Aerosol Remote Sensing
An introduction for aerosol experts

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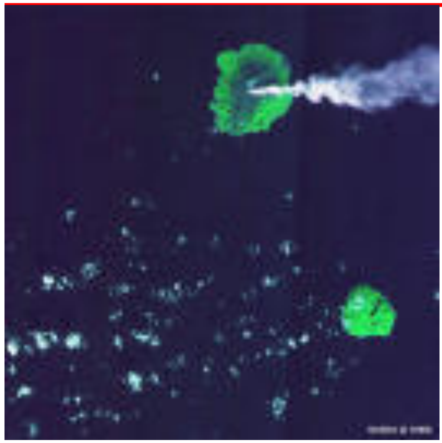
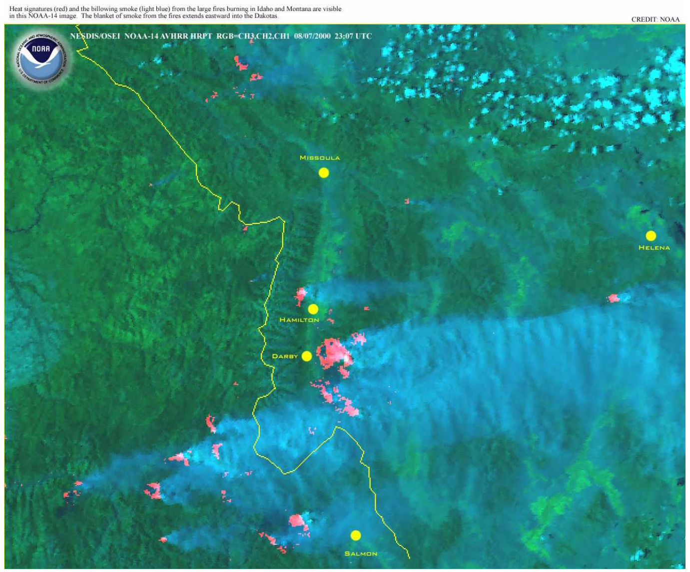
Aerosol plumes from space



Volcano (Japan)

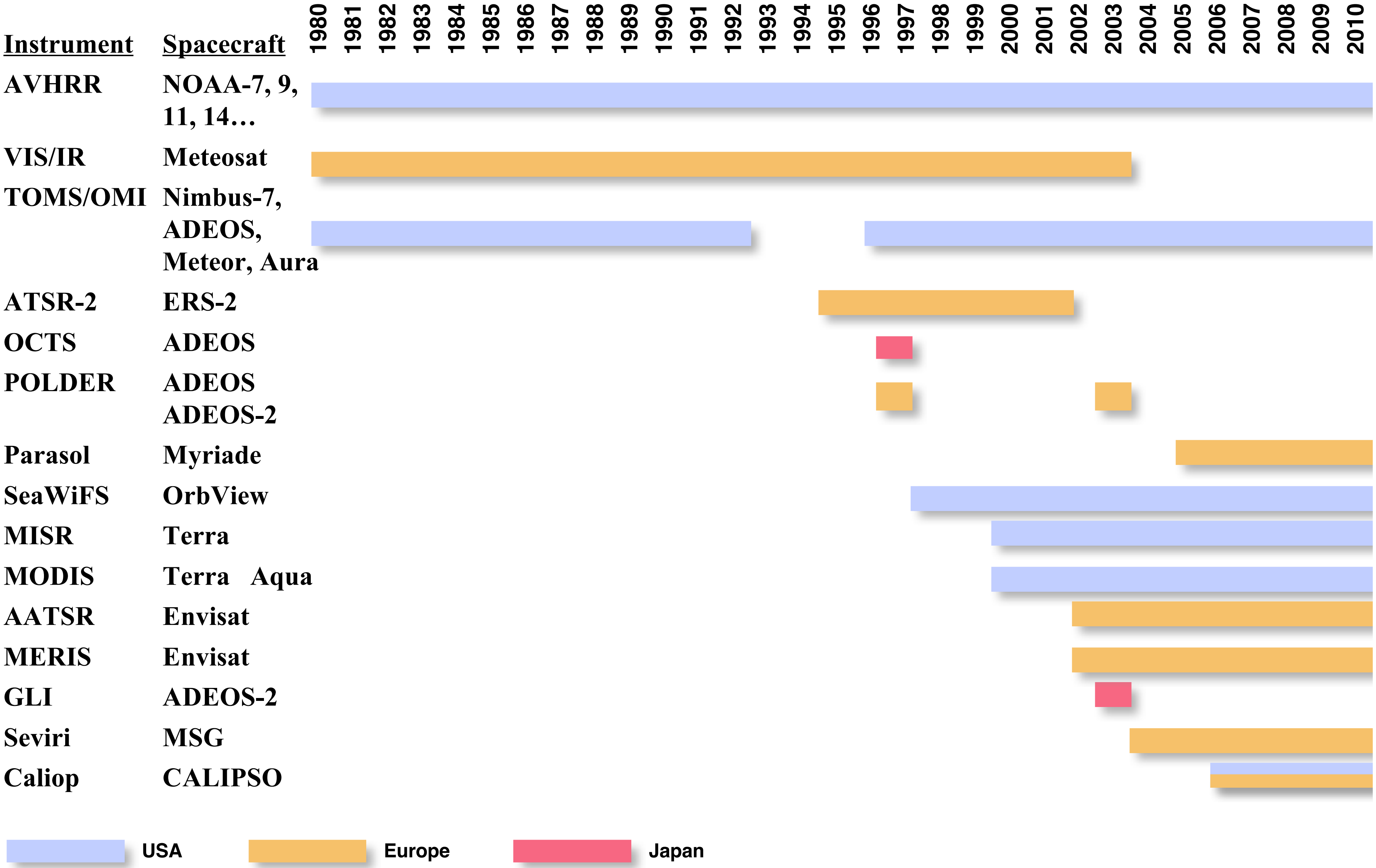


Forest Fire Smoke (Amazone)

