Advancements in the Assimilation of Spaceborne Radar Observations in the NASA GEOS Framework

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Outline

- Introduction & Importance
- The Discrete Dipole Approximation
- Bulk Scattering Properties
- The Radar Simulator
- Evaluation of Radar Simulator
- Assimilation of radar observations
- Conclusions

All-weather radiative transfer calculations

Cost function for 3D-Var Data Assimilation:

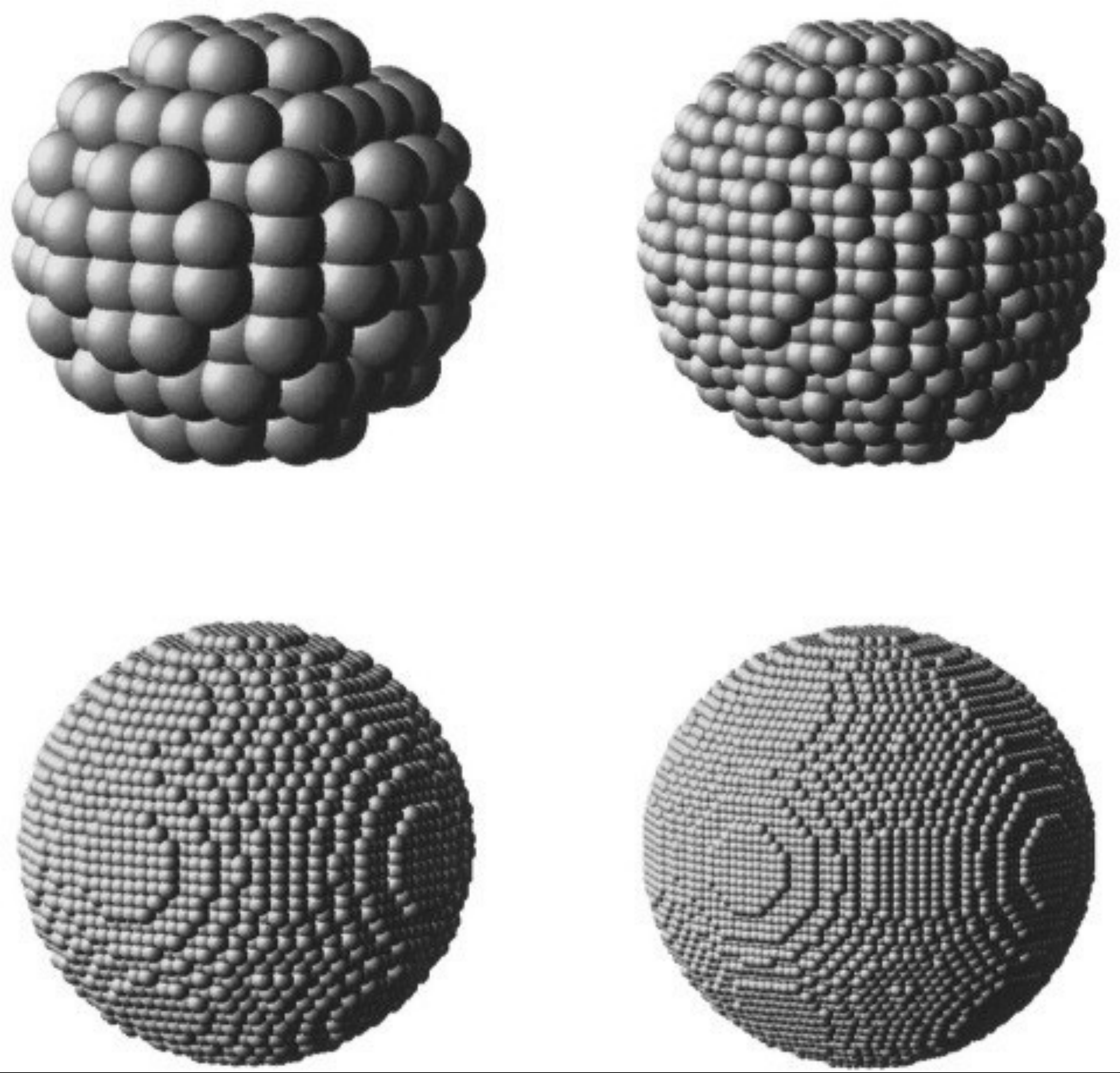
$$J(\vec{x}) = \overbrace{\frac{1}{2}(\vec{x} - \overrightarrow{x_b})^T \overrightarrow{B^{-1}} (\vec{x} - \overrightarrow{x_b})}^{J_b} + \overbrace{\frac{1}{2}(H(\vec{x}) - \vec{y})^T \overrightarrow{R^{-1}} (H(\vec{x}) - \vec{y})}^{J_o}$$

Relation between the observations (*y*) and the forward operator (*H*) can be expressed as:

$$y = H(\vec{x}, \overrightarrow{p_b}, \overrightarrow{p_s}) + E$$

x state vector, p_b parameters such as size distribution of hydrometers, p_s indicates the scattering parameters (e.g., phase function, scattering coefficient, asymmetry factor) The scattering parameters highly depend on the shape of hydrometeors and current CRTM cloud lookup tables assume spherical shapes for all hydrometeors (frozen or liquid)!

