Characterization and quantification of ice cloud from millimeter and sub-millimeter observations

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Motivations

Accurate and realistic radiative transfer (RT) simulations are strongly required for realistic cloudy and rainy scenes at microwave to millimeter frequencies. It is possible to reproduce RT processes for real scenes by coupling Numerical Weather Prediction (NWP) simulations with RT models, then to compare with passive and active satellite measurements. However, there are large discrepancies and inconsistencies in the scattering signatures, which can be explained by several possible reasons:

- Oversimplified microphysical processes implemented in the NWP models, which induce an inaccurate representation of the frozen particle properties;
- Uncertainties in the hypotheses when coupling the NWP model simulations to the RT models. The bulk optical properties of the hydrometeors, especially the frozen particles, are difficult to model: it involves critical assumption on the size, density, shapes of the particles that are not derived from the atmospheric cloud model.

This study presents a case study, where different assumptions are tested and compared with satellite observations.

Model Configurations

- **The ECMWF 4D-Var data assimilation system** provides the atmospheric situations and vertical profiles of hydrometeor concentration, including cloud water, cloud ice, total rain (rain water mixing ratio and rain fluxes), and snow. The simulations have been provided by Alan Geer from ECMWF.
- Radiative transfer calculations are performed with the Atmospheric Radiative Transfer Simulator (**ARTS**) Monte-Carlo module and the Radiative Transfer for the Television infrared observation satellite Operational Vertical Sounder (TOVS) (**RTTOV**) for the TRMM Microwave Imager TMI frequencies (10.65, 19.35, 37, and 85.5 GHz). The RTTOV simulations have been provided by Alan Geer from ECMWF.
- **The gas absorption model** includes the Liebe MPM87 absorption model (Liebe and Layton, 1987) for water vapor, the Liebe MPM92 absorption model (Liebe et al., 1992) for oxygen, and the Liebe MPM93 model (Liebe et al., 1993) for nitrogen.
- The cloud water and cloud ice **particle size distributions** are determined by a four parameter modified gamma distribution (MGD) (Petty and Huang, 2011), while the rain and snow particle size distributions are described by Marshall and Palmer (1948) size distributions.
- **The complex dielectric properties** are calculated by using the parameterizations in Liebe et al. (1993) for the pure water. For cloud ice, the Mätzler (2006) model is chosen. The Maxwell-Garnett (1904) formula is used to account for the dielectric property of mixed-phase snow particle.
- To provide accurately ocean **surface emissivities**, the fast microwave emissivity model (FASTEM-5, Liu et al., 2011) has been coupled with ARTS.

