Global Statistics on Microphysical and Optical Properties of Cloud-Top Ice Crystals

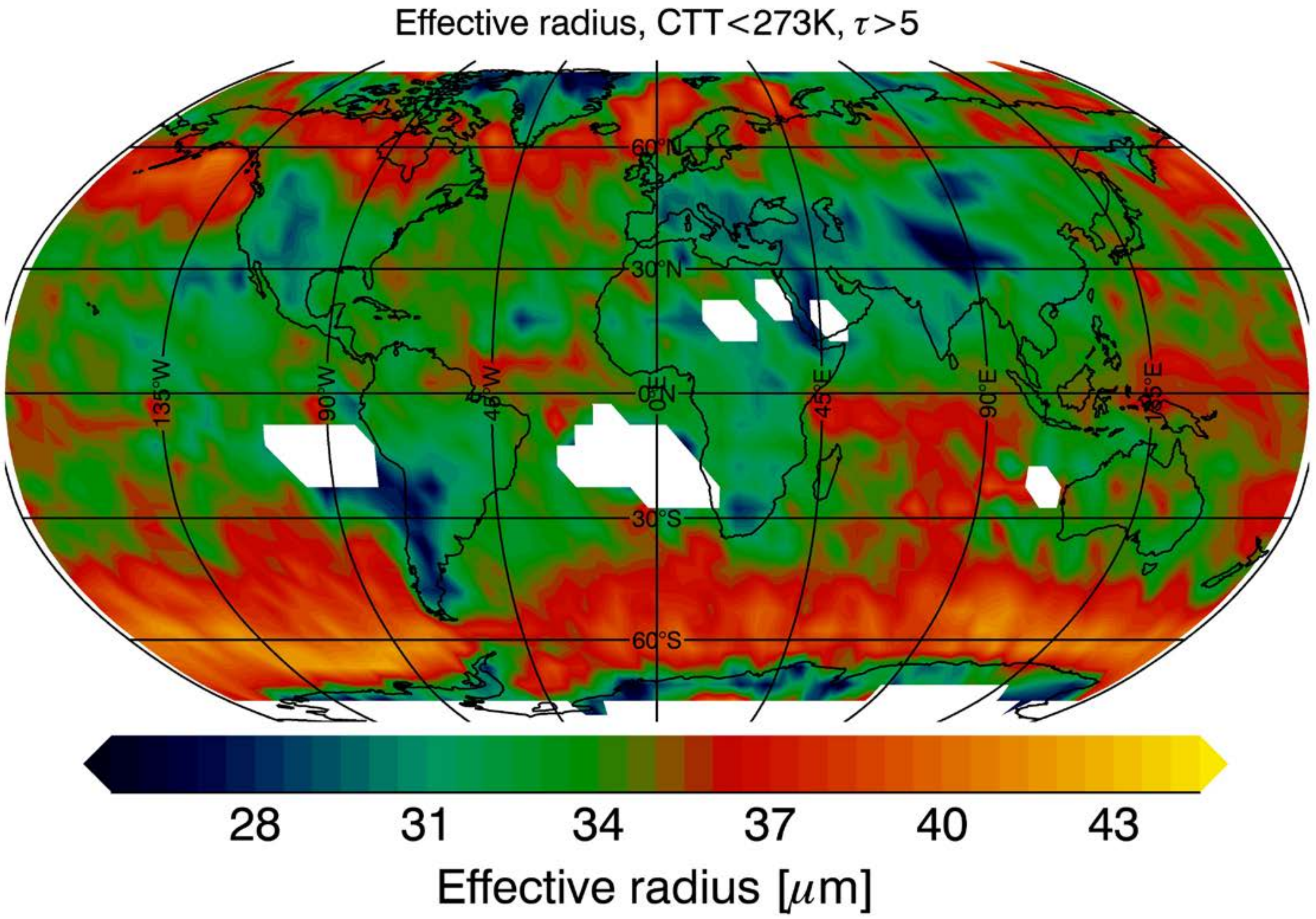
Bastiaan van Diedenhoven,

Ann Fridlind, Brian Cairns, Andrew Ackerman, Jerome Riedi

Funded by NASA ROSES Aqua-Terra 2013

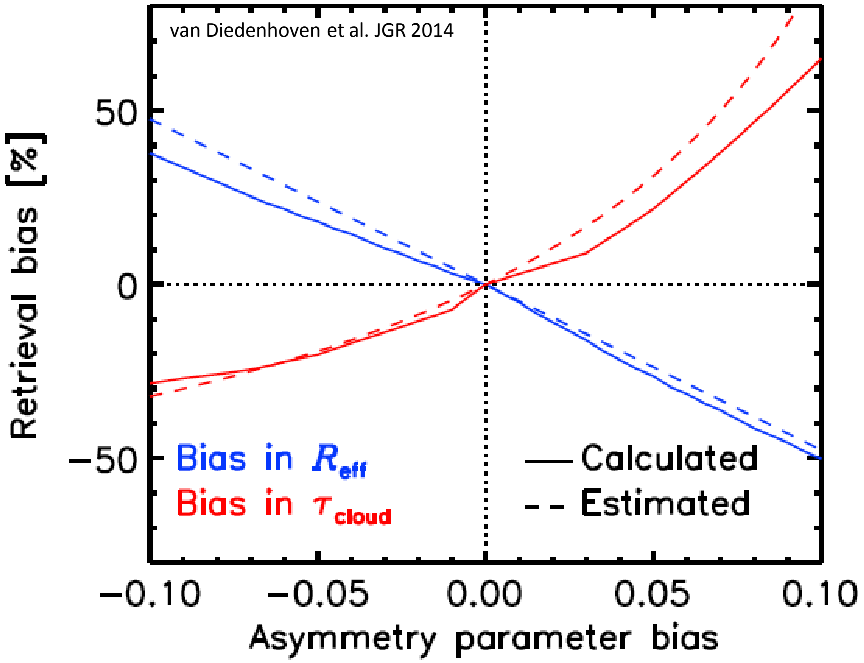
Ice effective radius from 2007 MODIS-Aqua data

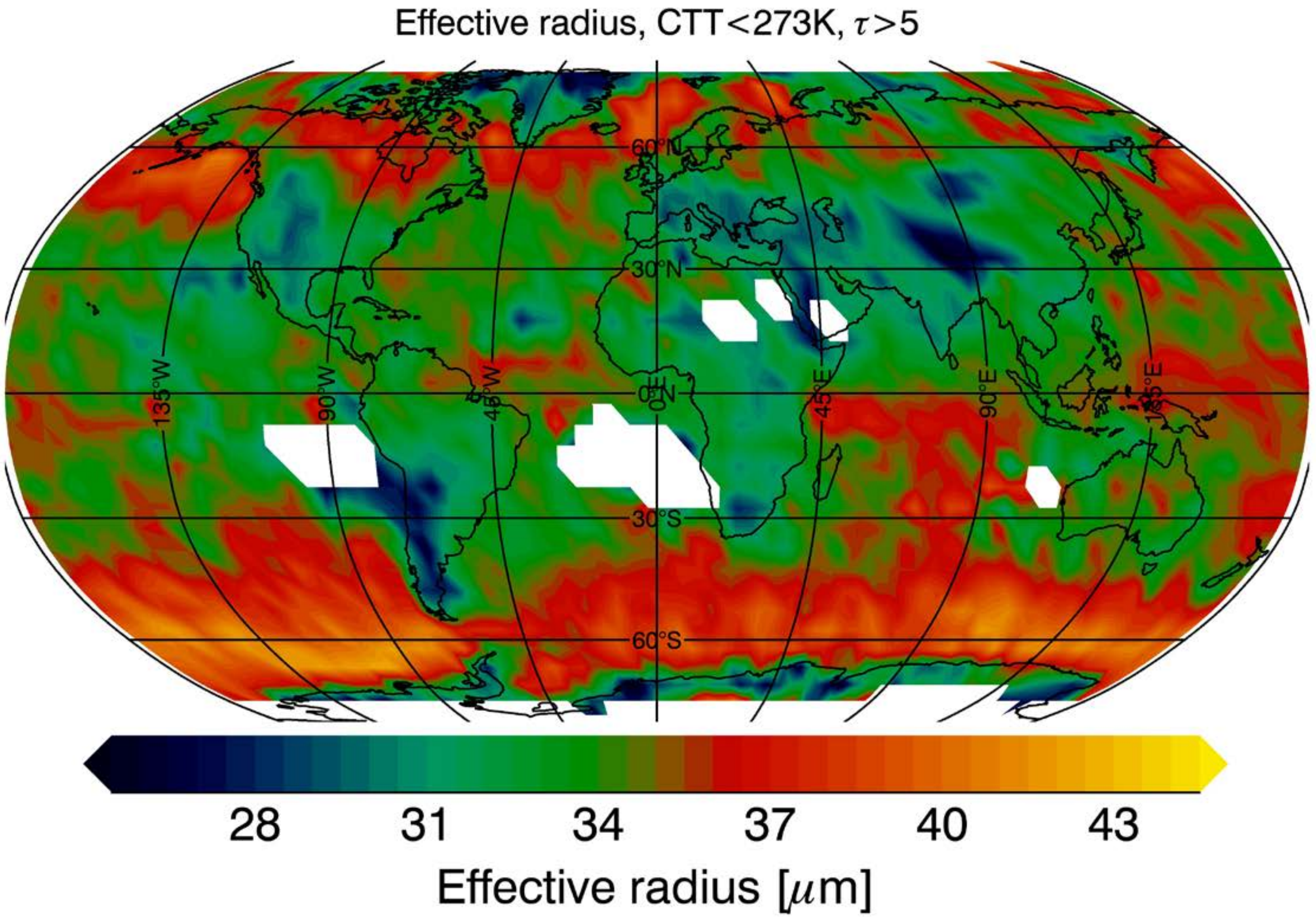
- Ice r_e at cloud top retrieved from shortwave infrared bands



Ice effective radius from 2007 MODIS-Aqua data

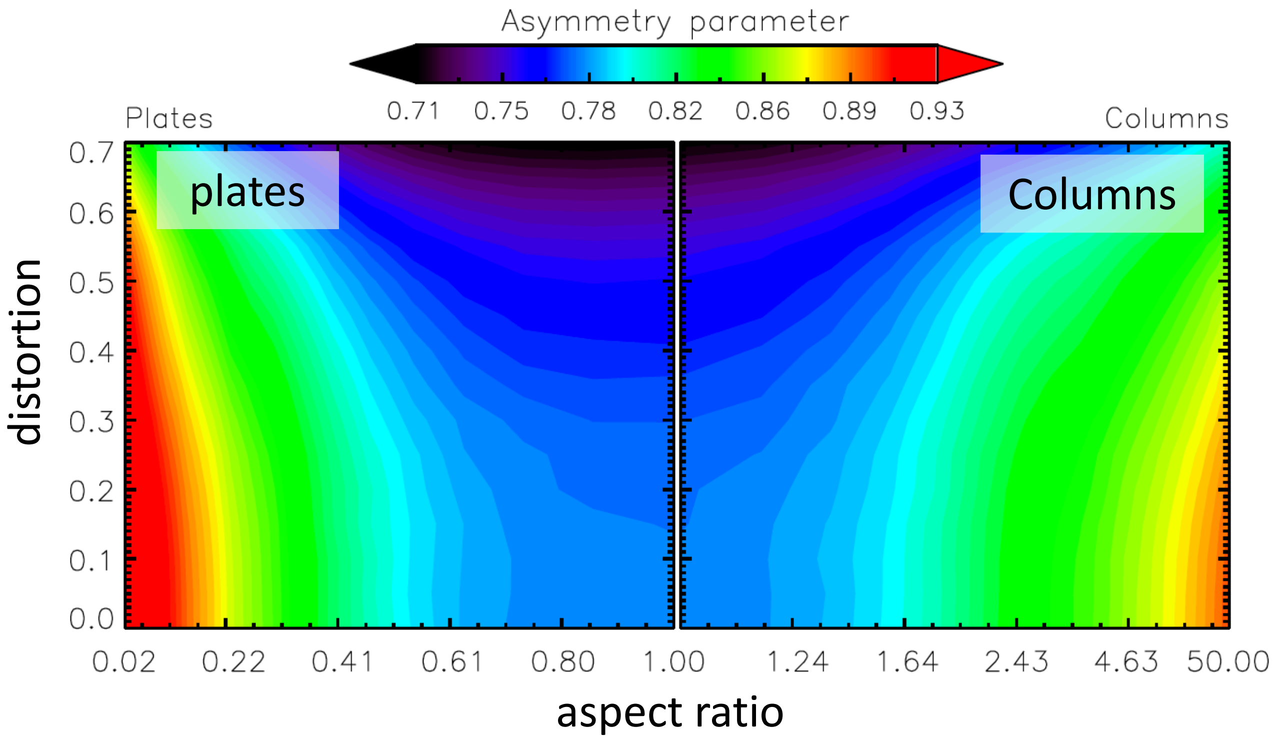
- Ice r_e at cloud top retrieved from shortwave infrared bands
- Retrievals depend on assumed ice optical model, specifically asymmetry parameter *g*

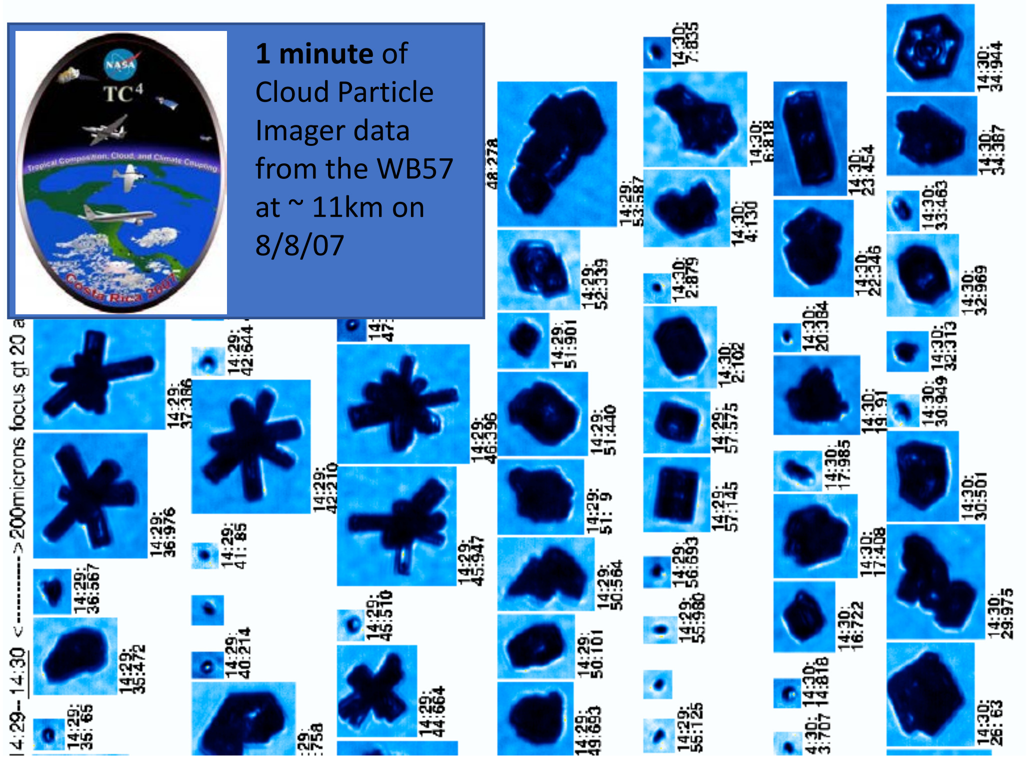


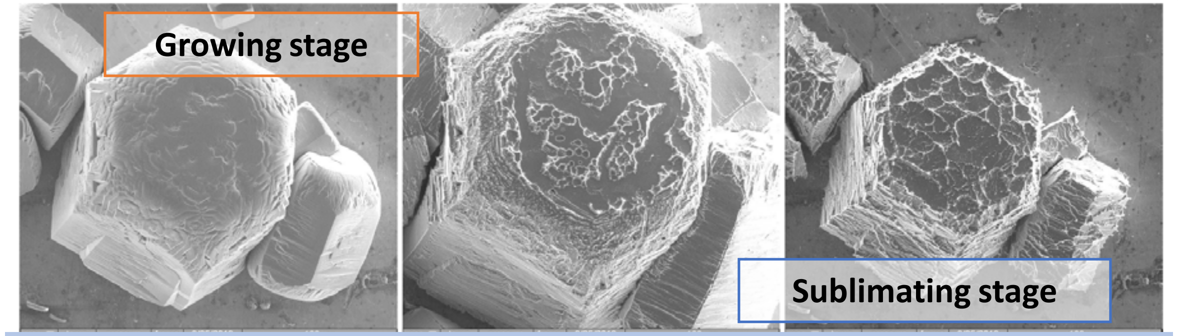


Ice shape and scattering properties

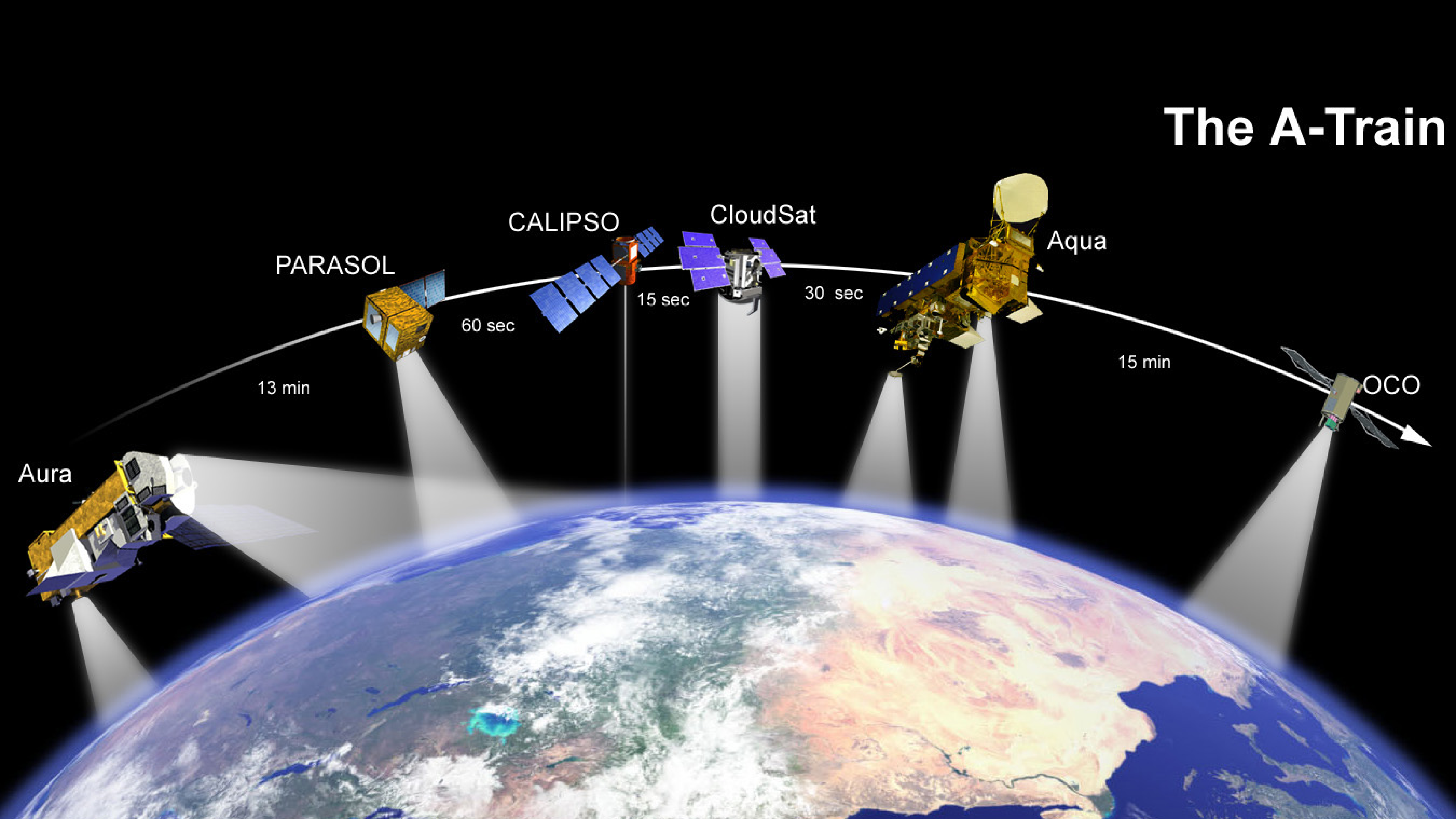
- Scattering properties depend on (in order of importance):
  1. Aspect ratio of crystal components
  2. Level of distortion/roughness
  3. General habit
- **Practical model**: simple plates & columns with variable aspect ratios and distortion as proxies for complex ice





