Coupling WRF Microphysics Parameterizations to Community Radiative Transfer Model Simulations of Microwave Frequencies, Towards Data Assimilation for TCs

PSU-UMD DA Workshop

27 June 2017

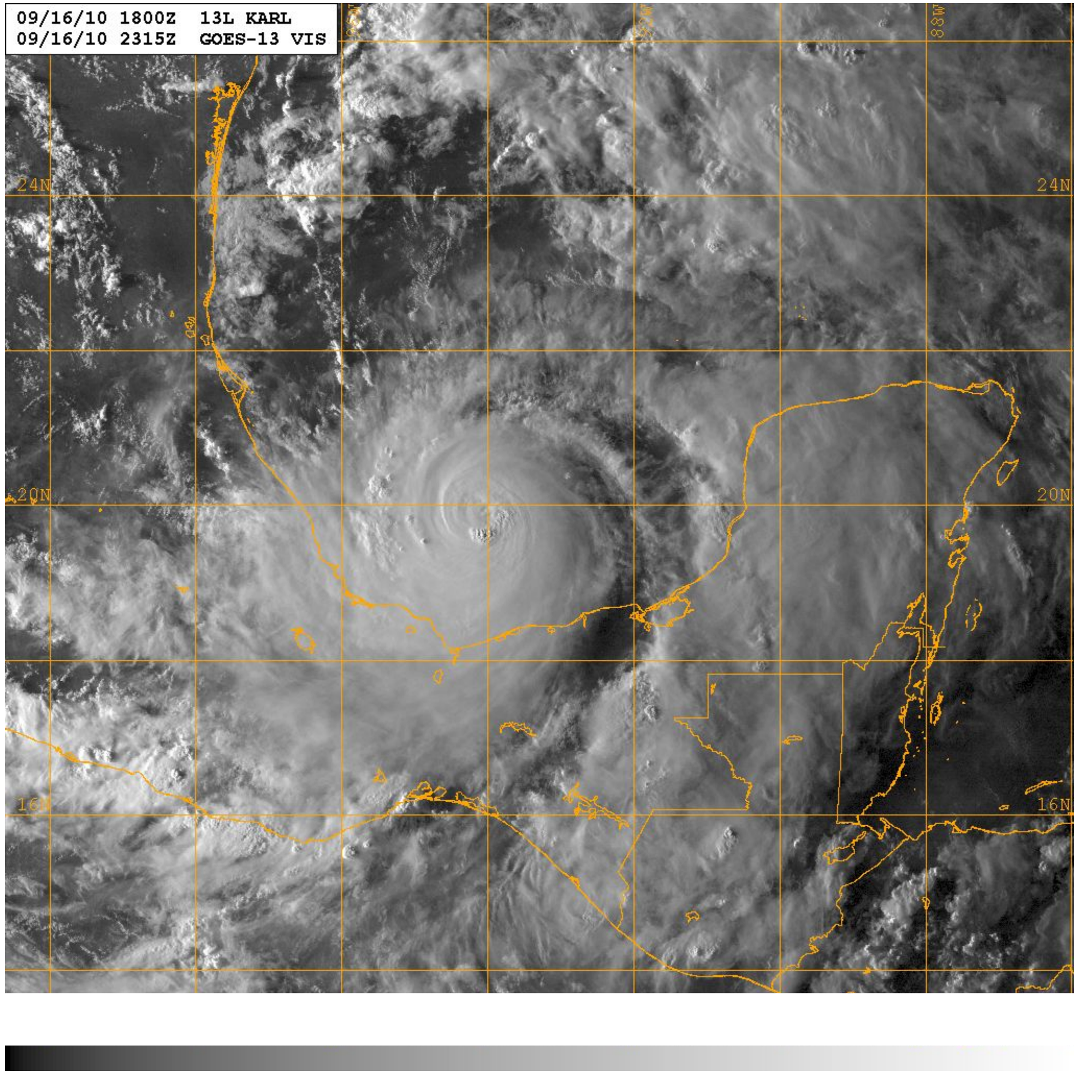
Scott Sieron

Advisors: Fuqing Zhang, Eugene E. Clothiaux

Major Collaborator: Lu Yinghui

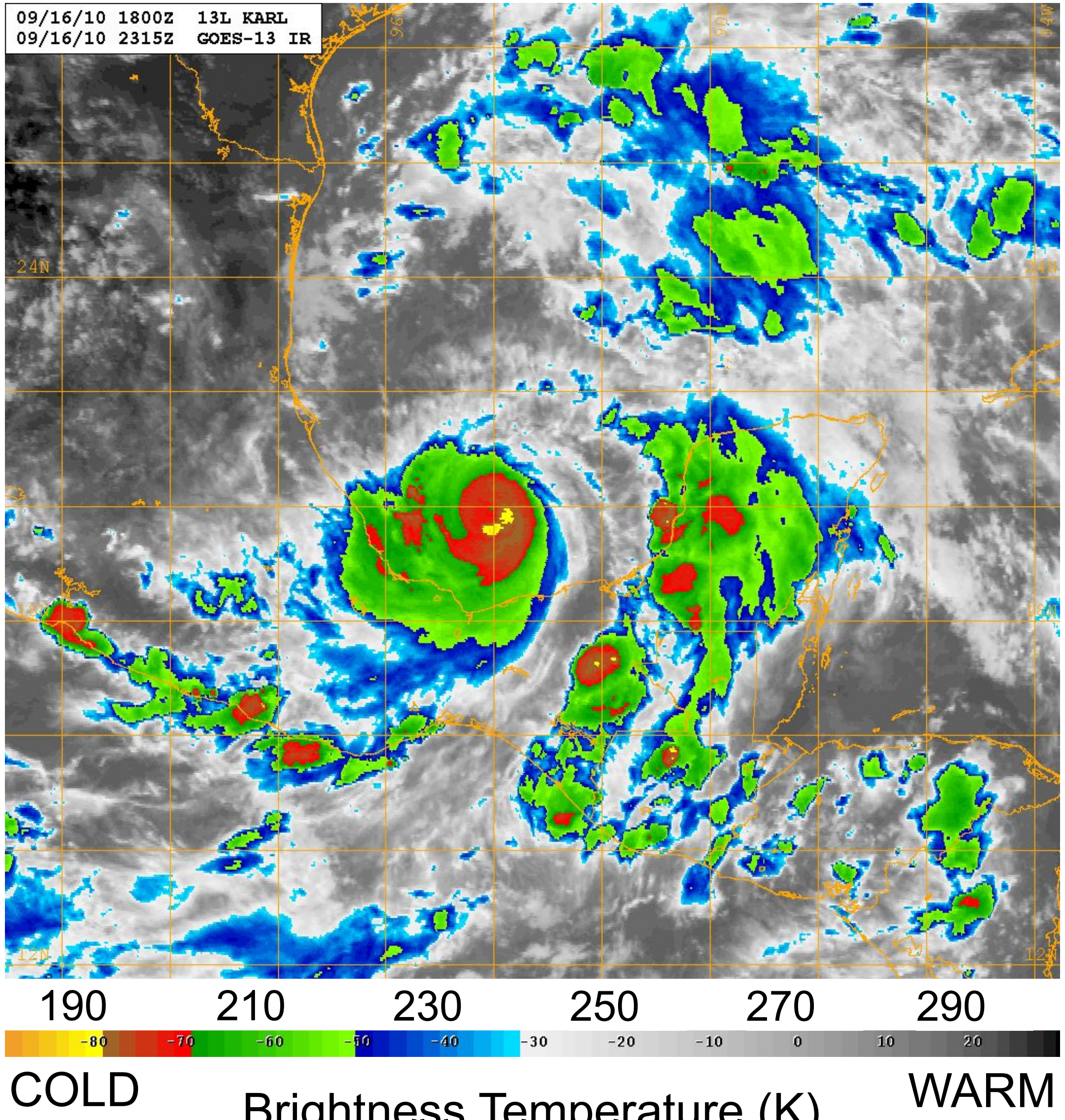
What are passive microwave brightness temperature (radiance) observations?

Visible (near sunset)



Hurricane Karl 09/16/10 2315Z
(GOES-13 VIS, image courtesy NRL)

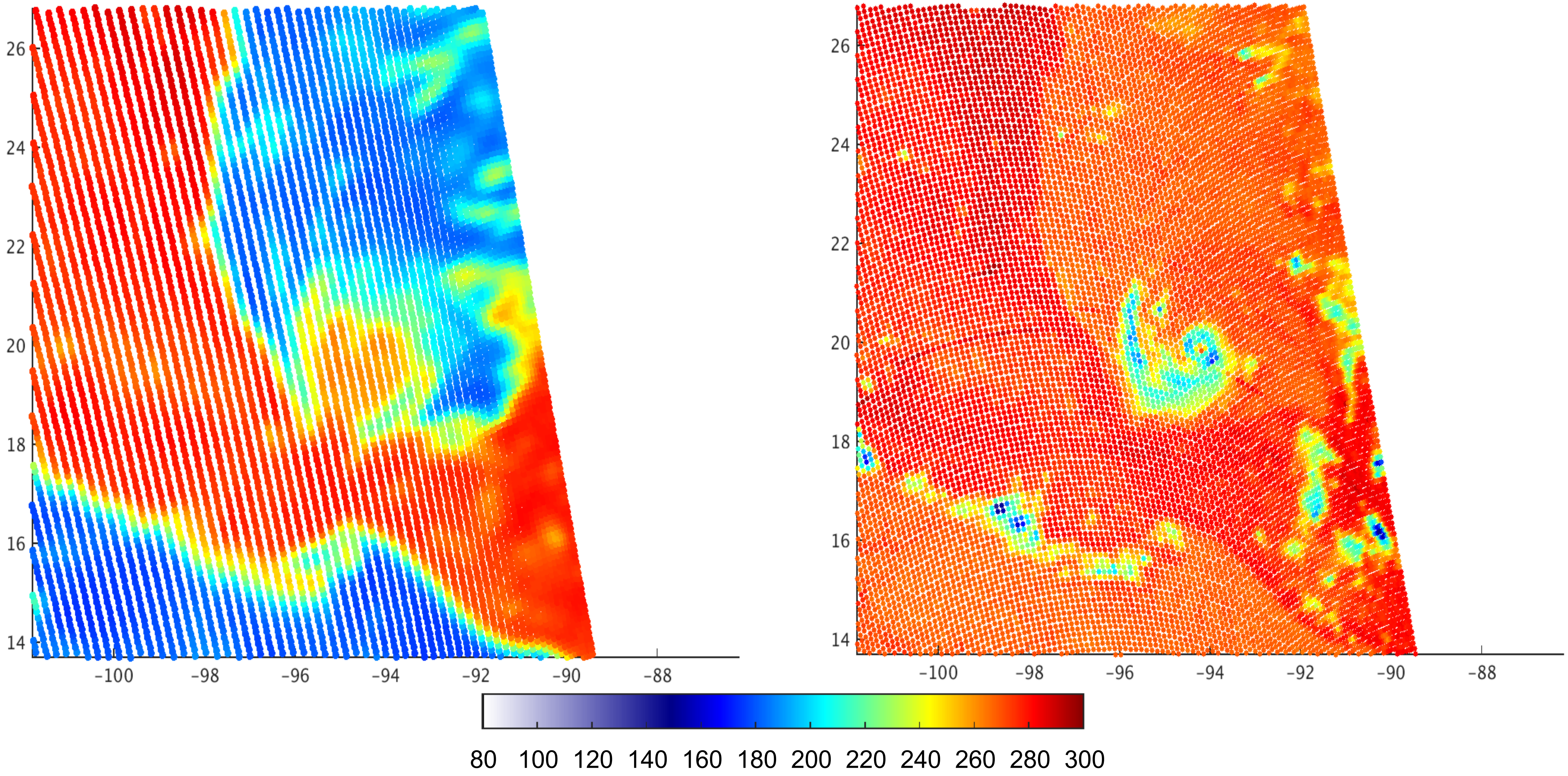
Infrared



Hurricane Karl 09/16/10 2315Z
(GOES-13 IR, image courtesy NRL)

