Comparing airborne sub-millimetre observations of ice clouds with model simulations

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Background

- The next generation of European polar-orbiting weather satellites (EPS-SG), due to be launched in the 2020s, will carry the Ice Cloud Imager (ICI) which has 13 channels measuring frequencies between 183 and 664GHz that are sensitive to scattering by cloud ice.
- As well as enabling retrievals of bulk ice mass, ICI observations could be assimilated directly into Numerical Weather Prediction (NWP) models using the "all-sky" approach. This requires a sufficiently accurate representation of cloud ice in NWP and radiative transfer models.
- Case studies of cloudy scenes from several campaigns with the UK FAAM BAe-146 aircraft are used to evaluate the ability of NWP and radiative transfer models to simulate realistic brightness temperatures between 89 and 874GHz.
- Modelled brightness temperatures at the ICI incidence angle are compared to observations from the ISMAR (Fox et al. 2017) and MARSS (McGrath&Hewison, 2001) radiometers on the FAAM aircraft.

Airborne observations

- Case studies taken from cloud overpasses during five UK-based FAAM flights in 2016 and 2019 (Table 1, Figure 1)
- Range of cloud conditions observed with ice water path up to 2.3 kg m^{-2}
- ISMAR and MARSS provide close matches to most ICI channels (Table 2). Along-track scanning permits observations close to the ICI incidence angle (~52°).
- Dual polarisation is available in some window channels.

Flight	Date	Max [mean] Ice Water Path (kg m^{-2})
B949	09-03-2016	0.80 [0.16]
B984	14-10-2016	1.46 [0.57]
C156	16-03-2019	0.85 [0.22]
C159	19-03-2019	1.86 [0.19]
C161	22-03-2019	2.30 [0.51]

Table 1: FAAM flights used for study

ISMAR/MARSS channel	ICI channel
89 GHz (mixed)	
157 GHz (H)	
183±7 GHz (H)	183±7 GHz (V)
183±3 GHz (H)	183±3.4 GHz (V)
183±1 GHz (H)	183±2 GHz (V)
243 GHz (H and V)	243 GHz (H and V)
325±9.5 GHz (V)	325±9.5 GHz (V)
325±3.5 GHz (V)	325±3.5 GHz (V)
325±1.5 GHz (V)	325±1.5 GHz (V)
448±7.2 GHz (V)	448±7.2 GHz (V)
448±3.0 GHz (V)	448±3.0 GHz (V)
448±1.4 GHz (V)	448±1.4 GHz (V)
664 GHz (V and H)	664 GHz (V and H)
874 GHz (V and H)	

Table 2: ISMAR/MARSS and equivalent ICI channels. Letters in parentheses correspond to polarisations

