Comments on “Investigation of ice cloud modeling capabilities for the irregularly shaped Voronoi models in climate simulations” by Li et al.

Anonymous Referee #4

General comments

The paper by Li et al. presents an analysis of a proposed broadband ice cloud scheme based on the Voronoi ice cloud particle model. The comparisons of model simulations using RRTMG and CAM5 between Voronoi and other four ice cloud schemes were carried out, indicating that the Voronoi scheme is superior to the other conventional schemes and should be sufficient for ice cloud modeling. I believe this study can be valuable to the relevant community, and it helps to better understand the ice cloud optical properties and their impact on cloud radiative effects modeling.

Overall, the study established a straightforward objective and was done in a comprehensive way. The employed scheme seemed valid and the extensive comparison was performed and discussed properly. The draw conclusions are in line with the experimental results. From my point of view, the paper is suitable for Atmospheric Chemistry and Physics, although I do have some concerns that need to be responded. To enhance the potential of the proposed scheme, I would encourage the authors to submit a revised manuscript by addressing my specific comments below:

Response: Thank you very much for your significant comments.

Specific comments

1. As pointed out by the other reviewers, the English language of the current manuscript requires a substantial improvement. There are a number of grammatic and wording errors (not described here as most of them have been noted by the other reviewers) in the article. A careful proofreading throughout the manuscript would be necessary.

Response: According to the suggestions, we have proofread the manuscript.

2. Please check Equation (1) at line 138 since the current layout seems weird.

Response: According to the suggestions, we have moved Eq. (1) and its corresponding descriptions to the middle of section 2 on page 6.

3. Please consider to revise Figure 2 as the flowchart does not look very helpful to me. If possible, please also include a short overview of Figure 2 in the beginning of Section 3 or reorganize this section, particularly the first paragraph. Here, you do not have to provide equation indices since you will detail them in the following subsections anyway.

Response: According to the suggestions, we have redrawn the flowchart (Figure 2) and added a brief description in the beginning of section 3 (page 8) as shown below.

Page 8: "In this study, we develop the Voronoi scheme and assess its effectiveness in comparison with Mitchell, Baum-yang05, Fu and Yi schemes. The main flowchart of this study is described in Figure 2. Five schemes are derived first and evaluated through standalone simulations in the RRTMG and multi-year simulations in the CAM5. The simulations of cloud radiative properties from different ice cloud optical property parameterizations in CAM models are measured by CERES satellite observation products. The RRTMG is utilized to understand how the different optical properties of five schemes influence the upward/downward fluxes through standalone simulations. The CAM5 is employed to evaluate the ice cloud modelling performance of the Voronoi model compared with the other four schemes in the climate system."

Flowchart (Figure 2 on page 28):

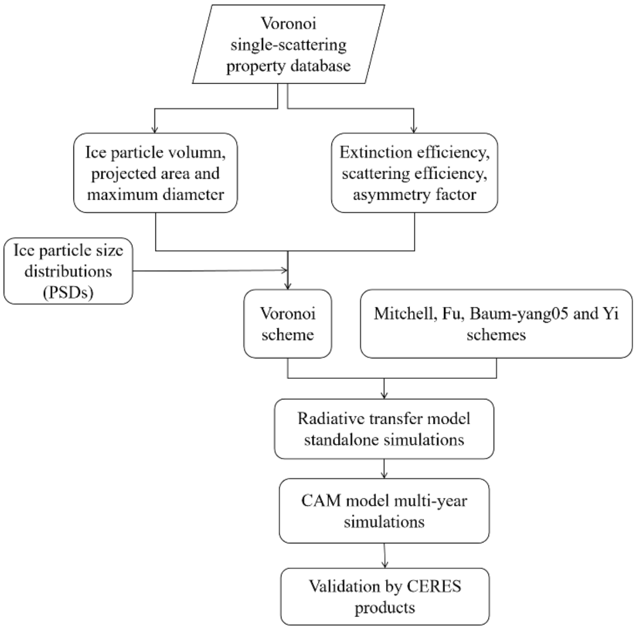

Figure 2. Flowchart of the study

4. Line 151: In Section 1, you actually only introduce the four conventional ice cloud schemes without sufficient (mathematical/technical) details. Readers would expect more details from Section 3. So, this could be another point to reorganize Section 3.

Response: According to the suggestions, we have added more descriptions of the other four schemes in section 3 (page 9, 10) as shown below.

Page 9, 10: "Mitchell, Yi and Baum-yang05 schemes are developed as functions of D_e following formulation of Eq. (1-4) below. Coefficients of Mitchell scheme are obtained from ice cloud band-averaged optical properties utilized in the CAM5. Coefficients of Yi and Baum-yang05 are provided from Zhao et al. (2018). Formulation of Fu scheme is similar to Eq. (1-4) except using the generalized effective diameter (Fu, 1996) and different coefficients. Coefficients of the Fu scheme (default scheme in RRTMG) are obtained from the existing ice cloud band-averaged optical properties from RRTMG."

$$D_e = \frac{3}{2}\frac{IWC}{\rho A} , \quad (1)$$

$$\beta = IWC(a_0 + a_1/D_e + a_2/D_e^2) , \quad (2)$$

$$1 - \omega = b_0 + b_1 D_e + b_2 D_e^2 + b_3 D_e^3 , \quad (3)$$

$$g = c_0 + c_1 D_e + c_2 D_e^2 + c_3 D_e^3 , \quad (4)$$

5. Section 3.1: I am okay with the contents. However, I would like to see a clearer structure. Each equation should normally follow the corresponding text.

