Comment on amt-2022-247

Anonymous Referee # 3

Referee comment RC2 on “Retrieval of Terahertz Ice Cloud Properties from airborne measurements based on the irregularly shaped Voronoi ice scattering models” by Ming Li et al.

General comments

The paper is about applying the Voronoi model to the retrieval of IWP and re using brightness temperature differences between 380, 640, and 874 GHz. Not surprisingly, the authors find the Voronoi model re-produces previous retrievals of IWP and re more accurately than the sphere. This aspect is not new in the microwave and sub-millimetre, see for instance, the study by Eriksson et al. (2015), https://amt.copernicus.org/articles/8/1913/2015/amt-8-1913-2015.pdf as to why the authors find the sphere to be an inadequate representation of non-spherical ice scattering in the microwave and sub-mm regions. The important aspect of this paper is that the Voronoi model has been previously applied to simulate solar and infrared observations, and now it is being applied over the Terahertz region to see how well the model performs there. However, as to how skillfully it performs against other ice crystal models is yet to be tested. The authors find very good correlations between the Voronoi-based retrievals and Evan’ s Bayesian retrievals using data from the CoSSIR instrument. The paper is relatively well-written and can be followed. The figures are also well represented, and the analysis is quantitative, with no obvious flaws. Further proof-reading is recommended to help improve the flow of the paper. This paper could be significantly improved, which if followed, would make the paper a more important contribution to the remote sensing of ice cloud in the microwave and sub-millimetre regions of the spectrum.

Response: Thank you very much for your significant comments.

Major comments

1. It is felt that the authors missed an opportunity to test the veracity of the Voronoi model in the microwave and sub-mm by not comparing their results with another more representative ice crystal scattering model. For instance, why not use the scattering models contained in the ARTS database of single-scattering properties? One model from the ARTS collection of models to try and test against the Voronoi model is the large column aggregate model. This model was shown by Fox (2020) to simulate better than some of the other models, the microwave and sub-millimeter brightness temperature measurements between the frequencies of 183 and 664 GHz. I recommend the authors compare their retrievals and simulations against more realistic ice crystal scattering models such as the ARTS large column aggregate. See, Fox, S. An Evaluation of Radiative Transfer Simulations of Cloudy Scenes from a Numerical Weather Prediction Model at Sub-Millimetre Frequencies Using Airborne Observations. Remote Sens. 2020, 12, 2758. https://doi.org/10.3390/rs12172758.

Response: Thanks for the comments. We have added the hexagonal column ice crystal scattering (ICS) model from the ARTS collection of models to compare with our results in this study. We also cited the document of Fox (2020) in section 1 as follows.

Lines 85-87: "Fox (2020) found that the randomly-oriented large column aggregate can simulate observed brightness temperatures between 183 and 664 GHz with high accuracy."

The descriptions of the hexagonal column ICS model are added in section 2.1 as shown below.

Lines 149-151: "The randomly-oriented hexagonal column (referred to as the Column hereafter) ICS model was defined by Yang et al. (2000a). Their aspect ratios a/L (defined as the ratio of the semiwidth a of a particle to its length L) of Column ICS models are defined as 0.35 and 3.48 respectively when L is less than 100 μm and greater than or equal to 100 μm. The single-scattering property database of the Column ICS model used in the study is developed by Hong (2007, 2009) using the discrete dipole approximation method at frequencies of 100-1000 GHz."

2. The authors make use of existing retrievals of re and IWP to test the Voronoi model but do not make use of the independent measures of IWP and re as derived from the in-situ aircraft during TC4. Why is this? Is the in-situ aircraft data not available? Was there no in-situ data co-incident with the radiometric measurements? The problem with comparing with the existing CoSSIR retrievals is that those retrievals are based on differing assumptions of mass, ice crystal shape and PSDs – comparing apples and oranges. It could be said that the CoSSIR ice crystal shape and mass assumptions are just as valid as the Voronoi model, yet they may be entirely different. It would be much better to compare retrievals with in-situ measures if those are available.

Response: Thanks for the comments. As you mentioned, the main reason is that there was no in-situ measurement data of IWP and re co-incident with the radiometric measurements.

