Spatial heterogeneity and ice crystal shape: Effects on remote sensing of ice cloud properties - Case study results

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Prof. Manfred Wendisch's Atmospheric Radiation Group

Research projects + platforms:

- Arctic mixed-phase clouds
- boundary layer-clouds
- tropospheric ice clouds
- new: HALO

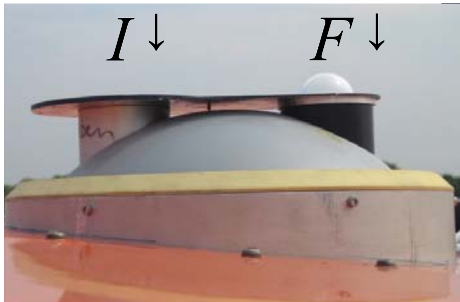
- desert dust impact on global radiative budget
- surface reflectivity maps of megacities

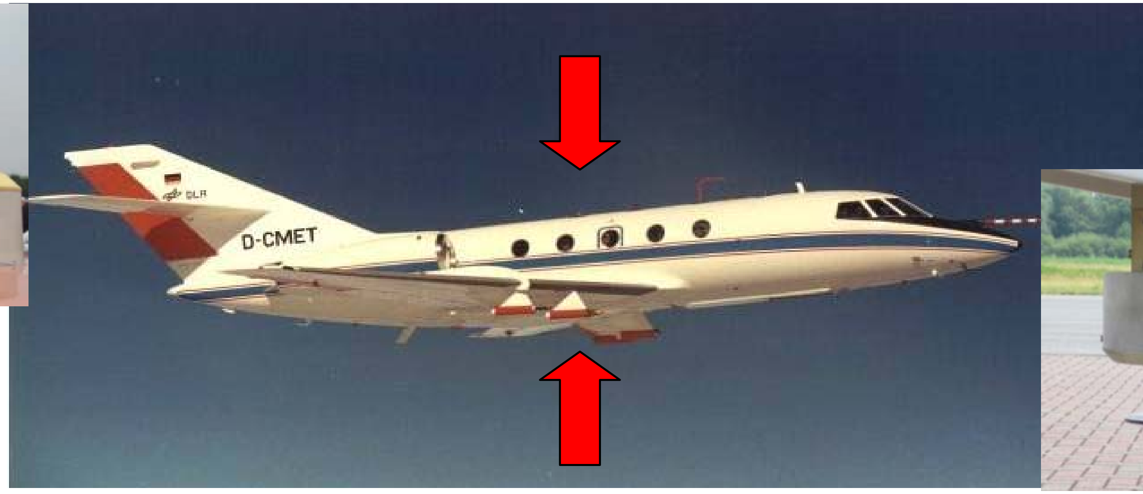
- vertical structure of convective clouds
- marine cloud type detection

- long-term ground-based standard radiometric and lidar measurements

Instrumentation development:

SMART-Albedometer: Spectral Modular Airborne Radiation Measurement System





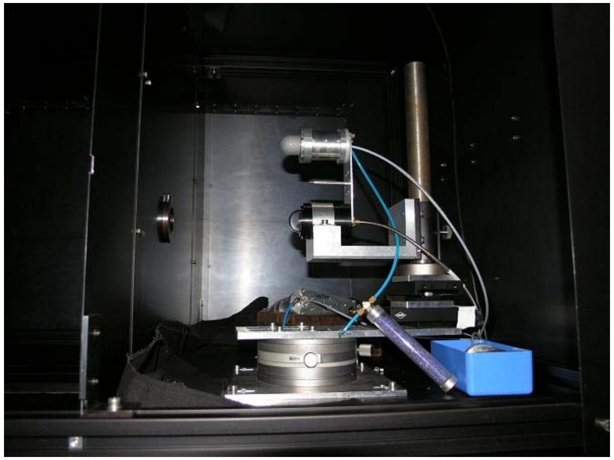
- set of optical inlets: radiances *I*, irradiances *F*, actinic flux densities
- upper and lower hemisphere measurements
- optical inlets with active horizontal stabilization
- inlets ⟶ optical fibers ⟶ up to 6 grating spectrometers

name	spectral range	spectral resolution	PDA-pixels
MCS UV-NIR	300-1000 nm	2-3 nm	1024
PGS NIR 2.2	900-2200 nm	16 nm	256

➡ albedo, reflectance, absorptance, transmittance, photolysis frequencies

Laboratory facilities:

Integrating sphere (diameter = 500 mm)	Absolute calibration (radiance)
Integrating sphere (diameter = 150 mm)	Field transfer calibration
PTB/NIST traceable 1000 W tungsten halogen lamps	Absolute calibration (irradiance, actinic flux densities)
200 W tungsten halogen lamps	Angular response measurement
Spectral lamps (Hg, Neon, Argon)	Wavelength calibration
Monochromator	Wavelength calibration

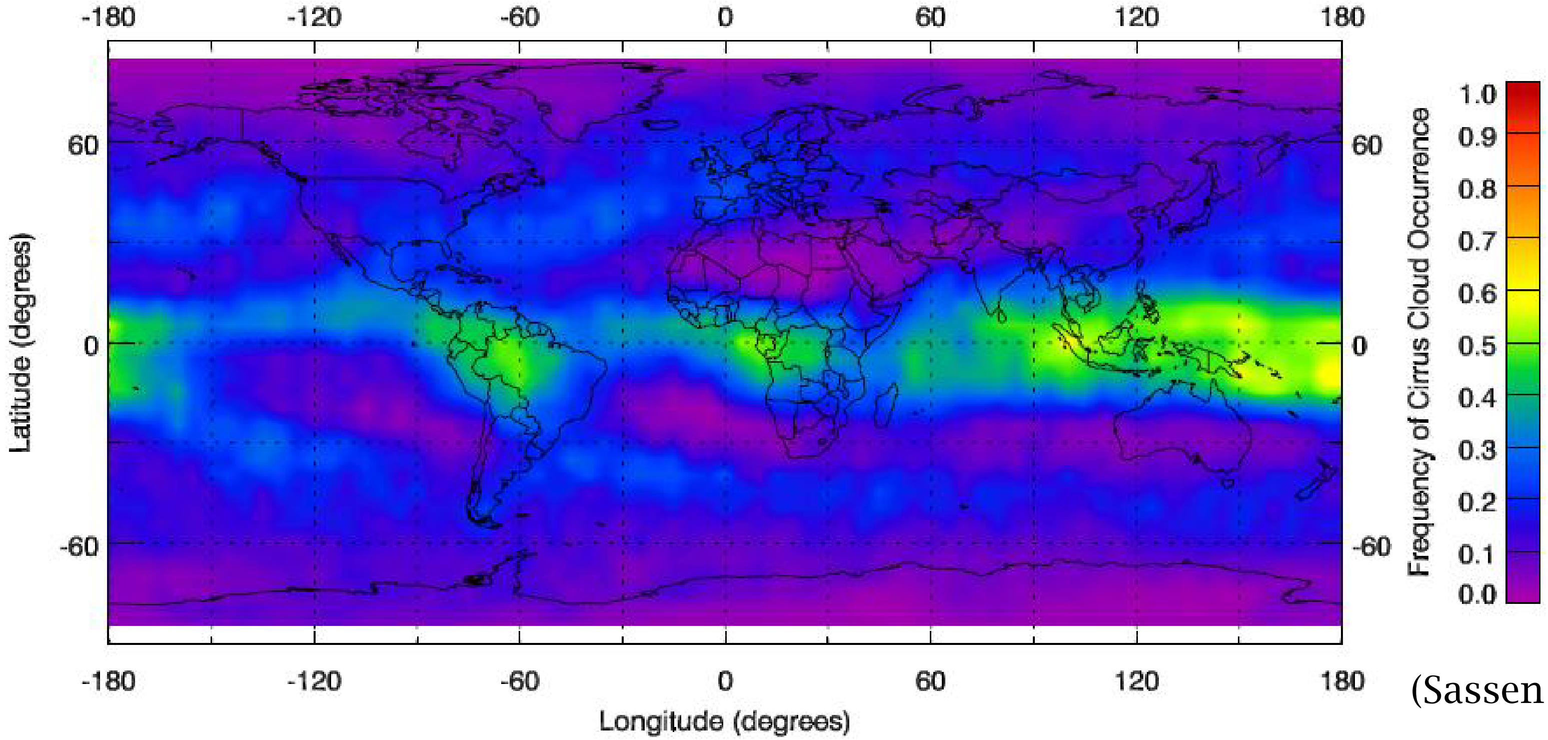


Outline

1. Motivation
2. Problems in remote sensing of ice clouds
3. Theory & definitions
4. Retrieval methodology & radiative transfer model
5. CIRCLE-2 field experiment
6. TC^4 field experiment - Influence of spatial heterogeneities and ice particle shape
7. Summary

Motivation – global distribution of cirrus clouds

1-year average (June 2006 – July 2007) of satellite measurements



(Sassen et al., 2008)

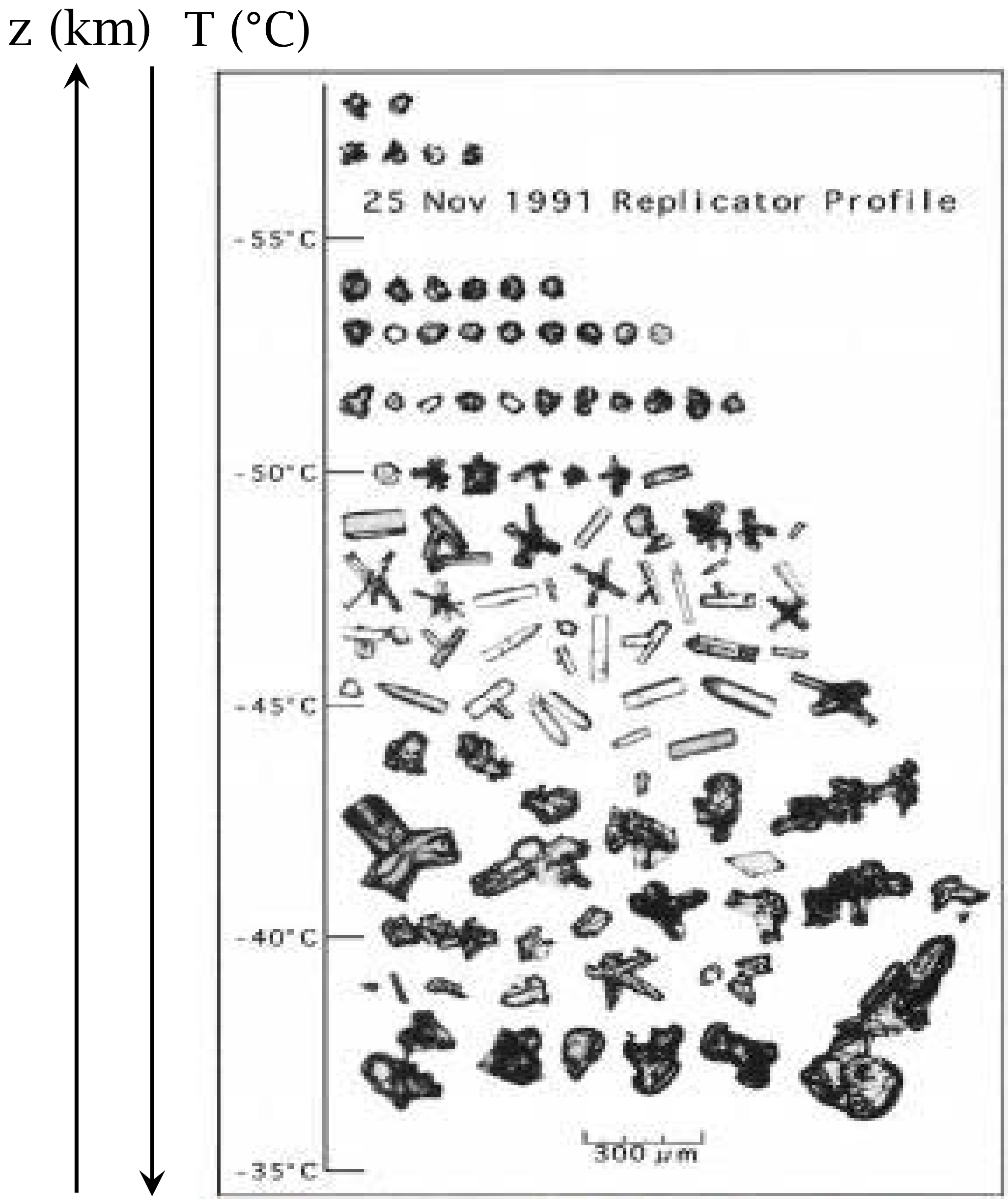
- mean global cirrus cover: 13-27 %
- important regulators of Earth's radiative balance
- radiative properties depend on: vertical position (T), cloud optical thickness τ , ice crystal shape and size (effective radius r_{eff}), ice crystal concentration