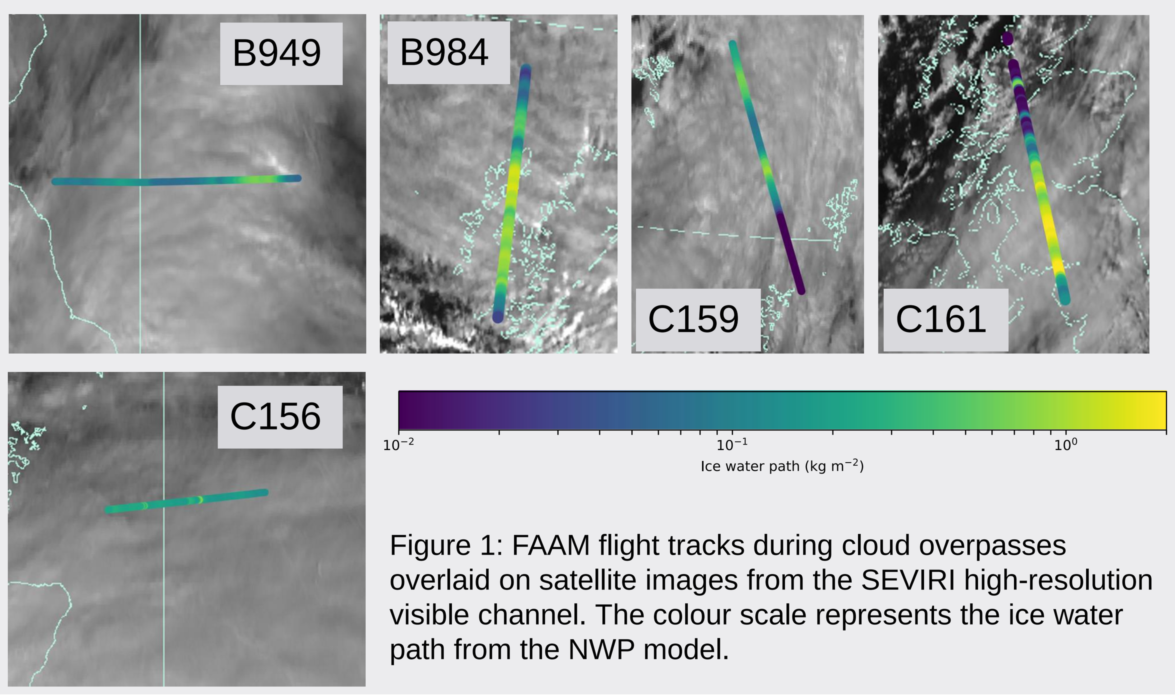

Figure 1: FAAM flight tracks during cloud overpasses overlaid on satellite images from the SEVIRI high-resolution visible channel. The colour scale represents the ice water path from the NWP model.

NWP model configuration

- Atmospheric fields from Met Office Unified Model (UM) [UKV domain, RA2-M configuration]
  - Horizontal resolution ~1.5km
  - 90 vertical levels on hybrid height grid between surface and 40km
  - 1-minute timestep (with output every 15 minutes)
  - Initialised from closest available operational UKV analysis
- Fields used from 15-minute timestep closest to midpoint of aircraft run
  - Maximum time difference between model fields and observation ~32 minutes
- Fields required for simulations are:
  - Pressure, temperature, specific humidity, ice water content, graupel water content, cloud liquid water content, rain water content, surface temperature, surface windspeed
- 3D fields are interpolated vertically to 90 constant pressure levels for compatibility with ARTS radiative transfer model

Radiative Transfer model configuration

- Radiative transfer simulations using the Atmospheric Radiative Transfer Simulator (ARTS) 2.3.1277.
  - Aim to achieve consistent cloud microphysics in the radiative transfer and NWP models.
- 3D Monte Carlo simulation using 3D NWP fields.
  - Reference calculation (slow). Not suitable for data assimilation, which requires fast solvers.
- Hydrometeors assumed to be evenly distributed within each grid cell, i.e. cloud fraction = 1.
- Particle single scattering properties from ARTS scattering database (Eriksson et al., 2018). Random orientation for all particles. Particle size distributions (PSDs) follow NWP model microphysics scheme:
  - **Ice**: Different particle habits (Figure 2), selected to span a wide range of bulk optical properties when integrated over the PSD. PSD parametrized according to ice water content and in-cloud temperature following Field et al. (2007), tropical distribution[1].
  - **Cloud liquid water**: "LiquidSphere" scattering properties (Mie-Lorenz calculations). PSD follows gamma distribution with parameters from Geer&Baordo (2014)[2]
  - **Rain**: "LiquidSphere" scattering properties. PSD follows exponential distribution with parameters from Abel&Boutle (2012).
  - **Graupel**: "GemGraupel" scattering properties[3]. PSD follows gamma distribution with same parameters as NWP model.
- Gas absorption properties:
  - H_2O: line parameters from AER v3.6 database, MT-CKD v3.2 continuum
  - O_2: MPM93 absorption model (Liebe et al. 1993) with updates from Tretyakov et al. (2005)
  - N_2: Continuum parametrization from Rosenkranz (1993)
- Pencil-beam view (i.e. no antenna pattern) following observation line-of-sight (~52° incidence).
- Two frequencies simulated per channel (at the centre of each of the dual sidebands), averaged.
- Surface emissivity: TESSEM2 (Prigent et al., 2016) for sea, fixed (0.9) for land

