Bluing of Aerosols near Clouds: Results from a Simple Model and MODIS Observations

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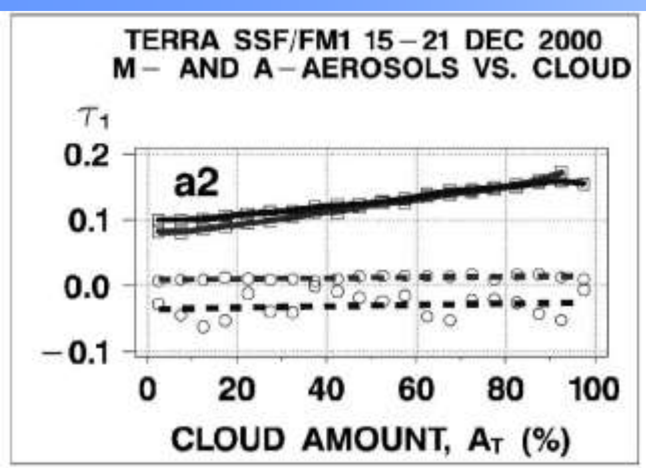
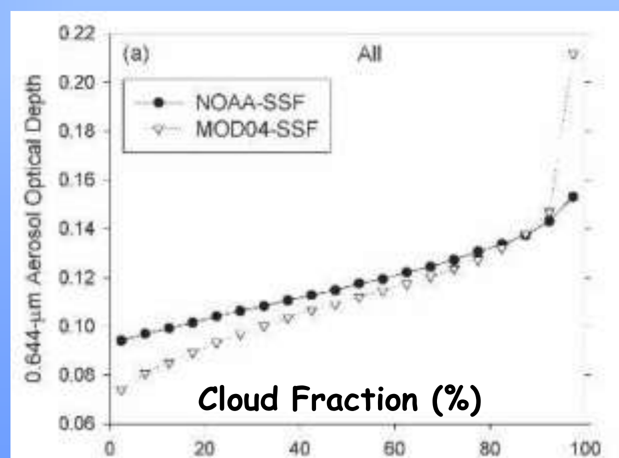
What happens to aerosol in the vicinity of clouds?

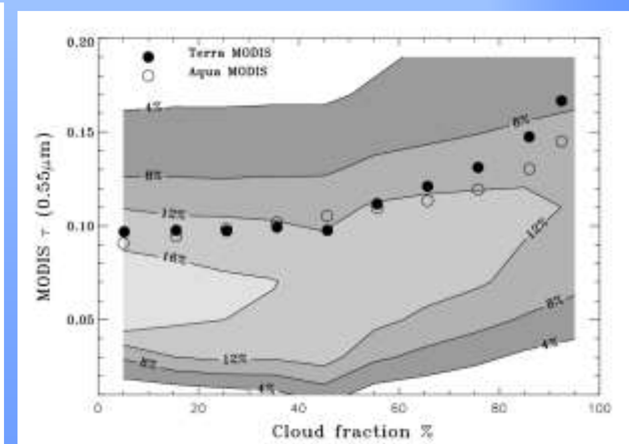
All observations show that aerosols seem to grow near clouds

or

(to be safer) "most satellite observations show a positive correlation between retrieved AOT and cloud cover", e.g.:







from Ignatov et al., 2005

from Loeb and Manalo-Smith, 2005

from Zhang et al., 2005

What happens to aerosol in the vicinity of clouds?

All observations show that aerosols seem to grow near clouds.

However, it is not clear yet how much grows comes from

- "real" microphysics, e.g.
  - increased hydroscopic aerosol particles,
  - new particle production or
  - other in-cloud processes.
- ("artificial") the 3D cloud effects in the retrievals:
  - cloud contamination,
  - extra illumination from clouds

How do clouds affect aerosol retrieval?

Both

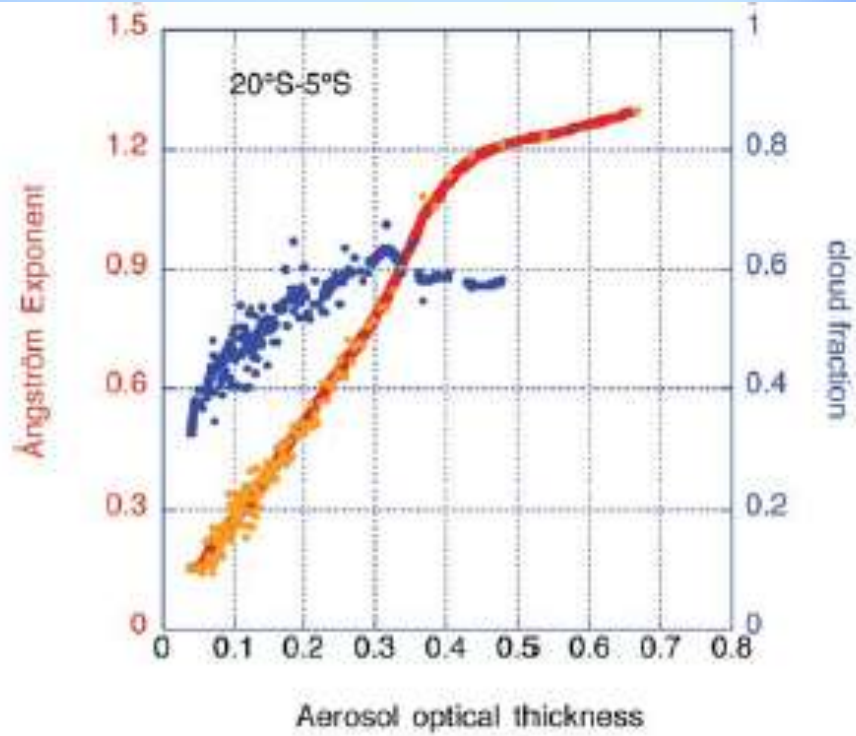
- cloud contamination (sub-pixel clouds)
- cloud adjacency effect (a clear pixel with in the vicinity of clouds)

may significantly overestimate AOT.

But they have different effects on the retrieved AOT: while cloud contamination increases “coarse” mode, cloud adjacency effect increases “fine” mode.

The Ångström exponent and the cloud fraction vs. AOT

- Atlantic ocean, June-Aug. 2002; each point is aver. on 50 daily values with similar AOT in 1^{o} res.;
- for AOT < 0.3, as AOT increases CF and the Ångström exponent also increase;
- the increase is due to transition from pure marine aerosol to smoke (or pollution);
- the increase in AOT cannot be explained by cloud contamination but rather aerosol growth.



from Kaufman et al., IEEE 2005

Fig. 8. Aerosol Ångström exponent [a measure of (solid red line) the aerosol size] and (dashed blue line) cloud fraction, as a function of the aerosol optical thickness. Cloud fraction is plotted only for AOT < 0.5 to avoid effects of aerosol on the cloud fraction [39].

More clouds go with larger AOT and larger (not smaller!) Ångström exponent

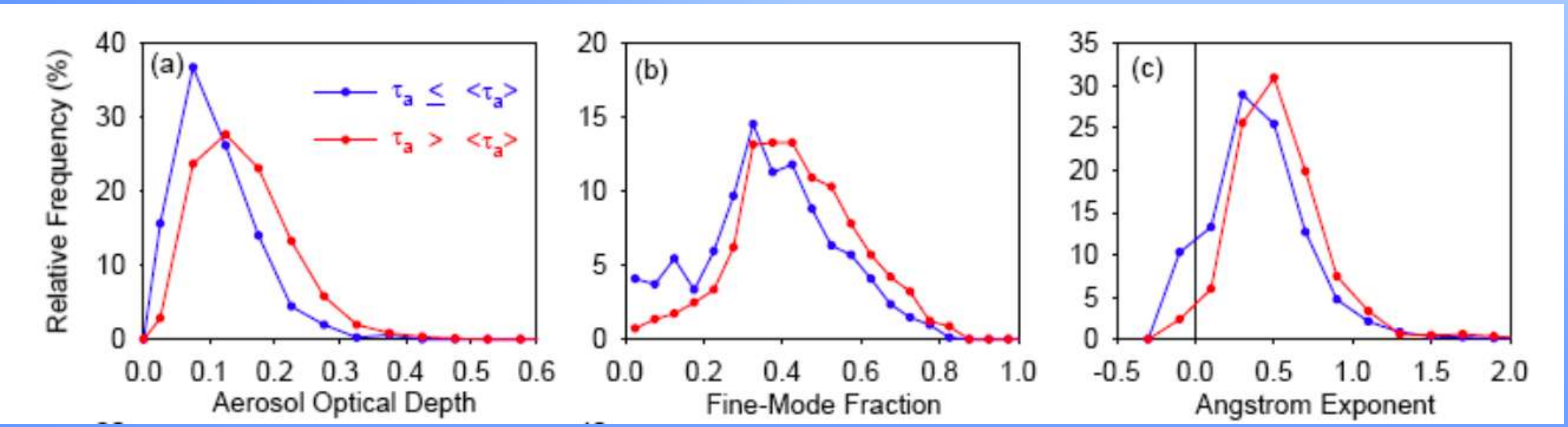
- one month of data: 25 1°x1° in each 5°x5° region over ocean (off the cost of Africa) are subdivided into two groups with

$$\tau_a < \langle\tau_a\rangle$$

and

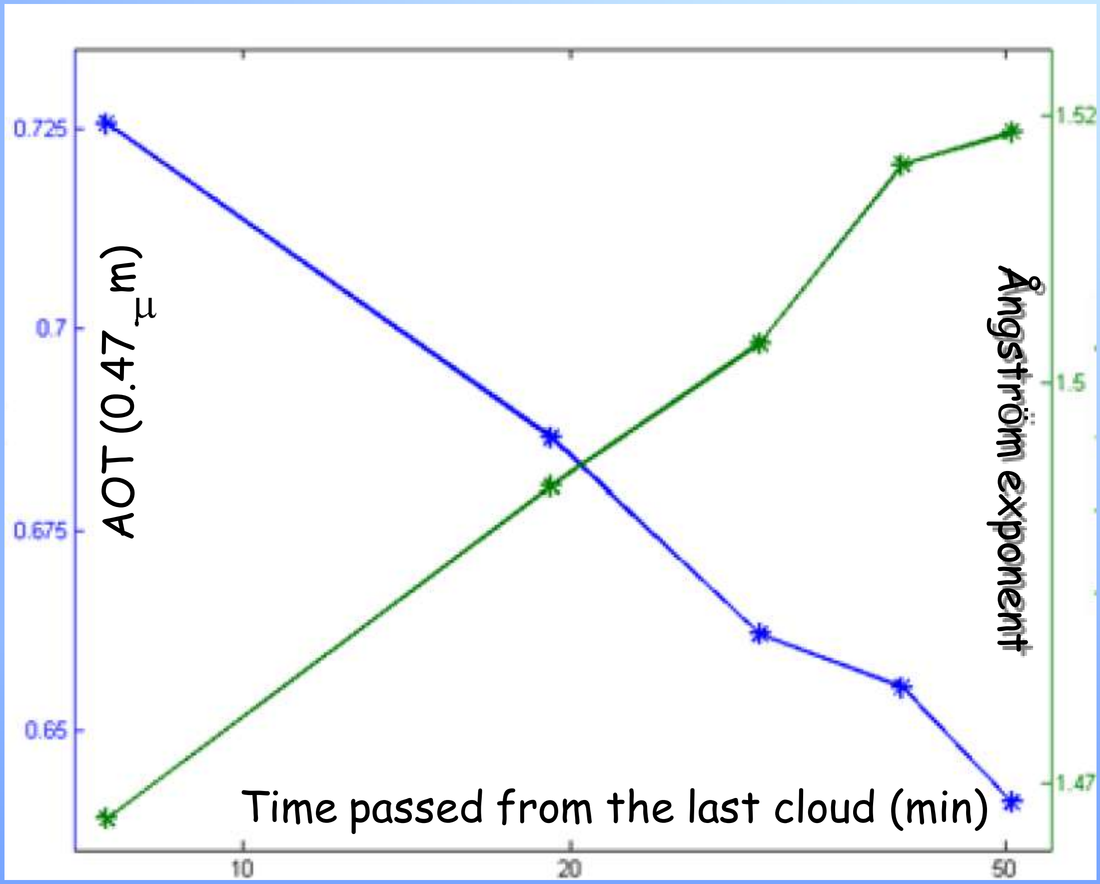
$$\tau_a > \langle\tau_a\rangle$$

- meteorology has been checked as similar for two groups



from Loeb and Schuster (JGR, 2008)

