

Article ID: 1006-8775(2026)01-0001-18

Improvement of Low-cloud Simulations with a Revised Cloud Microphysics Scheme in an Atmospheric General Circulation Model

LI Jia-bo (李佳播)^{1,2,3}, PENG Xin-dong (彭新东)^{3,1}, LI Xiao-han (李晓涵)⁴, GU Juan (谷娟)⁵,
DUAN Sheng-ni (段升妮)⁶

(1. State Key Laboratory of Severe Weather Meteorological Science and Technology, Chinese Academy of Meteorological Sciences, Beijing 100081 China; 2. College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049 China; 3. CMA Earth System Modeling and Prediction Centre, China Meteorological Administration, Beijing 100081 China; 4. State Key Laboratory of Climate System Prediction and Risk Management (CPRM)/Key Laboratory of Meteorological Disaster, Ministry of Education/School of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing 210044 China; 5. College of Aviation Meteorology, Civil Aviation Flight University of China, Guanghan, Sichuan 641419 China; 6. Yunnan Provincial Meteorological Bureau, Kunming 650034 China)

Abstract: Clouds play an important role in global atmospheric energy and water vapor budgets, and the low cloud simulations suffer from large biases in many atmospheric general circulation models. In this study, cloud microphysical processes such as raindrop evaporation and cloud water accretion in a double-moment six-class cloud microphysics scheme were revised to enhance the simulation of low clouds using the Global-Regional Integrated Forecast System (GRIST) model. The validation of the revised scheme using a single-column version of the GRIST demonstrated a reasonable reduction in liquid water biases. The revised parameterization simulated medium- and low-level cloud fractions that were in better agreement with the observations than the original scheme. Long-term global simulations indicate the mitigation of the originally overestimated low-level cloud fraction and cloud-water mixing ratio in mid- to high-latitude regions, primarily owing to enhanced accretion processes and weakened raindrop evaporation. The reduced low clouds with the revised scheme showed better consistency with satellite observations, particularly at mid- and high-latitudes. Further improvements can be observed in the simulated cloud shortwave radiative forcing and vertical distribution of total cloud cover. Annual precipitation in mid-latitude regions has also improved, particularly over the oceans, with significantly increased large-scale and decreased convective precipitation.

Key words: low cloud; cloud microphysics scheme; general circulation model; accretion process; raindrop evaporation

CLC number: P435

Document code: A

Citation: Li, J. B., X. D. Peng, X. H. Li, J. Gu, and S. N. Duan, 2026: Improvement of Low-cloud Simulations with a Revised Cloud Microphysics Scheme in an Atmospheric General Circulation Model. *J. Trop. Meteor.*, **32**, 1–18, <https://doi.org/10.3724/j.1006-8775.2025.038>.

1 INTRODUCTION

Clouds play an important role in the global energy budget through the reflection and absorption of solar radiation. Low clouds contribute to the cooling effect by reflecting incoming solar radiation and emitting longwave radiation (Hartmann 2015; Klein and Hartmann 1993; Wild 2019). The Coupled Model Intercomparison Project rounds 3 (Soden and Vecchi 2011) and 5 (Andrews et al. 2012) found that low clouds primarily contribute to the variability in cloud feedback among coupled climate models.

However, the accurate simulation of low clouds remains a significant challenge in many general circulation models (GCMs) (Ahlgren and Forbes 2014; Donner et al. 2011; Lin et al. 2012; Ong et al. 2024; Trenberth and Fasullo 2010; Tsushima et al. 2006) because of a lack of understanding of the detailed microphysical processes and interaction mechanisms (Bretherton 2015; Wyant 2015). Many studies have revealed systematic biases in the simulation of low cloud coverage and their responses to climate change (Bony and Dufresne 2005; Clement et al. 2009; Zhang et al. 2005). For example, the sharp transition from coastal stratocumulus to offshore shallow cumulus in subtropical oceans remains a significant source of bias in the Community Atmospheric Model (CAM) version 5 (Hannay et al. 2009; Park et al. 2014; Xiao et al. 2014). Qin et al. (2018) showed that low clouds over the mid-latitude oceans were typically overestimated. Several GCMs added more shortwave radiation absorption in the Southern Ocean regions because few clouds are simulated (Trenberth and Fasullo 2010; Tsushima et al. 2006). Trenberth and Fasullo (2010) highlighted the importance of Southern Ocean

Received 2025-03-10; **Revised** 2025-04-18; **Accepted** 2025-05-27

Funding: National Natural Science Foundation of China (42375153, 42105153, 42205157); Development of Science and Technology at Chinese Academy of Meteorological Sciences (2023KJ038)

Biography: LI Jia-bo, doctoral student, primarily undertaking research on atmospheric numerical modeling.

Corresponding author: PENG Xin-dong, e-mail: pengxd@cma.gov.cn

clouds in climate regulation, affecting the local energy input and interactions with deep ocean circulation. Therefore, improving the simulation of low cloud cover is crucial for enhancing model credibility and performance.

As a moist physical process, cloud microphysics significantly influences cloud formation and evolution in numerical simulations (Ding et al. 2005). Changes in cloud microphysics directly affect the macro-properties and energy balance of clouds (Fan et al. 2018; Garrett and Zhao 2006; Ma et al. 2018), including the introduction of more predictive variables to represent the mass and number concentrations of hydrometeors (Milbrandt and Yau 2005; Morrison et al. 2009; Thompson and Eidhammer 2014; Zhao et al. 2021), whereas atmospheric water and energy cycles are largely influenced by microphysical processes (Tan et al. 2016; Wood 2012). Wang et al. (2022) demonstrated an improvement in cloud fraction simulation using a two-moment cloud microphysics scheme compared with a one-moment scheme. The double-moment six-class cloud microphysics scheme (WDM6; Lim and Hong 2010), which was developed for regional weather forecasting using the weather research and forecasting (WRF) model, predicts the concentration of cloud droplets, rain, and cloud condensation nuclei, in addition to the mixing ratio of all hydrometeors, that is, cloud droplets, rain, ice, snow, and graupel/hail (Comin et al. 2018; Kim et al. 2022; Ko et al. 2022; Lim et al. 2020; Song and Sohn 2018). In a case study, Zhang et al. (2018) confirmed the consistency of the simulated rainfall amount and its distribution with WDM6 and observations, which improved the simulation using the single-moment six-class cloud microphysics scheme (WSM6) and National Centers for Environmental Prediction five-class scheme. Hong et al. (2010) observed that WDM6 eliminates the systematic bias of oceanic rainfall associated with the WSM6 scheme. WDM6 has been frequently used for simulating mid-latitude storms with the WRF model, but it is not certain whether WDM6 works well for long-lived cloud (e.g., low-level stratiform and thin cirrus cloud) simulations in regional and global climate models. In this study, a revised WDM6 (RWDM6) scheme was tested using an atmospheric GCM to improve the long-term global simulation of low clouds. In contrast to Ikuta et al. (2025), who implemented non-spherical hydrometeor parameterization using a microphysics scheme, and Shan et al. (2024), who reduced positive aerosol radiative forcing biases by including aerosol wet removal, this study specifically addressed the systematic overestimation of liquid water content and cloud fraction in long-term climate simulations found in WDM6.

The Global-Regional Integrated Forecast System (GRIST) is a unified system designed for global climate simulations and weather predictions (Zhang et al. 2019, 2020, 2021). Two physical suites are coupled to the dynamics in GRIST for application in weather and climate modeling (Li et al. 2020, 2022, 2023; Zhou et al. 2023). GRIST employs a stretching-grid technique for local

refinement with unstructured hexagonal/pentagonal meshes, allowing high-resolution simulations of any region without significantly increasing the computational burden. The physical suite for climate simulation was originally developed in CAM version 5.3 with a sequential dynamic-physical coupling operator (Li et al. 2020). The cloud macrophysics scheme was updated from that of Park et al. (2014) to a Gauss probability density function (Gauss-PDF) scheme (Li et al. 2021; Qin et al. 2018; Qin and Lin 2018), whereas for microphysics, we used the Morrison and Gettelman (2008) (MG) scheme. To improve the simulation of the cloud and energy balance, we introduced the WDM6 scheme into the GRIST model to better describe the interaction between water vapor and hydrometeors. First evaluated with a uniform resolution configuration (120 km) of the GRIST model, WDM6 showed an overestimation of stratiform clouds at mid- and high-latitudes, leading to reduced solar radiation at the surface because of the unrealistic representation of cloud water. The distribution and size of hydrometeors are influenced by microphysical processes in microphysical parameterizations. Therefore, tuning and revising the cloud microphysics scheme are necessary for reducing biases.

The remainder of this paper is organized as follows. Section 2 briefly describes the revised WDM6 cloud microphysics scheme, as well as the GRIST-single-column atmospheric model (GRIST-SCM) and three-dimensional (3D) GRIST model. The numerical experiments and data used in the simulations are also presented in Section 2. The numerical results of both the 3D simulations and GRIST-SCM runs using the revised microphysics scheme are presented in Section 3 and compared with those of the original WDM6 (OWDM6) scheme. In Section 4, the summary and discussion are presented.

2 NUMERICAL MODEL AND EXPERIMENTS

2.1 GRIST dynamic core

The GRIST model formulates a fully compressible atmosphere discretized on global unstructured icosahedral grids with hexagonal/pentagonal meshes on the sphere and generalized mass-based vertical coordinates (Zhang et al. 2019). A horizontal Arakawa-C grid and vertical Lorenz staggering were used for the predictive quantity distribution. An unstructured grid allows a flexible switch between quasi-uniform and variable-resolution meshes. Horizontally explicit and vertically semi-implicit arrangements ensure exact mass conservation in the numerical transportation under a finite volume definition. No time splitting of the dynamic processes was included, whereas tracer advection was handled in a splitting manner. Physics is considered a forcing term, which is sequentially coupled with the dynamic core with relatively large time steps in high-resolution simulations (Li et al. 2020, 2022). The dynamic solver has been assessed in various configurations (e.g., Wang et al. 2019; Zhang et al. 2021; Zhou et al. 2020) and demonstrates reasonable physical and remarkable computational performance.

2.2 Single-column model

Considering horizontal advection as a given forcing term, GRIST-SCM contains a simplified dynamic core to handle the vertical advection of temperature (T) and water vapor (q_v) within an atmospheric column:

$$\frac{\partial T}{\partial t} = -(\mathbf{V} \cdot \nabla T)_{\text{LS}} - \omega_{\text{LS}} \frac{\partial T}{\partial p} + \frac{R_d T}{p c_p} \frac{dp}{dt} + \left(\frac{\partial T}{\partial t} \right)_{\text{phys}} \quad (1)$$

$$\frac{\partial q_v}{\partial t} = -(\mathbf{V} \cdot \nabla q_v)_{\text{LS}} - \omega_{\text{LS}} \frac{\partial q_v}{\partial p} + \left(\frac{\partial q_v}{\partial t} \right)_{\text{phys}} \quad (2)$$

where p and ω are the pressure and pressure-based vertical velocity; $\mathbf{V}$ is the horizontal wind vector; R_d represents the gas constant for dry air; and c_p is the heat capacity at constant pressure for dry air. Subscript “phys” denotes the physical parameterizations, and “LS” represents the large-scale processes. Vertical transport was numerically determined when horizontal advection was forced under the given conditions. No relaxation terms for the observations were considered in the model.

2.3 Physical parameterization schemes

The physical parameterization suite consisted of the Zhang–McFarlane deep convection scheme (Neale et al. 2008; Zhang and McFarlane 1995) and Gauss-PDF macrophysics scheme (Qin et al. 2018), University of Washington shallow cumulus convection and moist local boundary-layer turbulence scheme (Bretherton and Park 2009; Park and Bretherton 2009), and the rapid radiative transfer model for GCMs short- and long-wave radiation (Iacono et al. 2008). In addition, the Noah-MP land surface model has been used to describe the land-atmosphere interaction processes (Niu et al. 2011). The OWDM6 cloud microphysics scheme was used to parameterize grid-scale condensation and interconversion of the corresponding hydrometeors.

2.4 RWDM6 scheme

The OWDM6 scheme from WRF model version 4.2.1 was revised, including the parameterizations of raindrop evaporation and cloud water accretion.

2.4.1 EVAPORATION OF RAINDROPS

2.4.1.1 Temperature adjustment

In microphysical parameterization, the determination of the saturated mixing ratio is critical because it affects the computation of certain cloud microphysics processes, such as the evaporation of raindrops. In a clear-sky environment, it is appropriate to calculate the saturated mixing ratio using the grid mean temperature at the beginning of a time step. However, in cloudy environments, an appropriate method is to define the saturated mixing ratio using the grid-mean temperature before the water vapor undergoes a phase change. The temperature adjustment based on Qian et al. (2018) can be expressed as

$$T' = T - \frac{L_v}{c_p} q_c - \left(\frac{L_v}{c_p} + \frac{L_f}{c_p} \right) q_i \quad (3)$$

where T is the grid mean temperature employed to

compute the saturation mixing ratio in the OWDM6 scheme; T' is the adjusted temperature; L_v is the latent heat of evaporation; L_f is the latent heat of melting; and q_c and q_i are the cloud water and ice masses, respectively. A lower adjusted temperature helps determine a lower saturated mixing ratio and reduces the amount of raindrop evaporation. The adjusted temperature is only used within the microphysics scheme for the saturated mixing ratio determination, without updating the corresponding quantity in other physics schemes and the dynamic core.