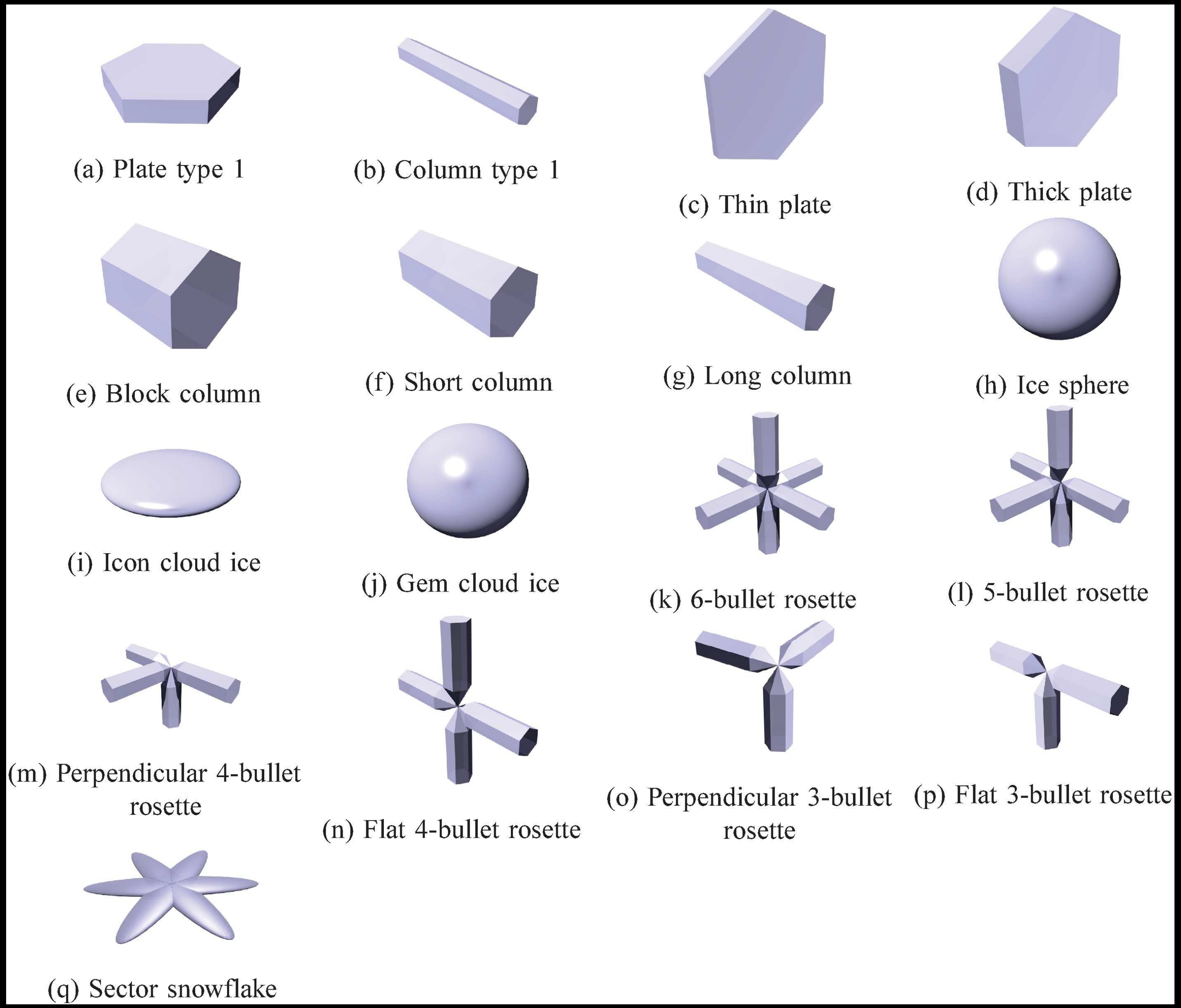
The Discrete Dipole Approximation

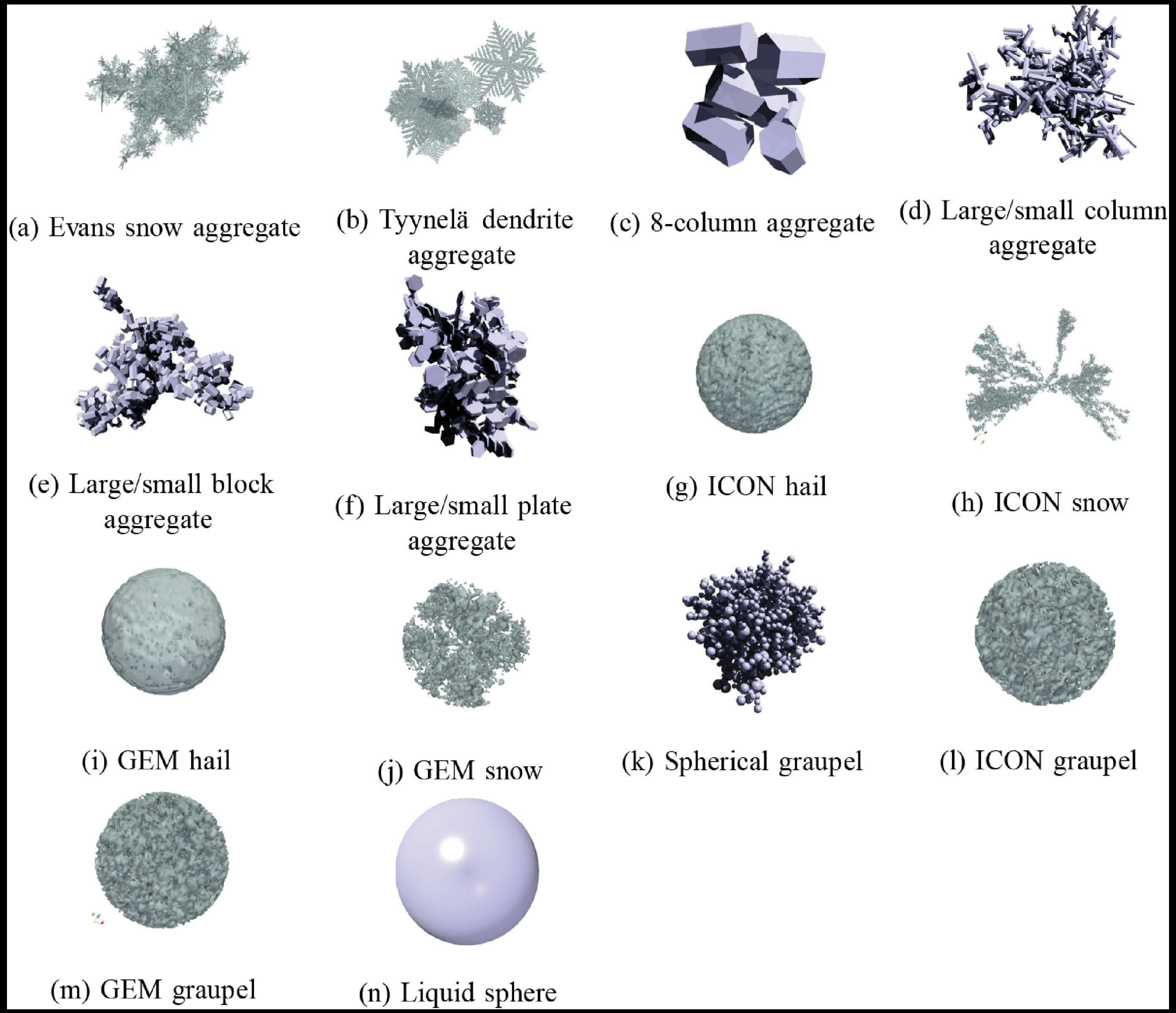


Laczik et al., Appl. Opt. 35, 3736-3745 (1996) Used with permission

In the DDA technique, scattering and absorption are approximated by a finite array of small polarized dipoles. DDA was originally introduced by DeVoe in 1964. The dataset was developed by Eriksson et al (2018) using the Amsterdam DDA (ADDA, Yurkin et al., 2020) and includes single scattering properties of a large number of frozen and liquid habits.