Response: According to the suggestions, we have reorganized the layout of equations and corresponding illustrations in section 3 (page 8, 9) as shown below.

Page 8, 9:

"To better understand the ice cloud modelling capabilities of …to the extinction coefficient in the form of Eq. (4), respectively.

$$\beta_{e,s,a} = \int_{L_{min}}^{L_{max}} \sigma_{e,s,a} n(L) dL \ , \tag{3}$$

$$\varpi = \frac{\beta_s}{\beta_e} \text{ ,or } 1 - \varpi = \frac{\beta_a}{\beta_e} \tag{4}$$

where $\sigma_{e,s}$ is the…can be defined by Eq. (5).

$$\tau = \int_z^{\infty} \beta_e \, dz \ , \tag{5}$$

where z is … can be given by Eq. (6).

$$J(\tau;\mu;\phi) = \frac{\varpi}{4\pi}\int_0^{2\pi}\int_{-1}^{1} I(\tau;\mu';\phi')\,P(\mu,\phi;\mu',\phi')d\mu' d\phi'$$

$$+\frac{\varpi}{4\pi}F_\Theta P(\mu,\phi;-\mu_0,\phi_0)e^{-\tau/\mu_0} + (1-\varpi)B[T(\tau)] \ , \tag{6}$$

where P is the phase function ...."

6. Line 269: It sounds unclear to me based on what quality criteria the authors ranked the five models.

Response: Five schemes were sorted from large to small values of upward/downward fluxes.

7. Lines 293-296: Please explain Figure 9 in detail, more explicitly, why the Voronoi model performed the best. So far, I am not convinced by the statement in the current manuscript "...differences box of Voronoi scheme are most concentrated on the zero ...".

Response: According to the suggestions, the box plot is to describe the data of five statistic: the minimum, first quartile, median, and the third quartile and the maximum value. The closer the median line is to the zero line, the more evenly the boxes are distributed on both sides of the zero line, the better the scheme is.

8. An additional appendix including all acronyms and abbreviations used in the manuscript would be useful to readers.

Response: According to the suggestions, we have added a table (Table 1) contains all acronyms in the manuscript.

Page 21, 22:

Table 1. Nomenclature

L	Particle maximum diameter (μm)
λ	Wavelength (μm)
SZP	Size parameter (unitless)
$n(L)$	Particle concentration (cm^{-3})
N_0	Intercept coefficient of $n(L)$ (unitless)
λ^*	Slope coefficient of $n(L)$ (unitless)
μ	Dispersion coefficient of $n(L)$ (unitless)
PSD	Particle size distribution defined by N_0, λ^*, μ and L
TOA	Top of atmosphere
$\beta_{e,s,a}$	Extinction, scattering and absorption coefficients
$\sigma_{e,s,a}$	Extinction, scattering, absorption cross section
θ	Inclination to the upward normal direction scattering angle
μ, μ'	Cosines of θ, incoming and outgoing intensity direction, respectively
φ, φ'	Incoming and outgoing intensity azimuthal angle in reference to the x axis, respectively
P	Phase function regulated by μ, ϕ, μ', ϕ'
z	Upper limit of the outer boundary
τ	Optical thickness
I	Total (direct plus diffuse) radiance
$B[T]$	Planck's function
$J(\tau; \mu; \varphi)$	Source function
D_e	Effective particle diameter
$Q_{ext,sca,}(\lambda, L)$	Extinction efficiency and scattering efficiency
$V(L)$	Ice particle volume (μm^3)
$A(L)$	Average geometrical cross section (μm^2)
$K_{ext}(\lambda), \tilde{K}_{ext}$	Spectral and band-averaged of mass extinction coefficients
$\varpi(\lambda), \tilde{\varpi}$	Spectral and band-averaged single-scattering albedo
$g(\lambda), \tilde{g}$	Spectral and band-averaged asymmetry factor
N	Cloud fraction
F_{cloudy}	Net fluxes of cloudy conditions
F_{clear}	Net fluxes of clear conditions
FSDS	Downwelling solar flux at surface
FLDS	Downwelling longwave flux at surface

FSUTOA	Upwelling solar flux at top of atmosphere
FLUTOA	Upwelling longwave flux at top of atmosphere
SWCF	Shortwave cloud forcing
LWCF	Longwave cloud forcing

Reference

Fu, Q. A.: An accurate parameterization of the solar radiative properties of cirrus clouds for climate models, J Climate, 9, 2058-2082, Doi 10.1175/1520-0442(1996)009<2058:Aapots>2.0.Co;2, 1996.

Zhao, W. J., Peng, Y. R., Wang, B., Yi, B. Q., Lin, Y. L., and Li, J. N.: Comparison of three ice cloud optical schemes in climate simulations with community atmospheric model version 5, Atmos Res, 204, 37-53, 2018.