

# Addressing Current Problems with Achieving Physical Consistency Across the Electromagnetic Spectrum Between Ice Crystal Models, Remote-Sensing, and Large-Scale Models

Anthony Baran<sup>1</sup>

<sup>1</sup>Met Office, UK

November 26, 2022

## Abstract

During the forthcoming decade and beyond there will be a plethora of global space-based active and passive measurements of cirrus and ice cloud. These measurements will be across the electromagnetic spectrum, from the ultra-violet to the far-infrared, through to the sub-millimeter, where there are no current radiance observations in the latter spectral regions. To take advantage of these unprecedented high-resolution and spectral-like measurements, ice crystal models are required that are physically consistent throughout the electromagnetic spectrum, and which are consistent with microphysics assumptions in weather and climate models. Achieving such physical consistency between ice crystal models, remote-sensing, and large-scale models to meet the challenges posed by the forthcoming measurements over the next decade or so is problematic. However, it is necessary to overcome this difficulty to improve the predictive quality of weather and climate models to address extreme weather events and climate change, respectively. However, cirrus and ice cloud types consist of ice crystals that vary considerably both in shape and size between the cloud top and bottom. Not surprisingly, with such variability in the shapes and sizes, obtaining models that are coherent across the spectrum while at the same time being consistent with microphysics assumptions in weather and climate models is difficult. In this talk, to address the above issues, an approach using an ensemble model of cirrus ice crystals to predict consistently the observed radiative properties of cirrus from the ultra-violet to the far-infrared will be discussed using aircraft and satellite-based high-resolution radiance measurements. In this analysis, different shapes of the particle size distribution are utilized that are consistent with a weather and climate model, remote-sensing, and with an in-situ mass power law. Here, the need for improved simultaneous in-situ and aircraft remote-sensing spectral characterization of cirrus across the electromagnetic spectrum will be emphasized. Moreover, an example of the development of a new ice crystal model that follows in-situ ice crystal mass and area power laws, which are consistent with a weather and climate model is described, with some preliminary results, to help address the radiative issues.



# Addressing current problems with achieving physical consistency across the electromagnetic spectrum between ice crystal models, remote-sensing, and large-scale models

**Anthony J. Baran (Met Office & University of Hertfordshire, UK), Antigoni Kleanthous (UCL, UK), Christopher Westbrook (Reading University, UK), Timo Betcke (UCL, UK), David Hewitt (UCL, UK), and Stuart Fox (Met Office, UK)**

***AGU 2021 session on 'Microphysical and Macrophysical Properties and Processes of Ice and Mixed-Phase Clouds: Linking in Situ, Remote-Sensing Observations and Multiscale Models' 16<sup>th</sup> December 2021***





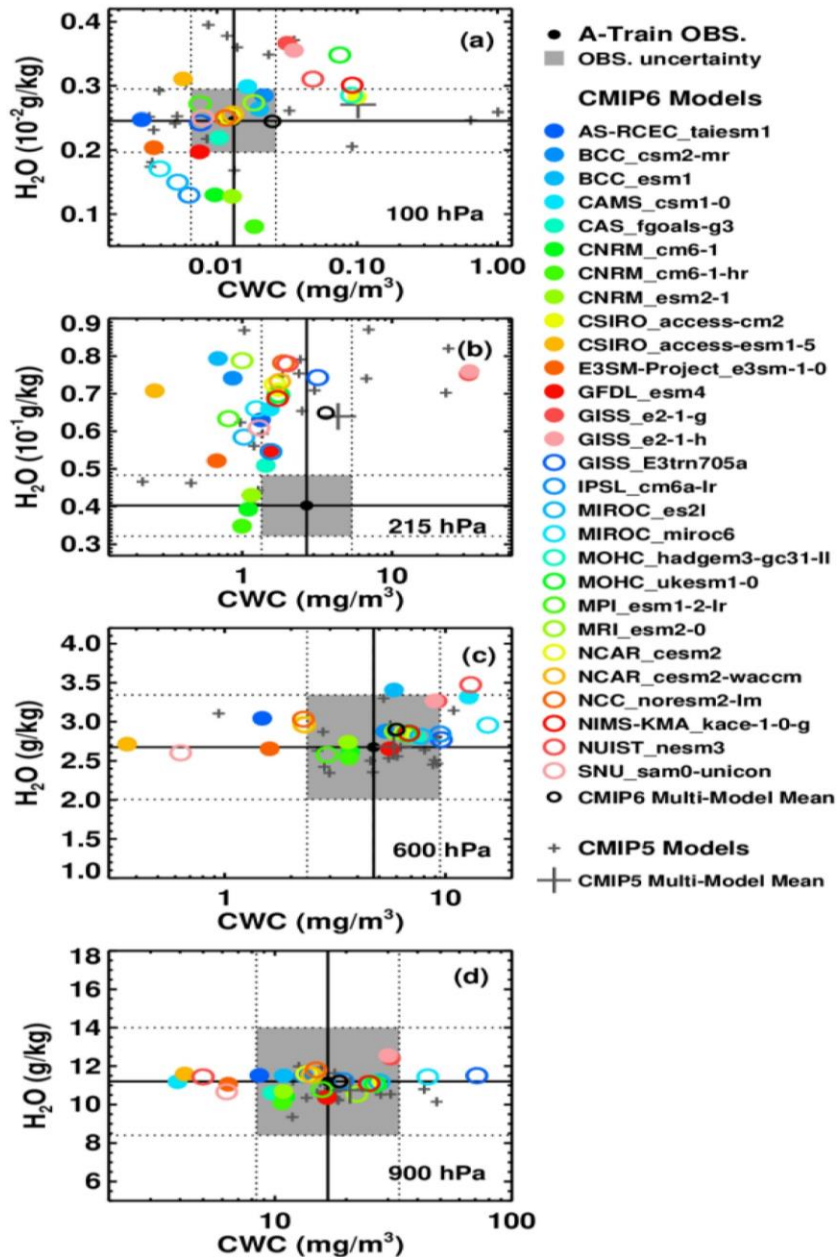
# Contents

- Current problems with large-scale model predictions of cirrus properties
- The challenge of modelling ice crystals – the fundamental difficulty
- Evidence for the breakdown of some current ice crystals models in the long-wavelength region of the electromagnetic spectrum
- An example of developing the next generation of ice crystal models based on global aircraft in-situ observations
- An aircraft campaign to address the problem of applying consistent cirrus microphysics across the electromagnetic spectrum
- Discussion



# Current problems with large-scale model predictions of cirrus properties





CMIP6 and CMIP5 models used by IPCC to predict cloud water content (CWC) compared to A-train observations

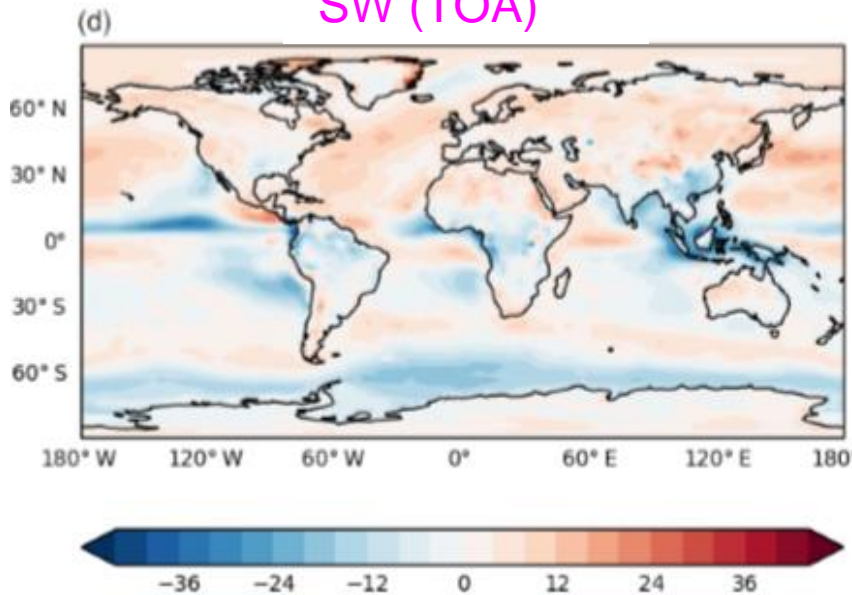
From Jiang et al., 2021  
Earth and Space Science, 8,  
e2020EA001520.