ARTS DDA Database

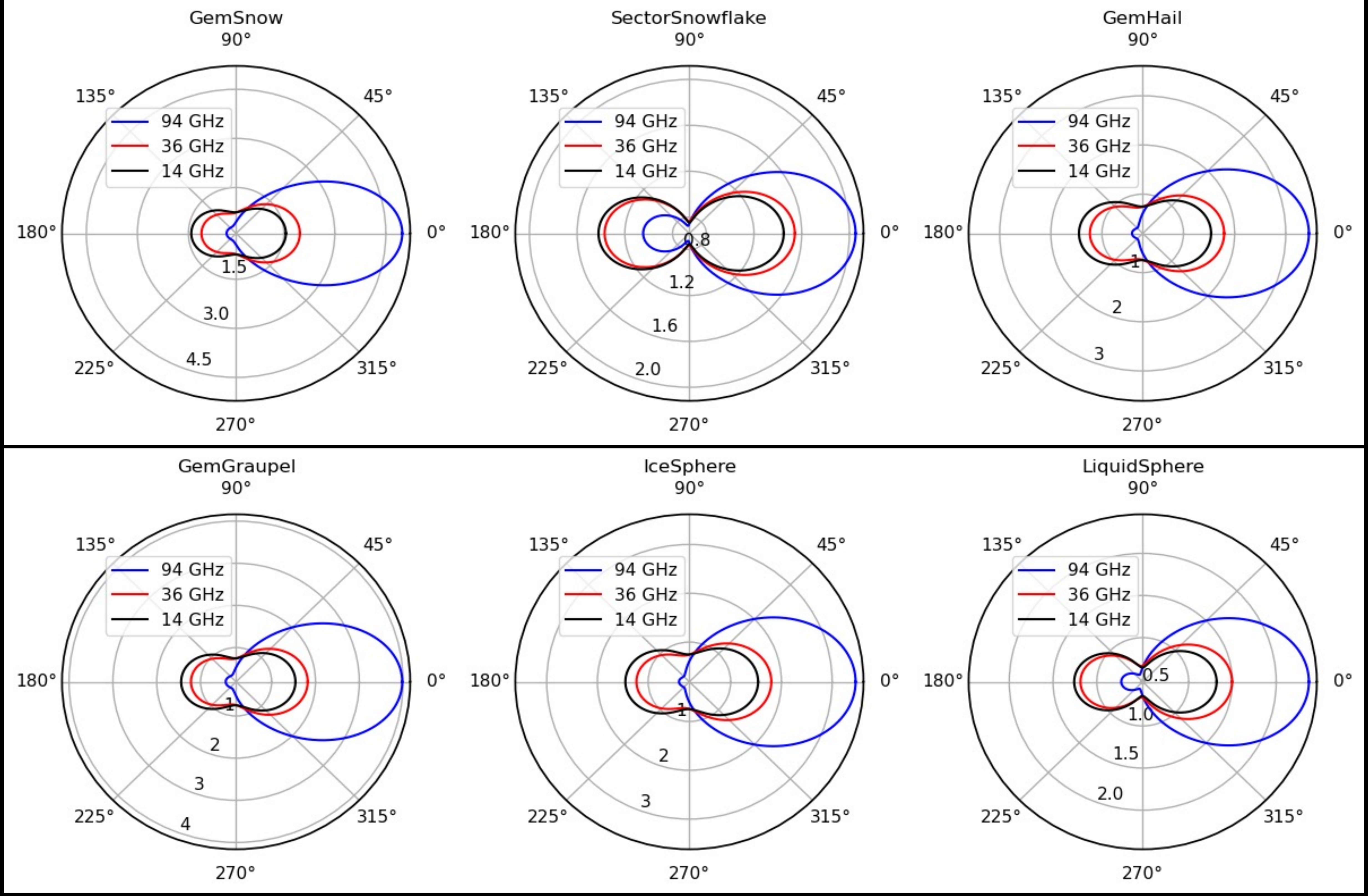




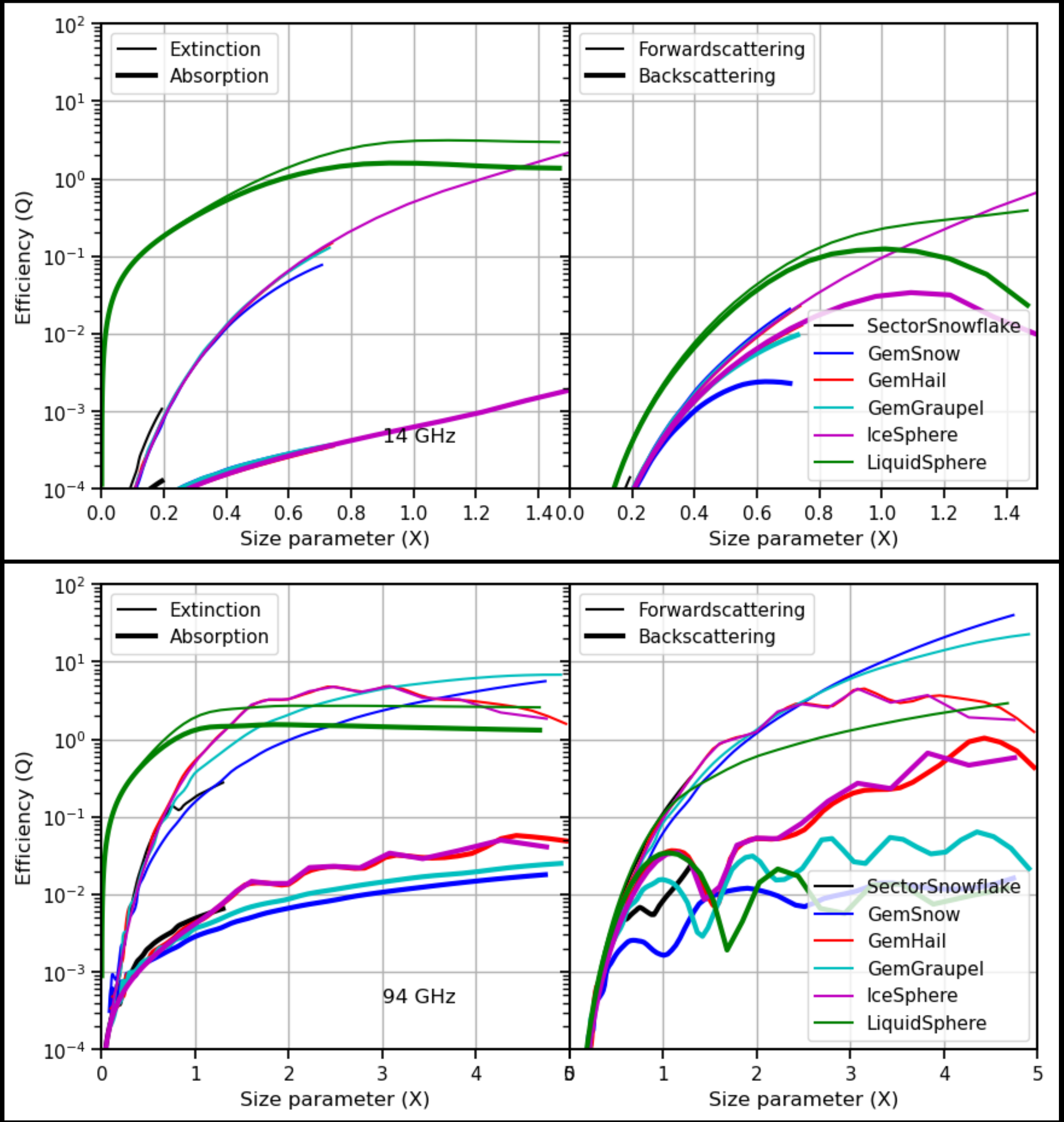
(a) Single crystal. (b) Aggregates and liquid habits

Single crystal, aggregate, and liquid habits included in the database generated by Eriksson et al. (2018).

