSIP-Nm1000, ALLSIP-Nm1000 cases. The small boxes in these panels are the profiles of the 11-18 km (anvil layer) in a linear scale.

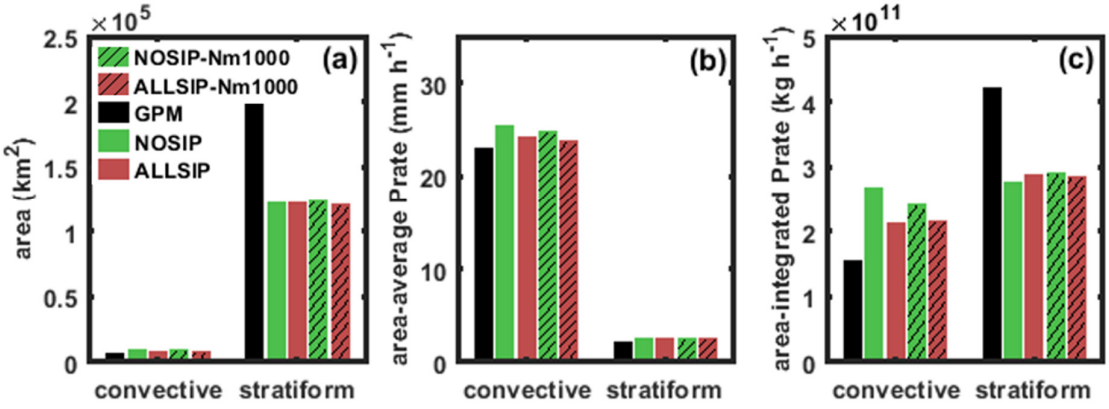


Figure S2. The temporal average of precipitation area (a), temporal and area-average precipitation rate (b), and the temporal average of area-integrated precipitation rate (c) of the convective and stratiform region for the GPM observation, NOSIP case, ALLSIP case, NOSIP-Nm1000 case, and ALLSIP-Nm1000 case.

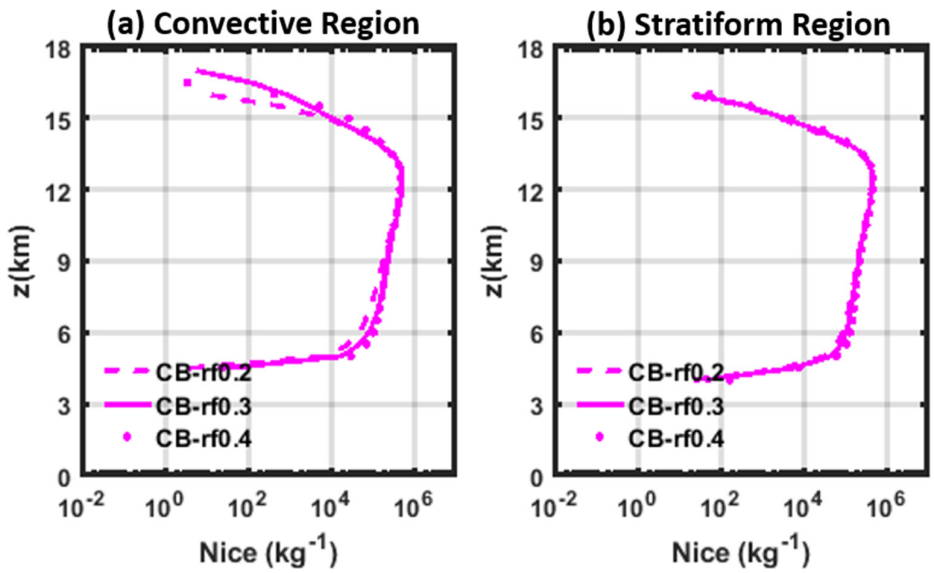


Figure S3. The number concentration of ice crystals averaged in the convective and stratiform region during 17:00 to 19:00 BJT for the CB-rf0.2, CB-rf0.3, and CB-rf0.4 cases.

