A Model for Polarized Microwave Radiative Transfer in the CRTM

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Introduction

Many satellite instruments exploit polarization to observe properties of clouds, precipitation, aerosols and different surface types. For example, observations at millimeter-wave wavelengths have detected frequent polarization signatures generated by large horizontally-oriented non-spherical ice particles in precipitating systems from the tropics to the high latitudes.[1,2] Using these observations effectively in NWP data assimilation requires an accurate polarized radiative transfer (RT) model. This can be largely achieved by assuming non-spherical particles instead of soft spheres for scattering calculations and matching the particle size distributions (PSDs) assumed in computing the bulk scattering properties with those used in the NWP models.[3,4]

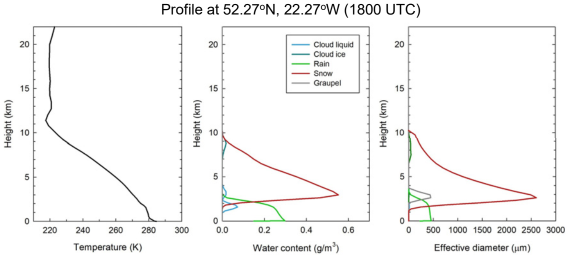
Our goal is to develop a new RT model for computing polarimetric microwave radiances for use in the JCSDA Community Radiative Transfer Model (CRTM). We will examine the polarization signatures of snow for the GPM Microwave Imager (GMI) 89 and 166 GHz channels for simulated clouds using state-of-the-art single scattering properties of non-spherical particles while ensuring that the PSD used in computing the bulk scattering properties is consistent with the cloud simulation.

Methods

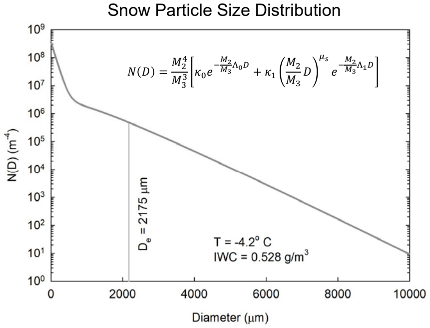
Cloud simulation

- Large-scale Weather Research & Forecasting (WRF) model v2.2 simulation for 4 June 2005 (6 km horizontal grid spacing).
- Thompson microphysics (cloud liquid, cloud ice, rain, snow, graupel)[5]; snow PSD is a combination of exponential and gamma distributions (see below); snow habit assumed to be primarily fractal-like aggregates of crystals.

Profile at 52.27°N, 22.27°W (1800 UTC)



Snow Particle Size Distribution



Bulk scattering properties of snow

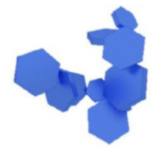
- Ice particle scattering database for frequencies 1-874 GHz, 12 ice habits and maximum particle dimensions from 2 mm to 10 mm.[6] Randomly oriented particles are assumed. Calculations are based on Invariant Imbedding T-Matrix method and the Improved Geometric Optics Method; includes temperature dependence of ice refractive index.
- Snow particles were represented as an aggregate of 10 plates (see below).
- Bulk properties (extinction coefficient σ_{ext}, scattering coefficient σ_{sca}, single-scattering albedo ω_0, phase matrix $\mathbf{P}(\Theta)$) were integrated over the snow PSD as follows:

$$\sigma_{ext} = \int_{D_{min}}^{D_{max}} A(D) Q_{ext}(D) N(D) dD$$

$$\sigma_{sca} = \int_{D_{min}}^{D_{max}} \omega_0(D) A(D) Q_{ext}(D) N(D) dD$$

$$\omega_0 = \frac{\sigma_{sca}}{\sigma_{ext}}$$

A is projected area of particle
Q_{ext} is extinction efficiency

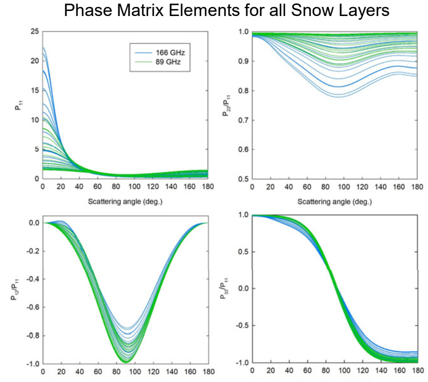


10-plate aggregate

$$\mathbf{P}(\Theta) = \frac{1}{\sigma_{sca}} \int_{D_{min}}^{D_{max}} \mathbf{P}(\Theta, D) \omega_0(D) A(D) Q_{ext}(D) N(D) dD$$

$$\mathbf{P}(\Theta, D) = \begin{bmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{21} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & P_{34} \\ 0 & 0 & P_{43} & P_{44} \end{bmatrix}$$