The Phase Function



Backscattering Coefficients

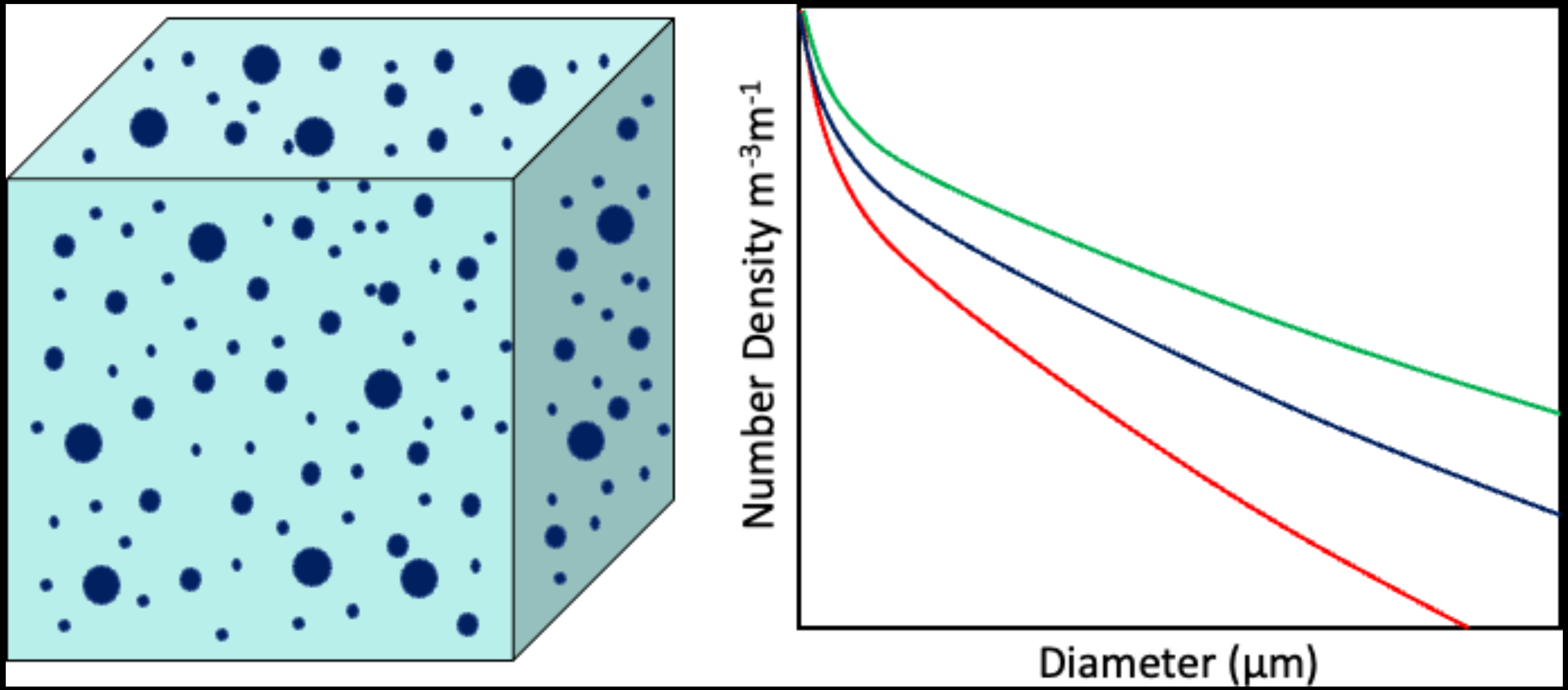


$$Q_\lambda = \frac{\sigma_\lambda}{\pi r^2}$$

$$x = \frac{\pi D}{\lambda}$$

Extinction and backscattering efficiencies from the ARTS database for several different habits (Temp: 260 K)

Particle Size Distribution



Particle size distribution is used to compute bulk scattering properties from single scattering data

Modified Gamma Size Distribution: $N(D) = N_0 D^{\mu} \exp(-\Lambda D^{\gamma}) \quad m^{-3}m^{-1}$

Mass Scattering Coefficients: $k_x = \frac{\int \sigma_x(D)n(D)dD}{\int m(D)n(D)dD} = \frac{\int \sigma_x(D)n(D)dD}{\int \rho(D)V(D)n(D)dD} \; m^2.kg^{-1}$

The Radar Equation

The radar equation can be formalized as follows:

$$R = \frac{10^{18}\lambda^4}{\pi^5|k_w|^2}\beta_b \qquad m^4\, m^2 m^{-4} m^1 \Rightarrow mm^6\, m^{-3}$$

$$R_a = \frac{10^{18}\lambda^4}{\pi^5|k_w|^2}\Gamma\beta_b \qquad m^4\, m^2 m^{-4} m^1 \Rightarrow mm^6\, m^{-3}$$

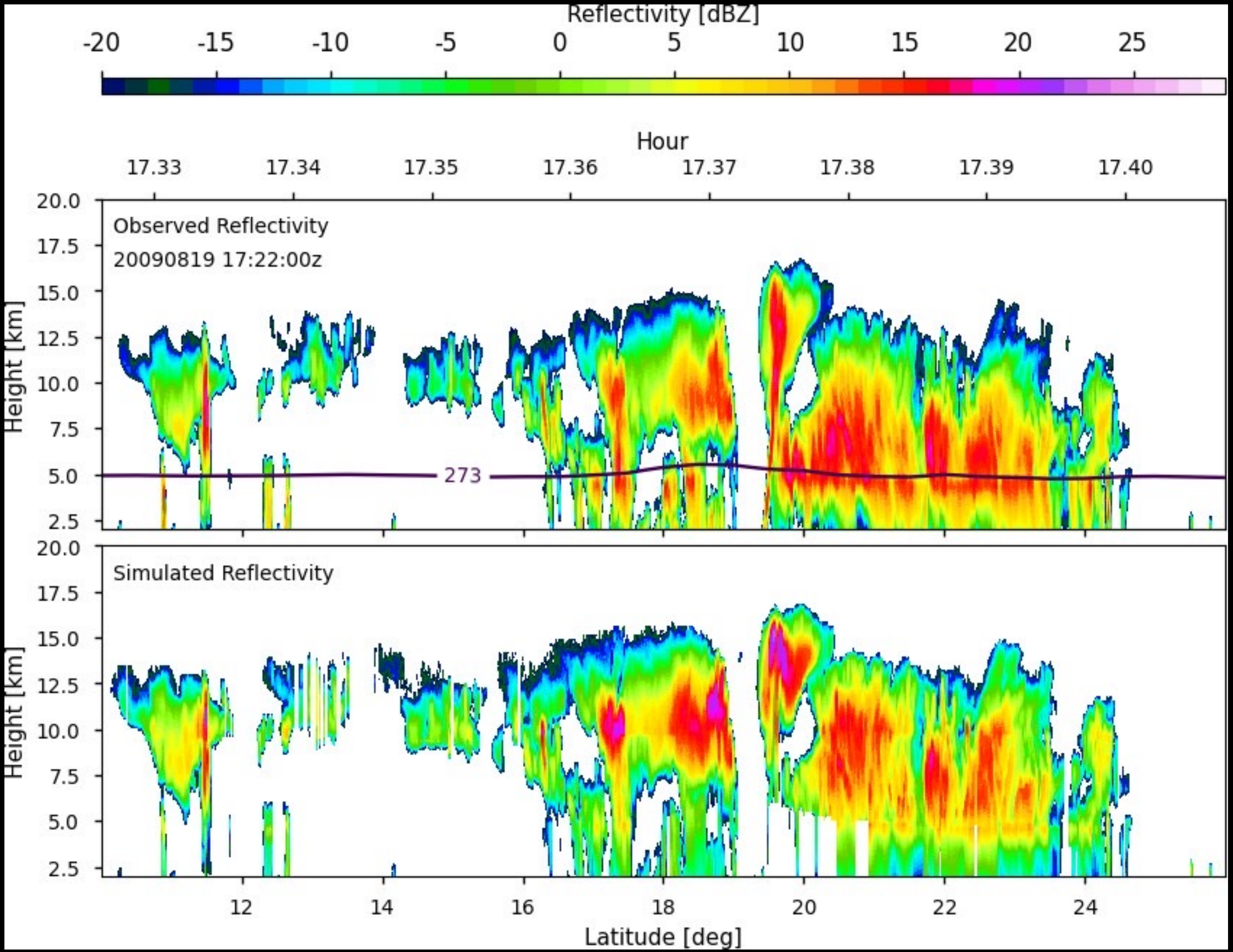
$$\beta_b = \int_0^\infty \sigma_b(D)n(D)\mathrm{d}D \qquad m^2 m^{-4} m^1 \Rightarrow m^{-1}$$

The unit for R (reflectivity) and R_a attenuated reflectivity are in $m^6\, m^{-3}$ and 10^{18} is used to convert the unit to $mm^6\, m^{-3}$. This is in turn converted to dBz or decibels by taking $R_e = 10log_{10}(R)$ or $R_{ea} = 10log_{10}(R_a)$. The dielectric factor (k_w) is calculated using the complex permittivity of the liquid water, $|k_w|^2 = 0.75$.

