Passive microwave radiative transfer modeling considering spatiotemporal variability of ice particle shapes

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IPWG International Precipitation Working Group

YONSEI UNIVERSITY 1885 연세대학교

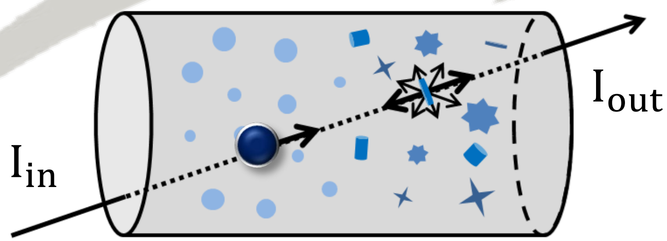
Background & Motivation

Microwave Radiative Transfer Model (RTM)

INPUT:

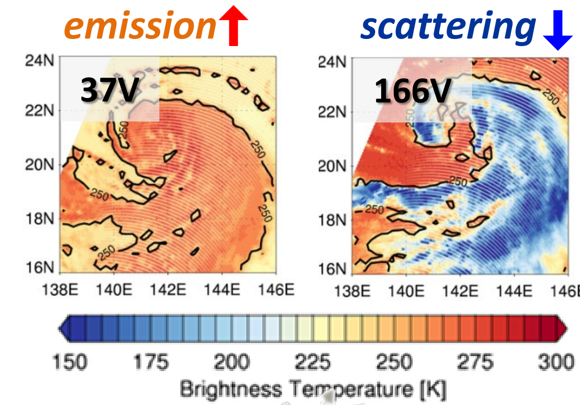
Environmental &
hydrometeor variables

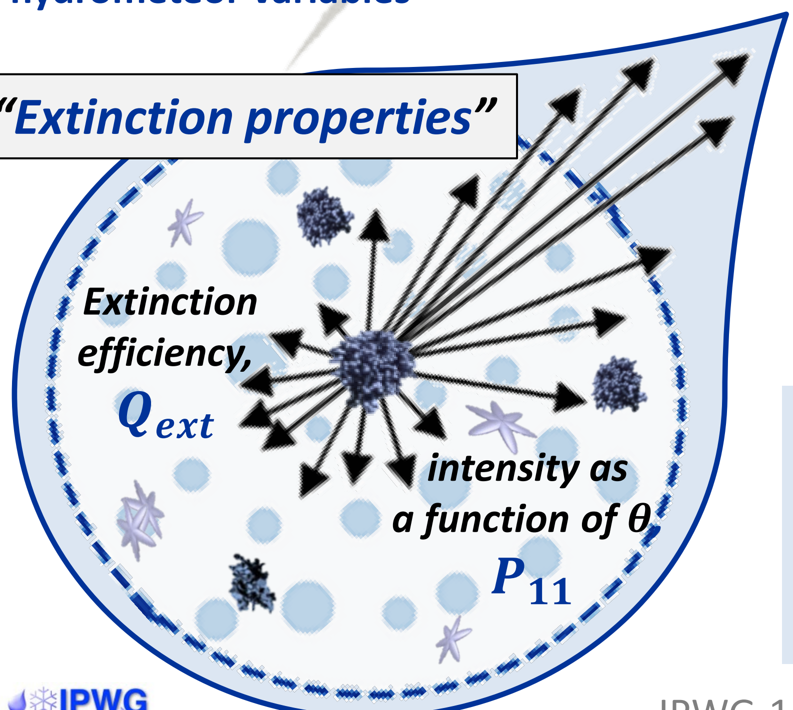
RTM:

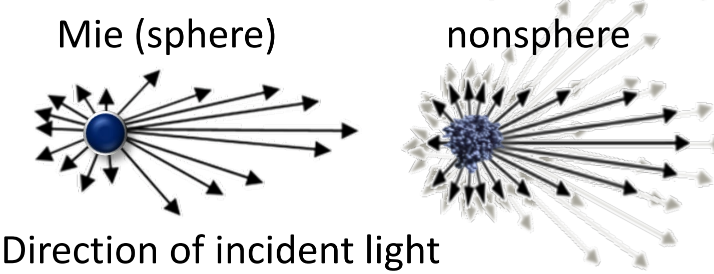


OUTPUT:

RTM-simulated **TB**



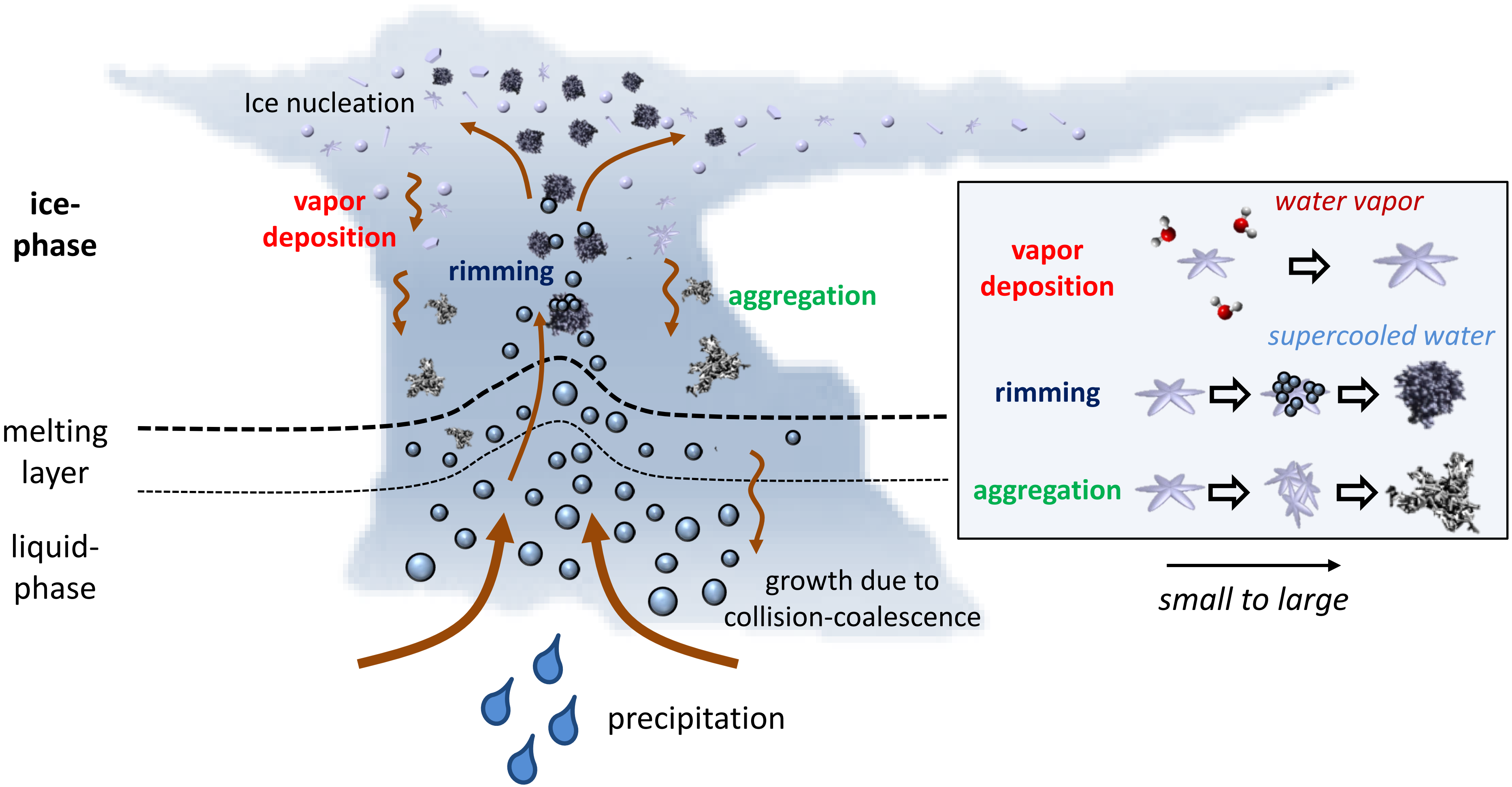




"**Brightness temperatures (TBs)** generated by **passive microwave RTMs** are significantly influenced by **the shape of ice particles** and their distribution."