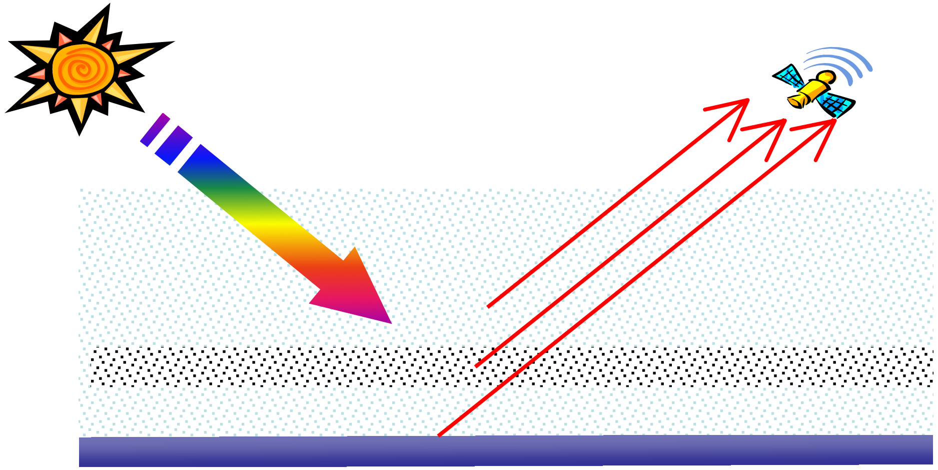
Desert Dust (Sahara)

Satellite observation is well suited to monitor atmospheric aerosol sources and transport

Aerosol measurements from space



Over the oceans…

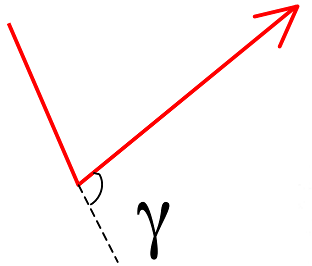


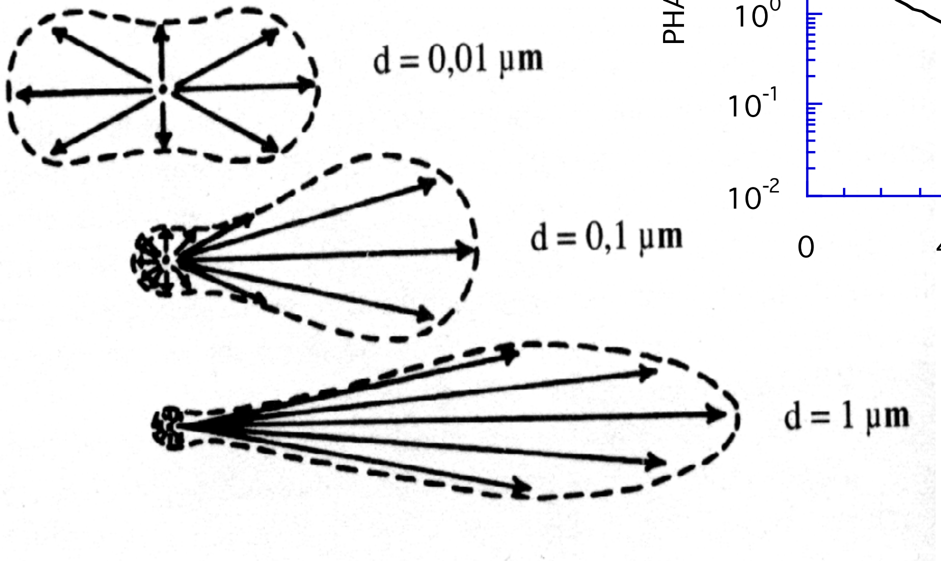
$$R_{sat} = \frac{\varpi\ \tau_{aer} P_{aer}(\gamma)}{4\ \mu_s\ \mu_v}$$ Aerosol contribution

