Solar energy attenuated in a Solar Thermal Energy plant, due to aerosol extinction between the heliostats and the optical receiver

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Solar Thermal Energy plant.

The approach

AERONET for aerosols, ...

3 input data:

. AERONET → Direct and scattered solar radiation **(few λ)** ⇄ **Aerosol** microphysical and optical properties **in the atmospheric column**

. Aerosol vertical profile → **in the atmospheric column**

. Aerosol Extinction Coefficient at Surface level ⇄ **validation** ⇄ in the column **& at surface level**

Objectives:

Aerosol impact at surface level,
seasonal and inter-annual variabilities
& spectral behaviour

Formulae and hypothesis

Solar energy attenuated at surface level

$$E_{tower} = E_{TOA} \times T_{col} \times T_{surf} \times EF_{CSP}$$

$$E_{att} = E_{TOA} \times T_{col} \times (T_{surf} - 1) \times EF_{CSP}$$

Atmospheric component

E_{tower}: Solar irradiance/energy effectively received at the tower, taking into account the atmospheric attenuation in the two pathways.

E_{att}: Solar irradiance/energy attenuated by aerosols and molecules **at surface level**.

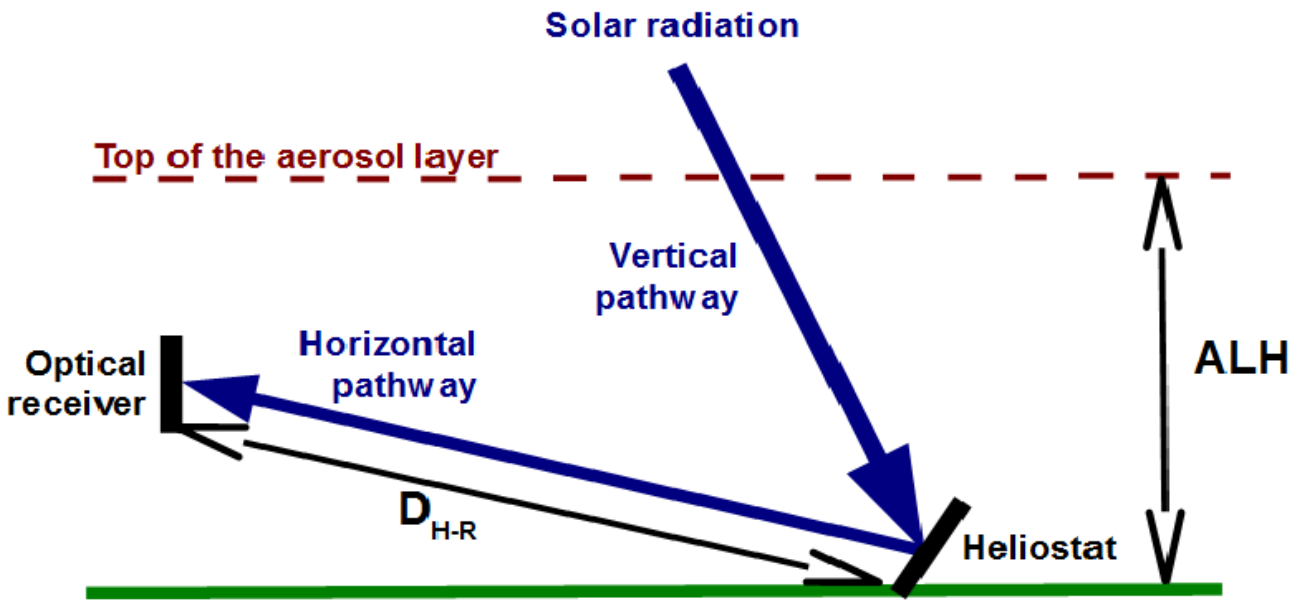
E_{TOA}: extra-terrestrial solar irradiance/energy.

$T_{col/surf}$: column/surface level atmospheric transmittance.

EF_{CSP}: optical performance of the STP optical system (also function of solar/STP geometry, ...)

Formulae and hypothesis

Attenuation at surface level by aerosols and molecules



AEC(z): aerosol extinction coefficient at altitude z

P, P_0: atmospheric pressure, at the site, standard

RSC: Rayleigh scattering coefficient (**molecules**) at P_0

D_{H-R}: Heliostat - optical receiver distance.

$$T_{surf} = \prod_{D_{H-R}} \exp\left(-\left(AEC(z) + \frac{P(z)}{P_0} RSC\right)\Delta D\right)$$

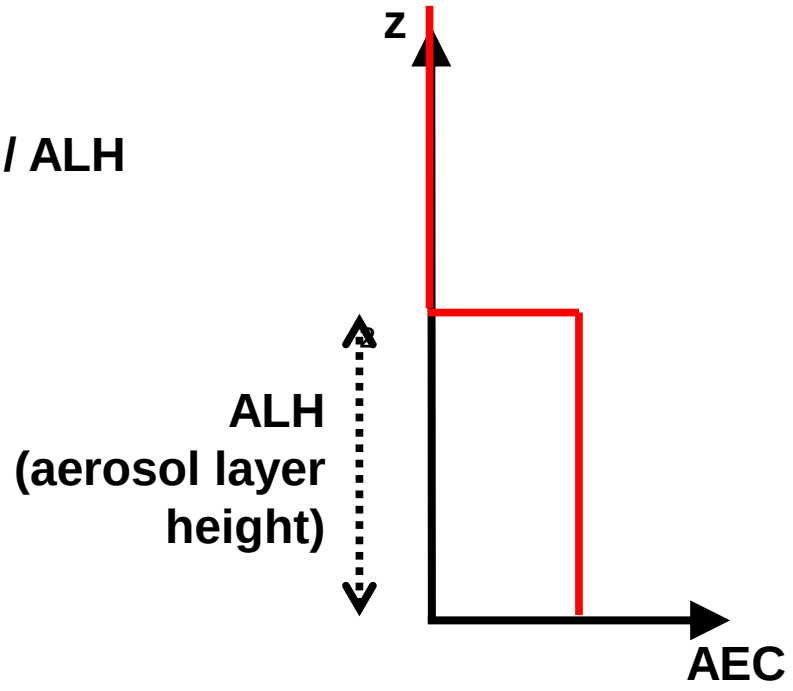
?