2.4.1.2 Correction to the number concentration of raindrops

In the OWDM6 cloud-microphysics scheme, the raindrop-mixing ratio changes continuously during each microphysical process. During raindrop evaporation, the raindrop number concentration varied only when the raindrop mixing ratio was entirely evaporated. If part of the raindrop evaporates into water vapor during this process, the raindrop number concentration remains unchanged. Thus, an inconsistency between raindrop mass and number concentration is observed, leading to uncertainties in the rain particle size distribution. Parameterized raindrop evaporation is largely influenced because it is highly sensitive to and nonlinearly dependent on particle size (Zhao et al. 2021).

To address this issue, a continuous variation in raindrop number concentration was considered in the evaporation process to ensure a more reasonable raindrop particle size and precipitation distribution. The raindrop number concentration is given as

$$\left(\frac{\partial N_r}{\partial t} \right)_{\text{evap}} = \frac{\left(\frac{\partial q_r}{\partial t} \right)_{\text{evap}}}{\frac{4\pi\rho_w}{3\rho_a} \left(\frac{D_r}{2} \right)^3} \quad (4)$$

where $\left(\frac{\partial N_r}{\partial t} \right)_{\text{evap}}$ and $\left(\frac{\partial q_r}{\partial t} \right)_{\text{evap}}$ are the time tendencies of

raindrop number concentration and rain mixing ratio, respectively; q_r and N_r represent the mixing ratio and number concentration of raindrops, respectively; $\rho_w = 1000 \text{ kg m}^{-3}$ is the density of water; ρ_a is the air density; and $D_r = \frac{1}{\lambda_r} (24)^{\frac{1}{3}}$ is the mean-volume-drop diameter of rainwater, where λ_r is the raindrop slope parameter.

Evaporation of rain droplets was activated in the OWDM6 scheme when the grid-mean relative humidity (RH) was less than 100%, and direct condensation to raindrops occurred when the grid-mean RH exceeded 100%. Water vapor rarely condenses directly into raindrops, forming cloud droplets first. Therefore, in the RWDM6 scheme, we only consider the raindrop evaporation process.

2.4.2 ACCRETION OF CLOUD WATER TO RAINDROPS

Microphysical processes related to cloud and rain droplets, including cloud condensation nuclei activation,

accretion of cloud water to rain, auto conversion between cloud and rain droplets, rain evaporation, enhanced melting of snow, and rain evaporation as the diameter of rain droplets becomes smaller than 82 μm (Lim and Hong 2010), were examined.

The accretion of cloud water to raindrops in the OWDM6 scheme was derived from Cohard and Pinty (2000). The equation is given as

$$\left\{ \begin{aligned} \left(\frac{\partial q_c}{\partial t} \right)_{\text{accr}} &= \frac{\pi \rho_w}{6 \rho_a} K_1 \frac{N_c N_r}{\lambda_c^3} \left(\frac{2}{\lambda_c^3} + \frac{24}{\lambda_r^3} \right), \text{ if } D_r \geq 100 \mu\text{m} \\ \left(\frac{\partial q_c}{\partial t} \right)_{\text{accr}} &= \frac{\pi \rho_w}{6 \rho_a} K_2 \frac{N_c N_r}{\lambda_c^3} \left(\frac{6}{\lambda_c^6} + \frac{5040}{\lambda_r^6} \right), \text{ if } D_r < 100 \mu\text{m} \end{aligned} \right. \quad (5)$$

where $\lambda_c = \left(\frac{\pi \rho_w}{6 \rho_a} \frac{N_c}{\rho_a q_c} \right)^{\frac{1}{3}}$ represent the slope parameters of

cloud droplet sizes; $\lambda_r = \left(4\pi \rho_w \frac{N_r}{\rho_a q_r} \right)^{\frac{1}{3}}$; N_c represents the

number concentration of cloud water; K_1 and K_2 are Long's collection kernel coefficients, which are 3.03×10^3 and $2.59 \times 10^{15} \text{ m}^{-3} \text{ s}^{-1}$, respectively. A transition of the accretion rate is assumed at $D_r = 100 \mu\text{m}$. In both early and late stages of rain growth, the accretion rate is sensitive to the mean particle mass (q_c/N_c and q_r/N_r), particularly in the drizzling stage ($D_r < 100 \mu\text{m}$), indicating that the accurate prediction of number concentrations is required. In a GCM with relatively coarse spatiotemporal resolution, uncertain results of cloud water variation may be obtained owing to errors in the number concentration prediction. Therefore, we adopted the formulation of Khairoutdinov and Kogan (2000) to parameterize accretion with only bulk mass concentrations:

$$\left(\frac{\partial q_c}{\partial t} \right)_{\text{accr}} = 67(q_c q_r)^{1.15} \quad (6)$$

$$\left(\frac{\partial N_c}{\partial t} \right)_{\text{accr}} = \frac{N_c}{q_c} \left(\frac{\partial q_c}{\partial t} \right)_{\text{accr}} \quad (7)$$

for application in global simulations. This parameterization is a fitting result of large eddy simulations (Khairoutdinov and Kogan 2000) without distinguishing the stages of rain growth and has been implemented in microphysics schemes such as those of Morrison and Gettelman (2008) and the Predicted Particle Properties (P3) scheme (Milbrandt and Morrison 2016). Differences between the OWDM6 and RWDM6 schemes are shown in Table 1.

2.5 Diagnostic treatment of liquid stratus and shallow cumulus

The GRIST model includes two categories of cloud types: stratus and cumulus. The stratus includes both liquid and ice, and the cumulus is described as deep or shallow. The ice stratus and deep cumulus were diagnosed based on the findings of Park et al. (2014), whereas the liquid stratus and shallow cumulus were represented as one type in the Gauss-PDF scheme (Qin et al. 2018). The cloud fraction (R) and cloud water (q_c) for large-scale condensation in the

Gauss-PDF macrophysics scheme are as follows:

$$R = \frac{1}{2} \left[1 + \text{erf} \left(\frac{Q_1}{\sqrt{2}} \right) \right] \quad (8)$$

$$\frac{q_c}{2\sigma_s} = Q_1 R + \frac{e^{-\frac{Q_1^2}{2}}}{\sqrt{2\pi}} \quad (9)$$

$$Q_1 = a(\bar{q}_w - \bar{q}_{sl}) / (2\sigma_s) \quad (10)$$

where erf is the Gaussian error function; Q_1 is a dimensionless variable describing the deviation of the mean state from saturation. The overbar indicates the quantity from the microphysics scheme. The grid-mean total water mixing ratio is $\bar{q}_w = \bar{q}_v + \bar{q}_c$, where $\bar{q}_v$ and $\bar{q}_c$ are the grid-mean vapor mixing ratio of water and cloud, respectively; $\bar{q}_{sl}$ is the grid-mean saturated mixing ratio over water; and σ_s is the subgrid-scale variance of total water, which is related to the turbulence and shallow convection. More details can be found in Qin et al. (2018).

2.6 Experiments and data

RWDM6 was first evaluated using the GRIST-SCM model because most of the dynamic forces were excluded; then, it was compared with the OWDM6 scheme in the 3D GRIST model with full physics processes. Data observed in a field experiment, the Tropical Warm Pool International Cloud Experiment (TWP-ICE), were used to initiate GRIST-SCM and evaluate the SCM results. The SCM included 30 levels in the vertical direction, with the top at 2.25 hPa. A 1200 s time step was used in the numerical integrations. Single-column experiments and global simulations are introduced later.

TWP-ICE was performed on January 18 and February 13, 2006, over an oceanic underlying surface (Davies et al. 2013) and has been widely used to study oceanic rainfall and clouds associated with tropical convection. There were four episodes in the TWP-ICE experiment: active convection (January 18–25), suppressed convection (January 26–February 2), clear sky (February 3–5), and monsoon breaking (February 6–13) episodes (Kim et al. 2014). The duration of the simulation was 26 d, from January 18 to February 12. The large-scale forcing data for the model were obtained from Xie et al. (2010).

The retrieved cloud fraction (Xie et al. 2010) was used for the model evaluation. The ice water content (IWC) was obtained from European research projects CLOUDNET and DENG (Deng and Mace 2006). The liquid water content (LWC) was obtained from Continuous Baseline Microphysical Retrieval, one of the cloud retrieval products of ground-based atmospheric radiation measurements. The LWC retrieval contained rain and drizzle. A quality check of the LWC data was performed to eliminate uncertainty in the retrieval product. Uncertainties of the IWC retrievals were reported to be 30%–85% (Zhao et al. 2012), which are related to the accuracy of the assumptions in the forward model,

Table 1. Differences between the OWDM6 and RWDM6 schemes.

Processes	RWDM6	OWDM6
Accretion of cloud to rain	$\left(\frac{\partial q_c}{\partial t}\right)_{\text{accr}} = 67(q_c q_r)^{1.15}$	$\left(\frac{\partial q_c}{\partial t}\right)_{\text{accr}} = \frac{\pi \rho_w K_1 N_c N_r}{6 \rho_a \lambda_c^3} \left(\frac{2}{\lambda_c^3} + \frac{24}{\lambda_r^3} \right)$, if $D_r \geq 100 \mu\text{m}$ $\left(\frac{\partial q_c}{\partial t}\right)_{\text{accr}} = \frac{\pi \rho_w K_2 N_c N_r}{6 \rho_a \lambda_c^3} \left(\frac{6}{\lambda_c^6} + \frac{5040}{\lambda_r^6} \right)$, if $D_r < 100 \mu\text{m}$
Rain evaporation	$\left(\frac{\partial N_r}{\partial t}\right)_{\text{evap}} = \frac{\left(\frac{\partial q_r}{\partial t}\right)_{\text{evap}}}{\frac{4\pi \rho_w}{3\rho_a} \left(\frac{D_r}{2}\right)^3}$	—
Temperature adjustment	$T' = T - \frac{L_v}{c_p} q_c - \left(\frac{L_v}{c_p} + \frac{L_f}{c_p} \right) q_i$	—

Symbol “—” indicates that this parameter/process is not included.

uncertainty of the power-law fitting parameters in the forward model, and observational errors.

In addition, Atmospheric Model Intercomparison Project-type global long-term simulations using three-dimensional GRIST were performed on 30 vertical levels with a horizontal resolution of approximately 120 km. A time step of 20 min was used. Model outputs for the last 5 years of a 5.5-year simulation were used for the analysis. In the global validation, observational datasets, including precipitation from the Global Precipitation Climatology Project (GPCP; Huffman et al. 2009), longwave and shortwave cloud radiative forcing from the Cloud and the Earth’s Radiant Energy System Energy Balanced and Filled (CERES-EBAF; Loeb et al. 2009) at the top of the atmosphere (TOA), cloud fraction, and vertical distribution from the GCM-Oriented CALIPSO Cloud Product (CALIPSO-GOCCP; Chepfer et al. 2010) were used for comparison.

3 RESULTS

3.1 Cloud and precipitation simulation in the TWP-ICE experiment

The results of the hydrometeor simulation were compared between the RWDM6 and OWDM6 schemes. The root-mean-square errors (RMSEs) are shown in Table 2. The RMSE was calculated in the convection-activating period during January 18 and 25, and the convection-suppressed period during January 26 and February 2. RWDM6 displayed relatively smaller RMSEs in the cloud fraction and LWC simulations, even though it simulated a

marginally larger IWC error.

Figure 1 illustrates the evolution of the IWC, LWC, and cloud fraction throughout the TWP-ICE period in both simulations. The two schemes exhibit a significant difference in the LWC and cloud fraction during the monsoon-active period, which contrasts with their behavior during the monsoon-suppressed period. During the active period, a smaller cloud fraction was displayed below 500 hPa in RWDM6, which agrees better with the observation, compared with that in OWDM6 (Figs. 1a–1c). In RWDM6, ice was observed below the melting level because of the inclusion of snow particles, which have a higher fall speed than cloud ice (Fig. 1e). A significantly weaker LWC was observed in the lower troposphere (Fig. 1h) than in OWDM6 (Fig. 1i) during the convection-active period. Although the simulated LWC was still overestimated, a clear improvement was confirmed in comparison with the OWDM6 results. As shown in Eqs. (8) and (10), the low-level cloud fraction is proportional to the cloud-water mixing ratio. The decrease in the low-level cloud fraction during the convection-active period was a result of the significant reduction in LWC simulated by RWDM6.

The profiles of the cloud fraction, IWC, and LWC are shown in Fig. 2 for both the convection active and suppressed periods. The RWDM6 result, which showed better agreement with the observational profile (Fig. 2a), exhibited a smaller cloud fraction than OWDM6 below 200 hPa during the monsoon active period. Overestimation of the cloud fraction below 500 hPa was significantly

Table 2. RMSEs of the cloud hydrometeors and cloud fraction.