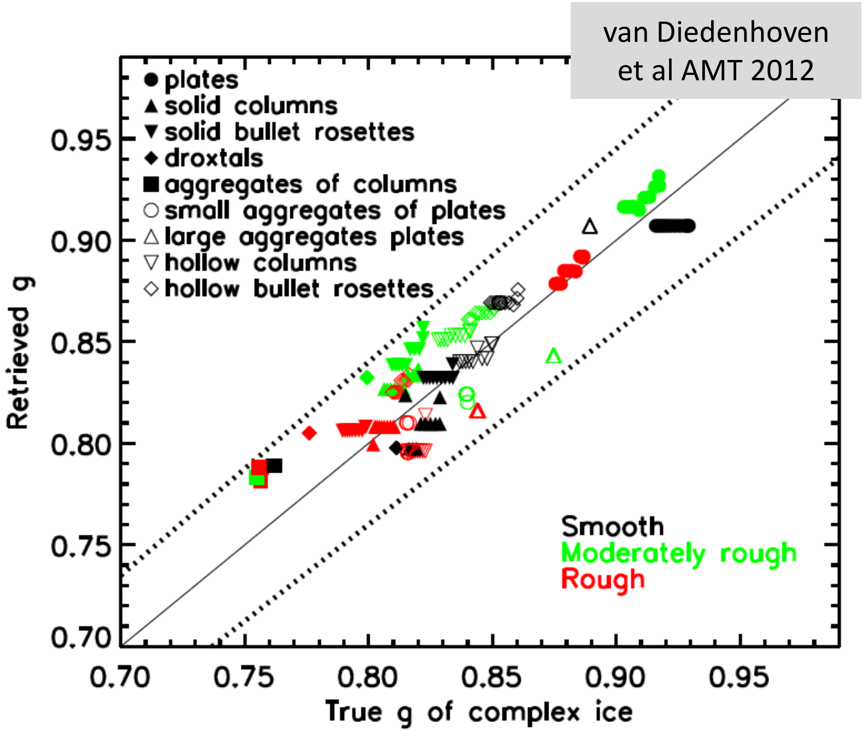


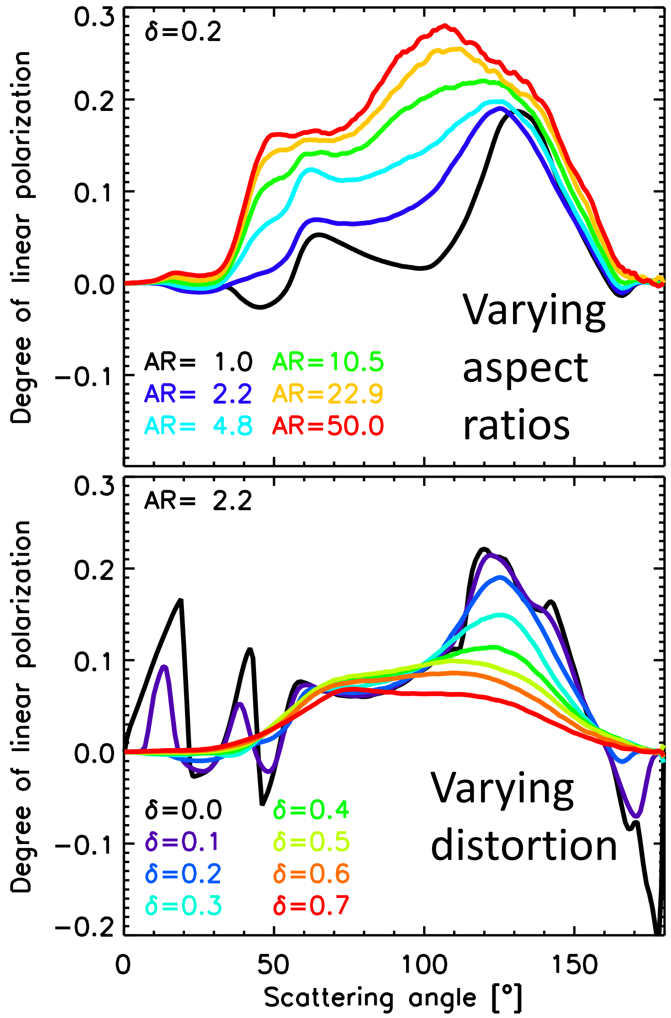
Ice roughness structures on Electron microscope in the lab
Nathan Magee – College on New Jersey


The A-Train
Aura
13 min
PARASOL
60 sec
CALIPSO
15 sec
CloudSat
30 sec
Aqua
15 min
OCO

Ice shape and asymmetry parameter from multi-angle polarization measurements

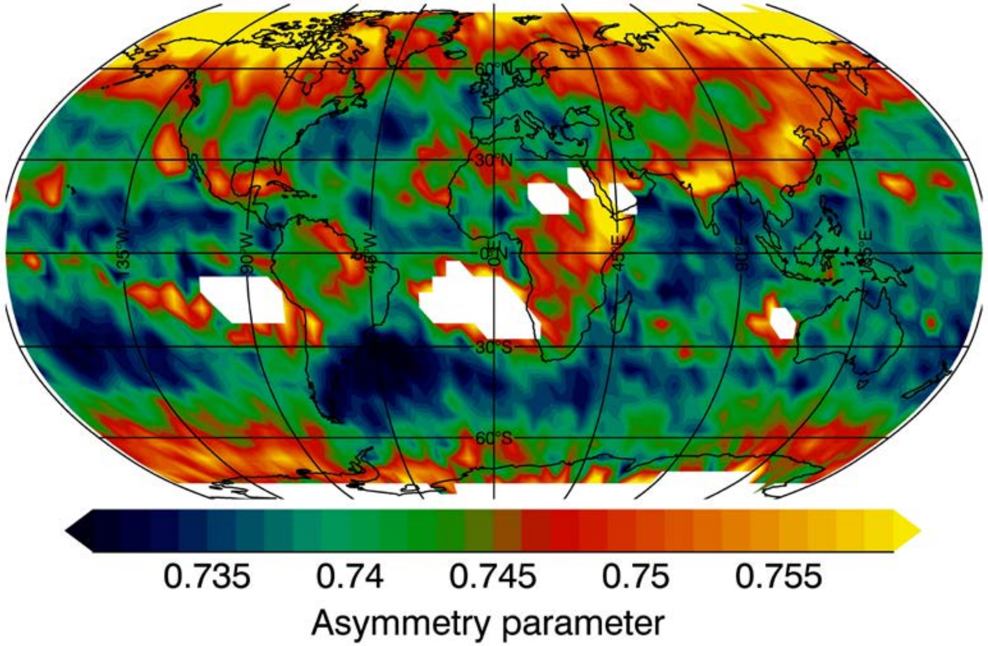
- Polarized reflectance samples cloud single scattering features
- Multi-angle polarization depends on shape
- Use simple hexagonal model to retrieve distortion and mean aspect ratio of crystal components
- Asymmetry parameter determined by AR & δ

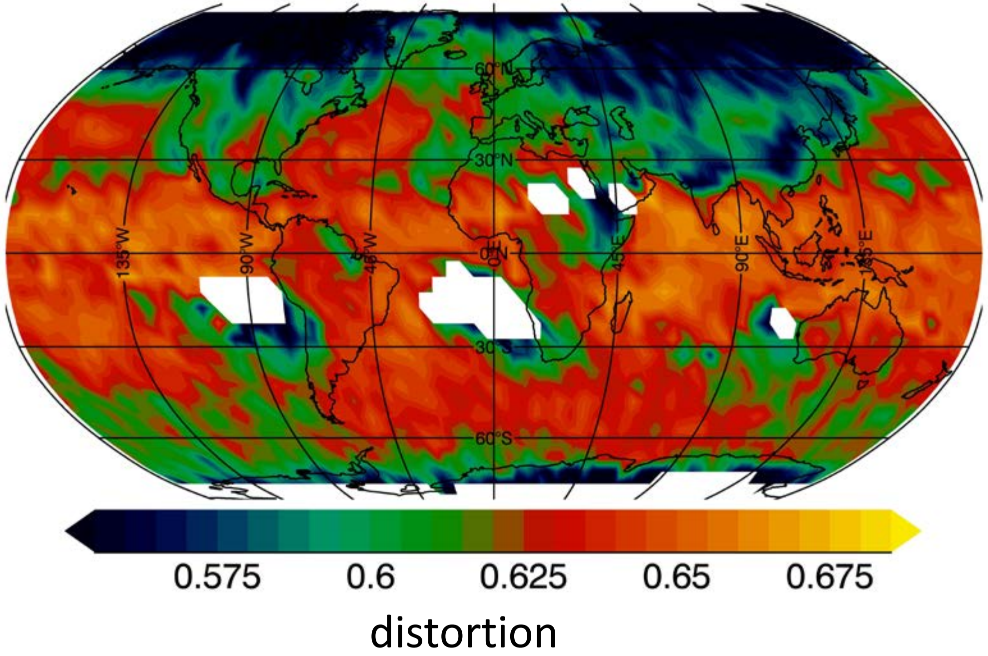


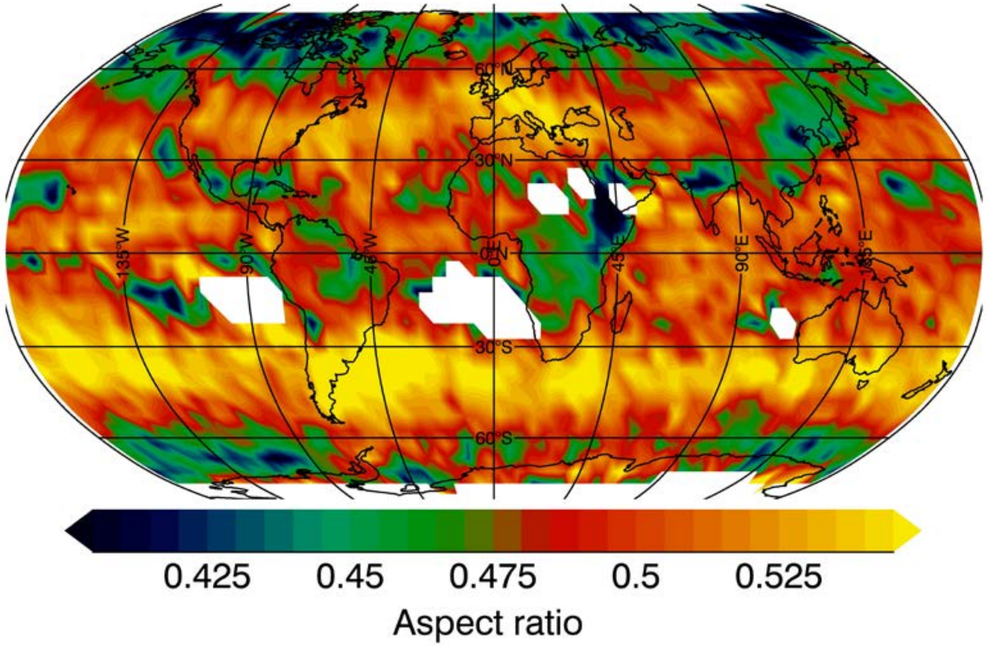


Ice shape and asymmetry parameter from 2007 POLDER

- Filters applied (>84 million valid retrievals):
  - Conservative goodness of fit
  - Optical thickness > 5
  - MODIS/POLDER phase flags + ‘liquid index’







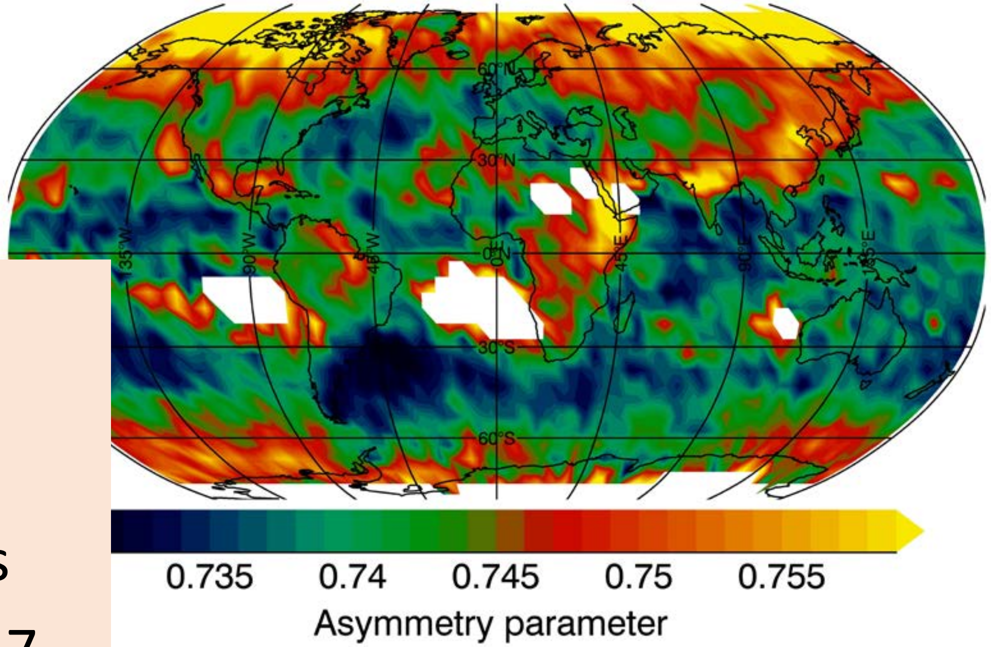
Ice shape and asymmetry parameter from 2007 POLDER

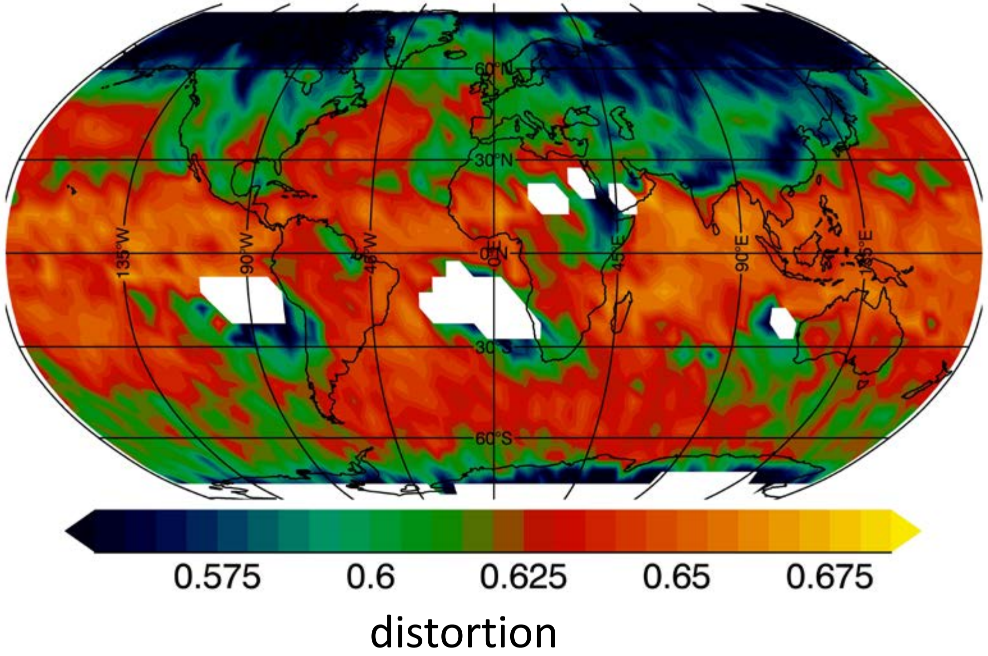
Retrieved averages:

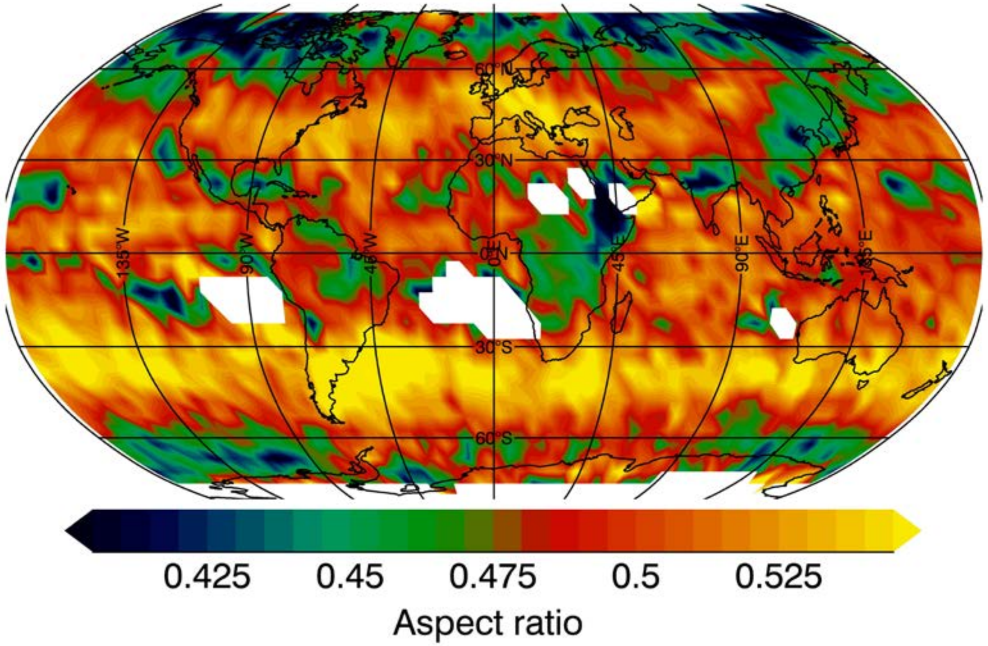
- $g = 0.75$
- aspect ratio = 0.55
- ~90% plate-like
- distortion = 0.65

MODIS C6 assumed:

- $g = 0.75$
- aspect ratio ≈ 0.65
- aggregate of columns
- distortion $= \sqrt{0.5} \approx 0.7$

