From ice crystal single-scattering to climate prediction: the way forward?

Anthony Baran, Met Office, Exeter, UK.

EGU, Vienna, April 2011

Acknowledgements !

Professor Ping Yang (Texas A & M, USA),

Dr Joseph Ulanowski (University of Hertfordshire, UK),

Dr Stephen Langdon (University of Reading, UK),

Professor Simon Chandler-Wilde (University of Reading, UK)

Dr David Hewitt (University of Reading, UK)

Dr Paul Connolly (University of Manchester, UK),

and Dr James Manners (Met Office, UK)

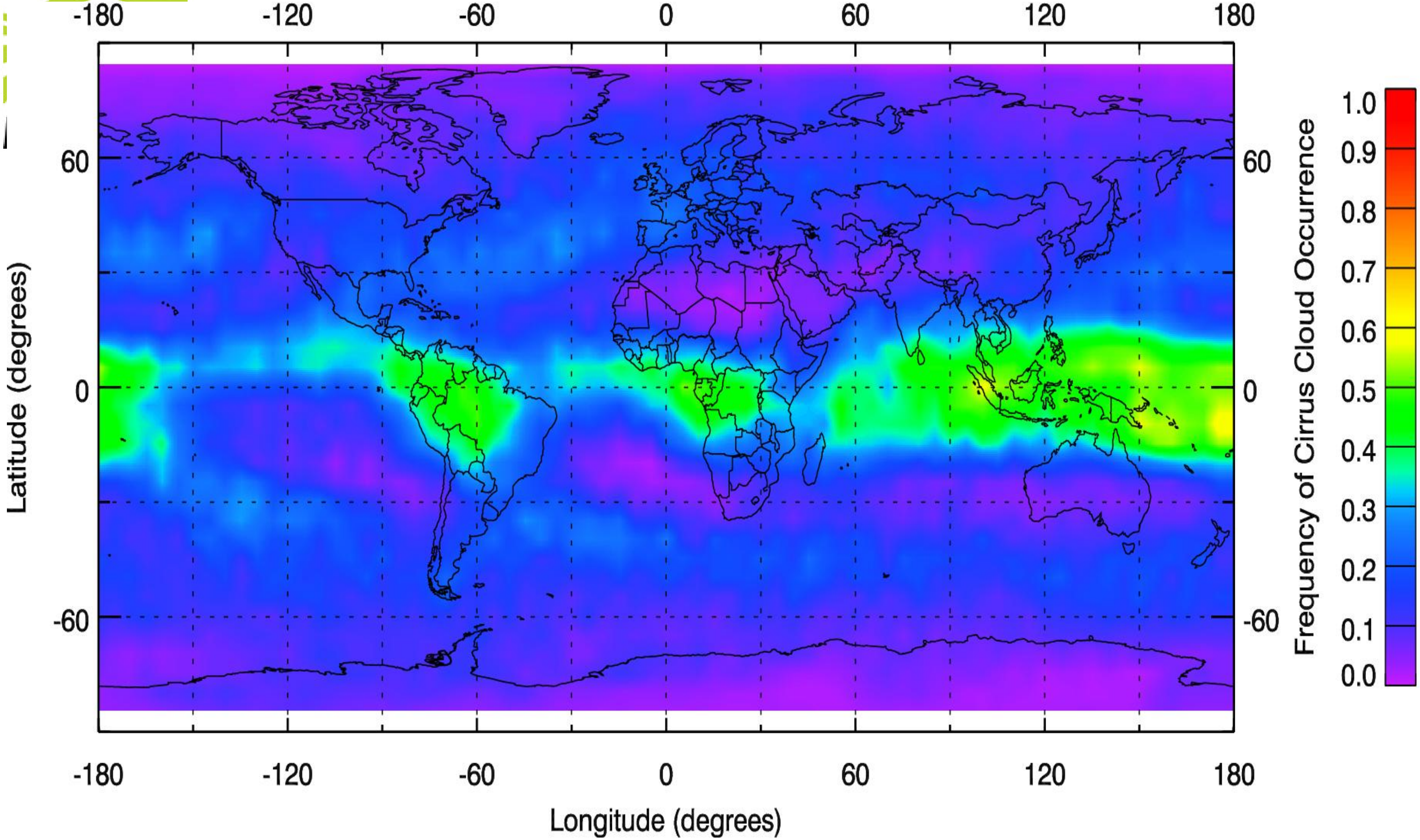
Contents

This presentation covers the following areas

- Uncertainties in the cirrus radiative effect & contribution to the hydrological cycle
- New era of remote sensing & the need for a consistent set of ice crystal single-scattering properties across EM spectrum
- The natural variability of cirrus & proposed models to represent ensembles of ice crystals
- Define single-scattering properties & scattering solutions
- Coupling the single-scattering properties to bulk cloud properties: No need for “effective dimension”
- Example of a GCM parameterization
- Issues

Current global cirrus uncertainties

Sassen et al. (2008)



Uncertainties

Ice Mass ± 50%

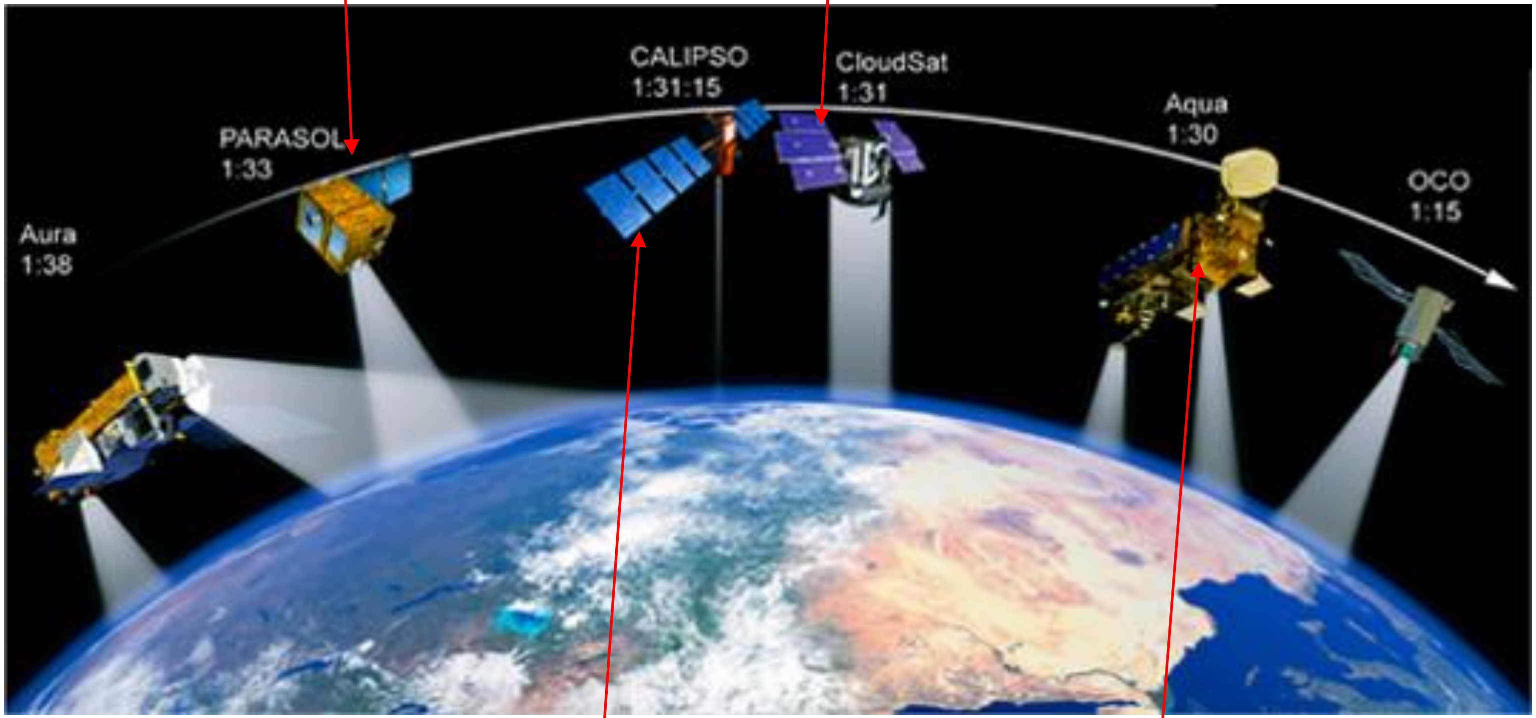
SW flux ~± 30 Wm^{-2}

The remote sensing problem & the need for a consistent set of single-scattering properties