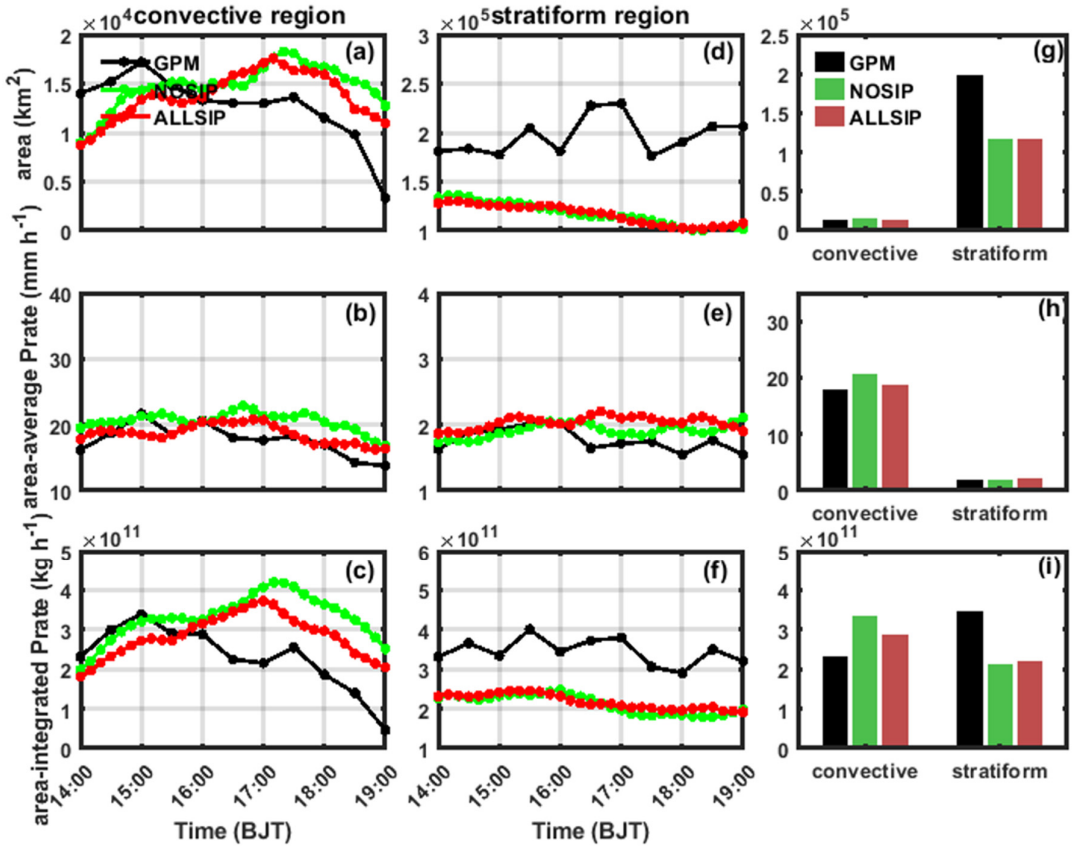


Figure S4. (a)(b)(c): The time series of convective area, area-average precipitation rate, and the area-integrated precipitation rate for the convective region. (d)(e)(f): The same as in (a)(b)(c), but for the stratiform region. (g)(h)(i): The temporal average of area, area-average precipitation rate, and the area-integrated precipitation rate of the convective and stratiform region, respectively. The convective and stratiform region are defined by threshold of 10 mm h^{-1}.