Spatial inhomogeneities & non-sphericity of ice crystals

- size range:
  <10 µm – several hundred µm

- increase of ice crystal size and shape complexity towards cloud base

- different crystal shapes exhibit different optical properties as function of particle size + wavelength of incoming radiation

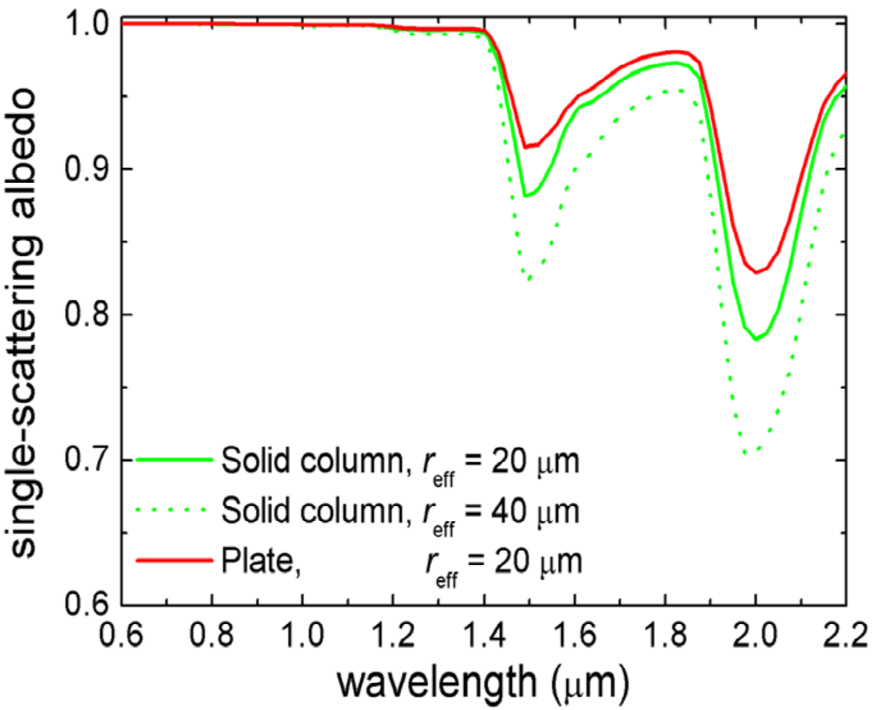


Heymsfield and Miloshevich, 2003

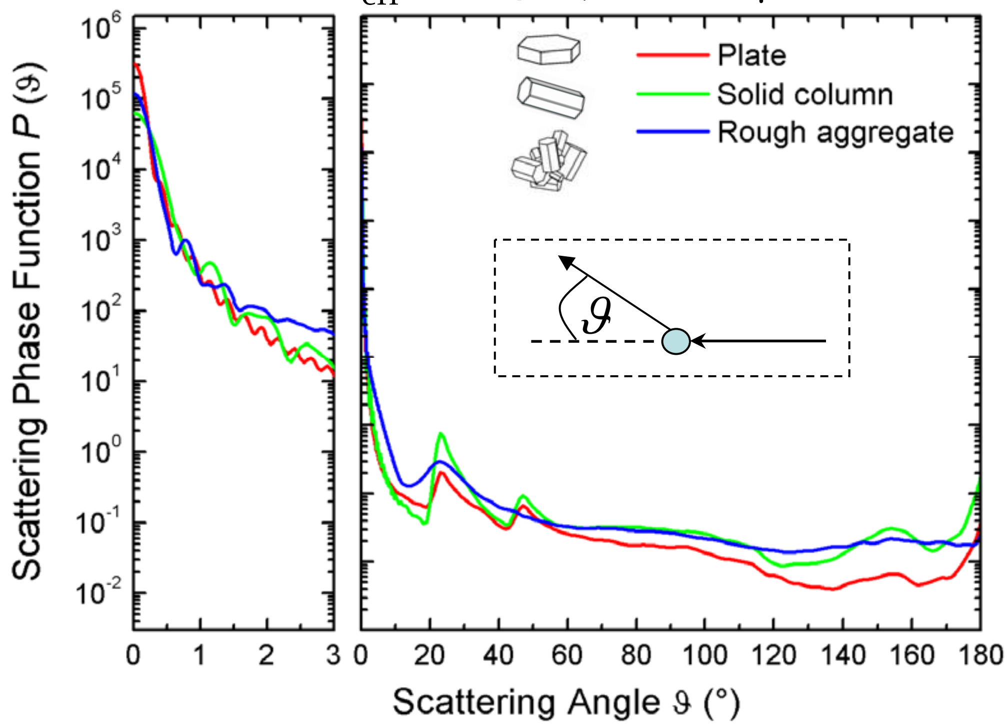
Theoretical basis: single-scattering properties of ice crystals

- extinction cross section
- single-scattering albedo (0 = purely absorbing, 1 = purely scattering)
- scattering phase function *P*

→ depend on: cross-section area and shape of ice particles



r_{eff} = 25 μm, λ = 0.67 μm



Remotely sensed cloud properties - definitions

cloud optical thickness τ :

$$\tau = \int_{z_1}^{z_2} b_{ext}(z)\,\mathrm{d}z$$

measure of how much incident solar radiation is transmitted through or reflected by the cloud

effective radius r_{eff} (µm):

$$r_{\mathrm{eff}} = \frac{3}{4}\frac{\text{total volume}}{\text{total cross section}}$$

area-weighted mean radius characterizing an ice particle size distribution in radiative transfer calculations

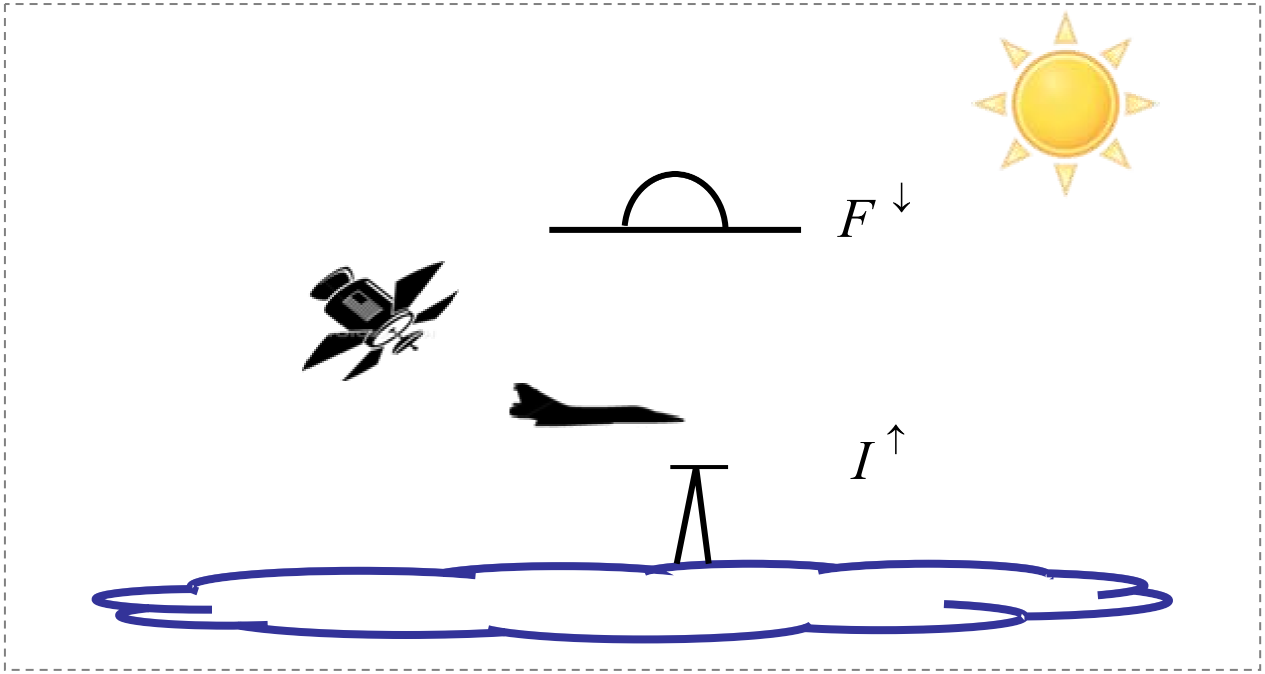
relation between τ and r_{eff} :

$$\tau = \frac{3}{2}\frac{IWC}{\rho_{\mathrm{ice}}}\frac{\mathrm{d}z}{r_{\mathrm{eff}}}$$

ice water content *IWC* (g m^{-3}):

mass concentration of the ice particles in a cloud volume

Passive remote sensing of cirrus clouds: reflectance measurements



$F^{\downarrow}$ (W m^{-2} nm^{-1})

- downwelling spectral irradiance (flux density)

$I^{\uparrow}$ (W m^{-2} sr^{-1} nm^{-1})

- upwelling spectral radiance

cloud reflectance r_c:

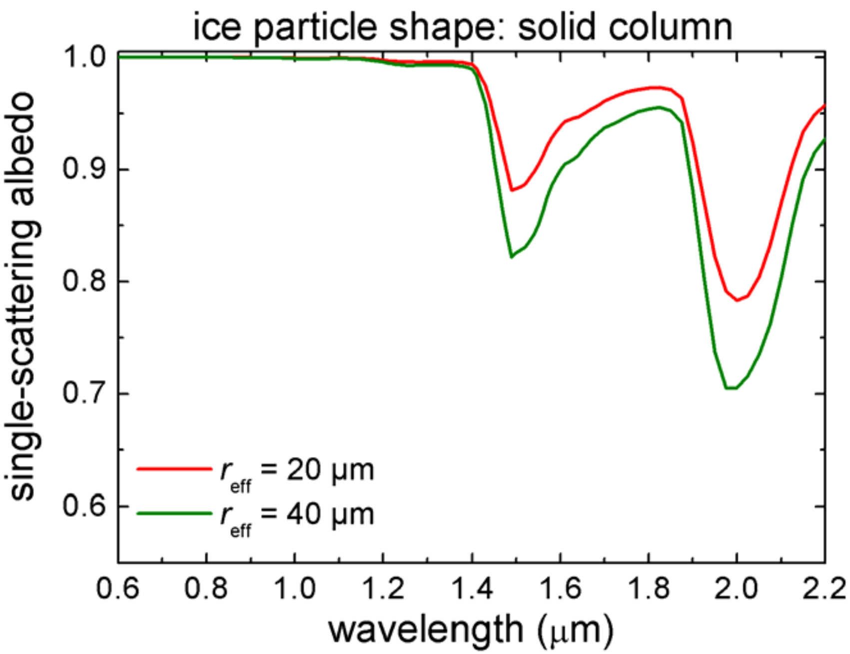
$$r_c = \frac{I^{\uparrow}}{F^{\downarrow}} \pi \text{ sr}$$

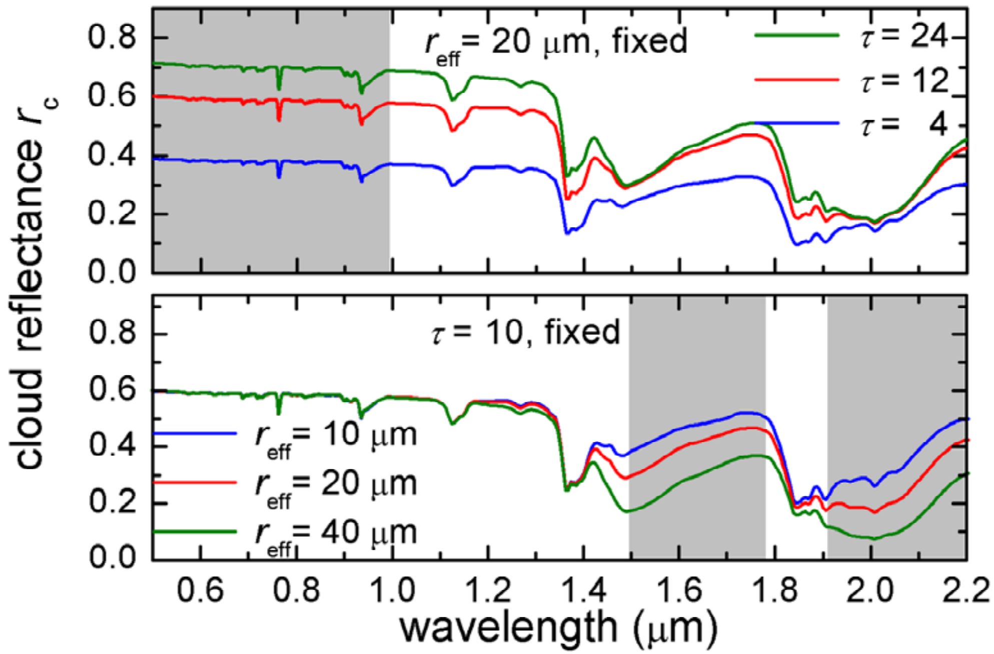
$$F^{\downarrow} = F_0^{\downarrow} \cdot \mu_0$$

μ_0 = cosine of solar zenith angle

wavelength-dependencies of ice cloud reflectance

- visible – very near IR: ice = non-absorbing, r_c controlled by τ
- NIR-bands: ice = absorbing, r_c controlled by r_{eff}





→ τ - retrieval at 0.67 µm or 0.87 µm (land/ocean)
→ r_{eff} –retrieval at 1.6 µm or 2.13 µm

Retrieval Method and Radiative Transfer Model

Method - classical bispectral retrieval method Nakajima & King, 1990

Employ radiative transfer modelling to find the ice cloud which has the same reflectances (0.87 µm, 2.13 µm) as the measured one and retrieve τ and r_{eff} from it.