The A-Train Constellation measures radiative properties & ice mass

Total & polarized solar reflection

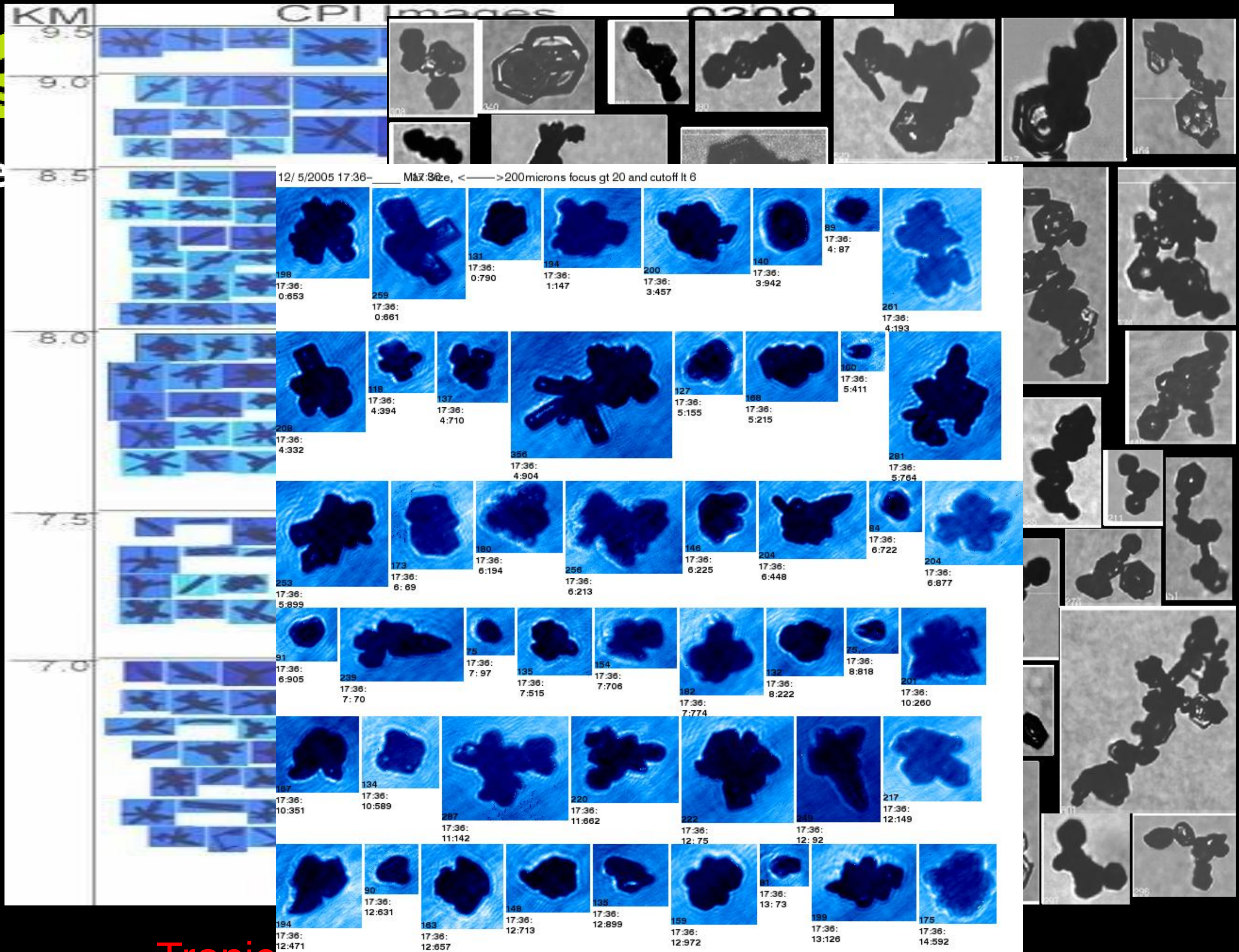
94 GHz cloud-profiling radar



Lidar

Solar reflection & Infrared transmission

The natural variability of ice crystals & proposed models



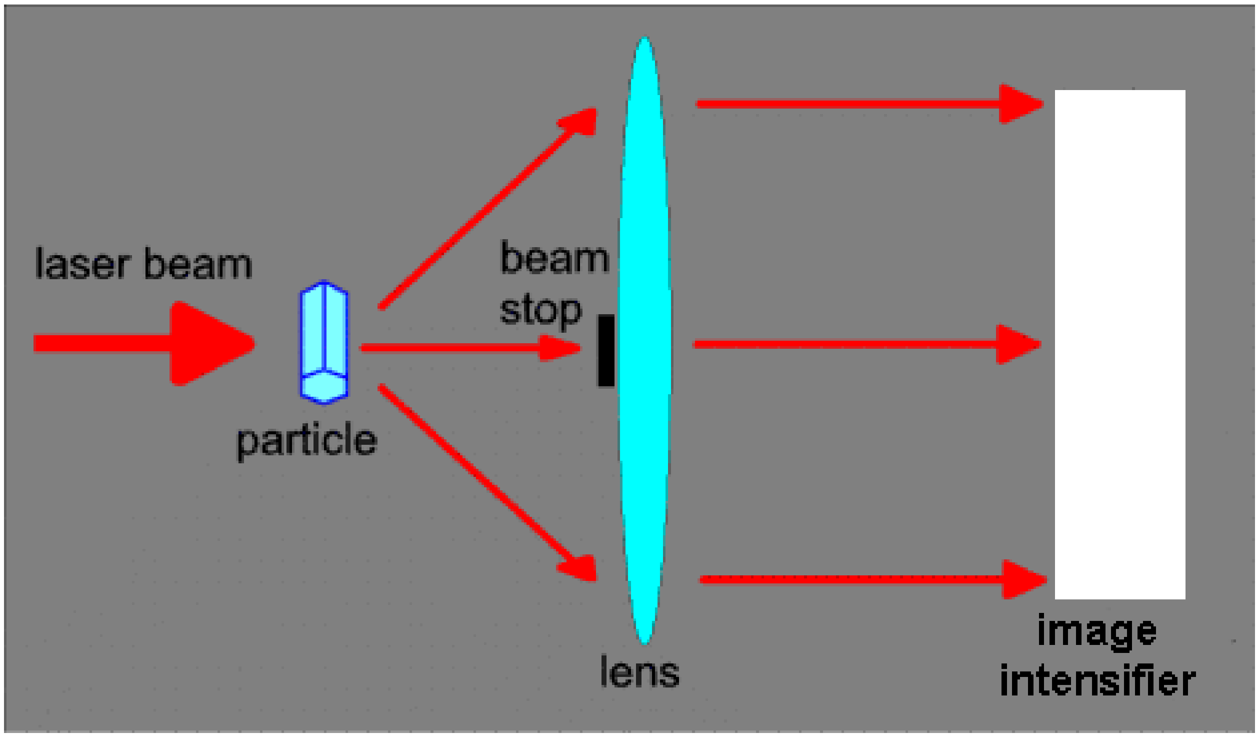
Tropic
Heyms

University of Manchester

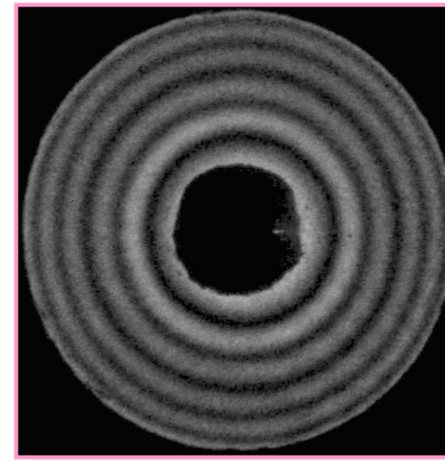
McFarquhar

SID-3 2D scattering pattern formation

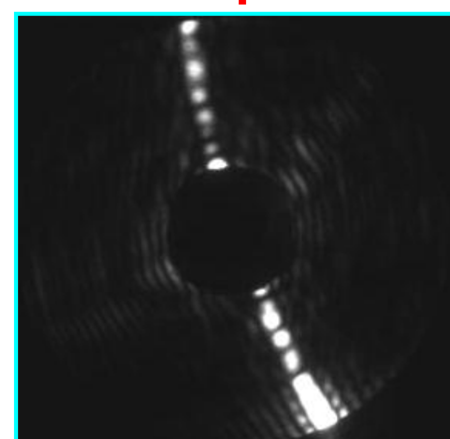
SID-3 circumvents optical resolution limits of imaging cloud probes by acquiring 2D scattering patterns



