Effects of Liquid Phase Cloud Microphysical Processes in Mixed Phase Cumulus Clouds over the Tibetan Plateau

Xiaoqi Xu¹, Chunsong Lu¹*, Yangang Liu²*, Wenhua Gao³, Yuan Wang¹, Yueming Cheng¹, Shi Luo¹, Kwinten Van Weverberg⁴

1. Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing, China

2. Environmental and Climate Sciences Department, Brookhaven National Laboratory, Upton, US

3. State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, China

4. Met Office, Exeter, UK

* Correspondence: luchunsong110@gmail.com; lvg@bnl.gov
Key points:

1. The accretion process plays more important roles than other examined liquid-phase processes.

2. Considering raindrop size in accretion process suppresses liquid-phase rain and mitigates the overprediction of precipitation over the TP.

3. Increasing the model resolution can reduce precipitation overprediction.
Abstract
Numerical simulations often overpredict precipitation over the Tibetan Plateau. To examine the factors causing precipitation overprediction, a typical summer plateau precipitation event is simulated with the Weather Research and Forecasting (WRF) model by exploring different parameterizations of liquid-phase microphysical processes into the commonly used Morrison scheme, including autoconversion, accretion, and entrainment-mixing. All simulations can reproduce the general spatial distribution and temporal variation of precipitation, but overpredict precipitation rate. The results show that the accretion process is more important than other examined liquid-phase processes in simulating precipitation. Further investigation reveals that accretion parameterization that takes into account the raindrop size produces the most accurate results in terms of the total surface precipitation, which is supported by the Heidke skill scores. Such parameterizations suppress spurious accretion and liquid-phase precipitation when cloud droplets are too small to initiate precipitation. It is also confirmed that increasing the model resolution can reduce precipitation overprediction. Results from the case study are confirmed by use of a one-month simulation.
1. Introduction

The Tibetan Plateau (TP) is the highest and largest plateau of the world with an average elevation of more than 4 km above the sea level and an area larger than $2.5 \times 10^6$ km$^2$. Its active exchanges of heat and moisture have significant influences on climate and environmental change, not only in China but also over East Asia and even the entire northern hemisphere through strong thermal and dynamic forcing (Yeh, 1950; Flohn, 1957; Hahn and Manabe, 1975; Ye, 1981; Wu and Chen, 1985; Yanai et al., 1992; Ding et al., 2001; Wang et al., 2008; Molnar et al., 2010; Yang et al., 2014; Qie et al., 2005; Fu et al., 2006; Li and Zhang, 2017; Li et al., 2020). Many studies have reported that the tropospheric heating over the TP has decisive effects on the maintenance of the Asian summer monsoon (Luo and Yanai, 1983; 1984; Ueda and Yasunari, 1998). The upward transport of sensible heat and the release of latent heat due to convective clouds are important heat sources in the upper troposphere, driving the summer monsoon and associated precipitation (Nitta, 1983; Luo and Yanai, 1984; Yanai and Li, 1994; Ueda et al., 2003; Hsu and Liu, 2003; Fan et al., 2013; Jiang et al., 2004; Li et al., 2013).

During the summer monsoon, deep convection develops over the TP with a marked diurnal cycle in precipitation (Fujinami and Yasunari, 2001; Kurosaki and Kimura, 2002; Chen et al., 2017a), frequently associated with mesoscale vortices (Shen et al., 1986; Wang et al., 1993; Li et al., 2008b). Summer precipitation on the plateau can be characterized by frequent, but rather weak convection (Li et al., 2008b; Li and Zhang, 2016; Gao et al., 2016; Chen et al., 2017a). Undoubtedly, these characteristics are
heavily influenced by the unique terrain of the TP (Porcù et al., 2014; Chen et al., 2017b; Wu and Liu, 2017).

The particularity of the TP makes it one of the most challenging areas for precipitation simulation. Many studies find simulated precipitation to be overpredicted (Maussion et al., 2011; Xu et al., 2012; Gao et al., 2016). There are several reasons for this overprediction, including model resolution (Sato et al., 2008, Xu et al., 2012) and the initial and boundary conditions (Gerken et al., 2013). Moreover, the assumptions in the parameterization of microphysics could be another culprit for the overprediction of precipitation over the TP region. Maussion et al. (2011) found a significant sensitivity to changing the microphysics parameterization for convective precipitation over the TP. They compared different physical schemes with different statistical evaluation scores and the results showed that the effects of microphysics schemes were larger than other physical schemes including cumulus schemes, land surface schemes, and boundary-layer schemes.

The high elevation of the TP, and hence the typically low melting level, enables plenty of supercooled liquid water, even in summer (Gao et al., 2016; Zhao et al., 2017; Tang et al., 2019). Therefore, it is likely that liquid precipitation processes play a role in the precipitation overestimation in this region. For instance, Zhao et al. (2017) confirmed that supercooled cloud water dominated in precipitating cumulus clouds over the Naqu area at a temperature of -2.5 to -3.5°C. By analyzing the raindrop size distribution at Maqu over the TP, Li et al. (2006) argued that liquid-phase processes
were important for surface precipitation, despite dominant ice/mixed-phase rain processes over the region. Gao et al. (2016) investigated the role of liquid-phase processes by excluding ice-phase microphysics, doubling the condensation rate, halving the evaporation rate and increasing the initial droplet radius, and found significant effects from all these sensitivity tests on the surface precipitation; they also suggested that liquid-phase rain processes could be more important than ice-phase processes over the precipitation cores during weak convection over the TP.

However, it is still unknown how liquid-phase processes affect precipitation over the TP, and whether improving the parameterizations of liquid-phase processes can mitigate the problem of overpredicted precipitation. Also unknown is which liquid-phase process is the most important in affecting TP precipitation, and which parameterization can best describe the most important process and why. This study fills these gaps by comparing simulations of a typical precipitation event over the TP with different parameterizations of autoconversion, accretion, and entrainment-mixing processes (hereafter referred to as liquid-phase processes for convenience) and dissecting the underlying physical mechanisms. This is done using a case study, as well as a one-month simulation. Moreover, the impact of model resolution is investigated following Sato et al. (2008) and Xu et al. (2012).

Three parameterized liquid-phase processes related to precipitation are investigated in this paper: autoconversion, accretion, and entrainment-mixing. These three processes are likely to be intertwined. It is expected that accretion and ice/mixed-
phase processes matter in the precipitation events over TP. But also, autoconversion and
entrainment-mixing process may be important. The reason is that accretion is the
collection process between liquid raindrops and cloud droplets, and the number
concentration and size of liquid droplets are affected by autoconversion and
entrainment-mixing process. Autoconversion is expressed as the mass conversion rate
from cloud to rain due to the collision-coalescence of cloud droplets while accretion is
defined as the rate of mass conversion from cloud to rain due to the collection of cloud
droplets by raindrops (Wood et al., 2009; White et al., 2017; Liu and Daum, 2004; Liu
et al., 2011; Jing et al., 2019; Fan et al., 2016; Wang et al., 2019b). The sum of
autoconversion and accretion is calculated as the total mass conversion from cloud to
raindrop populations during the collision-coalescence process (Wood, 2005b). Wang et
al. (2012) and Gettelman et al. (2013) highlighted that autoconversion was important
for the initiation of precipitation whereas accretion was responsible for the amount of
precipitation. The process of entrainment and mixing between cloud and environment
is one of the most uncertain processes in cloud physics (Kollias and Albrecht, 2000;
Grabowski, 2006; Lu et al., 2013; Hoffmann and Feingold, 2019; Gao et al., 2020). The
key issue of the entrainment-mixing process is whether evaporation due to mixing
causes a reduction of only droplet size (homogeneous mixing), only droplet number
(extremely inhomogeneous mixing), or both. Therefore, different entrainment-mixing
mechanisms can affect cloud microphysical properties and hence cloud-related
processes such as radiation and precipitation (Lasher-Trapp et al., 2005; Grabowski,
This paper is organized as follows: A brief introduction of the precipitation event and experimental setup are given in section 2. Section 3 discusses the influences of liquid-phase processes on precipitation overprediction and underlying physical mechanisms. Section 4 extends the case study to one-month simulations. The effects of resolutions on precipitation overprediction are discussed in section 5. Section 6 presents the summary and conclusions.