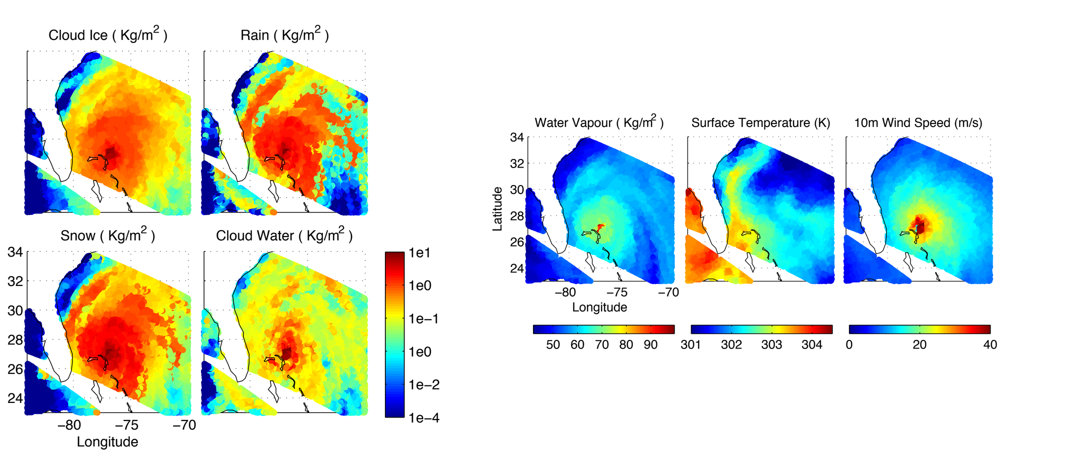
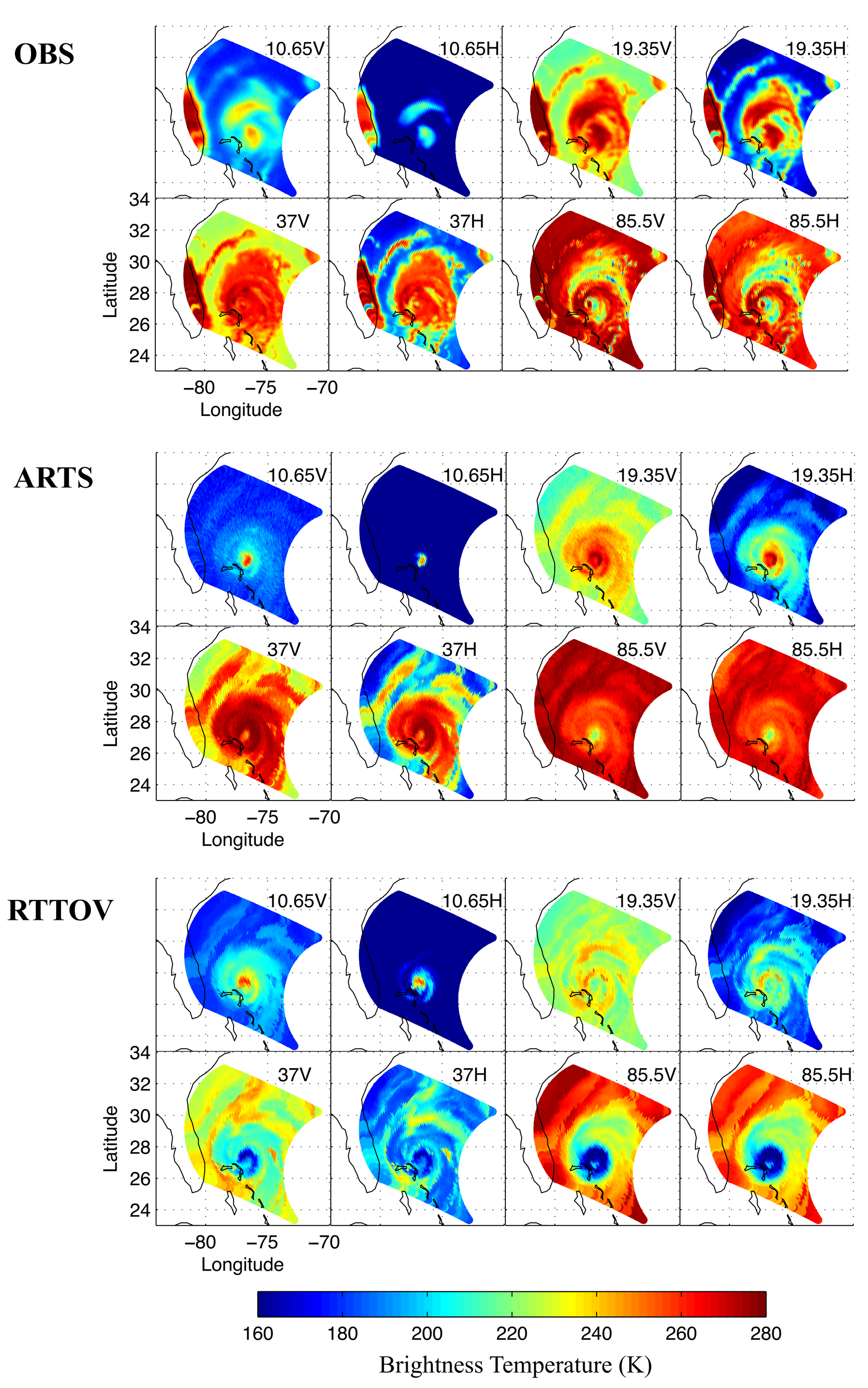


Fig-1. The hydrometeors and water vapor mass concentrations, surface temperature, and the 10 m wind speed of the hurricane Irene obtained from the ECMWF 4D-Var data assimilation system for Irene case on 25 August 2011 at TMI over-pass time (21:18 UTC).
The hurricane Irene was a large and strongly destructive tropical cyclone, which impacted significantly the Caribbean and the regions along the United States east coast during 20-30 August 2011.