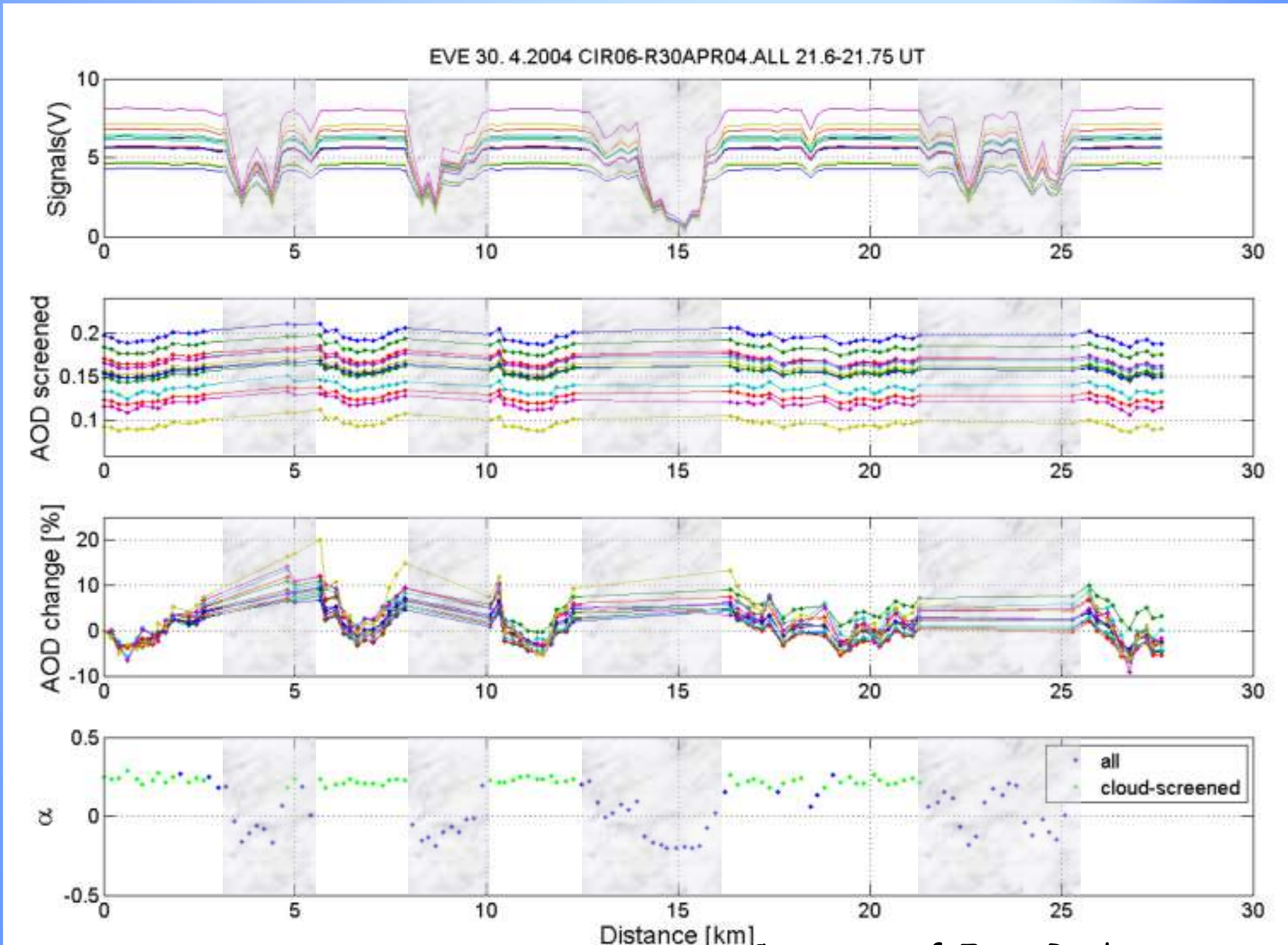
AOT and Ångström exponent vs. distance from the nearest cloud (AERONET data)



The Ångström exponent increases with distance to the nearest cloud while the AOT increases

from Koren et al., GRL, 2007

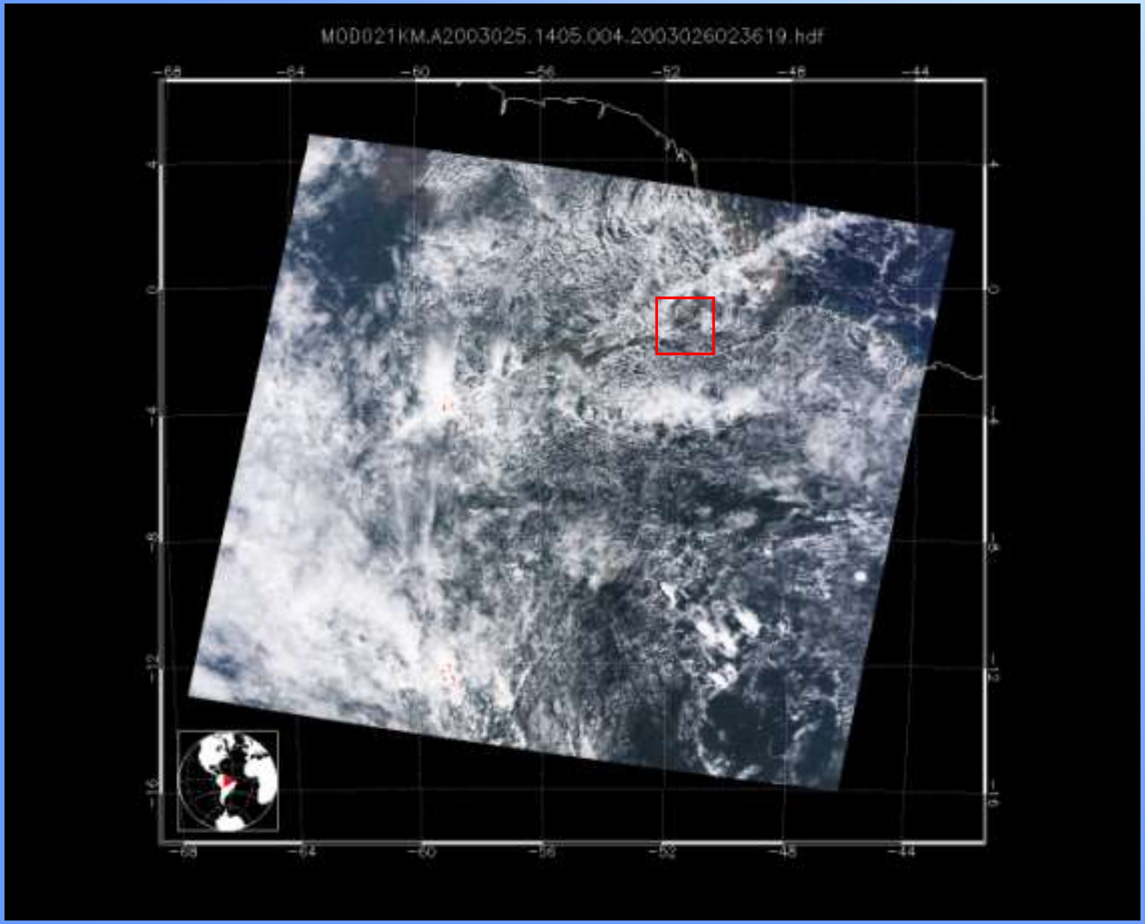
Airborne aerosol observations in the vicinity of clouds



From airborne extinction rather than scattering observations 3D effects decrease AOT rather than increase it

Courtesy of Jens Redemann

Aerosol-cloud radiative interaction
(a case study)

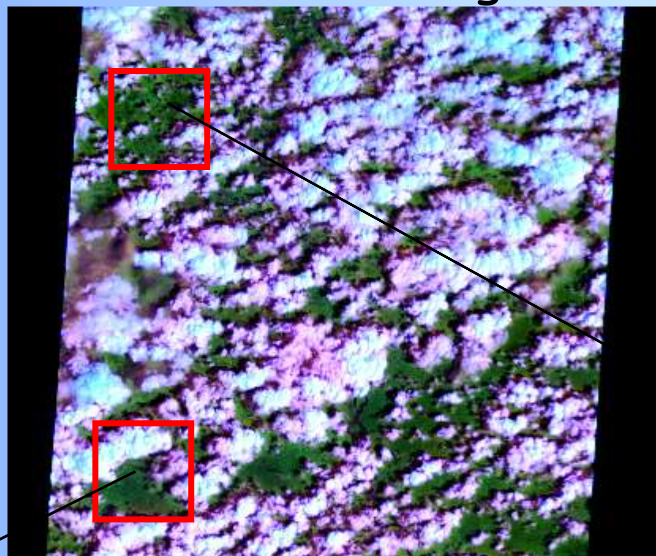


Collocated MODIS and ASTER image of Cu cloud field in biomass-burning region in Brazil at 53° W on the equator, acquired on Jan 25, 2003

