Recent Developments in the Assimilation of Microwave and Radar Observations Into NWP Models

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With thanks to: Benjamin Johnsson, Patrick Stegmann, Alan Geer,
Patrick Eriksson, Ronald Gelaro, Satya Kalluri, Will McCarty

ESSIC Seminar Series
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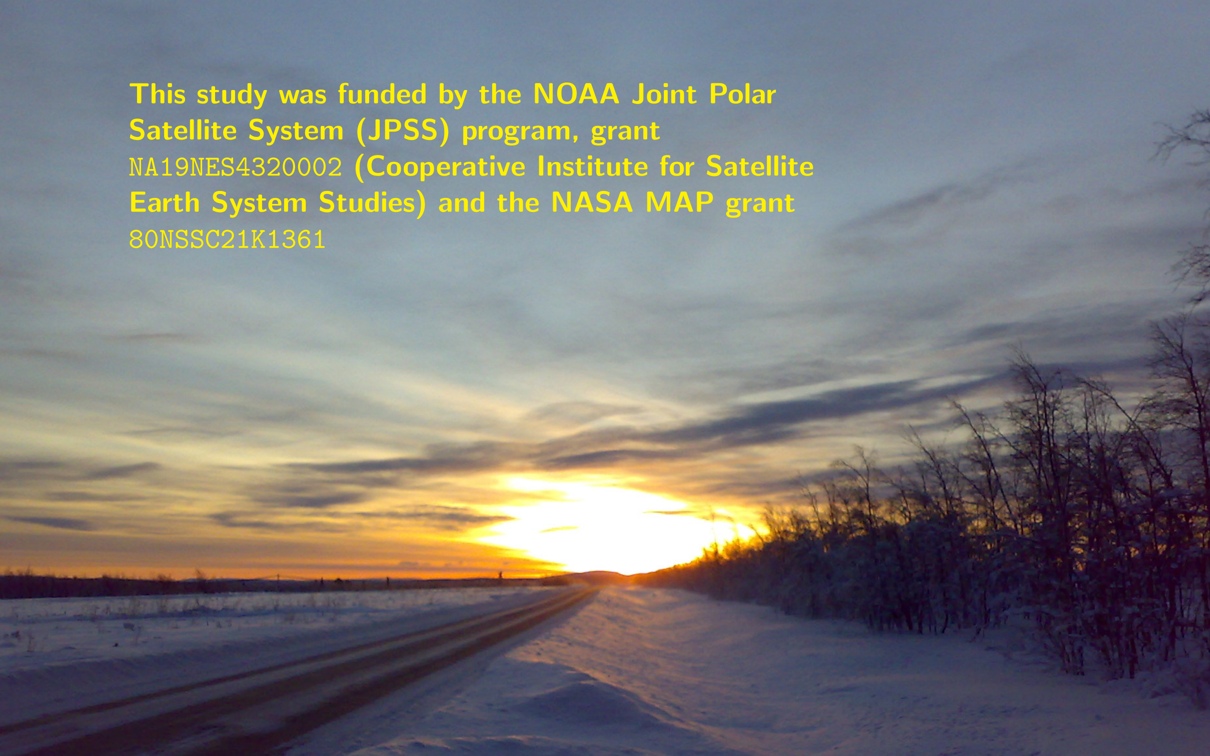

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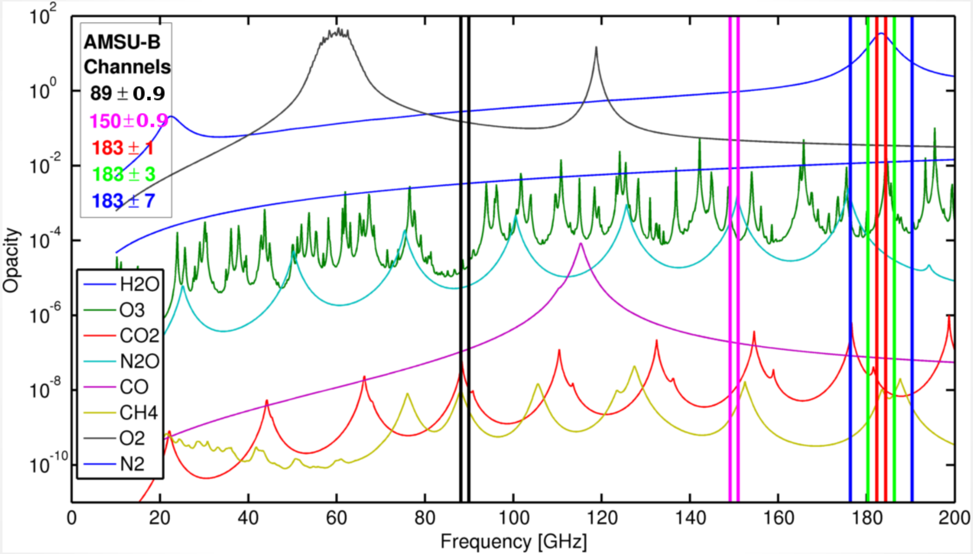
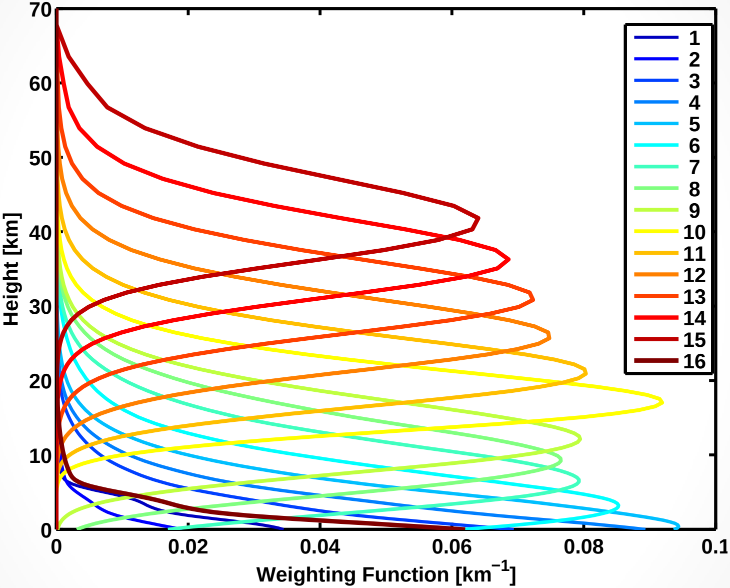
Outline

