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The quest for consistent ice optical properties across the spectrum

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The importance of cirrus in model prediction of weather and climate

The importance of cirrus in weather and climate prediction

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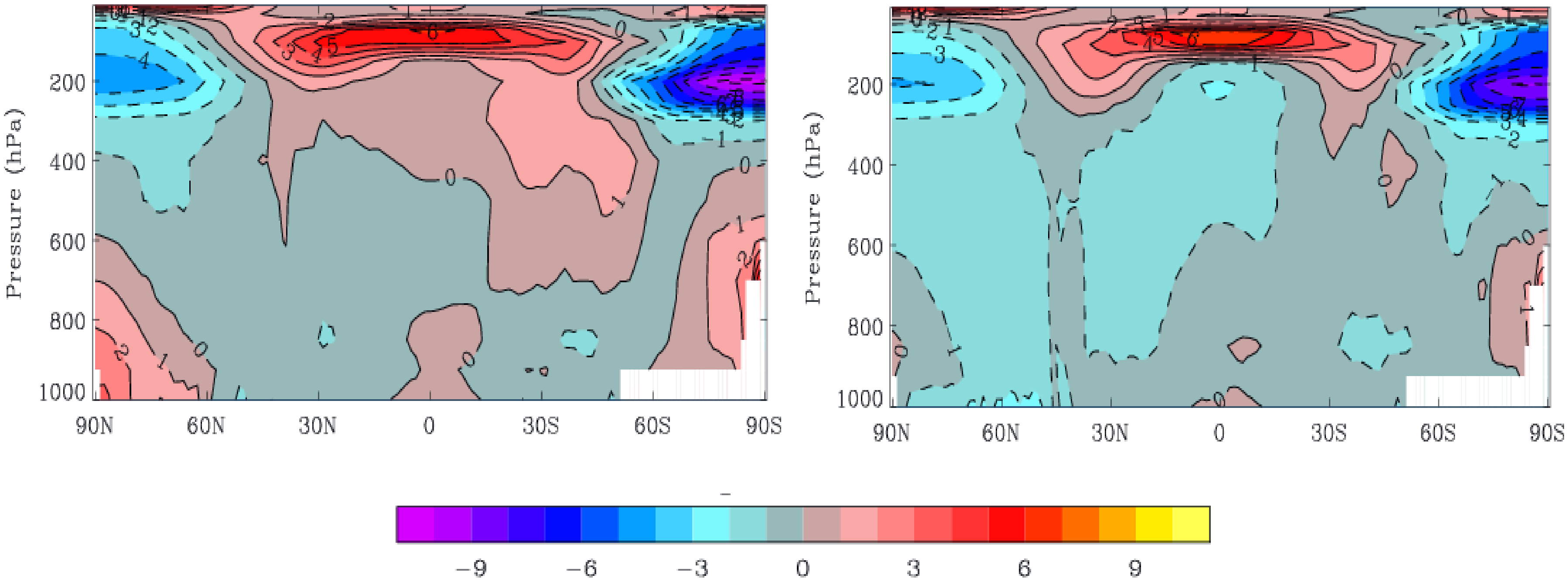
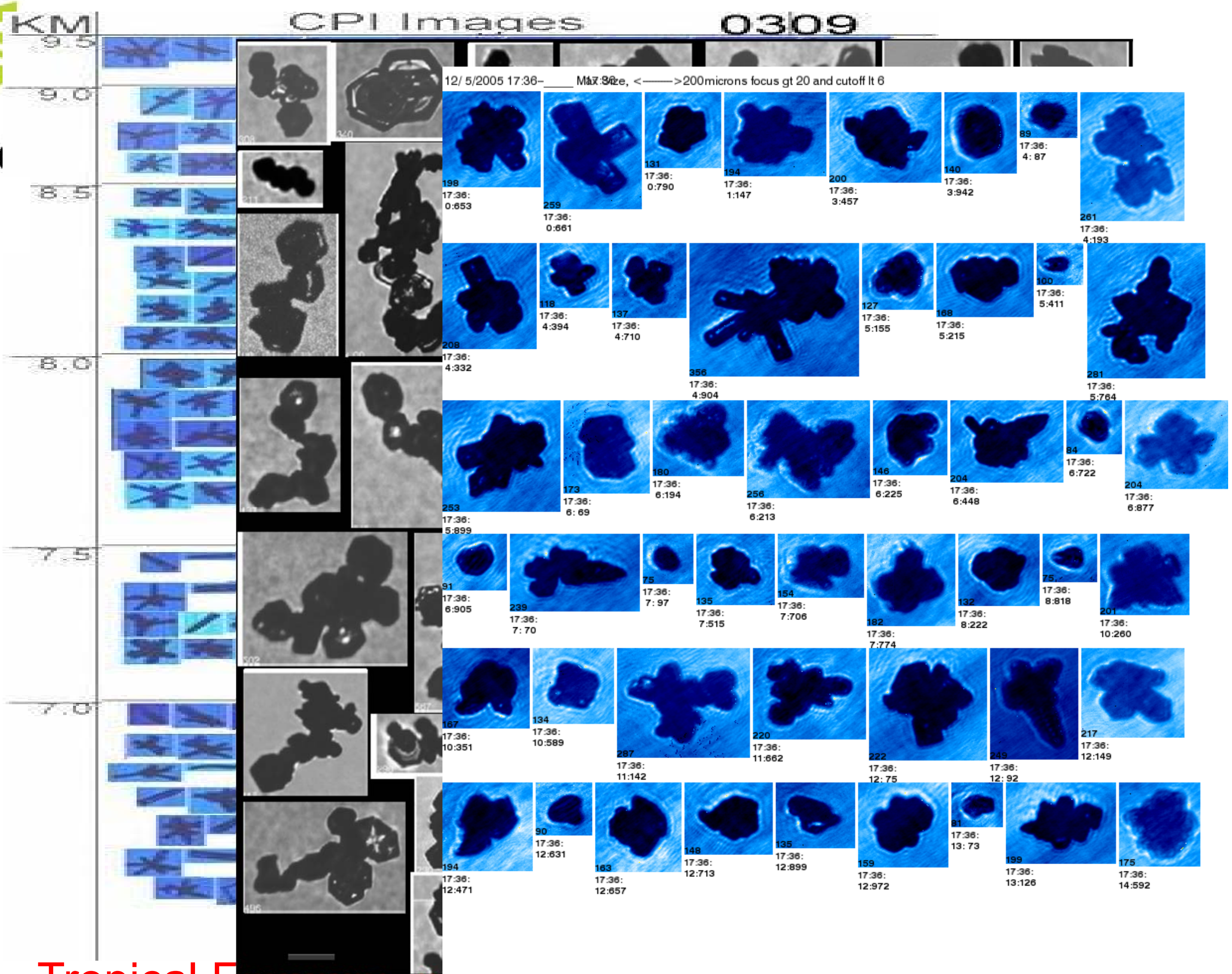
Weighted towards simple ice crystals **in the PSDs**

Same PSDs but weighted towards more aggregated ice crystals



Model minus ERA-Interim temperature product



Tropical Example, A Heymsfield

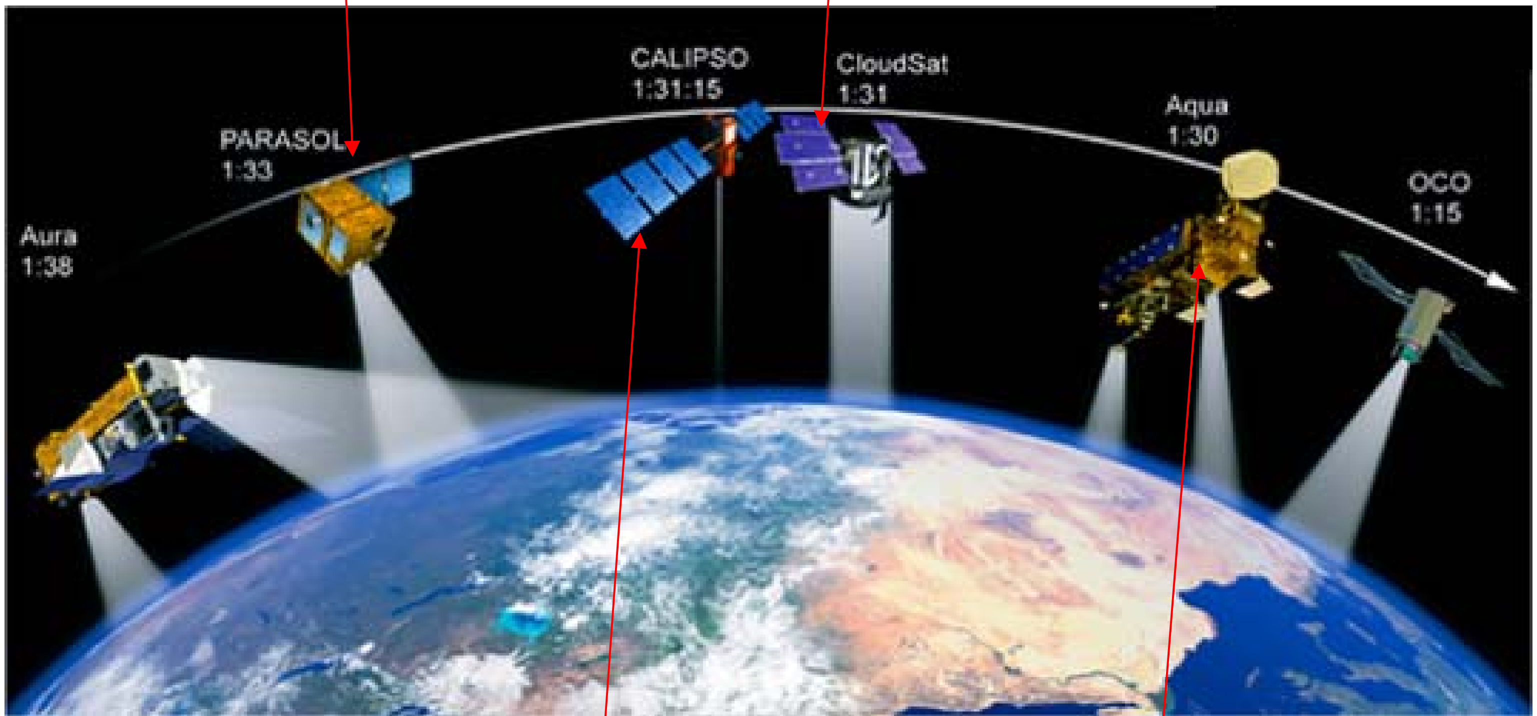
University of Manchester

2008.