Formulae and hypothesis

Two parameters to describe the aerosol vertical profile

Hypothesis 1:

We suppose that ALH exists as: **AEC(z=0-300 m) = AOT / ALH**



Hypothesis 2:

We suppose that we can use the boundary layer height (BLH) instead of ALH, as:

AEC = AOT / BLH

$$T_{surf} = \exp\left(-\left(\frac{AOT}{BLH} + \frac{P}{P_0} \cdot RSC\right) \cdot D_{H-R}\right)$$

Formulae and hypothesis

Solar energy attenuated at surface level

$$E_{tower} = E_{TOA} \times \exp\left(-\frac{AOT + \frac{P}{P_0} \cdot ROT}{\cos SZA}\right) \times \exp\left(-\left(\frac{AOT}{BLH} + \frac{P}{P_0} \cdot RSC\right) \cdot D_{H-R}\right)$$

$$E_{att} = E_{TOA} \times exp\left(-\frac{AOT + \frac{P}{P_0} \cdot ROT}{\cos SZA}\right) \times \left(exp\left(-\left(\frac{AOT}{BLH} + \frac{P}{P_0} \cdot RSC\right) \cdot D_{H-R}\right) - 1\right)$$

ROT: Rayleigh Optical thickness

SZA: solar zenith angle

$D_{H\text{-}R}$ = 1 km

Validation of AEC

Validated at Ouarzazate, Morocco

SAMUM field experiment in May-June 2006 in Morocco [Heintzenberg, 2009]:

AOT = 0.32 by AERONET

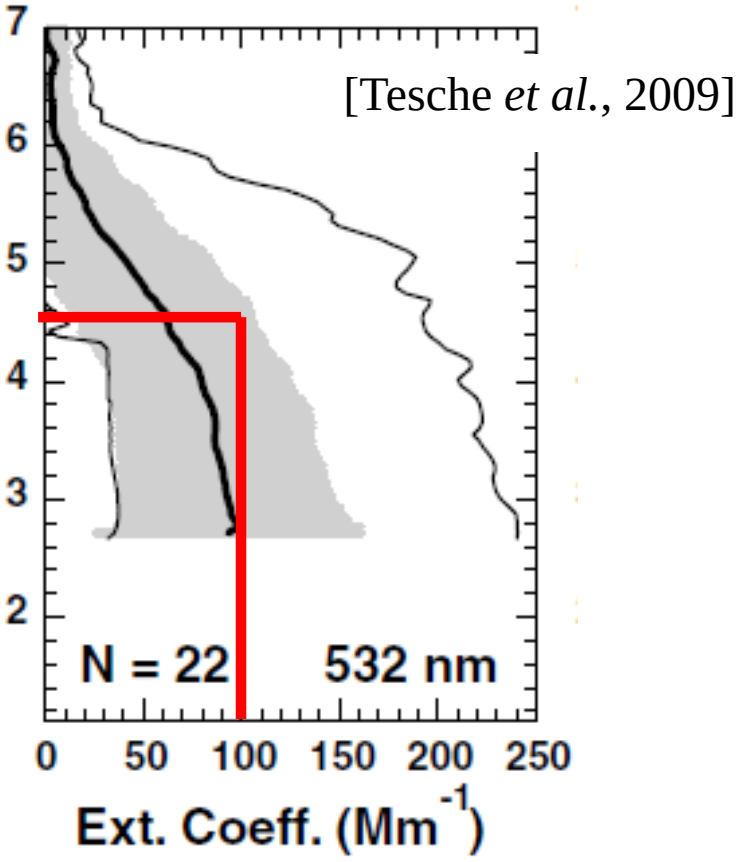
AEC = 100±50 Mm^{-1} by lidar [Tesche et al., 2009]

ALH = AOT / AEC = **3.2 km**

BLH from EMCWF (operational analysis).

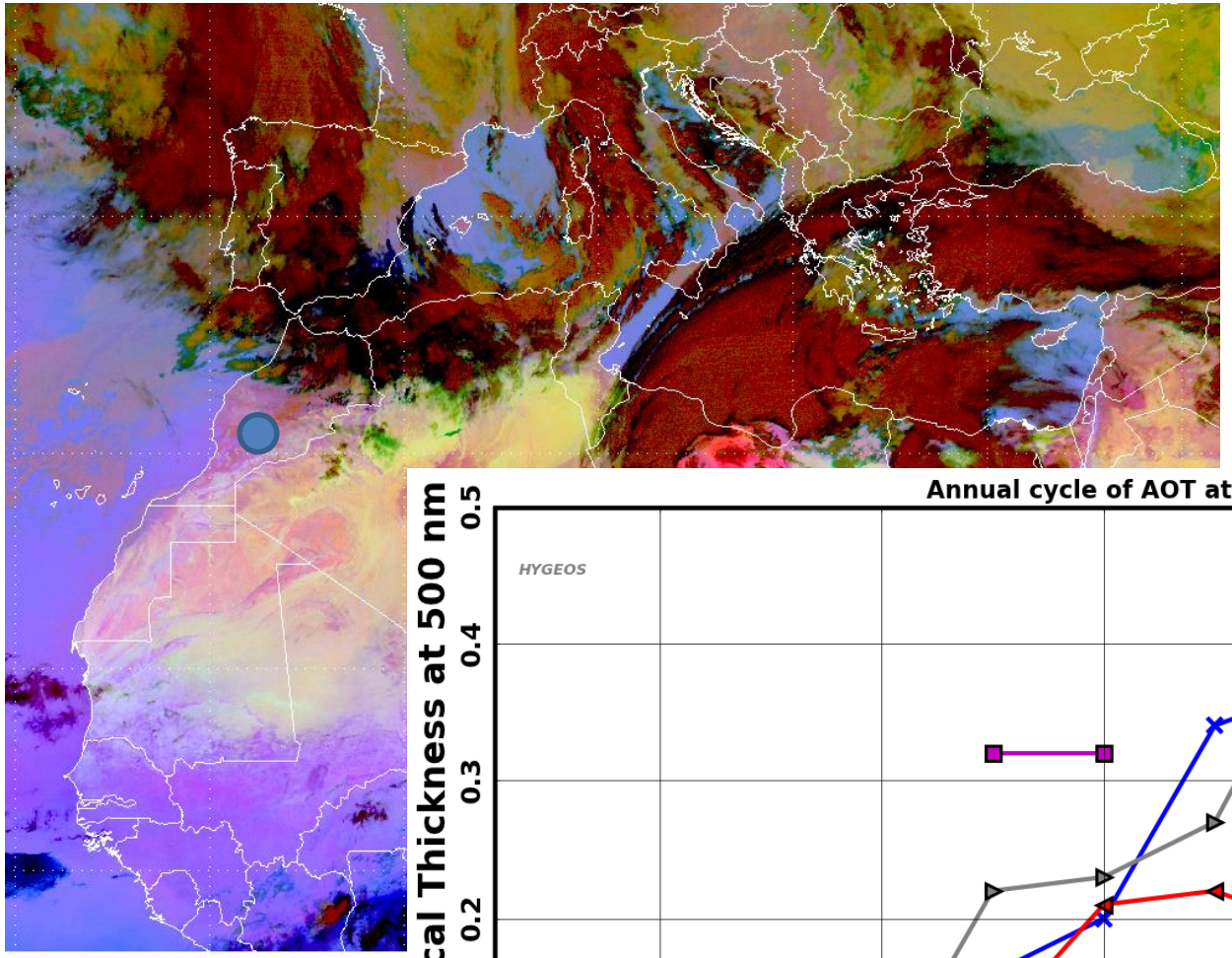
The month averages of BLH at 12-15:00 in May-June varied between **2.9±0.7 and 3.6±0.7 km**.

