A unified approach to cirrus microphysics, remote sensing and climate prediction, and its impact in a climate model

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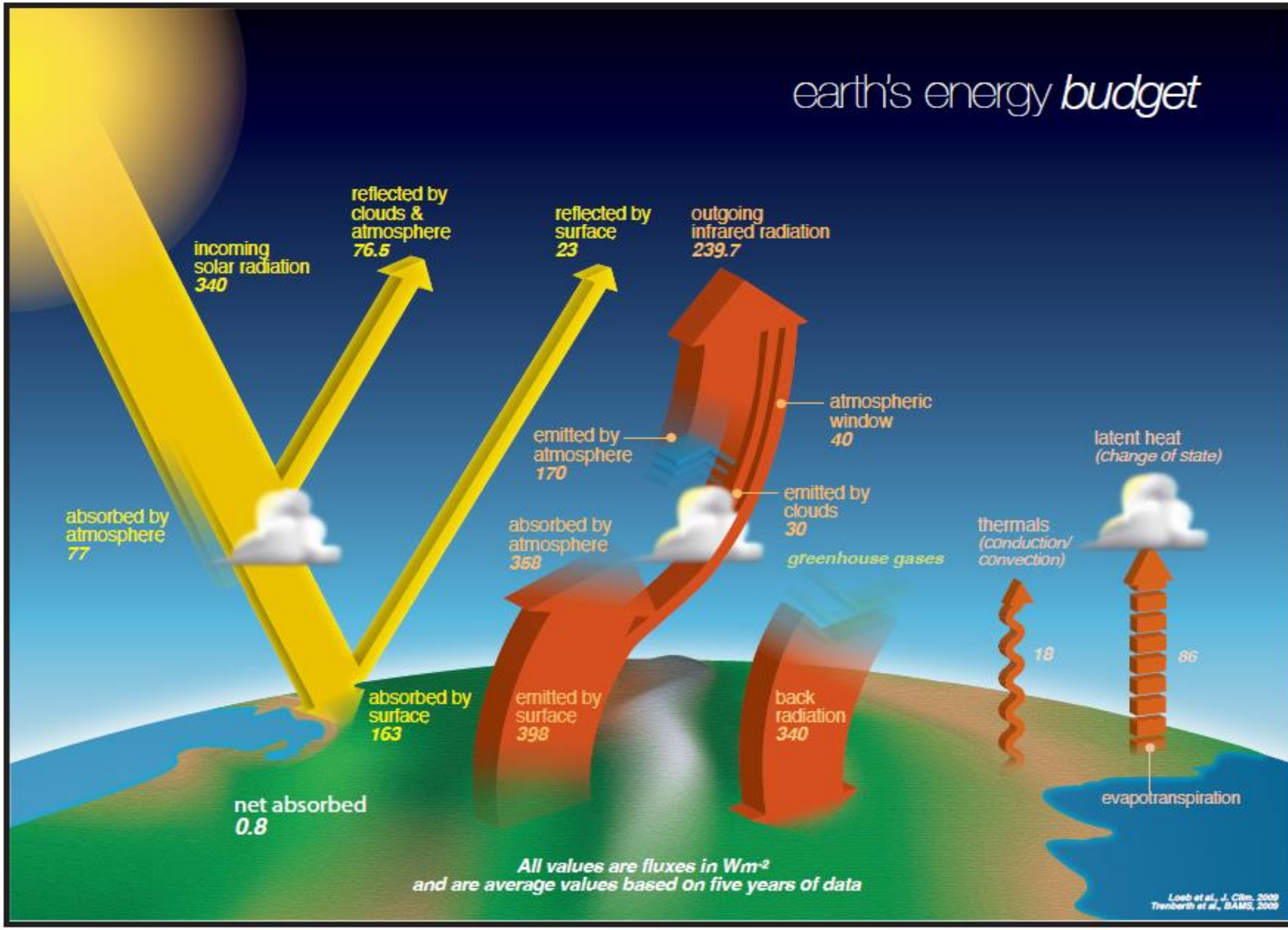
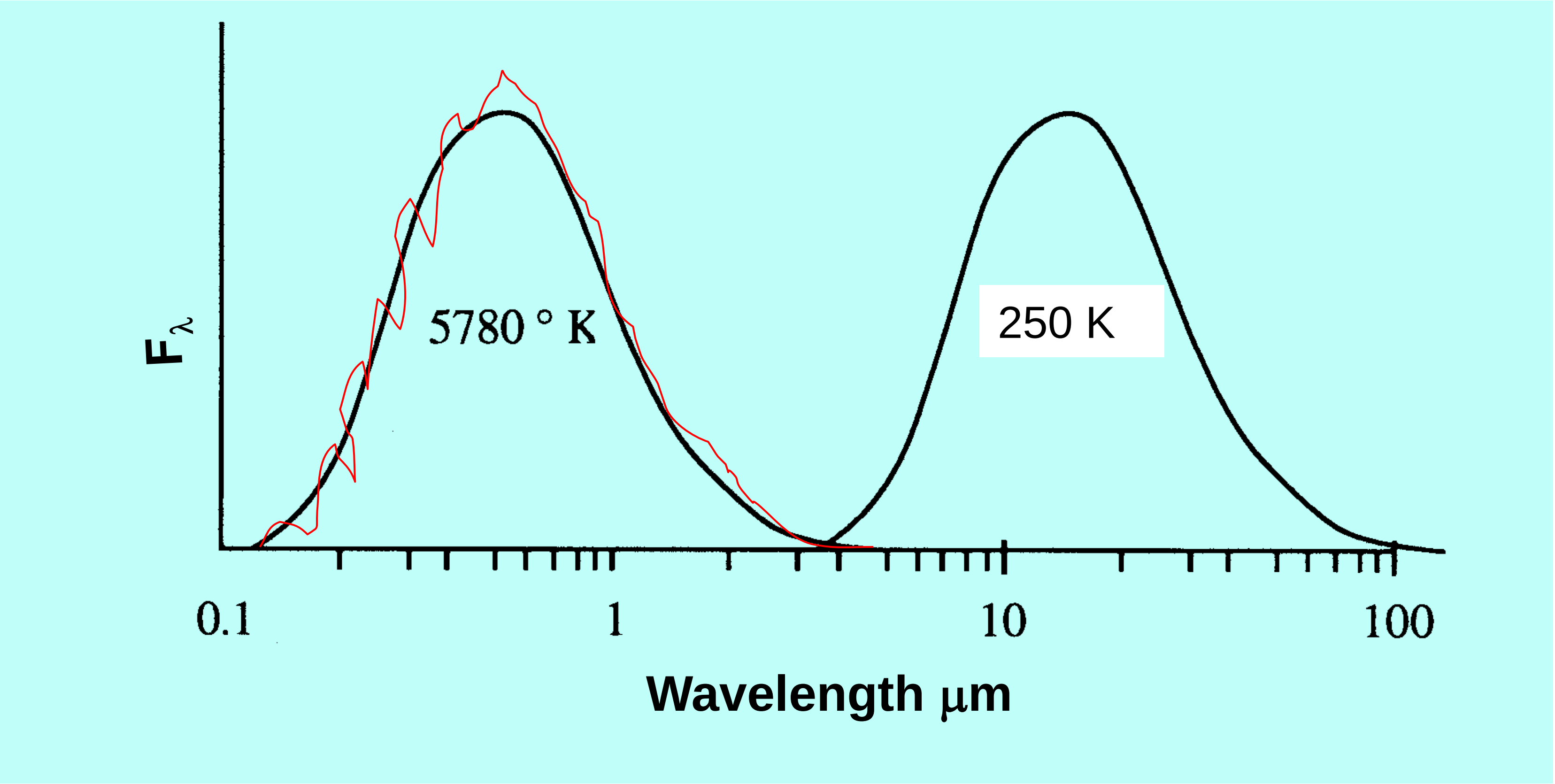

earth's energy *budget*
incoming solar radiation 340
reflected by clouds & atmosphere 76.5
reflected by surface 23
outgoing infrared radiation 239.7
atmospheric window 40
emitted by atmosphere 170
latent heat (change of state)
emitted by clouds 30
absorbed by atmosphere 77
absorbed by atmosphere 358
greenhouse gases
thermals (conduction/ convection)
18
86
absorbed by surface 163
emitted by surface 398
back radiation 340
evapotranspiration
net absorbed 0.8
All values are fluxes in Wm-2 and are average values based on five years of data
Loeb et al., J. Clim. 2009
Trenberth et al., BAMS, 2009

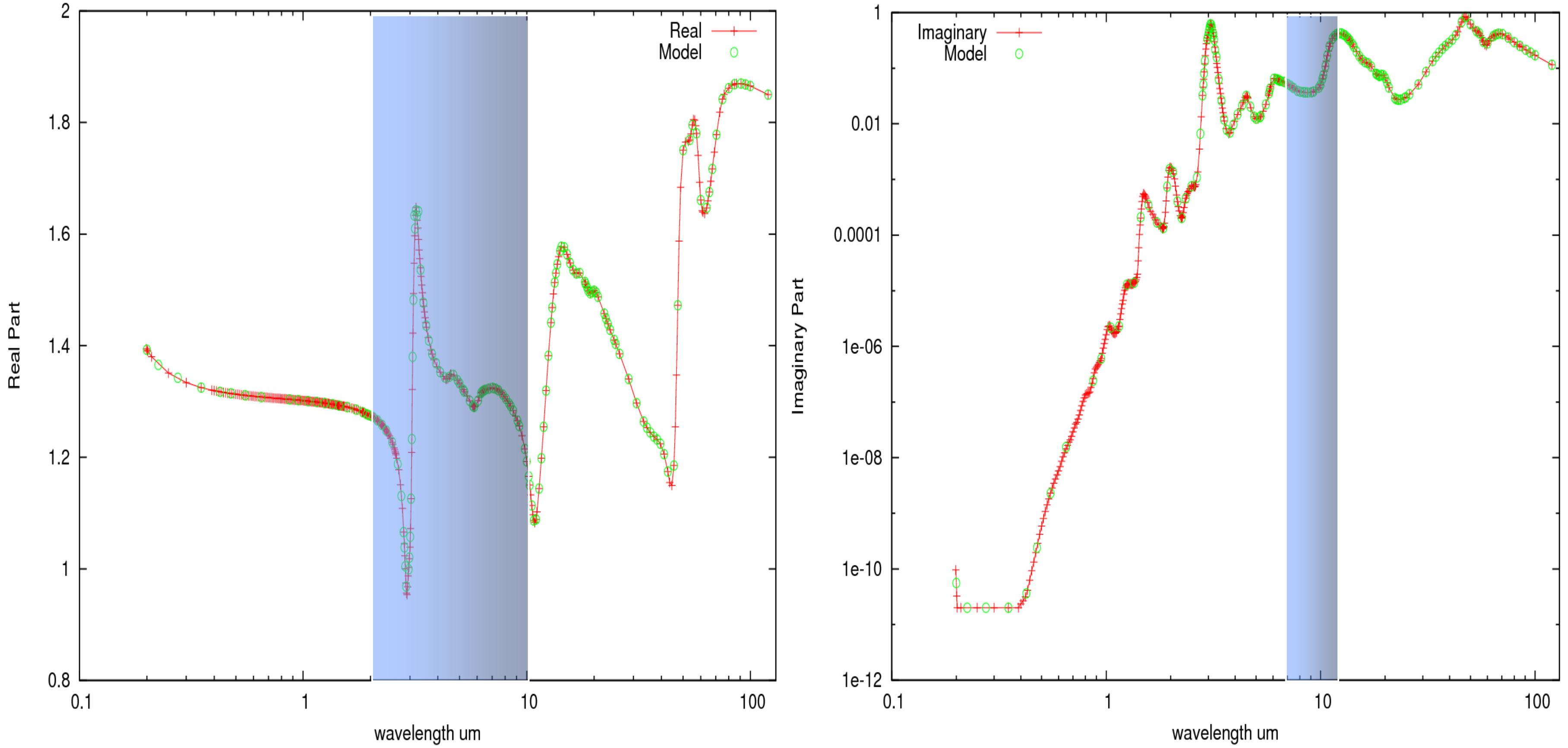
www.nasa.gov

Wavelength range of importance to the energetics of the Earth's atmosphere: Solar and terrestrial Planck emission spectrum



kL~1000s ⟷ kL<<1

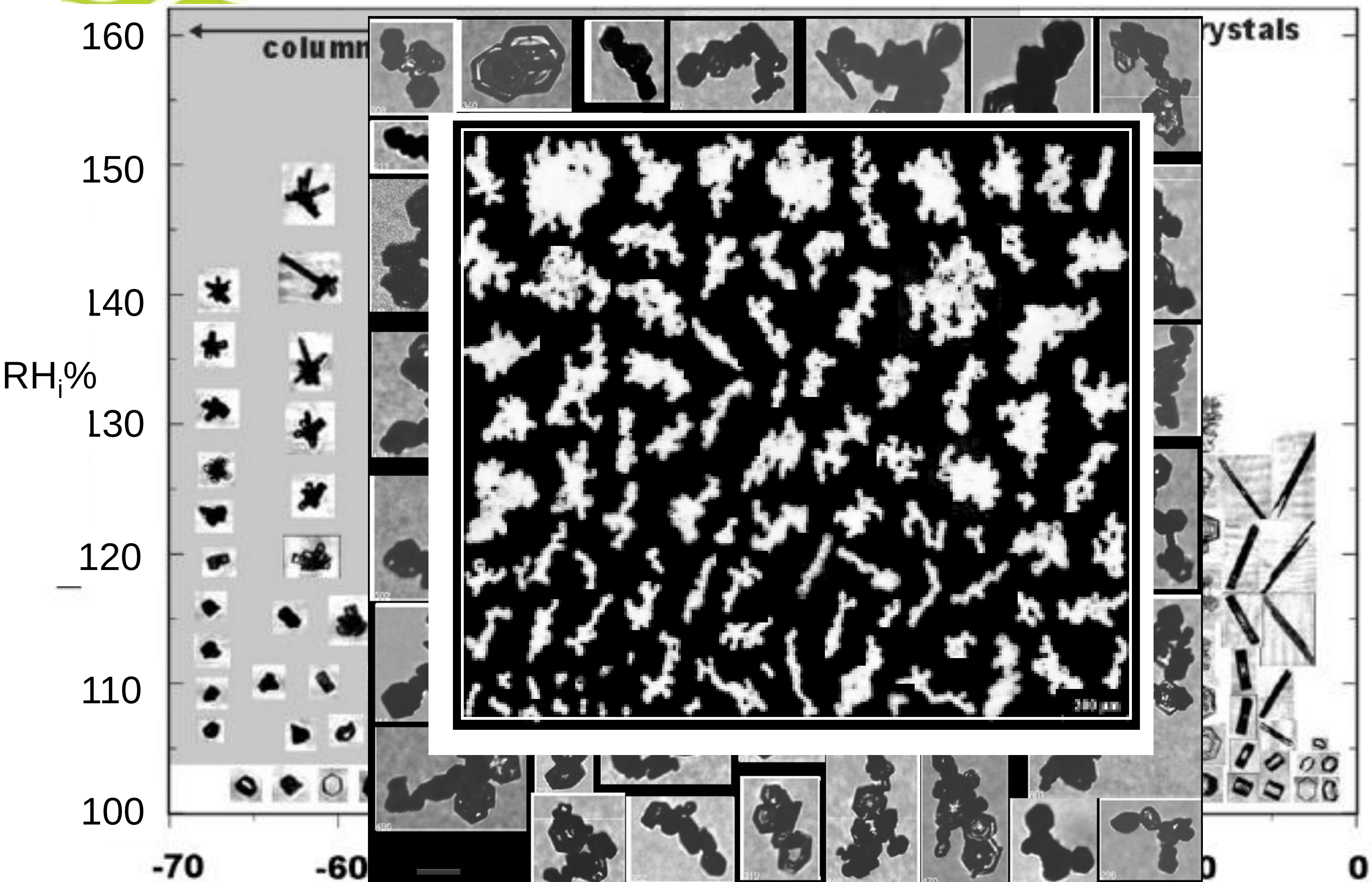
Complex refractive index of ice (Warren and Brandt 2007)



Scattering properties weighted by solar and terrestrial irradiances over wavelength bands in a climate model

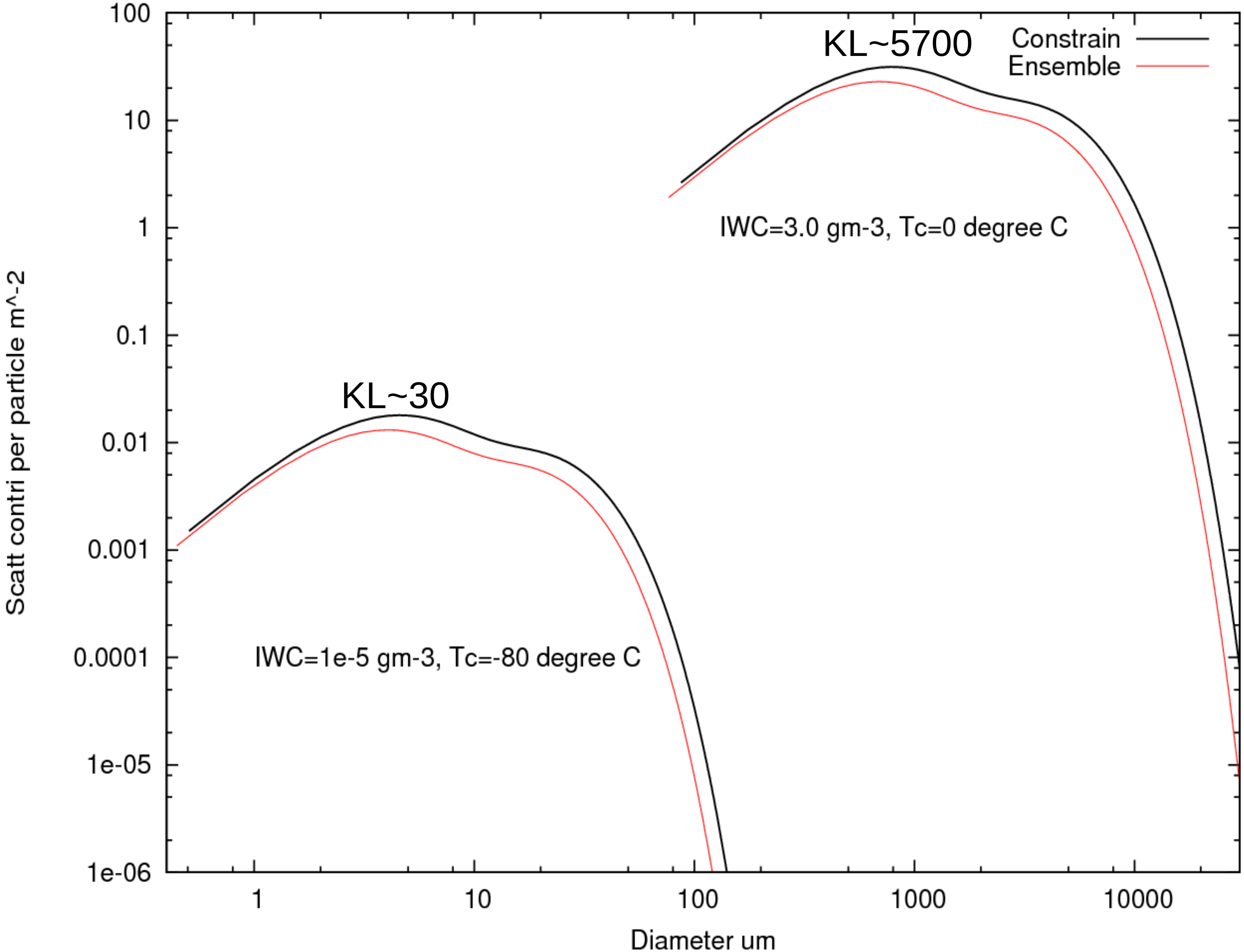
A myriad of ice crystal size and shape

Some observations: Laboratory (Bailey and Hallet 2009)



Fresh Anvils, Um and McFarquhar 2008.