3. The authors propose a convoluted and unnecessary method of relating re to Dme. This is surprising, since in the terahertz region the scattering cross sections are more dependent on mass rather than area. Why use an area-weighted size such as re rather than a mass-weighted size such as Dme? The problem with using re in the terahertz region is nicely explained in the study by Seiron et al. (2017), see https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2017JD026494. In the region of interest, a mass-weighted size would be the more appropriate characteristic size of the PSD to utilize in this paper.

Response: Thanks. In this study, the ice crystal size parameter entered into the radiative transfer model (RSTAR) used in our study is the effective model radius R_e rather than mass-weighted particle size D_{me}. And the R_e and D_{me} are defined according to the following formula,

$$R_e = \frac{\int_0^\infty r^3 n(r) dr}{\int_0^\infty r^2 n(r) dr} , \tag{1}$$

$$D_{me} = \frac{\int_0^\infty D m(D) n(D) dD}{\int_0^\infty m(D) n(D) dD} , \tag{2}$$

where r is the equivalent-volume sphere' s particle radius, D is the maximum particle dimension of ice particles, m is the particle mass, n is the particle size distribution. Hence, we developed a conversion relationship between R_e (independent variable) and D_{me} (dependent variable) combined with different particle size distributions. Based on this relationship, we have unified all the R_e into D_{me} in the revised manuscript.

4. No evidence is presented as to how representative the PSDs used in the analysis are for the TC4 cases considered in the paper. The best way to do this is to derive the moments of the assumed PSDs and in-situ PSDs and show how well correlated they are. Of course, if the insitu PSDs are not available, this cannot be done!

Response: As you mentioned, the main reason is that the in-situ PSDs during the TC4 mission are not available. However, we use in-situ measurements of PSD data (Heymsfield et al., 2013) from 11 field programs spanning a wide range of locations (ranging from 12°S to 70°N latitudes and from 148°W to 130°E longitudes) and encompassing the temperature range 0° to -86°C, and with altitudes from near the surface to 18.7 km. This dataset is representative of the wide range of conditions where ice clouds are found in the troposphere and lower stratosphere on a near-global scale (Li et al., 2022; Heymsfield et al., 2013). Relationships expressing PSDs and the maximum particle dimensions are presented in terms of their temperature, as shown below (Figure 1). The relationships developed can serve as a basis for developing reliable parameterizations.

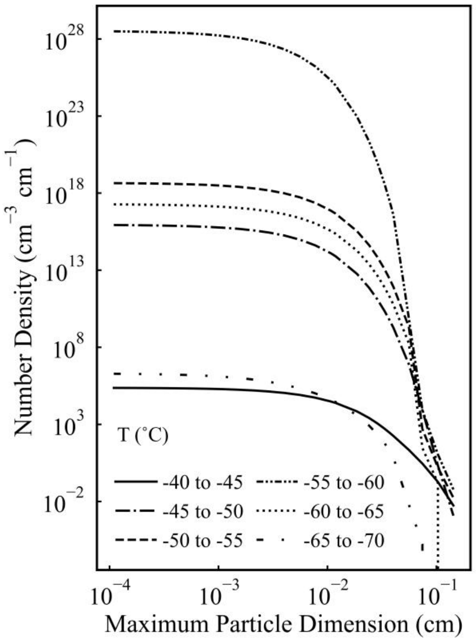

Figure 1. Ice cloud particle size distributions for different temperatures.

5. Related to 4, is the question of how representative is the ERA5 re-analysis product for a couple of TC4 cases? The temperature, water vapour and ozone profiles are important in the radiative transfer simulations. If the ERA5 re-analysis product is not representative of the actual state of the atmosphere for those few days, this could bias the brightness temperature difference results. The authors should compare some of the ERA5 atmospheric profiles with the aircraft profiles, if the latter are available.

Response: As you mentioned, the main reason is that the in-situ aircraft atmospheric profiles during the TC4 mission are unavailable. However, many documents have verified the high accuracy of the ERA5 products. For example, Graham et al. (2019) evaluated five atmospheric reanalyses, including ERA5, ERA-Interim, Japanese 55-year Re-Analysis (JRA-55), Climate Forecasting System Reanalysis-version 2 (CFSv2), and Modern Era Retrospective analysis for Research and Applications-version 2 (MERRA-2) using observations from 50 radiosondes. Overall, the newly released ERA5 has higher correlation coefficients than any other reanalysis (Graham et al., 2019).

