Uncertainty characterization of sub-mm and MW in all-sky radiative transfer

Vasileios Barlakas, Patrick Eriksson, Robin Ekelund
Why ice clouds?

- Cover ~30% of the Earth
- A significant role in the energy budget
- Large uncertainties in numerical weather prediction (NWP) and climate models
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- Sensitive to both large and small ice hydrometeors.
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Ice Cloud Imager (ICI)
- 183.31–664 GHz (15 km footprint)
- Improved ice cloud representation
- Extend the scope of MW assimilations
In stand-alone retrievals and data assimilation (DA), several assumptions are still employed:

- particle size distributions (PSDs) and particle models (PMs) are poorly considered,
- three-dimensional (3D) radiative transfer is ignored.

① Can combined active and passive measurements be used to constrain ice PMs?
② Are retrievals at mm/sub-mm wavelengths affected by 3D effects?
Using passive and active microwave observations to constrain ice particle model

Can we constrain ice particle models?

Synthetic scenes

- DARDAR IWC
- ERA data
- Scene generator
- ARTS

Data and tools:
- CloudSat orbits: 59 (July 2015) over Tropics
- PSD: (a) Field et al., 2007 (F07)
  - (b) McFarquhar & Heymsfield, 1997 (MH97)
- GMI-wise simulations vs observations
- ICI-wise simulations

ARTS scattering database
- 34 freq.: 1-886.4 GHz
- 34 particle models (PM)
- 35-45 sizes per PM
- Method: DDA
  - Eriksson et al., 2018
Can we constrain ice particle models?

Brightness temperature distributions – 190.31 GHz

Input: DARDAR IWC

Input: CloudSat dBZ

PSD used: F07

Ekelund et al., 2019
Can we constrain ice particle models?

Brightness temperature distributions – 190.31 GHz

Input: DARDAR IWC

- 8-column aggregate
- Evans snow aggregate
- ICON cloud ice
- ICON snow
- Large block aggregate

Input: CloudSat dBZ

- Large column aggregate
- Large plate aggregate
- Sector snowflake
- DARDAR spheroid
- GMI

PSD used: F07

Ekelund et al., 2019
Can we constrain ice particle models?

Brightness temperature distributions – 190.31 GHz

**PSD: F07t**
- 8-column aggregate
- Evans snow aggregate
- ICON cloud ice
- ICON snow
- Large block aggregate

**PSD: MH97**
- Large column aggregate
- Large plate aggregate
- Sector snowflake
- DARDAR spheroid
- GMI

Ekelund et al., 2019
Can we constrain ice particle models?

Brightness temperature distributions – 668.20 GHz

Compared to 190.31 GHz:

- Larger spread at intermediate $T_b$
- DARDAR spheroid the most significant outlier

Input: CloudSat dBZ

PSD used: F07

Ekelund et al., 2019
Summary

- Overall, $T_B$-distributions agree well with GMI observations.
- Most particle models perform well compared to GMI at intermediate $T_B$-values.
- Of tested PSDs, the one by McFarquhar and Heymsfield (1997) leads to smaller discrepancies.
- At sub-mm wavelengths, a significantly higher sensitivity to the assumed particle models is found.

Outlook

- Apply methodology to ICI measurements when available.
Three Dimensional Radiative Effects in Passive mm/sub-mm All-sky Observations

Barlakas and Eriksson., *Remote Sens.*, 2020
Calculation modes – 3D, IBA, 1D

1) A 3D mode (ARTS-MC)
Calculation modes – 3D, IBA, 1D

1) A 3D mode (ARTS-MC)

\[
\begin{array}{ccc}
\beta_1 & \beta_2 & \beta_3 \\
\beta_4 & \beta_5 & \beta_6 \\
\beta_7 & \beta_8 & \beta_9 \\
\end{array}
\]

2D slice of 3D
Calculation modes – 3D, IBA, 1D

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1) A **3D** mode (ARTS-MC)

<table>
<thead>
<tr>
<th>$\beta_1$</th>
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Calculation modes – 3D, IBA, 1D

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3D Radiative effects

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1) 2D slice of 3D

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2) IBA

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2) IBA

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Calculation modes – 3D, IBA, 1D

1) A 3D mode (ARTS-MC)
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3) Plane-parallel approx. (1D) mode (DISORT)
   ✓ Hydrometeor Number Density – average (HND-avg)
   ✓ Hydrometeor Content – average (HC-avg)
3D Radiative effects

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Settings:
- Freq.: 186.3 & 668 GHz
- FOV–Gauss: 6 & 15 km

2D slice of 3D

IBA

1D
**Calculation modes – 3D, IBA, 1D**

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**Post-processing:**
- Simulations in 2km grid
- Average over FOV

**Settings:**
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**Hydrometeor Impact:**

\[ \Delta T_B = T_{B,\text{cloudy}} - T_{B,\text{clear}} \]