Range of the size spectrum in a climate model

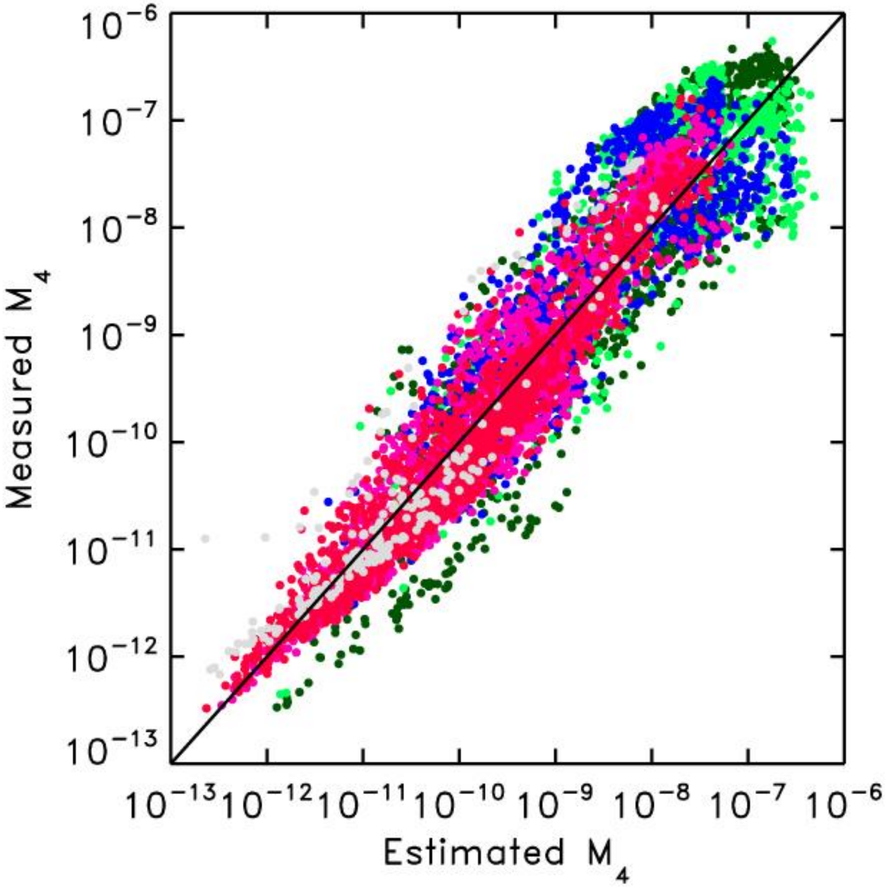


Moment estimation parameterization, Field et al. (2007)

$$\mathcal{M}_n = \int \mathrm{d}D D^n f,\ n \geq 0$$

$$\mathcal{M}_n = A(n) \exp[B(n)T_c]\ M_2^{C(n)}$$

$$M_2 = aD^{b=2}$$



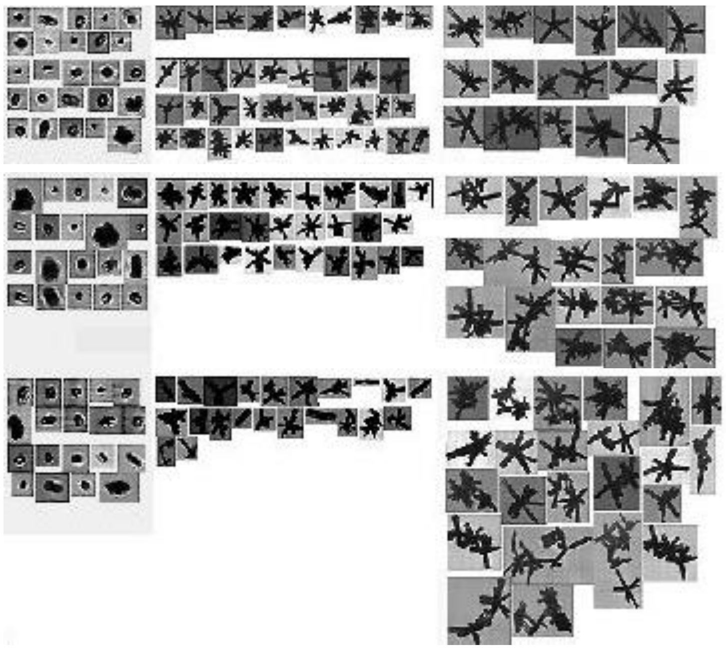
Links PSD to ice mass (climate model prediction) and T_c. Moments are used to predict cloud evolution

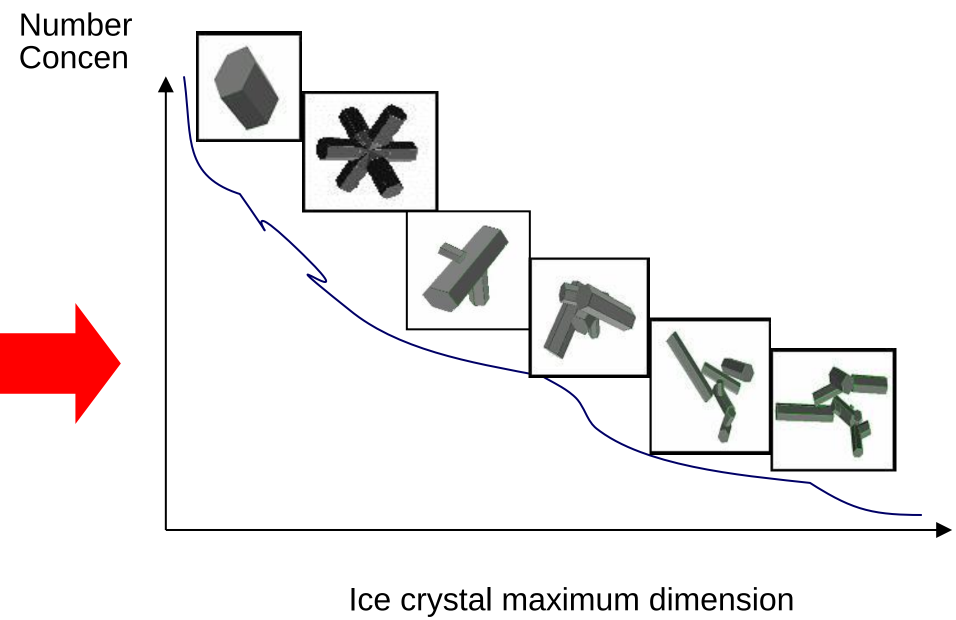
PSDs in climate model cloud microphysics scheme same as radiation scheme & mass-D relationship same in both

Idealized Habit mixture models and their consistency with observation

Generalise

An example image

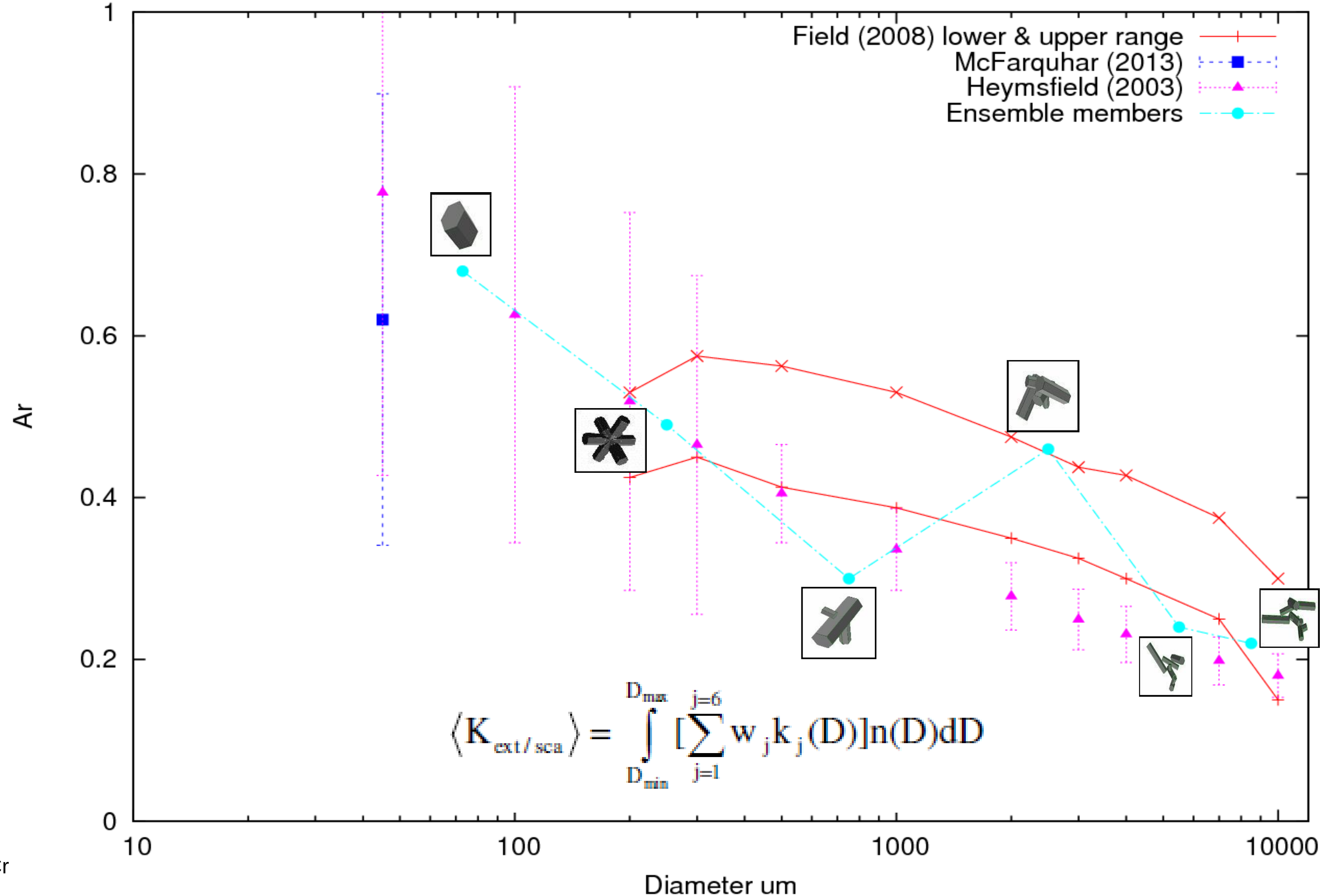


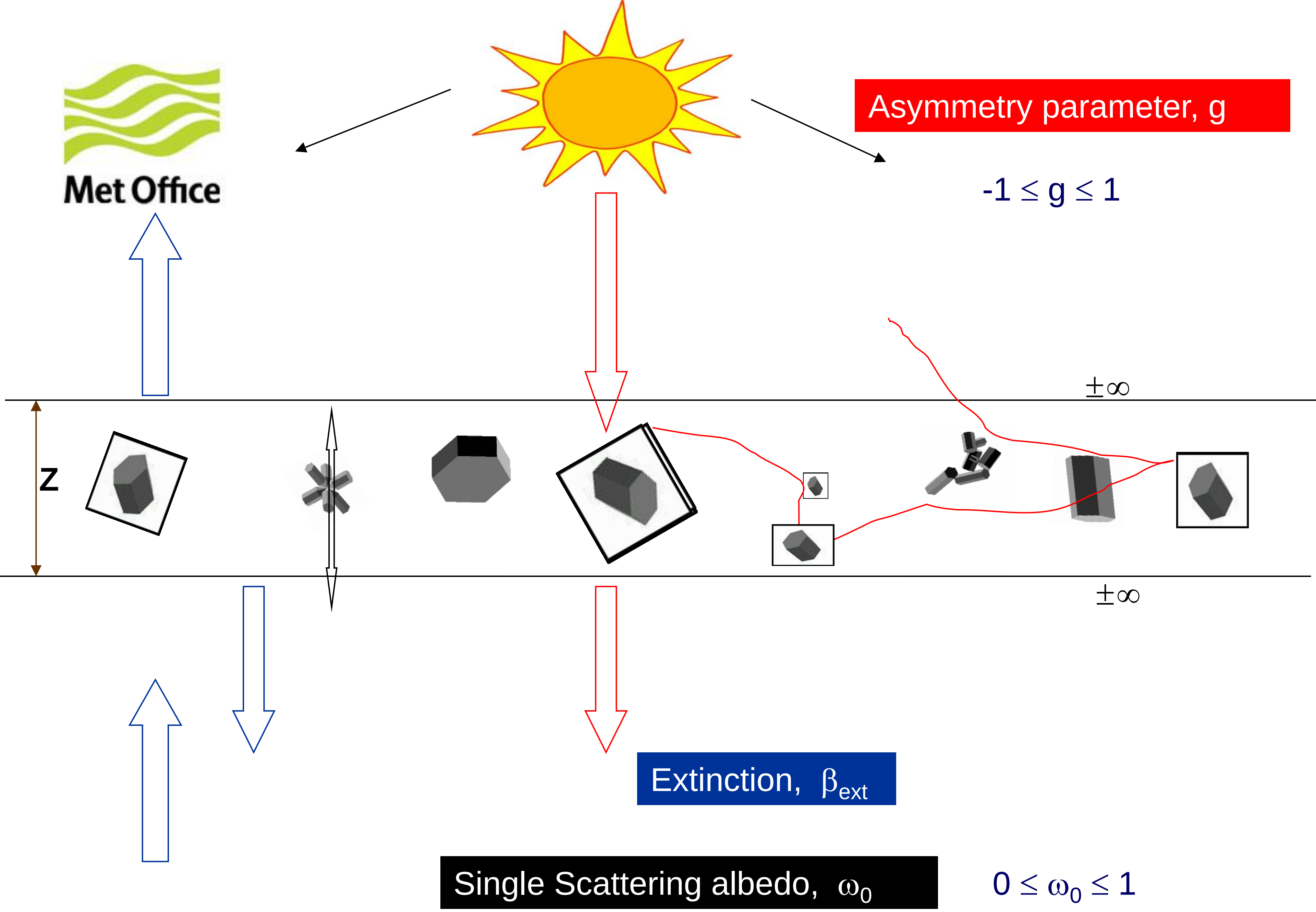


Baran & Labonnote (2007)

Microphysical Consistency

Observed area Relationships: Area ratio: $A(D)/A_c(D)$




Met Office
Asymmetry parameter, g
$-1 \leq g \leq 1$
$\pm\infty$
z
$\pm\infty$
Extinction, β_{ext}
Single Scattering albedo, ω_0
$0 \leq \omega_0 \leq 1$

Scattering methods applied to compute the single-scattering properties

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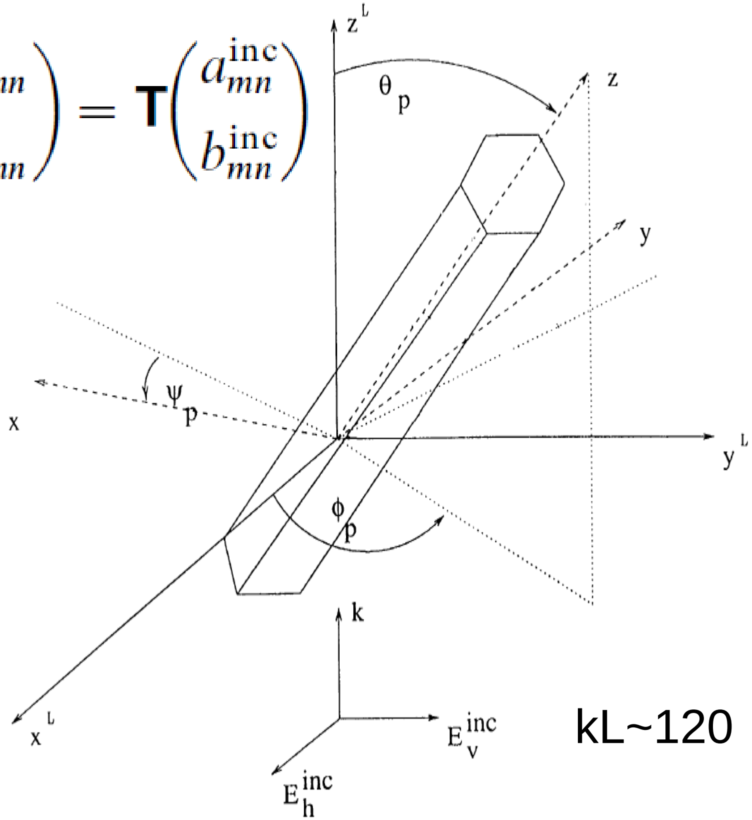
T-matrix (Havemann & Baran 2001) & Mischenko & Travis (1997)

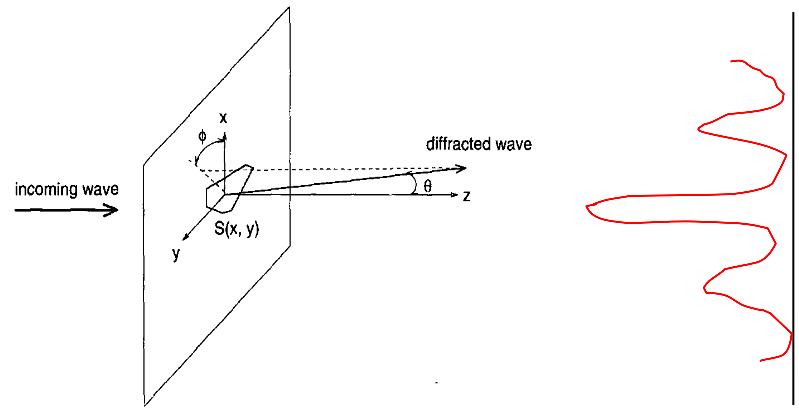
$$\begin{pmatrix} a^{s}_{mn} \\ b^{s}_{mn} \end{pmatrix} = \mathbf{T}\begin{pmatrix} a^{inc}_{mn} \\ b^{inc}_{mn} \end{pmatrix}$$



kL~120

Physical Optics (Macke et al. 1996)