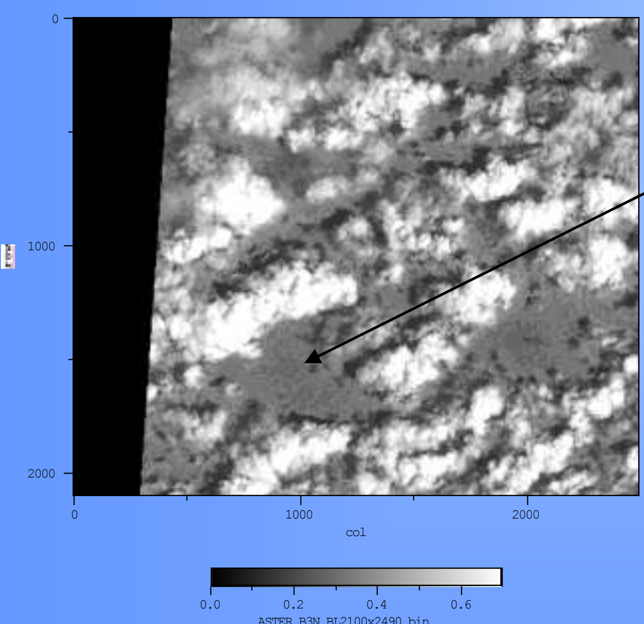
Wen et al., 2006

ASTER image and MODIS AOT

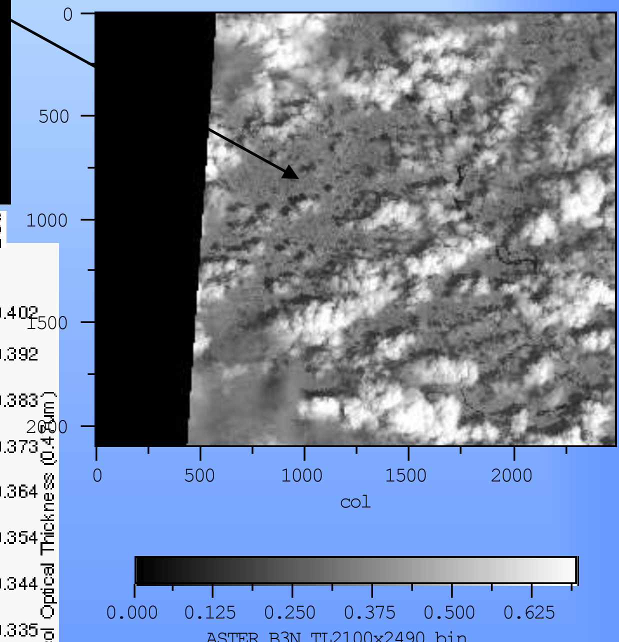
ASTER image

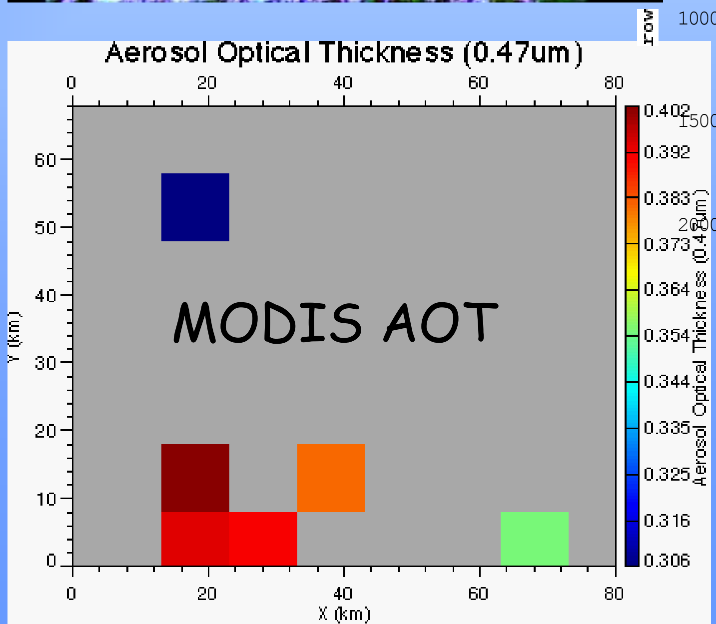


Thick clouds



Thin clouds



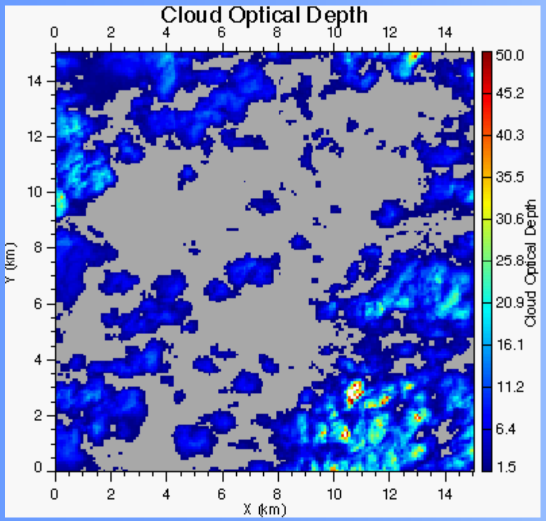


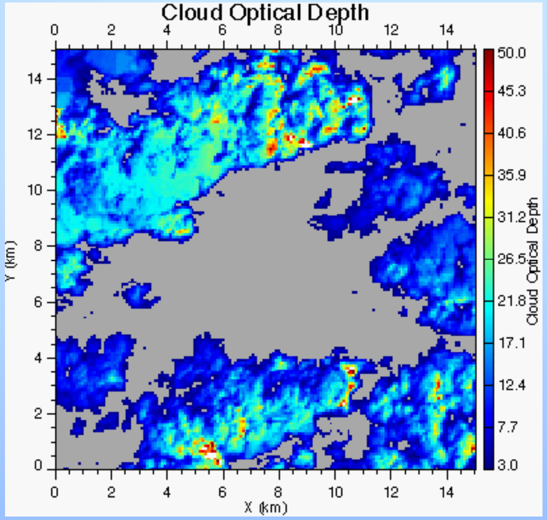
from Wen et al., JGR, 2007

Cloud effect at 90-m resolution

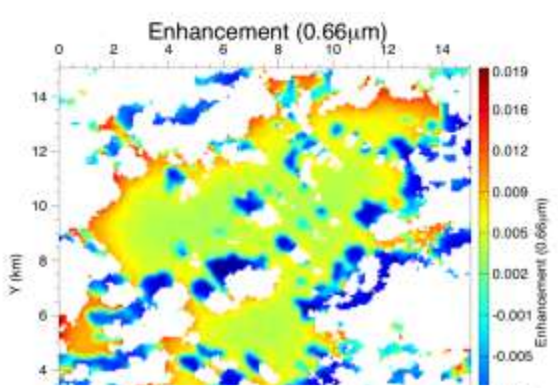
Thin clouds, $\langle\tau\rangle=7$

Thick clouds, $\langle\tau\rangle=14$





$AOT_{0.66}=0.1$

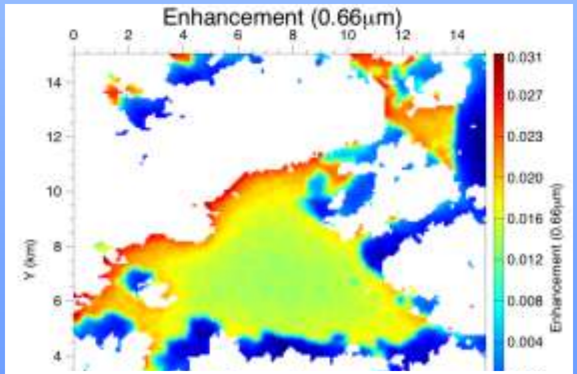


$\Delta\rho \sim 0.0046$

$\Delta\tau \sim 0.05 \approx 50\%$

enhancement:

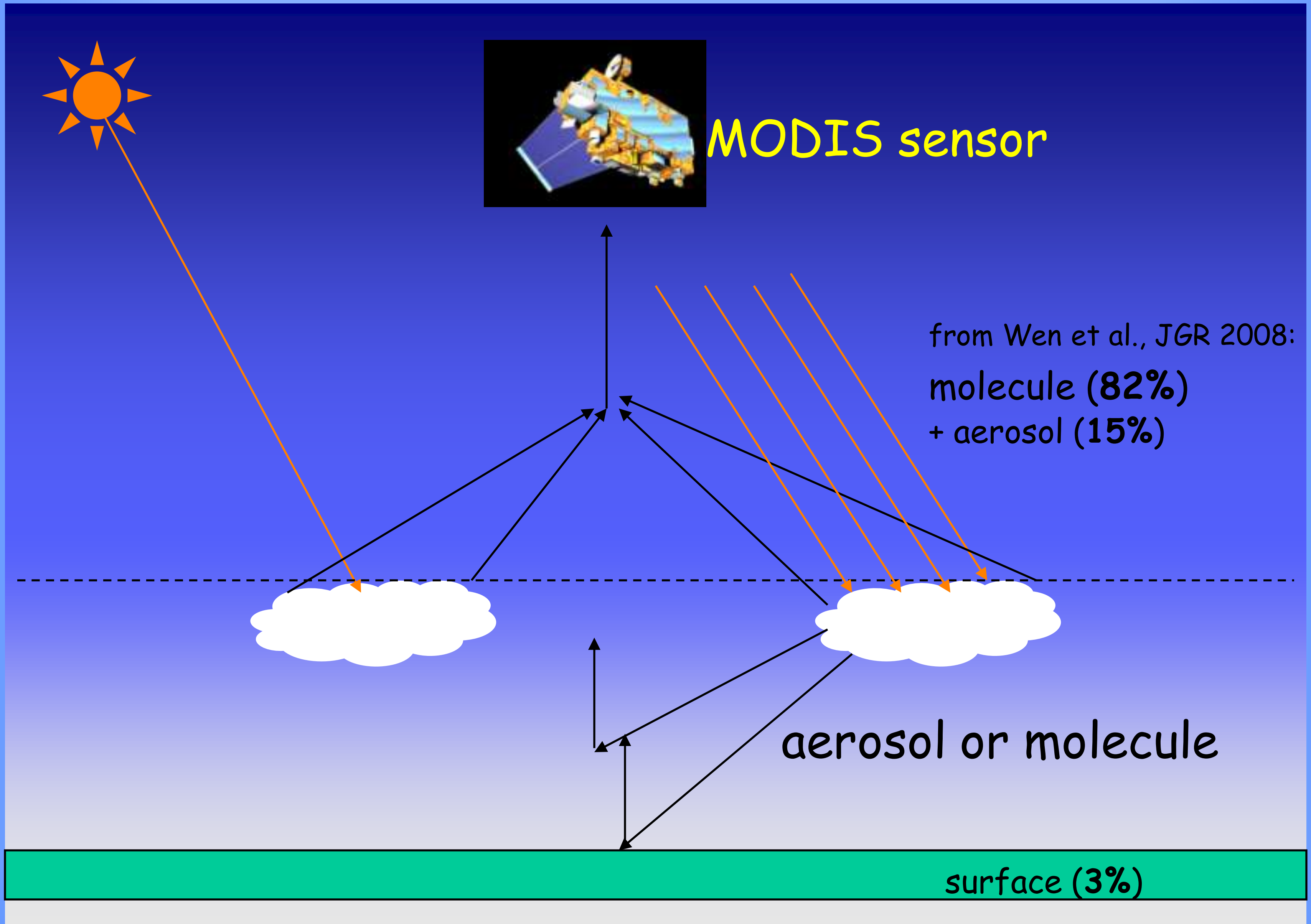
$\Delta\rho = \rho_{3D} - \rho_{1D}$



$\Delta\rho \sim 0.014$

$\Delta\tau \sim 0.14 \approx 140\%$

Conceptual model to account for the cloud enhancement (at 0.47 μm)



Assumption for a simple model

Molecular scattering is the main source for the enhancement in the vicinity of clouds

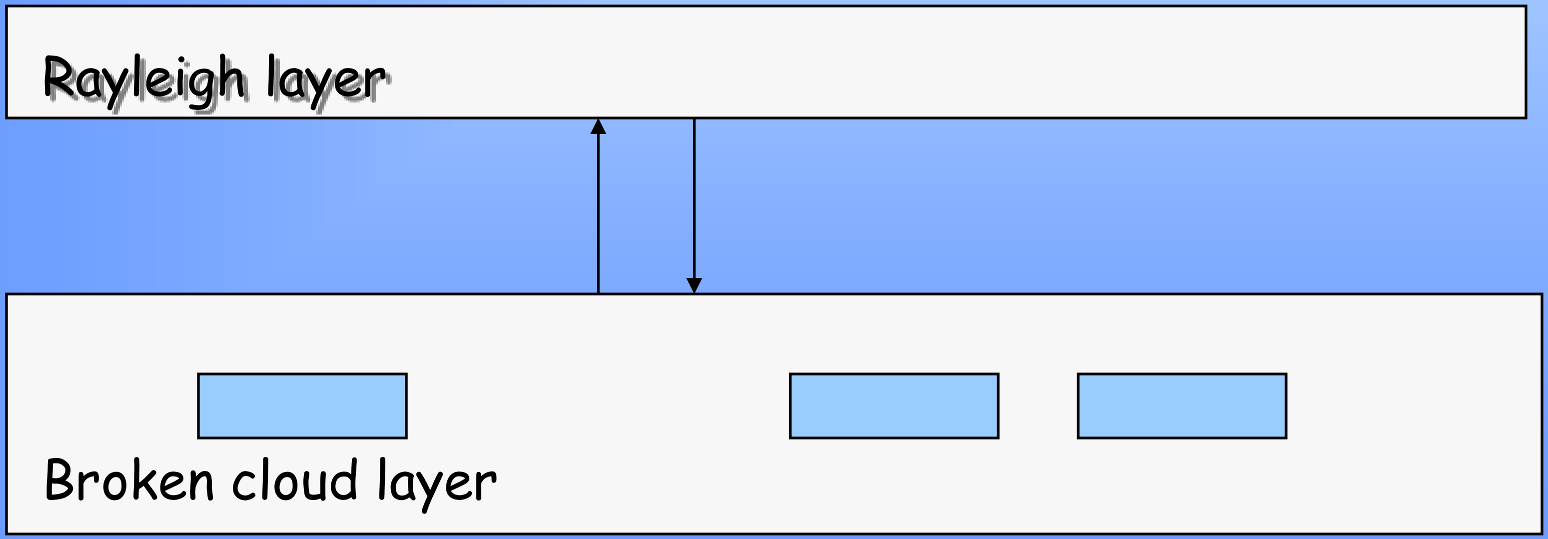
thus

we retrieve larger AOT and fine mode fraction

How to account for the 3D cloud effect on aerosols?

The *enhancement* is defined as the difference between the two radiances:

• one is reflected from a broken cloud field with the scattering Rayleigh layer above it
• and one is reflected from the same broken cloud field but with the Rayleigh layer having extinction but no scattering

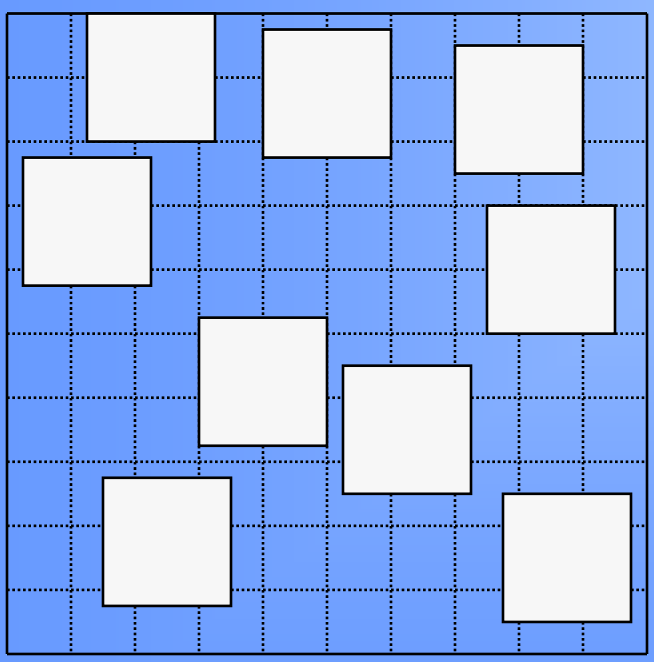


from Marshak et al., JGR, 2008

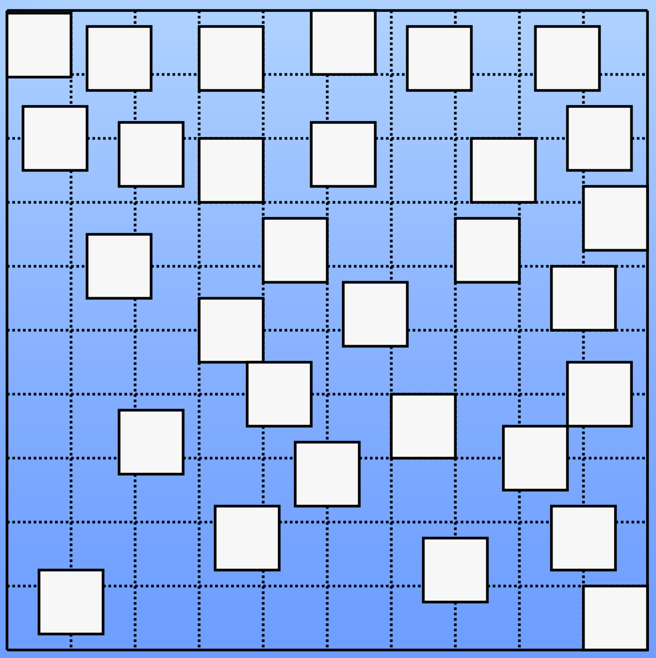
Stochastic model of a broken cloud field

Clouds follow the Poisson distr. and are defined by

- average optical depth, $\langle\tau\rangle$
- cloud fraction, A_c
- aspect ratio, AR = hor./vert.