Scheme	Simulation period	Cloud fraction	IWC	LWC
OWDM6	Active	0.22	18.86	225.13
	Suppressed	0.12	6.80	32.40
RWDM6	Active	0.20	19.48	32.91
	Suppressed	0.12	7.10	15.73

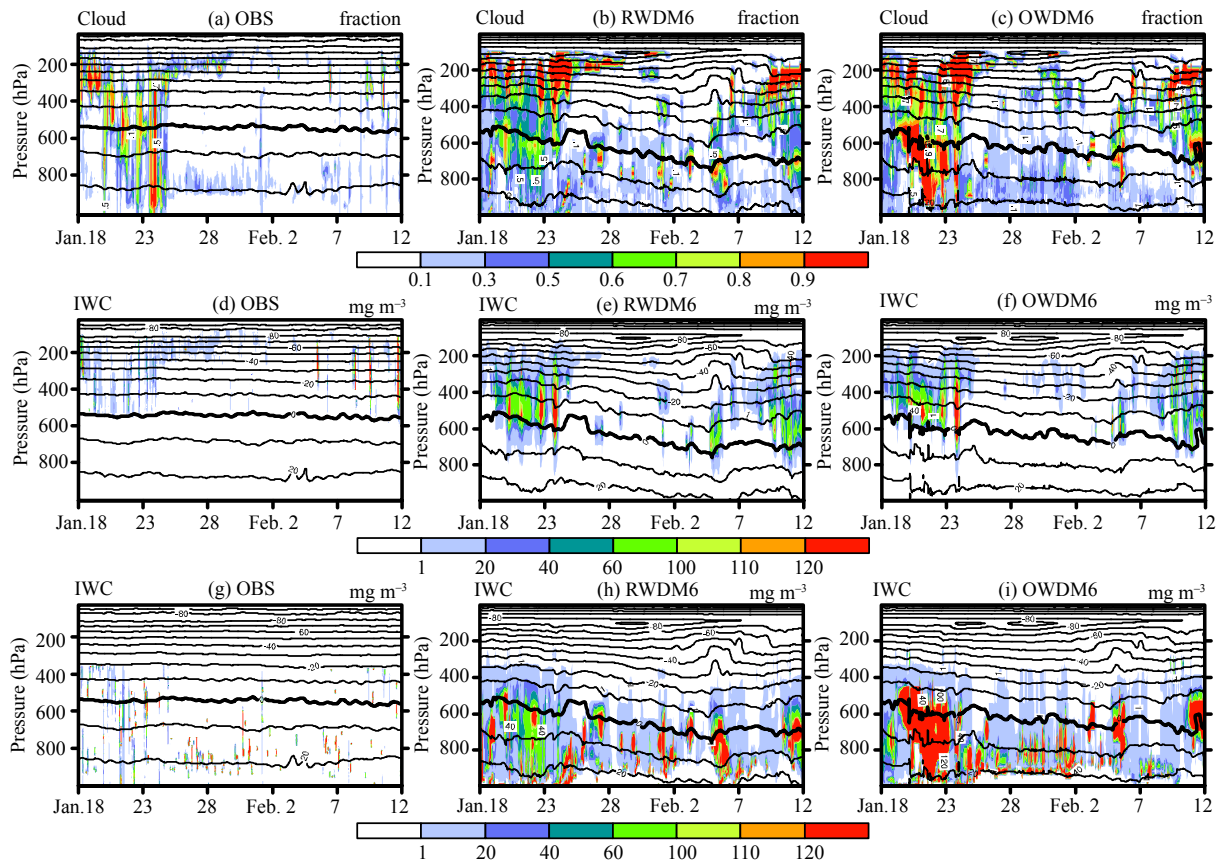


Figure 1. Temporal evolution of (top) cloud fraction, (middle) IWC, and (bottom) LWC profiles with the (b, e, h) RWDM6 and (c, f, i) OWDM6 schemes in comparison with the observations (OBS) or (a, d, g) retrievals. The melting level is marked with a bold line in each plot.

improved in RWDM6, corresponding to a 9.09% reduction in the RMSE of the cloud fraction (Table 2). The cloud fraction above 200 hPa, which is mainly an anvil of convective clouds, remains unchanged because the cumulus convective scheme is not considered here.

The averaged IWC profiles were extremely similar between RWDM6 and OWDM6, with a clear underestimation in the upper troposphere and an overestimation in the middle troposphere (700–300 hPa). LWC was largely cut by RWDM6 and was consistent with the retrieval data (Fig. 2c). The RMSE of the simulated LWC decreased by 85.38%. Sensitivity experiments were conducted on accretion and raindrop evaporation. The OWDM6 scheme with the modified accretion process effectively reduced the overestimation of LWC observed in the OWDM6 scheme. Thus, the modified accretion process enhanced the conversion of cloud water to raindrops. The use of temperature adjustment reduces the cloud fraction in the convection-active period and increases the cloud fraction in the convection-suppressed period (Figs. 2a and 2d).

The changes in IWC are less significant than the LWC variations when the microphysics are shifted to the RWDM6 scheme because the accretion is modified to target the improvement of conversion between cloud and rainwater, whereas the direct conversion between cloud

water and ice remains unchanged. In addition, temperature adjustment showed a weak effect on the IWC because of the low cloud ice content.

The simulated precipitation showed proper temporal variation in RWDM6, with a peak of 125 mm d^{-1} on January 24 (Fig. 2g). The precipitation is significantly improved with the RWDM6 scheme, which illustrates an RMSE and correlation coefficient (CC) of 9.69 and 0.88, respectively, being significantly better than those of 15.81 and 0.65 with the OWDM6. The spurious rainfall peak around January 21 observed in OWDM6 was removed, despite the precipitation peak around January 24 being slightly weakly simulated, and a spurious rainfall peak was observed on January 26. When the temperature adjustment was used with the revised accretion, the spurious peak on January 26 disappeared. However, the peak time lagged slightly during the convection-active period. When the continuous variation in the number concentration was considered in raindrop evaporation, the simulated precipitation peaks were similar to the observations. As a result, the revisions improved the performance of the microphysics scheme, which simulated a significantly better cloud distribution and precipitation variation.

During the convection-suppressed period, the cloud fraction simulated with RWDM6 dropped below 200 hPa (Fig. 2d), which showed less deviation from the retrieval

data than OWDM6. However, in the upper troposphere above 200 hPa, RWDM6 displayed a higher cloud fraction, leading to an increased RMSE of the cloud fraction compared to that of the observations. However, both schemes failed to simulate the IWC properly in convection-active and suppressed periods, which may result from the lack of subgrid-scale vertical transport of ice water. A significantly lower level (500 hPa) of the IWC peak was simulated compared to that observed (100 hPa) during the convection-active period (Fig. 2b). As shown by LWC, RWDM6 predicted slightly more (substantially less) cloud water above (below) 800 hPa than OWDM6 during

the monsoon-suppressed period (Fig. 2f). With only accretion modification, the overestimation of LWC was reduced during the monsoon-suppressed period, similar to the active period. The impact of the temperature adjustment was not as evident in the monsoon-suppressed period as in the active period (Figs. 2c and 2f) because of the low cloud water and cloud ice contents.

Raindrop evaporation is not as effective as accretion and temperature adjustments, as shown in Fig. 2, particularly during the convection-active period. However, in the convection-suppressed period, the LWC was largely eliminated in the lower troposphere (600–800

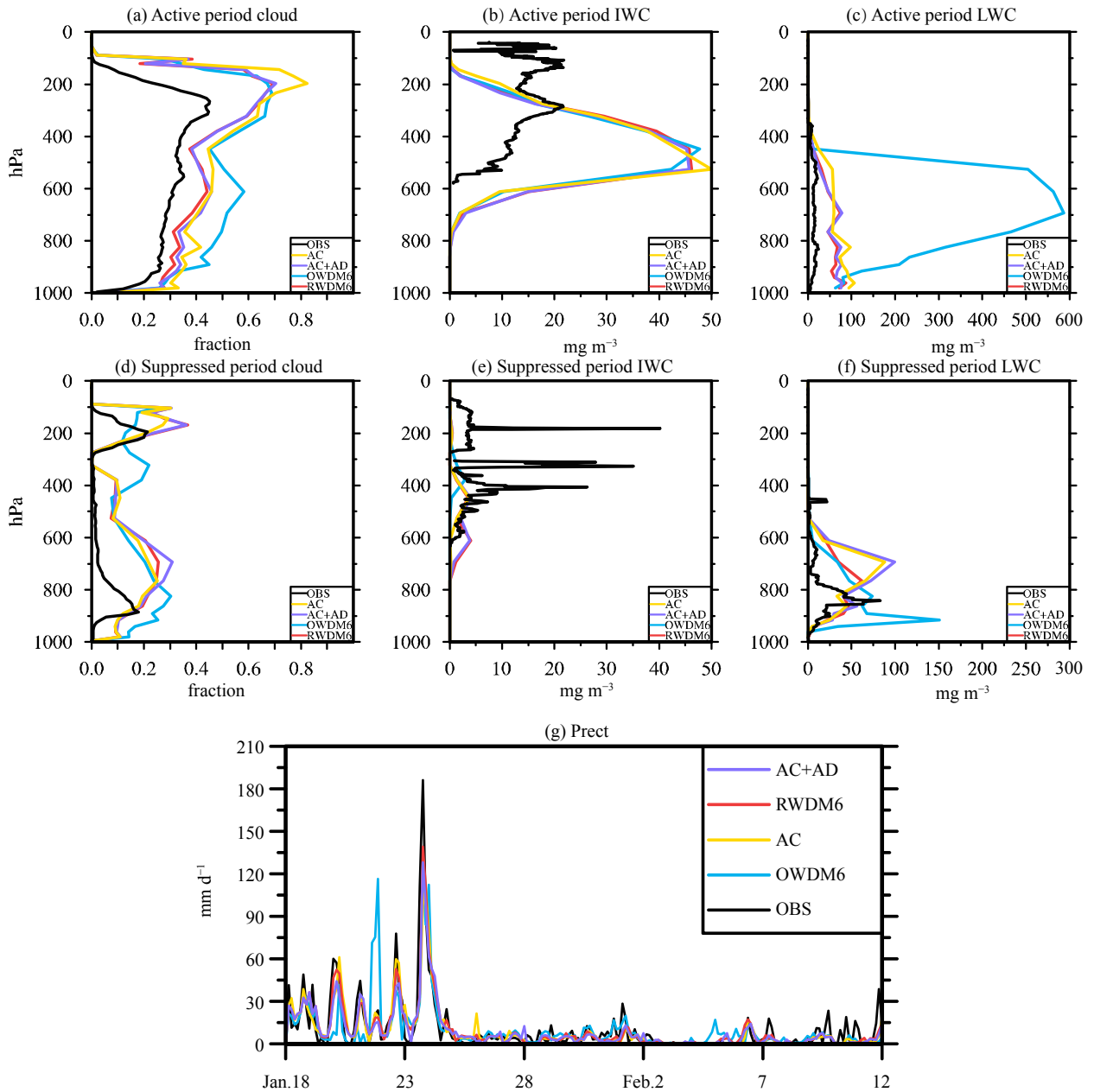


Figure 2. Vertical profiles of the cloud (a, d) fraction, (b, e) IWC, and (c, f) LWC averaged in the convection-active (January 18–25, top) and suppressed (January 26–February 2, middle) periods, respectively, and (g) precipitation rate variation from January 18 to February 12. Red, blue, and black lines show the RWDM6 and OWDM6 simulations and observations, respectively. Yellow and purple lines correspond to results with only the modification of the accretion process (AC) and both the accretion and temperature adjustment (AD), respectively.

hPa) when raindrop evaporation was considered in RWDM6, in comparison with the results of the AC+AD run (Fig. 2f). In the OWDM6 scheme, if $D_r < 82 \mu\text{m}$ in an unsaturated environment, all the raindrops are converted to cloud water. The reduction in the number concentration associated with raindrop evaporation in this study increased the mean raindrop diameter, weakening the conversion of raindrops to cloud water. The cloud water then decreased (Figs. 2c and 2f). In the convection-active period, the proportion of small-radius raindrops ($D_r < 82 \mu\text{m}$) is lower than that in the convection-suppressed period. Therefore, raindrop evaporation does not have as significant an impact on LWC in the convection-active period as in the suppressed period.

The cloud fraction directly impacts radiative transfer and energy balance in climate models. The simulated daily mean net short- and long-wave radiative energy fluxes are shown in Fig. 3 for comparison with observations. The amelioration of the radiative energy fluxes is also shown in Fig. 3, particularly for the convection-active period. RWDM6 explicitly simulated larger net downward

shortwave fluxes, similar to the observations, at both the surface and TOA compared to OWDM6 in convection-active and clear-sky periods (Figs. 3a and 3b). The relatively smaller cloud fraction predicted by RWDM6 on January 20 and 24 led to enhanced shortwave radiation because dense clouds impeded shortwave transmission, reduced surface flux, and reflected more solar radiation. The differences in the net longwave flux at the surface and the outgoing longwave radiation (OLR) on the TOA between the RWDM6 and OWDM6 simulations were not pronounced, except during the active period (Figs. 3c and 3d). Marginally stronger upward longwave radiation was observed during the convective period, driven by higher surface temperatures resulting from stronger incoming shortwave radiation and less cloud absorption of longwave radiation in the RWDM6.

The quantitative measurements of the RMSE and CC of the radiation fluxes are listed in Table 3. Smaller RMSEs of the net shortwave and longwave radiation fluxes at the surface and outgoing longwave and shortwave fluxes on TOA were found in RWDM6 than in OWDM6.

