Testing parameterization schemes for simulating depositional growth of ice crystal using Koenig and Takahashi parameters: a pre-summer rainfall case study over Southern China

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Abstract

In this study, the three (Hsie, Krueger and Zeng) schemes that parameterize depositional growth of ice crystal are tested using Koenig and Takahashi parameters in modeling China pre-summer torrential rainfall event. The Krueger scheme with the Takahashi parameter produces the closest simulations to the observations because it increases cloud ice and snow in the upper troposphere. The increased ice hydrometeor enhances and suppresses infrared radiative cooling above and below 12 km, respectively. The suppressed infrared cooling reduces net condensation while the enhanced infrared cooling suppresses hydrometeor loss through the reduction in melting of ice hydrometeor.

Keywords: depositional growth of ice crystal; parameterization schemes; cloud and rainfall response; infrared radiative cooling; cloud-resolving model simulation

1. Introduction

One of the greatest uncertainties in global and regional climate modeling comes from the presentation of clouds and associated microphysical processes (e.g. Cess et al., 1997). One way to reduce such uncertainties is to use cloud-resolving models with fine spatial resolutions and explicit microphysical parameterization schemes. However, there are uncertainties associated with simulations of ice anvil clouds, the important part of cloud systems. Ice hydrometeors are the major players in producing precipitation through the melting of precipitation ice and in regulating radiative energy balance through the reflection of incoming solar radiation back to the space and prevention of emitted infrared radiative energy from out of the Earth. The one of uncertain processes in modeling ice clouds may be related to the simulation of the Bergeron–Findeisen (Bergeron, 1935; Findeisen, 1938) process in which water vapor from cloud droplets is transferred to ice crystals due to the fact that the saturation vapor pressure over ice is lower than one over liquid water.

Most of the modern bulk schemes explicitly simulate the Bergeron–Findeisen process directly by calculating the growth rate of ice particles (e.g. Walko et al., 1995; Morrison et al., 2005; Phillips et al., 2007; Thompson et al., 2008). But there are the uncertainties due to the scheme-dependent parameterizations of the Bergeron–Findeisen process such as the depositional growth of snow from cloud ice (PSFI) and the growth of cloud ice by the deposition of cloud water (PIDW). Hsie et al. (1980) used the mass of a natural ice nucleus (1.05 × 10^{-13} g) and the 50 μm radius of ice crystal in the calculations of PIDW and PSFI, respectively, whereas Krueger et al. (1995) replaced a natural ice nucleus with an averaged mass of ice crystal in the calculation of PIDW and increased the radius of ice crystal to 100 μm in the calculation of PSFI. Li et al. (1999) showed that the mixing ratios of cloud ice and snow simulated by the Krueger scheme are significantly larger than those simulated by the Hsie scheme. Zeng et al. (2008) abandoned the assumption that the ice crystal density is independent of the size in above two schemes and proposed a linear relation between the number and mass of ice crystal in the small range of ice crystal radius (less than 50 μm) in the development of new schemes for PSFI and PIDW. The other uncertainties may come from the parameter of Koenig (1971)’s formula that are used in the schemes of PIDW and PSFI. Westbrook and Heymsfield (2011) conducted a comparison study between the parameters from Koenig (1971) and derived by laboratory experiment data from Takahashi and Fukuta (1988) and Takahashi et al. (1991). The significant differences are found in temperature-dependent parameters of depositional growth of a single ice crystal (Koenig, 1971).