<https://doi.org/10.1029/2020EA001520>

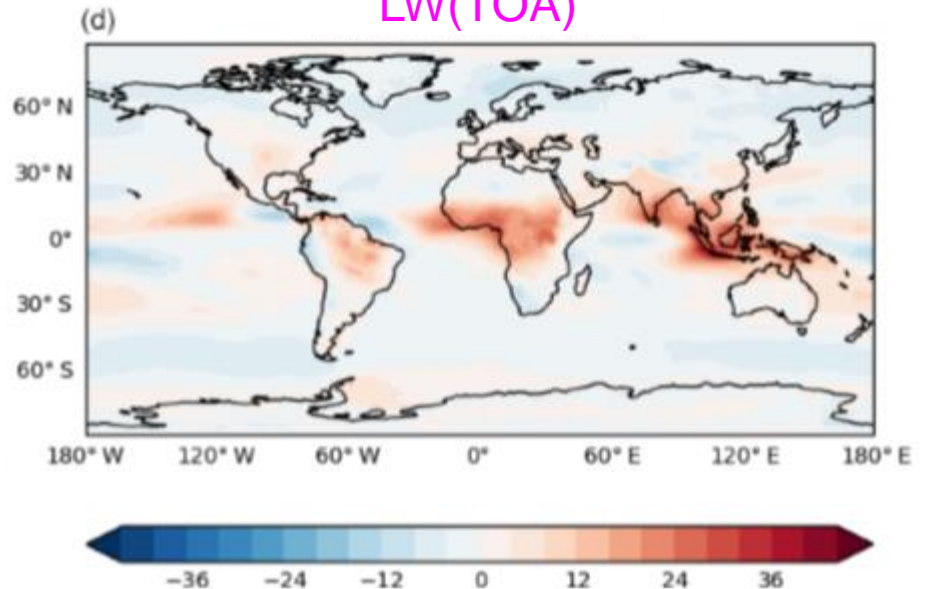


# Met Office Earth System Model 1 – CERES EBAF (20-yr averaged)

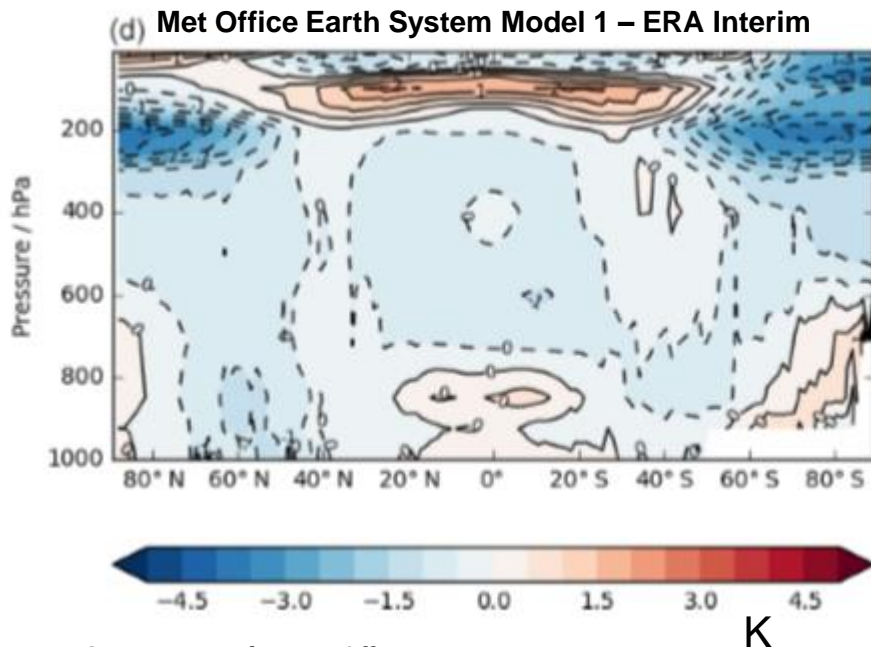
SW (TOA)



LW(TOA)