Low-mid frequency (37 GHz)

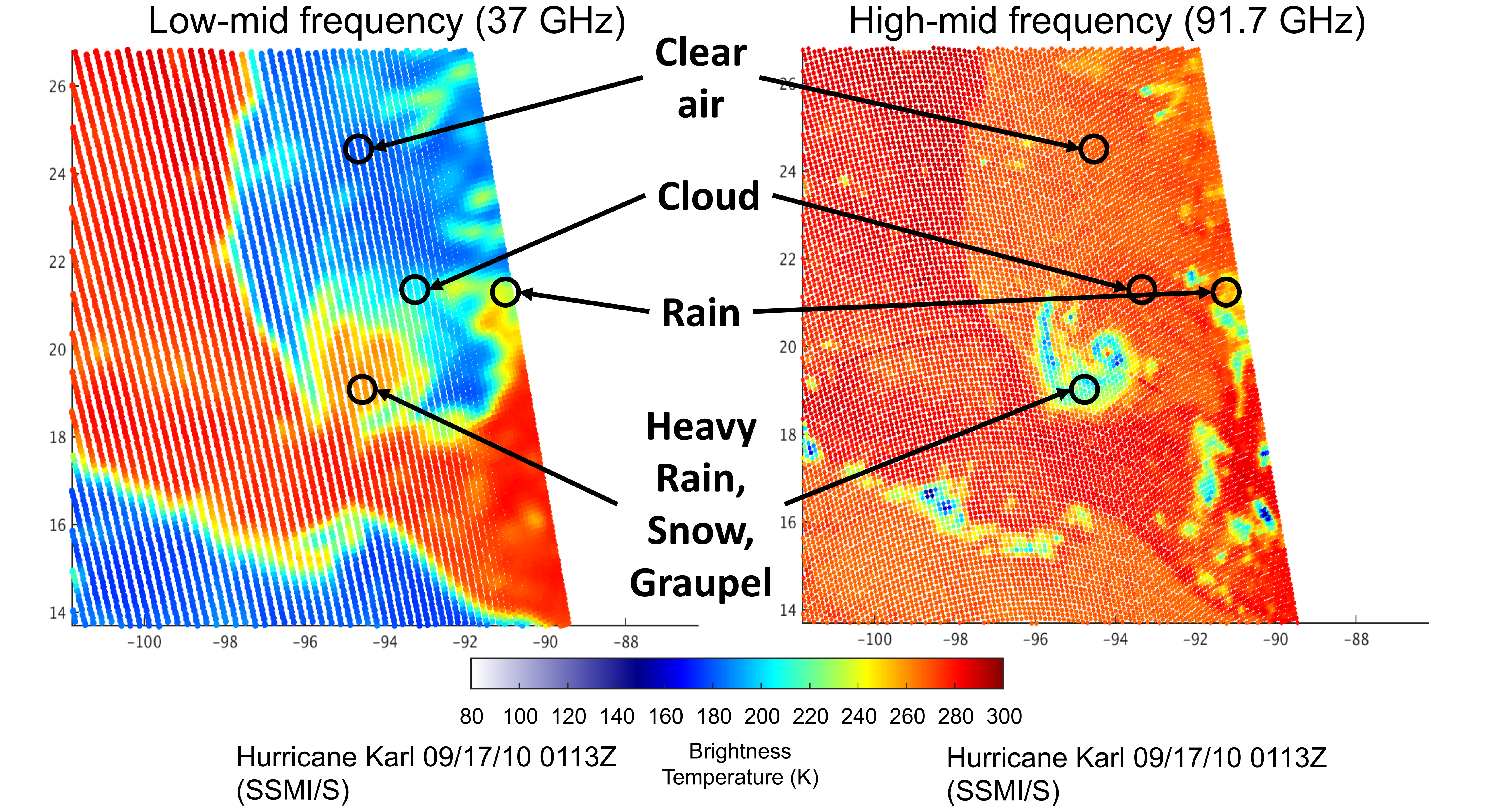
High-mid frequency (91.7 GHz)



Hurricane Karl 09/17/10 0113Z
(SSMI/S)

Brightness
Temperature (K)

Hurricane Karl 09/17/10 0113Z
(SSMI/S)


Low-mid frequency (37 GHz)
High-mid frequency (91.7 GHz)
Clear air
Cloud
Rain
Heavy Rain, Snow, Graupel
26
24
22
20
18
16
14
-100
-98
-96
-94
-92
-90
-88
80 100 120 140 160 180 200 220 240 260 280 300
Hurricane Karl 09/17/10 0113Z (SSMI/S)
Brightness Temperature (K)
Hurricane Karl 09/17/10 0113Z (SSMI/S)

What are microphysics parameterizations?

(in mesoscale weather models)

Bulk Microphysics Schemes

- Categorize different physical states of water (hydrometeor species)
- Prescribe each species a **particle size distribution** form
- Predict one or more physical quantities that relate to a moment of the particle size distribution
  - “Single-moment:” predict mass
  - “Double-moment:” predict another quantity such as number concentration
- Interaction of species are specified by functions of predicted physical quantities

How Bulk Schemes Can Differ – Snow PSD

Goddard (Lang et al. 2007)

$N_s(D_s) = N_{0,s} e^{-\lambda_s D_s}$ with $N_{0,s}[m^{-3} \cdot m^{-1}] = 1.6{\times}10^7$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi \rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}$

How Bulk Schemes Can Differ – Snow PSD

Goddard (Lang et al. 2007)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[m^{-3} \cdot m^{-1}] = 1.6\times10^7$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi\rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}$

WSM5/6 (Hong et al. 2004)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[m^{-3} \cdot m^{-1}] = 2.0\times10^6 e^{0.12(273.15-T)}, with\ T[K]\ where\ N_{0,s} \leq 10^{11}$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi\rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}, where\ \lambda_s \leq 10^5$

- Temperature-dependent intercept parameter
- Upper limit on slope parameter

How Bulk Schemes Can Differ – Snow PSD

Goddard (Lang et al. 2007)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[m^{-3} \cdot m^{-1}] = 1.6 \times 10^7$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi \rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}$

WSM5/6 (Hong et al. 2004)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[m^{-3} \cdot m^{-1}] = 2.0 \times 10^6 e^{0.12(273.15-T)}, with\ T[K]\ where\ N_{0,s} \leq 10^{11}$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi \rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}, where\ \lambda_s \leq 10^5$

Morrison (Double-Moment; Morrison et al. 2009)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[kg^{-1} \cdot m^{-1}] = N_s \lambda_s$ and

$$\lambda_s[m^{-1}] = \left(\frac{\pi \rho_s N_s}{q_s}\right)^{1/3}, where\ \frac{1}{2000.0 \times 10^{-6}} \leq \lambda_s \leq \frac{1}{10.0 \times 10^{-6}}$$

- Double-moment
- Upper and lower limits on slope parameter

How Bulk Schemes Can Differ – Snow PSD

Goddard (Lang et al. 2007)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[m^{-3}\cdot m^{-1}] = 1.6{\times}10^7$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi\rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}$

WSM5/6 (Hong et al. 2004)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[m^{-3}\cdot m^{-1}] = 2.0{\times}10^6 e^{0.12(273.15-T)}, with\ T[K]\ where\ N_{0,s} \le 10^{11}$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi\rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}, where\ \lambda_s \le 10^5$

Morrison (Double-Moment; Morrison et al. 2009)

$N_s(D_s) = N_{0,s}e^{-\lambda_s D_s}$ with $N_{0,s}[kg^{-1}\cdot m^{-1}] = N_s\lambda_s$ and

$\lambda_s[m^{-1}] = \left(\frac{\pi\rho_s N_s}{q_s}\right)^{1/3}, where\ \frac{1}{2000.0{\times}10^{-6}} \le \lambda_s \le \frac{1}{10.0{\times}10^{-6}}$

Thompson (Thompson and Eidhammer 2014)

$N_s(D_s) = \frac{\mathscr{M}_2^4}{\mathscr{M}_3^3}\left[\kappa_0 e^{-(\mathscr{M}_2/\mathscr{M}_3)\Lambda_0 D} + \kappa_1\left(\frac{\mathscr{M}_2}{\mathscr{M}_3}D\right)^{\mu_s} e^{-(\mathscr{M}_2/\mathscr{M}_3)\Lambda_1 D}\right]$, with $\mathscr{M}_n$ the *n*th moment of PSD, …

- Much more complex…

The Community Radiative Transfer Model (CRTM)

And Effective Radius

Basics of CRTM Operation

- Input:
  - Vertical profile of
    - Temperature
    - Pressure (also vertical discretization variable)
    - Water vapor
    - Cloud water, pristine cloud ice, rain, snow, graupel, hail
      - Water content (kg m^{-3}), <u>effective radius (μm)</u>
  - Surface composition, temperature and wind
    - Surface wind → geometry of water surface → water surface emissivity
  - Sensor and viewing angle
- Output: Brightness Temperature

obtain from weather model output

Effective Radius

- A scalar representation of the sizes of particles in a cloud
- The community defines effective radius as

