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Influences of Entrainment-Mixing Parameterization on Numerical Simulations of Cumulus and Stratocumulus Clouds

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Abstract

Different entrainment-mixing processes can occur in clouds; however, a homogeneous mixing mechanism is often implicitly assumed in most commonly used microphysics schemes. Here, we first present a new entrainment-mixing parameterization that uses the grid-mean relative humidity without requiring the

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relative humidity of the entrained air. Second, the parameterization is implemented in a microphysics scheme in a large eddy simulation model. Third, sensitivity experiments are conducted to compare the new parameterization with the default homogeneous entrainment-mixing parameterization. The results indicate that the new entrainment-mixing parameterization has a larger impact on the number concentration, volume-mean radius, and cloud optical depth in the stratocumulus case than in the cumulus case. This is because inhomogeneous and homogeneous mixing mechanisms dominate in the stratocumulus and cumulus cases, respectively, which is mainly due to the larger turbulence dissipation rate in the cumulus case. Because stratocumulus clouds break up during the dissipation stage to form cumulus clouds, the effects of this new entrainment-mixing parameterization during the stratocumulus dissipation stage are between those during the stratocumulus mature stage and the cumulus case. A large aerosol concentration can enhance the effects of this new entrainment-mixing parameterization by decreasing the cloud droplet size and evaporation time scale. This study sheds new light on the improvement of entrainment-mixing parameterizations in models.

1. Introduction

The process of entrainment and subsequent mixing between clouds and their environment is one of the most uncertain processes in cloud physics, which is thought to be crucial to many outstanding issues, including warm-rain initiation and subsequent precipitation characteristics, cloud-climate feedback, and evaluating the indirect effects

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of aerosol (Paluch and Baumgardner, 1989; Yum, 1998; Ackerman et al., 2004; Kim et al., 2008; Huang et al., 2008; Del Genio and Wu, 2010; Lu et al., 2011; Lu et al., 2014; Kumar et al., 2013; Zheng and Rosenfeld, 2015; Fan et al., 2016; Gao et al., 2020; Gao et al., 2021; Zhu et al., 2021; Xu et al., 2021; Kumar et al., 2013; Yang et al., 2016; Yang et al., 2021). The most well-studied concepts are homogeneous/inhomogeneous entrainment-mixing mechanisms. During homogeneous mixing, all droplets experience evaporation, and no droplet is evaporated completely. During extremely inhomogeneous mixing, some droplets near the entrained air evaporate completely, while the remaining droplets maintain their original sizes. If the situation is somewhere between these two extreme scenarios, an inhomogeneous mixing process occurs. Some studies suggest that homogeneous mixing is likely to be typical (Jensen et al., 1985; Burnet and Brenguier, 2007; Lehmann et al., 2009), whereas others have claimed that extremely inhomogeneous scenario is dominant (Pawlowska et al., 2000; Burnet and Brenguier, 2007; Haman et al., 2007; Freud et al., 2008; Freud et al., 2011). Different mechanisms can be undistinguishable when the relative humidity in the entrained air is high (Gerber et al., 2008).

Some sensitivity studies assuming homogeneous or extremely inhomogeneous mixing have found that different mixing mechanisms can significantly influence the microphysics and radiative properties of clouds (Lasher-Trapp et al., 2005; Grabowski, 2006; Chosson et al., 2007; Slawinska et al., 2008). For example, Grabowski (2006) used a cloud-resolving model and found that the amount of solar energy reaching the

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surface in the pristine case, assuming the homogeneous mixing scenario, is the same as in the polluted case with extremely inhomogeneous mixing. This result was verified by Slawinska et al. (2008) using a large-eddy simulation (LES) model. Although the influence of different mixing mechanisms in simulations is lower when two-moment microphysics schemes are used (Hill et al., 2009; Grabowski and Morrison, 2011; Slawinska et al., 2012; Xu et al., 2020), Hill et al. (2009) also claimed that there are still many uncertainties in the entrainment-mixing process, and the effect of different mixing mechanisms can be more important over the entire cloud life-cycle.

In recent years, methods have been developed to describe general entrainment-mixing processes, with homogeneous and extremely inhomogeneous scenarios as special cases (Andrejczuk et al., 2006; Andrejczuk et al., 2009; Lehmann et al., 2009; Lu et al., 2011). Hoffmann et al. (2019) and Hoffmann and Feingold (2019) conducted LES at the subgrid-scale with turbulent mixing, using a linear eddy model. Andrejczuk et al. (2009) used the results of direct numerical simulation (DNS) to establish a relationship between instantaneous microphysical properties and Damköhler number (D_a, Burnet and Brenguier, 2007), and developed a parameterization of the entrainment-mixing process. Lu et al. (2013) developed a parameterization of the entrainment-mixing process based on the relationship between the homogeneous mixing degree (ψ) and transition scale number (N_L) in the explicit mixing parcel model (EMPM), as well as aircraft observation data. Gao et al. (2018) investigated how ψ is related to D_a and N_L in a DNS, to improve the parameterization of the entrainment-mixing process. Luo

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et al. (2020) simulated more than 12,000 cases with EMPM by changing a variety of parameters affecting entrainment-mixing processes and developed a parameterization that improved the one proposed by Lu et al. (2013).

Although several entrainment-mixing parametrizations have been proposed, to the best of our knowledge, only one study (Jarecka et al., 2013) has coupled an entrainment-mixing parameterization with cloud microphysics to consider the change in cloud droplet concentration during the entrainment-mixing process. Jarecka et al. (2013) applied an entrainment-mixing parameterization, in terms of the Damköhler number, to a two-moment microphysics scheme and found small impacts of entrainment-mixing parameterization in shallow cumulus clouds. To further explore the influences of entrainment-mixing processes, this study first modifies the entrainment-mixing parameterization in terms of the transition scale number proposed by Luo et al. (2020) to couple it more easily with microphysics schemes. The parameterization is then implemented in the two-moment Thompson aerosol-aware scheme (Thompson and Eidhammer, 2014). Finally, the effects of parameterization on the physical properties of clouds are examined in both cumulus and stratocumulus clouds.

The rest of this paper is organized as follows: Section 2 describes the new entrainment-mixing parameterization, simulated cases, and modelling setup. The major results are presented and discussed in Section 3. The influences of the new entrainment-mixing parameterization on cloud physics and the underlying mechanisms are examined, and the effects of turbulence dissipation rate (ε) and aerosol concentration

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are also discussed. Some concluding remarks are presented in Section 4.

