Enhancement of Clear Sky Radiance in the Vicinity of Cumulus Clouds

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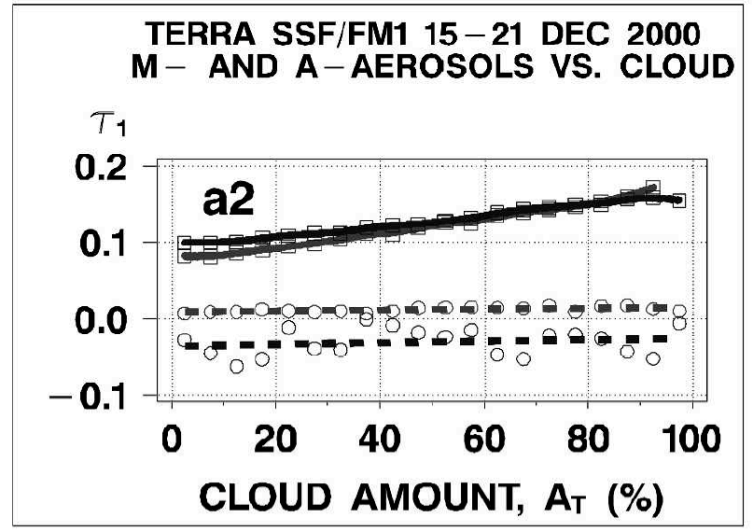
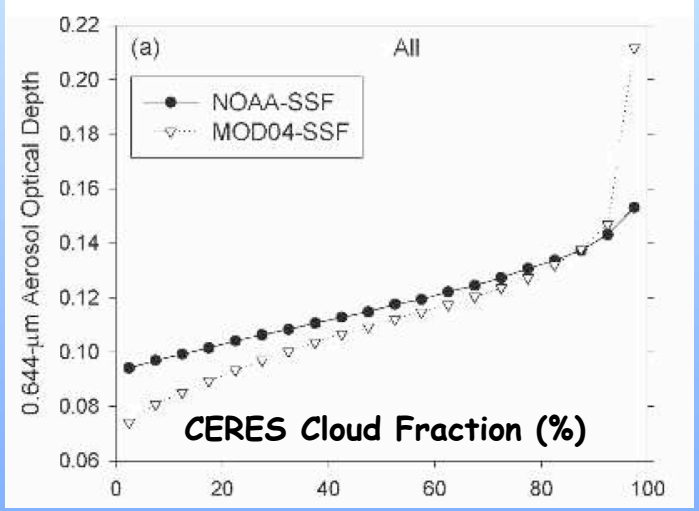
What happens to aerosol in the vicinity of clouds?

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

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?

clouds are complex and "satellite analysis may be affected by potential cloud artifacts" (Kaufman and Koren, 2006);

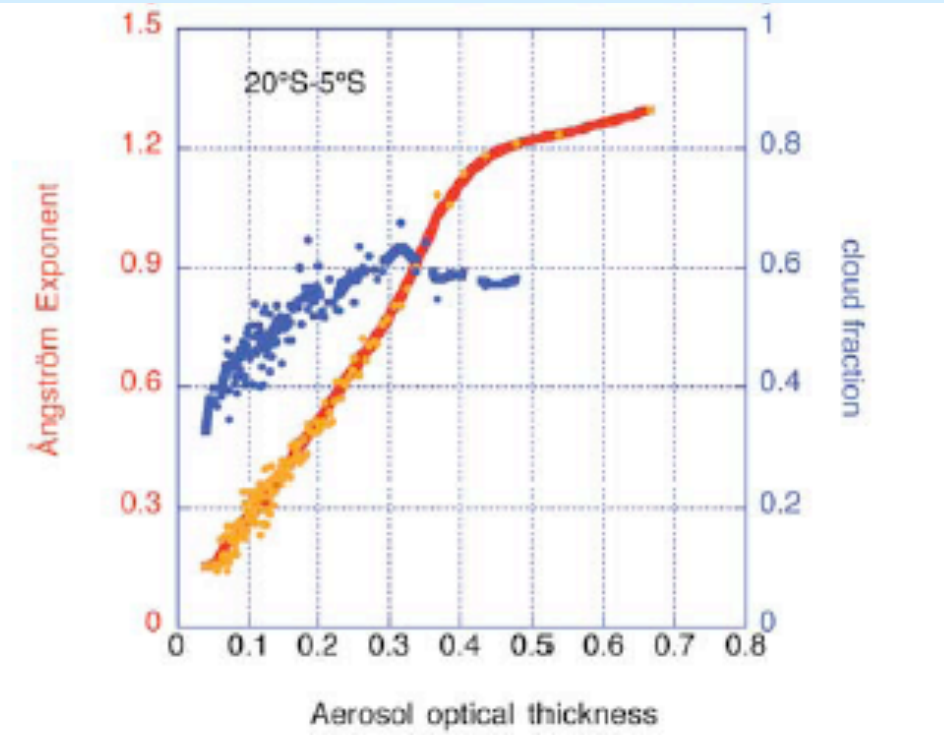
Both
- cloud contamination (sub-pixel clouds)
- cloud adjacency effect (a clear pixel with in the vicinity of clouds)

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

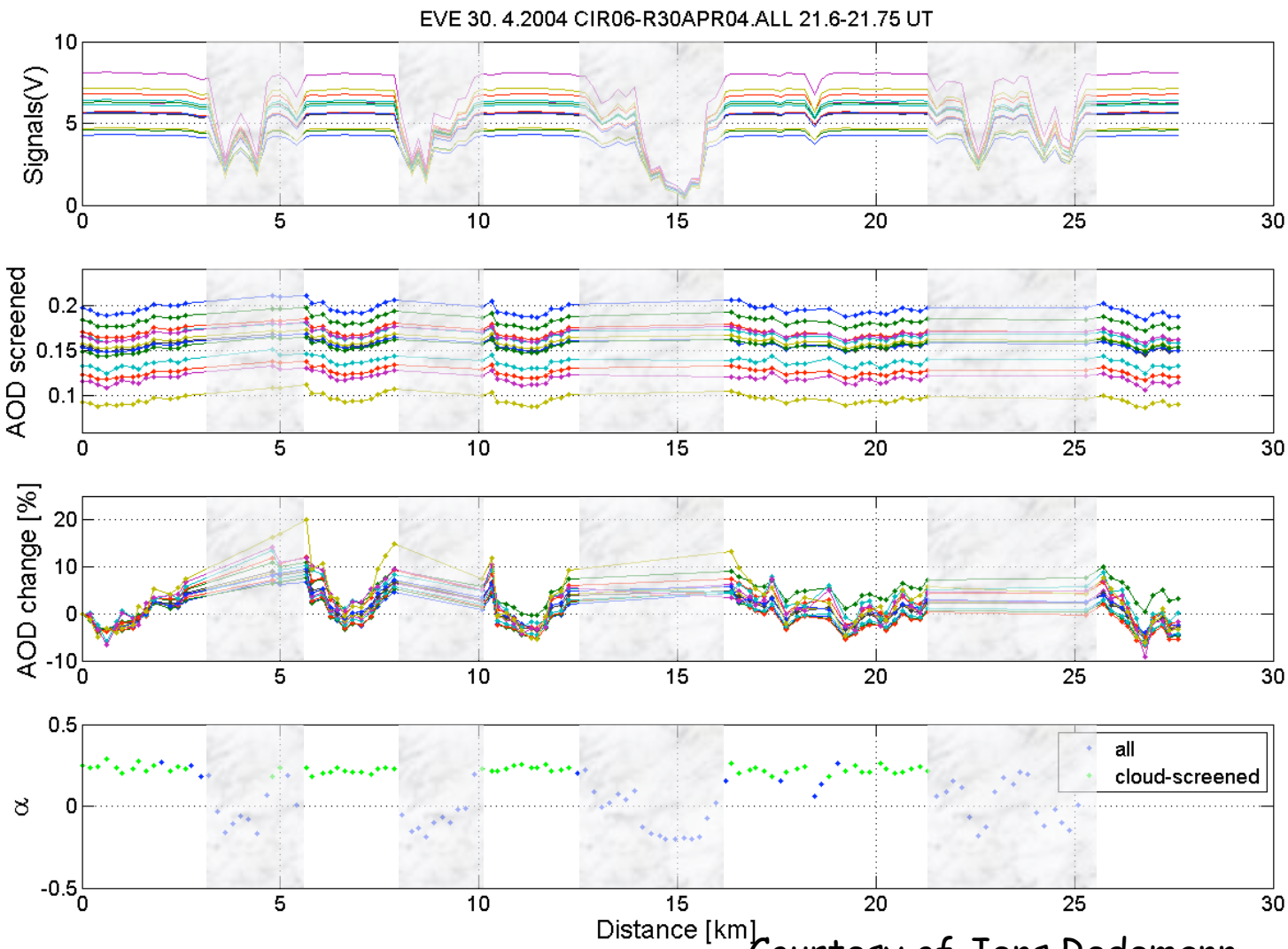
- Atlantic ocean, June-Aug. 2002; each point is aver. on 50 daily values with similar AOT in 1° res.;
- for AOT < 0.3, as AOT increases CF and the Ångström exponent also increase;
- the increase is due to transition from pure marine aerosol to smoke (or pollution);
- the increase in AOT cannot be explained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



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].

Airborne aerosol observations in the vicinity of clouds

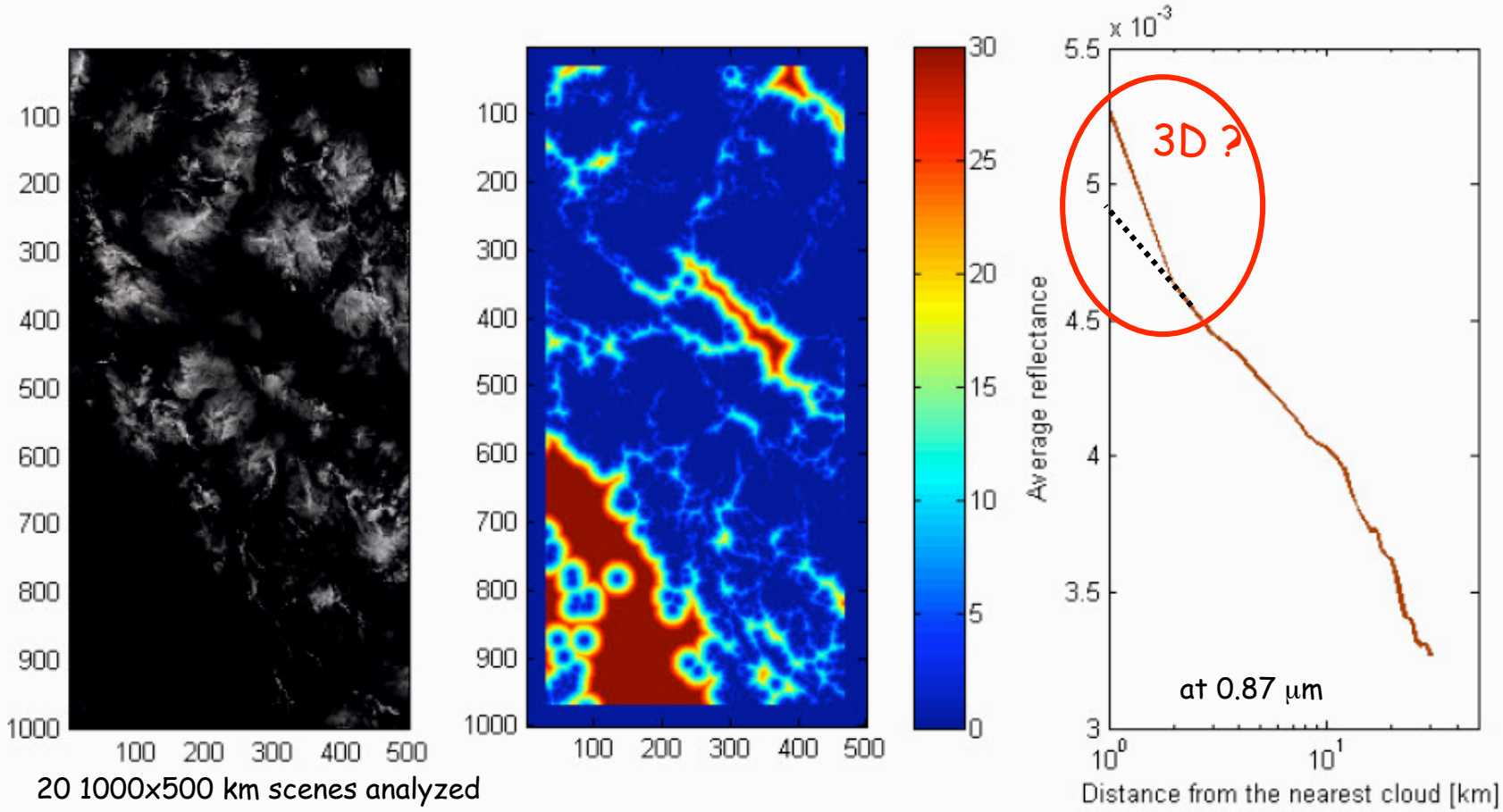


From airborne extinction rather than scattering observations 3D effects decrease AOT rather than increase it