$AR = 2$



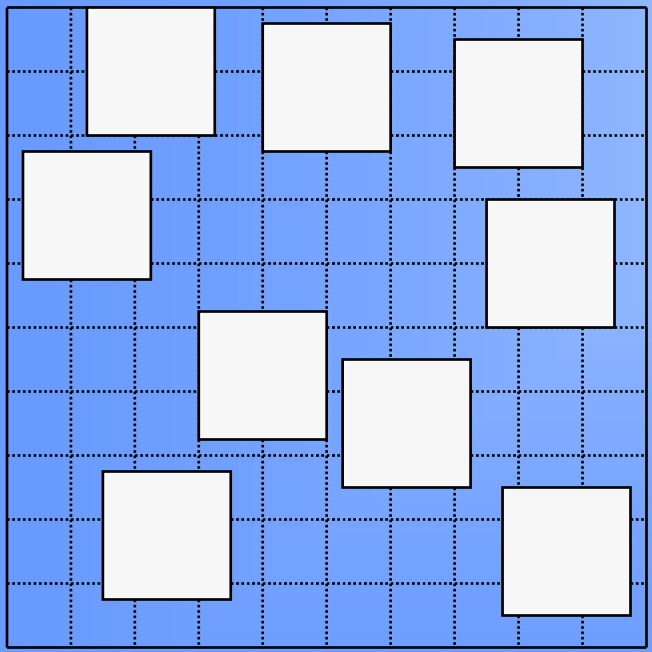
$AR = 1$

$A_c = 0.3$

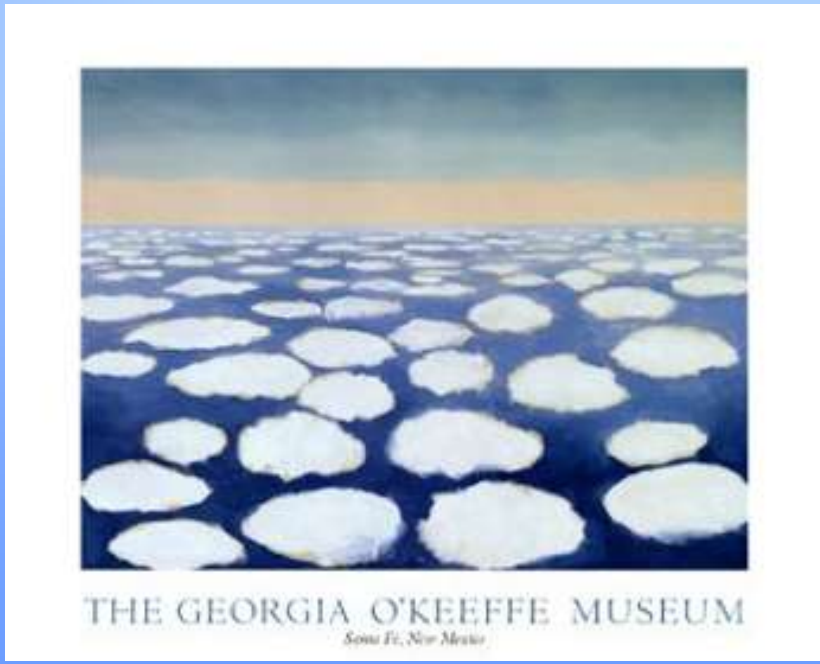
Stochastic model of a broken cloud field

Clouds follow the Poisson distr. and are defined by

- average optical depth, $\langle\tau\rangle$
- cloud fraction, A_c
- aspect ratio, AR = hor./vert.



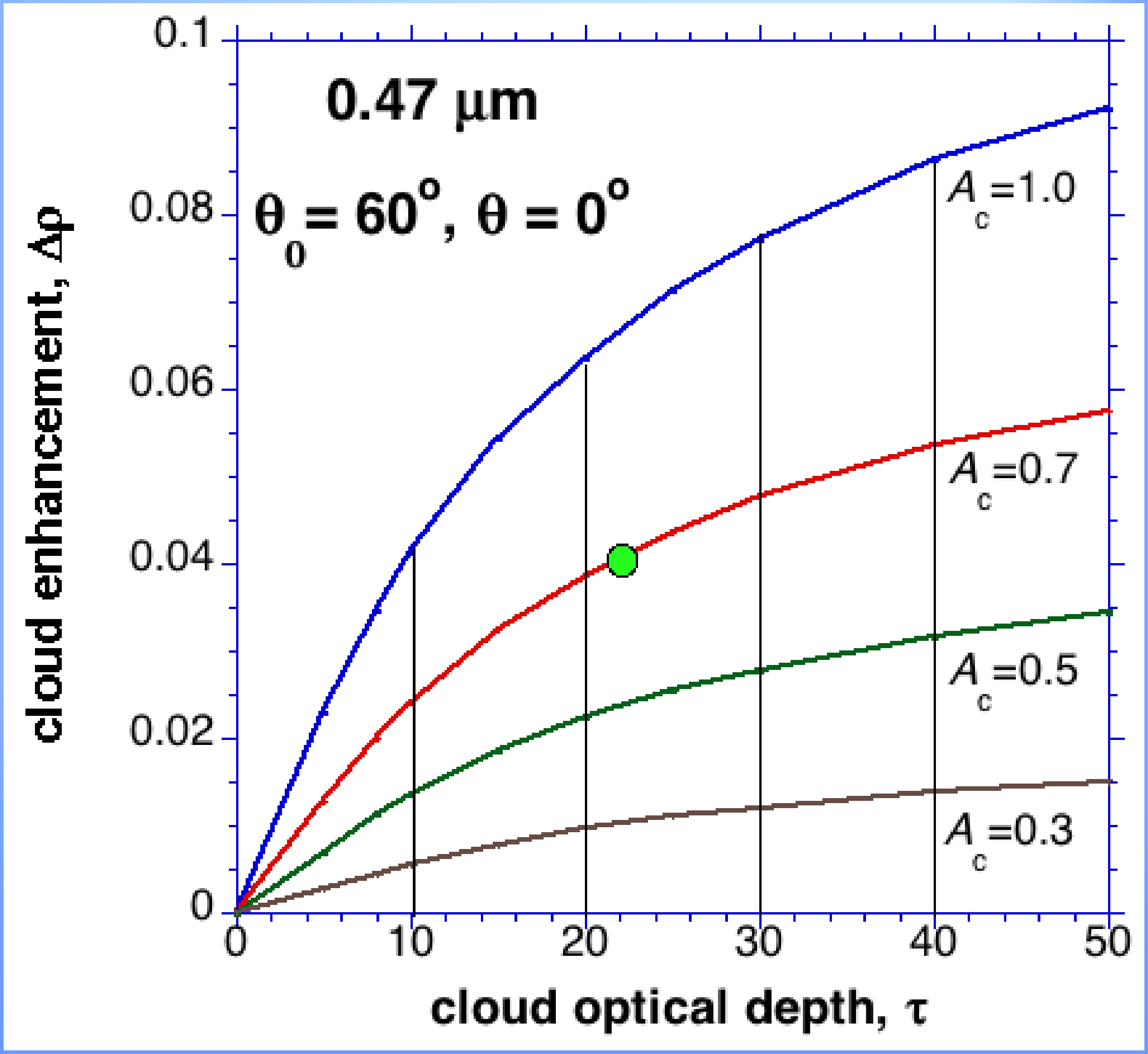
AR = 2



AR = 1

$A_c = 0.3$

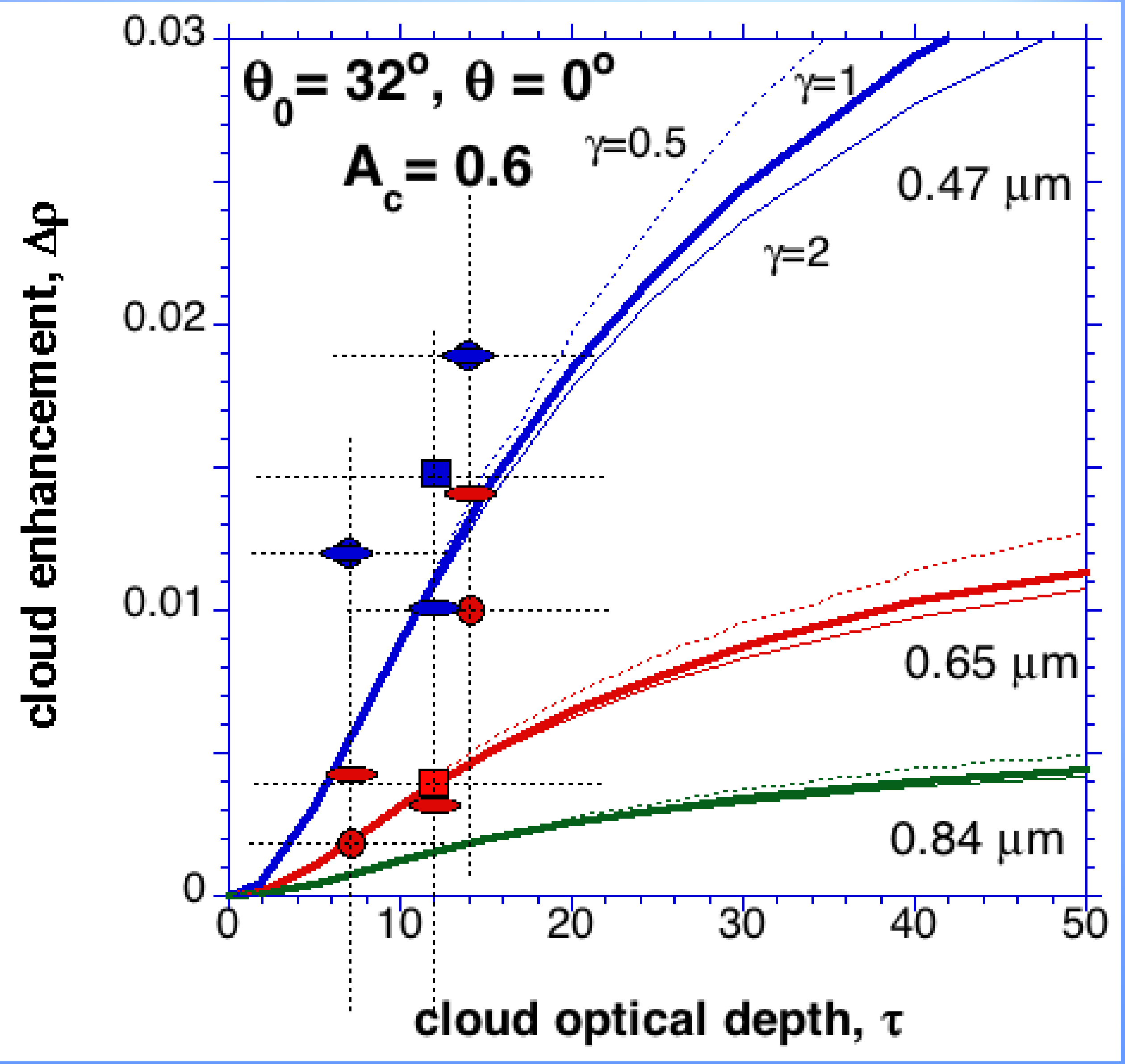
Cloud-induced enhancement at 0.47 μm



LUT:
The enhancement vs $\langle\tau\rangle$ for AR = 1. A_c=1 corresponds to the pp approximation.

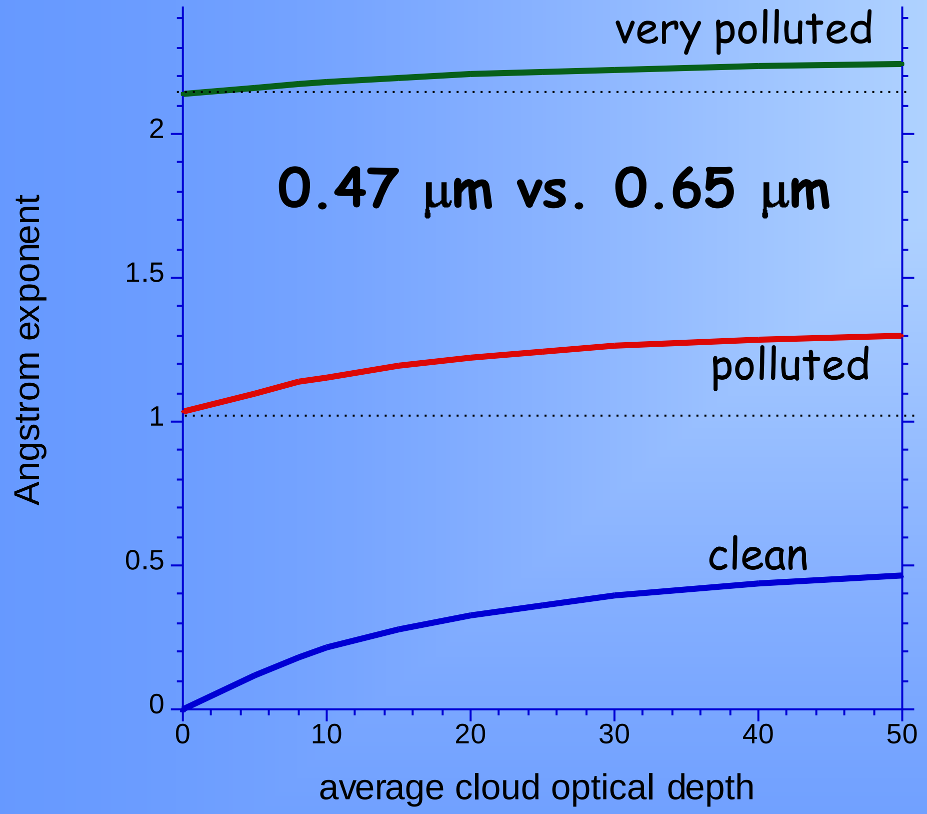
Cloud-induced enhancement: our simple model and 3D RT calculations