2. Precipitation event, experiment description, and method

2.1 Case description and observations

As mentioned in Gao et al. (2016), the entire plateau experienced a large frontal system from 21 to 23 July 2014 and observed precipitation initiated at 0400 UTC (Coordinated Universal Time) 22 July. The motivation of using this case is that WRF can capture the main precipitation pattern (Gao et al., 2016). Gao et al. (2016) and this study focus on different periods and different scientific questions. As mentioned in the introduction, Gao et al. (2016) studied the sensitivity of precipitation to doubling droplet concentration, halving raindrop evaporation, and increasing initial cloud droplet size. This study focuses on different parameterizations of autoconversion, accretion, and entrainment-mixing. The simulations are compared against the precipitation dataset that Ma et al. (2018) derived from sparse gauge observations and multiple satellite precipitation datasets, including Tropical Rainfall Measuring Mission (TRMM)
Multisatellite Precipitation Analysis (TMPA) 3B42RT and 3B42V7 (Huffman et al., 2007), Climate Prediction Center MORPHing technique (CMORPH) (Joyce et al., 2004) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN-CDR) (Ashouri et al., 2015). This rain gauge dataset developed by Ma et al. (2018) is more accurate than individual gauges for complex terrains such as the TP region. This dataset also has higher spatial (0.1°) and temporal (1 h) resolution than TRMM, which is usually used in this region (Fu et al., 2007; Yin et al., 2008; Maussion et al., 2011; Xu et al., 2012; Qie et al., 2014).

2.2 Model and experiment description

The WRF model version 3.8.1 is used to simulate this typical summer TP precipitation event. The WRF model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. Here, WRF is used as a cloud-resolving model with 1 km horizontal grid spacing for the innermost domain (referred to as domain 03) with 276×276×45 grid points, which covers most of the plateau center; the spatial resolutions for the two outer domains (01 and 02) are 25 km and 5 km with 200×200×45 and 176×176×45 grid points, respectively (Figure 1). Initial and boundary conditions are provided by the National Center for Environmental Prediction Final operational global analysis data with 1° spatial and 6 h temporal resolution. The simulation starts at 1200 UTC 21 July and ends at 0000 UTC 24 July, with a total of 60 h integration time. We focus on the
The microphysics scheme used in the control run is the Morrison double-moment scheme (Morrison and Grabowski, 2008). Note that this bulk scheme is different from the default version released in the WRF model with a fixed cloud droplet number concentration \(N_c\) (e.g. \(N_c = 250 \text{ cm}^{-3}\)). This version can predict the number concentration and mass mixing ratios of cloud droplets \((N_c, q_c)\), raindrops \((N_r, q_r)\), ice crystals \((N_i, q_i)\), snow particles \((N_s, q_s)\), and graupel particles \((N_g, q_g)\) followed Morrison et al. (2005). The main liquid-phase conversion processes, i.e. autoconversion rate \(A_u\); kg/kg/s) and accretion rate \(A_c\); kg/kg/s), are both based on Khairoutdinov and Kogan (2000), further referred to as the KK00 schemes:

\[
A_u = 1350 \times q_c^{2.47} (N_c \times 10^{-6} \times \rho_a)^{-1.79}, \tag{1}
\]

\[
A_c = 67 \times (q_c q_r)^{1.15}, \tag{2}
\]

where \(\rho_a\) is the air density.

To explore the influence of liquid-phase cloud microphysical processes in mixed-phase clouds, we implement several different expressions for autoconversion, accretion, and entrainment-mixing into the Morrison scheme, and examine the model sensitivity.

In addition to the default KK00 schemes, three commonly-used autoconversion schemes are employed and referred to as Be68, Bh94, and LD04 for convenience, respectively:

1) Be68:

\[
A_u = \frac{3.5 \times 10^{-2} q_c^2}{0.12 + 1.0 \times 10^{-12} N_c^{q_c}}, \tag{3}
\]
This is the default scheme in several global climate models, such as Model for Interdisciplinary Research on Climate version 5 (MIROC5; Michibata and Takemura, 2015; Jing and Suzuki, 2018).

2) Bh94:

\[ A_u = 6.0 \times 10^{28} n^{-1.7} (q_c \times 10^{-3})^{4.7} (N_c \times 10^{-6})^{-3.3}, \quad (4) \]

where \( n \) is set to 10 in Eq. 4, which is related to the width of cloud droplet size distribution (Beheng, 1994).

3) LD04:

\[ A_u = P_0 T, \quad (5a) \]

\[ P_0 = 1.1 \times 10^{13} \left[ \frac{(1+3\varepsilon^2)(1+4\varepsilon^2)(1+5\varepsilon^2)q_c^3}{(1+\varepsilon^2)(1+2\varepsilon^2)} \right] N_c, \quad (5b) \]

\[ T = \frac{1}{2} (x_c^2 + 2x_c + 2)(1 + x_c)e^{-2x_c}, \quad (5c) \]

\[ x_c = 9.7 \times 10^{-14} N_c^{3/2} q_c^{-2}. \quad (5d) \]

LD04 derived by Liu and Daum (2004) and Liu (2005) considers relative dispersion \( \varepsilon \) (the ratio of the standard deviation to the mean radius) in addition to droplet concentration and liquid water mixing ratio. This scheme was implemented into the WRF double-moment schemes (Xie and Liu, 2011; Xie et al., 2013). \( P_0 \) and \( T \) represent the rate function and threshold function, respectively; \( x_c \) is the normalized critical mass and can be written as a function of \( N_c \) and \( q_c \) (Liu et al., 2005); \( \varepsilon \) is set to 0.4 as the average value based on Zhao et al. (2006) and Wang et al. (2019a).

Considering that most accretion schemes only consider mass mixing ratios of cloud droplets and raindrops (i.e. \( q_c \) and \( q_r \)) (e.g. Beheng, 1994; Khairoutdinov and...
Kogan, 2000; Kogan, 2013), a parameterization that relates the accretion process to liquid droplet number concentration and size is adopted from Cohard and Pinty (2000), named as CP2k:

\[
A_c = \frac{\pi}{6} \rho_w \rho_a K_1 \frac{N_c N_r}{\lambda_c^3} \left( A_1 \lambda_c^3 + B_1 \right),
\]

if \( R_r \geq 50 \mu m \), and

\[
A_c = \frac{\pi}{6} \rho_w \rho_a K_2 \frac{N_c N_r}{\lambda_c^6} \left( A_2 \lambda_c^6 + B_2 \right),
\]

if \( R_r < 50 \mu m \),

(6a)

(6b)

where \( \rho_w \) is the water density; \( R_r \) is the raindrop radius; \( K_1 \) and \( K_2 \) are empirical constants; the subscripts \( c \) and \( r \) denote cloud droplets and raindrops, respectively; \( A_1 \), \( A_2 \), \( B_1 \), and \( B_2 \) are functions related to the two dispersion parameters of the modified Gamma size distribution (Cohard and Pinty, 2000) and their expressions are given in Appendix B; \( \lambda \) is the slope parameter and is derived from the dispersion parameter, number concentration and mixing ratio of the species (see Morrison et al., 2005). Given the specified dispersion parameters for raindrops, \( \lambda_r = (\pi \rho_w N_r / q_r)^{1/3} \) which is inversely proportional to the mean volume radius of the raindrops. Another accretion scheme (Ko13, Kogan, 2013) is also tested:

\[
A_c = 8.53 \times q_c^{1.05} q_r^{0.98},
\]

(7)

A single parameter \( \alpha \) is used to represent the effect of entrainment-mixing process in this microphysical scheme (Morrison and Grabowski, 2008; Lu et al., 2013):

\[
N_c = N_{c0} \left( \frac{q_c}{q_{c0}} \right)^\alpha,
\]

(8)

where the \( N_c \) and \( N_{c0} \) are the number concentrations of cloud water droplets after and
before the evaporation process, respectively; \( q_c \) and \( q_{c0} \) represent the corresponding mixing ratios, respectively. It is noteworthy that \( q_c \) is mainly determined by \( q_{c0} \), relative humidity, air pressure, and temperature when new saturation is achieved after evaporation. The parameter \( \alpha \) can be set to any value between 0 and 1 corresponding to a different degree of the subgrid-scale mixing homogeneity. When \( \alpha = 0 \), homogeneous mixing is assumed (the control run). On the contrary, when \( \alpha = 1 \), extremely inhomogeneous mixing is assumed (the INHOMO run).

