We would like to thank the reviewer for giving constructive comments/suggestions, which are very helpful in improving the manuscript. We have revised the manuscript based on the comments/suggestions. Below are our detailed responses (blue) to the reviewer's comments/suggestions.

Responses to reviewer #2

Review of "Influences of Entrainment-Mixing Parameterization on Numerical Simulations of Cumulus and Stratocumulus Clouds" by Xu et al. (ACP-2021-937)

The character of entrainment-mixing can have substantial impacts on the microphysical composition of clouds, with commensurate effects on the cloud optical properties and hence their role in the climate system. Nonetheless, most cloud models neglect the natural variability in the mixing process and assume homogeneous mixing as the default. For the application in bulk cloud models, this study develops a parameterization to consider the natural range between homogeneous and extreme inhomogeneous mixing based on simulation data derived from a high-resolution stochastic turbulence model applied in a previous study of the authors (Luo et al. 2020). After development, the parameterization is applied to a cumulus and a stratocumulus case and the results are analyzed. The manuscript is generally well-written, interesting, and of relevance. However, there might be a fundamental flaw in the assumptions made in the parameterization development that can invalidate the entire manuscript, as I will outline further below. Therefore, I cannot recommend the publication of the manuscript at this stage.

Reply: Thank you very much for your comments on our work. Please see the detailed responses to your specific comments below and changes in the revised manuscript. Hope the revised manuscript can eliminate your concern.

Major Comments

Developing an entrainment-mixing parameterization that depends on the grid-averaged relative humidity. While I understand that it is necessary to simplify physical processes for parameterization purposes, the presented parameterization glances over crucial factors in the entrainment-mixing process. The entrainment-mixing process depends heavily on the relative humidity RH of the entrained air. While I agree that this variable is not directly accessible in most models, using the grid averaged RH can be misleading if the fraction of entrained air f is unknown. To illustrate this, we make the simplifying assumption that RH mixes linearly. (More rigorous calculations can be based on, e.g., Paluch (1979).) With this simplification, we find that

$$RH_{entrained} = \frac{RH_{grid} - (1-f)RH_{cloud}}{f},$$

where the subscripts *entrained*, *cloud*, and *grid* indicate the RH in the entrained, cloudy, and grid averaged air, respectively. While one can assume that RH_{cloud} is approximately 100%, $RH_{entrained}$ can vary substantially for a given RH_{grid} if f is not constrained. And when $RH_{entrained}$ is not constrained, the predicted character of entrainment-mixing may be not based in physics. Thus, getting information on f is crucial for the success of the entrainment-mixing parameterization. The authors might want to refer to Jarecka et al. (2009, 2013) on possible pathways to determine f. Furthermore, I would like to emphasize that the original data on which the parameterization of this study is based uses mainly an $f = 0.2$ (Luo et al. 2020), while larger f have only been addressed in that study briefly. In fact, Luo et al. (2020) state that different f can change the character of mixing. Without addressing these issues, I cannot support the publication of the manuscript.

Reply: We agree with the reviewer that the entrainment-mixing process depends heavily on the relative humidity of the entrained air, and that the fraction of entrained air (f) is a critical parameter.

First, we would like to clarify that the original data on which the parameterization of this study is based uses a range of f values from 0.1 to 0.7, instead of just $f = 0.2$. (Please see Table R1 (Table 1 in Luo et al. (2020)). To avoid such potential misunderstanding, we add some description in Lines 163-165: "It is also worth noting that a wide range of ε, S_e, and fraction of entrained air (f) are taken into account when establishing the parameterization with EMPM."

Table R1. Table 1 from Luo et al. (2020)

Table 1
Parameters for EMPM Simulations of Entrainment-Mixing Processes

Parameter	Value
Domain size, D	20 m
Vertical velocity, w	2 m s^{-1}
Entrained blob size, l	2 m
Initial droplet number concentration, n_d	63.8, 127.6, 191.5, 255.3, 319.2, 383.1 cm^{-3}
Entrained air fraction, f	0.1–0.7
Dissipation rate, ε	10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 5×10^{-5}, 5×10^{-4}, 5×10^{-3}, 5×10^{-2} m^2 s^{-3}
Entrainment heights (above cloud base)	200, 300, 400 m
Sounding data (July and August 2014)	23 days