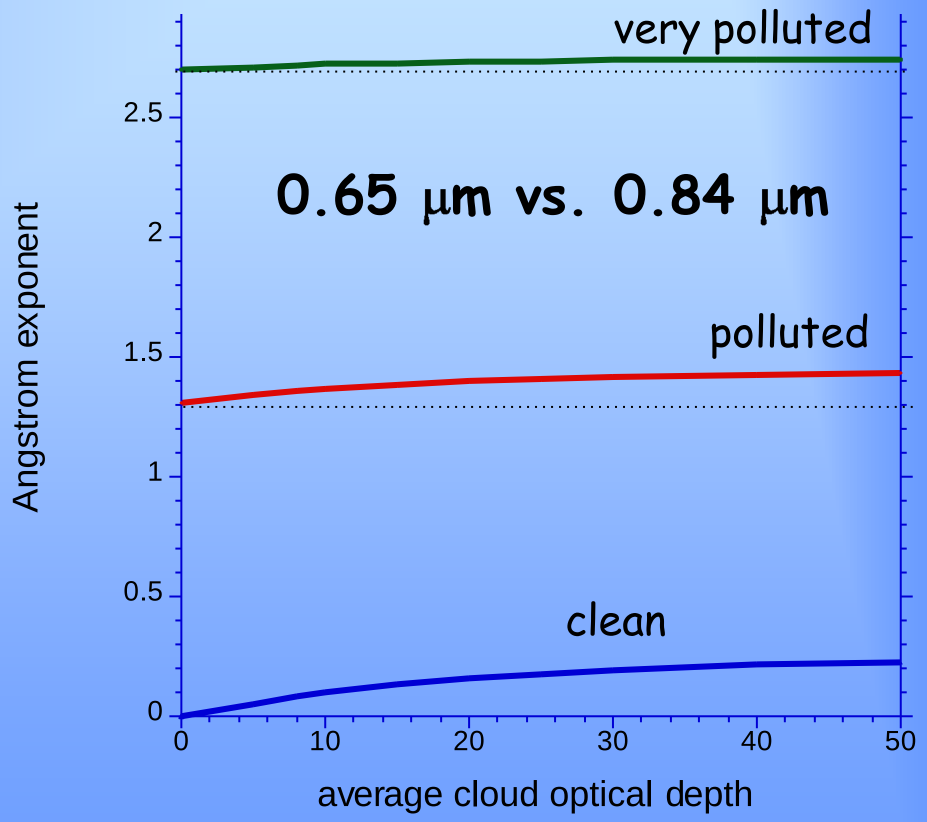
The enhancement vs <τ> for A_c= 0.6 and 3 cloud AR = 0.5, 1 and 2. Different dots are from Wen et al. (2007) MC calculations for the thin and thick clouds.



Ångström exponent

Ångström exponent vs <τ> for A_c= 0.5 and AR = 2.
Three cases: clean, polluted and very polluted.



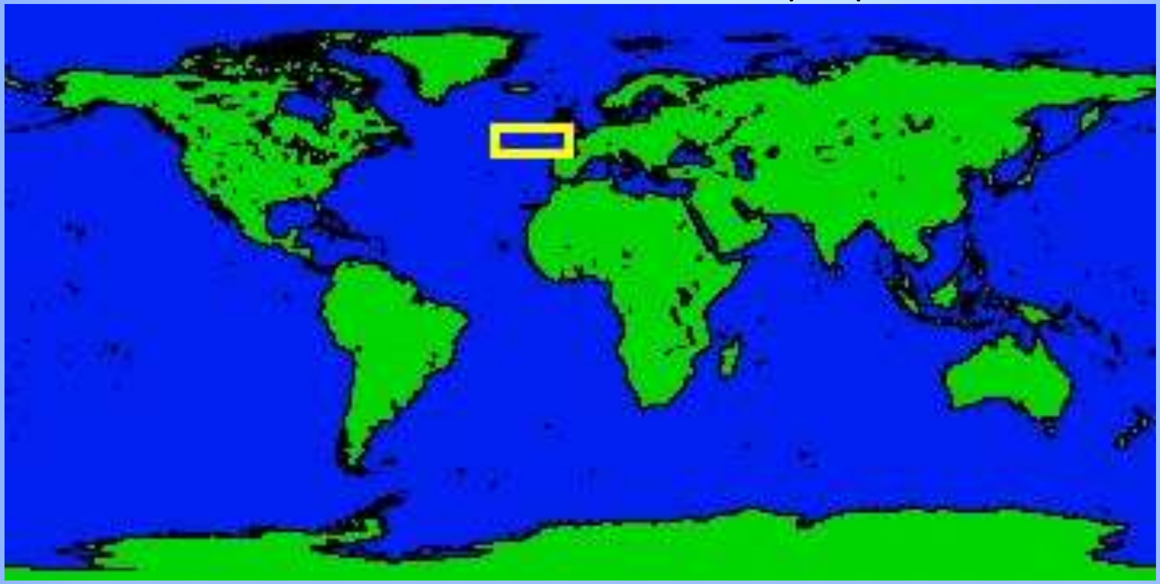


The cloud adjacency effect increases the Ångström exponent

from Marshak et al., JGR, 2008

MODIS observations

(Várnai and Marshak, 2008, in preparation)

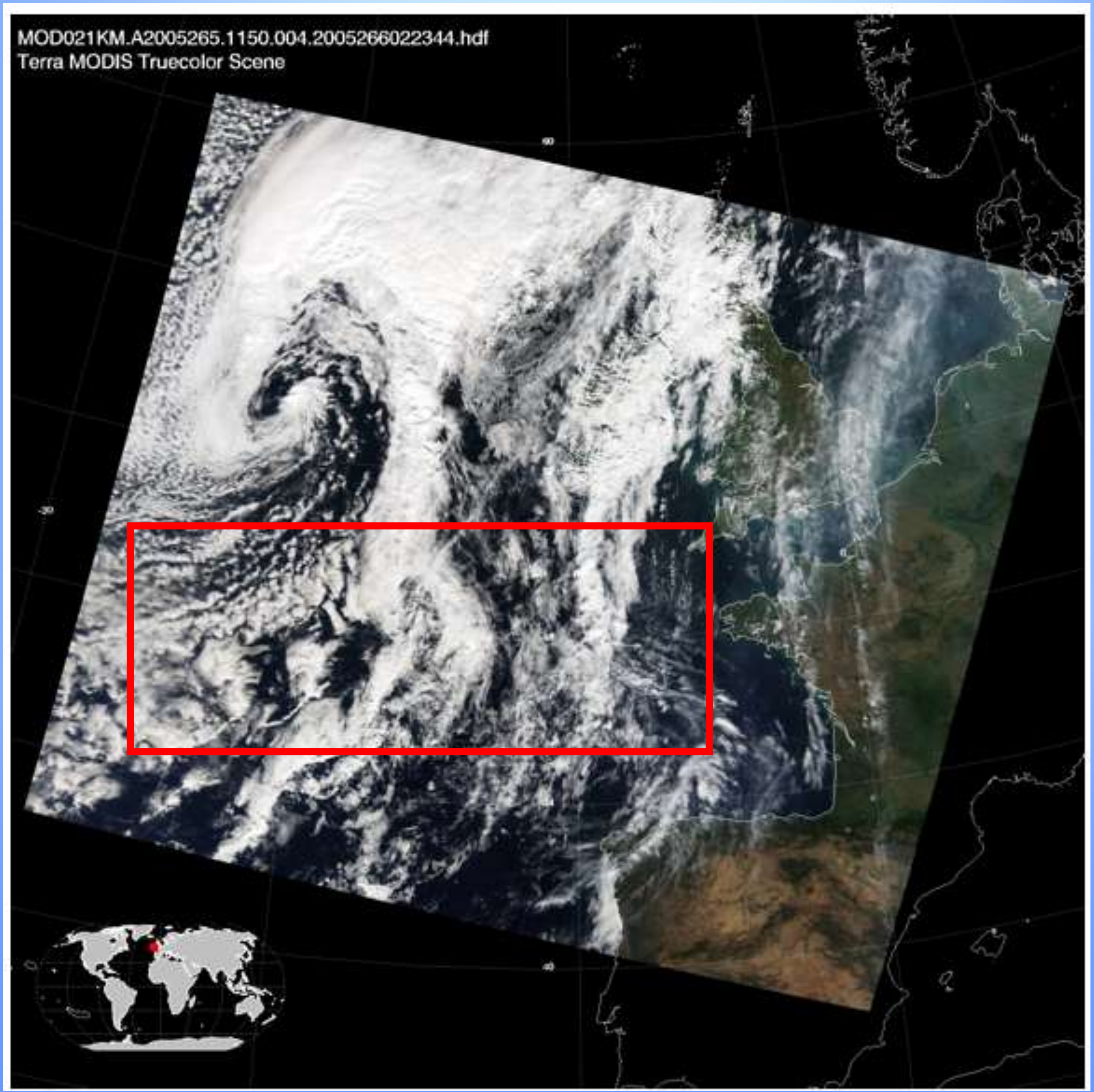


- Collection 5 MOD02, MOD06, MOD35 products
- 2 weeks in Sep. and March in 2000-2007 (2x2 weeks in 8 years)
- North-East Atlantic (45° -50° N, 5° -25° W), south-west from UK
- Viewing zenith angle < 10°

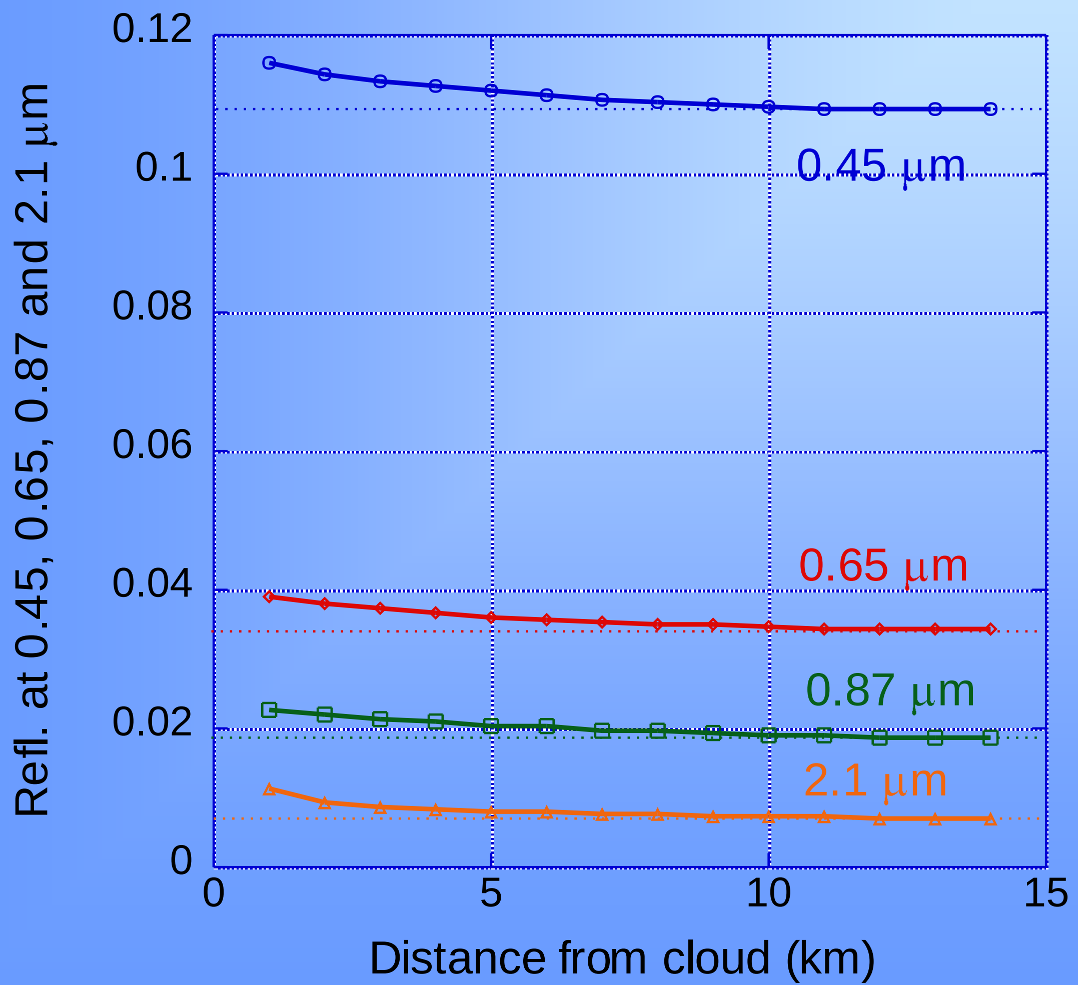
Pixels included in plots:

- Ocean surface with no glint or sea ice
- MOD35 says "confident clear", all 250 m subpixels clear
- Highest cloud top pressure nearby > 700 hPa (near low clouds)
- Nearby pixels are considered cloudy if MOD35 says definitely cloud.