Table 1. Definition of particle size distribution, shapes, and densities

Hydrometeor	PSD function	PSD parameters	Shape	Density (kg m^{-3})
Rain	$n(D) = n_0 e^{-\Lambda D}$	$n_0 = 8\times10^6$ $\lambda = 41R^{-0.12}$ cm^{-1} R is the rate of rainfall in mm hr^{-1}	sphere	1000
Snow	$n(D) = n_0 e^{-\Lambda D}$	$n_0 = 8\times10^6$ $\lambda = 41R^{-0.12}$ cm^{-1} R is the rate of snowfall in mm hr^{-1}	sphere	100
Cloud water	$n(D) = n_0 D^{\mu} e^{-\Lambda D}$	$\Lambda = 2.13\times10^5$ $\mu = 2$	sphere	1000
Cloud ice	$n(D) = n_0 D^{\mu} e^{-\Lambda D}$	$\Lambda = 2.05\times10^5$ $\mu = 2$	sphere	900

Comparison Between Satellite Observations and Simulations



- At lower frequencies (10.65, 19.35, and 37 GHz), the warmer brightness temperature areas observed by TMI are correctly represented by ARTS but with some spatial shifts related to the imperfect ECMWF reproductions.
- At 85 GHz, a significant overestimation of simulated radiance by ARTS appears especially in the region covered by abundant cloud frozen quantities, which demonstrates the sensitivity of this channel to the frozen contents.
- RTTOV-SCATT produces stronger scatter signals than observations at 37 and 85.5 GHz. The strong scattering at 37 GHz is very questionable and puzzeling.

Fig-2. TMI observations as compared with ARTS-MC and RTTOV-SCATT simulations using the initial parameters in ECMWF microphysical scheme.

Sensitivity of the Microwave Simulations to the Hydrometeor Characteristics

Eight simulations (described in Table 1) are performed with various changes in the snow microphysical parameters. All the tests were implemented under the precondition that we keep the same total mass for snow particles, except for the tests D and I.

Table 2. Summary of the experiments

Test	The changes of parameters
A	The original ECMWF microphysical scheme
B	The perfect spheres are replaced by horizontally aligned spheroids with aspect ratio 1.6
C	The original particle size distribution is changed to Field et al. (2007) particle size distribution
D	The snow mass content is multiplied by 1.25
E	The fixed snow density is changed with a size-density relationship from Fabry and Szyrmer (1999)
F	The density of snow is set to 250 kg m^{-3}
G	The discrete dipole approximation (DDA) calculation from Lui for sector particles are used to calculated the single scattering properties (SSPs)
H	The DDA Liu dendrite are used to calculated the SSPs
I	The DDA Liu sector are used to calculated the SSPs and the snow mass content is multiplied by 1.25

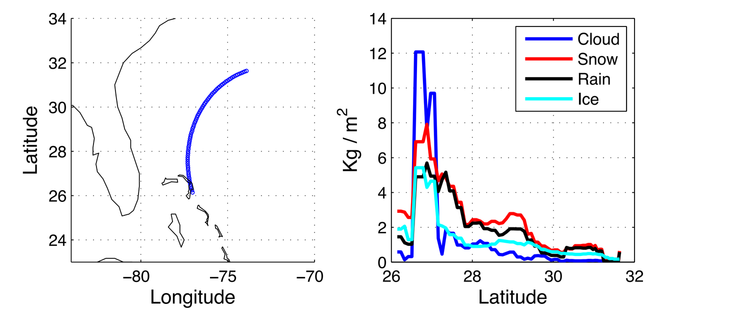


Fig-3. Left panel: location of selected transect for our sensitivity studies with the TMI. Right panel : integrated mass concentrations of the different ECMWF hydrometeors along both transects mentioned in left panel.