The A-Train Constellation measures radiative properties & ice mass

Total & polarized solar reflection

94 GHz cloud-profiling radar



Lidar

Solar reflection &
Infrared transmission

The previous cirrus ice optics parametrisation

Edwards et al., (2007), Ice crystal model - the moderately surface roughened eight-branched hexagonal aggregate (Yang & Liou, 1997)

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→ $\omega_0(D_e), g(D_e), K_{ext}(q_i, D_e); D_e(T_c)$

Prognostic variable in microphysics

Diagnosed variable **in radiation**

$$D_e = 3/2 \int m(\underline{q})\, n(\underline{q})\, d\underline{q} \,/\, \rho_I \int \langle S(\underline{q}) \rangle\, n(\underline{q})\, d\underline{q}$$ Foot (1988)

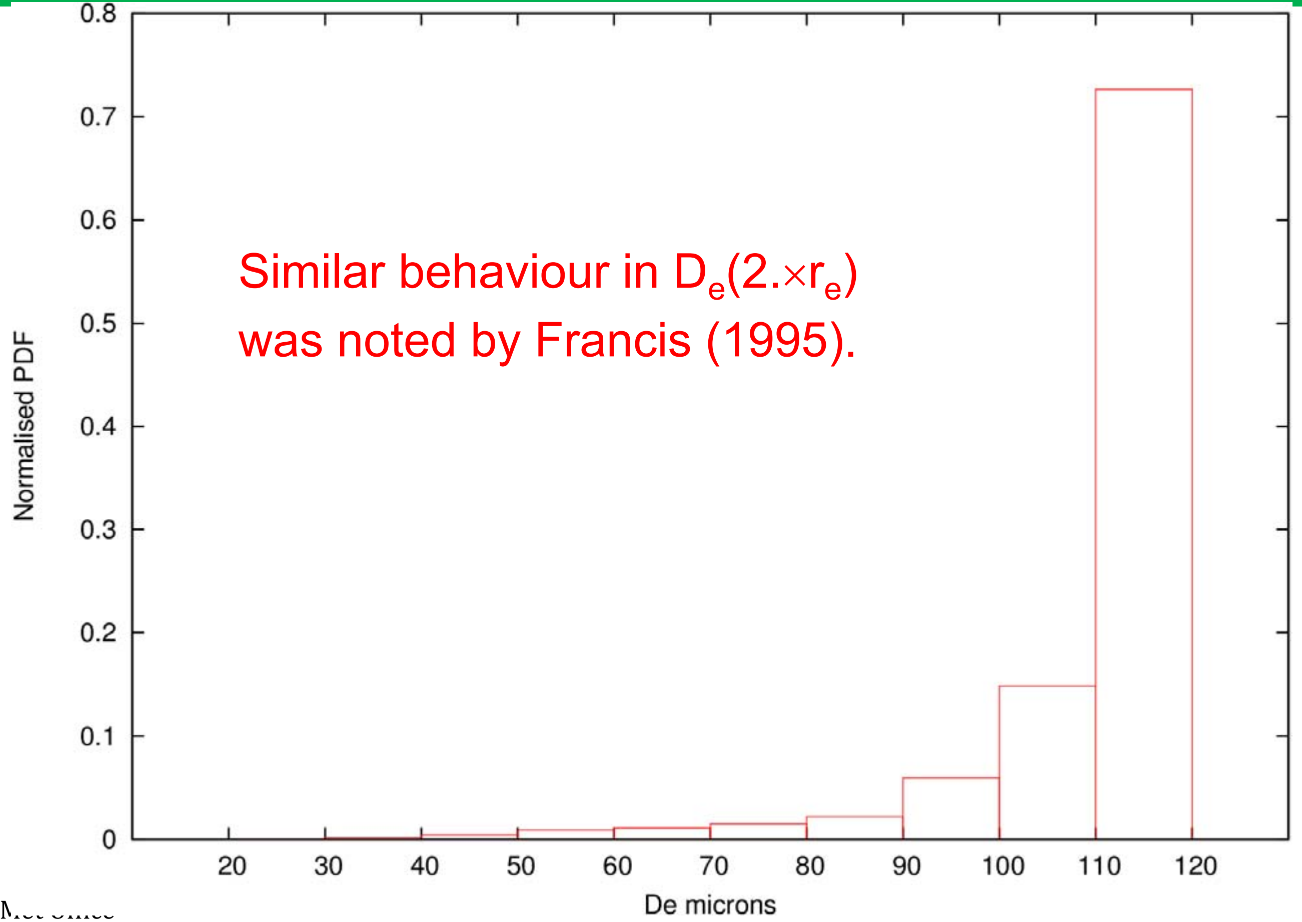
Sieron et al, 2017 [JGR, 122,7027-7046]Microwave simulations at 91.665 GHz

Table 1. Scattering Optical Depths and Brightness Temperatures Output From CRTM Simulations With the Same Water Content, Effective Radius, and Particle Properties but With Different Particle Size Distributions[a]

Effective Radius (microns)	$\tau_s m/\tau_s exp$	Water Content ($g\ m^{-3}$)	Monodisperse: Scattering Optical Depth	Monodisperse: Brightness Temperature (K)	Exponential: Scattering Optical Depth	Exponential: Brightness Temperature (K)
0		0	0	276.18	0	276.18
103.7	4.32	1.15×10^{-4}	4.03×10^{-6}	272.96	1.74×10^{-5}	272.96
184.3	3.92	1.15×10^{-3}	2.24×10^{-4}	272.91	8.79×10^{-4}	272.79
327.8	2.88	1.15×10^{-2}	1.21×10^{-2}	270.57	3.49×10^{-2}	267.94
582.9	1.81	1.15×10^{-1}	5.54×10^{-1}	204.09	$1.00 \times 10^{+0}$	200.35
1037	1.77	$1.15 \times 10^{+0}$	$1.16 \times 10^{+1}$	75.57	$2.05 \times 10^{+1}$	74.74

$D_e = 3/2 \int m(D)\, n(D)\, dD / \rho_I \int \langle S(D) \rangle\, n(D)\, dD$

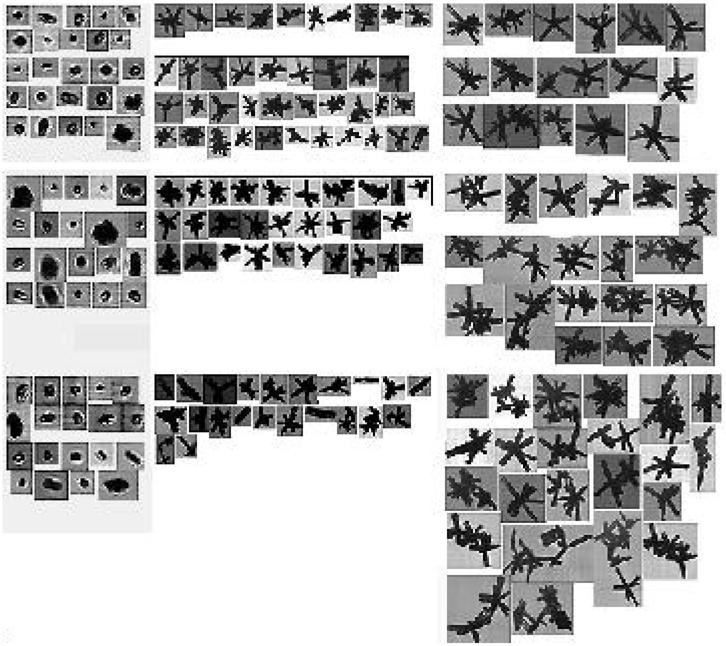
Let us assume a cloud of ice in which the ice crystals become aggregated after about 200 μm (Schmitt & Heymsfield, 2010) $\langle S(D) \rangle = cD^{1.76}$, let us assume that these ice crystals have $m(D)=0.0257D^2$ (Cotton et al., 2013). At sizes less than this, we assume ρ=700 kg m^{-3} and $\langle S(D) \rangle = kD^{1.86}$ (Kuhn and Heymsfield, 2016). Apply these mass- and area-dimension relations to D_e integrated over 20662 PSDs, the normalised PDF of D_e for such a simulation is:

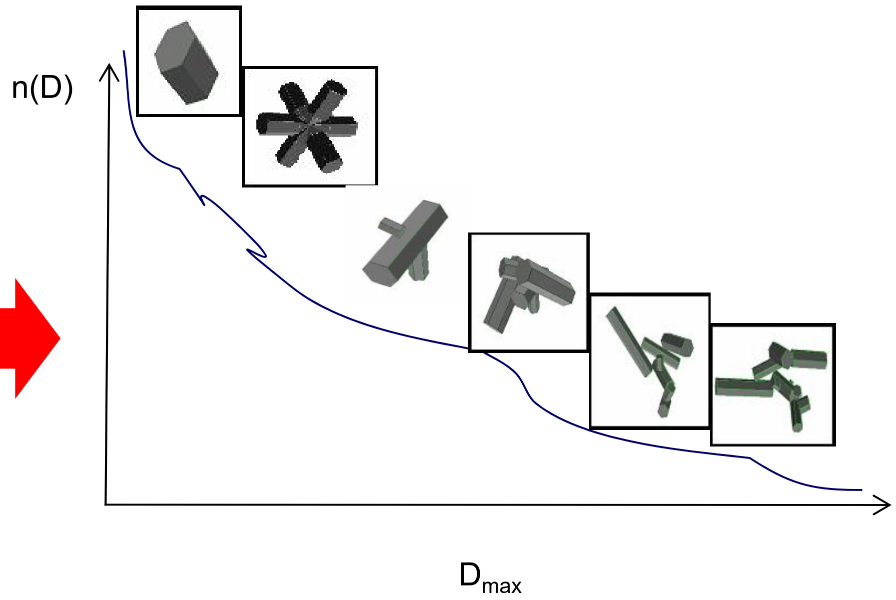


Similar behaviour in $D_e(2.\times r_e)$ was noted by Francis (1995).