Background & Motivation

Ice Particle Growth Processes Within Mixed-Phase Clouds

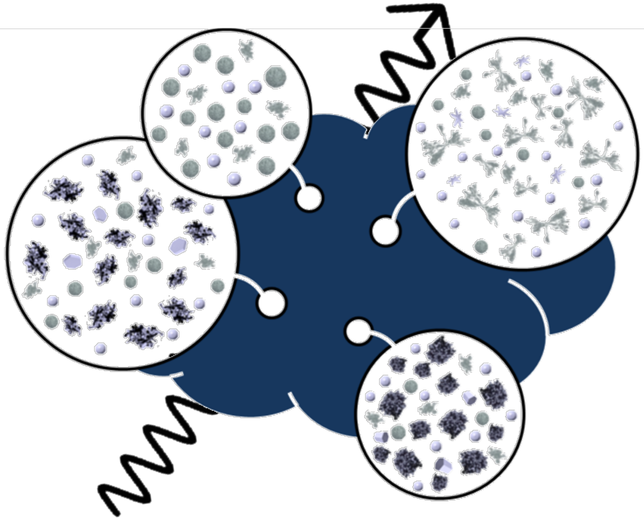


Background & Motivation

"Realistic microphysical representation in passive microwave forward modeling"

- Because of **ice particles' morphological and distributional complexity**, it remains **a big challenge** to accurately simulate ice scattering in the radiative transfer models (RTMs).

- We propose a physics-based approach using **a mixture of nonspherical ice habits that ensure microphysics-consistent scattering properties.**



Model Descriptions

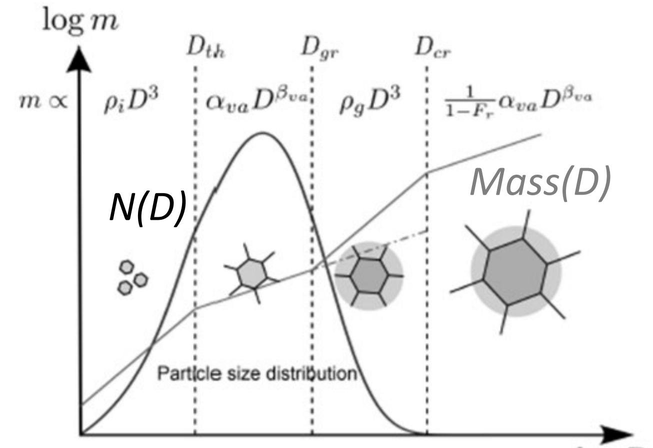
Specifications of the RTM

Absorption model: Liebe93 *(Liebe et al., 1993)*
Emissivity model: FASTEM-6 *(Kazumori and English, 2015)*
Scattering model: Mie solution for spherical particles
① DDA for nonspherical particles
② SSRGA for nonspherical particles

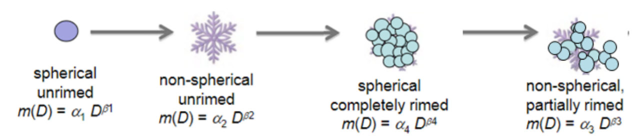
Solver: Delta-Eddington approx.,
Plane Parallel *(Kummerow, 1993)*
Others: cloud subgrid *(Geer et al. 2009)*
refractive index *(Matzler 2006)*
polarization correction *(Barlakas et al. 2021)*
mass conservation approx. *(Geer et al. 2021)*

Input model: P3 microphysics schemes
✓ The key is to maintain consistency with the microphysical assumptions of the input model.

P3 microphysics
(Morrison and Milbrandt, 2015)



(Dietlicher et al., 2018)



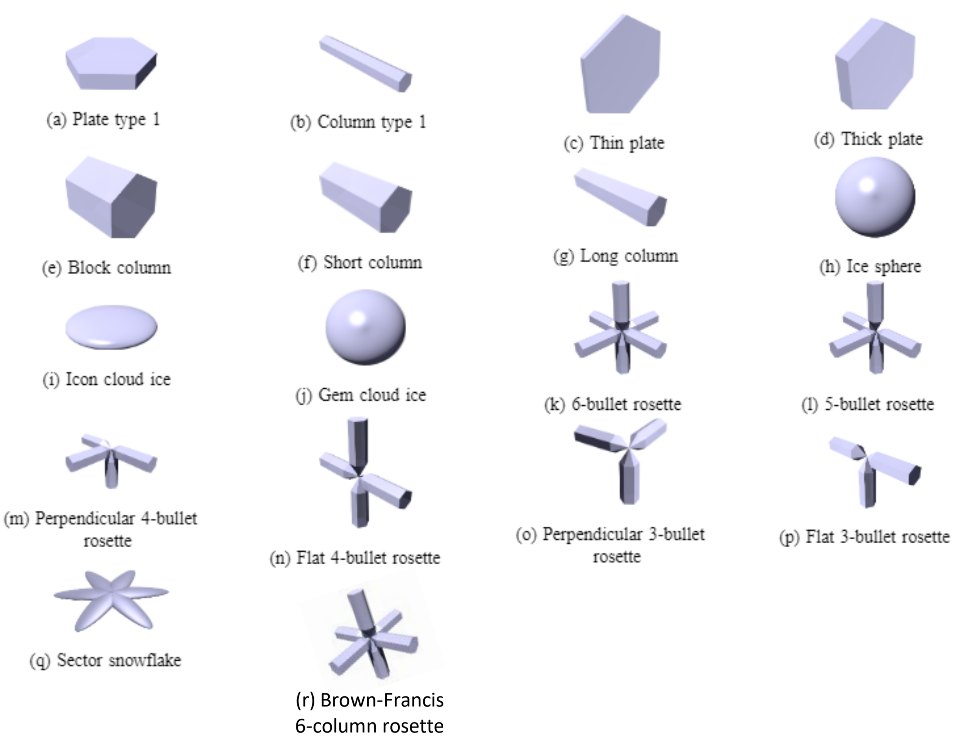
(Morrison, 2014)

Free ice-category
(thus freely evolving type)

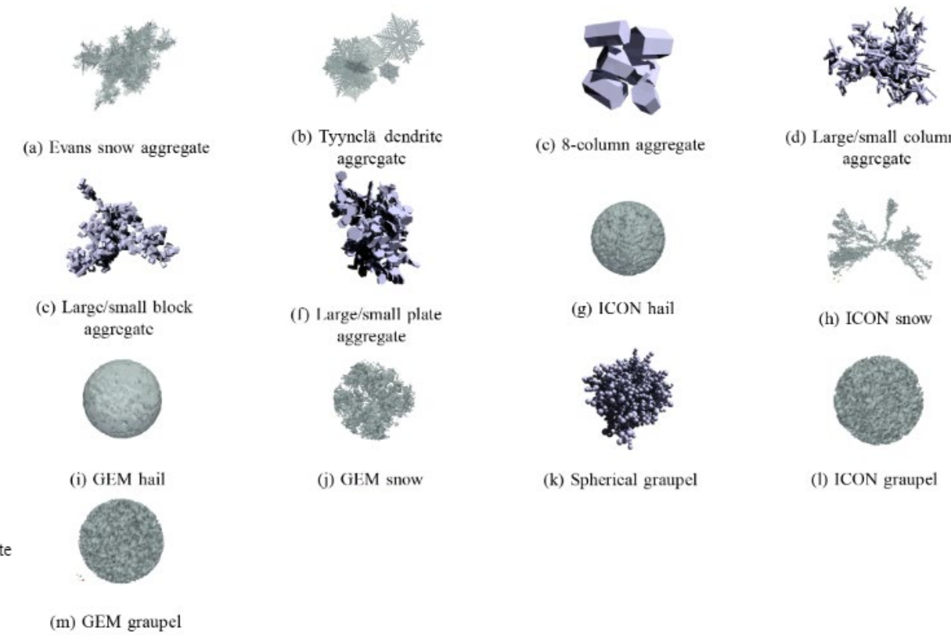
DDA: Optimal Ice Habits

ARTS Database (Eriksson et al., 2018)

Single crystals



Aggregates and rimed ice particles



34 types of ice particle

"Which shapes are the best representations of ice hydrometeors in reality?"