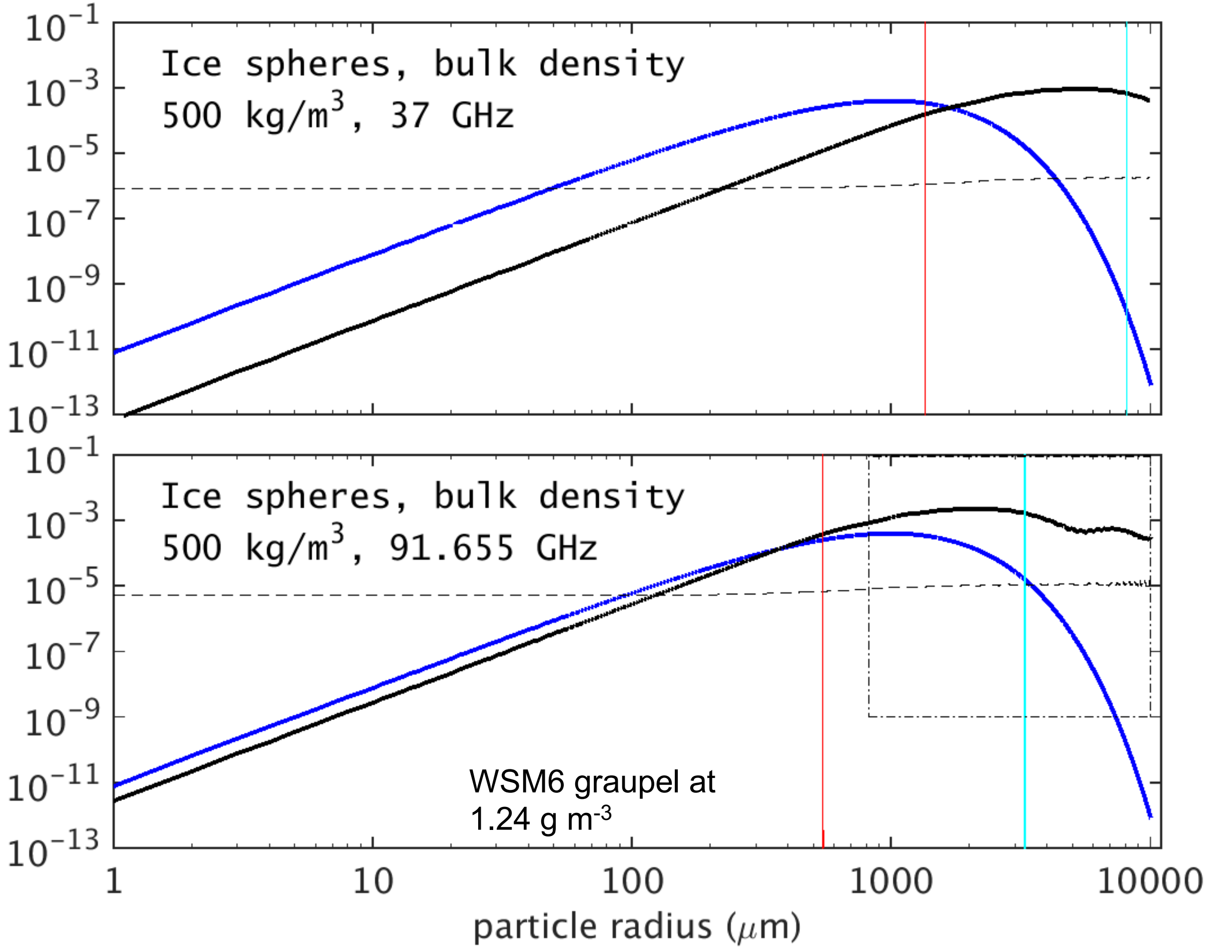
$$r_{eff} = \frac{\int r^3 N(r) dr}{\int r^2 N(r) dr}$$

  - This is "mean radius for scattering" for scattering by a particle $\propto r^2$ (Hansen and Travis 1974)
  - For a monodisperse PSD, r_{eff} is the radius of the particles
  - For generalized gamma PSD, $r_{eff} = (\mu + 3)\lambda^{-1}$

$$\lambda_s[m^{-1}] = \left(\frac{\pi \rho_s N_{0,s}}{\rho_a q_s}\right)^{1/4}$$

CRTM Effective Radius (cont.)

- For precipitation in microwave, scattering by a particle is NOT $\propto r^2$
  - This assumption works for particles much greater than wavelength
  - Most mass are in particles less than or close to wavelength
  - Particle size << wavelength (radar): scattering $\propto r^6$
- Therefore, effective radius does not represent scattering between different particle size distributions with inherent accuracy

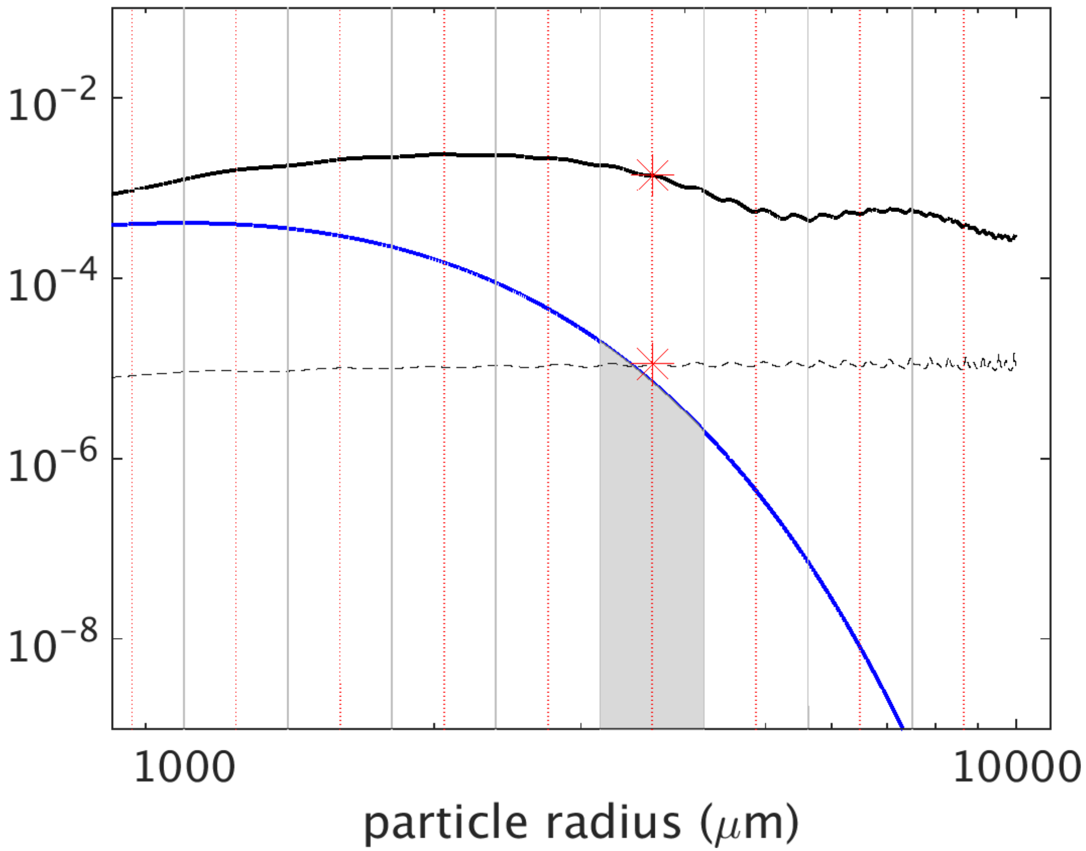


Black: scattering coeff. (m^2 kg^{-1})
Dashed: absorption coeff. (m^2 kg^{-1})
Blue: sample particle mass distribution (kg m^{-3} μm^{-1}) of graupel-like ice spheres

Light blue: wavelength
Red: one-sixth wavelength

Microphysics Scheme-Consistent CRTM

- "Distribution-Specific": scheme-specific cloud single-scattering property lookup tables
  - Integrating the product of microphysics-specified particle mass distributions, and particle radiative properties

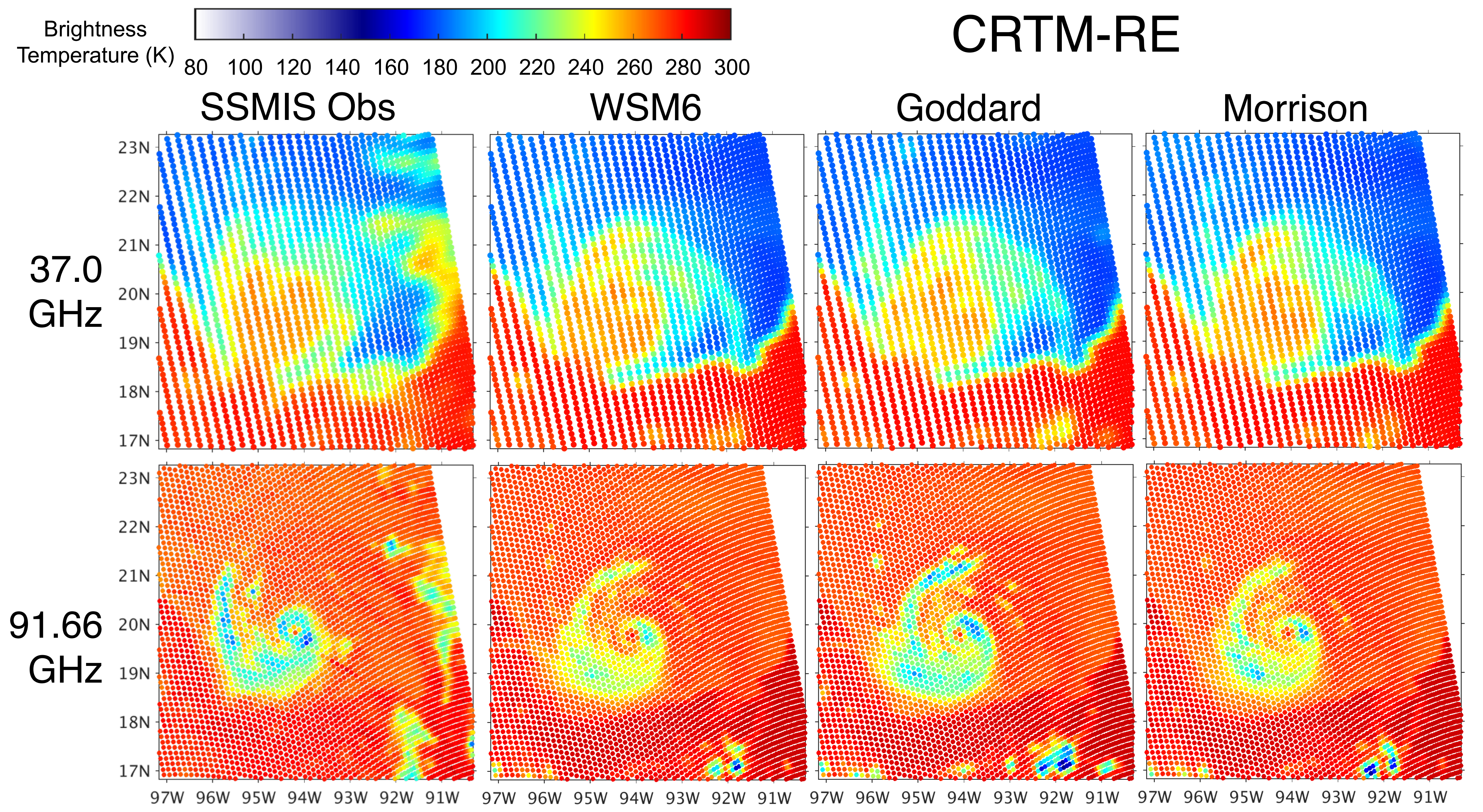


Black: scattering coeff. ($m^2\ kg^{-1}$)
Dashed: absorption coeff. ($m^2\ kg^{-1}$)
Blue: sample particle mass distribution ($kg\ m^{-3}\ \mu m^{-1}$) of graupel-like ice spheres