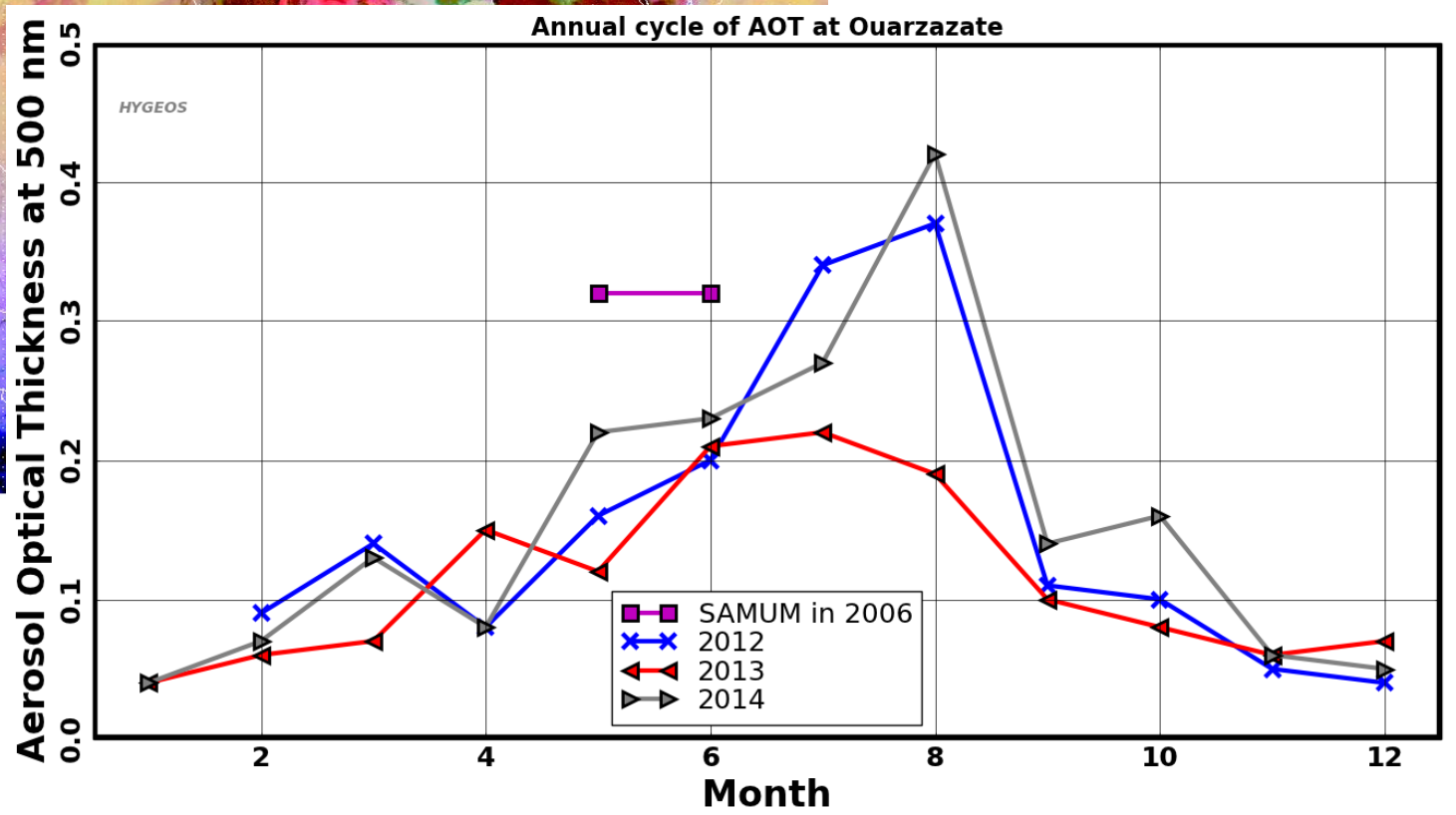
VALIDATED



Results at Ouarzazate (Morocco)