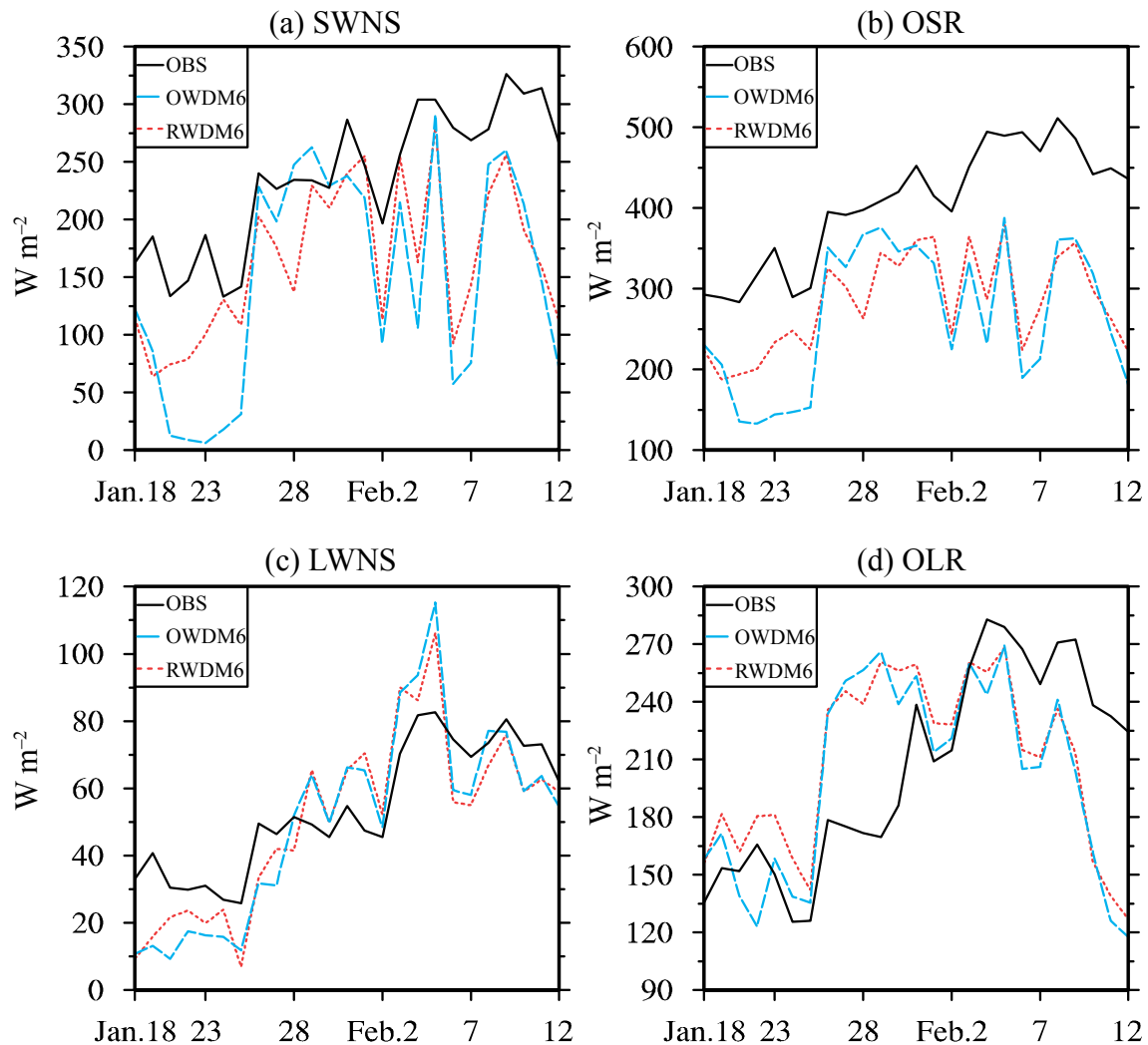


Figure 3. Daily mean net (a) shortwave and (c) longwave radiation fluxes at the surface, and outgoing (b) shortwave and (d) longwave radiation fluxes at the TOA. The blue dotted and red dashed lines show the RWDM6 and OWDM6 simulations, respectively, and the solid black represents the observations from the intensive observation period data.

Table 3. RMSEs and CCs of the simulated radiative fluxes.

Item	RMSE		CC	
	RWDM6	OWDM6	RWDM6	OWDM6
Surface net shortwave flux	88.88	114.50	0.63	0.63
Outgoing shortwave radiation	135.02	157.73	0.65	0.58
Surface net longwave flux	14.16	15.32	0.86	0.88
Outgoing longwave radiation	51.16	54.06	0.43	0.43

The improved simulation of outgoing longwave and shortwave fluxes using RWDM6 confirms the contribution of the revised microphysics to the amelioration of the global energy balance in long-term climate simulations.

3.2 Impacts of RWDM6 on global simulations

The RWDM6 scheme was further tested using the global circulation model GRIST to demonstrate its performance in simulating low clouds and their corresponding quantities. A Taylor plot depicting the correlation and standard deviation of the global total precipitation (PRECT), shortwave cloud forcing (SWCF), longwave cloud forcing (LWCF), low cloud fraction (CLDLow), medium cloud fraction (CLDMED), high cloud fraction (CLDHGH), and total cloud fraction (CLDTOT) is shown in Fig. 4.

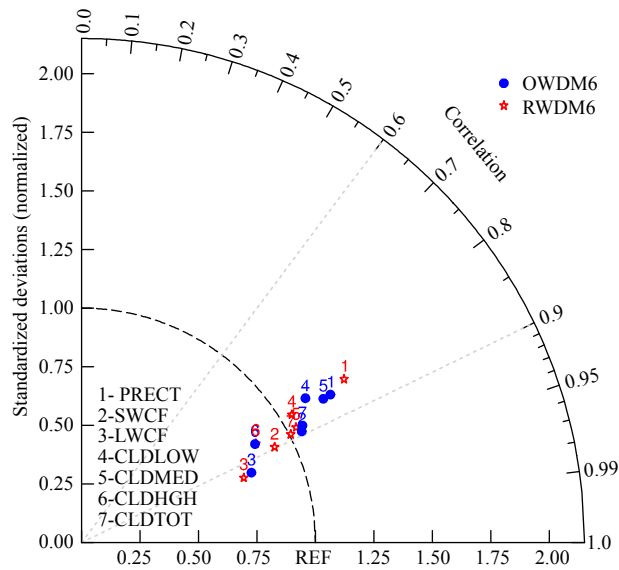


Figure 4. Taylor diagram showing the correlation and deviation of PRECT, SWCF, LWCF, CLDLow, CLDMED, CLDHGH, and CLDTOT using the RWDM6 (red) and OWDM6 (blue) schemes. The radial coordinate indicates the standard deviation normalized by observations, and the angular coordinate shows the corresponding correlations with observations.

Points closer to the reference state (dashed arc line) show a smaller standard deviation, and smaller elevation angles indicate a stronger correlation with the observations. All of these quantities illustrate high correlations (>0.8) with the observational data introduced in Section 2.5. CLDLow, CLDMED, and CLDTOT simulated by RWDM6 were significantly ameliorated, and their

standard deviations decreased from 1.138, 1.202, and 1.068 to 1.052, 1.041, and 1.007, respectively, despite the marginal improvement in spatial correlation. The results indicate that the modifications of the microphysics parameterization describe a more accurate cloud fraction (CLDLow, CLDMED, and CLDTOT) with a lower standard deviation than that of the original scheme; however, the spatial distribution is not significantly changed in the global coarse-resolution climate simulations.

The distribution of low clouds is primarily concentrated over the western coasts of the continents, the eastern tropical Pacific, and the mid-latitude oceanic regions of the Southern Hemisphere, which are associated with subsiding branches of the Hadley Cell and mid-latitude storm activities (Klein and Hartmann 1993; Wood 2012). Both schemes underestimate CLDLow (below 700 hPa) at the subtropical stratocumulus decks west of the American, African, and Australian continents, while overestimating CLDLow in the tropical Indian Ocean, western Pacific Ocean, and mid- to high-latitude regions. The underestimation of CLDLow in these regions, owing to the coarse vertical resolution in the GCMs, cannot resolve the sharp temperature and moisture gradients at the top of the subtropical stratocumulus layers (Bogenschütz et al. 2021; Lee et al. 2021).

The RMSEs of CLDLow in the tropical region are 2.17 and 2.16 for RWDM6 and OWDM6, respectively. With the exception of the overestimation of the low cloud fraction in the eastern equatorial Pacific by RWDM6, the low cloud fraction simulated by RWDM6 was better than that simulated by OWDM6. A clear reduction in CLDLow was observed at 60° latitude in RWDM6. Low clouds typically appear over thermally stable ocean surfaces, such as the west coast of America and at 60° latitude. Theoretically, the structure and stability of the atmospheric boundary layer are essential for low-level cloud simulations. In a convective environment in the tropics, such as the tropical western Pacific, the low cloud fraction is significantly smaller than that at mid- and high-latitudes. Cloud water content is an important indicator of cloud coverage. Because the low cloud fraction is proportional to the total water mass (the sum of cloud water and water vapor) in the macrophysics scheme, the large amount of water vapor in the tropics conceals the difference in cloud water between the two schemes. However, in the mid-latitudes, the difference in cloud water is easily revealed, and CLDLow is significantly improved with the RWDM6 scheme. Compared to

OWDM6, RWDM6 predicted a reasonable CLDLLOW distribution in mid- to high-latitude (45° – 90° N/S) regions, where the overestimation of the low cloud fraction was reduced (Figs. 5d and 5e). A smaller RMSE (11.26) and larger CC (0.854) of CLDLLOW were obtained using RWDM6 compared to those (RMSE=13.42, CC=0.841) using OWDM6.

Figure 6 shows the OLR at the TOA for the two schemes. Underestimation of the OLR was observed over Southeast Asia in both simulations because of the high-frequency and low-intensity problem of deep convection in the GRIST model (Li et al. 2022), which produces few high clouds. RWDM6 displayed a positive bias compared with OWDM6 in tropical regions, primarily because of a decrease in cloud water. The reduction in cloud water

further affects the conversion of cloud water to cloud ice, such as the heterogeneous freezing of cloud water, leading to a decrease in the cloud ice mass and high clouds. Longwave radiation was then reduced.

Although RWDM6 overestimates OLR in Southeast Asia, it alleviates the negative OLR bias in the tropical Pacific and Indian Oceans. Similar to the single-column model results, RWDM6 mitigated the overestimation of the low-cloud fraction and thereby improved the OLR simulation, particularly in the mid- to high-latitudes of the Southern Hemisphere and Arctic region.

Low clouds exert a net cooling effect by reflecting incoming solar radiation and emitting longwave radiation at relatively high temperatures (Hartmann 2015; Klein and Hartmann 1993). The representation of low clouds in a

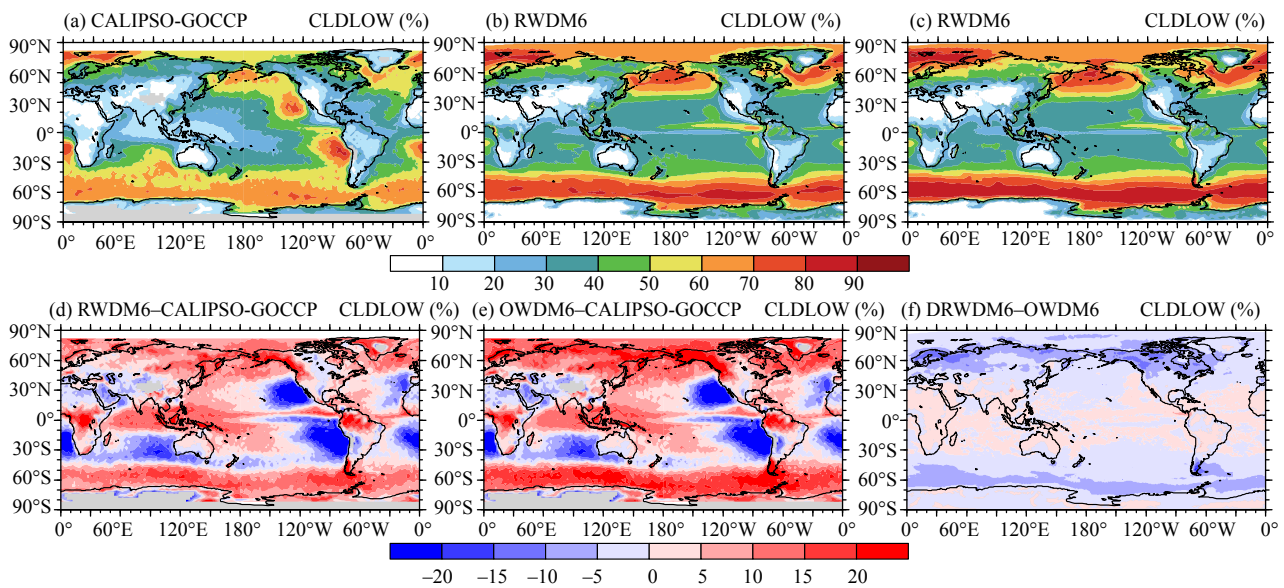


Figure 5. Annual mean low-cloud fraction. (a) CAPLISO-GOCCP, (b) RWDM6, (c) OWDM6, (d) RWDM6 minus CAPLISO-GOCCP, (e) OWDM6 minus CAPLISO-GOCCP, and (f) RWDM6 minus OWDM6.