**3D vs IBA** ➔ **Horizontal Photon Transport (HPT) effect**

\[ \Rightarrow \text{Neglect of HPT along areas with different properties} \]

**IBA vs 1D** ➔ **Beam–Filling (BF) effect**

\[ \Rightarrow \text{Neglect of domain heterogeneities} \]

**3D vs 1D** ➔ **Total Effect**
CloudSat dBz

ERA data

Scene generator

3D fields of dBz

CloudSat dBz

CloudSat overpasses:
- Tropics: 30 (July 2015) => 55 scenes
- Mid-Latitudes: 29 (January 2015) => 58 scenes
- Each scene: 160 km by 200 km
CloudSat dBz
ERA data
Scene generator

PSD: MH97 F07

3D fields of dBz

3D fields of IWC & RWC

x = F(y) - 1

3D Radiative effects – Synthetic scene

Filtering radar reflectivity
Example slice of surrogate radar reflectivity
Maximum of surrogate radar reflectivity
3D Radiative effects – Synthetic scene

ERA data

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CloudSat dBz

3D fields of dBz

x = F(y) – 1

PSD: MH97 F07

3D fields of IWC & RWC

SSP

TESSEM2 Lambertian Reflection

ARTS

$T_B$

Filtered radar reflectivity

Example slice of surrogate radar reflectivity

Maximum of surrogate radar reflectivity
Overall: $\text{mean} < 0.43 \text{ K}$

(a) 186.3 GHz, 6 km

$\alpha = 0.988 \pm 0.001$

$R^2 = 0.999$

RMSE: 1.17 K

RMSE$_c$: 1.00 K

(b) 668 GHz, 6 km

$\alpha = 0.988 \pm 0.001$

$R^2 = 0.999$

RMSE: 1.96 K

RMSE$_c$: 1.87 K

(c) 186.3 GHz, 15 km

$\alpha = 0.991 \pm 0.001$

$R^2 = 0.999$

RMSE: 0.92 K

RMSE$_c$: 0.88 K

(d) 668 GHz, 15 km

$\alpha = 0.990 \pm 0.001$

$R^2 = 0.999$

RMSE: 1.41 K

RMSE$_c$: 1.32 K

Barlakas and Eriksson., 2020
Overall:
mean < 5.97 K
mean < 4.10 K
Overall:
mean < 5.97 K
mean < 4.10 K

(a) 186.3 GHz, 6 km
\( \alpha: 0.972 \pm 0.002 \)
\( R^2: 0.997 \)
\( \alpha: 0.993 \pm 0.001 \)
\( R^2: 0.999 \)
RMSE: 1.98 K
RMSE\(_c\): 1.72 K

(b) 668 GHz, 6 km
\( \alpha: 0.938 \pm 0.003 \)
\( R^2: 0.986 \)
\( \alpha: 0.954 \pm 0.003 \)
\( R^2: 0.991 \)
RMSE: 7.10 K
RMSE\(_c\): 6.20 K

(c) 186.3 GHz, 15 km
\( \alpha: 0.925 \pm 0.004 \)
\( R^2: 0.990 \)
\( \alpha: 0.968 \pm 0.002 \)
\( R^2: 0.996 \)
RMSE: 3.97 K
RMSE\(_c\): 3.06 K

(d) 668 GHz, 15 km
\( \alpha: 0.853 \pm 0.005 \)
\( R^2: 0.957 \)
\( \alpha: 0.884 \pm 0.004 \)
\( R^2: 0.969 \)
RMSE: 13.1 K
RMSE\(_c\): 10.2 K
Summary

- The horizontal photon transport effect induces a slight overestimation and chiefly random errors. Thus, 3D simulations could be replaced by a bias correction in the forward model.

- The total effect is consistent with the BF effect. The root mean square error (RMSE) in:
  - 1DVAR\(^1\) retrievals, it can be \(\sim14\) K at the highest frequency and footprint size.
  - Data assimilation (183 GHz and footprints between 9 and 36 km) is above \(\sim4\) K.

- A significant beam-filling (BF) effect that increases primarily with frequency and secondly, with footprint size and slant path; RMSE up to \(\sim14\) K.

- Independent beam approximation (IBA) is a necessity (e.g., retrieval databases).

- A statistical correction scheme by means of a multiplication factor has been developed that compels the errors induced by the 3D effects to be more symmetric (up to 3.2 K).

Outlook

- Explore the use or the development of correction schemes for the BF effect at mm/sub-mm.

- Particle orientation and 3D effects including polarization.

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1D variational retrievals: AMSU-B ATMS, GMI, MHS, SSMIS, ICI, MWI,…

Barlakas and Eriksson., *Remote Sens.*, 2020
Intercomparison

- ARTS vs RRTOV (-SCATT):
  - Clear sky conditions
  - All-sky conditions

Particle orientation and polarization

- Adapt/extend RRTOV-SCATT:
  - Polarization treatment
  - Particle orientation

Thank you so much for your attention!