2. Parameterization, simulated cases, and modeling setup

2.1 The new entrainment-mixing parameterization

According to Morrison and Grabowski (2008), the effect of the entrainment-mixing process on cloud microphysical properties can be expressed as follows:

$$N_c = N_{c0}\left(\frac{q_c}{q_{c0}}\right)^{\alpha}, \tag{1}$$

where N_c and N_{c0} are the cloud droplet number concentrations after and before the evaporation process, respectively, and q_c and q_{c0} represent the corresponding cloud water mixing ratios. It is noteworthy that when a new saturation is achieved after evaporation, q_c is determined by q_{c0}, relative humidity, air pressure, and temperature. The parameter α can be pre-set to any value between 0 (homogeneous mixing) and 1 (extremely inhomogeneous mixing) to represent a different degree of subgrid-scale mixing homogeneity. In this study, instead of specifying α as a predetermined constant, here it is determined through expressions (Lu et al., 2013; Luo et al., 2020)

$$\alpha = 1 - \psi, \tag{2a}$$

$$\psi = c\exp(aN_L^b). \tag{2b}$$

where a, b and c are the three fitting parameters (Luo et al., 2020). The dimensionless number N_L is a dynamical measure of the degree of subgrid-scale mixing homogeneity (Lu et al., 2011) defined by

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$$N_{\mathrm{L}}=\frac{L^{*}}{\eta}, \tag{3a}$$

$$\eta=\left(\nu^{3}/\varepsilon\right)^{1/4}, \tag{3b}$$

$$L^{*}=\varepsilon^{1/2}\tau_{\mathrm{evap}}^{3/2}, \tag{3c}$$

where L^* is the transition length (Lehmann et al., 2009), η is the Kolmogorov microscale, fν is the kinematic viscosity; ε is estimated following the method of Andrejczuk et al. (2009):

$$\varepsilon=\left\langle\frac{1}{3}\left(u^{2}+v^{2}+w^{2}\right)\right\rangle^{3/2}\Big/L, \tag{4}$$

where u, v, and w are the characteristic velocities in the horizontal and vertical directions, respectively, and L is the model grid size. The evaporation time scale (τ_{evap}) is defined as the time taken for droplets to evaporate completely in an unsaturated environment, and is calculated as

$$\tau_{\mathrm{evap}}=-\frac{r^{2}}{2AS_{\mathrm{e}}}, \tag{5a}$$

$$A=\frac{1}{\left[\left(\frac{L_{\mathrm{h}}}{R_{\mathrm{v}}T}-1\right)\frac{L_{\mathrm{h}}\rho_{\mathrm{L}}}{KT}+\frac{\rho_{\mathrm{L}}R_{\mathrm{v}}T}{De_{\mathrm{s}}(T)}\right]}, \tag{5b}$$

where r is the volume-mean radius of cloud droplets, A is a function of pressure and temperature, S_{e} is the sub-saturation (relative humidity RH-1) of entrained air, L_{h} is the latent heat, R_{v} is the specific gas constant for water vapour, T is air temperature, ρ_{L} is the density of liquid water, K is the coefficient of thermal conductivity of air, D is the diffusion coefficient of water vapour in the air, and $e_{\mathrm{s}}(T)$ is the saturation vapour pressure over a plane water surface at temperature T.

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Unfortunately, S_e in Equation (5a) is generally unavailable in atmospheric models, including LES models. Thus, the entrainment-mixing parameterization developed by Luo et al. (2020) based on the properties of entrained air cannot be used directly. To solve this problem, we modify the entrainment-mixing parameterization of Luo et al. (2020) by replacing S_e with the domain-averaged relative humidity in the EMPM, after entrainment but before evaporation, based on 12,218 cases:

$$\psi = 107.19 \exp(-1.99 N_L^{-0.29}). \quad (6)$$

Figure 1 shows the fitting results of the modified new entrainment-mixing parameterization. Compared to the parametrization proposed by Luo et al. (2020), the modified parameterization has similar ψ-N_L distributions, but with a larger N_L for the same ψ, because the EMPM domain-averaged RH is larger than the entrained-air RH. With this modification, N_L, ψ, and thus the effect of the entrainment-mixing processes on droplet concentration can be directly calculated using the LES grid RH. It is important to note that we do not assume that the RH of entrained air is equal to that of the LES grid. Such a modification is only for the convenience of parameterization applications in microphysics schemes. The details of the EMPM simulations and related calculations are provided by Luo et al. (2020).

2.2 LES model, simulation cases, and modelling setup

The LES model is built by applying the large-scale forcing module presented in Endo et al., 2015) to the Weather Research and Forecasting (WRF) model tailored for

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solar irradiance forecasting (WRF-Solar, Hacker et al., 2016; Haupt et al., 2016). The large-scale forcing data (VARANAL) used in this process is derived from the constrained variational analysis (CVA) approach developed by Zhang et al. (2001) and provided by the U.S. Department of Energy's Atmospheric Radiation Measurement Program (www.arm.gov). The modified entrainment-mixing parameterization is implemented in the two-moment Thompson aerosol-aware scheme (Thompson and Eidhammer, 2014).

To investigate the behaviours of the new entrainment-mixing parameterization in different cloud types, cumulus and stratocumulus cases are simulated. For both the cumulus and stratocumulus cases, the horizontal resolution of the model is 100 m × 100 m with a domain area of 14.4 km × 14.4 km. The vertical direction is divided into 225 layers with a resolution of 30 m.

For each cloud case, ψ is first set to 1 for the *default* experiment because most LES models assume a homogeneous entrainment-mixing mechanism. The simulation with the new entrainment-mixing parameterization (Equations (1-6)) is hereafter referred to as *new*. First, N_L is diagnosed for each grid, and ψ is then calculated using Equation (6). Finally, the variation in N_c during entrainment-mixing is obtained using Equations (1) and (2a).

Considering the significant impacts of ε and initial droplet number concentration on the entrainment-mixing process (Luo et al., 2020; Lu et al., 2013; Grabowski, 2006; Hoffmann and Feingold, 2019), an alternative method that calculates ε from the subgrid

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turbulent kinetic energy (Deardorff, 1980) is also investigated and is referred to as *new_tke*:

$$\varepsilon = CE^{3/2} / L, \tag{7}$$

where C = 0.70 is an empirical constant and E is the subgrid turbulent kinetic energy. To examine the influence of the aerosol number concentration on the entrainment-mixing process, we conduct the numerical experiments *default_10* and *new_10* by multiplying the initial aerosol number concentrations, for the *default* and *new* models, respectively, by a factor of 10. Thus, five sets of numerical experiments are conducted for both the cumulus and stratocumulus cases; the names of the experiments and corresponding descriptions are summarized in Table 1.

3. Results

3.1 Cumulus case

For the cumulus case, the simulation starts at 9:00 UTC on 11 June 2016 and ends at 03:00 UTC on 12 June 2016 with an output interval of 10 min and spin-times of 3 h. Figure 2 shows the temporal evolution of the cloud fraction from the five numerical experiments. Grid points with q_c larger than 0.01 g/kg are defined as "cloudy areas". Also shown for comparison is observational data with a one-hour temporal resolution, which is provided by the LES Atmospheric Radiation Measurement Symbiotic Simulation and Observation (LASSO) campaign (Gustafson et al., 2020). The observations show that the cloud forms at 12:00 UTC on 11 June and dissipates

208 completely by 01:00 UTC on 12 June with a maximum cloud fraction of 0.47 at 16:00 UTC on 11 June. All simulations capture the evolution of the cloud fraction and exhibit similar values to the observational data.