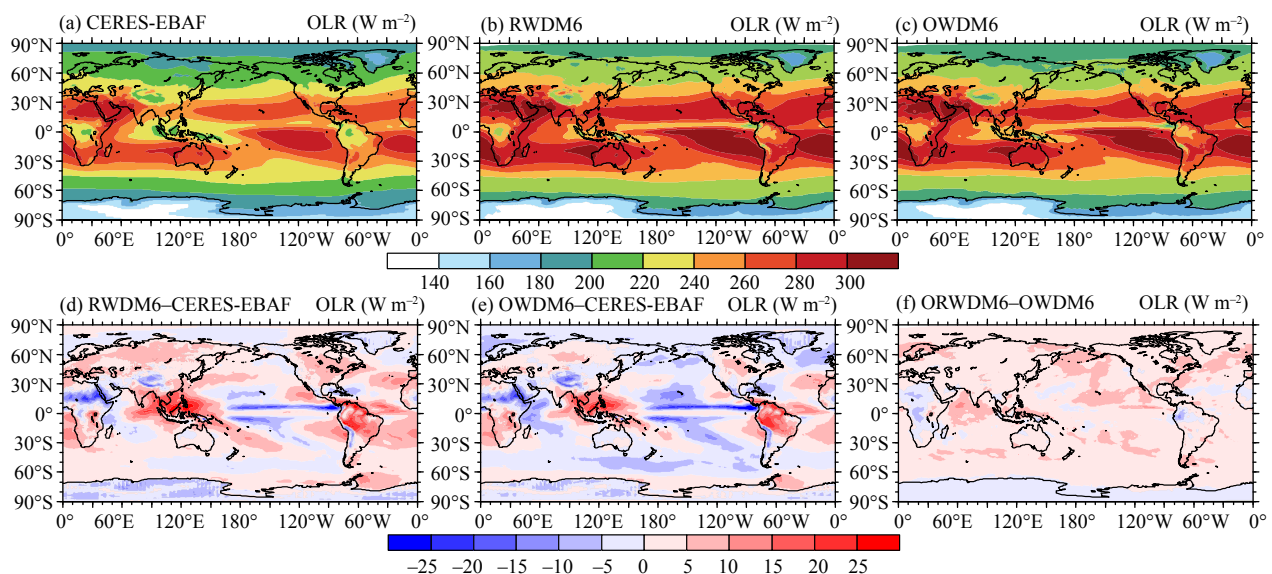


Figure 6. Annual mean OLR at the TOA. (a) CERES-EBAF, (b) RWDM6, (c) OWDM6, (d) RWDM6 minus CERES-EBAF, (e) OWDM6 minus CERES-EBAF, and (f) RWDM6 minus OWDM6.

climate model strongly affects the TOA shortwave radiation. The global mean SWCF intensity decreases from -55.11 W m^{-2} in OWDM6 to -48.65 W m^{-2} in RWDM6, which is close to the observation (-40.14 W m^{-2}). The SWCF intensity decreases over the entire globe, particularly in mid- to high-latitude regions, with a net reduction in the cooling effect of $15\text{--}25 \text{ W m}^{-2}$ (Fig. 7f). Reduced cloud water at mid- to high-latitudes contributed to the reduction of shortwave reflection and longwave emission, which improved the simulation of the proper energy balance with RWDM6 (Fig. 7). The RMSE of the SWCF decreased from 15.79 to 11.32, whereas the CC increased from 0.893 to 0.896 in the RWDM6 simulation.

Figure 8 presents the simulated vertical distribution of the zonal mean cloud fraction compared to the observations. As shown in Fig. 8a, with the CALIPSO-GOCCP data, the cloud fraction peaks over the equator above 200 hPa, whereas clouds primarily appear in mid- to high-latitude regions from 700 to 200 hPa. However, in the lower troposphere, clouds cover all latitudes and show

extremes at 60°S and the North Pole. Both schemes simulated the overall pattern with a slight overestimation, particularly for the mid- and high-latitude cloud belts below 400 hPa. RWDM6 alleviated the overestimation of the mid-latitude cloud fraction below 700 hPa by OWDM6. Because of the enhanced accretion in RWDM6, the cloud water mass decreases, which is related to the reduction of medium and low clouds in the tropical troposphere where the ascending branch of the Hadley cell is located. In the descending branch of the Hadley circulation over subtropical regions, the simulated mid-level clouds, which were similar to the observations, were also reduced by RWDM6. Overestimation of the low-level cloud peaks in the OWDM6 simulation was significantly weakened at 60°S and in the northern polar region using the RWDM6 scheme. As shown in Figs. 8b and 8c, the revised scheme exhibits improved statistical properties, that is, RMSE and CC, referencing the CALIPSO-GOCCP observations.

Mixed-phase low clouds predominate at mid-latitudes and are critically important for atmospheric radiative

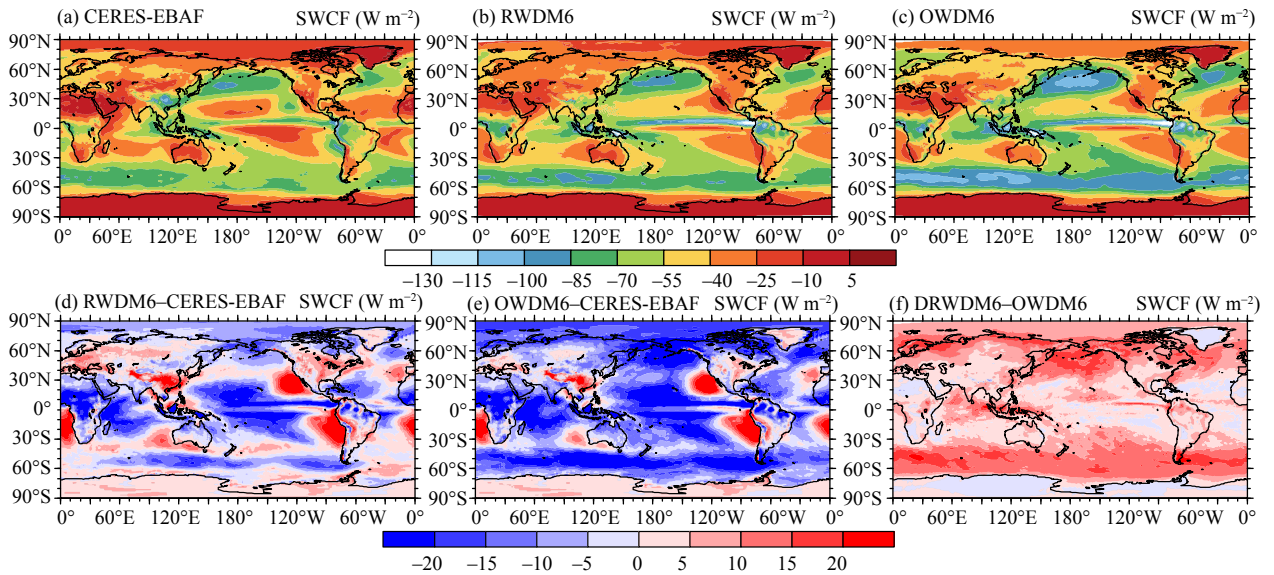


Figure 7. Annual mean shortwave cloud radiative forcing. (a) CERES-EBAF, (b) RWDM6, (c) OWDM6, (d) RWDM6 minus CERES-EBAF, (e) OWDM6 minus CERES-EBAF, and (f) RWDM6 minus OWDM6.

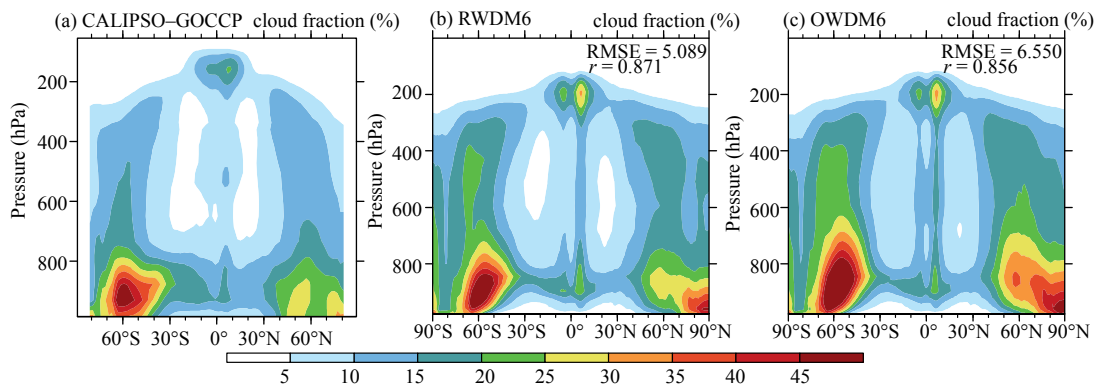


Figure 8. Vertical cross-section of the annual averaged zonal-mean cloud fraction. (a) CALIPSO-GOCCP observation, (b) RWDM6, and (c) OWDM6 simulations. The CC and RMSE are listed in the panels.

processes. Fig. 9 presents the vertical cross-sections of the liquid and ice clouds averaged at 60°N and 60°S, where the mixed-phase low clouds are primarily composed of liquid clouds. The reduction of the mid-latitude low cloud fraction in RWDM6 is primarily contributed to by liquid clouds, and ice clouds are mainly reduced below 600 hPa. Because the temperature adjustment targets only raindrop evaporation by defining a lower dew-point temperature, the cloud ice is not significantly affected. Because mixed-phase clouds significantly impact radiative processes in mid-latitudes, the aforementioned improvement in cloud shortwave radiative forcing is understandable as a result of the refinement of low-cloud simulation.

The zonal mean net cloud condensation rate, which was calculated using Eq. (9), is illustrated in Fig. 10 to depict the macrophysics results associated with the microphysics modifications. Negative net cloud condensation was observed below 900 hPa in both OWDM6 and RWDM6, with peaks at 60° latitude. This indicates that the grid is unsaturated, and cloud water evaporates. A positive net condensation was observed above 800 hPa, where significantly weaker condensation was observed in RWDM6 in comparison with OWDM6. The decrease in the diagnosed cloud fraction and cloud condensation in the mid-latitude regions was closely related to the cloud water reduction in the RWDM6 scheme.

The contributions of the revised accretion and temperature adjustment to the cloud simulation were

investigated by showing the annual mean of meridionally averaged cloud-fraction increment over mid- and high-latitude regions ($\geq 30^\circ\text{N/S}$) (Fig. 11). Both temperature adjustment and modified accretion parameterization significantly reduced low and medium clouds over mid- and high-latitude regions. The reduction in cloud fraction is predominantly observed over ocean regions, particularly in the Pacific and Atlantic Oceans. A large peak was observed in the Pacific between 150°E and 120°W, where an evident low-cloud bias was observed in the OWDM6 simulation.

Temperature adjustment had a more significant impact on the cloud fraction than accretion modification. The reduction in cloud fraction by the temperature adjustment exceeded 6% at approximately 800 hPa because a lower temperature from before condensation was used as the dew point temperature for saturation determination. The adjusted temperature is a temporary quantity used only for saturation calculations in raindrop evaporation parameterization in the microphysics scheme, without considering the temperature prediction in the dynamic core and cloud diagnosis in the macrophysics scheme. The reduced (i.e., dew point) temperature indicates less saturated water vapor, a lower saturation deficit, and lower rates of raindrop evaporation in the microphysics scheme, suggesting that the grid is more difficult to saturate in the macrophysics scheme. Therefore, a reduction in the diagnosed cloud fraction was achieved.

The meridional-averaged cloud water decrease due to

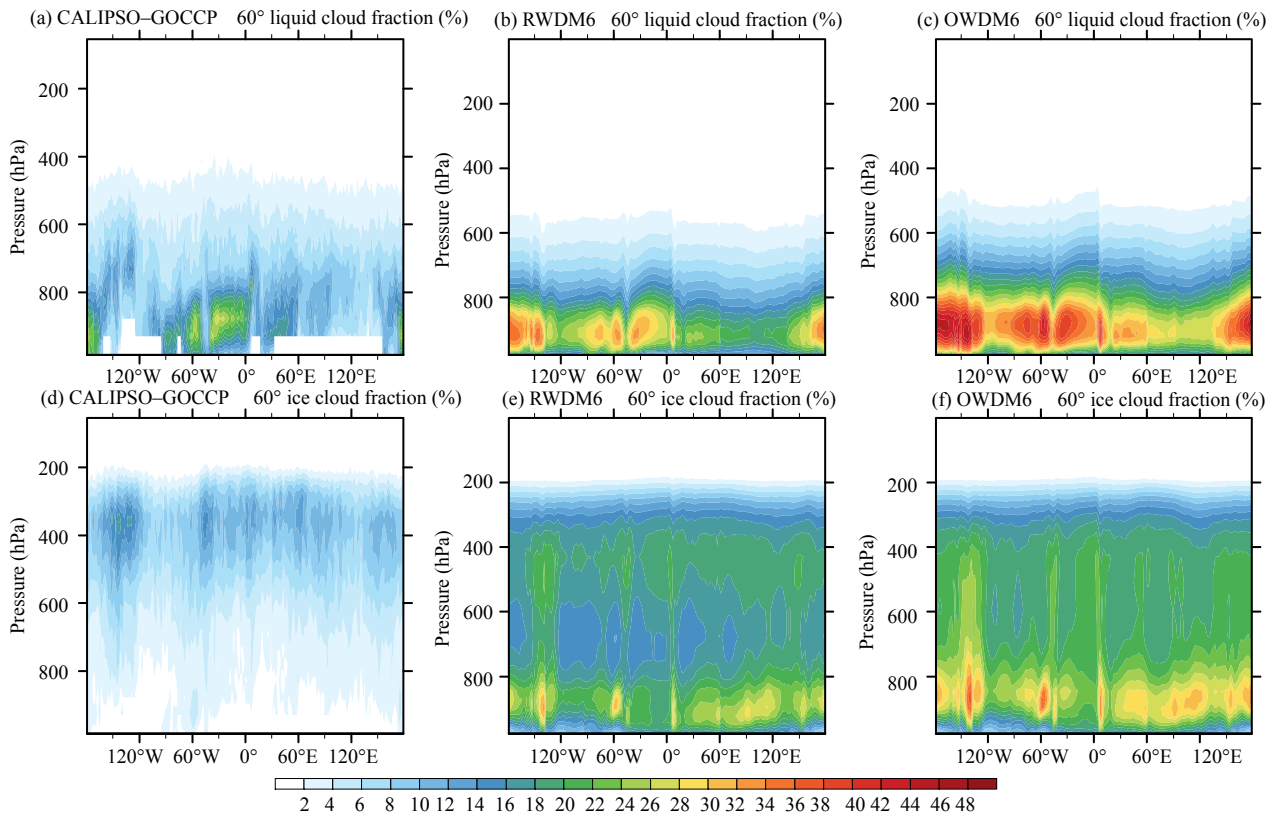


Figure 9. Vertical cross-section of the annual averaged liquid and ice cloud fraction at 60° latitude. (a, d) CALIPSO-GOCCP observation, (b, e) RWDM6, and (c, f) OWDM6 simulations.