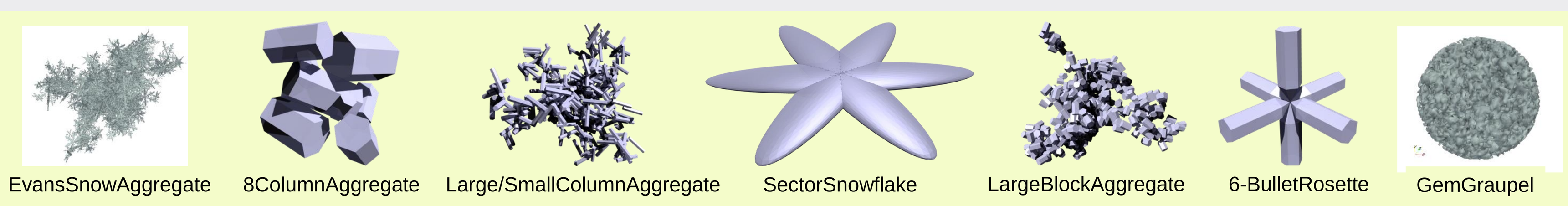

Figure 2: Representative ice particle shapes from ARTS single-scattering database used for radiative transfer modelling

[1] The mass-dimension relationships for ARTS database particles may differ from NWP model, so although both NWP and radiative transfer models use the Field et al. (2007) PSD parametrization, the exact PSD shape may not be identical for a given ice mass

[2] Not strictly consistent with NWP model, but impact will be small due to negligible scattering from cloud liquid drops

[3] This habit has a mass-dimension relationship close to the NWP model assumption of a sphere with density of 500 kg m^{-3}

Example flight – C161

- Figure 3 shows the NWP model cloud field along the flight track during C161. Figure 4 compares the observed brightness temperatures to the ARTS simulations using different ice particle habits (for selected frequencies).
- Simulated brightness temperatures are strongly sensitive to the ice particle habit but exact behaviour is frequency dependent
- Higher frequencies are sensitive to upper cloud layers that are not seen at 183GHz and below (e.g. between 200 and 300km along-track)
- General cloud features reproduced but exact details different (e.g. large spike in observations at 664 and 874 GHz around 400km is not in model).