Phase Matrix Elements for all Snow Layers



Polarized microwave model

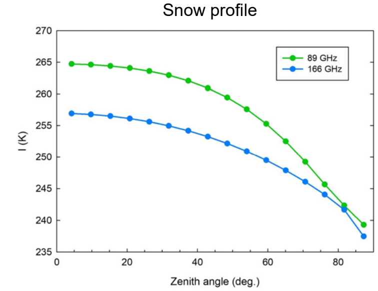
- Extension of the Successive Order of Interaction (SOI) model[7], developed at UW and one of the multiple scattering solvers in the CRTM.
- Assumes Fresnel surface reflectance
- For randomly oriented particles of arbitrary shape; azimuthal mean phase matrix is computed numerically.[8]
- Only I and Q Stokes parameters are considered since U=V=0 for an azimuthally-averaged radiance field

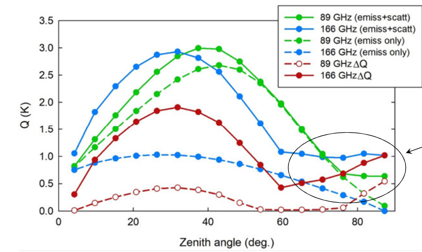
Comparison of current model with a polarized doubling-adding model for a 2-layer atmosphere test case.[9]

Quad point	Polarized DA		Polarized SOI	
	I	Q	I	Q
0.09501	111.89	0.68	112.79	2.14
0.28160	154.71	2.81	154.54	2.29
0.45802	184.41	4.66	183.76	4.86
0.61788	200.67	5.44	199.84	6.21
0.75540	208.90	4.71	208.16	5.70
0.86563	212.88	3.08	212.35	3.94
0.94458	214.70	1.41	214.38	1.79
0.98940	215.43	0.28	215.26	0.30

Results

Snow profile





Anomalous values suggest a phase matrix normalization issue

- At 89 GHz, Q almost entirely results from depolarization of the highly polarized ocean surface by atmospheric absorption/emission
- At 166 GHz, a polarization signature (ΔQ) of almost 1 K is generated by the snow particles at the GMI Earth-incidence (zenith) angle of 52.8°. However, the maximum signature of 1.9 K occurs at a zenith angle of about 32°.

Conclusions

- A new microwave RT model has been developed to study the polarization characteristics of randomly-oriented non-spherical snow particles
- Early results show these particles can generate significant polarization signatures.
- Further tests of the model are needed as well as a reformulation for consistency with the Advanced Matrix Operator Method[10] in CRTM alpha v3.0.

References

[1]Galligani et al., 2013, J. Geophys. Res. Atmos., 118, 5667–5678, doi:10.1002/jgrd.50431.
[2]Zeng et al., 2019, J. Climate, 32, 3-13, https://doi.org/10.1175/JCLI-D-18-0293.1.
[3]Kulie et al., 2010, J. Atmos. Sci., 67, 3471-3487, https://doi.org/10.1175/2010JAS3520.1.
[4]Sieron et al., 2017, J. Geophys. Res. Atmos., 122, 7027–7046, doi:10.1002/2017JD026494.
[5]Thompson et al., 2008, Mon. Wea. Rev., 136, 5095-5115, https://doi.org/10.1175/2008MWR2387.1.
[6]Ding et al., 2017, J. Quant. Spectrosc. Rad. Transfer, 190, 26-37, doi.org/10.1016/j.jqsrt.2016.11.026
[7]Heidinger et al., 2006, J. Appl. Meteorol. Climatol., 45, 1388-1402, https://doi.org/10.1175/JAM2387.1.
[8]Liou et al. 2005, J. Atmos. Sci., 62, 2542-2554, https://doi.org/10.1175/JAS3476.1.
[9]Evans, K. F., and G. L. Stephens, 1991, J. Quant. Spectrosc. Rad. Transfer, 46, No. 5, 413-423.
[10]Liu, Q., and C. Cao, 2019, J. Quant. Spectrosc. and Rad. Transfer, 226, 115-126.

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