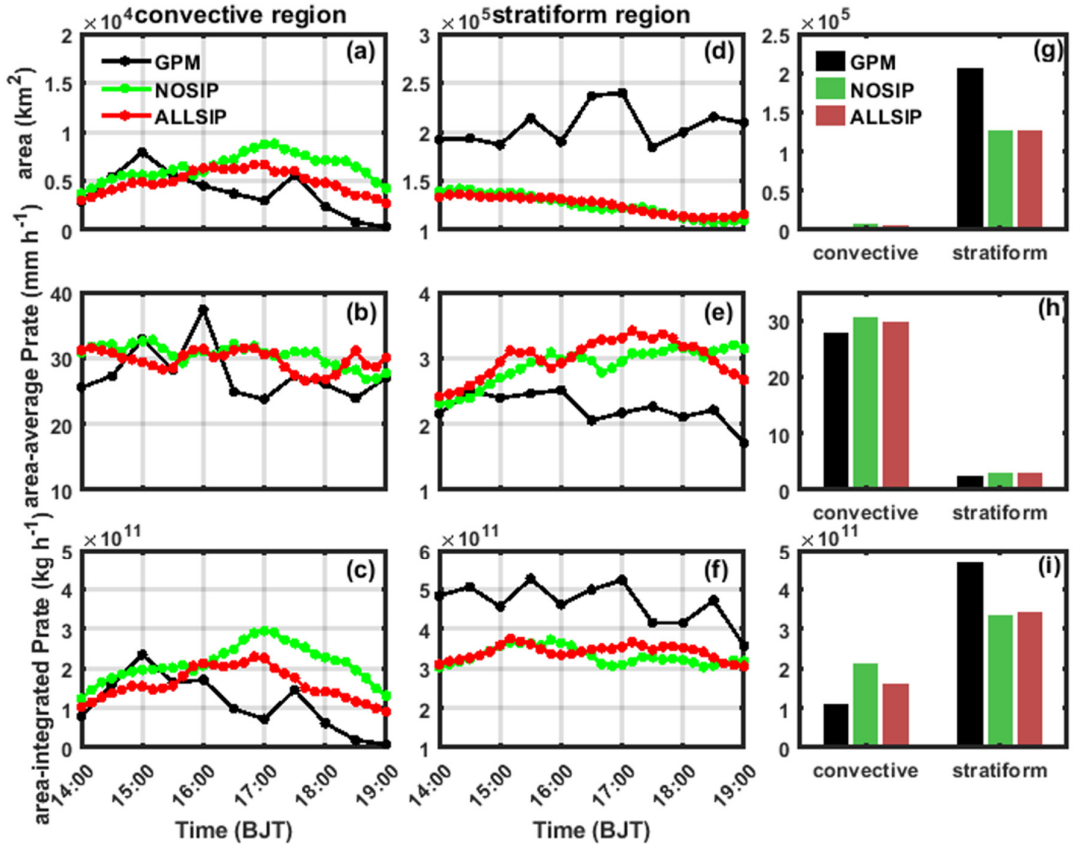


Figure S5. The same as Figure S4, but the convective region and stratiform region are defined by threshold of 20 mm h^{-1}.

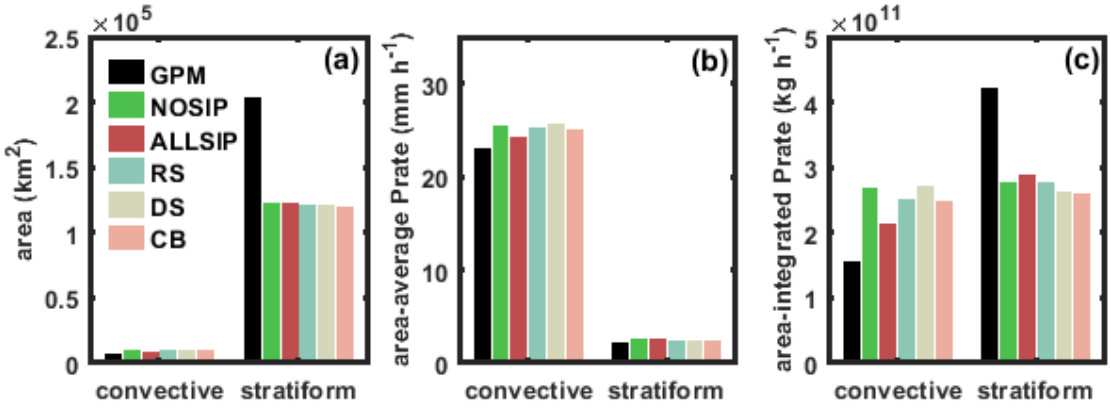


Figure S6. The temporal average of precipitation area (a), temporal and area-average precipitation rate (b), and the temporal average of area-integrated precipitation rate (c) of the convective and stratiform region for the GPM observation and five simulations. The analysis time range is 14:00-19:00 BJT.