$\text{W m}^{-2}$



Zonally averaged temperatures

From Walters et al., 2019

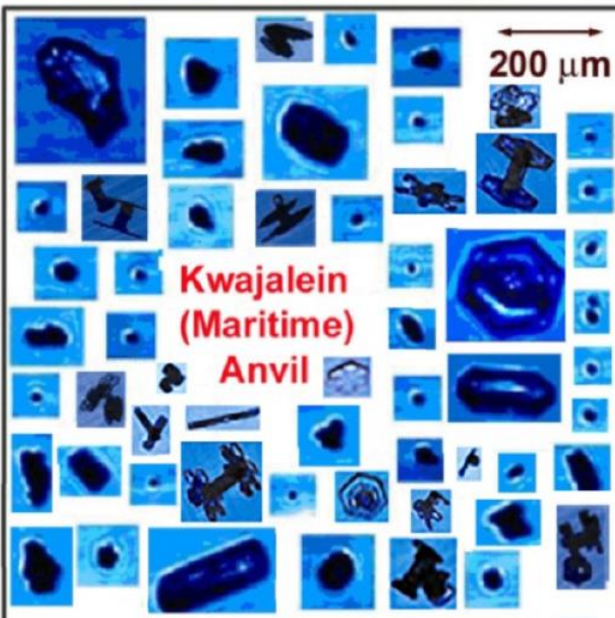
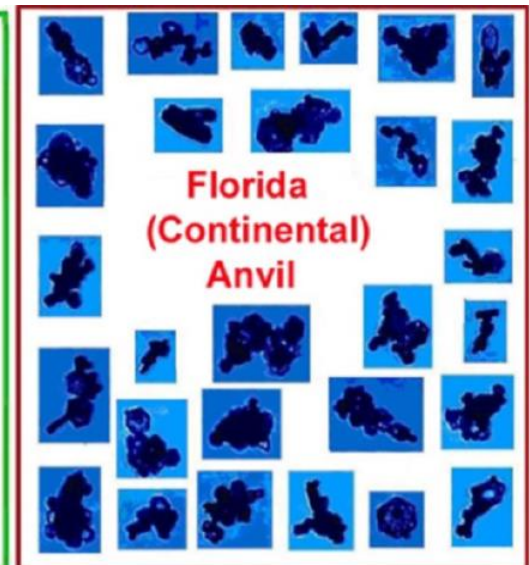
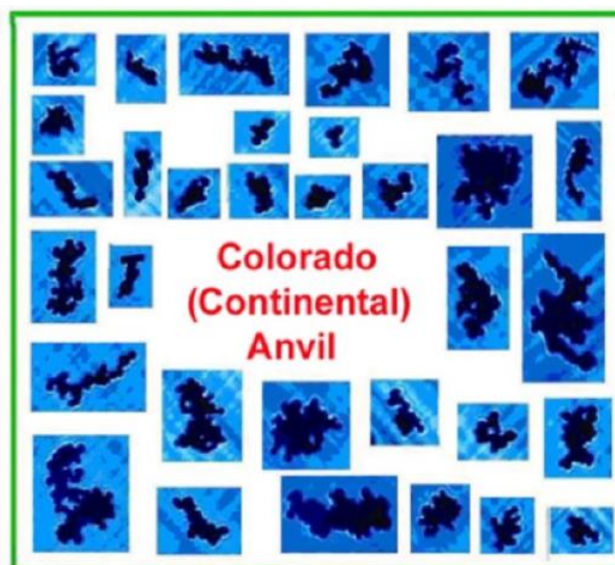
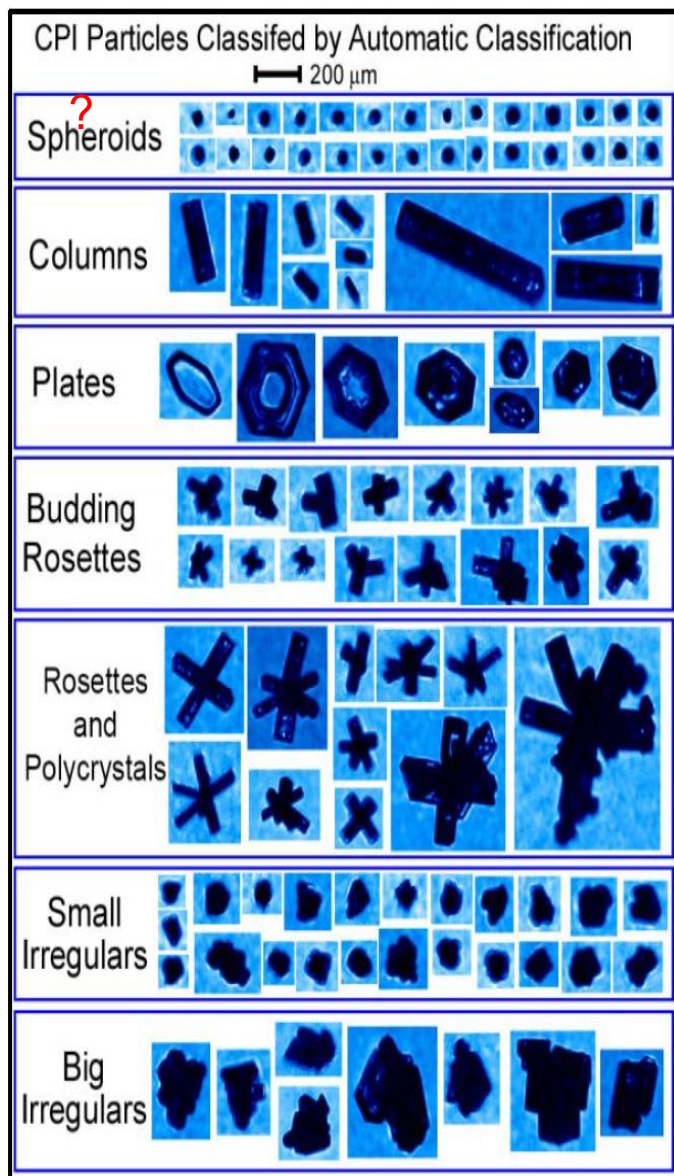
Geosci. Model Dev., 12, 1909-1963

IPCC 2021 reports a “low confidence” in the tropical cirrus feedback on the climate owing to the lack of modelling evidence



# The challenge of modelling ice crystals – the fundamental difficulty

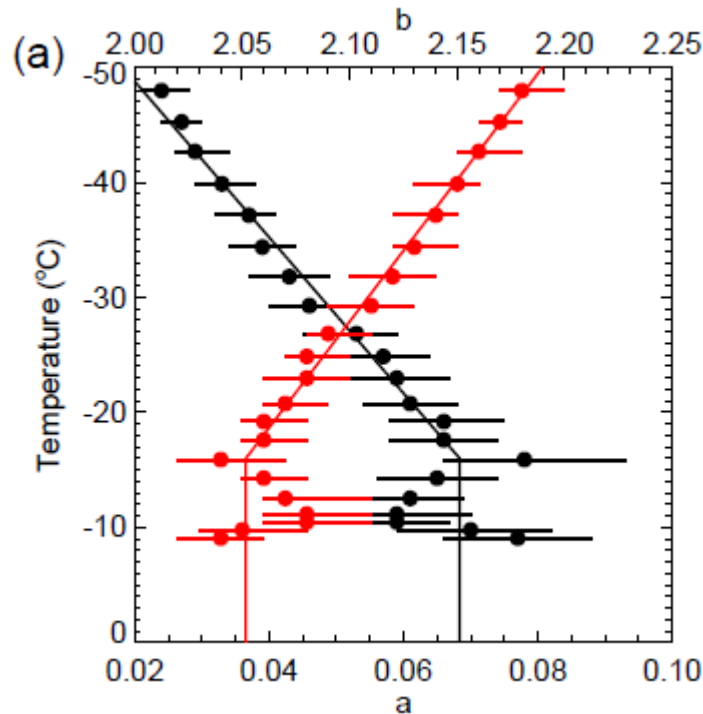




Lawson et al. 2006; 2003; 2019

*Is there a general pattern of shapes for each of the cloud regimes, mass-D and area-D relationships?*

## Why such large variations in mass power laws?



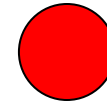
Abel et al., (2014), AMT

The problem with most ice crystal model SSPs that are available from the UV to the  $\mu$ wave is that they are scaled rather than evolved to follow observed mass relations so their mass  $\propto$

$D_{\max}^3$



pre-factor (a)



Exponent (b)

As ice crystals evolve through the cloud from top to bottom most measurements suggest that their mass  $\propto D^{>2}$   $\rightarrow D \sim 2$  as their mass is temperature dependent.

