Forward modelling with application to A-Train observations

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Thanks: Mark Webb, Mark Ringer, Yoko Tsushima, Jonny Williams

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Outline

- Motivation
- Radiative transfer
- Examples of model evaluation using satellite data

- Retrievals and forward modelling
- Initial applications

- Applications to A-Train
- COSP
- Concluding remarks

Motivation

•Improve models (parameterizations) to produce better predictions

•Model evaluation: How well do models represent the real world?

•How can we answer this question?
Using observations (satellite data)

“the most scientifically valuable thing that can come out of a comparison of measurements with model results is to show that the model has failed”

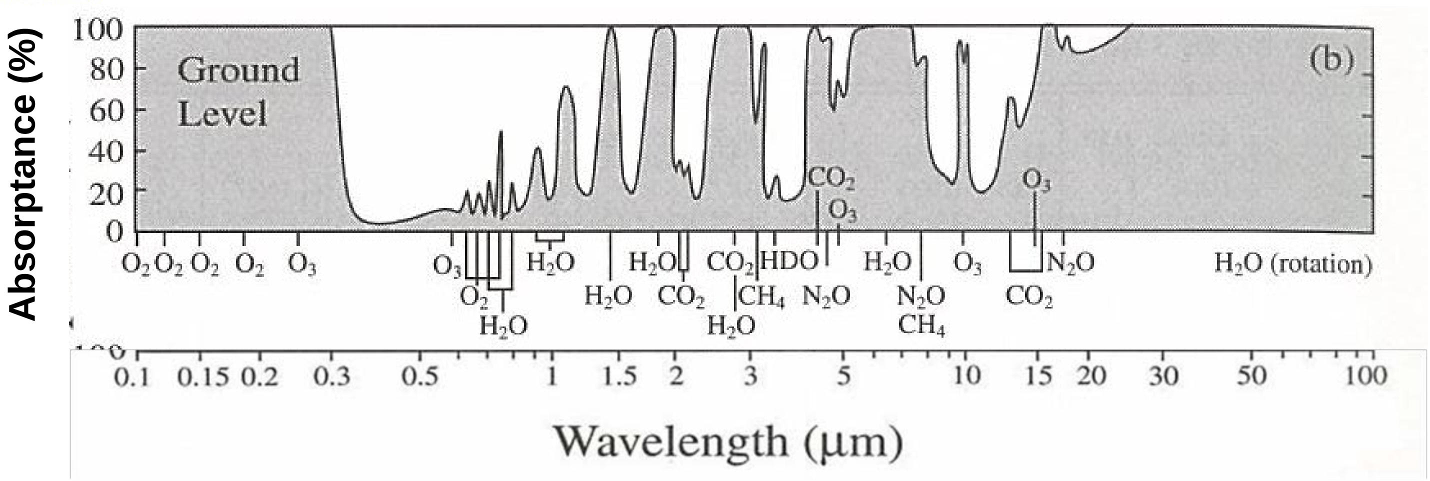
(Randall and Wielicki, *BAMS*, 78(3), 1997)

How can we best exploit observations in this context?

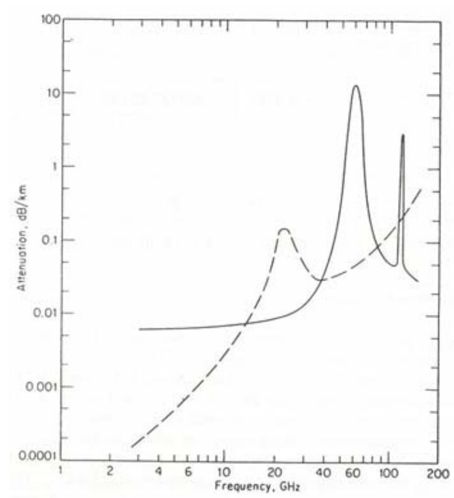
- Forward modelling: useful tool to make optimal use of observations
- A-Train: new perspective of clouds/precipitation and interactions with radiation

Radiative transfer

Absorption

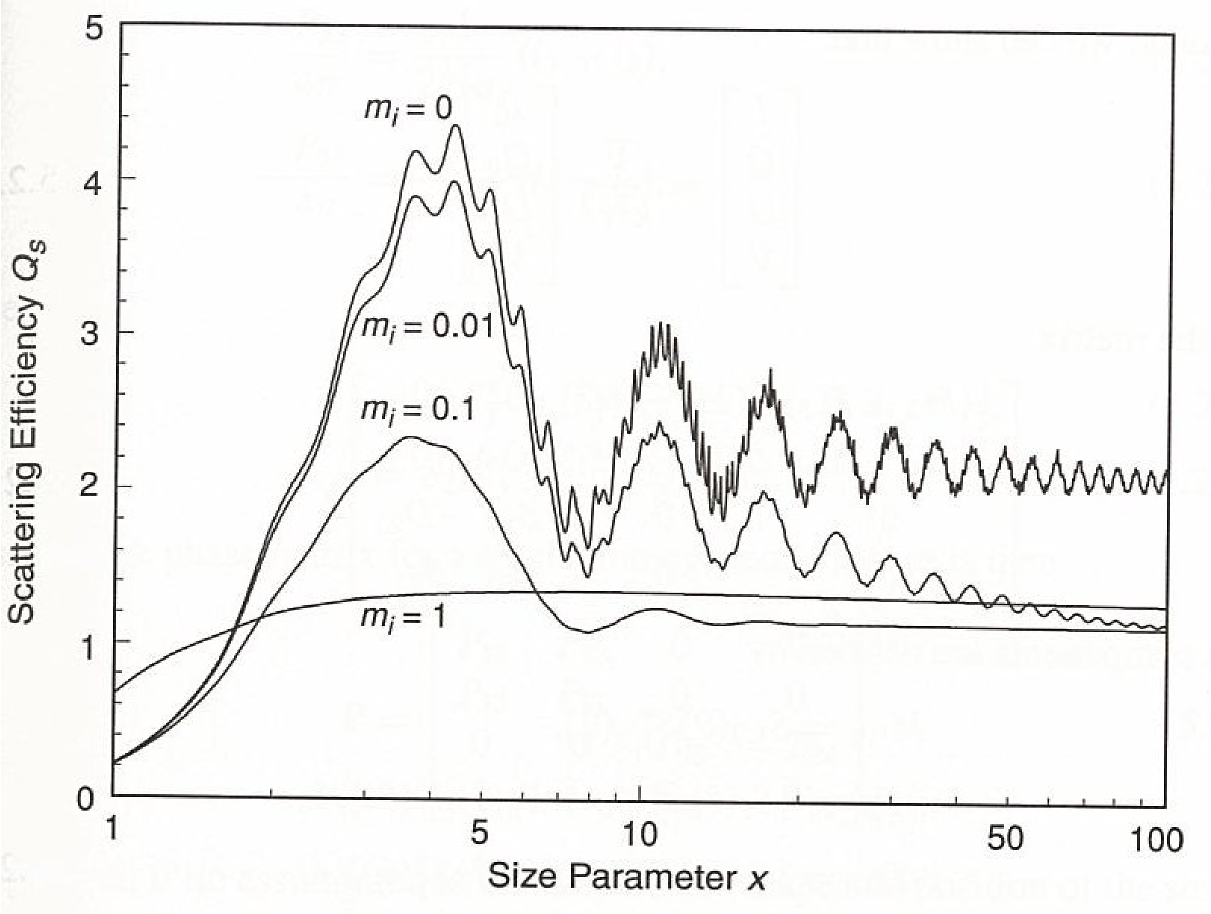


(Thomas and Stamnes, *Radiative transfer in the atmosphere and ocean*, 2002. Fig 11.2)



(Sauvageot, Radar meteorology, 1992. Fig 2.13)

Scattering by particles

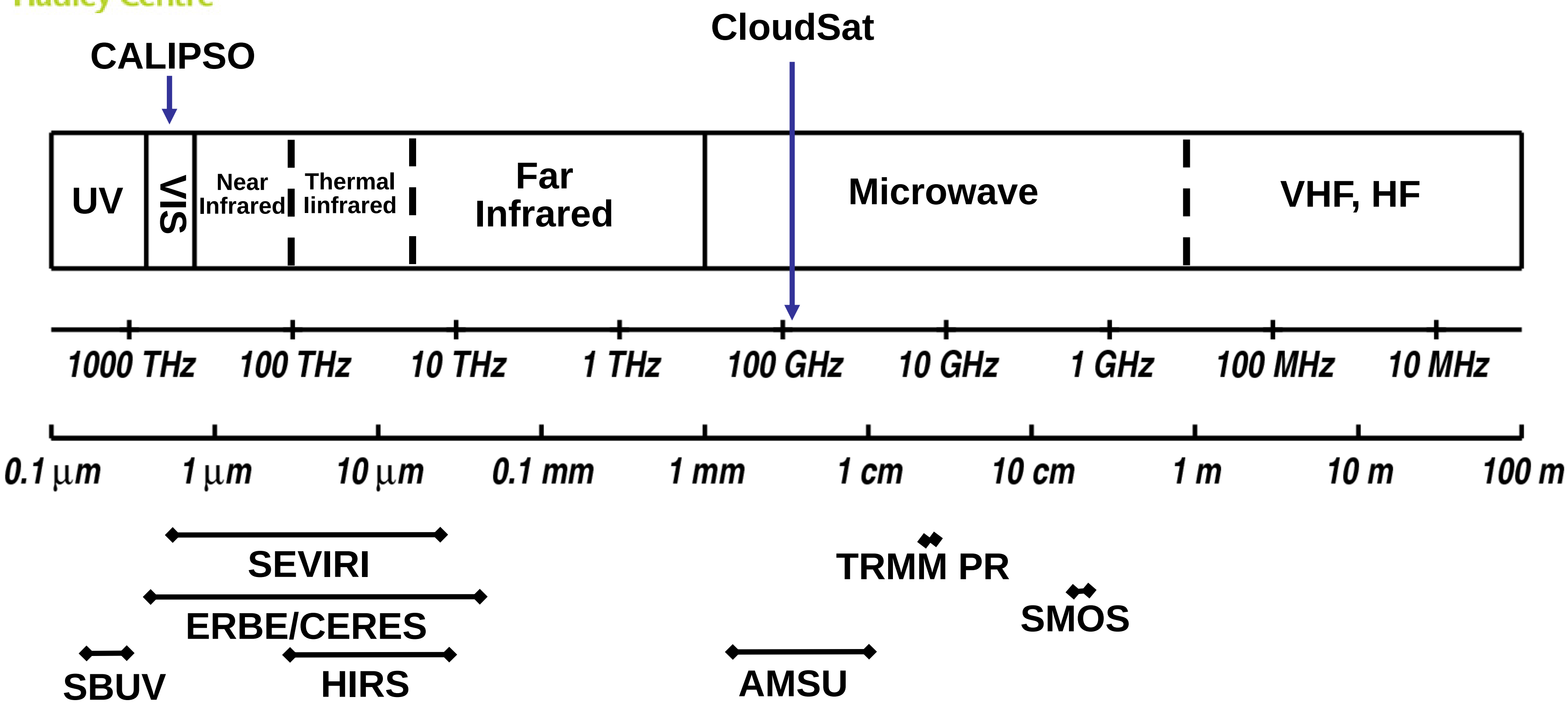


$$x = \frac{2\pi r}{\lambda}$$

Dependency on the *ratio* size/wavelength

(Liou, *An introduction to atmospheric radiation*, 2002. Fig 5.7)

Electromagnetic spectrum

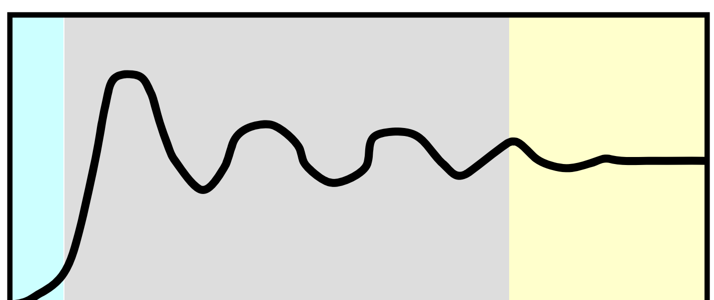


Size parameter

	Size (a)	Size parameter		
		λ=0.5 μm	λ=10 μm	λ=1 cm
Aerosol	1 μm	1.26×10^{1}	6.3×10^{-1}	6.3×10^{-4}
Water droplet	10 μm	1.26×10^{2}	6.3×10^{0}	6.3×10^{-3}
Ice crystal	100 μm	1.26×10^{3}	6.3×10^{1}	6.3×10^{-2}
Raindrop	1 mm	1.26×10^{4}	6.3×10^{2}	6.3×10^{-1}
Snowflake	1 cm	1.26×10^{5}	6.3×10^{3}	6.3×10^{0}

Rayleigh	Mie	G. Optics

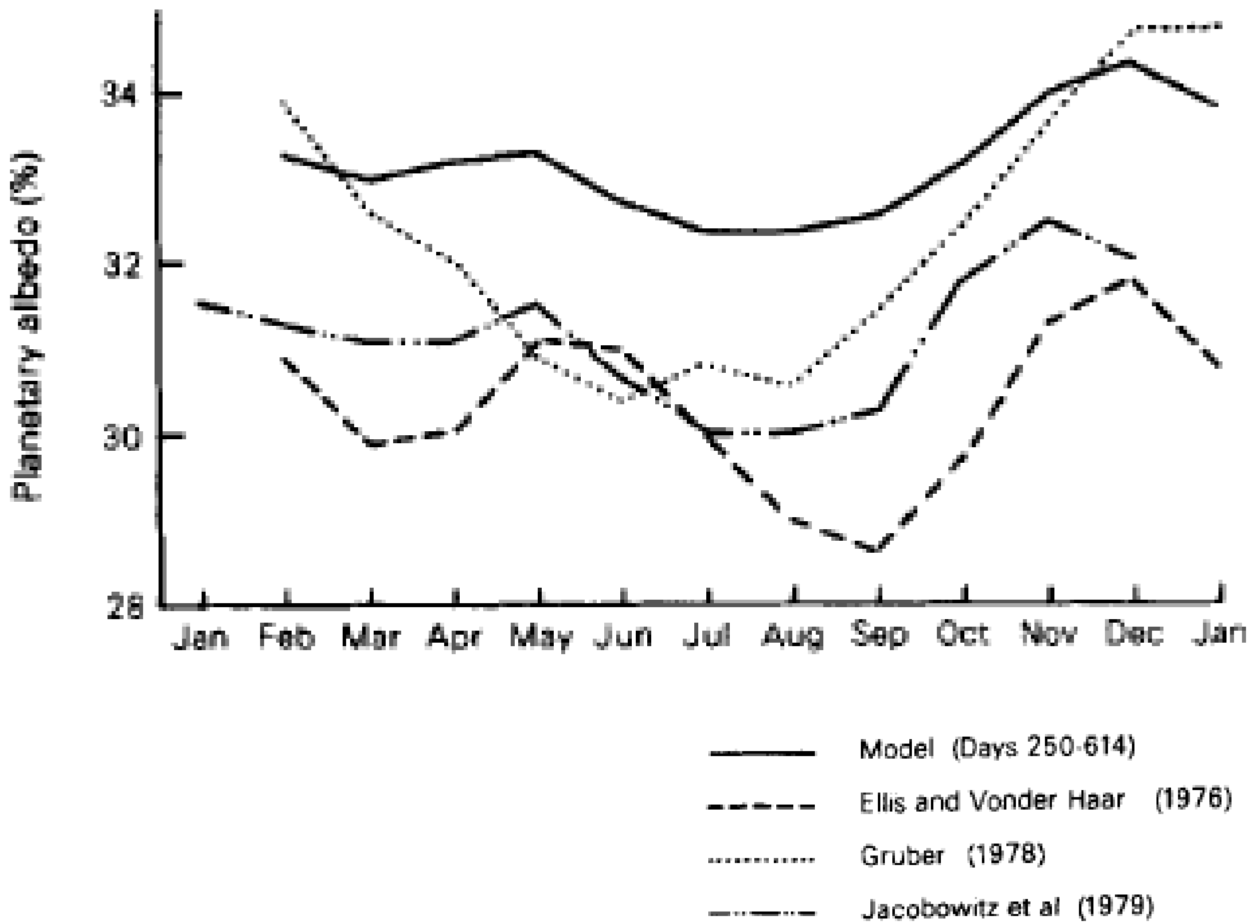
(Adapted from Liou, *An introduction to atmospheric radiation*, 2002. Table 5.1)



Met Office
Hadley Centre

Examples of model evaluation using satellite retrievals

A global view



(Slingo, *QJRMS*, 108, 1982. DOI:10.1002/qj.49710845606)

A more detailed view

Met Office
Hadley Centre

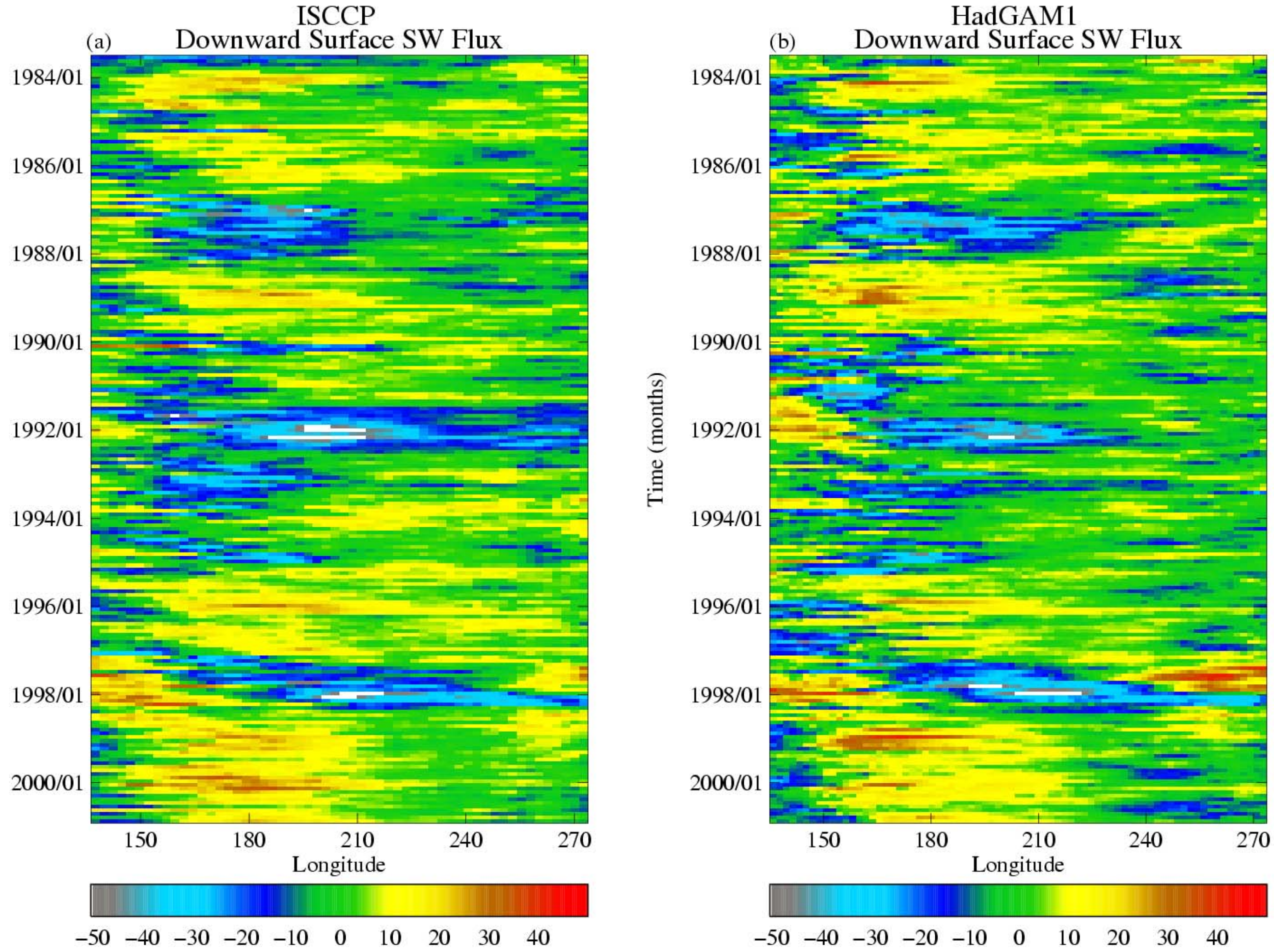


FIG. 10. Hovmoeller plots of the tropical Pacific (10°S, 10°N) as derived from satellite data and simulated by HadGAM1. (a) $S_{s,d}$ from ISCCP-FD, (b) $S_{s,d}$ from HadGAM1, (c) $L_{s,d}$ from ISCCP-FD, and (d) $L_{s,d}$ from HadGAM1.