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Nakajima & King, 1990

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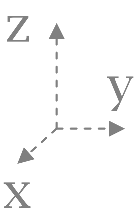
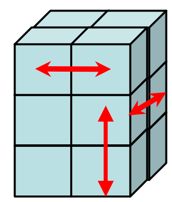
Radiative Transfer Modelling

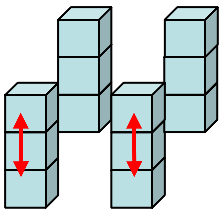
Mayer & Kylling, 2005; Mayer, 2009



1D-model **libRadtran**:
lookup tables (LUT)



3D-solver
MYSTIC



Independent Pixel
Approximation (IPA) mode

- libRadtran: library of radiative transfer
- MYSTIC: Monte Carlo code for the physically correct tracing of photons in cloudy atmospheres

Retrieval Method and Radiative Transfer Model

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Nakajima & King, 1990

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Radiative Transfer Modelling

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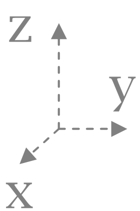

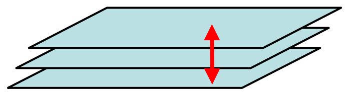

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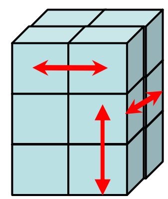

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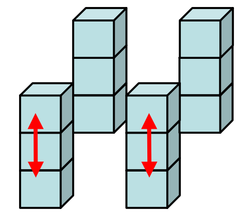
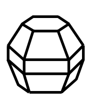
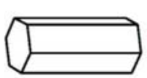
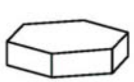


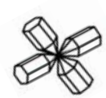
Independent Pixel
Approximation (IPA) mode

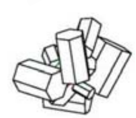
Variation of ice particle shape in model cloud

droxtals 

columns 

plates 

rosettes 

aggregates 

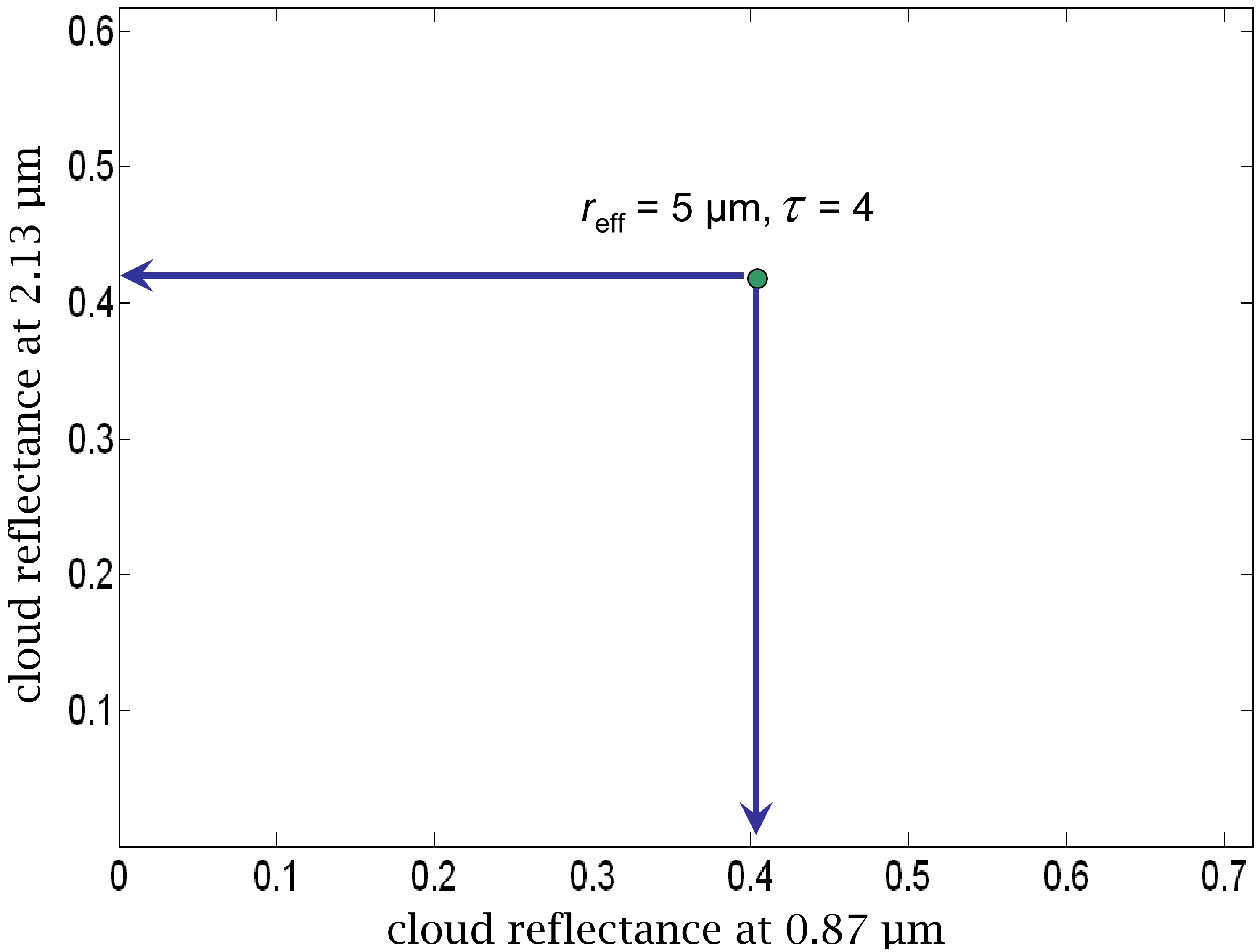
mixture of shapes

ice particle parameterizations:

- HEY (Hong-Emde-Yang)/B.Baum
- exact scattering phase function, single scattering albedo, extinction cross section
- random orientation

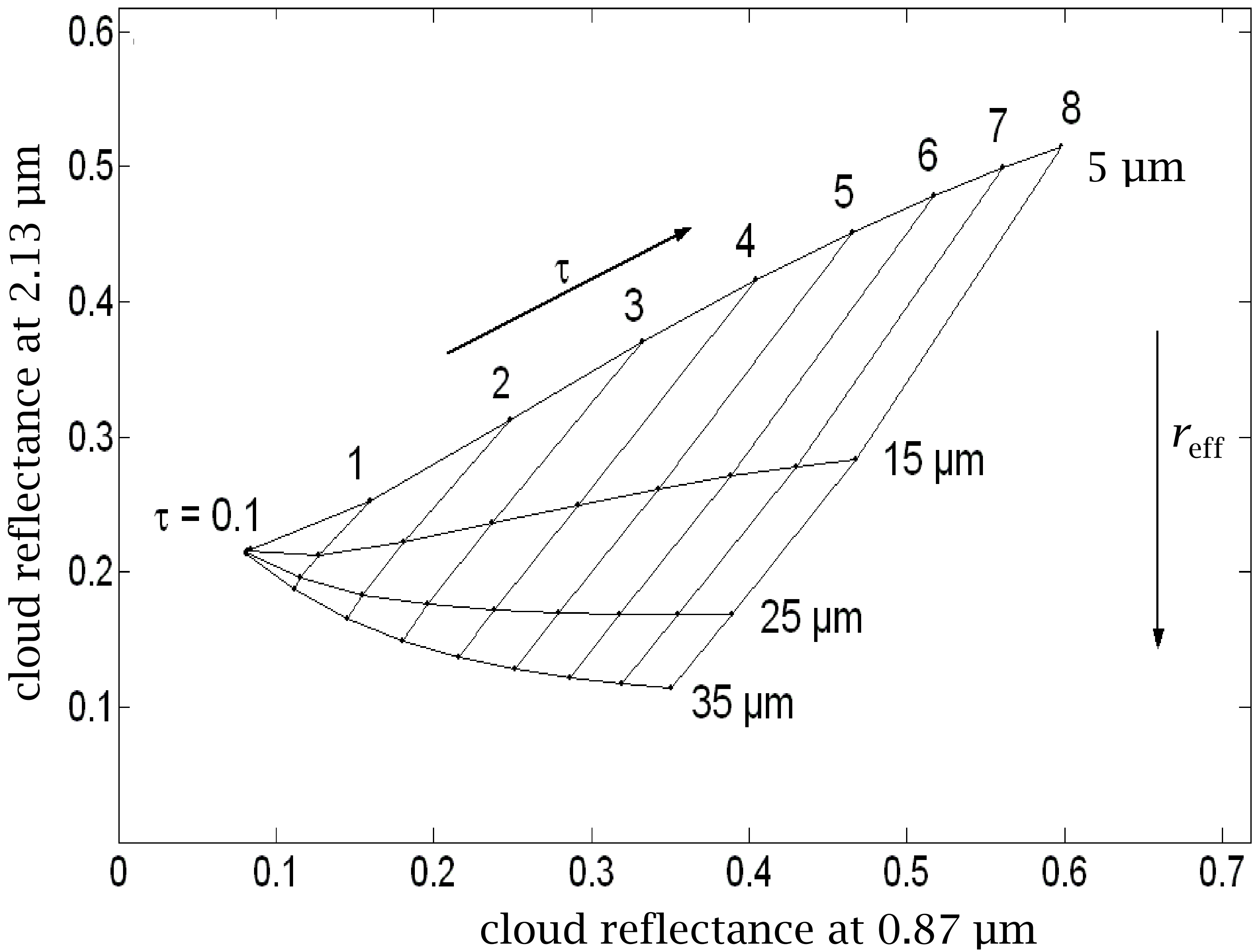
Algorithm – retrieval of τ and r_{eff}

1. modelling of the cloud reflectance r_c



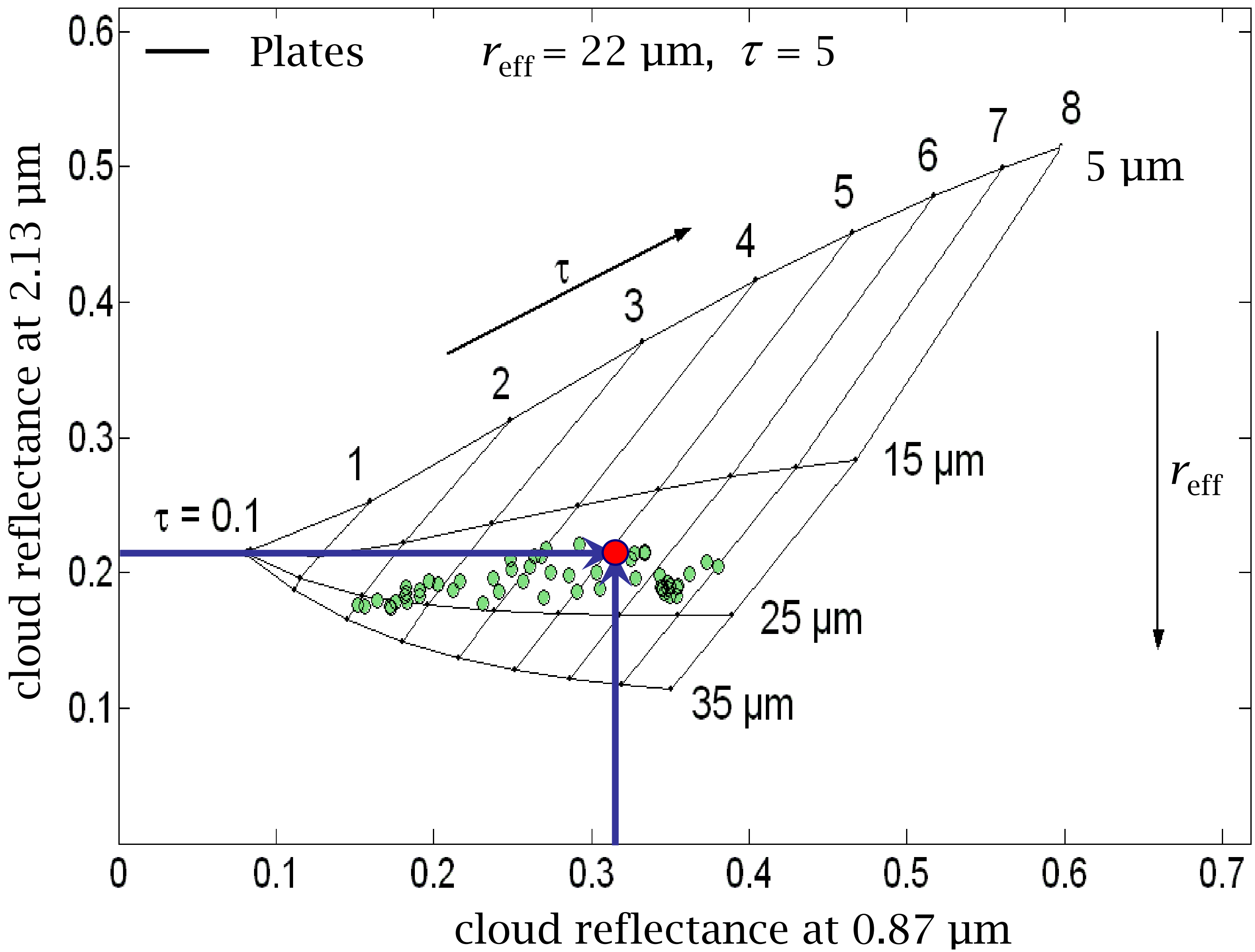
Algorithm – retrieval of τ and r_{eff}

2. result: reflectance table for τ and r_{eff} (lookup table, LUT)