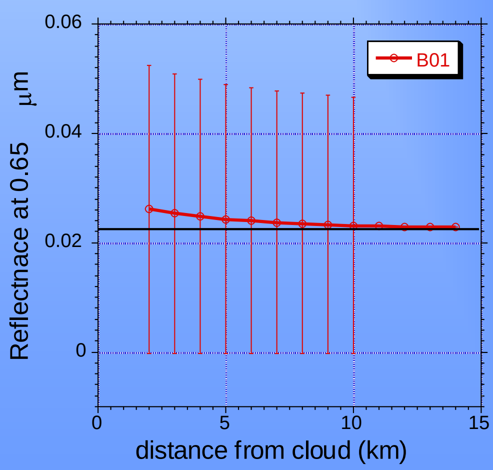
Example of the region: Sep 22, 2005



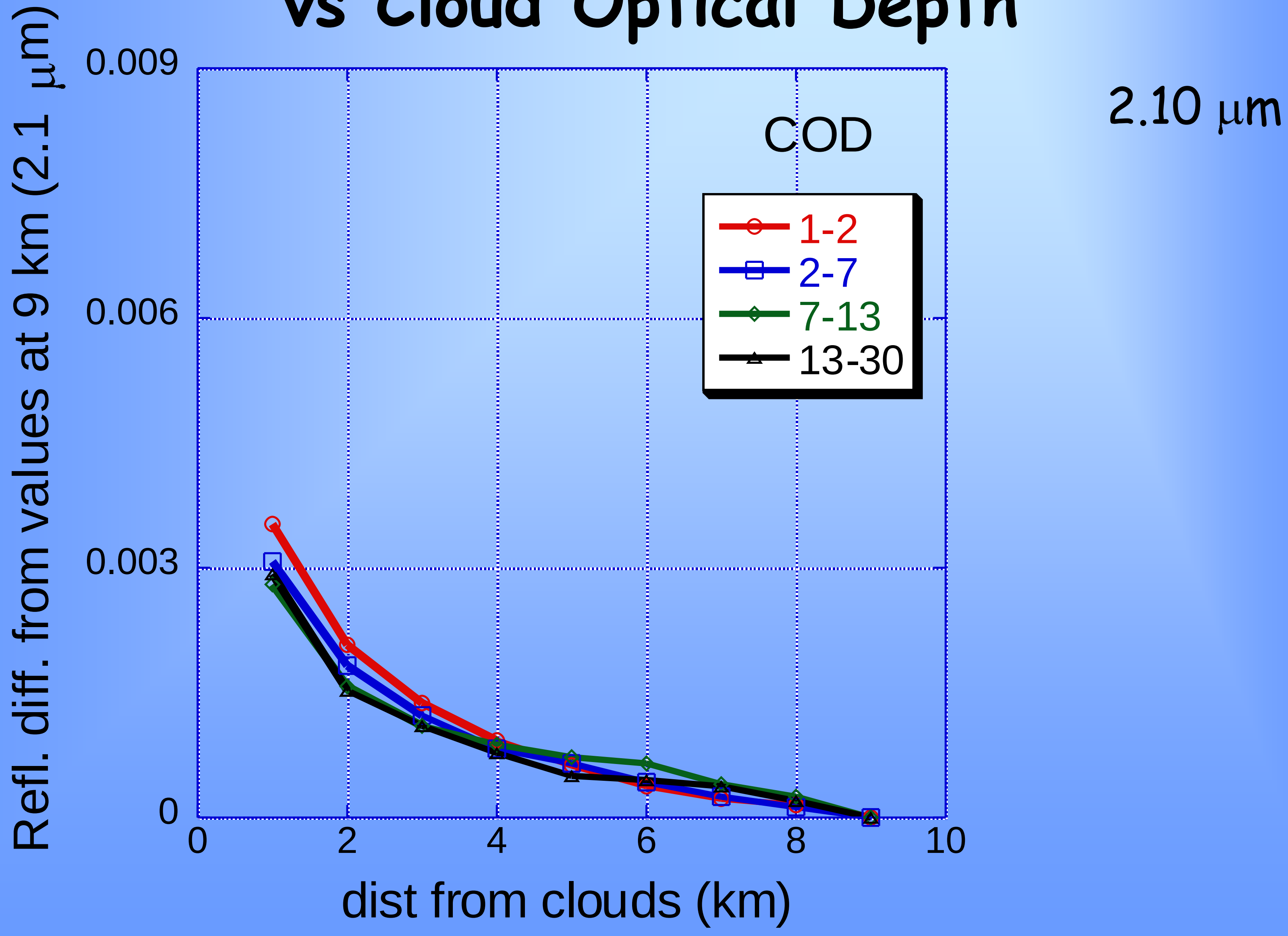
Average reflectance vs. dist. to clouds for 0.45, 0.65, 0.87, and 2.1 μm