AN ALTERNATIVE APPROACH: THE ENSEMBLE MODEL OF CIRRUS ICE CRYSTALS…

Generalise



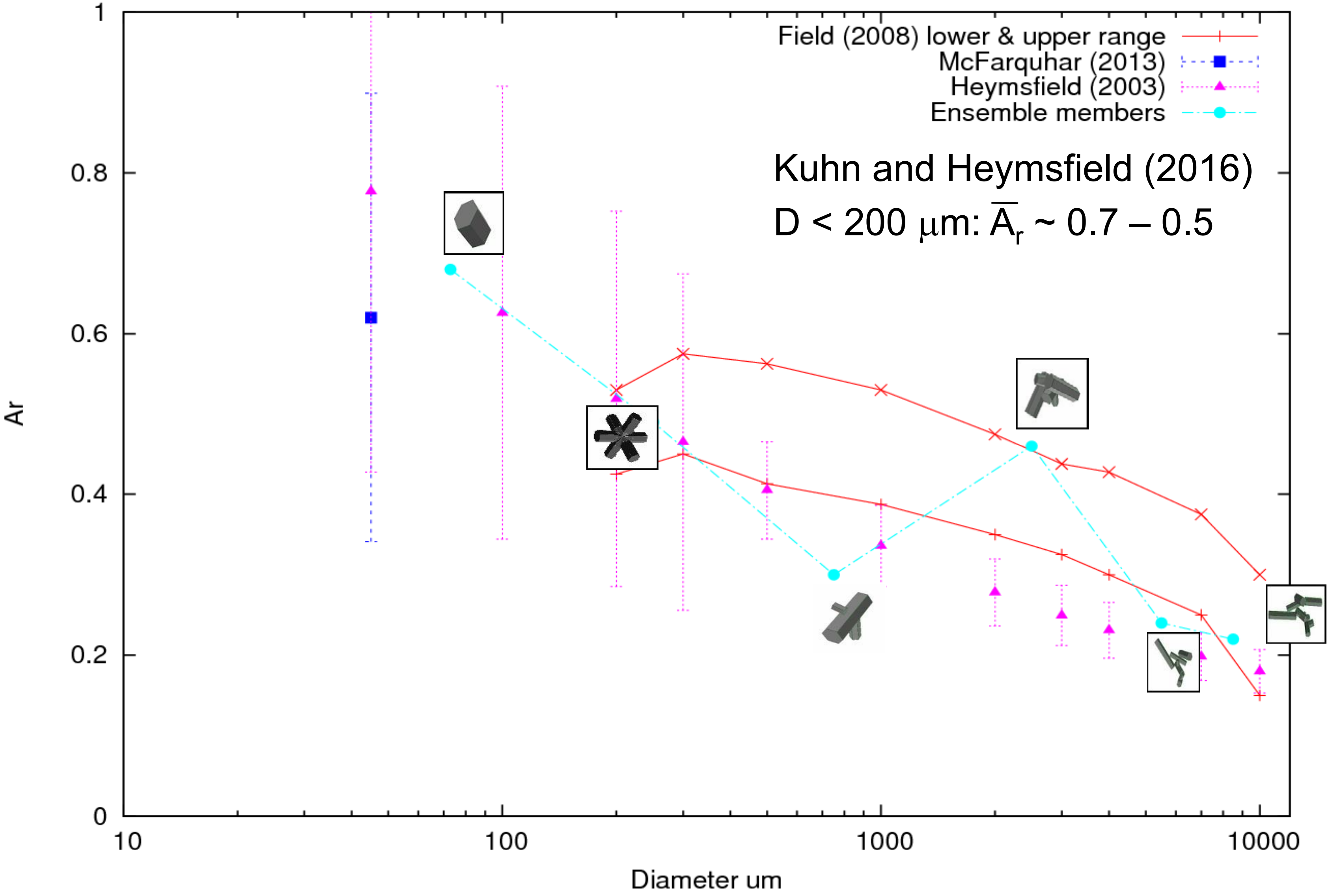


Baran & Labonnote (2007)

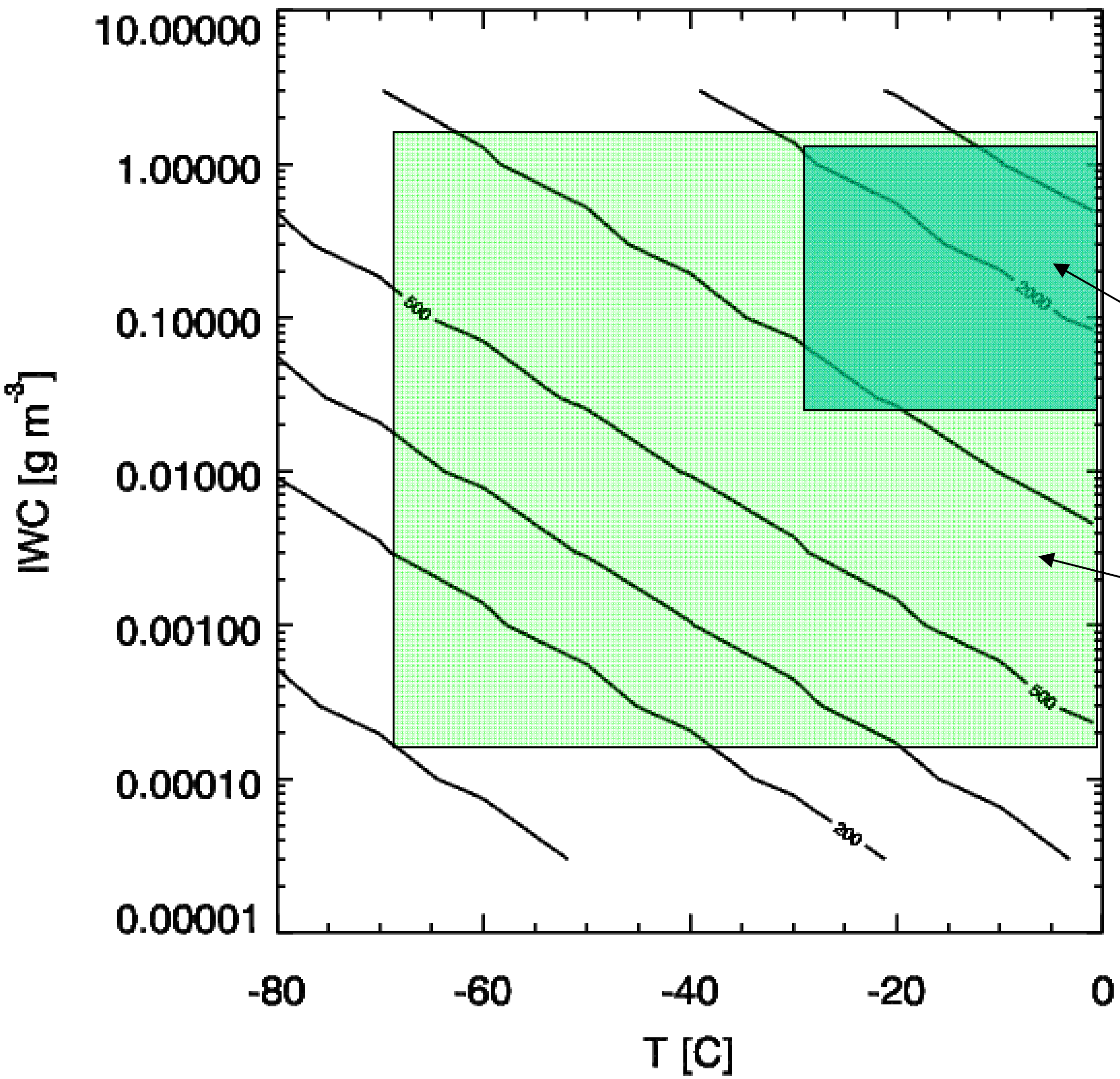
Microphysical Consistency

Observed area Relationships: Area ratio:

$A(D)/A_c(D)$



Require PSDs: we use moment parametrisation by Field et al., (2007)



Houze et al. 1979
39 in-situ PSDs (current PSD assumption in global operational model, where PSD shape is kept constant At temperatures < -30^{o}C)

Field et al. 2007
10000 in-situ measurements obtained in tropics and mid-latitudes.

Moment estimation parameterization, Field et al. (2007)

$$M_n = \int D^n f(D)\, dD,\ n \geq 0$$

$$M_n = \alpha_n \exp(\sigma_n T_c) M_2^{\beta_n}$$

$$M_2 = aD^{b=2},\ a = 0.0257 \text{ (Cotton et al., 2013)}$$

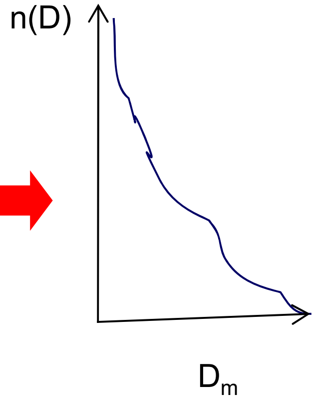
Links PSD to ice mass and T_c. Moments are used to predict cloud evolution

PSDs in climate model cloud microphysics scheme same as radiation scheme & mass-D relationship same in both to generate PSDs

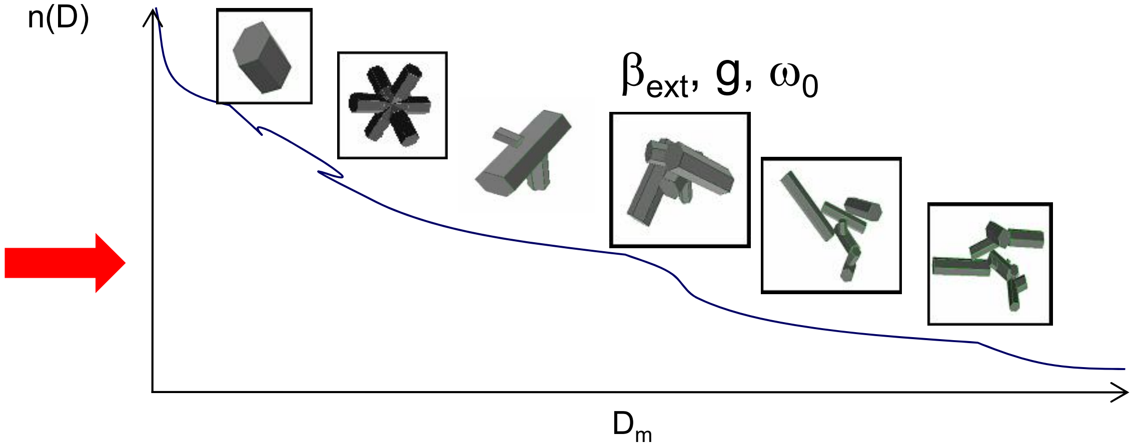
We apply tropical normalisation

To obtain bulk cirrus scattering properties

IWC, T_c



Field et al. 2007



$$\langle \beta_{ext} \rangle = \int_{D_{min}}^{D_{max}} n(D) \left[\sum_{j=1}^{j=6} wt_j \langle C_{ext_j} \rangle \right] dD$$

IWC (Closure)

Same PSDs as in cirrus microphysics

Bulk K_{ext}, g, ω_0

Directly related to IWC, T_c

Baran et al. 2009

Derivation of ensemble short-wave and long-wave single-scattering properties

Short-wave: Assume geometric optics approximation: Apply Monte-Carlo Ray-tracing Method (Macke et al. 1996) to compute scattering phase matrix & total optical properties

Each element of the ensemble is **randomised** by **distortion** of the ray paths after each reflection/refraction event **and inclusions, assuming spherical air bubbles to mimic multiple-scattering between inclusions within each ice crystal element**