Second, we agree that entrained air RH can vary substantially for a given grid-mean RH if f is not constrained and it is a good way to parameterize entrainment-mixing process with the properties of entrained air. Here, the reason for using grid-mean RH is that we want to propose a more convenient choice for most atmospheric models. We agree that it is necessary to verify the results of the entrainment-mixing parameterization shown in the original manuscript by using the entrained air RH with the entrainment-mixing parameterization proposed by Luo et al. (2020)

$$\psi = 107.96 \exp(-0.95 N_L^{-0.35}), \quad \text{(R1)}$$

Jarecka et al. (2009) and Jarecka et al. (2013) added an equation to predict f for each grid. In principle, this is a good choice if this method is available in models. Here, to obtain f at 100 m, a parameterization of f is developed based on the simulations for both the cumulus and stratocumulus cases with a higher resolution of 10 m; the other configurations are the same as those in the experiment *default*. The 10 m-resolution simulation results are then averaged to the resolution of 100 m. Following Xu and Randall (1996), "1 - f" can be fitted by the function

$$1-f=RH_{\mathrm{grid}}^{\gamma}\left[1-\exp\left(-\beta q_{\mathrm{c}}\right)\right], \tag{R2}$$

where γ and β are empirical parameters. The correlation coefficient between the parameterized and "real" 1 - f is 0.89 with a significant level p-value <0.01 (Figure R1).

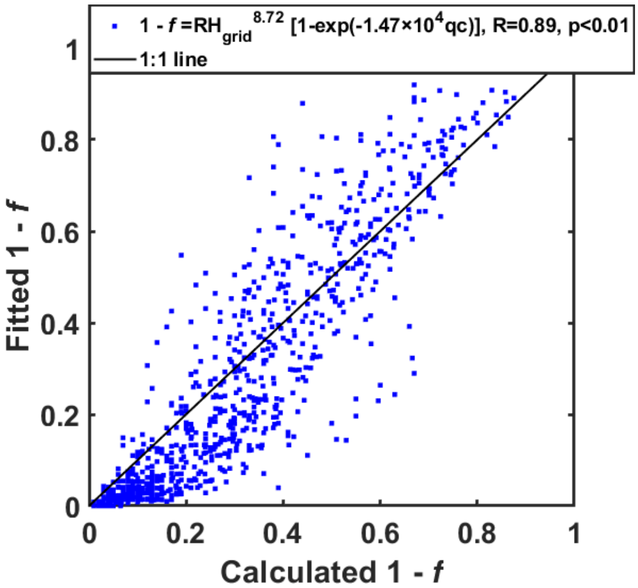

Figure R1. The fitted 1 - f as a function of the calculated 1 - f, where f is fraction of entrained air. The fitted 1 - f is obtained by the fitting function with grid-mean relative humidity (RH_{grid}) and cloud water mixing ratio (q_c). The black line denotes the 1:1 line.

Then, entrained air RH is calculated following Grabowski (2007) and Jarecka et al. (2009)

$$RH_{\mathrm{entrained}}=\frac{RH_{\mathrm{grid}}-(1-f)RH_{\mathrm{cloud}}}{f}, \tag{R3}$$

where the subscripts *entrained*, *cloud*, and *grid* indicate the RH of the entrained, cloudy, and grid point air, respectively. Equations (R1-R3) are applied in the simulations for both the cumulus and stratocumulus cases with different aerosol background (hereafter *new_f* and *new_f_10*).

The above description and discussions are added (Lines 394-421). We also add some discussion on the method used in Jarecka et al. (2009, 2013) in Lines 430-432: "It is worth noting that instead of parameterizing the entrained air fraction, Jarecka et al. (2009) and Jarecka et al. (2013) added an equation to predict f for each grid. In principle, this is a good choice if this method is available in models."