**There is no one single mass or area-D relationship.**

**Could there be a generalisation that takes into account uncertainties in the a and b parameters?**





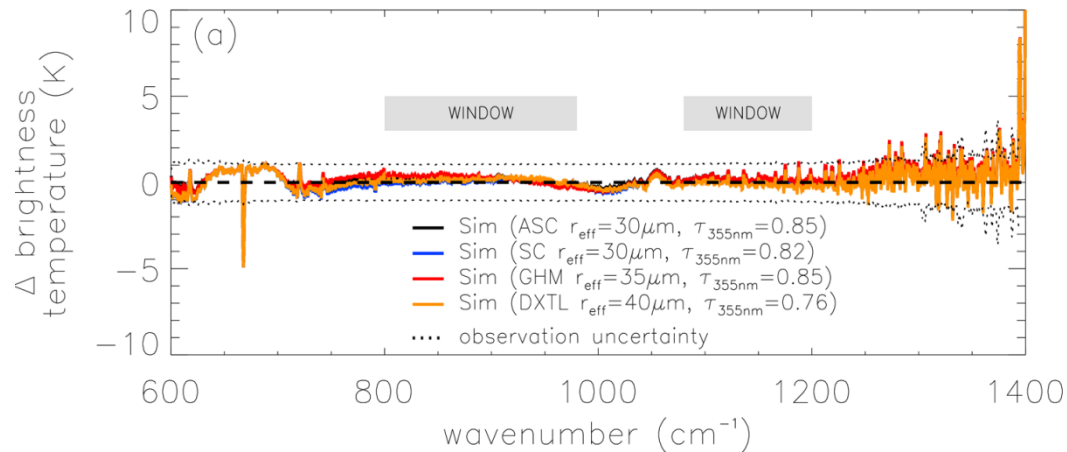
# Evidence for the breakdown of some current ice crystals models in the long-wavelength region of the electromagnetic spectrum



## Breakdown in the far-infrared !

From Bantges et al. (2020), ACP, 20, 12889-12903

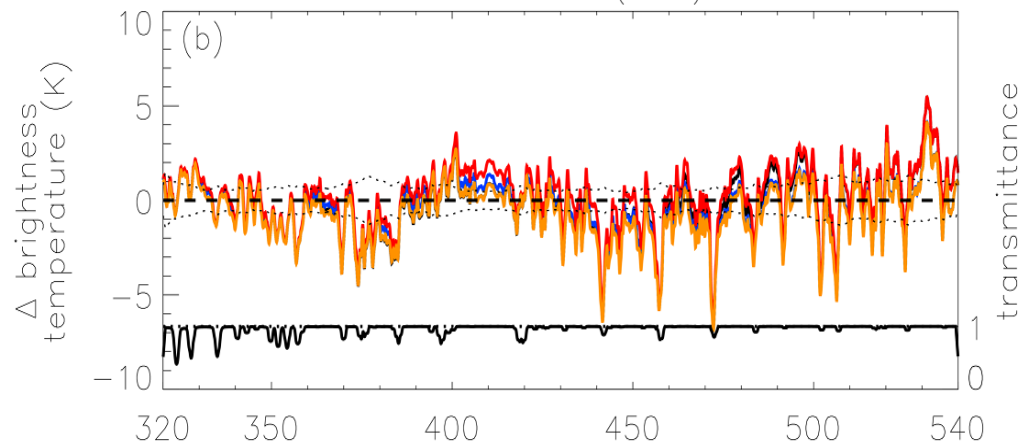
### Mid-infrared 16.6 – 7.14 $\mu\text{m}$



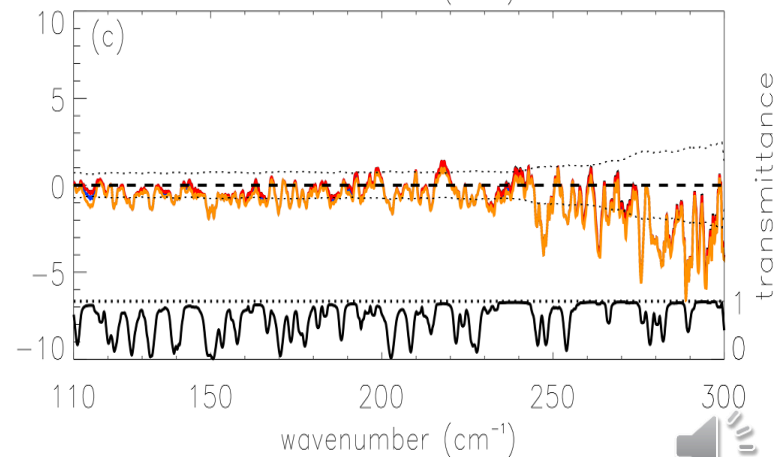
Ice crystal models from Baum et al., (2014) and Yang et al. (2013) obtained over mid-latitude cirrus, see O'Shea et al. 2016 for case details

Is this true for all models ?

### Far-infrared 31 – 18 $\mu\text{m}$

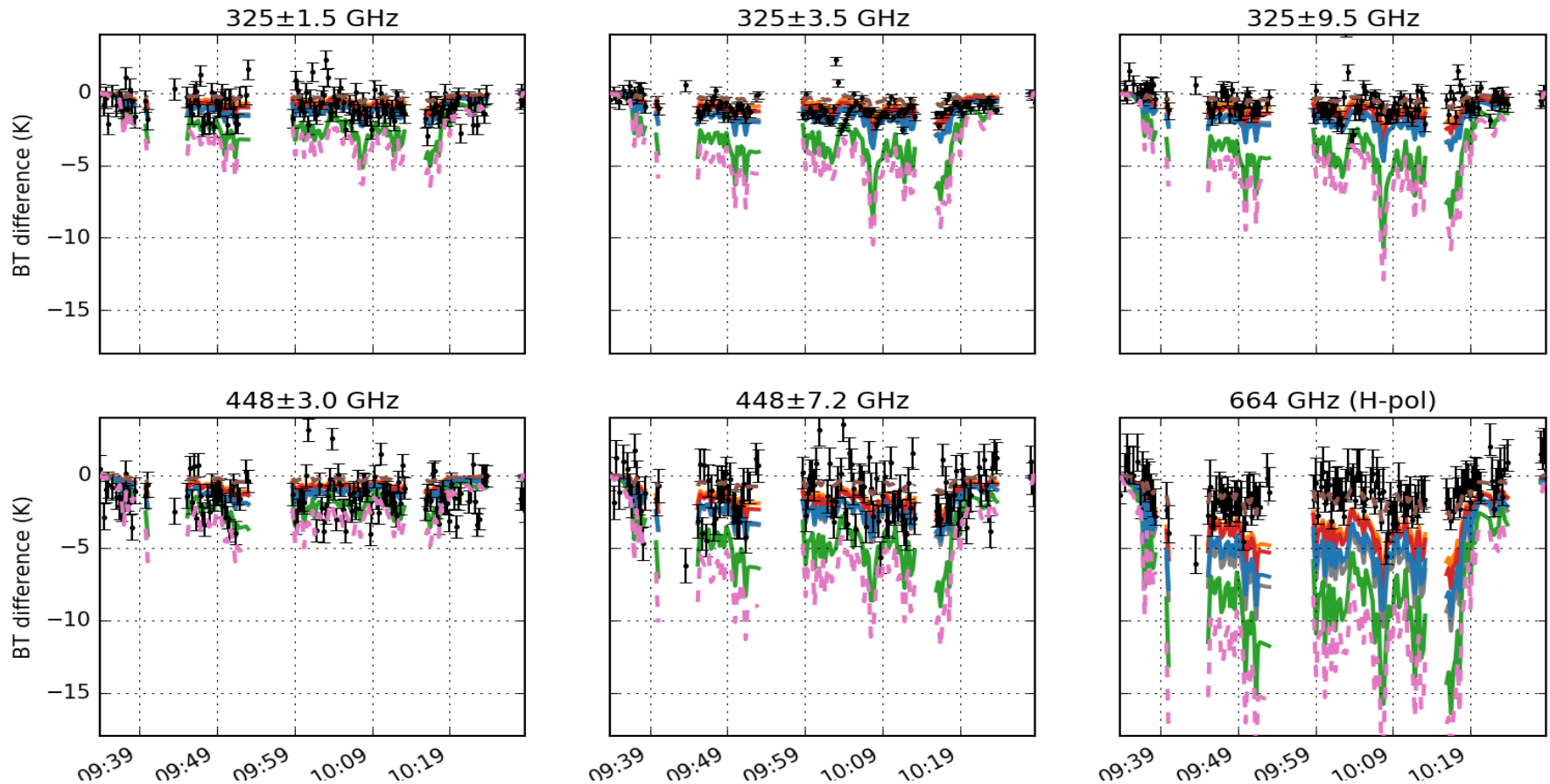


### Far-infrared 91 – 33 $\mu\text{m}$





Evidence from the sub-mm from Fox et al. 2019, see <https://www.atmos-meas-tech.net/12/1599/2019/> for details