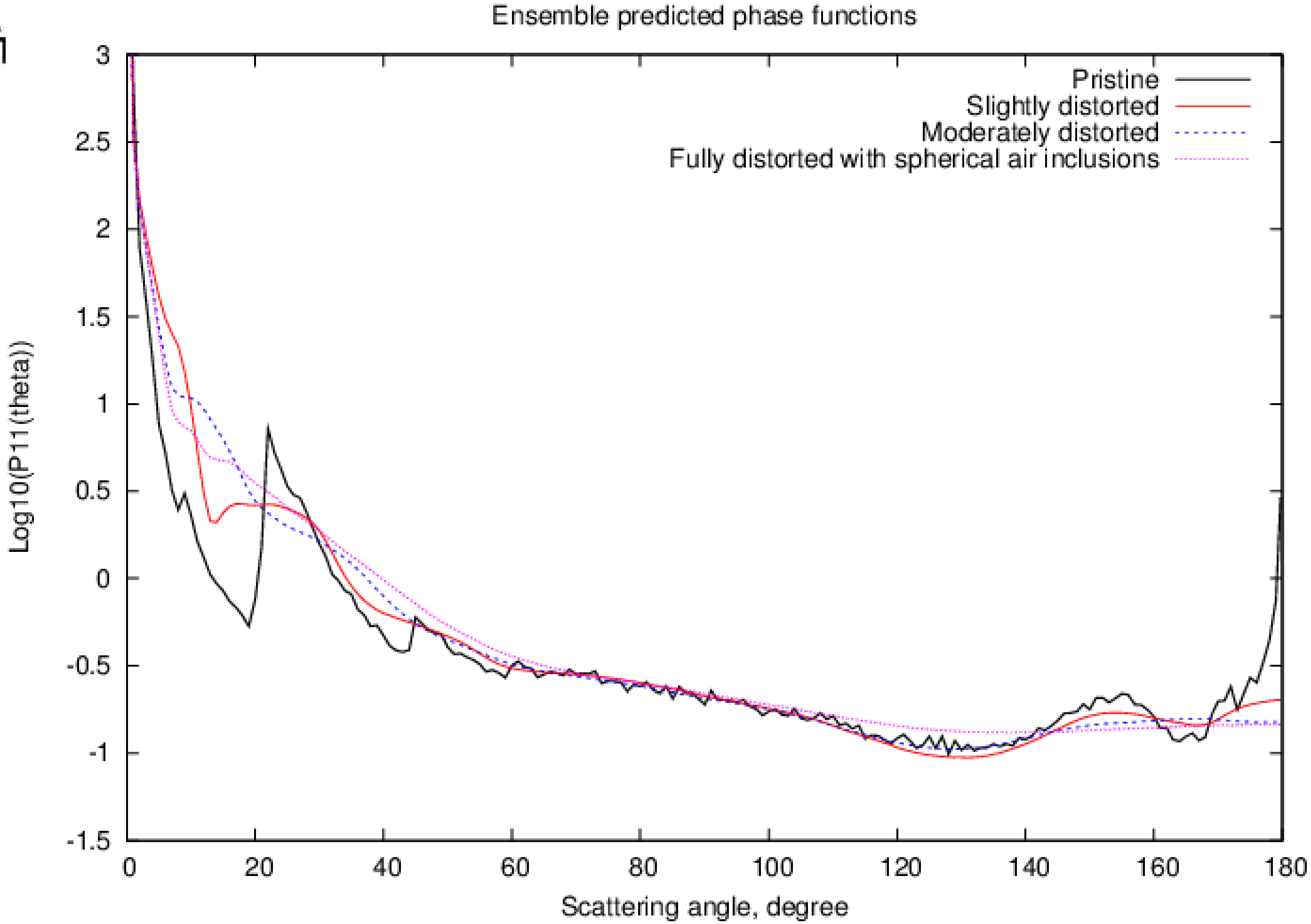
Each ensemble member is randomized from zero (pristine ice crystals) to fully randomized (distortions plus inclusions have been applied)

Long-Wave: Electromagnetic theory applied (T-matrix, Mischenko & Travis, 1998) + asymptotic approximation (Baran 2003).

The single-scattering properties properties are then integrated over the F07 tropical PSDs, as a function of IWC and $T_{c,}$ to predict the bulk scattering properties

Ensemble model phase functions

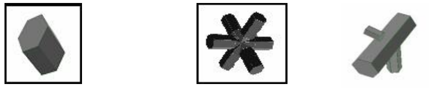
Baran et al. 2015



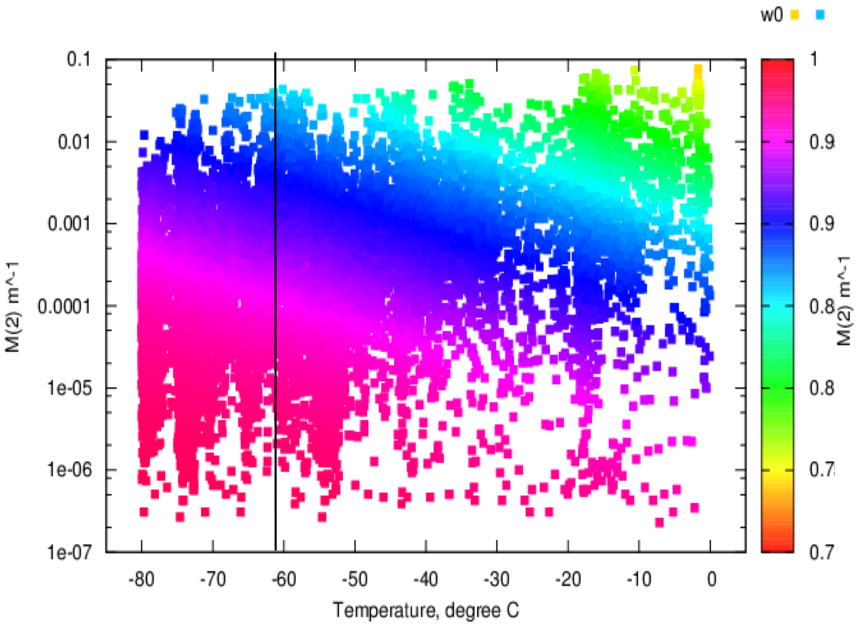
ω_0 and g in M_2-T_C space: λ=1.575 μm

$K_{ext}(\lambda_{E\text{-}S},q_i,T_c)$, $\omega_0(\lambda_{E\text{-}S},q_i,T_c)$, $g(\lambda_{E\text{-}S},q_i,T_c)$ Baran et al. (2016)

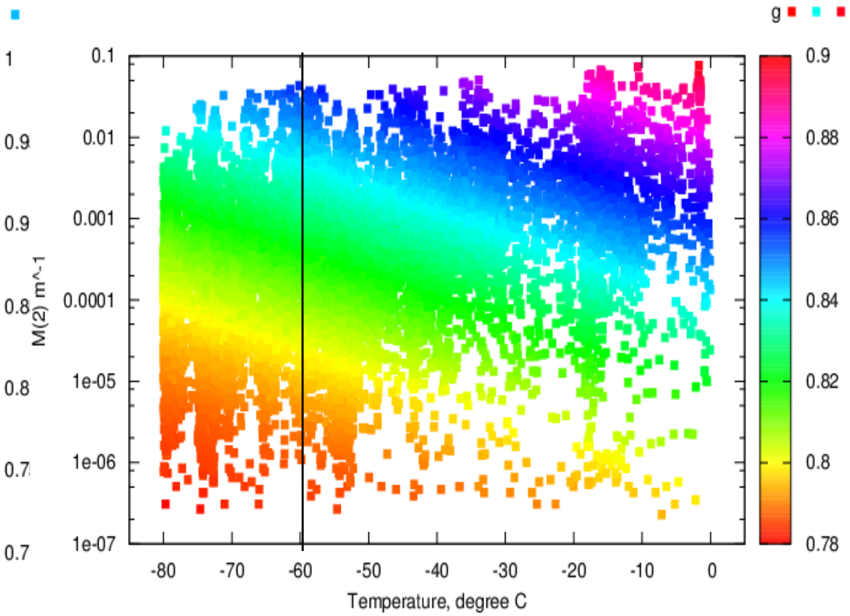
wt_j= 0.50 0.20 0.30



ω_0



g



Baran et al. (2016)

The IWC and cloud temperature were obtained from a number of field campaigns including CAESAR (UK), CEPEX (Tropics), FRAMZY (Europe)

A total number of 20662 PSDs were generated & randomly generated

The parametrisation

$K_{ext}(\lambda_{E\text{-}S},q_i,T_c) = a_\lambda(q_i/T^4)$; $\omega_0(\lambda_{E\text{-}S},q_i,T_c) = b_\lambda + c_\lambda\, q_i T$

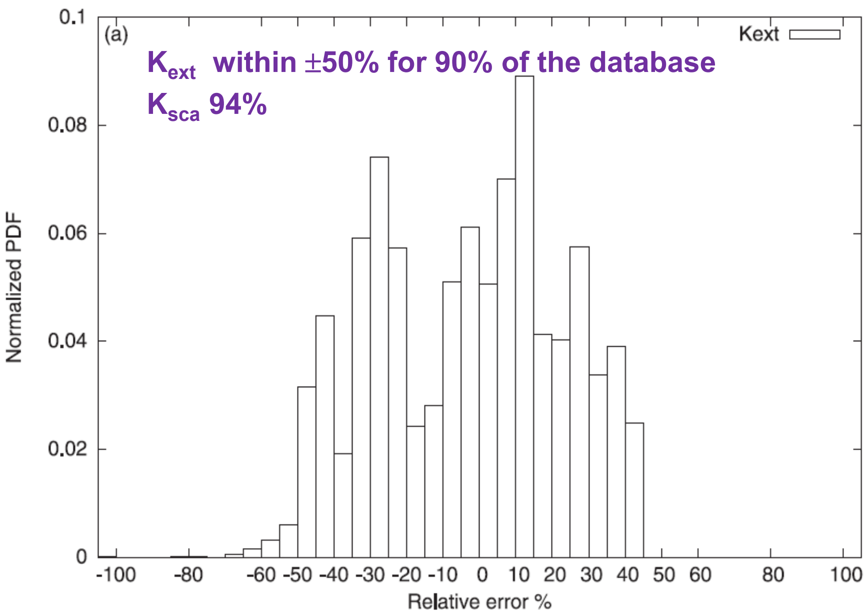
$g(\lambda_{E\text{-}S},q_i,T_c) = d_\lambda + e_\lambda\, q_i T$

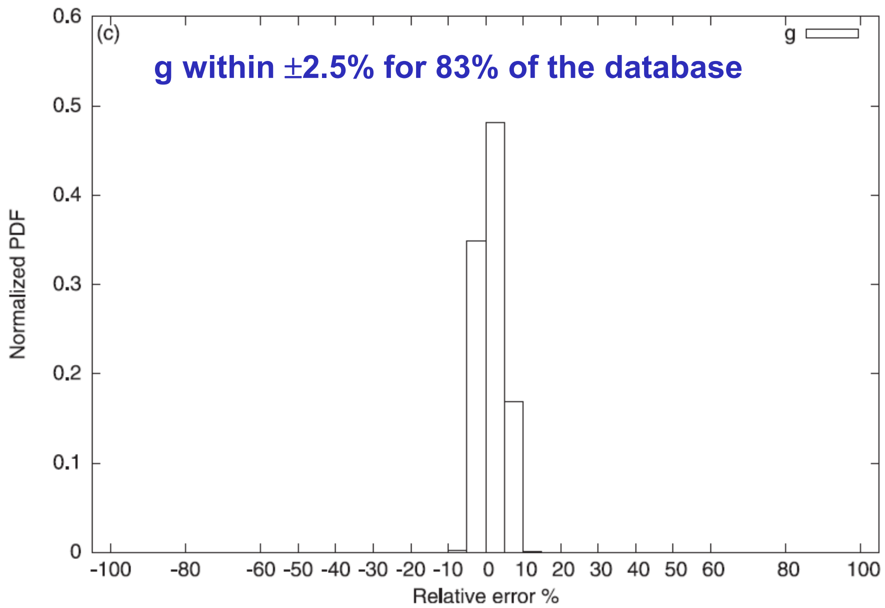
If $q_i > 10^{-3}$ kg/kg, then

$\omega_0 = \omega_0(q_i = 10^{-3}\text{ kg/kg})$

$g = g(q_i = 10^{-3}\text{ kg/kg})$

Relative % errors in the K_{ext} and g parametrisations at E-S(SW B5 1.19-2.38 μm)





The impact of the ice optics parametrisation in GA 7 relative to observations & the previous parametrisation