Figure 3 shows the evolution of the microphysical and optical properties of clouds in the cloudy areas of all simulation experiments, including q_c, N_c, droplet volume-mean radius (r_v), cloud water path (CWP), and cloud optical depth (τ). To visually and simultaneously compare the change in cloud droplet concentration under different aerosol concentrations, the maximum cloud droplet concentration (N_{cmax}) from *default* is used to normalize N_c in *default*, *new*, and *new_tke*, while N_{cmax} from *new_10* is used to normalize N_c in *default_10* and *new_10*. The CWP is calculated as:

$$\mathrm{CWP} = \int_0^H \rho_a q_c(z) dz, \quad (8)$$

where ρ_a is the air density, $q_c(z)$ is the cloud water mixing ratio at each height (z), and H is the cloud thickness. The optical depth τ is estimated with

$$\tau = \frac{3}{2}\frac{1}{\rho_w}\int_0^H \frac{\rho_a q_c(z)}{r_e(z)} dz, \quad (9)$$

where ρ_w is the water density and $r_e(z)$ is the effective radius of the cloud droplets at each height (z). The time-averaged values of these physical properties of the clouds are listed in Table 2 for convenience.

For the low aerosol number concentration, the simulations with the new entrainment-mixing parameterization have smaller N_c (34.91 cm^{-3} and 35.53 cm^{-3} for *new* and *new_tke*, respectively) and larger r_v (13.34 μm and 13.29 μm for *new* and *new_tke*, respectively) than the default homogeneous simulation (35.78 cm^{-3} for N_c and

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13.27 μm for r_v in *default*). However, comparing *new* to *default*, the relative changes in N_c (–2.43%), r_v (+0.53%), and τ (–0.99%) are small. The relative changes in *new_tke* are even smaller. When the aerosol concentration increases ten-fold (*default_10* and *new_10*), q_c, CWP, and τ increase according to the aerosol indirect effect (Peng et al., 2002; Wang et al., 2019; Li et al., 2011; Wang et al., 2011). Meanwhile, r_v decreases significantly owing to the larger cloud number concentration. The effects of the new entrainment-mixing parameterization also increase, for example, the change in N_c increases from –2.43% (*new* compared to *default*) to –4.45% (*new_10* compared to *default_10*), r_v increases from +0.53% to +0.85%, and τ from –0.99% to –1.18%; the reasons for these changes are discussed later. These small changes are similar to those identified in previous cumulus studies (Jarecka et al., 2013; Hoffmann et al., 2019).

3.2 Stratocumulus case

The stratocumulus case is simulated from 9:00 UTC on 19 April 2009 to 03:00 UTC on 20 April 2009; the first three hours are set to be spin-up times. We examine the stratocumulus region of the cloud base at ~2.1 km and the cloud top at ~2.3 km (cloud thickness of ~200 m). The time series of the cloud fraction in the observed values and five simulated datasets from 12:00 UTC to 24:00 UTC are shown in Figure 4. The observed data show that the cloud fraction increases with time and peaks at 16:00 UTC. All the simulations capture the main features of the cloud fraction. The simulated cloud fraction has a value of 1 before 16:00 UTC, fluctuates from 16:00 UTC to 21:00 UTC,

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and decreases sharply after 21:00 UTC. This period can be divided into three stages, namely the mature stage, pre-dissipation stage, and dissipation stage.

As with the cumulus case, the temporal evolutions of the physical properties (q_c, N_c, r_v, CWP, and τ) of the clouds are shown in Figure 5. In contrast to the oscillating changes exhibited by the physical quantities in the cumulus case (Figure 3), the physical properties in the stratocumulus case exhibit a mostly smooth temporal evolution. Furthermore, *default* and *new* exhibit clear distinctions during the early periods, but these differences decrease during the dissipation stage. This is also the case with *default_10* and *new_10*.

To compare the different behaviours of the simulation experiments at different stages, the results at the mature and dissipation stages are analysed in detail. The mean values of the main microphysical and optical properties of the clouds are summarised in Table 3. As expected, the cloud microphysical and optical properties at the mature stage are all larger than those at the dissipation stage. The effects of the new entrainment-mixing parametrization are also more significant at the mature stage. Compared to *default*, the *new* model results in a 7.27% smaller N_c, 2.42% larger r_v, and 5.77% smaller τ during the mature stage. During the dissipation stage, the changes in N_c, r_v, and τ are –4.35%, +0.80%, and –2.56%, respectively. In contrast to the cumulus case, *new_tke* is close to *new* and even has a slightly larger influence on cloud properties than *new*, when compared to *default*, during both stages. The largest influence of the new entrainment-mixing parametrization occurs during the mature stage when the

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aerosol concentration is ten times greater. The differences in N_c, r_v, and τ between *new_10* and *default_10* are –9.67%, +2.91%, and –5.39%, respectively, averaged over the mature stage. The maximum differences in N_c, r_v, and τ are –10.71%, +6.37%, and –7.72%, respectively. These differences are much larger than those reported by Hill et al. (2009) who found that assuming extremely inhomogeneous mixing has a negligible effect on stratocumulus simulations. Our results also prove the speculation of Hill et al. (2009) that the mixing process might play an important role when the stratocumulus is thin (~200 m in this study). Furthermore, implementing the new entrainment-mixing parameterization has similar effects on cloud properties to those described by Hoffmann and Feingold (2019) who used the linear eddy model to represent subgrid-scale turbulent mixing. Note that stratocumulus clouds occur in most regions around the world and are important contributors to the surface radiation budget (Wood, 2012; Zheng et al., 2016; Wang et al., 2021; Wang and Feingold, 2009). Stratocumulus clouds dominate in some regions and occur over 60% of the time as vast long-lived sheets, such as the *semi-permanent subtropical marine stratocumulus sheets* (Wood, 2012). In these regions, a 5.39%–5.77% decrease in τ, caused by the new entrainment-mixing parameterization is expected to have significant effects on the simulation of regional radiative properties and climate change.

The averaged influences of the new entrainment-mixing parametrization over all the simulation periods are also examined (Table 4). Quantitatively, the effect of the new entrainment-mixing parameterization is much greater on stratocumulus clouds than on

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cumulus clouds. Compared to *default*, *new* has an average change of –5.90% in N_c, +1.49% in r_v, and –3.98% in τ. When the aerosol concentration increases ten-fold, the differences in N_c, r_v, and τ between *default_10* and *new_10* are −8.97%, +2.77%, and −3.56%, respectively. These differences are larger than the largest changes in the cumulus case.