(Bodas-Salcedo et al., *J. Climate*, 21, 2008. DOI:10.1175/2008JCLI2097.1)

Large differences in models

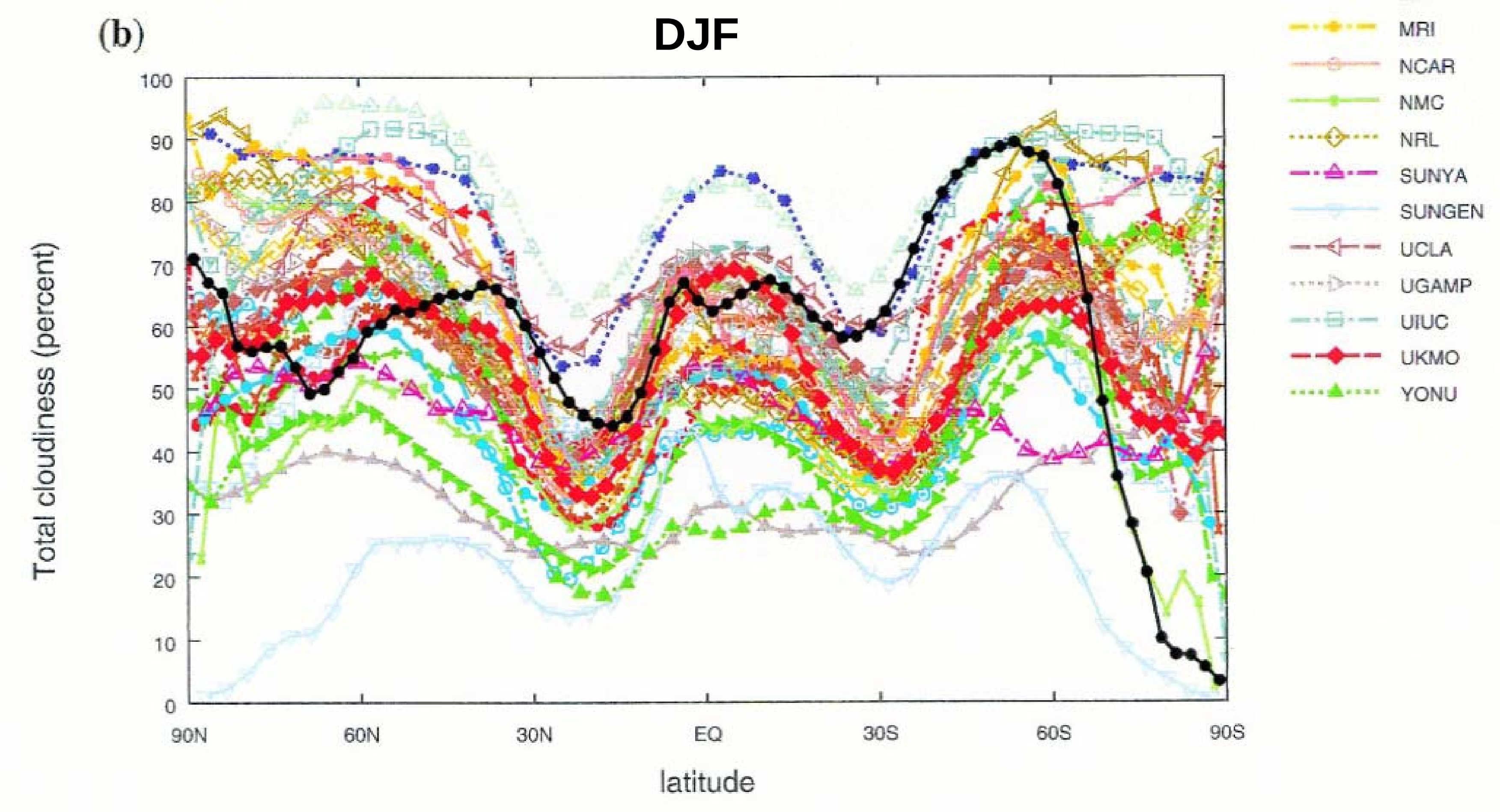
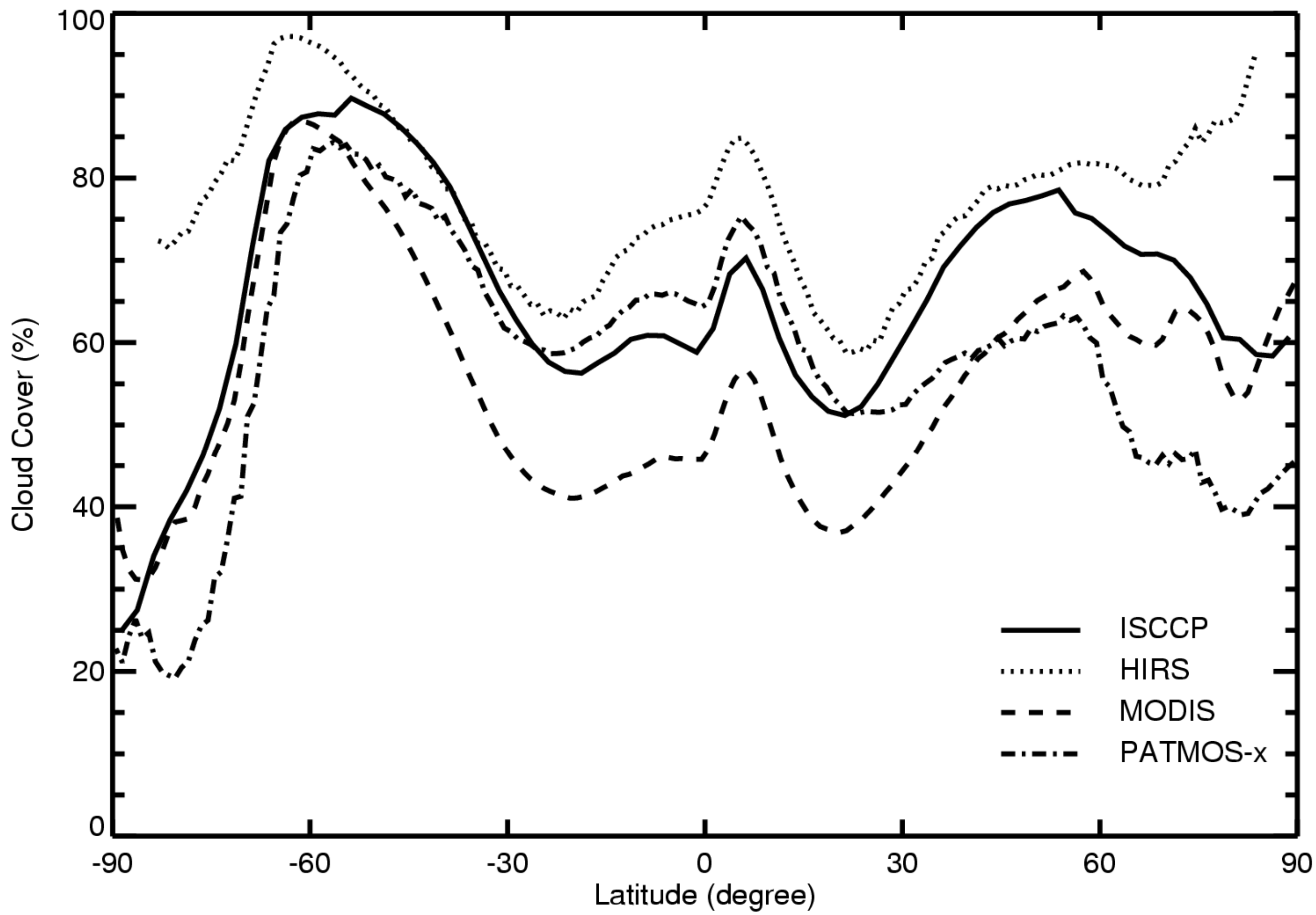


FIG. 7. As in Fig. 6 except for the (a) the outgoing longwave radiation, with observations from the NCEP database (Gruber and Krueger 1984); (b) total cloudiness with observations from ISCCP for 1983–90 (Rossow et al. 1991).

(Gates et al., *BAMS*, 80, 29-55, 1999)

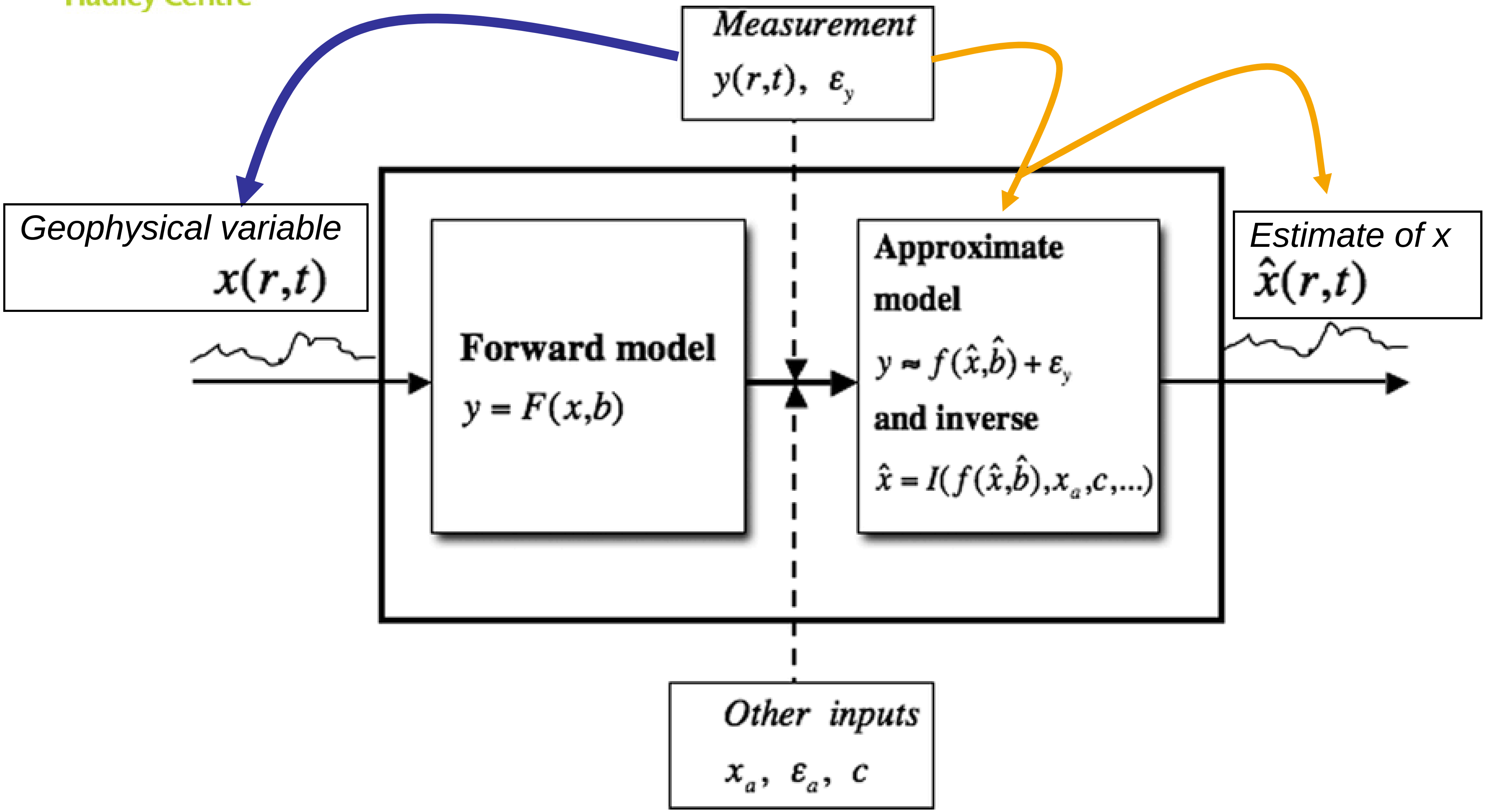
And the retrievals?



(Courtesy of J. Williams)

Retrievals and forward modelling

Forward modelling at the core of retrievals



(Stephens et al., *JAS*, 64, 2007. DOI:10.1175/2006JAS2375.1)

The importance of a priori information

$$\hat{\mathbf{x}} - \mathbf{x_0} = \mathbf{W} \cdot (\mathbf{y_m} - \mathbf{y_c}[\mathbf{x_0}])$$