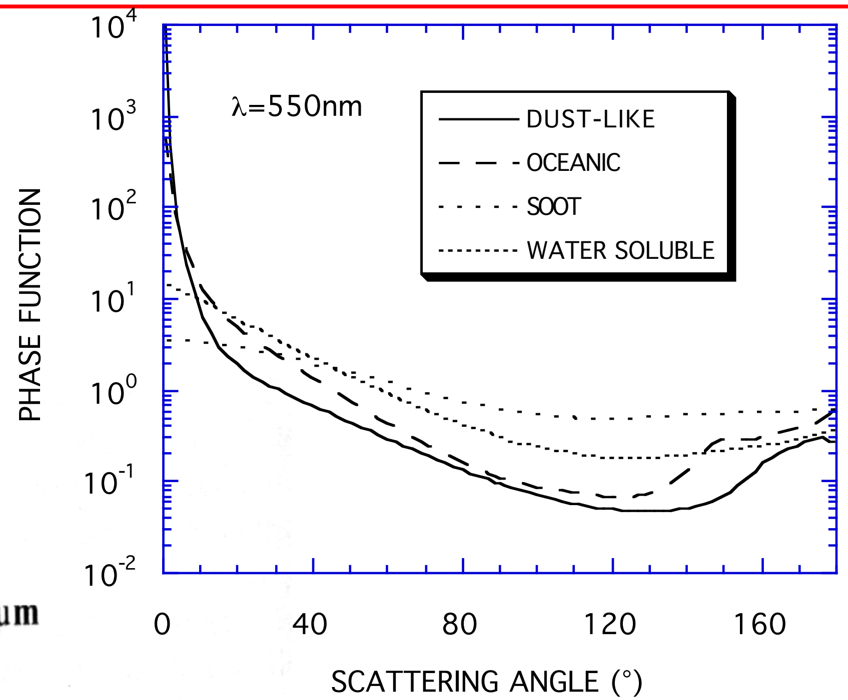
$$+\frac{\tau_{mol} P_{mol}(\gamma)}{4\ \mu_s\ \mu_v}$$ Molecule contribution; Well known

$$+R_{surf}\ T_{atm}^{\Downarrow\Uparrow}$$ Surface contribution; Small

$$R_{aer} = \frac{\varpi\, \tau_{aer} P_{aer}(\gamma)}{4\, \mu_s\, \mu_v}$$







The good news : P_{aer} varies with the aerosol type ➽ Potential to retrieve aerosol model

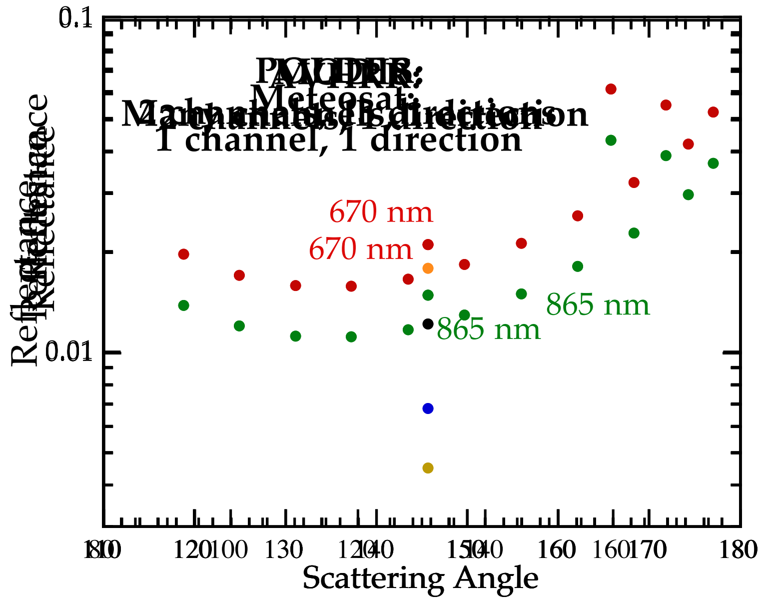
The bad news: P_{aer} varies with the aerosol type ➽ Large variations on the relationship between measurement (R_{aer}) and optical depth (τ_{aer})

Estimation of τ from reflectance meas.

$$R_{aer} = \frac{\varpi\, \tau_{aer} P_{aer}(\gamma)}{4\, \mu_s\, \mu_v}$$

Select a proper value for ωP_{aer}

(i) Assume an aerosol model
(ii) Choose among several models based on spectral signature
(iii) Choose among several models based on directional signature
(iv) Choose among several models with some information on polarized signature

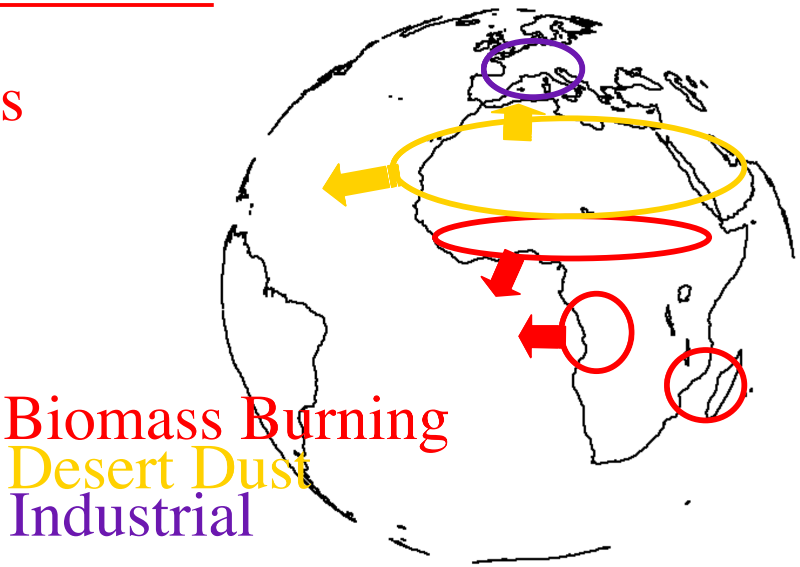


Use of Meteosat (1990s)