Ice crystal size down to ~ 1 µm



2D scattering pattern: droplet



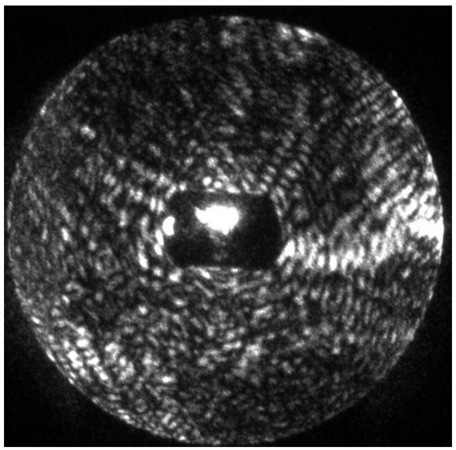
2D scattering pattern: ice column

Ack: Z. Ulanowski

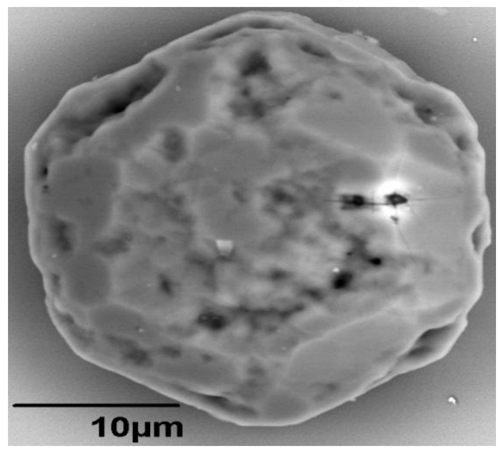
- SID-3 data from mid-latitude cirrus and mixed phase clouds shows strong roughness in the majority of ice particles.

2D scattering SID-3

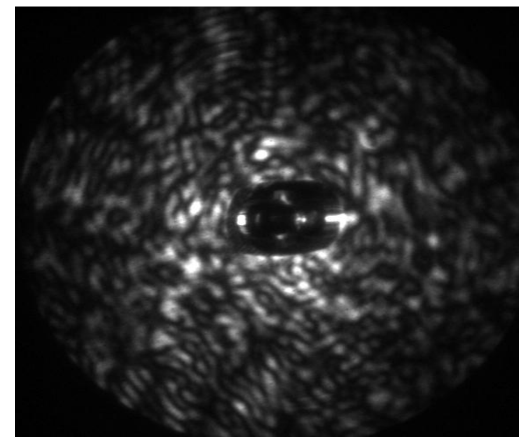
Cirrus ice



Rough ice model



Rough ice model



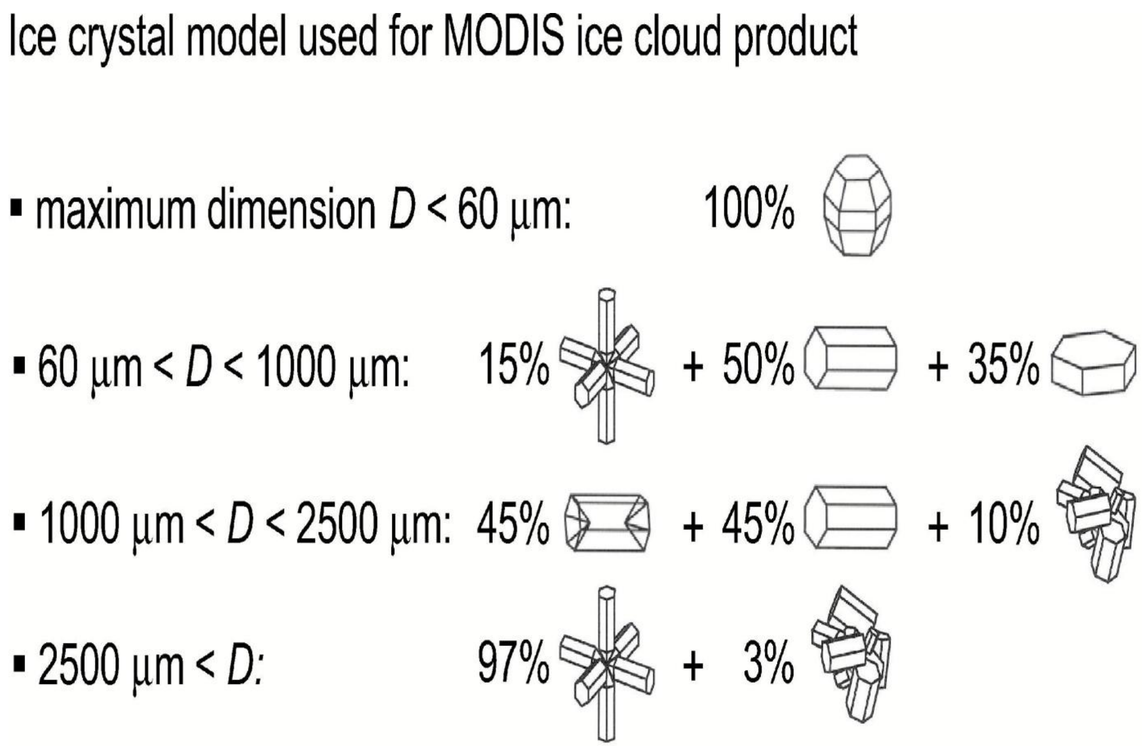
Z. Ulanowski et al. (2010) *12th ELS Conf.*, Helsinki.

Cases studied so far by Ulanowski suggest that small cirrus ice crystals are predominantly rough

Ack: Z. Ulanowski

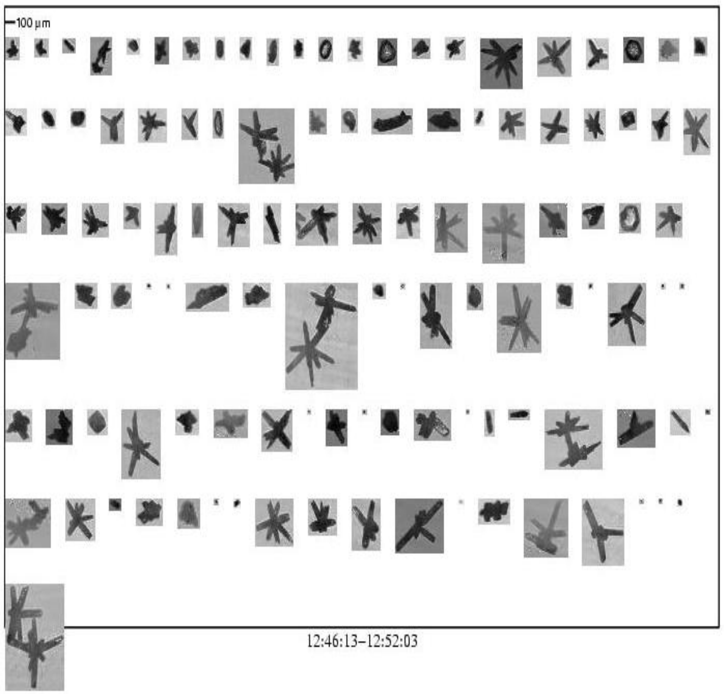
Bulk properties consider an ensemble of ice crystals