$\hat{\mathbf{x}}$: vector of retrieved parameters

$\mathbf{x_0}$: first guess

$\mathbf{y_m}$: vector of measurements

$\mathbf{y_c}$: corresponding vector for first guess

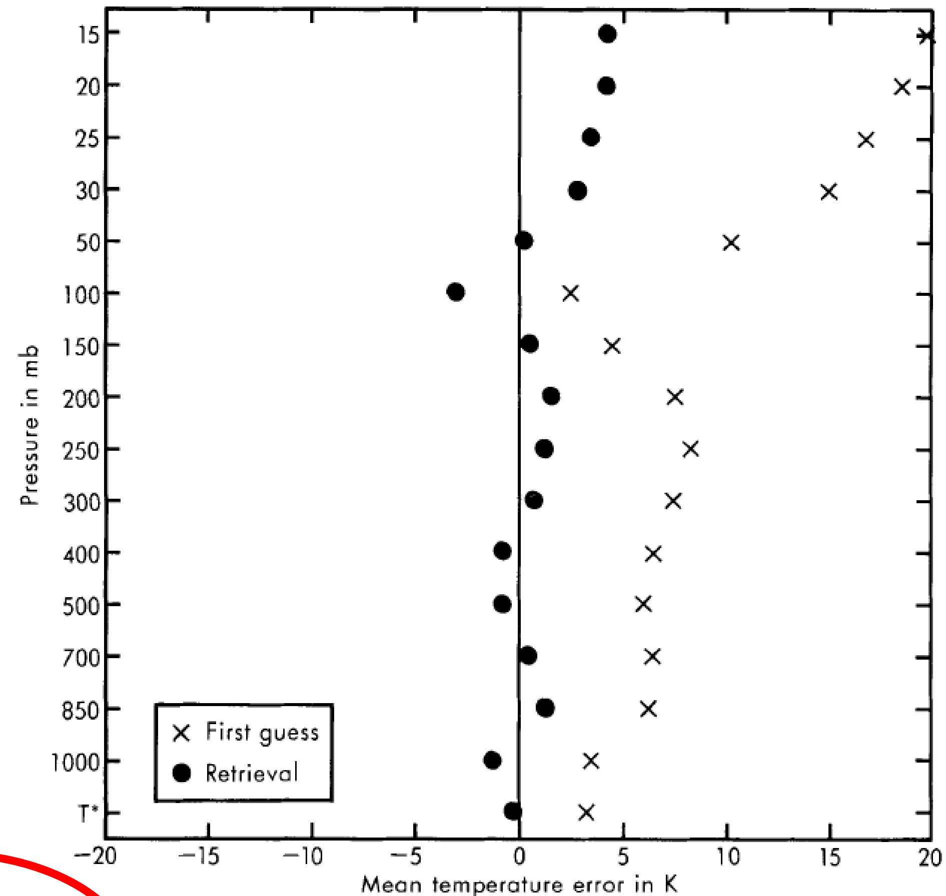
$\mathbf{W}$: inverse matrix

$\mathbf{K}$: forward matrix

$\mathbf{R} = \mathbf{W} \cdot \mathbf{K}$: averaging kernel

$\mathbf{I}$: identity matrix

$\mathbf{R} \neq \mathbf{I}$

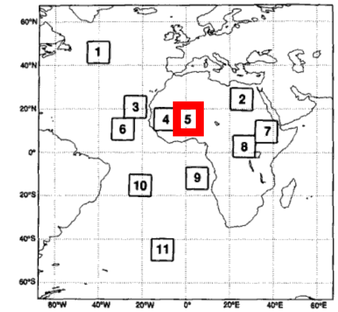


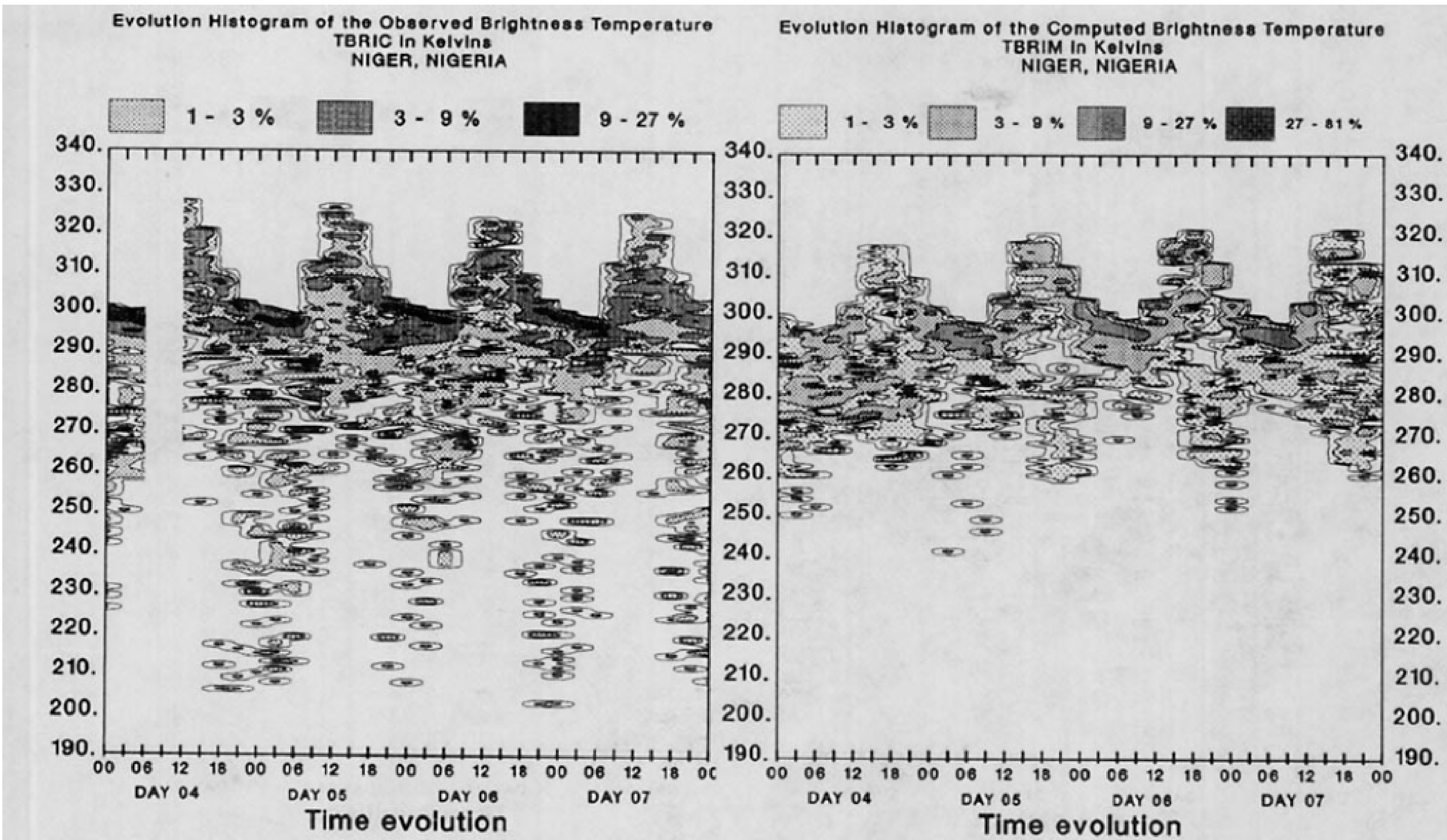
$$\overline{(\hat{\mathbf{x}} - \mathbf{x_T})} = (\mathbf{I} - \mathbf{R}) \cdot \overline{(\mathbf{x_0} - \mathbf{x_T})} + \mathbf{W} \cdot \overline{\epsilon_m}$$

(Eyre, *QJRMS*, 113, 279-292, 1987)

Initial applications of forward modelling and simulators

Diurnal cycle of surface temperature and cloudiness

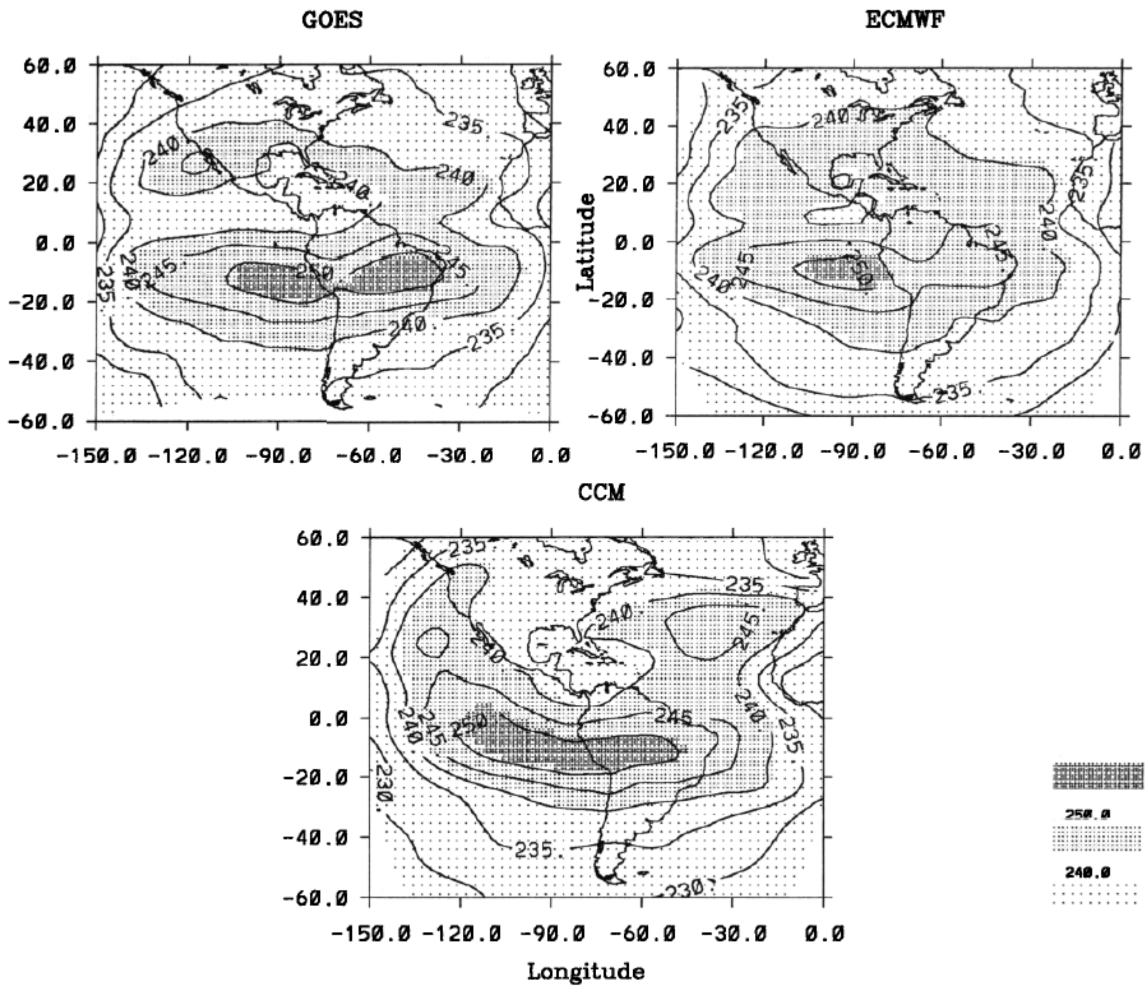




(Morcrette, *MWR*, 119, 1205-1224, 1991)

Upper tropospheric humidity and circulation

July 1987



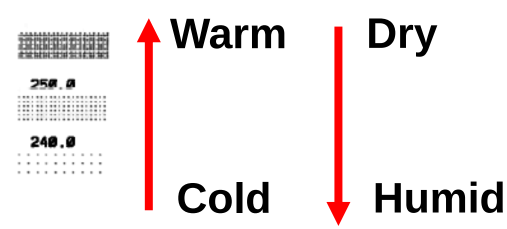
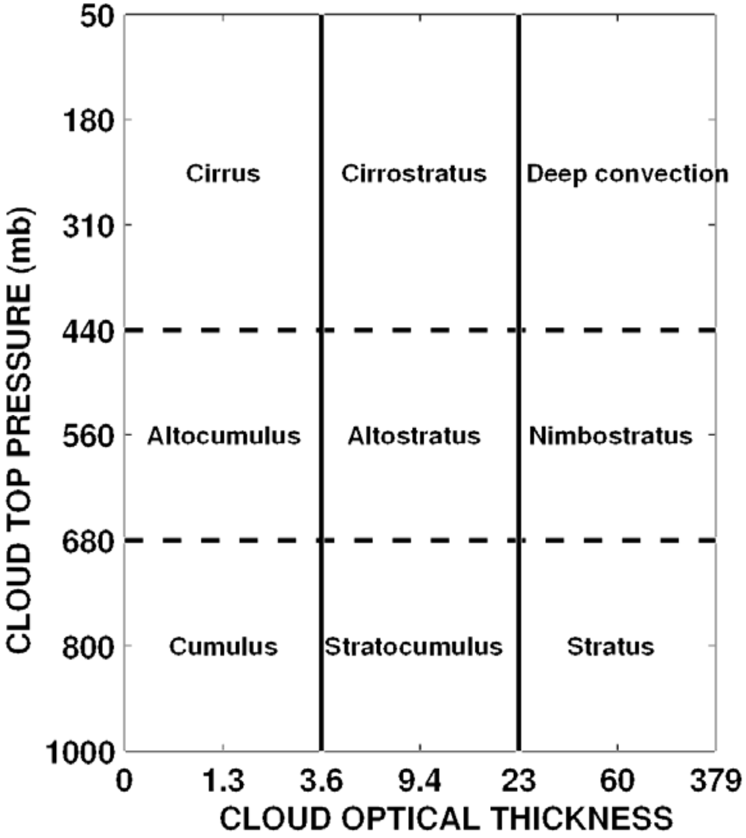


Fig. 12. Monthly mean $T_{6.7}$ from GOES observations, ECMWF analyses, and CCM simulations for (a) July 1987 and (b) Janaury 1988. Units are Kelvin.

(Soden and Bretherton, *JGR*, 99, 1187-1210, 1994)

The International Satellite Cloud Climatology Project (ISCCP) simulator

ISCCP-D cloud classification

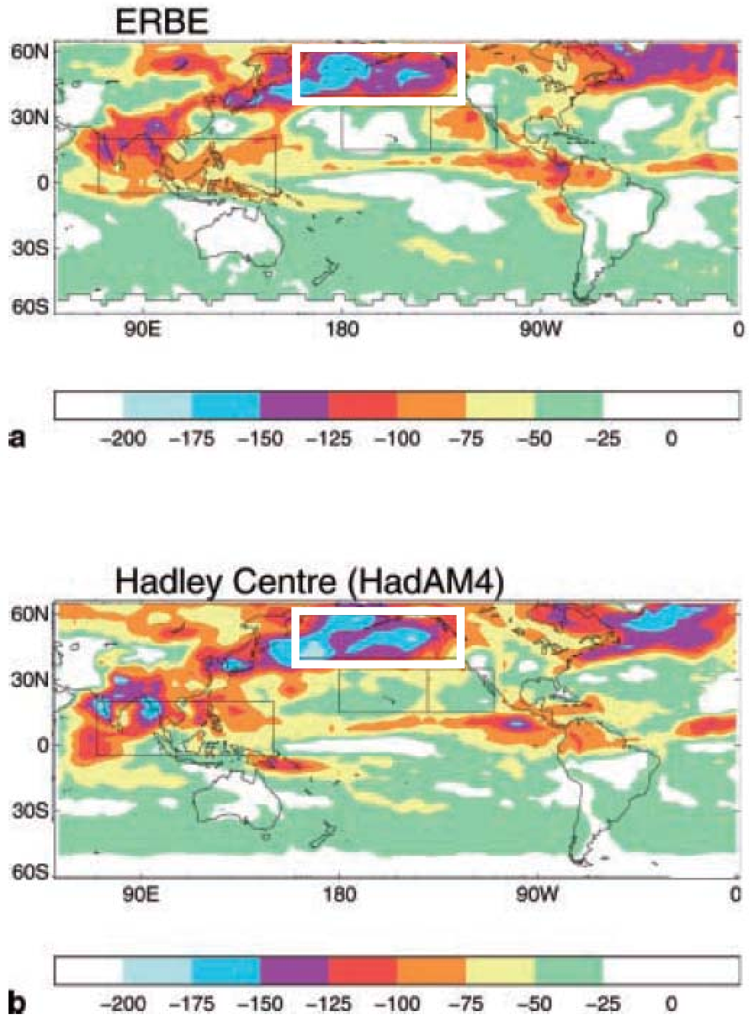


(Rossow et al., *BAMS*, 80, 2261-2287, 1999)

- **The ISCCP simulator was developed by S. Klein[1] and M. Webb[2] to simulate ISCCP cloud data from model data**

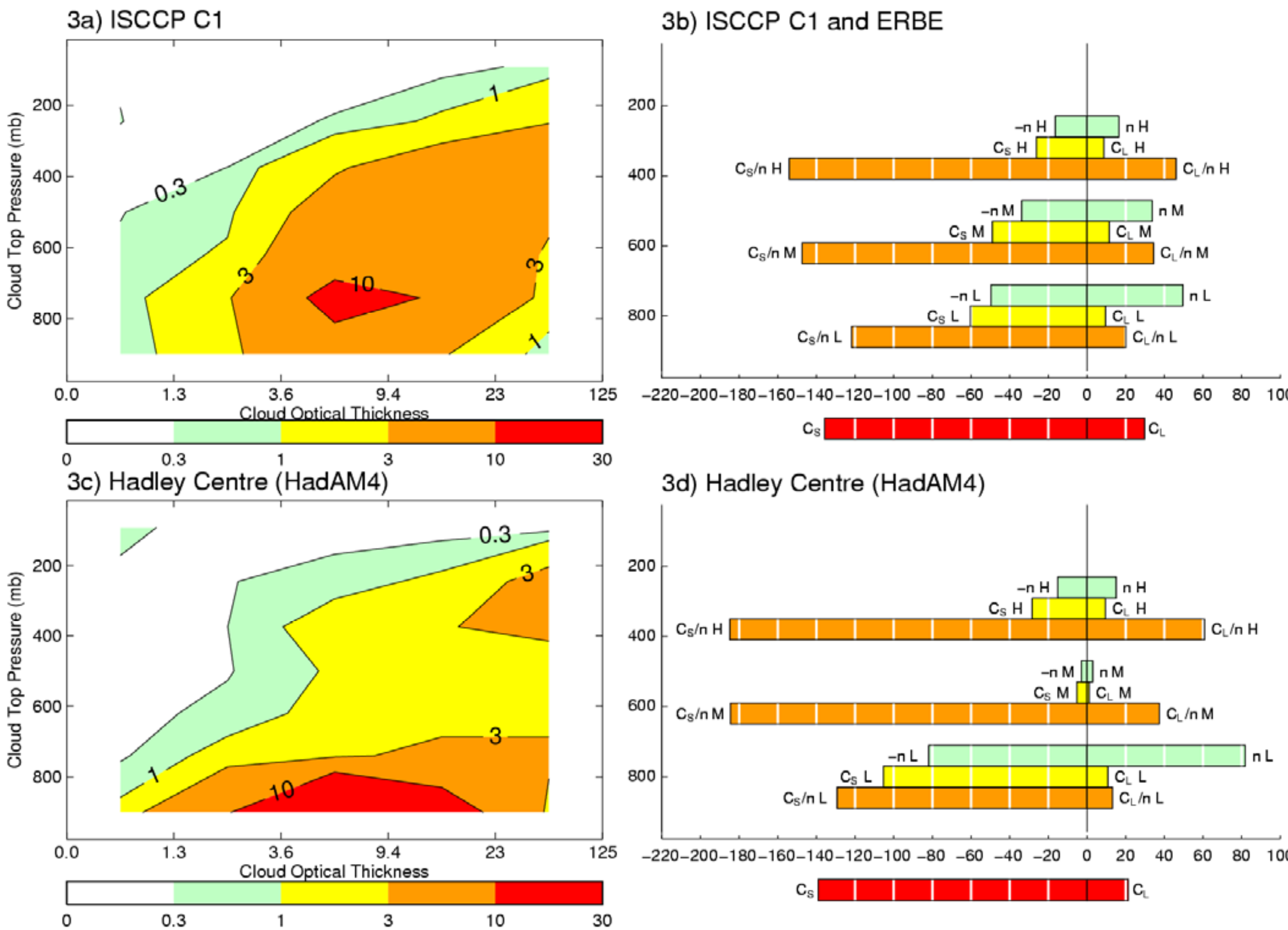
1:Klein and Jakob, *MWR*, 127, 2514-2531, 1999.
2:Webb et al., *Clim. Dyn.*, 17(12), 2001.