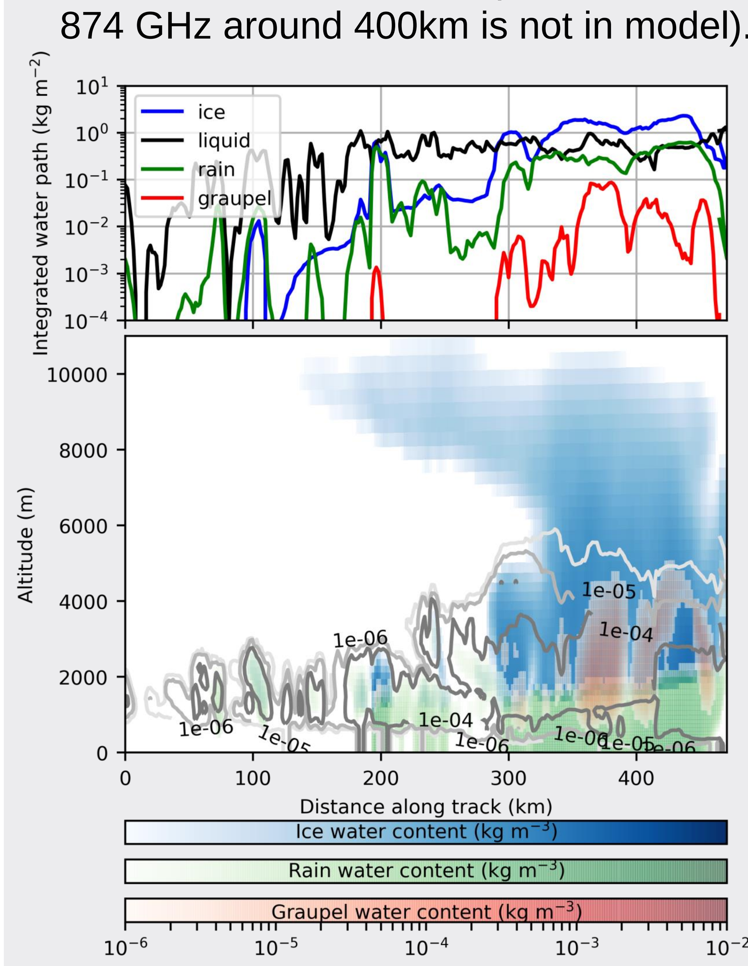

Figure 3: Integrated water paths and condensed water content along flight track. Grey contours show cloud liquid water content