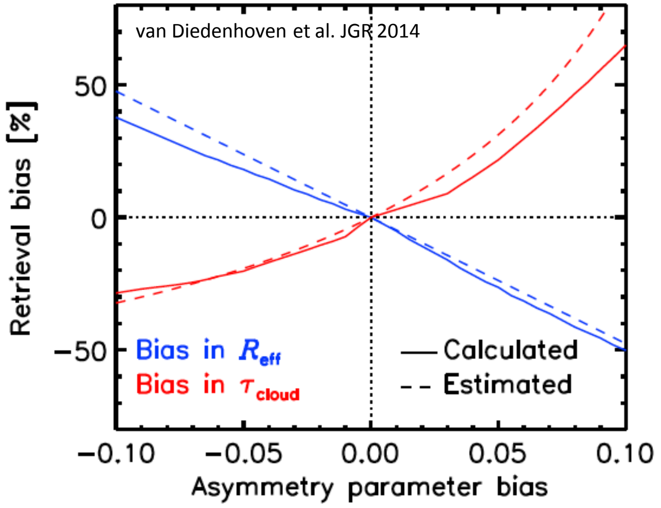


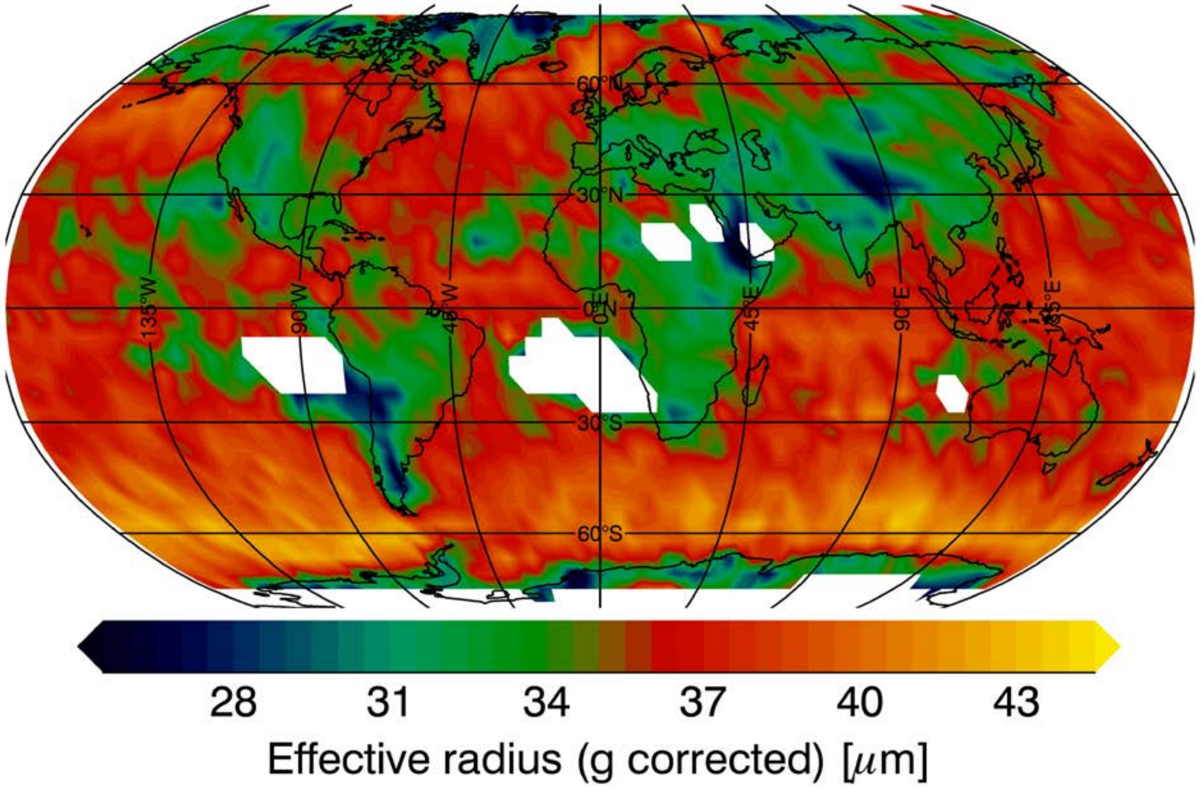


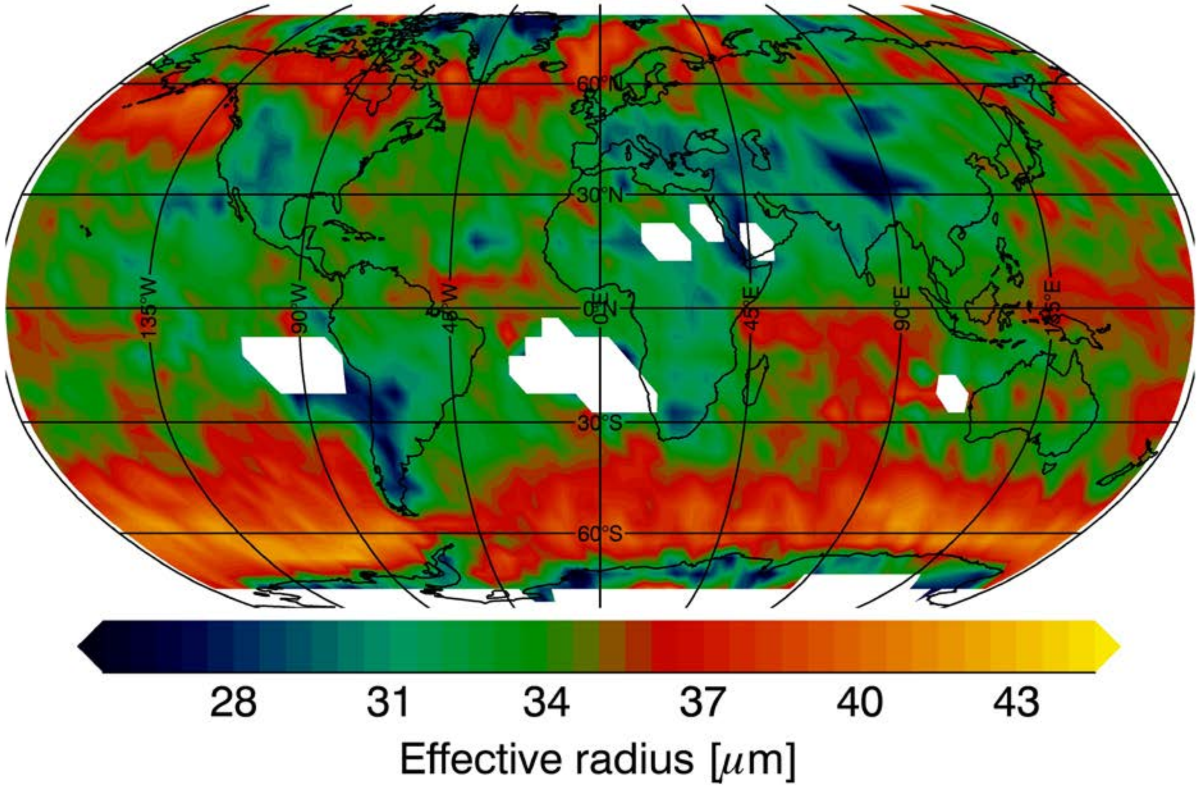


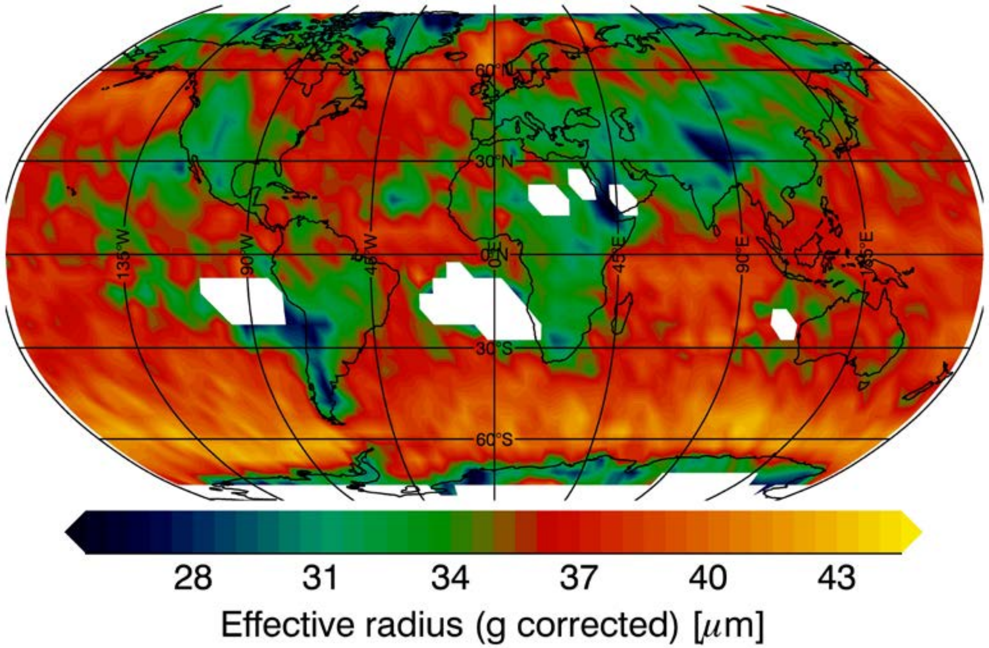
Ice effective radius corrected for *g* variation

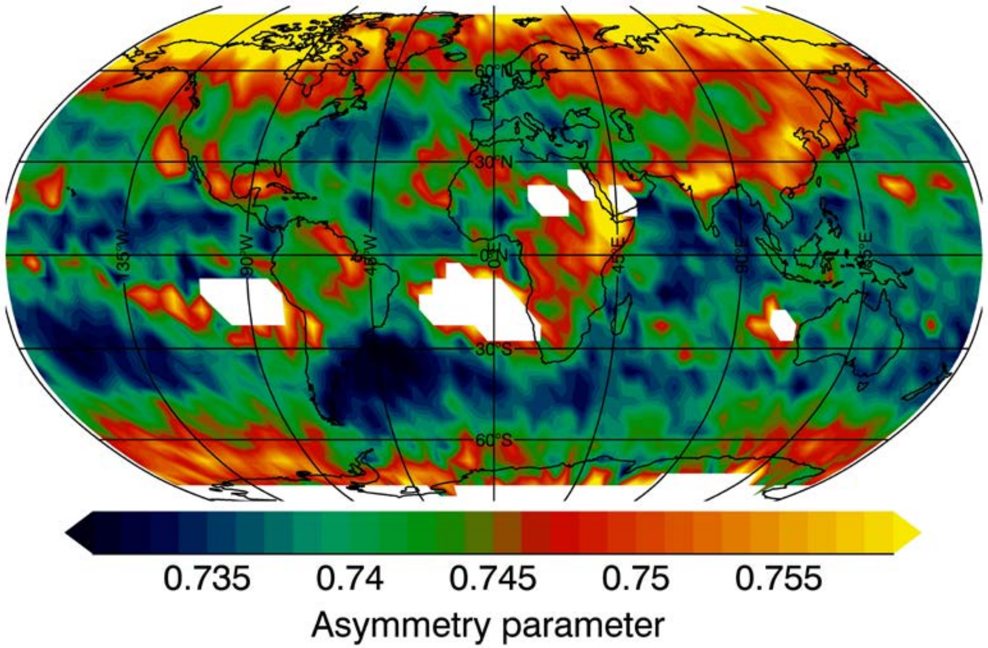
$$r_{e,corr} = r_{e,C6} * \frac{(1-g_{C6})}{(1-g_{POLDER})})$$

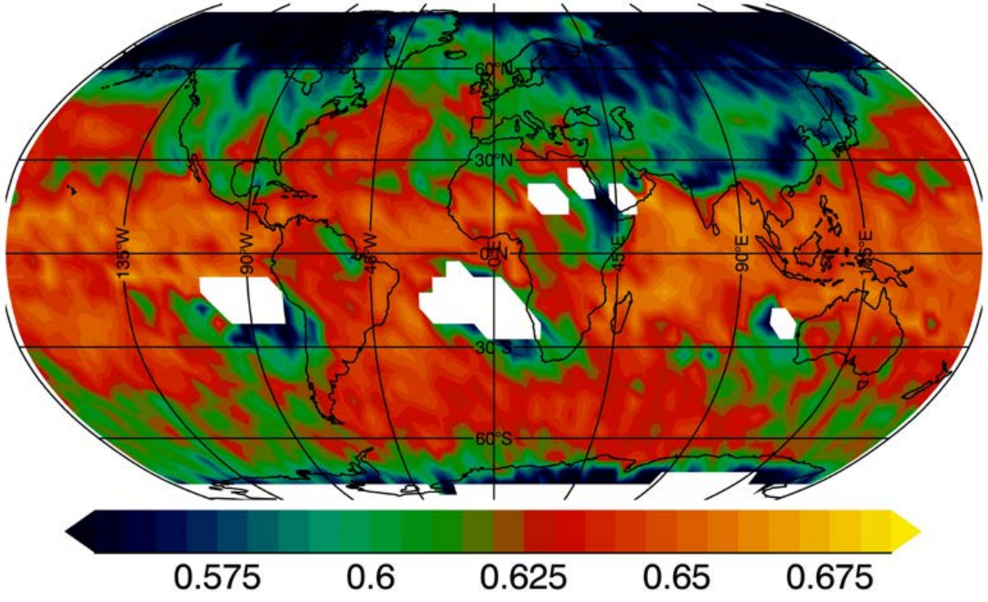




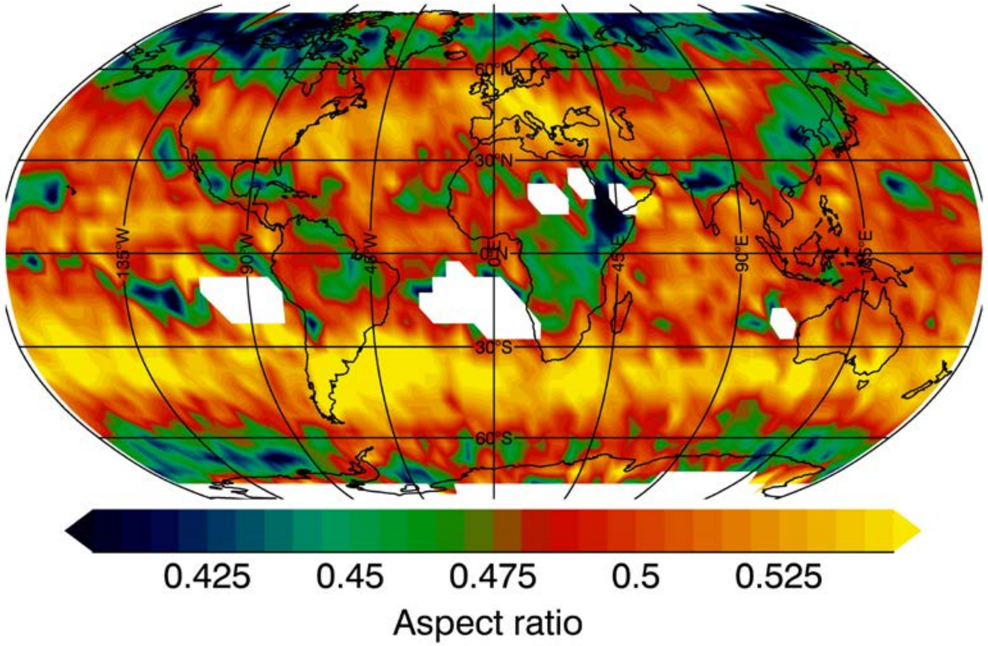



60°N
30°N
0°N
30°S
60°S
135°W
90°W
45°W
45°E
90°E
135°E
28
31
34
37
40
43
Effective radius (g corrected) [μm]

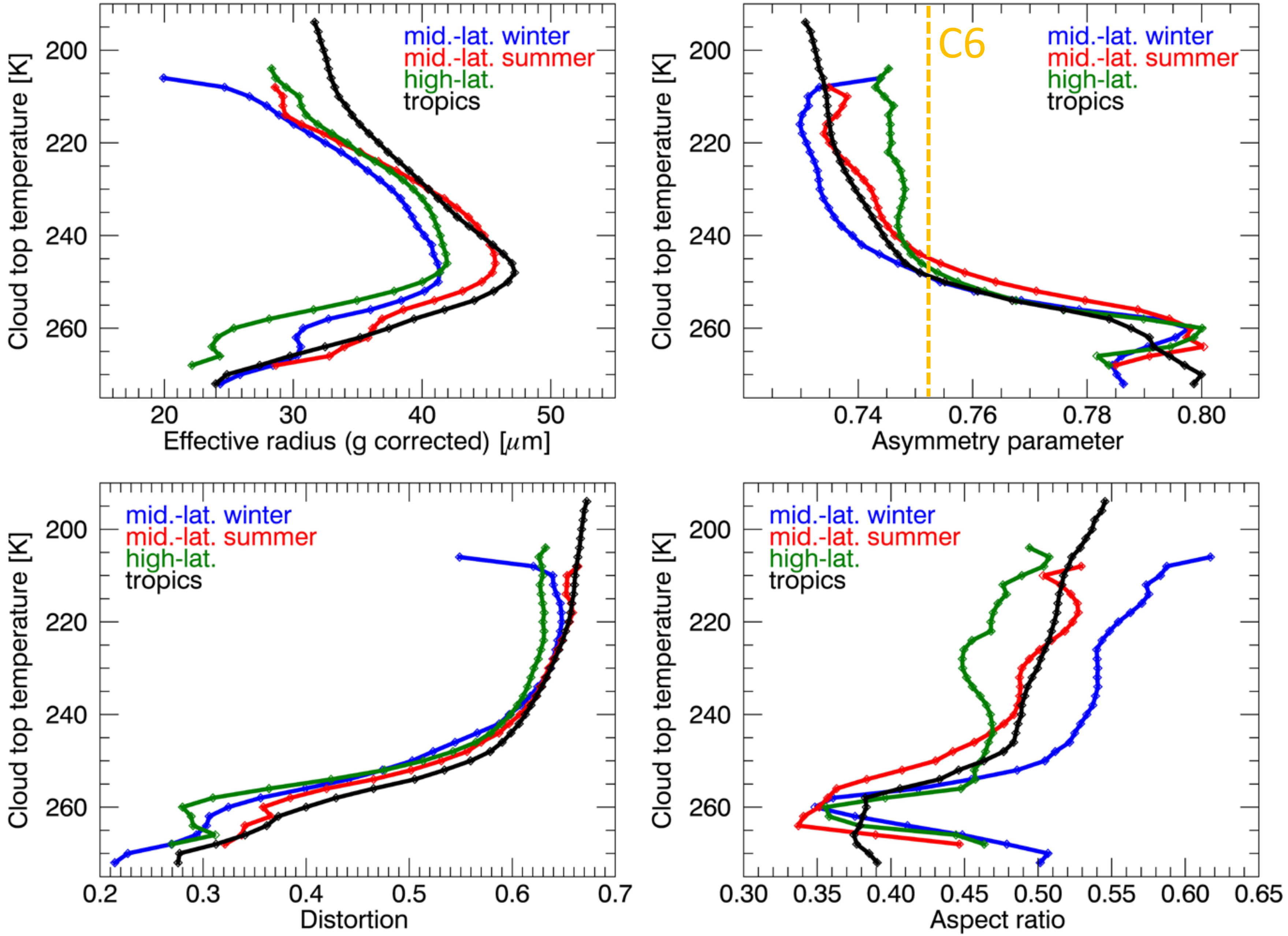

60°N
30°N
0°N
30°S
60°S
135°W
90°W
45°W
45°E
90°E
135°E
0.735
0.74
0.745
0.75
0.755
Asymmetry parameter


60°N
30°N
0°N
30°S
60°S
135°W
90°W
45°W
45°E
90°E
135°E
0.575
0.6
0.625
0.65
0.675

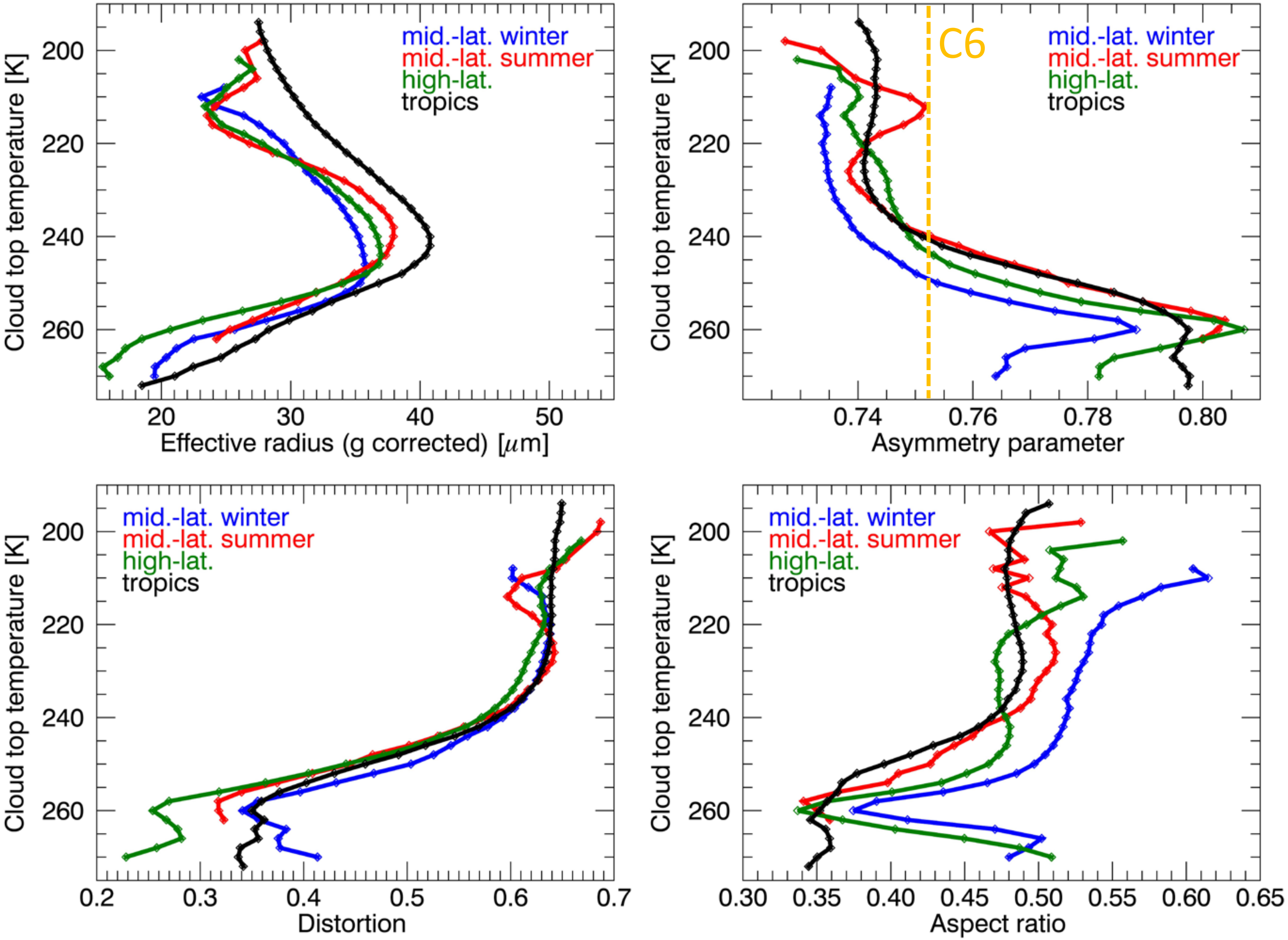
distortion


60°N
30°N
0°N
30°S
60°S
135°W
90°W
45°W
45°E
90°E
135°E
0.425
0.45
0.475
0.5
0.525
Aspect ratio