Models from Eriksson et al., (2018) see <https://www.earth-syst-sci-data.net/10/1301/2018/> -  
These models follow specific mass-D relations but none fit the data at the same time across the frequencies





An example of developing the next generation of ice crystal models based on global aircraft in-situ observations



## From Lawson et al., 2019 JGR-published article located here

<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018JD030122>

### Projects

ACRONYM	ACRONYM EXPANDED	PRIMARY SPONSOR(S)
ACTIVE	Aerosol and Chemical Transport in Tropical Convection	UK NERC
ATTREX	Airborne Tropical Tropopause Experiment	NASA
CCOPE	Cooperative Convective Precipitation Experiment	NSF/BOR
CR-AVE	Costa Rica AURA Validation Experiment	NASA
CRYSTAL-FACE	Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cumulus Experiment	NASA
DC3	Deep Convective Clouds and Chemistry Project	NASA/NSF
EOS	Earth Observing System	DOE
EMERALD-I & II	Egrett Microphysics Experiment with Radiation, Lidar, and Dynamics	UK NERC
FIRE-ACE	First ISCCP Regional Experiment Arctic Cloud Experiment	NASA/DOE
FIRE-II	First ISCCP Regional Experiment	NASA
ICE-T	Ice in Clouds Experiment-Tropical	NSF
ISDAC	Indirect and Semi-Direct Aerosol Campaign	DOE, NASA
MIDCIX	Midlatitude Cirrus Cloud Experiment	DOE
POSIDON <b>TTL</b>	Pacific Oxidants, Sulfur, Ice, Dehydration, and Convection Experiment	NASA
SEAC4RS	Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys	NASA
SCCP	Sierra Cooperative Pilot Project	BOR
SPARTICUS	Small Particles in Cirrus Project	DOE
TC4	Tropical Composition, Cloud and Climate Coupling	NASA
TRMM KWAJEX	Tropical Rain Measurement Mission Kwajalein Experiment	NASA
TRMM TEFLUN-A	TRMM Texas and Florida Under Flights – A (Texas)	NASA
TRMM TEFLUN-B	TRMM Texas and Florida Under Flights – B (Florida)	NASA
TWP-ICE	Tropical Warm Pool – International Cloud Experiment	DOE

The idea is to group together most of the campaigns that have utilised the CPI ( $10^7$  images) to see if the ice crystal shape distributions from differing ice cloud regimes are different ? If so, which are the most common ice crystal shape distributions as a function of ice cloud regime ?

Choose the most common ice crystal shape distributions to model and obtain their SSPs to improve RT within NWP, climate, and in the remote-sensing of ice cloud ?

*All these campaigns took place over weeks, months and years*



# Which ice cloud regimes?

The data were collected in convective anvils and from in-situ cirrus in a variety of geographical locations in

Tropical Maritime (pure – i.e. no influence from nearby land masses), Tropical Continental and Mid-Latitude Continental anvils.

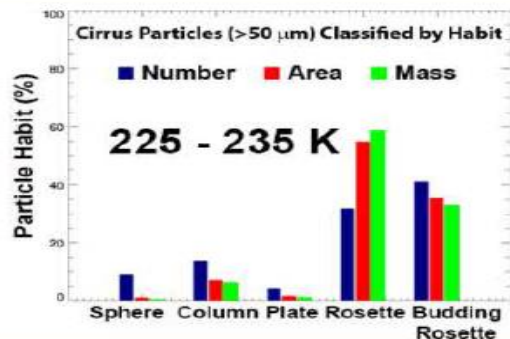
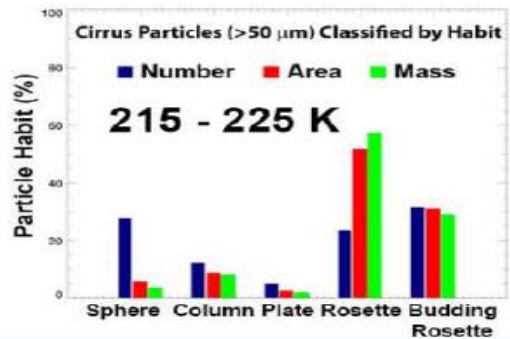
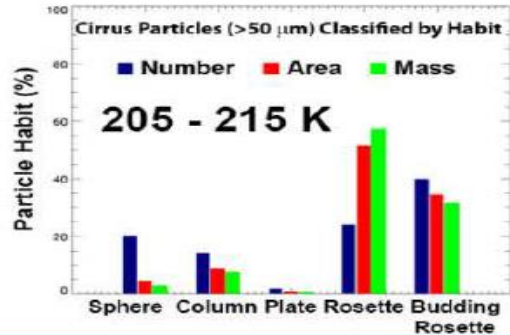
The in-situ cirrus (synoptic lifting, orographic lifting, and gravity waves, regeneration of “seed” ice from anvil outflows). The in-situ cirrus measurements were obtained in the mid- and upper troposphere at temperatures as cold as  $-60^{\circ}\text{C}$ . The analysis also includes TTL cirrus, which was sampled at temperatures down to  $-90^{\circ}\text{C}$ .

For details see the paper:

<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018JD030122>



# In-Situ Cirrus (SPARTICUS)



Lawson et al. 2019





Developing a new ice aggregate model based on Lawson et al., 2019 for in-situ generated cirrus

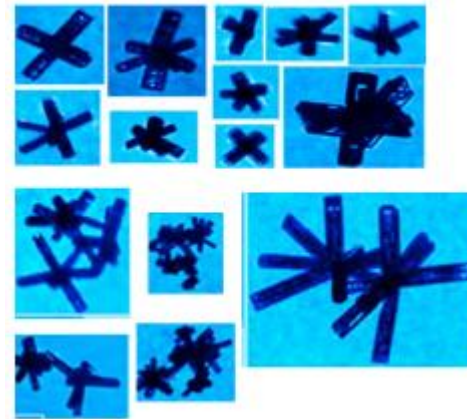
Example CPI images of budding rosettes



Construct rosette mass models such that:

- Mass  $\sim D^3$  for the budding rosettes
- Mass  $= 0.0257D^2$  for the rosette aggregates, following observations by Cotton et al. (2013) to within  $\pm 30\%$