- Introduction & Importance
- The Discrete Dipole Approximation
- CRTM Bulk Scattering Properties
- CRTM Simulations for Hurricane Irma
- The CRTM Radar Simulator
- Evaluation of Radar Simulator
- Hyperspectral MW Photonic Instrument (HyMPI)

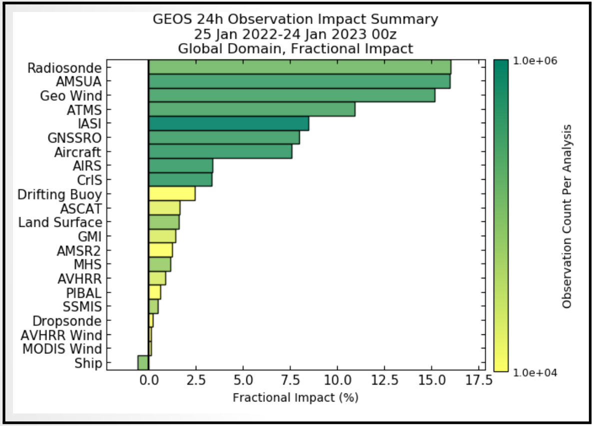
Microwave spectrum

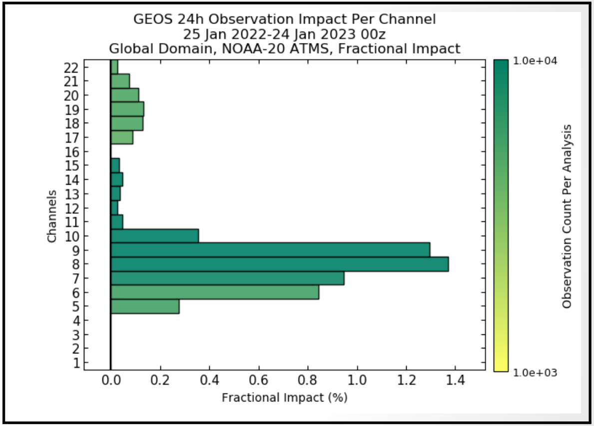


Weighting Functions



Impact of Observations on NWP Forecasts





All-weather radiative transfer calculations

Cost function for 3D-Var Data Assimilation:

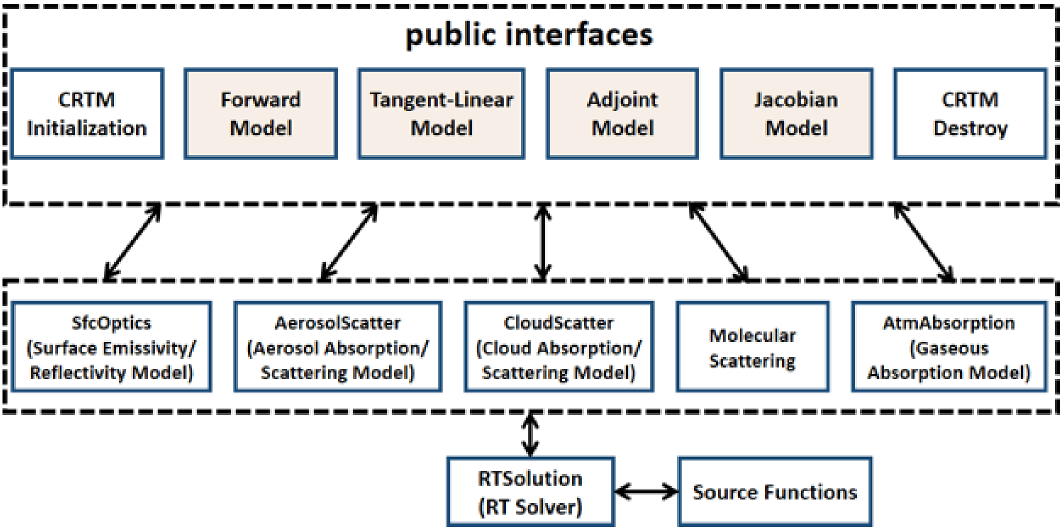
$$J(\mathbf{x}) = \overbrace{\frac{1}{2}(\mathbf{x} - \mathbf{x_b})^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x_b})}^{J_b} + \overbrace{\frac{1}{2}(H(\mathbf{x}) - \mathbf{y})^T \mathbf{R}^{-1} (H(\mathbf{x}) - \mathbf{y})}^{J_o}$$

Relation between the observations (y) and the forward operator (H) can be expressed as: $y = H(\mathbf{x}, \mathbf{p_b}, \mathbf{p_s}) + \epsilon$

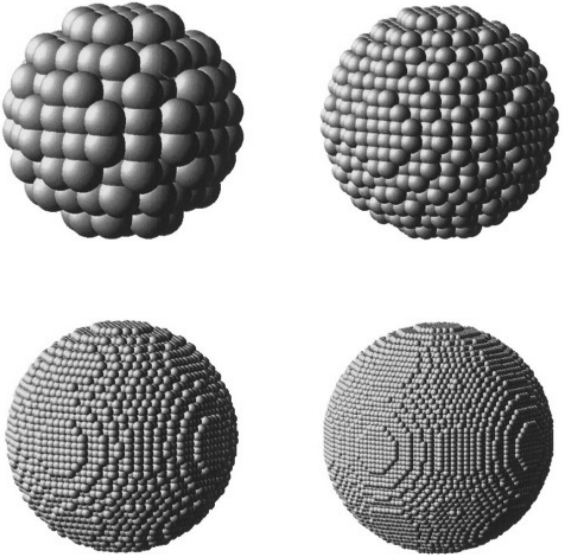
$\mathbf{x}$ state vector, $\mathbf{p_b}$ parameters such as size distribution of hydrometers, $\mathbf{p_s}$ indicates the scattering parameters (e.g., phase function, scattering coefficient, asymmetry factor)

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)!