In total, we have 7 simulations: the control run with the KK00 schemes for autoconversion and accretion, and homogeneous mixing, and sensitivity tests with three autoconversion schemes (Be68, Bh94, and LD04), two accretion schemes (CP2k and Ko13), and one entrainment-mixing scheme (INHOMO). The case names and corresponding formulations are summarized in Table 1.

### 2.3 Calculations of microphysical/radiative properties

The liquid cloud water path (LCWP) is calculated by

\[
\text{LCWP} = \int_0^H \rho_a q_c(z) dz, \quad (9)
\]

where \( q_c(z) \) is the cloud water mixing ratio at each height \( z \). The equation for cloud optical depth (\( \tau \)) is:

\[
\tau = \frac{3}{2} \frac{1}{\rho_w} \int_0^H \frac{\rho_a q_c(z)}{r_e(z)} dz, \quad (10)
\]

where \( r_e(z) \) is the effective radius of cloud droplets at each height \( z \); the extinction efficiency is assumed to equal to 2 (appropriate at visible wavelengths) (Grabowski,
2006); $H$ is the cloud top height. With equations (9) and (10), the column mean effective radius ($\bar{r}_e$) is given by

$$\bar{r}_e = \frac{3}{2} \frac{LCP}{\rho w^t},$$  

(11)

Note that only the cloud data in the grid boxes with hydrometeor mixing ratios larger than 0.01 g/kg are included.

3. Case study Analysis

3.1 Control run

3.1.1 Precipitation from the control run and observations

The 48 h accumulated precipitation from 0000 UTC 22 July to 0000 UTC 24 July 2014 from the control run over domain 02 and domain 03 are averaged to the resolution of 0.1° to compare with observations (Figure 2). The results from domain 02 indicate that the control run can reproduce the primary rainband. The observed precipitation in most regions is less than 50 mm and the maximum value is approximately 80 mm. Although the control run is spatially consistent with the observations, the maximum simulated precipitation is about 200 mm, largely exceeding the observed value. Similar biases were reported in Xu et al. (2012) and Gao et al. (2016). For domain 03, when the simulated precipitation is averaged to 0.1°, there are only about 27x27 data points; this data volume is insufficient to compare the spatial distribution of precipitation between simulations and observations. This could explain the spatial precipitation bias shown in Figures 2c and 2d. Besides spatial comparison, Figures 3a and 3b show the
temporal evolutions of area-averaged hourly precipitation rate from the observation and
the control run over domain 02 and domain 03, respectively. The black solid lines
denote the observations. The simulations of both domains temporally correlate well
with observations, but the domain 03 is clearly closer to the observations in terms of
precipitation rate. The observations for domain 03 show that there are two peaks of
precipitation in the local afternoon (UTC + 6 h). The first precipitation event starts from
0400 UTC and ends at 1800 UTC with the maximum precipitation rate of 1.0 mm/h
attained at 0900 UTC. The other precipitation peak is weak with a maximum
precipitation rate of only about 0.4 mm/h. The time of the peaks in the simulations is
about 2 hours later than that in the observations, which was also reported in Gao et al.
(2018).

Generally speaking, the control run captures the main features of the precipitation
evolution (the peaks and the trends). However, compared with the observations of 48 h
accumulated precipitation over the corresponding areas, the control run overpredicts
precipitation by 51.5% in domain 02 and by 20.8% in domain 03.

3.1.2 Microphysical processes in the control run

To examine the origin of the precipitation biases discussed above, a more in-depth
analysis of the microphysics is performed for both domains 02 and 03. For domain 02,
considering that the altitude of the southeastern corner is lower than the other regions,
liquid-phase precipitation is expected to be stronger. Therefore, domain 02 is divided
into two parts: the southeastern corner and the other regions. For domain 03, the two precipitation peak periods are studied separately.

Figure 4 shows the mean vertical profiles of five types of hydrometeors and their primary microphysical processes for the two separate regions over domain 02 and the two precipitation peaks (5 hours) over domain 03, respectively. For domain 02, mixing ratios of ice-phase hydrometeors (ice, snow, and graupel) and rates of microphysical processes (RIM-s, RIM-g, MELT) over the southeastern corner (Figures 4c and d) are generally equivalent to or smaller than those over the other regions (Figures 4a and b).

Mixing ratios of liquid-phase hydrometeors (cloud and rain) and microphysical processes (ACCR-r, AUTO-r) are larger over the southeastern corner than those over the other regions. As mentioned above, liquid droplets will grow more favorably over the southeastern corner because of its lower terrain. For domain 03, mixing ratios of ice-phase hydrometeors (ice, snow, and graupel) and rates of microphysical processes (EVAP-r, ACCR-s, RIM-s, RIM-g, MELT) are smaller during the second peak period (Figures 4g and h) than those during the first peak (Figures 4e and f). On the other hand, accretion of cloud droplets by rain (ACCR-r) is larger for the second peak than for the first one, while melting still dominates. By calculating the vertical accumulated conversions of liquid-phase processes (ACCR-r and AUTO-r) and ice-phase processes to raindrops, the contributions of ACCR-r and AUTO-r are 32.86%, 65.20%, 27.03%, and 35.41% for other regions in domain 02 except southeastern corner, the southeastern corner in domain 02, and two precipitation peaks in domain 03, respectively. Therefore,
the liquid-phase processes over the southeastern corner in domain 02 and the second precipitation peak in domain 03 are more important than those over the other regions in domain 02 and the first precipitation peak in domain 03, respectively. However, this happens for different reasons. While ice phase processes are equally important across the entire domain 02, the higher temperature in the lower southeastern corner allows for more liquid-phase precipitation. In domain 03, however, the second peak is clearly associated with smaller ice-related conversion rates.

3.2 Sensitivity of precipitation overprediction to different liquid-phase processes

Precipitation, microphysical properties, and their related processes from the sensitivity simulations are discussed in this section, including Be68, Bh94, LD04, CP2k, Ko13, and INHOMO. The effects of these schemes on precipitation overprediction are examined in detail.

3.2.1 Evaluation of surface precipitation

The results for precipitation from the sensitivity tests are shown in Figures 5 and 6. All sensitivity tests reproduce a similar location, trend, and precipitation rate, compared to the control run, except the CP2k experiment. CP2k has distinctly weaker precipitation than the other simulations especially over the southeastern corner in domain 02 and during the second precipitation peak period in domain 03. CP2k overestimates precipitation by 30.2% in domain 02, which is an improvement compared
to the control and other sensitivity tests (48.8%-52.5%); in domain 03, the
overprediction in the CP2k is only 10.9%, also much smaller than the 15.1% in
INHOMO and 20.8%-26.9% in the control and other sensitivity tests. Some previous
studies found large variation of precipitation by using different autoconversion schemes
(Li et al., 2008a; Wang et al., 2013), while other studies showed that surface
precipitation was insensitive to the choice of autoconversion schemes (Morrison and
Grabowski, 2007; Michibata and Takemura, 2015). It seems that such a sensitivity may
vary by cloud regimes and even case by case. The limited effects of different
autoconversion schemes on the surface precipitation rate in this study could be related
to the dominance of melting and accretion in raindrop formation, and large precipitation
amount

The Heidke skill score (HSS) is used to further quantitatively evaluate the
simulations with different schemes:

$$\text{HHS} = \frac{2(ad - bc)}{(a + c)(c + d) + (a + b)(b + d)},$$  \hspace{1cm} (12)

where the four elements $a$-$d$ for HSS, representing the numbers of “hits”, “false alarms”,
“misses” and “correct negatives”, respectively, are calculated from a contingency table
(Table 2). HSS can not only judge well-simulated events (both hits and correct
negatives, element $a$ and $d$) but also account for the erroneous forecast ($b$ and $c$)
(Barnston, 1992). A higher HSS (0-1) represents better skill. As shown in Table 2, $p_t$ is
the threshold value and is set to be 2 mm covering most of the observed and simulated
precipitation area, $p_s$ and $p_o$ are the values from simulations and observations,
The elements $a-d$ and HSS for all sensitivity tests over domains 02 and 03 are shown in Table 3. All the cases in domain 02 have the HSS scores exceeding 0.4 and are close to each other except for CP2k. The impacts of changing autoconversion schemes and mixing mechanisms on HSS are limited. The CP2k accretion scheme, however, has significantly higher HSS than other cases, particularly due to its high value of $d$, the “correct negatives” mainly over the southeastern region for domain 02. The high HSS scores in CP2k indicate that changing the accretion scheme is a possible way to improve the much-overestimated precipitation in simulations over this region. The HSS scores of all simulations for domain 03 are small because there are too few data points for evaluation, as mentioned above; slight changes in any of the four factors can cause a large difference in the final scores. However, the CP2k case still has the highest HSS of 0.152, much larger than the maximum and mean HSS of other cases, 0.110 and 0.076, respectively.