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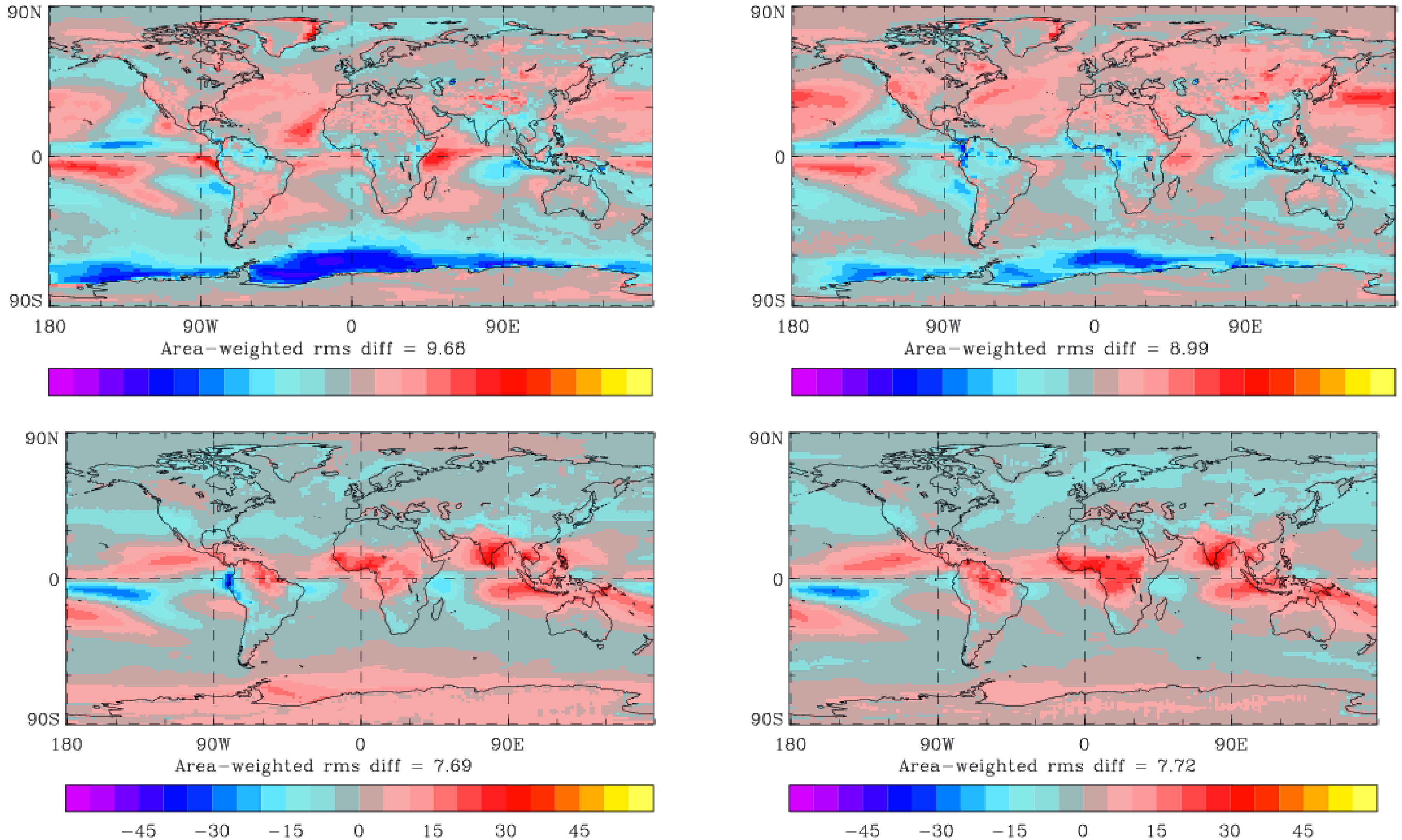
Annual 20-year TOA area-averaged annual mean of coupled ocean-atmosphere model minus CERES EBAF SW reflection and OLR

Inconsistent model GC2

Consistent model (GC3) next CMIP



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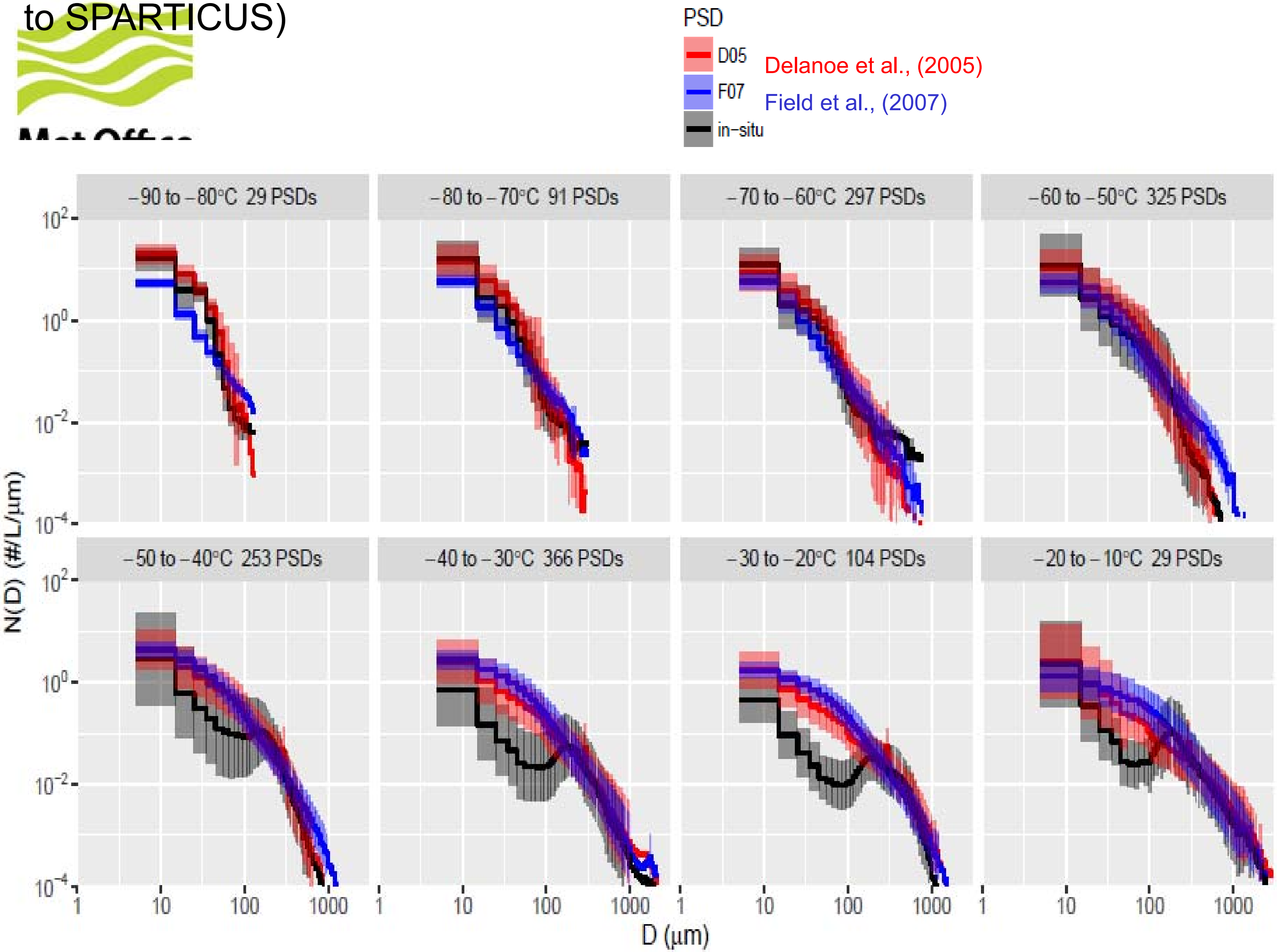
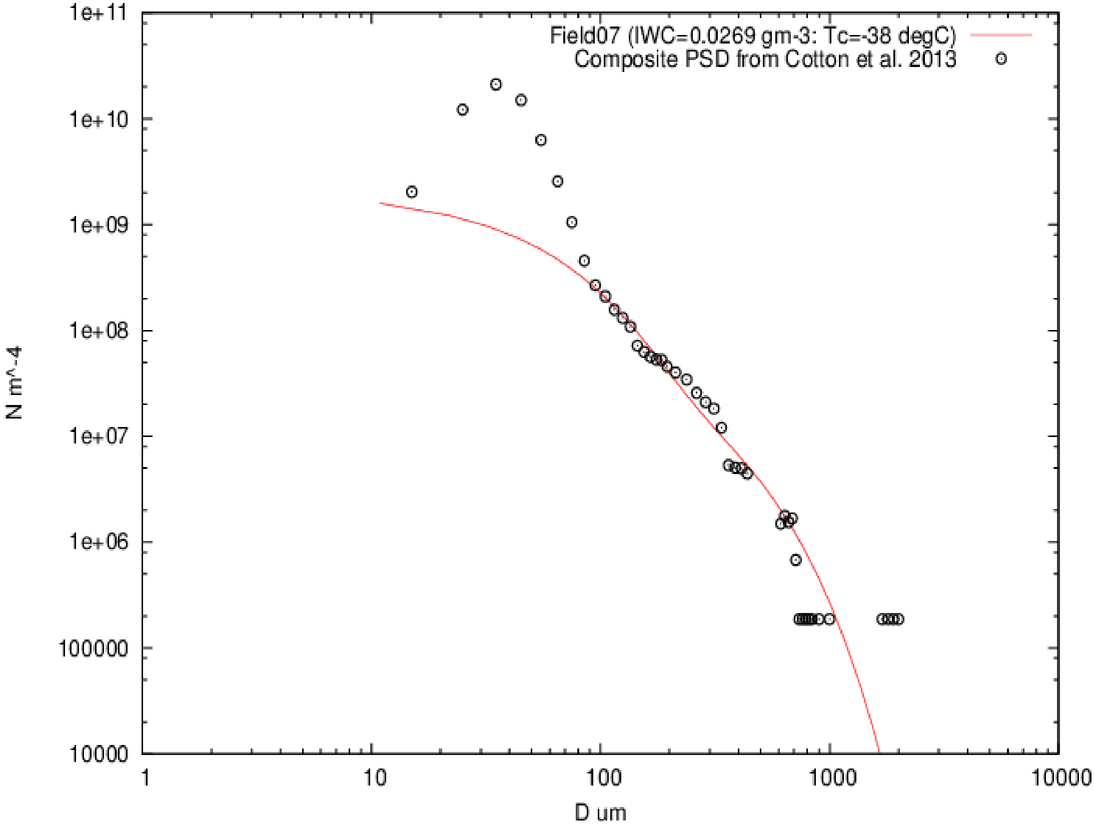
The global validity of the PSD assumption & ice optics

Comparison of PSD parametrisations against in-situ measured PSDs (From ATTREX to SPARTICUS)