The objective of this study is to examine the responses of rainfall, clouds and associated radiation to the changes in schemes that parameterize the Bergeron–Findeisen process. A series of
Table 1. Model setup.

| Prognostic equations | Potential temperature, specific humidity, perturbation zonal wind and vertical velocity, and mixing ratios of five cloud species |
|----------------------|----------------------------------------------------------------------------------------------------------------------------------|
| Cloud microphysical parameterization schemes | Hsie et al. (1980); Lin et al. (1983); Rutledge and Hobbs (1983, 1984); Tao et al. (1989); Krueger et al. (1995) and Zeng et al. (2008) |
| Radiative parameterization schemes | Chou et al. (1991, 1998) and Chou and Suarez (1994) |
| Boundary conditions | Cyclic lateral boundaries; model top is 42 hPa |
| Basic parameter set | Model domain (768 km), horizontal grid (1.5 km), time step (1.5 s) and 33 vertical levels |

Figure 1. Temporal and vertical distribution of (a) vertical velocity (cm s$^{-1}$) and (b) zonal wind (m s$^{-1}$) imposed in the experiments. Ascending motion in (a) and westerly wind in (b) are shaded.
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Figure 2. Parameters \( \log_{10}(a_i) \) and \( a_i \) for Koenig (1971)’s formula \( (dm/dt = a_i m^3) \) as a function of air temperature. Closed and open circles denote the Koenig predicted parameters and the Takahashi laboratory-derived parameters by Westbrook and Heymsfield (2011), respectively. Cross denotes parameters interpolated from the Takahashi laboratory-derived parameters from −22 to −3 °C and the Koenig predicted parameters from −31 to −23 °C and −2 to −1 °C, which are used in H80T, K80T and Z80T.

two-dimensional cloud-resolving sensitivity experiments of pre-summer torrential rainfall event occurred during June 2008 will be conducted using different bulk schemes of depositional growth of ice crystal with Koenig to Takahashi parameter. In the next section, model, and control and sensitivity experiments are described. The results are presented in Section 3. A summary is given in Section 4.

2. Model and experiments

The model used here is the version of Goddard Cumulus Ensemble Model developed by Soong and Ogura (1980); Soong and Tao (1980) and Tao and Simpson (1993) and modified by Sui et al. (1994, 1998) and Li et al. (1999). The model was used to study pre-summer torrential rainfall event over southern China during June 2008 (Wang et al., 2010; Shen et al., 2011b). Before convection occurred, the subtropical high extended westward and southwesterly winds were strong. Warm and humid air transported by southwesterly winds encountered cold air from the north over southern China. A trough moved into southern China to trigger the development of a squall-line convection, which causes torrential rainfall. The maximum rain amount of 482.2 mm occurred in Yangjiang, Guangdong on 6 June. The maximum hourly rain rate was 51.3 mm h\(^{-1}\). The surface southerly winds increased to 15 m s\(^{-1}\). The model setup used in this study is summarized by Table 1. The two-dimensional framework is used in this study because of similarities in two- and three-dimensional model simulations in terms of thermodynamics, surface heat fluxes, rainfall, precipitation efficiency and vertical transports of mass, sensible heat and moisture (e.g. Tao and Soong, 1986; Tao et al., 1987; Grabowski et al., 1998; Tompkins, 2000; Khairoutdinov and Randall, 2003; Sui et al., 2005). Detailed model dynamic framework and associated physical package can be found in Gao and Li (2008) and Li and Gao (2011). All experiments are integrated from 0200 local standard time (LST= UTC + 8h) 3 June to 0200 LST 8 June 2008 (a total of 5 days).

Table 2. Summary of schemes that parameterize the growth of cloud ice by the deposition of cloud water \( (P_{\text{DW}}) \) and the depositional growth of snow from cloud ice \( (P_{\text{SI}}) \).