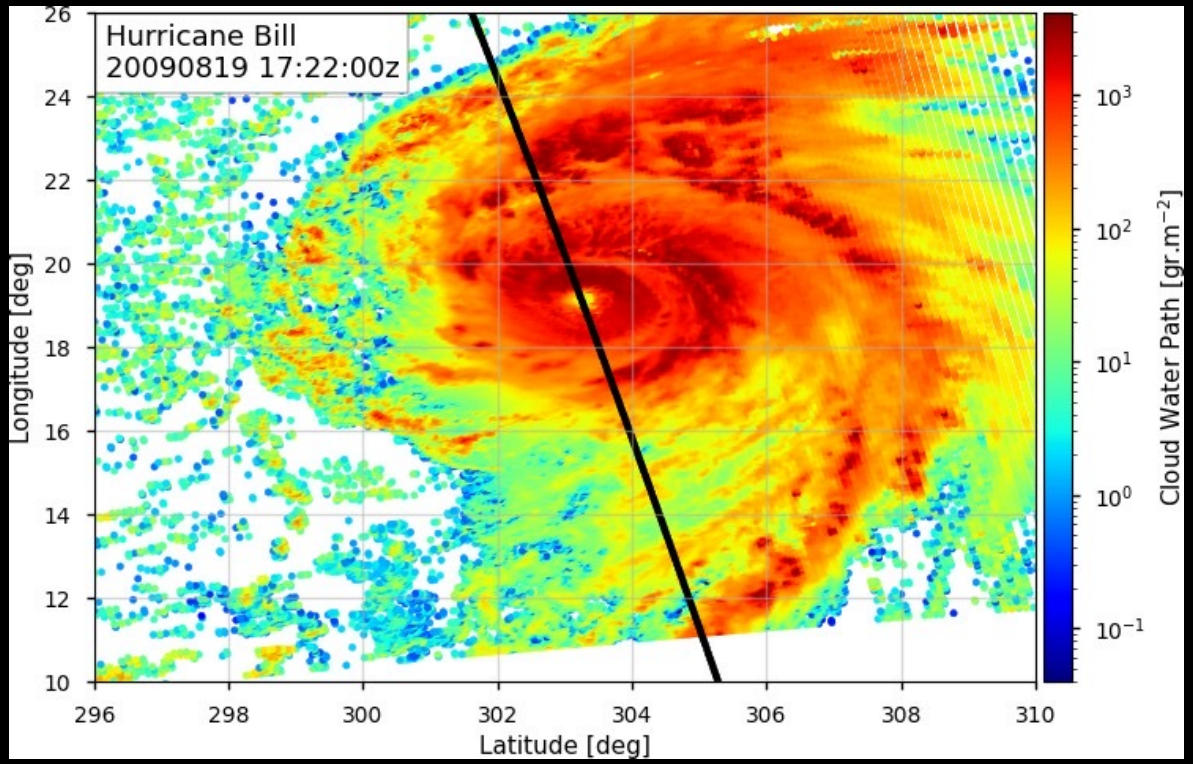
Transmittance (attenuation) depends on both scattering and absorption coefficients.

$$\Gamma(\mathrm{r}) = \exp\left(-2\int_{\mathrm{r}_1}^{\mathrm{r}_{sat}} \mathrm{k_e(r)dr}\right) = \exp\left(-2\sum_{\mathrm{i=r_1}}^{\mathrm{r}_{sat}} \tau(\mathrm{i})\right)$$