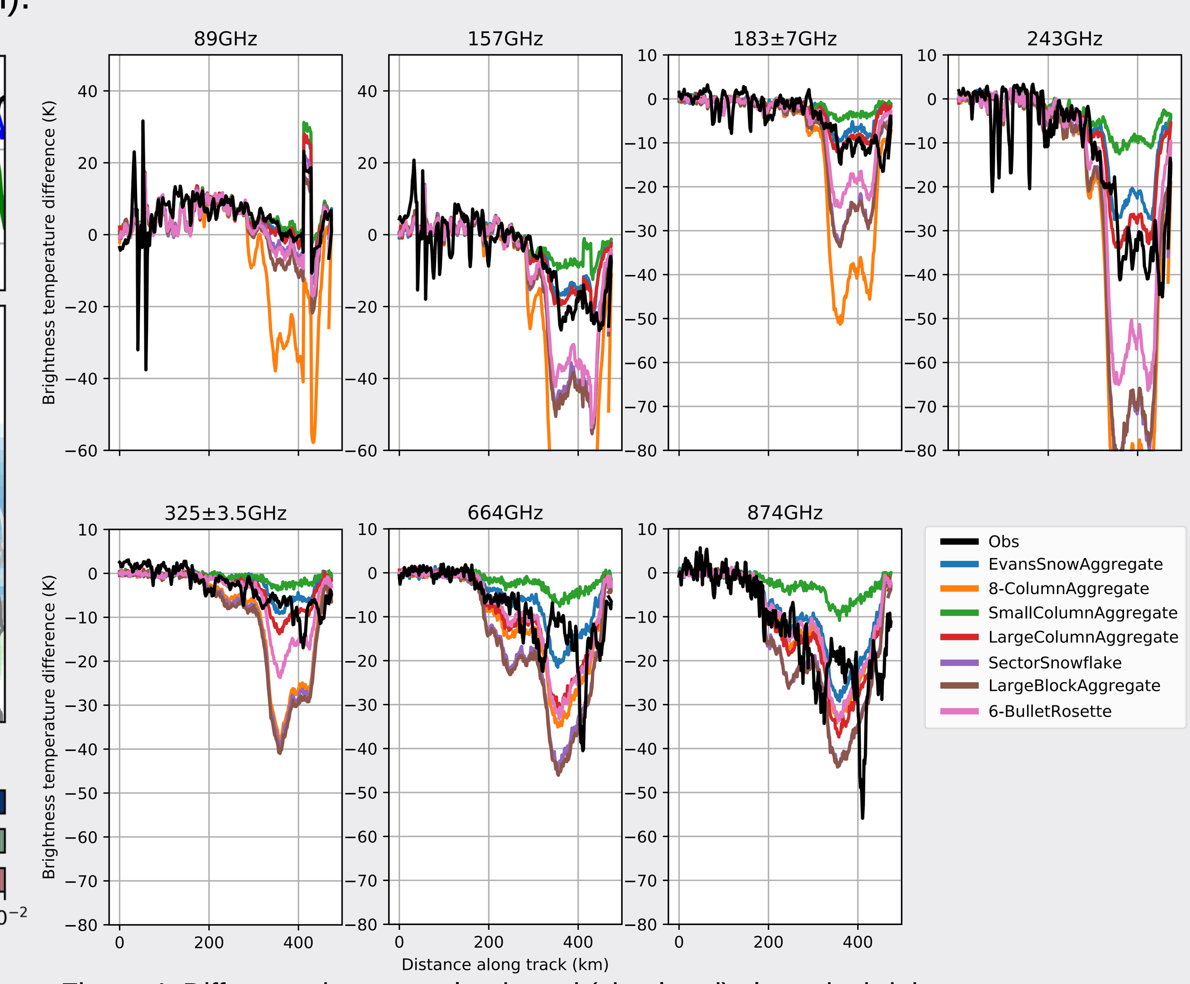

Figure 4: Difference between cloudy and (simulated) clear-sky brightness temperatures for different ice particle habits compared to observations at selected frequencies

Statistical comparisons for all cases

- RMS difference between observed and simulated brightness temperatures across all flights shown in Figure 5 (top panel) for different ice particle habits
  - Combines both errors in radiative transfer simulations and representation of cloud in the NWP model
  - Up to 25K error, largest for channels sensitive to full depth of cloud.
  - Strong sensitivity to cloud ice particle habit, particularly between 183 and 325 GHz
- RMSD is sensitive to "double penalty" effect where there is a mislocation of cloud in NWP model. Comparisons of brightness temperature histograms (figure 6) are more robust to this effect
  - Geer & Baordo (2014) propose the metric $h = \left(\sum_{bins} \left|\log \frac{\#simulated}{\#observed}\right|\right) / \#bins\ observed$ to compare histograms, where smaller values indicate a better fit. This is shown in Figure 5 (bottom panel).
- Results are generally consistent for both RMSE and *h.* No single habit gives the best results across all frequencies.
- "LargeColumnAggregate" habit gives good performance across frequencies, but slightly underpredicts occurrence of low brightness temperatures

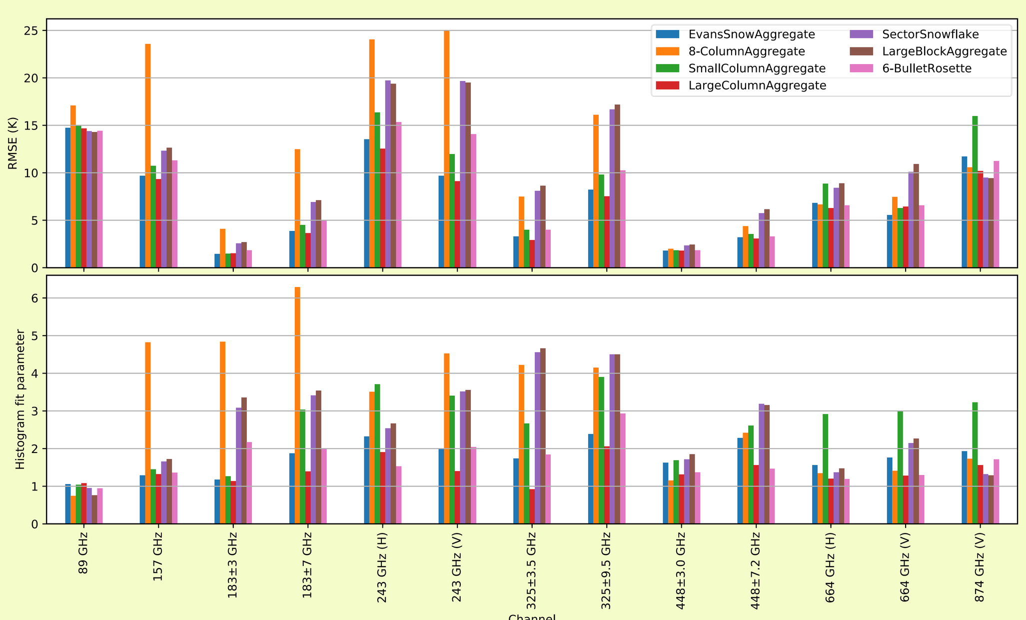

Figure 5: RMS error (top) and histogram fit parameter (bottom) for different ice particle habits for all flights