Courtesy of Jens Redemann

Enhancement of radiance near clouds

Cumulus clouds over Atlantic

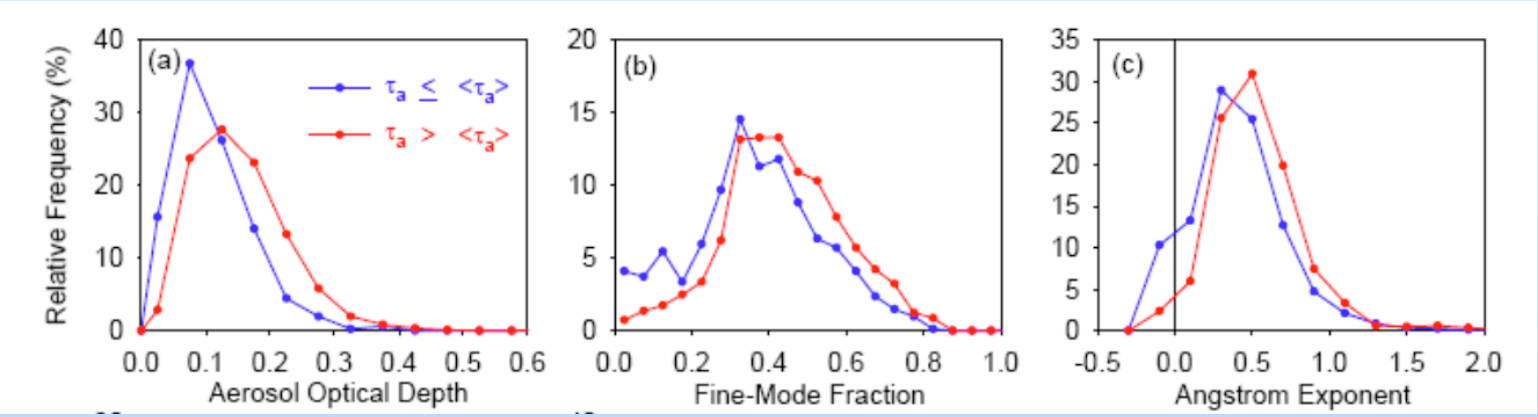


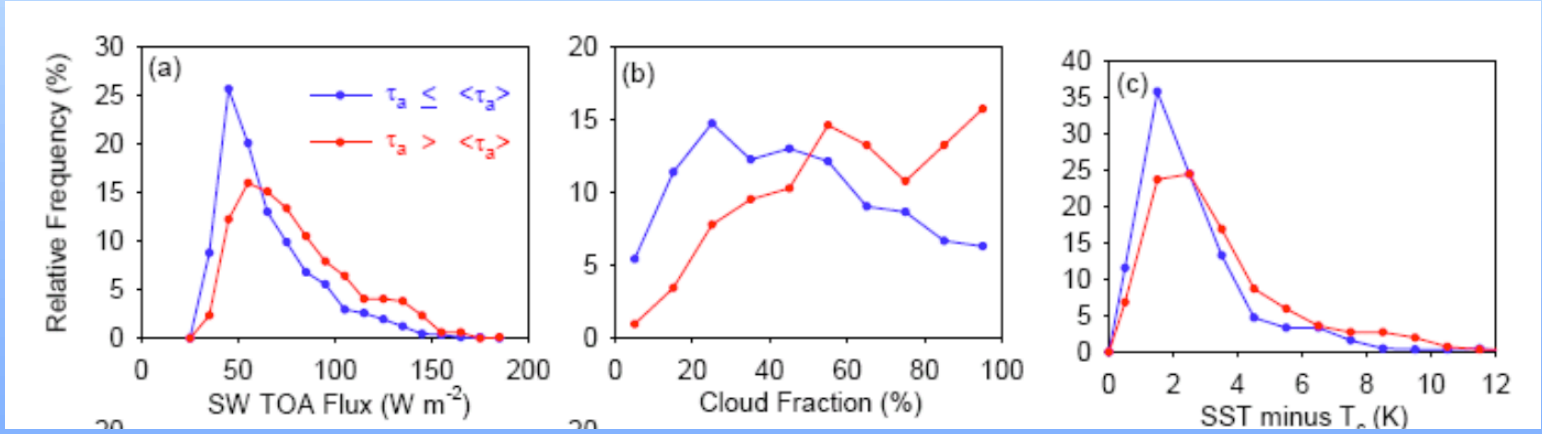
20 1000x500 km scenes analyzed

from Koren et al., GRL, 2006

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

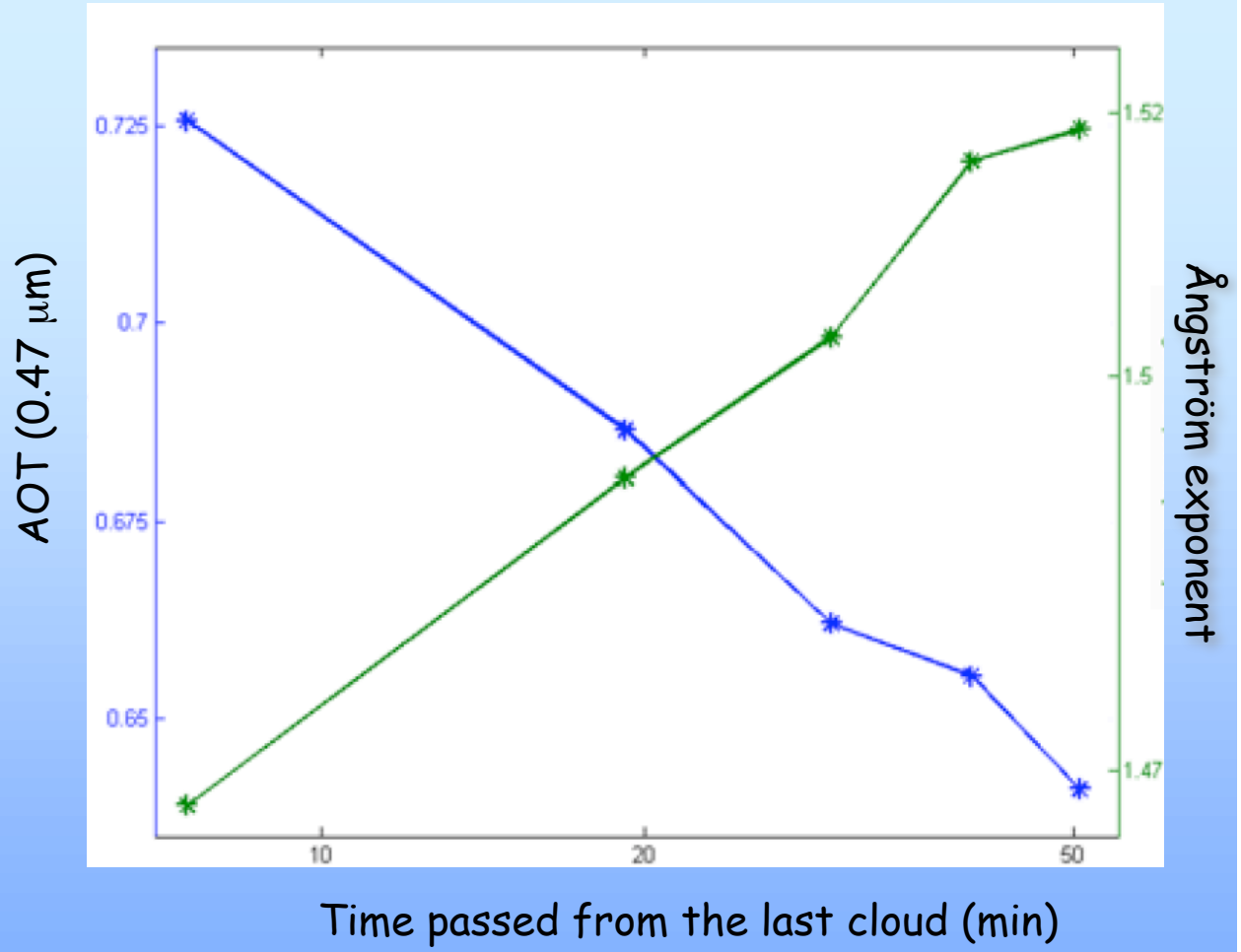
- 25 1°x1° in each 5°x5° region over ocean are subdivided into two groups with
  $\tau_a < \langle\tau_a\rangle$
  and
  $\tau_a > \langle\tau_a\rangle$
- meteorology has been checked as similar for two groups





from Norman Loeb's A-train presentation, Lille Oct. 2007

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

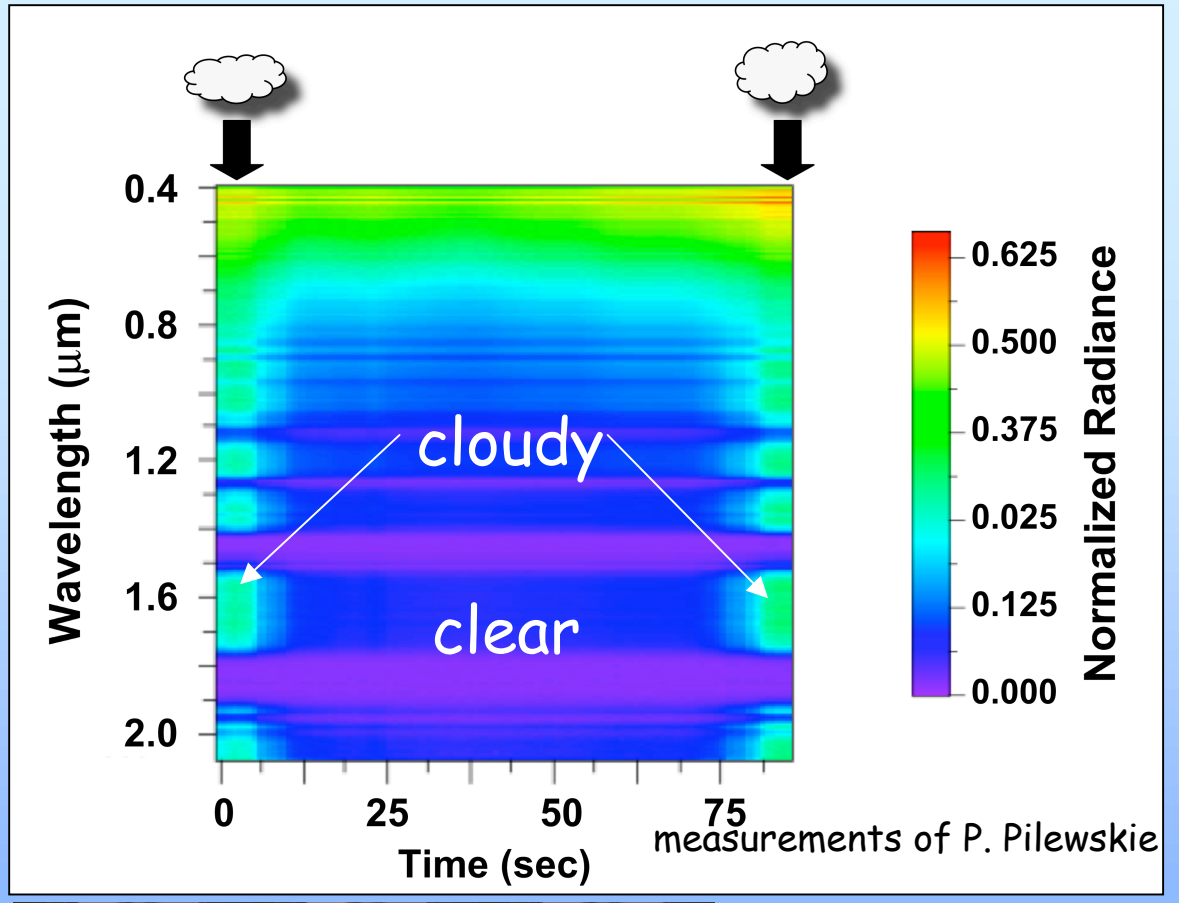


The Ångström exponent increases with distance to the nearest cloud while the AOT increases

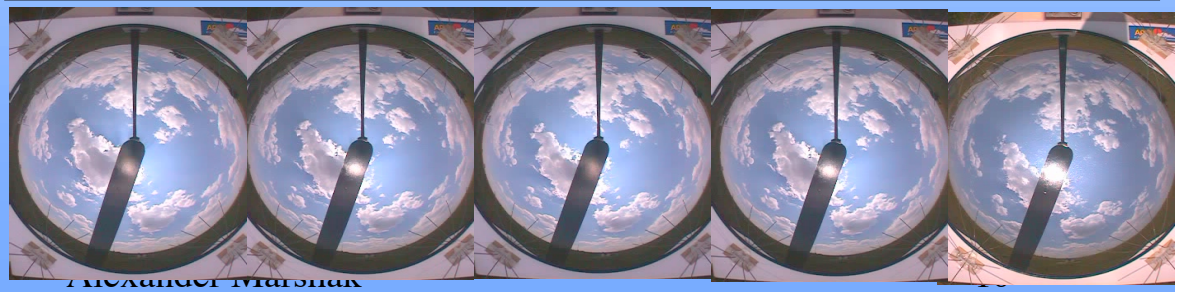
from Koren et al., GRL, 2007

ARM Shortwave Spectrometer transition between cloudy and clear skies

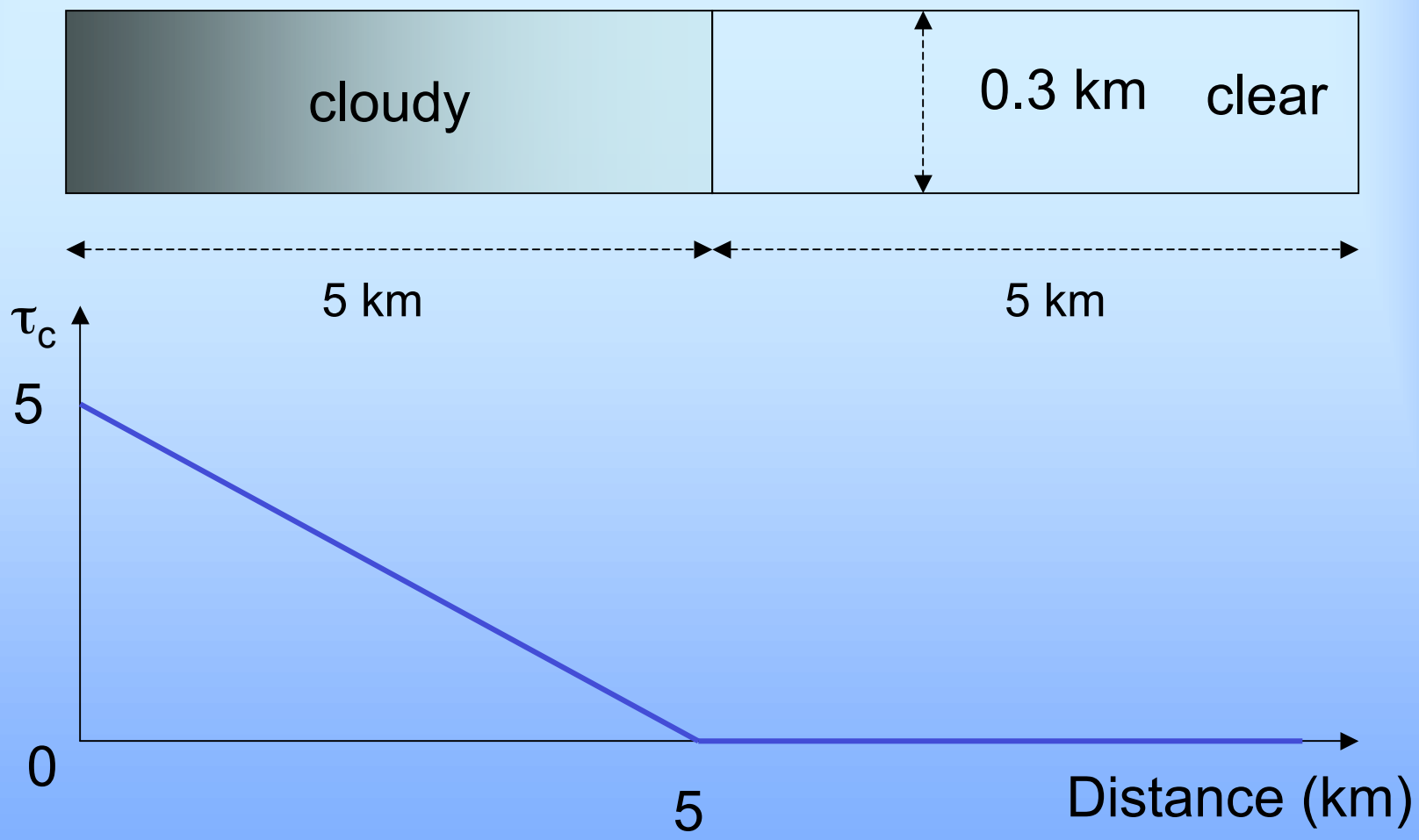
- two Cu clouds during the first and last 5 to 8 sec.
- clear sky is evident about 15 sec. away from these periods;
- the measurements in the intervening period (5 to 12 s and 75 to 82 s) are difficult to classify;
- depending on the remote sensing criterion used for cloud detection, would be called either cloudy or clear.