Example CPI images of rosettes and rosette aggregates



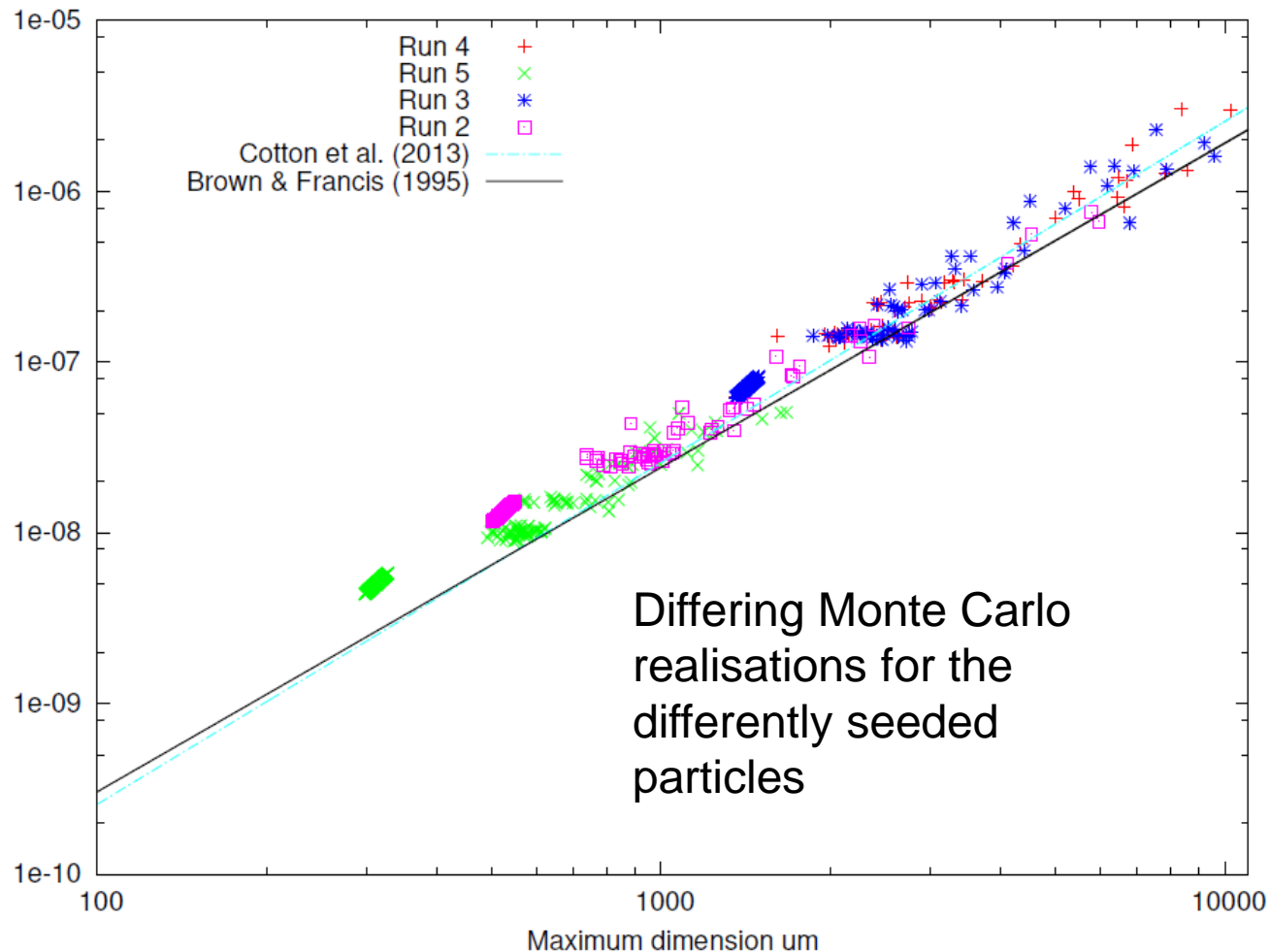
**The Cotton et al. (2013) mass-D relation is the current cirrus microphysics assumption in the Met Office's suite of NWP and Climate models**



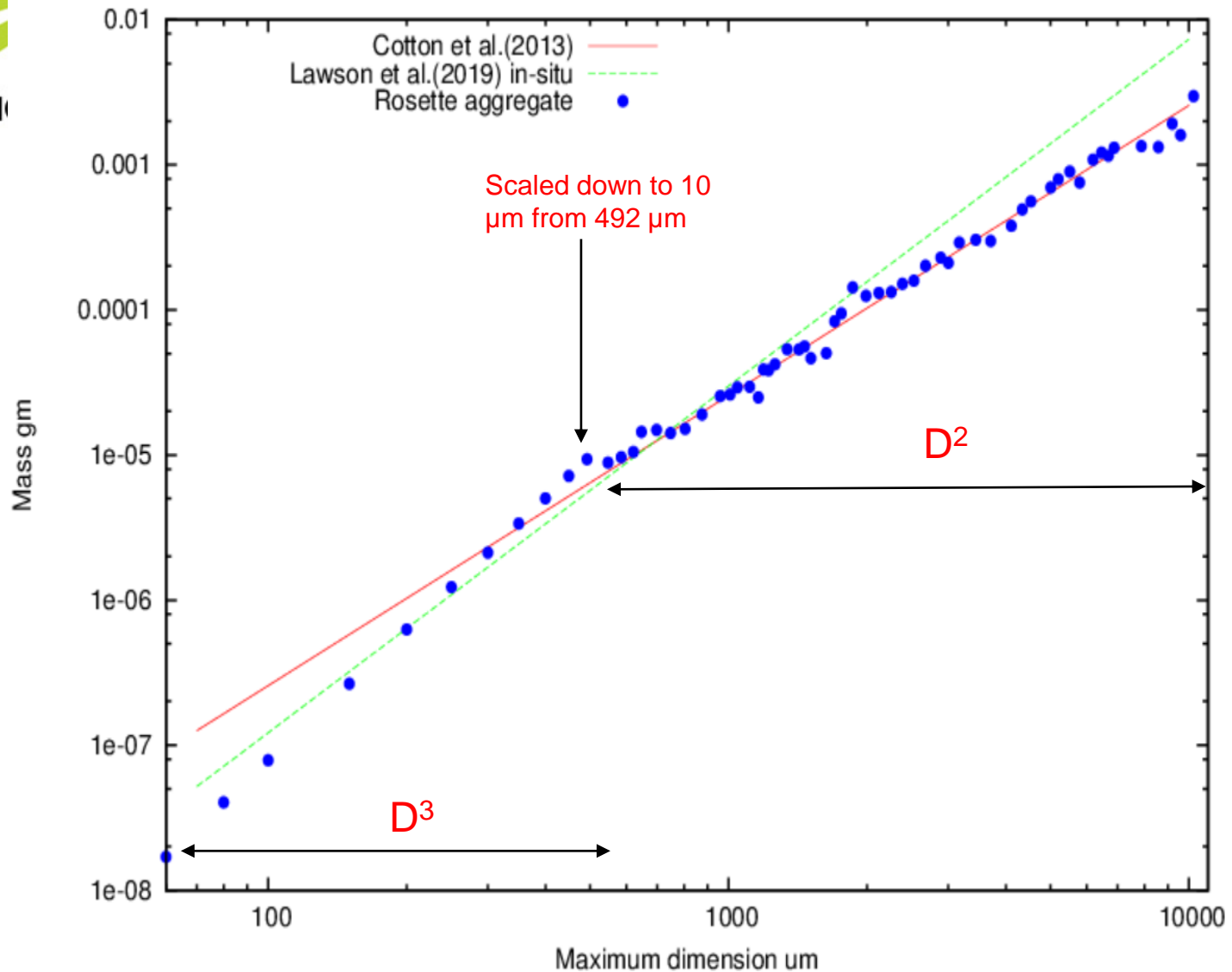
Generate rosette aggregate models from Chris Westbrook's Monte Carlo ice aggregation scheme, inclusive of fall speeds. See for details, Westbrook et al., Phys. Rev. E, 70 021403, 2004.