| Scheme | Description |
|--------|-------------|
| Hsie et al. (1980) | \( P_{\text{DW}} = \frac{n_k \Delta t}{\rho \Delta t} a_i (m_i) \), \( P_{\text{SI}} = \frac{\Delta t}{\partial m_i} \), where \( n_k = 10^{-9} \text{m}^{-1} \), \( T_f = 0^\circ \text{C} \), \( m_i = 1.05 \times 10^{-15} \text{g} \), \( \rho \) is the air density which only is a function of height; \( a_i \) and \( a_s \) are the positive temperature-dependent coefficients. \( q_i \) is the mixing ratio of cloud ice; \( \Delta t_i = \left( m_{I50}^b - m_{I40}^a \right) / a_i \) is the timescale needed for a crystal to grow from radius \( r_{I50} \) to \( r_{I40} = 4.8 \times 10^{-15} \text{g} \) is the mass of an ice crystal \( m_{I50} = 50 \mu \text{m} \) and \( m_{I40} = 2.46 \times 10^{-15} \text{g} \) is the mass of an ice crystal \( r_{I40} = 40 \mu \text{m} \). |
| Krueger et al. (1995) | \( P_{\text{DW}} = \frac{n_k \Delta t}{\rho \Delta t} a_i \left( \frac{m_i}{m_i} \right) \), \( P_{\text{SI}} = \frac{\Delta t}{\partial m_i} \), where \( \Delta t_i = \left( m_{I100}^b - m_{I80}^a \right) / a_i \) is the timescale needed for a crystal to grow from radius \( r_{I100} \) to \( r_{I80} = 3.84 \times 10^{-15} \text{g} \) is the mass of an ice crystal \( m_{I100} = 10 \mu \text{m} \) and \( m_{I80} = 2.4 \times 10^{-15} \text{g} \) is the mass of an ice crystal \( r_{I80} = 8 \mu \text{m} \). |
| Zeng et al. (2008) | \( P_{\text{DW}} = \frac{n_k \Delta t}{\rho \Delta t} \left[ a_i \left( 1 - a_s \right) m_{I80} \mu_{\text{FW}} N_i \right] / \left( s_b + s_a \right) \), \( P_{\text{SI}} = \left( 2a_i \left( 1 - a_s \right) m_{I80} \mu_{\text{FW}} N_i \right) / \left( s_b + s_a \right) \), where \( N_i = n_k \rho \varphi(t - 1) \), \( \beta \) varies from 0.4 to 0.6, and \( n_k \) varies from \( 10^{-9} \) to \( 10^{-6} \) cm\(^{-3}\). (Fletcher, 1962); \( \mu (1.2) \) is the ice particle enhancement factor due to a riming–splintering mechanism (Hallet and Mossop, 1974). |
The model is imposed with the large-scale vertical velocity and zonal wind (Figure 1) as well as horizontal advections (not shown) averaged over 108°–116°E, 21°–22°N. The experiment (K95K in this study) has been validated with rain gauge observation and temperature and specific humidity data from National Centers for Environmental Prediction/Global Data Assimilation System (NCEP/GDAS) (Wang et al., 2010; Shen et al., 2011b). The experiments have been conducted to study thermodynamic aspect of precipitation efficiency (Shen and Li, 2011) and the responses of pre-summer torrential rainfall to vertical wind shear (Shen et al., 2013) and cloud radiative processes (Shen et al., 2011b) and ice (Wang et al., 2010; Shen et al., 2011c) and water (Shen et al., 2011a) clouds and ice microphysical processes (Shen et al., 2012).

The temperature-dependent parameters (a₁ and a₂) of Koenig formula for simulating the Bergeron–Findeisen process,

\[ \frac{dm}{dt} = a_1 m^{a_2} \]

where m is mass of a single ice crystal. Figure 2 shows the two parameters as a function of air temperature. The differences between Koenig prediction and Takahashi laboratory data reach their peaks for both parameters at −14.4°C, where the Takahashi experiment-derived a₁ is about two orders of magnitudes larger than the Koenig predicted a₁ and the Takahashi experiment-derived a₂ also is larger than the Koenig predicted a₂. Takahashi parameter is smaller than the Koenig parameter when temperatures vary from −3.7 to −10.2°C and from −18.2 to −22.0°C.