Fresnel,snells law,Fraunhoffer

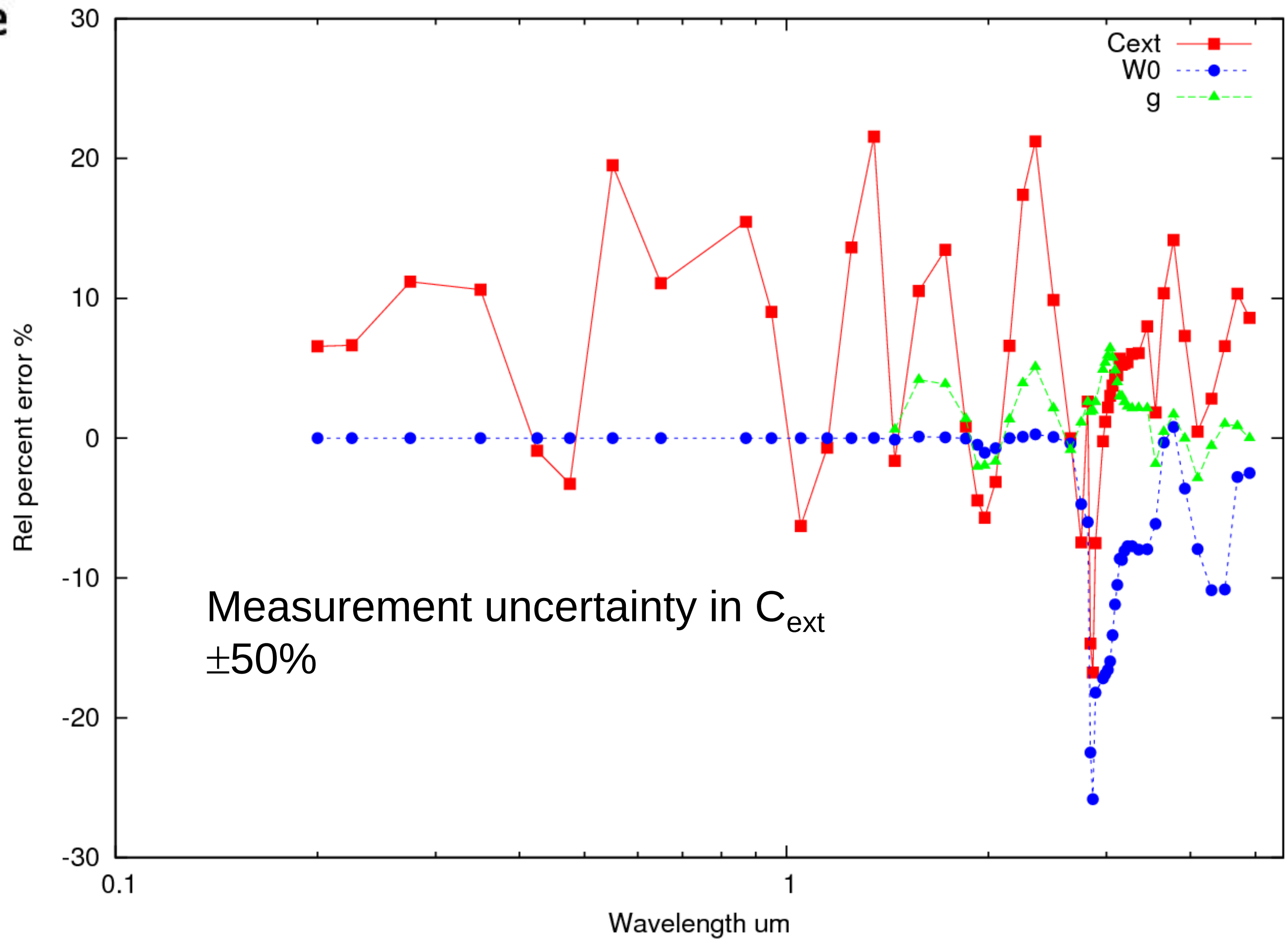


$g_{total}= 1/2(g_{diff}+g_{rt})$ for $\omega_0=1$

$C_{ext}=2\langle G\rangle$

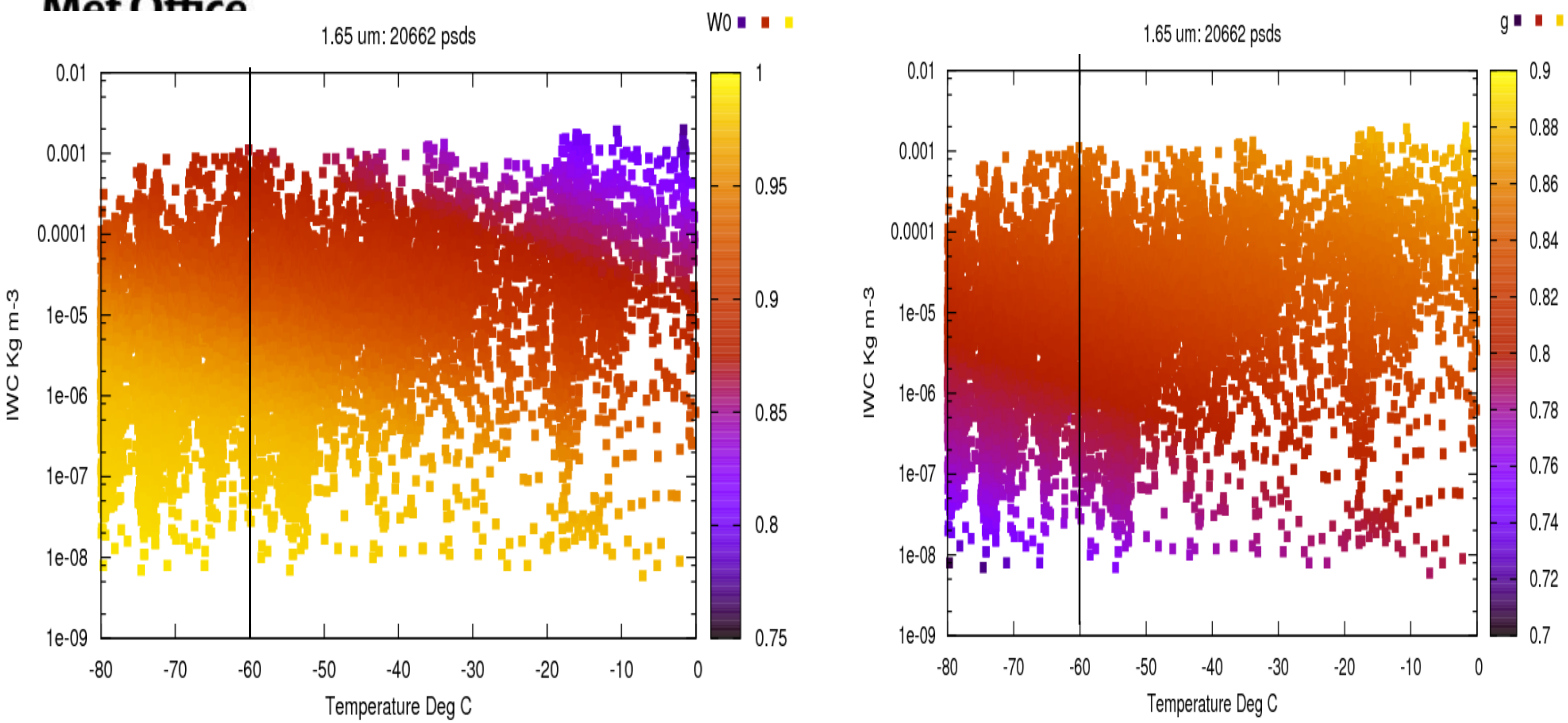
$1/2 < \omega_0 < 1$

Relative error in physical optics in the transition region between the two methods at a distinct ice crystal size



ω_0 and g in IWC-T_C space: λ=1.65 μm

$K(\lambda, IWC)_{ext(sca)} = a_\lambda IWC$: $g(\lambda, IWC) = b_\lambda IWC^{c(\lambda)}$

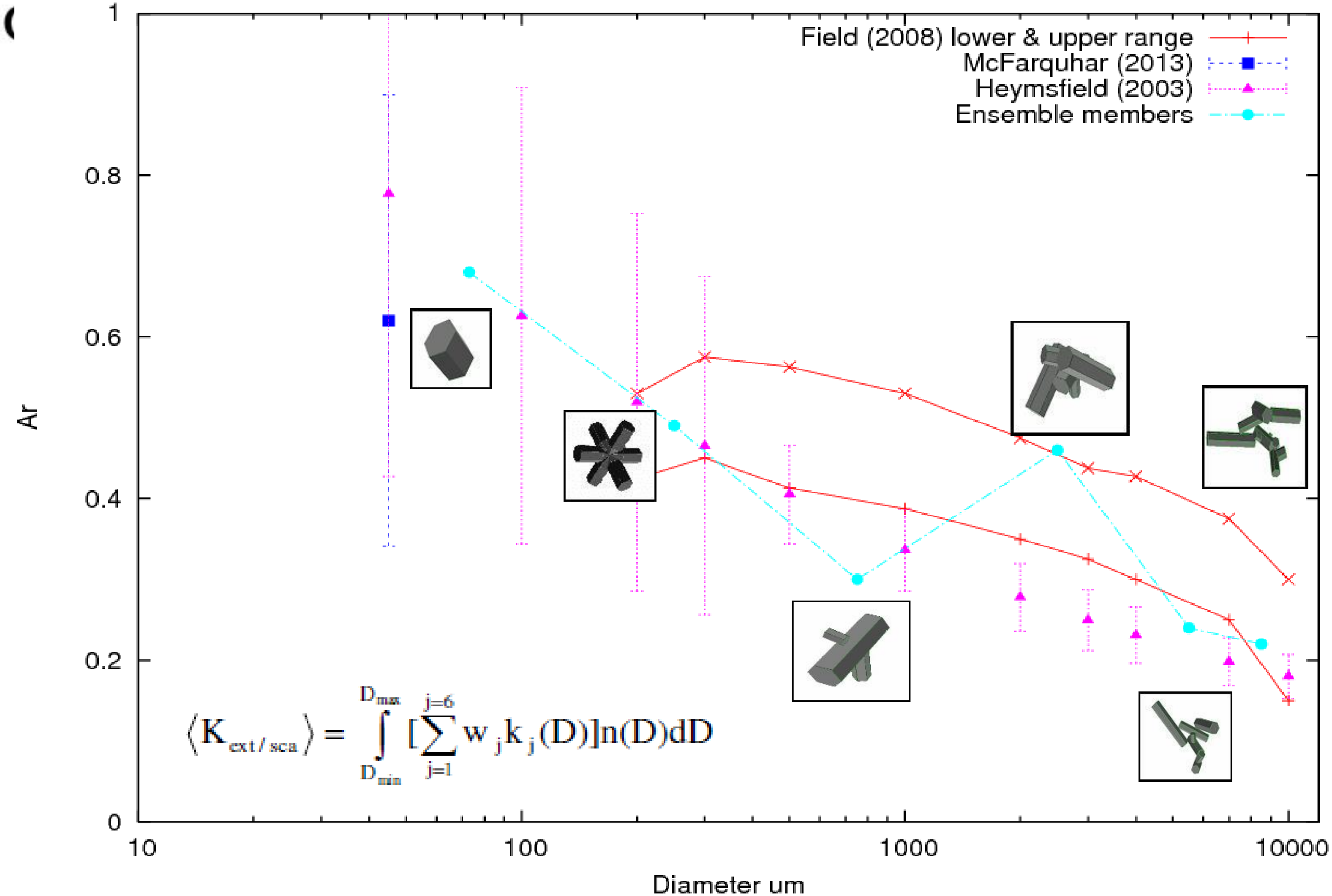


The IWC and cloud temperature were obtained from a number of field campaigns including CAESAR (UK), CEPEX (Tropics), FRAMZY (Europe)

A total number of 20662 PSDs were generated & randomly generated

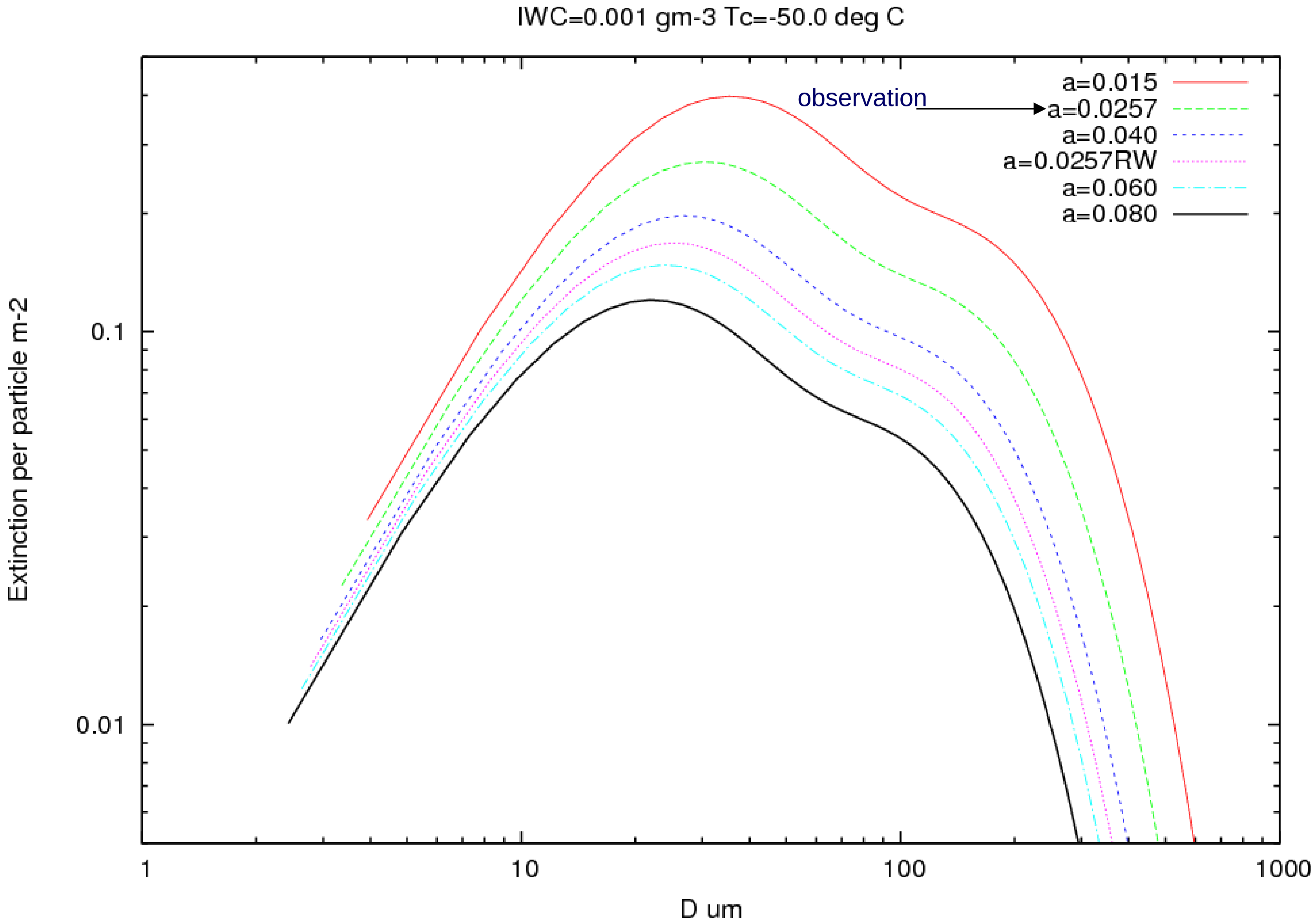
The effect on the climate model of fixing PSD and varying habit mixture model

Ensemble area ratios compared against in situ measurements



$$\langle K_{ext/sca} \rangle = \int_{D_{min}}^{D_{max}} [\sum_{j=1}^{j=6} w_j k_j(D)] n(D) dD$$

Varying the transmission properties of ice cloud



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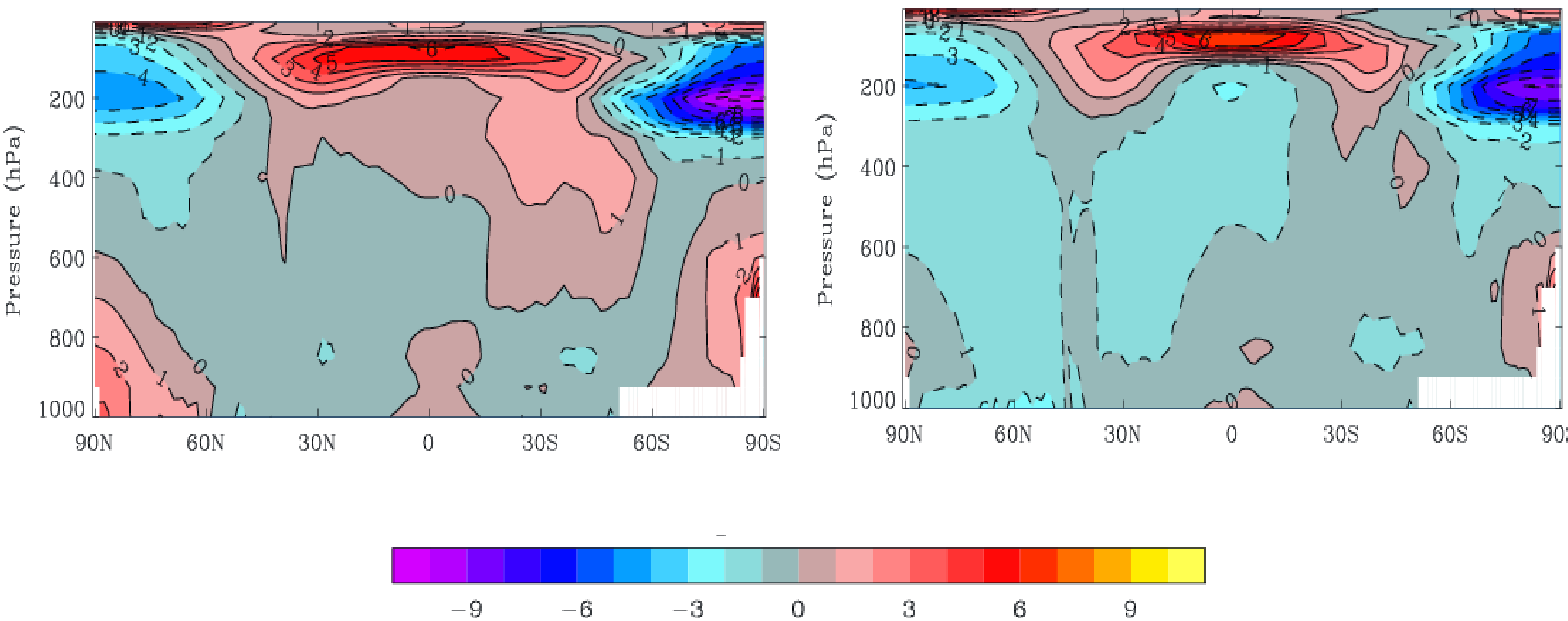
Broader PSD

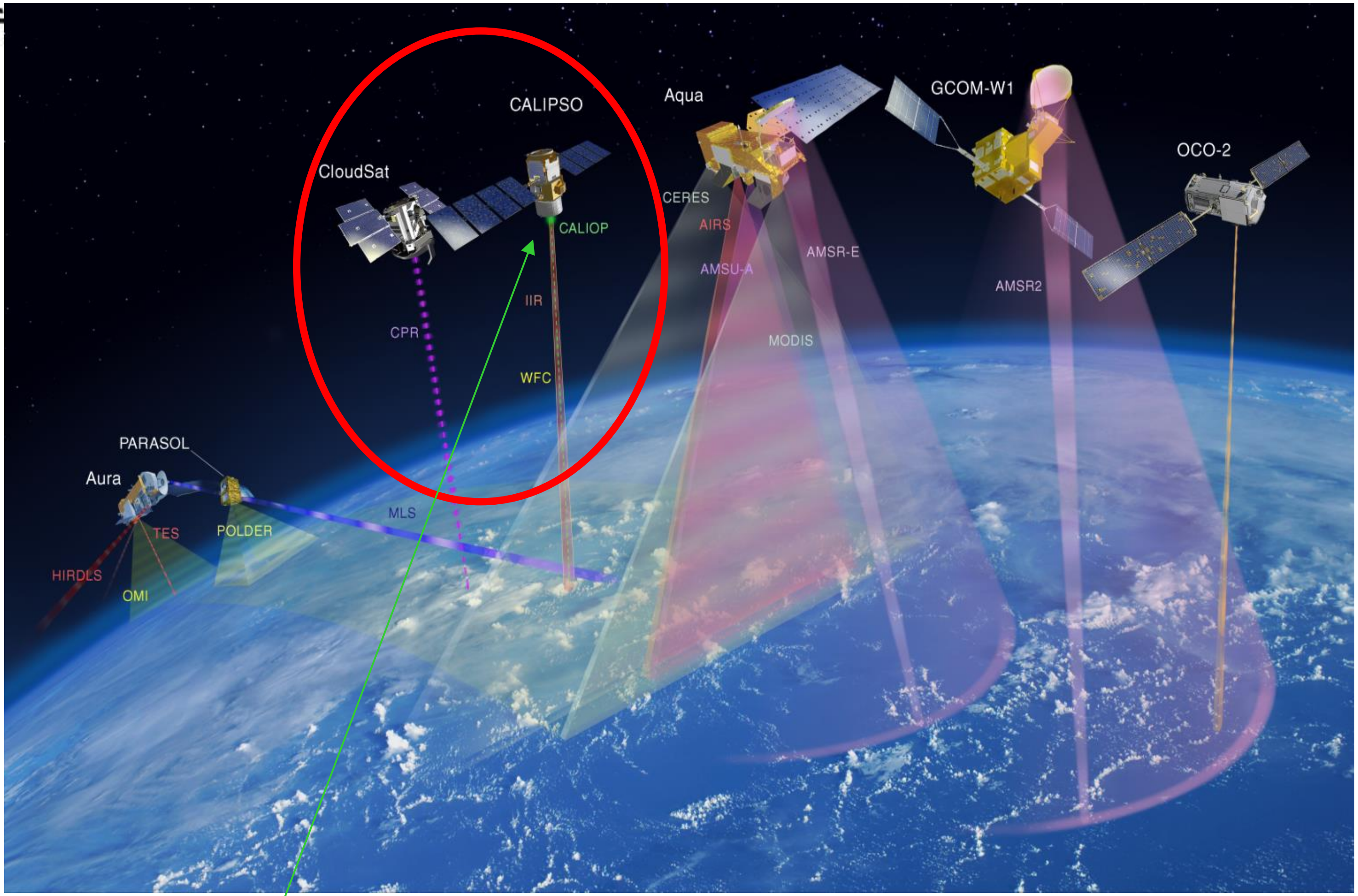
Same PSD but weighted towards more aggregated members