3.3 Mechanisms of the effects of the new entrainment-mixing parameterization

The different effects of the new entrainment-mixing parameterization on different types of clouds and even on different stages of stratocumulus clouds are likely be related to variations in the dominant mixing mechanism. To confirm this, we calculate the average ψ at all grid points experiencing evaporation, the proportion of inhomogeneous mixing grid points to all grid points experiencing evaporation, and the average ψ at the inhomogeneous mixing grid points in *new*, *new_tke*, and *new_10* (Table 5) for the cumulus case, and mature and dissipation stages in the stratocumulus case.

For the cumulus case, all three simulations exhibit large ψ and a small proportion of inhomogeneous mixing, indicating that homogeneous mixing is the dominant entrainment-mixing mechanism in all three simulations (Luo et al., 2020; Lu et al., 2013), especially in *new_tke*. Correspondingly, the influences of the new entrainment-mixing parameterization on the cloud physical properties are not significant, as shown in Figure 3 and Table 2. The *new_10* model exhibit a smaller average ψ and a larger proportion of inhomogeneous mixing than *new* and *new_tke*, which results in larger

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changes in cloud physics, as mentioned in Section 3.1.

For the stratocumulus case, Table 5 shows the average ψ at all grid points experiencing evaporation, the proportion of inhomogeneous mixing grid points to all grid points experiencing evaporation, and the average ψ at the inhomogeneous mixing grid points during the two stages. The mature stage always has a smaller ψ but a larger proportion of inhomogeneous mixing than the dissipation stage. The inhomogeneous mixing process dominates the mature stage in *new* and *new_tke*, because more than 60% of the grid points experience inhomogeneous mixing. The inhomogeneous mixing process is more dominant in *new_10*, because less than 3% of the cloudy grid points experience a homogeneous mixing process during the mature stage, which explains why *new_10* has the largest influence when implementing the new entrainment-mixing parametrization. Meanwhile, the average ψ in both stages is smaller than that in the cumulus case for the same simulation configuration. Thus, the effects of the new entrainment-mixing parameterization are more significant for stratocumulus than for cumulus clouds, especially at the mature stage. It is noted that the average ψ and the proportion of inhomogeneous mixing at the dissipation stage of *new* and *new_tke* in the stratocumulus case are very close to the results of *new_10* in the cumulus case. This is because the cloud fraction decreases sharply during the dissipation stage; the stratocumulus clouds break up and produces cumulus clouds with small cloud droplet radius.

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3.4 The effects of dissipation rate and aerosol concentration on the entrainment-mixing process

Previous studies have shown the notable effects of the dissipation rate and aerosol concentration on the entrainment-mixing process. For example, Luo et al. (2020) changed ε from 10^{-5} m^2 s^{-3} to 10^{-2} m^2 s^{-3} and noted huge differences in the corresponding ψ. Small et al. (2013) compared aircraft observations with different background concentrations and found that higher pollution flights tended to slightly more inhomogeneous mixing; Jarecka et al. (2013) also showed various homogeneities of subgrid mixing when aerosol concentration increases ten-fold. To explain the different behaviours of different simulations with the new entrainment-mixing parameterization, the influences of ε and aerosol concentration are examined. Figure 6 shows the probability distribution functions (PDFs) of ε, r_v, τ_{evap}, and N_L for cloud grids experiencing entrainment-mixing processes in *new*, *new_tke*, and *new_10* for the cumulus and stratocumulus cases, respectively. The PDFs from the mature and dissipation stages of the stratocumulus case are shown in Figure 7.

3.4.1 Dissipation rate

According to Equation (3), N_L is a function of $\varepsilon^{3/4}$; hence, the PDF of ε directly affects N_L and further results in different ψ. For the cumulus case, the mean ε (0.0032 m^2 s^{-3}) in *new* is close to the value of 0.0043 m^2 s^{-3} in *new_tke*; these values are similar to those obtained for cumulus clouds in previous studies (e.g. Lu et al., 2016; Hoffmann

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et al., 2019). The different ε distributions cause a significant difference in the proportion of inhomogeneous mixing (Table 5). As shown in Figure 1, cloud grids experience a homogeneous mixing process if N_L is larger than ~10^5, the limited distribution of N_L values less than 10^5 in *new_tke* results in a very small number of cloud grid points undergoing inhomogeneous mixing process. Even at the cloud grid points that undergo inhomogeneous mixing, the average ψ is large (98.62%), because most of the N_L values are larger than 10^3. Therefore, the cloud properties in *new_tke* are close to those in *default*. The *new* model contains more frequent occurrences of small ε and N_L values, resulting in more cloud grid points undergoing a more inhomogeneous mixing process and exhibiting a smaller ψ, compared to those in the *new_tke* model (Table 5); however, the results of *new* are still close to those of *default*, because of the dominance of N_L values larger than 10^5.

For the stratocumulus case, the mean values of ε (2.7×10^{-4} m^2 s^{-3} in *new* and 2.9×10^{-4} m^2 s^{-3} in *new_tke*) are an order of magnitude less than those in the cumulus case. Therefore, compared with the cumulus case, the distribution of N_L is reduced in the stratocumulus case, while the peak values of *new* and *new_tke* are similar and almost reach the criterion of inhomogeneous mixing (~10^5). For the two stages of stratocumulus clouds, ε is an order of magnitude smaller, but r_v was larger (Figure 7) during the mature stage than during the dissipation stage. According to Equation (5a), droplets with smaller r_v are more prone to complete evaporation and have a smaller τ_{evap}. The combination of smaller ε and larger r_v results in a smaller N_L (Equation (3)). This

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is the reason for the new entrainment-mixing parametrization having more significant effects during the mature stage than during the dissipation stage. In addition, the similarity of the ε and r_v values during the dissipation stage of the stratocumulus case in *new*, compared to the cumulus case in *new_10* (Figures 6a and 6b), explains the similar average ψ values of these scenarios and the proportion of inhomogeneous mixing (Table 5).

Therefore, the distribution of ε has a vital impact on the influence of the new entrainment-mixing parameterization. Smaller values of ε result in the new entrainment-mixing parameterization having a more significant influence. Moreover, the r_v in the stratocumulus case is smaller than that in the cumulus case, which is also conducive to a more inhomogeneous mixing process. These are the reasons why the implementation of the new entrainment-mixing parameterization has a larger influence in the stratocumulus case than in the cumulus case, when compared to a homogeneous mixing mechanism.

3.4.2 Aerosol concentration

The aerosol concentration affects the entrainment-mixing process by decreasing the cloud droplet radius. As r_v decreases, the distributions of τ_{evap} in *new_10* moves to a smaller overall value, while the mean value is an order of magnitude smaller than that in *new*, which causes a much smaller N_L because N_L is proportional to $\tau_{evap}^{3/2}$ (Equations (3a) and (3b)). The larger percentage of smaller N_L values indicates that in *new_10*,

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more grid points undergo an inhomogeneous mixing process, and the proportion of such grid points is much larger than in the *new* model (Table 5). Therefore, compared to *new*, *new_10* exhibit a smaller ψ and the effects of the new entrainment-mixing parameterization on cloud properties are more obvious, for both the cumulus and stratocumulus cases.