Three pairs of sensitivity experiments that use schemes of Hsie et al. (1980; H80), Krueger et al. (1995; K95) and Zeng et al. (2008; Z08) will be carried out. The three parameterization schemes are briefly described in Table 2. Each pair of experiments use the Koenig parameter (Koenig, 1971) and Takahashi parameter derived by Westbrook and Heymsfield (2011) using the laboratory data from Takahashi and Fukuta (1988) and Takahashi et al. (1991). The experiment designs are summarized in Table 3.

Note that the Takahashi parameter is interpolated at 1°C interval from −22 to −3°C, which is used in H80T, K80T and Z08T. The Koenig parameter from −31 to −23°C and from −2 to −1°C is used in the experiments.

### 3. Results

Before the model responses to schemes and parameters of P_{SPI} and P_{IDW} are examined, the vertical profiles of P_{SPI} and P_{IDW} are calculated using the vertical profiles of cloud ice mixing ratio and air temperature at a zonal grid point of 482 and 1000 LST 6 June 2008 in K95K. Solid, short dash and long dash lines denote H80, K95 and Z08, respectively. Red and blue lines denote calculations with the Koenig predicted parameters (K) and the Takahashi laboratory-derived parameters (T), respectively. The values of P_{IDW} in H80K, H80T and K95K are not shown in (b) because of negligibly small values.

![Figure 3](image)

**Figure 3.** Vertical profiles of (a) P_{SPI} (g kg⁻¹ h⁻¹) and (b) P_{IDW} (10⁻² g kg⁻¹ h⁻¹) calculated using vertical profiles of cloud ice mixing ratio and air temperature at a zonal grid point of 482 and 1000 LST 6 June 2008 in K95K. Solid, short dash and long dash lines denote H80, K95 and Z08, respectively. Red and blue lines denote calculations with the Koenig predicted parameters (K) and the Takahashi laboratory-derived parameters (T), respectively. The values of P_{IDW} in H80K, H80T and K95K are not shown in (b) because of negligibly small values.
domain mean analysis reveals that $P_{\text{SFI}}$ is at least two orders of magnitudes larger than $P_{\text{IDW}}$ (Table 4). The Takahashi parameter generally increases depositional growth of snow from cloud ice except that it barely changes $P_{\text{SFI}}$ in the Hsie scheme.

The surface rain rate, temperature and specific humidity are compared with rain gauge data and NCEP/GDAS data, respectively. Their root mean squared differences (RMSD) between simulations and with rain gauge data and NCEP/GDAS data show that the RMSDs generally increase from H80K and Z08K to H80T and Z08T, respectively, whereas they decrease from K95K to K95T (Table 5). K95T has the smallest RMSDs among the six simulations for surface rain rate, temperature and specific humidity. This indicates that the Krueger scheme with the Takahashi parameter produces the best cloud-resolving model simulations.

The 5-day and model domain mean surface rain rates are lower in the simulations with the Takahashi parameter than those in the simulations with the Koenig parameter (Table 6). The largest decrease in the mean rain rate occurs from K95K to K95T, among the three pairs of simulations. Because all the mean simulated rain rates are higher than the mean observed rain rate, the mean rain rate simulated in K95T appears to be the closest to the mean observed rain rate, which is consistent with the analysis of the RMSD. The mean rain rates decrease from H80K and K95K to H80T and K95T, respectively, whereas Z08K and Z08T have similar mean rain rates (Table 6). To examine the change in the mean rain rate from the experiment with the Koenig parameter to the experiment with the Takahashi parameter, cloud budget is analyzed. Following Gao et al. (2005) and Cui and Li (2006), the model domain mean mass-integrated cloud budget is expressed by

$$P_s = Q_{\text{NC}} + Q_{\text{CM}}$$

where

$$Q_{\text{NC}} = \dot{S}q_v$$

and

$$Q_{\text{CM}} = -\frac{\partial q_v}{\partial t}$$

Here $Q_{\text{NC}}$ is the net condensation ($S_qv > 0$) or evaporation ($S_qv < 0$) [see (1.2b) in Li and Gao (2011)]; $Q_{\text{CM}}$ is the hydrometeor loss ($Q_{\text{CM}} > 0$) or gain ($Q_{\text{CM}} < 0$) since advection term is canceled due to the cyclic lateral boundary condition in the model used in this study; total hydrometeor mixing ratio $q_v$ is the sum of mixing ratios of cloud water ($q_c$), raindrops ($q_r$), cloud ice ($q_i$), snow ($q_s$) and graupel ($q_g$).