Temperature measurements-Observations

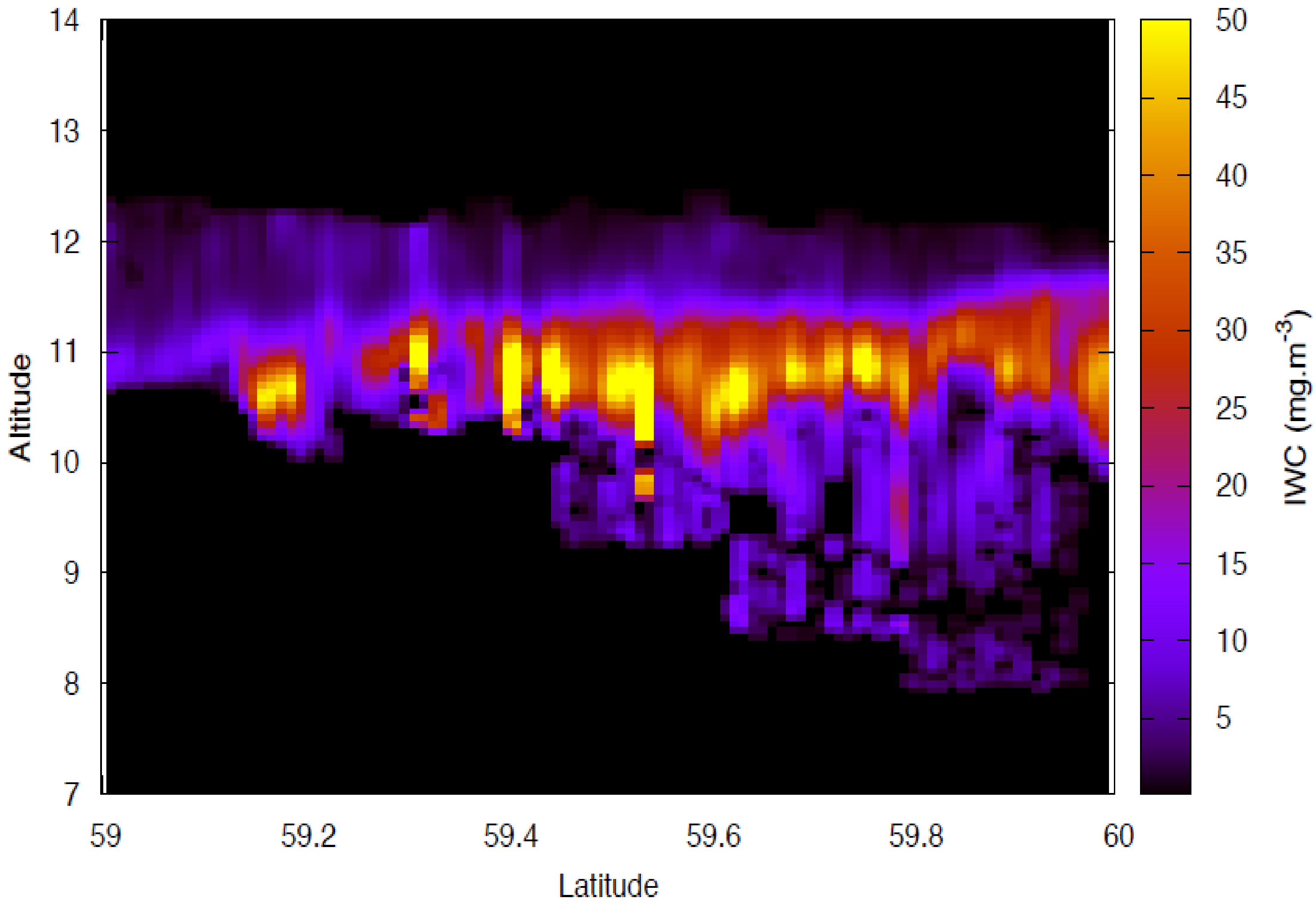
Fix the PSD to best observational evidence but vary the weights to determine which weights are best to satisfy radiometric measurement

Combine radar and lidar to obtain cloud profiles



IIR centred at 8, 11 and 12 µm

cloud profiles of IWC

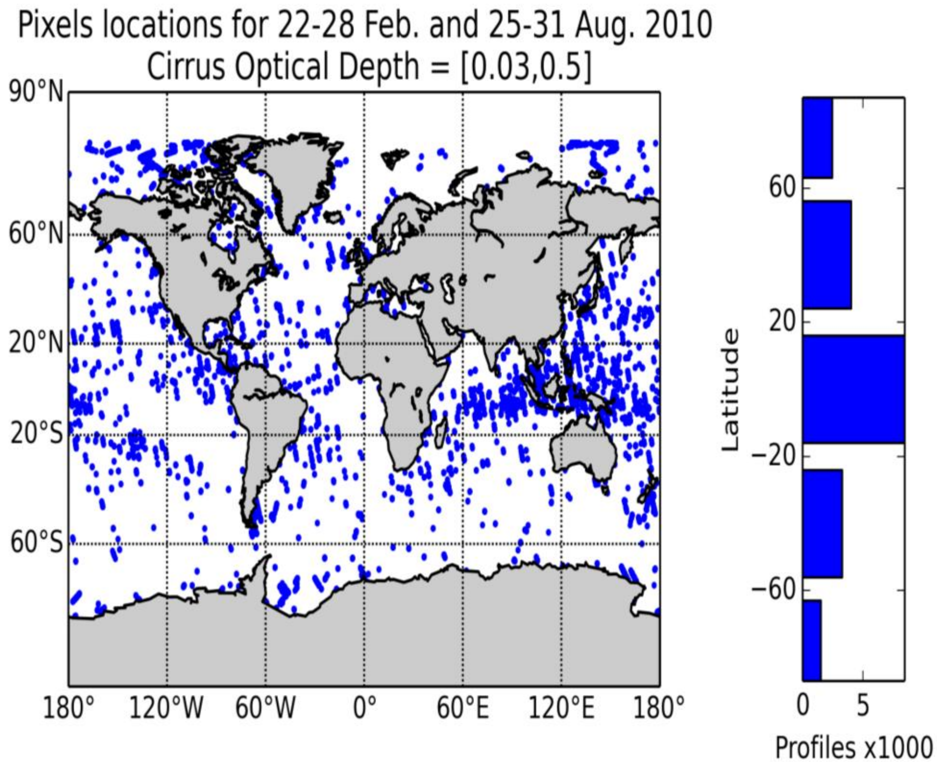


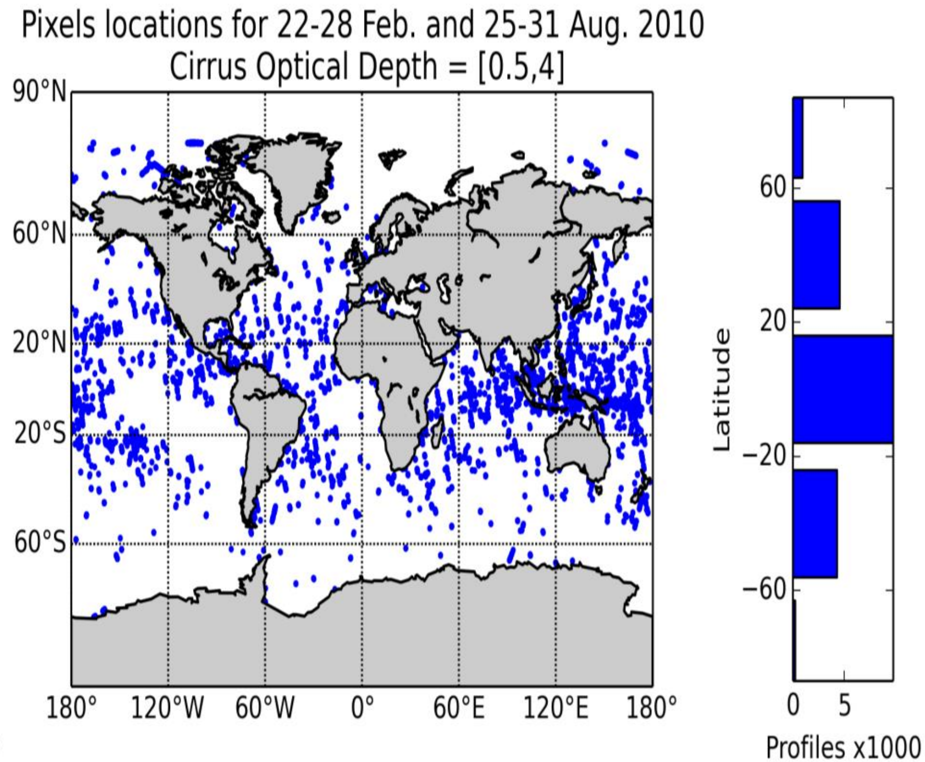
Global distribution of cirrus cases

N=26791

0.03 $<\tau<$ **4 Semi-transparent cirrus**

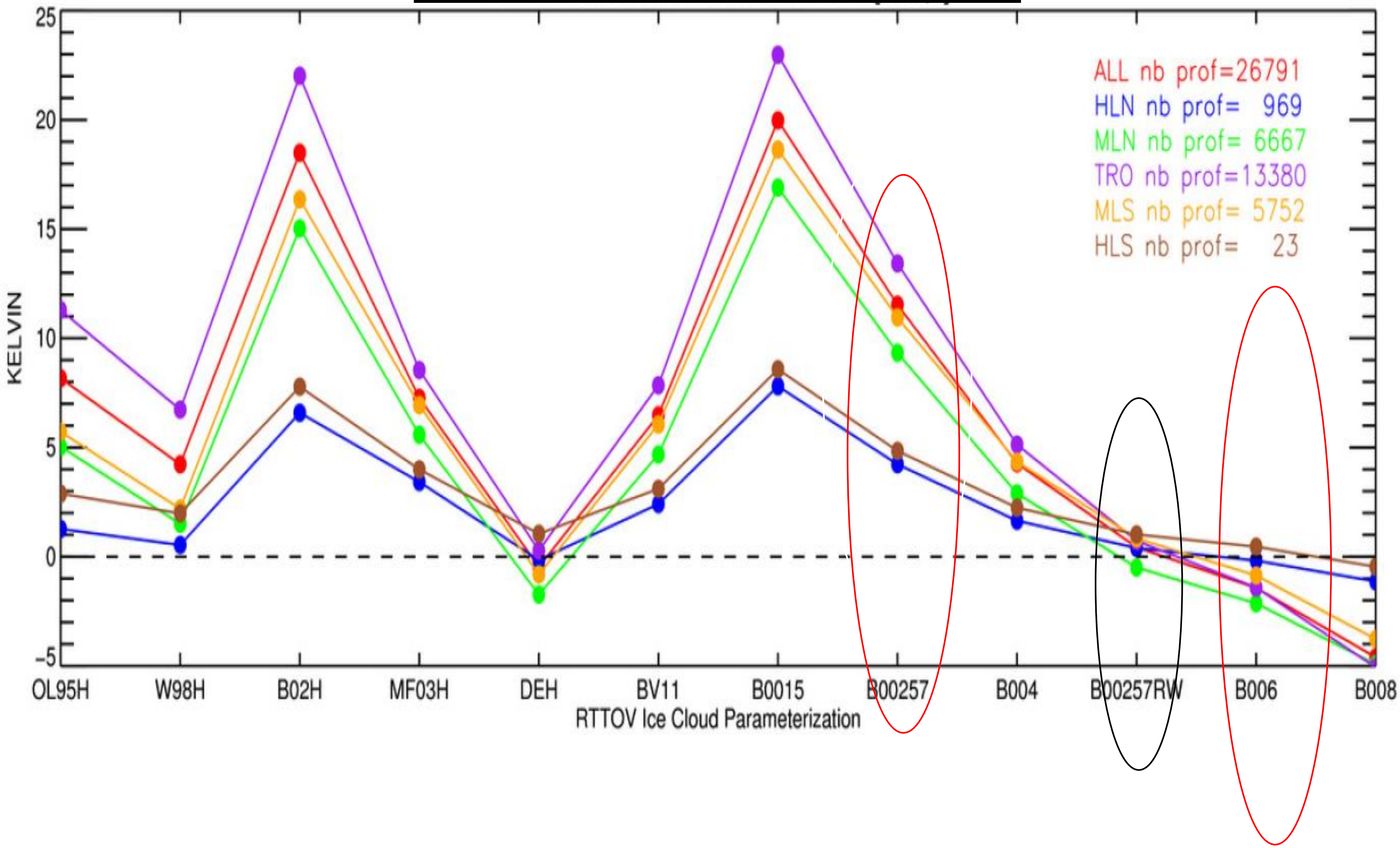
Altitudes high troposphere to stratosphere





Results

Measurement - Simulation

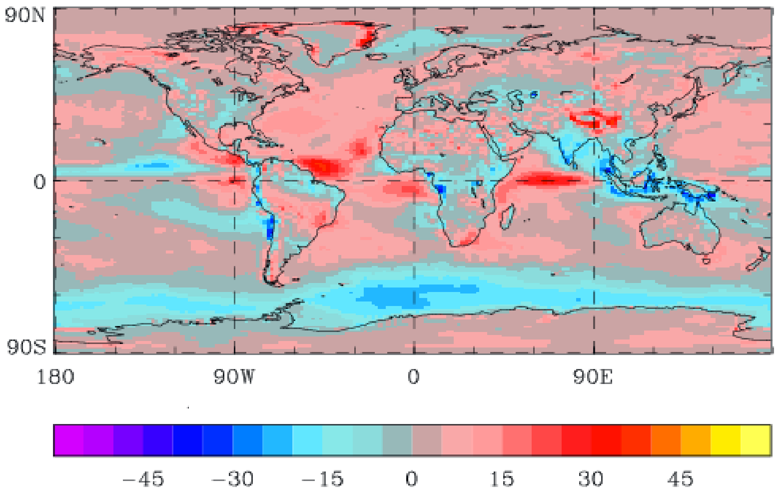


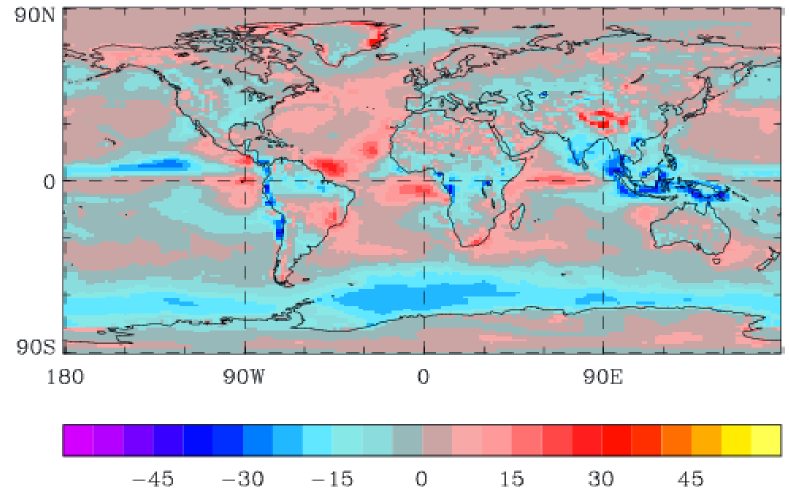
What effect does this solution have in the next version of the Met Office global model?