6. The authors need to provide images of the Voronoi model with increasing ice crystal size, such that it can be seen by readers how the model aggregation varies with size. What are also required in the revised paper are the Voronoi model's mass– and area–dimension power laws. These power law relations will go some way to explaining the single-scattering results and sensitivities of the Voronoi model to IWP and the characteristic size of the PSD in the brightness temperature difference sensitivity analysis. The fractal dimensions of mass and area of the Voronoi model are important in these respects.

Response: Thanks. The images of a set of seven Voronoi model shapes with increasing ice crystal size have been shown (Fig.3) in the literature of Ishimoto et al. (2012) as shown below. The geometrical characteristics of seven Voronoi model shapes can also be found in Table 1 of Ishimoto et al. (2012). Thus we cited the images and their geometrical characteristics of the Voronoi ice crystal models from Ishimoto et al. (2012) in section 2.1 as shown below. (See, Ishimoto, H., Masuda, K., Mano, Y., Orikasa, N., and Uchiyama, A.: Irregularly shaped ice aggregates in optical modeling of convectively generated ice clouds, J Quant Spectrosc Ra, 113, 632-643, doi:10.1016/j.jqsrt.2012.01.017, 2012.)

Lines 145 - 147:

"As the particle size increases, the shape of the Voronoi ICS model changes and become complicated. The details of Voronoi model shapes with increasing ice crystal size have been shown and discussed in Ishimoto et al. (2012)".

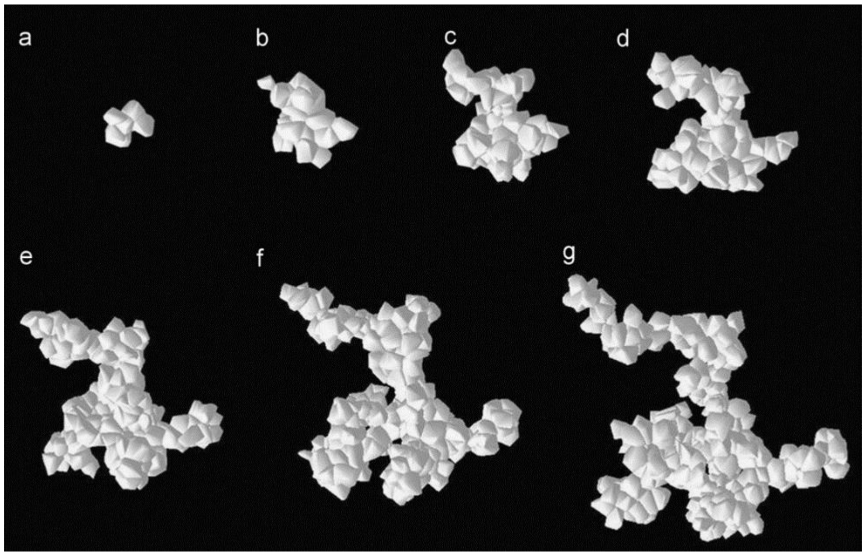

Figure 2. Numerically created Voronoi aggregates for a model of irregular ice particles. See Fig. 3. cited from Ishimoto et al. (2012).

According to your comments, we have also added the Voronoi ice crystal model' s mass- and area-dimension power laws in the revised manuscript. The mass-dimension and area-dimension power-law relationships of the Voronoi ice crystal model are defined by Ishimoto et al. (2012) and are described in Equation (1) - (3) as shown below.

$$m = 0.00528D^{2.1} \text{ (in cgs)} \tag{1}$$

$$A_r = 4G/\pi D^2 \tag{2}$$

$$A_r = 0.20D^{-0.29} \tag{3}$$

where the m is the mass, G is the cross-sectional area, A_r is the area ratio and the D is the maximum dimension of the Voronoi ice crystal model.

7. Apart from plotting the retrieved quantities, a further measure of how well the

Voronoi model represents the measured brightness temperatures at the three channels is to plot the residuals (i.e. brightness temperature differences between the forward model and measurements) as a function of time for all three channels.

Response: Thanks for the comments. The problem is the assumed water vapour, ozone and atmospheric profiles in the forward model can bring errors when converting the IWP and D_{me} to the BTDs. So it is hard to explain the smallest brightness temperature differences between the forward model and measurements is due to the Voronoi model.

Specific comments

1. Introduction line 34. Since the authors discuss 20-30% of the global cloud mass, would it not be better to cite more updated studies that more directly measure the ice mass such as studies using CloudSat global retrievals of ice mass? As well as mm-wave retrievals of ice mass?