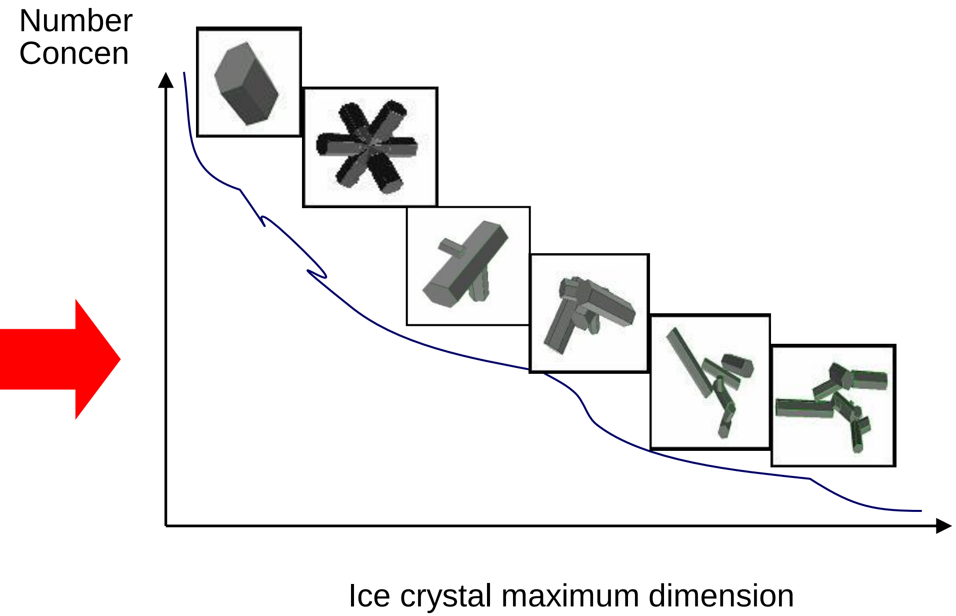
Try to model what is observed



Ack: P Yang, B Baum and G Hong

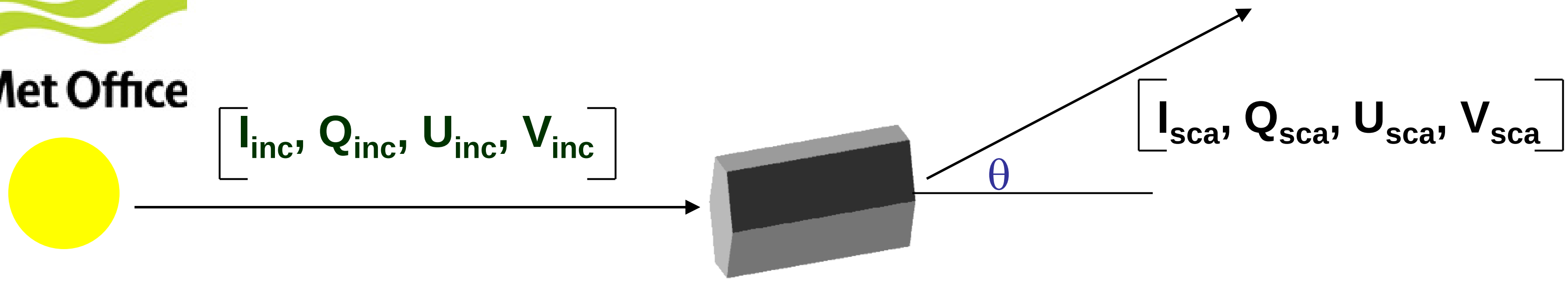
or Generalise





Baran & Labonnote (2007)

Single-Scattering properties and their solutions



$$\begin{pmatrix} I_{sca} \\ Q_{sca} \\ U_{sca} \\ V_{sca} \end{pmatrix} = \frac{C_{sca}}{4\pi r^2} \begin{pmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{21} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & -P_{34} \\ 0 & 0 & P_{43} & P_{44} \end{pmatrix} \begin{pmatrix} I_{inc} \\ Q_{inc} \\ U_{inc} \\ V_{inc} \end{pmatrix}$$

$$\frac{1}{2}\int_{-1}^{1} P_{11}(\theta)\sin\theta d\theta = 1$$

P_{12}/P_{11} describes the degree of linear polarization (DLP)

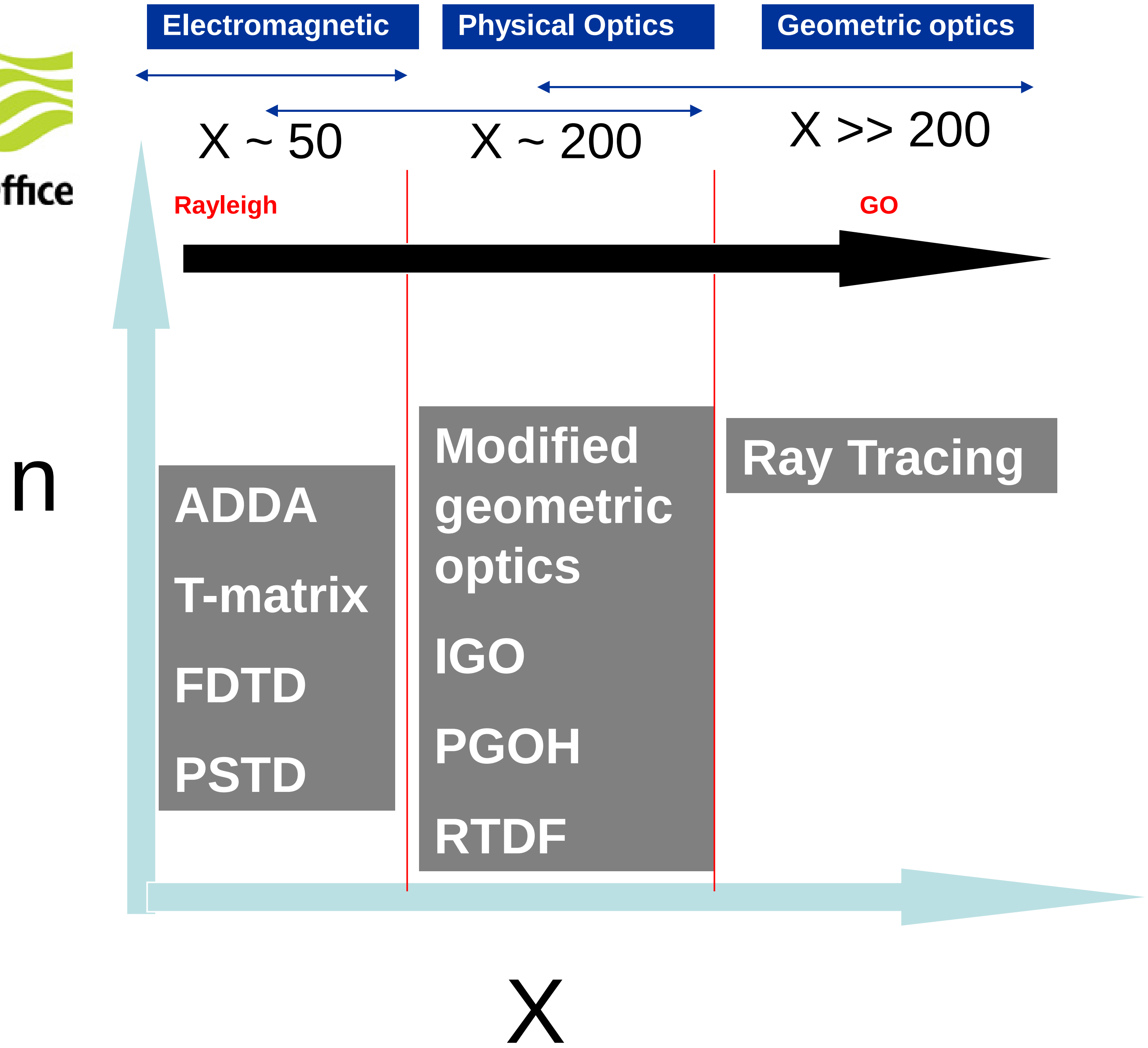
$(P_{11}-P_{22})/(P_{11}+P_{22})$ describes the linear depolarization ratio