3.2.2 Impact of liquid-phase parameterization on cloud properties

Table 4 summarizes the microphysical properties for all the simulations, including LCWP, $\bar{r}_e$ and $N_c$ over domains 02 and 03, respectively. It is noteworthy that the CP2k scheme has the largest effect on LCWP and $\bar{r}_e$ among all the sensitivity tests. Compared to the control run, differences of the CP2k case over domain 02 (03) are +64.6% (+51.0%) in LCWP and +7.9% (+5.6%) in $\bar{r}_e$ while the other accretion
sensitivity test, using Ko13, is much closer to the control run. The reasons will be analyzed in Section 3.3.2. Cloud observational data from Clouds and the Earth’s Radiant Energy System (CERES) project with 1 h time resolution and 1° spatial resolution are also provided in Table 4. Among all the simulations, the CP2k case has the results of LCWP and \( r_e \) closest to the observations.

The difference between all autoconversion sensitivity tests and the control run for LCWP and \( r_e \) are, respectively, from -13.7% to 10.6% and -1.9% to 2.3% over domain 02, and from -11.1% to 13.9% and -1.2% to 3.5% over domain 03. The wide ranges are mainly caused by one order of magnitude difference of \( A_u \) amongst the different sensitivity tests (Figures 7a and b). However, the magnitude of the difference is much smaller than that in typical marine boundary layer clouds (Wood, 2005b), because of the thinner liquid-phase layer and the involvement of ice/mixed-phase processes over the TP. The sign of the difference between the schemes is consistent with previous studies, e.g., Be68 and LD04 have larger \( A_u \) than KK00 (Figures 7a and b) (Lee and Baik, 2017).

For the entrainment-mixing process, the INHOMO experiment has the largest effect on \( N_c \) among all the sensitivity tests. Even so, there is only a modest reduction of only 2.6 (4.9) /cm³ compared to the control run, resulting in 0.9% (1.5%) larger \( r_e \) over domain 02 (03). It seems that the influence of INHOMO in domain 03 is greater than that in domain 02 since the relevant scales involved in the entrainment-mixing process are usually small and domain 03 has a higher resolution than domain 02. Such a
variation of $\bar{r}_e$ over domain 03 is comparable with that in all the autoconversion schemes and Ko13. The variation of LCWP is smaller than that in the liquid conversion process. Sensitivity tests of all autoconversion and accretion schemes in Table 4 are also conducted assuming different mixing mechanisms (See supplement for details). The effects are also small, similar to several previous studies using double-moment microphysics schemes (Hill et al., 2009; Grabowski and Morrison, 2011; Slawinska et al., 2012). One important reason is that the relative humidity in entrained air is high (Slawinska et al., 2012; Hoffmann and Feingold, 2019).

3.3 Reasons for improvements of precipitation overprediction in CP2k

As mentioned before, CP2k reduces the precipitation overprediction more significantly than other sensitivity tests. The reasons are discussed in this section.

3.3.1 Detailed microphysical processes in CP2k

CP2k experiences an $A_c$ rate that is one to two orders of magnitude smaller than in the control run and other sensitivity tests (Figures 7c and d). The reason for why $A_c$ in the control run and other sensitivity tests is so close is that the KK00 and the Ko13 schemes have similar functions of rain and cloud water content (Eqs. 2 and 7) and similar variation trends in Figure 9 (which is analyzed in Section 3.3.2 in detail). In each case, larger $A_u$ enhances $A_c$ by providing more rain drops. Therefore, the trend of $A_c$ corresponds well to that of $A_u$. The result between different cases is different
from that in each case. Compared with the control run, $A_c$ in CP2k is smaller, and thus fewer cloud droplets are collected by raindrops; these surviving cloud droplets are then available for autoconversion, which leads to the larger $A_u$ in CP2k (e.g. Gettelman et al., 2013; Posselt and Lohmann, 2008). As shown in Figures 7a and b, $A_u$ in CP2k is much larger than that in the control run; the difference is close to the value from applying different autoconversion schemes. Therefore, CP2k has the lowest ratio $A_c/A_u$ with the mean value of 2.88 (2.81) over domain 02 (03) mainly because of small $A_c$. Bh94 has the largest ratio $A_c/A_u$ with a mean value of 151.24 (144.60) over domain 02 (03). Indeed, Bh94 exhibits the smallest $A_u$ (Figures 7e and f) of all schemes tested here. $A_c/A_u$ of all schemes is in the range of 0.1-296.3, consistent with previous studies (Gettelman et al., 2013; Lee and Baik, 2017; Michibata and Takemura, 2015; Seifert and Onishi, 2016; Jiang et al., 2010). In domain 03, $A_c/A_u$ larger than 1 usually corresponds to larger precipitation intensity; $A_c/A_u$ smaller than 1 usually corresponds to smaller precipitation at the start or the end of precipitation events. This correspondence is consistent with the arguments as to accretion-dominated and autoconversion-dominated regimes (Jiang et al., 2010; Wood et al., 2009; Michibata and Takemura, 2015). In domain 02, most of $A_c/A_u$ is larger than 1; some $A_c/A_u$ values are smaller than 1 but still with strong precipitation likely caused by the influence of ice/mixed-phase processes.

Combining two dominant liquid-phase rain formation processes (autoconversion and accretion), less cloud water is depleted in CP2k; as a result, the mean value of
LCWP is over 50.0% larger than that of the control run, as shown in Table 4. Figure 8 shows the vertical profiles of the mean differences of the dominant conversion process rates between CP2k and the control run (CP2k-Control) over the two regions in domain 02 and during the two precipitation peak periods in domain 03. Similar to Figure 7, CP2k has a much smaller $A_c$ and larger $A_u$. Despite the larger $A_u$, many cloud droplets are suspended above the 0 °C isotherm, beneficial for riming of cloud droplets onto snow or graupel particles (RIM-s + RIM-g). Figure S1 in the supplementary material shows the microphysical processes conversion rates in CP2k with riming minus those without riming. Riming suppresses the liquid-phase rain formation processes through reducing $A_c$, but enhances ice/mixed-phase rain formation processes through increasing melting rate. The sensitivity of warm/cold rain formation to riming ultimately trickles down to uncertainties in the simulation of surface precipitation.

Note that the smaller melting rate near 6 - 6.5 km in CP2k over domain 03 is because of the lower melting level in CP2k than in the control run. Given the larger water content, CP2k also has a larger optical depth $\tau$ (14.3) than the control run (11.1), which means more solar radiation is reflected to the upper atmosphere and less short-wave radiation reaches the ground (219.6 W/m² in CP2k vs 226.5 W/m² in the control run). Qualitatively, such a difference in radiation could be one reason responsible for a lower temperature in CP2k in the low atmosphere than in the control run, other things being equal (e.g., latent heating release). Therefore, the melting level is lower in CP2k.