Third, cloud properties in these two extended simulations (*new_f* and *new_f_10*) are compared with the results shown in the original manuscript. Generally, the two different ways of representing entrainment-mixing yield similar cloud microphysical and optical properties (Figures R2-3), with the maximum difference of mean cloud microphysical and optical properties (Table R2) between using grid RH and entrained air RH being less than 1%. The comparison suggests that the results shown in the original manuscript are reliable. These are discussed in Lines 421-429: "Same as Figures 3 and 5, the temporal evolutions of the cloud physical properties (q_c, N_c, r_v, CWP, and τ) in *default*, *default_10*, *new_f*, and *new_f_10* are shown in Figures 9 and 10. The results are similar to Figures 3 and 5. The mean values of these properties of *new_f* and *new_f_10* for the cumulus and stratocumulus cases are also shown in Table 6, the results of *new* and *new_10* are also shown in the parentheses for the convenience of comparison. The results of *new_f* and *new* are very similar, with the maximum difference being no more than 1%, so are the results of tenfold aerosol background. Such a close agreement suggests that the results of the new entrainment-mixing parametrization with grid-mean RH are reliable."

All the above discussions are added as Section 3.5 in the revised manuscript.

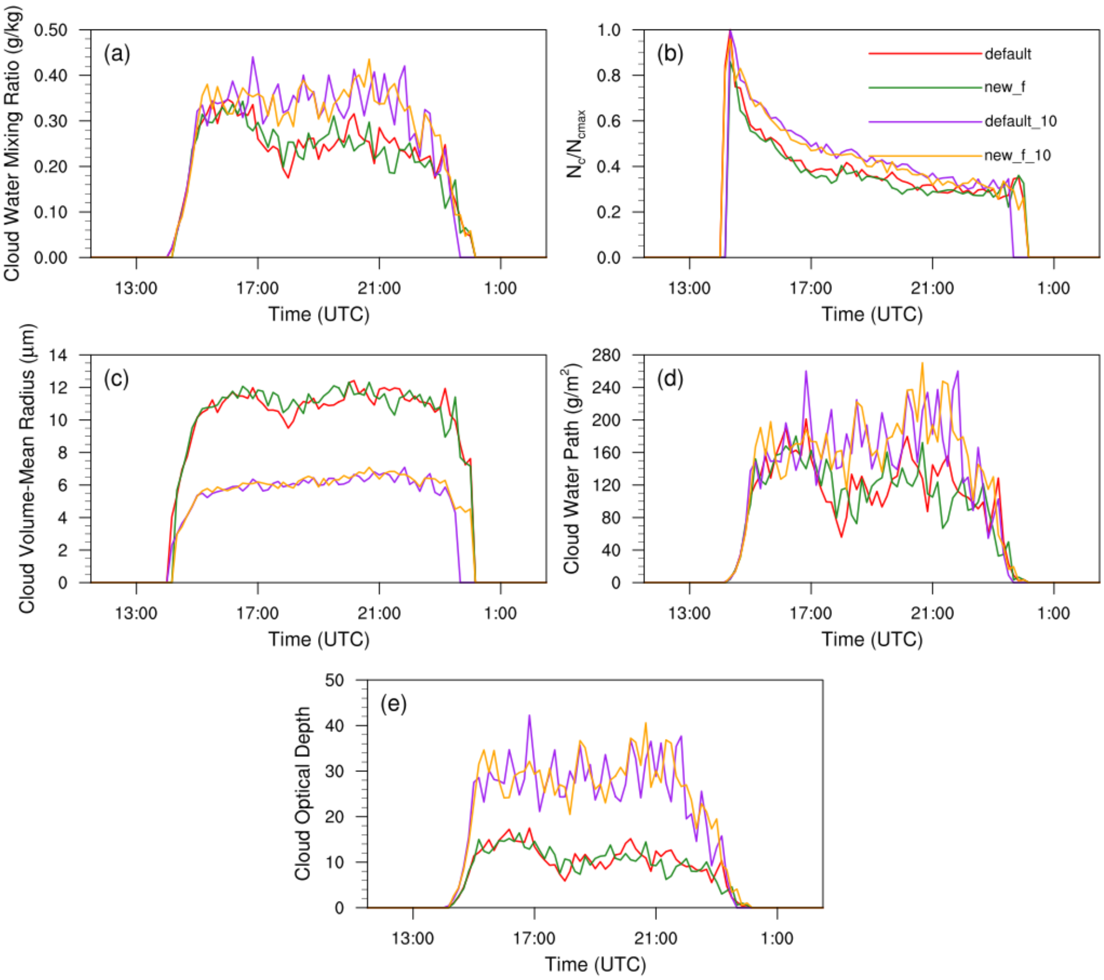

Figure R2. The temporal evolutions of main cloud microphysical and optical properties in all simulation experiments for the cumulus case, including (a) cloud water mixing ratio (q_c) (g/kg), (b) cloud droplet number concentration (N_c) (/cm^3), (c) cloud droplet volume-mean radius (r_v) (μm), (d) cloud water path (CWP) (g/m^2), and (e) cloud optical depth (τ). In (b), N_c in the experiments *default* and *new_f* are normalized by the maximum cloud droplet concentration (N_{cmax}) from *default*, respectively; N_c in the experiments *default_10* and *new__f_10* are normalized by N_{cmax} from *default_10*, respectively. *new_f* and *new_f_10* are the experiments using entrained air relative humidity.

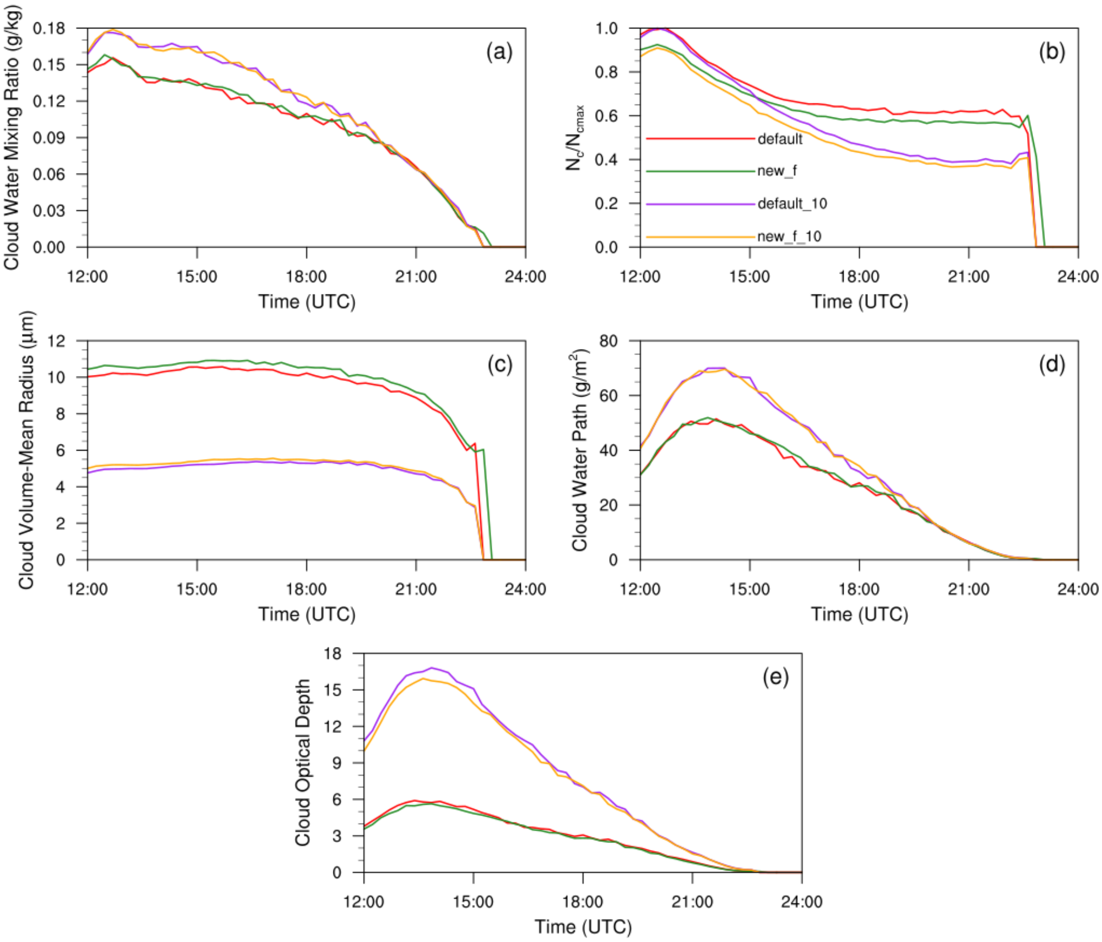

Figure R3. The temporal evolutions of main cloud microphysical and optical properties in all simulation experiments for the stratocumulus case, including (a) cloud water mixing ratio (q_c) (g/kg), (b) cloud droplet number concentration (N_c) (/cm^3), (c) cloud droplet volume-mean radius (r_v) (μm), (d) cloud water path (CWP) (g/m^2), and (e) cloud optical depth (τ). In (b), N_c in the experiments *default* and *new* 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. *new_f* and *new_f_10* are the experiments using entrained air relative humidity.