Total Optical Properties

$$g = \langle \cos\theta \rangle = \int_{-1}^{1} d(\cos\theta) P_{11}(\cos\theta)\cos\theta$$

$$K_{ext} = \int (Q_s(\vec{q}) + Q_a(\vec{q})) < S(\vec{q}) > n(\vec{q}) d\vec{q}$$

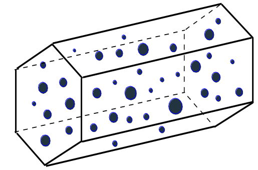
$$\omega_0 = K_{sca} / (K_{sca} + K_{abs})$$

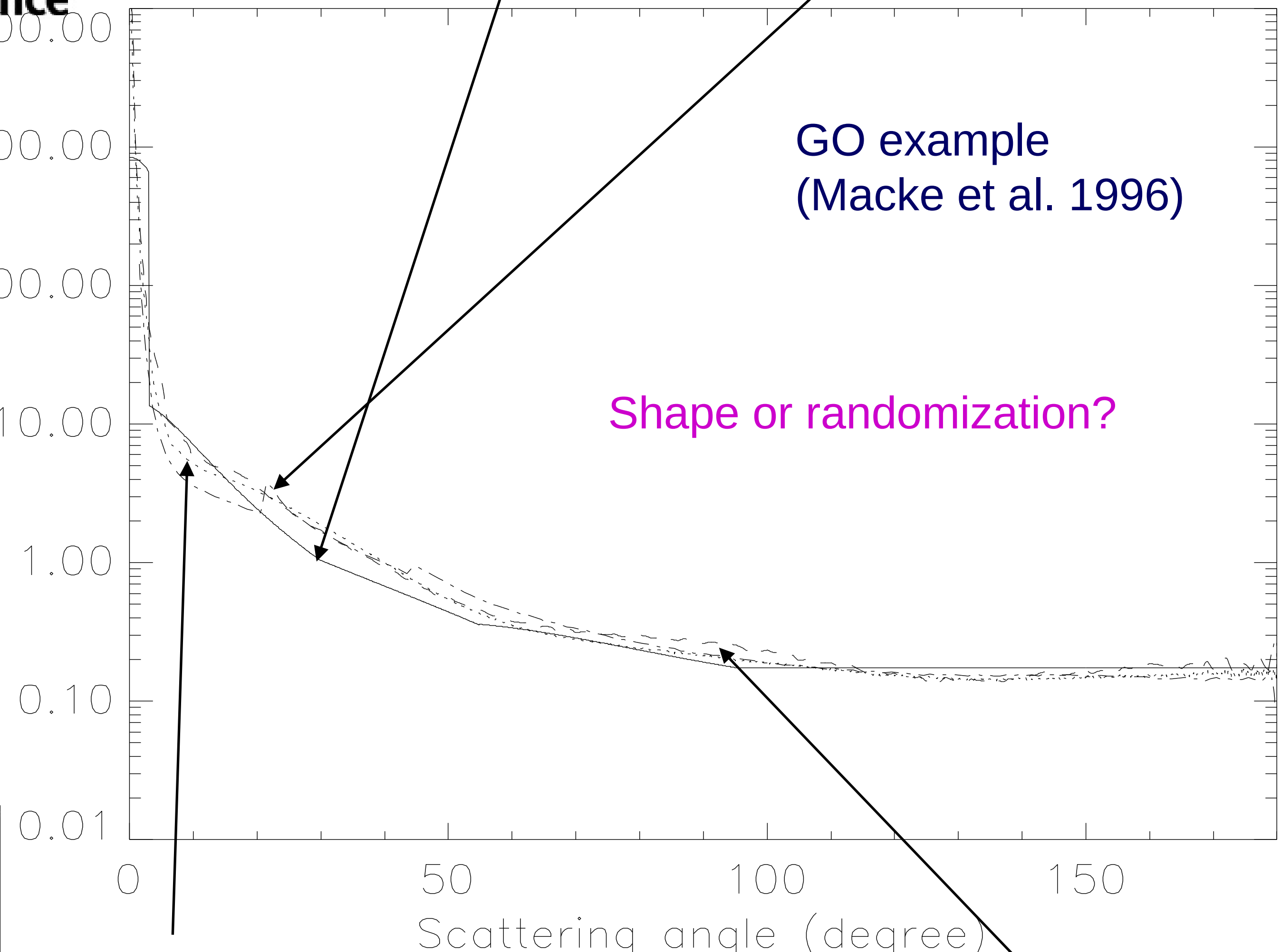


Electromagnetic
Physical Optics
Geometric optics
X ~ 50
X ~ 200
X >> 200
Rayleigh
GO
n
ADDA
T-matrix
FDTD
PSTD
Modified geometric optics
IGO
PGOH
RTDF
Ray Tracing
X

Analytic Baran et al. (2001)

Labonnote et al. 2001





GO example
(Macke et al. 1996)

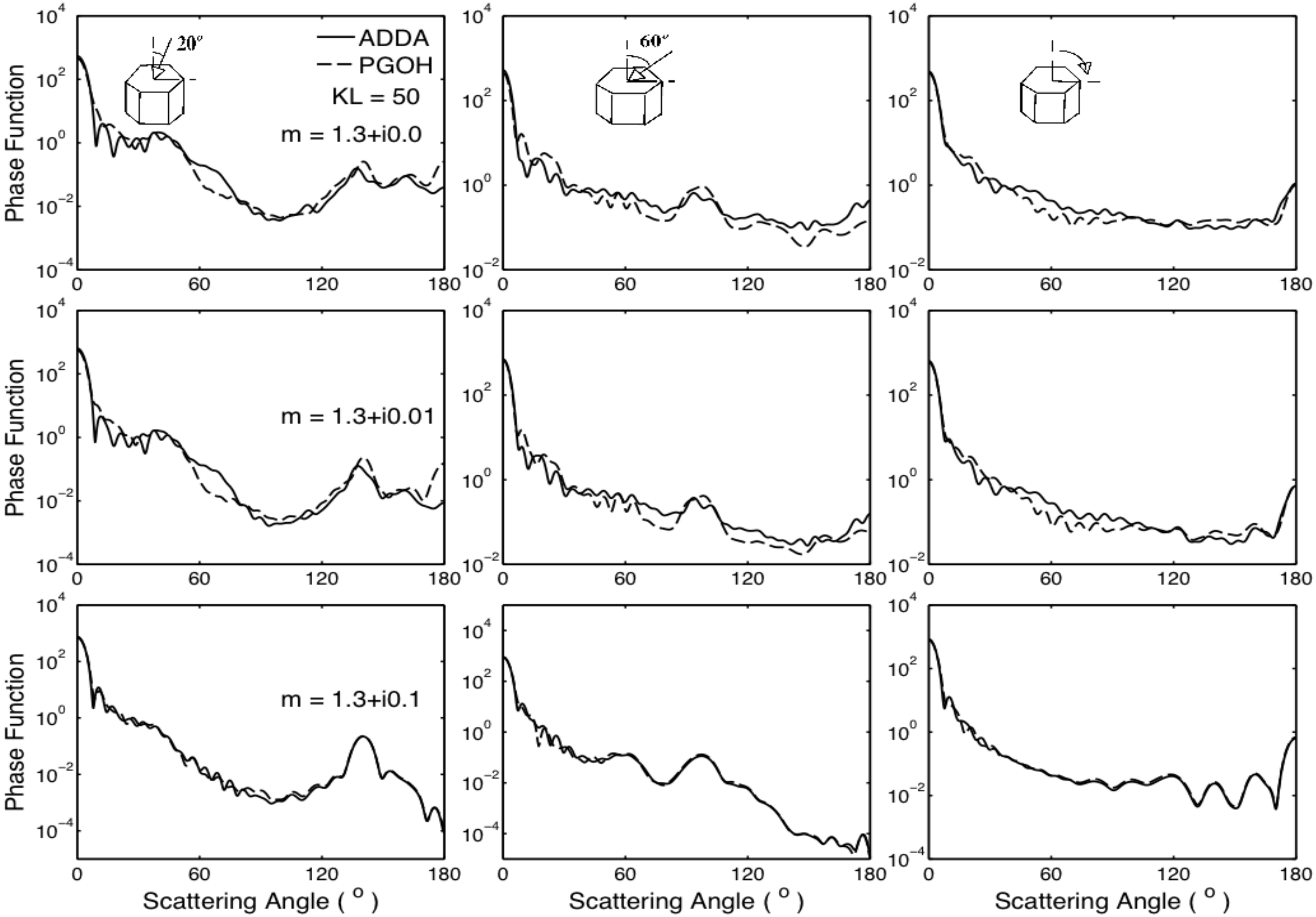
Shape or randomization?