Mass kg



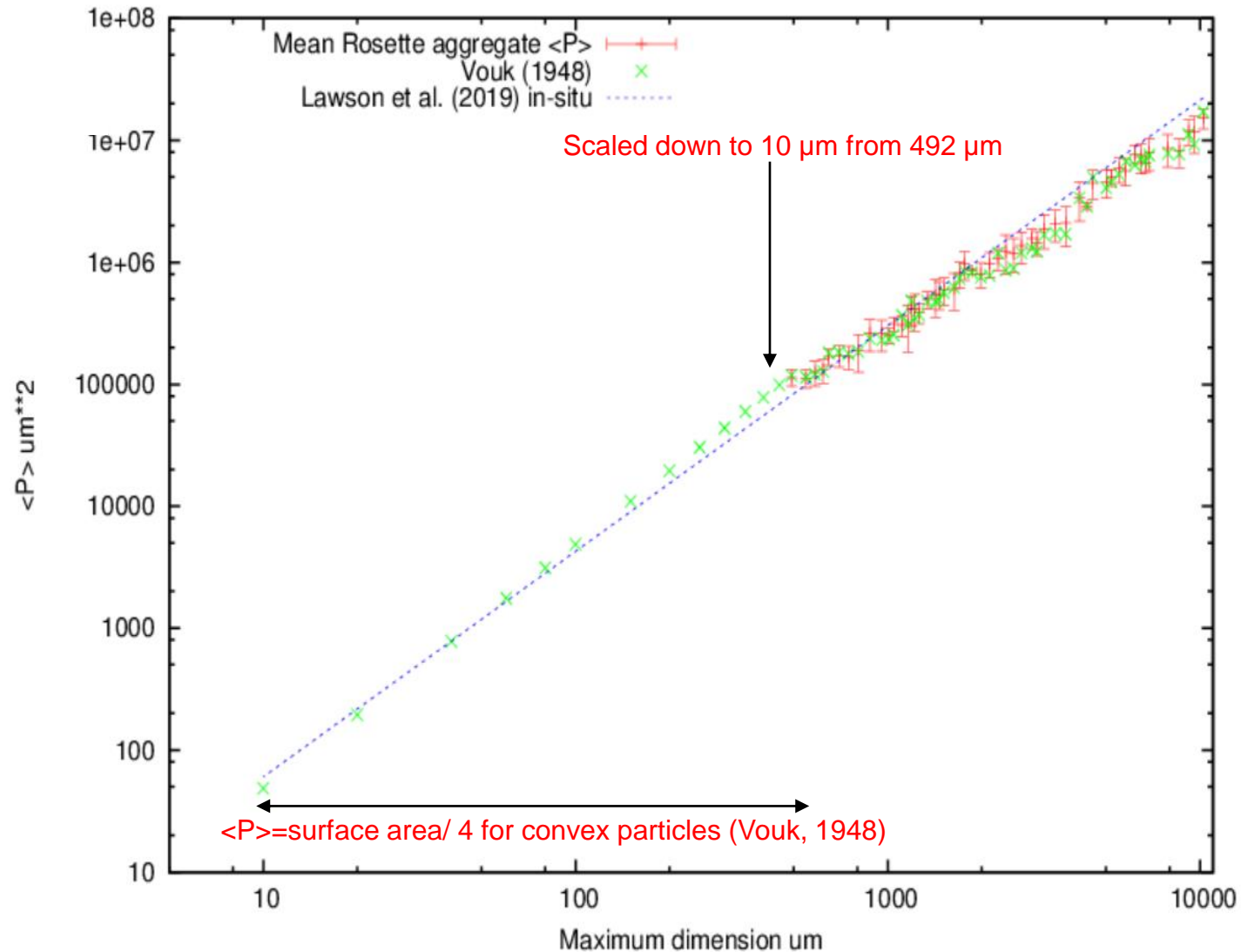
# The selected models of rosette aggregates compared against the in-situ derived mass power laws