Community Radiative Transfer Model



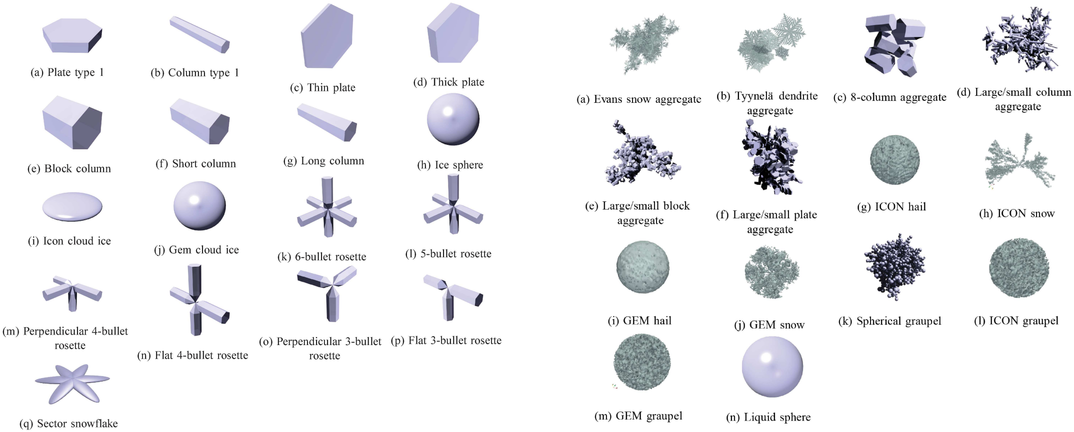
The Discrete Dipole Approximation



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.

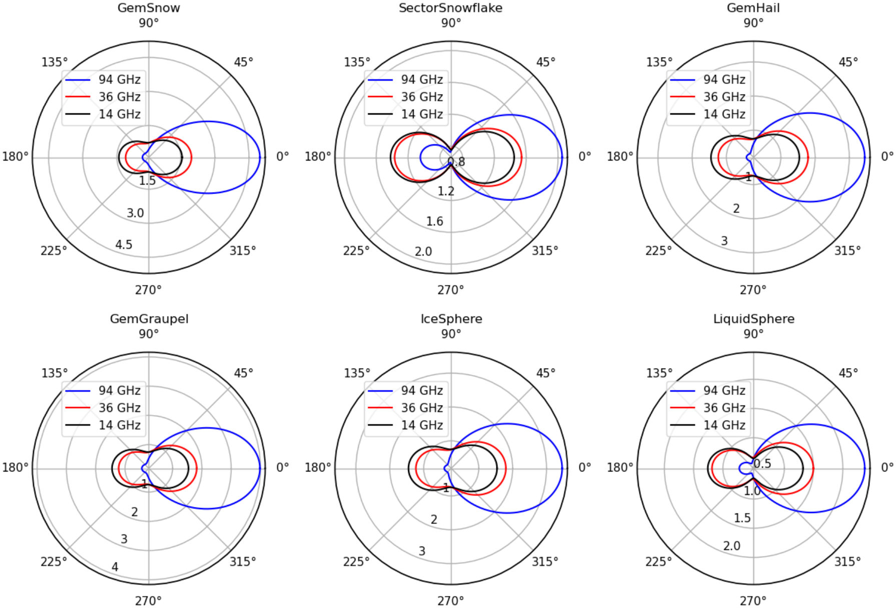
ARTS DDA Database



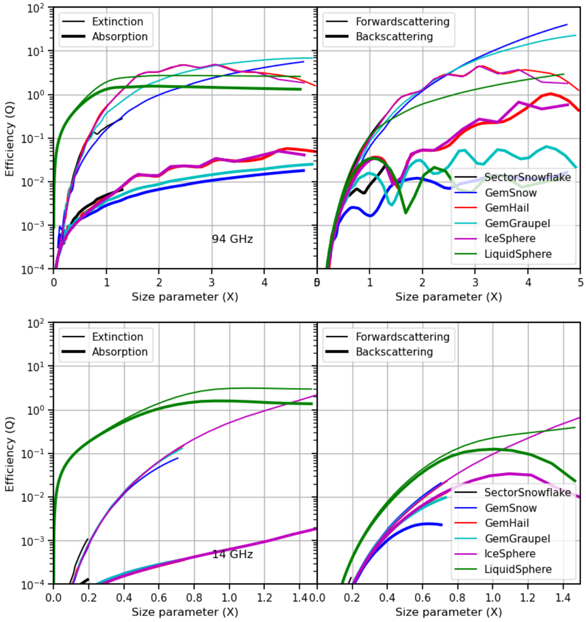
(a) Single crystal (b) Aggregates and liquid habits

Figure 4: Single crystal, aggregate, and liquid habits included in the database generated by *Eriksson et al.* (2018). Note that although habits "h" and "j" may look identical in the image, they have different aspect ratio.