DDA: Optimal Ice Habits

Finding optimal habits in a given ρ-D relationship

(Kim et al., 2024)

effective density $$\rho_{eff}(D) = \frac{6\alpha}{\pi} D^{\beta-3}$$

(mass-size relation, $m(D) = \alpha D^{\beta}$)

"ρ_{eff} can also provide an insight into particle morphology"

Solid sphere (no voids)

$\rho_{eff} = \rho_i$ (constant)

Soft sphere (internal voids)

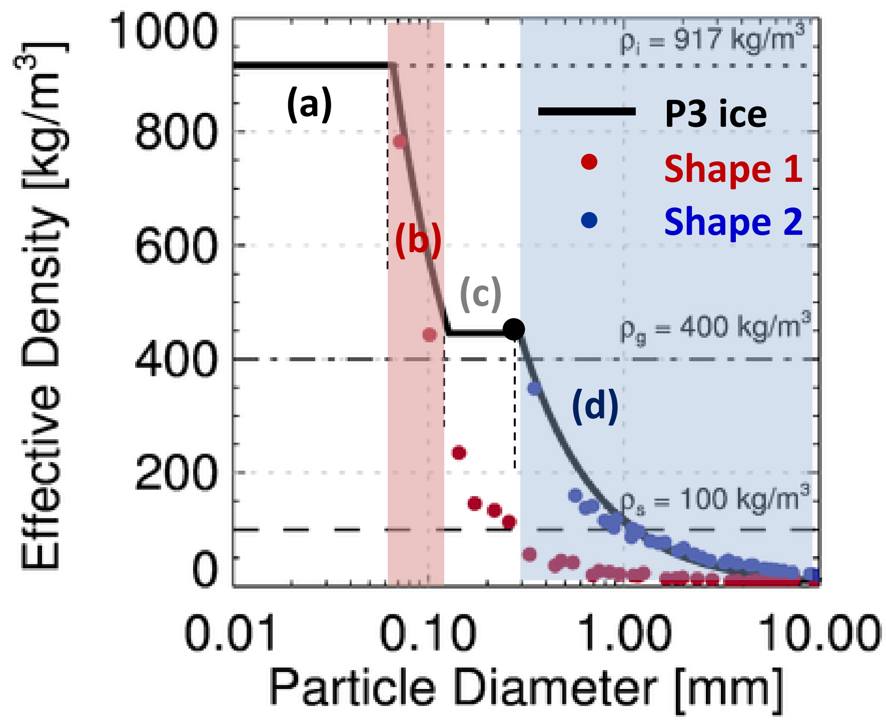
$\rho_{eff} < \rho_i$ (constant)

Nonsphere

$\rho_{eff} < \rho_i$

(ρ_{eff} varies inversely with diameter)

"Habit selection is based on minimizing RMSE"

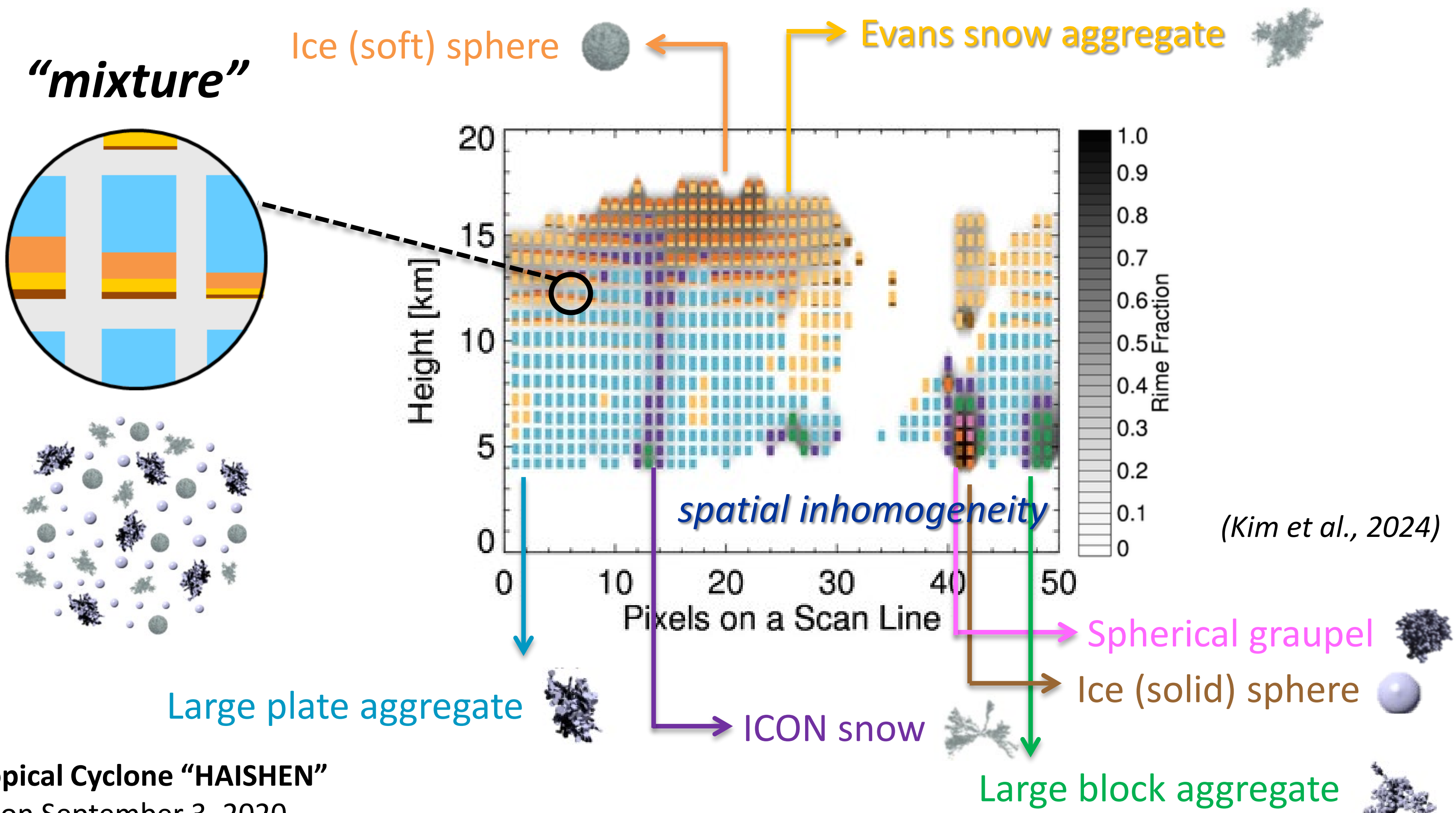


(a) Solid sphere **(b)** Evans snow agg.

(c) Soft sphere **(d)** Large block agg.

DDA: Optimal Ice Habits

Habit Selection Example

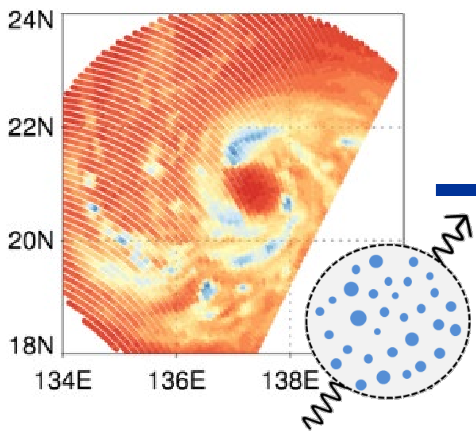


Tropical Cyclone "HAISHEN"
on September 3, 2020

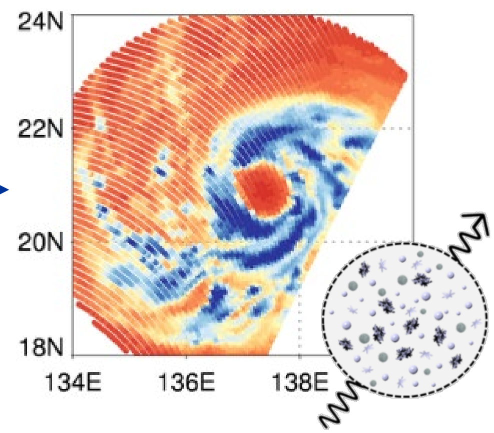
DDA: Optimal Ice Habits

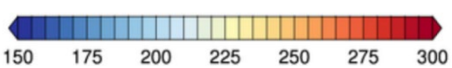
TB Simulations (MIE v.s. DDA)

a. P3 sim. (MIE: soft sphere)



b. P3 sim. (DDA: optimal habit)