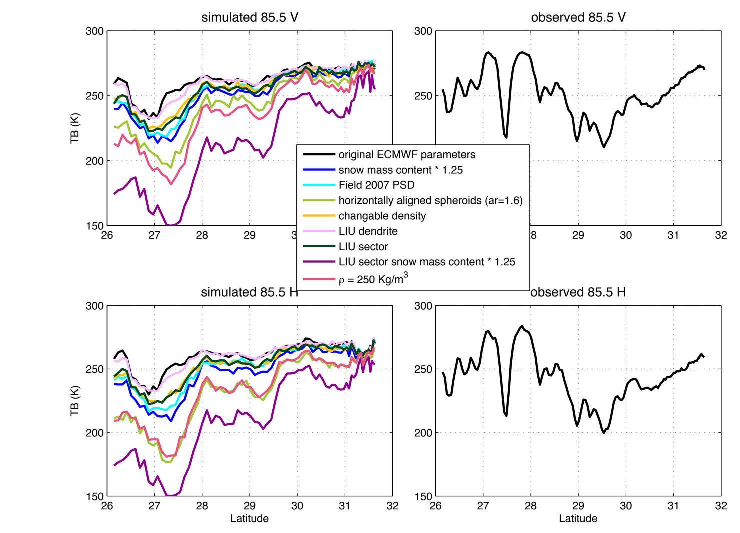


Fig-4. The observed and simulated brightness temperatures under different microphysical properties of snow at 85.5 GHz for the transect of interest.

- When we change some assumptions about the snow particle mass content, particle shape, and PSD, the changes in the brightness temperatures are less than 10 K.
- Density is a key parameter in calculating the bulk properties. The larger snowflakes could not scatter efficiently with the lower density.
- The DDA Liu database for sector snowflakes is very effective in reproducing realistic scattering parameterizations for snowflakes under the condition of a reasonable snow content.

Comparison between RT models RTTOV and ARTS

The ARTS and RTTOV simulations are performed with the same atmospheric profiles from ECMWF for clear sky and cloudy conditions.

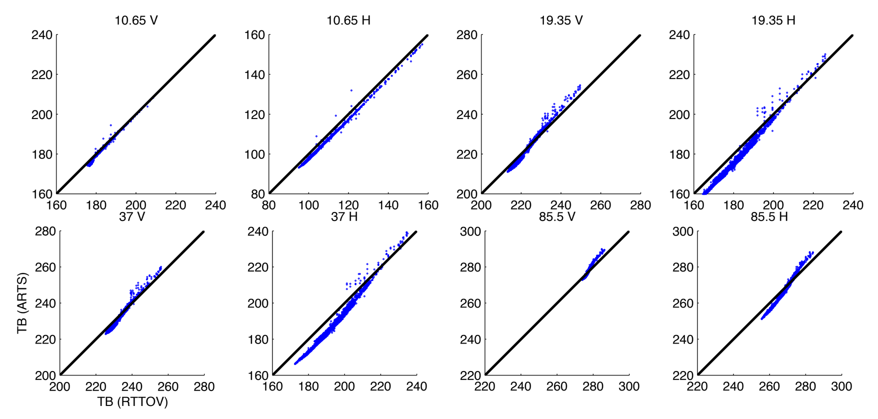


Fig-5. TBs simulated by RTTOV-SCATT against the TBs simulated by ARTS at TMI frequencies under 'clear sky' for Irene case, which means we did not consider the cloud particles in the RT simulations.

- The radiances from RTTOV-SCATT and ARTS reach a good agreement under clear sky.
- When four hydrometeors (cloud liquid water, cloud ice, rain, and snow contents) are considered, radiance differences from the two models are substantially greater, at 37 and 85.5 GHz.