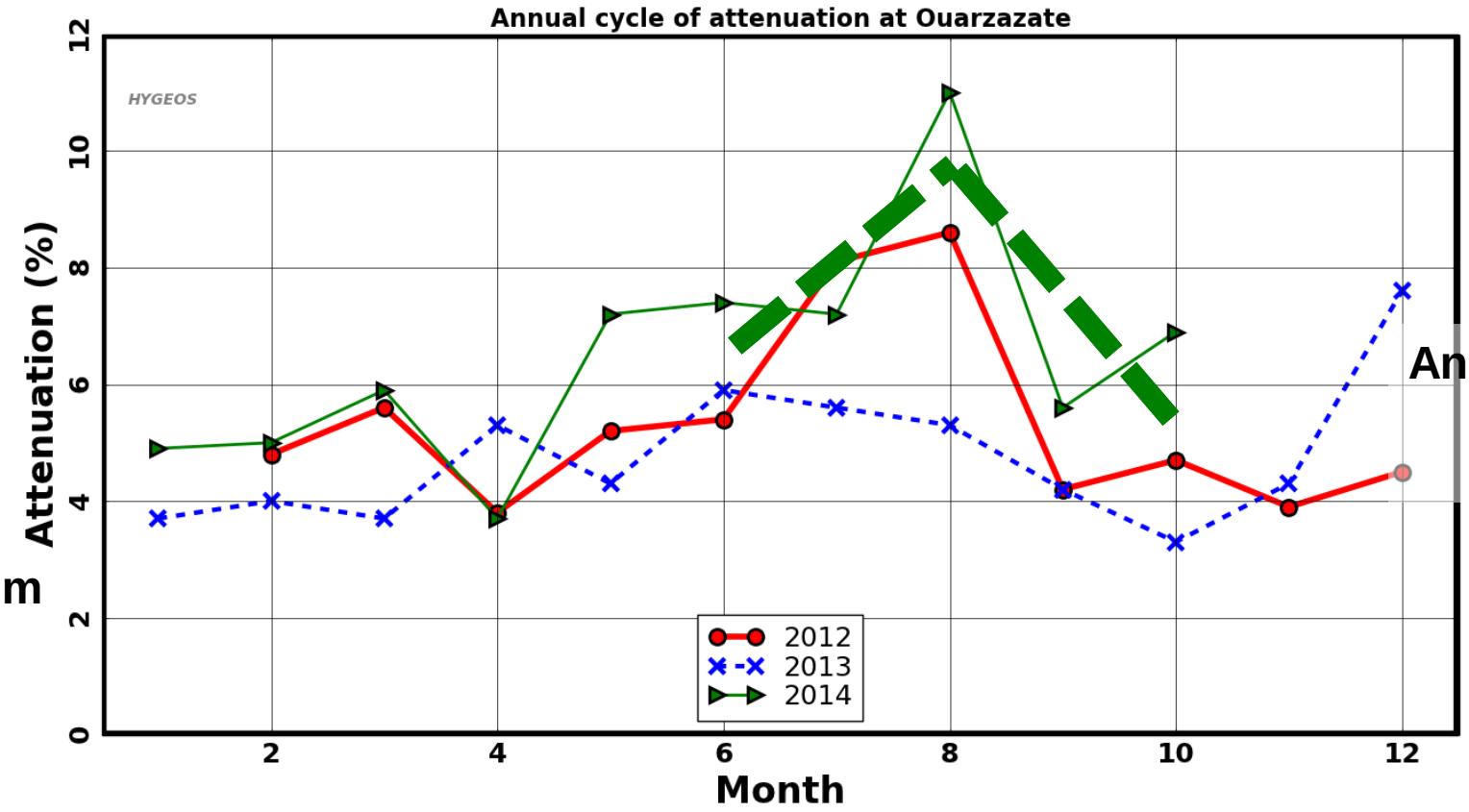
Desert dust season in summer





Results at Ouarzazate (Morocco)

Annual cycle of the attenuation caused by desert dust episodes



at 500 nm

Annual averages :