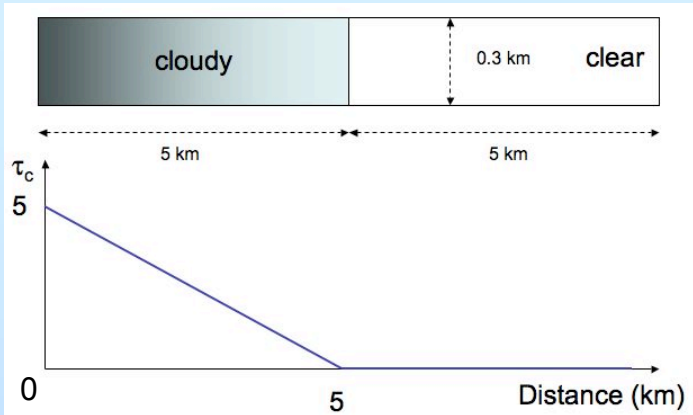
measurements of P. Pilewskie



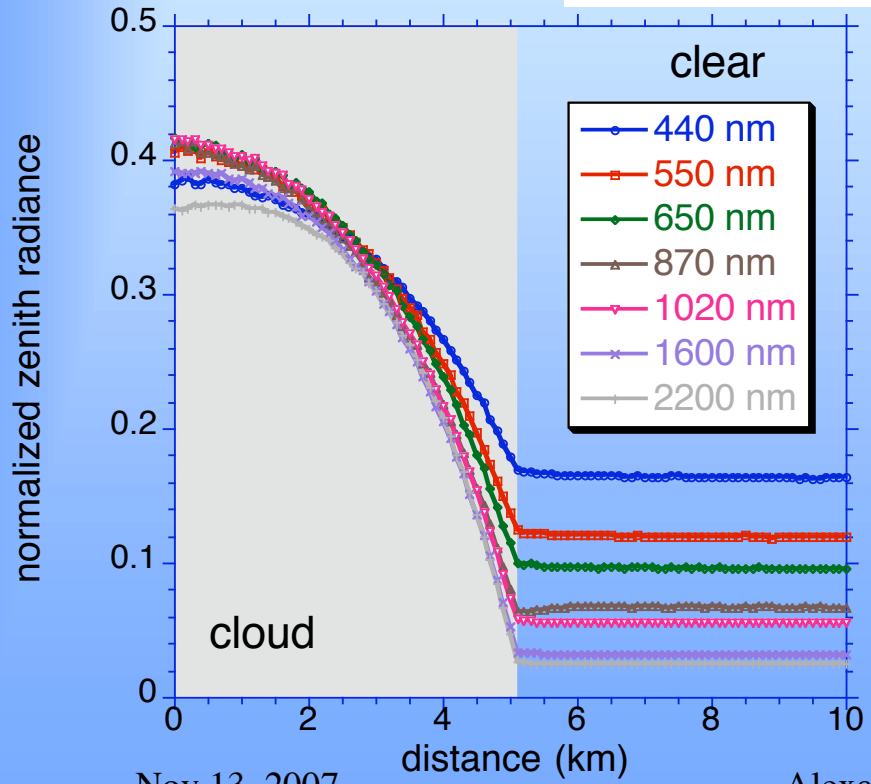
A simple 3D RT experiment



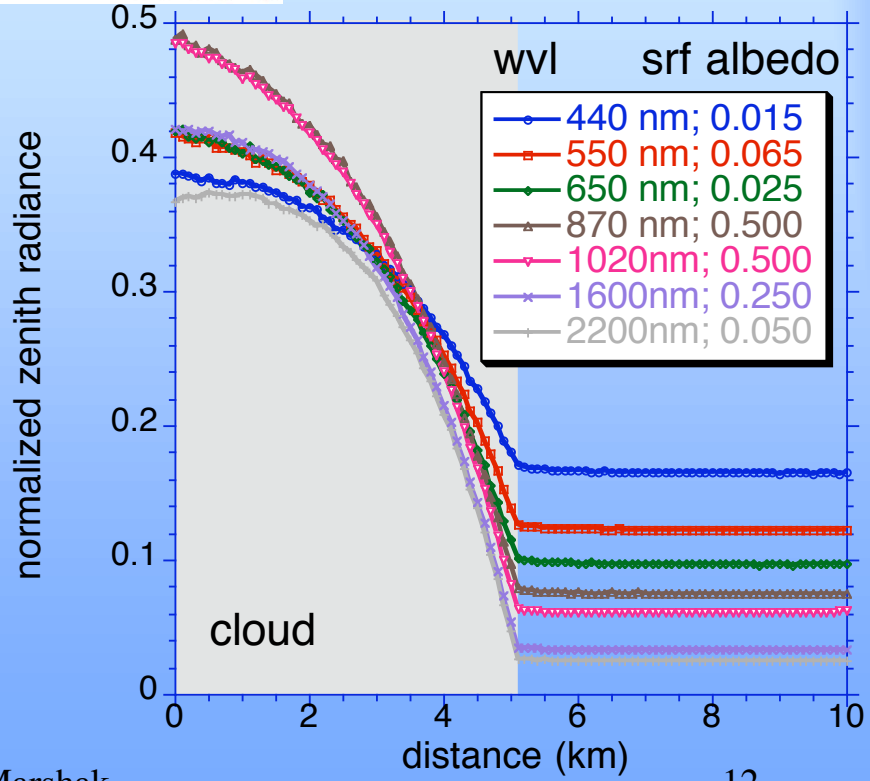
A simple 3D RT experiment



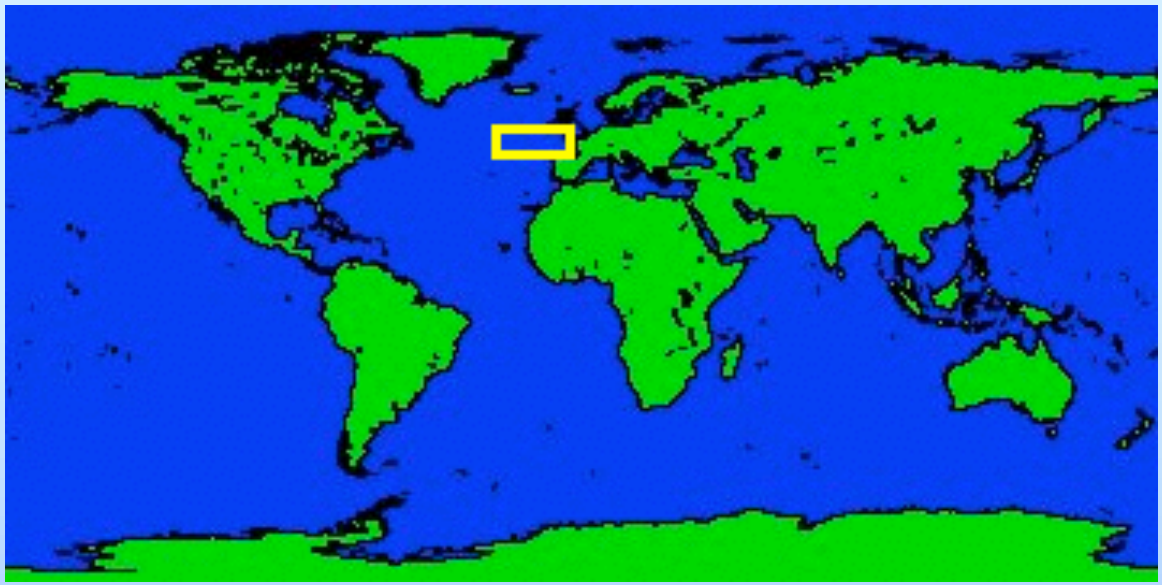
black surface



vegetated surface



Data used

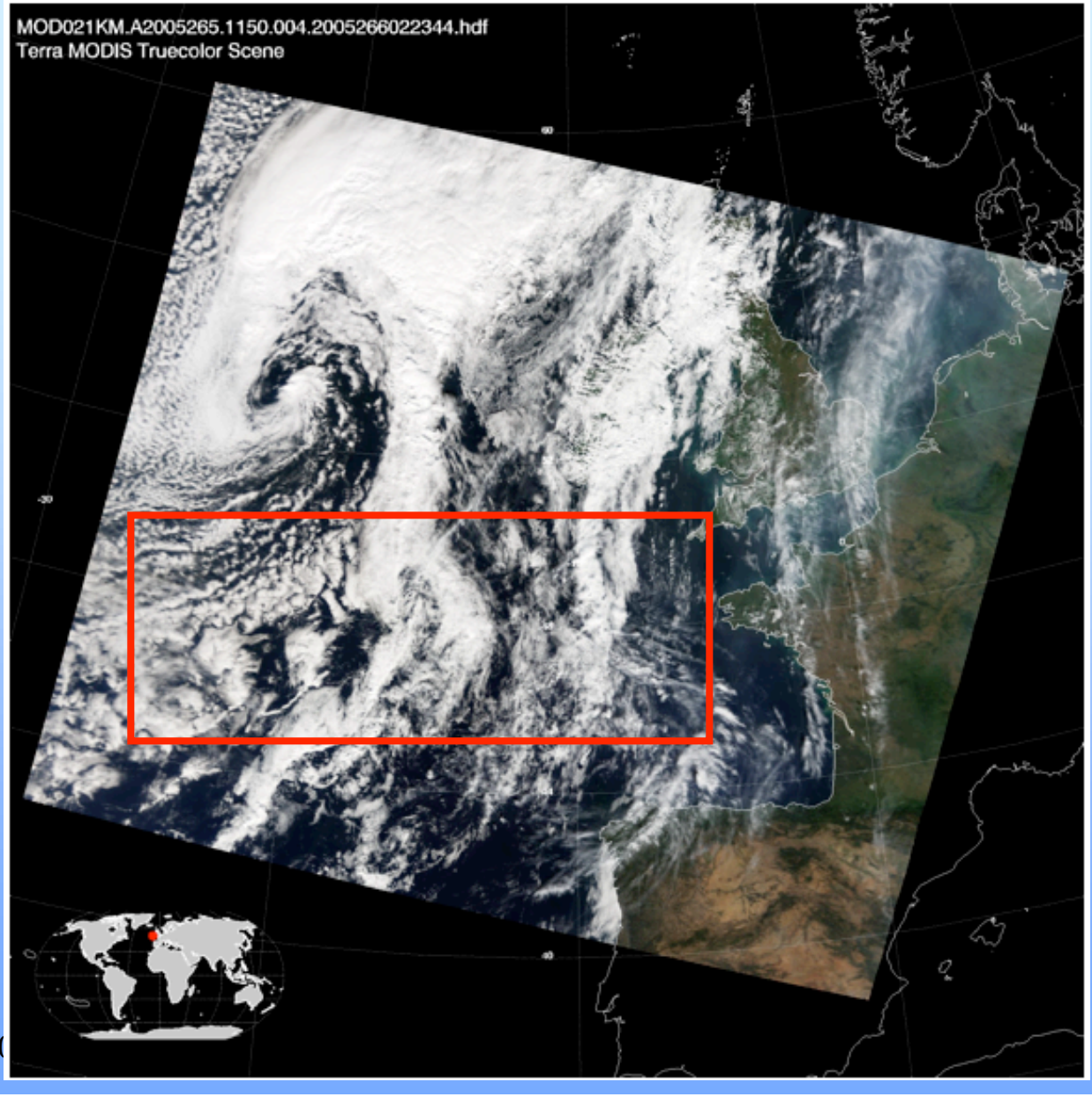


- Collection 5 MOD02, MOD06, MOD35 products
- September 14-29 in 2000-2006 (2 weeks in 7 years)
- North-East Atlantic (45°-50°N, 5°-25°W), south-west from UK
- Viewing zenith angle < 10°