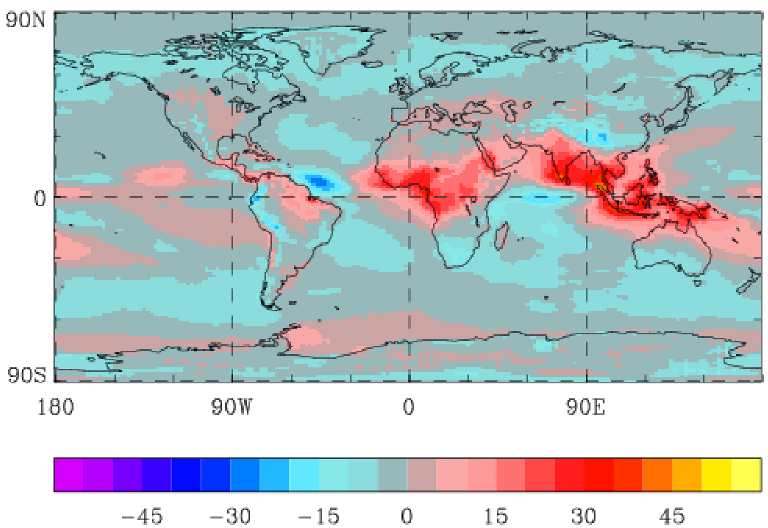
SW reflected flux and LW – Measurements at TOA

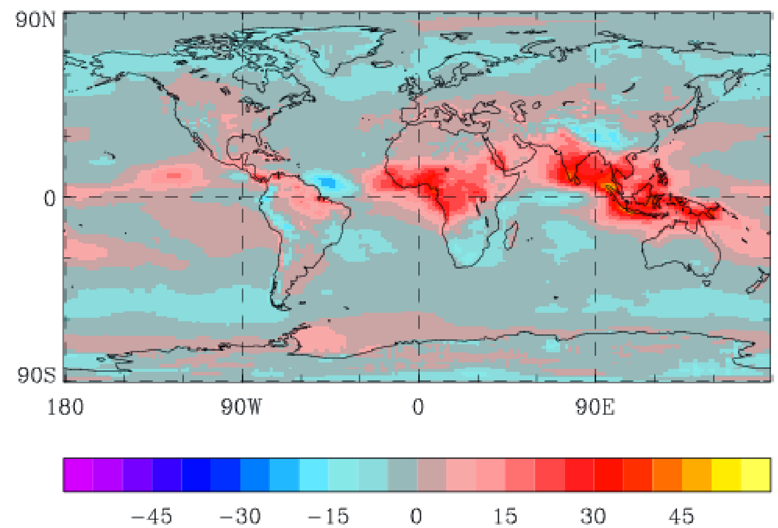
Likely MO/HC global model-inconsistent

consistent







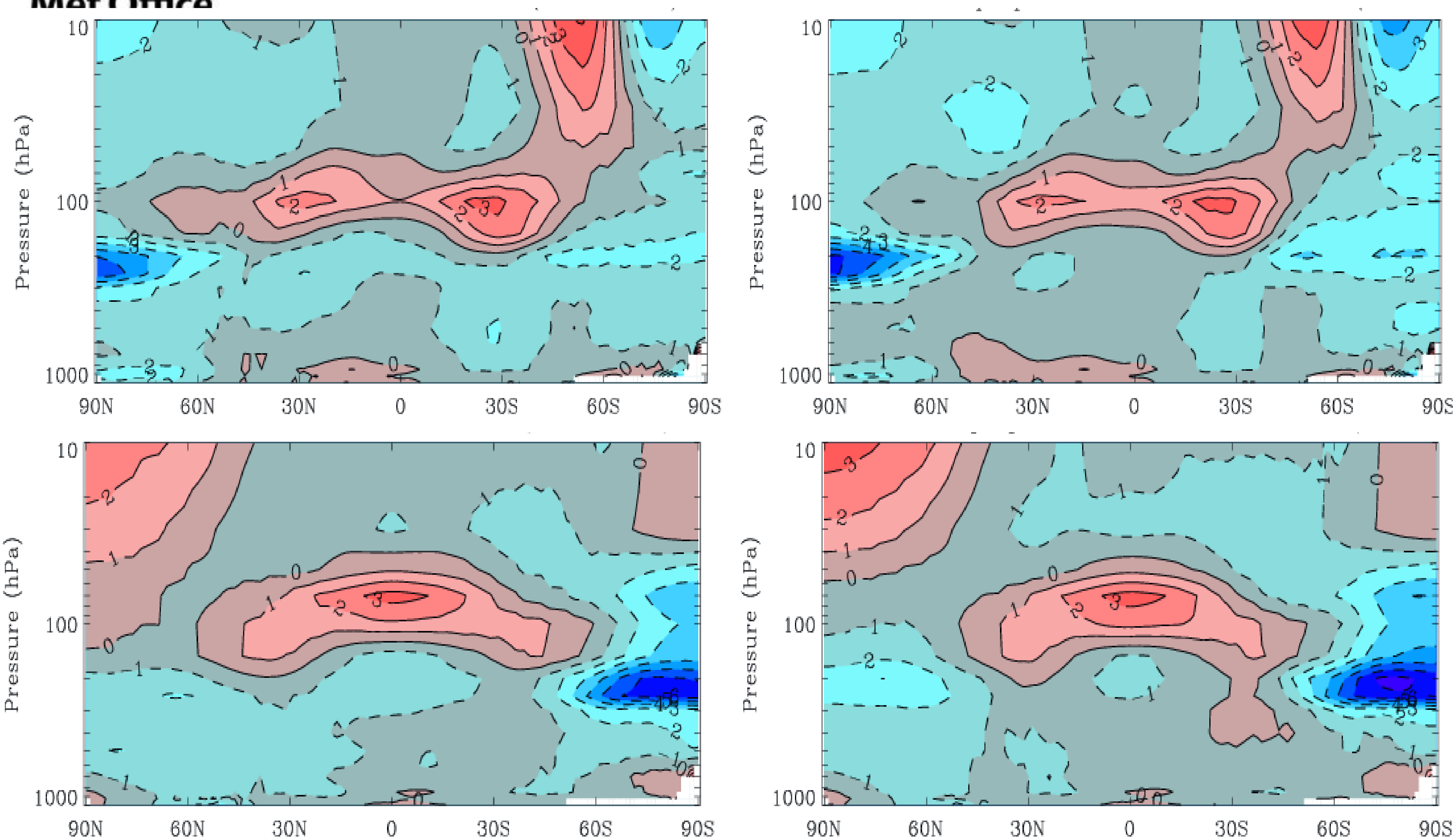


Climate model - Measurement

Effect on temperature averaged over JJA, DJF

Likely MO/HC global model-inconsistent

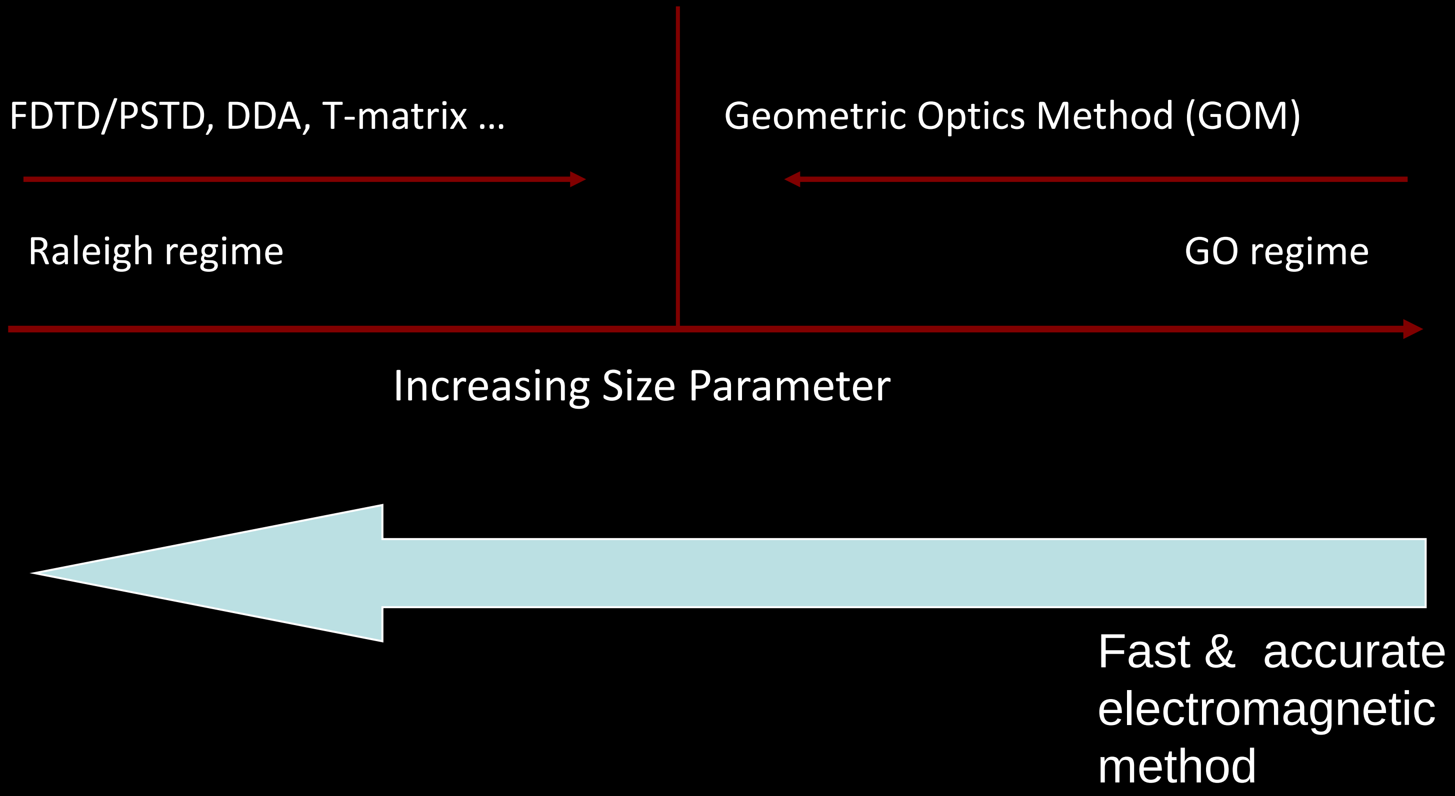
Unified-consistent



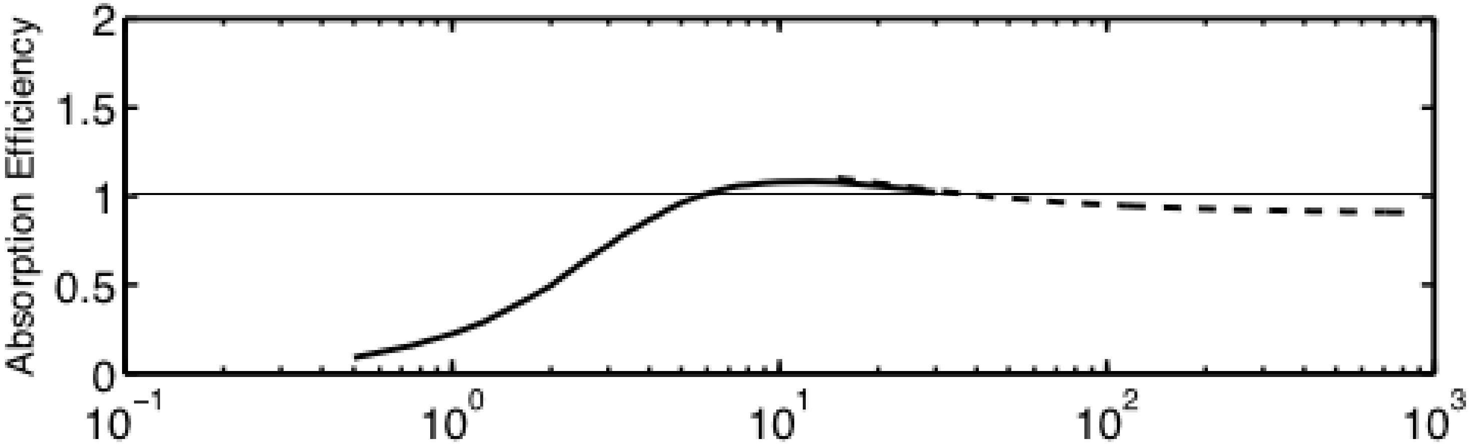
Temperature measurements-Observations

Discussion

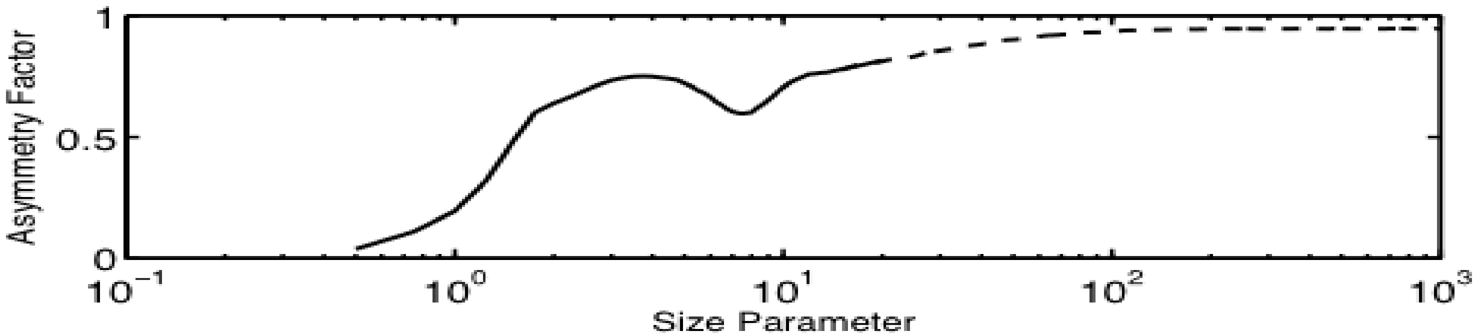
Specific Research Goals



NEED ELECTROMAGNETIC SOLUTIONS TO COVER SMALL TO GEOMETRIC OPTICS REGIONS BECAUSE



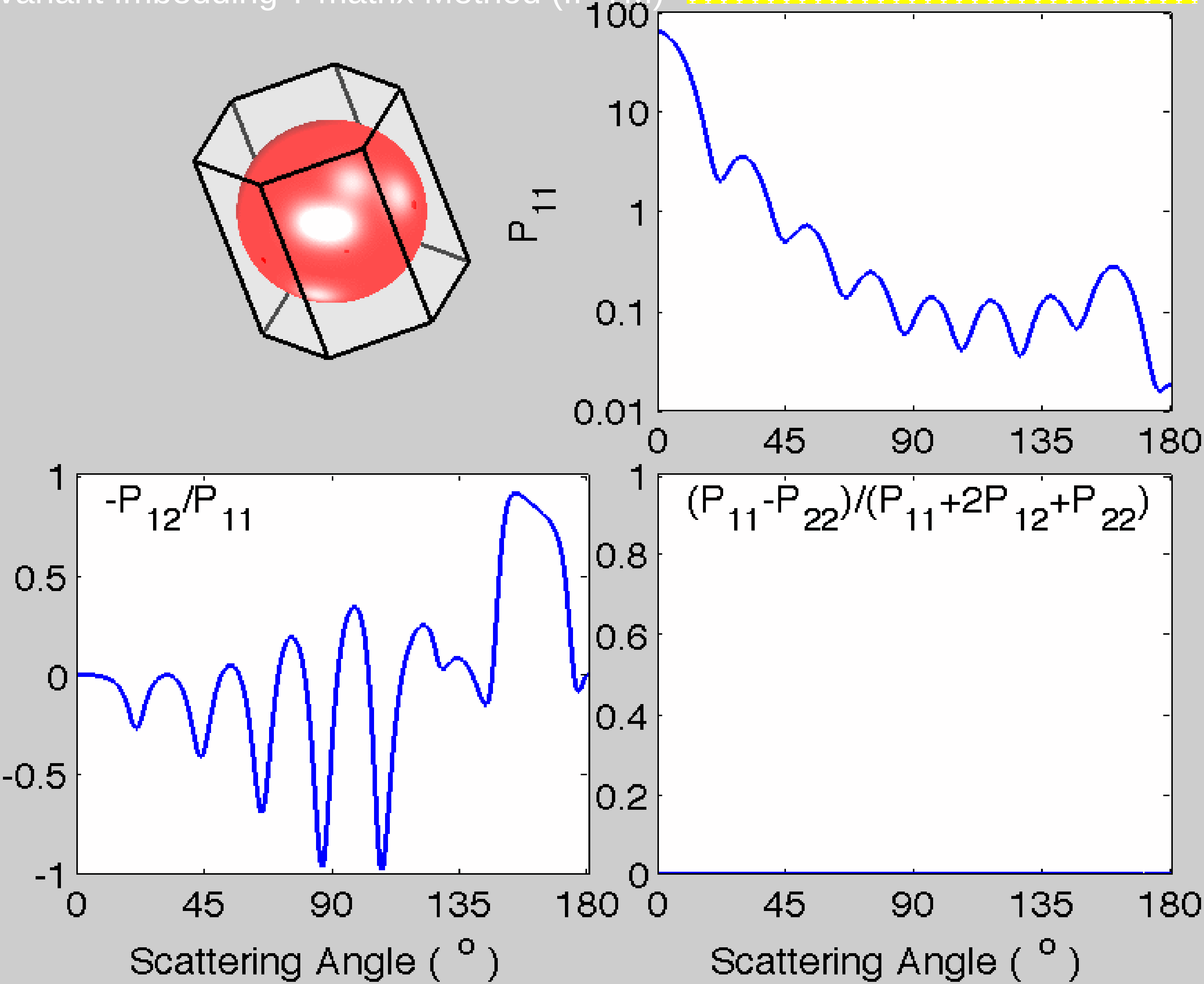
Particles with strong absorption. The absorption efficiency factor may be larger than unity. However, the physical optics results are always smaller than unity.



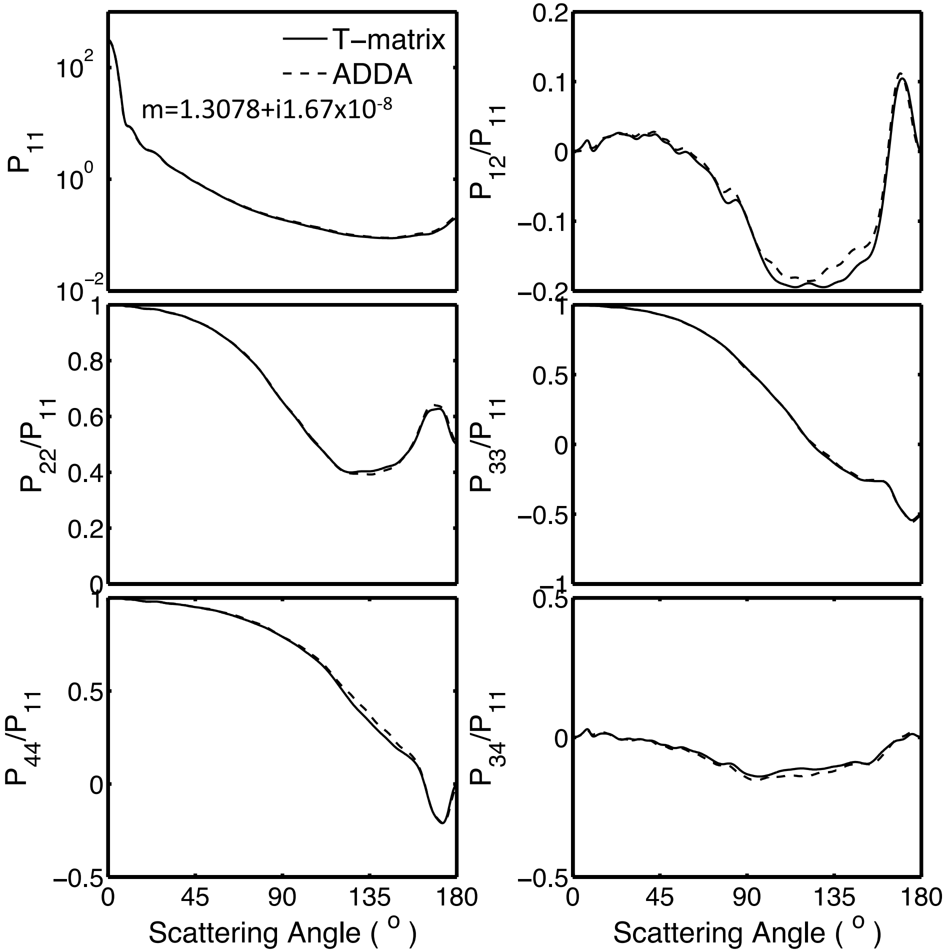
Non-absorptive or weak-absorptive particles. The asymmetry factor has a valley at some resonant sizes. This is impossible for physical optics

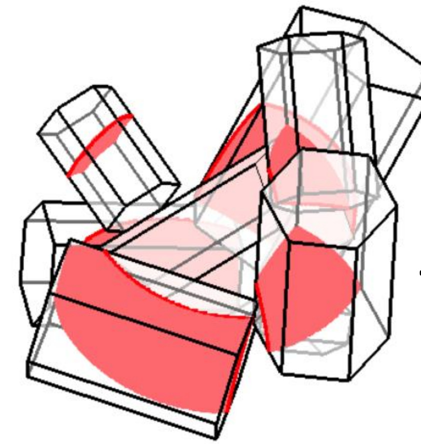
Invariant Imbedding T-matrix Method (II–TM)

Bi , L., and P. Yang, 2014: Accurate simulation of the optical properties of atmospheric ice crystals with invariant imbedding T-matrix method.