The Phase Functions



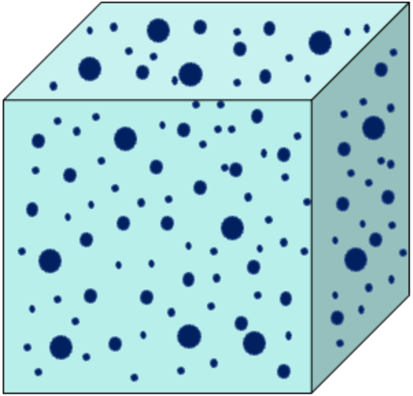
Single Scattering Efficiencies

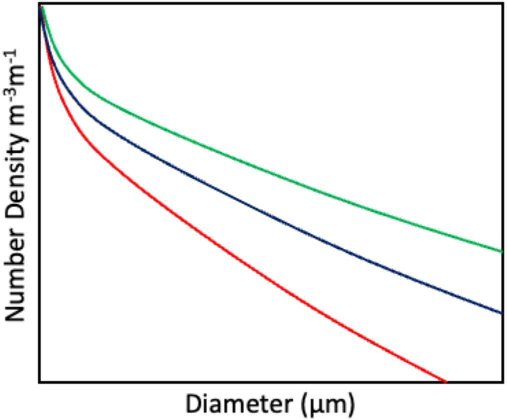


$$Q_\lambda = \frac{\sigma_\lambda}{\pi r^2} \qquad x = \frac{\pi D}{\lambda}$$

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

Particle Size Distribution

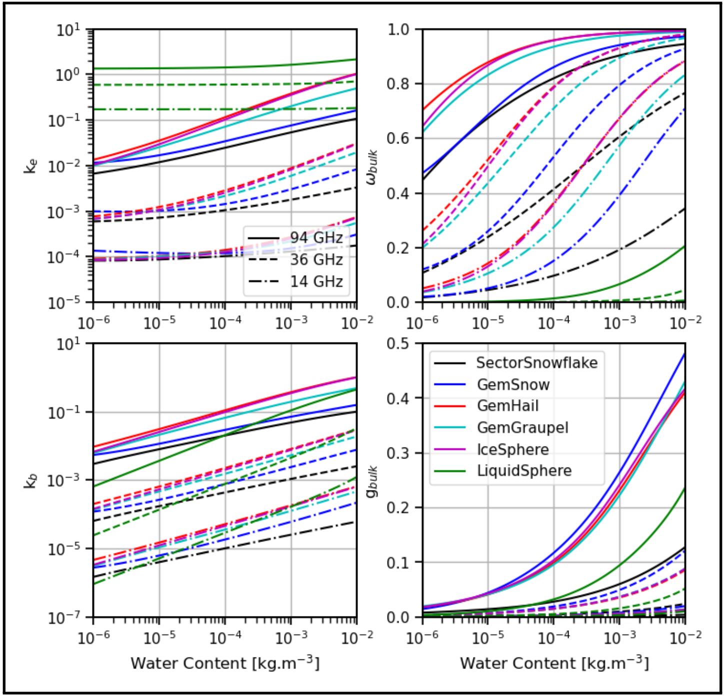




Particle size distribution is used to compute bulk scattering properties from single scattering data

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

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



CRTM mass scattering parameters computed from the ARTS database for different habits at 94 GHz, 36 GHz, and 14 GHz and a temperature of 260 K

Lookup Tables Grids

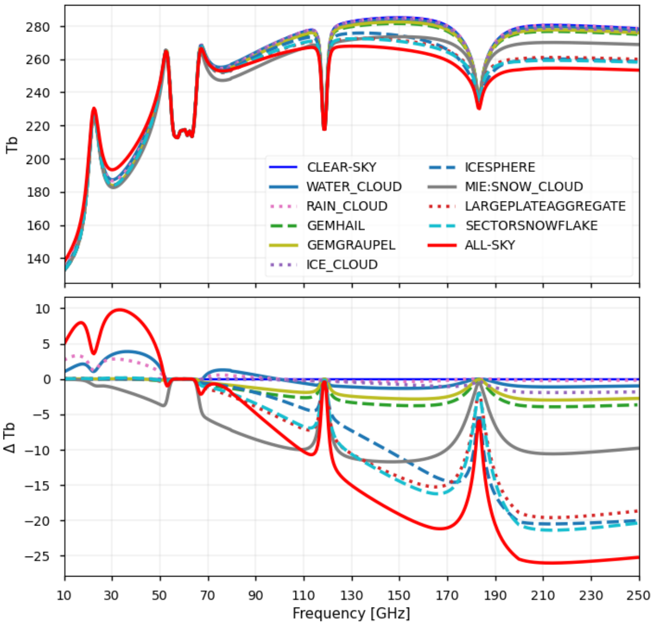
Current CRTM CloudCoeff:
dimensions:
n_MW_Frequencies = 31 ;
n_MW_Radii = 10 ;
n_IR_Frequencies = 61 ;
n_IR_Radii = 10 ;
n_Temperatures = 5 ;
n_Densities = 3 ;
n_IR_Densities = 4 ;
n_Legendre_Terms = 39 ;
n_Phase_Elements = 1 ;

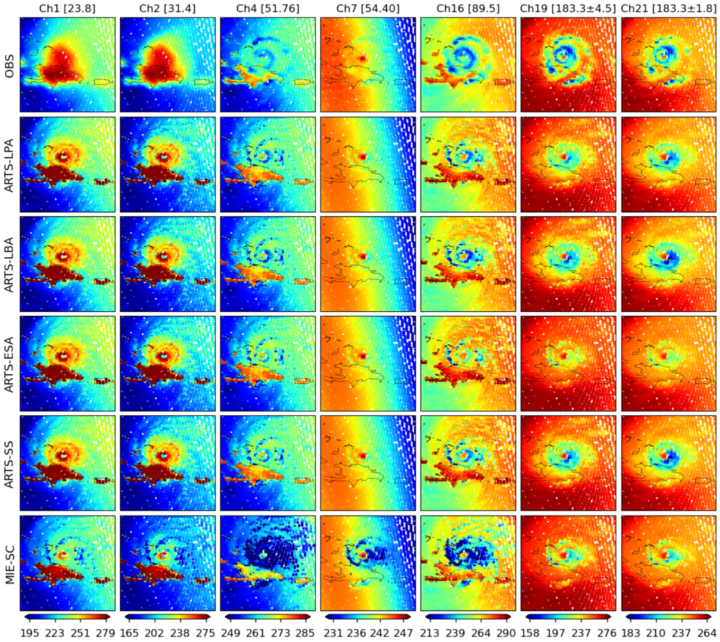
New DDA CloudCoeff:
dimensions:
n_MW_Frequencies = 200; 1-200 GHz ;
n_IR_Frequencies = 61 ;
n_MW_Radii = 200 ;
n_IR_Radii = 10 ;
n_Temperatures = 8 ;
n_MW_Densities = 18 ;
n_Phase_Elements = 1 ;
n_Legendre_Terms = 39 ;
n_IR_Densities = 4 ;