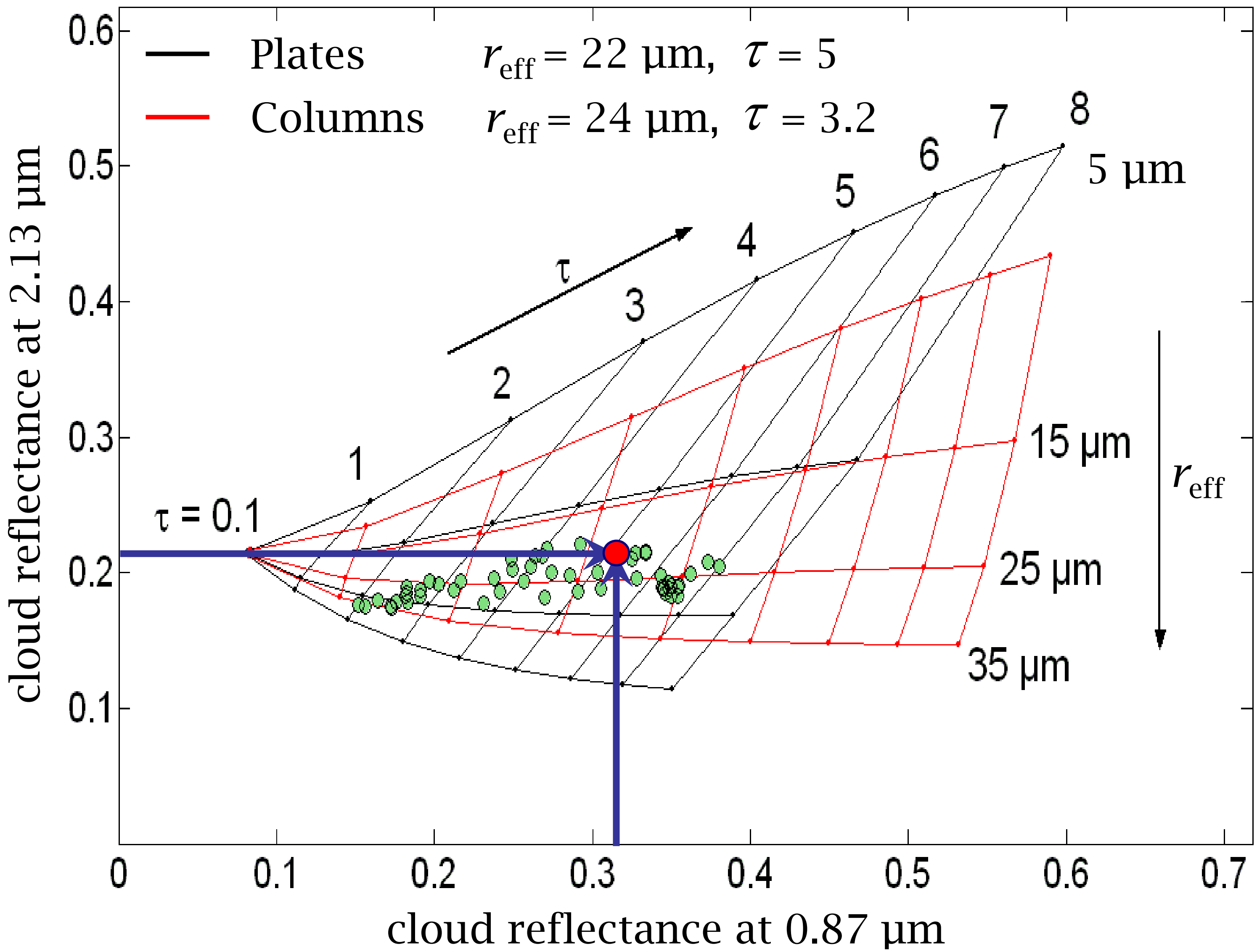
Algorithm – retrieval of τ and r_{eff}

3. retrieval of τ and r_{eff} for measured r_c- pairs



Algorithm – retrieval of τ and r_{eff}

4. retrieval of τ and r_{eff} for different ice crystal shape assumptions



Airborne remote sensing of cirrus

CIRCLE-2 (CIRrus CLoud Experiment-2) - Europe, May 2007

Instrumentation

- SMART-Albedometer (**S**pectral **M**odular **A**irborne **R**adiation measurement sys**T**em)
  - spectral $I\uparrow$ along flight track
  - no measurement of 3D cloud structure
- downward-looking LIDAR
- in situ cloud microphysics (FSSP-300; CPI)

Flight strategy

- above cloud leg for remote sensing
- in cloud leg for microphysical measurements

Case study

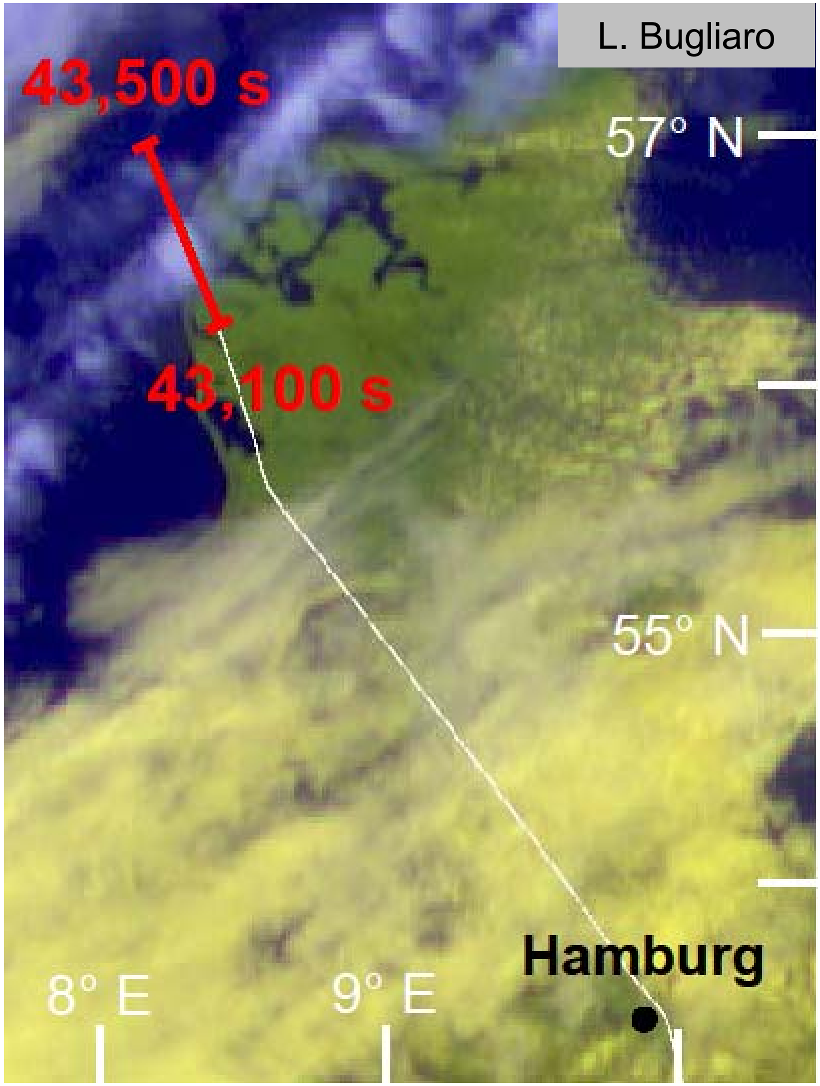
- Influence of **ice particle shape** on the remote sensing of τ and r_{eff}

Publication

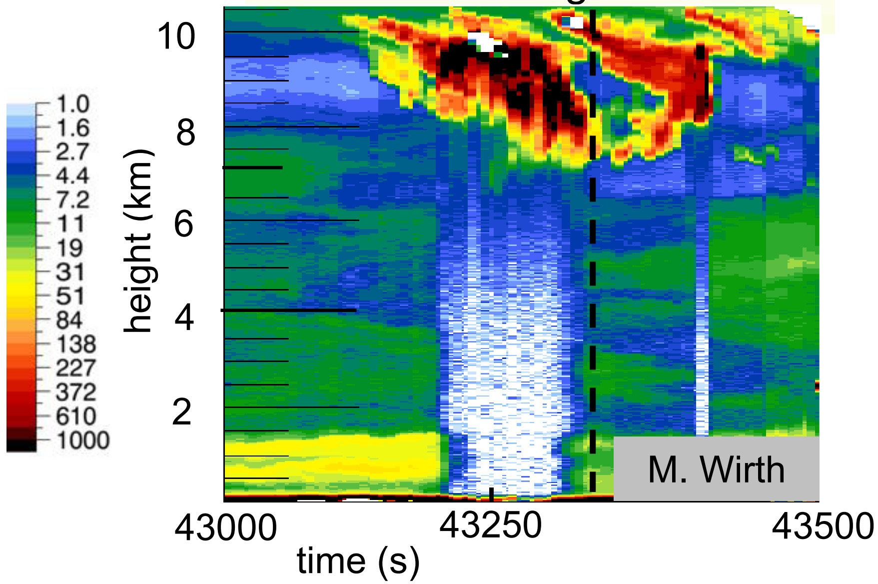
Eichler et al., 2009, Journal of Geophysical Research

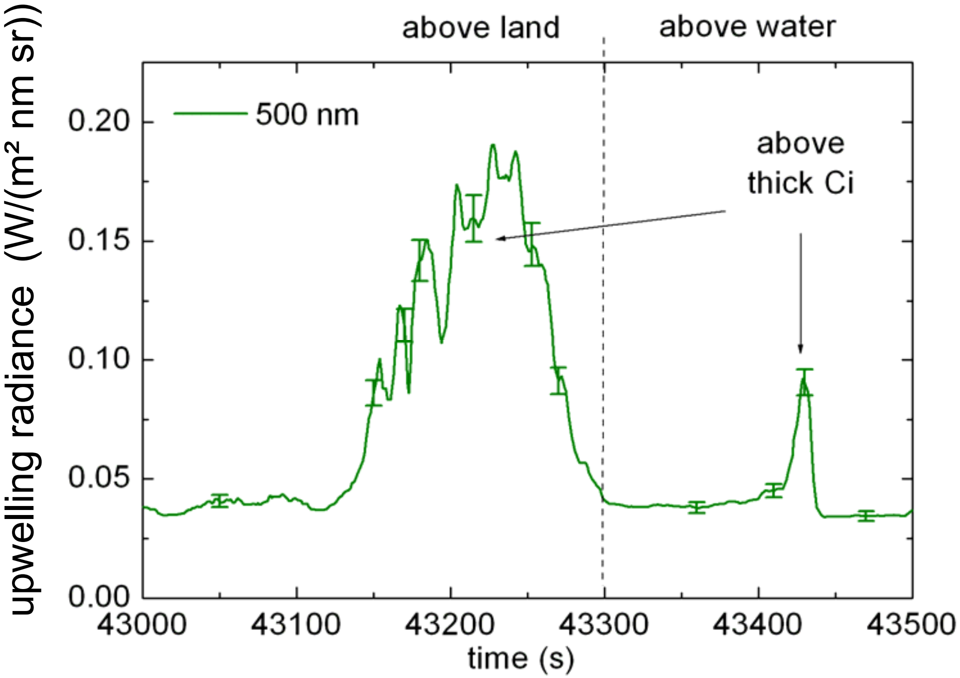
Case study : Flight 22 May 2007 – West Denmark