Simulated vs. Observed Reflectivity

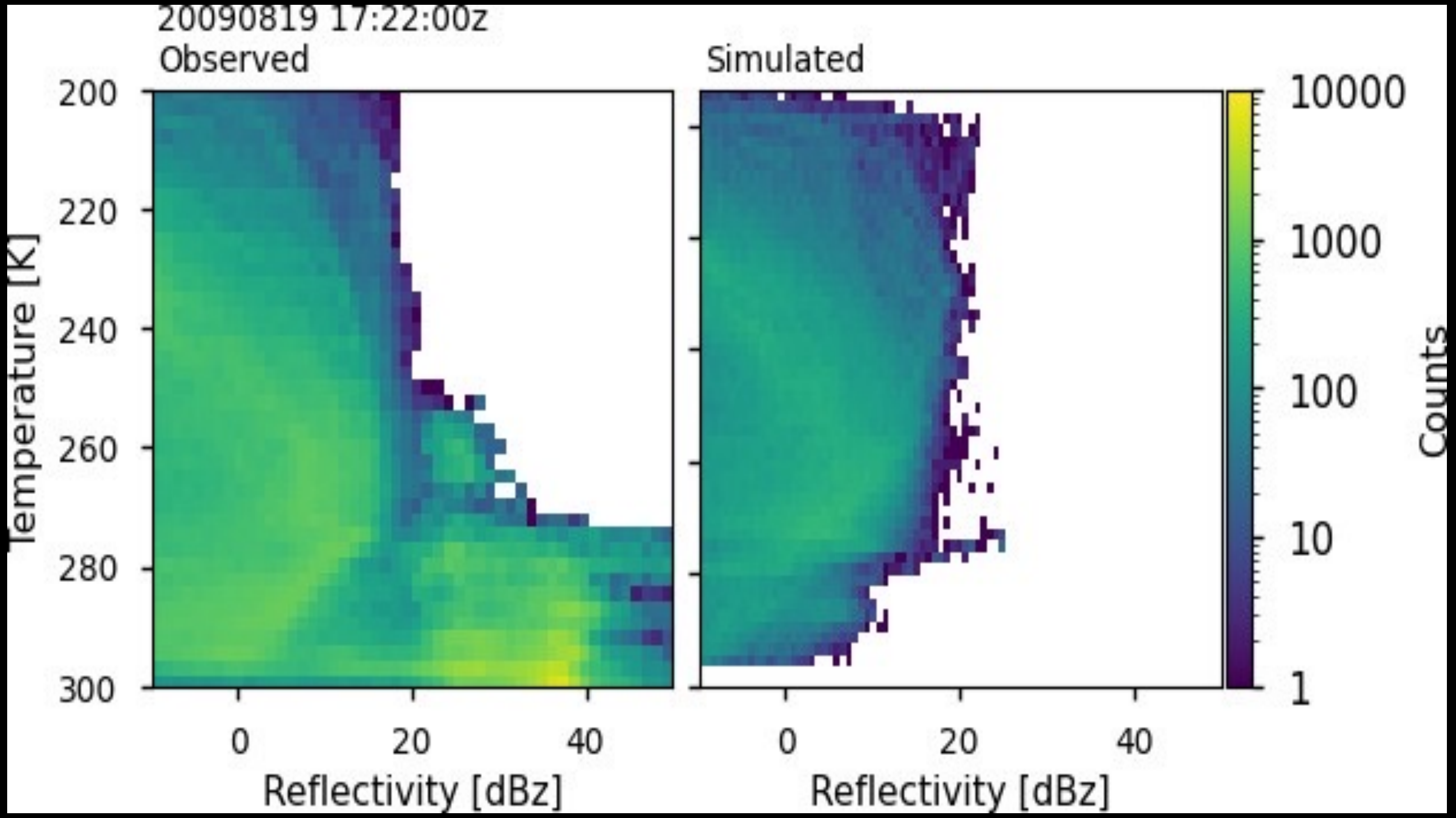


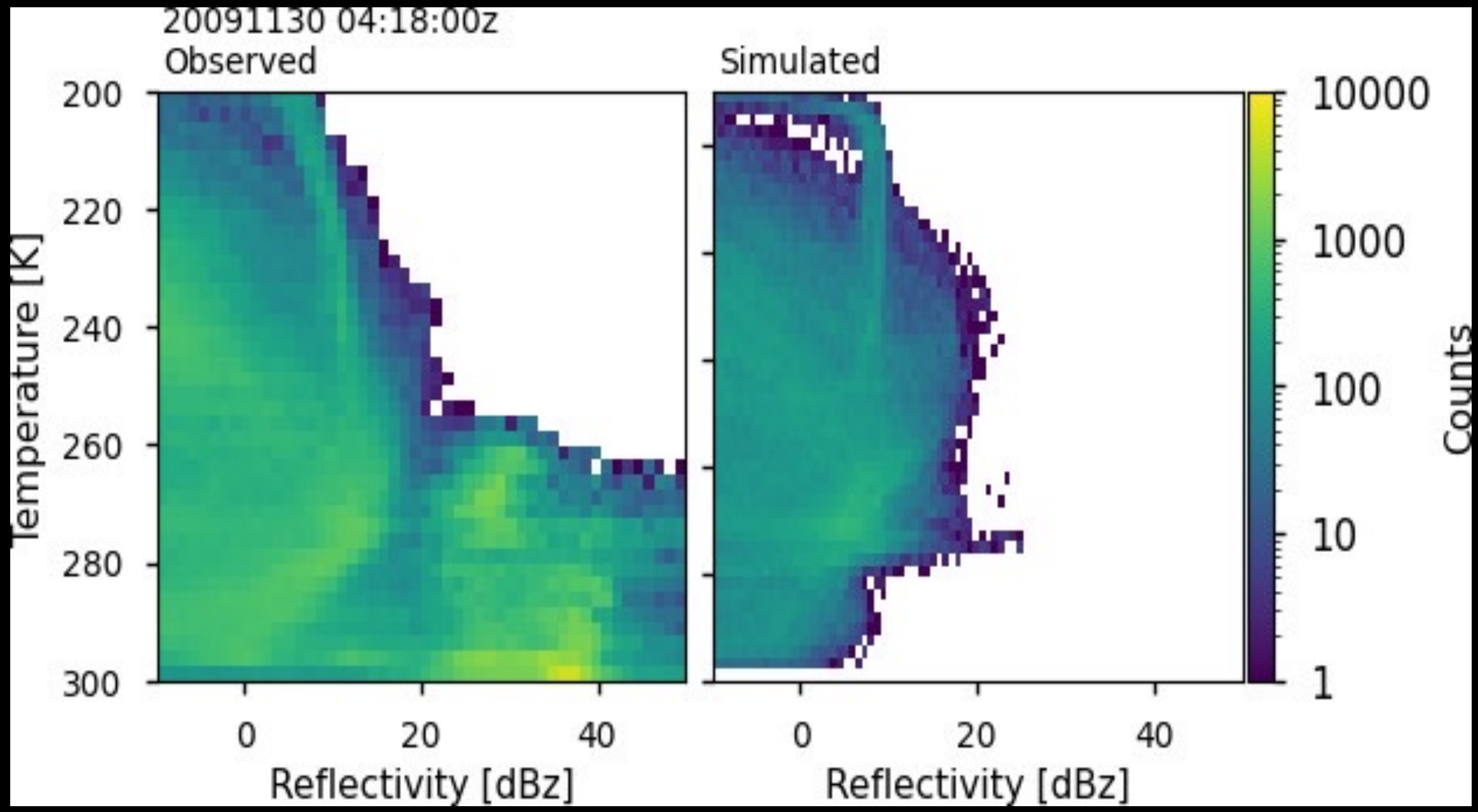
Observed and simulated reflectivities for Hurricane Bill.