Vertical variation of ice properties over **ocean**

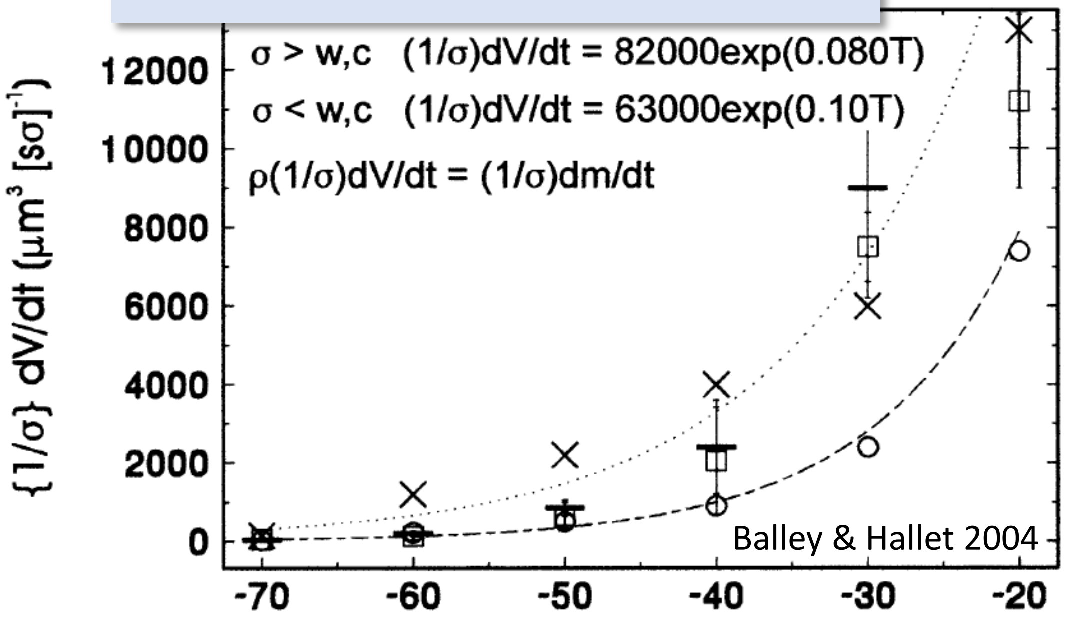


Vertical variation of ice properties over **land**

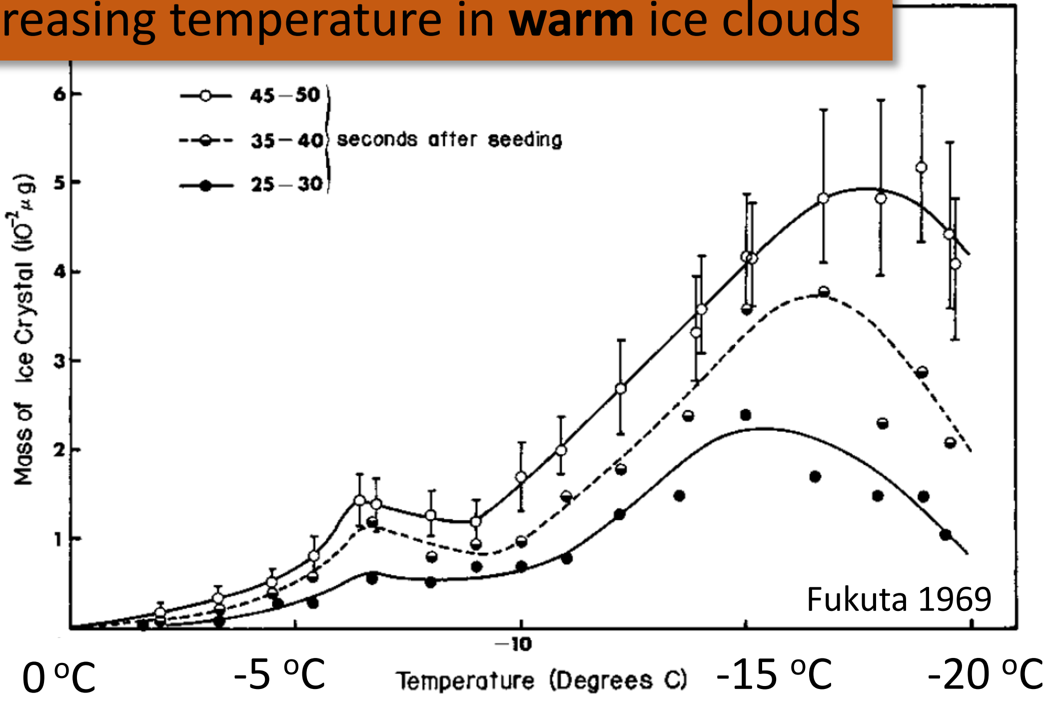


Ice growth theory predicts sizes to decrease/increase with decreasing temperature for cold/warm clouds

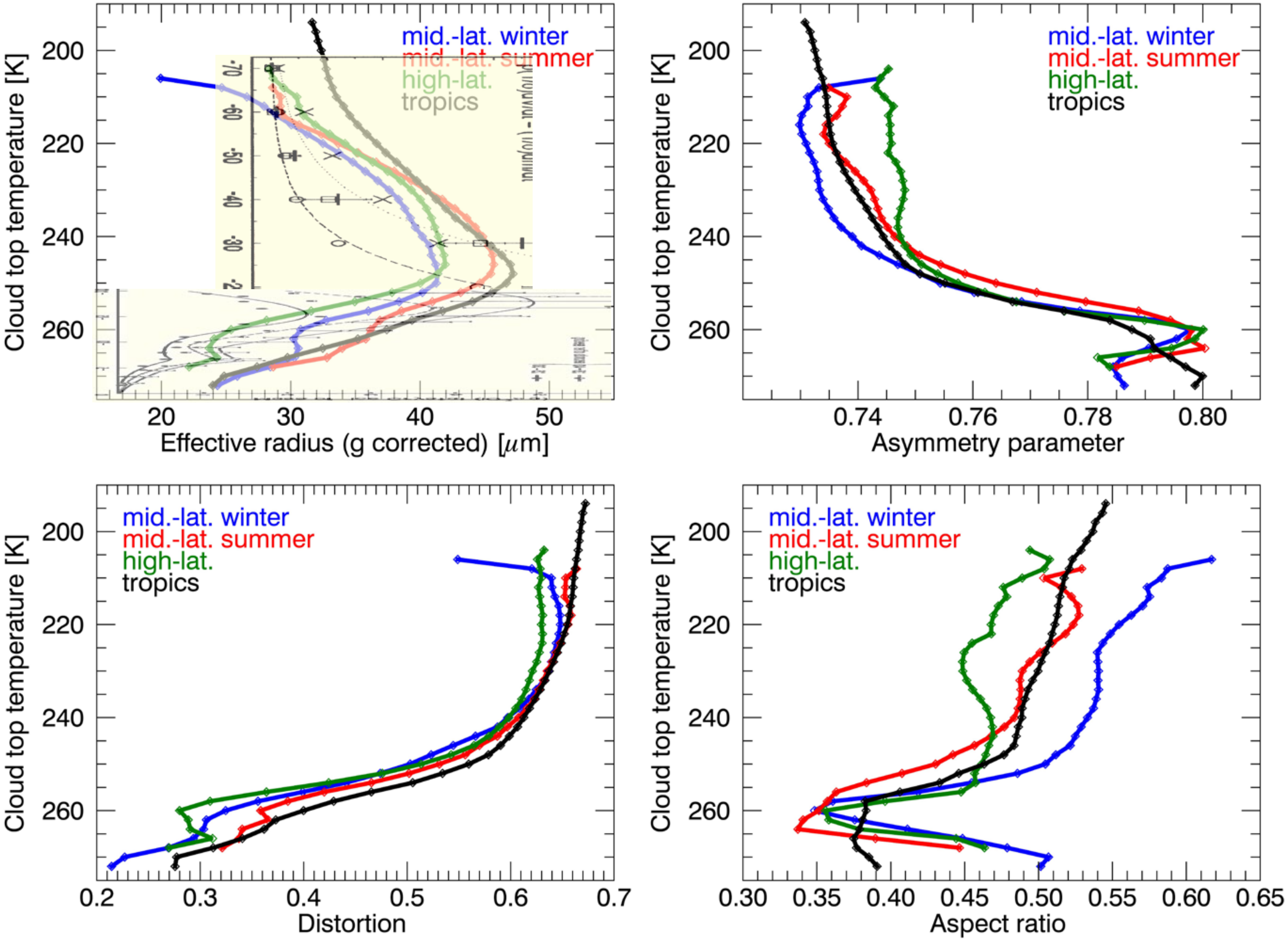
Ice mass growth rate *decreases* with decreasing temperature in **cold** ice clouds



Ice mass growth rate *increases* with decreasing temperature in **warm** ice clouds

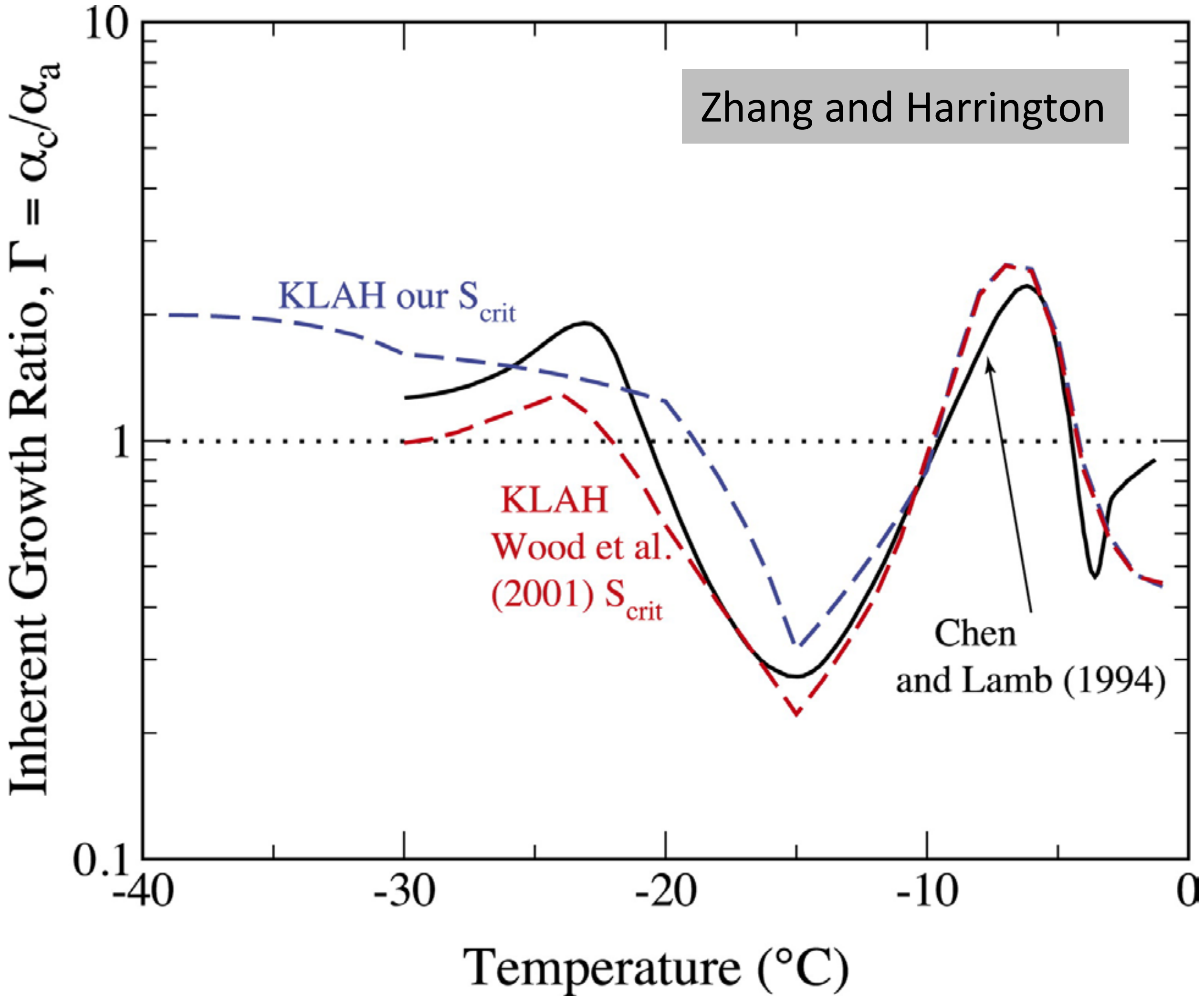


Vertical variation of ice properties over ocean



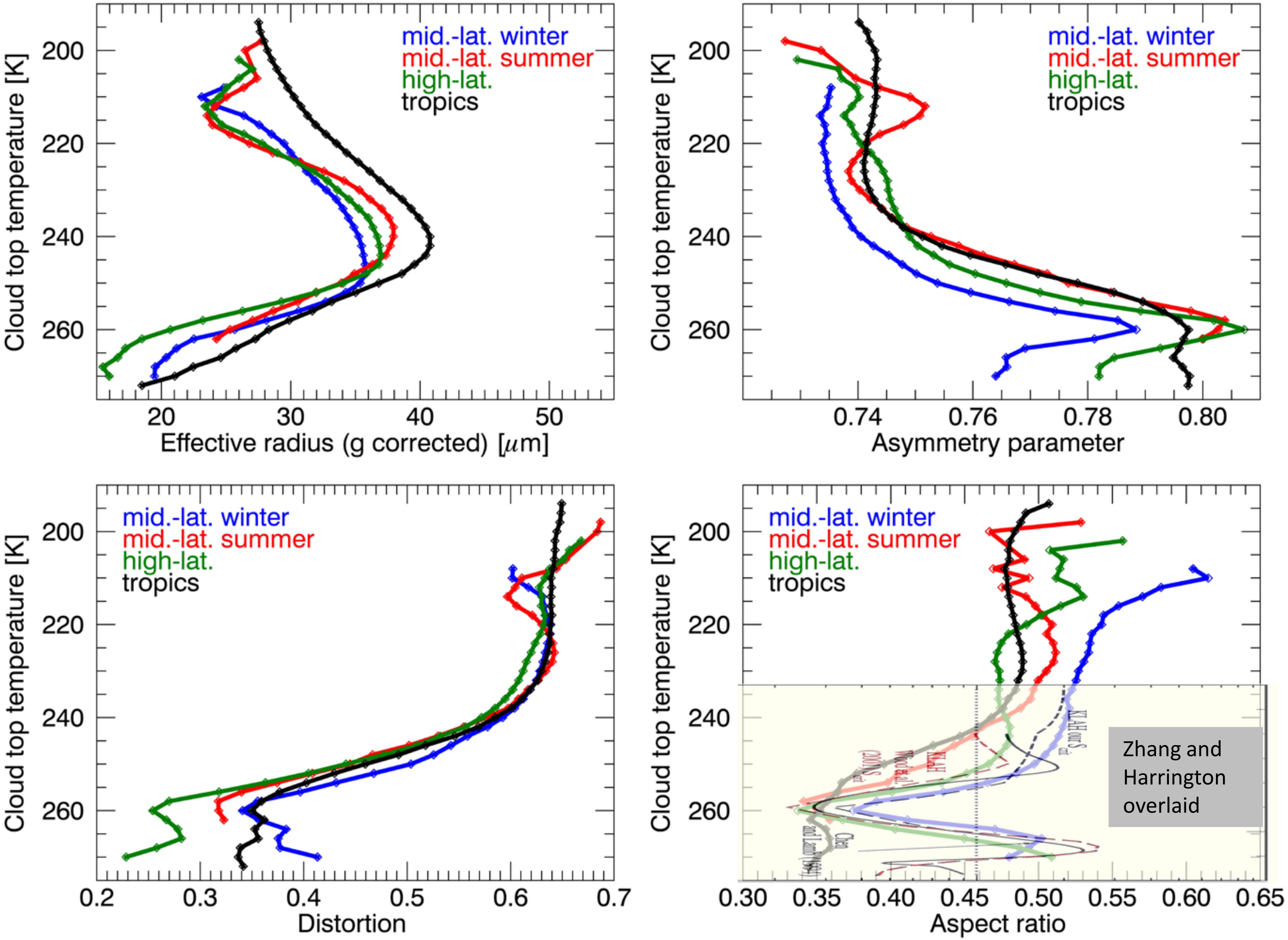
Observations and theory of aspect ratio evolution from vapor deposition

- Aspect ratios:
  - close to 0.5 (i.e. 1/2)
  - dip to ~0.3 at -15°C (258K)
- Change from columns to plates to columns

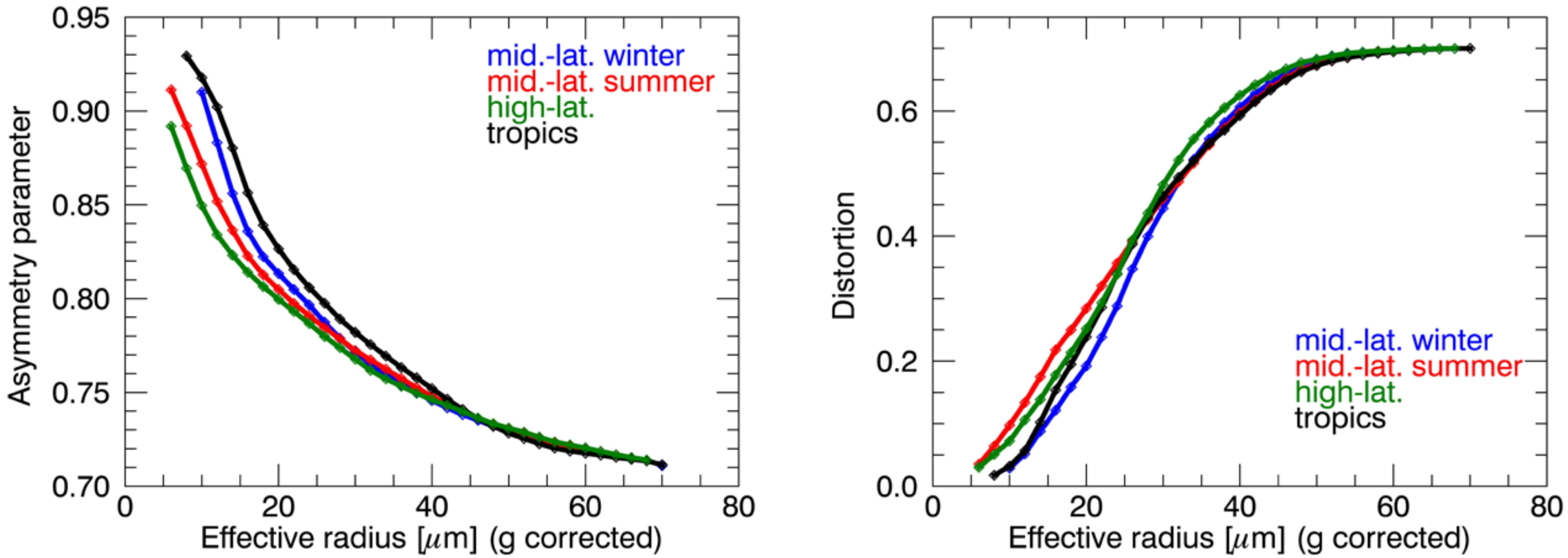


Vertical variation of ice properties over land

- Cloud top ice shape and sizes determined by vapor deposition growth
- Aggregation, size sorting, riming, etc. expected to lead to more complex picture *inside* clouds