mean and std

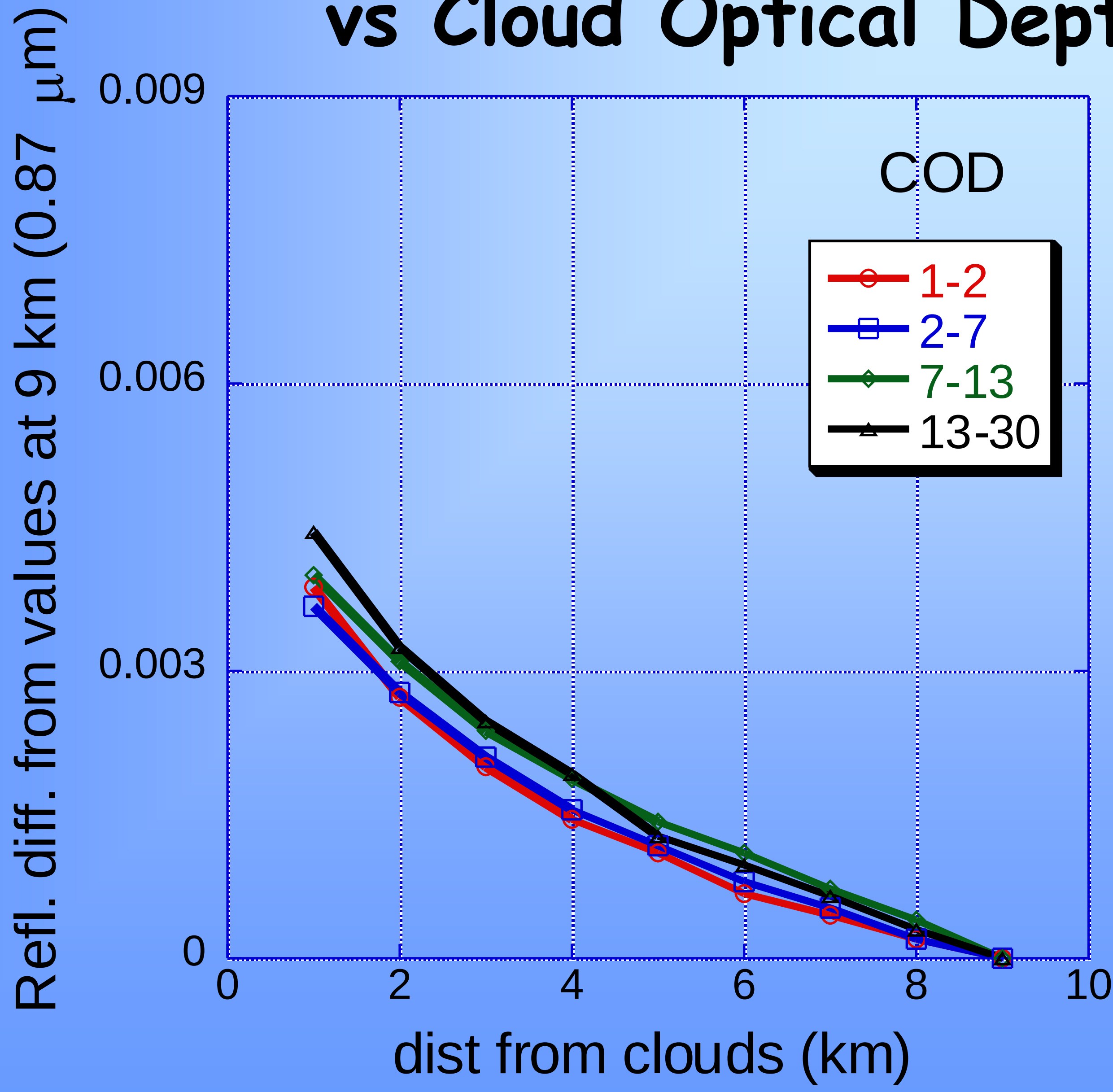


Reflect. Diff from Values at 10 km vs Cloud Optical Depth

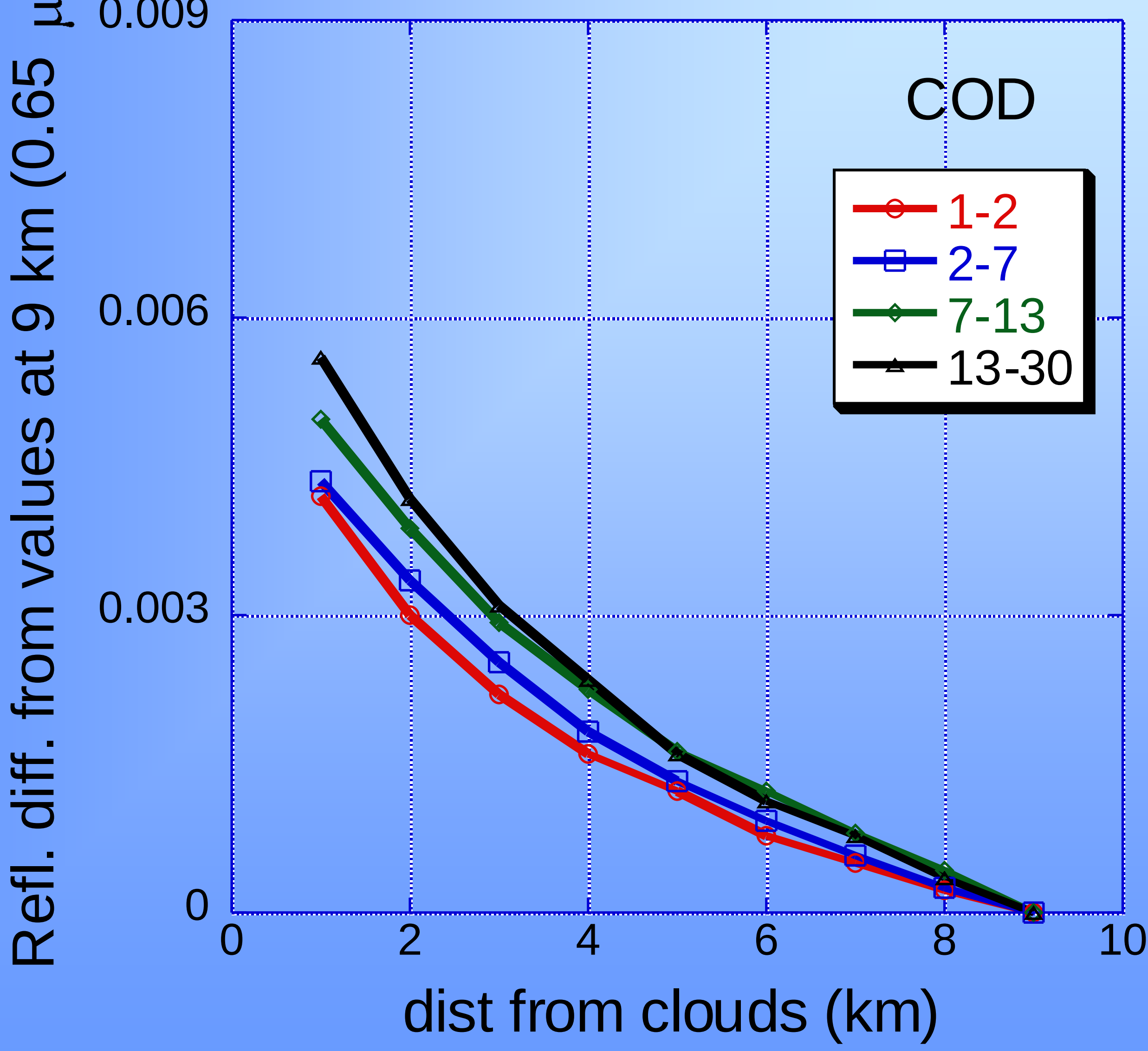


Reflect. Diff from Values at 10 km vs Cloud Optical Depth

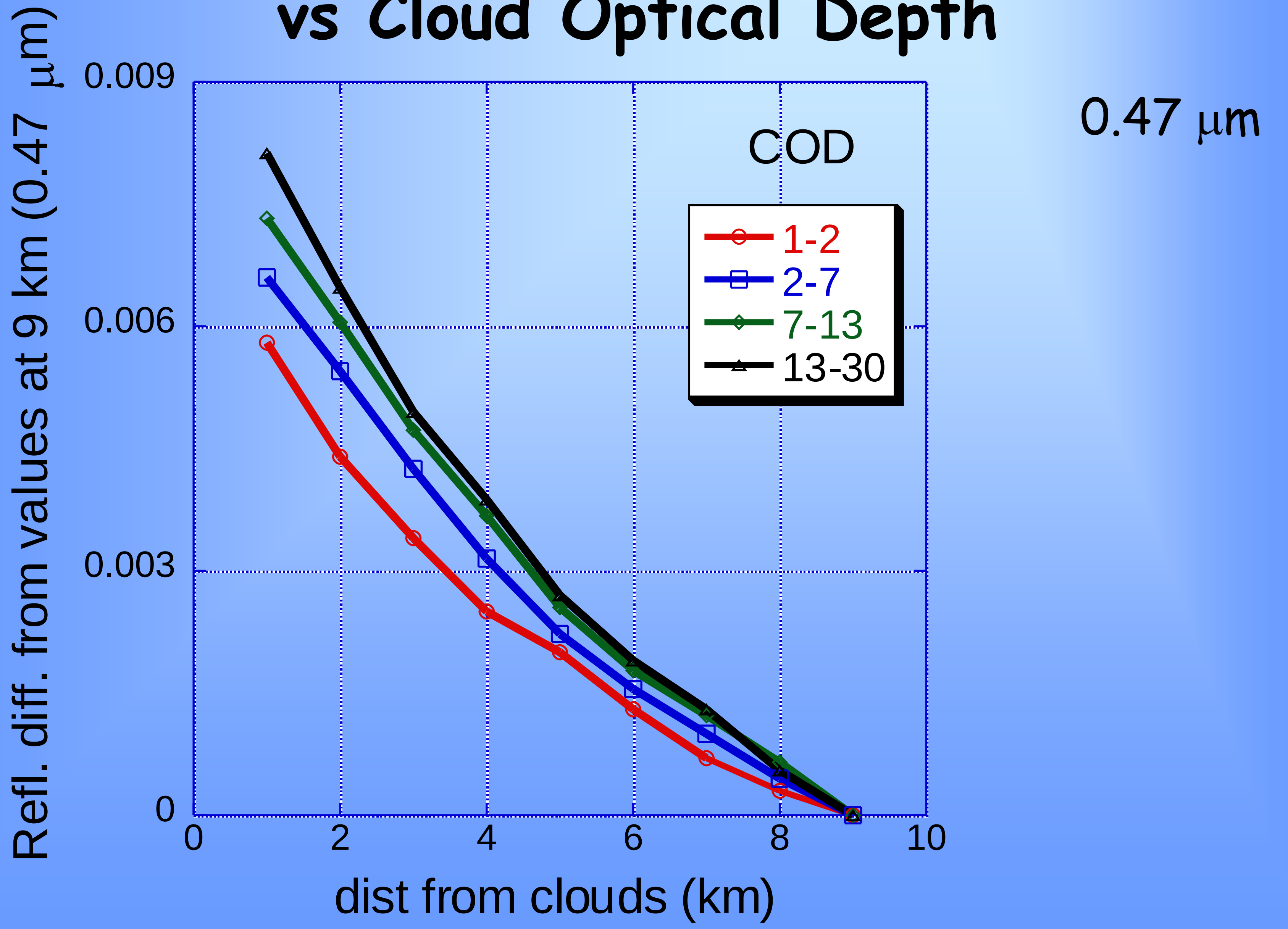
0.87 μm



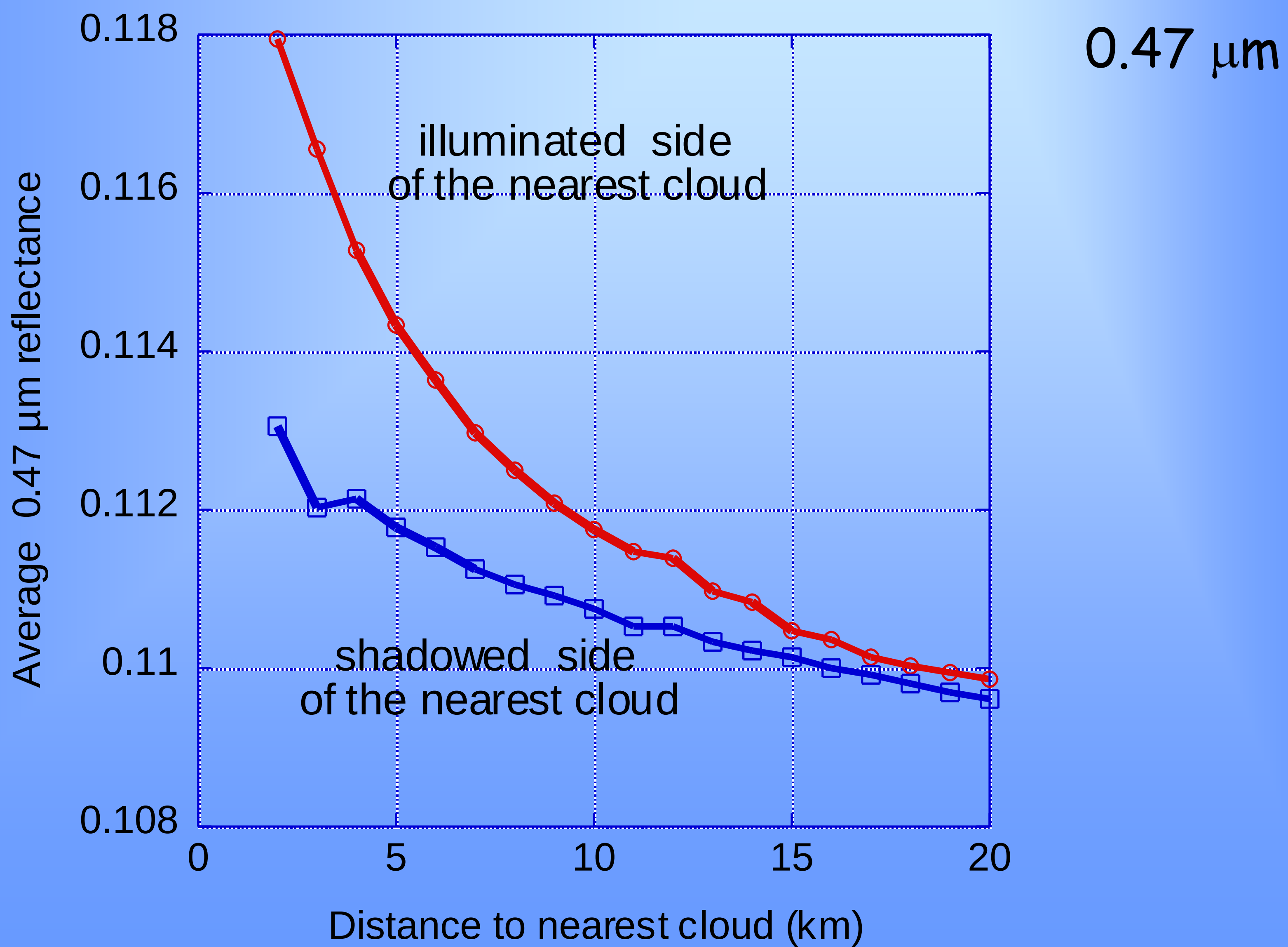
Reflect. Diff from Values at 10 km vs Cloud Optical Depth



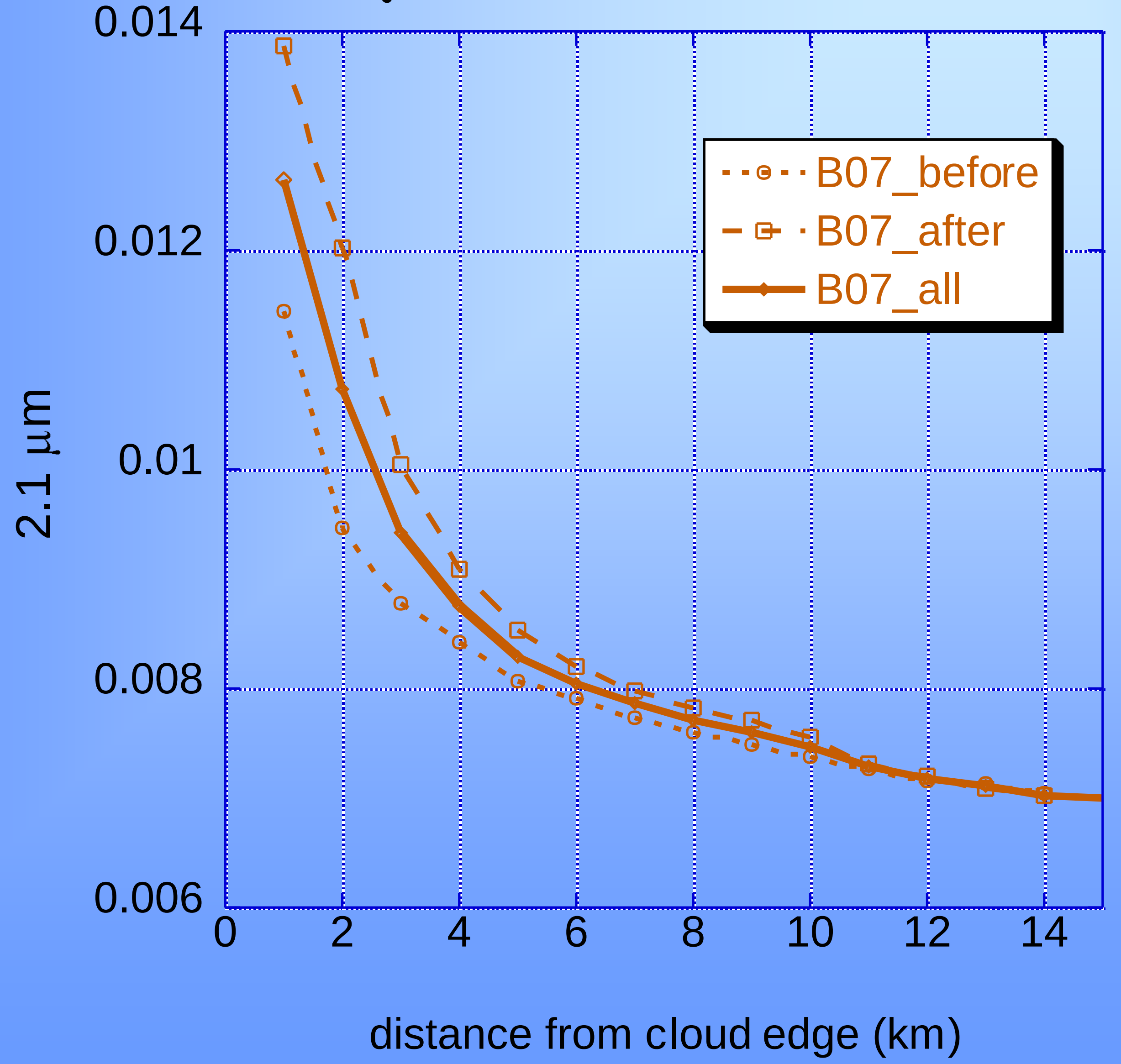
Reflect. Diff from Values at 10 km vs Cloud Optical Depth