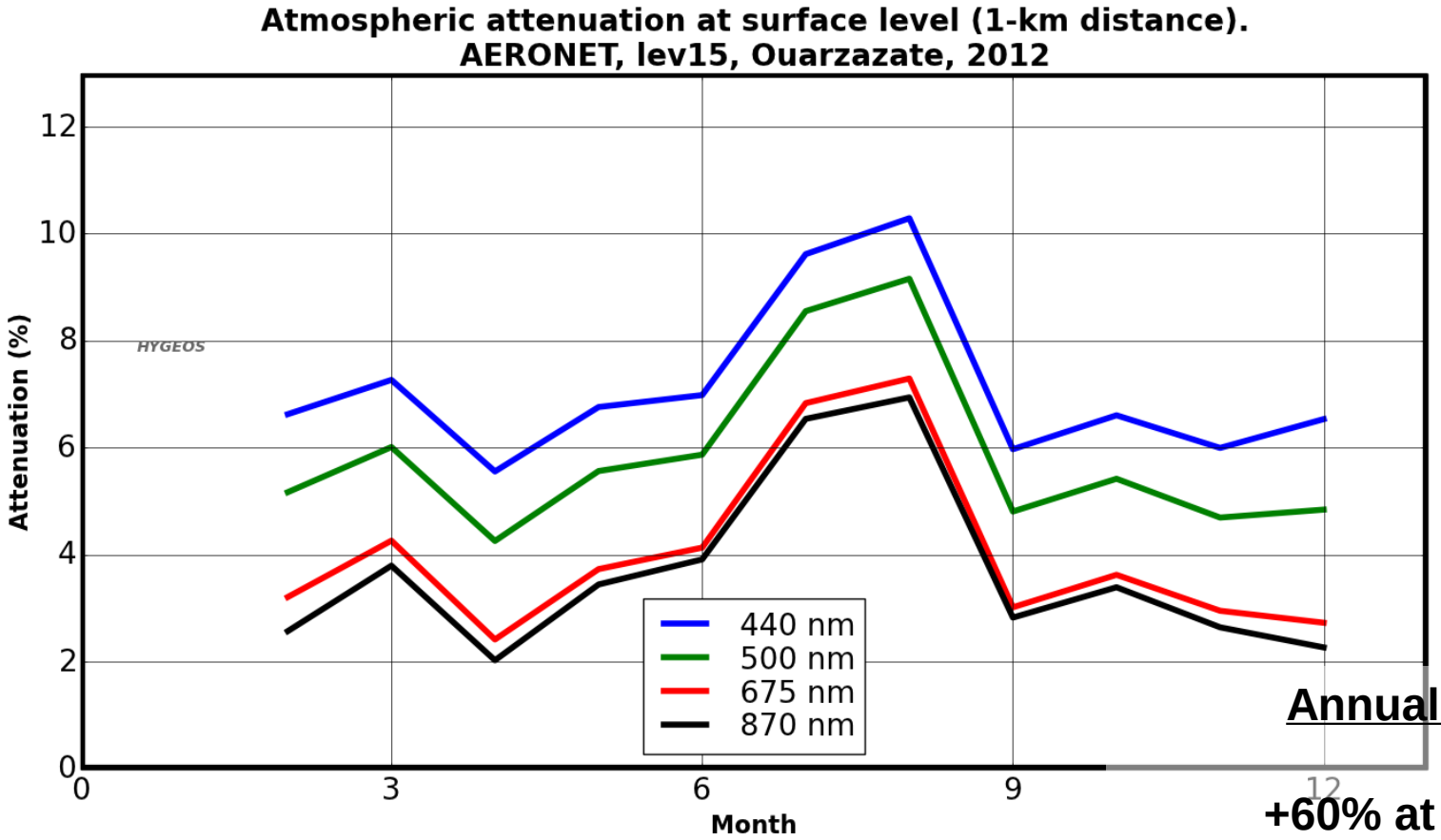
4.8 %

6.2 %

Annual cycle due to desert dust in summer.
Maximum (>8%) in June-August, minimum (<4%) in November-January.
Inter-annual changes: due to intensity and duration of the desert dust season

Results at Ouarzazate (Morocco)

Spectral dependence

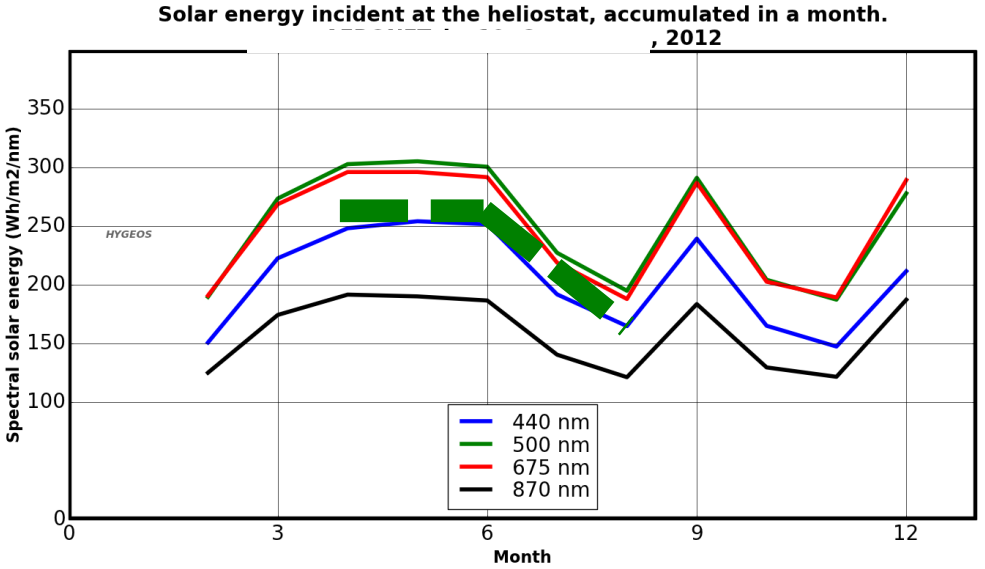


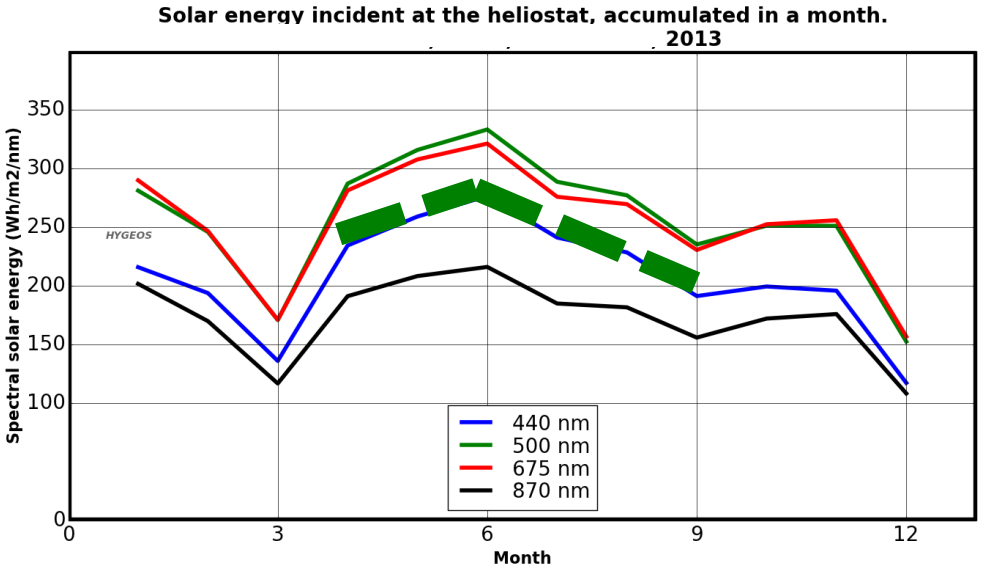
Annual cycle:

+60% at 440 nm
Factor 2 at 500 nm
Factor 3 at 675-870 nm

Results

Energy incident at the heliostat



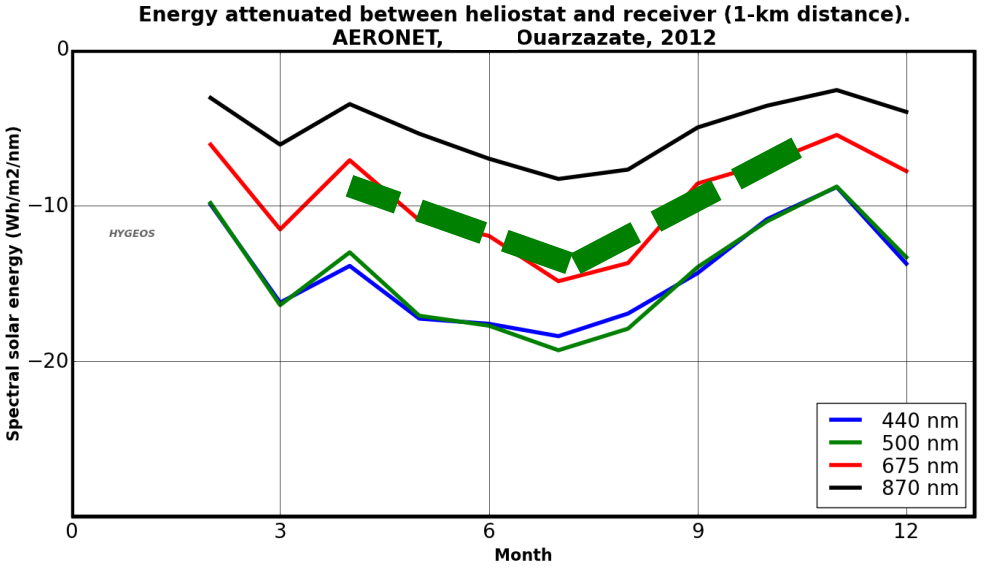


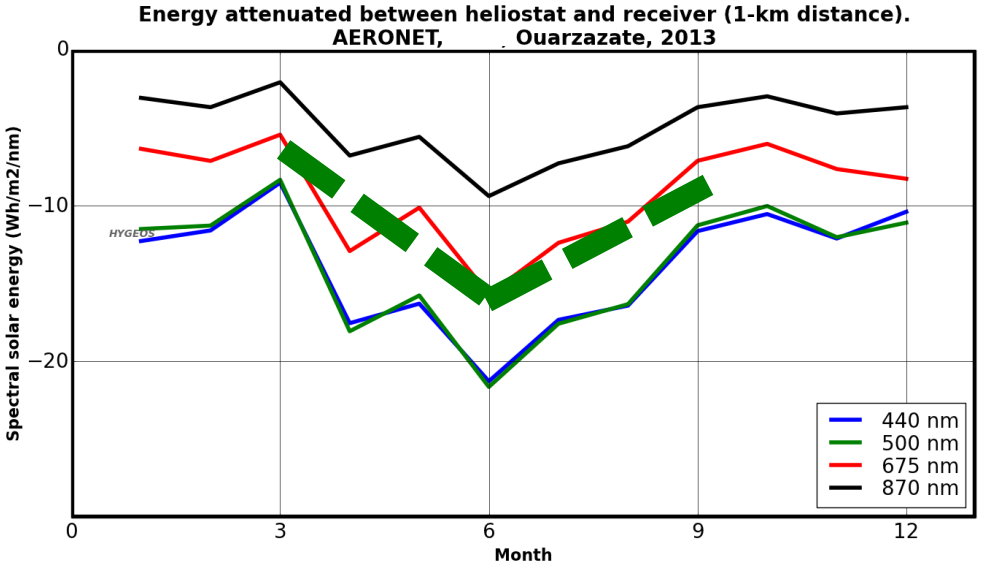
Max of ~300 Wh/m^2/nm
at 500-675 nm
in April-May-June,
Because of
- small SZA,
- long days,
- few clouds,
- medium AOT (0.08-0.23)

Min of ~150 Wh/m^2/nm
At 440 and 875 nm
in August, November, March, December
Because of
- clouds

Results

Energy attenuated between the heliostat and the optical receiver





Max of ~-20 Wh/m^2/nm
at 440-500 nm
in June-July,
Because of
- max of energy incident at heliostat,
- large attenuation (5-8%)
(Rayleigh/annual cycle)

Min of ~-5 Wh/m^2/nm
at 675-870 nm
in October-November, March-April,
Because of
- small energy at heliostat (clouds)
- small attenuation (<4%)

Summary & perspectives

Attenuation at surface level: min in winter, max in August (desert dust), +60% to +200%

Incident energy at heliostat: Max in May-June
Min during cloudy months (~-100 Wh/m^2/nm)

Energy attenuated between the heliostat and the optical receiver
-10 to -20 Wh/m^2/nm because of aerosols
Solar resource most affected by aerosols in May-August (max incident, max scattering)
Min at 670-875 nm and during cloudy months

We need ground-based proof for validation: diffusometer, nephelometer, …

Future work:
1. Broad band computations
To complete the radiative budget, with absorbing gases (H_2O, O_3, ...)

2. Aerosol impact observed by satellite: the ASoRA project
(EDF-HYGEOS collaboration)
To replace AERONET by satellite
To replace BLH by ALH from CALIOP/CALIPSO

Thank you

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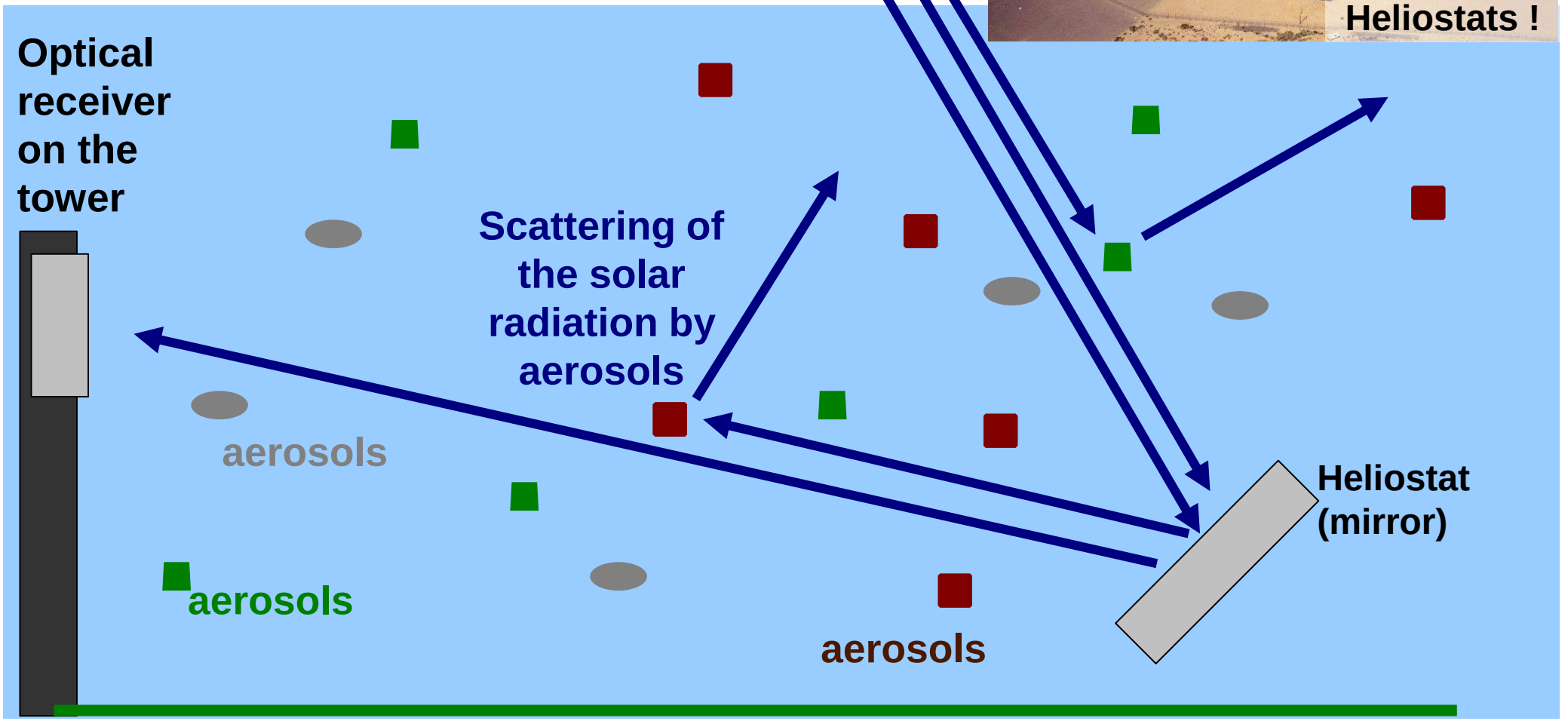
HYGEOS http://www.hygeos.com/