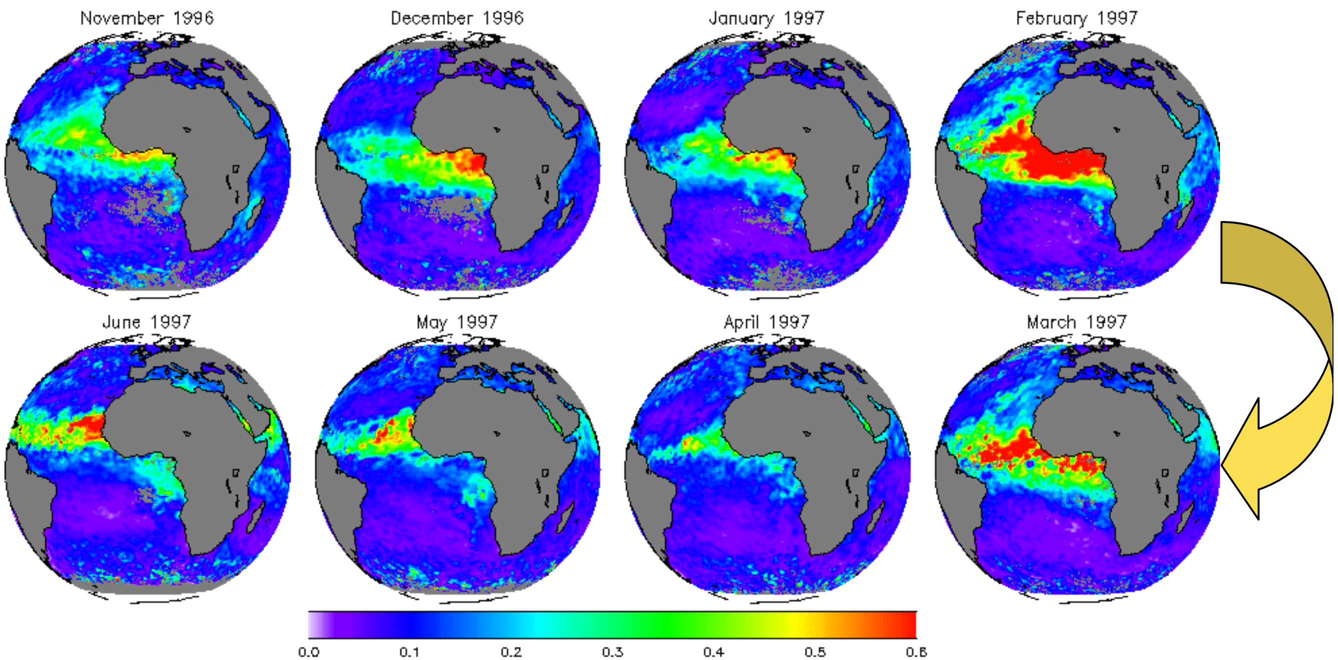
FOV well suited to observe major sources of aerosols and their transport