4. Concluding remarks

The entrainment-mixing process near cloud edges has important effects on cloud microphysics, but the most commonly used microphysics schemes simply assume one extreme mechanism, that is, homogeneous entrainment-mixing. This study first improves the entrainment-mixing parameterization proposed by Luo et al. (2020), which connects the homogeneous mixing degree and transition scale number to estimate the homogeneity of the subgrid mixing process and its impact on the droplet number concentration. The improved parameterization uses grid-mean relative humidity and can be implemented directly into microphysics schemes; there is no need to know the relative humidity of the entrained air. Second, the modified entrainment-mixing parameterization is implemented in the two-moment Thompson aerosol-aware scheme of the LES version of WRF-Solar, to examine its effects on the microphysical and optical properties of cumulus and stratocumulus clouds. Third, several sensitivity experiments are conducted to investigate the effects of the new entrainment-mixing parameterization under different conditions of turbulence dissipation rate and aerosol

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number concentration.

Unlike the commonly assumed homogeneous mixing scenario, the new entrainment-mixing parameterization produces a smaller cloud droplet number concentration and larger cloud droplet radius, with the degree of difference depending on cloud types and stages. Sensitivity tests show that in the cumulus case, the largest average influence of the new entrainment-mixing parameterization occurs under a high aerosol background, but results in only a 4.45% decrease in cloud droplet number concentration and a 0.85% increase in cloud droplet volume-mean radius. The changes become even smaller with a low aerosol background because of the larger cloud droplet radius. In contrast, the new entrainment-mixing parameterization has a larger influence on the microphysical and optical properties of stratocumulus clouds, especially under a high aerosol background and during the mature stage, with a cloud fraction equal to 1. The largest changes resulting from the new entrainment-mixing parameterization are −9.67%, +2.91%, and −5.39%, for cloud number concentration, cloud droplet volume-mean radius, and cloud optical depth, respectively. The new entrainment-mixing parameterization has less of an influence on the dissipation stage than on the mature stage of the stratocumulus case, but affects this case more than the cumulus case.

The varying effects of the new entrainment-mixing parameterization are caused by variations in the dominant entrainment-mixing mechanism between different cloud types and stages. Compared to the cumulus case, the stratocumulus case has a much smaller homogeneous mixing degree and a larger proportion of inhomogeneous mixing

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grid points, especially during the mature stage, which indicates that the inhomogeneous mixing mechanism dominates in the stratocumulus case, while the homogeneous mixing mechanism dominates in the cumulus case. As mentioned above, the changes in physical properties of stratocumulus clouds in the dissipation stage are between those in the mature stage and those of the cumulus case; this is because stratocumulus clouds dissipate sharply to form small cumulus clouds, and the degree of homogeneous mixing during the dissipation stage is therefore between that which occurs during the mature stage and the cumulus case.

Sensitivity studies show that how turbulence dissipation rate and aerosol concentration are treated in a simulation can have notable effects on the subgrid homogeneity of the mixing process. A larger dissipation rate can accelerate the mixing process, which results in a larger transition scale number and homogeneous mixing degree; and therefore a mostly homogenous mixing mechanism. This is why the cumulus case exhibit smaller changes than the stratocumulus case after the new entrainment-mixing parameterization is implemented. Larger aerosol number concentrations cause a smaller cloud droplet radius. Smaller droplets evaporate more easily, which leads to a smaller transition scale number and a smaller homogeneous mixing degree. Thus, the entrainment-mixing mechanism tends to be inhomogeneous. Therefore, a larger aerosol number concentration increases the influence of the new entrainment-mixing parameterization in both the cumulus and stratocumulus cases.

Note that the new entrainment-mixing parameterization could be more important

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in the LES model if the relative humidity near the cloud is more accurately simulated, because numerical diffusion may humidify the entrained air (Hoffmann and Feingold, 2019). The artificially increased relative humidity limits the influences of the new entrainment-mixing parameterization, because homogeneous and inhomogeneous entrainment-mixing processes are close to each other under conditions of high relative humidity.

Author contributions. XX, CL and YL designed the experiments. XX carried out the experiments and conducted the data analysis with contributions from all coauthors. XX, CL, XZ, and SE developed the model code. XX prepared the paper with help from CL, YL, YW, SL, and LZ.

Competing interests. The authors declare that they have no conflict of interest.

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can be downloaded from the U.S. Department of Energy's Atmospheric Radiation Measurement Program with https://adc.arm.gov/discovery/#/results. The LASSO data can be downloaded from https://archive.arm.gov/lassobrowser.

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Table 1. Summary of names and corresponding descriptions of the five experiments for each case of cumulus and stratocumulus. The meaning of each symbol for each experiment can be found in the text.

	Entrainment-mixing parameterization	Dissipation rate	Aerosol number concentration
default	$\alpha = 0$	-	default
new	$\alpha = 1 - \psi$, $\psi = 107.19\exp(-1.99 N_L^{-0.29})$.	$\varepsilon = \left\langle \frac{1}{3}\left(u^2 + v^2 + w^2\right) \right\rangle^{3/2} \Big/ L.$	default
new_tke	$\alpha = 1 - \psi$, $\psi = 107.19\exp(-1.99 N_L^{-0.29})$.	$\varepsilon = CE^{3/2} / L.$	default
default_10	$\alpha = 0$	-	default×10
new_10	$\alpha = 1 - \psi$, $\psi = 107.19\exp(-1.99 N_L^{-0.29})$.	$\varepsilon = \left\langle \frac{1}{3}\left(u^2 + v^2 + w^2\right) \right\rangle^{3/2} \Big/ L.$	default×10

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Table 2. Summary of the case mean values of the key quantities in all the simulations of the cumulus case, containing cloud water mixing ratio (q_c), cloud droplet number concentration (N_c), cloud droplet volume-mean radius (r_v), cloud water path (CWP), and cloud optical depth (τ). The experiments are detailed in Table 1.

	default	*new*	*new_tke*	*default_10*	*new_10*
q_c(g/kg)	0.44	0.44	0.44	0.56	0.57
N_c(cm^{-3})	35.78	34.91	35.53	278.80	266.37
r_v(μm)	13.27	13.34	13.29	7.05	7.11
CWP(g/m^2)	142.30	143.15	144.25	186.52	187.82
τ	13.07	12.94	13.02	31.29	30.92

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688 Table 3. Summary of the case mean values of the key quantities in all the simulations
689 of the stratocumulus case, including cloud water mixing ratio (q_c), cloud droplet number
690 concentration (N_c), cloud droplet volume-mean radius (r_v), cloud water path (CWP),
691 and cloud optical depth (τ). The numbers in and out of the parentheses are the results at
692 the mature and dissipation stages, respectively. The experiments are detailed in Table 1.