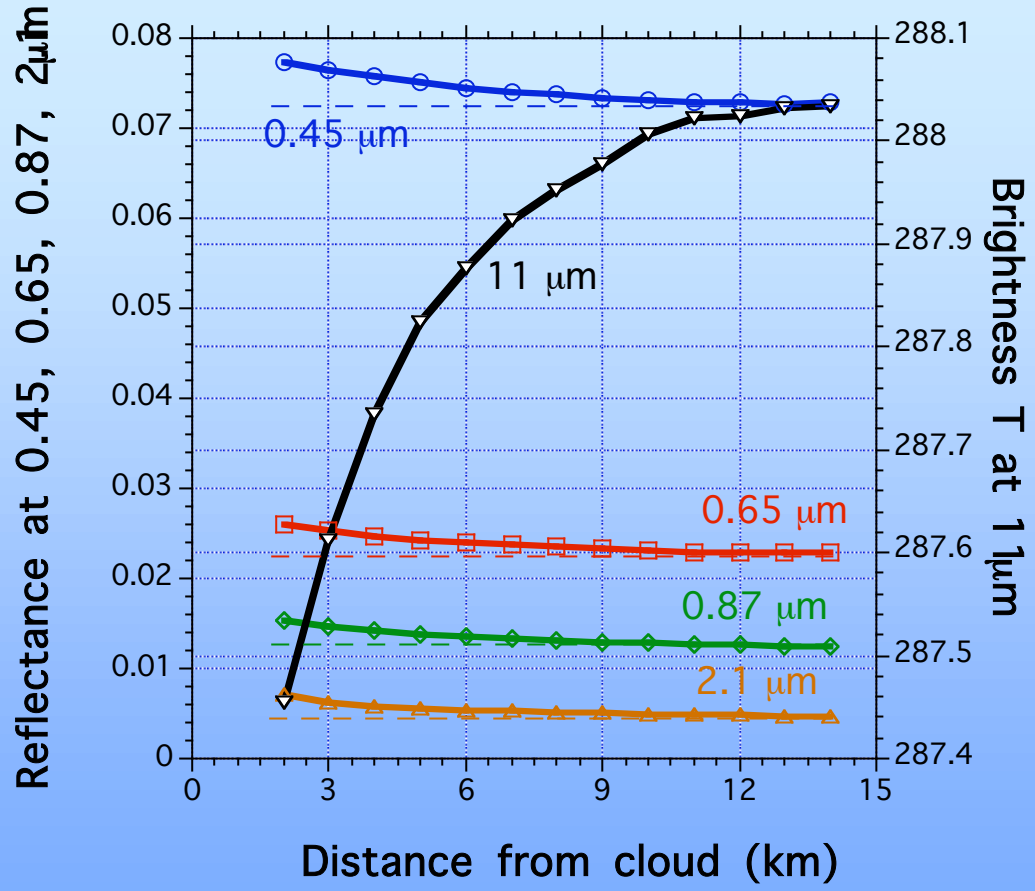
Pixels included in plots:

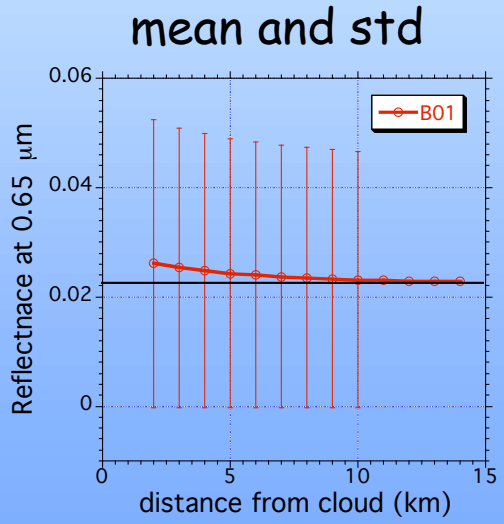
- Ocean surface with no glint or sea ice
- MOD35 says "confident clear", all 250 m subpixels clear
- Highest cloud top pressure nearby > 700 hPa (near low clouds)
- Nearby pixels are considered cloudy if MOD35 says definitely (or prob.) cloud.

Example of the region: Sep 22, 2005

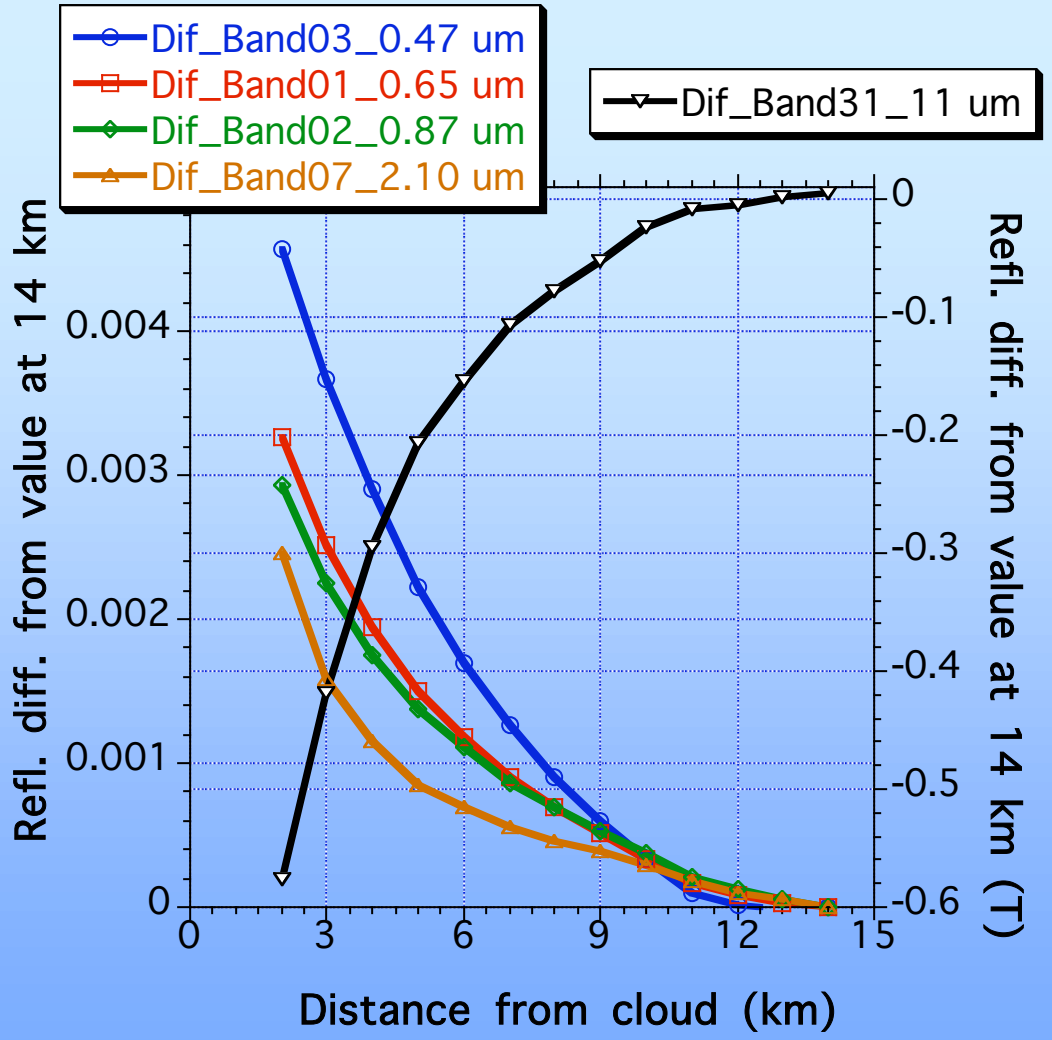


Average reflectance vs. dist. to clouds for 0.45, 0.65, 0.87, 2.1 and 11 μm

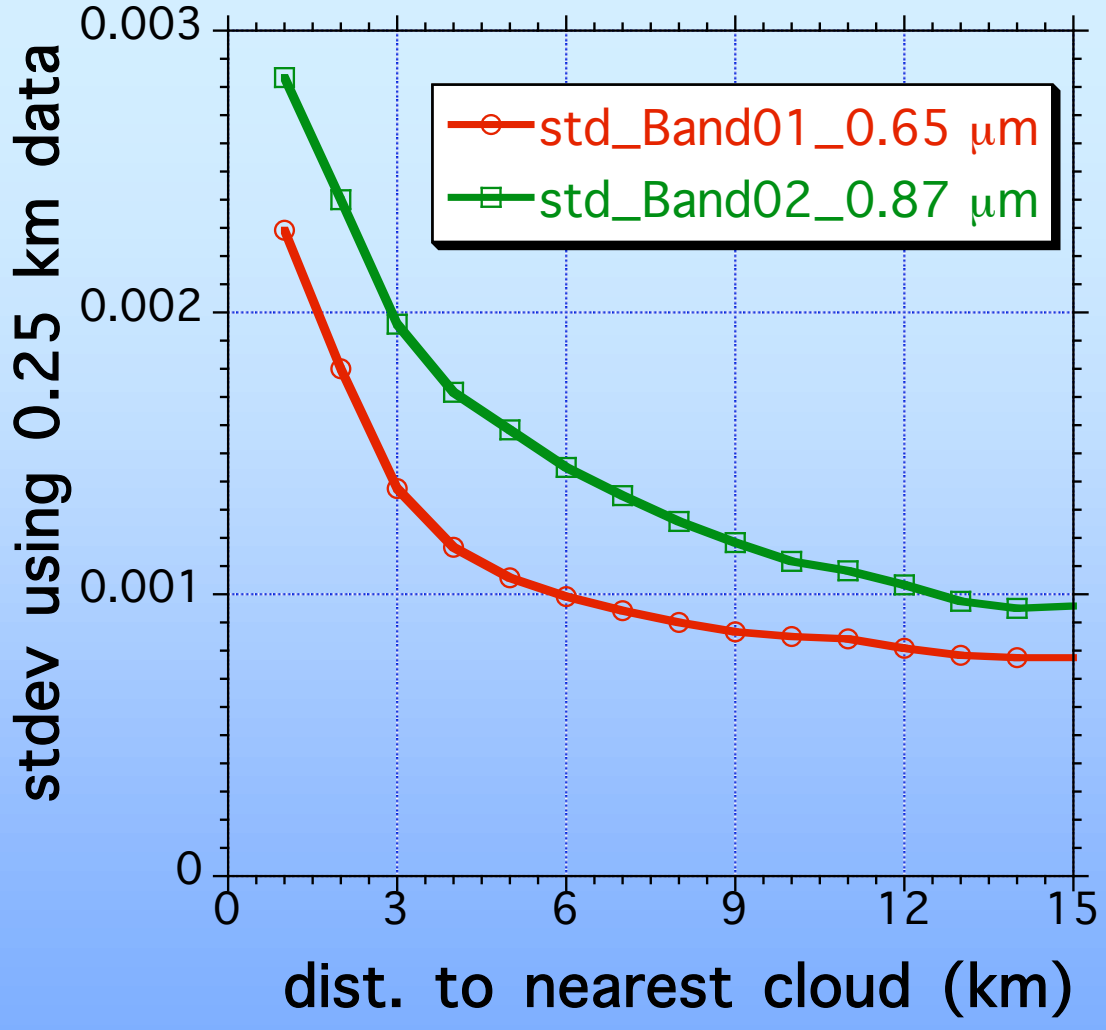




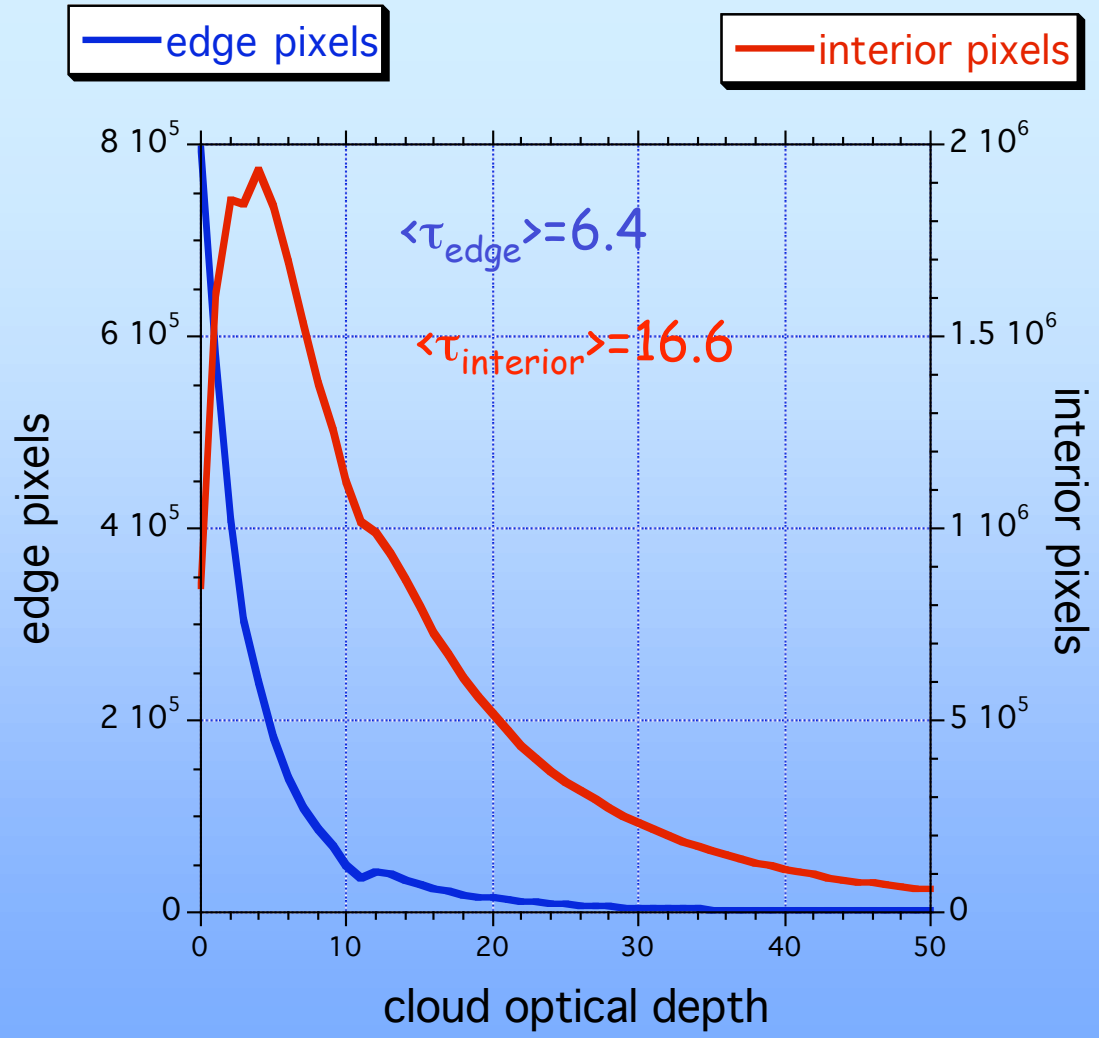
Cloud enhancement vs. dist. to clouds for 0.45, 0.65, 0.87, 2.1 and 11 μm