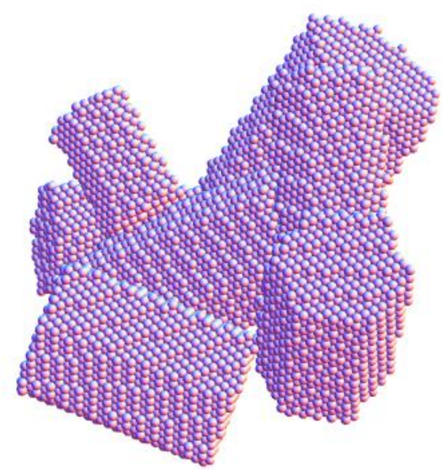


Comparison





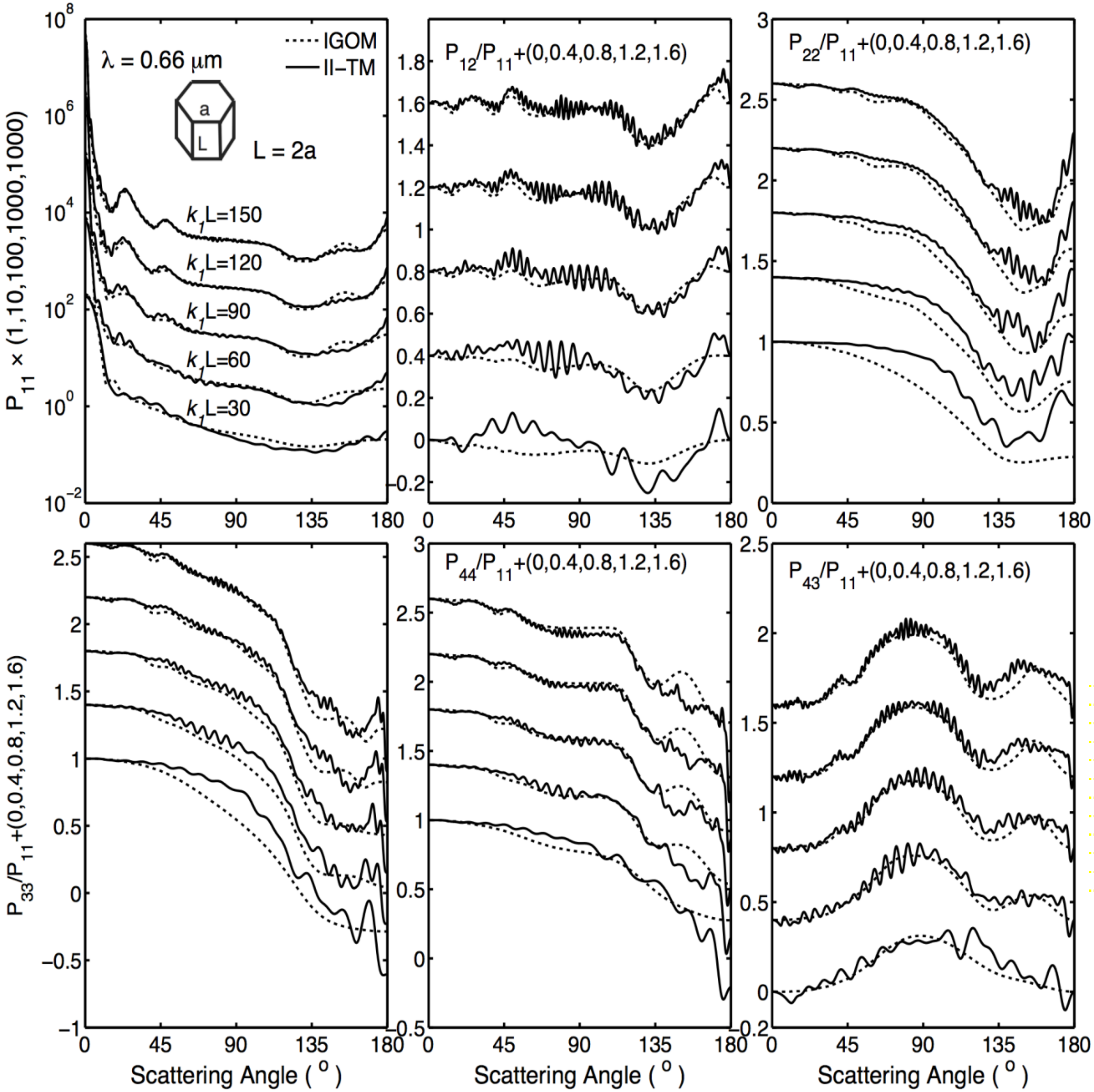
T-matrix



DDA

the Discrete-dipole-approximation(DDA)simulation, 1056 orientations with 128 scattering planes are set to achieve the randomness. Data from Bi and Yang (2014)

Comparison between IGOM and II–TM



Simulations were carried out at the EOS cluster at Texas A&M University; each single node contains 8 64-bit 2.8Ghz processors. The computational time of the II-TM increases quickly as the size parameter increases. The computational wall time (8 processors) is about 21 hours at the size parameter of 100.

Bi , L., and P. Yang, 2014: Accurate simulation of the optical properties of atmospheric ice crystals with invariant imbedding T-matrix method.

- Current models contrived – designed to re-produce observations in the form of m-D and A-D relationships
- Predict PSD and ice crystals given an initial atmospheric state?
- How does the PSD and ice crystals evolve as a function of distance from cloud-top?
- How is ice crystal complexity related to atmospheric state?
- Relate the two problems to electromagnetic theory – synergy between ice crystal growth and electromagnetic theory via Boundary Element Methods?

The single-scattering properties

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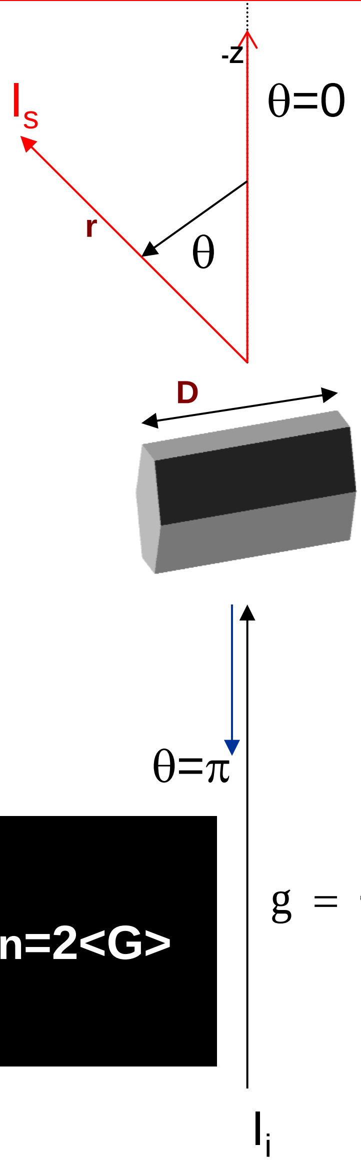


$I_s \; \alpha \; M \; I_i$

$W_{sca}=C_{sca}I_i$

$W_{abs}=C_{abs}I_i$

$W_{ext}=(C_{sca}+ C_{abs})I_i$

$I_s=P_{11}(\theta)I_i$

$Q_s=P_{12}(\theta)I_i$

$$\omega_0 = \frac{C_{sca}}{(C_{abs} + C_{sca})}$$

$$\frac{1}{2}\int_0^{\pi} \langle P_{11}(\theta) \rangle \sin\theta \, d\theta = 1$$

$$g = \langle \cos\theta \rangle = \frac{1}{2}\int_0^{\pi} \langle P_{11}(\theta) \rangle \cos\theta \sin\theta \, d\theta$$

$D >> \lambda$

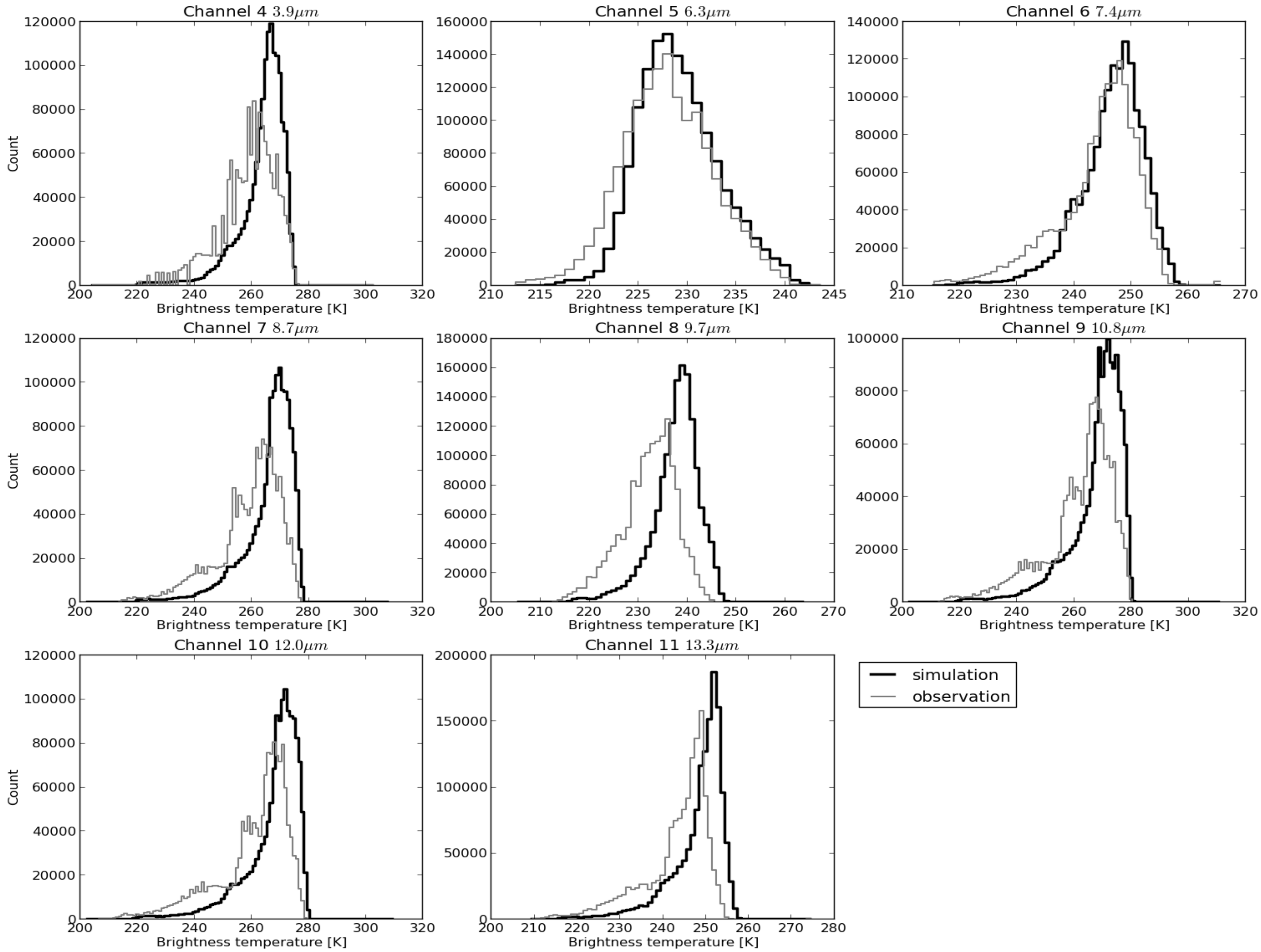
$C_{sca}=C_{ext}$=Geometrical+Diffraction=2<G>

$Q_{ext}=2$

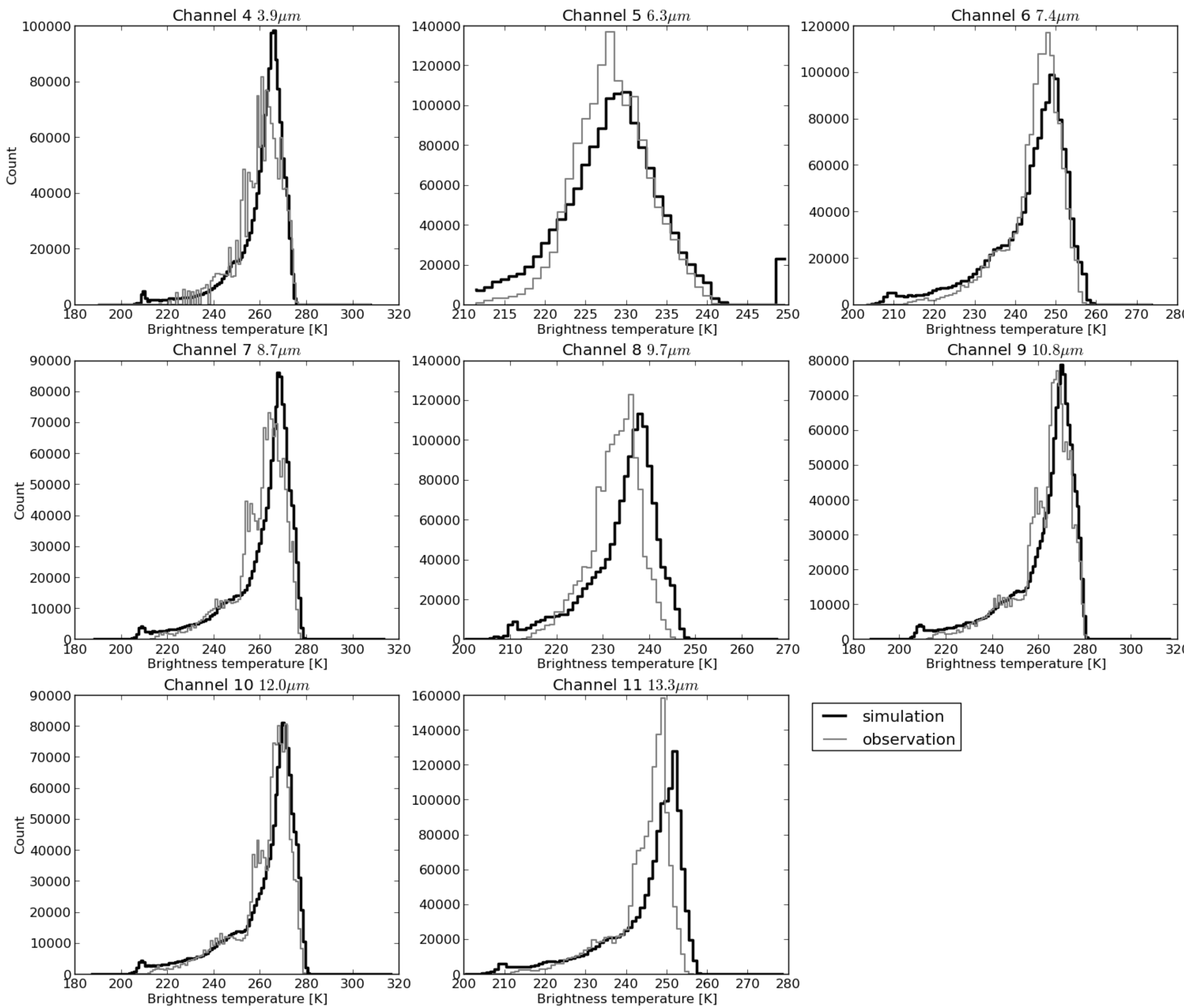
$D << \lambda$

$C_{sca} \propto mass^2/\lambda^4$

Brightness Temperature histograms – 1 month data -Inconsistent



Brightness Temperature histograms – 1 month data : Consistent microphysics & radiation



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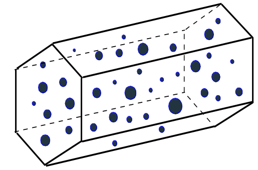
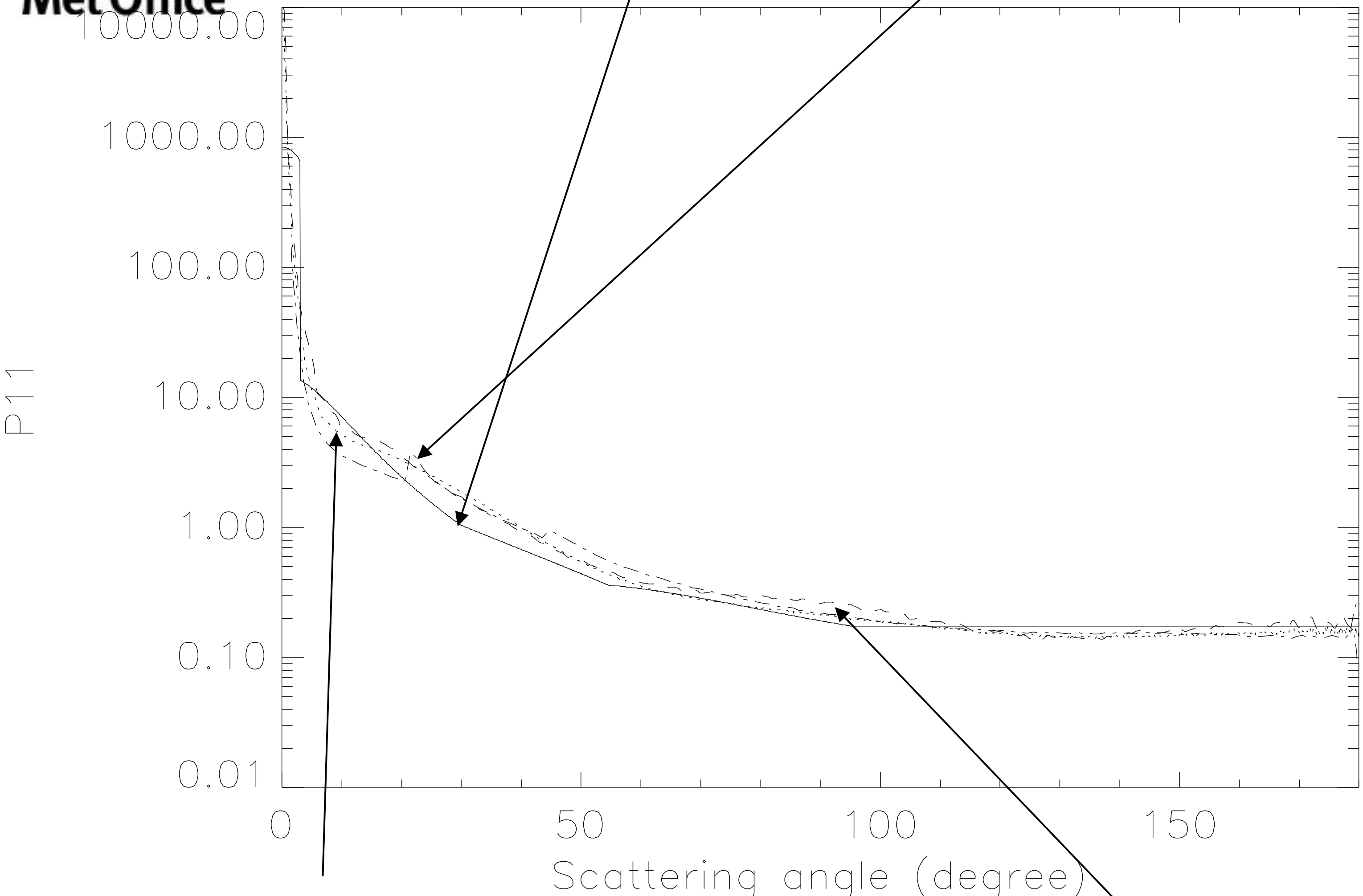
Analytic Baran et al. (2001)