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. Aerosol Extinction Coefficient at Surface level ⇄ **validation** ⇄ in the column **& at surface level**

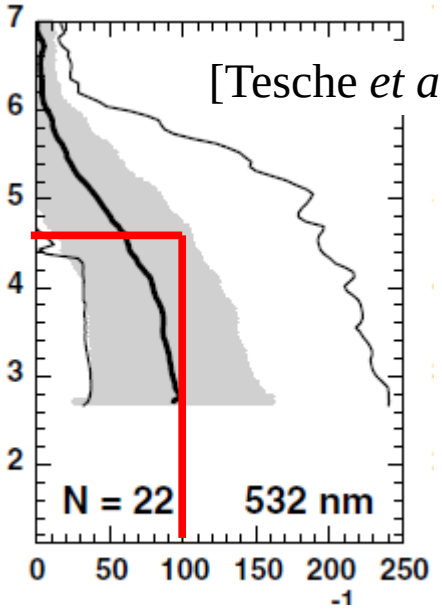
. Absorbing gases → in the column & at surface level

. DNI ⇄ **validation** ⇄ in the column & at surface level **& broadband**

Validation of AEC

Validated at Ouarzazate, invalidated at Banizoumb

[Tesche *et al.*, 2009]



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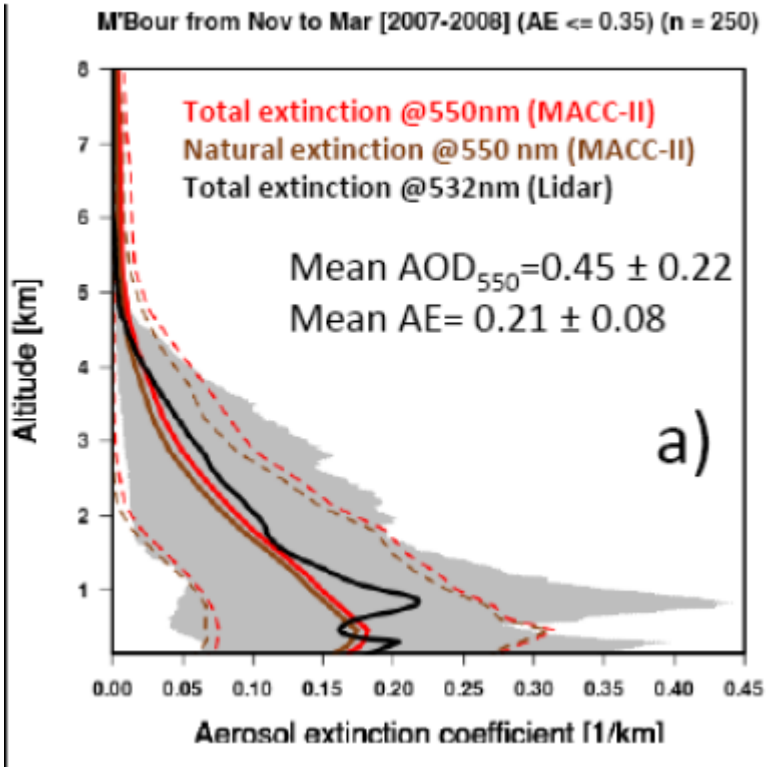
The month averages of BLH at 12-15:00 in May-June varied between 2.9±0.7 and 3.6±0.7 km.