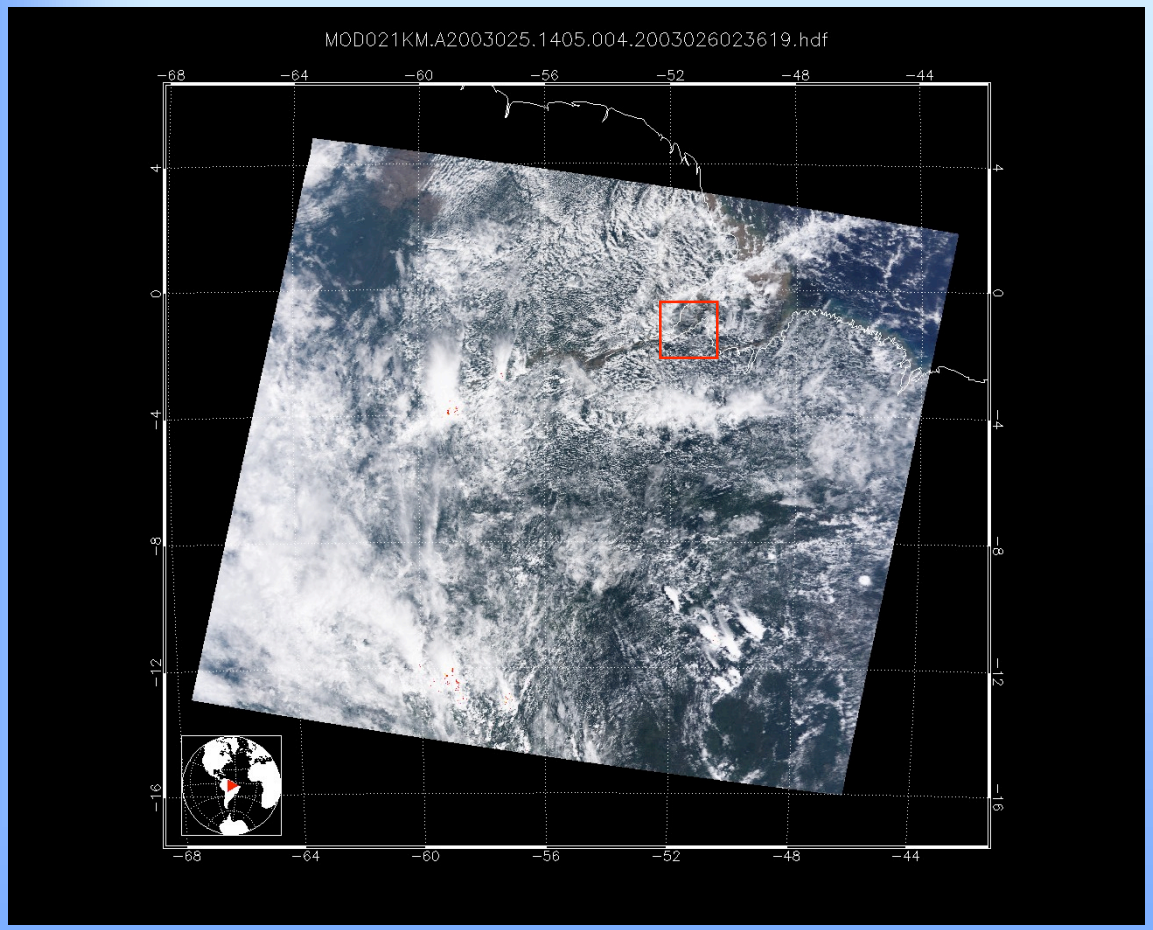
Variability inside 1km-size pixel



COD
interior vs cloud edge



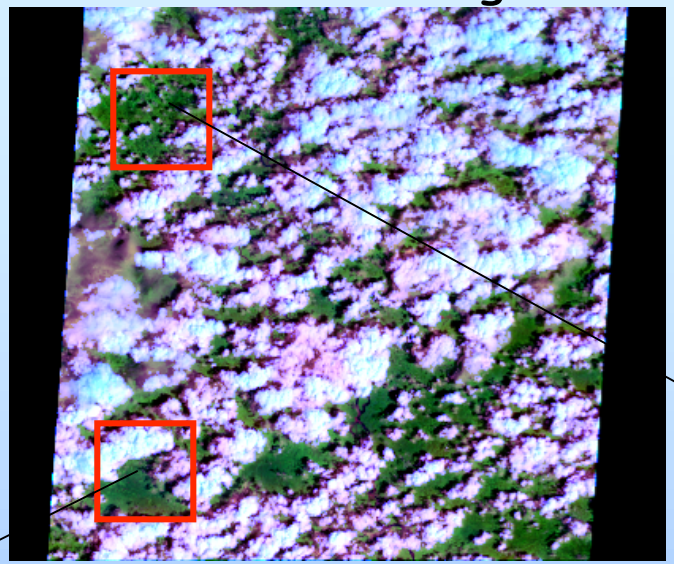
Aerosol-cloud radiative interaction (a case study)



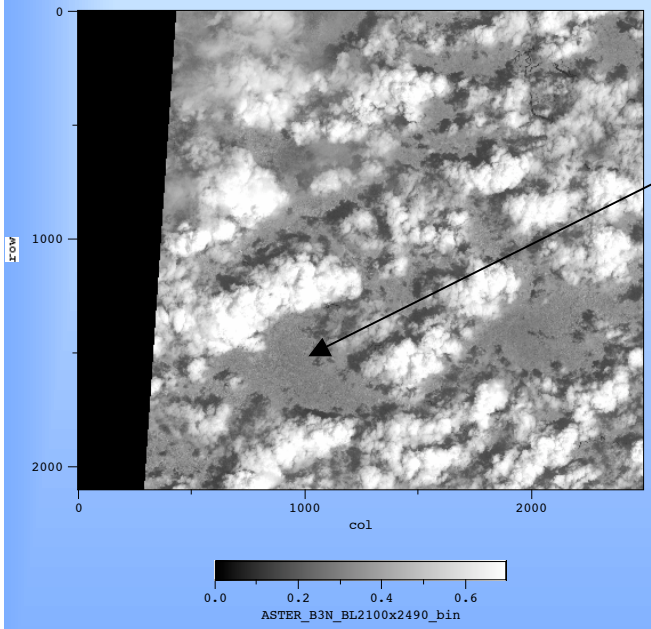
Collocated MODIS and ASTER image of Cu cloud field in biomass-burning region in Brazil at 53° W on the equator, acquired on Jan 25, 2003

ASTER image and MODIS AOT

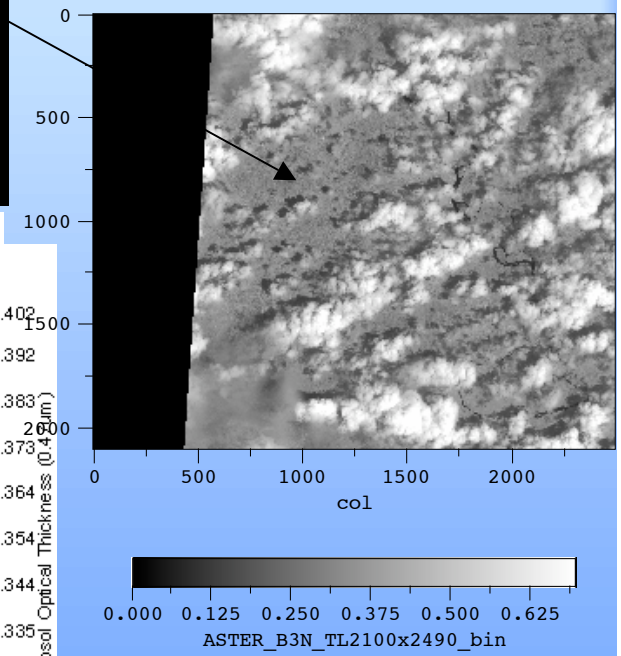
ASTER image

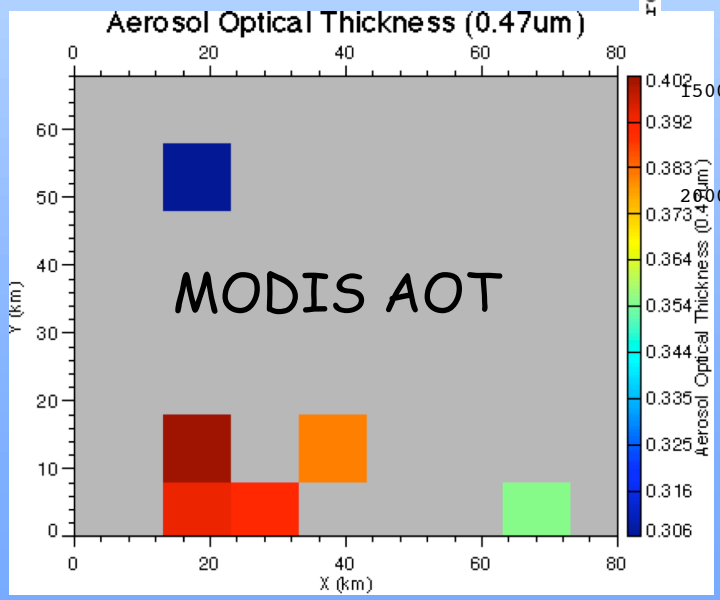


Thick clouds



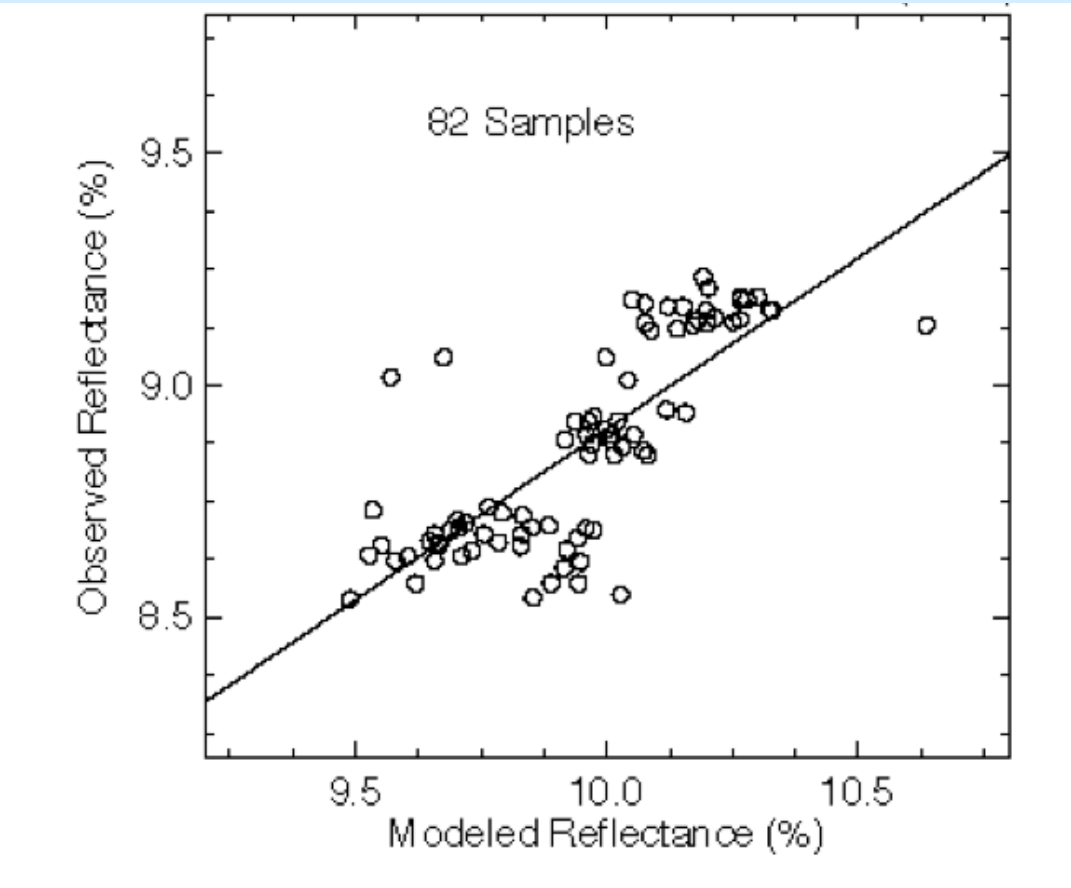
Thin clouds





from Wen et al., JGR, 2007

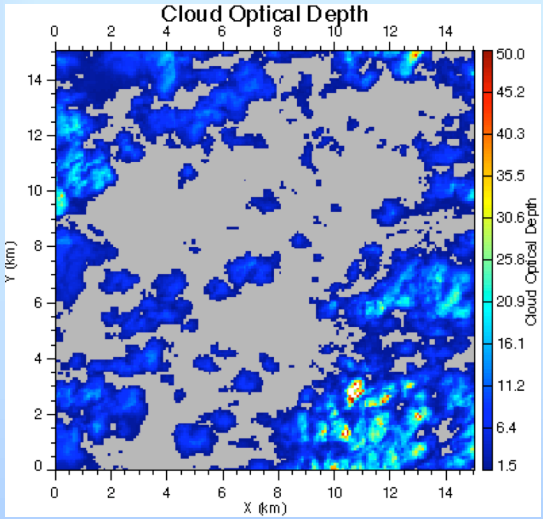
A striking example: const AOT



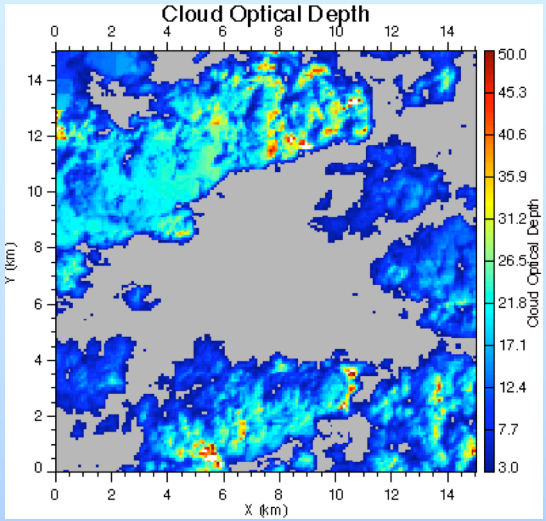
Modeled (with *const* AOT but MODIS 3D cloud structure) vs Observed Reflectance.
Cor. coef. = 0.77

Cloud effect at 90-m resolution

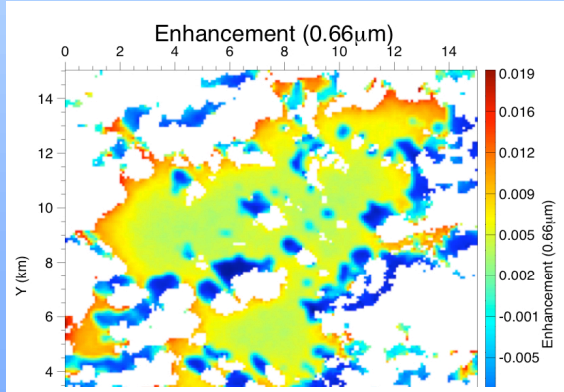
Thin clouds, <τ>=7



Thick clouds, <τ>=14



$AOT_{0.66}$=0.1

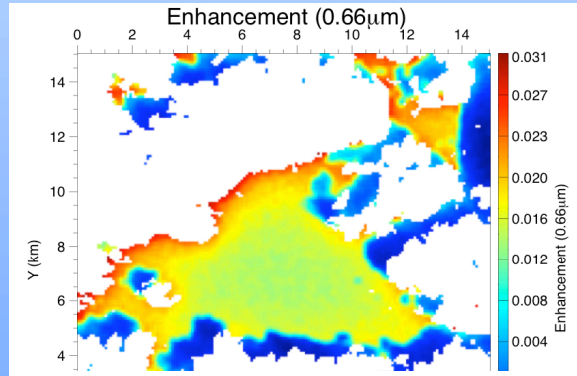


Δρ ~ 0.0046

Δτ ~0.05 ≈50%

enhancement:

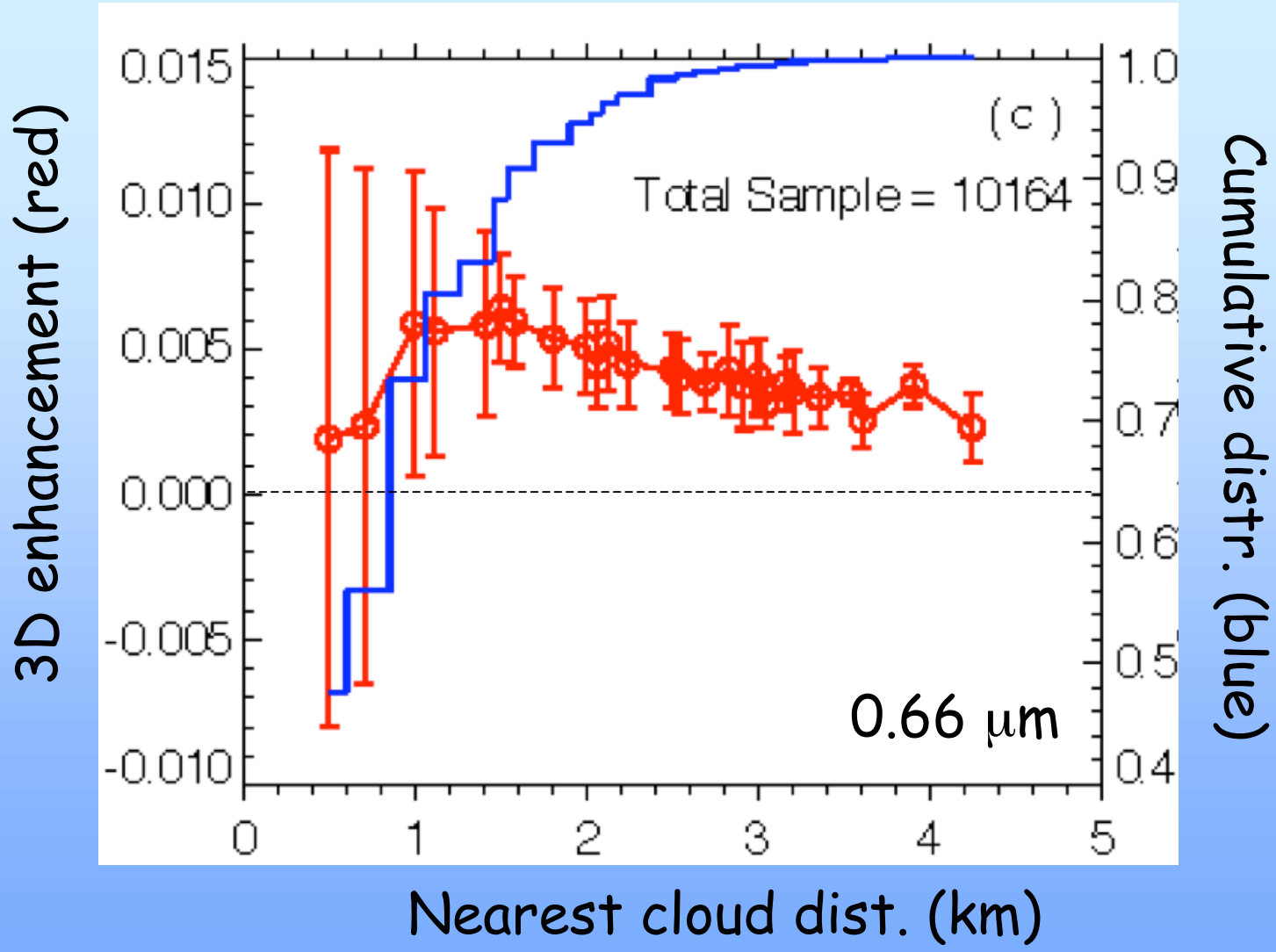
$\Delta\rho = \rho_{3D} - \rho_{1D}$



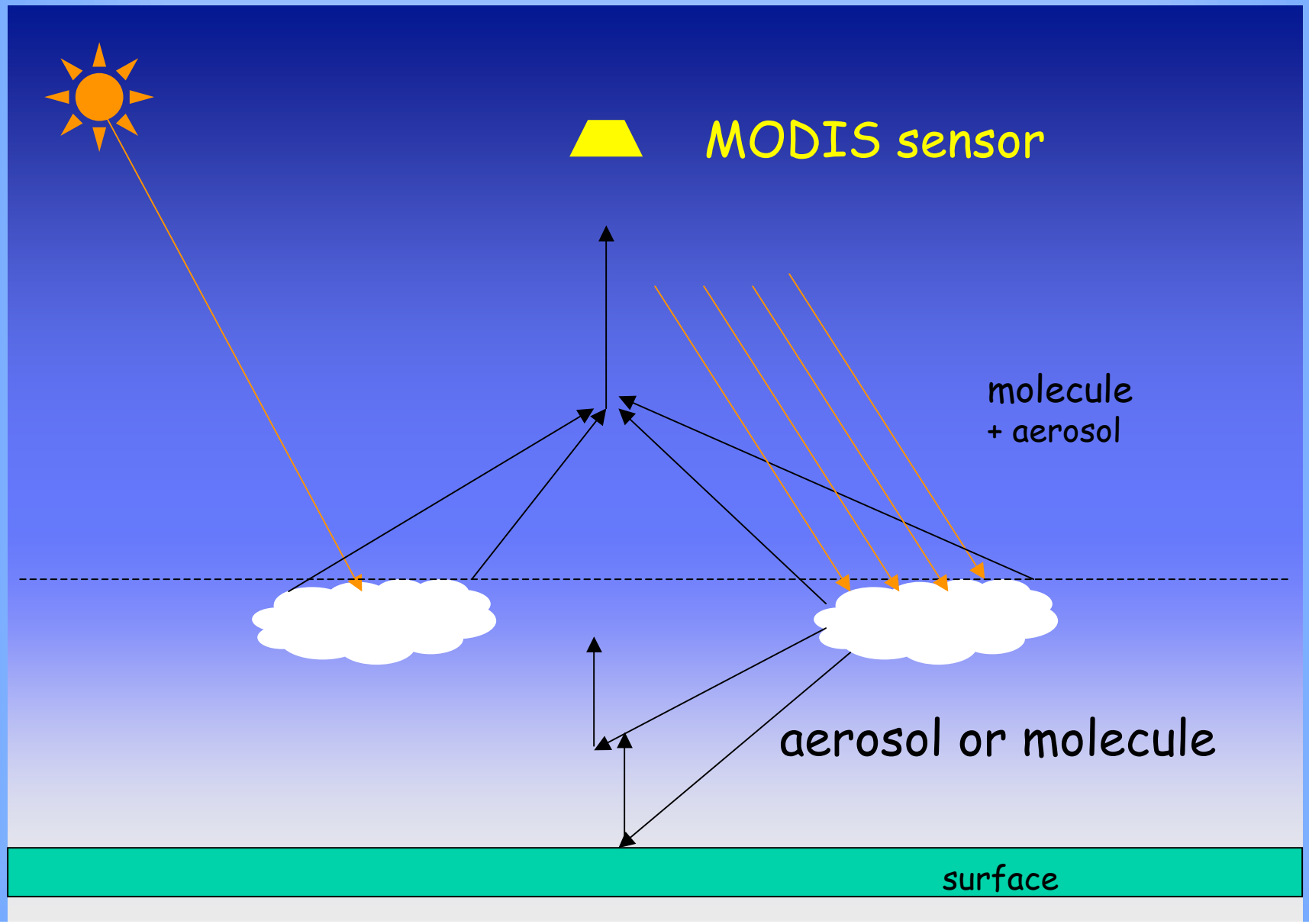
Δρ ~ 0.014

Δτ ~0.14 ≈140%

Effect of distance to a cloudy pixel

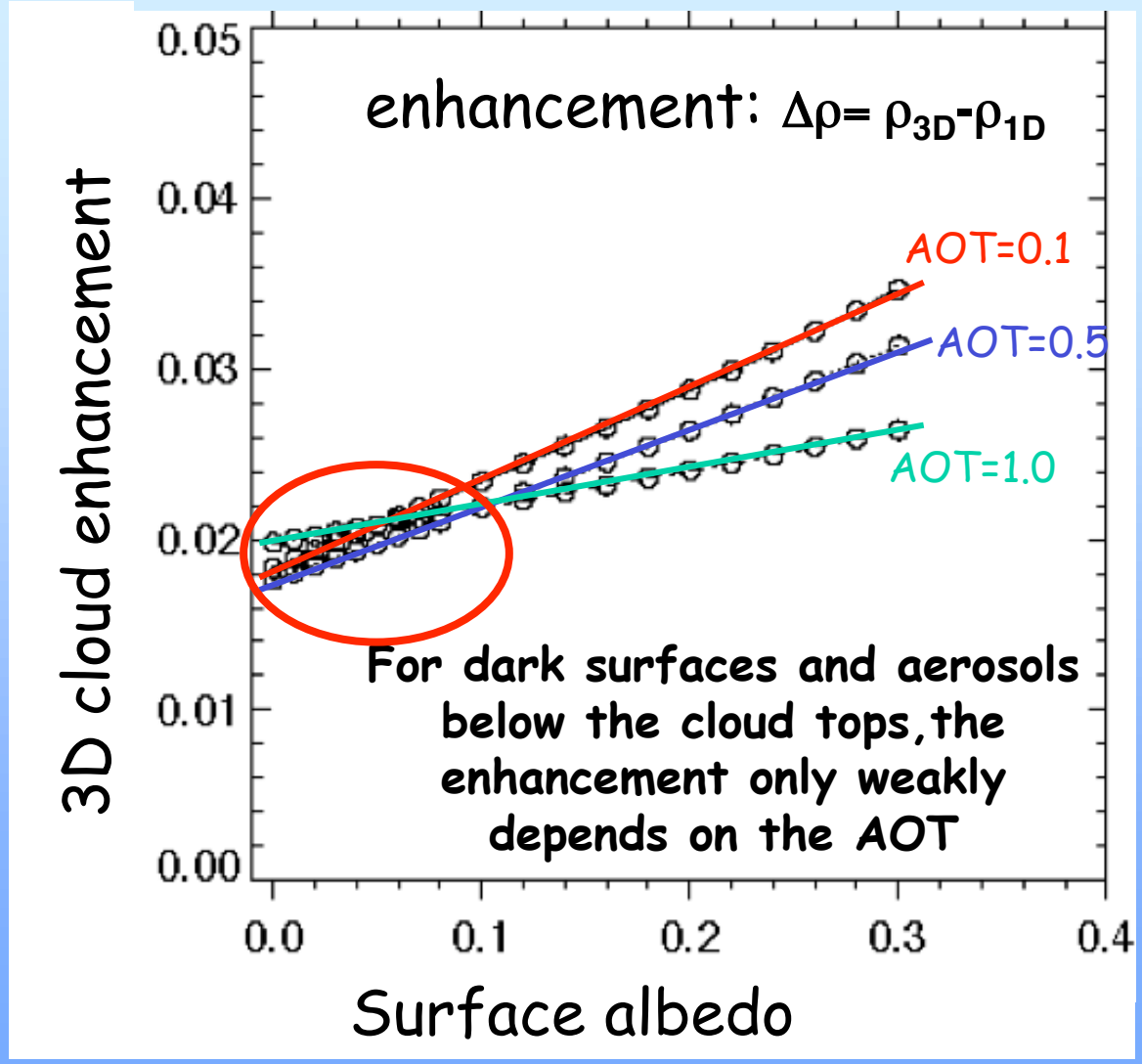


Conceptual model to account for the cloud-induced enhancement

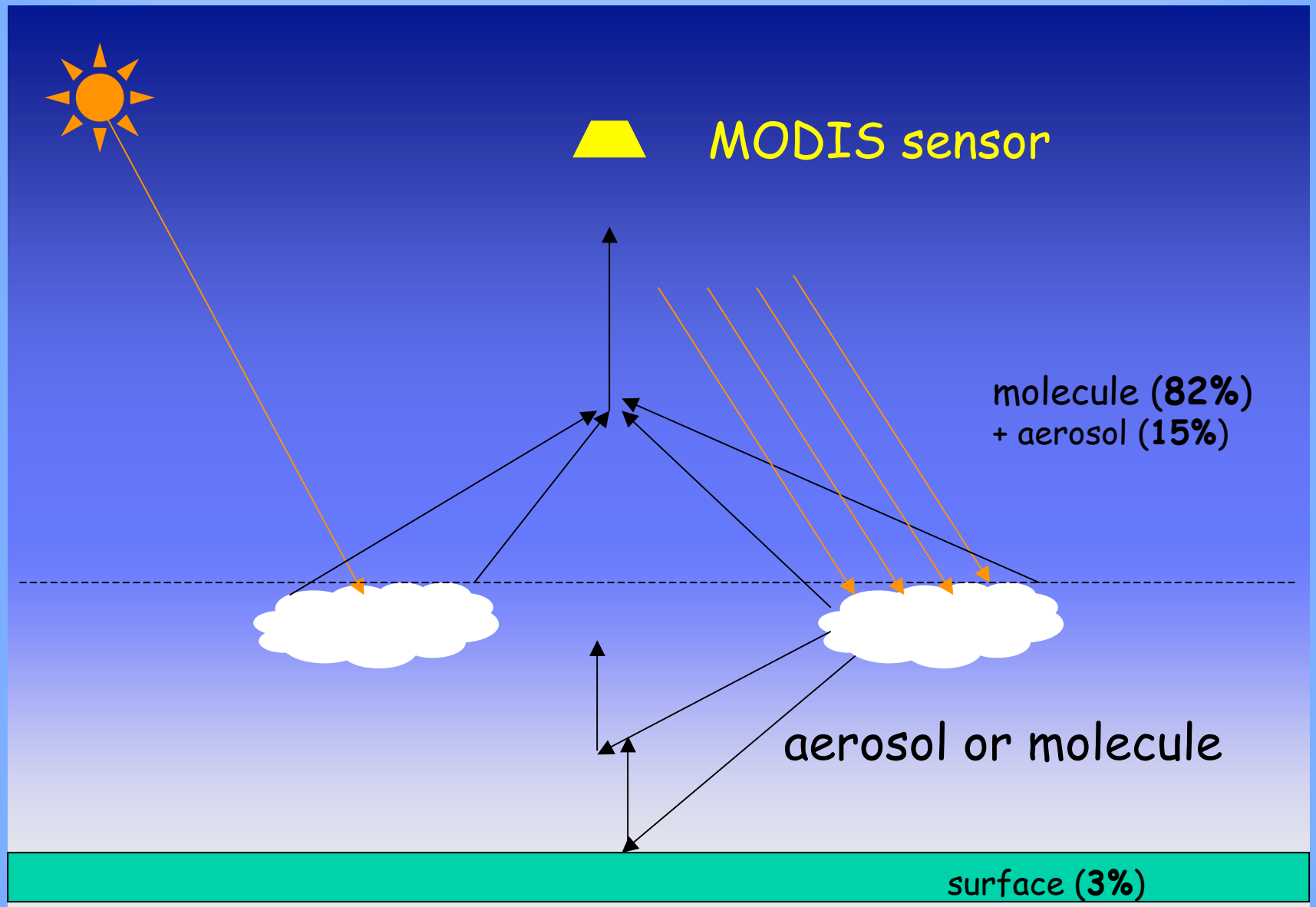


Contributors to cloud enhancement

- Rayleigh scattering
- Aerosols
- Surface reflectance



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



Assumption for a simple model

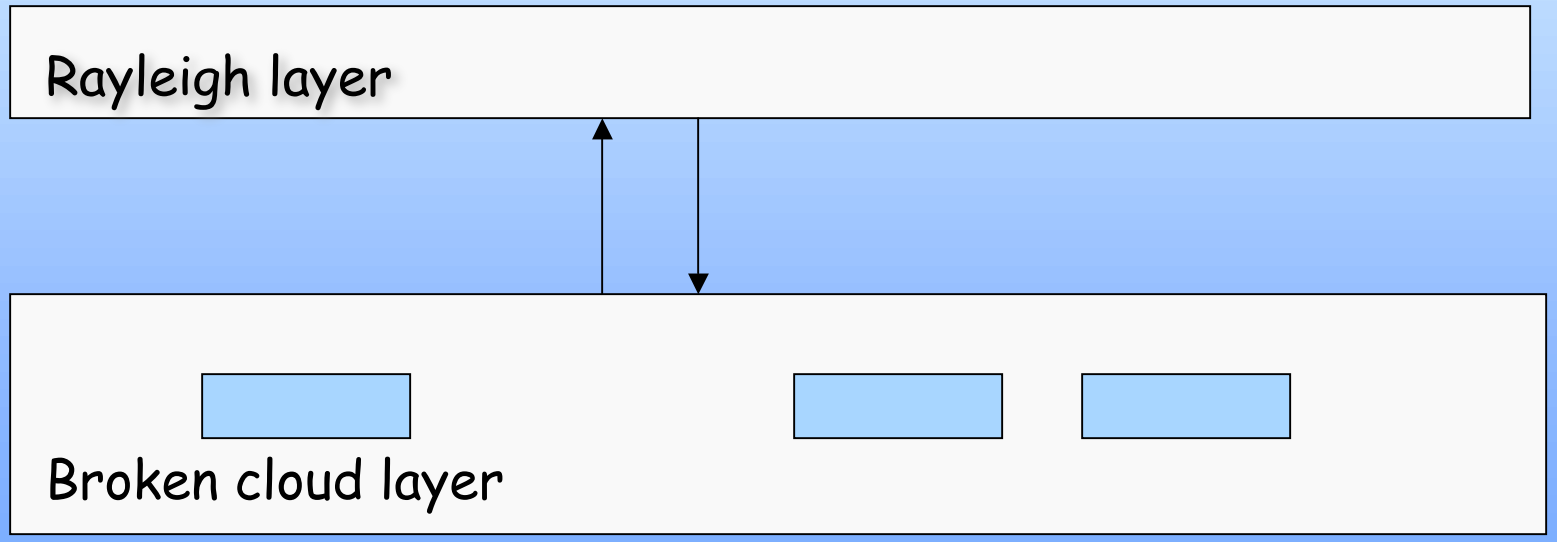
Molecular scattering is the main source for the enhancement in the vicinity of clouds

thus
we retrieve larger AOT and fine mode fraction