• MSG (Meteosat Second Generation)

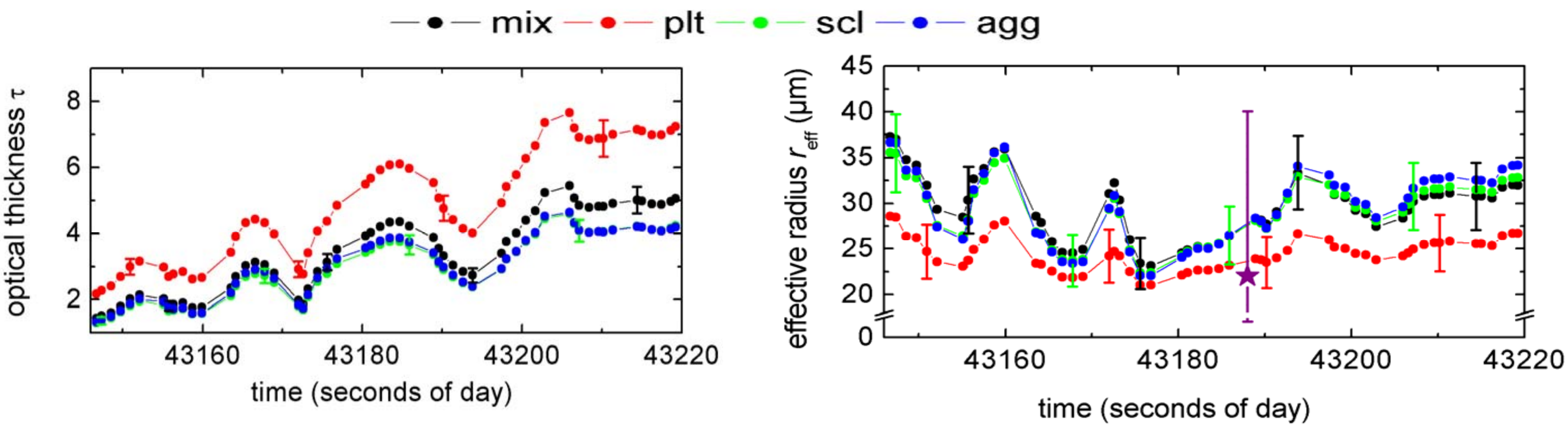


• Lidar Backscatter Signal at 1064 nm





CIRCLE-2 results: Influence of shape effect on retrieval

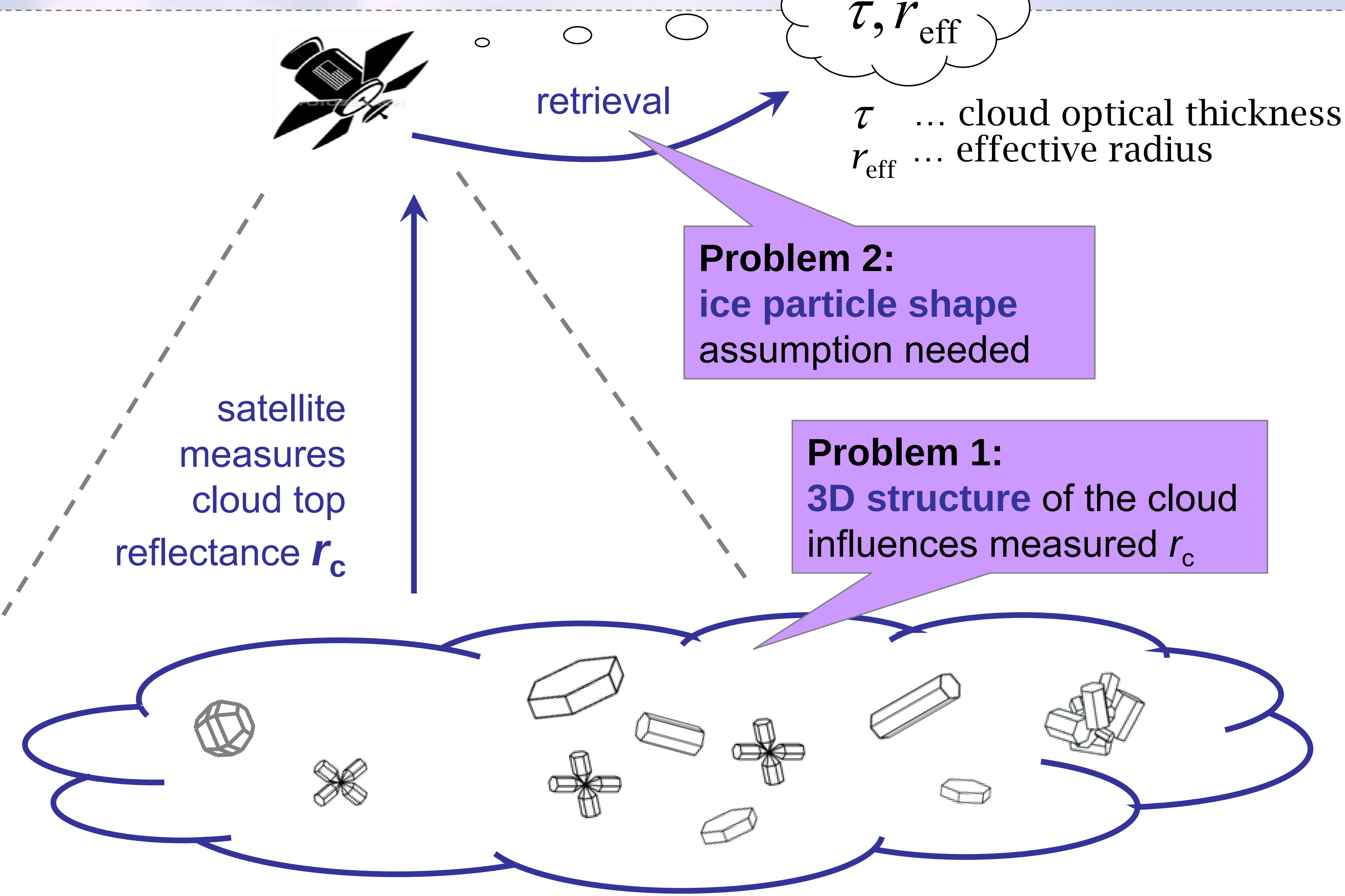


- strong dependence of retrieved properties on assumed ice particle shape
- larger influence of ice particle shape on τ

difference in retrieved properties up to:		other publications:
r_{eff}	**20 %**	McFarlane: 30 % Knap: 11 %
τ	**70 %**	McFarlane: 50 % Key: 60 %

(McFarlane et al., 2005; Key et al., 2002; Knap et al., 1999)

Remote sensing of cirrus



Remote sensing of cirrus – TC⁴ experiment

TC⁴ (NASA Tropical Composition, Cloud, and Climate Coupling experiment)

- tropical anvil cirrus; summer 2007; Costa Rica and tropical Pacific

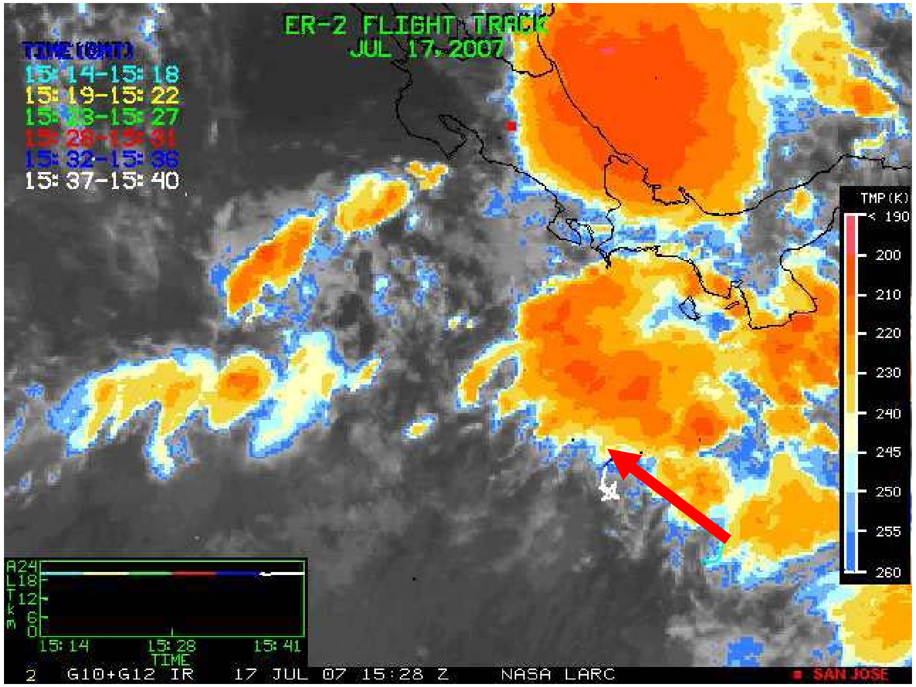
ER-2 aircraft instrumentation

- MAS (**M**ODIS **A**irborne **S**imulator)
- CRS (**C**loud **R**adar **S**ystem)

Case study (July 17, 2007)

- reconstruction of the microphysical 3D cloud structure

→ model input cloud: τ^{inp} r_{eff}^{inp}



GOES G10 and G12

Remote sensing of cirrus – TC4 experiment

TC4 (NASA Tropical Composition, Cloud, and Climate Coupling experiment)

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ER-2 aircraft instrumentation

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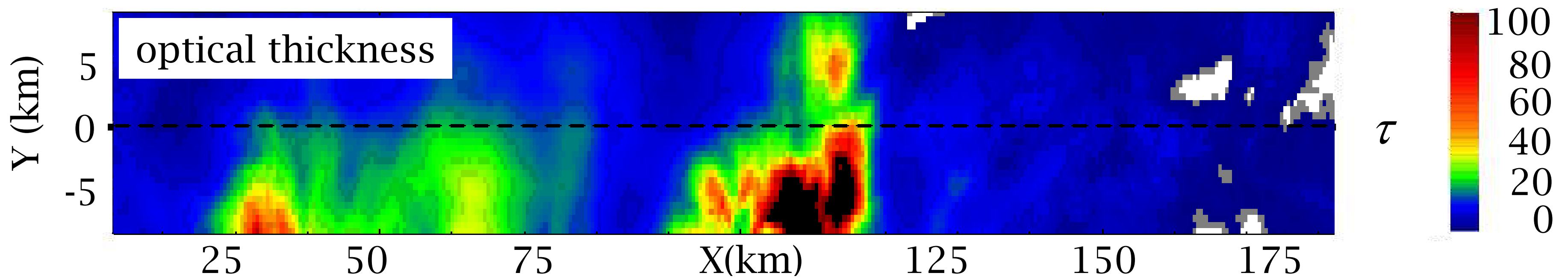