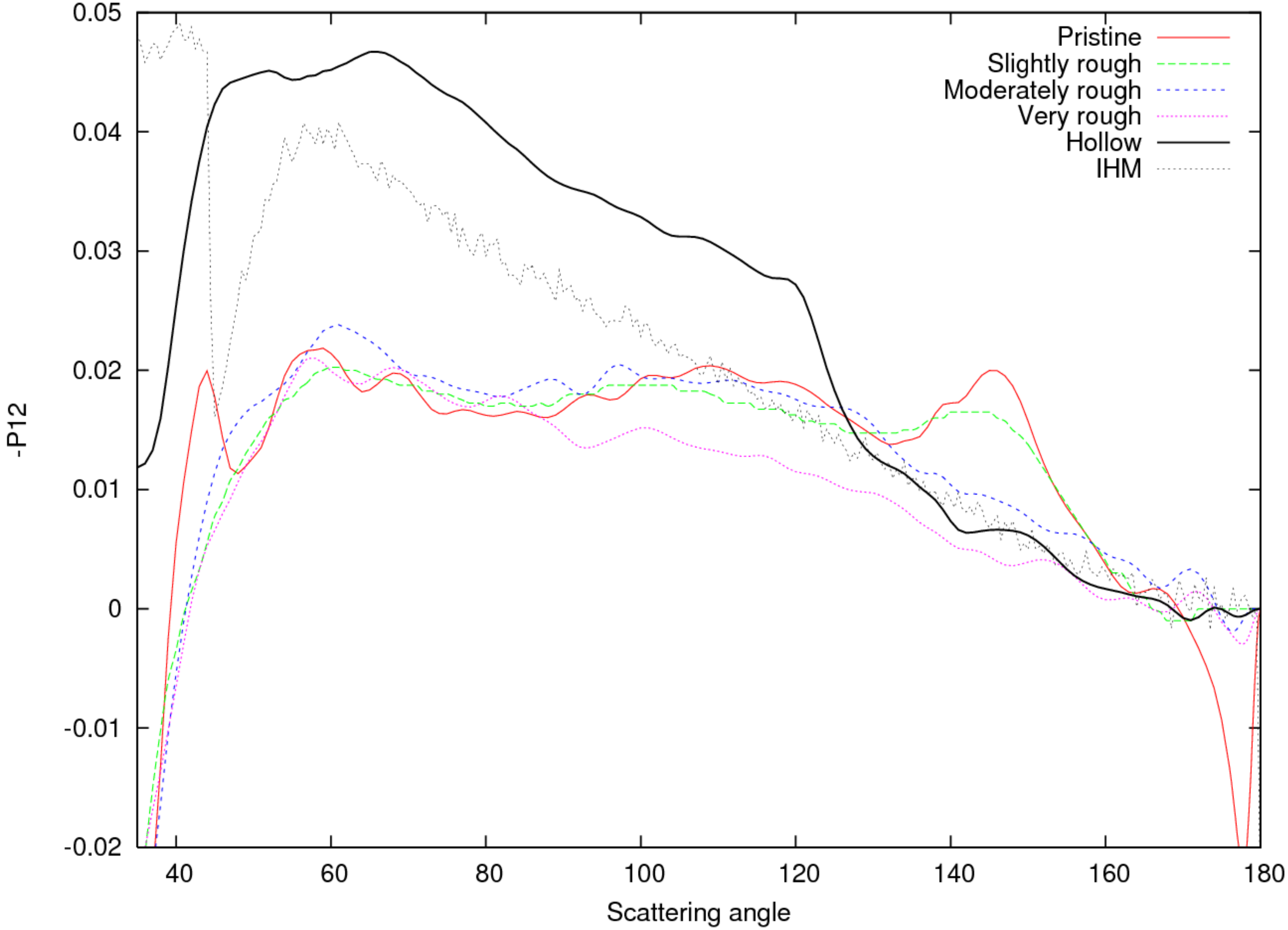




Ensemble distortion and inclusions

Fully randomized

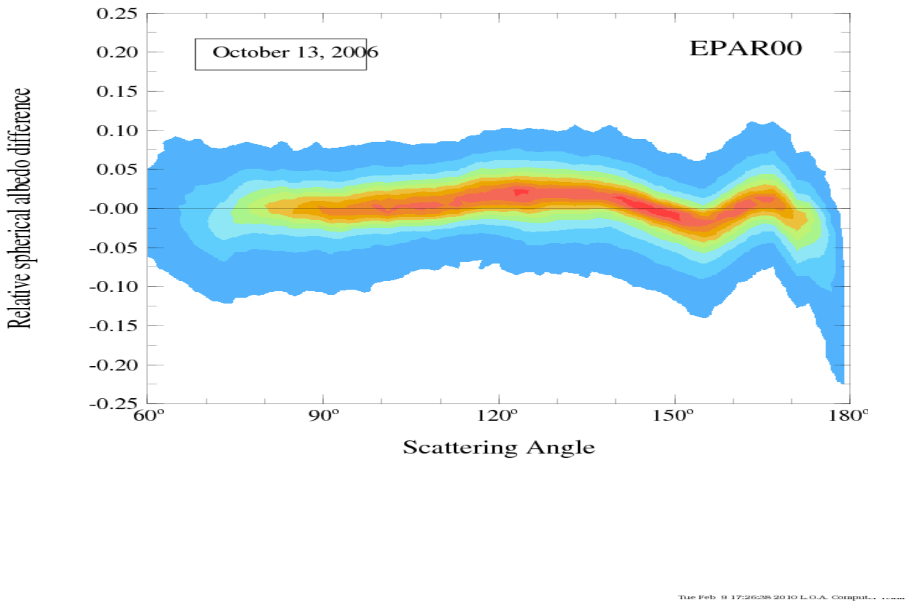
Ensemble distortion only

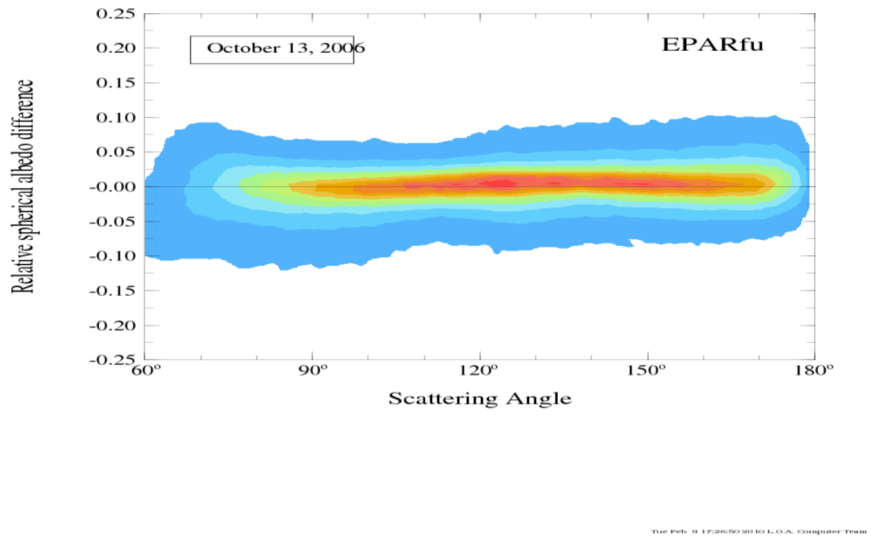


0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-P12
40
60
80
100
120
140
160
180
Scattering angle
Pristine
Slightly rough
Moderately rough
Very rough
Hollow
IHM

Tests against PARASOL total reflectance (up to 14 scattering angles 60º-180º)

8 λ’s 0.443 – 0.910 µm; 434000 scattering angles sampled





Inappropriate: Pristine ensemble

Fully Randomised Ensemble

Is the scattering phase function really featureless??

Lille Methodology: Optimal estimation (Rodgers,1976)

Minimization of the cost function

$$J(x) = (x-x_0)^T B^{-1} (x-x_0) + (y-y(x))^T R^{-1} (y-y(x))$$

x is the state vector (log10(IWC), liquid water cloud τ,mid-level cloud τ,water r_e, mid-level r_e) (x_0 is the a-priori)

y is the measurement vector

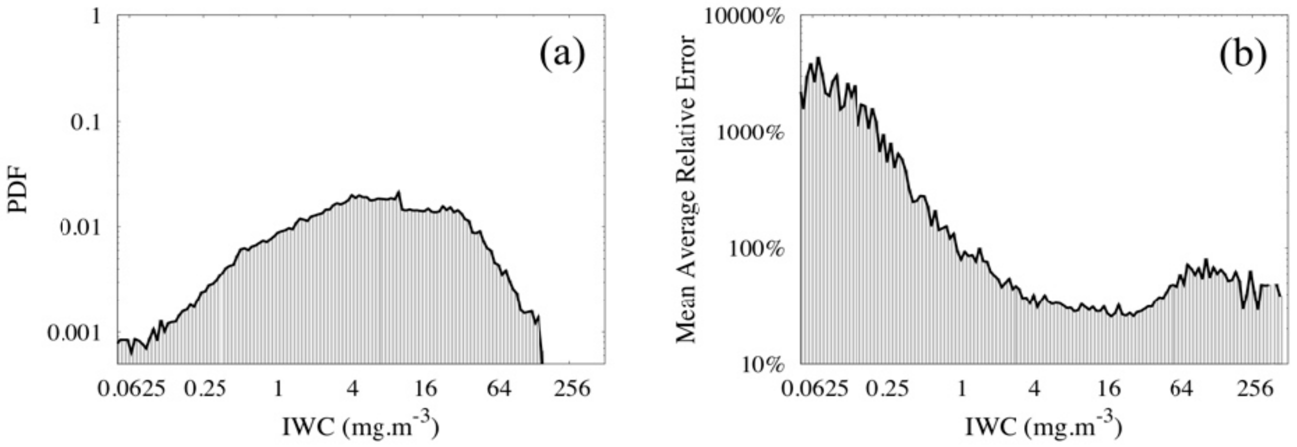
(IIR 8.65, 10.60 12.05 um and MODIS 0.86 and 2.13 µm)

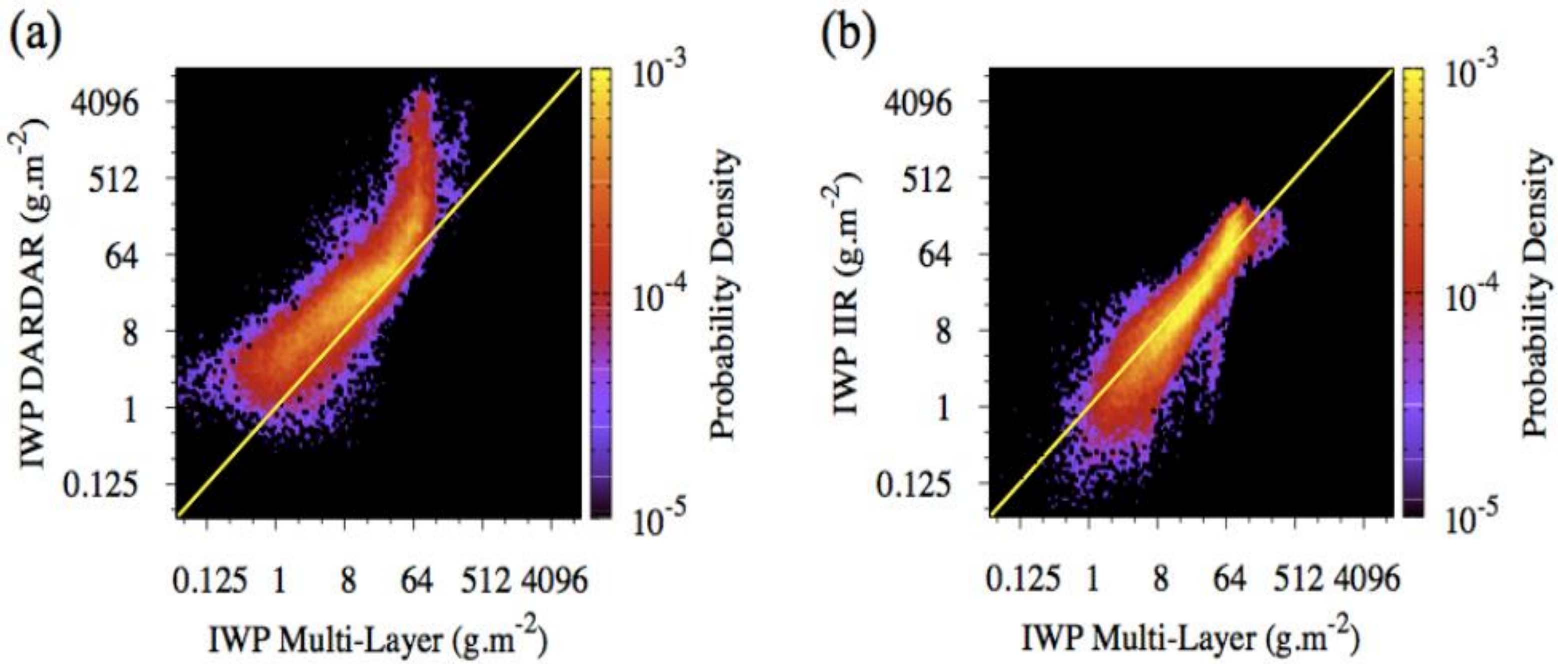
y(x) is forward model (ensemble optical properties plus fully randomized ensemble phase function; single-homogeneous cirrus, full multiple scattering radiative transfer solar+thermal)

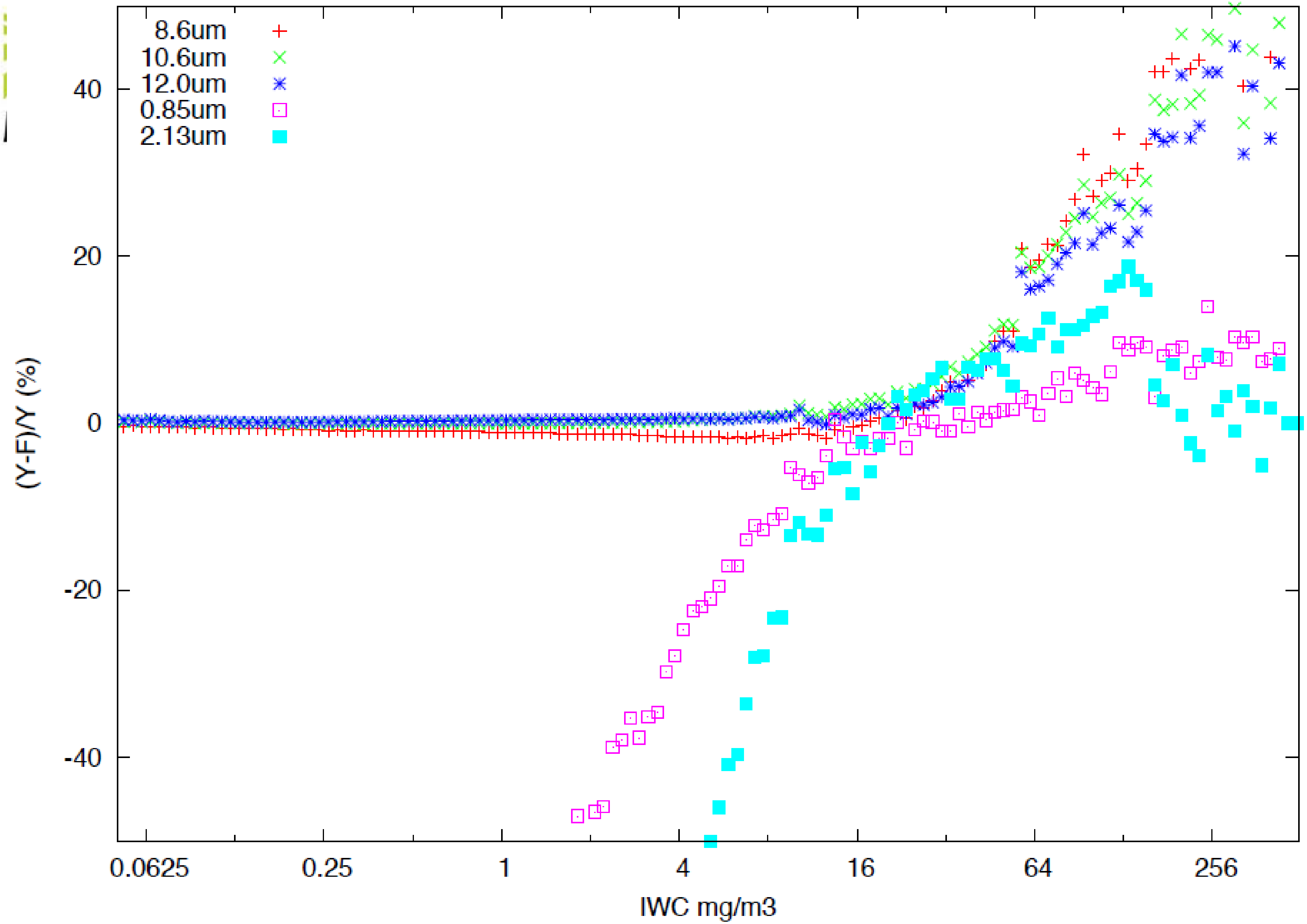
$$\log10(\beta(\lambda,IWC,T_c)) = a1(\lambda) + b1(\lambda)T_c + c1(\lambda)\log10(IWC)$$
$$\omega_0(\lambda,IWC,T_c) = a2(\lambda) + b2(\lambda)T_c + c2(\lambda)\log10(IWC)$$
$$g(\lambda,IWC,T_c) = a3(\lambda) + b3(\lambda)T_c + c3(\lambda)\log10(IWC)$$

B is the background error covariance matrix

R is the observations+model error covariance matrix


(a)
PDF
1
0.1
0.01
0.001
0.0625 0.25 1 4 16 64 256
IWC (mg.m^{-3})
(b)
Mean Average Relative Error
10000%
1000%
100%
10%
0.0625 0.25 1 4 16 64 256
IWC (mg.m^{-3})


(a)
IWP DARDAR (g.m^{-2})
4096
512
64
8
1
0.125
0.125 1 8 64 512 4096
IWP Multi-Layer (g.m^{-2})
Probability Density
10^{-3}
10^{-4}
10^{-5}
(b)
IWP IIR (g.m^{-2})
4096
512
64
8
1
0.125
0.125 1 8 64 512 4096
IWP Multi-Layer (g.m^{-2})
Probability Density
10^{-3}
10^{-4}
10^{-5}

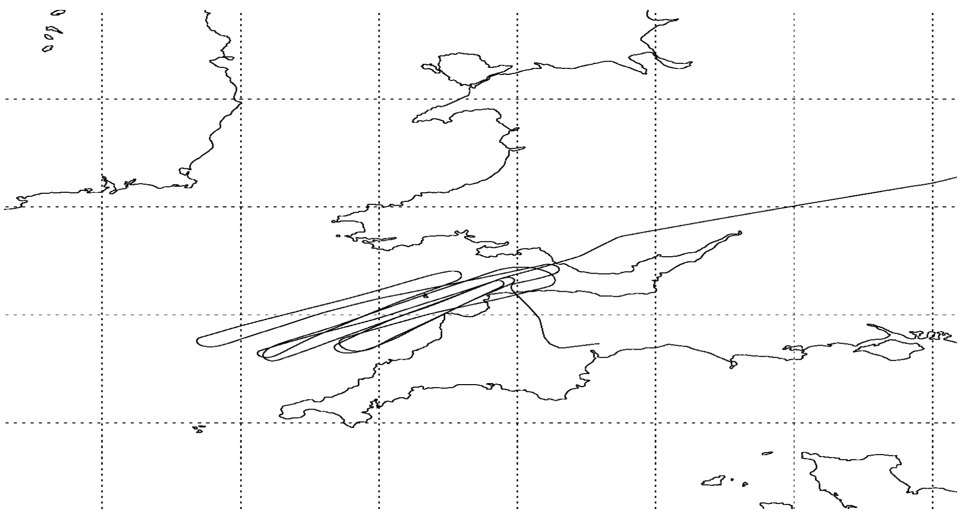


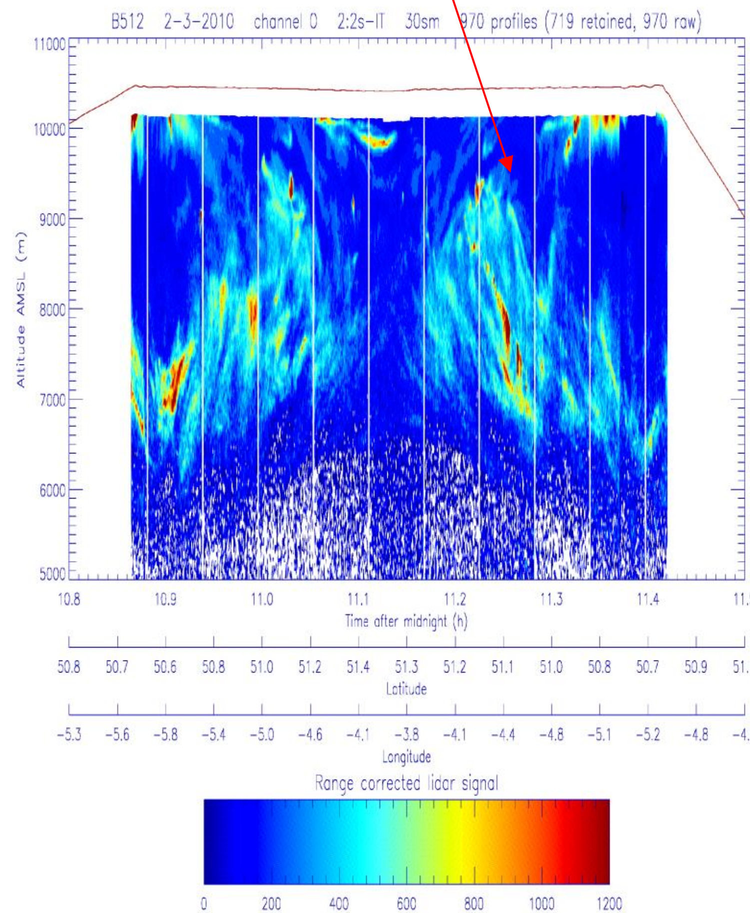
8.6um
10.6um
12.0um
0.85um
2.13um
40
20
0
-20
-40
(Y-F)/Y (%)
0.0625
0.25
1
4
16
64
256
IWC mg/m3

