A New Outlook on Ice Cloud through Sub-millimetre-Wave Scattering

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Contents

This presentation covers the following areas

• The International Sub-mm Airborne Radiometer (ISMAR)

• Example ice cloud case, microphysics, particle size distributions (PSDs)

• Particle models & their single-scattering properties (SSPs)

• Results from radiative transfer modelling of the measured sub-mm-wave brightness temperatures

• Discussion
The International Sub-millimetre Airborne Radiometer (ISMAR) (Met Office & ESA)

Adapted from Walliser et al, 2009

Demonstrator for Ice Cloud Imager (ICI)
~2022 footprint ~ 15 km

5 central mm & sub-mm channels
118(V), 243(V,H), 325(V), 448(V), & 664 (V,H) GHz.
From Rydberg et al., 2007.
Example ice cloud case, microphysics and PSDs
Ice cloud case
09/02/2016 off East Coast of UK

UV lidar extinction m⁻¹

IWC gm⁻³

From probes PSDs

\[ \langle \beta_{\text{ext}} \rangle = 2 \int <A(D_{\text{max}})> N(D_{\text{max}}) dD_{\text{max}} \]

\[ \text{IWC} = 90.06 \beta^{1.21} \]
In-situ PSDs and other PSD assumptions

PSDs can be quite different, no universal representation.
Particle models & their SSPs
Particle models:

- Five-branched hexagonal aggregate
- Ten-branched hexagonal aggregate
- Voronoi model

Baran & Labonnote, 2007

Ishimoto et al., 2012

Based on observed density-size relation derived by Cotton et al. (2013) [C13]

Observed density-size relations can be quite different no universal prediction

Xu and Mace (2017) ±80% uncertainty in mass-D prefactor (i.e., density) – which to choose for electromagnetic scattering?
SSPs ($<P_{11}>$, $<\beta_{ext}>$, $<\omega_0>$, $<g>$)


1 $< X \leq 70$ : FDTD (Ishimoto et al., 2006)  
X $> 70$ : DDSCAT (Draine and Flateau, 1994)  
$X = \pi D_{max}/\lambda$

1 $< X \leq 18$ : T-matrix (Havemann & Baran, 2001)  
X $> 18$ : GO (Macke et al., 1996)  
$\delta = 0.6$

T-matrix SSPs based on equal area ratio hexagonal columns

Area ratio = $<P_{ns}(D_{max})>/<P_s(D_{max})$
Test of equal area ratio hexagons \( X < 18 \) compared at 664 GHz

\[
\langle \beta_{\text{ext}} \rangle = 0.0056 \text{ m}^{-1} \quad \langle \omega_0 \rangle = 0.84 \\
\langle g \rangle = 0.64
\]

\[
\langle \beta_{\text{ext}} \rangle = 0.0059 \text{ m}^{-1} \quad \langle \omega_0 \rangle = 0.83 \\
\langle g \rangle = 0.67
\]

\[
\langle \beta_{\text{ext}} \rangle = 0.0001 \text{ m}^{-1} \quad \langle \omega_0 \rangle = 0.91 \\
\langle g \rangle = 0.63
\]

\[
\langle \beta_{\text{ext}} \rangle = 0.0001 \text{ m}^{-1} \quad \langle \omega_0 \rangle = 0.90 \\
\langle g \rangle = 0.63
\]

\[
X_D = 24
\]

\[
X_D = 1.7
\]
Further simplification owing to dielectric properties

\[ X=42 (\text{RTDF, Hesse 2008, JQSRT v 109}) \text{ 664 GHz} \]
The bulk integral optical properties and bulk phase function comparisons for an ice aggregate.
The bulk calculations

\[ \langle \beta_{\text{ext}} \rangle = \int_{D_{\text{min}}}^{D_{\text{max}}} n(D) \left[ \sum_{j=1}^{3} w_t j \langle C_{\text{ext}_j} \rangle \right] dD \]

The other SSPs similarly follow..