	default	*new*	*new_tke*	*default_10*	*new_10*
q_c(g/kg)	0.13	0.13	0.13	0.16	0.16
	(0.039)	(0.039)	(0.039)	(0.041)	(0.041)
N_c(cm^{-3})	35.74	33.14	33.11	256.82	231.98
	(19.76)	(18.90)	(18.82)	(138.74)	(126.99)
r_v(μm)	10.32	10.57	10.65	5.15	5.30
	(7.53)	(7.59)	(7.69)	(4.02)	(4.11)
CWP(g/m^2)	41.39	41.33	41.78	56.21	57.12
	(2.57)	(2.45)	(2.43)	(2.71)	(2.77)
τ	4.68	4.41	4.40	13.17	12.46
	(0.39)	(0.38)	(0.38)	(0.78)	(0.78)

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694 Table 4. Cloud water mixing ratio (q_c), cloud droplet number concentration (N_c), cloud
695 droplet volume-mean radius (r_v), cloud water path (CWP), cloud optical depth (τ) in all
696 simulations for the entire lifetime of the stratocumulus case. The experiments are
697 detailed in Table 1.

	default	*new*	*new_tke*	*default_10*	*new_10*
q_c(g/kg)	0.11	0.11	0.11	0.13	0.13
N_c(cm^{-3})	29.98	28.21	28.12	223.65	203.59
r_v(μm)	9.38	9.52	9.57	5.06	5.20
CWP(g/m^2)	30.78	30.34	29.92	42.22	43.19
τ	4.02	3.86	3.89	10.39	10.02

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Table 5. Homogeneous mixing degree (ψ) at all grid points experiencing evaporation, the proportion of inhomogeneous mixing grid points to all grid points experiencing evaporation, and ψ at the inhomogeneous mixing grid points in the experiments *new*, *new_tke* and *new_10* (Table 1) for the cumulus (Cu) and stratocumulus (St) case. The numbers in and out of the parentheses are the results at the mature and dissipation stages in the stratocumulus (St) case, respectively. The experiments are detailed in Table 1.

	ψ at all grids (%)	Proportion of inhomogeneous mixing grids (%)	ψ at the inhomogeneous mixing grids (%)
new (Cu)	98.80	13.78	91.21
new_tke (Cu)	99.93	4.52	98.62
new_10 (Cu)	94.41	49.32	86.01
new (St)	79.38 (94.12)	60.22 (42.36)	71.33 (90.66)
new_tke (St)	78.56 (94.68)	63.07 (40.61)	71.56 (89.33)
new_10 (St)	68.23 (88.22)	97.11 (73.19)	65.18 (85.12)

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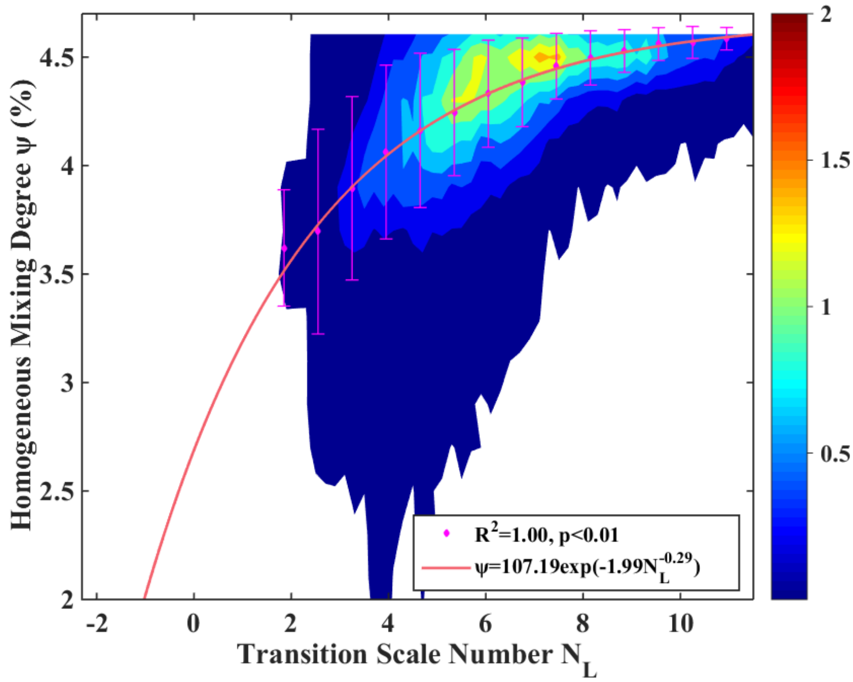

Figure 1. Parameterization of cloud entrainment-mixing mechanisms by relating homogeneous mixing degree (ψ) to transition scale number (N_L) from EMPM. The contours represent the joint probability distribution function (PDF) of ψ vs N_L. The magenta dots and error bars are mean values and standard deviations of ψ in each N_L bin, respectively. The mean values are fitted using a weighted least squares method with the number of data points in each N_L bin as the weight. The fitting equation, coefficient of determination (R^2), and p-value are also given. N_L is calculated by with the domain-averaged relative humidity after entrainment but before evaporation in the EMPM.

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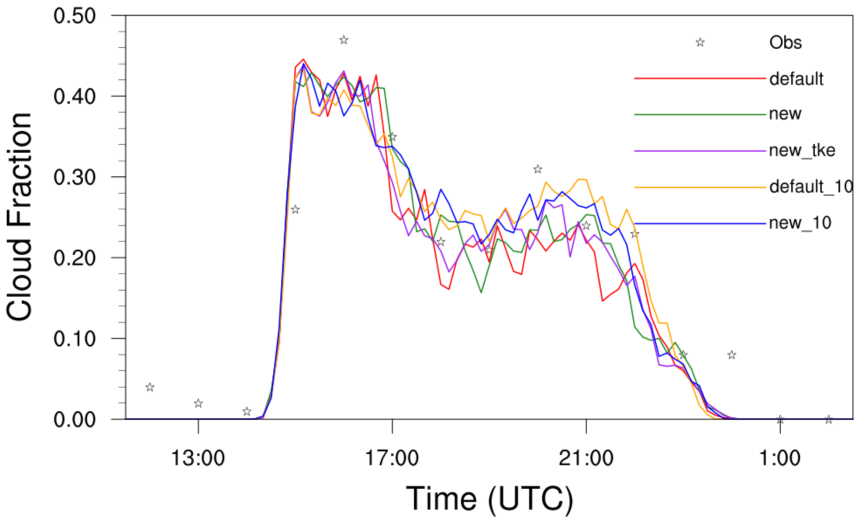

Figure 2. Time series of cloud fraction from 12:00 UTC on June 11, 2016, to 03:00 UTC on June 12, 2016, from the observation in LASSO and five simulation experiments in the cumulus case. The five experiments are detailed in Table 1.