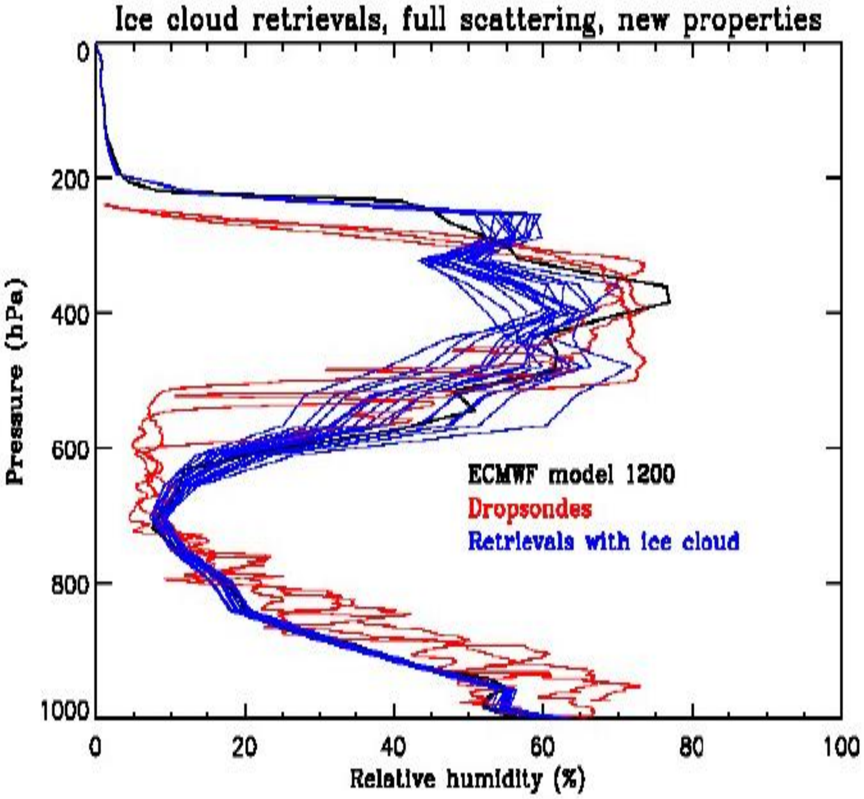
Cloudy Case Study (2nd March 2010)

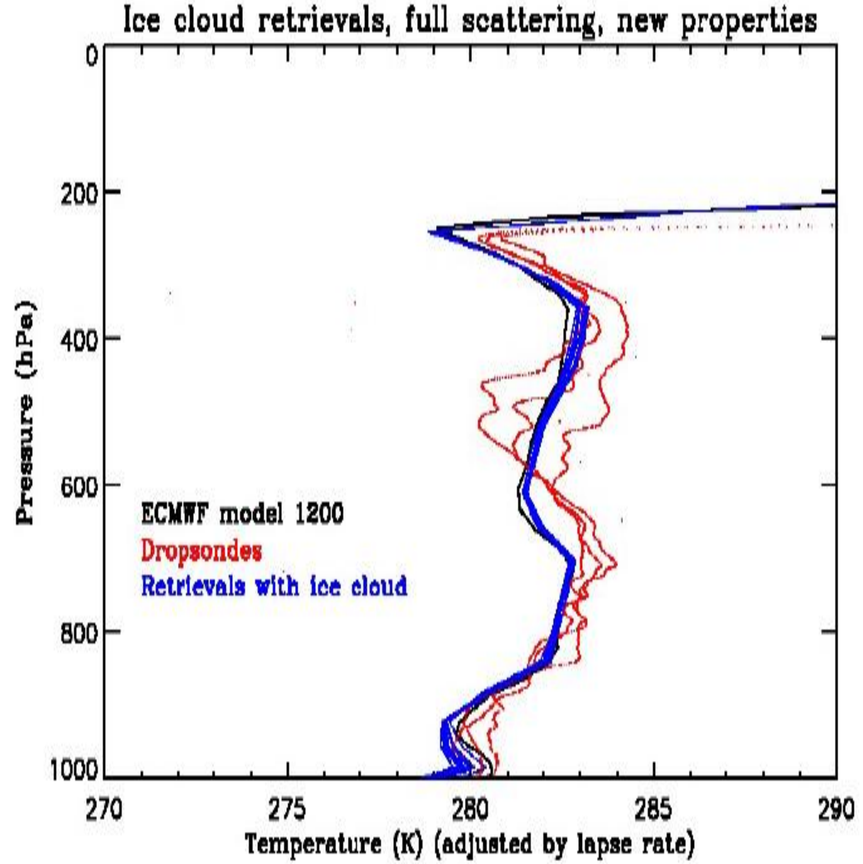
Assuming Ensemble: Single-scattering properties in IWC-T_C space

Aircraft location & lidar



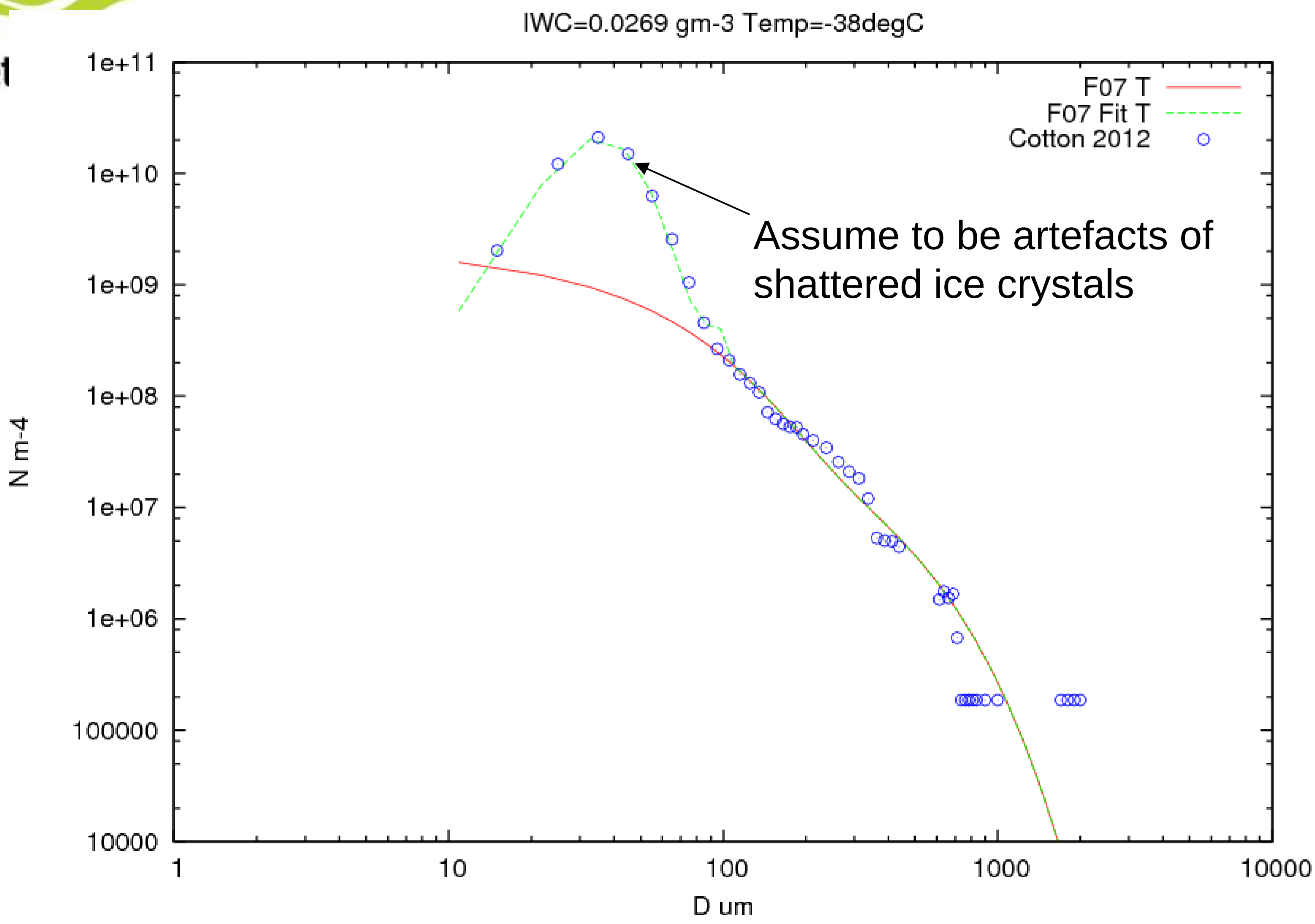


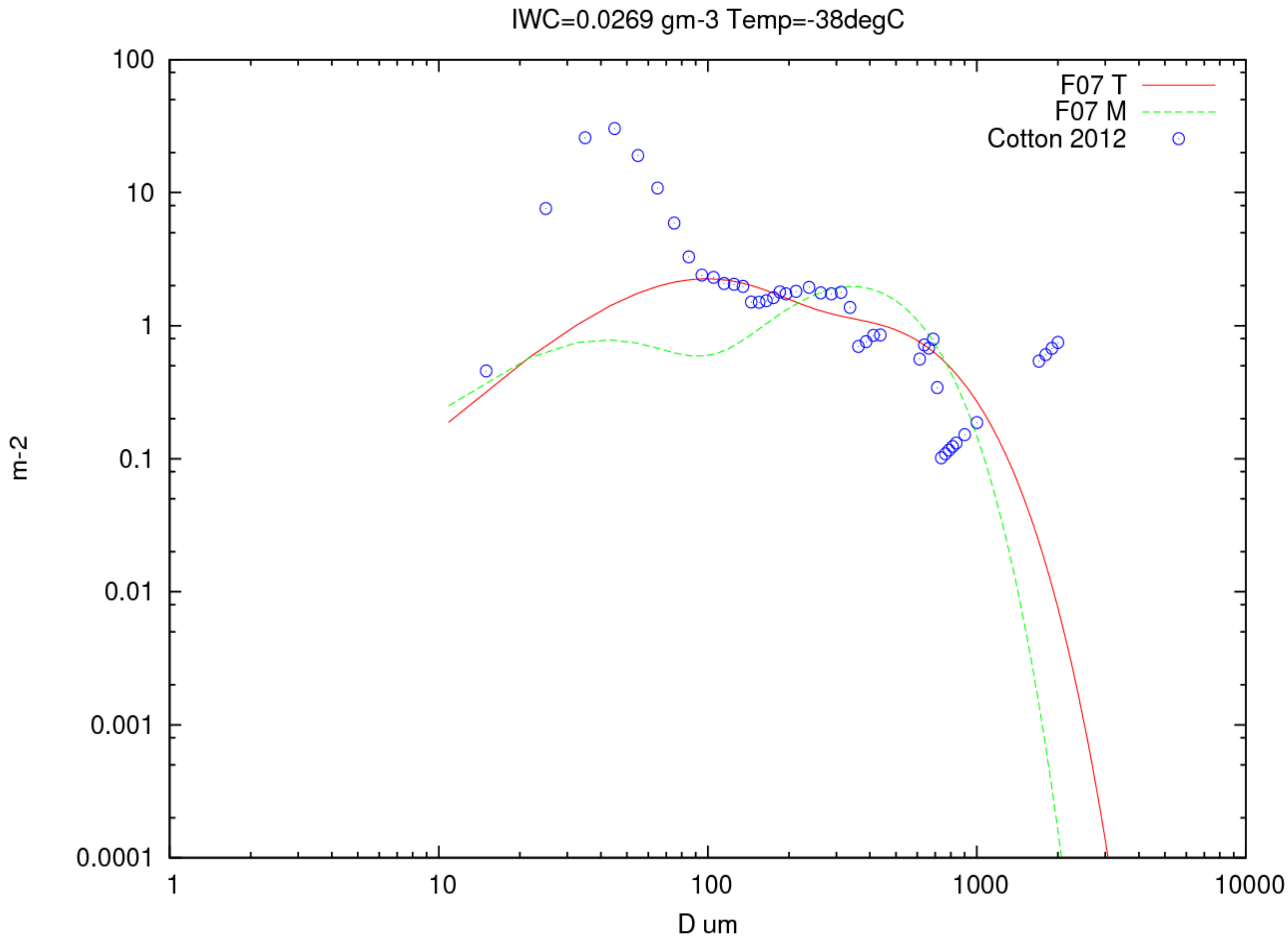

Ice cloud retrievals, full scattering, new properties
Pressure (hPa)
0
200
400
600
800
1000
0
20
40
60
80
100
Relative humidity (%)
ECMWF model 1200
Dropsondes
Retrievals with ice cloud

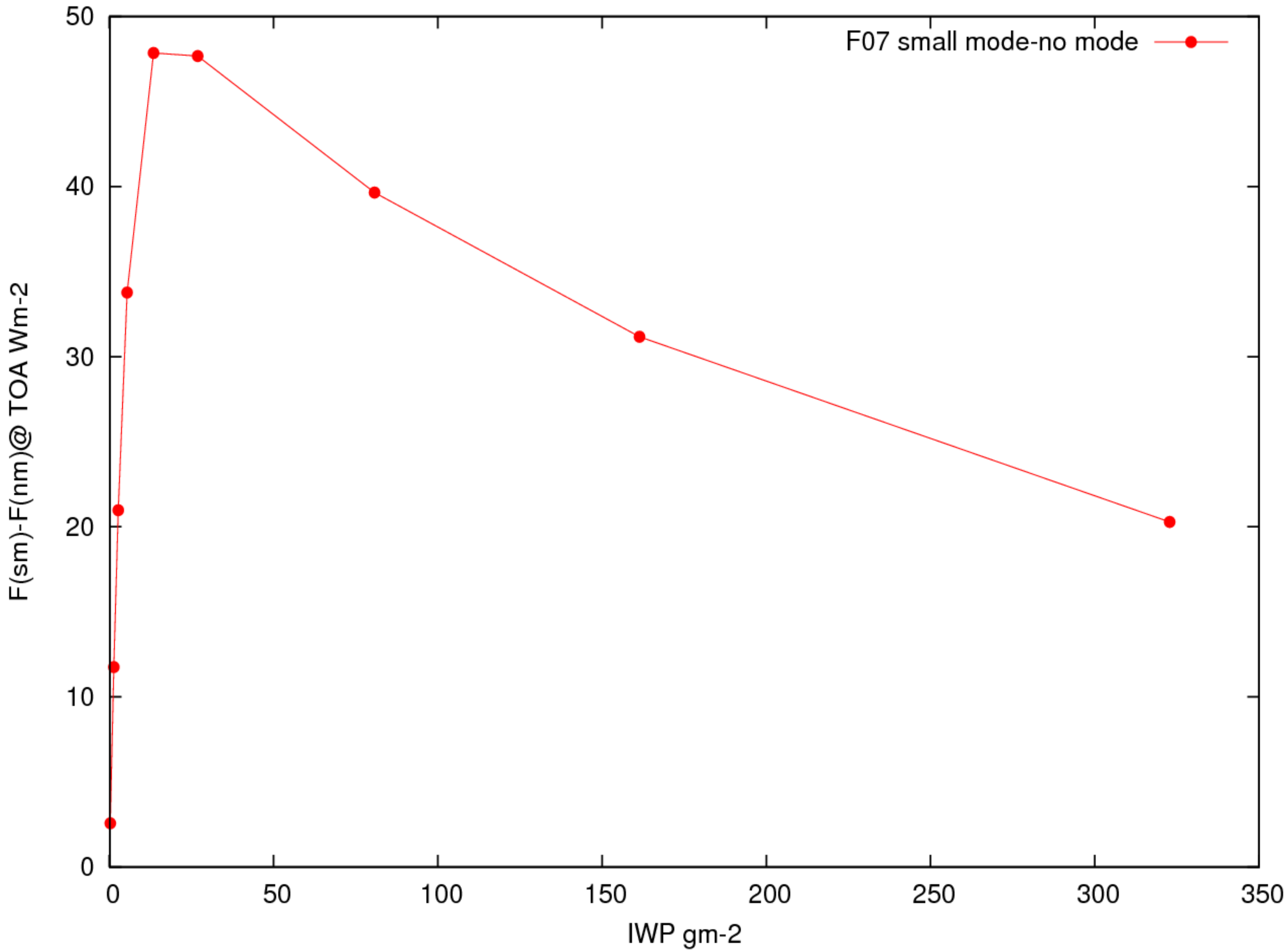

Ice cloud retrievals, full scattering, new properties
Pressure (hPa)
0
200
400
600
800
1000
270
275
280
285
290
Temperature (K) (adjusted by lapse rate)
ECMWF model 1200
Dropsondes
Retrievals with ice cloud

B512 IASI Cirrus cloud retrievals	First guess	Retrieval results [*Full scattering*]
Cirrus cloud ice water content $[mgm^{-3}]$	30.0 In-situ	19.8 ± 3.5
Cirrus cloud top pressure $[hPa]$	275.0	303.7 ± 6.1
Cirrus cloud thickness $[hPa]$	200.0	200.4 ± 1.4
Cirrus fraction	1.0	0.54 ± 0.05

A note on Shattering




IWC=0.0269 gm-3 Temp=-38degC
F07 T
F07 M
Cotton 2012
100
10
1
0.1
0.01
0.001
0.0001
m-2
1
10
100
1000
10000
D um



F07 small mode-no mode
F(sm)-F(nm)@ TOA Wm-2
IWP gm-2
0
10
20
30
40
50
0
50
100
150
200
250
300
350

Impact of Shattering on volume extinction coefficient

For the same IWC

β_{ext}=0.0021 m^{-1} assuming no shattering F07

β_{ext}=0.004 m^{-1} assuming shattering F07 with modelled small mode

For the same IWC Assume Hex cols

β_{ext}=7.86e-04 m^{-1} assuming no shattering F07

β_{ext}=0.002 m^{-1} assuming shattering F07 with modelled small mode !

Error cancellation particle geometry compensates exaggerated small mode.