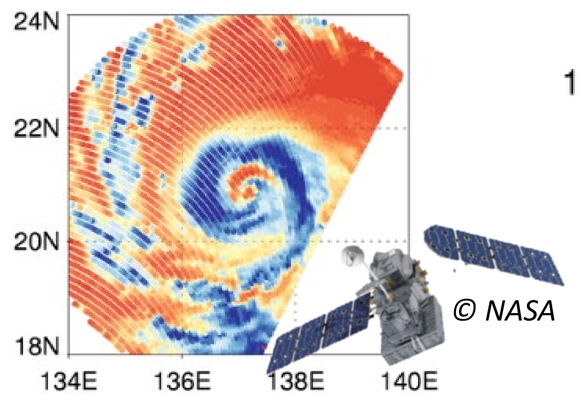
166 GHz V-pol TB

tropical cyclone

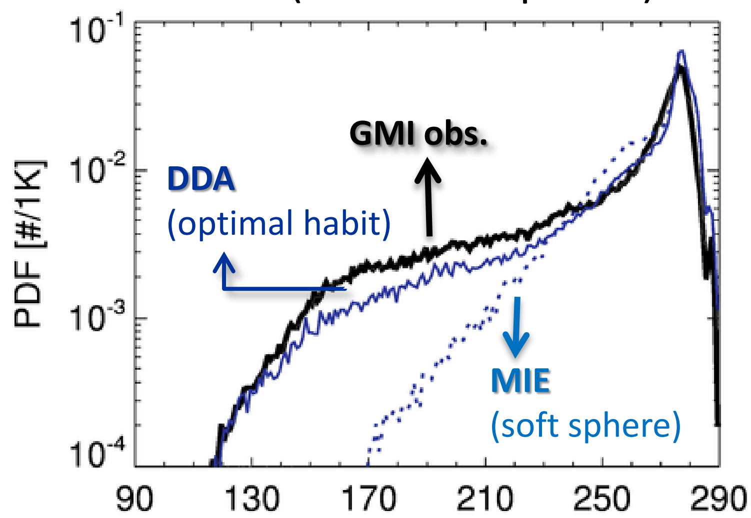
"HAISHEN"

on September 3, 2020

c. GMI obs.



d. PDF (166 GHz V-pol TB)



19 scenes of

11 tropical cyclones

SSRGA: M-Parameterization

The Self-Similar Rayleigh-Gans Approximation (SSRGA)

(Hogan and Westbrook, 2014; Hogan et al., 2017; Ori et al., 2021)

wavenumber f(refractive index)

$$\sigma_s(\theta) = \frac{9k^4|K|^2}{4\pi} V^2 \phi\{x\sin(\theta/2)\} \frac{1+\cos^2\theta}{2}$$

volume shape and inner structure

SSRGA applicability:

$|m-1| \ll 1$

$2kD|m-1| \ll 1$

The SSRGA form factor ϕ

$$\phi_{SSRGA}(x_\theta) = \frac{\pi^2}{4}\left[\cos^2(x_\theta)\left\{\left(1+\frac{\boldsymbol{\kappa}}{3}\right)\left(\frac{1}{2x_\theta+\pi}-\frac{1}{2x_\theta-\pi}\right)-\boldsymbol{\kappa}\left(\frac{1}{2x_\theta+3\pi}-\frac{1}{2x_\theta-3\pi}\right)\right\}^2 + \boldsymbol{\beta}\sin^2(x_\theta)\sum_{j=1}^{n}\boldsymbol{\zeta_j}(2j)^{-\gamma}\times\left\{\frac{1}{(2x_\theta+2\pi j)^2}+\frac{1}{(2x_\theta-2\pi j)^2}\right\}\right]$$

"The mean shape of particles"

(1) The effective aspect ratio, $\boldsymbol{\alpha_{eff}} = \overline{D/D_{max}}$

(2) The kurtosis parameter, $\boldsymbol{\kappa}$

"The internal structure of the particles"

(3) The slope of the power law, $\boldsymbol{\gamma}$

(4) The parameter of power law, $\boldsymbol{\beta}$

(5) The ratio of the actual and fitted power spectrum at j=1, $\boldsymbol{\zeta_1}$

"The five dimensionless parameters describe the internal mass distribution of the particles"

SSRGA: M-Parameterization

A Riming-Dependent Parameterization of Scattering using the SSRGA

Normalized rime mass, *M*:

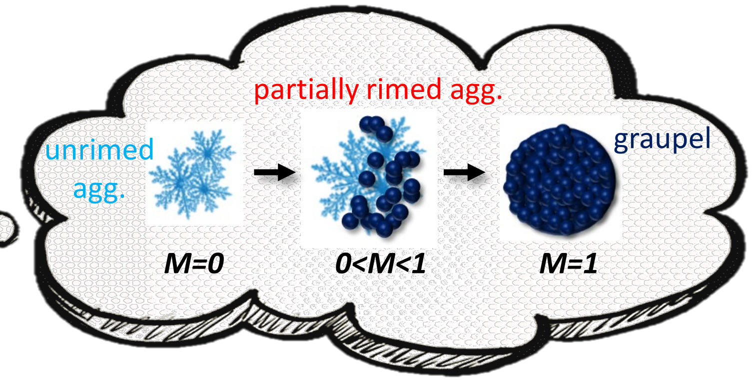
$$M = \frac{m_{rime}}{m_g}$$

rime mass (m_{rime})

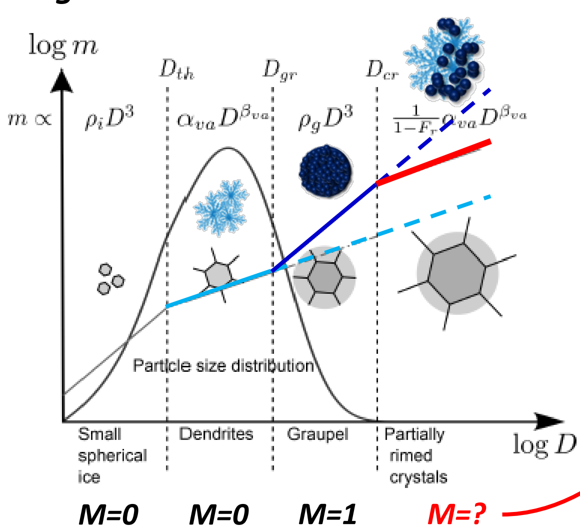
mass of size-equivalent spherical graupel particle (m_g)

(Seifert et al., 2019)

Riming process with growing particle size



Riming-induced ice mass distribution in P3



$$M = \frac{m_{rime}}{m_g} \approx \frac{\frac{1}{1-F_r}\alpha_{va} D^{\beta_{va}}}{(\pi/6)\rho_g D^3}$$