Variation of shape and asymmetry parameter with effective radius



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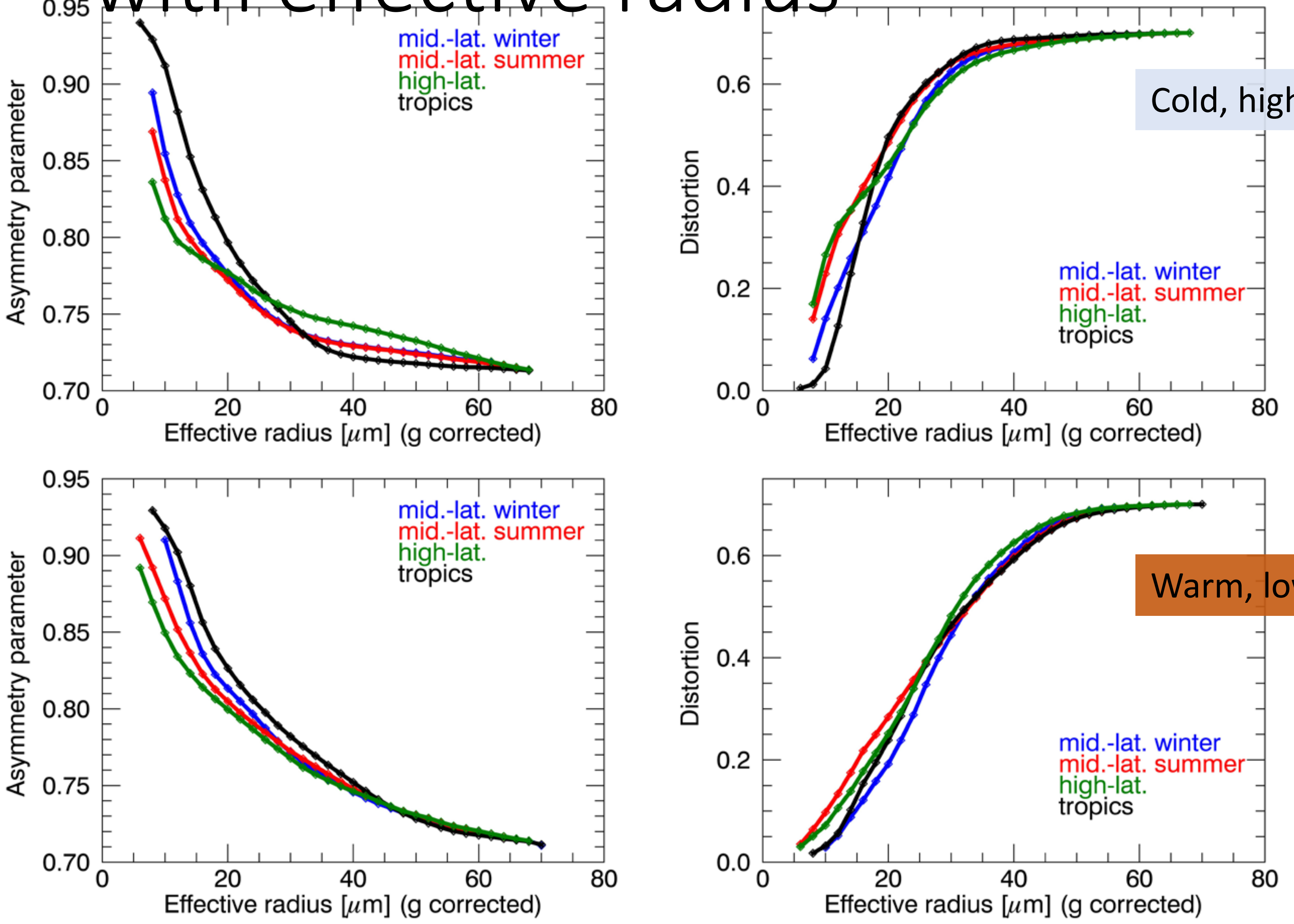
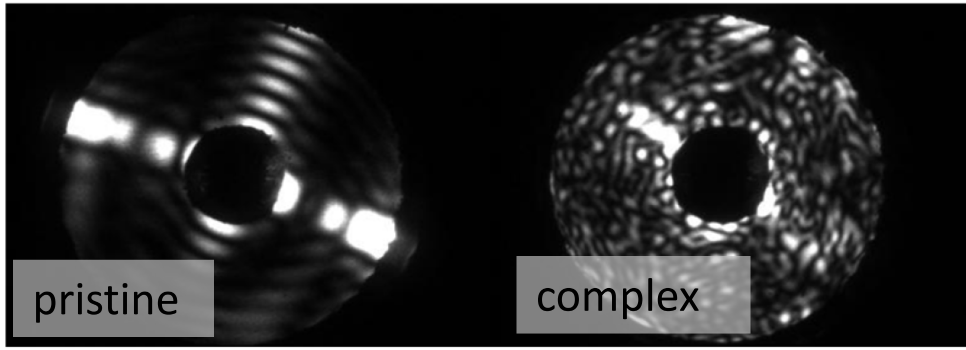


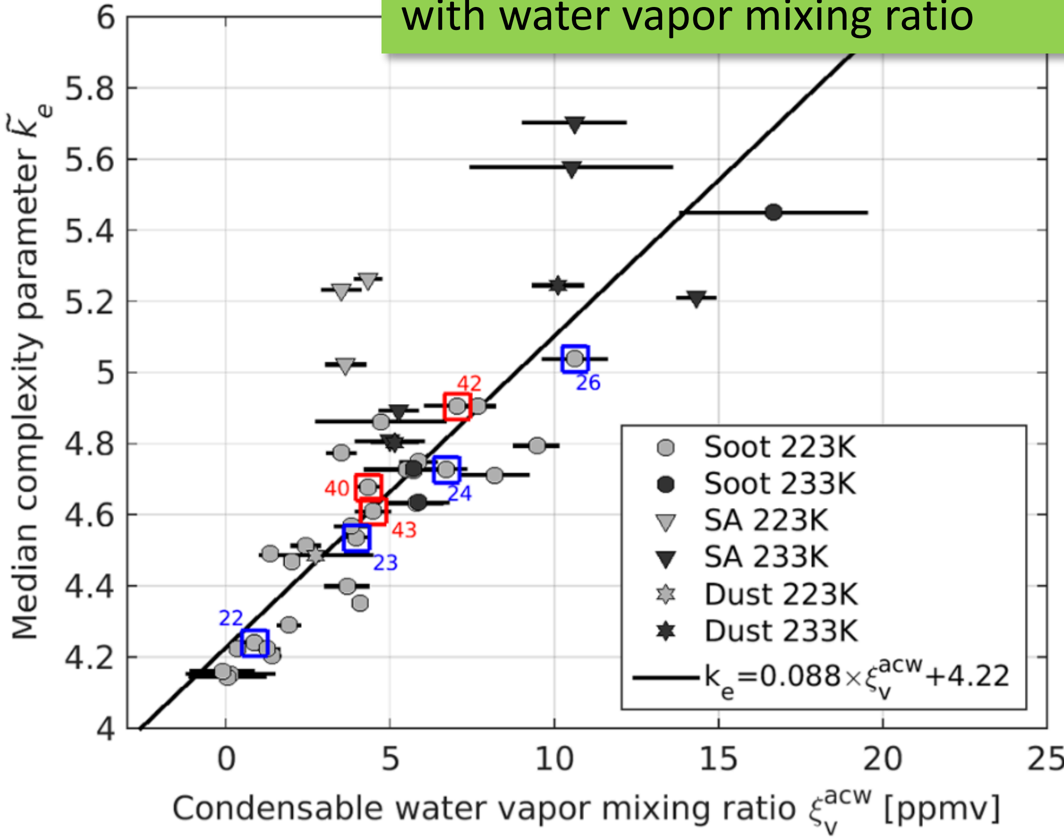
Cold, high ice clouds

Warm, low ice clouds

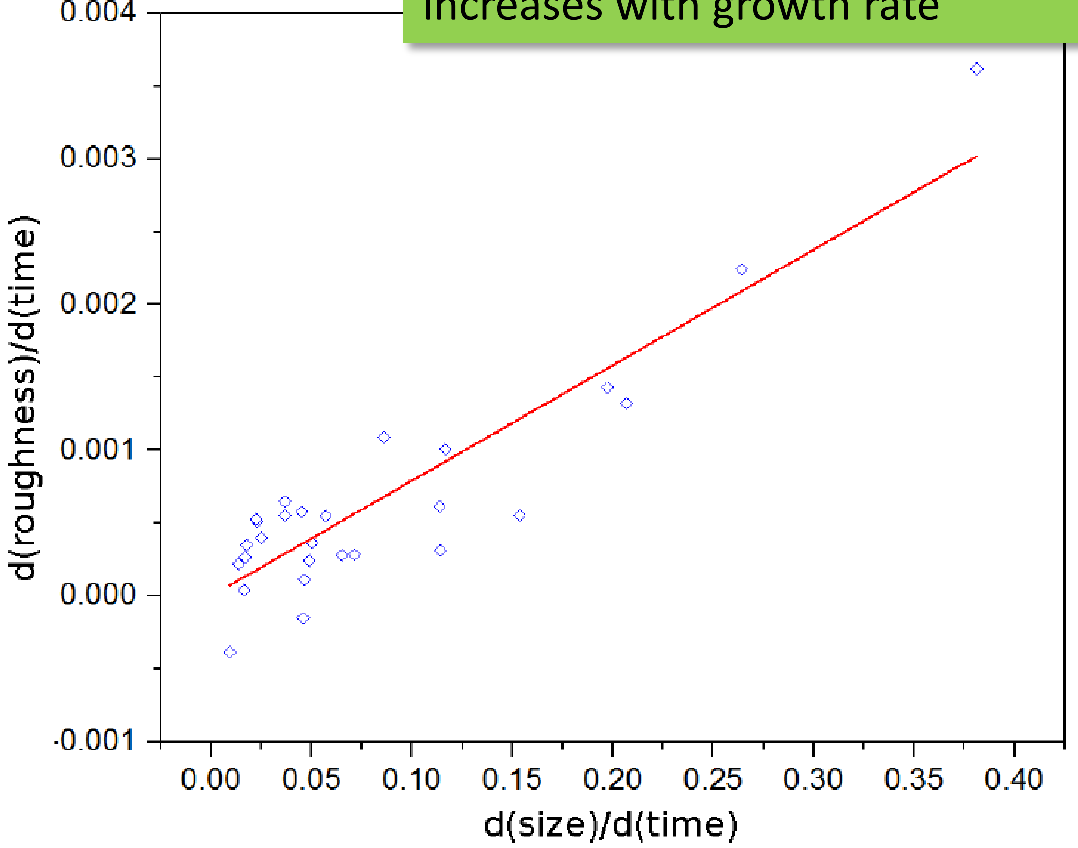
Cloud chamber and lab studies on roughness/complexity using Small Ice Detector (SID-3) probe



Schnaiter et al.: complexity increases with water vapor mixing ratio



Voigtländer et al.: complexity increases with growth rate



Particle complexity from CPI and PHIPS probes

Schmitt et al.: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Geophysical Research Letters

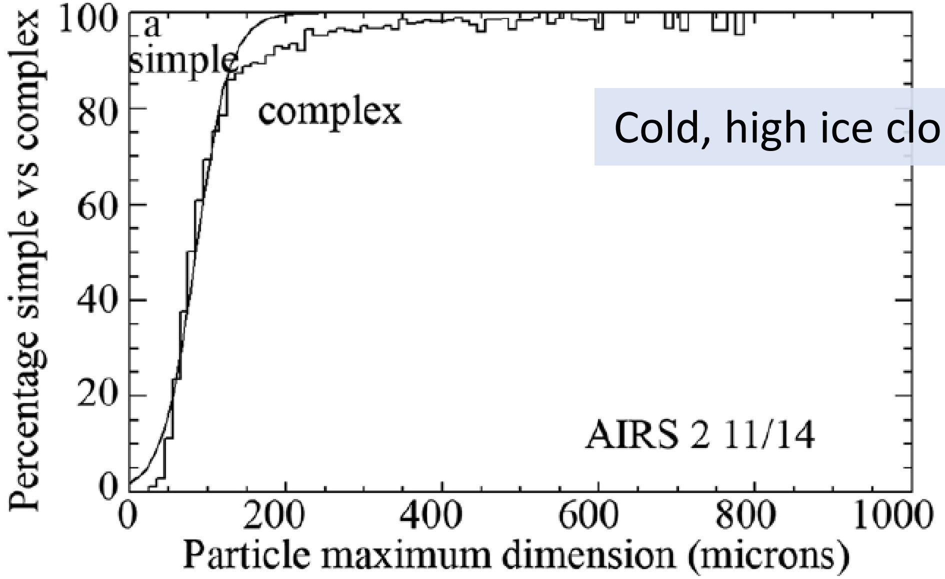
RESEARCH LETTER

10.1002/2016GL071267

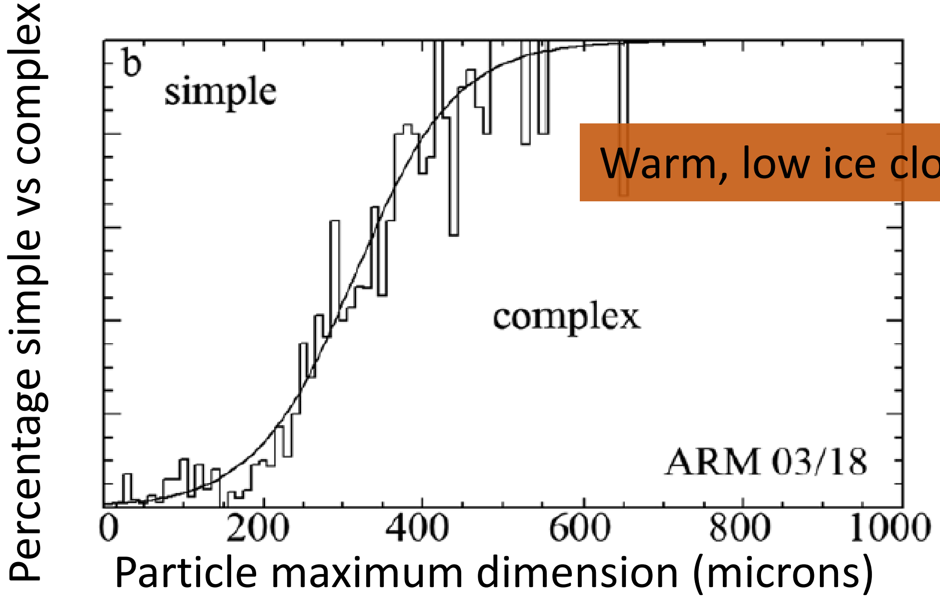
A global view of atmospheric ice particle complexity

Carl G. Schmitt[1], Andrew J. Heymsfield[1], Paul Connolly[2], Emma Järvinen[3], and Martin Schnaiter[3]

- Using Cloud Particle Imager (CPI) and Particle Habit Imaging and Polar Scattering (PHIPS) instrument
- **Small** crystals are **simple**
- **Large** particles are **complex**
- Transition from simple to complex depends to temperature

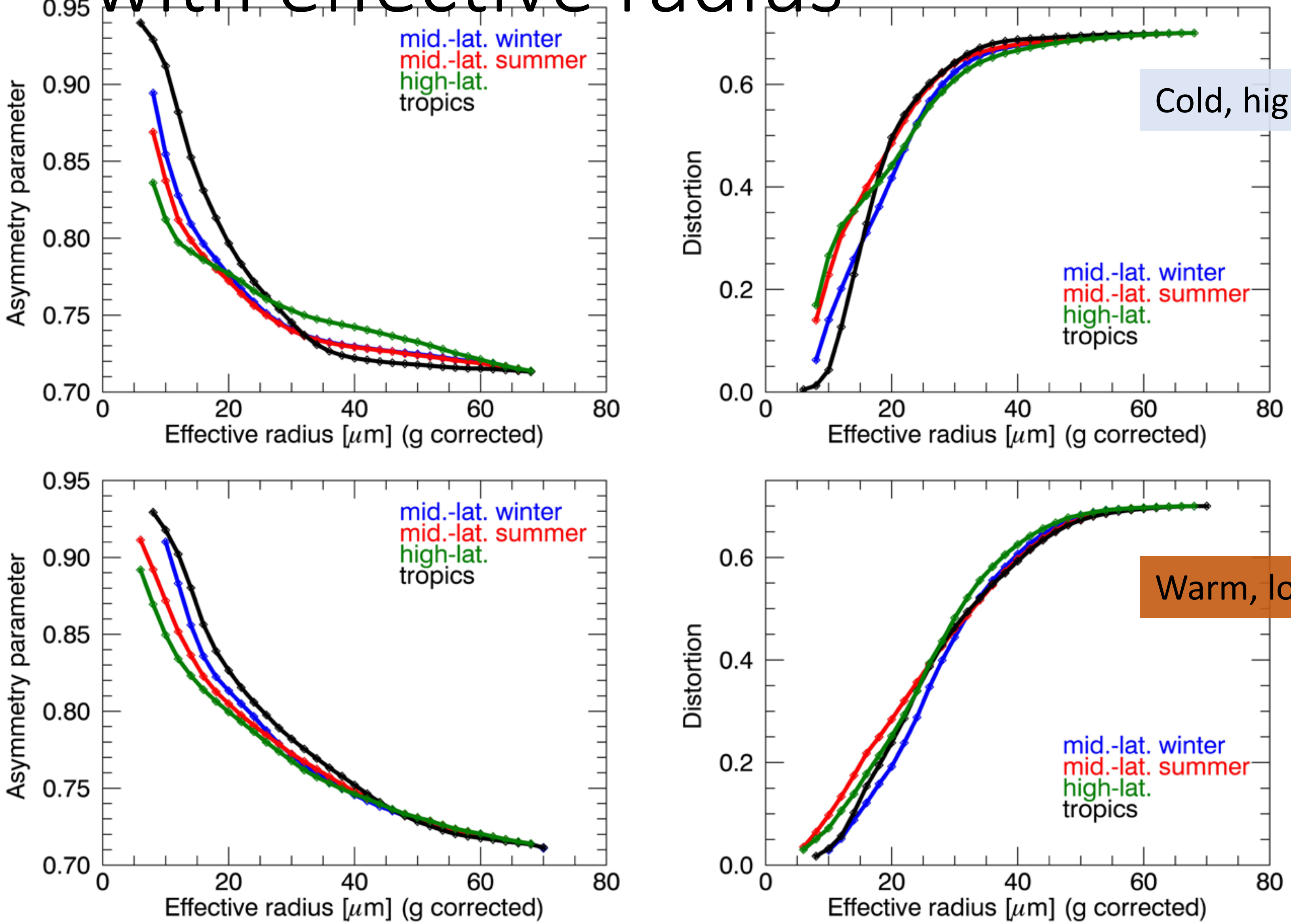


Cold, high ice clouds



Warm, low ice clouds

Variation of shape and asymmetry parameter with effective radius



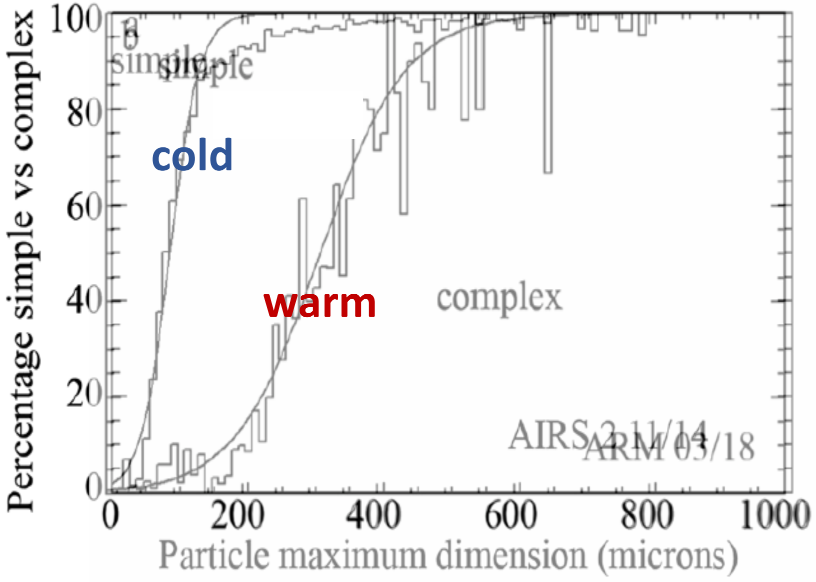
Cold, high ice clouds

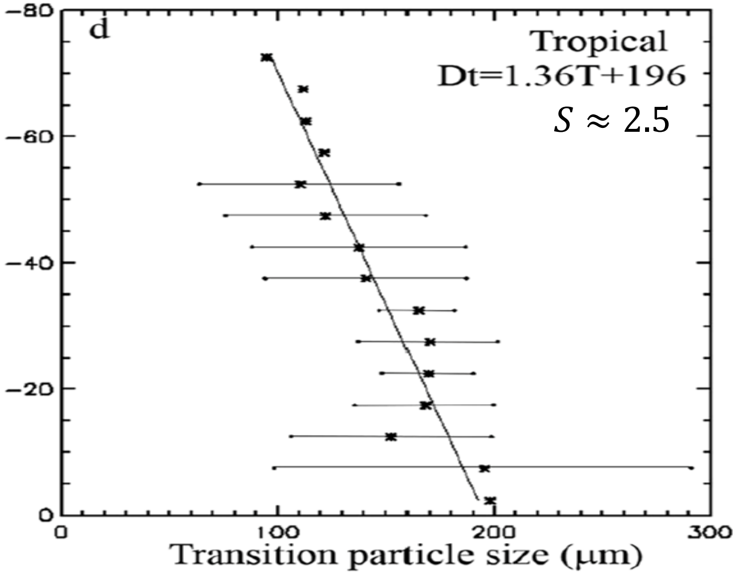
Warm, low ice clouds

Parametrization of distortion variation with r_e and T

Schmitt et al. 2016

$$f_{\text{complex}} = \left(\frac{\text{Tan}h(\frac{D_{max}}{D_t} - S)}{2} + 0.5\right)$$