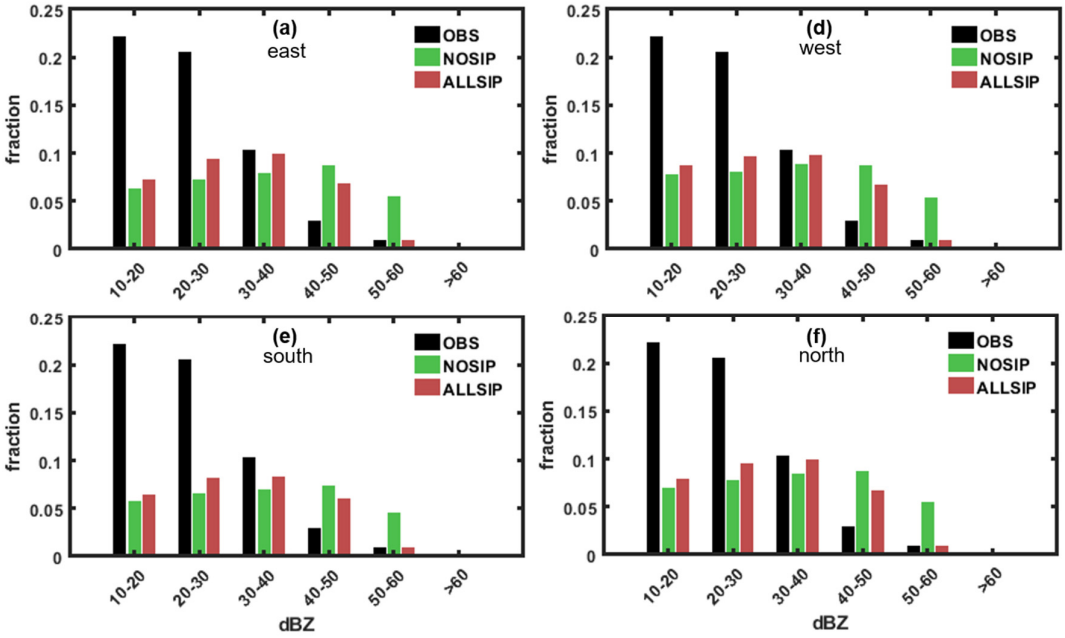


Figure S7. The histogram of the composite radar reflectivity. But the analysis region is shifting the simulation analysis region (37°N-43°N and 115°E-123°E) by 0.5° to the east (a), west (b), south (c), and north (d), respectively.