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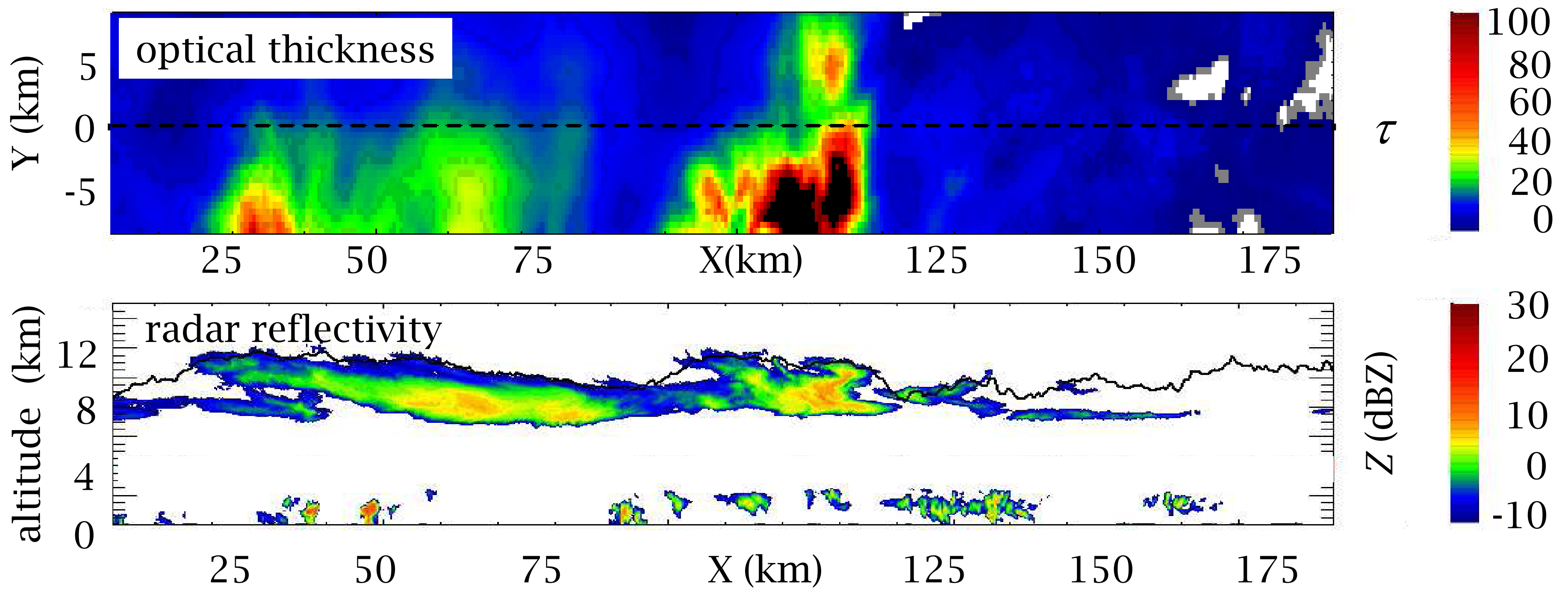
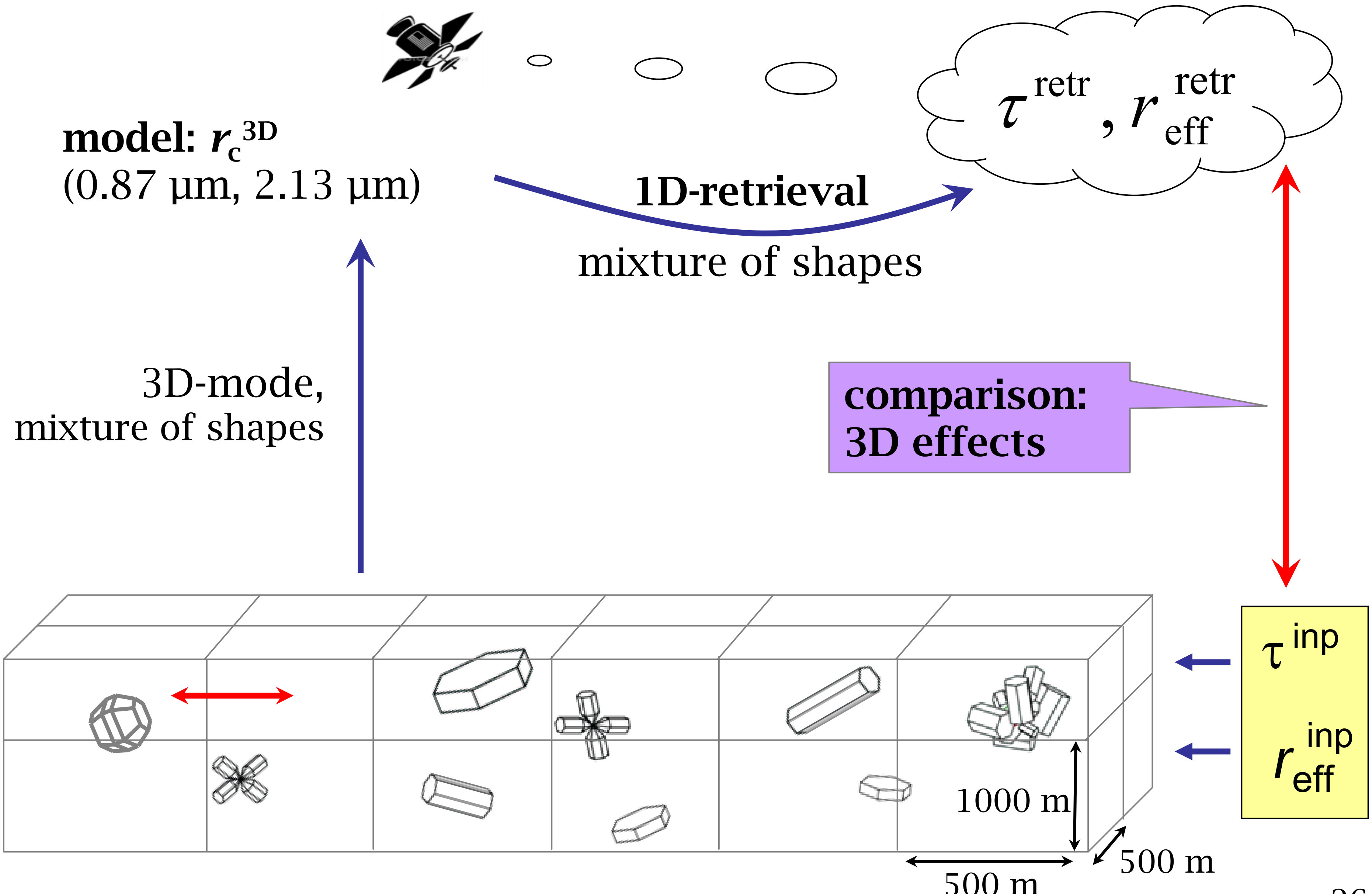
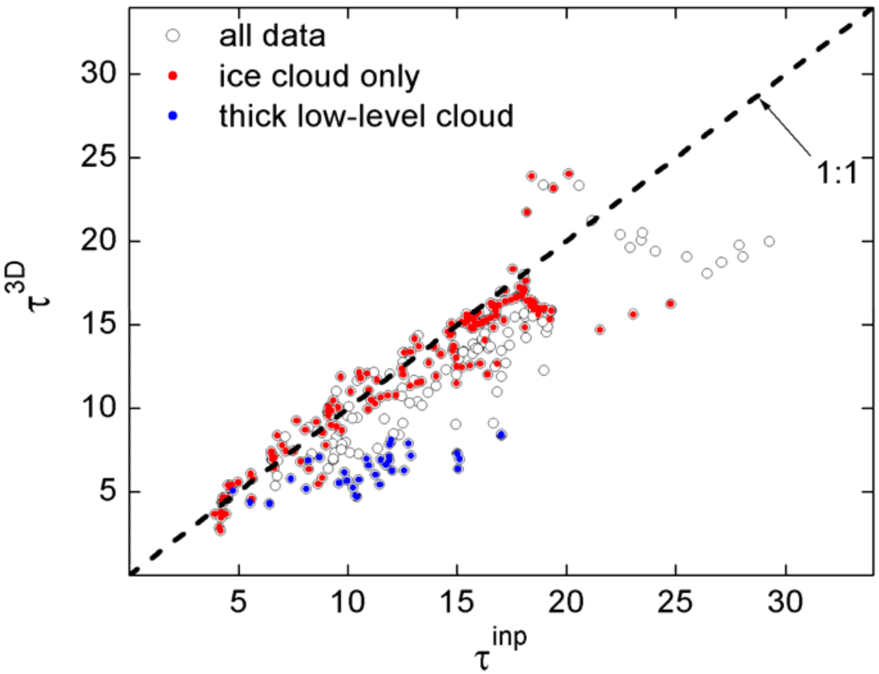


Method - Influence of spatial cloud inhomogeneities

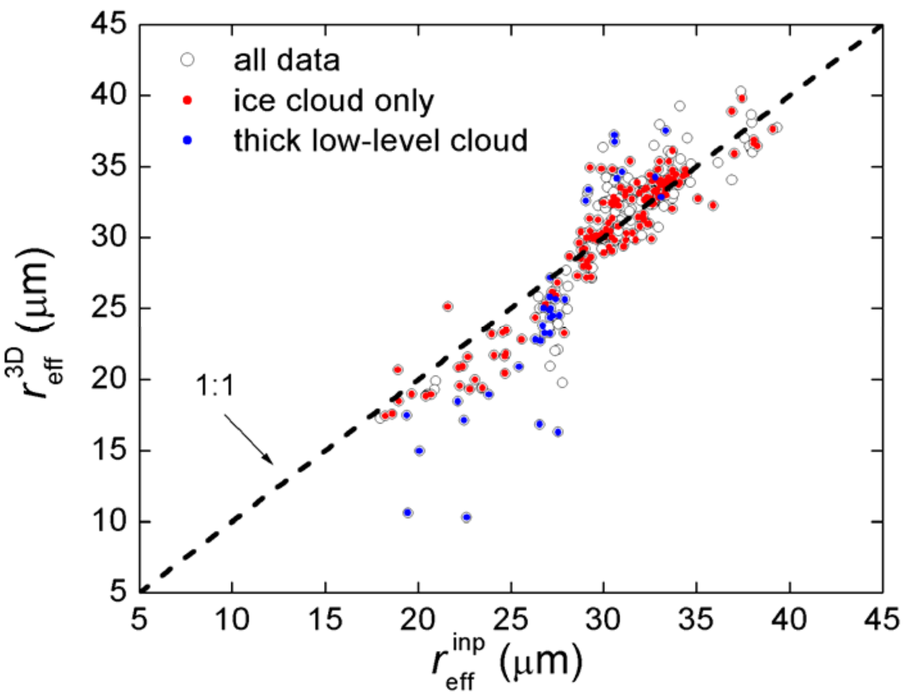


Influence of spatial cloud inhomogeneities

optical thickness:



effective radius:

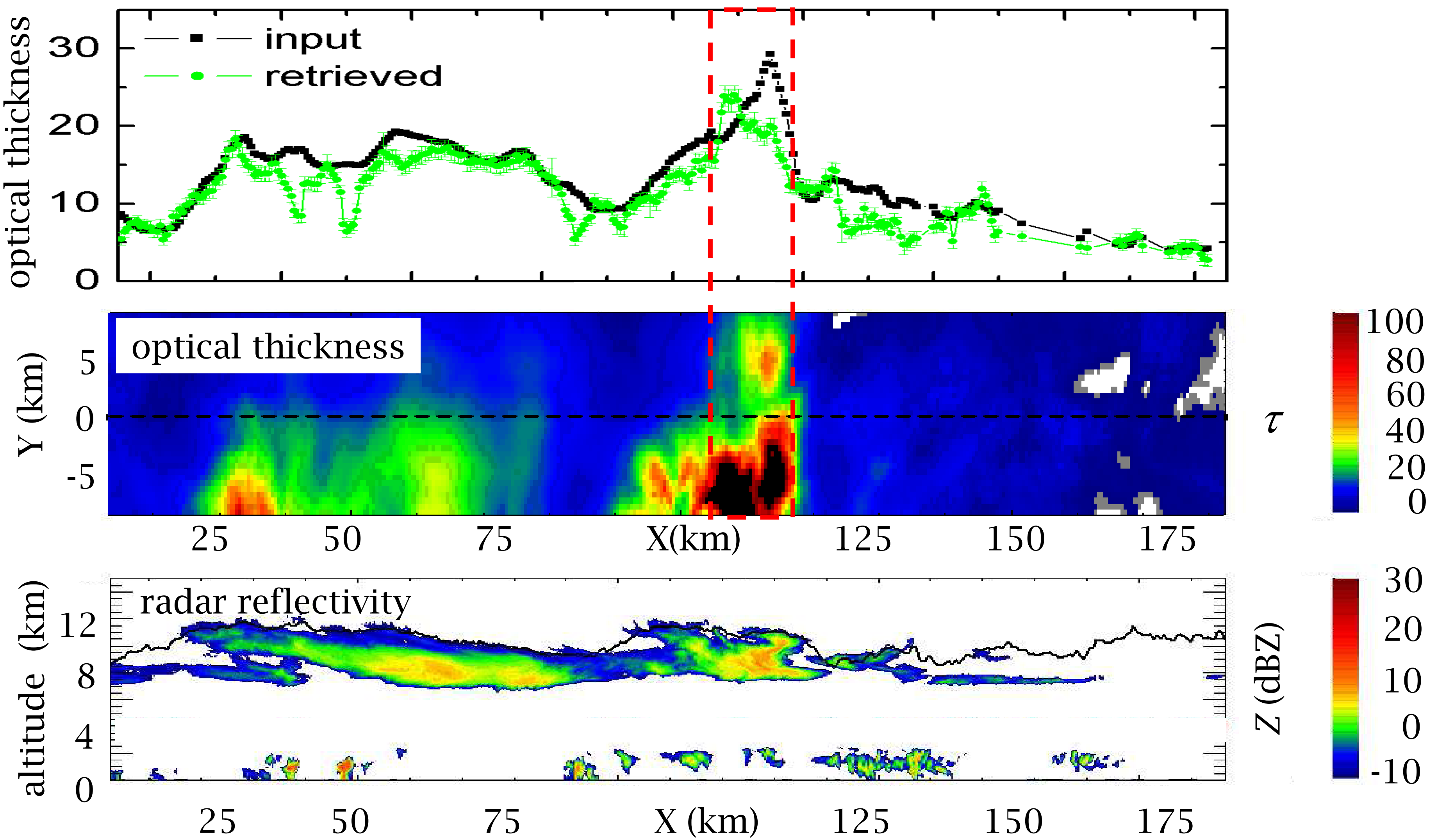


locally: 45 % under- to 30 % overestimation
mean: 7 % underestimation

locally: 25 % under- to 20 % overestimation
mean: 0 % bias

Influence of spatial inhomogeneities on τ

results for Y = 0 km



– – X = 110-120 km: horizontal photon transport

Method – Influence of assumed ice particle shape

model: r_c^{IPA}
(0.87 µm, 2.13 µm)