Parametrization of distortion variation with r_e and T

Schmitt et al. 2016

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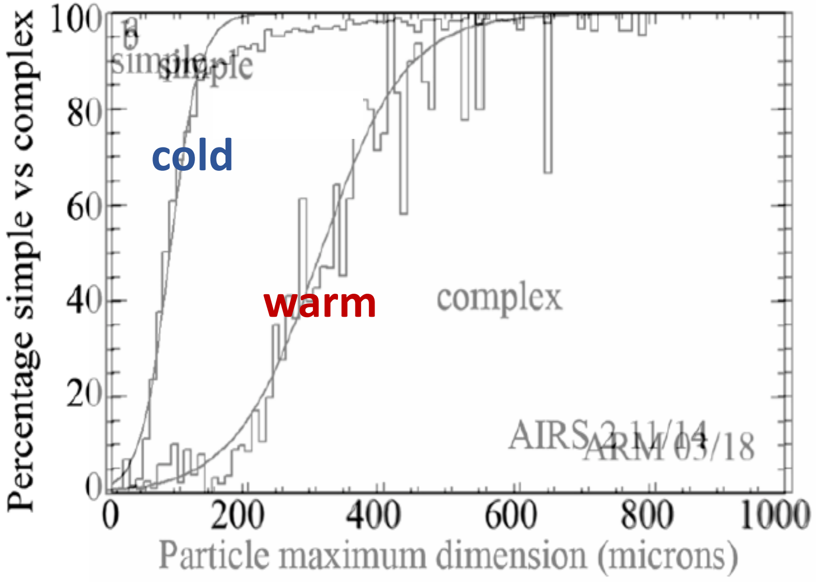
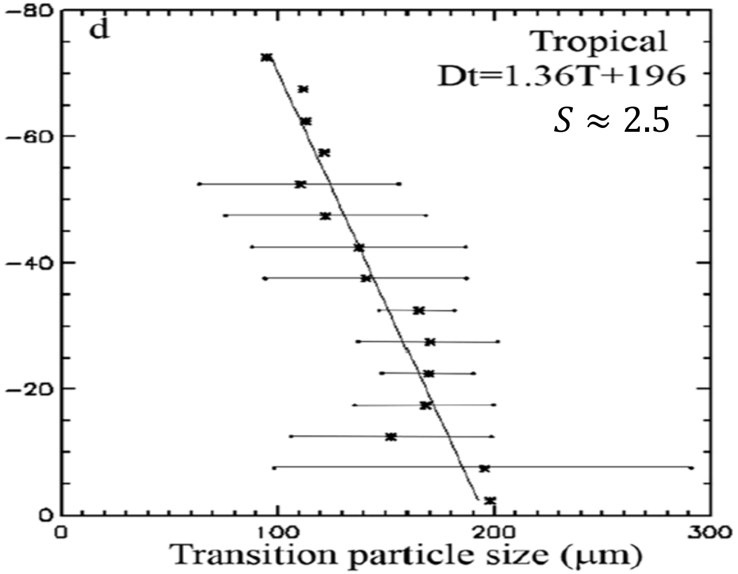
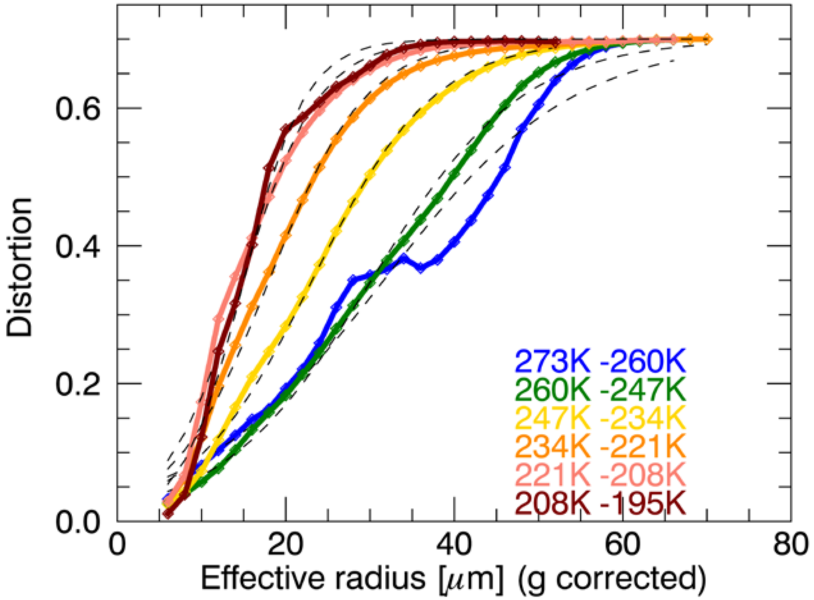
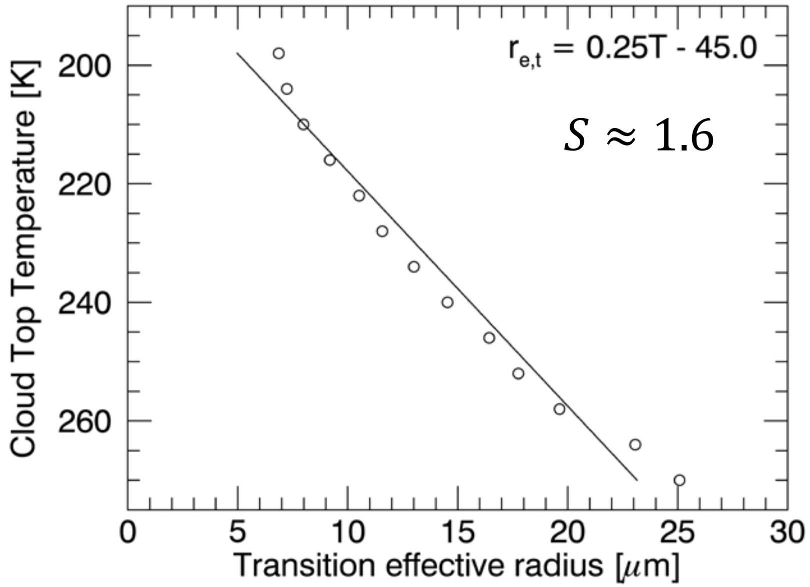




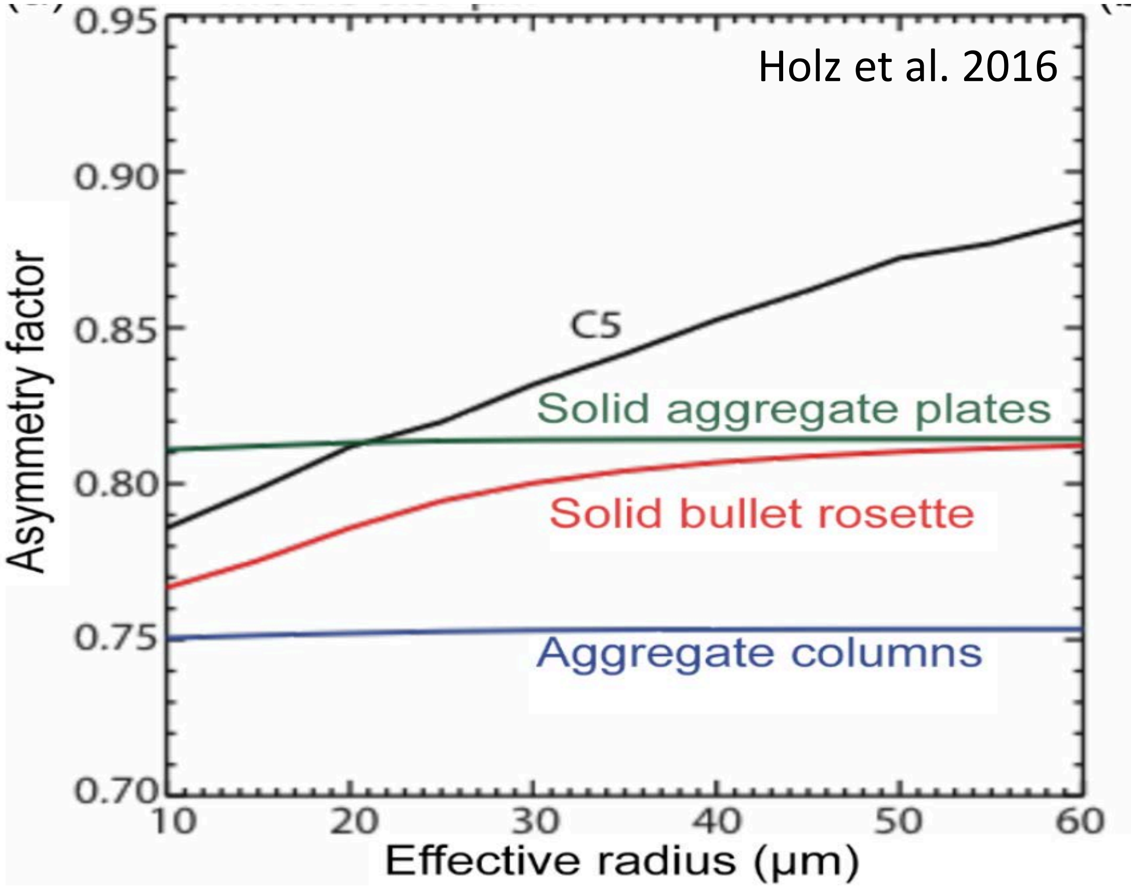
This work

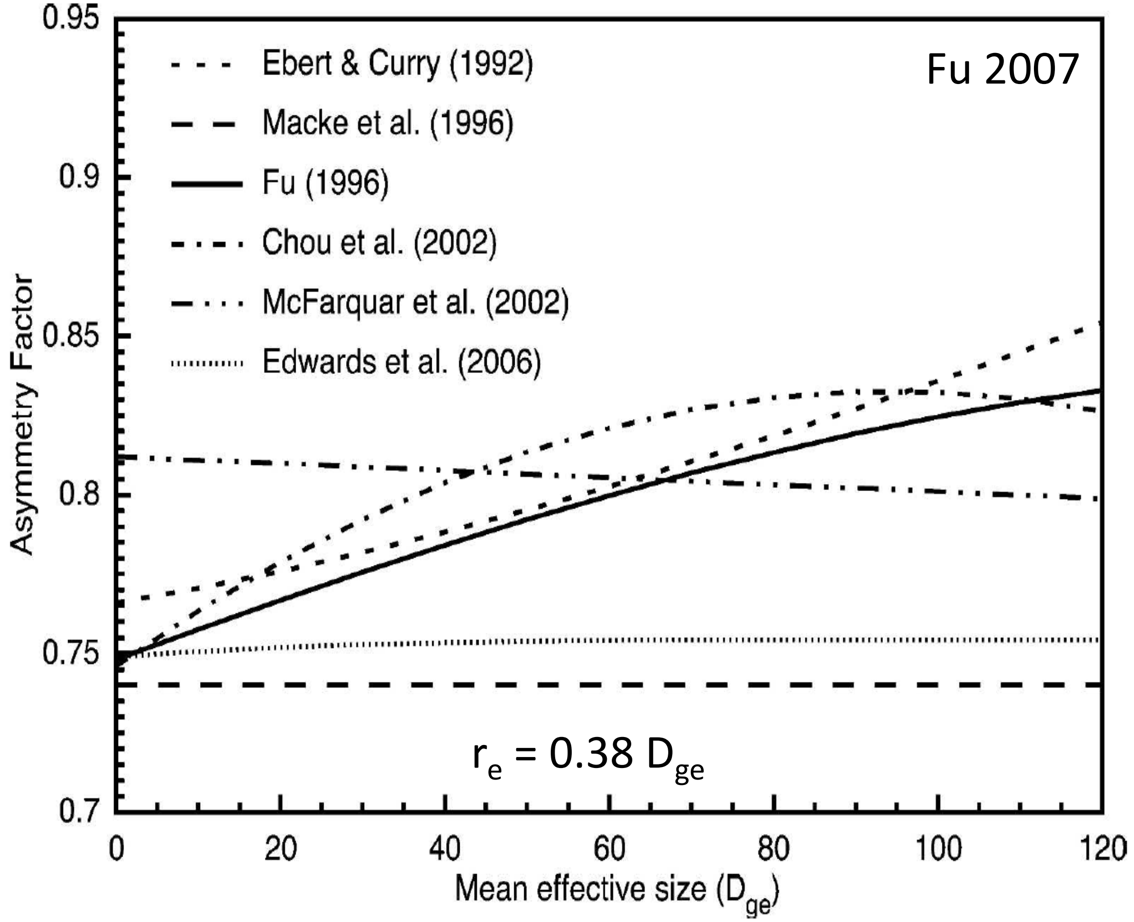
$$\delta_{\mathrm{fit}} = \left(\frac{\mathrm{Tan}h\left(\frac{r_e}{r_{e,t}} - S\right)}{2} + 0.5 \right)$$





Current ice optical models do not take into account distortion varying with size and temperature





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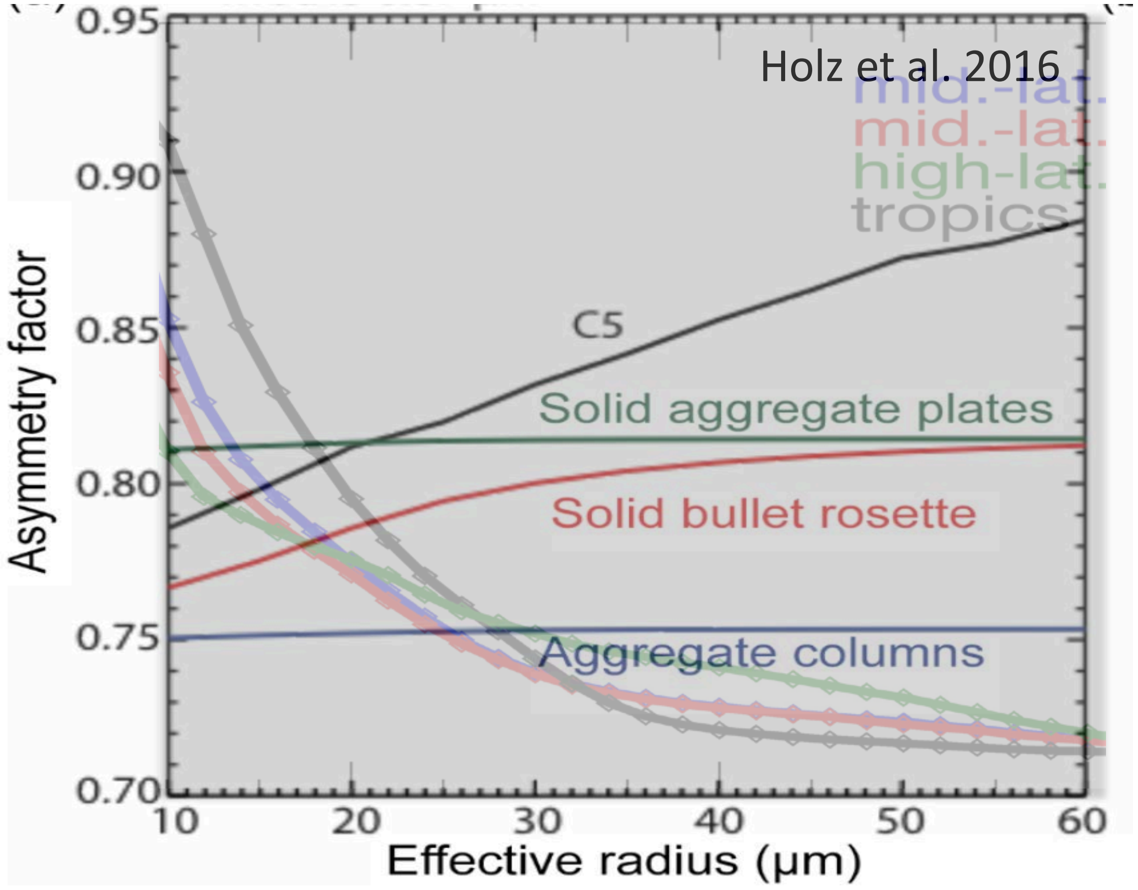
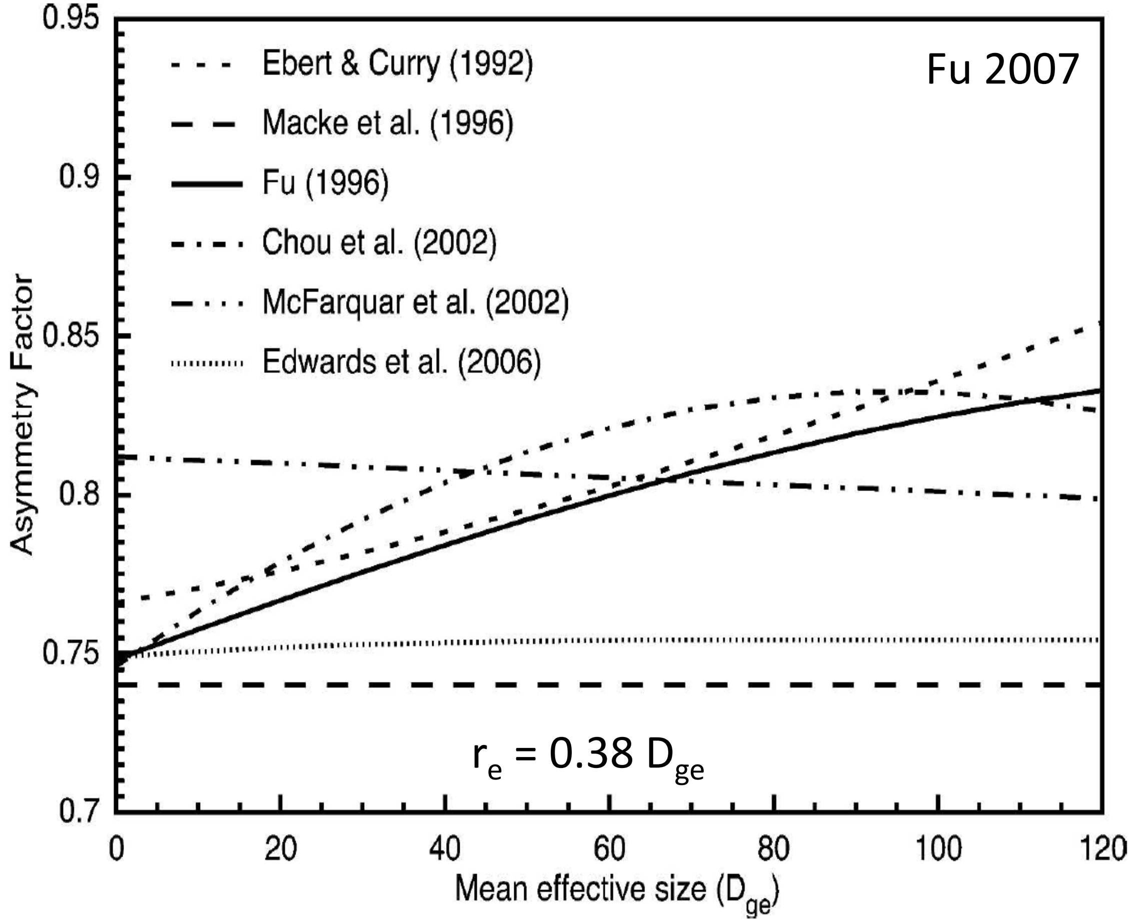