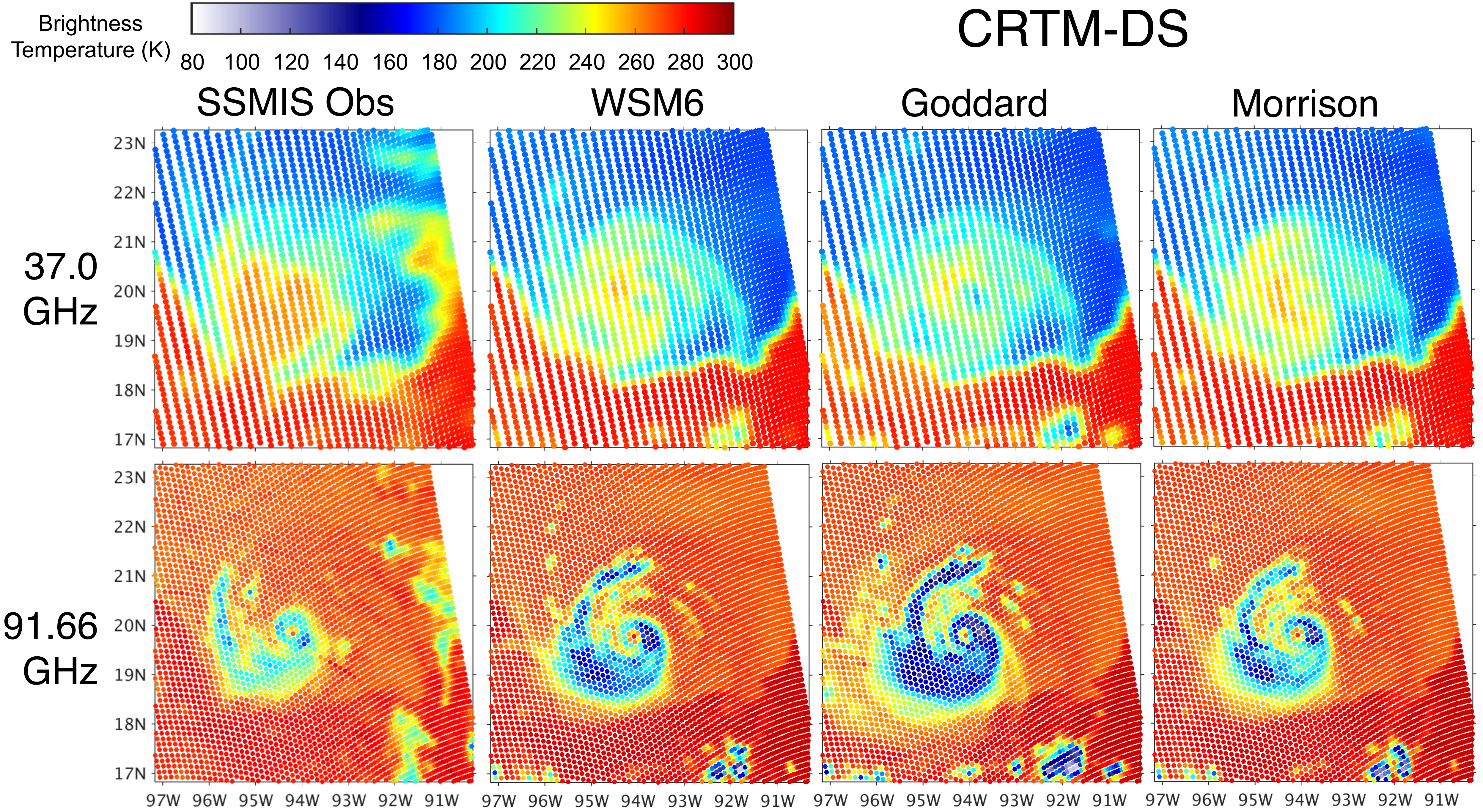
Testing the CRTM – WRF Simulations

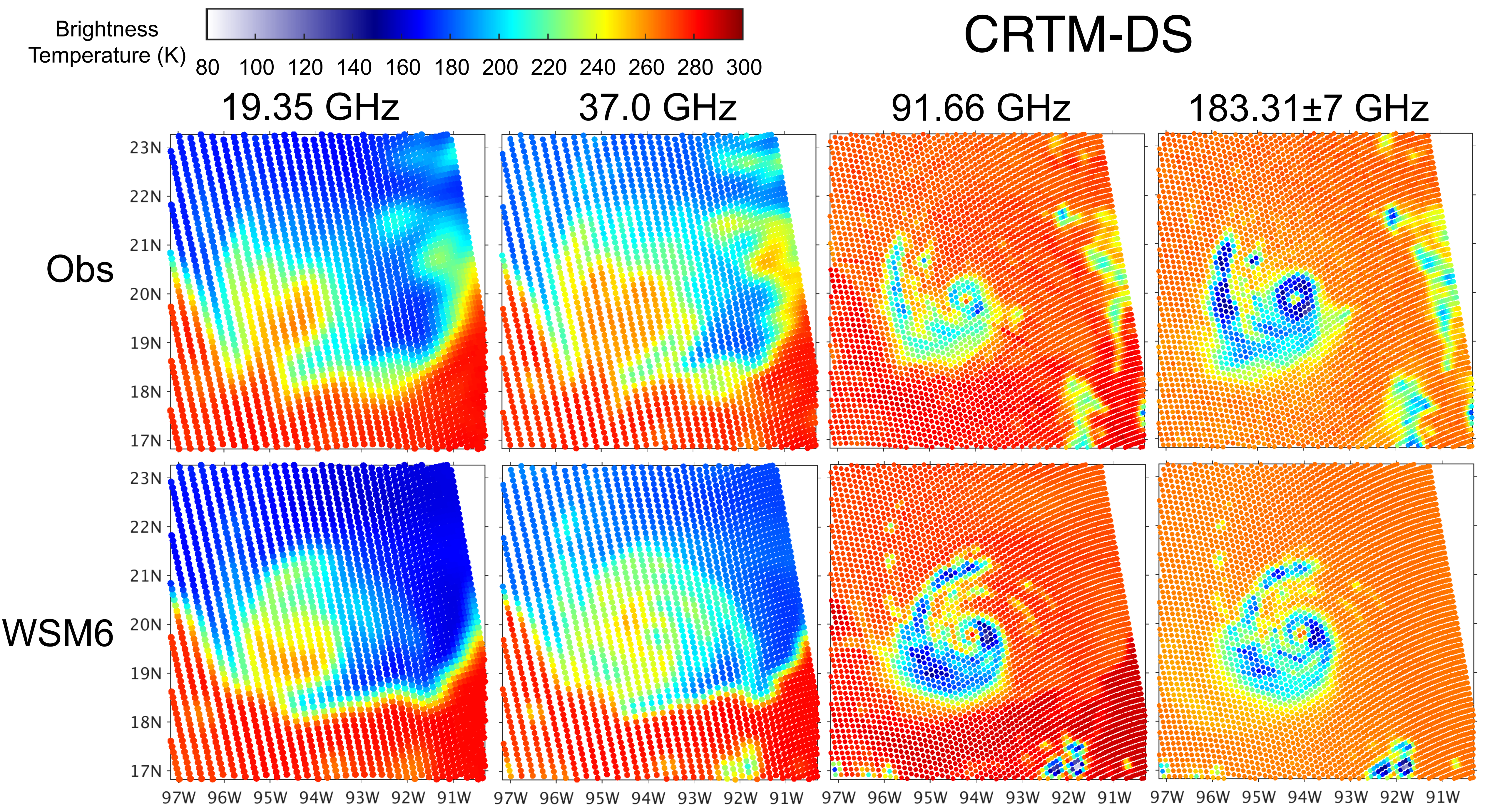
- Hurricane Karl (2010), initialized at 21Z 16 Sept. from **PSU WRF-EnKF** analysis after assimilating airborne Doppler radar radial velocities
  - Ensemble size: 60
  - WSM6 microphysics
  - Inner-domain grid spacing: 3 km

- 3-hour forecasts, each with a different microphysics scheme



Brightness Temperature (K)
80 100 120 140 160 180 200 220 240 260 280 300
CRTM-RE
SSMIS Obs
WSM6
Goddard
Morrison
37.0 GHz
91.66 GHz
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91W


Brightness
Temperature (K)
80
100
120
140
160
180
200
220
240
260
280
300
CRTM-DS
SSMIS Obs
WSM6
Goddard
Morrison
37.0
GHz
91.66
GHz
23N
22N
21N
20N
19N
18N
17N
97W
96W
95W
94W
93W
92W
91W



Brightness Temperature (K)
80 100 120 140 160 180 200 220 240 260 280 300
CRTM-DS
19.35 GHz
37.0 GHz
91.66 GHz
183.31±7 GHz
Obs
WSM6
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91W

Microphysics Scheme-Consistent CRTM

- Greater differences in T_B between MP schemes using CRTM-DS
  - Differences in PSD are fully resolved

- Bias to observations
  - CRTM-DS too cold at low and mid frequencies, matches well at higher frequencies
  - CRTM-RE too warm at higher frequencies (did not show), matches well at low and mid frequencies
- Caused by using the scattering properties of spheres?

Non-Spherical Particle Scattering

About Non-Spherical Particles

- Database from Guosheng Liu (2008 MWR)
- Optical properties simulated by Discrete Dipole Approximation (DDA; Draine and Flatau 1994)