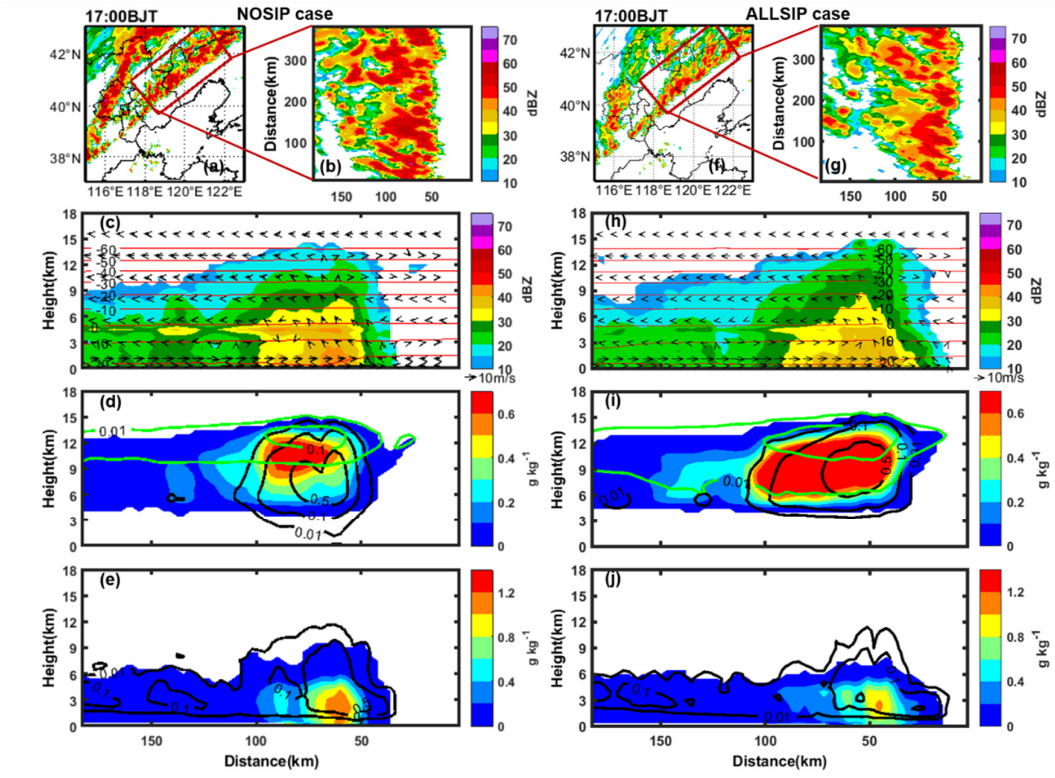


Figure S8. (a) and (b): Maximum (Composite) radar reflectivity at 17:00 BJT in the NOSIP case. (b) is the part of the red box in (a); (c): The vertical cross section of radar reflectivity (shading, unit: dbz), wind (arrows), and temperature (red line, unit: ℃) averaged along the horizontal axis in (b). (d): The vertical cross section of snow mass (shading, unit: g kg^{-1}), graupel mass (black line, unit :g kg^{-1}), and ice crystal mass (green line, unit: g kg^{-1}) averaged along the horizontal axis in (b). (e): The vertical cross section of rain water mass (shading, unit: g kg^{-1}) and cloud water mass (black line,

unit: g kg^{-1}) averaged along the horizontal axis in (b); Panels (f)-(j) are the same as in panels (a)-(e), but for the ALLSIP case.