Three-component model is weighted at each PSD bin size

\[ 0 \leq W_{t_1} \leq 1 \quad 0 \leq W_{t_2} \leq 1 \quad 0 \leq W_{t_3} \leq 1 \]

at each bin size \( \sum w_{t_j} = 1 \)
To constrain weights predict geometric optics-based IWC-extinction power law from three-component model

\[ IWC = 90.06 \beta^{1.21} \quad \text{In-situ derivation} \]

\[ IWC = 79.89 \pm 51.78 \beta^{1.09 \pm 0.1015} \quad \text{Model derivation} \]

\[ Wt_1 = 0.25 \quad Wt_2 = 0.65 \quad Wt_3 = 0.1 \]

Now apply this model to simulate the sub-mm observations.....
Shaded areas are the ±50% uncertainties in IWC estimates used in the RT modelling (RT model by Havemann et al., 2018, submitted to JQSRT)
Impact of SPARTICUS PSD assumption

SPARTICUS PSDs

In-situ PSDs

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Discussion
• At sub-mm-wave frequencies, there is considerable simplification of the physics not only due to shape complexity but also owing to the dielectric properties of ice. Thus allowing application of approximations of sufficient accuracy to enable rapid computation of SSPs.

• Consistency between geometric optics and the sub-mm-wave region has been preserved through the model prediction of the IWC-extinction power law relation derived from the in-situ measurements.

• The three-component model uncertainties generally shown to be within ISMAR uncertainties at 664 GHz. However, no one model describes the observations at all times.

• Voronoi model uncertainties outside observation uncertainties at beginning but within upper end of observation uncertainty at times thereafter.

• Voronoi model based on observed effective density-size relation, but other assumed effective density-size relations predicting higher effective densities might improve comparisons between model & observations at earlier times.

• Choice of PSD as important as choice of ice crystal model.

• As there is no universal PSD or effective density-size relation, require more general representations of these for application to the mm-wave and sub-mm-wave spectral regions.
Discussion extra slides
Differences in BT

Different density assumptions (PSD same)

Different PSD assumptions (Density same)

Doherty et al., 2007
Global models are poor at predicting the mean annual IWC.

From Waliser et al., 2009, JGR, D00A21
Why is the sub-mm region so useful for information on ice cloud?

The real and imaginary refractive indices of ice in the mm and sub-mm region at 266 K from Eriksson et al. (2015). Ice refractive index is temp dependent.
From the IWC-extinction power-law relation the following IWP values were derived:
$C_{\text{ext}} = 2.71 \times 10^7 \, \mu m^2$

$\omega_0 = 0.80 \, g = 0.75$

$C_{\text{ext}} = 2.20 \times 10^7 \, \mu m^2$

$\omega_0 = 0.79 \, g = 0.74$

Ray Tracing Diffraction at Facets (RTDF): Hesse, 2008: JQSRT vol 109, 1374-1383

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Eight-branched aggregate

Ding et al., 2016

$\omega_0=0.80: g=0.75$

$C_{ext}=2.71E+07 \, \mu m^2$

GO – 2 internal reflections

$\omega_0=0.83: g=0.75$

$C_{ext}=2.20E+07 \, \mu m^2$
X=42 (RTDF, Hesse 2008, JQSRT, vol 109)

Scattering angle, degree

-\frac{P_{12}}{P_{11}}
Equal volume Hexagonal ice column

Ding et al., 2016

$D_m \sim 1 \text{ cm}$ 664 GHz
Further simplification owing to dielectric properties

$P_{11}$ vs. scattering angle (degrees)

- $\lambda = 451.80 \mu m$
- $n = 1.33 + i 0.0094$
- $n = 1.77 + i 0.0094$

RTDF 1 internal reflection
RTDF 14 internal reflections

RTDF 1 internal reflection
RTDF 14 internal reflections
X=24 (BRTDF, Hesse et al. 2018 in rev JQSRT)

664 GHz

eight_aggregate_dm_3500.crystal
λ=451.80 μm
n=1.77+ i0.0094
DDA
- - - -
RTDF 1 internal reflection
RTDF 14 internal reflections

DDA
C_{ext}=2.3E6 μm^2
ω_0=0.94
g=0.64

RTDF
C_{ext}=1.4E6 μm^2
ω_0=0.95
g=0.65

scattering angle (degrees)