CRTM Interface Changes

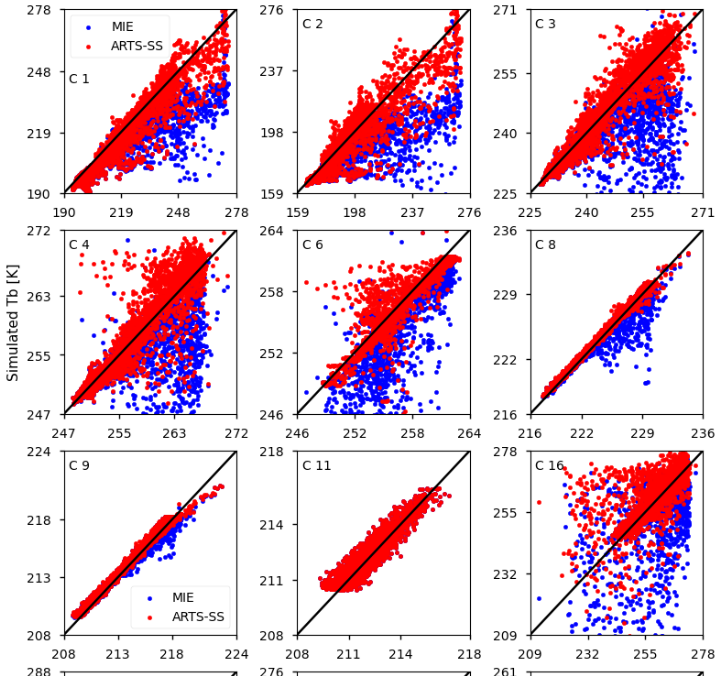
- Unless you want to use a new habit, no changes in the control files required!
- The code will check the CloudCoeff file and if Reff is not present then will use water vapor content for interpolation and ignore the effective radius even if provided.
- Effective radius is very subjective as cannot be measured so one would require to pick a method for calculating effective radius from water content, temperature, etc, but water content is often directly provided by the NWP model.
- In addition to the available cloud types (`WATER_CLOUD`, `RAIN_CLOUD`, `SNOW_CLOUD`, `GRAUPEL_CLOUD`, `ICE_CLOUD`, `HAIL_CLOUD`, which correspond to `LiquidSphere`, `LiquidSphere`, `SectorSnowflake`, `GemGraupel`, `IceSphere`, `GemHail`, the following cloud types can also be defined for the ARTS dataset (note that the word CLOUD is not required here):
  `PlateType1`, `ColumnType1`, `SixBulletRosette`, `Flat3_BulletRosette`, `Perpendicular4_BulletRosette`, `IconCloudIce`, `SectorSnowflake`, `EvansSnowAggregate`, `EightColumnAggregate`, `LargePlateAggregate`, `LargeColumnAggregate`, `LargeBlockAggregate`, `IconSnow`, `IconHail`, `GemGraupel`, `GemSnow`, `GemHail`, `IceSphere`.

Sensitivity of MW frequencies to clouds





ATMS observed vs. CRTM simulated Tbs for Hurricane Irma, Sept 07, 2017 at 18 UTC, using IFS as input (all clouds considered) and different CRTM CloudCoef files.



ATMS observed vs. CRTM simulated Tbs for Hurricane Irma, Sept 07, 2017 at 18 UTC, using IFS as input (all clouds considered) and different CRTM CloudCoef files.

Histogram Difference Index - Field 2007/Abel 2012 PSD

$$HDI = \left(\sum_{\text{bins}} \left| \log \frac{\#\text{simulated}}{\#\text{observed}} \right| \right) / \#\text{bins observed}$$

Chan Num	1	2	3	4	5	7	9	11	16	17	18	19	20	21	22	Sum
ARTS-PT1	23	39	15	30	43	44	35	49	35	58	52	40	32	26	24	546
ARTS-CT1	22	24	17	30	49	42	34	49	34	51	44	33	34	27	30	522
ARTS-SBR	23	25	16	31	49	42	34	49	39	65	60	50	39	38	30	591
ARTS-P4BR	22	24	18	32	49	43	33	49	42	64	62	49	44	36	33	601
ARTS-F3BR	22	24	18	32	46	43	33	49	42	64	62	49	43	33	32	591
ARTS-ICI	22	24	15	28	45	45	35	49	38	48	45	32	34	27	27	515
ARTS-SS	22	24	17	31	48	42	33	49	36	52	44	36	28	29	34	525
ARTS-ESA	23	25	17	35	49	42	32	49	52	74	73	62	58	54	50	696
ARTS-ECA	24	25	15	27	46	43	36	49	39	44	39	33	26	28	32	506
ARTS-LPA	24	25	14	31	40	45	35	49	37	60	56	44	37	30	28	554
ARTS-LCA	22	24	17	34	47	43	33	49	46	71	68	60	53	45	43	657
ARTS-LBA	24	25	14	29	37	44	34	49	33	50	47	34	30	33	27	509
ARTS-IS	22	24	17	30	47	43	33	49	39	66	60	47	42	32	30	582
ARTS-SC	22	24	17	31	48	42	33	49	36	52	44	36	28	29	34	525
MIE-SC	65	69	49	31	67	41	37	49	41	48	47	40	44	42	43	714

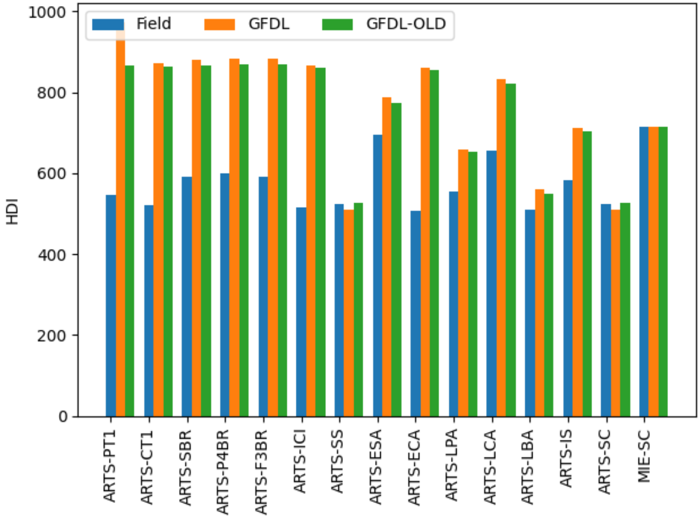
Renormalisation Factor & Choice of PSD

Geer et al. (2011) suggest using the ratio of input water content (Ψ) to implied or computed water content (Ψ_c), $r = \Psi/\Psi_c$, to scale the calculated n(D) as $n'(D) = n(D) \times r$. The implied water content (Ψ_c) can be calculated using the mass of the particles and number density as follows:

$$\Psi_c = \int_{D_{min}}^{D_{max}} m(D)n(D)dD = \int_{D_{min}}^{D_{max}} \alpha D^{\beta} n(D)dD \tag{1}$$