ISCCP simulator reveals compensation of errors



(Webb et al., *Clim. Dyn.*, 17(12), 2001. DOI:10.1007/s003820100157)

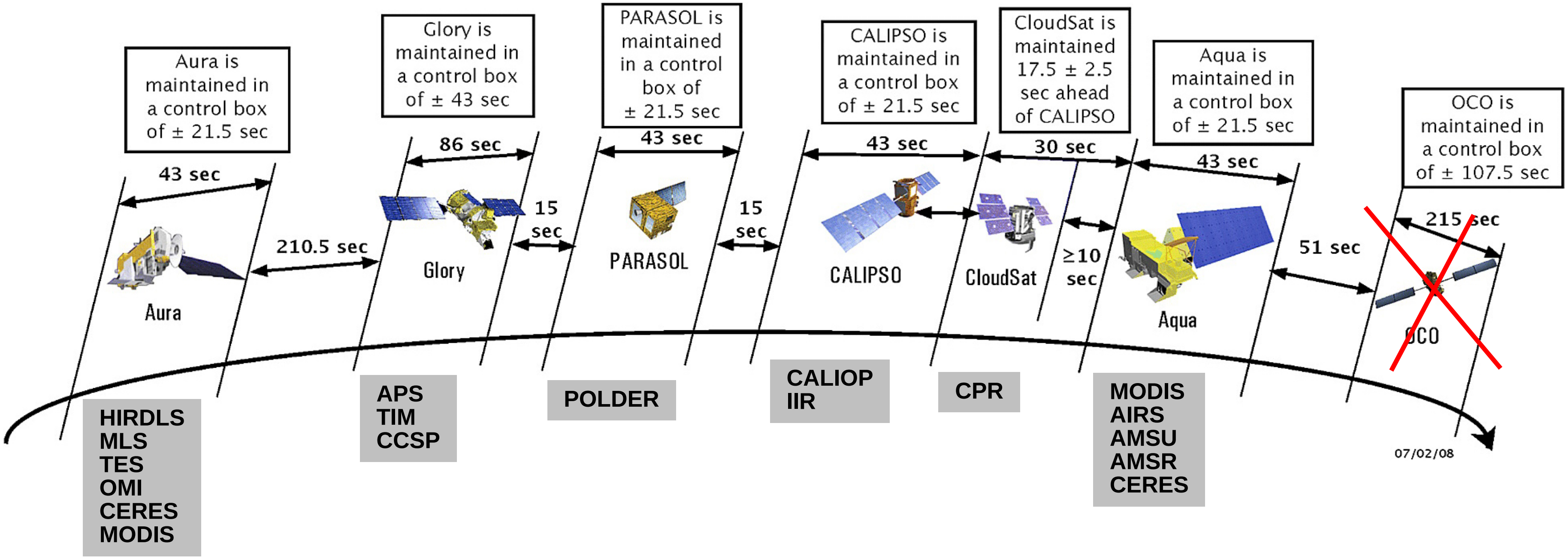
ISCCP simulator reveals compensation of errors



(Webb et al., *Clim. Dyn.*, 17(12), 2001. DOI:10.1007/s003820100157)

Applications to A-Train

The A-Train



-Synergy: many different instruments observing the same atmospheric column

-CALIPSO and CloudSat: active instruments

(Stephens et al., *JGR*, 113, 2008. doi:10.1029/2008JD009982)

CloudSat and CALIPSO

CloudSat:

- Near-nadir pointing 94GHz radar.

- 480m vertical resolution, oversampled at 240m.

- 1.4km x 2.5 km horizontal resolution

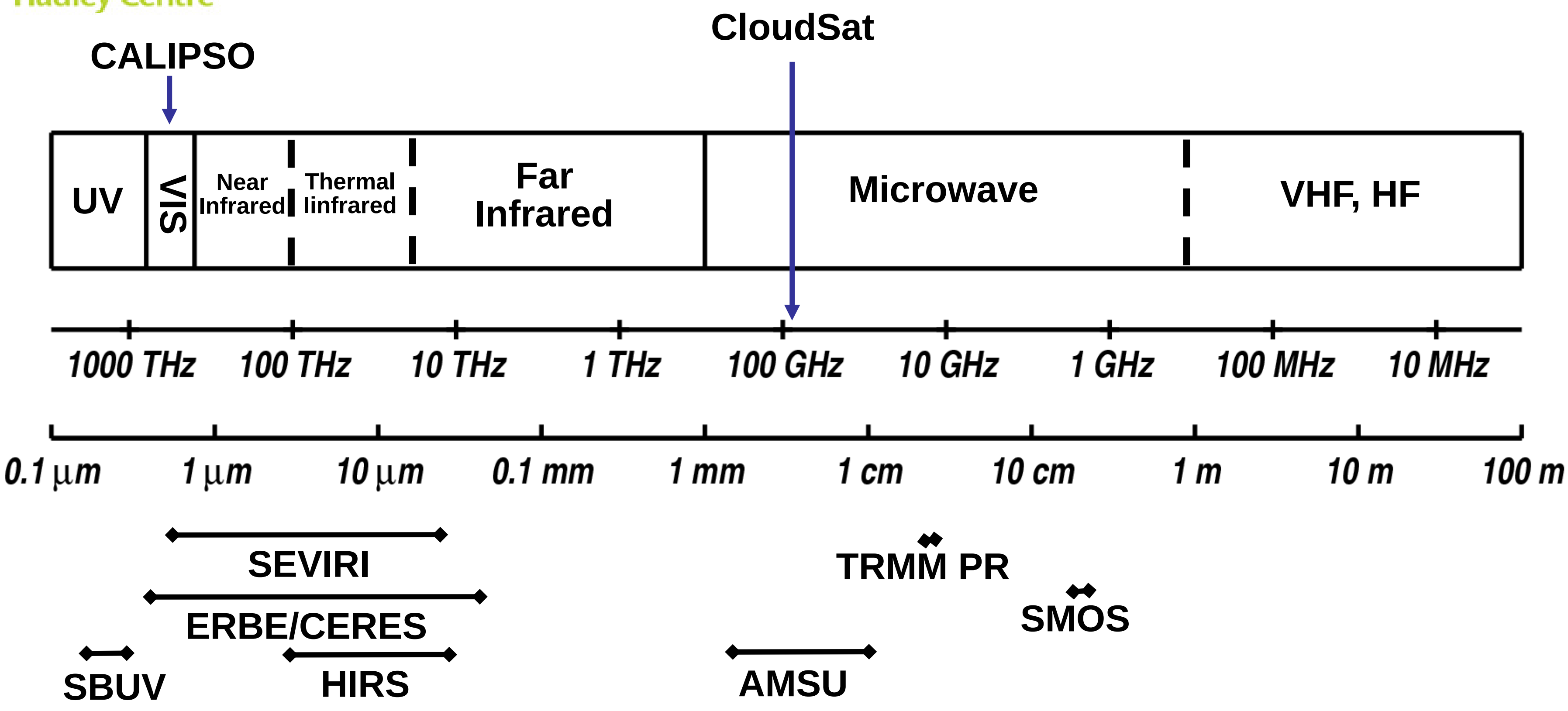
CALIPSO

- Near-nadir pointing lidar (532 and 1064 nm).

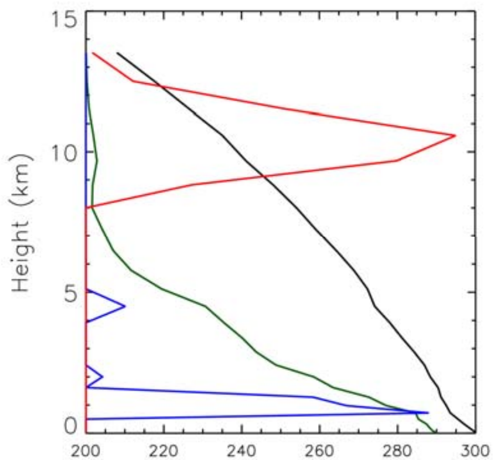
- 30m vertical resolution, 60m above 8km