The decrease in the mean rain rate from H80K to H80T is mainly associated with the reduction in the mean net condensation (Table 6). The decrease in the mean rain rate from K95K to K95T is related to both the suppressions in the mean net condensation and the mean hydrometeor loss ($Q_{\text{CM}} > 0$). The increase in the mean net condensation from Z08K to Z08T is offset by the decrease in the mean hydrometeor loss, which leads to the similar rain rates in the two experiments. The decrease in the mean rain rate from K95K to K95T is larger than that from H80K to H80T because the reduction in the mean hydrometeor loss from K95K to K95T is larger than that from H80K to H80T because the reduction in the mean hydrometeor loss from K95K to K95T is larger than that from K95K to K95T.

| Table 4. $P_{\text{SFI}}$ and $P_{\text{IDW}}$ averaged for 5 days over model domain in H80K, H80T, K95K, K95T, Z08K and Z08T. |
|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|
| $P_{\text{SFI}}$ | 3.18      | 3.16      | 1.42      | 1.81      | 4.44      | 4.66      |
| $P_{\text{IDW}}$| 0.00      | 0.00      | 0.00      | 0.00      | 0.03      | 0.03      |

Unit is mm day$^{-1}$.

| Table 5. Root mean squared differences in surface rain rate (RMSDP$_s$), temperature (RMSDT) and specific humidity (RMSD$$_{qv}$) between simulations and with rain gauge data and NCEP/GDAS data. |
|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|
|                | H80K      | H80T      | K95K      | K95T      | Z08K      | Z08T      |
| RMSDP$_s$       | 25.27     | 26.91     | 25.41     | 24.59     | 25.19     | 27.01     |
| RMSDT           | 0.65      | 0.69      | 0.65      | 0.61      | 0.69      | 0.72      |
| RMSD$q_v$       | 0.42      | 0.43      | 0.41      | 0.35      | 0.44      | 0.42      |

Units are mm day$^{-1}$ for surface rain rate, °C for temperature and g kg$^{-1}$ for specific humidity. RMSDP$_s$ is calculated using hourly data whereas RMSDT and RMSD$q_v$ are calculated using 6-h data.

| Table 6. (a) Cloud microphysical budgets ($P_s$, $Q_{\text{NC}}$, and $Q_{\text{CM}}$) averaged for 5 days over model domain in H80K, H80T, K95K, K95T, Z08K and Z08T and (b) their differences averaged over 5 days and model domain. |
|-----------------|-----------|-----------|-----------|-----------|-----------|-----------|
|                | H80K      | H80T      | K95K      | K95T      | Z08T      | Z08K      |
| $P_s$           | 32.86     | 32.33     | 32.74     | 31.96     | 33.08     | 32.96     |
| $Q_{\text{NC}}$| 32.16     | 31.70     | 31.99     | 31.67     | 31.54     | 32.45     |
| $Q_{\text{CM}}$| 0.69      | 0.63      | 0.75      | 0.28      | 1.54      | 0.52      |

(b) H80T–H80K, K95T–K95K, Z08T–Z08K

|                | H80T–H80K | K95T–K95K | Z08T–Z08K |
|----------------|-----------|-----------|-----------|
| $P_s$           | -0.53     | -0.78     | -0.12     |
| $Q_{\text{NC}}$| -0.46     | -0.32     | 0.91      |
| $Q_{\text{CM}}$| -0.06     | -0.47     | -1.02     |