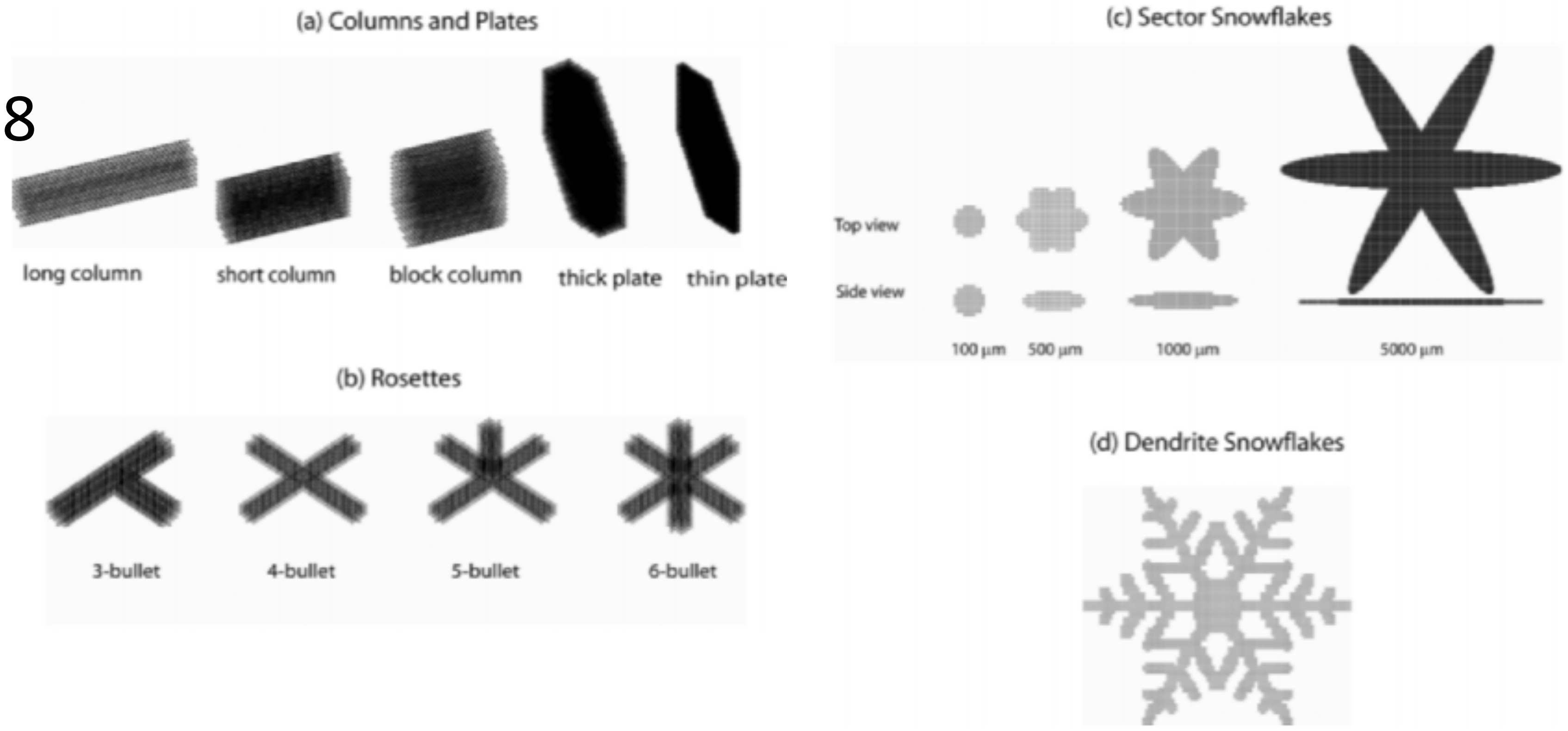
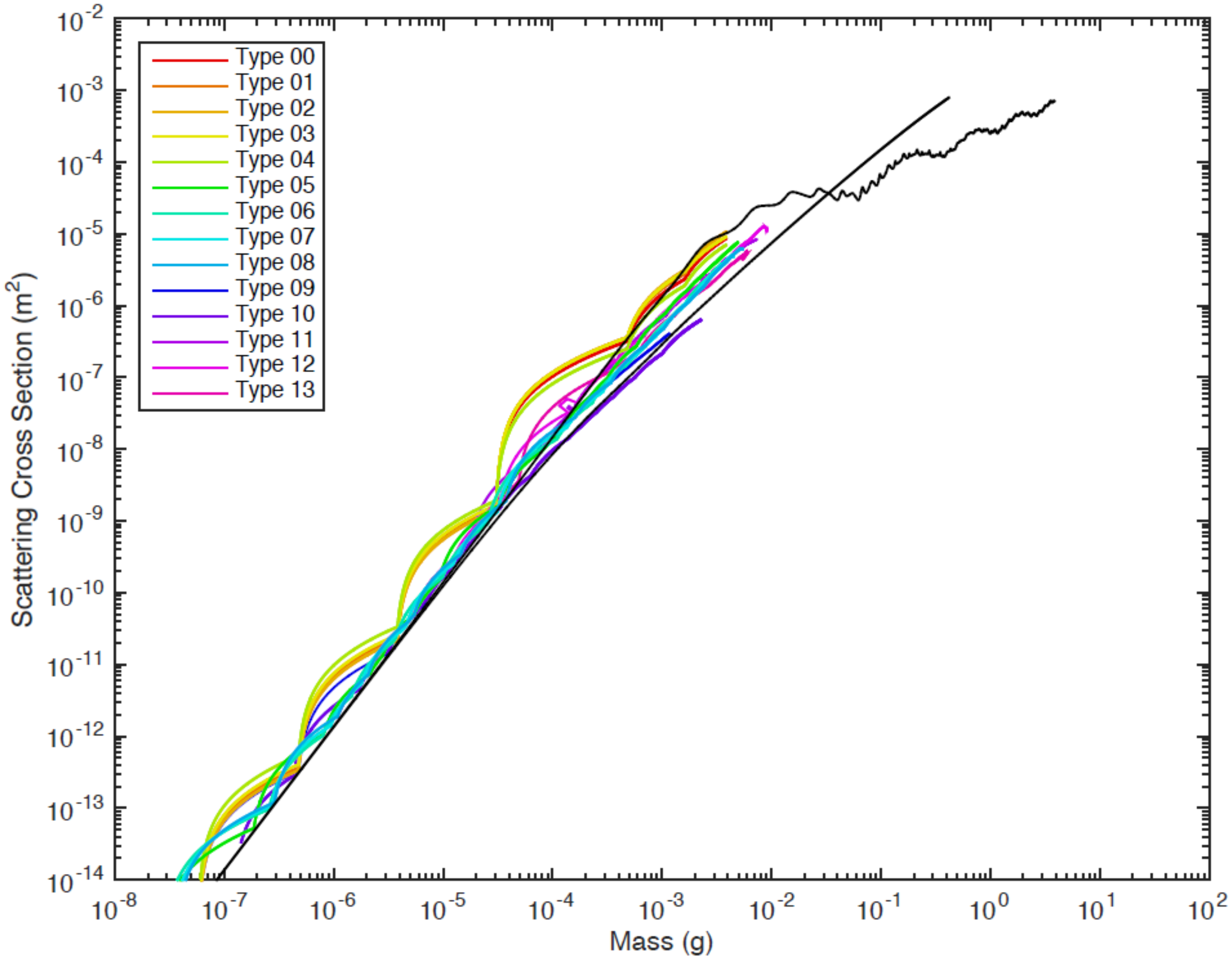


FIG. 1. Shapes of (a) columns and plates, (b) rosettes, (c) sector snowflakes, and (d) dendrite snowflakes. The drawings are made of small dots that are the dipoles used in DDA model simulations.