- Horizontal resolution: 333m x 75m, 1km x 75m above 8km

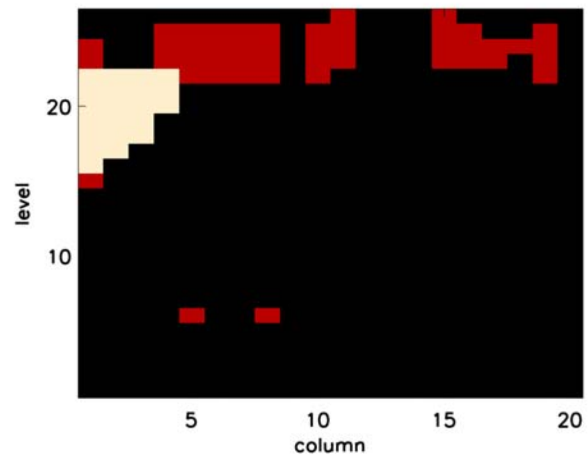
Electromagnetic spectrum



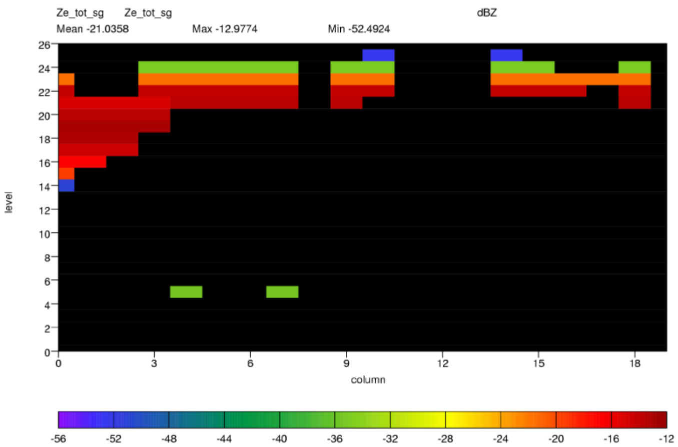
Methodology



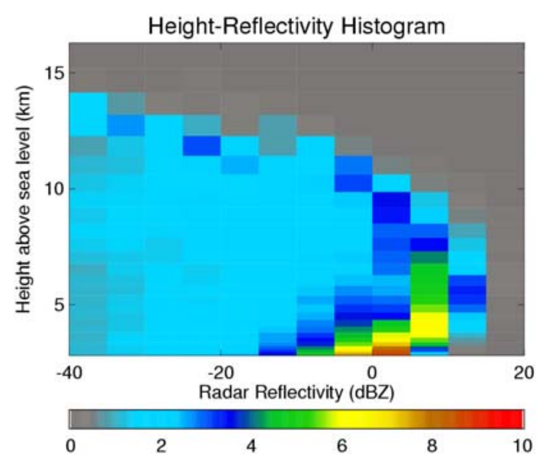
MAX/RANDOM



+ Forward model

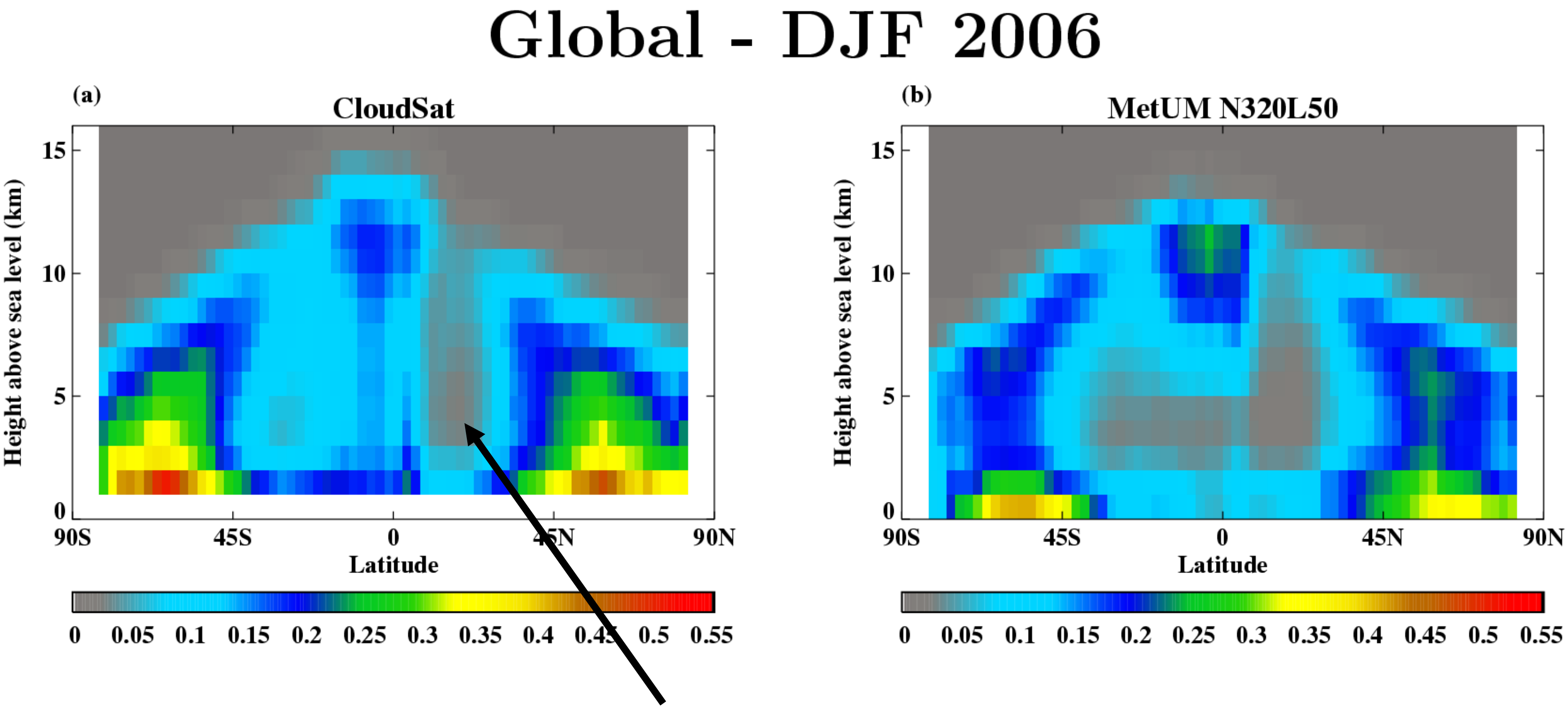


2.5ºx2.5º



CloudSat: a new dimension

Vertical distribution of hydrometeors

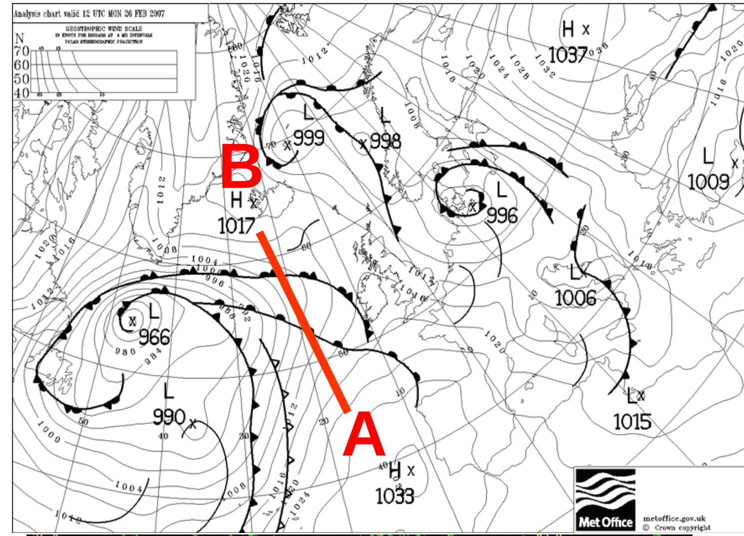


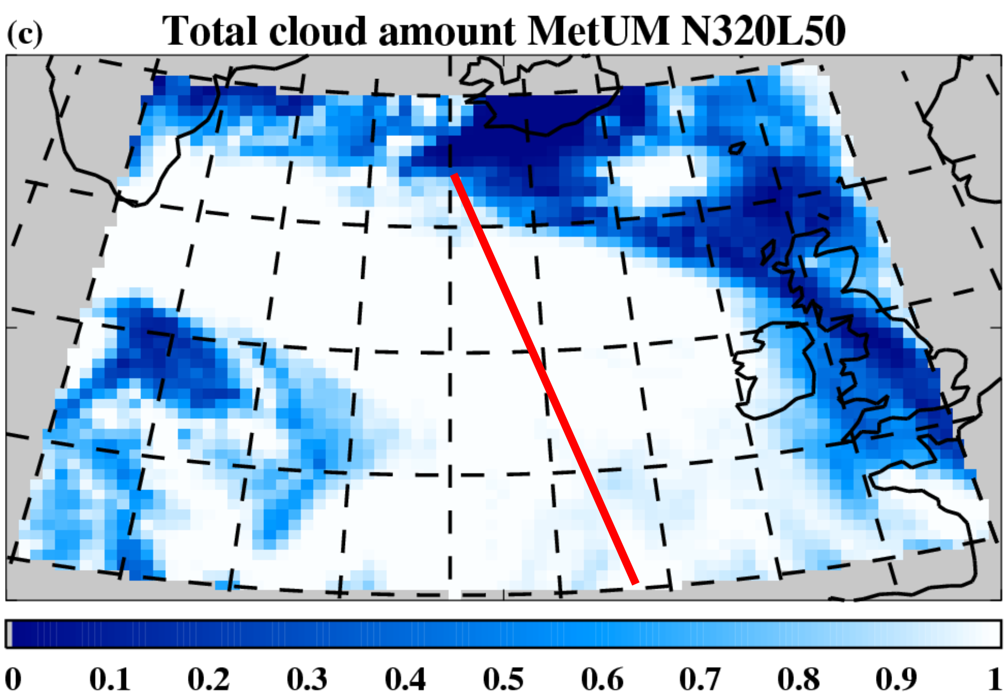
Stronger winter Hadley cell

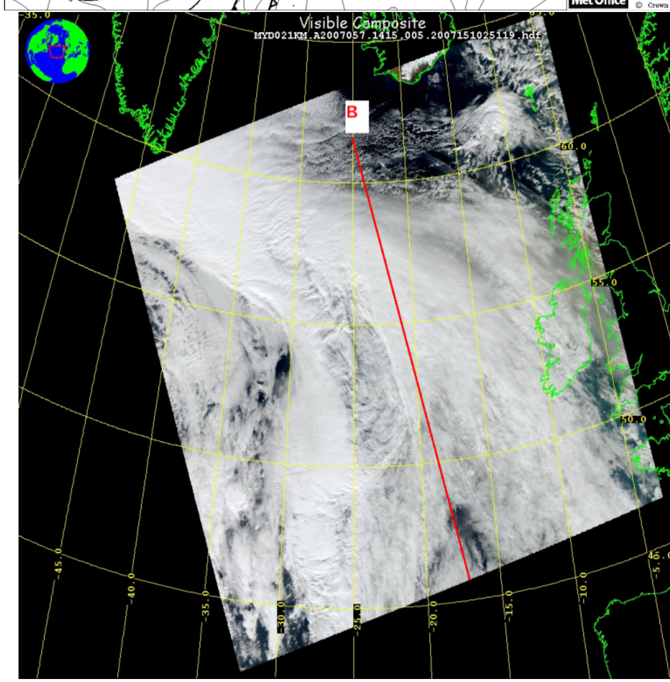
From 2D…

Case study 26/02/2007

- Analysis chart valid at 12 UTC
- CloudSat overpass at ~14:15 UTC





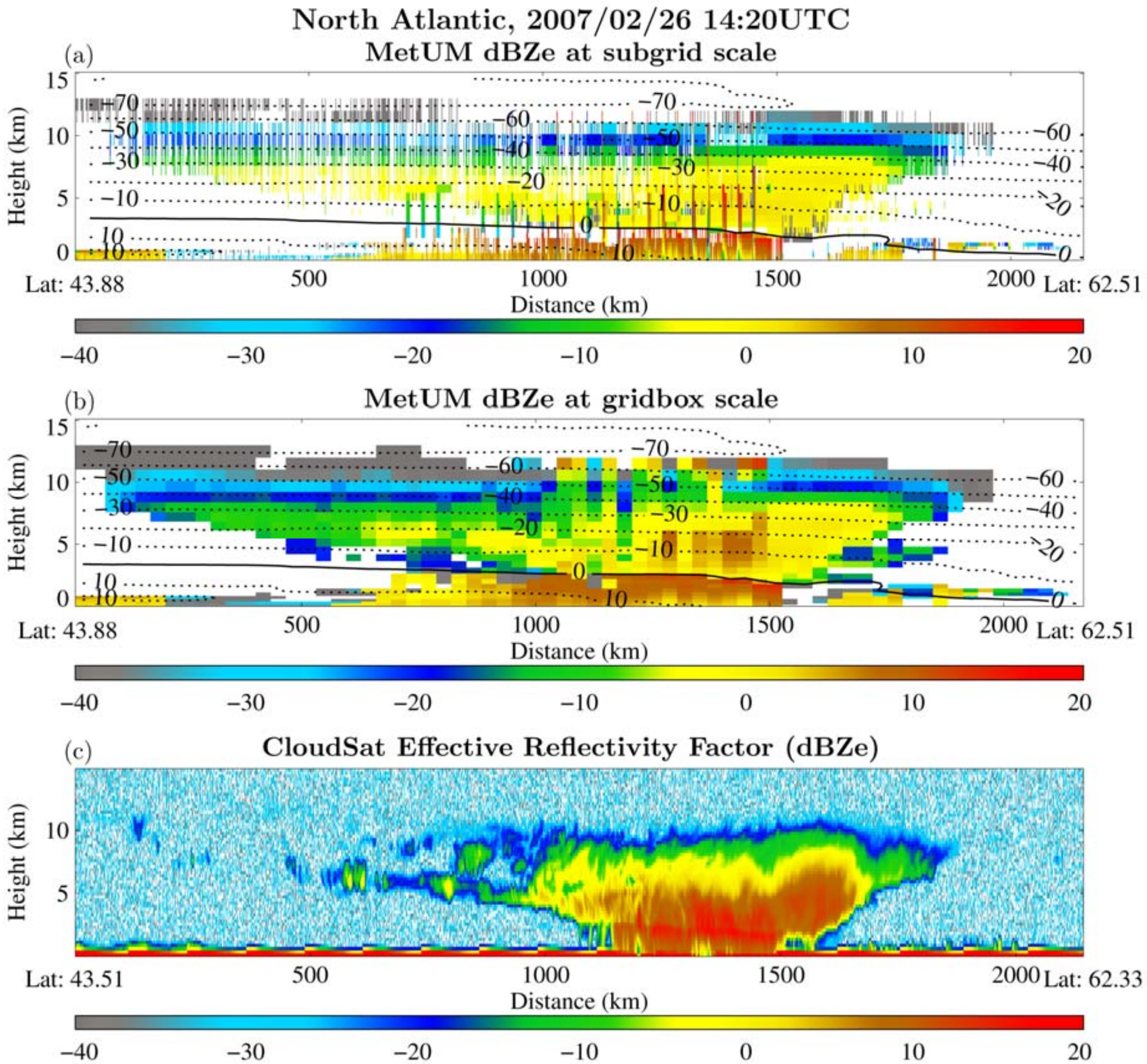


(Bodas-Salcedo et al., *JGR*, 113, 2008. DOI:10.1029/2007JD009620)

…to “3D”

Case study 26/02/2007

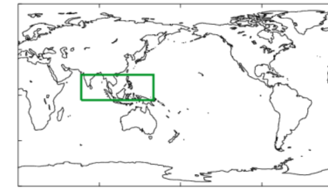
V



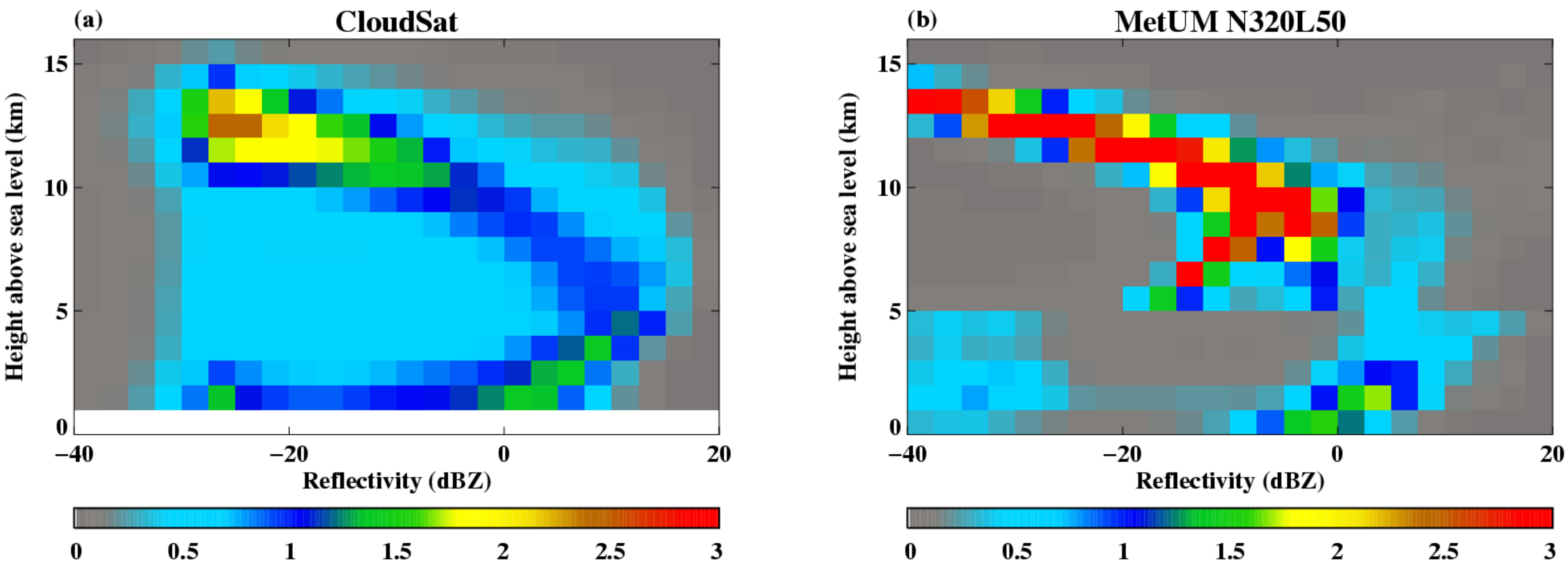
(Bodas-Salcedo et al., *JGR*, 113, 2008. DOI:10.1029/2007JD009620)

A more statistical approach

PDF(Z) as function of height



Tropical Warm Pool - DJF 2006-2007



$$Z = \int D^6 n(D) dD$$

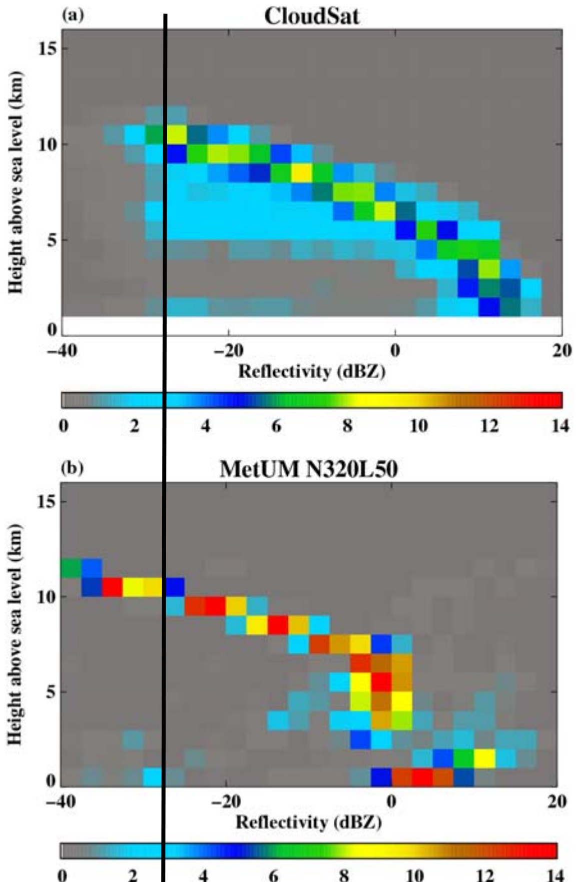
$$Z_e \propto \frac{q_h^a}{N^b} f_{Mie}(D_e) \quad e^{-2\int_0^z \sigma_e(z)dz}$$

(Bodas-Salcedo et al., *JGR*, 113, 2008. DOI:10.1029/2007JD009620)

Is the case study representative of the North Atlantic?

Met Office
Hadley Centre

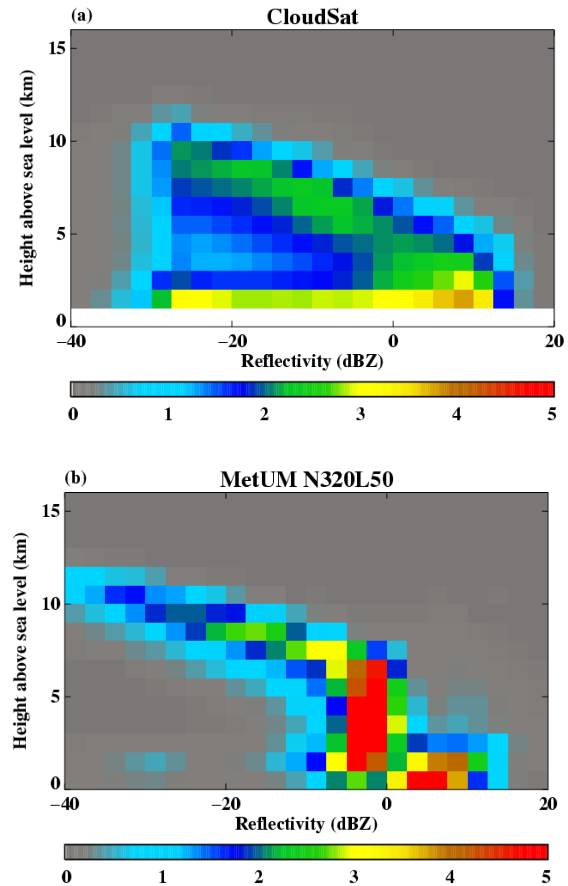
Case Study

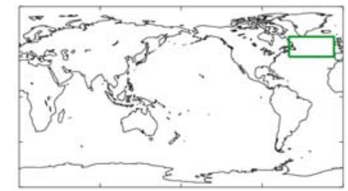


Clear<- | -> Cloudy

-27.5 dBZ

North Atlantic

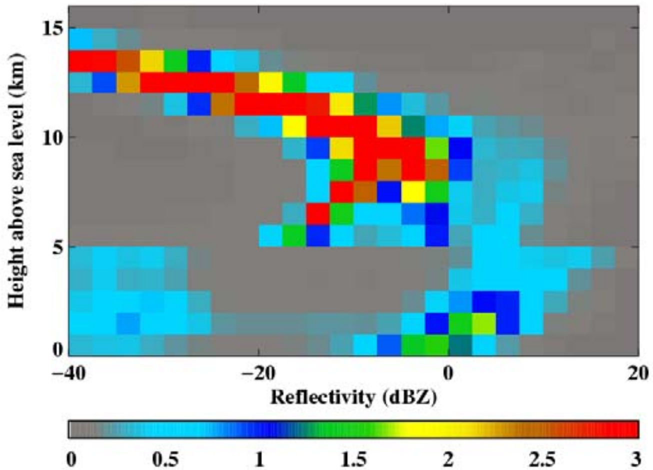




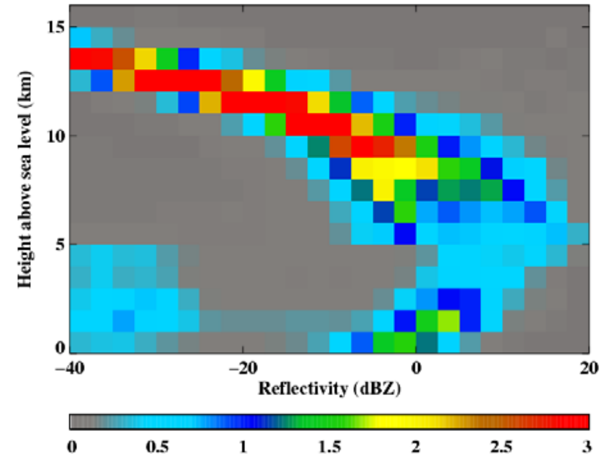
(Bodas-Salcedo et al., *JGR*, 113, 2008. DOI:10.1029/2007JD009620)

Flexibility of forward modelling: sensitivity tests

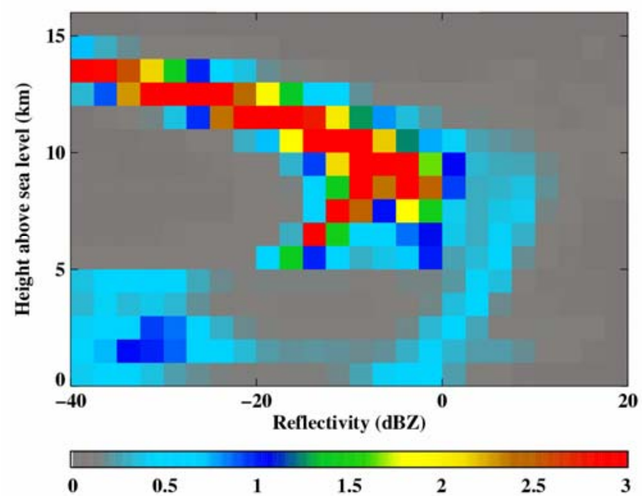
Control



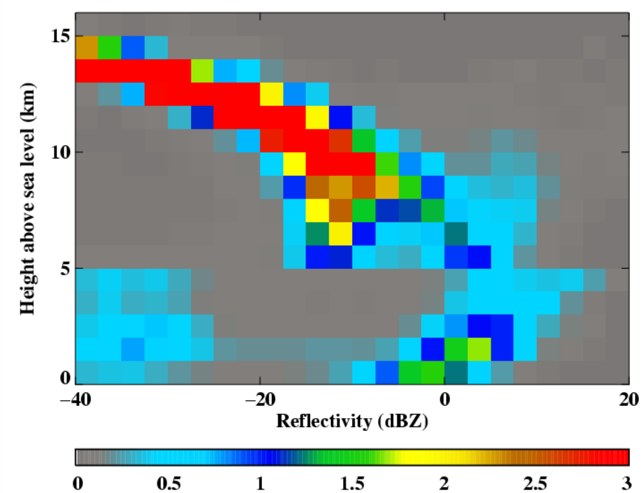
Rayleigh



No large-scale rainfall



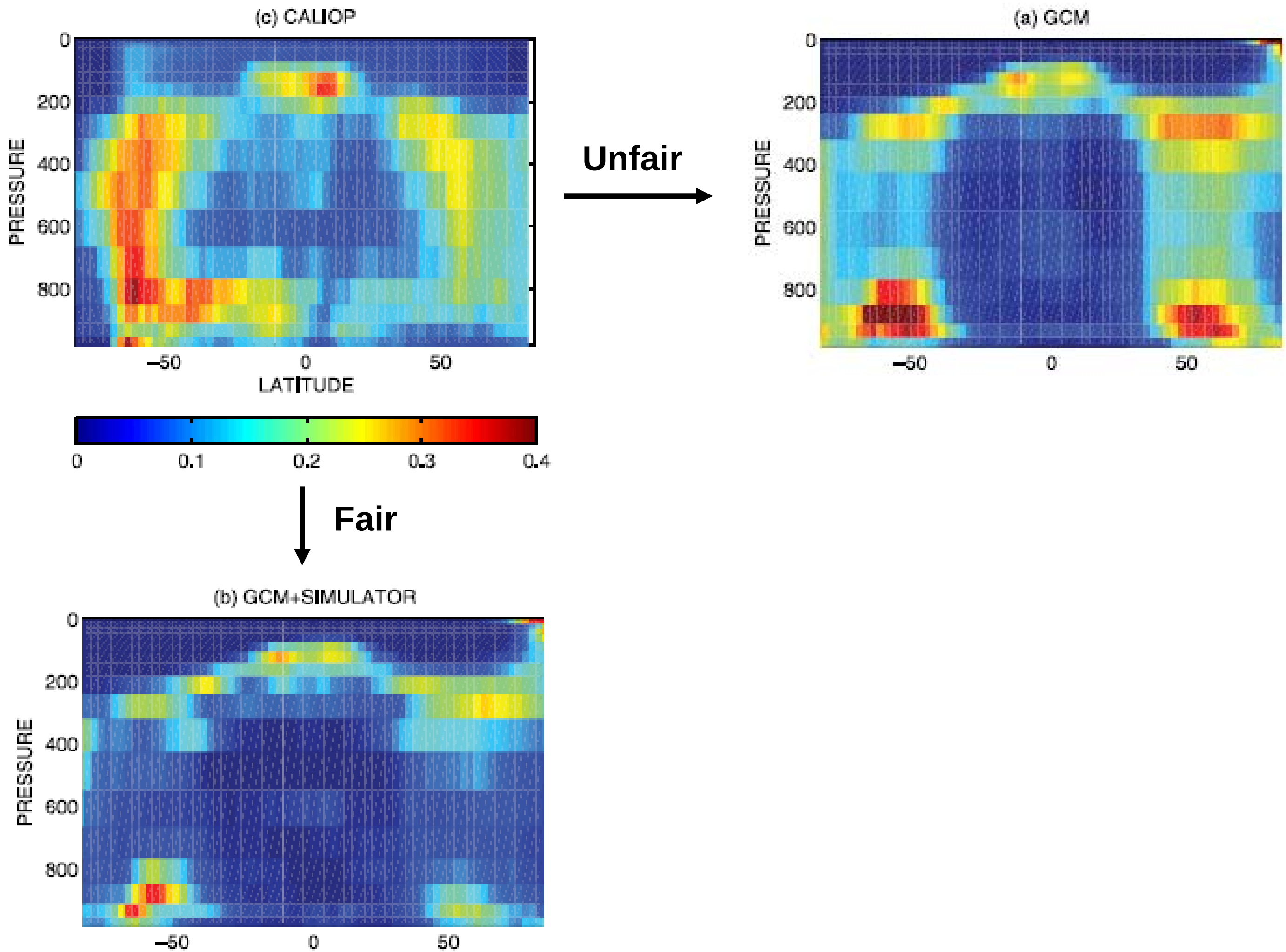
Hogan et al.,2006



(Bodas-Salcedo et al., *JGR*, 113, 2008. DOI:10.1029/2007JD009620)