The source of surface precipitation includes both the liquid-phase (mainly ACCR-
r) and the ice/mixed-phase. During the first precipitation peak period in domain 03, despite the smaller $A_c$ in CP2k than that in the control run, more riming leads to more melting. The combination of weaker accretion and stronger melting in CP2k offset each other, and hence the precipitation from CP2k and the control run is very close in this period (Figure 6b). A similar chain of events also occurs in domain 02 except for the southeastern corner (Figures 2b and 5d). However, in the control run, due to relatively low concentration of ice particles during the second peak period in domain 03, the liquid-phase processes, in particular accretion, become relatively more important (Figure 4h); for the southeastern corner of domain 02, the large mixing ratio of cloud droplets even causes $A_c$ to exceed the melting rate (Figure 4d). Surface precipitation is overestimated in the control run compared with the observations, as discussed in Section 3.2.1. In CP2k, the accretion is suppressed which appears to alleviate the overestimation of precipitation. Therefore, the total surface precipitation in CP2k is smaller than that in the control run over the southeastern corner in domain 02 and during the second peak period in domain 03, which is closer to observations.

### 3.3.2 Theoretical analysis of the CP2k parameterization

The large differences in cloud microphysics and precipitation between CP2k and other cases can be explained based on the different equations for autoconversion and accretion (Eqs. 2, 6 and 7). The different equations for the autoconversion and accretion can be separated into two basic methods as mentioned in Wood (2005b): the first one
integrates the stochastic collection equation for a wide range of drop size distributions and then uses a simple power-law fit, such as the KK00 scheme in the control run. The second method simplifies the collection kernel and parameterizes the autoconversion and accretion processes, such as the parametrization of the $A_u$ in LD04 and $A_c$ in CP2k. Autoconversion schemes commonly use one of these basic methods. However, the accretion schemes used in most of the microphysical schemes are based on the first method, and previous studies focus on comparing accretion schemes using this method (Wood, 2005b; Hill et al., 2015). As shown above and also below, the CP2k accretion parameterization is unique and appears superior to other parameterizations, but this parameterization is only used in a few microphysics schemes (e.g. WDM6 scheme in WRF, Lim and Hong, 2010).

Figure 9 compares the $A_c$ calculated as a function of raindrop radius for all the accretion schemes under the conditions of $q_c = 1$ g/kg, $R_c = 10$ μm, $N_t = 4000$ /m$^3$. It is obvious that the three schemes result in different relationships for the $A_c$. Considering the power-law form in the formula from the first method, i.e., the KK00 scheme in the control run and the Ko13 scheme, $A_c$ is linearly related to raindrop radius in the logarithmic space. However, CP2k has an inflection point at 50 μm due to the piecewise function in Eq. 6. Under the condition of adequate cloud water, the accretion process in the KK00 or the Ko13 scheme only depends on the rain water mixing ratio. However, in CP2k, if the raindrop radius is less than 50 μm, the $A_c$ is very small. As shown in Figure 9, the $A_c$ in the KK00 or the Ko13 scheme is always larger than that in CP2k
when the raindrop radius is smaller than 2000 μm. The difference between CP2k and
the other two schemes increases with decreasing raindrop radius; especially when the
raindrop radius is smaller than 50 μm, with the maximum difference being more than
two orders of magnitude. Therefore, the probability density distributions (PDFs) of
raindrop radius are important for the difference between different accretion schemes.

Figure 10 shows the PDFs of raindrop radius used in the accretion process in the
three schemes. All raindrops are smaller than 10^3 μm. The PDFs have peaks of ~30,
~30, and ~25 μm in the control run, Ko13, and CP2k, respectively, and the cumulative
PDF shows that the raindrops with radius smaller than 50 μm have frequencies of 58.8%,
53.8%, and 46.0%, respectively. The drop size distributions from both aircraft
observations and bin models also confirm that a large proportion of liquid droplets have
radii larger than 25 μm but smaller than 50 μm (Wood, 2005a; Morrison and Grabowski,
2007). Such a large percentage of small raindrops makes the \( A_c \) and precipitation in
CP2k quite different from that in other schemes (Figure 9). Furthermore, there is a
positive feedback mechanism, since accretion increases \( q_r \) and \( A_c \) is positively
correlated with \( q_r \). The overestimation of the \( A_c \) in KK00 or Ko13 hence feeds back on
itself. This is the reason why the precipitation and accretion rate differences between
KK00 and CP2k are so large over the southeastern corner in domain 02 and during the
second peak period in domain 03.

Previous studies have shown that to initiate liquid phase precipitation, the cloud
effective radius needs to reach about 14 μm (Rosenfeld et al., 2019). A closer look at
the cloud droplet sizes is hence informative to understand the differences in precipitation behavior between CP2k and the other experiments. Figure 11 shows the liquid-phase precipitation rate as a function of cloud droplet effective radius. The liquid-phase precipitation rate is estimated as the product of total precipitation and the ratio of liquid-phase process rates (autoconversion + accretion) and ice/mixed-phase process rates (melting from snow + graupel). The liquid-phase precipitation rate exceeds 2 mm/day when the cloud effective radius is 9 μm in the control run and Ko13. In CP2k, it is not until the cloud effective radius reaches about 15 μm, that the precipitation rate exceeds 2 mm/day. The contribution from autoconversion is close to 0 in the control run, which could be due to the consumption of cloud droplets by accretion after droplets reach 9 μm. The value of 9 μm, is much smaller than 14 μm needed to initiate liquid-phase precipitation, often suggested by observational studies (Rosenfeld et al., 2019). On the contrary, there is a significant increase in liquid-phase precipitation rate from the autoconversion and accretion processes in CP2k at 15 μm. Although $A_u$ in CP2k is larger than that in other schemes, $A_c$ ultimately determines the liquid-phase precipitation rate, which has been discussed in many previous studies (e.g., Jiang et al., 2010; Wood et al., 2009; Michibata and Takemura, 2015; Gettelman et al., 2015). The liquid-phase precipitation is suppressed by a weak $A_c$. Furthermore, large $A_u$ in CP2k can increase $q_t$ but decrease $q_c$, which may enhance or suppress $A_c$ (Posselt and Lohmann, 2008). In other schemes, the accretion process is triggered to a considerable amount with small liquid drops due to the overestimation of $A_c$ when...
confined to small drops. Therefore, the improvement in CP2k surface precipitation compared to the control, appears to occur for the right reasons.

4. Long-term analysis

While the analysis of the single case study has allowed for an in-depth analysis, it remains to be verified whether this case study is representative of the general behavior of the model. As pointed out by White et al., 2017), it is hard to be conclusive that one scheme is better than others based on a few cases. Hence, one-month simulations are performed from 0000 UTC 21 July to 0000 UTC 21 August 2014 with the same domains in Figure 1, using the three accretion schemes (the control run, CP2k, and Ko13). Only the results starting from 0000 UTC 22 July are analyzed. The horizontal resolutions for domains 01, 02 and 03 are 30, 10 and 3.3 km, respectively; except for the resolutions and simulation time, all other settings are the same as those in the two-days simulations in Section 3.

Figure 12 shows the temporal evolution of the area-averaged daily precipitation rate in domains 02 and 03 from the three accretion simulations and the observations. Compared with the observed precipitation, the control run significantly overestimates precipitation for most days, especially in domain 02. The average precipitation rate in the observation, the control run, Ko13, and CP2k are, respectively, 1.56, 2.46, 2.49, and 2.17 mm/day over domain 02, and 4.54, 5.80, 5.87, and 5.17 mm/day over domain 03. The results of Ko13 are very close to those in the control run, while CP2k significantly
reduces precipitation overprediction with p-values of student’s t-test less than 0.01 for both domain 02 and domain 03. Table 5 shows that CP2k has higher HSS scores than the control run and Ko13 over both domains 02 and 03. Therefore, the effects of CP2k on reducing precipitation overprediction are not limited to one specific case but appear to be a plausible way to improve precipitation overprediction, at least of the Tibetan Plateau.

The one-month simulations provide the opportunity to investigate the response of the PDF of the surface precipitation to the changes of accretion schemes over the TP region. The PDFs are based on the hourly precipitation rate from 0000 UTC 21 July to 0000 UTC 21 August 2014 with the three accretion schemes (the control run, CP2k, and Ko13). As expected, Figure 13 shows that CP2k has more weak precipitation (< ~0.2 mm/h) over both domains 02 and 03 than the control run and Ko13, corresponding to the smaller total surface precipitation in CP2k. The results indicate that the PDF of the surface precipitation is subject to the changes in the microphysical schemes over the TP region. Furthermore, considering the significant climate effects of the TP region, it is interesting to see whether microphysical schemes have significant effects on the historical trend of precipitation intensity distribution with simulations over years in the future research using the method in Wang et al. (2016).