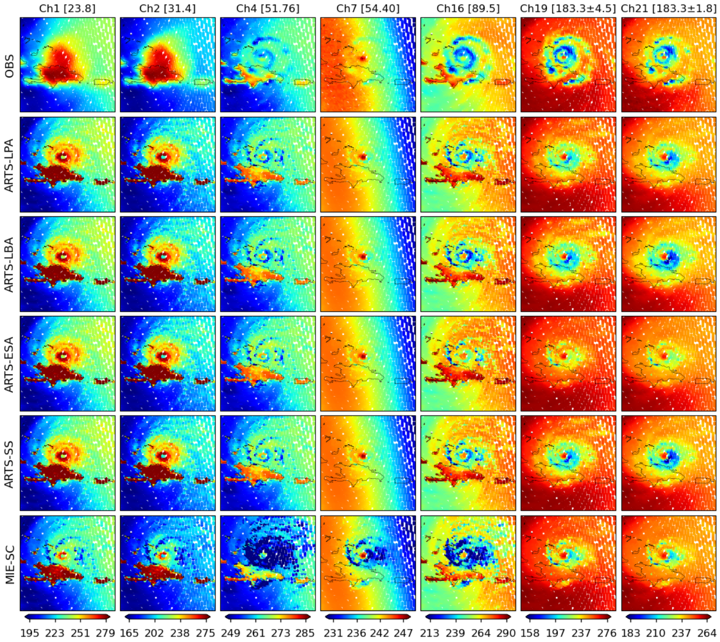
Most habits show a renormalisation magnitude ($|log10(r)|$) less than 0.1, except for `SectorSnowflake`, `LargePlateAggregate`, `LargeBlockAggregate`, and `LargeColumnAggregate` with a magnitude of renormalisation greater than 0.3. However, the renormalisation magnitudes can be very large for other PSDs.

PSD Impact on Results



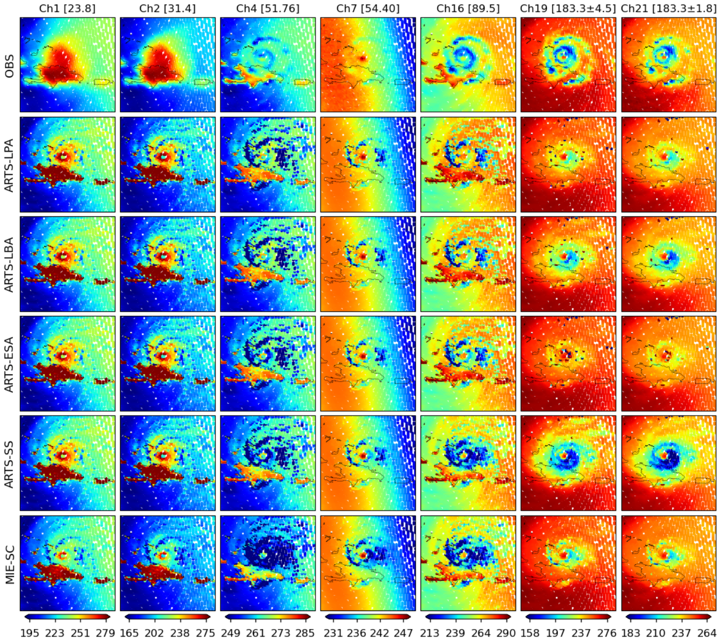
The impact of PSD on calculated Histogram Difference Index

Field 2007/Abel 2012 PSD



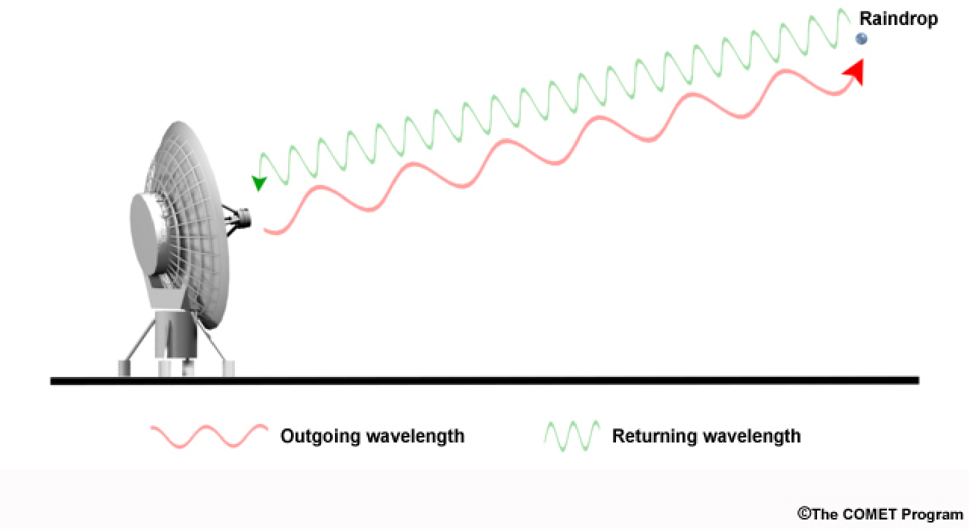
ATMS observed vs. CRTM simulated Tbs for Hurricane Irma, Sept 07, 2017 at 18 UTC, using IFS as input (all clouds considered) and different CRTM CloudCoef files.

GFDL PSD



ATMS observed vs. CRTM simulated Tbs for Hurricane Irma, Sept 07, 2017 at 18 UTC, using IFS as input (all clouds considered) and different CRTM CloudCoef files.

How active instruments work?



The radar equation

The radar equation can be formalized as follows:

$$R = \frac{10^{18}\lambda^4}{\pi^5 \left|k_w\right|^2}\beta_b \qquad m^4 \;\; m^2 m^{-4} m^1 => mm^6 \;\; m^{-3} \tag{2}$$

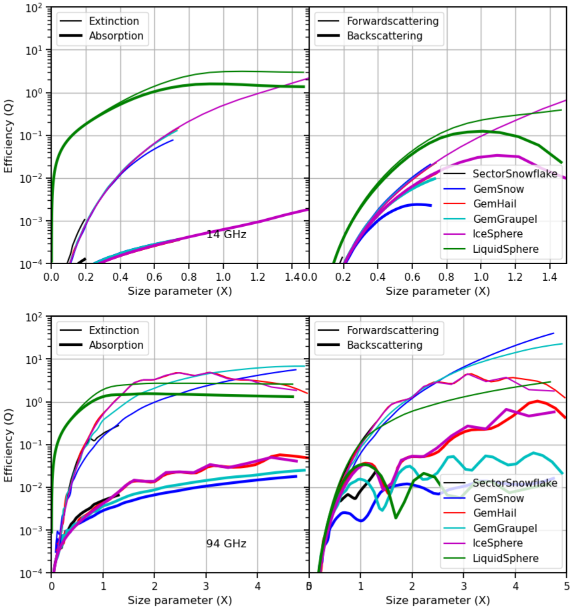
$$R_a = \frac{10^{18}\lambda^4}{\pi^5 \left|k_w\right|^2}\Gamma\beta_b \qquad m^4 \;\; m^2 m^{-4} m^1 => mm^6 \;\; m^{-3} \tag{3}$$

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

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.