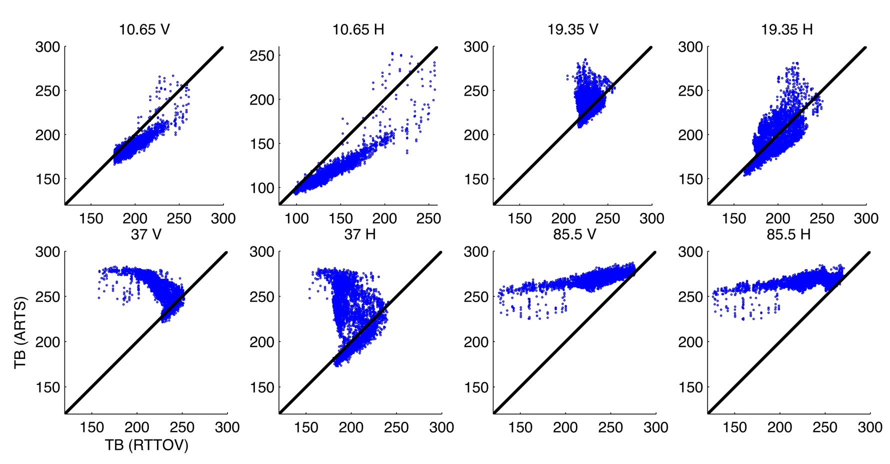


Fig-6. TBs simulated by RTTOV-SCATT against the TBs simulated by ARTS at TMI frequencies turning on the cloud box.

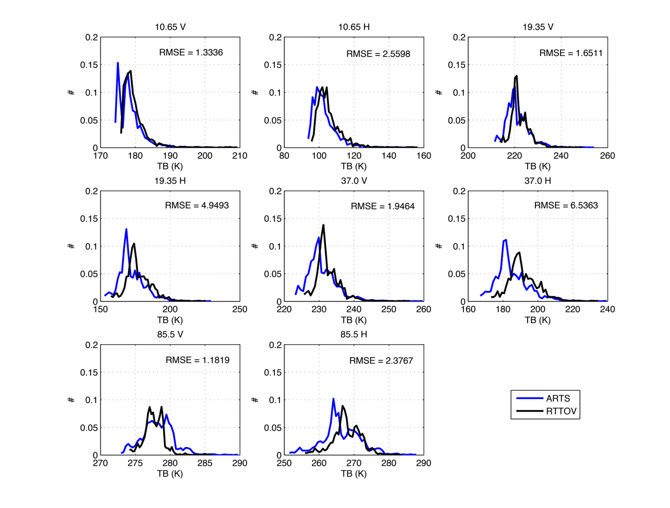


Fig-7. Normalized histograms of the simulated TBs by ARTS and RTTOV-SCATT in selected TMI channels for Irene case without considering the cloud cover.

Still work to be done to explain the differences in the models in the presence of clouds. Critical assumptions on the frozen quantities have to be refined and tested under a large range of conditions.

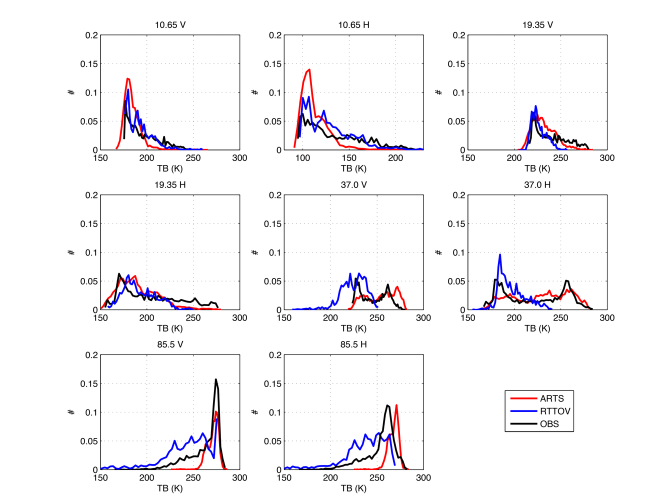


Fig-8. Normalized histograms of observed and simulated TBs (by ARTS and RTTOV-SCATT) in selected TMI channels.

Conclusions

- The RT processes are greatly sensitive to the details in microphysical properties (density, size, and shape) of frozen hydrometeors. The DDA Liu database for sector snowflakes appears very effective in reproducing realistic scattering for snowflakes under the condition of a reasonable snow content.

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