5. Sensitivity to horizontal resolution

Different resolutions in the two simulations (case study from 22 to 23 July 2014
and long-term one-month simulation from 22 July to 21 August 2014) provide a good opportunity to examine the effects of resolution on precipitation overprediction. The area-averaged precipitation rate during the first two days (from 22 to 23 July) from the one-month simulation is 0.36 mm/h in domain 03 with the resolution of 3.3 km (Figure 12b), which is larger than the 0.29 mm/h with the resolution of 1 km and the 0.24 mm/h from the observations (Figure 6b). Similarly, the first two-days area-averaged precipitation rate is 0.41 mm/h in domain 02 with the resolution of 10 km (Figure 12a), larger than 0.32 mm/h with the resolution of 5 km and 0.21 mm/h from the observations (Figure 6a). Furthermore, comparison with the precipitation in domains 02 and 03 also provides some hints on the effects of resolutions. For the one case study, domain 02 with the resolution of 5 km (Figure 6a) overpredicts 51.5% of precipitation compared with observations, and the number for domain 03 with the resolution of 1 km is only 20.8% (Figure 6b). For the one-month study, domains 02 and 03 overpredict precipitation by 57.7% and 27.8%, respectively (Figure 12). These results confirm that the model grid size plays an important role in the overprediction of precipitation over the TP.

Sato et al. (2008) showed that a higher resolution simulation was more accurate in reproducing the diurnal variation of precipitation, with precipitation rate more consistent with observations. They claimed that higher resolution (< 7 km) may resolve the convection initially occurred by the surface heating and consequently conduct a proper simulation of the precipitation. Xu et al. (2012) found that the WRF simulations
at a resolution of 3 km could reproduce the timing of precipitation events but the intensities were doubled. The first two-days comparison in our study shows that, when the horizontal resolution increases from 3.3 km to 1 km, the simulation of precipitation intensity can be effectively improved without affecting the trends of precipitation. This indicates that 1 km or even higher resolution is needed to accurately simulate the precipitation over the TP, possibly because such high resolutions can better resolve the orography of this region.

6. Summary and conclusions

In this paper, a typical summer plateau precipitation event over the Tibetan Plateau is simulated using the WRFv3.8.1 model with the Morrison double-moment scheme. The control run reproduces the primary spatial distribution and temporal evolution of precipitation rate. However, precipitation is significantly overestimated. To understand the role of liquid-phase microphysical processes in the overprediction of precipitation, sensitivity tests are conducted by introducing three parameterized liquid-phase processes into the Morrison double-moment scheme, including three autoconversion parameterizations (Be68, Bh94, and LD04), two accretion parameterizations (CP2k and Ko13), and one entrainment-mixing parameterization (INHOMO).

The precipitation overprediction is significantly reduced with the accretion scheme from Cohard and Pinty (2000). The Heidke skill scores with CP2k also show better results compared to other cases. Furthermore, each simulation is further divided
into two parts: one with dominant ice/mixed-phase processes, the other with dominant liquid-phase processes. The simulations have the largest differences when the liquid-phase processes dominate, and the improvement in the CP2k experiment is more pronounced. When the ice/mixed-phase processes are important, all the simulations are equivalent, including CP2k. There are several reasons for this behavior. The accretion rate is smaller in the CP2k experiment than that in the control run, which suppresses precipitation due to liquid-phase processes. Due to weaker accretion, more cloud droplets remain suspended in the atmosphere and are available for riming onto snow and graupel. Precipitation due to melting from snow and graupel is then enhanced. The combination of the weaker accretion and stronger melting in CP2k offset each other. That is the reason why the precipitation does not change much in CP2k when ice/mixed-phase processes dominate. When the ice/mixed-phase processes are relatively weak, the precipitation from the enhanced riming and melting processes cannot compensate for the loss of precipitation due to the suppression of accretion. Therefore, the precipitation rate is smaller in CP2k than in the control run.

To understand the physical reasons for the improved performance of CP2k, the equations for parameterizing accretion rate in CP2k, KK00, and Ko13 are compared directly. The accretion rate in CP2k is always smaller than in the KK00 or the Ko13 scheme when the raindrop radius is smaller than 2000 μm. Furthermore, the difference increases with decreasing raindrop radius and can amount to more than two orders of magnitude when the raindrop radius is smaller than 50 μm. The PDFs of raindrop radii
have their peaks around 30 μm. Around 50% of raindrops have radius less than 50 μm. This is the reason why CP2k suppresses accretion and liquid-phase precipitation compared to the other two schemes. Further insight into the reasons for different behavior in CP2k compared to the other schemes is provided through the relation of cloud droplet size and liquid phase precipitation rates. It is often claimed that, to initiate liquid-phase precipitation, the cloud effective radius needs to reach 14 μm. When the cloud effective radius is 9 μm in the control run and Ko13, the liquid-phase precipitation rate already exceeds 2 mm/day, however; in CP2k, on the other hand, liquid-phase precipitation does not start until the effective radius reaches about 15 μm, which is more consistent with observations.

The results in terms of precipitation sensitivity were confirmed in a long-term one-month simulation as well. The time series of daily precipitation rate indicates that the reduction in precipitation bias using CP2k is generally valid. CP2k also has the highest HSS scores. Hence, it is assumed that the CP2k scheme generally produces more accurate simulations of precipitation, at least over the Tibetan Plateau. More studies are needed to understand whether these findings are applicable to regions beyond the Tibetan Plateau as well. Theoretically, accretion is significantly affected by cloud droplet and raindrop sizes, and these sizes are related to number concentrations and liquid water mixing ratios of cloud droplets and raindrops. Therefore, it may be more convincing to simultaneously consider number concentrations and liquid water mixing ratios in the future development of the accretion parameterizations, similar to CP2k.
We also confirm that higher resolution simulations reduce precipitation overestimation compared to lower resolution simulations, as pointed out by previous studies (e.g., Sato et al., 2008, Xu et al., 2012). For the same simulation domains with different resolutions, the results in the high-resolution simulations are much closer to the observations.

It is noteworthy that small impacts of changing entrainment-mixing mechanisms and autoconversion schemes could be related to the cloud type in the Tibetan Plateau area. More studies are needed to further examine the impacts of these processes and accretion on cloud and precipitation under different conditions, with the ratio of accretion rate to autoconversion rate (Wood, 2005b; Gettelman et al., 2013; Lee and Baik, 2017; Michibata and Takemura, 2015; Seifert and Onishi, 2016; Jiang et al., 2010) and the entrainment-mixing parameterizations (Lu et al., 2013). Furthermore, although our research shows the importance of the accretion process, it cannot be ignored that the ice-phase processes are also important in this region. Therefore, it is necessary to study the parameterizations of different ice-phase processes in the Tibetan Plateau area in the future.

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Appendix A: Symbol List

\( N_C \): number concentration of cloud droplets

\( q_C \): mixing ratio of cloud droplet

\( N_R \): number concentration of raindrops

\( q_R \): mixing ratio of raindrops

\( N_I \): number concentration of ice crystals

\( q_I \): mixing ratio of ice crystals
$N_s$: number concentration of snow particles

$q_s$: mixing ratio of snow particles

$N_g$: number concentration of graupel particles

$q_g$: mixing ratio of graupel particles

$A_u$: conversion rate of accretion process

$A_c$: conversion rate of autoconversion process

$\rho_a$: air density

$\varepsilon$: dispersion

$\rho_W$: water density

$\lambda$: slope parameter

$N_{c0}$: number concentration of cloud water droplets before evaporation process

$q_{c0}$: mixing ratio of cloud water droplets before evaporation process

$p_t$: the threshold value of precipitation in the Heidke skill score

$p_s$: value of precipitation from simulations in the Heidke skill score

$p_o$: value of precipitation from observation in the Heidke skill score

$\tau$: cloud optical depth

$\bar{r}_e$: averaged effective radius of cloud water droplets

LCWP: liquid cloud water path

EVAP-r: evaporation of raindrops

ACCR-r: accretion of cloud liquid water by rain

AUTO-r: autoconversion from cloud droplets to raindrops
MELT: melting from snow or graupel particles to raindrops