Asymmetry with respect to the sun

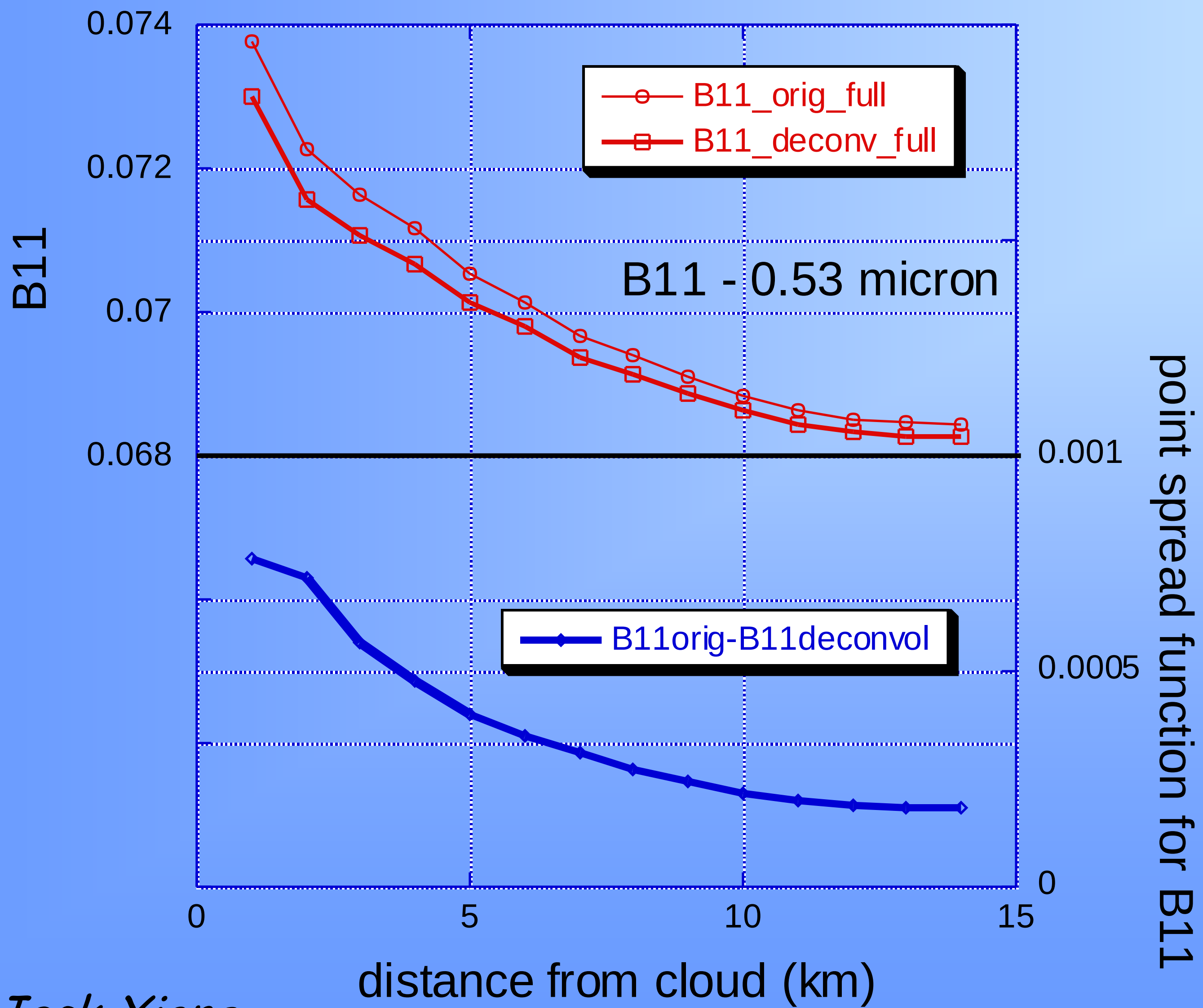


Latency effect for 2.1 um



Point spread function effect for 0.53 μm

(preliminary results)

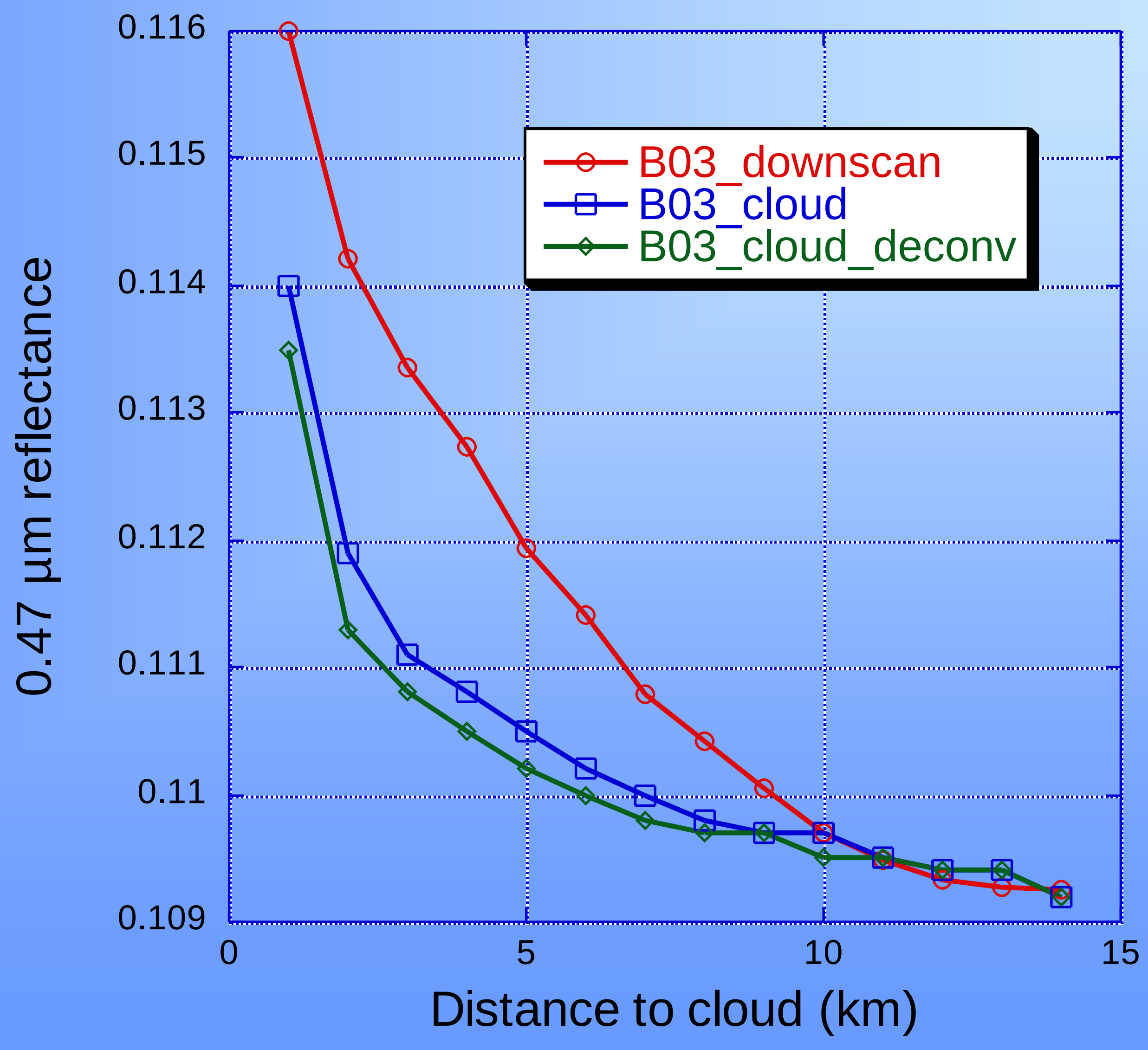


with Jack Xiong

Cloud contamination in 0.47 μm

(preliminary results)

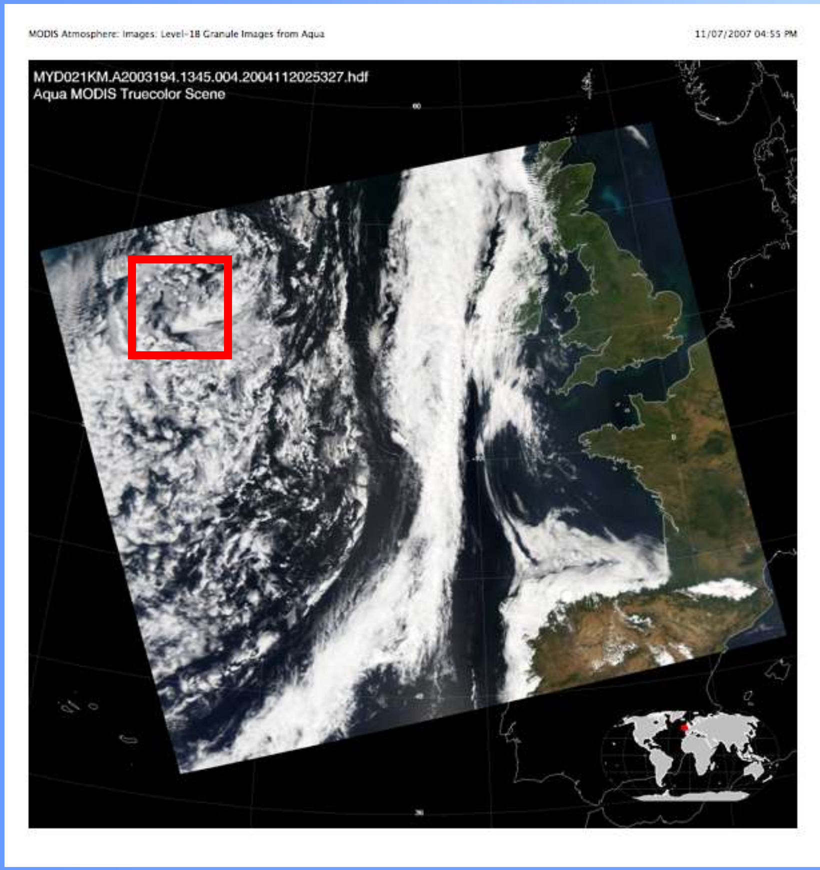
- latency effect removed (**red** curve);
- assumed that at 2.1 μm the increase is due to undetected subpixel clouds (**blue** curve)
- assumed that 2.1 μm has the same point spread function as 0.53 μm (**green** curve)



with Jack Xiong

Work in progress

with Norman Loeb and Lorraine Remer



- select a few MODIS subscenes with
  - broken low Cu;
  - retrieved AOT;
  - over ocean with no glint, etc;
- analyze AOT, CF, average COT over many 10 x 10 km areas;
- use a simple stochastic model and RT to estimate upward flux;
- use CERES fluxes to convert BB to spectral fluxes;
- use ADM to determine spectral fluxes from MODIS radiances;
- estimate cloud enhancement and compare the results;
- use a simple linearization model.

Conclusions

• No clear understanding from satellites alone of what happens to aerosols at the vicinity of clouds.

• Accounting for the 3D cloud-induced enhancement helps.

• For certain conditions, 3D cloud enhancement $\Delta\rho = \rho_{3D} - \rho_{1D}$ only weakly depends on AOT. Molecular scatt. is the key source for the enhancement.

•The enhancement increases the "apparent" fraction of fine aerosol mode ("bluing of the aerosols").

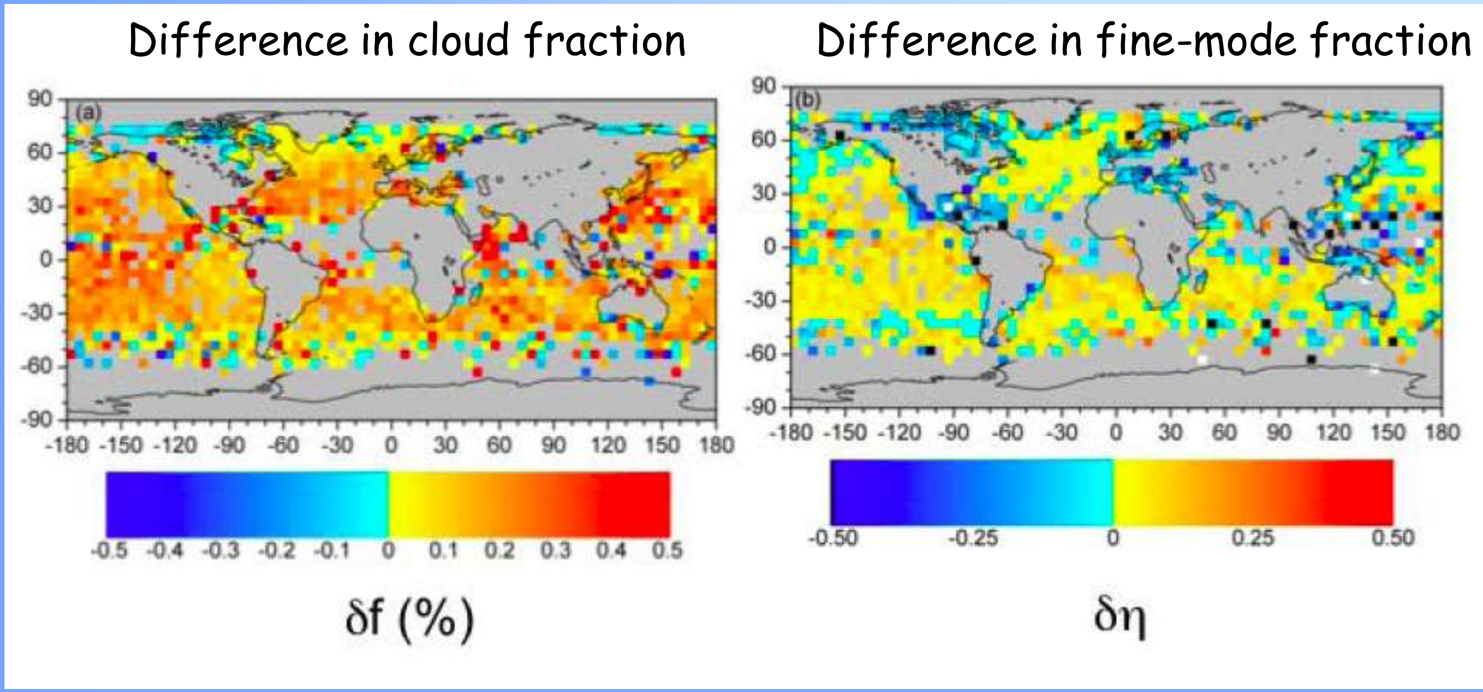
• MODIS observations confirm that the cloud induced enhancement increases with cloud optical depth.

• Retrieved AOT *can* be corrected for the 3D radiative effects.

More clouds go with larger AOT and larger (not smaller!) Ångström exponent

- 25 1°x1° in each 5°x5° region over ocean (over the entire globe) are subdivided into two groups with
  $\tau_a < \langle\tau_a\rangle$
  and
  $\tau_a > \langle\tau_a\rangle$

- meteorology has been checked as similar for two groups



from Loeb and Schuster (JGR, 2008)