Response: According to the comments, we have added more studies relevant to ice mass retrievals using CloudSat and millimeter-wave data as shown below.

Lines 48-56: "The visible and infrared spectrum are sensitive to the visible optical depth and cloud top (Minnis et al., 1993b; Minnis et al., 1993a). The millimeter-wave ice cloud remote sensing technique is more suited to detect vertical cloud properties. Sensors such as the Millimeter-wave Imaging Radiometer (MIR) (Racette et al., 1992) and Special Sensor Microwave Water Vapor Sounder (SSM/T-2) have been used in several studies of IWP and particle size retrievals (Lin and Rossow, 1996; Liu and Curry, 1998, 1999). MIR channels at 89, 150 and 220 GHz have been used by Deeter and Evans (2000) and Liu and Curry (2000) to retrieve IWP and particle size in cirrus anvils over tropical ocean. Compared to passive sensors, the Cloud satellite radar (CloudSat), with an onboard millimeter-wavelength (94.05 GHz) radar and the raDAR/liDAR cloud product (DARDAR) (Ceccaldi et al., 2013) present new opportunities to infer the microphysical properties of ice clouds on a global scale. "

2. Line 36. As the paper is discussing Terahertz frequencies, another important property of large ice crystals that contribute to the radiative properties of ice cloud is their orientation.

Response: Thanks. We have added the “orientation” in this sentence as shown below.

Line 36: “Microphysical properties such as the ice water content, ice particle size, orientation, shape and etc. are the main influencing factors of the scattering and radiative properties of ice clouds.”

3. List of citations on line 47. Fox (2020) should be added to this list?

Response: According to the comments, we have added the citation of the (Fox, 2020) in the list of citations on line 47 as shown below.

Lines 45-48: “Currently, large amounts of passive sensors (visible, infrared and microwave detectors) and related ice cloud retrieval algorithms (Nakajima and King, 1990; Nakajima et al., 1991, 2019; Nakajima and Nakajima, 1995; Platnick et al., 2003, 2017; Fox et al., 2019; Brath et al., 2018; Fox, 2020) have significantly developed.”

4. Line 51. The description of Fox et al. (2019) needs to be more accurate, the study also used sub-mm frequencies up to 664 GHz, and in Fox (2020). The works of Fox (2019,2020) includes the Terahertz region, and not just the microwave.

Response: Thanks for the comments, we have modified the irrational expressions on lines 50-51 as follows: “Additionally, microwave regions are mainly useful for large particles larger than 500 μm compared to the terahertz region (Fox, 2020; Fox et al., 2019).”.

5. Line 79, again ice crystal orientation is also an important consideration here.

Response: We have rewritten this sentence as follows: “Different assumptions of ice cloud microphysical properties (shape, size, orientation and particle size distribution of ice particles) in the forward physical model significantly affect the retrieval of the IWP and particle size of ice clouds.”.

6. Line 97. Another numerical method that could be included in this list is the Boundary Element Method, which has recently been applied to very complex ice crystals by Kleanthous et al. (2022): Antigoni Kleanthous, Timo Betcke, David P. Hewett, Paul Escapil-Inchauspé, Carlos Jerez-Hanckes, Anthony J. Baran, Accelerated Calderón preconditioning for Maxwell transmission problems, Journal of Computational Physics, Volume 458, 2022, 111099, ISSN 0021-9991,

https://doi.org/10.1016/j.jcp.2022.111099. A further paper here could be Mano (2000), who applied BEM to hexagonal ice columns. "Exact solution of electromagnetic scattering by a three-dimensional hexagonal ice column obtained with the boundary-element method," Appl. Opt. 39, 5541-5546.

Response: According to the comments, we have included the Boundary Element Method in the introduction section (Lines 97-99) as follows: "Moreover, the boundary element method (Groth et al., 2015; Kleanthous et al., 2022) has been recently applied to complex ice particles.".

7. Line 98. This GOA acronym has not been defined - should it be GOM?

Response: Thanks. We have added the definition of the "GOA" as shown below.

Line 98: ".. several improved Geometrical Optics Approximation (GOA) methods .."