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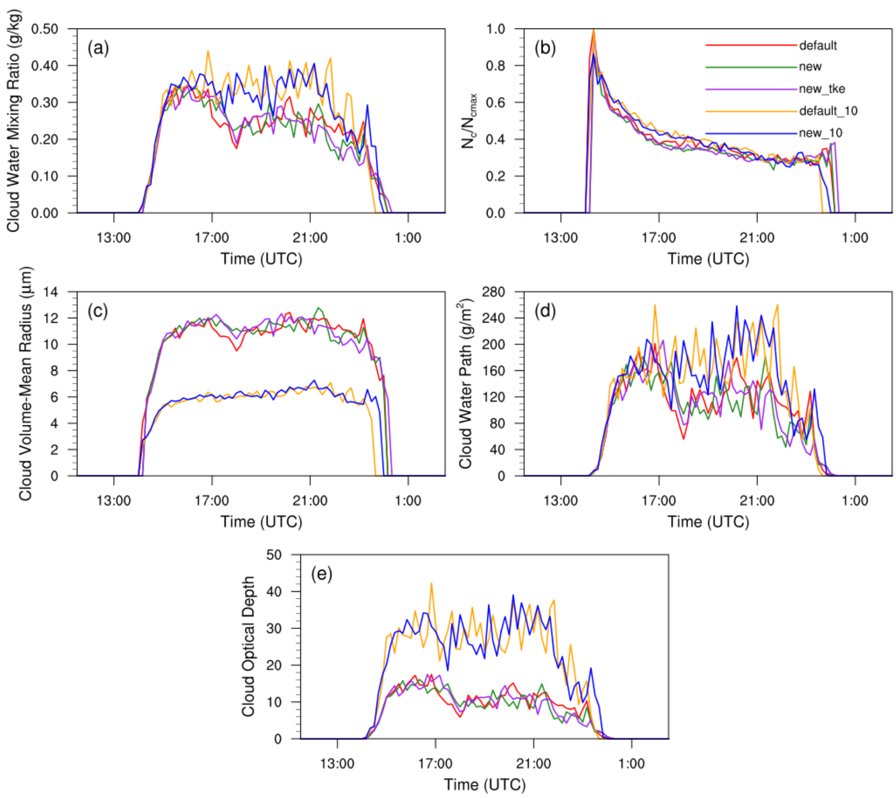

Figure 3. The temporal evolutions of main cloud microphysical and optical properties in all simulation experiments for the cumulus case, including (a) cloud water mixing ratio (q_c) (g/kg), (b) cloud droplet number concentration (N_c) (/cm^3), (c) cloud droplet volume-mean radius (r_v) (μm), (d) cloud water path (CWP) (g/m^2), and (e) cloud optical depth (τ). In (b), N_c in the experiments *default*, *new*, and *new_tke* are normalized by the maximum cloud droplet concentration (N_{cmax}) from *default*, respectively; N_c in the experiments *default_10* and *new_10* are normalized by N_{cmax} from *default_10*, respectively. The five experiments are detailed in Table 1.

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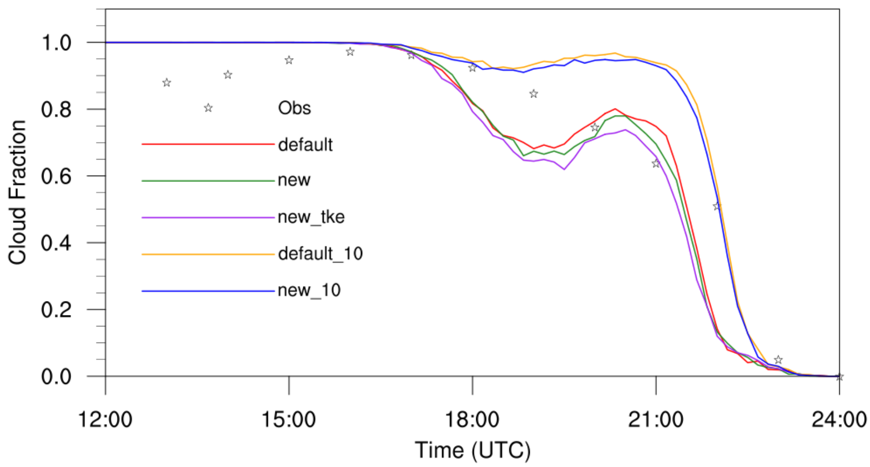

730

731 Figure 4. Time series of cloud fraction from the observation and five simulations in the

732 stratocumulus case. The five experiments are detailed in Table 1.