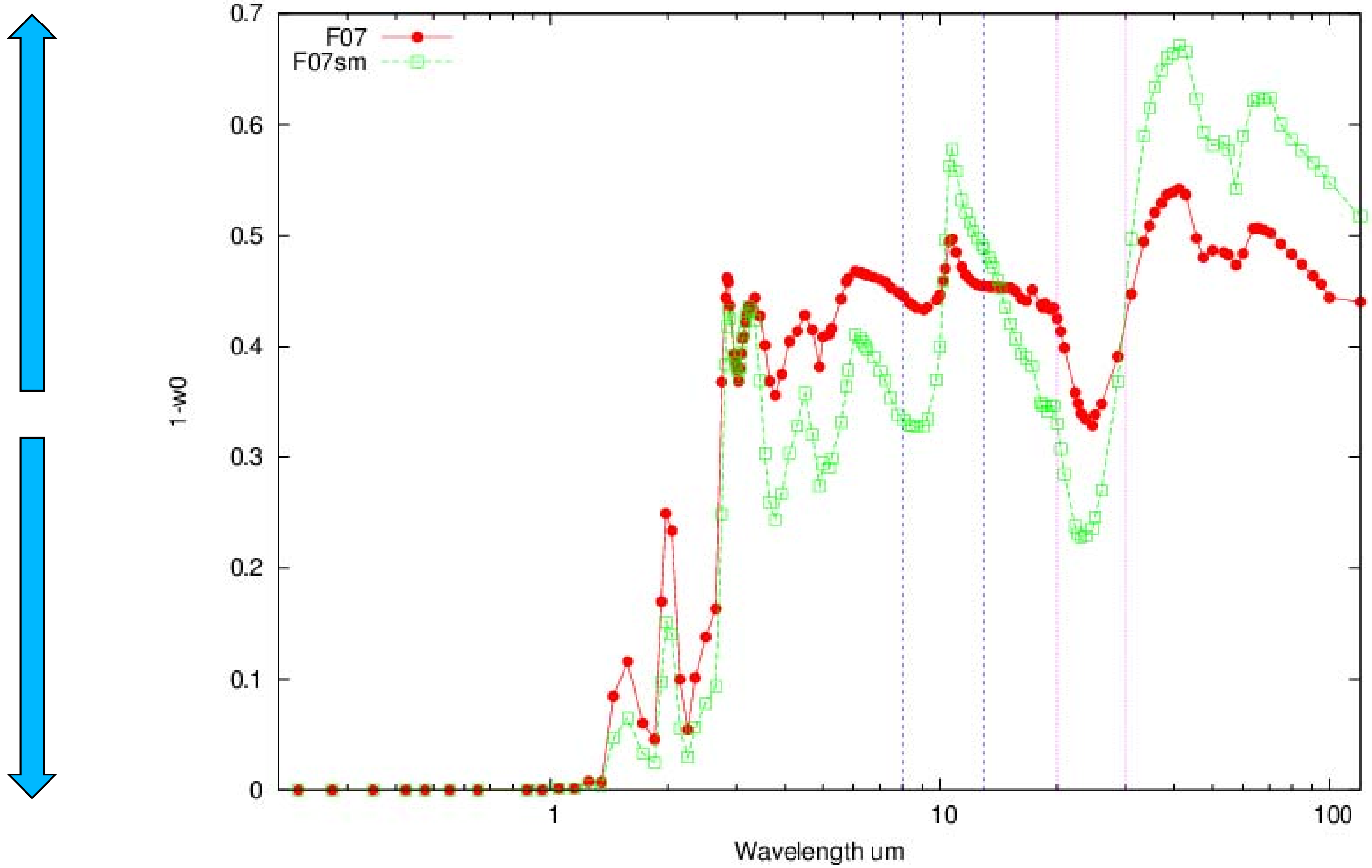
Courtesy of Odran Sourdeval (University of Leipzig)

PSD small ice uncertainty: which shape of the small ice mode?



The effect of small ice uncertainty on absorptivity

Absorption



Scattering

The effect of small ice uncertainty on absorptivity

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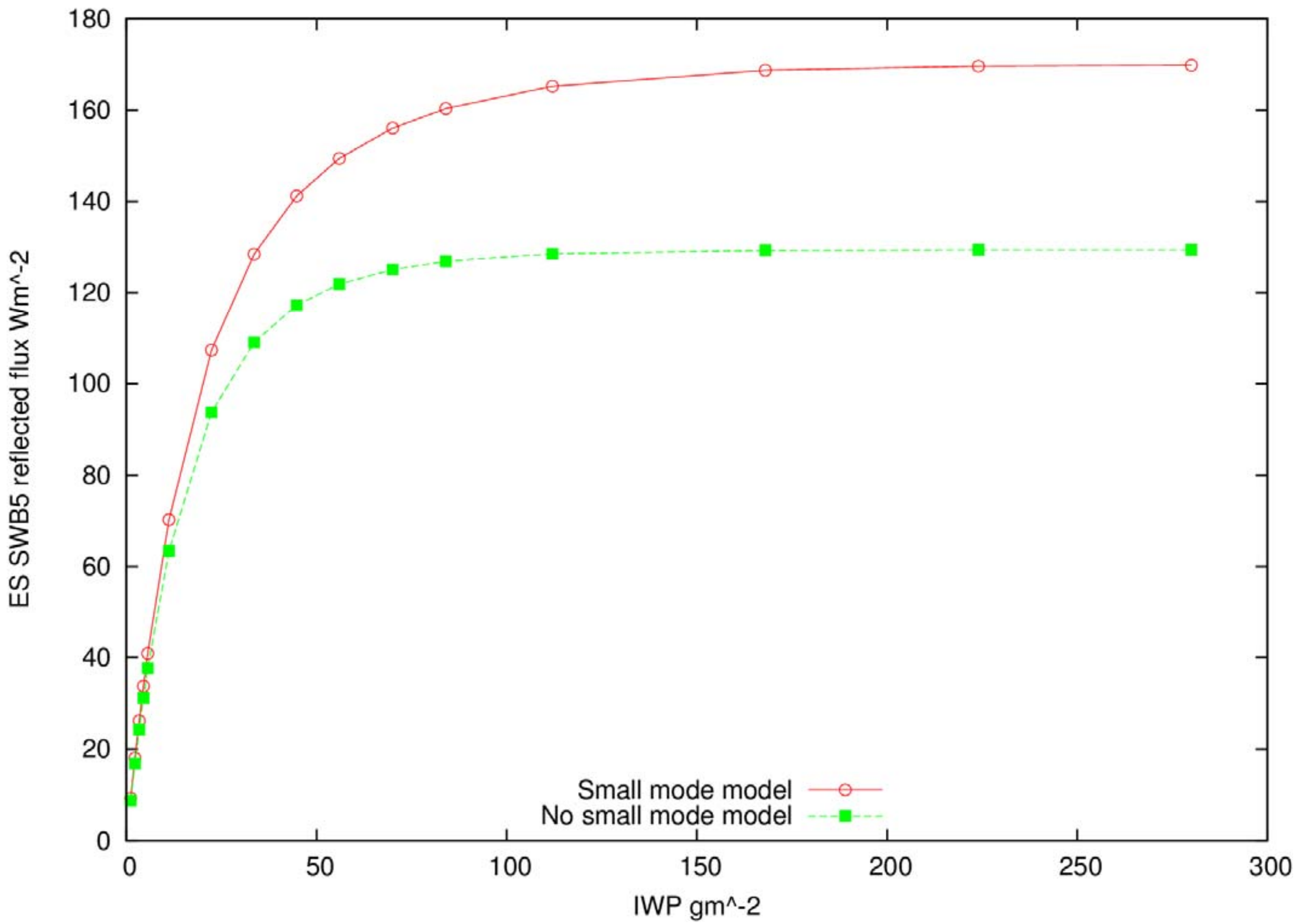
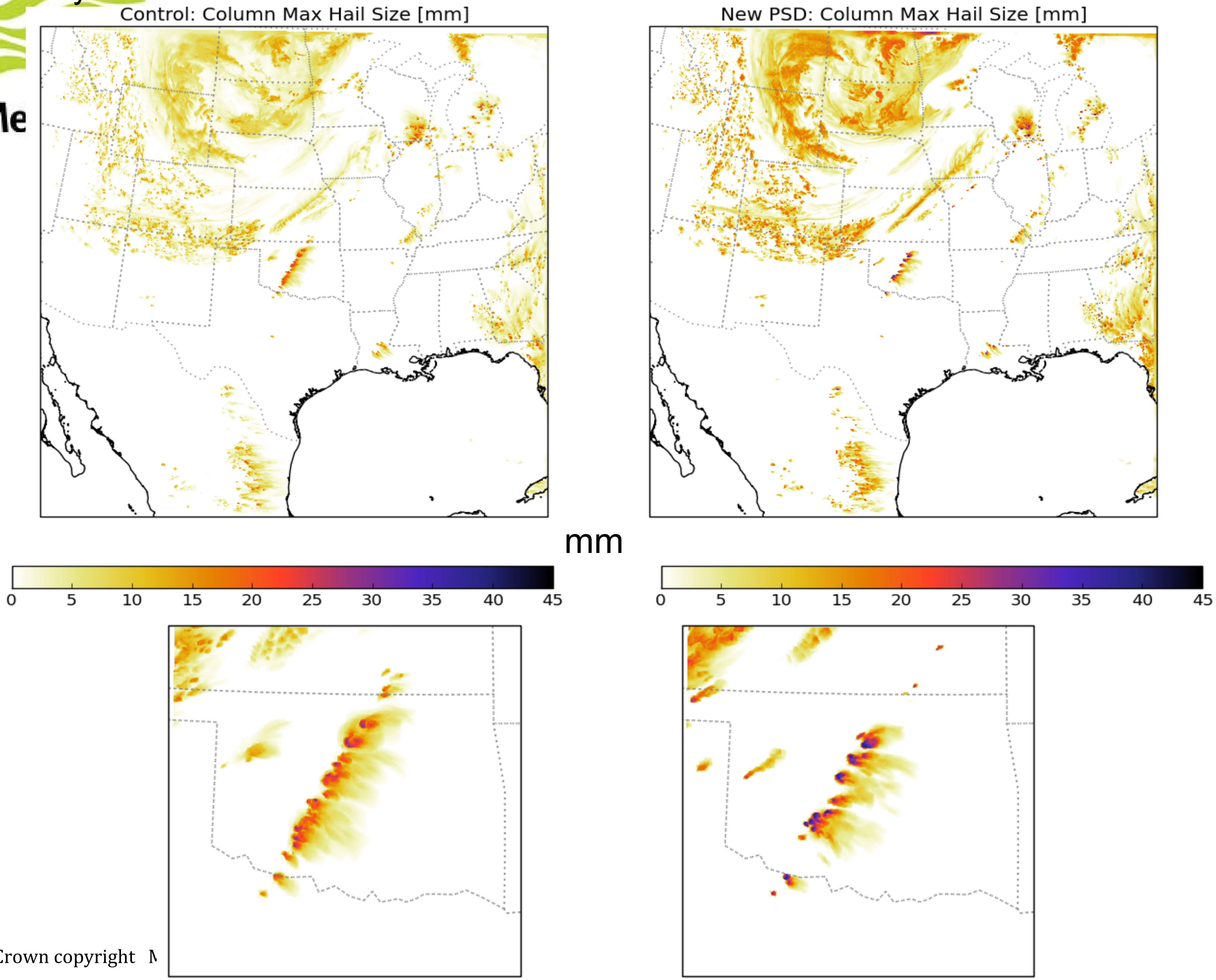
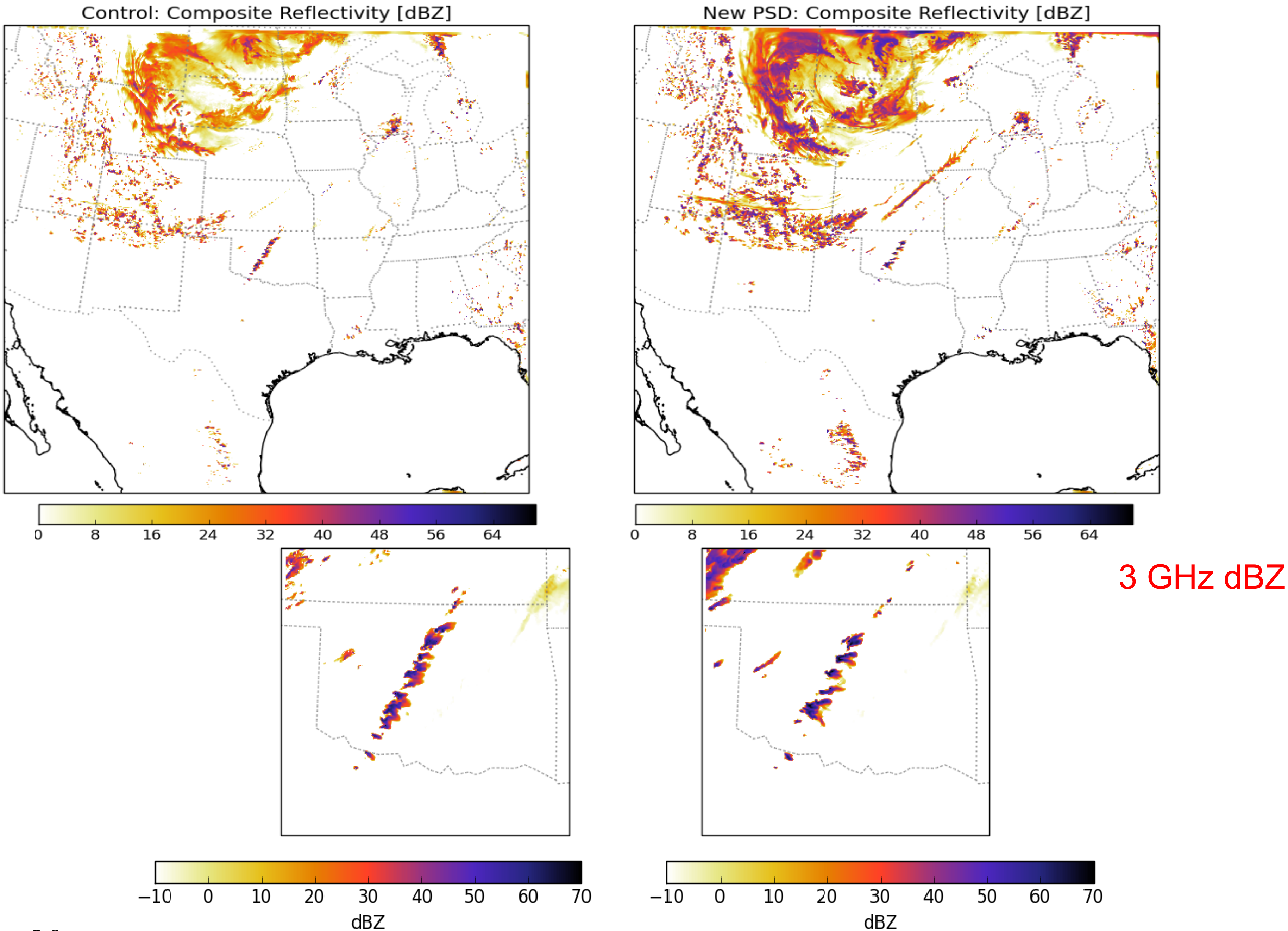
ES(SW B5 1.19-2.38 μm)