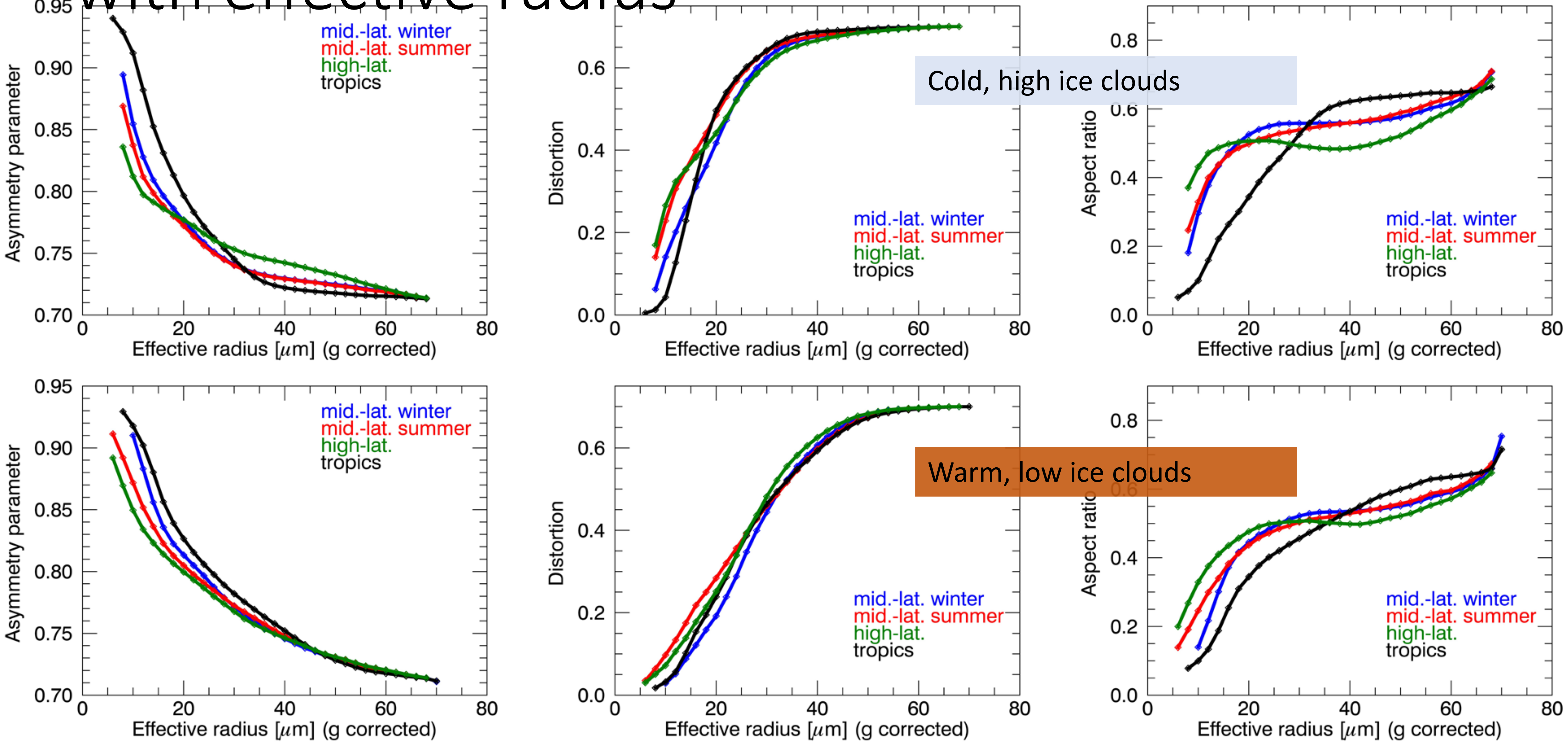


Conclusions

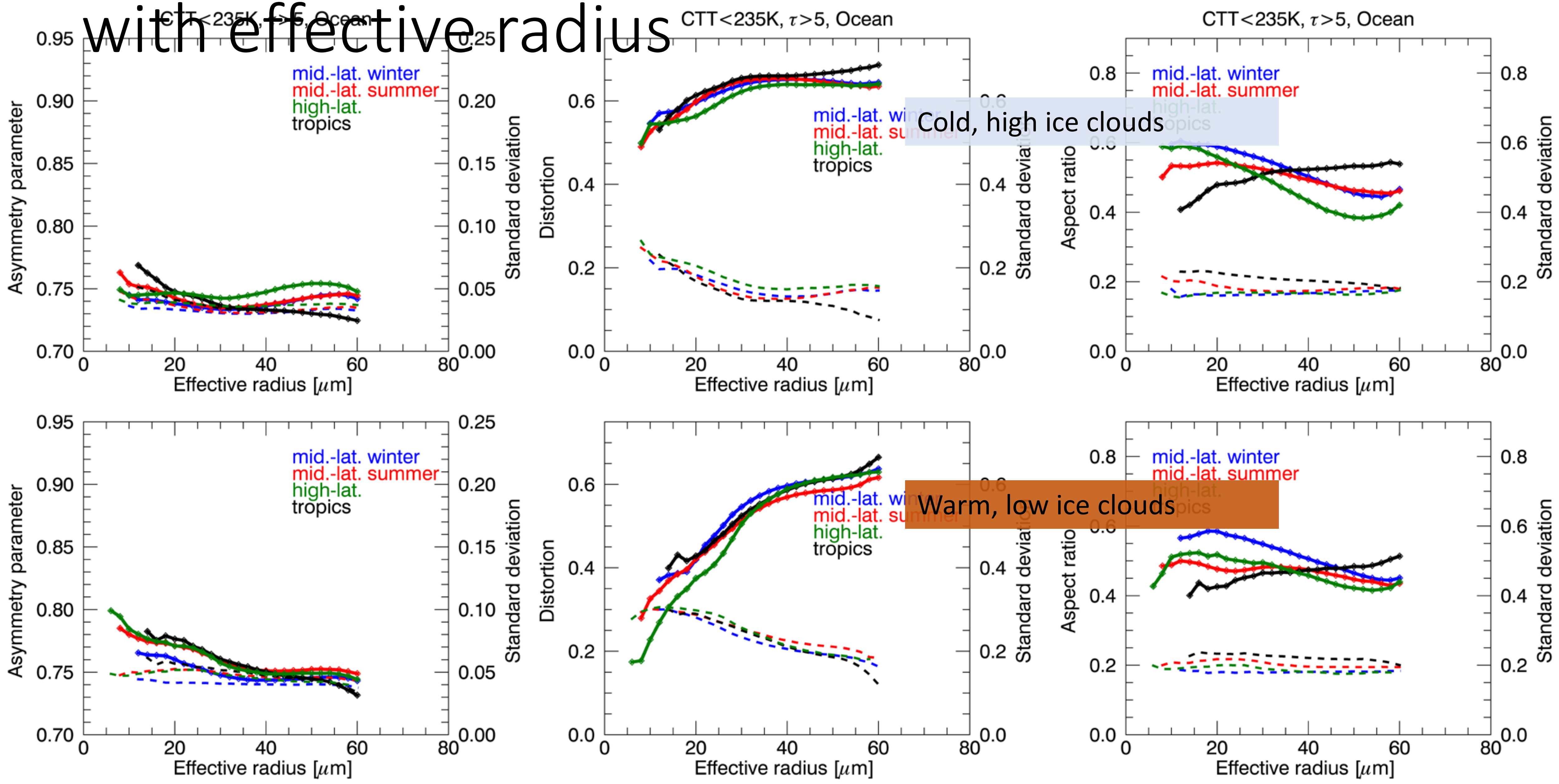
- Multi-angle polarimetry allows retrieval of ice shape characteristics
  - aspect ratio of crystal components
  - Degree of crystal distortion
- Suggests cloud top ice properties mostly determined by vapor growth
- Allows simple parameterization of distortion as function of effective radius and temperature
- Leads to asymmetry parameter decreasing with size in contrast to current models
- Ice shape retrievals method can be applied to
  - Airborne RSP
  - future missions:
    - 3MI
    - PACE polarimeters + Ocean Color Imager
    - CubeSat HARP

Backup

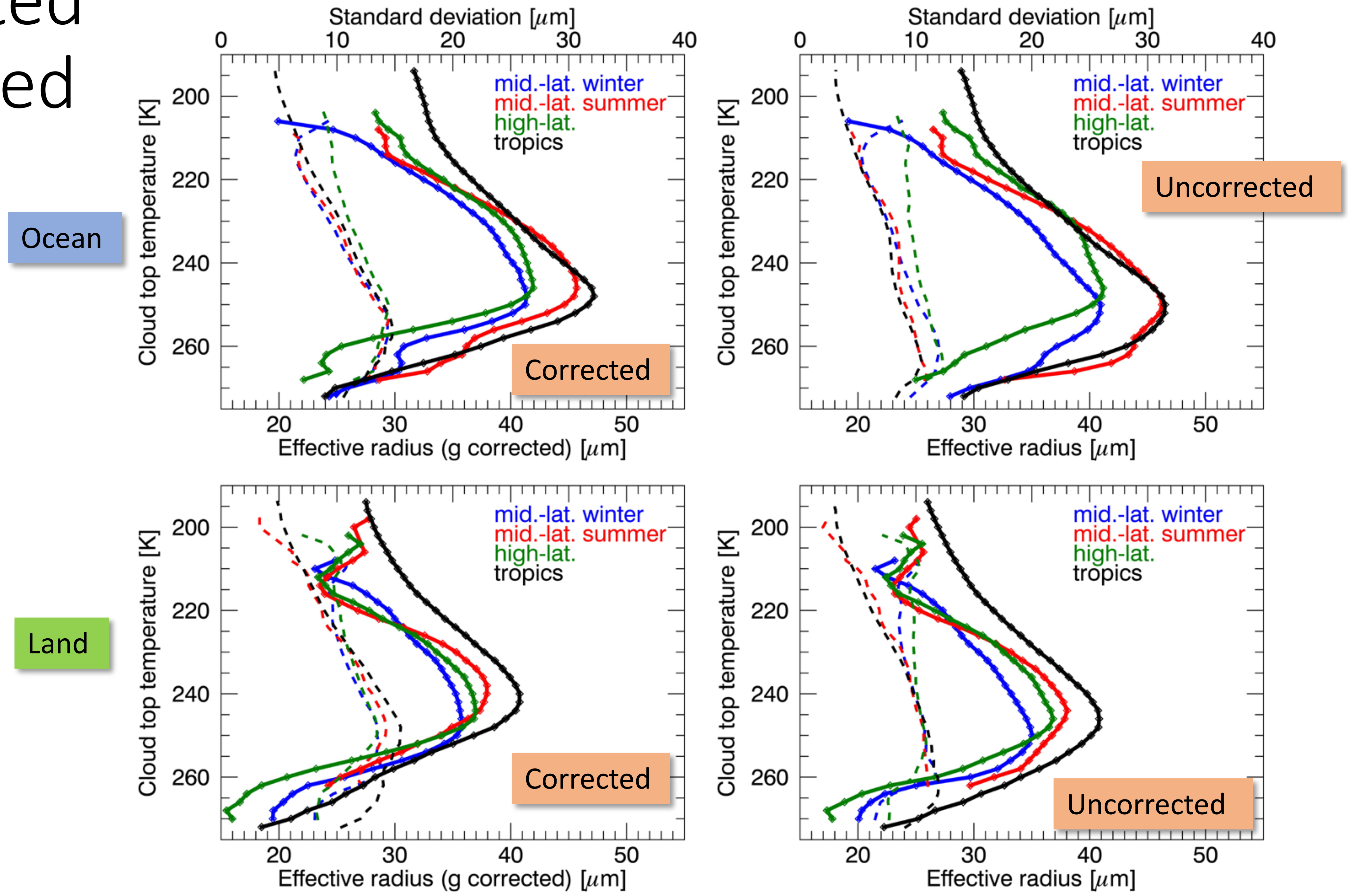
Variation of shape and asymmetry parameter with effective radius



Variation of shape and asymmetry parameter with effective radius

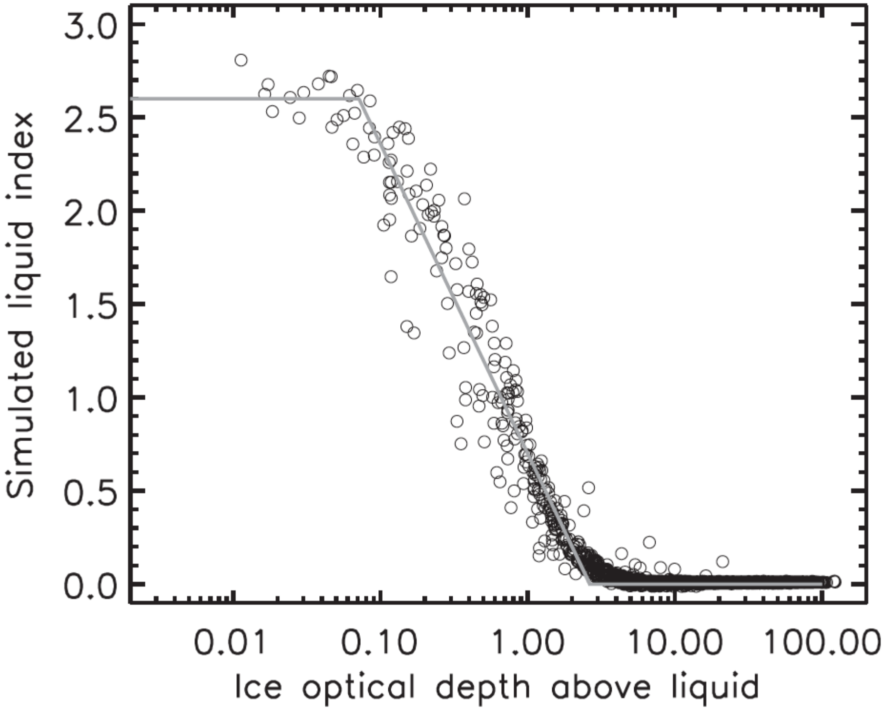


Uncorrected vs corrected

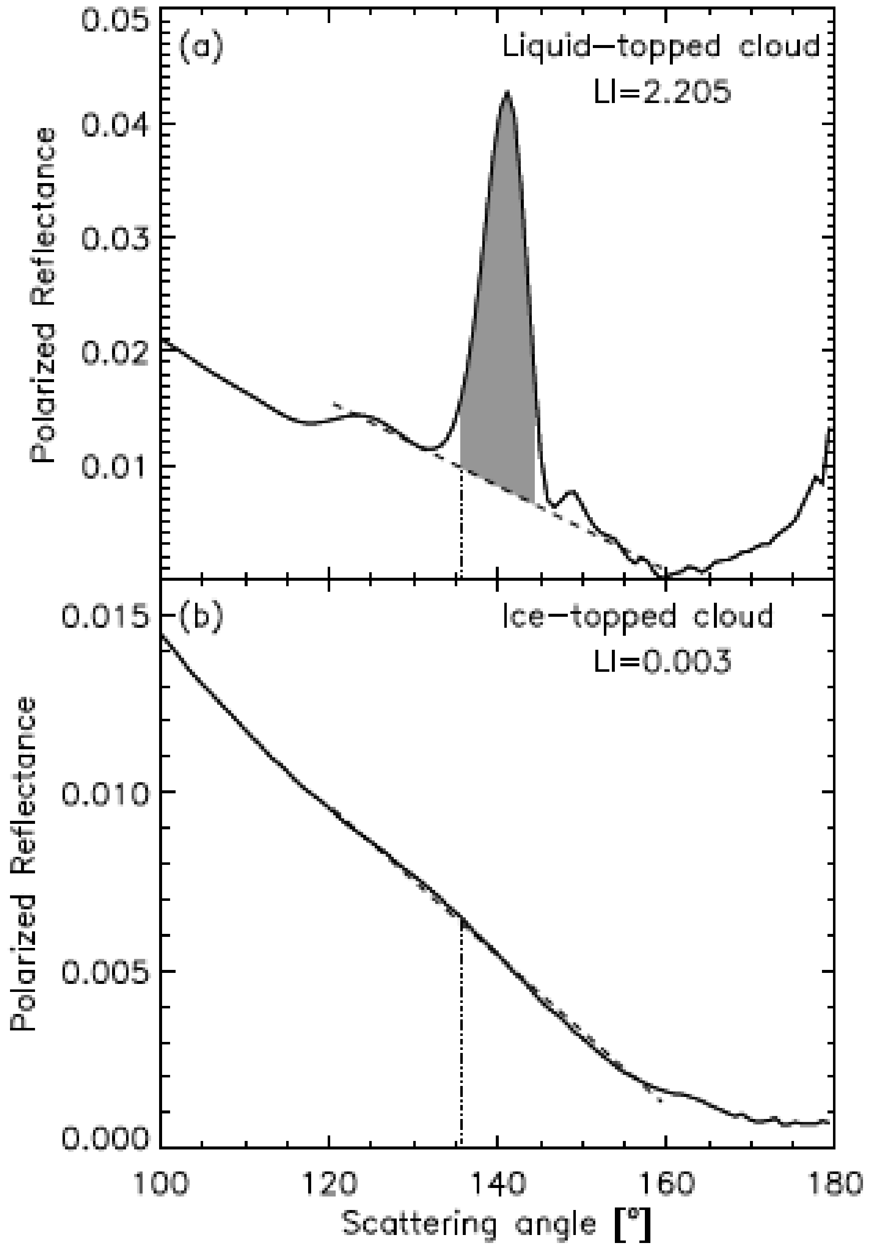


Polarimetry ‘liquid index’

- Fit straight line through 120°-160° measurements
- Liquid index = Mean(|fit-measurement|)
- Straight-forward to simulate from model
- Similar to POLDER technique (Goloub et al. 2000)
- LI>0.3 indicates liquid in the column