Large optical thickness of Saharan Dust

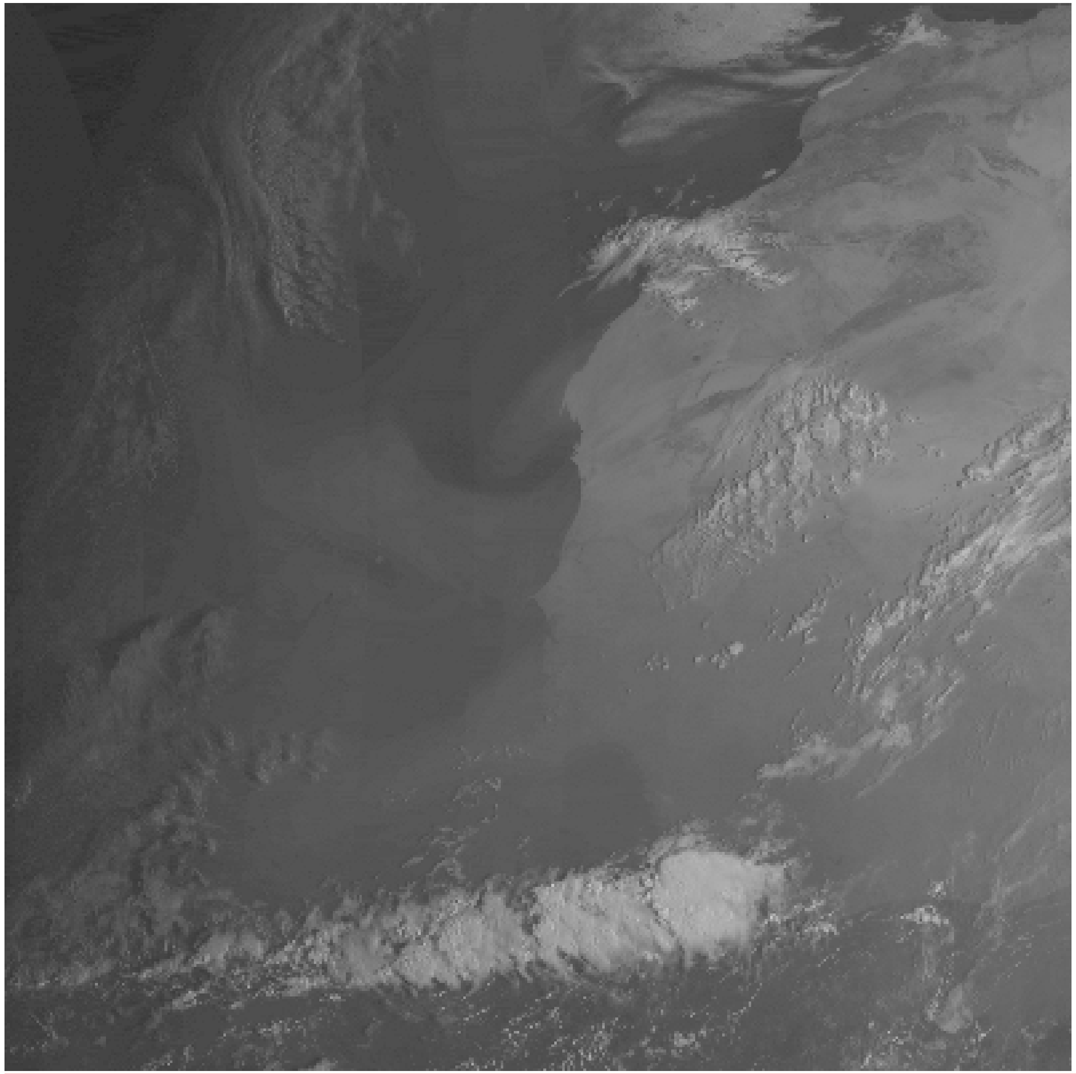
Long time series

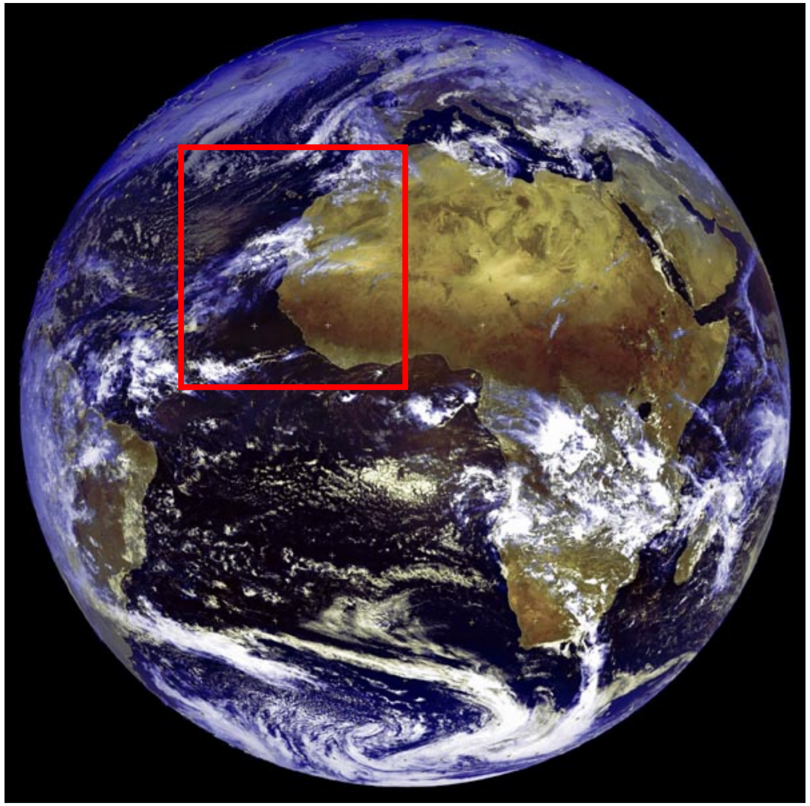


Mix of Saharan dust and biomass burning in January-March



Dust transport observed by Meteosat

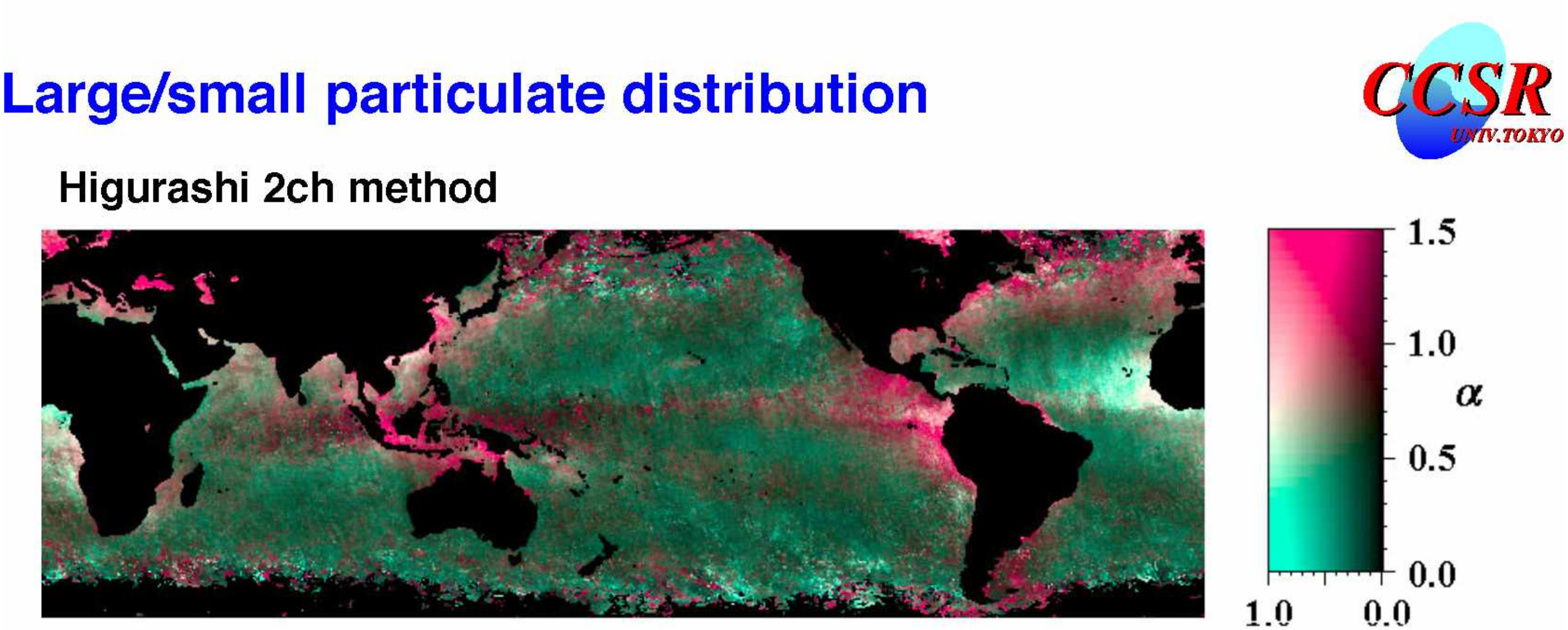


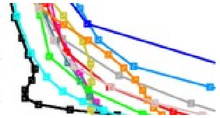


30 mn time step

AVHRR: 2 channels algorithm

Makes use of near IR channel, in addition to visible
Potential information on aerosol type
Uncertainties with calibration, water vapor absorption

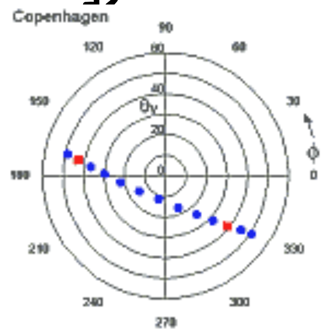




Dedicated Satellite missions !

ADEOS/POLDER (launched 1996; 2003; 2005 [Parasol])