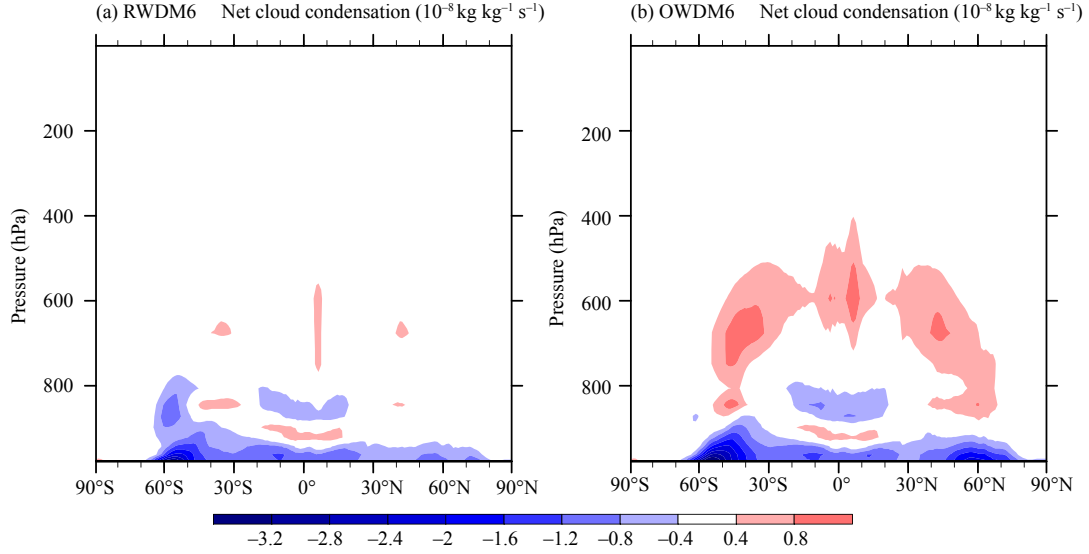


Figure 10. Vertical cross-section of annual averaged zonal-mean net cloud condensation rate ($10^{-8} \text{ kg kg}^{-1} \text{ s}^{-1}$) in the (a) RWDM6 and (b) OWDM6 simulations.

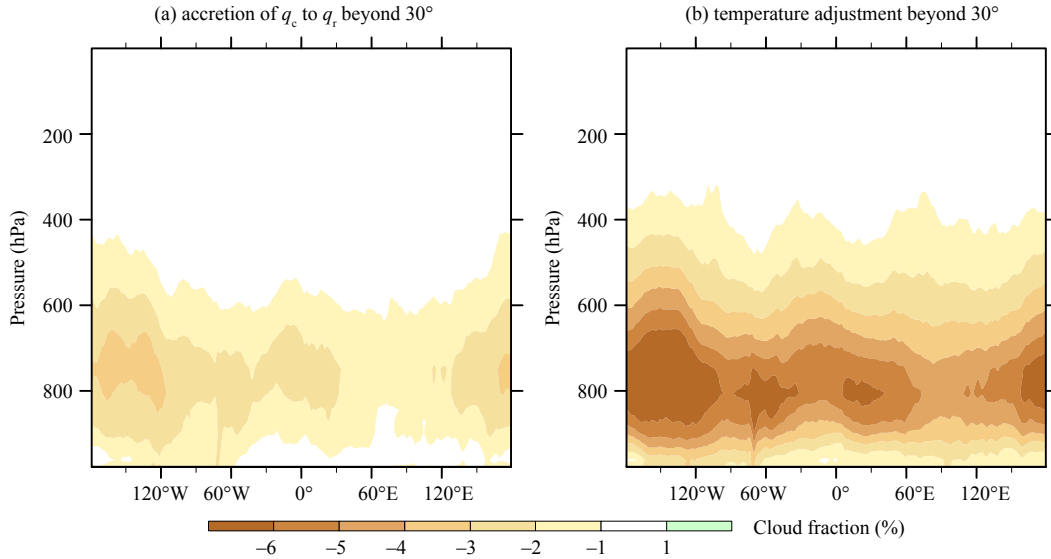


Figure 11. Annual mean of meridional-averaged ($\geq 30^\circ\text{N/S}$) cloud fraction increment corresponding to the (a) revised accretion process and (b) temperature adjustment, respectively.

accretion in mid- and high-latitude regions is shown in Fig. 12. Decreasing peaks were observed in storm-active oceanic areas. The cloud water decrease due to accretion in OWDM6 was approximately one-tenth that in RWDM6. As previously mentioned, a low-cloud fraction is diagnosed as proportional to total water and inversely proportional to the subgrid-scale variance of total water in the Gauss-PDF macrophysics scheme (Eqs. (8) and (10)). A small difference in the subgrid-scale variance of the total water was confirmed between the RWDM6 and OWDM6 schemes (not shown), and the simulated low clouds were positively correlated with the total water content. The results show that the accretion enhancement improves the representation of low clouds in the RWDM6 scheme, at least in cooperation with the Gauss-PDF macrophysics in the GRIST model.

The revision of the microphysics parameterization also impacts precipitation and cloud simulation. The simulated global annual mean precipitation is shown in Fig. 13. Compared with the observations, both the RWDM6 and OWDM6 schemes overestimated precipitation in the Indian monsoon zone, the African continent, and the Pacific Intertropical Convergence Zone, whereas underestimation was found in mid- to high-latitudes where large-scale precipitation predominates. RWDM6 reduced wet biases over the tropical North Pacific and Indian Ocean regions, as well as dry biases over the North Pacific and South American continents. The revised raindrop number concentration associated with raindrop evaporation also alleviated the overestimation of precipitation over the eastern equatorial Pacific Ocean (not shown), because raindrops

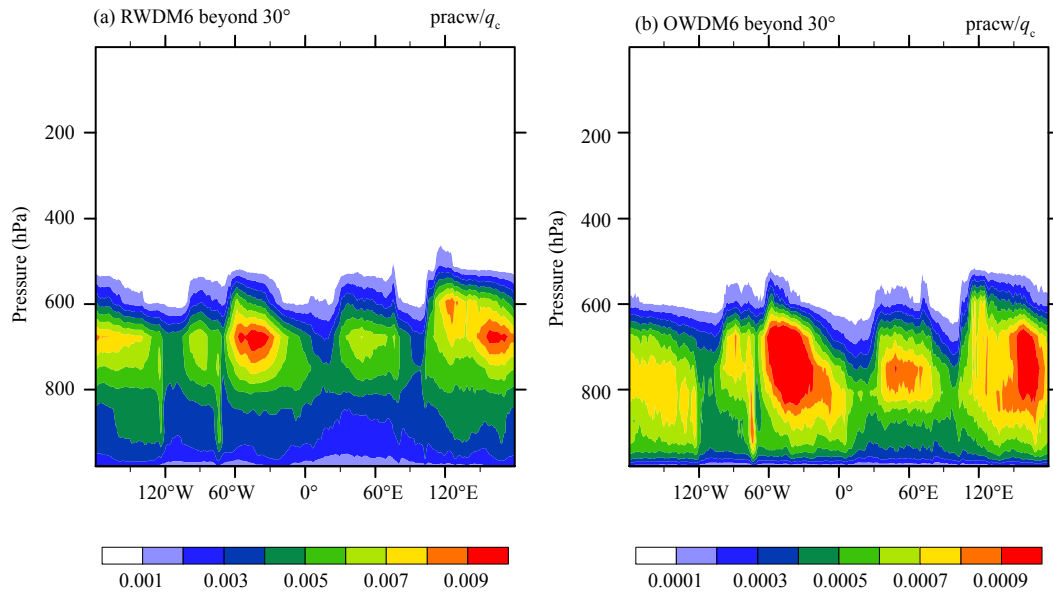


Figure 12. Meridional-averaged ratio of cloud water (kg kg^{-1}) related to the accretion process to the total cloud water (kg kg^{-1}) for (a) RWDM6 and (b) OWDM6 in mid- and high-latitude regions ($\geq 30^\circ\text{N/S}$).

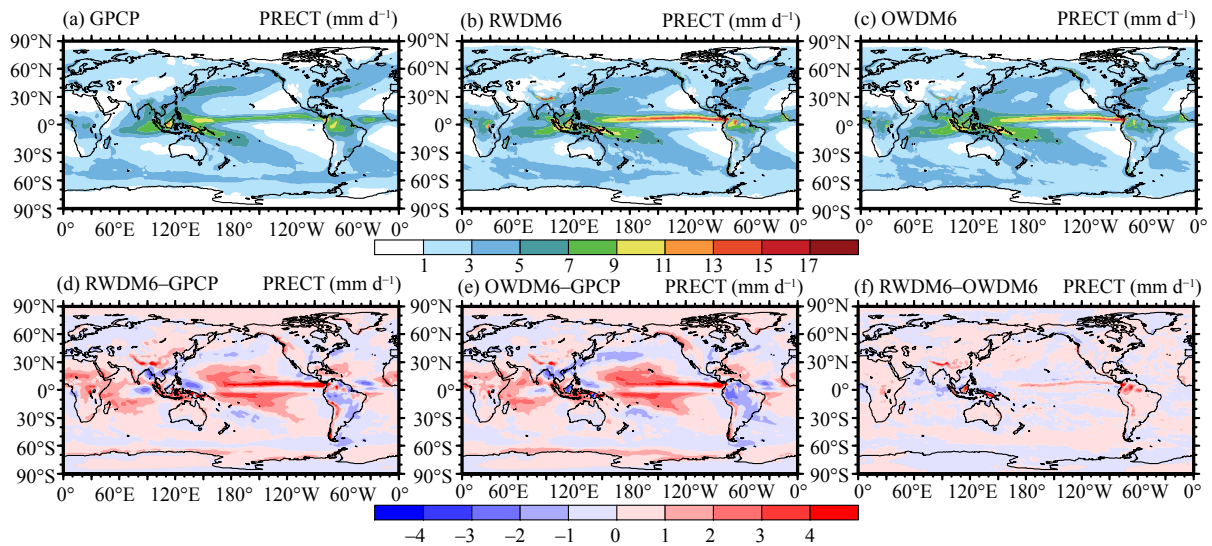


Figure 13. Annual mean precipitation of (a) GPCP analysis, and simulations with (b) RWDM6 and (c) OWDM6, (d) RWDM6 minus GPCP, (e) OWDM6 minus GPCP, and (f) RWDM6 minus OWDM6.

with larger sizes are difficult to convert to cloud water.

The meridional-averaged annual mean large-scale and convective precipitation over mid-latitudes is shown in Fig. 14. The enhanced accretion clearly increases large-scale precipitation, whereas cumulus-convective precipitation is weakened because of the competitive relationship between large-scale and convective condensation. An abrupt precipitation peak appeared near the Andes. In the Northern Hemisphere, variations in precipitation have been observed in both continental and oceanic regions. In oceanic areas, a clear increase in large-scale precipitation was observed, with a decrease in convective precipitation. The total precipitation was significantly improved in both the Northern and Southern Hemispheres by RWDM6.

4 SUMMARY AND DISCUSSION

The low-cloud simulation was refined in the GRIST model by revising the raindrop evaporation and cloud water accretion parameterization in the WDM6 scheme, which was confirmed in numerical experiments with a single-column model test, that is, the TWP-ICE, and a long-term simulation with the three-dimensional GRIST model. The RWDM6 microphysics scheme improved the simulation of precipitation and hydrometeors, in addition to clouds, resulting in a positive impact on the atmospheric energy balance in the numerical simulation.