1D-retrieval

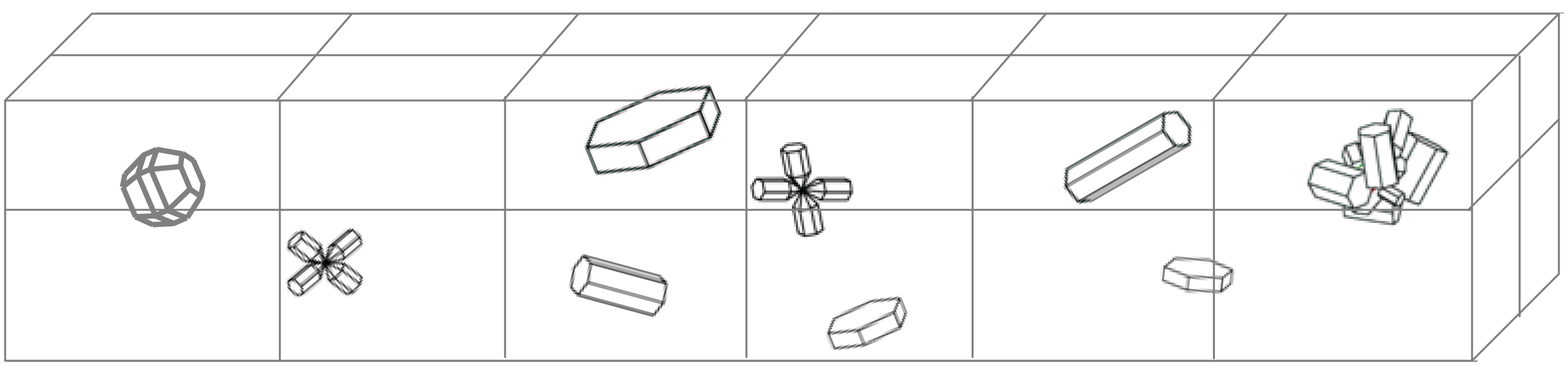
mixture of shapes

τ^{retr}, r_{eff}^{retr}

IPA-mode, shape variation:

- mixture
- plates
- columns
- aggregates

comparison: ice particle shape effects



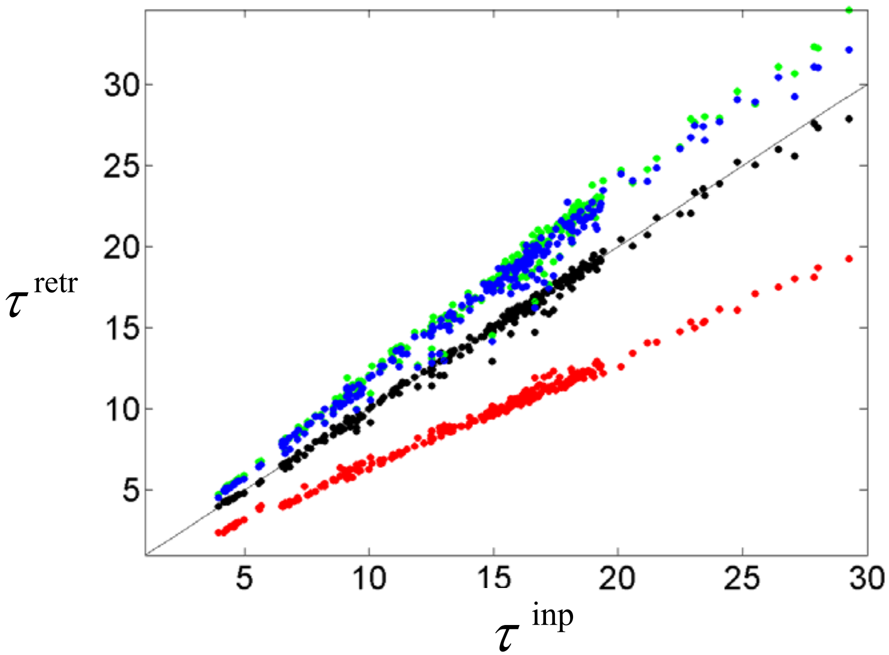
τ^{inp}

r_{eff}^{inp}

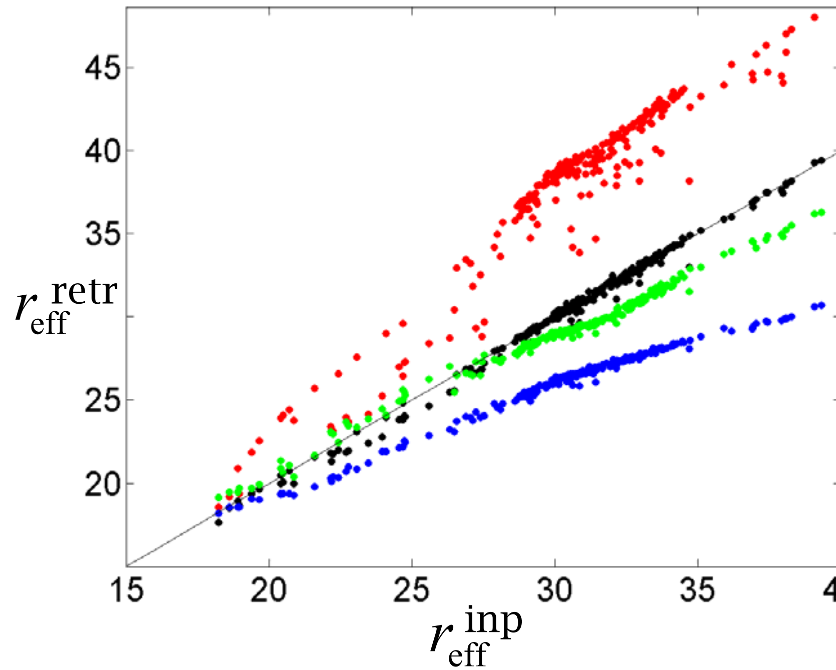
Influence of assumed ice particle shape

results for Y = 0 km

optical thickness

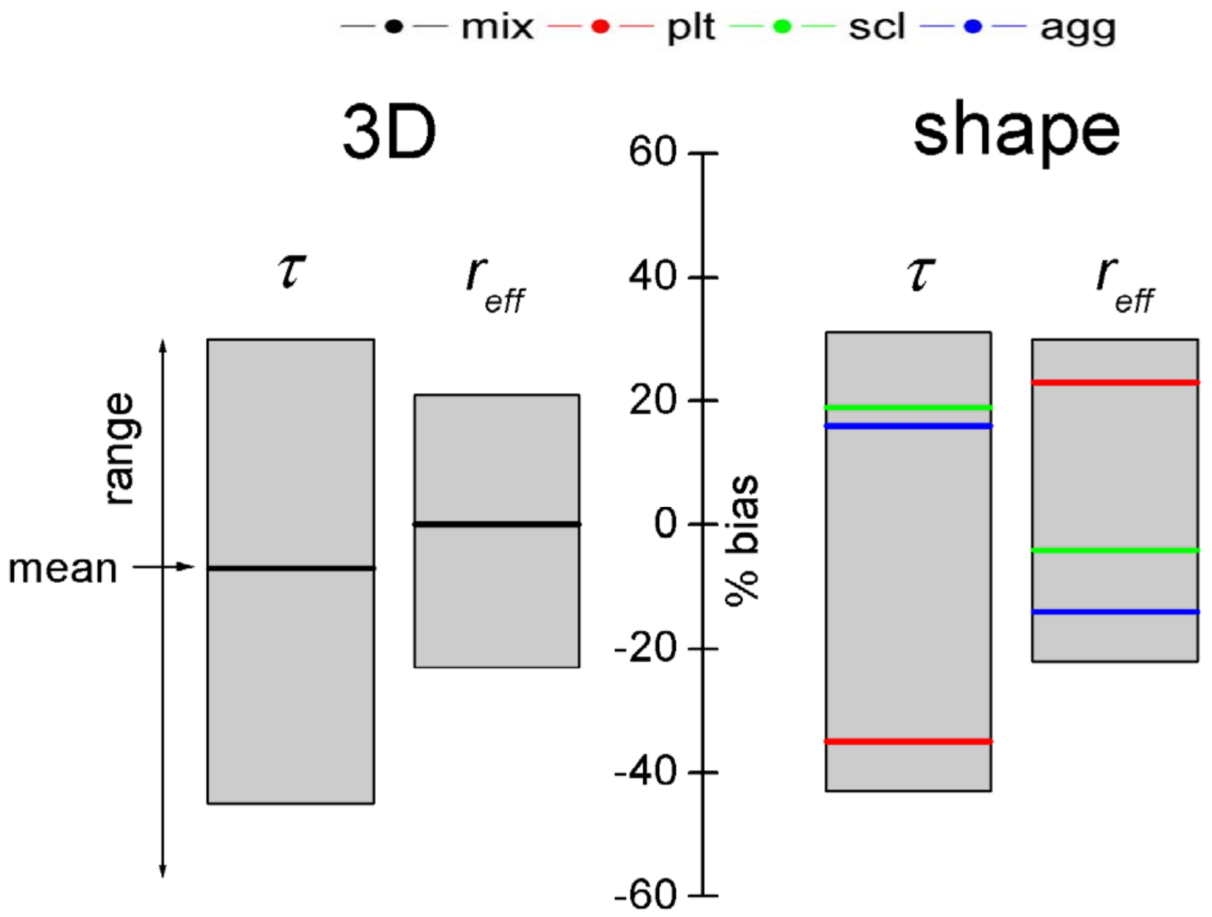


effective radius



shape	τ max. local bias	τ mean bias	r_{eff} max. local bias	r_{eff} mean bias
plate	- 45 %	- 35 %	+ 30 %	+ 25 %
column	+ 30 %	+ 20 %	- 10 %	- 5 %
aggregate	+ 25 %	+ 20 %	- 20 %	- 15 %

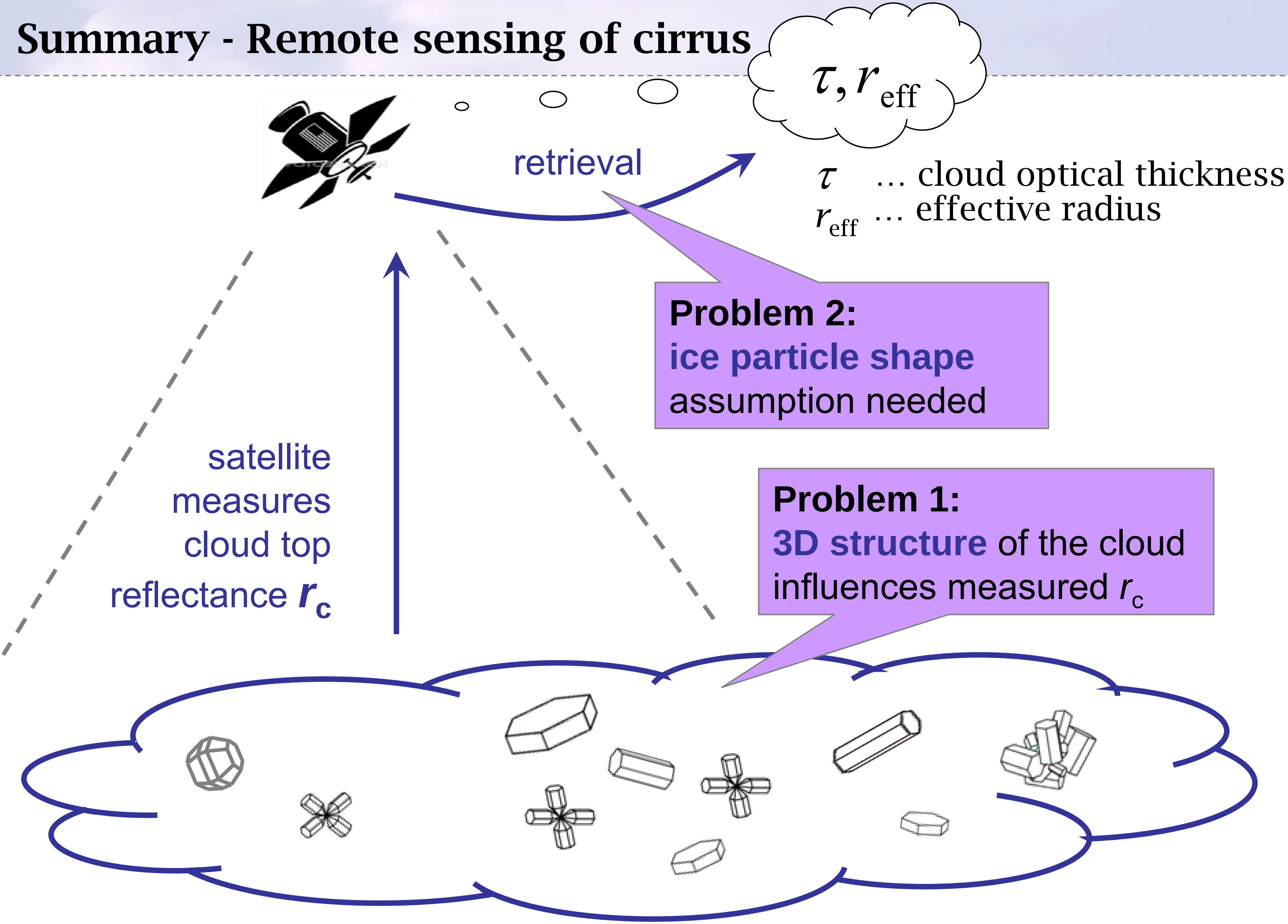
Comparison of both effects



- **locally:** both effects bias the retrieval results at same magnitude
- **on average:** ice particle shape bias is bigger