New graupel PSD param developed by Field and Heymsfield, 2018 (in review)

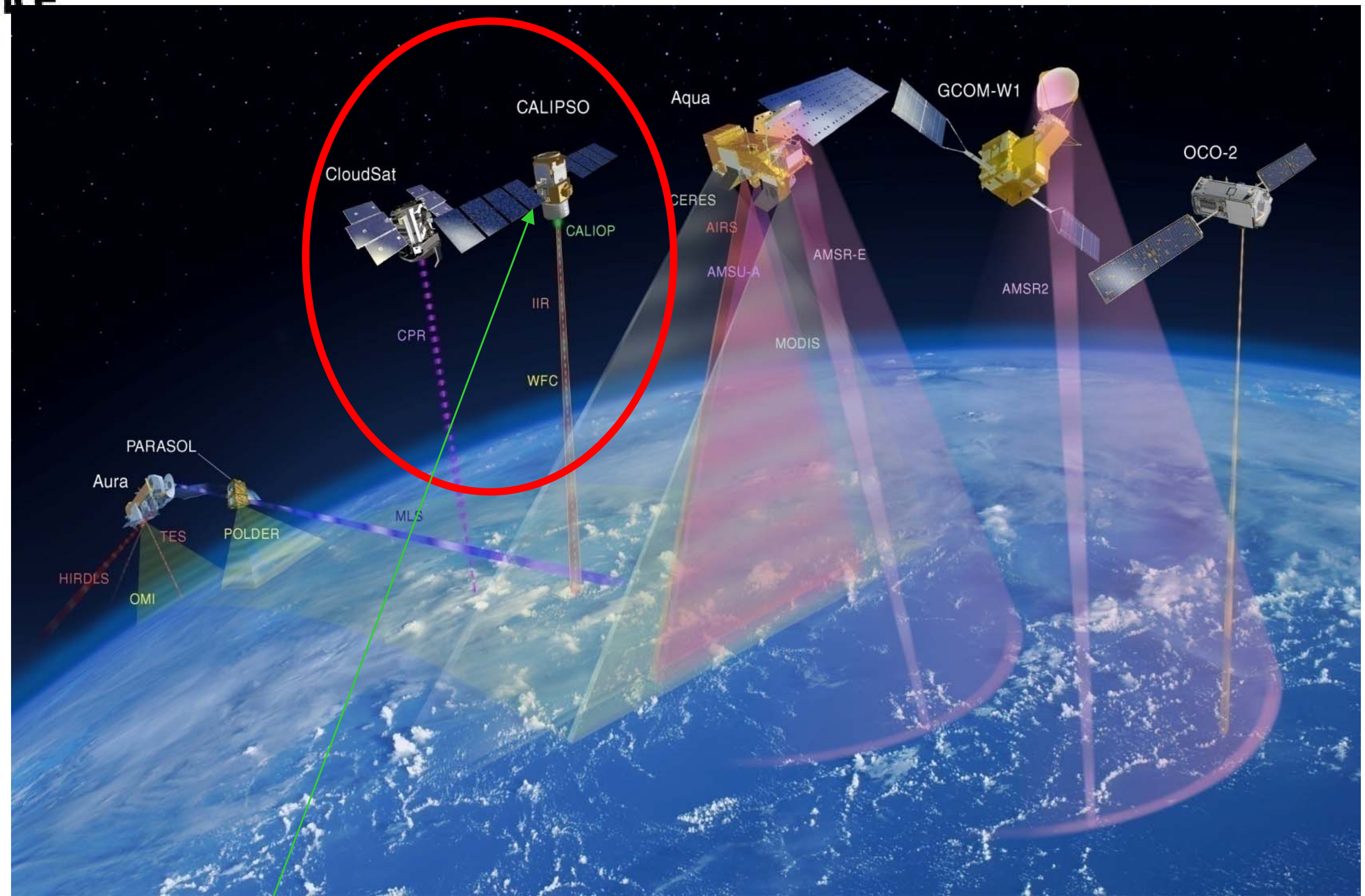
courtesy Jonathan Wilkinson





Control: Composite Reflectivity [dBZ]
New PSD: Composite Reflectivity [dBZ]
0 8 16 24 32 40 48 56 64
0 8 16 24 32 40 48 56 64
3 GHz dBZ
−10 0 10 20 30 40 50 60 70
dBZ
−10 0 10 20 30 40 50 60 70
dBZ

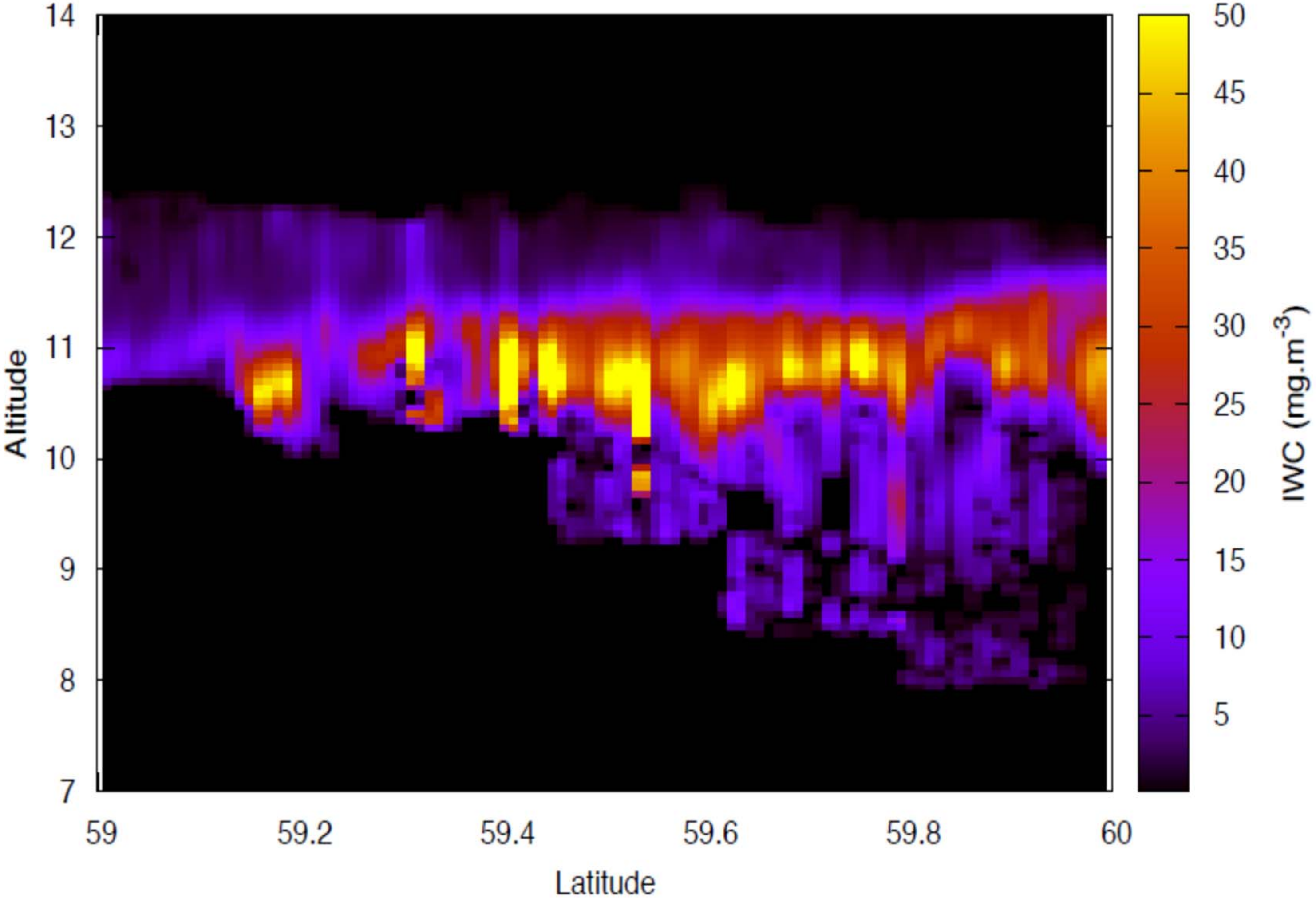
Combine radar and lidar to obtain cloud profiles (DARDAR) to obtain ensemble weightings and global radiometric equivalent brightness temperatures **(Vidot et al., 2015 JGR, 120, doi:10.1002/2015JD023462)**