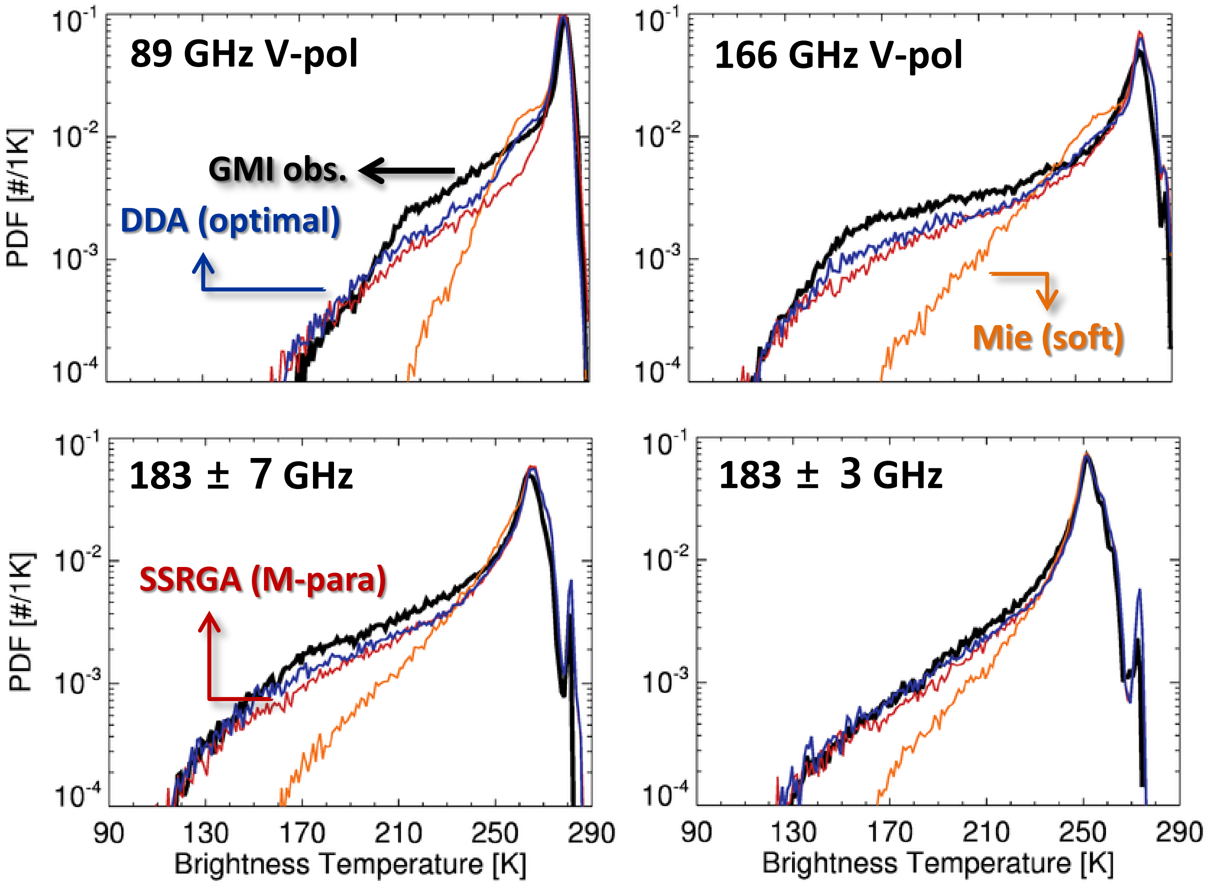
The SSRGA parameters depending only on *M*:

$$\alpha_e = 0.160\boldsymbol{M}^{1.028} + 0.187\boldsymbol{M}^{0.514} + 0.575$$
$$\kappa = -0.100\boldsymbol{M}^{1.028} + 0.068\boldsymbol{M}^{0.514} + 0.194$$
$$\gamma = -1.27\boldsymbol{M}^{1.028} + 1.79\boldsymbol{M}^{0.514} + 2.76$$
$$\beta = 4.06\boldsymbol{M}^{1.028} - 7.47\boldsymbol{M}^{0.514} + 5.42$$
$$\zeta_1 = 0.127\boldsymbol{M}^{1.028} - 0.091\boldsymbol{M}^{0.514} + 0.067$$

(Maherndl et al., 2024)

TB Simulations v.s. Observation

PDF: RTM-simulated (DDA, SSRGA, Mie) and GMI-observed TBs

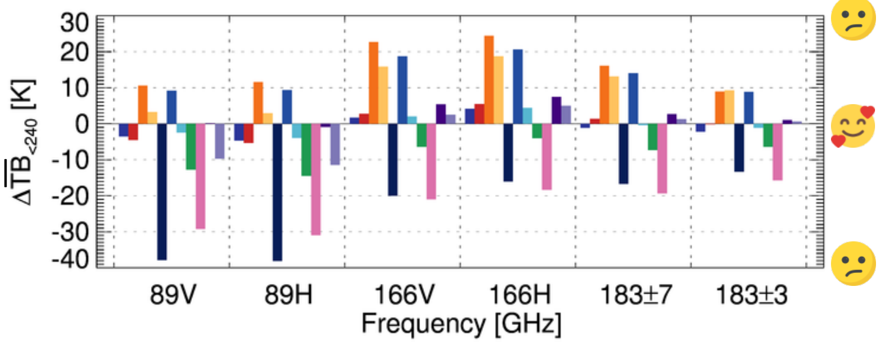


19 scenes of
11 tropical cyclones

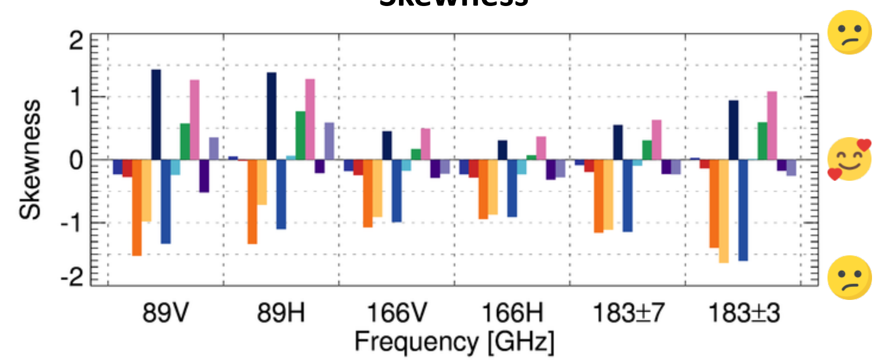
TB Simulations v.s. Observation

Measures of fit between the RTM-simulated and GMI-observed TBs

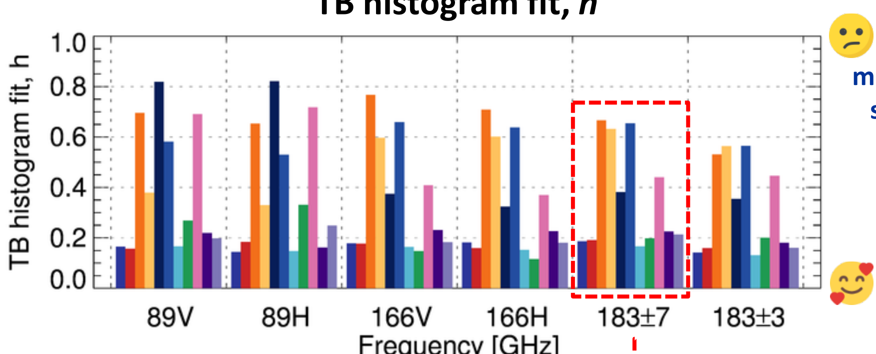
Mean TB differences below 240 K, $\Delta\overline{TB}_{<240}$

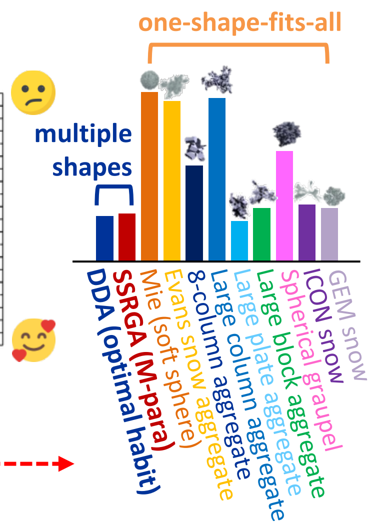


Skewness



TB histogram fit, *h*





	Accuracy	Simplicity	Physical realism
DDA (optimal)	**Higher**	Complex	High
SSRGA (M-para)	High	**Simpler**	Moderate
MIE (soft)	Low	Simple	Low
DDA (single)	Variable	Moderate	Low

Summary

- This study significantly improved the results of MW radiative transfer simulations by fully representing the spatiotemporal variability of ice particle shapes.

  1. **DDA** - It Invented an approach to optimize the selection of frozen hydrometeors' habits while ensuring microphysical consistency. Based on the optimal habit selection method, this study made flexible ice representations available in scattering models for the first time.