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

Backscattering Coefficients

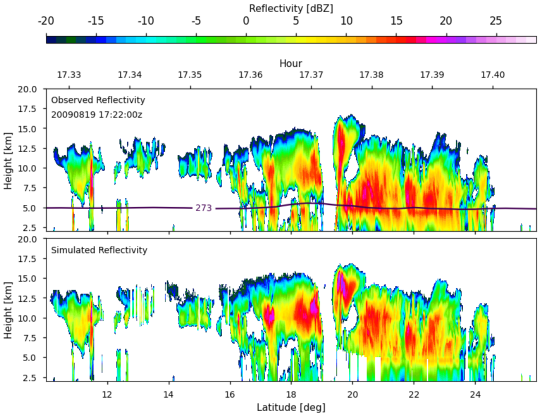


$$Q_\lambda = \frac{\sigma_\lambda}{\pi r^2} \qquad x = \frac{\pi D}{\lambda}$$

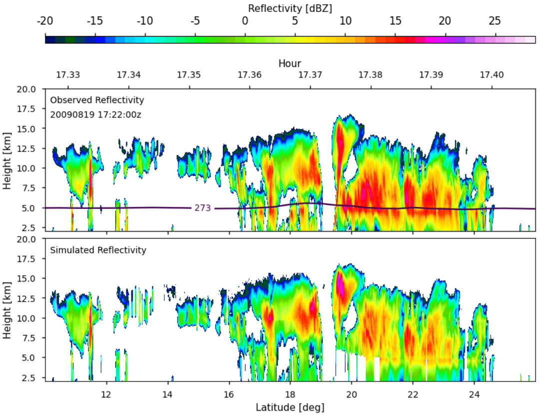
Extinction and backscattering efficiencies from the ARTS database for several different habits (Temp: 260 K)

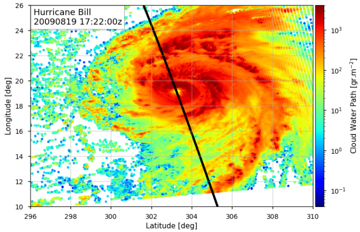
Attenuated Reflectivity (Sector Snowflake)

R_a dBz (IceSphere)



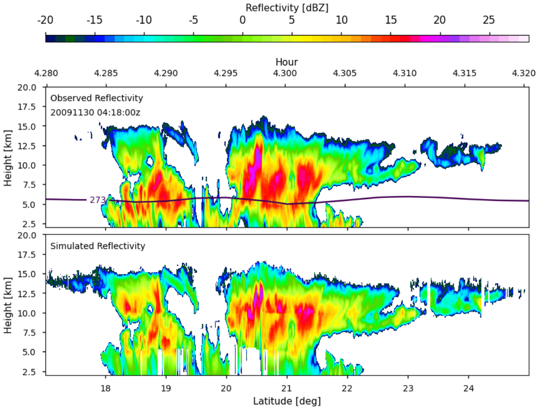
R_a dBz (ICE_CLOUD)



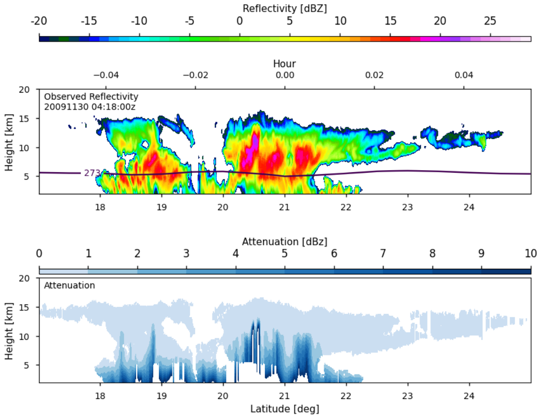


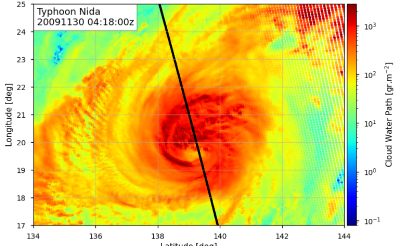
Attenuated Reflectivity (Sector Snowflake)

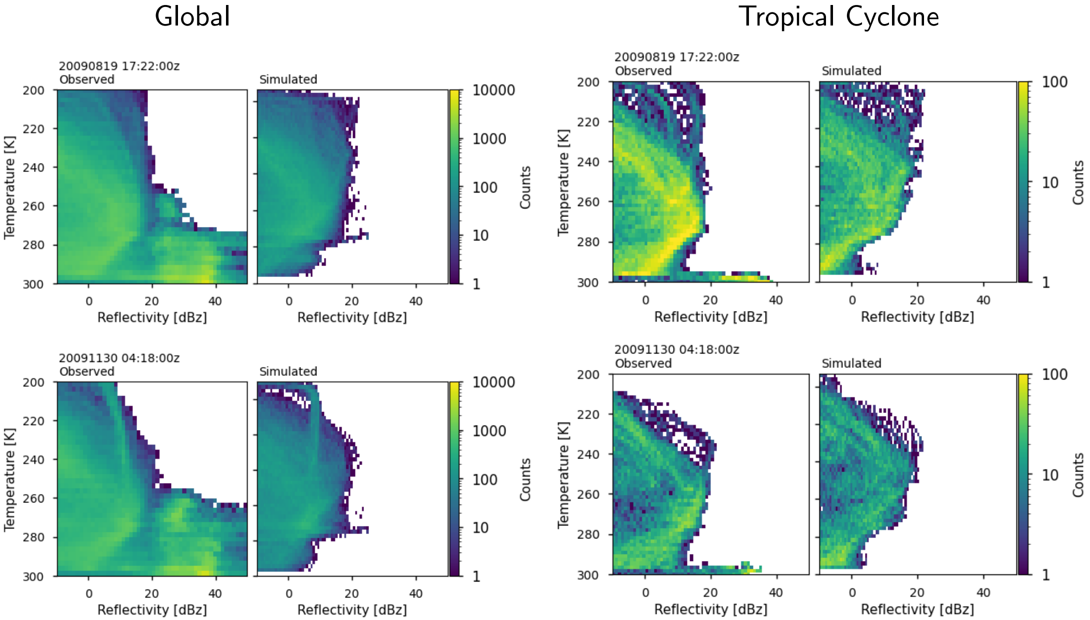
R_a dBz (IceSphere)