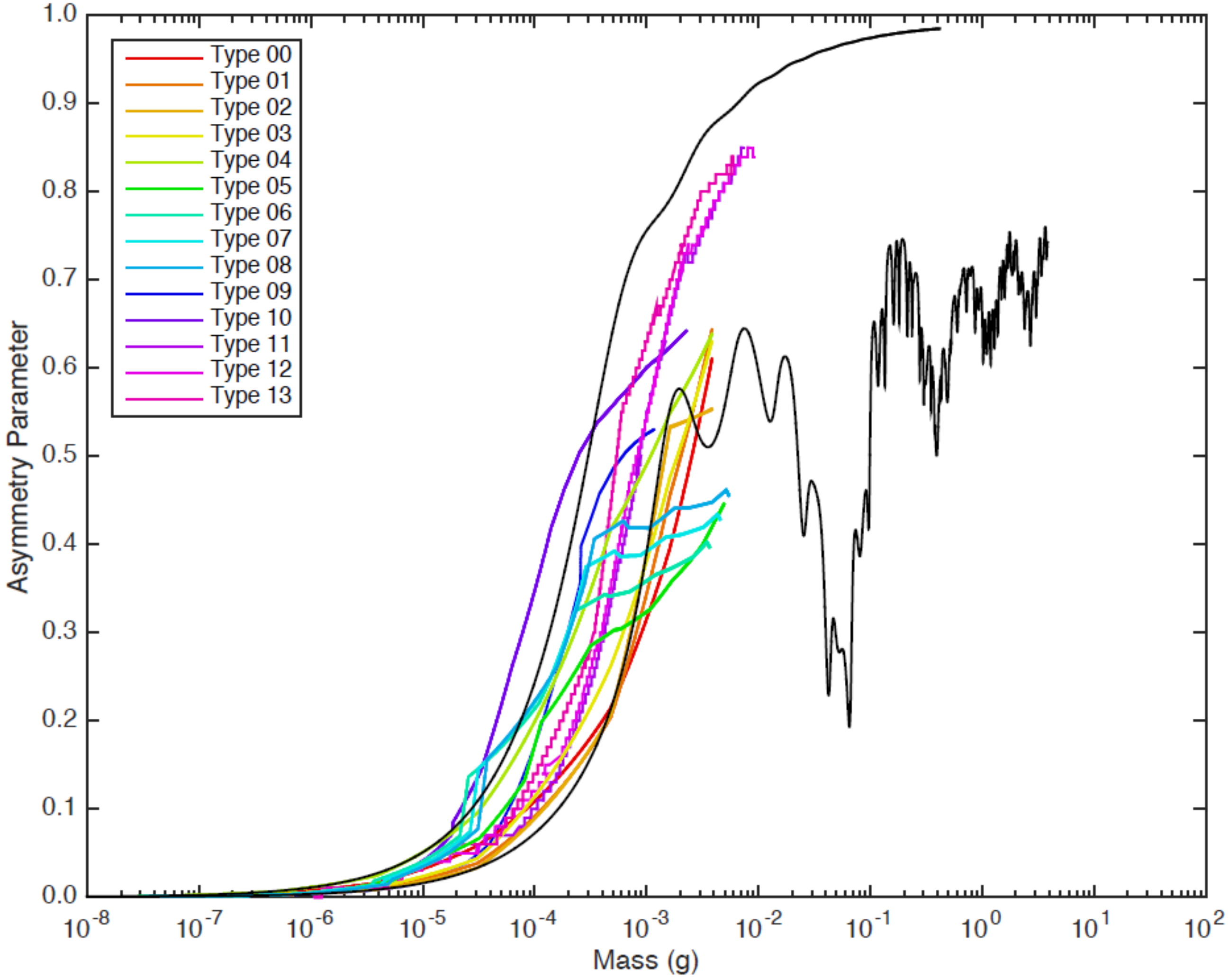
About Non-Spherical Particles

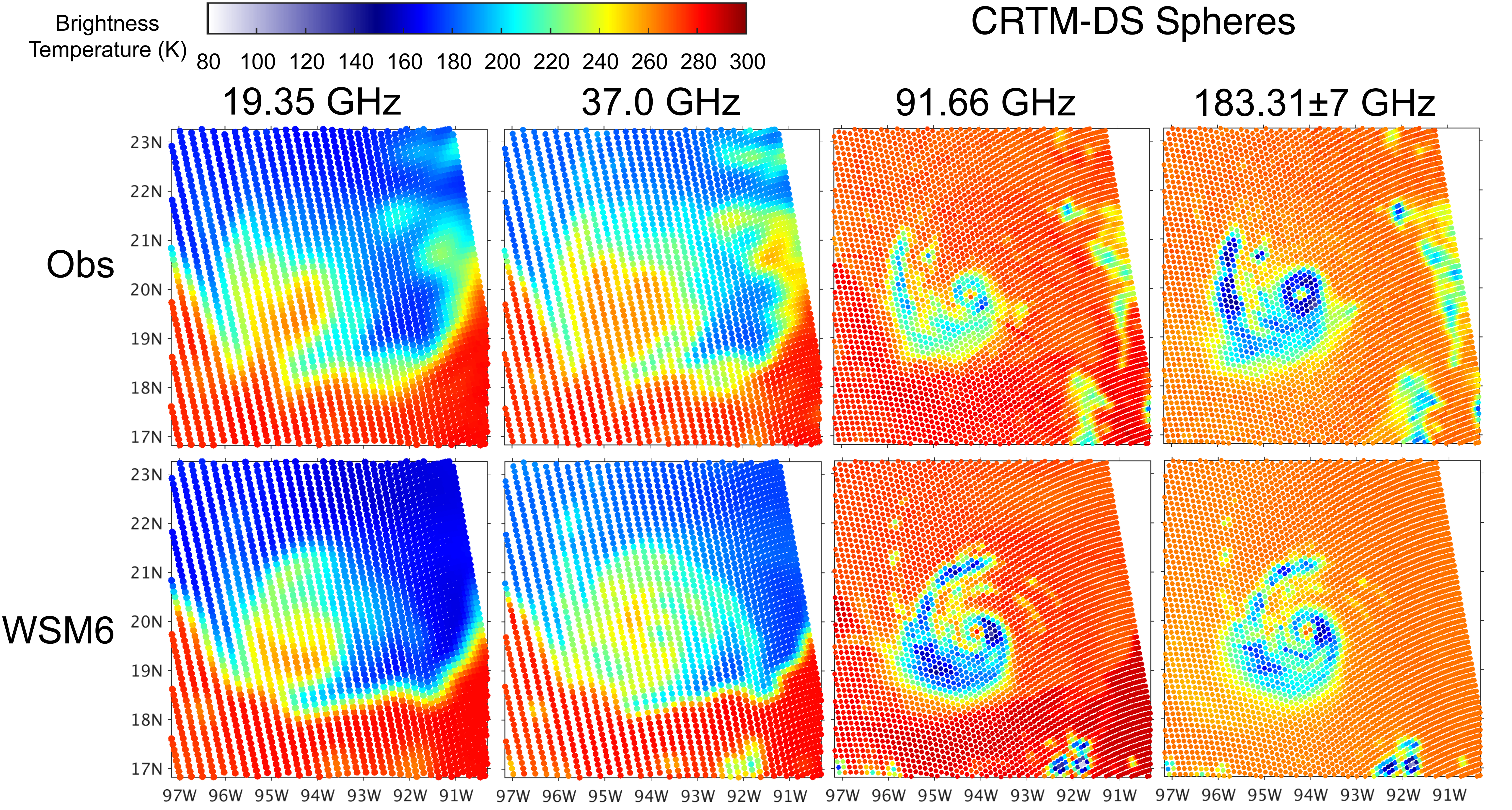
- Database from Guosheng Liu (2008 MWR)
- Optical properties simulated by Discrete Dipole Approximation (DDA; Draine and Flatau 1994)



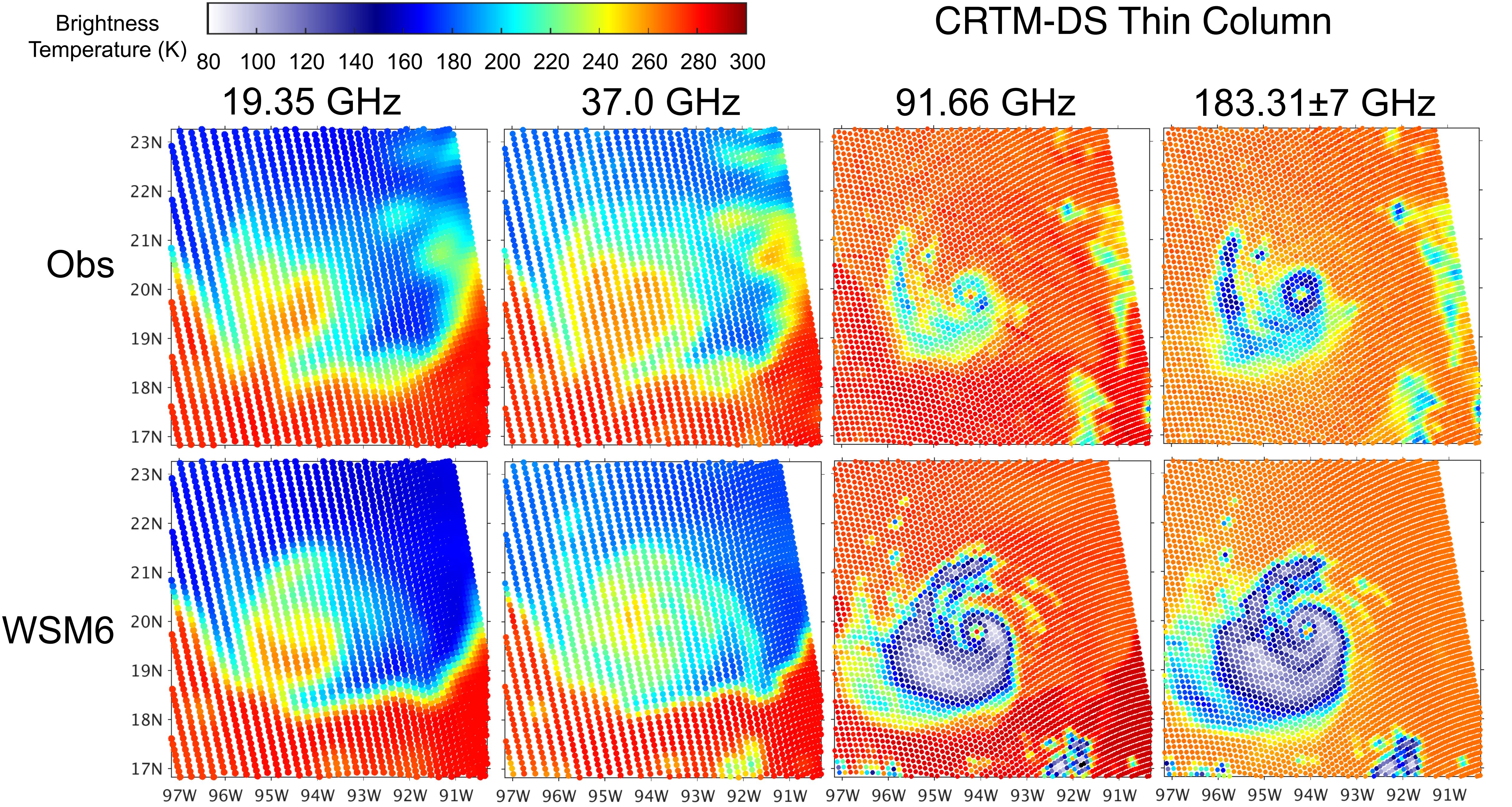
About Non-Spherical Particles

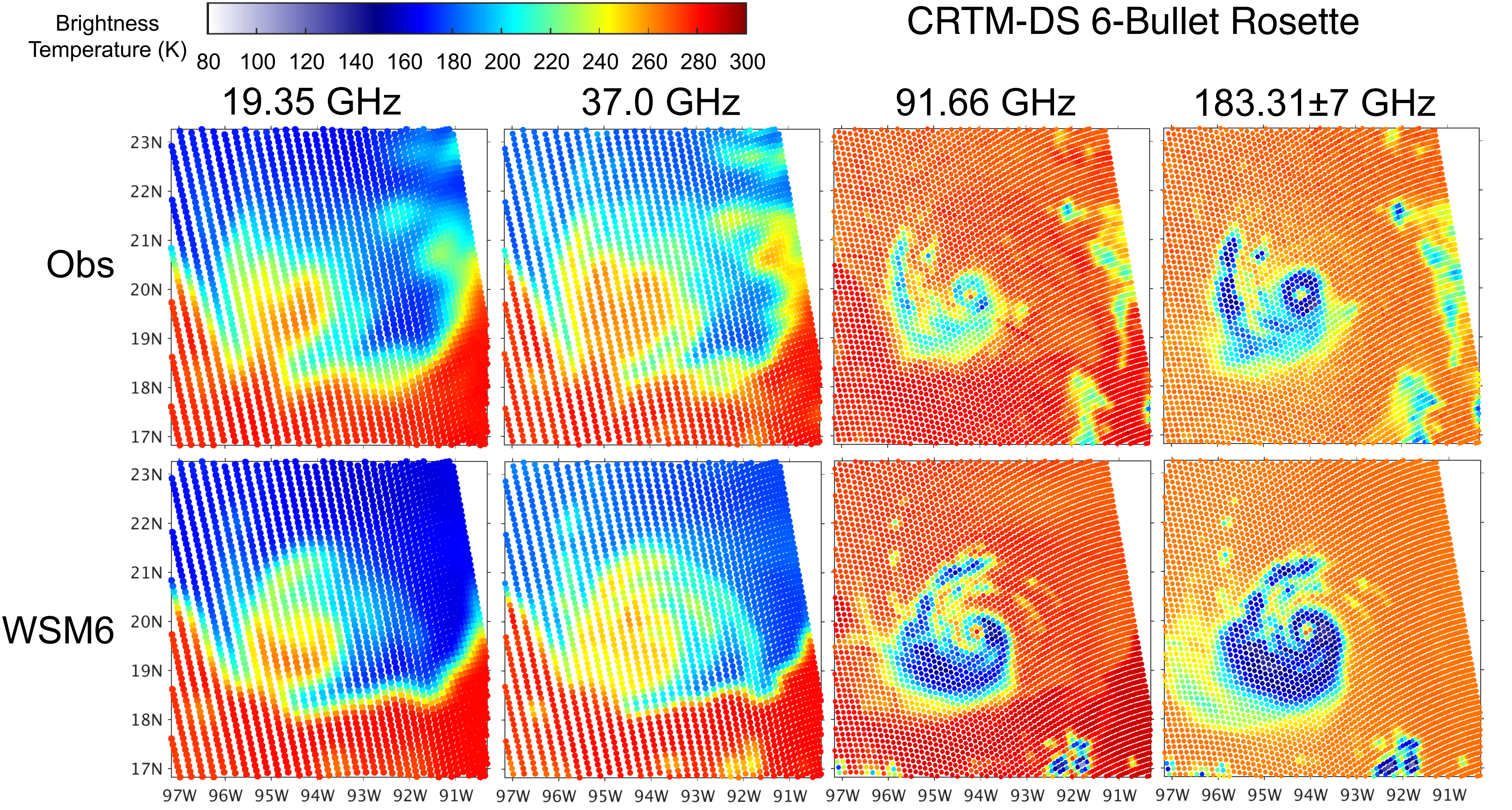
- Database from Guosheng Liu (2008 MWR)
- Optical properties simulated by Discrete Dipole Approximation (DDA; Draine and Flatau 1994)