AUTO-s: autoconversion of cloud ice to snow

ACCR-s: accretion of cloud ice by snow

RIM-s: accretion of cloud droplets by snow particle

RIM-g: accretion of cloud droplets by graupel particle

Appendix B: Four Parameters in Equation (6)

In Equation (6), $A_1$, $A_2$, $B_1$, and $B_2$ are the functions related to two dispersion parameters of the gamma size distribution given by:

$$A_1 = \frac{\Gamma(\nu_c + 6/\alpha_c)}{\Gamma(\nu_c)} \quad (B1a)$$

$$B_1 = \frac{\Gamma(\nu_c + 3/\alpha_c) \Gamma(\nu_i + 3/\alpha_i)}{\Gamma(\nu_i)} \quad (B1b)$$

$$A_2 = \frac{\Gamma(\nu_c + 9/\alpha_c)}{\Gamma(\nu_c)} \quad (B1c)$$

$$B_2 = \frac{\Gamma(\nu_c + 3/\alpha_c) \Gamma(\nu_i + 6/\alpha_i)}{\Gamma(\nu_i)} \quad (B1d)$$

where $\nu$ and $\alpha$ are the two dispersion parameters in normalized form of cloud–raindrop size distributions $n(D) = N \frac{\alpha}{\Gamma(\nu)} \lambda^\alpha D^{\alpha - 1} \exp[-(\lambda D)^\alpha]$; $\lambda$ is the slope parameter; $D$ and $N$ represent diameter and total number concentration, respectively.

Subscripts c and r in Eqs. (B1) represent cloud droplets and raindrops, respectively.
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**Caption List:**

Table 1. Summary of case names and corresponding formulations for the seven
experiments. The meaning of each symbol and references for each case can be found in
the text.

Table 2. Contingency table used to calculate the Heidke skill score (HSS). The elements
a-d represent the numbers of “hits”, “false alarms”, “misses” and “correct negatives”,
respectively. $p_t$ is the threshold value of precipitation in observation and simulations, $p_s$
is the value from simulations and $p_o$ is the value from observations.

Table 3. The values of four elements a-d and Heidke skill score (HSS) for all
simulations over domain 02 and domain 03 (d02/d03) of the control run, Be68, Bh94,
LD04 (different autoconversion schemes), CP2k, Ko13 (different accretion schemes)
and INHOMO run (different mixing mechanism).
Table 4. The area-averaged liquid cloud water path LCWP (g/m²), mean effective radius $\bar{r}_e$ (µm) and number concentration $N_c$ (/cm³) of cloud droplets over domains 02 and 03 (d02/d03) of the control run, Be68, Bh94, LD04 (different autoconversion schemes), CP2k, Ko13 (different accretion schemes) and INHOMO run (different mixing mechanism). The observation results from Clouds and the Earth’s Radiant Energy System (CERES) are also shown.

Table 5. The values of four elements a-d and Heidke skill score (HSS) for three one-month simulations over domain 02 and domain 03 of the control run and CP2k, Ko13 (different accretion schemes).

Figure 1. Geographic locations of the three domains used in the numerical simulation. The color bar represents the height (m) above the sea level.

Figure 2. Spatial distributions of 48 h accumulated precipitation (mm) during 0000 UTC 22 July to 0000 UTC 24 July 2014 from the observations and the control run over domain 02 (a, b) and domain 03 (c, d).

Figure 3. Time series of area-averaged hourly precipitation rate (mm/h) during 0000 UTC 22 July to 0000 UTC 24 July 2014 over (a) domain 02 and (b) domain 03 from the observations and the control run.

Figure 4. Mean vertical profiles of mixing ratios (g/kg) of cloud droplets ($q_c$), raindrops($q_r$), ice particles($q_i$), snow particles ($q_s$), graupel particles($q_g$) and their primary microphysical processes in the control run (a, b) averaged from 48 h over
domain 02 except southeastern corner, (c, d) averaged from 48 h at southeastern corner over domain 02, averaged during two precipitation peaks (e, f) 0700-1200 UTC 22 July 2014 and (g, h) 0700-1200 UTC 23 July 2014 over domain 03. The purple dot-dash lines denote the mean height of 0 °C isotherm.

Figure 5. Spatial distributions of 48 h accumulated precipitation (mm) during 0000 UTC 22 July to 0000 UTC 24 July 2014 from observations and all sensitivity simulations over (a-f) domain 02 and domain 03.

Figure 6. Time series of area-averaged hourly precipitation rate (mm/h) during 0000 UTC 22 July to 0000 UTC 24 July 2014 over (a) domain 02 and (b) domain 03 from the observations and all simulations.

Figure 7. The time series of area-averaged autoconversion rate, accretion rate, and the ratio of accretion rate to autoconversion rate ($A_c/A_u$) over (a, c, e) domain 02 and (b, d, f) domain 03 for all simulations, respectively.

Figure 8. Differences of mean vertical profiles of the dominated microphysical processes conversion rates between CP2k and the control run (CP2k-Control) from (a) domain 02 except southeastern corner, (b) the southeastern corner of domain 02, and during the two precipitation peak periods (c) 0700-1200 UTC 22 July and (d) 0700-1200 UTC 23 July over domain 03. The purple dot-dash lines denote the mean height of 0 °C isotherm.
Figure 9. The accretion rate as a function of raindrop radius with fixed cloud mixing ratio $q_c = 1$ g/kg, the radius of cloud droplet $R_c = 10 \, \mu m$, number concentration of raindrops $N_r = 4000 / m^3$ for the three accretion schemes.

Figure 10. Probability distribution function (PDF) and cumulative PDF of raindrop radius involved in the accretion process for (a) the control run, (b) CP2k, and (c) Ko13. The purple line denotes the radius of raindrop equal to 50 $\mu m$.

Figure 11. Dependence of warm rain intensity on cloud effective radius from the control run and CP2k during 0000 UTC 22 July to 0000 UTC 24 July 2014 over domain 03.

Figure 12. Time series of area-averaged daily precipitation rate (mm/day) from 0000 UTC 22 July to 0000 UTC 20 August 2014 over (a) domain 02 and (b) domain 03 in the observations and three accretion cases (the control run, CP2k and Ko13).

Figure 13. Probability distribution function (PDF) of precipitation rate (mm/h) from 0000 UTC 21 July to 0000 UTC 21 August 2014 over (a) domain 02 and (b) domain 03 in the three accretion cases (the control run, CP2k and Ko13).
Table 1. Summary of case names and corresponding formulations for the seven experiments. The meaning of each symbol and references for each case can be found in the text.

| Liquid-phase process | Case name | Formulations |
|----------------------|-----------|--------------|
| Autoconversion        | Be68      | $A_u = \frac{3.5 \times 10^{-2} q_c^2}{0.12 + 1.0 \times 10^{-12} \frac{N_c}{q_c}}$ |
|                      | Bh94      | $A_u = 6.0 \times 10^{28} n^{-1.7} (q_c \times 10^{-3})^{4.7} (N_c \times 10^{-6})^{-3.3}$ |
|                      | LD04      | $A_u = 1.1 \times 10^{13} \left[ \frac{(1 + 3\epsilon^2)(1 + 4\epsilon^2)(1 + 5\epsilon^2) q_c^3}{(1 + \epsilon^2)(1 + 2\epsilon^2) N_c} \right] \times \frac{1}{2} (x_c^2 + 2x_c + 2)(1 + x_c) e^{-2x_c}$ |
| Accretion            | Ko13      | $A_c = 8.53 \times q_c^{1.05} q_r^{0.98} \rho_d^{-2.03}$ |
|                      | CP2k      | $A_c = \frac{\pi}{6} \rho_W \rho_a K_1 \frac{N_c N_r}{\lambda_c^2} \left( \frac{A_1}{\lambda_c^2} + \frac{B_1}{\lambda_r^2} \right)$, if $R_r \geq 50 \mu m$, and $A_c = \frac{\pi}{6} \rho_W \rho_a K_2 \frac{N_c N_r}{\lambda_c^2} \left( \frac{A_2}{\lambda_c^2} + \frac{B_2}{\lambda_r^2} \right)$, if $R_r < 50 \mu m$. |
| Entrainment-mixing   | INHOMO    | $N_c = N_{c0} \left( \frac{q_c}{q_{co}} \right)^\alpha$, $\alpha = 1$. |
Table 2. Contingency table used to calculate the Heidke skill score (HSS). The elements $a$-$d$ represent the numbers of “hits”, “false alarms”, “misses” and “correct negatives”, respectively. $p_t$ is the threshold value of precipitation in observation and simulations, $p_s$ is the value from simulations and $p_o$ is the value from observations.