Ensemble distortion and inclusions

Fully randomized

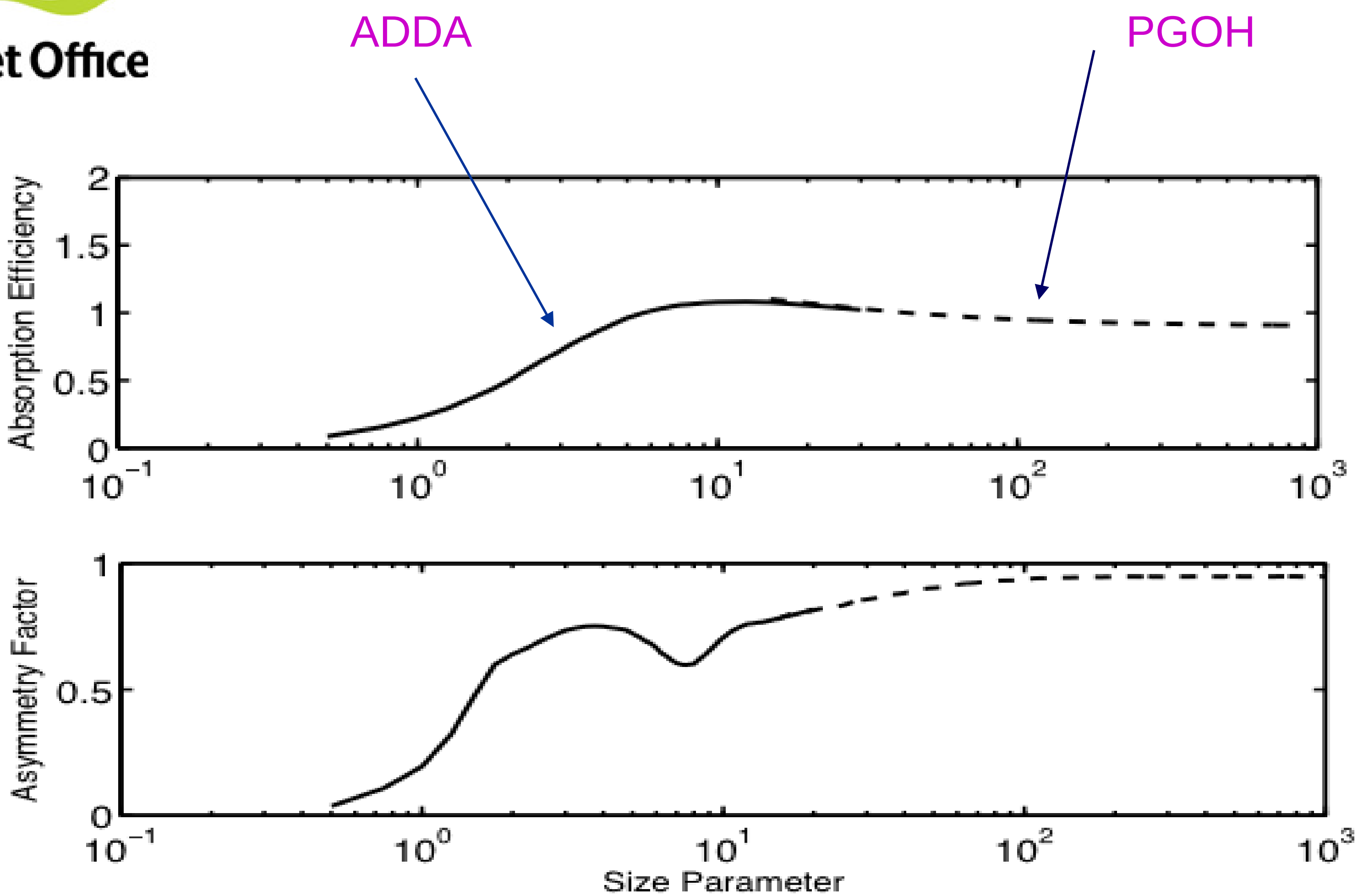
Ensemble distortion only

Physical Optics: PGOH method



"Scattering and absorption of light by ice particles: solution by a new physical-geometric optics hybrid method" by L. Bi, P. Yang, G. W. Kattawar, Y. Hu, and B. A. Baum, JQSRT (in press)

Problem with Physical Optics methods: Merging ADDA with PGOH



Ack: P. Yang

Scattering solutions for all X space ?

Interesting new area: can we learn from scalar wave scattering?

A solution for the high frequency limit ?

Currently: Based on scalar wave scattering from 2D and possible extension to 3D polygons

$$\nabla^2 u + k^2 u = 0$$

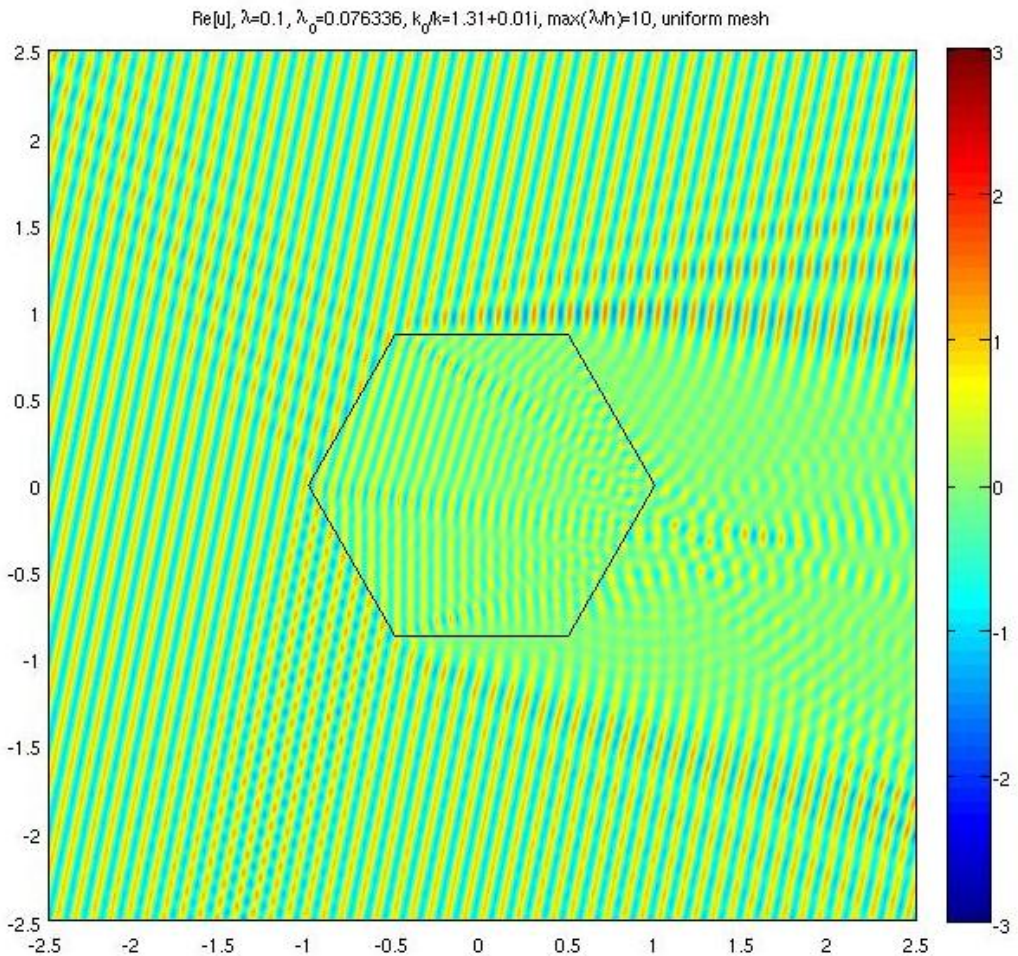
As $K = 2\pi/\lambda \rightarrow \infty$