IIR centred at 8, 11 and 12 μm

An RTTOV example

Cloud profiles of IWC from DARDAR product

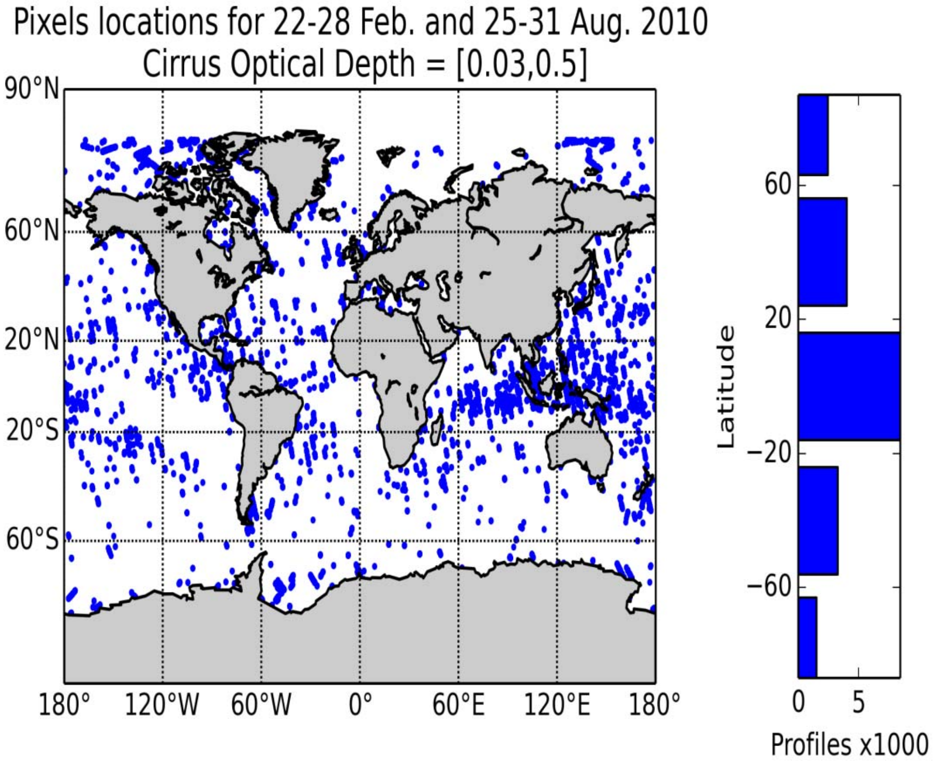


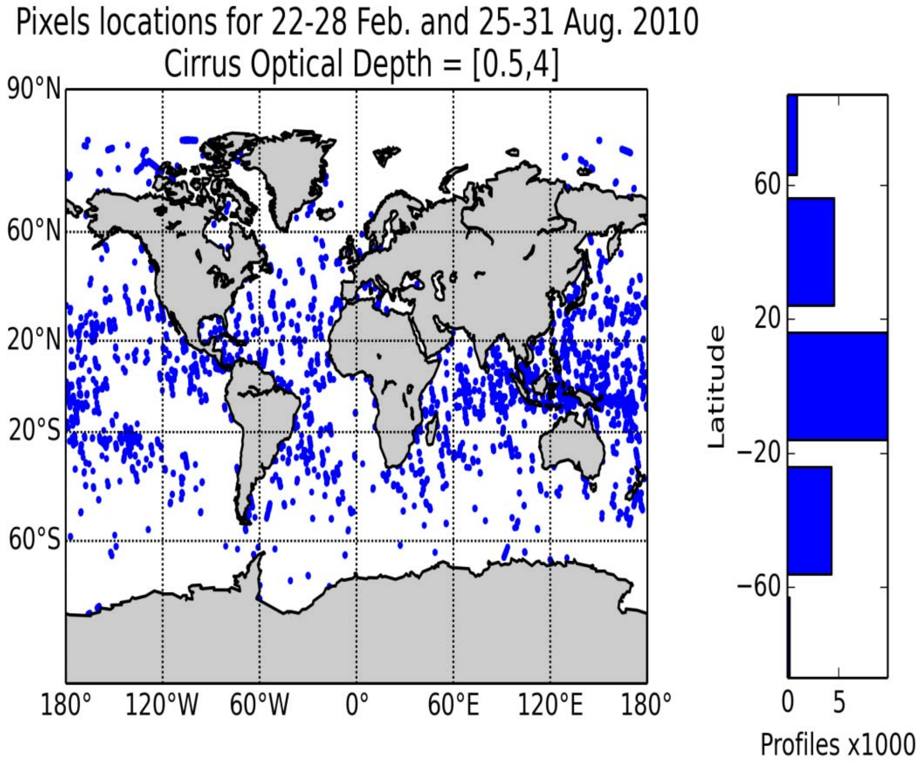
Global distribution of cirrus cases

N=26791

0.03 <τ **<4 Semi-transparent cirrus**

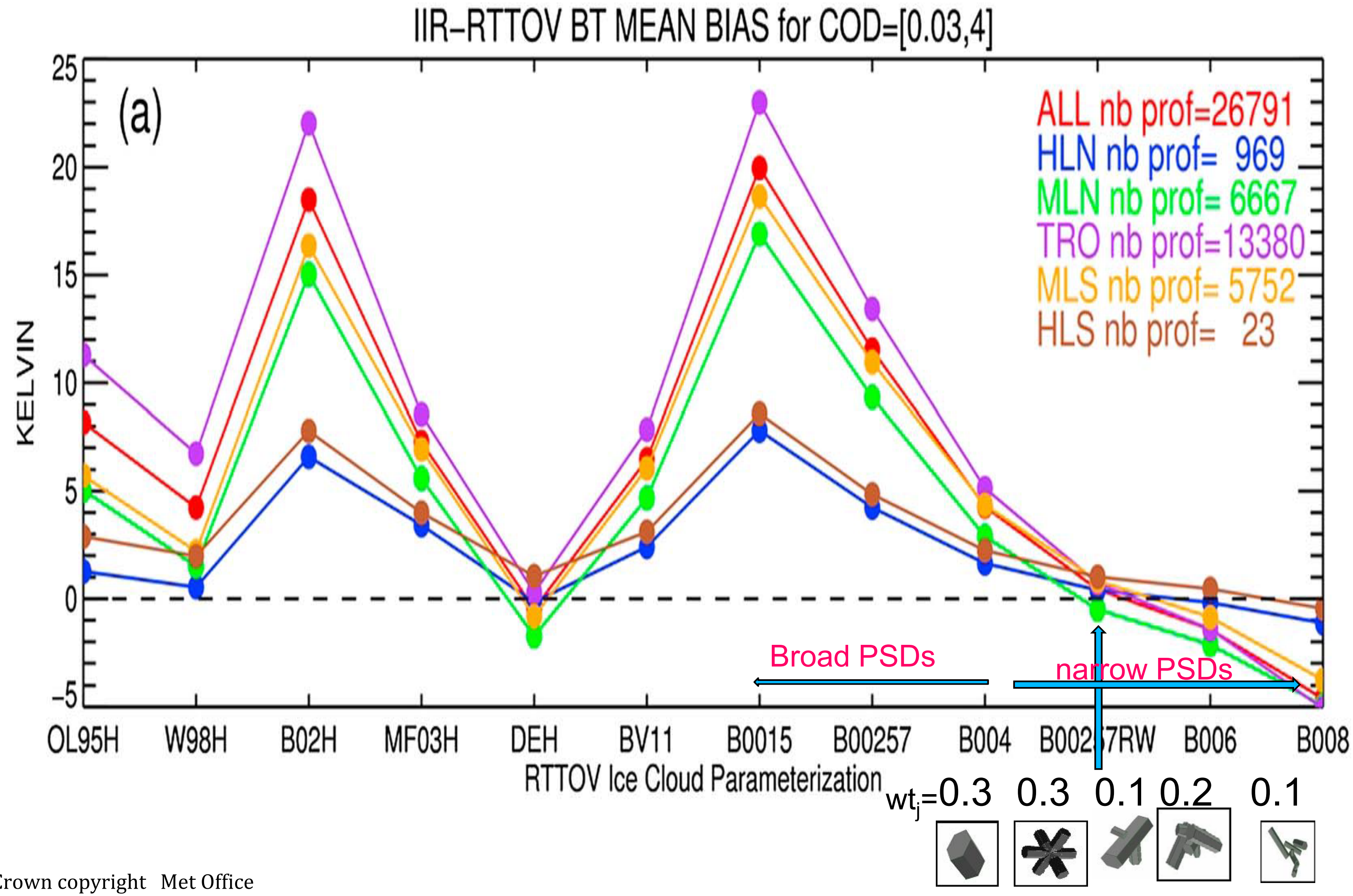
Altitudes high troposphere to stratosphere





Results

Measurements - simulations



The next parametrisations

How to parametrise ice crystals in cloud-aerosol interacting microphysics (CASIM) models ?

CASIM carries prognostic IN, being dust, and applies DeMott et al. (2014) parametrisation to convert to ice crystal number concentrations, so CASIM is a two-moment scheme in terms of M_2 and M_0
Thus we require:

$K_{ext}(\lambda_{E\text{-}S},M_2,M_0,T_c)$, $\omega_0(\lambda_{E\text{-}S}, M_2,M_0,T_c)$, $g(\lambda_{E\text{-}S}, M_2,M_0,T_c)$
or
$K_{ext}(\lambda_{E\text{-}S},M_2,T_c)$, $\omega_0(\lambda_{E\text{-}S}, M_2,T_c)$, $g(\lambda_{E\text{-}S}, M_2, T_c)$
or
$K_{ext}(\lambda_{E\text{-}S},M_0,T_c)$, $\omega_0(\lambda_{E\text{-}S}, M_0,T_c)$, $g(\lambda_{E\text{-}S}, M_0, T_c)$

But ice is split into pristine, snow, and graupel so how to include these within the PSD: Easy to do pristine and snow, but how to weight snow & graupel ? Currently, graupel is not radiatively active.

Discussion

We find that an ice optical parametrisation, based on the couple between q_i and $T_{c,}$ improves model performance relative to an inconsistent scheme.

The ice optics assumes the same mass-D relationship and PSDs as used in the microphysics scheme. Thus, the same mass of ice is carried between the two schemes.

This allows direct comparison between a model prognostic variable and radiative measurements.

Of course, the same direct coupling of ice optical properties can be applied in remote sensing, thus allowing direct retrieval of IWP (Sourdeval et al., 2016, QJRMS, 142, 3063-3081), rather than IWP being retrieved as a by-product via vis and IR wavelengths. Also ensemble P_{11} better predicts global SW PARASOL multi-angle observations compared to other commonly used P_{11} models (Letu et al., 2016, ACP, 16, 12287-12303)

Future ice optical parametrisations to consider double moment schemes in cloud resolving models and relations to atmospheric state, and how these relate to ice optics in terms of surface roughness. As well as, new realisations of phase functions inclusive of multiple scattering originating from surface roughness.

Need predictive ice crystal aggregation schemes that are related to temperature rather than contrived realisations.