- Multi-view, 8 channels (Vis=> near IR), polarization



Terra/MODIS (launched 1999)

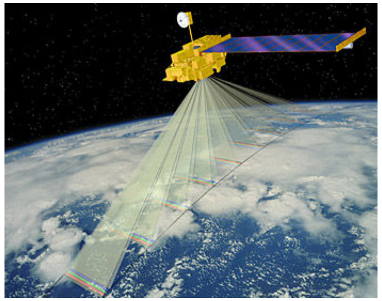
- Many channels Vis->IR

Ocean Color missions (several channels Vis=> near IR)

- SeaWifs (launched 1997)
- OCTS (launched 1996)

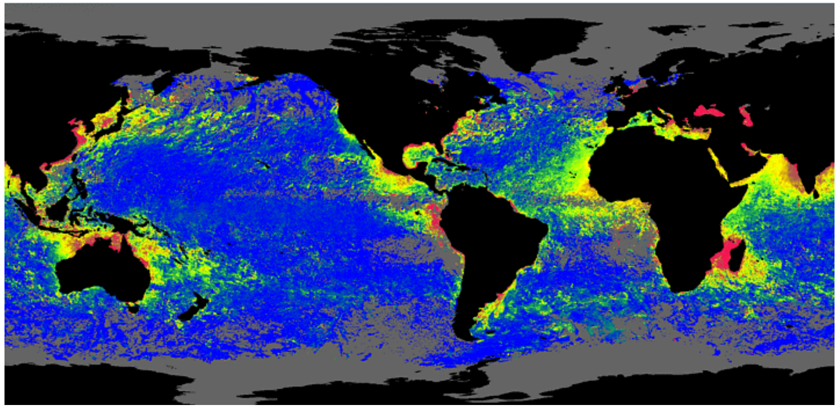
Other potential instruments

- ATSR-2 (launched 1995): dual view
- MISR (launched 1999): multi view

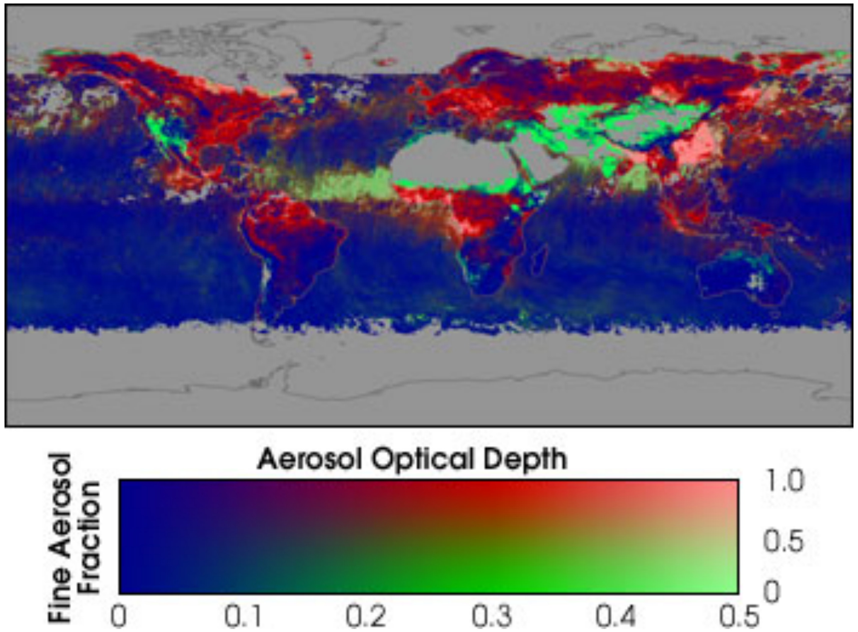


Second step: Aerosol speciation

- An indication of aerosol size is needed
- Angström exponent is useful, but unreliable for small AODs
- I prefer the Fine Mode AOD. Not affected by such bias.
- Validation shown later (stay tuned…)