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

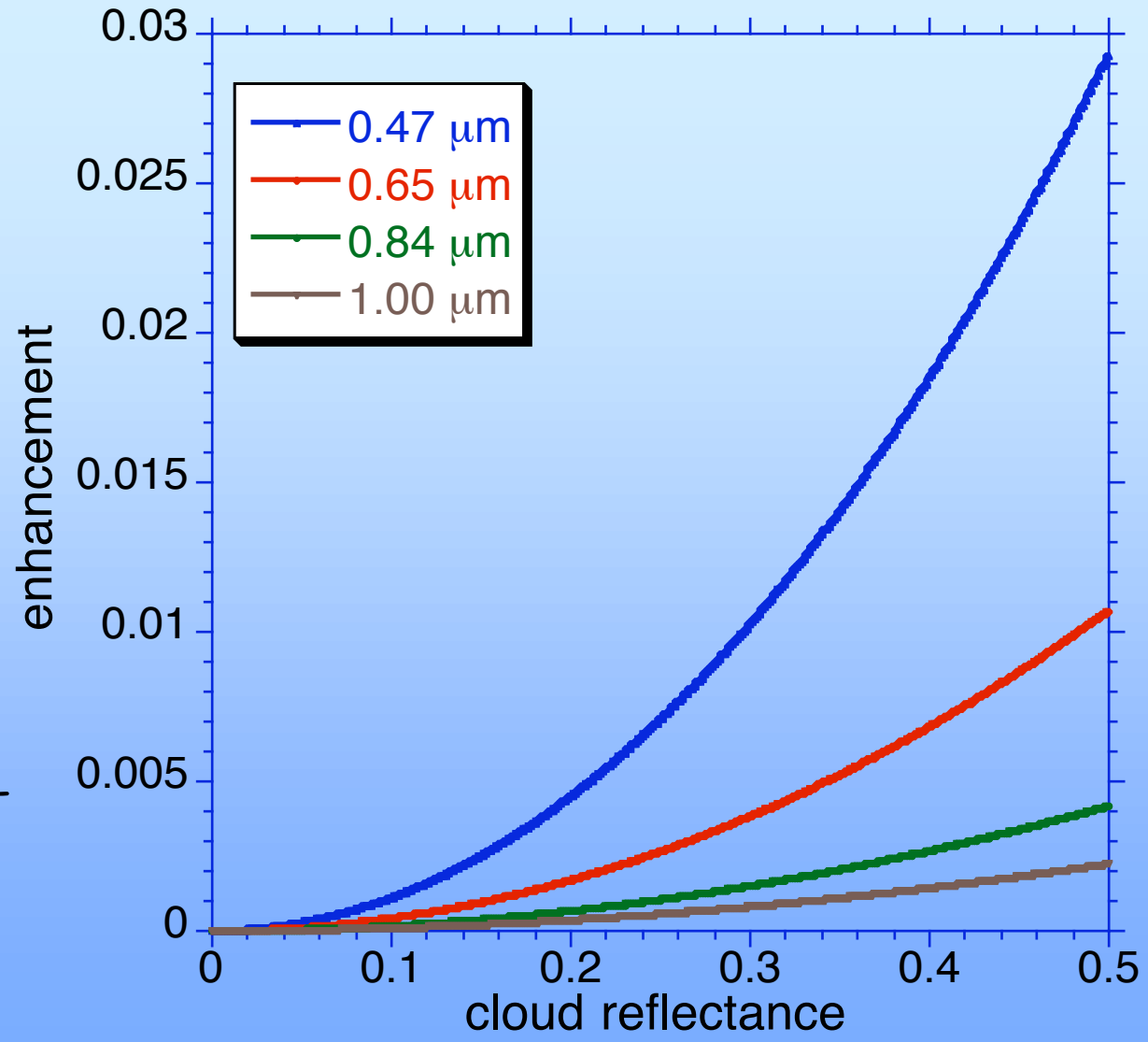
The *enhancement* is defined as the difference between the two radiances:

- 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

Cloud enhancement vs. cloud reflectance

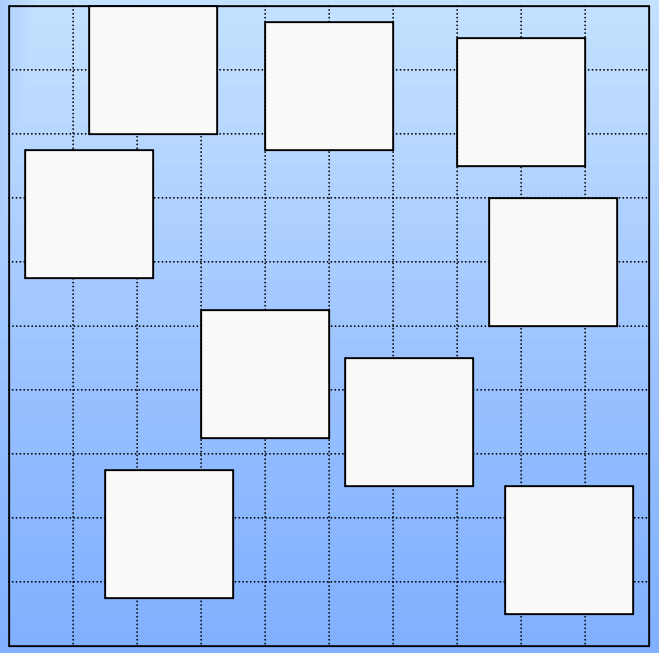


The upwelling flux is needed to estimate the cloud-induced enhancement of cloud-free pixels

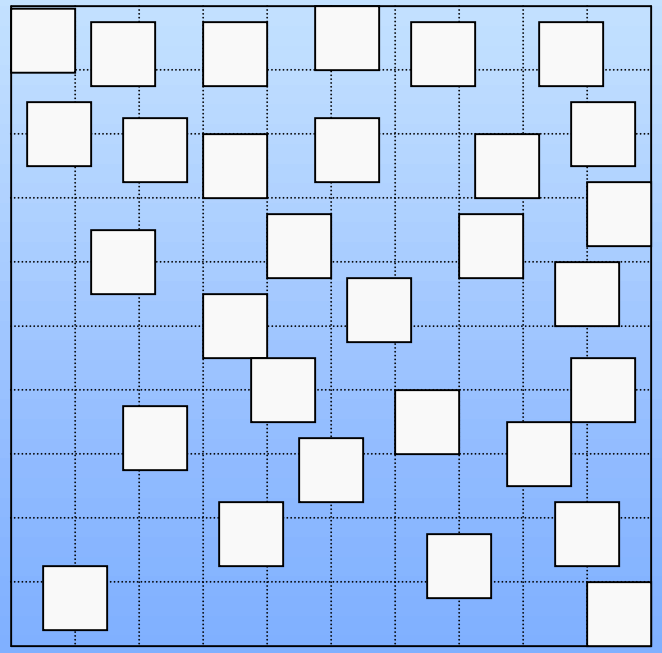
Stochastic model of a broken cloud field

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



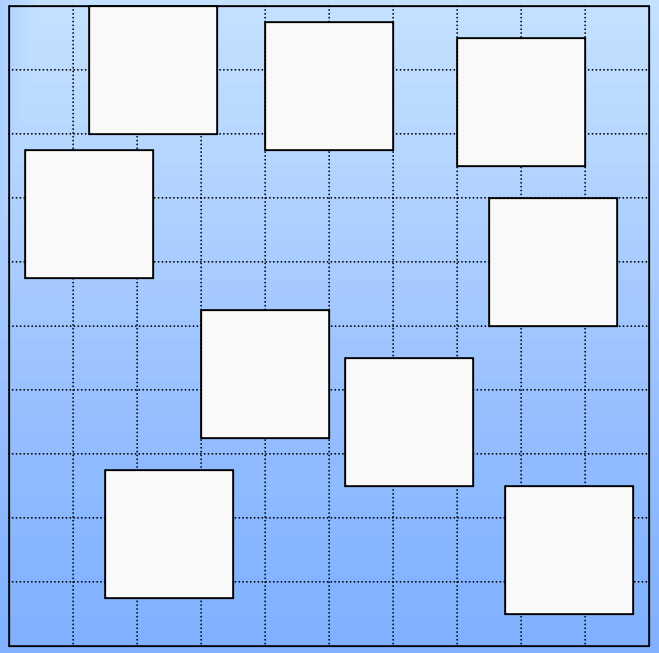
AR = 1

$A_c = 0.3$

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.