Kalesse et al., 2011, to be resubmitted to Journal of Geophysical Research

Summary - Remote sensing of cirrus



Remote sensing of cirrus

retrieval

τ, r_{eff}

τ … cloud optical thickness
r_{eff} … effective radius

Problem 2:
ice particle shape
assumption needed

satellite
measures
cloud top
reflectance r_c

Problem 1:
3D structure of the cloud
influences measured r_c

Literature

- **Baum**, B. A., Yang, P., Heymsfield, A. J., Platnick, S., King, M. D., Hu, Y. X..: Bulk scatt. prop. for remote sensing of ice clouds. Part II: Narrowband models, J. Appl. Meteor., 44, 1896–1911, 2005b.
- **Kalesse**, H., K.S. Schmidt, R. Buras, M. Wendisch, B. Mayer, P. Pilewskie, M.D. King, L. Tian, G. Heymsfield, S. Platnick. Cirrus spatial heterogeneity and ice crystal shape: Effects on remote sensing of cirrus optical thickness and effective crystal radius – A case study, to be submitted to JGR.
- **Key**, J. R., Yang, P., Baum, B. A., and Nasiri, S. L.: Parameterization of shortwave ice cloud optical properties for various particle habits, J. Geophys. Res., 107, Art. No. 4181, 2002.
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- **Mayer**, B.: Radiative transfer in the cloudy atmosphere, Eur. Phys. J. Conferences, 1, 75–99, 2009.
- **Nakajima**, T. and King, M.: Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation. Part I: Theory, J. Atmos. Sci., 47, 1878–1893, 1990.

Thank you for your attention!

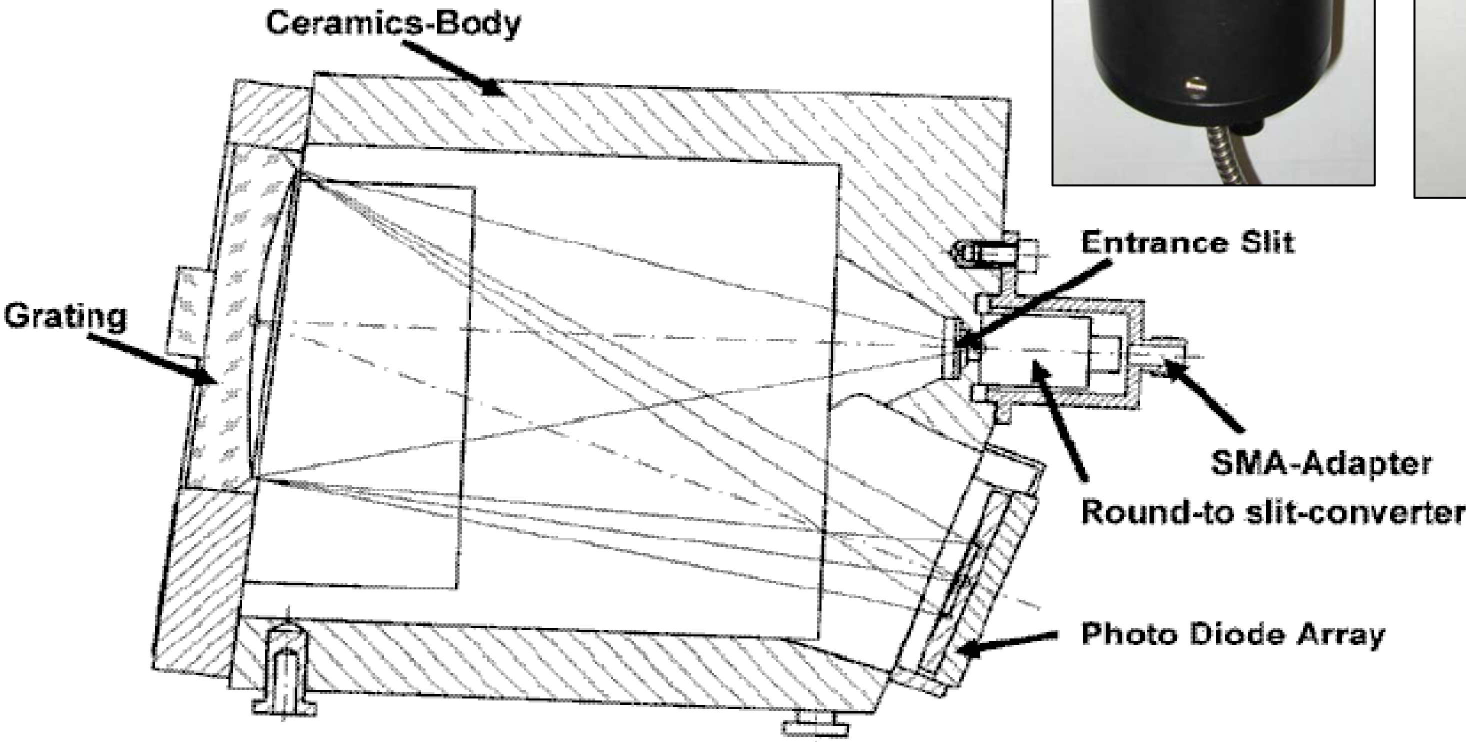
Outlook

What about the influence of …

- solar zenith angle (here: 36°) ?
- resolution of model input cloud (here: 500m x 500m x 1000m)?
- optically thinner cirrus
- …

TC^4 Experiment – Model Input cloud generation

- MAS: cloud top height; ice water path IWP_{MAS} (from tau and r_{eff})
- CRS: radar reflectivity --> IWC_{CRS} (z) along nadir track
- determine *IWC* profiles of each pixel (x,y) via distribution of IWP_{MAS} in the vertical with IWC_{CRS}
- assumptions:
  - *IWC* constant across MAS-track
  - optical thickness is column-integrated
  - r_{eff} constant with height
- generate 3D cloud (tau, *IWC*, r_{eff}) gridded to dx = dy = 500 m, dz = 1000 m


Ceramics-Body
Entrance Slit
Grating
SMA-Adapter
Round-to slit-converter
Photo Diode Array

Fernerkundungsmethodik - Definitionen

optische Dicke τ:

$$\tau = \int_{z_1}^{z_2} b_{ext}(z')dz'$$

Maß dafür, wieviel einfallende solare Strahlung durch die Wolke transmittiert bzw. reflektiert wird

effektiver Eispartikelradius R_{eff} (µm):

$$R_{eff} = \frac{3\int V(D')\cdot\frac{dN}{dD}(D')dD'}{4\int A(D')\cdot\frac{dN}{dD}(D')dD'}$$

Maß für die mittlere Teilchengröße einer Eispartikelanzahlgrößenverteilung in Strahlungstransferrechnungen

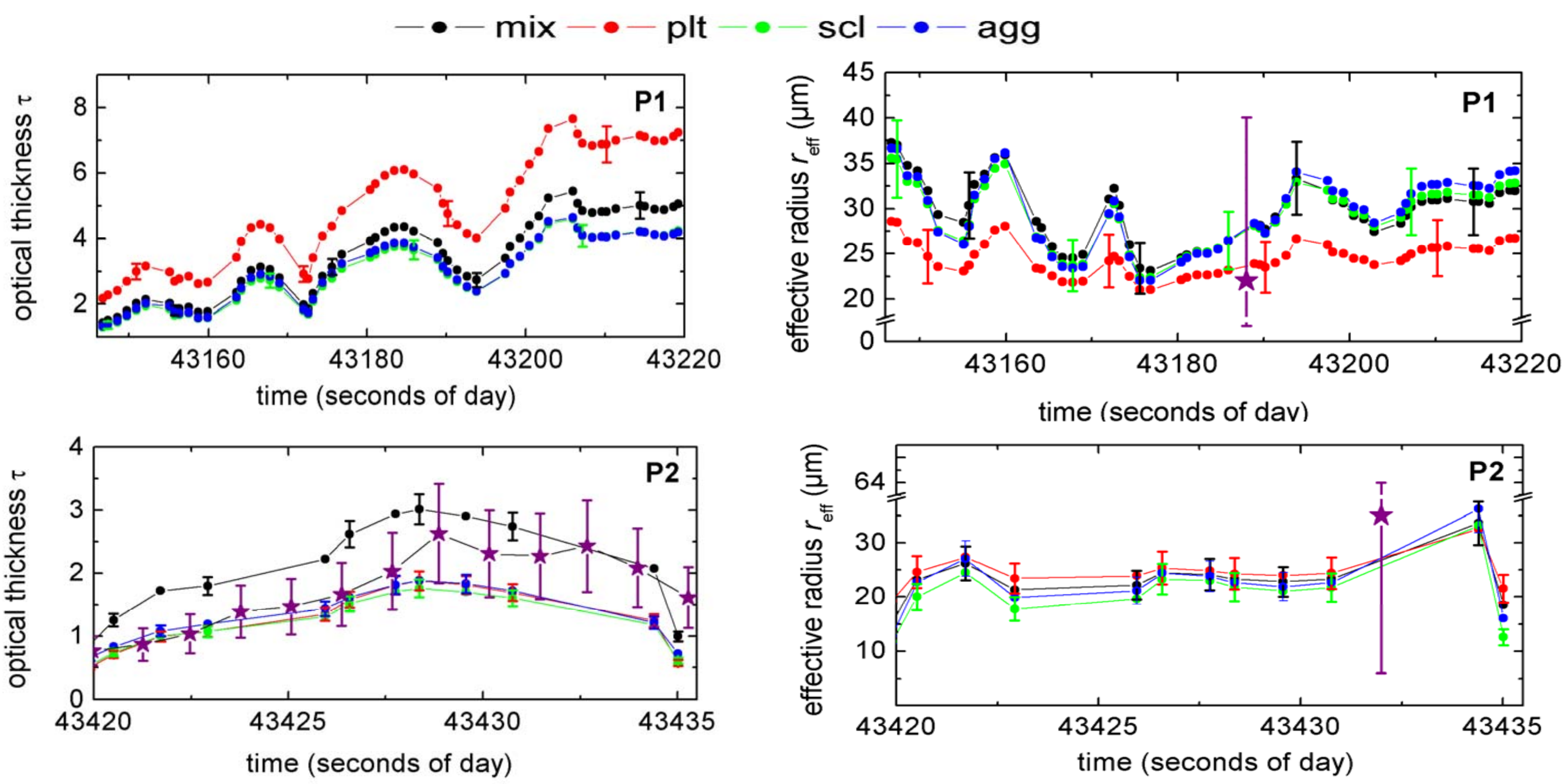
Zusammenhang von τ und R_{eff}:

$$\tau = \frac{3\cdot IWC\,dz}{2\cdot\rho_{Eis}R_{eff}}$$

Eiswassergehalt *IWC* (g m^{-3}):

Maß für Massenkonzentration der Eiskristalle in einem Wolkenvolumen

CIRCLE-2 results: Influence of shape effect on retrieval



Modis Airborne Simulater = MAS (King et al. 2004, JAOT)

• Flown aboard the NASA ER-2 aircraft, the MAS is a cross-track scanner with the maximum scan angle extending 43° on either side of nadir (**86° full-swath aperture**).

• At a nominal ER-2 altitude of 20 km, this yields a swath width of **37.2 km** at the earth's surface, centered on the aircraft ground track, with a total of **716 earth-viewing pixels** acquired per scan. With each pixel having a 2.5-mrad instantaneous field of view, the spatial resolution is **50 m** at nadir from the nominal aircraft altitude.

• MAS-channels: 50, MODIS-channels: 36

•The MAS has many channels that are similar to or comparable to those in MODIS, but it lacks a few channels that are important in the MODIS cloud mask (example: 1.38 µm-MODIS-band is comparable to the 1.88 µm MAS-band (both are in a strong water vapor absorption band – serve in the identification of subvisible, high-altitude cirrus clouds).

• <u>bands used for retrieval:</u>

0.65 µm = band 3 (tau over land)
0.87 µm = band 7 (tau over ocean)
2.13 µm = band 20 (Reff)

solar irradiance spectrum