  2. **SSRGA** – Additionally, it evaluated the performance of parameterizing scattering properties based on the SSRGA method. Despite its simplicity, this approach showed very good performance.

- Considering the spatial inhomogeneity of ice particle shapes in passive microwave RTMs is an effective strategy for achieving higher accuracy, making the models more realistic.

- In conclusion, this study takes a significant step forward in enhancing the realism and accuracy of passive microwave RTMs.

Thank You For Your Attention!

Jiseob Kim

Publications

<u>Kim Jiseob</u>, D.-B. Shin, and D. Kim, 2024: Effects of inhomogeneous ice particle habit distribution on passive microwave radiative transfer simulations, *IEEE Trans. Geosci. Remote Sens.*, 62, 1-20.

<u>Kim Jiseob</u>, D.-B. Shin, and D. Kim, 2022: Considering various multimoment bulk microphysics schemes for simulation of passive microwave radiative signatures, *IEEE Trans. Geosci. Remote Sens., 60, 1-15.*

Backup Slides

Bulk-Scattering Properties (K_{ext}, K_{sca}, and g)

- **Extinction coefficient**

$$K_{ext} = \frac{\pi}{4}\int_0^{\infty} D^2 \boldsymbol{Q_{ext}(D)N(D)}\, dD$$

- **Scattering coefficient**

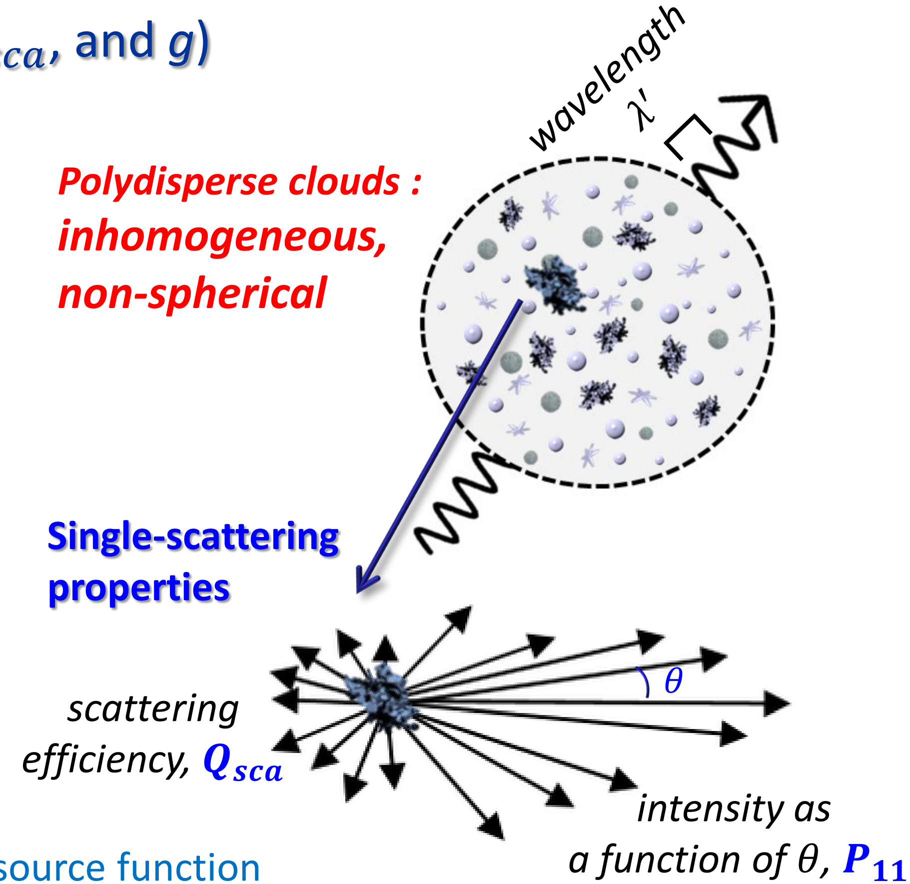
$$K_{sca} = \frac{\pi}{4}\int_0^{\infty} D^2 \boldsymbol{Q_{sca}(D)N(D)}\, dD$$

$\omega_0 = K_{sca}/K_{ext}$: single scattering albedo

- **Asymmetry parameter**

$$g = \frac{\pi}{4K_{sca}}\int_0^{\infty} \boldsymbol{g(D)}D^2\boldsymbol{Q_{sca}(D)N(D)}dD$$

$$^*\boldsymbol{g(D)} = \frac{1}{2}\int_0^{\pi} \boldsymbol{P_{11}(D,\theta)}cos\theta sin\theta d\theta$$



$$\mu\frac{dI_\nu(z,\mu,\varphi)}{dz} = -k_\nu(z)\left[I_\nu(z,\mu,\varphi) - J_\nu(z,\mu,\varphi)\right]$$

radiance at height z — source function

$$J_\nu(z,\mu,\varphi) = [1-\omega_\nu(z)]B_\nu[T(z)] + \frac{\omega_\nu(z)}{4\pi}\int_0^{2\pi}\int_{-1}^{+1} P_\nu(\mu,\varphi;\mu',\varphi')I_\nu(z,\mu',\varphi')d\mu' d\varphi'$$

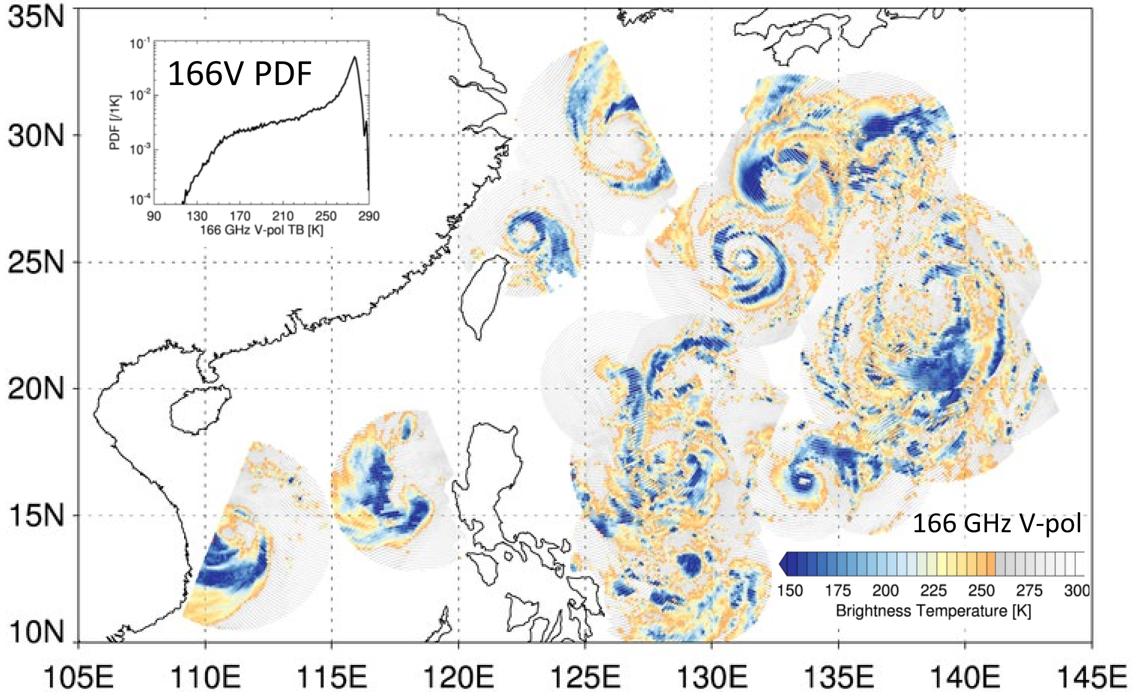
emitted radiance at height z — scattered radiance from the other direction

Backup Slides

Collecting Data for RTM Simulation

- Tropical cyclones (TCs) over the western North Pacific in 2020
- Maximum sustained wind speed ≥ 34 knots
- TC center over the GMI swath
- Error limits in the WRF simulation (location error ≤ 120 km and intensity error ≤ 20 hPa)
- Only pixels over the ocean surface and within a radius of the last closed isobar