POLDER "Fine Mode" AOD, accumulation mode fraction

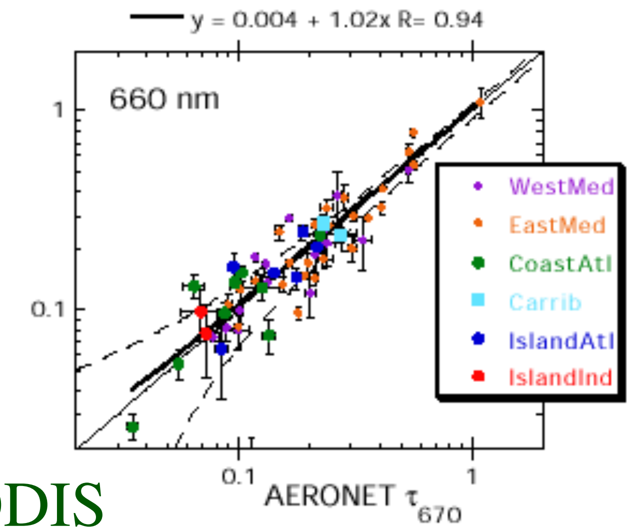


MODIS Combination of optical depth and particle size

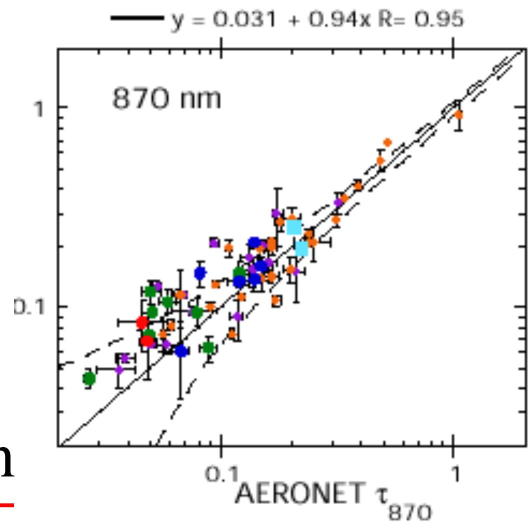
Aerosol over the oceans. Status

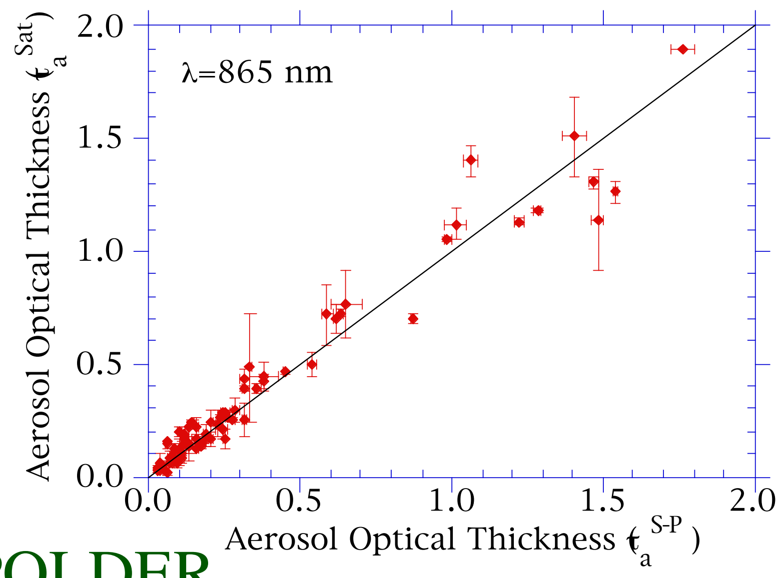
The retrieval of optical thickness over the oceans from remote sensing measurements is solved

Complete characterization of aerosol physical and chemical properties requires additional work



MODIS

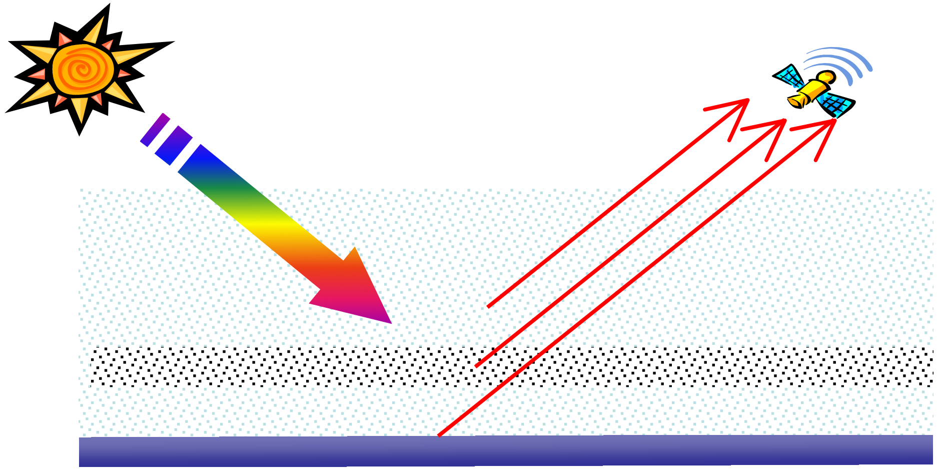




POLDER

Sunphotometer-satellite comparison

Over Land…



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$$+ \frac{\tau_{mol} P_{mol}(\gamma)}{4\, \mu_s\, \mu_v}$$ Molecule contribution; Well known