Find solution space so that computational cost ~ log(K) as $K \rightarrow \infty$

As $K \rightarrow \infty$ d.o.f small whilst accuracy is maintained for any K

See for rigorous proof Langdon et al. 2010

Example – Scalar wave scattering by 2D Hexagon



X=60

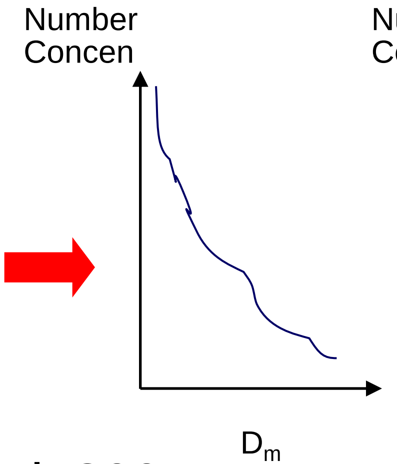
Ack: D. Hewitt, S. Langdon & S Chandler-Wilde

Coupling the single-scattering properties to bulk cloud properties: No need for “effective dimension”

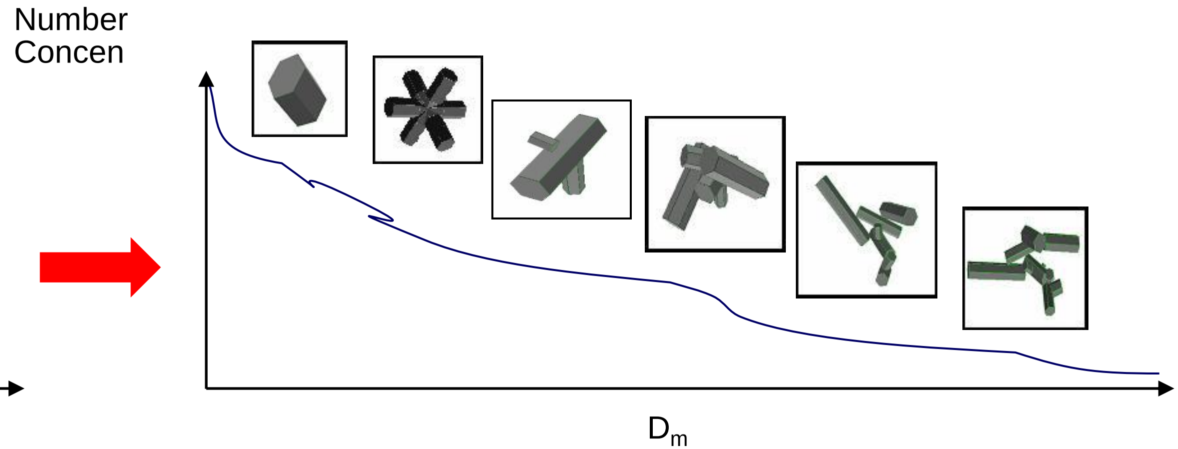
Consider an ensemble of ice crystals

Met Office

IWC, T_c



Field et al. 2007



GO

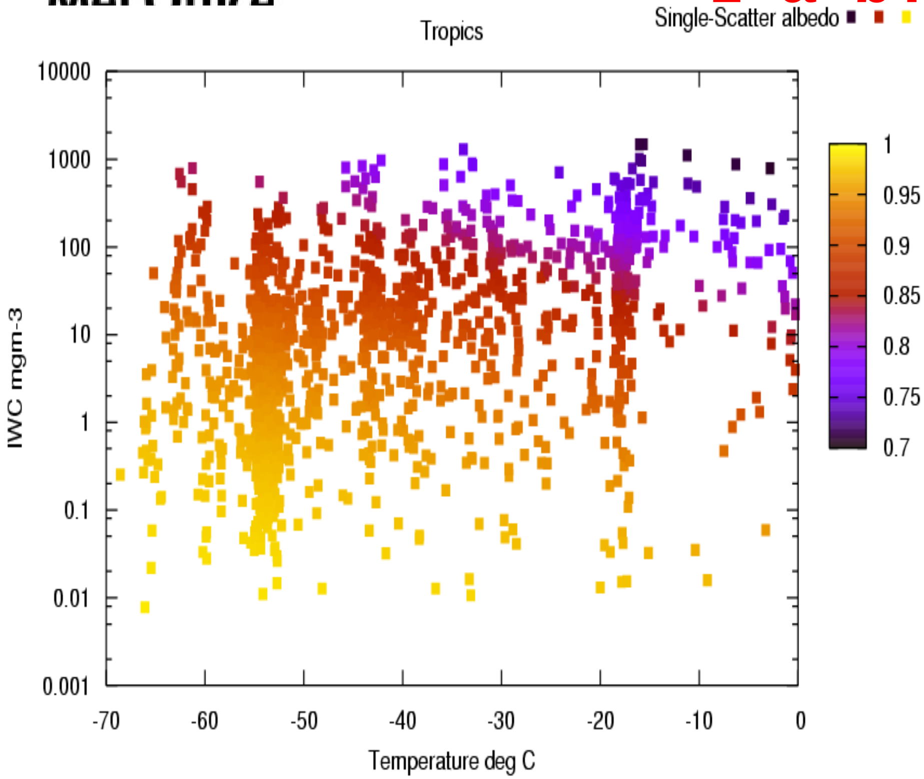
INTEGRATION

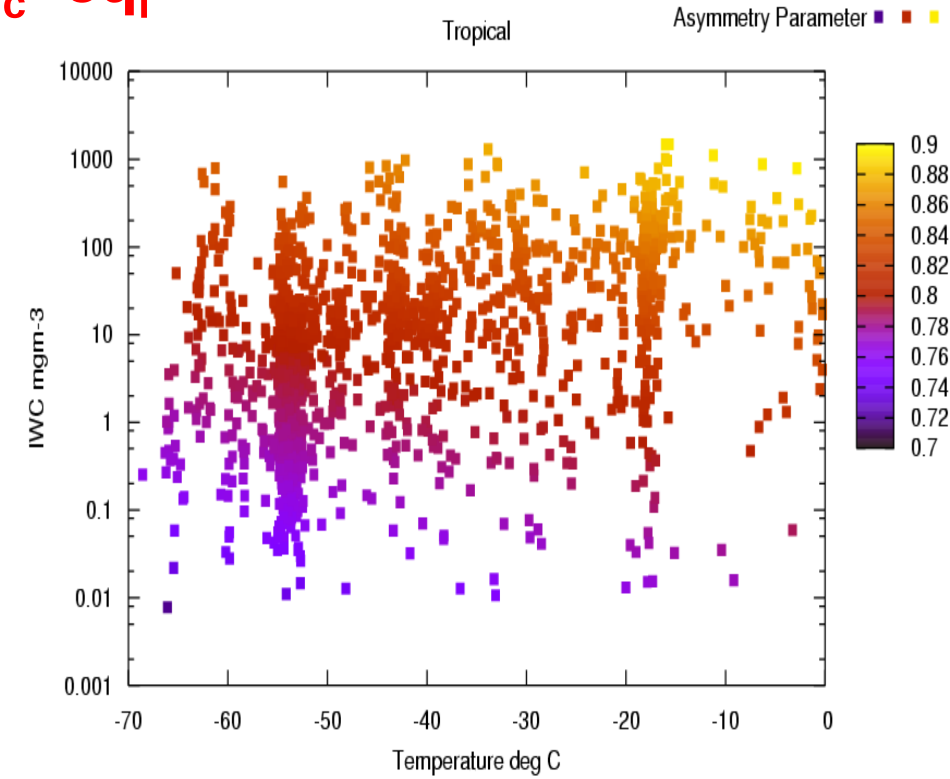
- **IWC (Closure)**
- **Total Optical Properties**
- **General Scattering matrix**
- **Related to IWC, T_c**
- **No D_e**