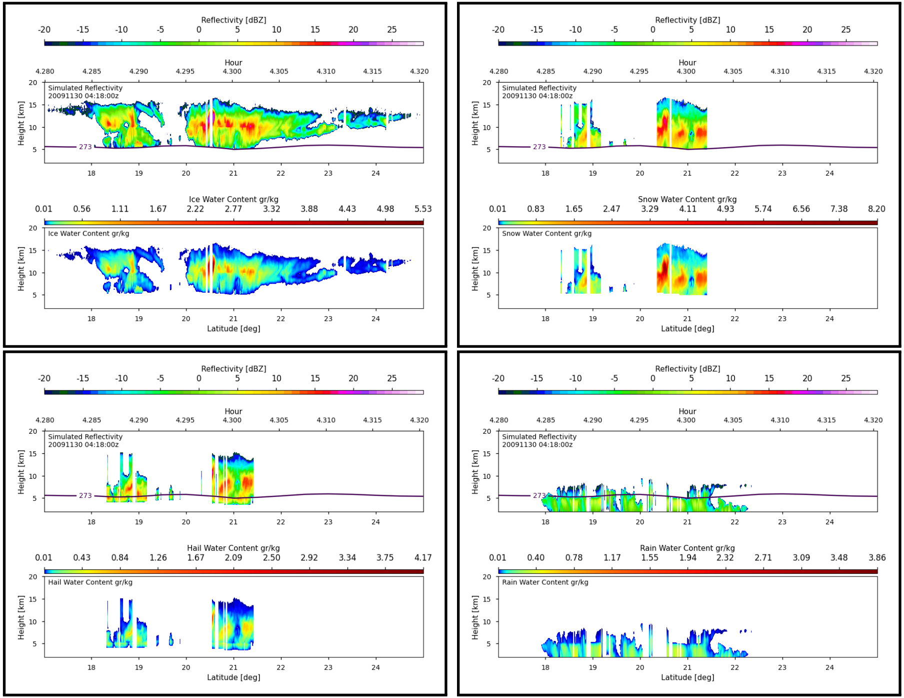
Attenuation dBz (IceSphere)







Global
Tropical Cyclone
20090819 17:22:00z
Observed
Simulated
20091130 04:18:00z
Observed
Simulated
Temperature [K]
Reflectivity [dBz]
Counts


Reflectivity [dBZ]
-20 -15 -10 -5 0 5 10 15 20 25
Hour
4.280 4.285 4.290 4.295 4.300 4.305 4.310 4.315 4.320
Simulated Reflectivity
20091130 04:18:00z
Height [km]
273
Ice Water Content gr/kg
0.01 0.56 1.11 1.67 2.22 2.77 3.32 3.88 4.43 4.98 5.53
Latitude [deg]
Snow Water Content gr/kg
0.01 0.83 1.65 2.47 3.29 4.11 4.93 5.74 6.56 7.38 8.20
Hail Water Content gr/kg
0.01 0.43 0.84 1.26 1.67 2.09 2.50 2.92 3.34 3.75 4.17
Rain Water Content gr/kg
0.01 0.40 0.78 1.17 1.55 1.94 2.32 2.71 3.09 3.48 3.86

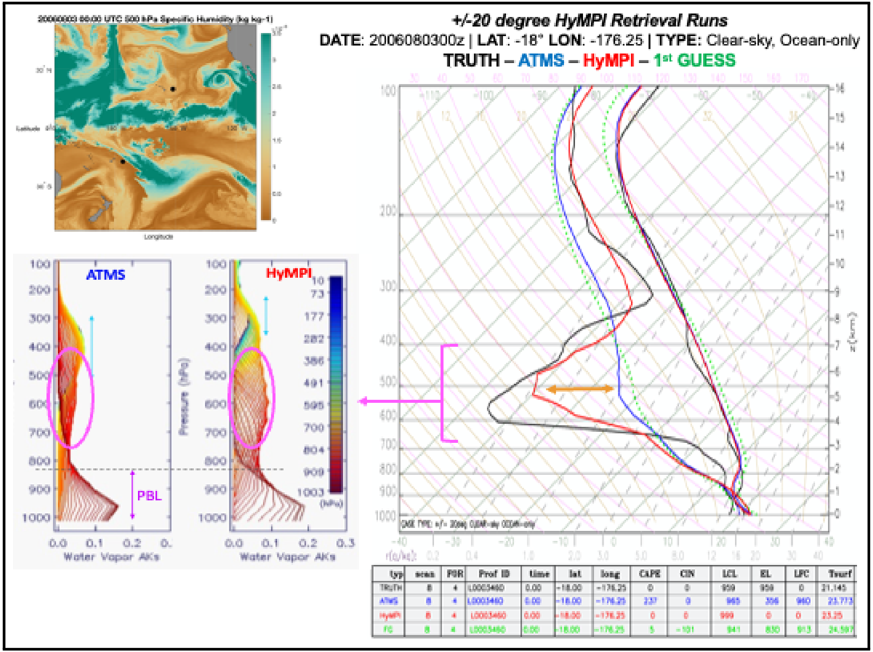
Tangent Linear and Adjoint of Active Radar Module

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

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

Hyperspectral Microwave Photonic Instrument (HYMPI)

See Gambacorta et al. (2022)



Conclusions

- A new scattering dataset generated using the DDA method was implemented into CRTM and evaluated using a collocated reanalysis and satellite dataset
- The new lookup tables no longer require parameters such as effective radius that are not provided by the model
- The new cloud coefficient is generated at much higher resolution for both frequency and mass/size
- The ARTS DDA lookup tables perform largely better than current CRTM cloud lookup tables
- CRTM radar simulator as well as its adjoint and tangent linear are implemented and tested
- 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.
- Work is in progress to evaluate the active module especially within the JEDI DA system

Thank you for your attention!

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, Under Review.

A. Gambacorta et al., "The Hyperspectral Microwave Photonic Instrument (HYMPI) - Advancing our Understanding of the Earth's Planetary Boundary Layer from Space," IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, Kuala Lumpur, Malaysia, 2022, pp. 4468-4471, doi: 10.1109/IGARSS46834.2022.9883151.

B. Johnsson, 2023. The Community Radiative Transfer Model (CRTM): Community-Focused Collaborative Model Development Accelerating Research to Operations. BAMS, Under Revision.