The observed 5-day mean rain rate is 29.23 mm day$^{-1}$. Unit is mm day$^{-1}$. Where

$$Q_{\text{CM}} = Q_{\text{CMR}} + Q_{\text{CMI}} + Q_{\text{CMS}} + Q_{\text{CMG}}$$

where

$$Q_{\text{CMI}} = -\frac{\partial q_i}{\partial t} = -\dot{S}q_i$$

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Here, $S_{qc}$, $S_{qr}$, $S_{qi}$, $S_{qs}$ and $S_{qg}$ are sources and sinks of cloud water, raindrops, cloud ice, snow and graupel, respectively [see (1.2c – 1.2g) in Li and Gao (2011)], and $S_{qc} + S_{qr} + S_{qi} + S_{qs} + S_{qg} = S_{qv}$. The mean cloud water is changed from the loss in H80K to the gain in H80T, whereas the mean cloud water gain is enhanced from K95K to K95T (Table 8). The mean raindrops loss is enhanced from H80K to H80T, whereas the mean raindrops gain in K95K is changed to the raindrops loss in K95T. The change in the mean cloud ice from the loss in K95K to the gain in K95T becomes larger than that from the loss in H80K to the gain in H80T. The mean snow loss is intensified from H80K to H80T, but the weak mean snow gain is barely changed from K95K to K95T. The mean graupel is changed from the gain in H80K to the loss in H80T, whereas the mean graupel loss is enhanced from K95K to K95T. Thus, the reduction brought by use of the Takahashi parameter weakened from the Hsie scheme to the Krueger scheme is associated with the changes in $Q_{CMI}$, $Q_{CMS}$ and $Q_{CMG}$. Following Li and Gao (2011), the sum of $Q_{CMI}$, $Q_{CMS}$ and $Q_{CMG}$ [(3c) + (3d) + (3e)] can be further written as

\[
\begin{align*}
Q_{CMI} + Q_{CMS} + Q_{CMG} &= - (S_{qi} + S_{qs} + S_{qg}) \\
&= - P_{HIOM} (T < T_{oo}) + P_{IMLT} (T > T_{oo}) \\
&- P_{IDW} (T_{oo} < T < T_{oo}) - P_{DEP} - P_{SACW} (T < T_{oo}) \\
&- P_{SFW} (T < T_{oo}) + P_{RACS} (T > T_{oo}) + P_{SMLT} (T > T_{oo}) \\
&- P_{SDEP} (T < T_{oo}) + P_{MLTS} (T > T_{oo}) - P_{GACR} (T < T_{oo}) \\
&- P_{JACR} (T < T_{oo}) - P_{GACR} (T < T_{oo}) - P_{GFR} (T < T_{oo}) \\
&+ P_{GMLT} (T > T_{oo}) + P_{GDEP} (T < T_{oo}) + P_{MLTG} (T > T_{oo}) \\
&- P_{SACR} (T < T_{oo})
\end{align*}
\]