|            | Observation $p_o > p_t$ | Observation $p_o \leq p_t$ |
|------------|-------------------------|----------------------------|
| Simulation $p_s > p_t$ | $a$                     | $b$                        |
| Simulation $p_s \leq p_t$ | $c$                     | $d$                        |
Table 3. The values of four elements $a$-$d$ and Heidke skill score (HSS) for all simulations over domain 02 and domain 03 (d02/d03) of the control run, Be68, Bh94, LD04 (different autoconversion schemes), CP2k, Ko13 (different accretion schemes) and INHOMO run (different mixing mechanism).

|        | $a$     | $b$     | $c$    | $d$     | HSS    |
|--------|---------|---------|--------|---------|--------|
| Control| 2636/304| 1224/148 | 773/76 | 2231/48 | 0.419/0.049 |
| Autoconversion |     |         |        |         |        |
| Be68   | 2645/309| 1261/142 | 764/71 | 2194/54 | 0.411/0.097 |
| Bh94   | 2533/306| 1148/138 | 876/74 | 2307/58 | 0.411/0.110 |
| LD04   | 2628/313| 1264/154 | 781/67 | 2191/42 | 0.405/0.043 |
| Accretion |     |         |        |         |        |
| CP2k   | 2583/304| 1063/129 | 632/76 | 2586/67 | 0.508/0.152 |
| K013   | 2620/303| 1223/146 | 770/77 | 2251/50 | 0.420/0.057 |
| Mixing mechanism |     |         |        |         |        |
| INHOMO | 2656/308| 1124/141 | 753/72 | 2214/55 | 0.420/0.100 |
Table 4. The area-averaged liquid cloud water path LCWP (g/m$^2$), mean effective radius $\overline{r}_e$ (μm) and number concentration $N_c$ (/cm$^3$) of cloud droplets over domains 02 and 03 (d02/d03) of the control run, Be68, Bh94, LD04 (different autoconversion schemes), CP2k, Ko13 (different accretion schemes) and INHOMO run (different mixing mechanism). The observation results from Clouds and the Earth’s Radiant Energy System (CERES) are also shown.

|                  | LCWP (g/m$^2$) | $\overline{r}_e$ (μm) | $N_c$ (/cm$^3$) |
|------------------|----------------|-----------------------|-----------------|
| **Control**      | 73.5/66.8      | 6.97/6.77             | 71.5/91.2       |
| **Autoconversion**|                |                       |                 |
| Be68             | 63.4/59.4      | 6.84/6.74             | 71.3/91.6       |
| Bh94             | 81.3/76.1      | 7.13/7.01             | 72.3/91.9       |
| LD04             | 63.8/60.9      | 6.85/6.69             | 71.6/91.3       |
| **Accretion**    |                |                       |                 |
| CP2k             | 121.0/97.0     | 7.52/7.15             | 72.4/90.1       |
| Ko13             | 74.4/64.4      | 6.92/6.72             | 71.5/91.0       |
| **Mixing mechanism** |            |                       |                 |
| INHOMO           | 72.9/66.7      | 7.03/6.87             | 68.9/86.3       |
| **Observation**  |                |                       |                 |
| CERES            | 100.4/91.2     | 9.13/8.75             | -               |
Table 5. The values of four elements $a$-$d$ and Heidke skill score (HSS) for three one-month simulations over domain 02 and domain 03 of the control run and CP2k, Ko13 (different accretion schemes).

|       | a  | b  | c  | d  | HSS |
|-------|----|----|----|----|-----|
| **domain 02** |    |    |    |    |     |
| Control  | 3780 | 5052 | 1924 | 24584 | 0.403 |
| CP2k    | 3749 | 4369 | 1955 | 25267 | 0.435 |
| Ko13    | 3764 | 4825 | 1940 | 24811 | 0.413 |
| **domain 03** |    |    |    |    |     |
| Control  | 1188 | 2856 | 93  | 2538  | 0.220 |
| CP2k    | 1163 | 2355 | 118 | 3084  | 0.262 |
| Ko13    | 1181 | 2908 | 100 | 2531  | 0.211 |


Figure 1. Geographic locations of the three domains used in the numerical simulation.

The color bar represents the height (m) above the sea level.
Figure 2. Spatial distributions of 48 h accumulated precipitation (mm) from 0000 UTC 22 July to 0000 UTC 24 July 2014 in the observations and the control run over domain 02 (a, b) and domain 03 (c, d).
Figure 3. Time series of area-averaged hourly precipitation rate (mm/h) from 0000 UTC 22 July to 0000 UTC 24 July 2014 over (a) domain 02 and (b) domain 03 in the observations and the control run.
Figure 4. Mean vertical profiles of mixing ratios (g/kg) of cloud droplets ($q_c$), raindrops ($q_r$), ice particles ($q_i$), snow particles ($q_s$), graupel particles ($q_g$) and their primary microphysical processes in the control run (a, b) averaged for 48 h over domain 02 except southeastern corner, (c, d) averaged for 48 h at the southeastern corner over domain 02, averaged during two precipitation peaks (e, f) 0700-1200 UTC 22 July 2014 and (g, h) 0700-1200 UTC 23 July 2014 over domain 03. The purple dot-dash lines denote the heights of 0 °C isotherm. The meanings of the symbols in the legends are shown in Appendix A.
Figure 5. Spatial distributions of 48 h accumulated precipitation (mm) during 0000 UTC 22 July to 0000 UTC 24 July 2014 from observations and all sensitivity simulations over (a-f) domain 02 and domain 03.
Figure 6. Time series of area-averaged hourly precipitation rate (mm/h) from 0000 UTC 22 July to 0000 UTC 24 July 2014 over (a) domain 02 and (b) domain 03 from the observations and all simulations.
Figure 7. The time series of area-averaged autoconversion rate, accretion rate, and the ratio of accretion rate to autoconversion rate ($A_c/A_u$) over (a, c, e) domain 02 and (b, d, f) domain 03 for all simulations, respectively.
Figure 8. Differences of mean vertical profiles of the dominated microphysical processes conversion rates between CP2k and the control run (CP2k-Control) from (a) domain 02 except the southeastern corner, (b) the southeastern corner of domain 02, and during the two precipitation peak periods (c) 0700-1200 UTC 22 July and (d) 0700-1200 UTC 23 July over domain 03. The purple dot-dash lines denote the heights of 0 °C isotherm. The meanings of the symbols in the legends are shown in Appendix A.
Figure 9. The accretion rate as a function of raindrop radius with fixed cloud mixing ratio $q_c = 1$ g/kg, the radius of cloud droplet $R_c = 10$ μm, number concentration of raindrops $N_r = 4000 / m^3$ for the three accretion schemes.
Figure 10. Probability distribution function (PDF) and cumulative PDF of raindrop.
radius involved in the accretion process for (a) the control run, (b) CP2k, and (c) Ko13.

The purple line denotes the radius of raindrop equal to 50 μm.
Figure 11. Dependence of liquid-phase precipitation intensity on cloud effective radius from the three accretion schemes during 0000 UTC 22 July to 0000 UTC 24 July 2014 over domain 03.
Figure 12. Time series of area-averaged daily precipitation rate (mm/day) from 0000 UTC 22 July to 0000 UTC 20 August 2014 over (a) domain 02 and (b) domain 03 in the observations and three accretion cases (the control run, CP2k and Ko13).
Figure 13. Probability distribution function (PDF) of precipitation rate (mm/h) from 0000 UTC 21 July to 0000 UTC 21 August 2014 over (a) domain 02 and (b) domain 03 in the three accretion cases (the control run, CP2k and Ko13).