Notable improvements were observed in the cloud fraction below 200 hPa using RWDM6, particularly below 500 hPa, in the TWP-ICE experiments. Additional snow

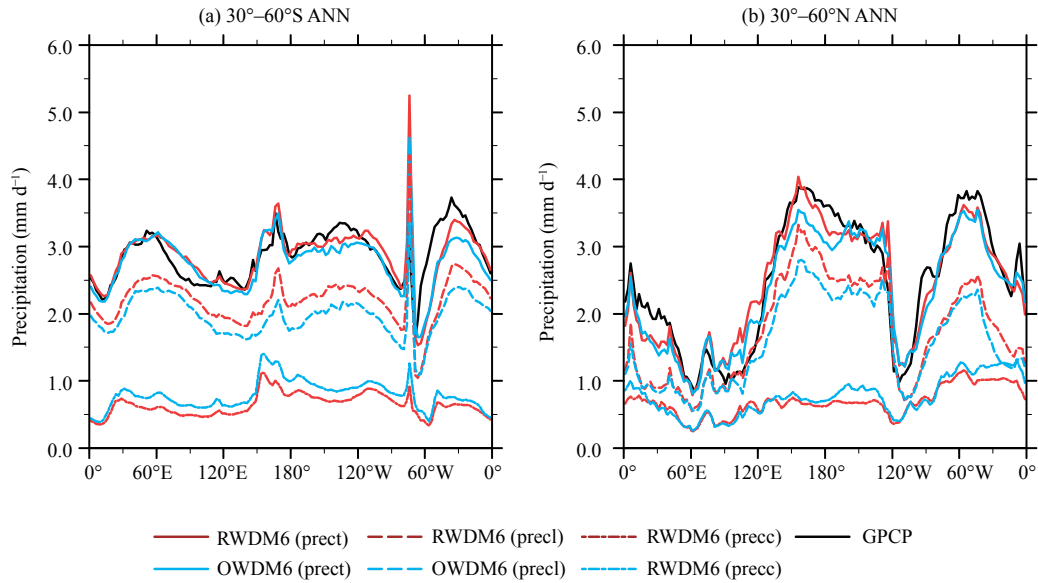


Figure 14. Meridional mean (30° – 60° latitude) of annual averaged total (prect, solid), convective (precc, dash-dot), and large-scale (precl, dashed) precipitation rates (mm d^{-1}) of the RWDM6 (red) and OWDM6 (blue) simulations, in comparison with the GPCP analysis (black) in the (a) South and (b) North Hemispheres.

occurrences below the melting point were simulated using this new scheme. A reasonable simulation of LWC was shown owing to the modifications of the cloud water accretion process and temperature adjustment, which significantly improved cloud diagnosis in the Gauss-PDF macrophysics scheme. The revision of the raindrop number associated with rain evaporation also improved the peak precipitation simulation. Refinement of precipitation, clouds, long- and short-wave radiation, and cloud hydrometeors was confirmed in the TWP-ICE experiment with RWDM6, particularly during the monsoon-active period when the LWC decreased. Proper simulation of clouds improves the radiative energy redistribution and interaction between clouds and moist processes, such as the net shortwave- and longwave-radiation fluxes at the surface and TOA in the convection-active period in the TWP-ICE simulation.

In the global simulations, the cloud fraction, cloud radiative forcing, and precipitation significantly improved, particularly the low clouds below 700 hPa in both the southern and northern hemispheres. Enhanced simulation of low clouds was confirmed at mid- to high-latitudes. The decrease in low clouds reflected a reduction in cloud water and vapor, which was attributed to the enhancement of cloud water accretion and temperature adjustment in RWDM6. The reduction in the low-cloud fraction in mid- and high-latitude regions corresponded to a decrease in longwave-radiation absorption, which improved the negative bias of the OLR on TOA. A reduced SWCF was observed in mid- to high-latitude regions in the RWDM6 simulation, which is consistent with the observations. The alleviation of shortwave-radiation biases indicates that RWDM6 played a crucial role in maintaining the modeled energy balance. RWDM6 also simulated reasonable annual mean total precipitation in the mid-latitude regions, with

large-scale precipitation increasing and convective precipitation decreasing.

With the revision of the parameterization of raindrop evaporation, cloud water accretion processes, and temperature adjustment, the overestimation of global cloud water content in the OWDM6 simulation was alleviated. A more reasonable and realistic global cloud water distribution was reproduced using the revised microphysics scheme, demonstrating a positive impact on long-term simulations using the GRIST model. Although only warm-rain processes were revised in the RWDM6, the ice cloud was affected by the complex interactions among the microphysical processes and the restraint of cloud water evaporation from the macrophysics scheme. Low-cloud refinement, benefitting from hydrometeor amelioration in the microphysics scheme, contributes significantly to the global radiative forcing and energy balance.

Although the RWDM6 scheme demonstrates significant improvements in simulating low-cloud fractions and liquid water content, systematic biases persist in the representation of ice water content and cloud fraction in tropical oceans. This overestimation of cloud ice content primarily stems from imbalanced partitioning between the cloud water and cloud ice mixing ratios within the scheme. These discrepancies suggest limitations in the current RWDM6 parameterization, highlighting the need for further optimization of key microphysical parameters, particularly the threshold of the mean raindrop radius for rain-to-cloud water conversion and the kernel coefficients. For example, increasing either the critical radius for raindrops or the kernel coefficients enhances the cloud-to-rain conversion rate. Such parameter adjustments would modulate hydrometeor size distributions, effectively mitigating the overestimation of ice water content and ultimately influencing cloud macrophysical properties and precipitation processes.

This was a preliminary application of the WDM6 scheme to a global long-term simulation using a coarse-resolution model. It is not clear whether the positive effect of the modifications to raindrop evaporation and cloud water accretion can be achieved in high-resolution models because the number concentrations of cloud water are more accurately simulated, and Cohard and Pinty (2000) accretion may produce much better results.

Acknowledgements: The authors appreciate two anonymous reviewers and the editor for their constructive comments to improve the manuscript in both science and expression.

REFERENCES

- Ahlgrimm, M., and R. Forbes, 2014: Improving the representation of low clouds and drizzle in the ECMWF model based on ARM observations from the Azores. *Mon. Weather Rev.*, **142**, 668–685, <https://doi.org/10.1175/MWR-D-13-00153.1>.
- Andrews, T., J. M. Gregory, M. J. Webb, and K. E. Taylor, 2012: Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models. *Geophys. Res. Lett.*, **39**, L09712, <https://doi.org/10.1029/2012GL051607>.
- Bogenschutz, P. A., T. Yamaguchi, and H. H. Lee, 2021: The Energy Exascale Earth System Model simulations with high vertical resolution in the lower troposphere. *J. Adv. Model. Earth Sys.*, **13**, e2020MS002239, <https://doi.org/10.1029/2020MS002239>.
- Bony, S., and J. L. Dufresne, 2005: Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophys. Res. Lett.*, **32**, L20806, <https://doi.org/10.1029/2005GL023851>.
- Bretherton, C. S. 2015: Insights into low-latitude cloud feedbacks from high-resolution models. *Phil. Trans. Roy. Soc. A*, **373**, 20140415, <https://doi.org/10.1098/rsta.2014.0415>.
- Bretherton, C. S., and S. Park, 2009: A new moist turbulence parameterization in the community atmosphere model. *J. Climate*, **22**, 3422–3448, <https://doi.org/10.1175/2008JCLI2556.1>.
- Chepfer, H., S. Bony, D. Winker, G. Cesana, J. L. Dufresne, P. Minnis, and S. Zeng, 2010: The GCM-oriented CALIPSO cloud product (CALIPSO-GOCCP). *J. Geophys. Res.: Atmos.*, **115**, D00H16, <https://doi.org/10.1029/2009JD012251>.
- Clement, A. C., R. Burgman, and J. R. Norris, 2009: Observational and model evidence for positive low-level cloud feedback. *Science*, **325**, 460–464, <https://doi.org/10.1126/science.1171255>.
- Cohard, J. M., and J. P. Pinty, 2000: A comprehensive two-moment warm microphysical bulk scheme. I: Description and tests. *Quart. J. Roy. Meteorol. Soc.*, **126**, 1815–1842, <https://doi.org/10.1002/qj.49712656613>.
- Comin, A. N., V. Schumacher, F. Justino, and A. Fernandez, 2018: Impact of different microphysical parameterizations on extreme snowfall events in the Southern Andes. *Weather Climate Extreme*, **21**, 65–75, <https://doi.org/10.1016/j.wace.2018.07.001>.
- Davies, L., C. Jakob, K. Cheung, A. D. Genio, A. Hill, T. Hume, and G. Zhang, 2013: A single-column model ensemble approach applied to the TWP-ICE experiment. *J. Geophys. Res.: Atmos.*, **118**, 6544–6563, <https://doi.org/10.1002/jgrd.50450>.
- Deng, M., and G. G. Mace, 2006: Cirrus microphysical properties and air motion statistics using cloud radar Doppler moments. Part I: Algorithm description. *J. Appl. Meteorol. Climate*, **45**, 1690–1709, <https://doi.org/10.1175/JAM2433.1>.
- Ding, S. G., C. S. Zhao, G. Y. Shi, and C. A. Wu, 2005: Analysis of global total cloud amount variation over the past 20 years. *J. Appl. Meteorol. Sci.*, **16**, 670–677, <https://doi.org/10.3969/j.issn.1001-7313.2005.05.014>. (in Chinese)
- Donner, L. J., B. L. Wyman, R. S. Hemler, L. W. Horowitz, Y. Ming, M. Zhao, and F. Zeng, 2011: The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3. *J. Climate*, **24**, 3484–3519, <https://doi.org/10.1175/2011JCLI3955.1>.
- Fan, T. Y., C. F. Zhao, X. Q. Dong, X. Liu, X. Yang, F. Zhang, and F. Wu, 2018: Quantify contribution of aerosol errors to cloud fraction biases in CMIP5 Atmospheric Model Inter-comparison Project simulations. *Int. J. Climatol.*, **38**, 3140–3156, <https://doi.org/10.1002/joc.5490>.
- Garrett, T. J., and C. F. Zhao, 2006: Increased Arctic cloud longwave emissivity associated with pollution from mid-latitudes. *Nature*, **440**, 787–789, <https://doi.org/10.1038/nature04636>.
- Hannay, C., D. L. Williamson, J. J. Hack, J. T. Kiehl, J. G. Olson, S. A. Klein, and M. Köhler, 2009: Evaluation of forecasted southeast Pacific stratocumulus in the NCAR, GFDL, and ECMWF models. *J. Climate*, **22**, 2871–2889, <https://doi.org/10.1175/2008JCLI2479.1>.
- Hartmann, D. L. 2015: *Global physical climatology*. Elsevier Science.
- Hong, S. Y., K. S. S. Lim, Y. H. Lee, J. C. Ha, H. W. Kim, S. J. Ham, and J. Dudhia, 2010: Evaluation of the WRF double-moment 6-class microphysics scheme for precipitating convection. *Adv. Meteorol.*, **2010**, 707253, <https://doi.org/10.1155/2010/707253>.
- Huffman, G. J., R. F. Adler, D. T. Bolvin, and G. Gu, 2009: Improving the global precipitation record: GPCP Version 2.1. *Geophys. Res. Lett.*, **36**, L17808, <https://doi.org/10.1029/2009GL040000>.
- Iacono, M. J., J. S. Delamere, E. J. Mlawer, M. W. Shephard, S. A. Clough, and W. D. Collins, 2008: Radiative forcing by long-lived greenhouse gases: Calculations with the AER radiative transfer models. *J. Geophys. Res.: Atmos.*, **113**, D13103, <https://doi.org/10.1029/2008JD009944>.
- Ikuta, Y., M. Satoh, W. Roh, S. Matsugishi, N. Kuba, T. Seiki, and H. Eito, 2025: Improvement of a single-moment cloud microphysics scheme consistent with dual-polarization radar. *J. Geophys. Res.: Atmos.*, **130**, e2024JD042139, <https://doi.org/10.1029/2024JD042139>.
- Khairoutdinov, M., and Y. Kogan, 2000: A new cloud physics parameterization in a large-eddy simulation model of marine stratocumulus. *Mon. Weather Rev.*, **128**, 229–243, [https://doi.org/10.1175/1520-0493\(2000\)128<0229:ANCPPI>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0229:ANCPPI>2.0.CO;2).
- Kim, K. B., K. S. S. Lim, and J. Lee, 2022: Numerical errors in ice microphysics parameterizations and their effects on simulated regional climate. *Asia-Pac. J. Atmos. Sci.*, **58**, 679–695, <https://doi.org/10.1007/s13143-022-00288-z>.
- Kim, S. Y., J. Y. Han, I. J. Choi, and S. Y. Bae, 2014: Evaluation of cloud and precipitation parameterization using a single-column model: A TWP-ICE case study. *Asia-Pac. J. Atmos.*