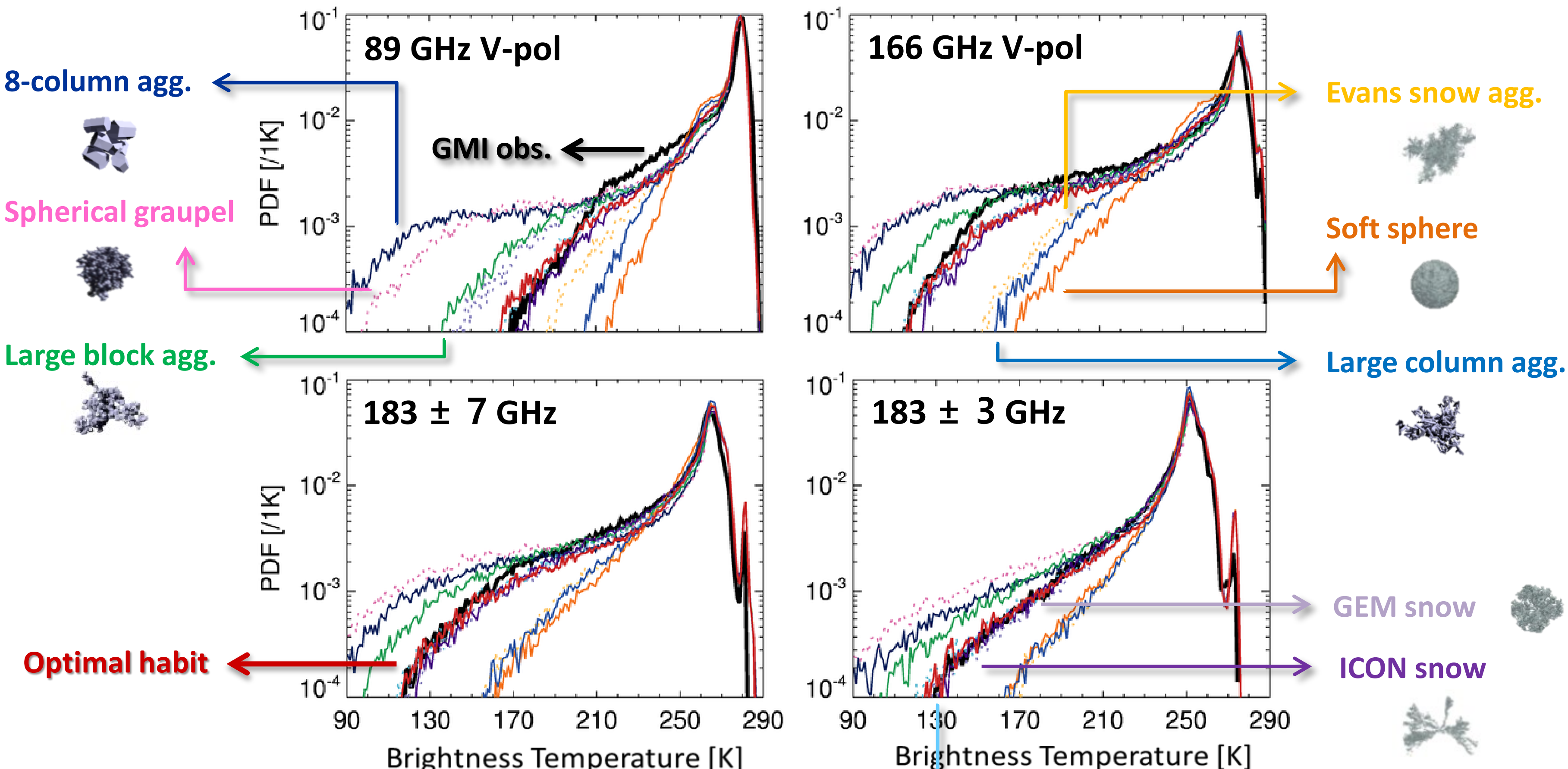
GPM GMI observations



19 TC Cases!

Backup Slides

TB Simulations (one-shape-fits-all v.s. optimal habit)

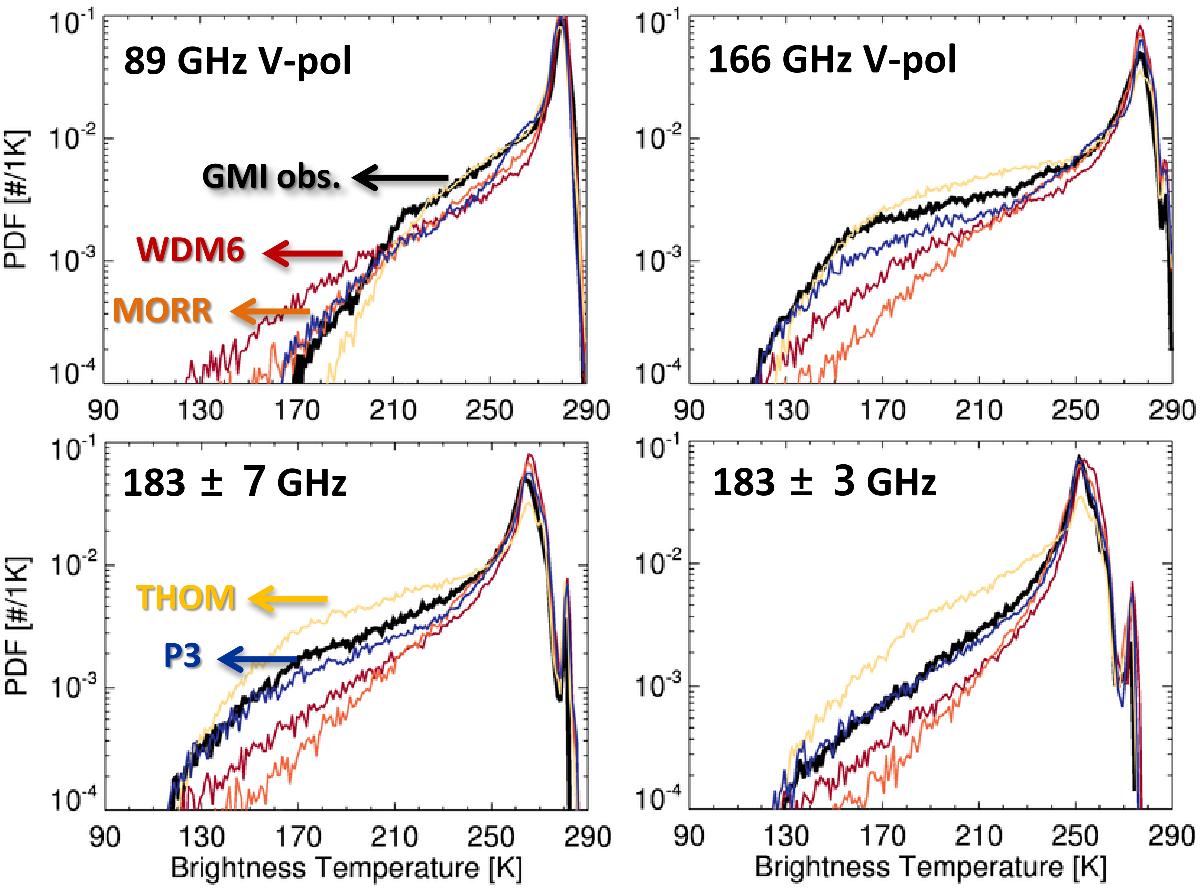


19 scenes of
11 tropical cyclones

Backup Slides

WDM6, MORR, THOM, and P3 Simulations

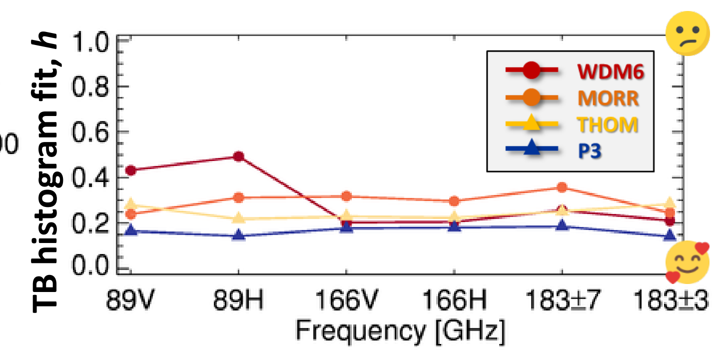
PDF:



19 scenes of
11 tropical cyclones

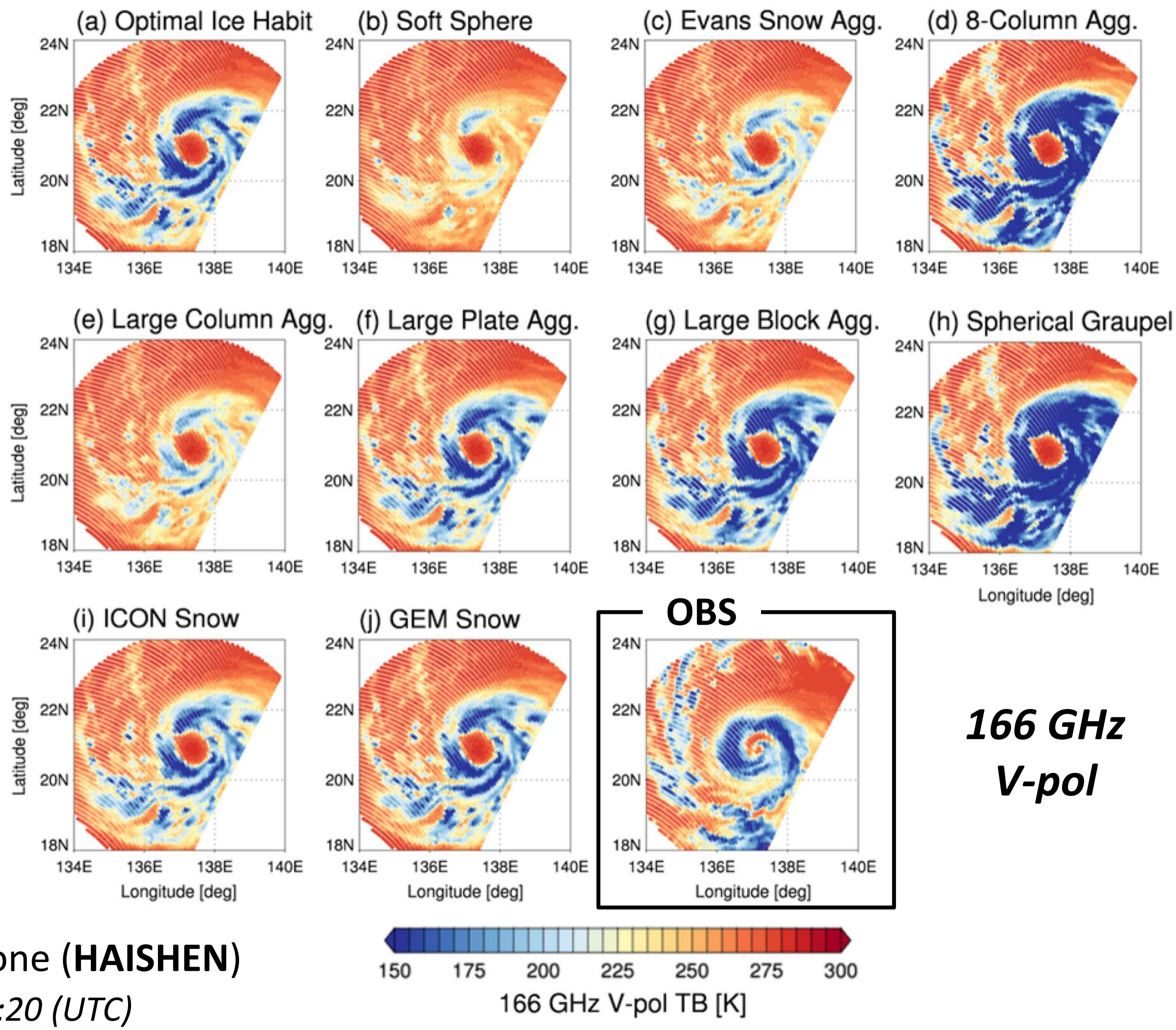
TB histogram fit (*h*)

$$h = \frac{\sum_{bins}\left|log\frac{\#simulated}{\#observed}\right|}{\#bins\ observed}$$



"P3 with the optimal habits exhibited the best performance"

Backup Slides



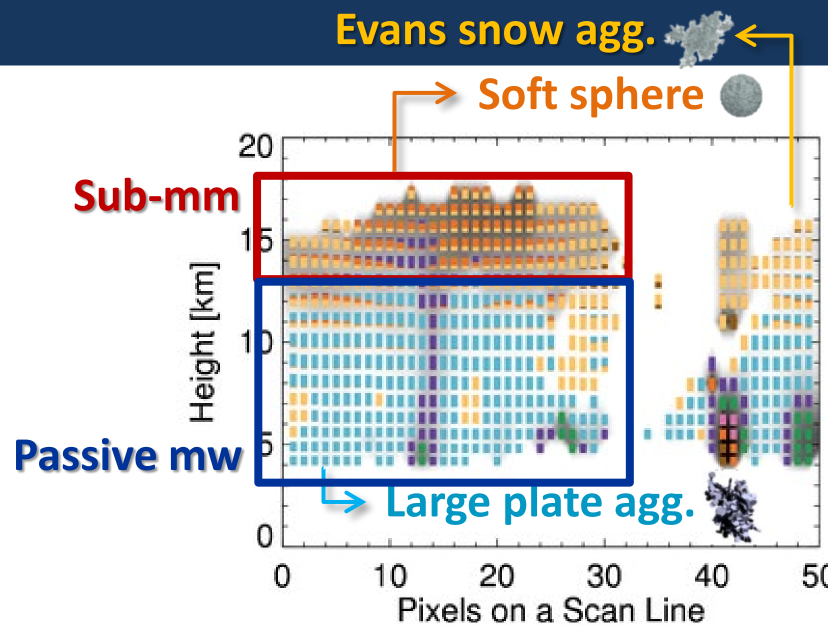
166 GHz
V-pol

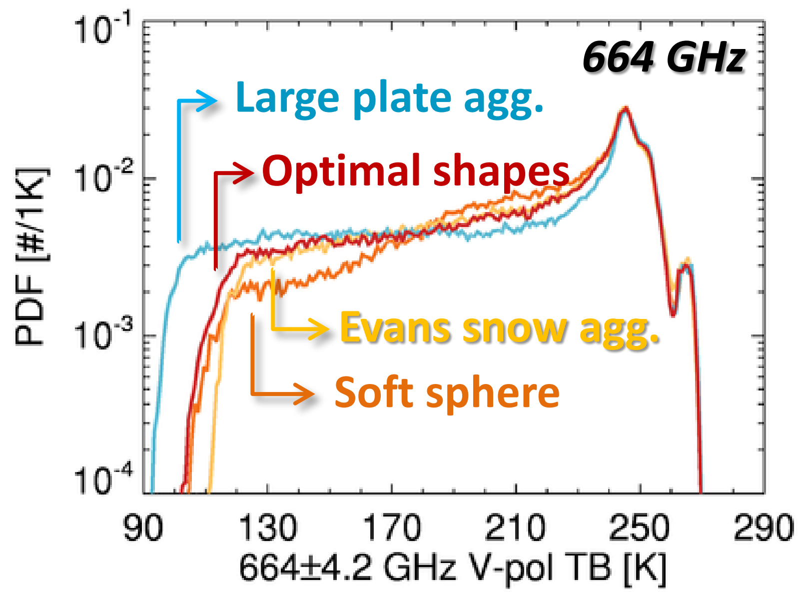
Tropical Cyclone (**HAISHEN**)
2020-09-03 09:20 (UTC)

Backup Slides

MetOp-SG

ICI sensor





"The anticipated launch of the ICI instrument in 2025 will expand **the frequency coverage from 183 GHz up to 664 GHz**, significantly enhancing the capability to detect **small ice particles within anvil clouds**."