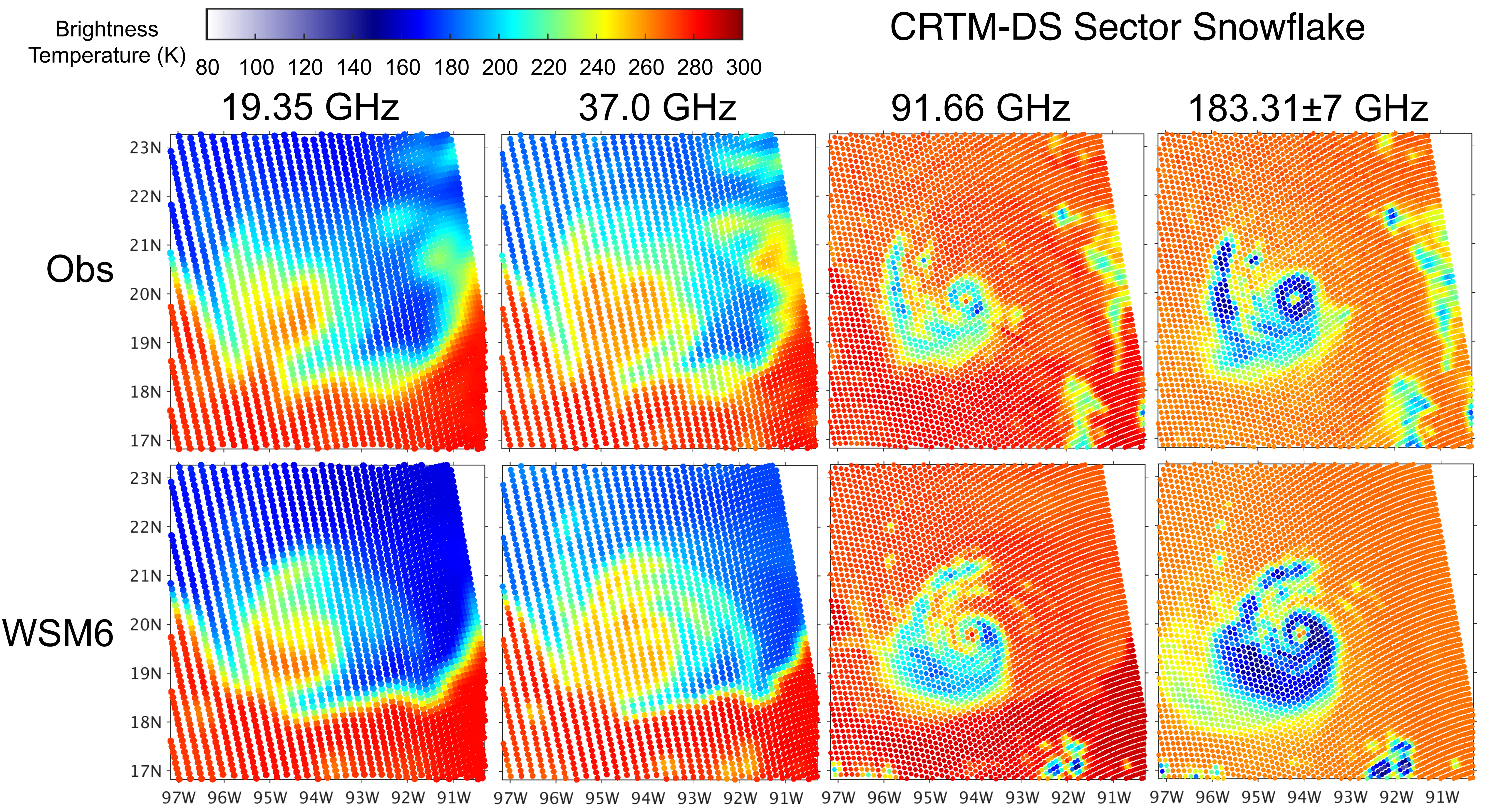


Brightness Temperature (K)
80 100 120 140 160 180 200 220 240 260 280 300
CRTM-DS Spheres
19.35 GHz
37.0 GHz
91.66 GHz
183.31±7 GHz
Obs
WSM6
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91W


Brightness Temperature (K)
80 100 120 140 160 180 200 220 240 260 280 300
CRTM-DS Thin Column
19.35 GHz
37.0 GHz
91.66 GHz
183.31±7 GHz
Obs
WSM6
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91W



Brightness Temperature (K)
80 100 120 140 160 180 200 220 240 260 280 300
CRTM-DS 6-Bullet Rosette
19.35 GHz
37.0 GHz
91.66 GHz
183.31±7 GHz
Obs
WSM6
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91W



CRTM-DS Sector Snowflake
Brightness Temperature (K)
80 100 120 140 160 180 200 220 240 260 280 300
19.35 GHz
37.0 GHz
91.66 GHz
183.31±7 GHz
Obs
WSM6
23N 22N 21N 20N 19N 18N 17N
97W 96W 95W 94W 93W 92W 91W

Particle Density

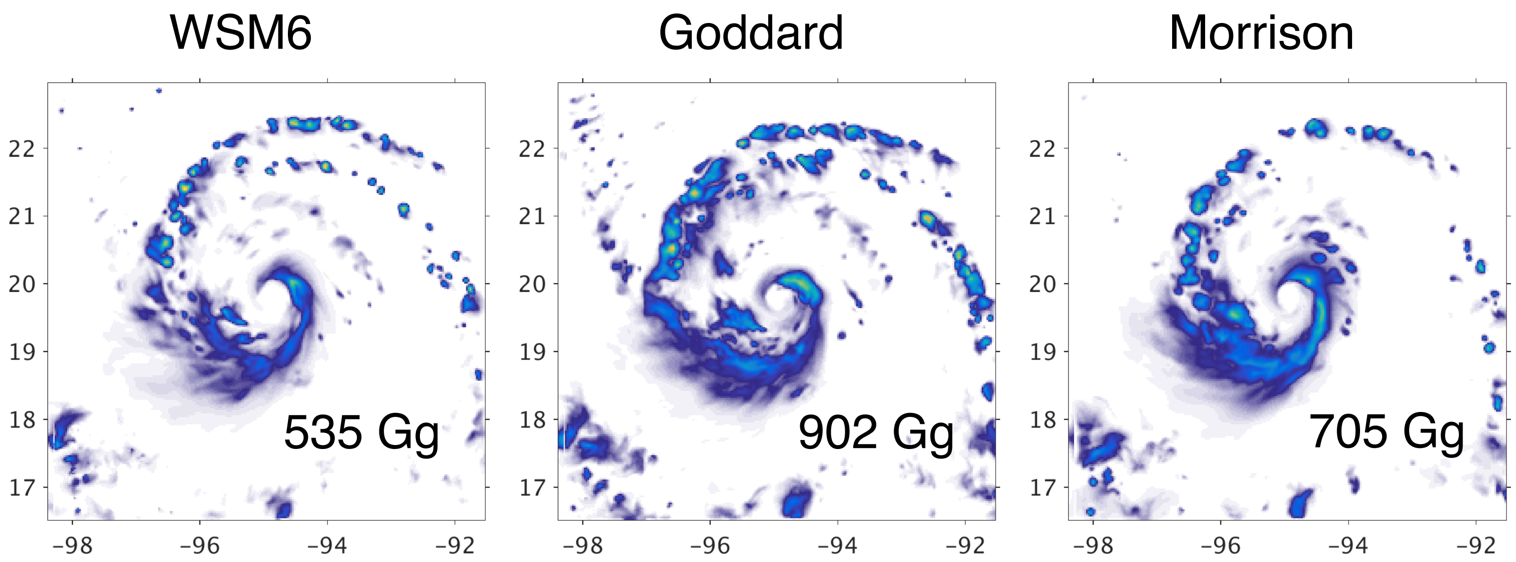
Particle Density

In what ways does particle (bulk) density impact simulated brightness temperatures?

- WRF model
- Particle mass distribution
- Radiative properties for a particle of a given size/mass

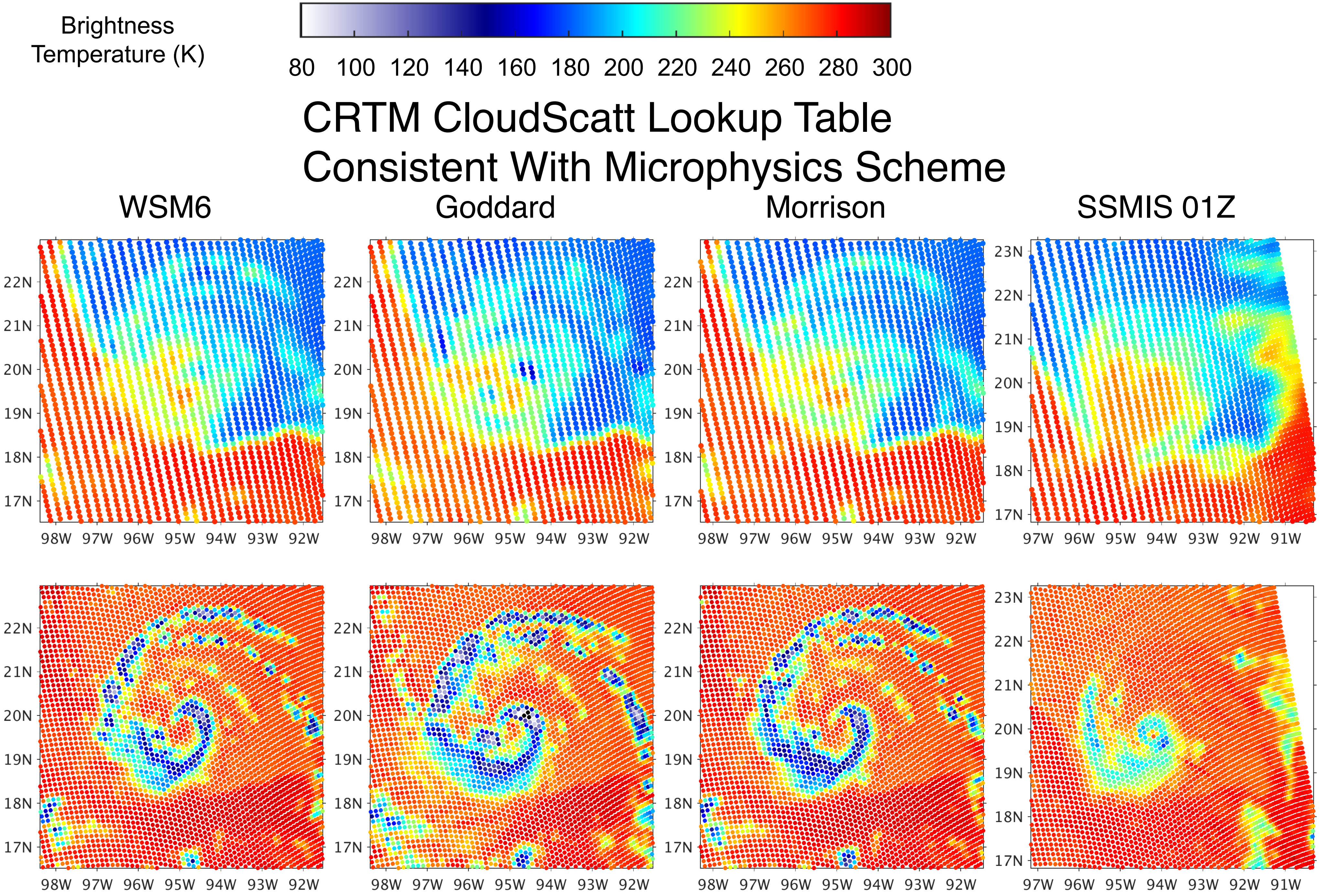
What are the significance of each of these influences?