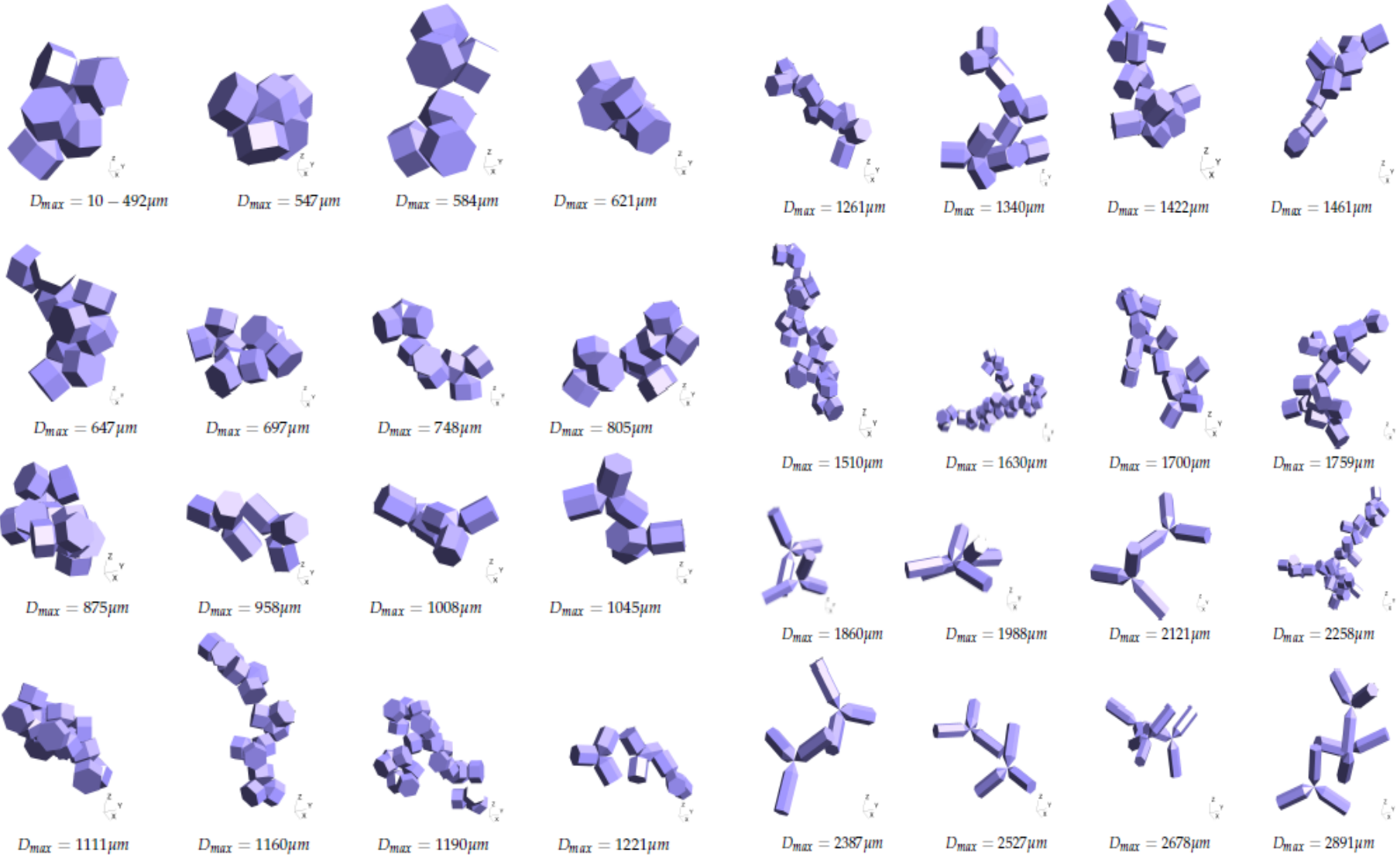
Met (

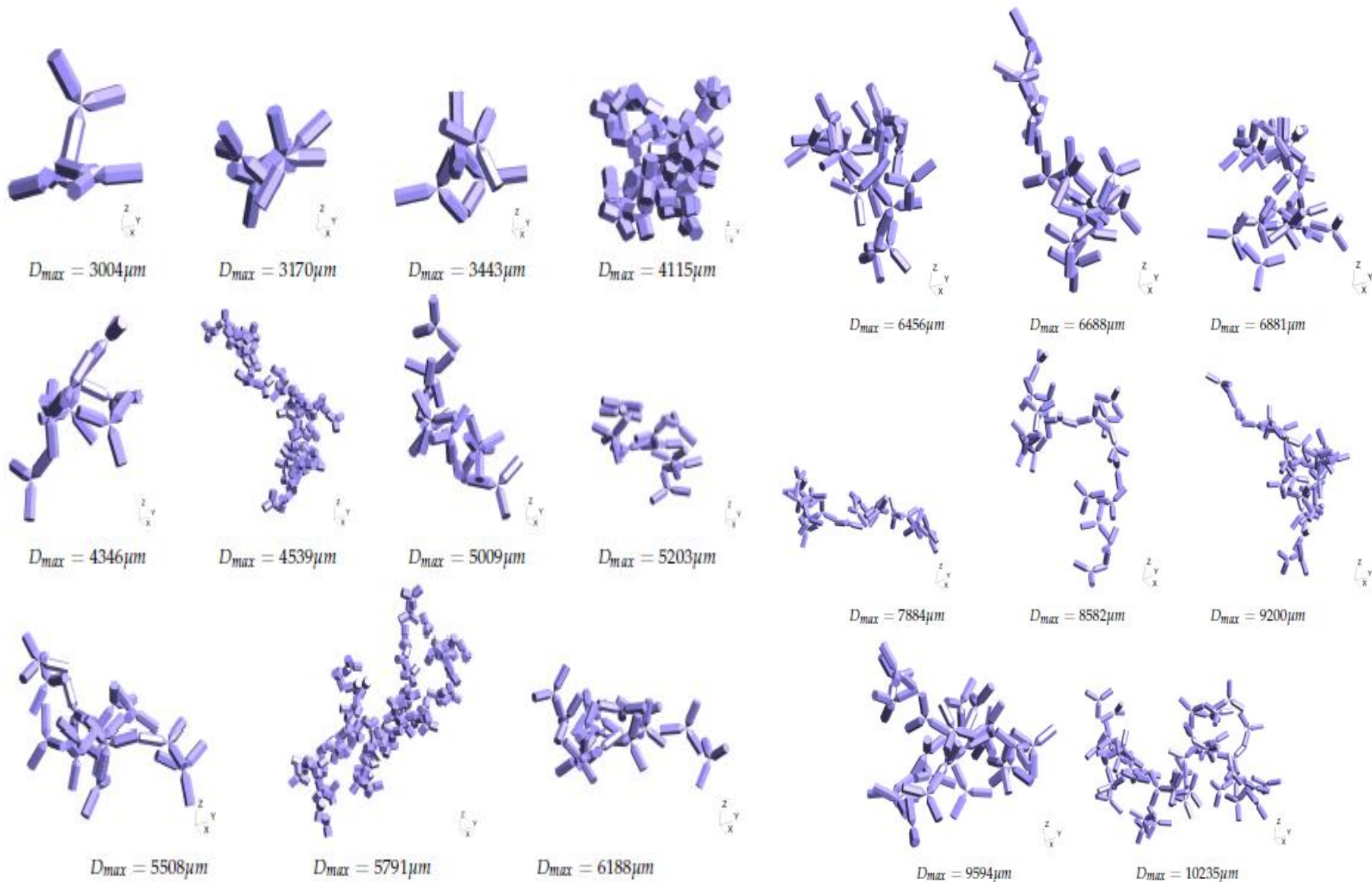
The selected models of rosette aggregates compared against the in-situ derived area power law derived from Lawson et al. (2019)





# What do these model realisations look like?





We are applying the boundary element method to solve for their single-scattering properties in random orientation (Kleanthous et al., 2022, in prep)





An aircraft campaign to address the problem of applying consistent cirrus microphysics across the electromagnetic spectrum





# CCREST

Characterising CiRrus and icE cloud across the specTrum



Planning underway for (multi-)aircraft field campaign, likely March 2024

- Confirmed participation of FAAM aircraft (funded through Met Office)
- Aiming for inclusion of DLR Falcon and Safire ATR-42 (funding TBC)
- Also exploring NERC funding options for UK university participation

Aim to reduce uncertainty associated with cirrus radiative properties to improve ice cloud representation in NWP and climate models, and enhance assimilation of cloud-affected satellite observations in NWP

**Goal is to combine passive and active remote sensing measurements across the electromagnetic spectrum with comprehensive up-to-date in-situ microphysics observations over the full range of particle sizes**

- Including passive microwave, sub-mm, far-IR, mid-IR and visible observations, and radar and Lidar
- Up-to-date in-situ observations with reduced uncertainties for small particle sizes
- Multiple aircraft required for full range of instrumentation and simultaneous in-situ and remote sensing

Location TBD – currently evaluating potential locations for frequency of occurrence of suitable cloud conditions

Contact: [anthony.baran@metoffice.gov.uk](mailto:anthony.baran@metoffice.gov.uk), [stuart.fox@metoffice.gov.uk](mailto:stuart.fox@metoffice.gov.uk)



# Discussion



- There are still ongoing inconsistencies with the standard ice crystal models commonly used to compute the SSPs from the UV to the microwave.
- This is probably owing to them being invariant as a function of ice crystal maximum dimension and so need to be scaled across ice crystal size.
- Evidence presented showing possible general breakdown of commonly used ice crystal scattering models in long-wave region of the electromagnetic spectrum. To improve on this need to:
- Combine many different datasets similar to Lawson et al. (2019) from differing cirrus/ice cloud regimes to find the possible emergence of most important shape distributions, mass- and area-D relationships with the uncertainties in the power law parameters (a, and b terms) to utilise in models and in remote-sensing.
- A new ice aggregating rosette model has been presented that follows observed area- and mass-D power laws for application to NWP and climate models, and remote-sensing across the electromagnetic spectrum. This model should be applicable across the spectrum in the case of in-situ generated cirrus. To address these issues:
- An aircraft field campaign is being formulated to take place in March 2024 to sample uniquely and simultaneously the microphysics and radiometric properties of cirrus across the electromagnetic spectrum to test and evolve the new generation of ice crystal scattering models.