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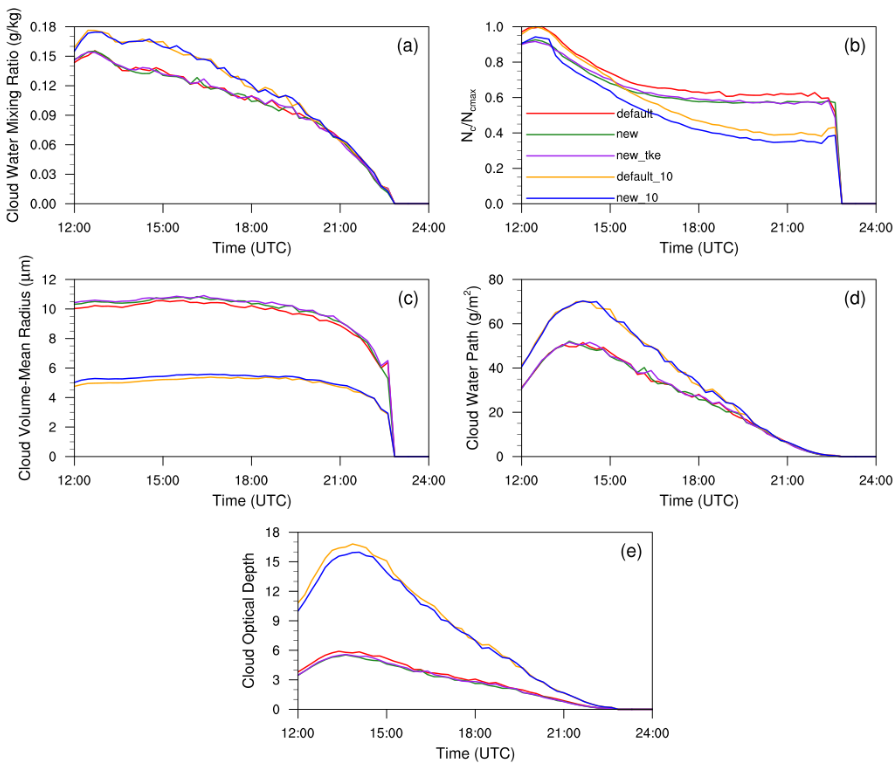
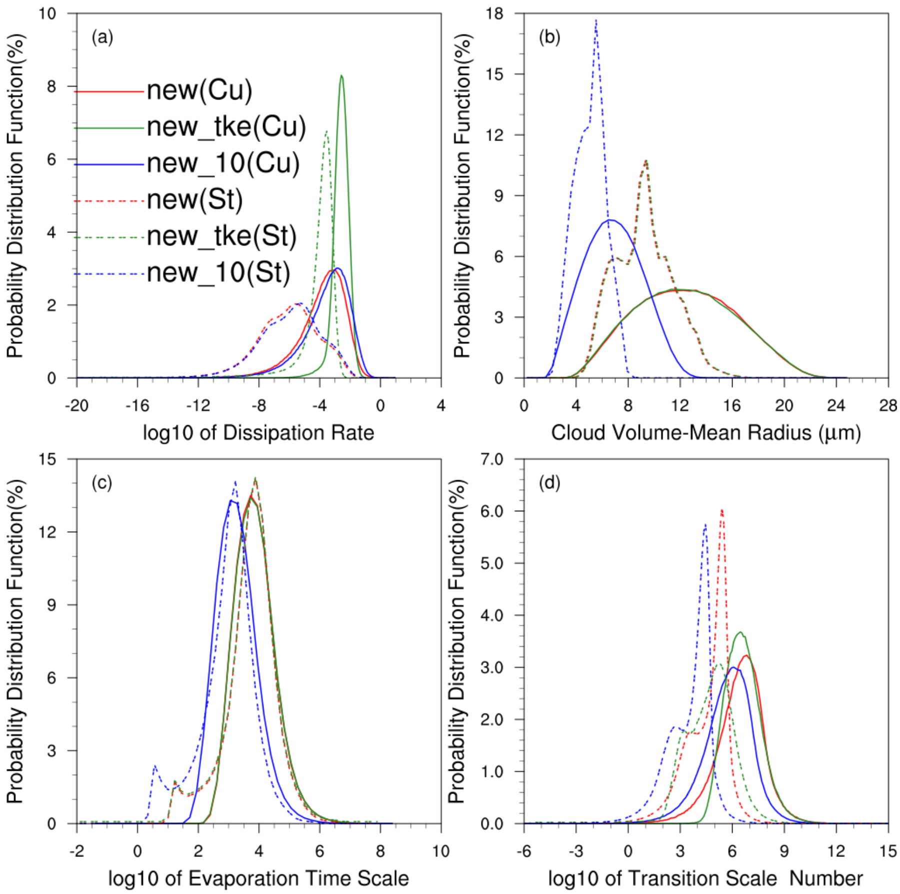


Figure 5. The temporal evolutions of main cloud microphysical and optical properties in all simulation experiments for the stratocumulus case, including (a) cloud water mixing ratio (q_c) (g/kg), (b) cloud droplet number concentration (N_c) (/cm^3), (c) cloud droplet volume-mean radius (r_v) (μm), (d) cloud water path (CWP) (g/m^2), and (e) cloud optical depth (τ). In (b), N_c in the experiments *default*, *new*, and *new_tke* are normalized by the maximum cloud droplet number concentration (N_{cmax}) from *default*, respectively; N_c in the experiments *default_10* and *new_10* are normalized by N_{cmax} from *default_10*, respectively. The five experiments are detailed in Table 1.



742

743 Figure 6. Probability distribution functions (PDFs) of (a) turbulence dissipation rate (ε),
744 (b) cloud droplet volume-mean radius (r_v), (c) evaporation time scale (τ_{evap}), and (d)
745 transition scale number (N_L) of cloud grids experiencing the entrainment-mixing
746 process in the simulations with the new entrainment-mixing parameterization for the
747 cumulus case (Cu, the solid lines) and the stratocumulus case (St, the dash lines),
748 respectively. The experiments are detailed in Table 1.

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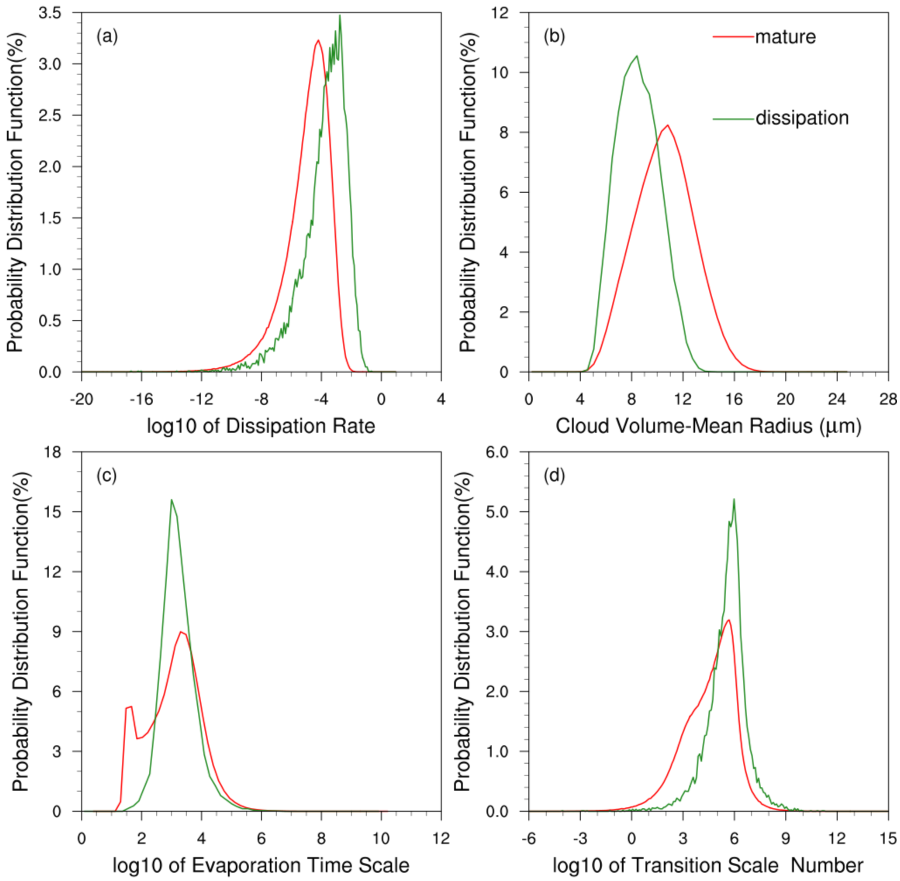

Figure 7. Probability distribution functions (PDFs) of (a) turbulence dissipation rate (ε), (b) cloud droplet volume-mean radius (r_v), (c) evaporation time scale (τ_{evap}), and (d) transition scale number (N_L) of cloud grids experiencing the entrainment-mixing process at the mature stage from 12:00 UTC to 16:00 UTC (the red lines) and the dissipation stage from 21:00 UTC to 24:00 UTC (the green lines) in *new* for the stratocumulus case. The experiment is detailed in Table 1.