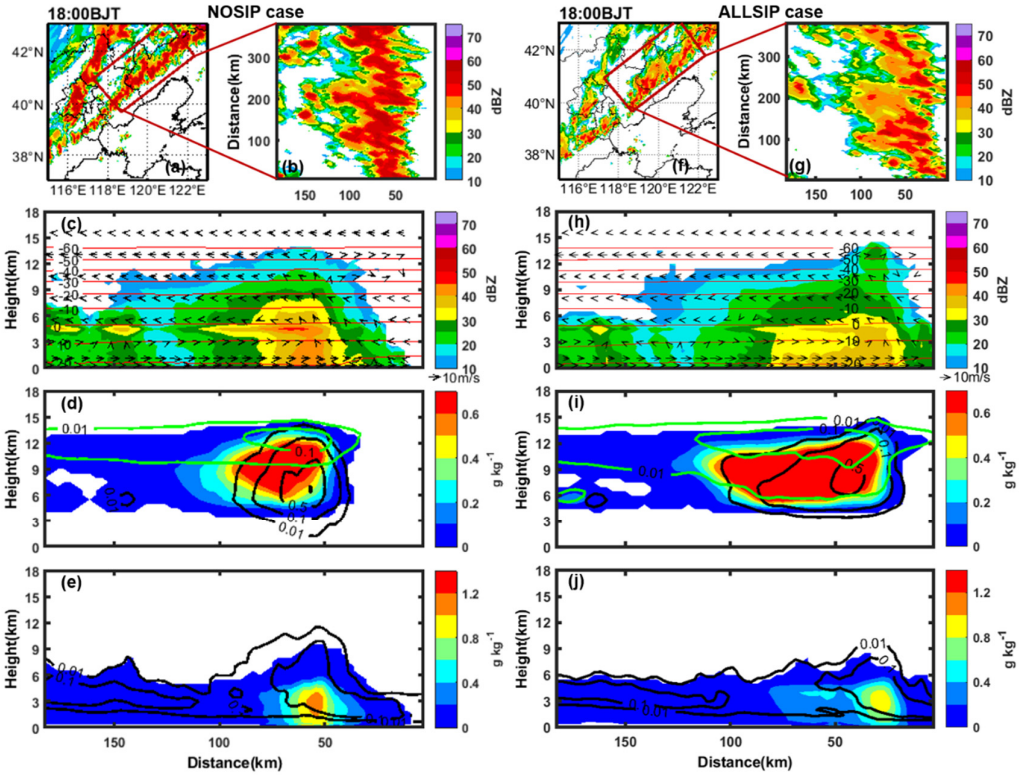


Figure S9. The same as Figure S8, but at 18:00 BJT.

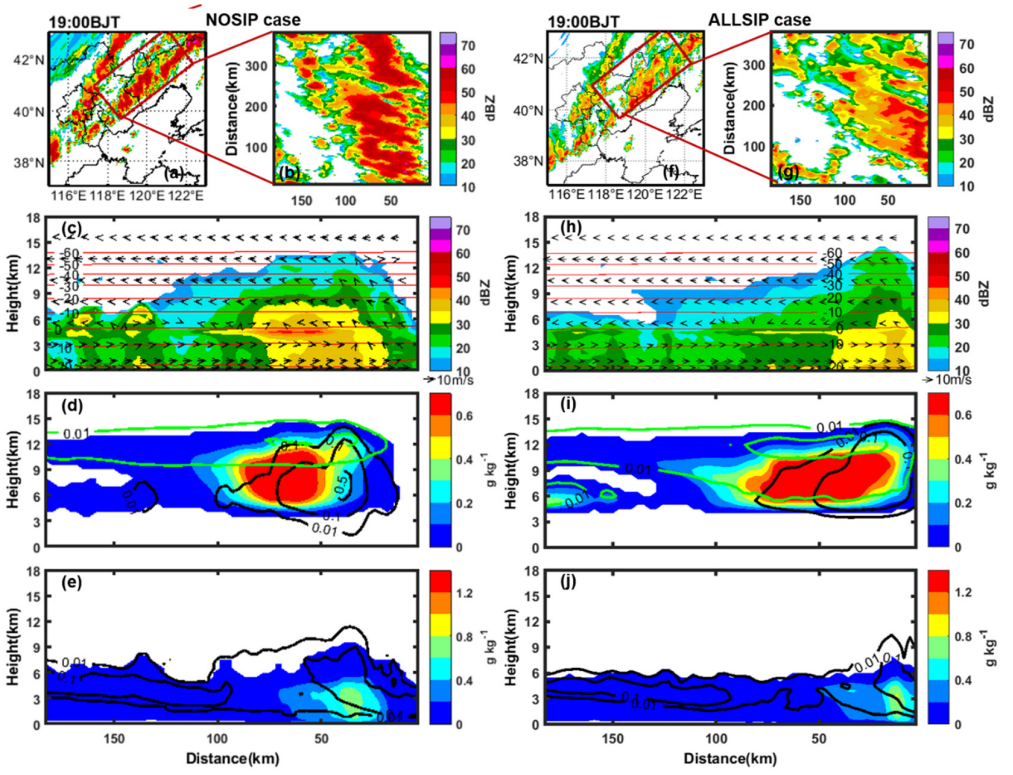


Figure S10. The same as Figure S8, but at 19:00 BJT.