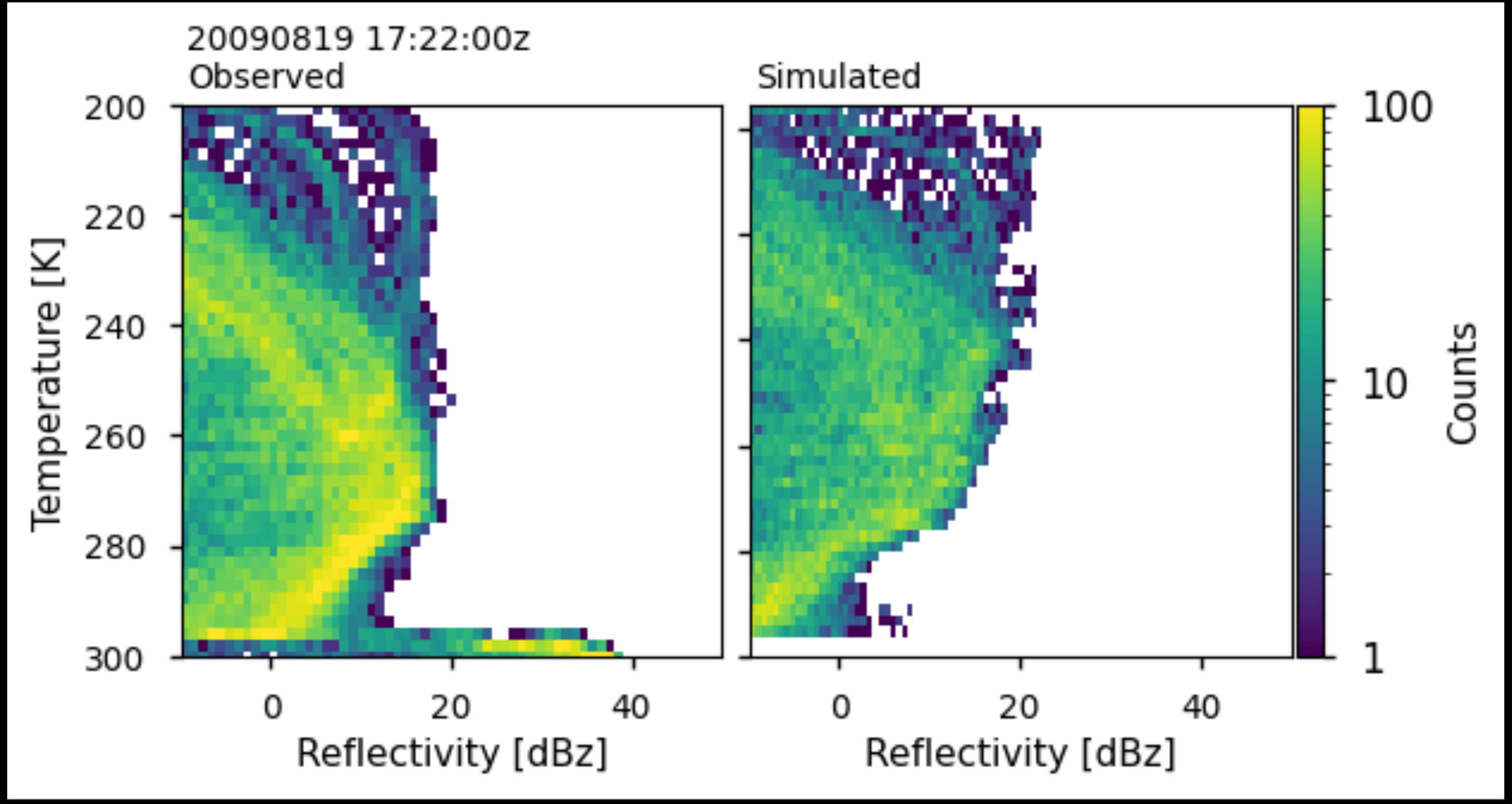
Simulated vs. Observed Reflectivity

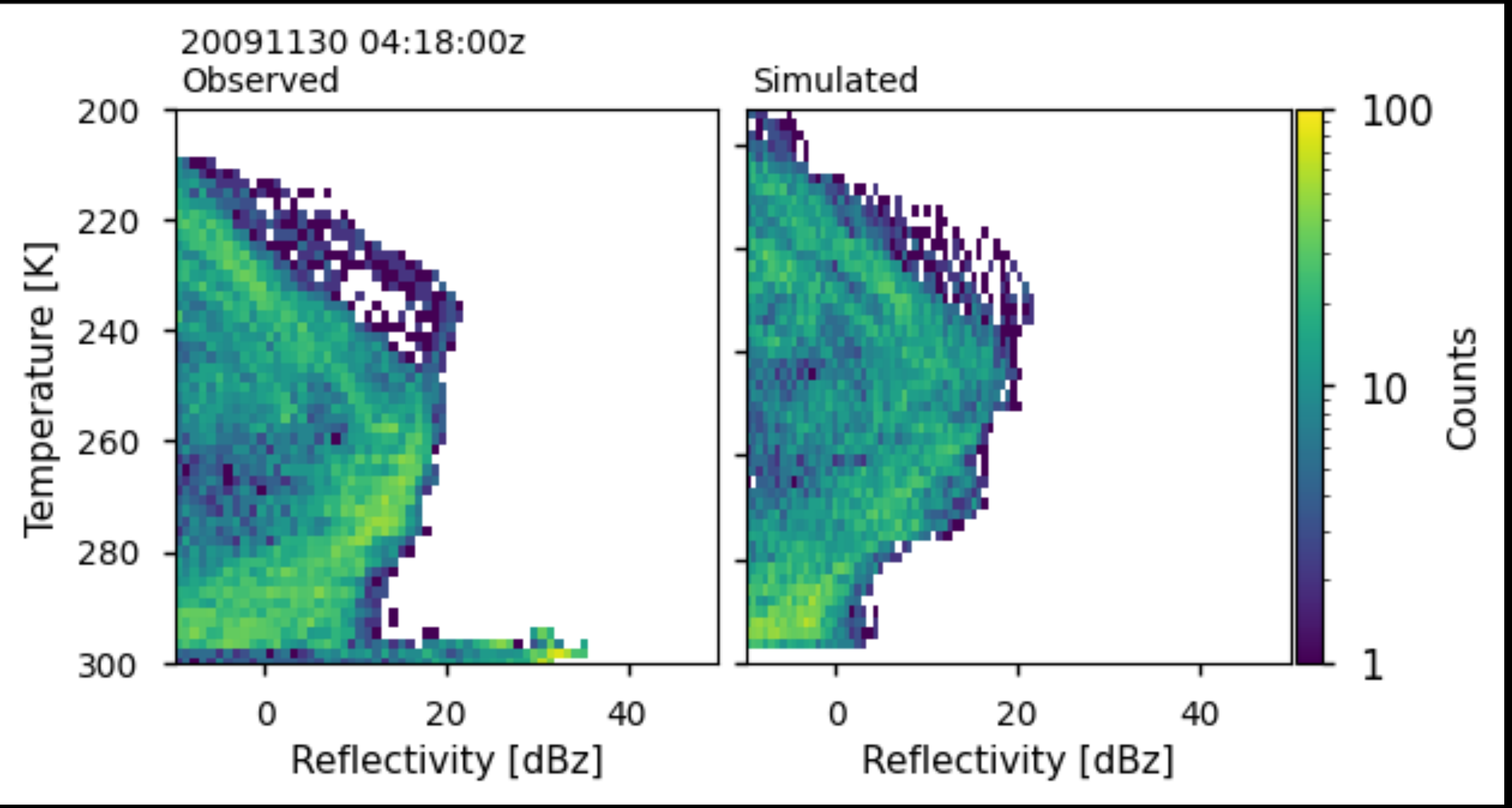
Global



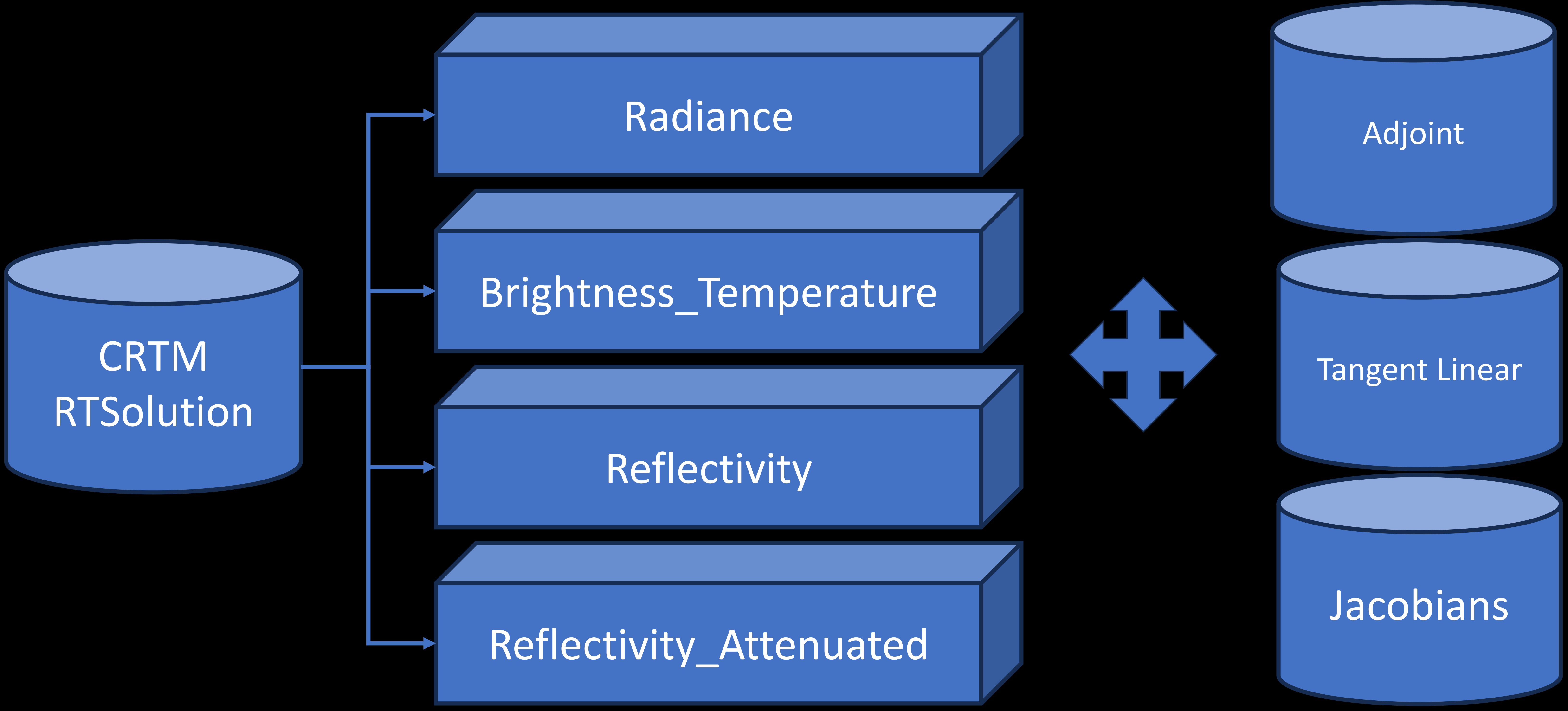


Tropical Cyclone

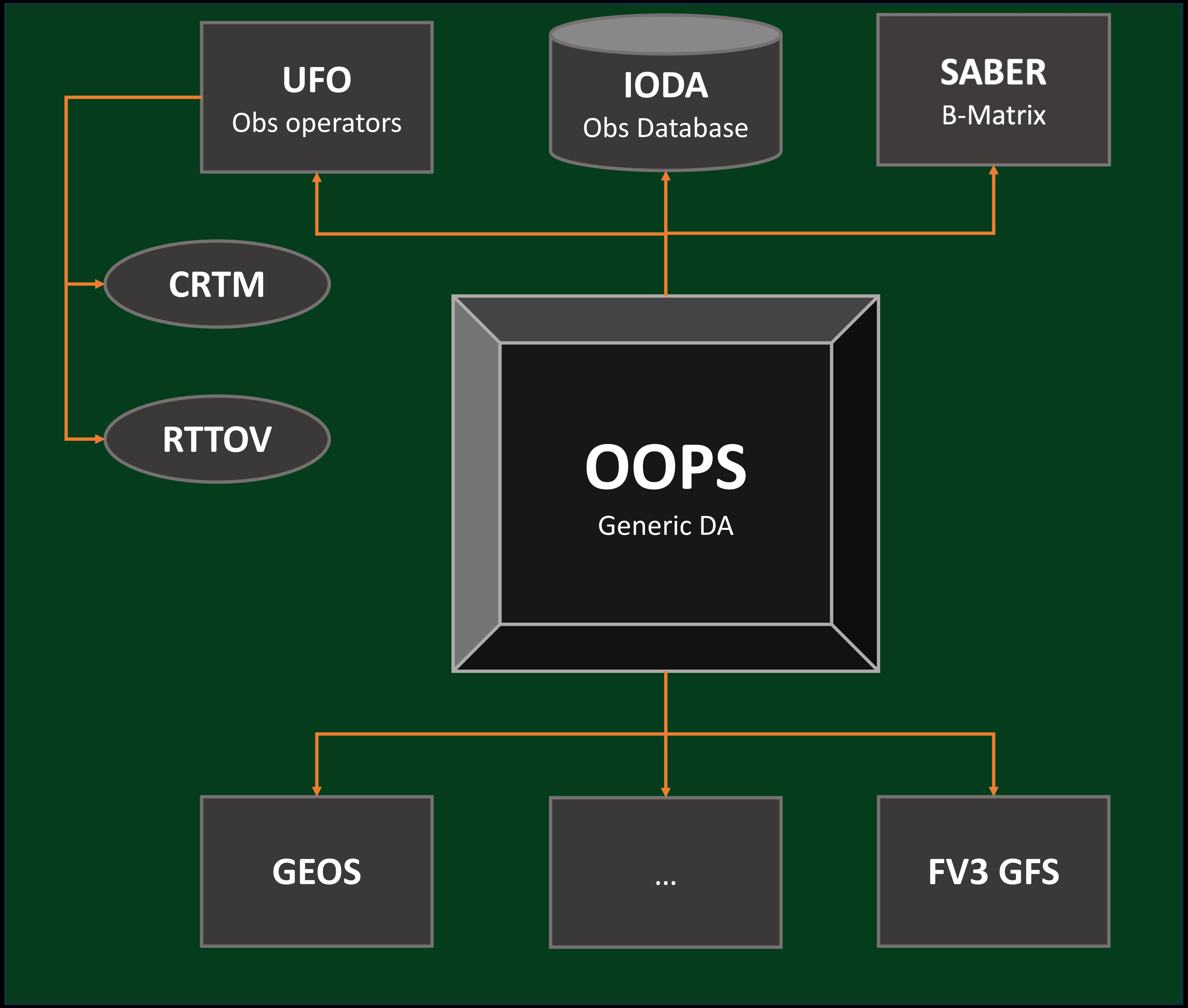




CRTM Simulated Reflectivity



Joint Effort for Data assimilation Integration (JEDI)



Adjoint & Tangent Linear

$$\begin{bmatrix} \partial\kappa_b \\ \partial\Gamma \\ \partial R \\ \partial R_a \\ \partial R_e \\ \partial R_{ae} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ P_1 & 0 & 0 & 0 & 0 & 0 \\ P_1\Gamma & P_1\kappa_b & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{10}{R\ln 10} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{10}{R_a\ln 10} & 0 & 0 \end{bmatrix} \begin{bmatrix} \partial\kappa_b \\ \partial\Gamma \\ \partial R \\ \partial R_a \\ \partial R_e \\ \partial R_{ae} \end{bmatrix}$$

$$\begin{bmatrix} \partial\kappa_b^* \\ \partial\Gamma^* \\ \partial R^* \\ \partial R_a^* \\ \partial R_e^* \\ \partial R_{ae}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & P_1 & P_1\Gamma & 0 & 0 \\ 0 & 1 & 0 & P_1\kappa_b & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{10}{R\ln 10} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{10}{R_a\ln 10} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \partial\kappa_b^* \\ \partial\Gamma^* \\ \partial R^* \\ \partial R_a^* \\ \partial R_e^* \\ \partial R_{ae}^* \end{bmatrix}$$

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Conclusions

- CRTM radar simulator as well as its adjoint and tangent linear are implemented and tested
- A new scattering dataset generated using the DDA method was implemented into CRTM and evaluated using a collocated reanalysis and satellite dataset
- The radar module takes advantage of different CRTM atmospheric absorption and cloud scattering modules
- The radar module can be used for the assimilation of observations from instruments such as CloudSat CPR, GPM DPR, and EarthCare CPR.
- The active module is implemented within JEDI/UFO and ready to go!
- Work is in progress to evaluate the active module within the JEDI DA system

- Moradi et al. (2022): Implementation of a discrete dipole approximation scattering database into community radiative transfer model. JGR-Atmospheres, 127, DOI: 10.1029/2022JD036957
- Moradi et al. (2023): Developing a Radar Signal Simulator for the Community Radiative Transfer Model. IEEE TGRS, Accepted.
- Moradi et al. (2020): Assimilation of Satellite Microwave Observations over the Rainbands of Tropical Cyclones. Mon. Wea. Rev., 148, 4729–4745, DOI: 10.1175/MWR-D-19-0341.1.

Thank you for your attention!