WRF Snow and Graupel Water Path



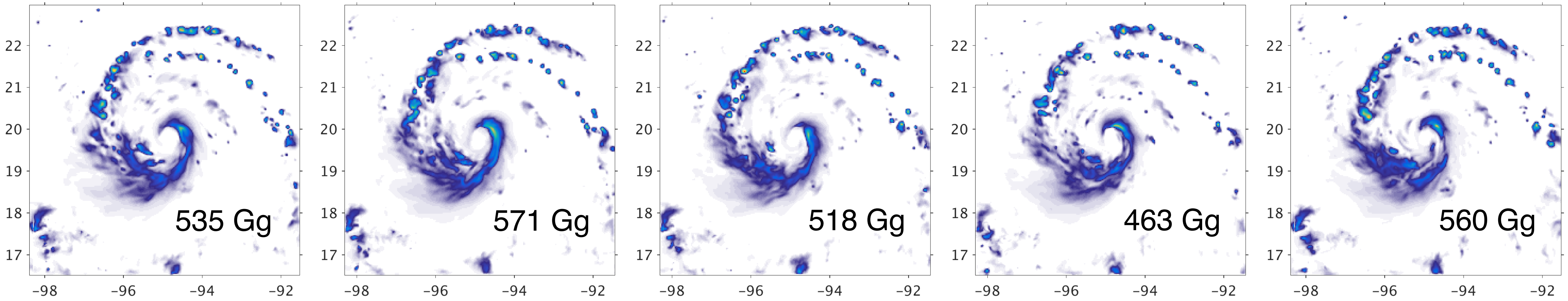
8-Hour Simulations

CRTM CloudScatt Lookup Table Consistent With Microphysics Scheme

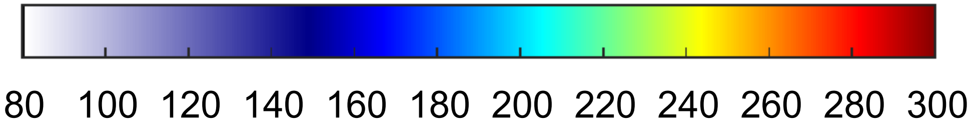


WRF Snow and Graupel Water Path,

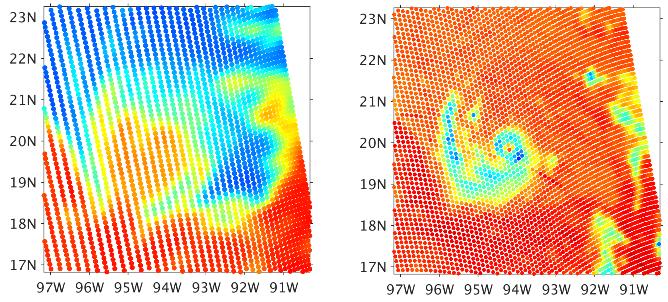
WSM6 control (Snow 100 kg/m³, Graupel 500 kg/m³) | Snow 50 kg/m³ | Snow 200 kg/m³ | Graupel 200 kg/m³ | Graupel 800 kg/m³



Brightness Temperature (K)



SSMIS 01Z



CRTM CloudScatt Lookup Table Consistent with WSM6 Control

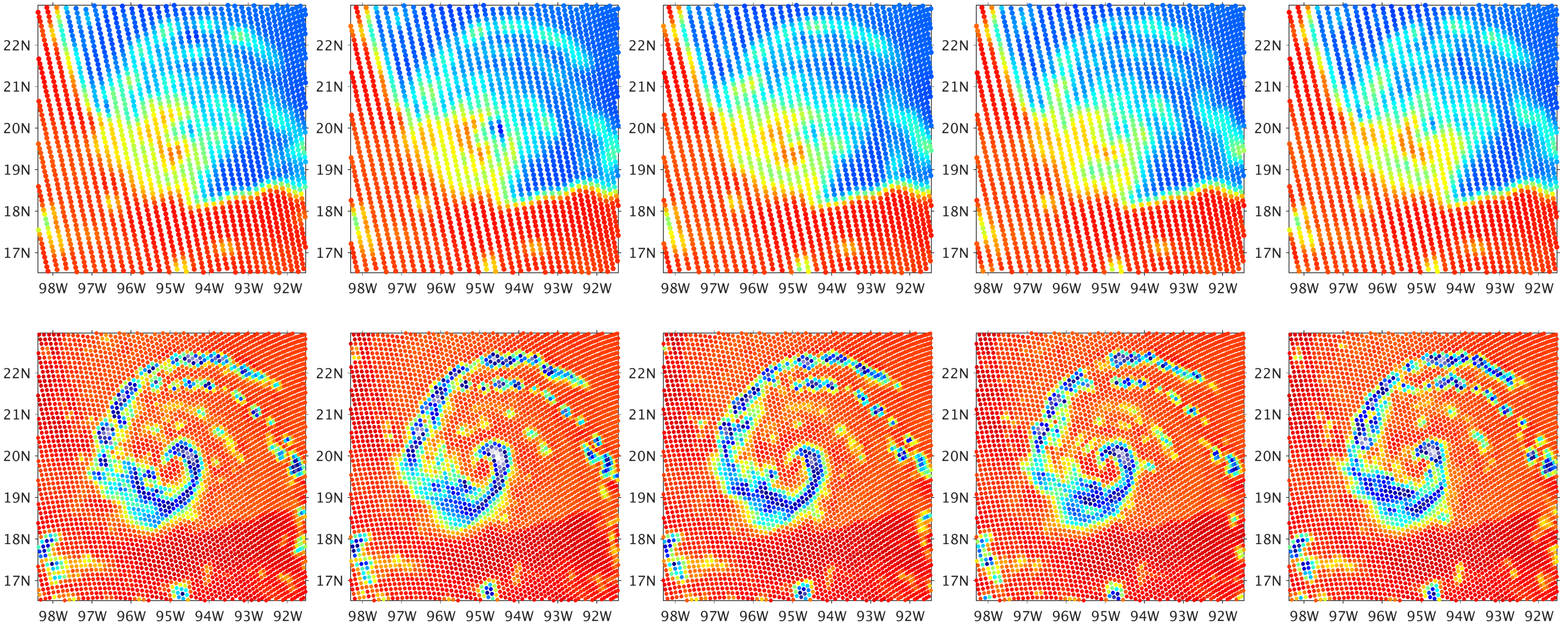
WSM6 control (Snow 100 kg/m³, Graupel 500 kg/m³)

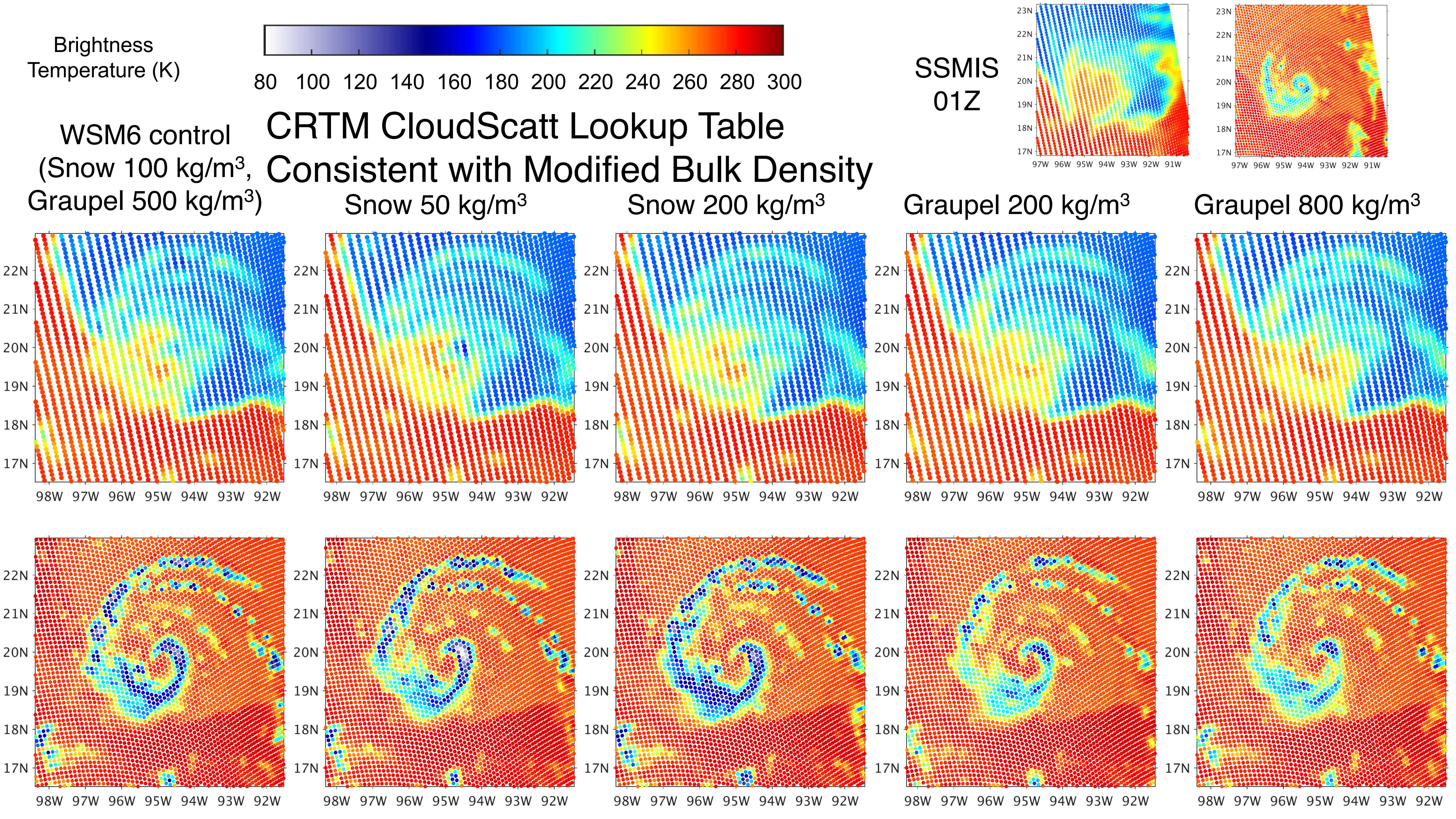
Snow 50 kg/m³

Snow 200 kg/m³

Graupel 200 kg/m³

Graupel 800 kg/m³





Brightness Temperature (K)
80 100 120 140 160 180 200 220 240 260 280 300
CRTM CloudScatt Lookup Table Consistent with Modified Bulk Density
SSMIS 01Z
WSM6 control (Snow 100 kg/m³, Graupel 500 kg/m³)
Snow 50 kg/m³
Snow 200 kg/m³
Graupel 200 kg/m³
Graupel 800 kg/m³
17N 18N 19N 20N 21N 22N 23N
97W 96W 95W 94W 93W 92W 91W
98W 97W 96W 95W 94W 93W 92W

Final Thoughts

- CRTM modified to have cloud scattering properties in microwave consistent with microphysics schemes
  - Demonstrates the variety in particle size distributions between schemes
- A tool for further research:
  - Support and study several more microphysics schemes
  - Understand sensitivities to particular species by changing parameter values
  - Assimilate observations for improved tropical cyclone forecasts