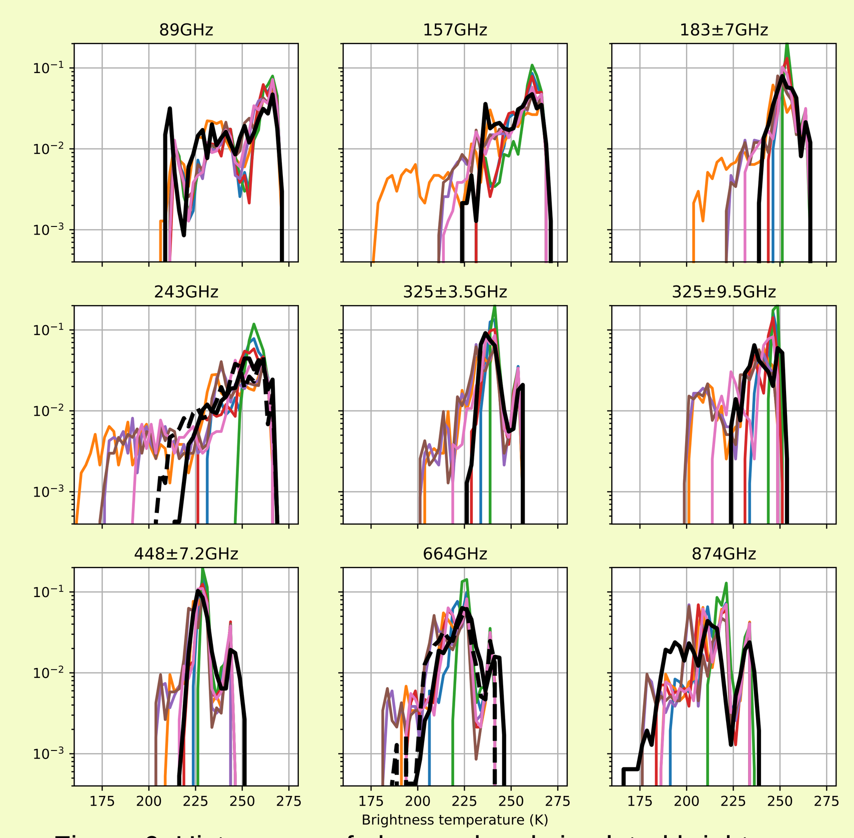

Figure 6: Histograms of observed and simulated brightness temperatures for all flights. Dashed lines represent H-polarised observations. Colours represent habits as in figure 5

Conclusions and future work

- Using atmospheric fields from the Met Office UKV NWP model to drive ARTS radiative transfer simulations for cloudy scenes it is possible to generate realistic brightness temperatures when compared to MARSS/ISMAR observations between 89 and 874 GHz.
- Simulated brightness temperatures are strongly sensitive to the assumed cloud ice particle scattering properties.
- A single set of ice particles ("LargeColumnAggregate" habit) provides reasonable performance across the whole microwave frequency range for the cases studied.
- Future work will include:
  - Considering the impact of polarisation due to oriented ice particles
  - Developing particle habit models which follow the NWP model mass-dimension relationship to give better consistency between the PSDs used in the NWP and radiative transfer models.
  - Evaluating the consistency of simulations with cloud radar and lidar to identify possible deficiencies in the cloud representation within the NWP model.
- Application to ICI will require an understanding of the implications of the large satellite footprint (e.g. sub-footprint heterogeneity), as well as ensuring sufficiently accurate polarised calculations from fast radiative transfer models such as RTTOV-SCATT

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