Table R2. Cloud water mixing ratio (q_c), cloud droplet number concentration (N_c), cloud droplet volume-mean radius (r_v), cloud water path (CWP), cloud optical depth (τ) the cumulus (Cu) and stratocumulus (Sc) cases. *new_f* and *new_f_10* are the simulations using entrained air RH with Equation (R1) while *new* and *new_10* are the simulations using grid-mean RH as shown in the original manuscript.

	Cu		Sc	
	new_f (*new*)	*new_f_10* (*new_10*)	*new_f* (*new*)	*new_f_10* (*new_10*)
q_c(g/kg)	0.44 (0.44)	0.57 (0.57)	0.11 (0.11)	0.13 (0.13)
N_c(cm^{-3})	35.52 (35.53)	270.56 (271.16)	28.08 (28.12)	202.99 (203.50)
r_v(μm)	13.30 (13.29)	7.10 (7.09)	9.60 (9.57)	5.21 (5.22)
CWP(g/m^2)	143.15 (144.25)	185.95 (187.13)	30.16 (29.92)	43.32 (43.13)
τ	13.00 (13.02)	31.08 (31.11)	3.89 (3.89)	9.93 (9.96)

References

Grabowski, W. W.: Representation of turbulent mixing and buoyancy reversal in bulk cloud models, Journal of the atmospheric sciences, 64, 3666-3680, 2007.

Jarecka, D., Grabowski, W. W., and Pawlowska, H.: Modeling of Subgrid-Scale Mixing in Large-Eddy Simulation of Shallow Convection, Journal of the Atmospheric Sciences, 66, 2125-2133, 10.1175/2009jas2929.1, 2009.

Jarecka, D., Grabowski, W. W., Morrison, H., and Pawlowska, H.: Homogeneity of the subgrid-scale turbulent mixing in large-eddy simulation of shallow convection, J. Atmos. Sci., 70, 2751-2767, 2013.

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Xu, K.-M. and Randall, D. A.: A semiempirical cloudiness parameterization for use in climate models, Journal of the atmospheric sciences, 53, 3084-3102, 1996.

Minor Comments

L. 1: I would add an “an” before “Entrainment-Mixing”.

Reply: Thanks, and added.

Ll. 130 –134: Why do you use definition (4) here? Equation (7) might be better as it is directly coupled to the subgrid-scale scheme of the dynamical model. Or do you recommend this approach for models that do not predict ε ? Please comment on this decision.

Reply: Thank you for your comment. We agree that Equation (7) is better to be directly coupled to the subgrid-scale scheme. We remove the results with Equation (4) in the original manuscript and replace these with the results with Equation (7). The general conclusions do not change (Section 3.1-3.4).

L. 140: The subsaturation is defined as 1-RH, the supersaturation as RH-1, and (5a) requires the supersaturation due to the minus.

Reply: We have revised the phrases accordingly.

Sec. 3: I generally agree with these results. However, the results depend significantly on how well the entrainment-mixing parameterization captures the *f* dependency. Thus, I do not like to add any more comments at this stage of the publication process.

Reply: The results of the parameterization with grid-mean RH in the original manuscript are verified by the parameterization with entrained air RH in Section 3.5 in the revised manuscript. Please also see the reply to Major comment.

Ll. 459 – 462: As most models suffer from numerical diffusion, too high supersaturations at the cloud edge are a common problem in most dynamical models, not only large-eddy simulation approaches.

Reply: We have changed the sentence to "Note that the new entrainment-mixing parameterization could be more important in the models if the relative humidity near the cloud is more accurately simulated, because numerical diffusion may spuriously humidify the entrained air".

Tab. 3: Add horizontal lines to associate the investigated variables more clearly with the presented values.

Reply: Added.

Fig. 1: I assume you show the logarithm of the transition scale number here?

Reply: Yes. Sorry for that and we have replotted Figure 1 in the revised manuscript.