Baran et al. 2007;2009, 2011

ω_0 and g in IWC-T_C space

$z=a+bT_c+cq_i$





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

A total number of 1530 Tropical and 1210 Mid-latitude PSDs were generated

Example of a GCM parameterization

Typically single ice crystal model

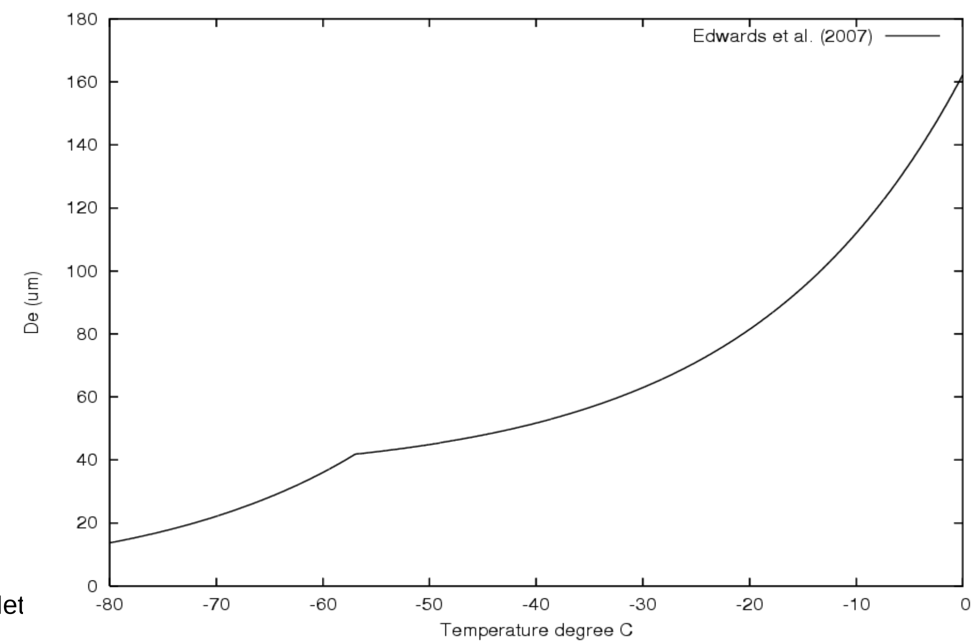
$$\rightarrow \omega_0, g \;\&\; K_{ext}$$

In a GCM

$$K_{ext} \sim \frac{q_i}{D_e}$$

Prognostic variable (q_i)

Diagnosed variable (D_e)



Problems with traditional approach

Cirrus composed of randomized habit mixtures

D_e & IWC are in-situ derived independent of GCM cloud scheme: Issues with ice crystal shattering for D_e

D_e diagnosed only & depends on definition

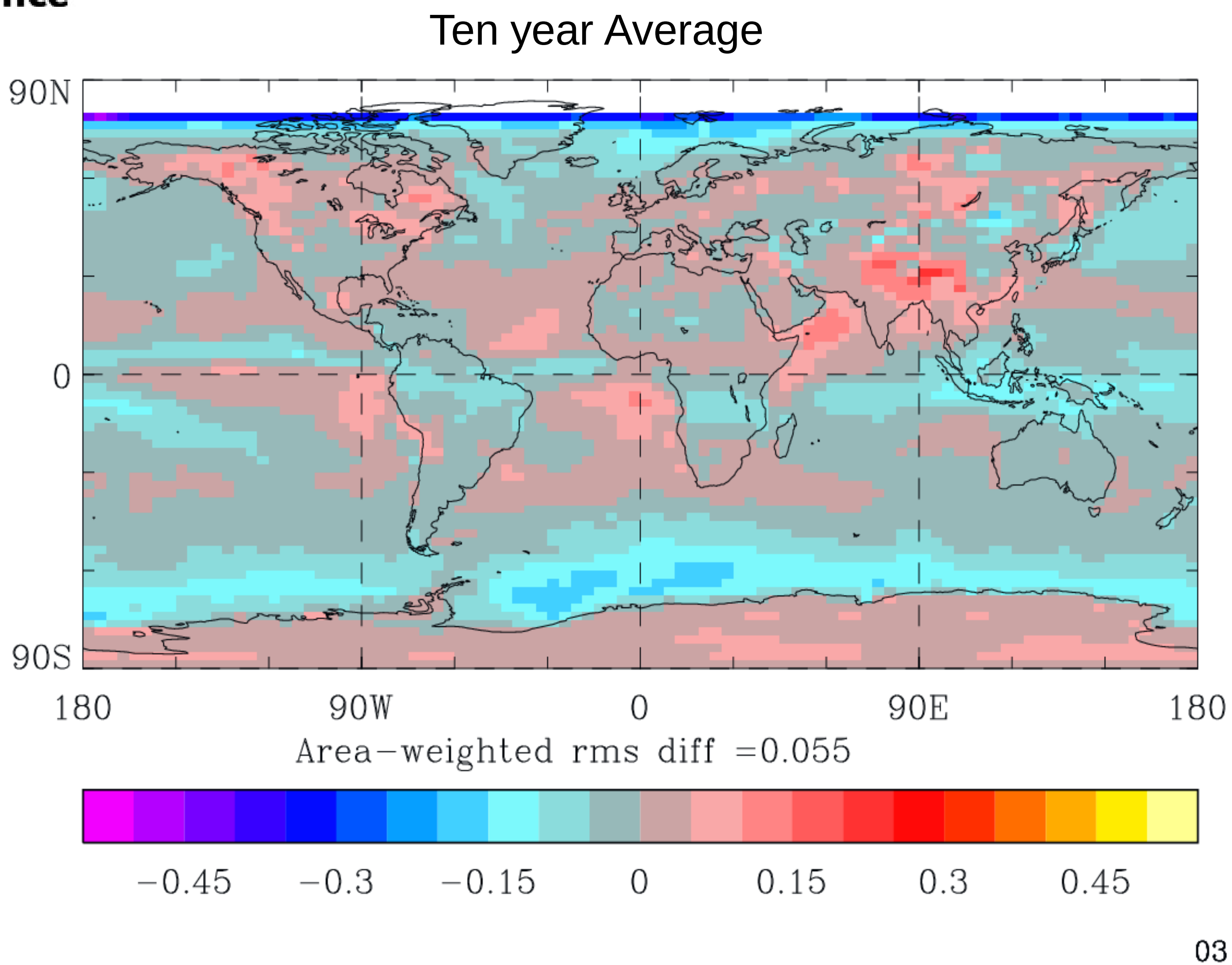
D_e (cloud scheme) $\neq$ D_e (Radiation)

Physical inconsistency between cloud and radiation GCM schemes

q_i & T_c are variables in GCM cloud schemes so link cirrus optical properties *directly* to these variables through the *same* PSD as used in the cloud scheme: *No requirement for D_e*

Observations: Ensemble – CERES (TOA Short-wave Albedo) averaged over Dec, Jan, Feb: No tuning:

Met Office



Met Office

Modelling & remote sensing issues

•There is however convergence between e-m and physical optics approaches at X~20 – but still not a fully solved problem

•Theory: Can we predict the observed scattered intensity using one single scattering theory – a different approach to the conventional methods may be needed – high frequency scattering seems promising…< 10 yrs ?

•Can we develop a model ensemble that is consistent across the electromagnetic spectrum – one theory – one model ?

•An ensemble model that is related to the atmospheric state

•Randomized scattering properties from pristine (P_{11}features) to full (P_{11} featureless): shape or randomization?

• It is important to parameterize GCM prognostic variables directly in terms of optical properties

• The concept of D_e is not required either in models or remote sensing as this property is merely diagnosed in models. For GCMs it is more important to retrieve IWC of thin cirrus.

• The above implies consistent PSDs between GCM cloud and radiation schemes