8. The discussion beginning on line 108. Another ICS model worthy of note in this context is the ensemble model of cirrus ice crystals developed by Baran and Labonnote (2007). The ensemble model attempts to be more representative of the evolution of the ice crystal aggregation process as a function of increasing size, see Baran, A.J. and Labonnote, L.-C. (2007), A self-consistent scattering model for cirrus. I: The solar region. Q.J.R. Meteorol. Soc., 133: 1899-1912.) https://doi.org/10.1002/qj.164), and Baran et al. 2014 (Baran, A.J., Cotton, R., Furtado, K., Havemann, S., Labonnote, L.-C., Marenco, F., Smith, A. and Thelen, J.-C. (2014), A self-consistent scattering model for cirrus. II: The high and low frequencies. Q.J.R. Meteorol. Soc., 140: 1039-1057. https://doi.org/10.1002/qj.2193).

Response: According to the comments, we have included the ensemble ice crystal model in the introduction section (Lines 108-110) and added corresponding descriptions as follows: "Furthermore, features including various habit ensembles were added into ice particles. For example, Baran and Labonnote (2007) and Baran et al. (2014a) developed an ensemble ice particle model made of hexagonal column ice particles for use in the Met Office Unified Model Global Atmosphere 5.0 (GA5) configuration (Baran et al., 2014b).".

9. Typo on line 117 Mo.,del -> Model

Response: We have corrected this error on line 117 as shown below.

Line 117: “the Community Integrated Earth System Model (CIESM).”

删除[liming]: Mo.,del

10. Line 118. The word effectiveness is sufficient, using the word “superiority” is inappropriate here because it has not been proven relative to all other models that are now available.

Response: According to the comments, we have removed the word “superiority” on line 118.

11. Line 122. ICI is not correct here, the instrument is ISMAR (International Sub-Millimeter wave Airborne Radiometer) described in Fox et al., 2017. ISMAR was jointly funded by the Met Office and ESA - not ICI.

Response: We have corrected this error on line 122 as shown below.

Line 122: “The database of the Voronoi ICS model in the terahertz region was adopted by Baran et al. (2018) as standard data for the modelling and evaluation of the ISMAR (International Sub-Millimeter wave Airborne Radiometer) which the European Space Agency (ESA) and the Met Office jointly developed (Kangas et al., 2014; Fox et al., 2017).”

12. Section 2.1. Which refractive indices are being used to compute the SSPs? The refractive indices in the microwave and sub-millimeter are temperature dependent - is this dependence considered in the simulations that follow? If not, which temperature has been assumed in the calculation of the SSPs? How have you justified the selection of this temperature?

Response: For the first question, according to the suggestions, we have added specifications and the reference on lines 148-149 as follows: “The calculation of the single-scattering property utilize the real and imaginary parts of ice from the newest library of the refractive index provided by Warren and Brandt (2008).”.

For the second question, we utilized the refractive indices of ice in the microwave and sub-millimeter at fixed temperature. In this study, the refractive indices of the Voronoi ICS model at the frequencies of 10-874 GHz are computed at temperature 266 K according to Warren and Brandt (2008). And the refractive indices of the Column ICS model added in this study at the frequencies of 89-340 GHz are derived from Warren (1984) at the temperature of -30°C.

For the third question, according to Warren and Brandt (2008), the updated refractive indices were shown only for a single temperature, 266 K. Furthermore, Kim (2006) has indicated that the dependence of refractive indexes of ice crystals on temperature causes only 1% difference in the SSPs at the microwave frequencies. Several studies (Hong, 2007; Hong et al., 2009) have also utilized the refractive indices of ice crystals at assumed temperature. Hence, in this study, the influence of the refractive indices of ice at the fixed temperature on the calculations of the SSPs is ignored here.

13. Section 2.3. Is the cloud between the boundaries assumed to be homogeneous? If so, please state this.

Response: According to the suggestions, we have added the statement of this assumption on lines 168-169 as follows: "The RSTAR radiative transfer model assumes the simulated scene is composed of a homogeneous ice cloud layer".

14. Equation 2, line 186. In the denominator, this is why you need to provide the model' s mass - dimension relationship.

Response: According to the comments, we have added the mass-dimension power-law relationship of the Voronoi ice crystal model as shown below.

$$m = 0.00528D^{2.1} \text{ (in cgs)} \tag{1}$$

where m is the mass and D is the maximum dimension of the Voronoi ice crystal model."