Here, $T_{oo} = 0^\circ C$ and $T_{oo} = -35^\circ C$. The cloud microphysical terms in (Equation (4)) are defined in Table 7. The mean ice hydrometer (sum of cloud ice, snow and graupel) is changed from the gain in H80K to the loss in H80T, but its loss is suppressed from K95K to K95T (Table 9), which leads to the enhanced reduction in the mean hydrometer loss (Table 8). Further breakdown of ice hydrometer into ice microphysical terms in Table 9 reveals the melting of cloud ice to cloud water ($P_{IMLT}$) only occurs in K95K, which leads to reduction in $P_{IMLT}$ from K95K to K95T. The melting of graupel to raindrops ($P_{GMLT}$) is enhanced from H80K to H80T,
but it is suppressed from K95K to K95T. This indicates that the change in the melting of ice hydrometeor to water hydrometeor (sum of cloud water and raindrops) brought by use of the Takahashi parameter from the increase in the Hsie scheme to the decrease in the Krueger scheme is responsible for the enhanced reduction in the mean hydrometeor loss from the Hsie scheme to the Krueger scheme. The Koenig and the Takahashi parameters affect vertical profile of radiation by changing vertical structures of cloud hydrometeors, which in turn changes the mean net condensation and hydrometeor loss. Thus, the vertical profiles of mixing ratios of cloud hydrometeor and radiation are averaged over 5 days and model domain and their differences between H80T and H80K, K95T and K95H and Z08T and Z08K are shown in Figures 4 and 5, respectively. The radiation here is calculated using $Q_R/c_p$, where $Q_R$ is the radiative heating rate due to convergence of net flux of solar and infrared radiative fluxes and $c_p$ is the specific heat of dry air at constant pressure. The increase in snow mixing ratio from H80K to H80T (Figure 4(a)) mainly weakens the mean infrared radiative cooling below 6 km (Figure 5(a)), while the reduction in graupel mixing ratio enhances the mean infrared radiative cooling above 6 km. The water mixing ratios decrease from H80K to H80T. The enhanced mean melting of graupel to raindrops from H80K to H80T corresponds to the suppressed mean infrared radiative cooling below 6 km.

The enhanced cloud ice and snow mixing ratios from K95K to K95T (Figure 4(b)) weakens the mean infrared radiative cooling below 12 km (Figure 5(b)). The mixing ratios generally decrease from H80K to H80T except for the increase in raindrops mixing ratio around 5 km. The decreases in the mean melting of cloud ice and graupel from K95K to K95T is associated with the strengthened mean infrared radiative cooling above 12 km. The reduction in mean net condensation from K95K to K95T corresponds to the suppressed mean infrared radiative cooling below 12 km.

The decrease in graupel mixing ratio from Z08K to Z08T is stronger than the increase in snow mixing ratio from 4 to 8 km and the reduction in snow mixing ratio occurs from 8 to 11 km (Figure 4(c)), which leads to the increase in the mean infrared radiative cooling above 4 km (Figure 5(c)). The water mixing ratios increases from Z08K to Z08T. The increase in the mean net condensation from Z08K to Z08T corresponds to the enhancement in the mean infrared radiative cooling.

### Table 8. Breakdown of $Q_{CM}$ in H80K, H80T, K95K and K95T and their differences averaged over 5 days and model domain.

|            | H80K | H80T | K95K | K95T | H80T–K80K | K95T–K95K |
|------------|------|------|------|------|-----------|-----------|
| $Q_{CM}$   | 0.69 | 0.63 | 0.75 | 0.28 | −0.06     | −0.47     |
| $Q_{CHIC}$ | 0.34 | −0.66 | −0.03 | −0.59 | −1.00     | −0.56     |
| $Q_{CHIR}$ | 0.58 | 0.86 | −0.12 | 0.23  | 0.28      | 0.35      |
| $Q_{CHI}$  | 0.09 | −0.07 | 0.50  | −0.10 | −0.16     | −0.60     |
| $Q_{CHS}$  | 0.10 | 0.40 | −0.10 | −0.06 | 0.30      | 0.04      |
| $Q_{CHG}$  | −0.42 | 0.09 | 0.51  | 0.80  | 0.51      | 0.29      |

Unit is mm day$^{-1}$.