Allowing for fair comparisons

LMDZ4 v CALIOP/CALIPSO



(Chepfer et al., *GRL*, 35, 2008. DOI:10.1029/2008GL034207)

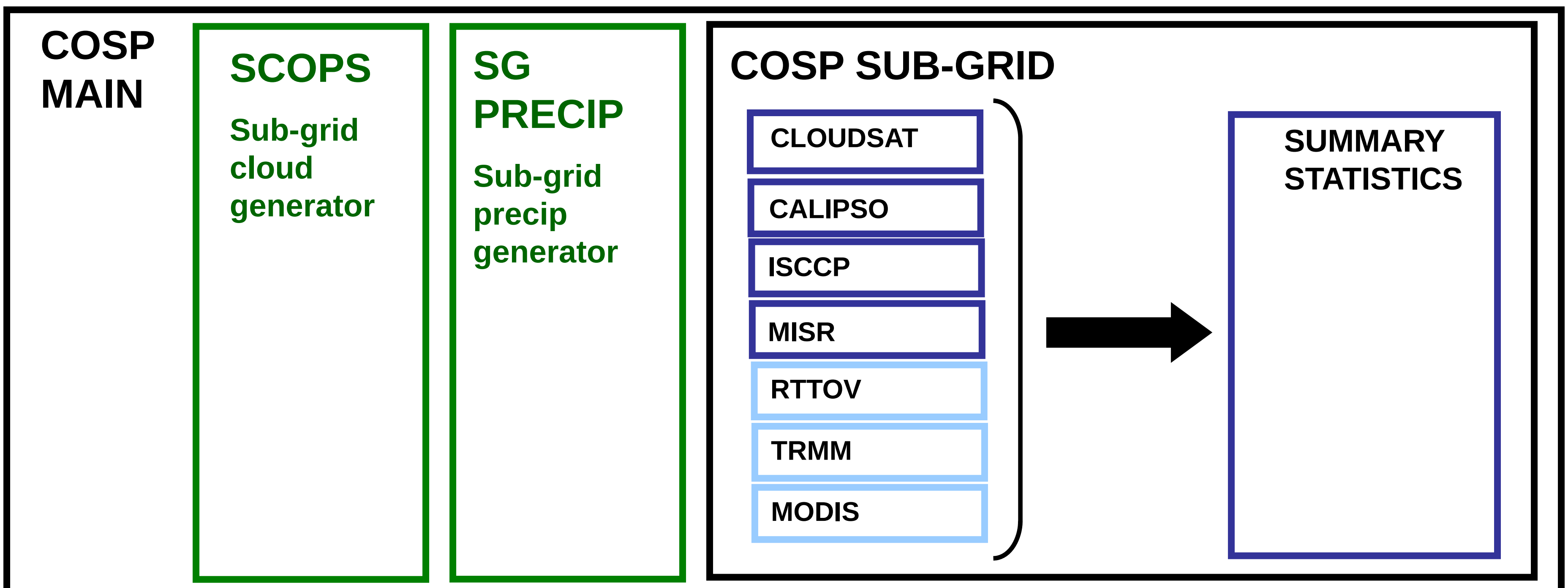
An integrated approach: the CFMIP Observational Simulator Package (COSP)

COSP collaborators

- Met Office: M. J. Webb
- LMD/IPSL: S. Bony, H. Chepfer, J.-L. Dufresne
- PCMDI/LLNL: S. Klein, Y. Zhang
- U. Washington: R. Marchand
- Monash U.: J. Haynes

COSP

- New modules can be plugged in without the need of interfacing
- Used in the Couple Model Intercomparison Project (experiments for next IPCC report)
- Designed to be used by climate, NWP and cloud-resolving models



Download from http://www.cfmip.net/

Output diagnostics

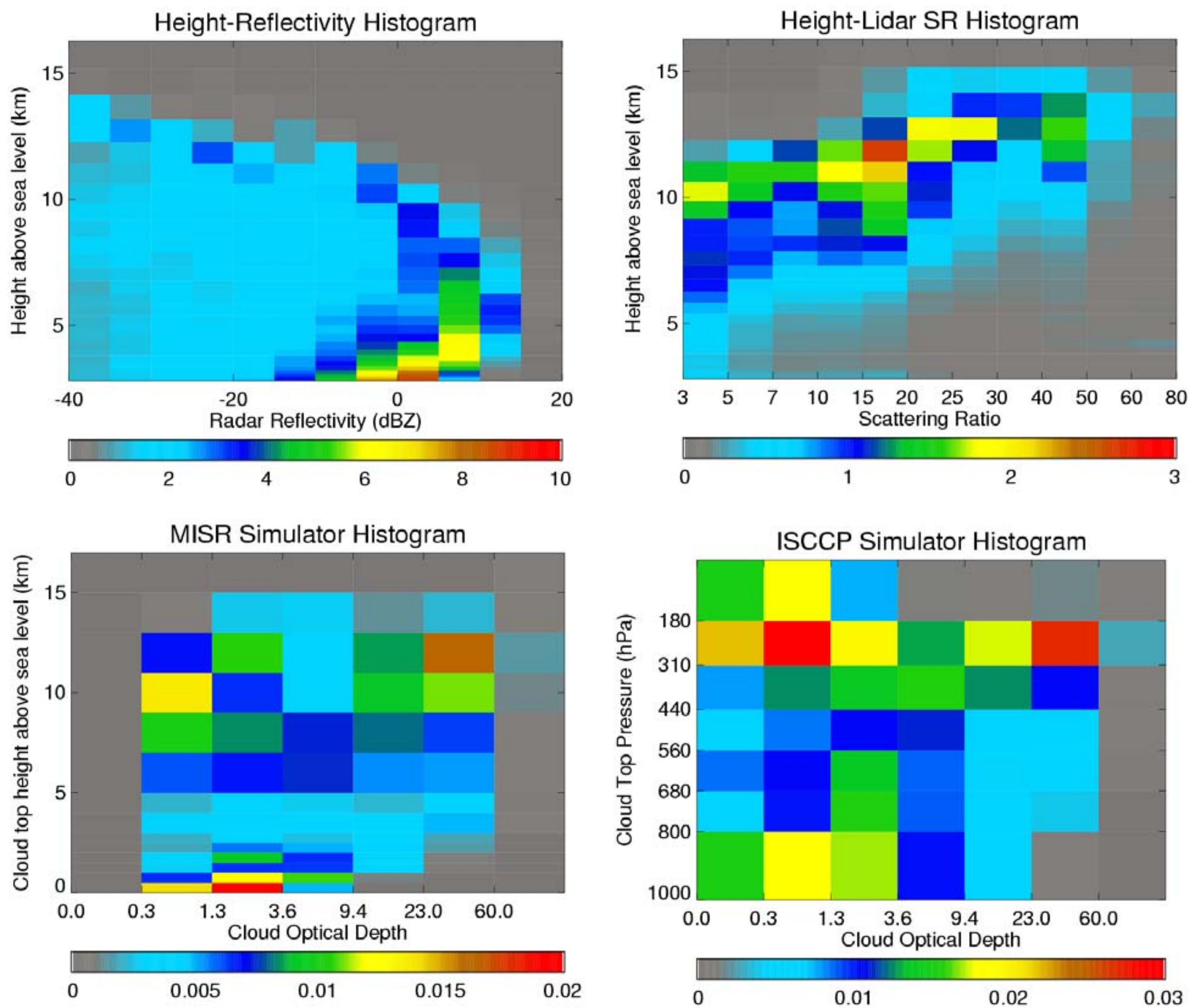
CloudSat
- Radar reflectivity in each subcolumn
- Height-reflectivity histograms

CALIPSO
- Lidar total backscatter (532 nm)
- Lidar molecular backscatter
- Height-scattering ratio histograms
- Low-level cloud fraction (CTP>680 hPa)
- Mid-level cloud fraction (440<CTP<680 hPa)
- High-level cloud fraction (CTP<440 hPa)
- 3D Cloud fraction
- Total cloud fraction

MISR,PARASOL and combined
- PARASOL mono-directional reflectance
- MISR CTH-Tau histograms
- Total cloud fraction from CALIPSO&CloudSat
- 3D cloud fraction as seen from CALIPSO but not CloudSat

ISCCP
- Mean cloud albedo
- Cloud optical depth in each subcoumn
- Mean cloud top pressure
- Mean 10.5 micron brightness temperature
- Mean clear-sky 10.5 micron brightness temperature
- Mean cloud optical depth
- Cloud top pressure in each subcolumn
- CTP-tau histograms
- Total cloud fraction

Examples


Height-Reflectivity Histogram
Height above sea level (km)
Radar Reflectivity (dBZ)
Height-Lidar SR Histogram
Height above sea level (km)
Scattering Ratio
MISR Simulator Histogram
Cloud top height above sea level (km)
Cloud Optical Depth
ISCCP Simulator Histogram
Cloud Top Pressure (hPa)
Cloud Optical Depth

Key messages

- **Use of satellite retrievals introduce uncertainties in model evaluation**
- **Forward modelling avoids some of these ambiguities**
  - **Real observations, bring models and observations onto the same grounds**
  - **Sensitivity tests can be easily carried out**
  - **But: Interpretation in observations space**
- **The A-train provides a new dimension in clouds and precipitation**
- **COSP as an integrated approach to exploit forward modelling in model evaluation**

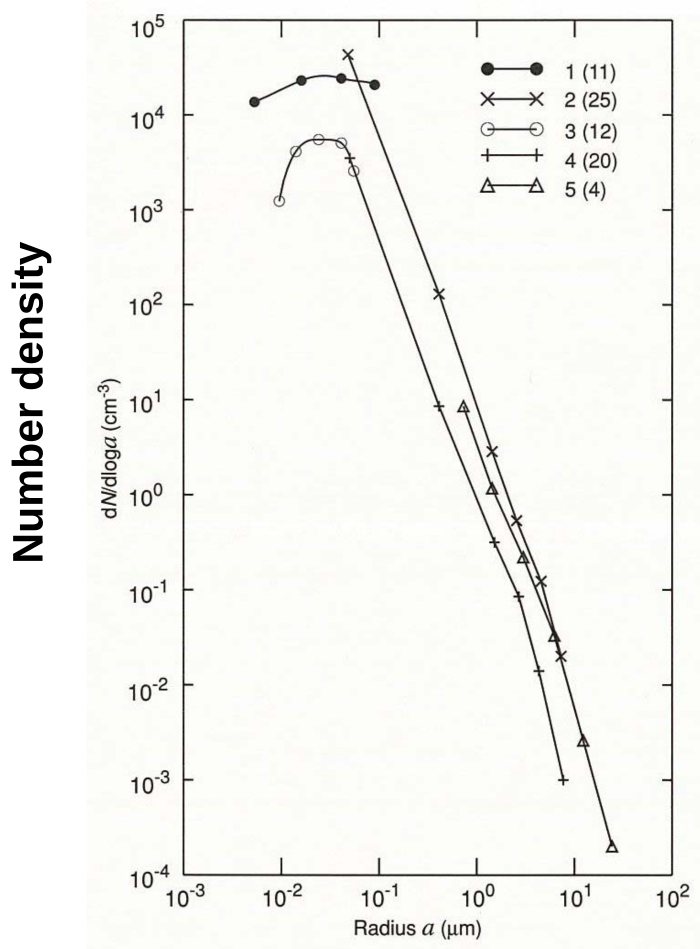
Future

- **Understand the uncertainties in forward modelling**
- **Exploit this approach in model intercomparisons**
- **Implement new forward models in COSP**
- **New synergistic diagnostics**

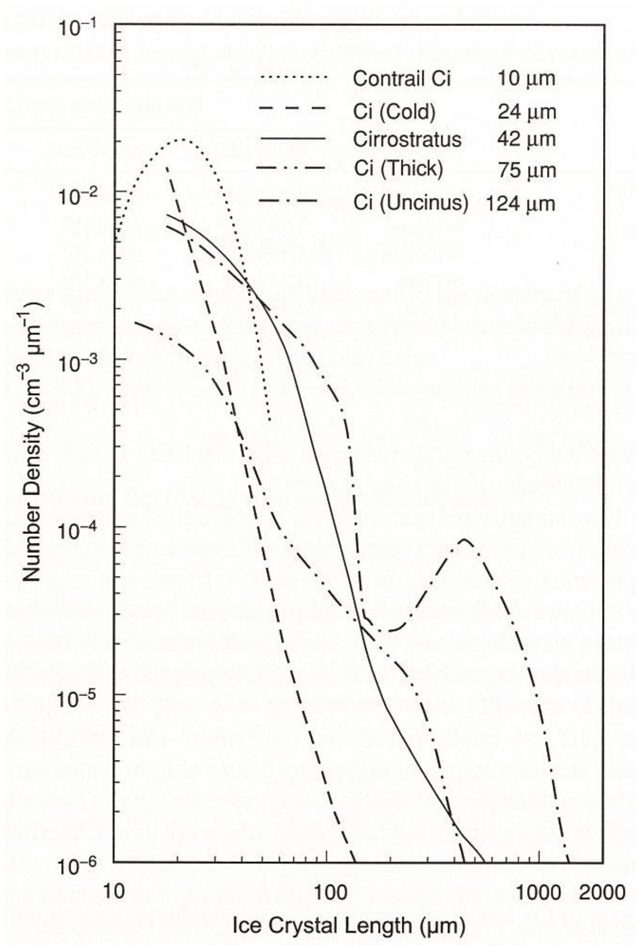
Thanks!

Size of atmospheric particles

Aerosols



Ice crystals

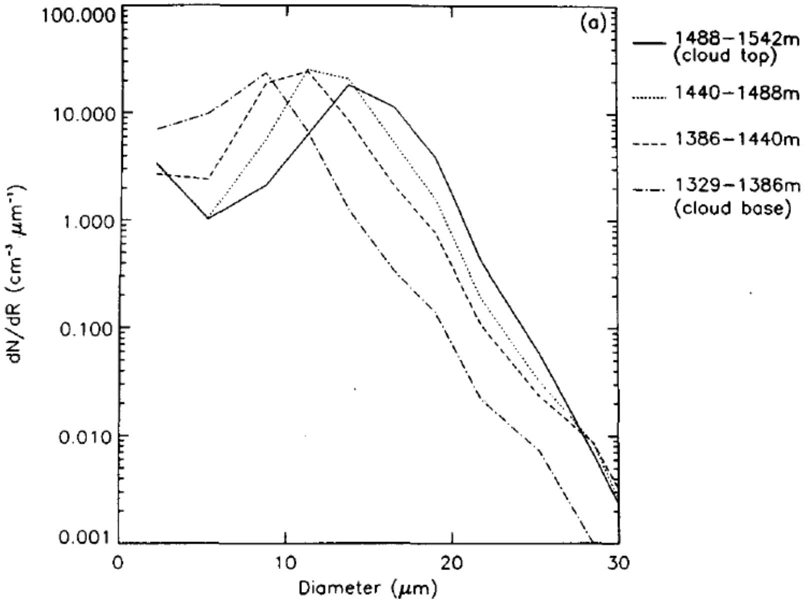


Particle size

(Liou, *An introduction to atmospheric radiation*, 2002. Figs 5.1 and 5.4)