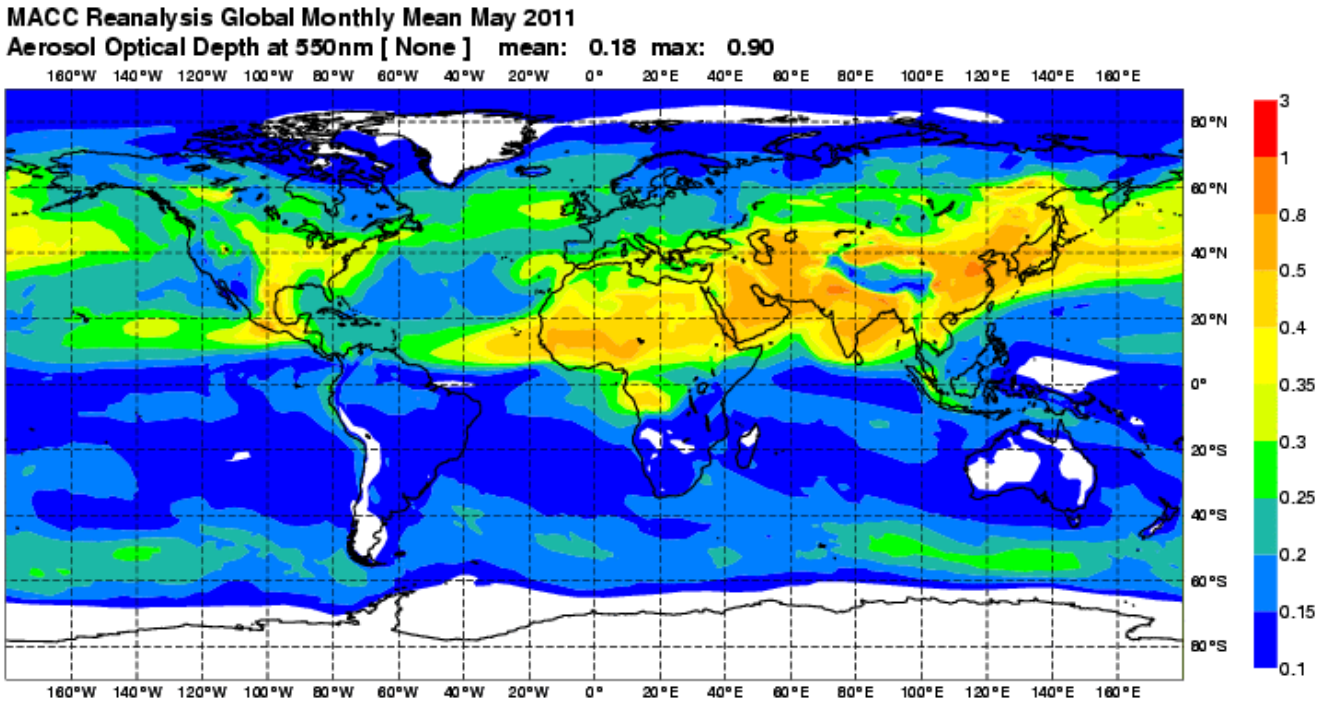
VALIDATED

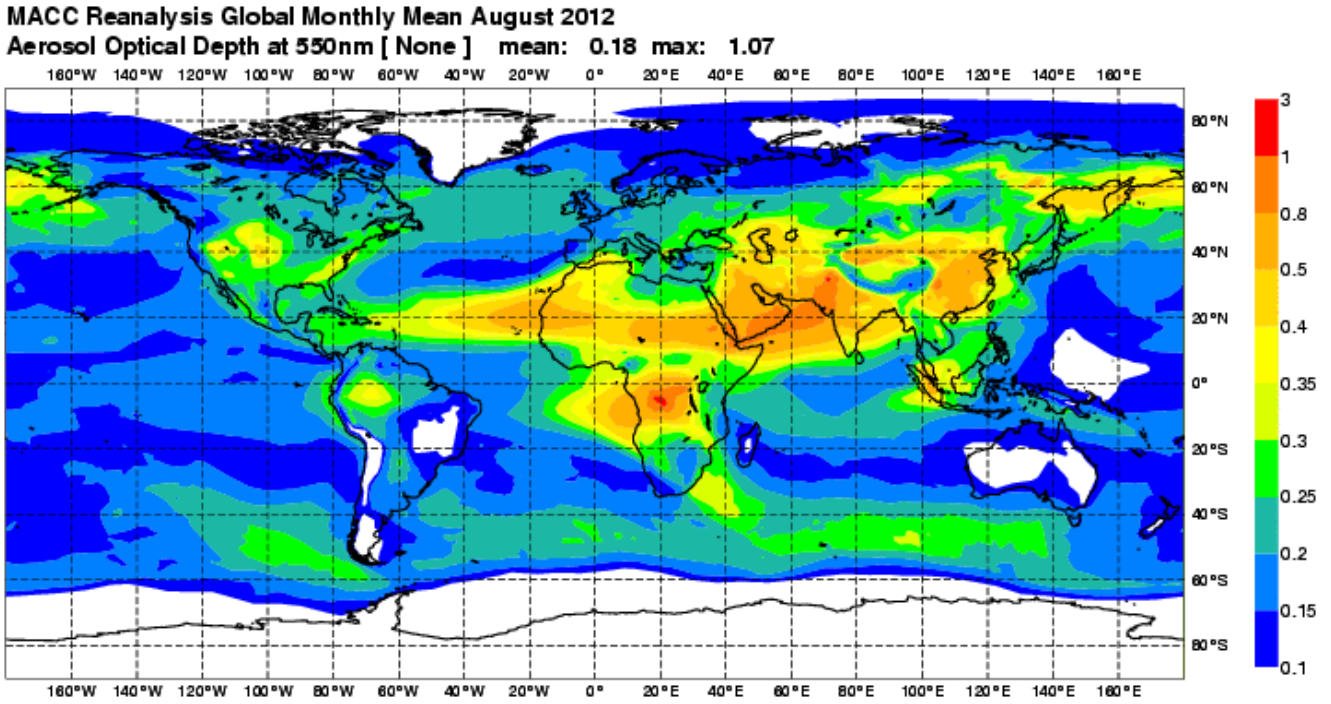
AMMA field experiment at Banizoumbou:
ALH = 3.7±1.9 km in January 2006
ALH = 2.6±1.4 km in February 2006

But
BLH = 1.4±0.3 km in January 2006
BLH = 1.7±0.3 km in February 2006.

INVALIDATED




MACC Reanalysis Global Monthly Mean May 2011
Aerosol Optical Depth at 550nm [None] mean: 0.18 max: 0.90
160°W 140°W 120°W 100°W 80°W 60°W 40°W 20°W 0° 20°E 40°E 60°E 80°E 100°E 120°E 140°E 160°E
80°N 60°N 40°N 20°N 0° 20°S 40°S 60°S 80°S
3 1 0.8 0.5 0.4 0.35 0.3 0.25 0.2 0.15 0.1


MACC Reanalysis Global Monthly Mean August 2012
Aerosol Optical Depth at 550nm [None] mean: 0.18 max: 1.07
160°W 140°W 120°W 100°W 80°W 60°W 40°W 20°W 0° 20°E 40°E 60°E 80°E 100°E 120°E 140°E 160°E
80°N 60°N 40°N 20°N 0° 20°S 40°S 60°S 80°S
3 1 0.8 0.5 0.4 0.35 0.3 0.25 0.2 0.15 0.1