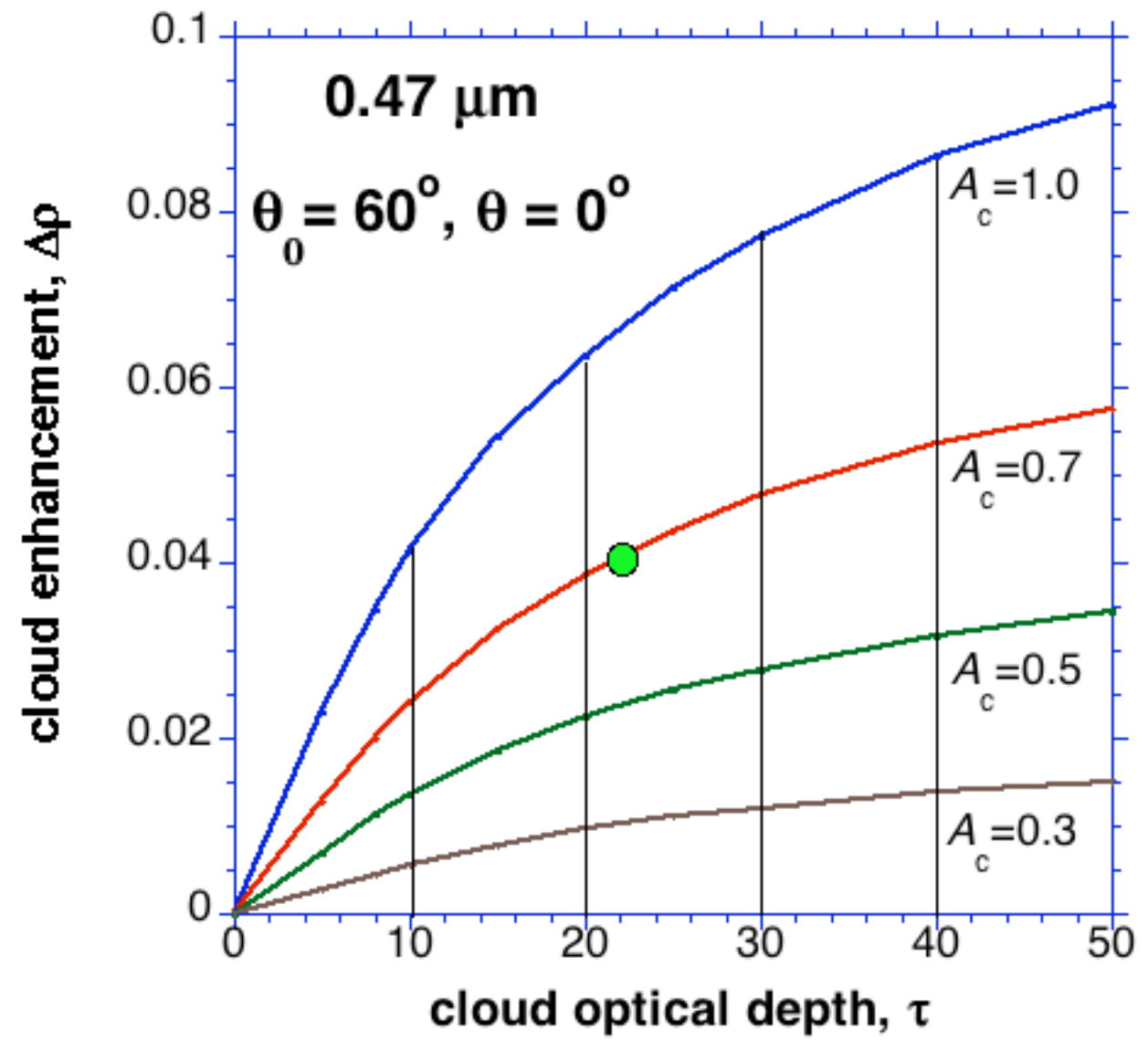


AR = 2

A_c = 0.3

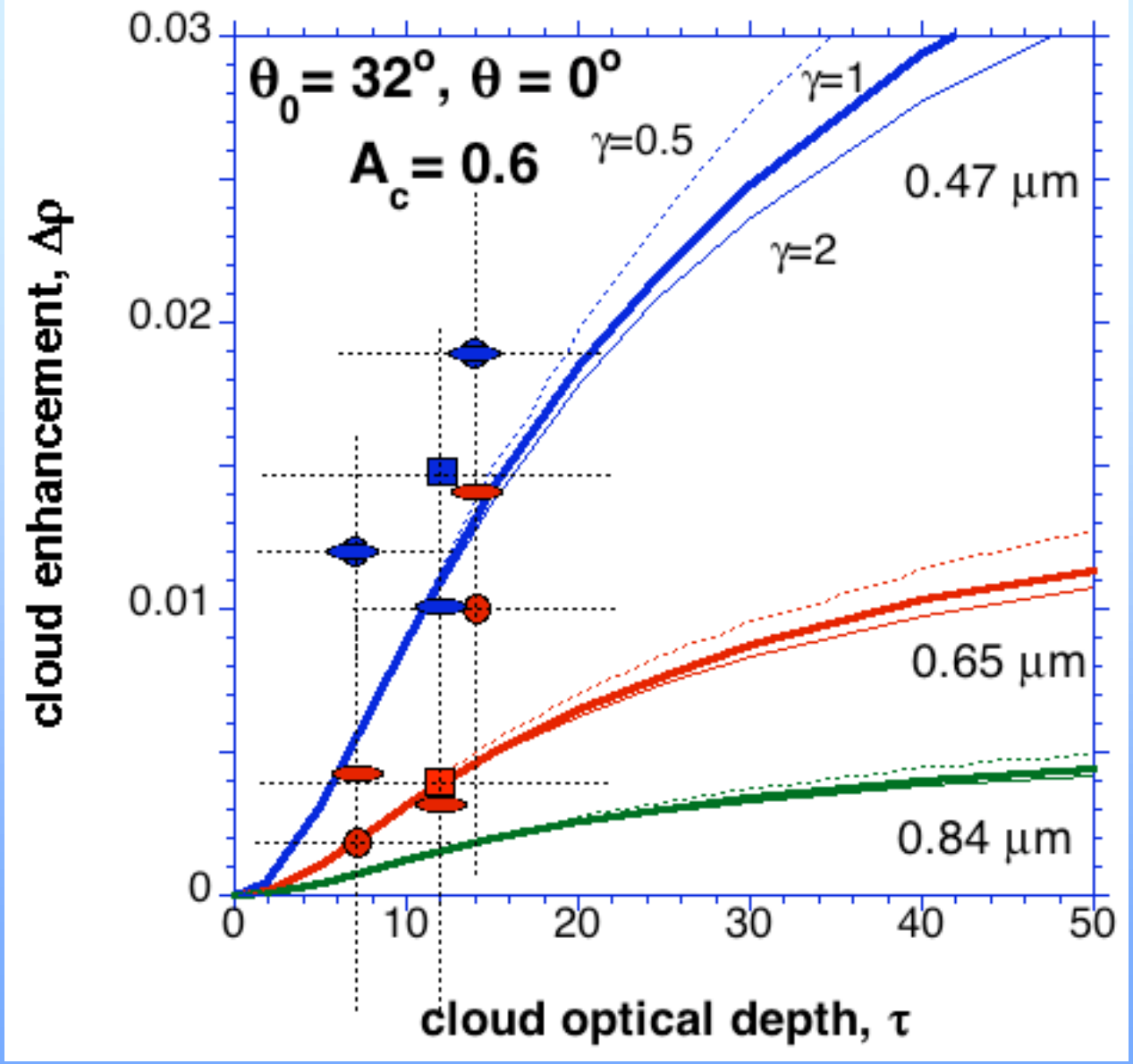
AR = 1

Cloud-induced enhancement at 0.47 μm



LUT:
The enhancement vs <τ> for AR = 1. A_c=1 corresponds to the pp approximation.

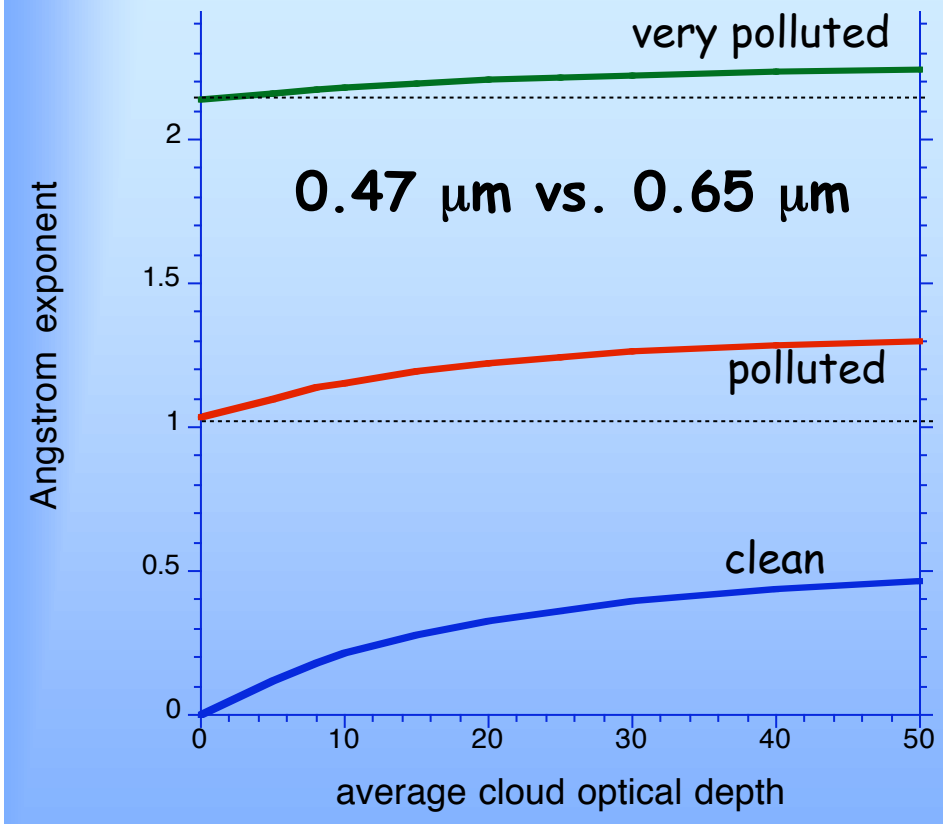
Cloud-induced enhancement: our simple model and 3D RT calculations

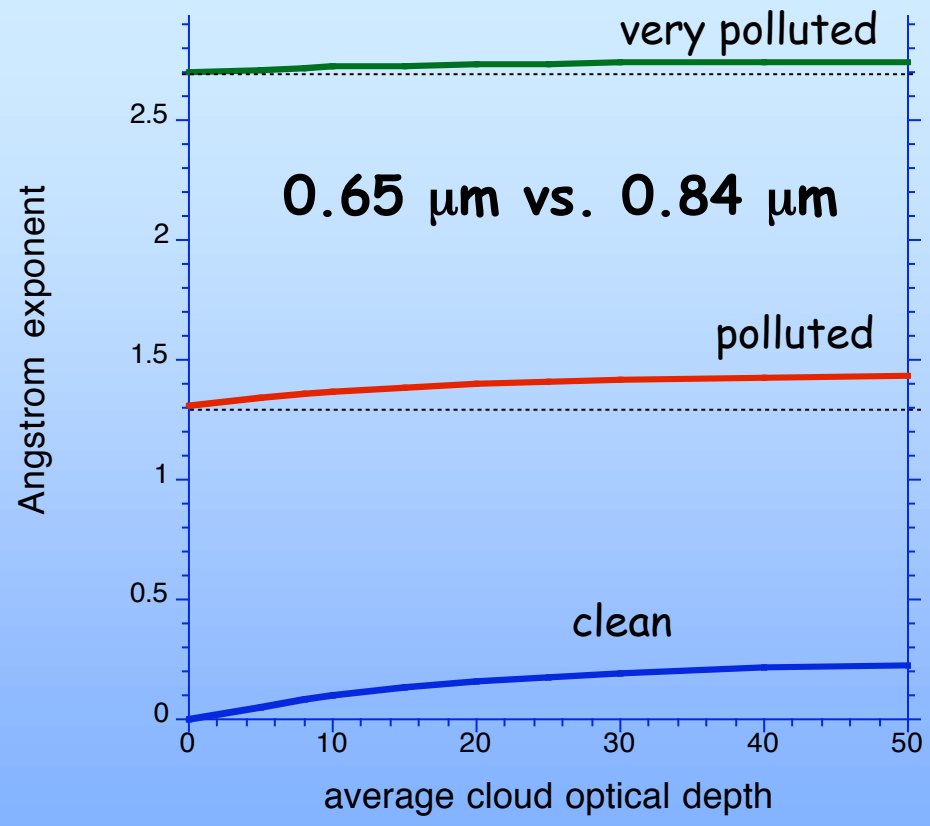


The enhancement vs <τ> for A_c= 0.6 and 3 cloud AR = 0.5, 1 and 2. Different dots are from Wen et al. (1997) MC calculations for the thin and thick clouds.

Ångström exponent

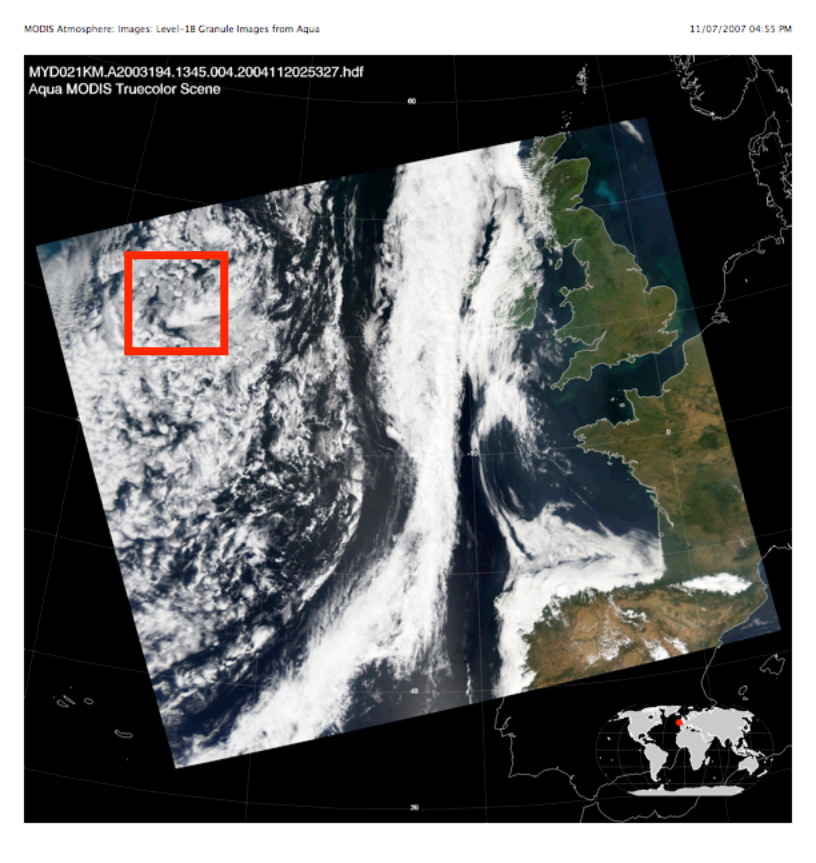
Ångström exponent vs <τ> for A_c= 0.5 and AR = 2.
Three cases: clean, polluted and very polluted.





The cloud adjacency effect increases the Ångström exponent

Work in progress



- select a few MODIS subscenes with
  - broken low Cu;
  - retrieved AOT;
  - over ocean with no glint, etc;
- analyze AOT, CF, average COD 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. (The twilight zone?)
- Accounting for the 3D cloud-induced enhancement helps.
- For certain conditions, 3D cloud enhancement only weakly depends on AOT and molecular scatt. is the key source for the enhancement.
- The enhancement increases the "apparent" fraction of fine aerosol mode ("bluing of the aerosols").
- Retrieved AOT *can* be corrected for the 3D radiative effects.