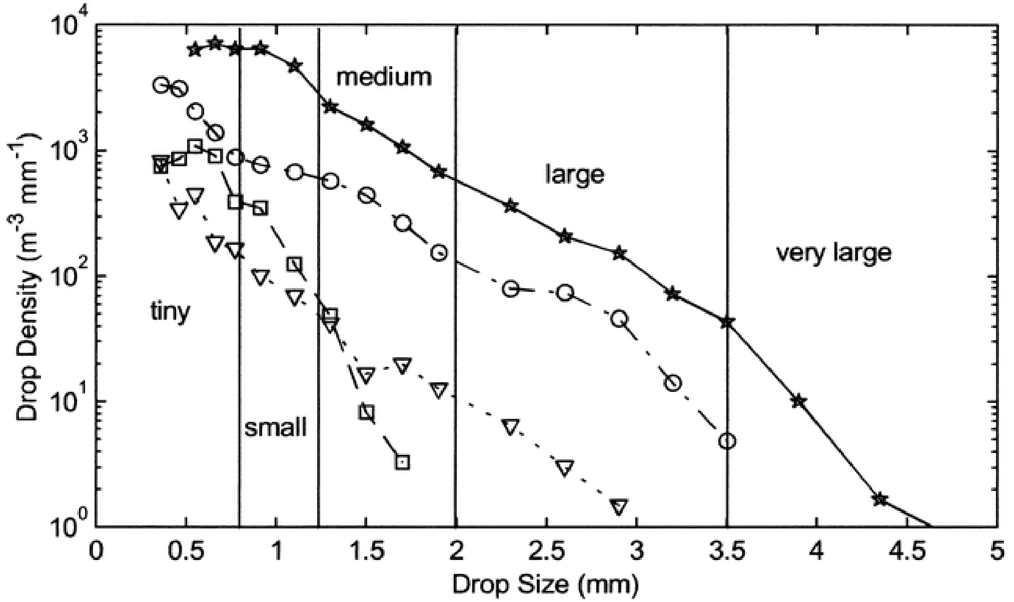
Size of atmospheric particles

Liquid cloud droplets



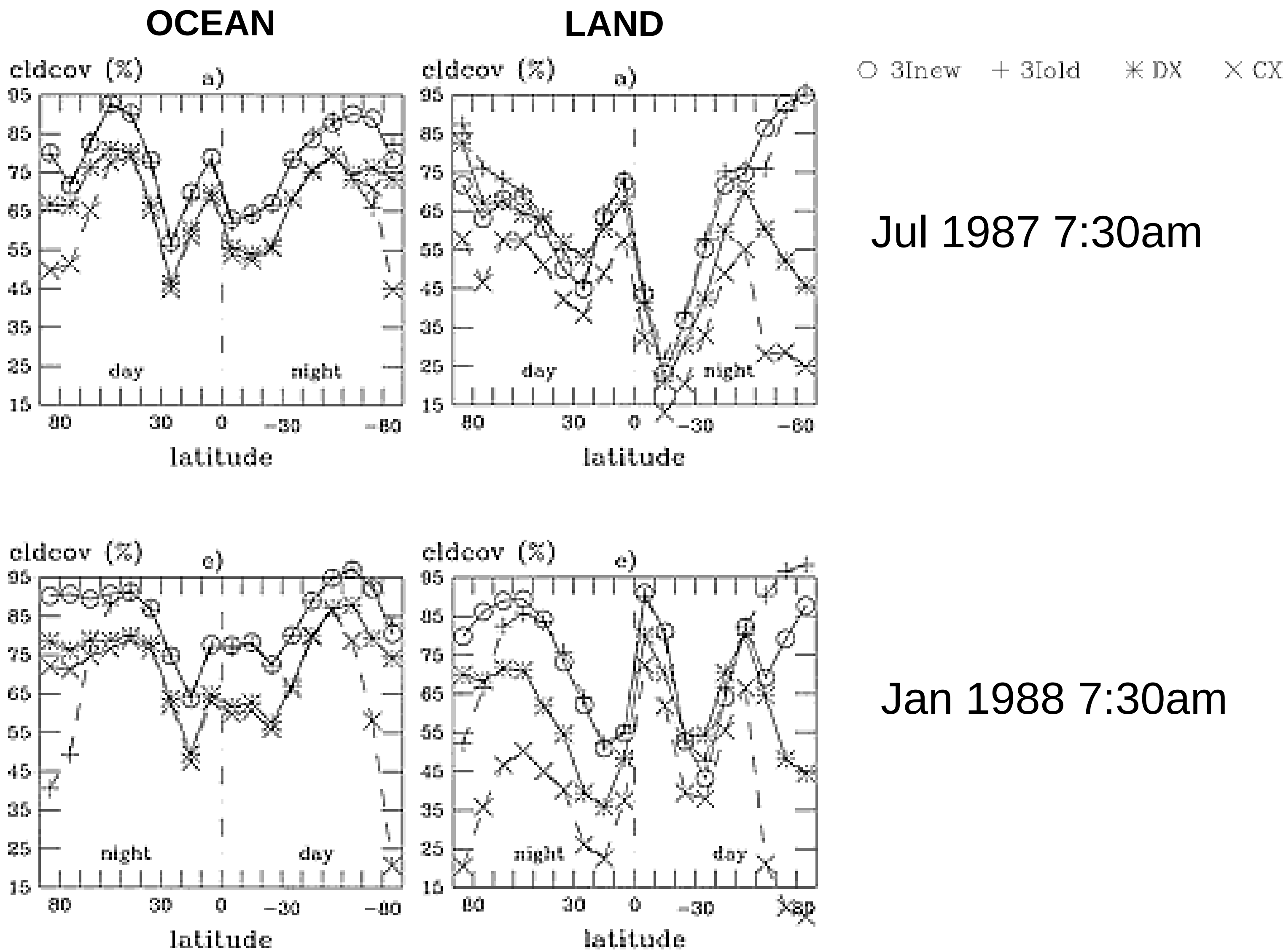
(Martin et al., *JAS*, 51, 1823-1842, 1994)

Rain drops



(Nystuen, *JAOT*, 18(10), 2001.
DOI: 10.1175/1520-0426(2001)018<1640:LTRFUA>2.0.CO;2)

And the obs?



Jul 1987 7:30am

Jan 1988 7:30am

(Stubenrauch et al., *J. Climate*, 12(8), 2189-2213, 1999)

T_B from TOVS

ECMWF

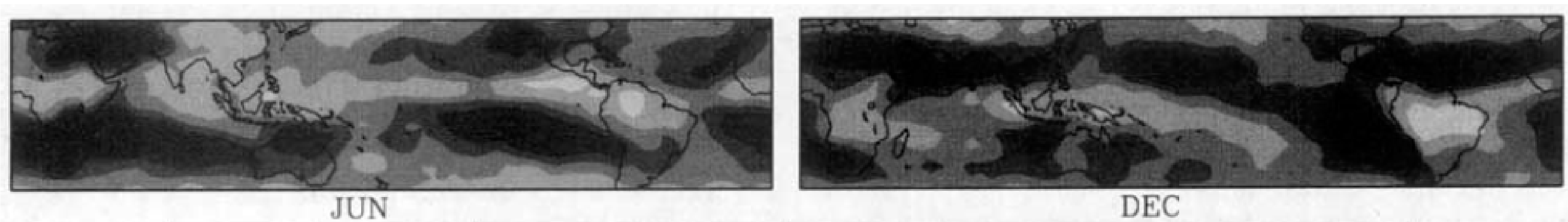


FIG. 3. Monthly averages of TOVS brightness temperature T^* computed from ECMWF analyses of tropospheric temperature and moisture in 1989. The same gray scale is used for comparison with the corresponding TOVS-observed radiances presented in Fig. 1, where the dry regions are more intense than in these simulated radiances.

TOVS

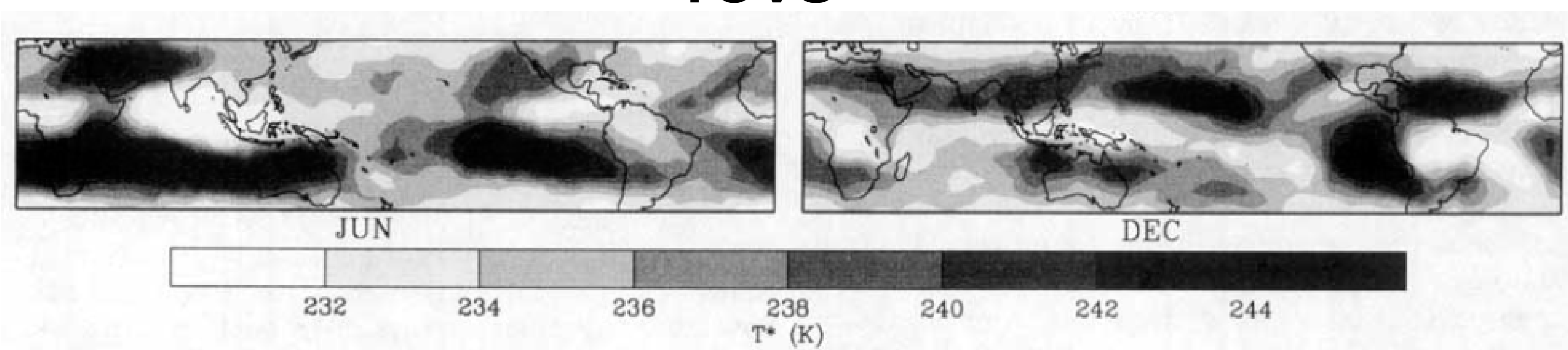
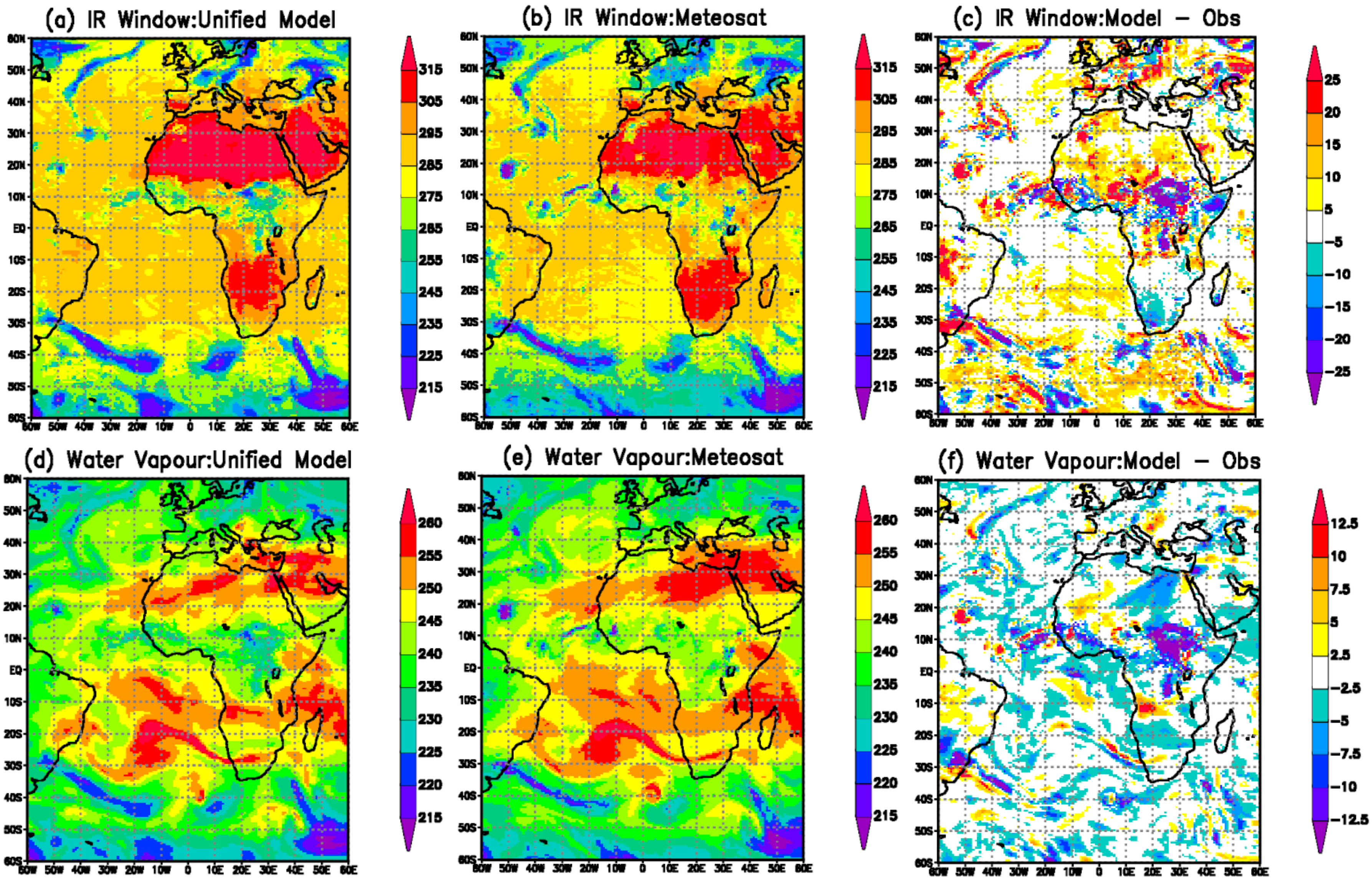


FIG. 2. Monthly averaged fields of TOVS brightness temperature T^* observed by the NOAA weather satellites during 1989. Darker shades indicate the higher brightness temperatures observed where persistent dry regions allow heat to escape from deeper in the troposphere, principally in the winter subtropical regions.

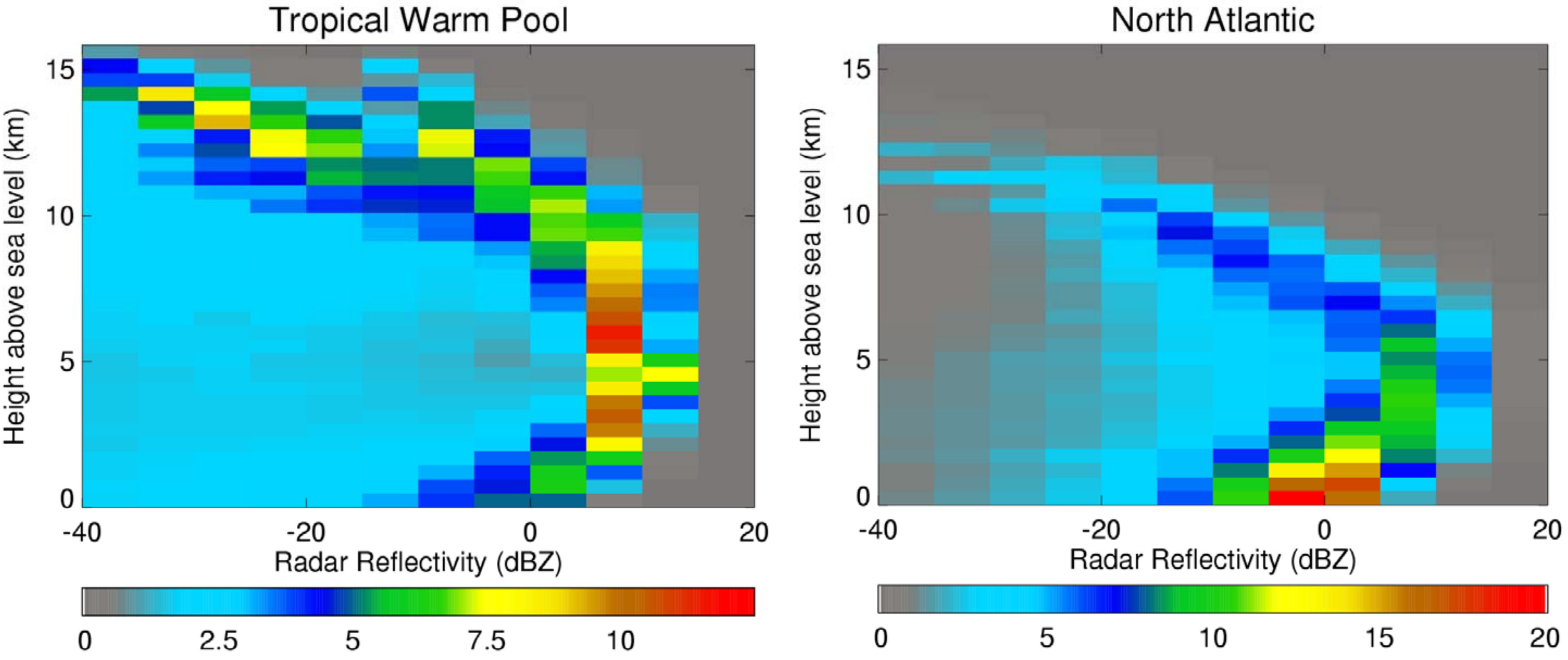
(Salathé and Chesters, *J. Climate*, 8, 120-132, 1995)

IRW&WV from METEOSAT

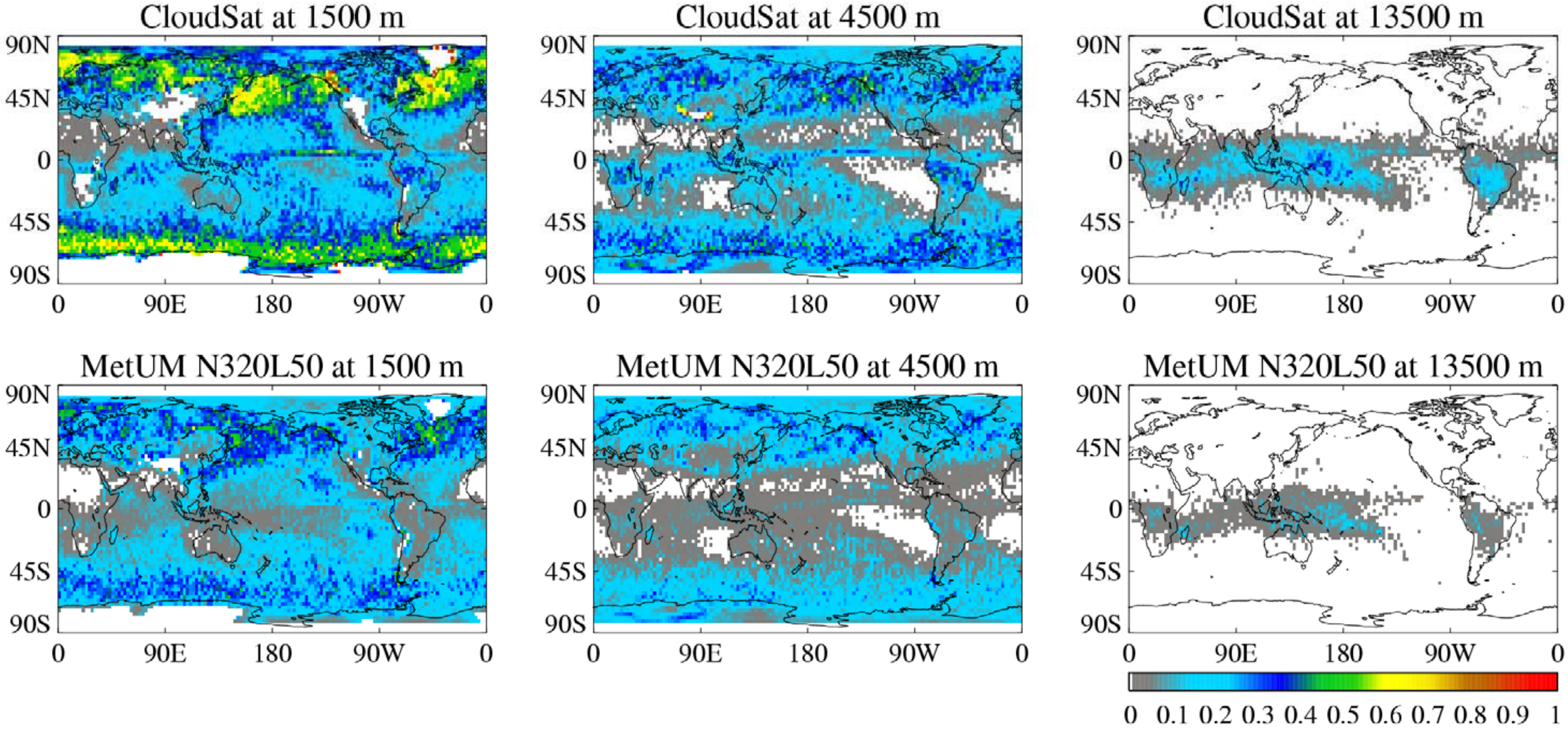


(Ringer et al., *QJRMS*, 129, 2003. DOI: 10.1256/qj.02.61)