### Table 9. Breakdown of $Q_{CM} + Q_{CMS} + Q_{CMG}$ in H80K, H80T, K95K and K95T and their differences averaged over 5 days and model domain.

|            | H80K | H80T | K95K | K95T | H80T–K80K | K95T–K95K |
|------------|------|------|------|------|-----------|-----------|
| $Q_{CM} + Q_{CMS} + Q_{CMG}$ | −0.23 | 0.42 | 0.91 | 0.64 | 0.65      | −0.27     |
| $-P_{HOM}$ | −0.02 | −0.02 | −0.07 | −0.05 | 0.00      | 0.02      |
| $P_{MLT}$  | 0.00  | 0.00  | 0.84  | 0.00  | 0.00      | −0.84     |
| $-P_{CEP}$ | −6.87 | −2.02 | −6.81 | −6.78 | −0.15     | 0.03      |
| $-P_{TACW}$ | −2.03 | −1.97 | −2.12 | −2.05 | 0.06      | 0.07      |
| $-P_{TAC}$ | −0.28 | −0.24 | −0.02 | −0.03 | 0.04      | −0.01     |
| $P_{RAC}$  | 0.32  | 0.47  | 0.13  | 0.12  | 0.15      | −0.01     |
| $P_{GLT}$  | 0.55  | 0.57  | 0.64  | 0.62  | 0.02      | −0.02     |
| $-P_{DEP}$ | −1.11 | −1.17 | −1.14 | −1.23 | −0.06     | −0.09     |
| $P_{METS}$ | 0.04  | 0.04  | 0.04  | 0.05  | 0.00      | 0.01      |
| $-P_{TACW}$ | −9.50 | −9.02 | −9.21 | −8.65 | 0.48      | 0.56      |
| $-P_{TAC}$ | −0.48 | −0.42 | −0.39 | −0.29 | 0.06      | 0.10      |
| $-P_{TAC}$ | −0.17 | −0.36 | −0.37 | −0.09 | −0.19     | 0.28      |
| $P_{GLT}$  | 20.01 | 20.42 | 20.30 | 19.67 | 0.41      | −0.63     |
| $-P_{DEP}$ | −1.24 | −1.23 | −1.20 | −1.23 | −0.01     | −0.03     |
| $P_{METS}$ | 0.77  | 0.76  | 0.71  | 0.64  | −0.01     | −0.07     |
| $-P_{TAC}$ | −0.22 | −0.37 | −0.41 | −0.05 | −0.15     | 0.36      |

Unit is mm day$^{-1}$.

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Zeng et al., 2008 (Z08)] and the two parameter sets [Koenig (K) and Takahashi (T)]. The pre-summer torrential rainfall event occurred over southern China during June 2008 is chosen as the simulated rainfall case in this study. The major results include the followings:

- The analysis of RMSD in surface rain rate, temperature and specific humidity between the simulations and observations shows that the experiment K95T produces the best simulation.

- The calculations of 5-day and model domain mean rain rates reveal that the three schemes with the Takahashi parameter tend to reduce the mean rain rate compared to the three schemes with Koenig parameter. K95T generates the closest mean rain rate to the mean observational rain rate due to the largest decrease from K95K to K95T among the three pairs of experiments.

- The reduction in the rain rate enhanced by use of the Takahashi parameter from the Hsie scheme to the Krueger scheme corresponds to the strengthened slowdown in hydrometeor loss; it is related to the change in the melting of ice hydrometeor from the increase associated with the weakened infrared radiative cooling below 6 km brought by use of the Takahashi parameter in the Hsie scheme to the decrease associated with enhanced infrared radiative cooling above 12 km in the Krueger scheme.

- The reduction in the rain rate enhanced by use of the Takahashi parameter from the Zeng scheme to the Krueger scheme corresponds to the change in net condensation from the increase associated with the strengthened infrared radiative cooling in the Zeng scheme to the decrease associated with weakened infrared radiative cooling in the Krueger scheme.

The Takahashi parameter has been linearly interpolated into the model in this study, which may cause uncertainty. But the uncertainties may not be important compared to the uncertainties caused by different schemes listed in Table 2. The tests are carried out using the two-dimensional model only for one torrential rainfall event in this study. Therefore, further tests are required using three-dimensional cloud-resolving models for more torrential rainfall events under different environmental thermodynamic conditions to generalize the results from this study.
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