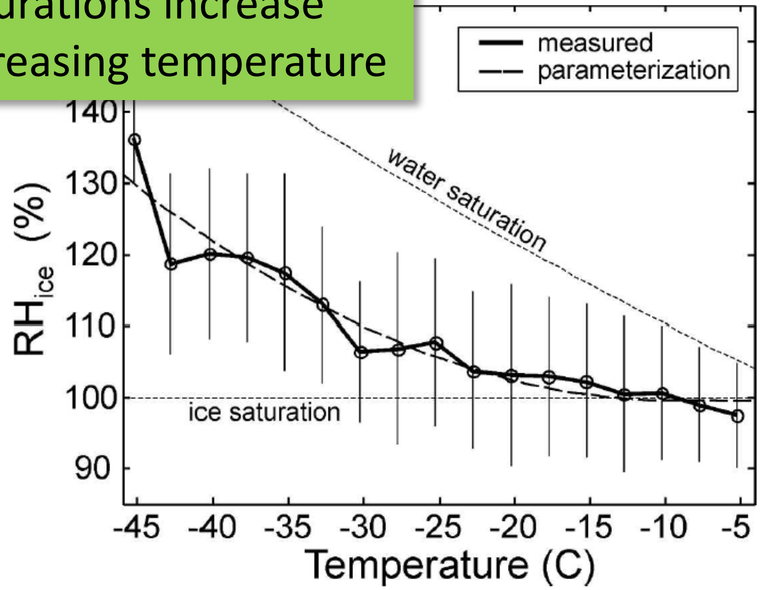


See also
van Diedenhoven et al., JAS, 2012

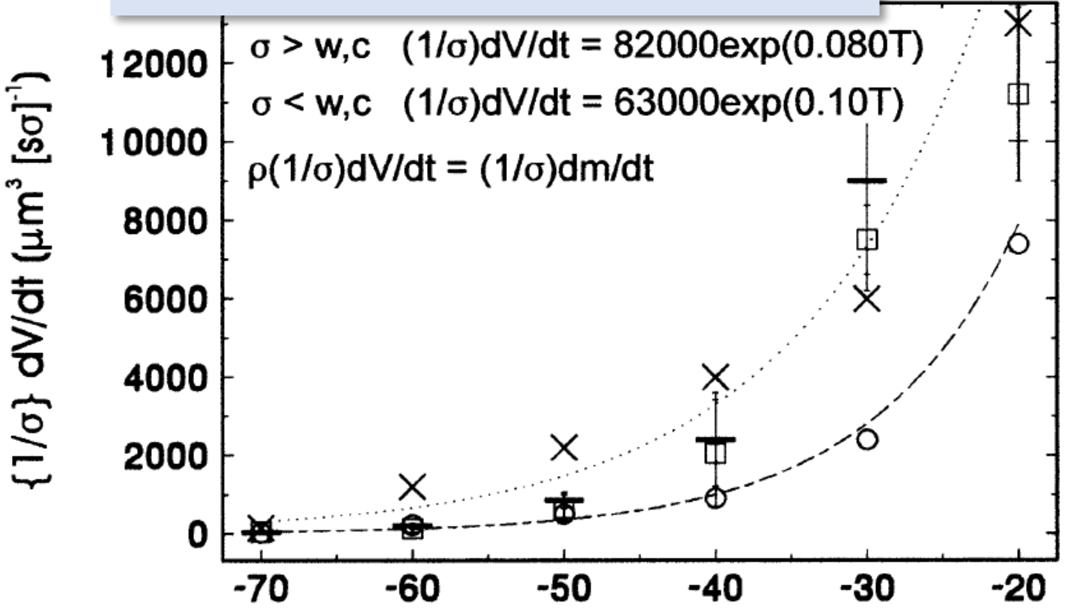


Ice growth theory predicts sizes to decrease/increase with decreasing temperature for cold/warm clouds

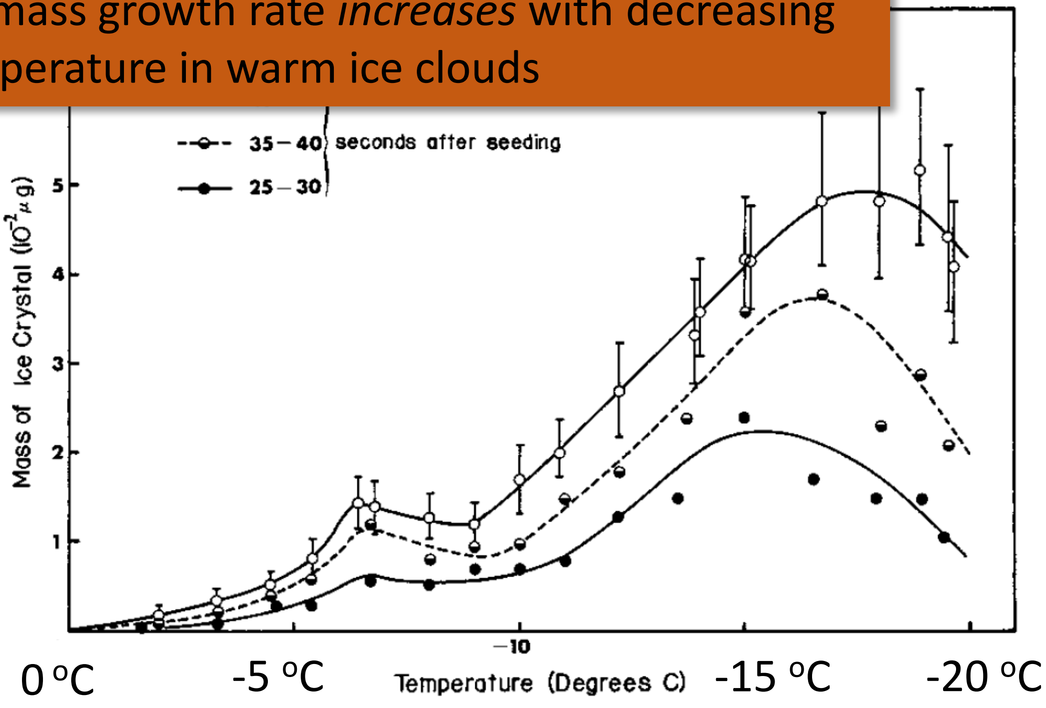
Supersaturations increase with decreasing temperature



Ice mass growth rate *decreases* with decreasing temperature in cold ice clouds



Ice mass growth rate *increases* with decreasing temperature in warm ice clouds



Cloud reflectance is determined by LWP, effective radius and asymmetry parameter

Visible cloud reflectance:

$$R \approx \frac{\tau(1-g)}{2\mu_0 + \tau(1-g)}$$

μ_0 = solar zenith angle

τ = optical thickness

g = asymmetry parameter of phase function

$$\tau \approx LWP \frac{3}{2\rho_i r_e}$$

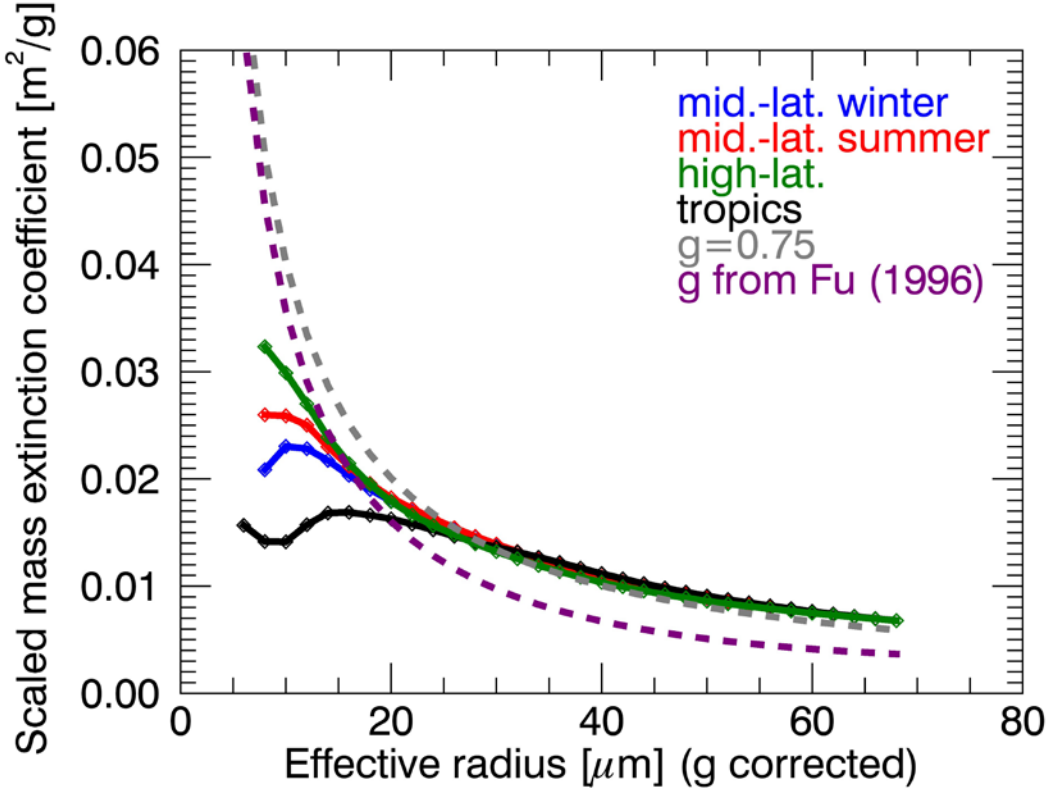
effective radius $r_e = \frac{3V}{4A_p}$

When $\varpi \neq 1$:
$R = f(\tau, g, \varpi, \mu_0)$

For ice:
$\varpi = f(r_e)$

Variation of asymmetry parameter reduces sensitivity of cloud reflection on crystal size

- Studies show ice size can increase *or* decrease because of cloud-aerosol interactions
- This work shows increased contribution to cloud reflectance by small crystals is diminished by increase of *g*



Visible reflectance:

$$R \approx \frac{\tau(1-g)}{2\mu_0 + \tau(1-g)}$$

$$\tau \approx M\Delta z \frac{3}{2\rho_i r_e}$$

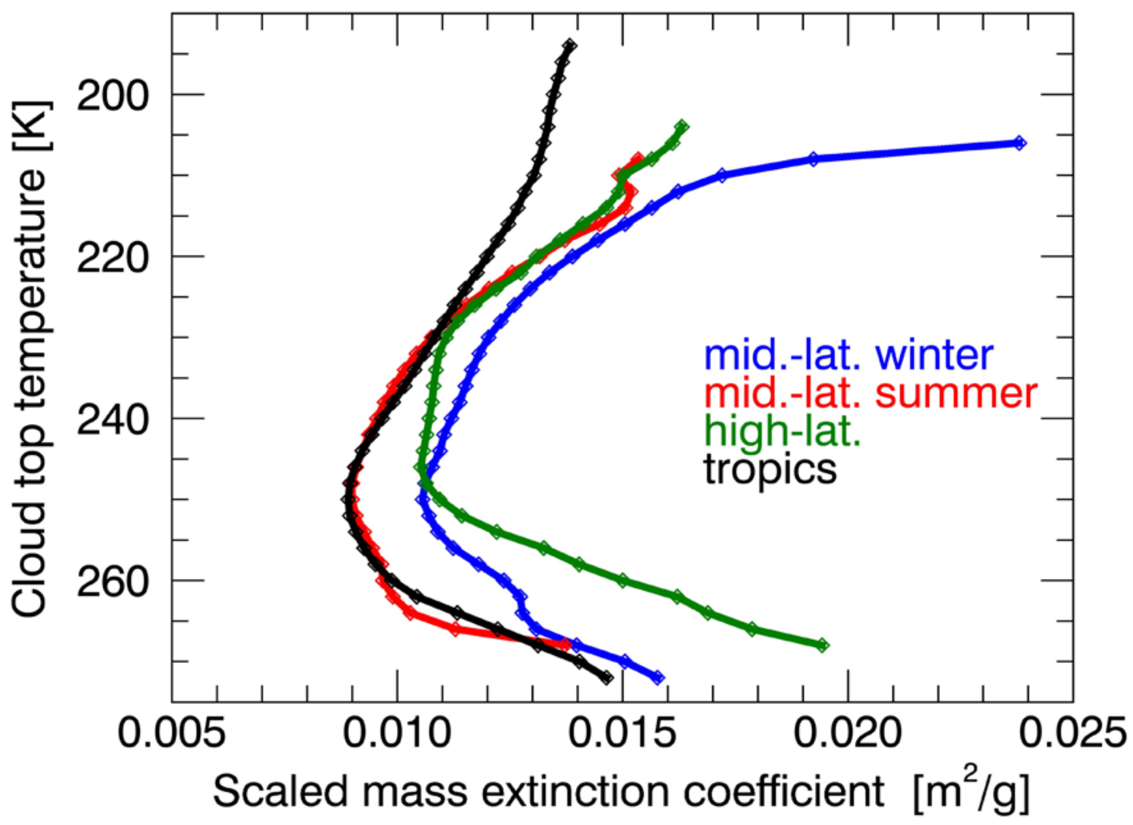
Mass extinction coefficient:

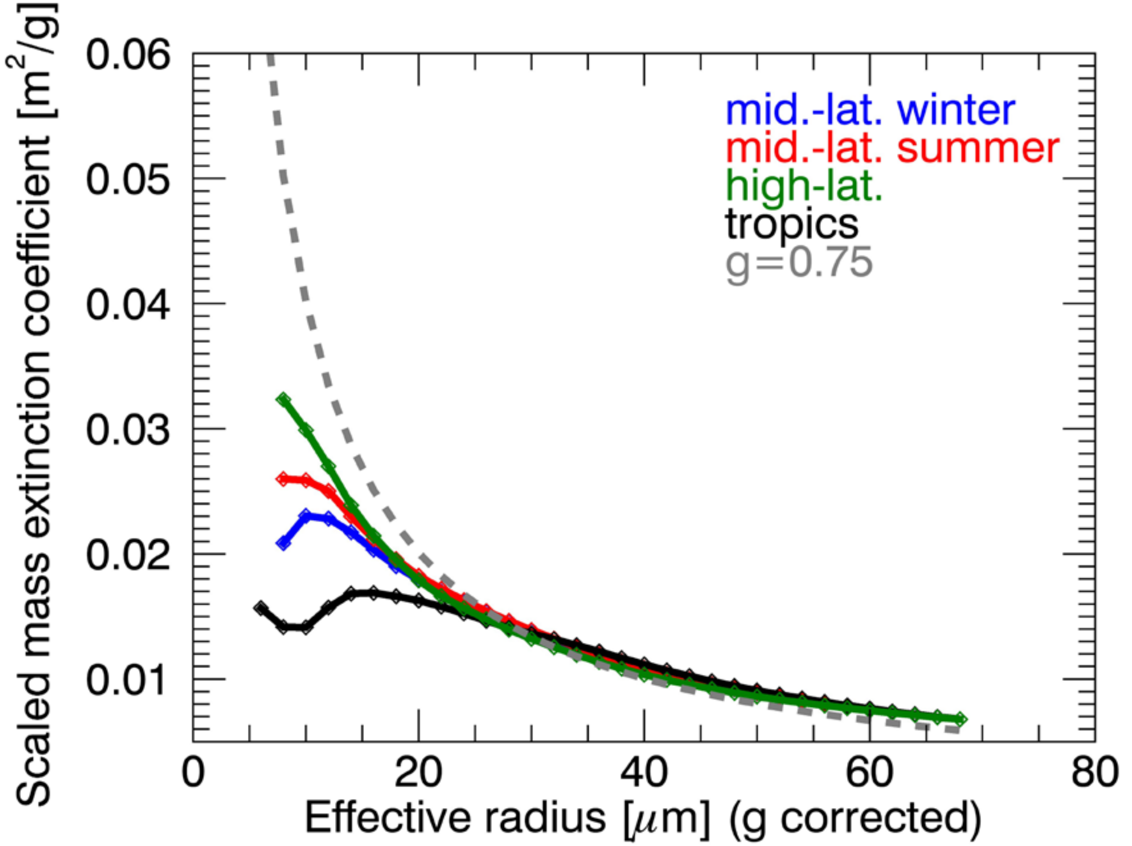
$$\beta_M = \frac{3}{2\rho_i r_e}$$

Scaled mass extinction coefficient

$$\beta_M = \frac{3}{2\rho_i r_e}(1-g)$$

scaled mass extinction and size





Single-scattering properties of aggregates of plates

Junshik Um* and Greg M. McFarquhar
Dept. of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

Projected area decreases with decreasing aggregation index (increasing compactness)
>>>
Effective radius increases with decreasing aggregation index (increasing compactness)
>>>
g decreases with increasing effective radius
&
'Effective' aspect ratio increases with effective radius (as components are more stacked)

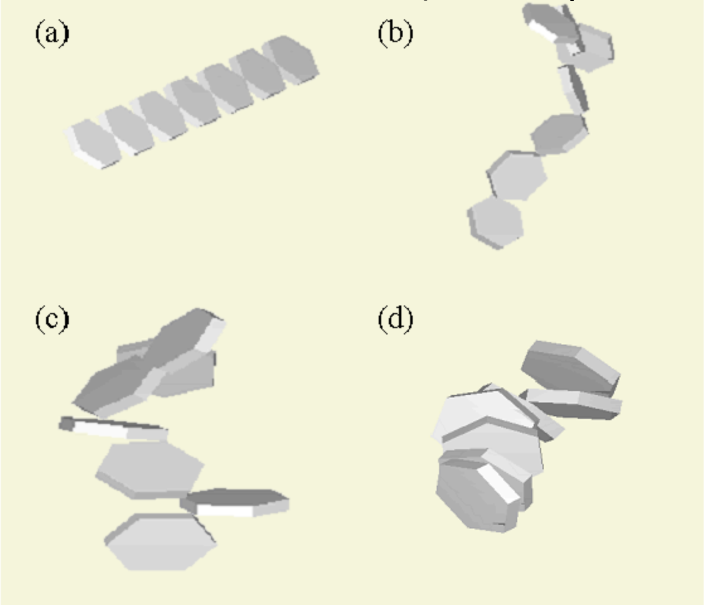


Figure 8. Examples of idealized aggregates of plates with different AI values: (a) $AI = 1.0$, (b) $AI = 0.81$, (c) $AI = 0.61$, and
This figure is available in colour online at www.interscience.wiley.com/journal/qj

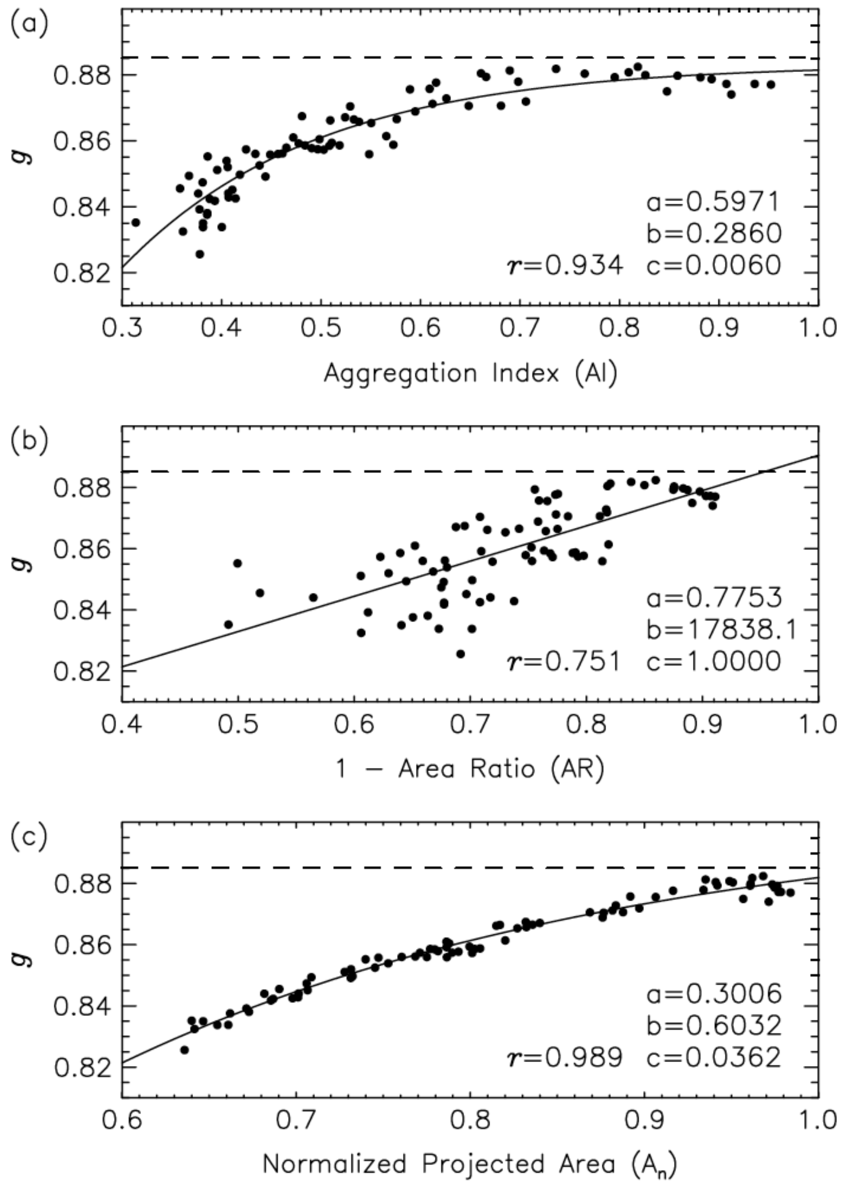


Figure 9. Asymmetry parameter (g) at $\lambda = 0.55$ µm of 80 different aggregates of seven 100 µm plates attached together, as functions of (a) AI, (b) $1 - AR$, and (c) A_n. The correlation coefficient and constants for a fitting equation, $y = a + b(1 - c^x)$, are embedded