Application to HadGAM1

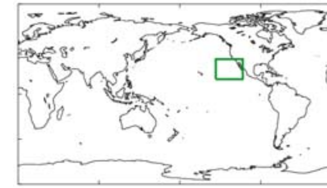


Hydrometeor frequency of occurrence

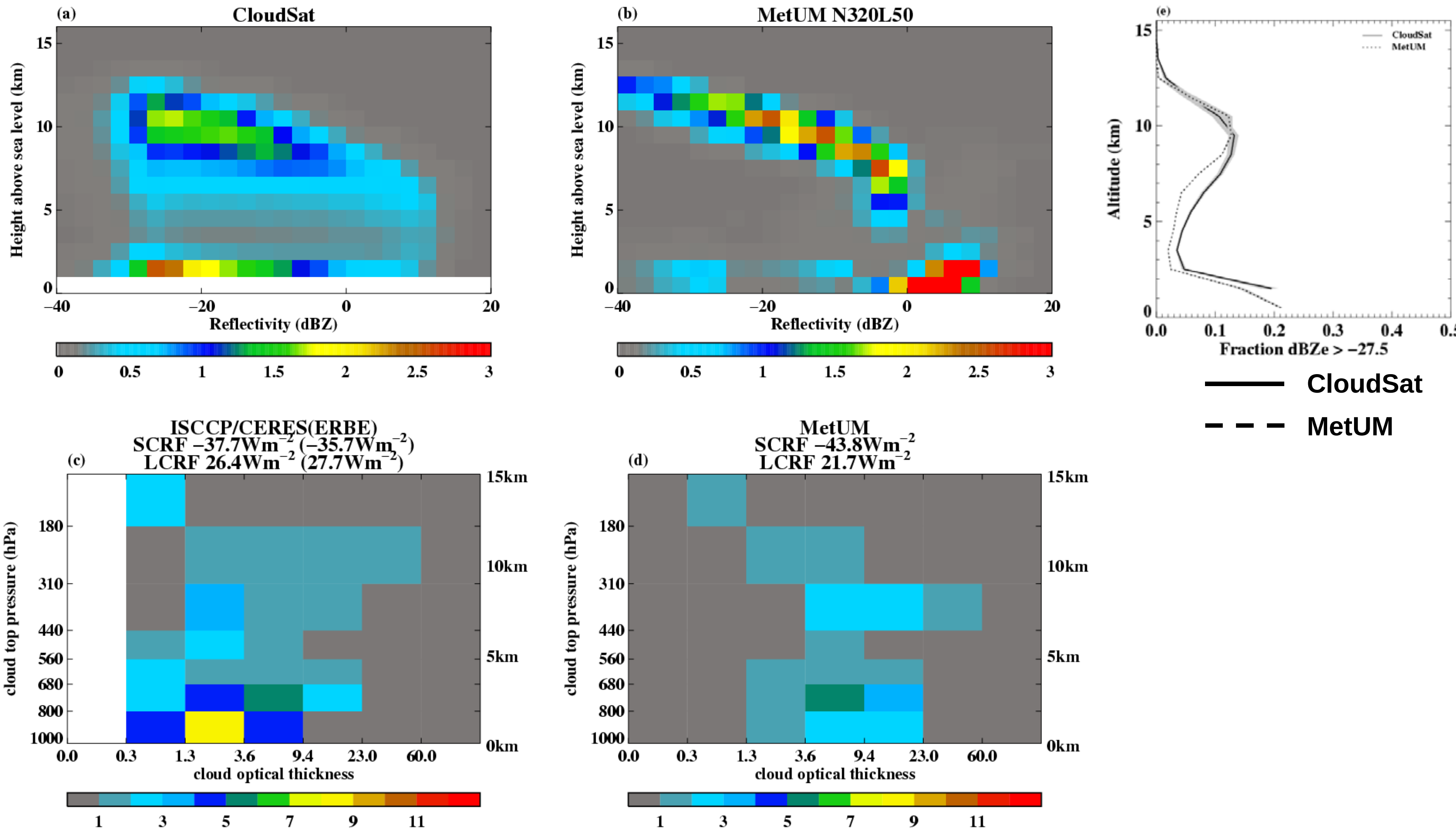


(Bodas-Salcedo et al., *JGR*, 113, 2008. DOI:10.1029/2007JD009620)

Californian Sc

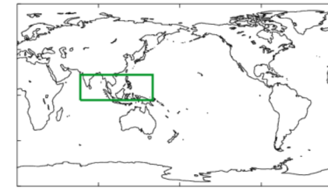


Observations MetUM

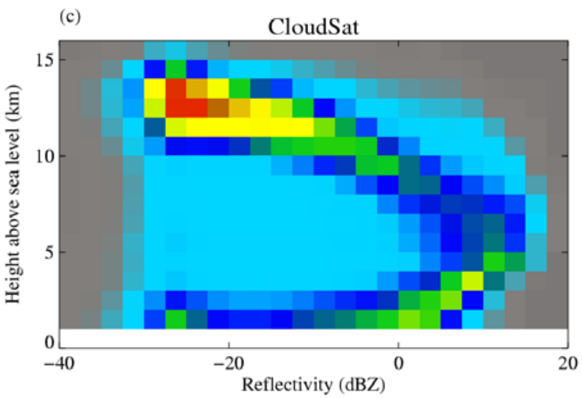


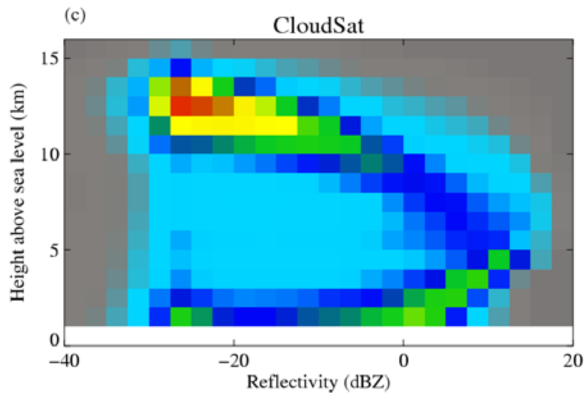
(Bodas-Salcedo et al., *JGR*, 113, 2008. DOI:10.1029/2007JD009620)

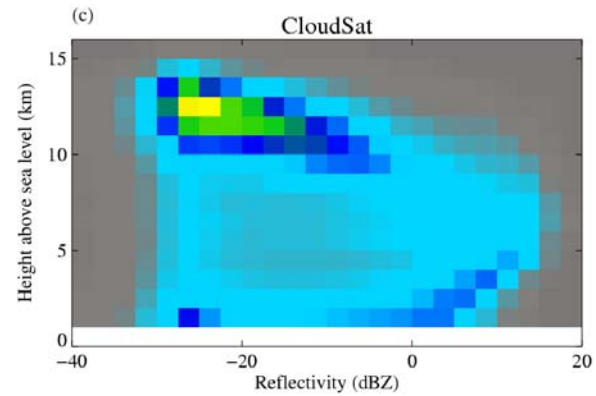
Impact of sampling

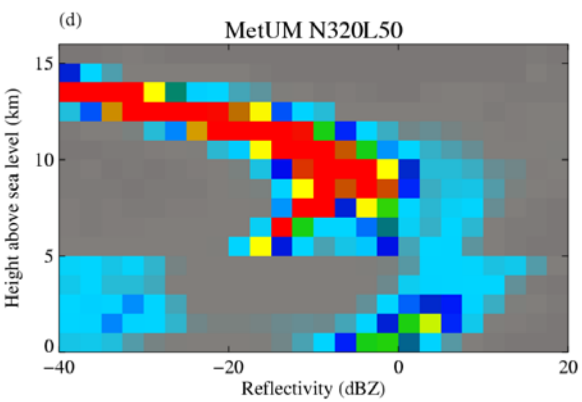


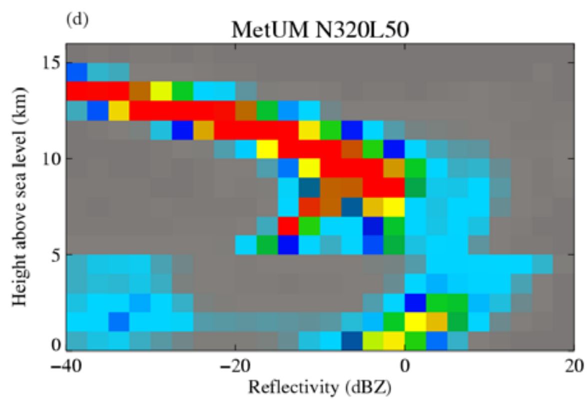
December | January | February

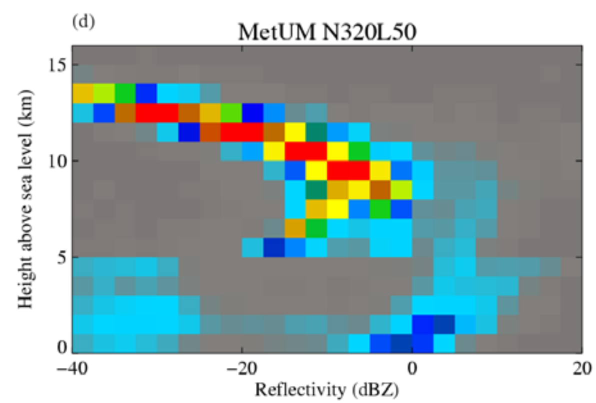




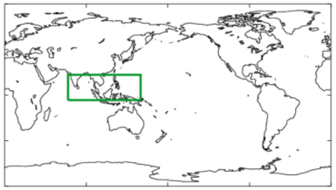








Sensitivity to PSD



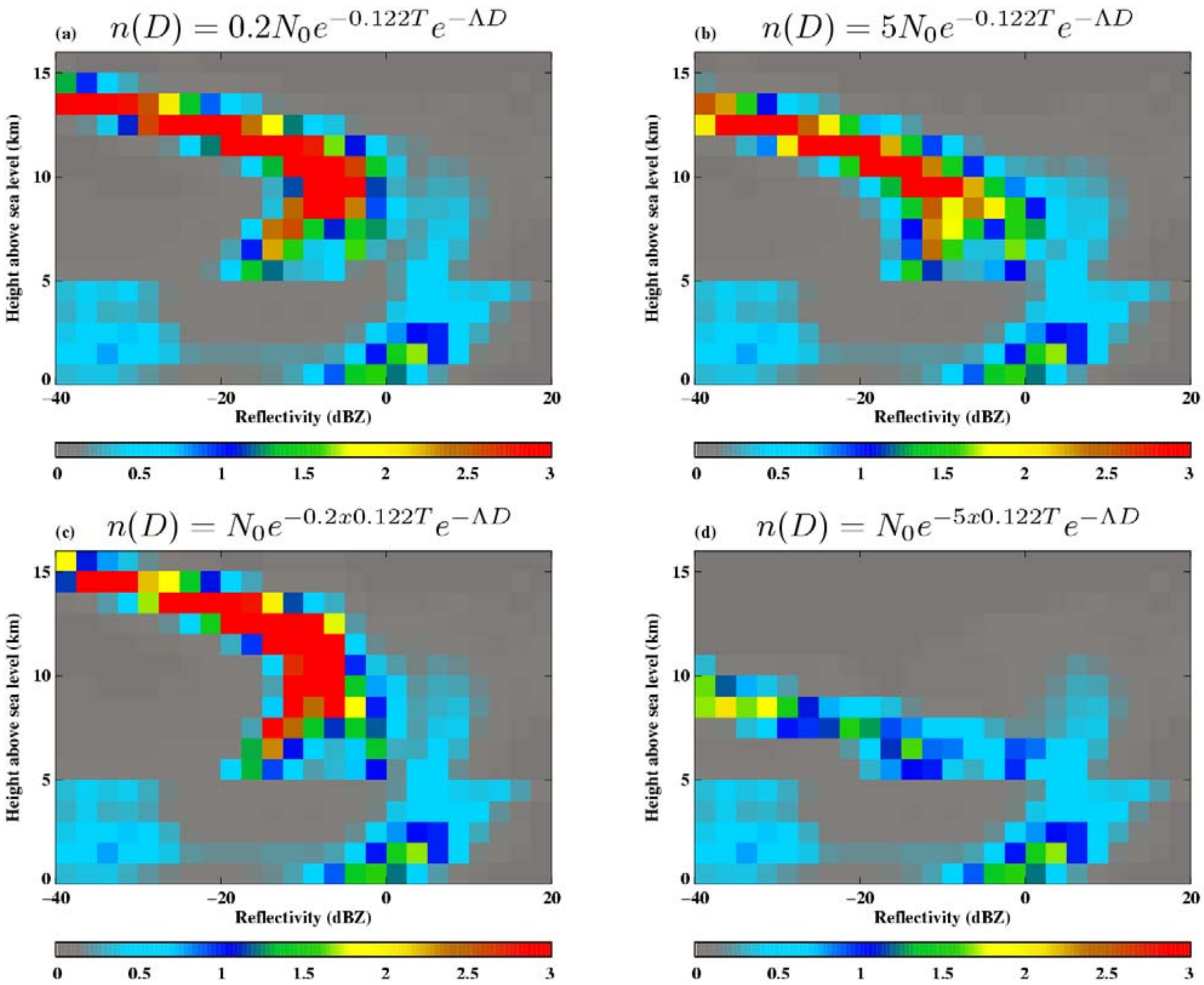
$$n(D) = N_0 e^{-C_0 T} e^{-\Lambda D}$$

$N_0/5$

$5xN_0$

$C_0/5$

$5xC_0$



Lidar backscatter

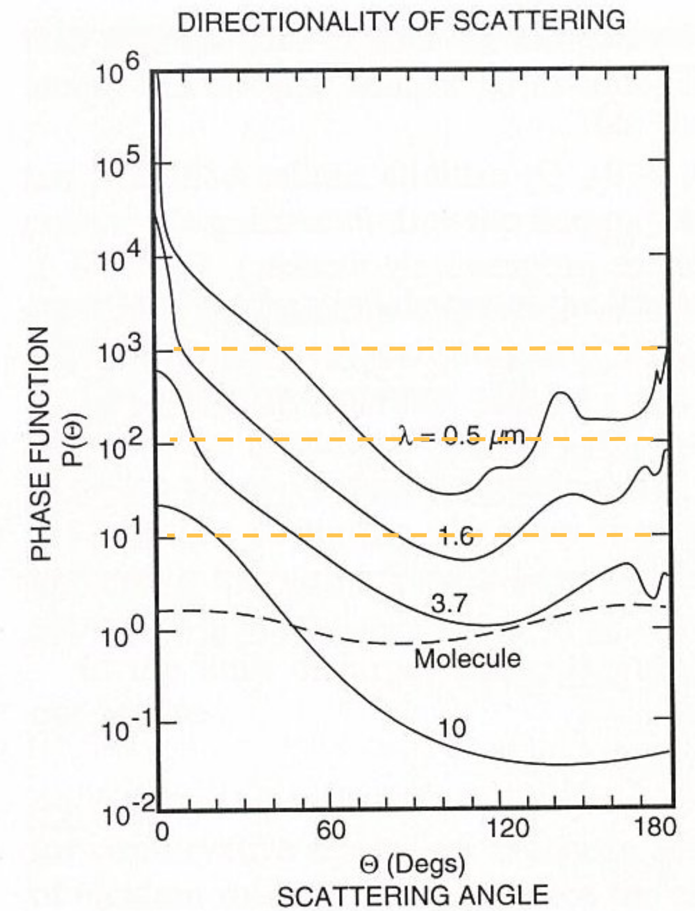
$$ATB(z) = \beta_s(z)e^{-2\alpha\int_0^z \sigma_s(z)dz}$$

$$\beta_s = \sigma_s \frac{P(\pi)}{4\pi}$$

$$\int_\Omega \frac{P(\Theta)}{4\pi} d\Omega = 1$$

$$\sigma_s(z) = \int \pi r^2 Q(r) n(r; z) dr$$

(Chepfer et al., *GRL*, 35, 2008. DOI:10.1029/2008GL034207)



(Salby, *Fundamentals of Atmos. Physics*, 1996. Fig 9.27)

Radar reflectivity

$$Z_e = \frac{|K(\nu,T)|^2}{|K_w|^2} Z f_{Mie}(D_e) \quad e^{-2\int_0^z \sigma_e(z)dz}$$

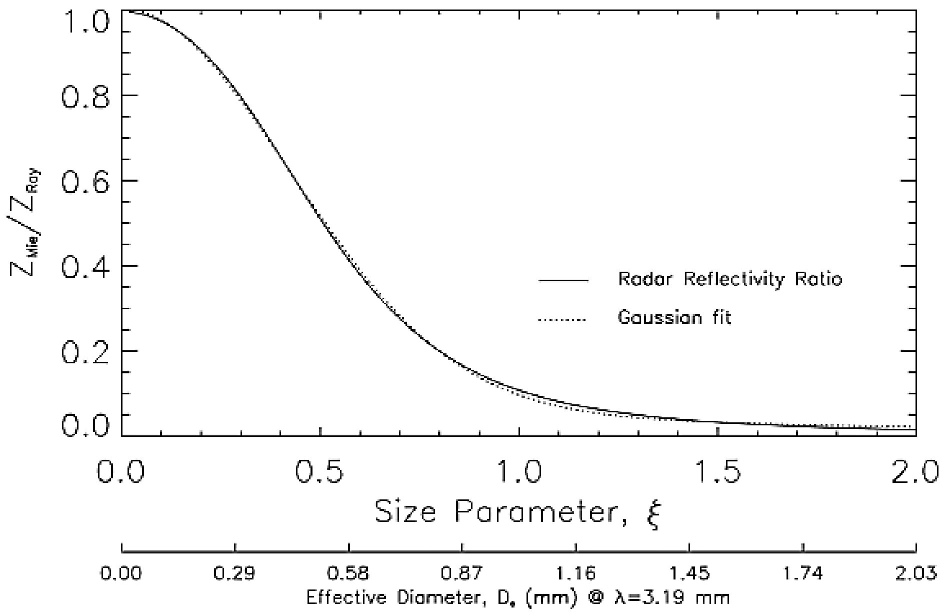
$$\eta = \int \beta(D) n(D) dD$$

$$\beta(D) = \frac{\pi^5}{\lambda^4} |K|^2 D^6$$

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 \int D^6 n(D) dD$$

$$Z = \int D^6 n(D) dD$$

$$Z_e = \frac{\lambda^4}{\pi^5 |K_w|^2} \eta$$



(Benedetti et al., *JGR*, 108, 2003. DOI:10.1029/2002JD002693)

COSP v2.0

- New instruments
  - RTTOV. Fast RT code for IR and PMW (Optional)
  - MODIS. Daytime only
    - CF, CTP, size, and OT
    - All, liquid and ice
    - Joint CTP/OT histogram
    - Matching Level3 product to be produced by NASA
  - TRMM PR sf-conv precip
  - Others…
- Compatibility with CMOR 2
- New diagnostics
- Expected to be released by Jan/Feb 2009