15. Equation 4, line 205. In the denominator, this is why you need to provide the model' s area - dimension relationship.

Response: We have added the area-dimension power-law relationship of the Voronoi ice crystal model as shown below.

$$A_r = 4G/\pi D^2 \tag{1}$$

$$A_r = 0.20D^{-0.29} \tag{2}$$

where G is the cross-sectional area, A_r is the area ratio and D is the maximum dimension of the Voronoi ice crystal model.

16. Equation 7, there is a missing wavelength dependence in the denominator for the scattering cross section.

Response: We have corrected this error in Equation 7 as shown below.

$$g(\lambda) = \frac{\int_{L_{min}}^{L_{max}} g(\lambda,L)\sigma_{sca}(\lambda,L)n(L)dL}{\int_{L_{min}}^{L_{max}} \sigma_{sca}(\lambda,L)n(L)dL} \ , \tag{7}$$

17. Equations 9 -12, how accurate are the parametric fits as a function of De?

Response: For the equations (9)-(12), the mean single-scattering properties are functions of wavelengths and depend on the particle size distribution. There are diverse ways to define the effective particle size of nonspherical ice crystals in the literature. Following Pollack and Cuzzi (1980), Foot (1988) and Mitchell (2002), for irregularly-shaped large particles the absorption coefficient depends on the volume of the particle, and the scattering coefficient depends on the cross-sectional area. Hence, the effective particle size of nonspherical particles associated with a given size distribution is defined as follows:

$$D_e = \frac{3}{2}\frac{\int_{L_{min}}^{L_{max}} V(L)n(L)dL}{\int_{L_{max}}^{L_{max}} A(L)n(L)dL} \ , \tag{4}$$

where D_e is the effective particle diameter, V and A are the volume and projected area of Voronoi and Sphere models. The effective particle diameter D_e can account for the shape of irregular ice crystals and provide a measure of the average size of the cloud particles for a given size distribution. Currently, the parametric fits as a function of D_e has been used in several general parameterization schemes (Baum et al., 2005a; Baum et al., 2005b; Fu, 1996; Mitchell et al., 1996b; Mitchell et al., 2006; Yi et al., 2013).

18. Figure 9, this figure might be better plotted as a PDF of the retrievals, and statistically measure how different the distributions are from the reference PDFs using some statistical measure.

Response: According to the suggestions, we have modified the scatter plot in Figure 9 to a PDF plot, as shown below.

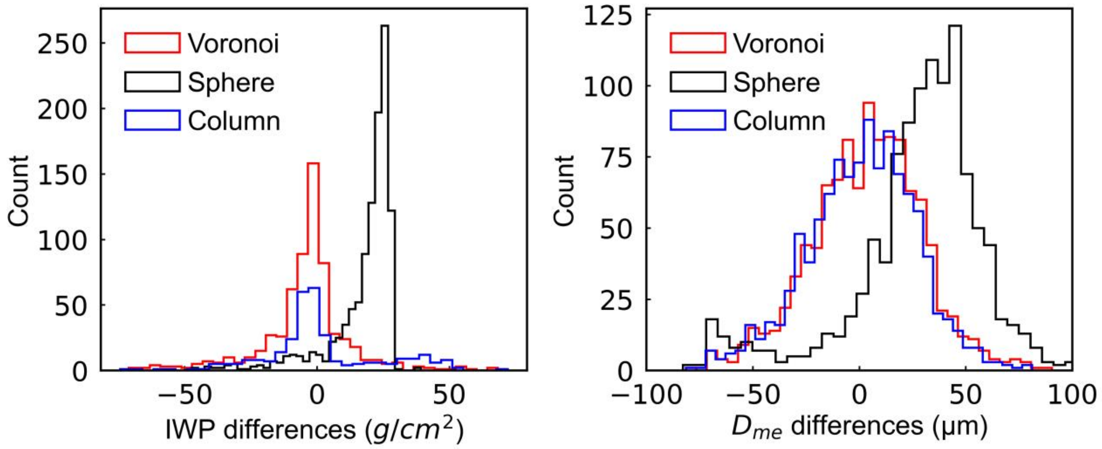

Figure 9: The joint histogram of differences of (a) the IWP and (b) Dme between the retrieved results and the CoSSIR-MCBI algorithm results for the Voronoi (red line), Sphere (black line) and Column models (blue line), separately.

Reference

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