- Sci.*, **50**, 469–480, <https://doi.org/10.1007/s13143-014-0037-2>.
- Klein, S. A., and D. L. Hartmann, 1993: The seasonal cycle of low stratiform clouds. *J. Climate*, **6**, 1587–1606, [https://doi.org/10.1175/1520-0442\(1993\)006<1587:TSCOLS>2.0.CO;2](https://doi.org/10.1175/1520-0442(1993)006<1587:TSCOLS>2.0.CO;2).
- Ko, J. S., K. S. S. Lim, K. Kim, G. Lee, G. Thompson, and A. Berne, 2022: Simulated microphysical properties of winter storms from bulk-type microphysics schemes and their evaluation in the Weather Research and Forecasting (v4.1.3) model during the ICE-POP 2018 field campaign. *Geosci. Model Dev.*, **15**, 4529–4553, <https://doi.org/10.5194/gmd-15-4529-2022>.
- Lee, H. H., P. Bogenschütz, and T. Yamaguchi, 2021: The implementation of framework for improvement by vertical enhancement into Energy Exascale Earth System Model. *J. Adv. Model. Earth Sys.*, **13**, e2020MS002240, <https://doi.org/10.1029/2020MS002240>.
- Li, J., X. Peng, X. Li, Y. Lin, and W. Chu, 2021: Evaluation of a flexible single ice microphysics and a Gaussian probability-density-function macrophysics scheme in a single column model. *Atmosphere*, **12**, 638, <https://doi.org/10.3390/atmos12050638>.
- Li, X. H., X. D. Peng, and Y. Zhang, 2020: Investigation of the effect of the time step on the physics–dynamics interaction in CAM5 using an idealized tropical cyclone experiment. *Climate Dyn.*, **55**, 665–680, <https://doi.org/10.1007/s00382-020-05284-5>.
- Li, X. H., Y. Zhang, X. D. Peng, W. Chu, Y. Lin, and J. Li, 2022: Improved climate simulation by using a double-plume convection scheme in a global model. *J. Geophys. Res.: Atmos.*, **127**, e2021JD036069, <https://doi.org/10.1029/2021JD036069>.
- Li, X. H., Y. Zhang, X. Peng, B. Zhou, J. Li, and Y. Wang, 2023: Intercomparison of the weather and climate physics suites of a unified forecast–climate model system (GRIST-A22.7.28) based on single-column modeling. *Geosci. Model Dev.*, **16**, 2975–2993, <https://doi.org/10.5194/gmd-16-2975-2023>.
- Lim, K. S. S., E. C. Chang, R. Y. Sun, K. Kim, F. J. Tapiador, and G. Lee, 2020: Evaluation of simulated winter precipitation using WRF-ARW during the ICE-POP 2018 field campaign. *Weather Forecast.*, **35**, 2199–2213, <https://doi.org/10.1175/WAF-D-19-0236.1>.
- Lim, K. S. S., and S. Y. Hong, 2010: Development of an effective double-moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models. *Mon. Wea. Rev.*, **138**, 1587–1612, <https://doi.org/10.1175/2009MWR2968.1>.
- Lin, Y. L., L. J. Donner, J. Petch, P. Bechtold, J. Boyle, S. A. Klein, and C. Schumacher, 2012: TWP-ICE global atmospheric model intercomparison: Convection responsiveness and resolution impact. *J. Geophys. Res.: Atmos.*, **117**, D09111, <https://doi.org/10.1029/2011JD017018>.
- Loeb, N. G., B. A. Wielicki, D. R. Doelling, G. L. Smith, D. F. Keyes, S. Kato, and T. Wong, 2009: Toward optimal closure of the Earth's top-of-atmosphere radiation budget. *J. Climate*, **22**, 748–766, <https://doi.org/10.1175/2008JCLI2637.1>.
- Ma, Z. S., Q. J. Liu, C. F. Zhao, X. Shen, Y. Wang, J. H. Jiang, and Y. Yung, 2018: Application and evaluation of an explicit prognostic cloud-cover scheme in GRAPES global forecast system. *J. Adv. Model. Earth Sys.*, **10**, 652–667, <https://doi.org/10.1002/2017MS001234>.
- Milbrandt, J. A., and H. Morrison, 2016: Parameterization of cloud microphysics based on the prediction of bulk ice particle properties. Part III: Introduction of multiple free categories. *J. Atmos. Sci.*, **73**, 975–995, <https://doi.org/10.1175/JAS3535.1>.
- Milbrandt, J. A., and M. K. Yau, 2005: A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description. *J. Atmos. Sci.*, **62**, 3065–3081, <https://doi.org/10.1175/JAS3535.1>.
- Morrison, H., and A. Gettelman, 2008: A new two-moment bulk stratiform cloud microphysics scheme in the Community Atmosphere Model, version 3 (CAM3). Part I: Description and numerical tests. *J. Climate*, **21**, 3642–3659, <https://doi.org/10.1175/2008JCLI2105.1>.
- Morrison, H., G. Thompson, and V. Tatarskii, 2009: Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: Comparison of one- and two-moment schemes. *Mon. Weather Rev.*, **137**, 991–1007, <https://doi.org/10.1175/2008MWR2556.1>.
- Neale, R. B., J. H. Richter, and M. Jochum, 2008: The impact of convection on ENSO: From a delayed oscillator to a series of events. *J. Climate*, **21**, 5904–5924, <https://doi.org/10.1175/2008JCLI2244.1>.
- Niu, G. Y., Z. L. Yang, K. E. Mitchell, F. Chen, M. B. Ek, M. Barlage, and Y. Xia, 2011: The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *J. Geophys. Res.: Atmos.*, **116**, D12109, <https://doi.org/10.1029/2010JD015139>.
- Ong, C. R., M. Koike, T. Hashino, and H. Miura, 2024: Responses of simulated Arctic mixed-phase clouds to parameterized ice particle shape. *J. Atmos. Sci.*, **81**, 125–152, <https://doi.org/10.1175/JAS-D-23-0015.1>.
- Park, S., and C. S. Bretherton, 2009: The University of Washington shallow convection and moist turbulence schemes and their impact on climate simulations with the Community Atmosphere Model. *J. Climate*, **22**, 3449–3469, <https://doi.org/10.1175/2008JCLI2557.1>.
- Park, S., C. S. Bretherton, and P. J. Rasch, 2014: Integrating cloud processes in the Community Atmosphere Model, version 5. *J. Climate*, **27**, 6821–6856, <https://doi.org/10.1175/JCLI-D-14-00087.1>.
- Park, S. Y., and K. S. S. Lim, 2023: Implementation of prognostic cloud ice number concentrations for the Weather Research And Forecasting (WRF) Double-Moment 6-class (WDM6) microphysics scheme. *J. Adv. Model. Earth Sys.*, **15**, e2022MS003009, <https://doi.org/10.1029/2022MS003009>.
- Qian, Q. F., Y. L. Lin, Y. L. Luo, X. Zhao, Z. Zhao, Y. Luo, and X. Liu, 2018: Sensitivity of a simulated squall line during Southern China Monsoon Rainfall Experiment to parameterization of microphysics. *J. Geophys. Res.: Atmos.*, **123**, 4197–4220, <https://doi.org/10.1002/2017JD027734>.
- Qin, Y., and Y. Lin, 2018: Alleviated double ITCZ problem in the NCAR CESM1: A new cloud scheme and the working mechanisms. *J. Adv. Model. Earth Sys.*, **10**, 2318–2332, <https://doi.org/10.1029/2018MS001343>.
- Qin, Y., Y. L. Lin, S. M. Xu, H. Y. Ma, and S. Xie, 2018: A diagnostic PDF cloud scheme to improve subtropical low clouds in NCAR Community Atmosphere Model (CAM 5). *J. Adv. Model. Earth Sys.*, **10**, 320–341, <https://doi.org/10.1002/2017MS001095>.
- Shan, Y. P., J. W. Fan, K. Zhang, J. Shpund, C. Terai, G. J. Zhang, and S. Xie, 2024: Improving aerosol radiative forcing and climate in E3SM: Impacts of new cloud microphysics and

- improved wet removal treatments. *J. Adv. Model. Earth Sys.*, **16**, e2023MS004059, <https://doi.org/10.1029/2023MS004059>.
- Soden, B. J., and G. A. Vecchi, 2011: The vertical distribution of cloud feedback in coupled ocean-atmosphere models. *Geophys. Res. Lett.*, **38**, L12704, <https://doi.org/10.1029/2011GL047632>.
- Song, H. J., and B. J. Sohn, 2018: An evaluation of WRF microphysics schemes for simulating the warm-type heavy rain over the Korean Peninsula. *Asia-Pac. J. Atmos. Sci.*, **54**, 225–236, <https://doi.org/10.1007/s13143-018-0006-2>.
- Tan, I., T. Storelvmo, and M. D. Zelinka, 2016: Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352**, 224–227, <https://doi.org/10.1126/science.aad5300>.
- Thompson, G., and T. Eidhammer, 2014: A study of aerosol impacts on clouds and precipitation development in a large winter cyclone. *J. Atmos. Sci.*, **71**, 3636–3658, <https://doi.org/10.1175/JAS-D-13-0305.1>.
- Trenberth, K. E., and J. T. Fasullo, 2010: Simulation of present-day and twenty-first-century energy budgets of the southern oceans. *J. Climate*, **23**, 440–454, <https://doi.org/10.1175/2009JCLI3152.1>.
- Tsushima, Y., S. Emori, T. Ogura, M. Kimoto, M. J. Webb, K. D. Williams, and N. Andronova, 2006: Importance of the mixed-phase cloud distribution in the control climate for assessing the response of clouds to carbon dioxide increase: A multi-model study. *Climate Dyn.*, **27**, 113–126, <https://doi.org/10.1007/s00382-006-0127-7>.
- Wang, H. B., H. Zhang, B. Xie, X. Jing, J. He, and Y. Liu, 2022: Evaluating the impacts of cloud microphysical and overlap parameters on simulated clouds in global climate models. *Adv. Atmos. Sci.*, **39**, 2172–2187, <https://doi.org/10.1007/s00376-021-0369-7>.
- Wang, L., Y. Zhang, J. Li, Z. Liu, and Y. Zhou, 2019: Understanding the performance of an unstructured-mesh global shallow water model on kinetic energy spectra and nonlinear vorticity dynamics. *J. Meteorol. Res.*, **33**, 1075–1097, <https://doi.org/10.1007/s13351-019-9004-2>.
- Wild, M., M. Z. Hakuba, D. Folini, P. Dörig-Ott, C. Schär, S. Kato, and C. N. Long, 2019: The cloud-free global energy balance and inferred cloud radiative effects: An assessment based on direct observations and climate models. *Climate Dyn.*, **52**, 4787–4812, <https://doi.org/10.1007/s00382-018-4413-y>.
- Wood, R. 2012: Stratocumulus clouds. *Mon. Weather Rev.*, **140**, 2373–2423, <https://doi.org/MWR-D-11-00121.1>.
- Wyant, M. C., C. S. Bretherton, R. Wood, G. R. Carmichael, A. Clarke, J. Fast, and Q. Yang, 2015: Global and regional modeling of clouds and aerosols in the marine boundary layer during VOCALS: The VOCA intercomparison. *Atmos. Chem. Phys.*, **15**, 153–172, <https://doi.org/10.5194/acp-15-153-2015>.
- Xiao, H., C. R. Mechoso, R. Sun, J. Han, H. L. Pan, S. Park, and J. Teixeira, 2014: Diagnosis of the marine low cloud simulation in the NCAR community earth system model (CESM) and the NCEP global forecast system (GFS)-modular ocean model v4 (MOM4) coupled model. *Climate Dyn.*, **43**, 737–752, <https://doi.org/10.1007/s00382-014-2067-y>.
- Xie, S. C., T. Hume, C. Jakob, S. A. Klein, R. B. McCoy, and M. Zhang, 2010: Observed large-scale structures and diabatic heating and drying profiles during TWP-ICE. *J. Climate*, **23**, 57–79, <https://doi.org/10.1175/2009JCLI3071.1>.
- Zhang, G. J., and N. A. McFarlane, 1995: Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian Climate Centre General Circulation Model. *Atmos. Ocean*, **33**, 407–446, <https://doi.org/10.1080/07055900.1995.9649539>.
- Zhang, M. H., W. Y. Lin, S. A. Klein, J. T. Bacmeister, S. Bony, R. T. Cederwall, and J. H. Zhang, 2005: Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements. *J. Geophys. Res.-Atmos.*, **110**, D15S02, <https://doi.org/10.1029/2004JD005021>.
- Zhang, M., H. Wang, X. Zhang, Y. Peng, and H. Che, 2018: Applying the WRF double-moment six-class microphysics scheme in the GRAPES_Meso model: A case study. *J. Meteorol. Res.*, **32**, 246–264, <https://doi.org/10.1007/s13351-018-7066-1>.
- Zhang, Y., J. Li, R. Yu, S. Zhang, Z. Liu, J. Huang, and Y. Zhou, 2019: A layer-averaged nonhydrostatic dynamical framework on an unstructured mesh for global and regional atmospheric modeling: Model description, baseline evaluation, and sensitivity exploration. *J. Adv. Model. Earth Sys.*, **11**, 1685–1714, <https://doi.org/10.1029/2018MS001539>.
- Zhang, Y., J. Li, R. Yu, Z. Liu, Y. Zhou, X. Li, and X. Huang, 2020: A multiscale dynamical model in a dry-mass coordinate for weather and climate modeling: Moist dynamics and its coupling to physics. *Mon. Wea. Rev.*, **148**, 2671–2699, <https://doi.org/10.1175/MWR-D-19-0305.1>.
- Zhang, Y., R. C. Yu, J. Li, X. Li, X. Rong, X. Peng, and Y. Zhou, 2021: AMIP simulations of a global model for unified weather-climate forecast: Understanding precipitation characteristics and sensitivity over East Asia. *J. Adv. Model. Earth Sys.*, **13**, e2021MS002592, <https://doi.org/10.1029/2021MS002592>.
- Zhao, C. F., S. C. Xie, S. A. Klein, A. Protat, M. D. Shupe, S. A. McFarlane, and Z. Wang 2012: Toward understanding of differences in current cloud retrievals of ARM ground-based measurements. *J. Geophys. Res.-Atmos.*, **117**, D10206, <https://doi.org/10.1029/2011JD016792>.
- Zhao, X., Y. L. Lin, Y. L. Luo, Q. Qian, X. Liu, X. Liu, and B. A. Colle, 2021: A double-moment SBU-YLIN cloud microphysics scheme and its impact on a squall line simulation. *J. Adv. Model. Earth Sys.*, **13**, e2021MS002545, <https://doi.org/10.1029/2021MS002545>.
- Zhou, Y. H., Y. Zhang, J. Li, R. Yu, and Z. Liu 2020: Configuration and evaluation of a global unstructured mesh atmospheric model (GRIST-A20.9) based on the variable-resolution approach. *Geosci. Model Dev.*, **13**, 6325–6348, <https://doi.org/10.5194/gmd-13-6325-2020>.
- Zhou, Y. H., R. C. Yu, Y. Zhang, and J. Li, 2023: Dynamic and thermodynamic processes related to precipitation diurnal cycle simulated by GRIST. *Climate Dyn.*, **61**, 3935–3953, <https://doi.org/10.1007/s00382-023-06779-7>.

Citation: Li, J. B., X. D. Peng, X. H. Li, J. Gu, and S. N. Duan, 2026: Improvement of Low-cloud Simulations with a Revised Cloud Microphysics Scheme in an Atmospheric General Circulation Model. *J. Trop. Meteor.*, **32**, 1–18, <https://doi.org/10.3724/j.1006-8775.2025.038>.