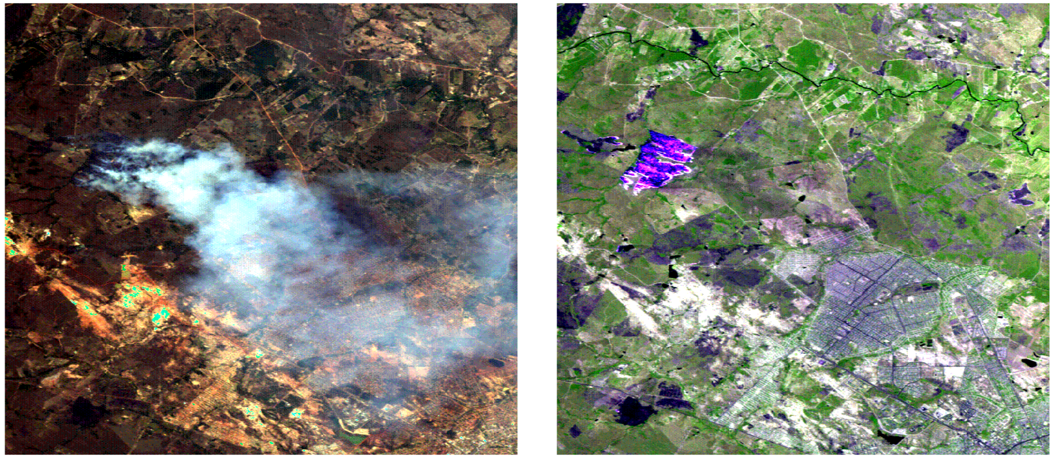
$$+ R_{surf}\, T_{atm}^{\Downarrow\Uparrow}$$ Surface contribution; Large, variable

The difficulty is therefore to separate the contribution of aerosols and the surface

Spectral signature of reflectances

Using the spectral information to sense aerosol over the land

ER-2, AVIRIS spectral image from SCAR-B of smoke over Cuiaba on Aug. 25, 1995



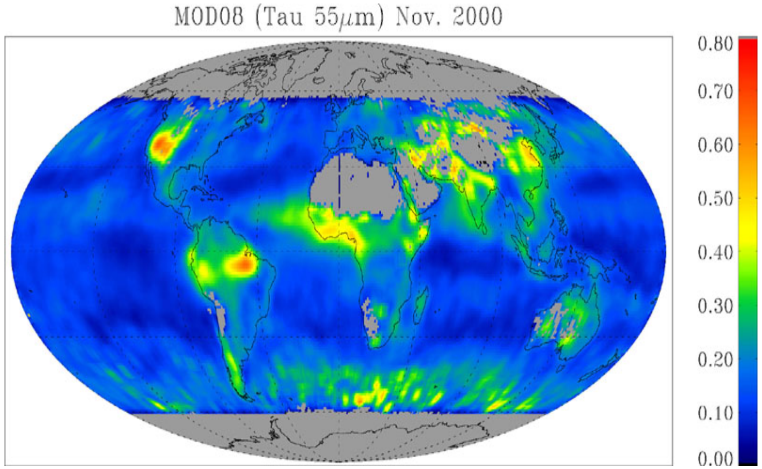
RGB: 0.47 μm, 0.55 μm, 0.66 μm

Heavy smoke. The image resembles human vision.

Near-IR RGB: 2.1 μm, 1.2 μm, 1.65 μm

The smoke is almost transparent in the mid-IR, surface features are visible.

(From Kaufman et al., 1997)

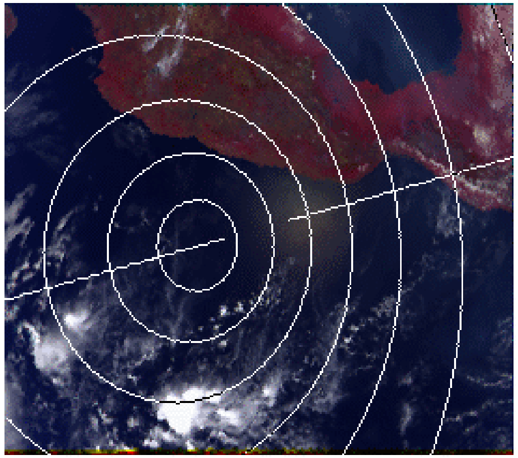


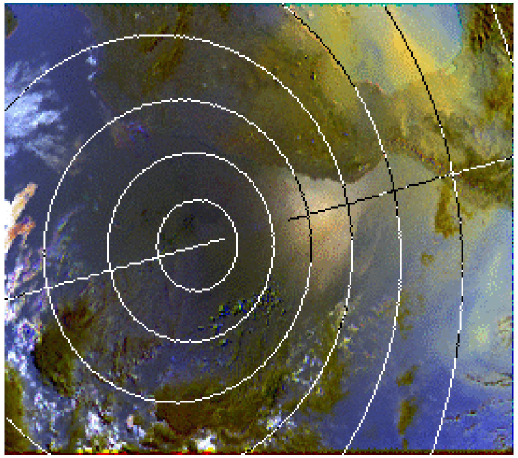
Aerosol "transparent" at 1.6-2 μm

Surface reflectance highly correlated at 0.66 and 2 μm

Use both reflectance measurements to derive aerosol contribution

Aerosol monitoring over land: Polarization

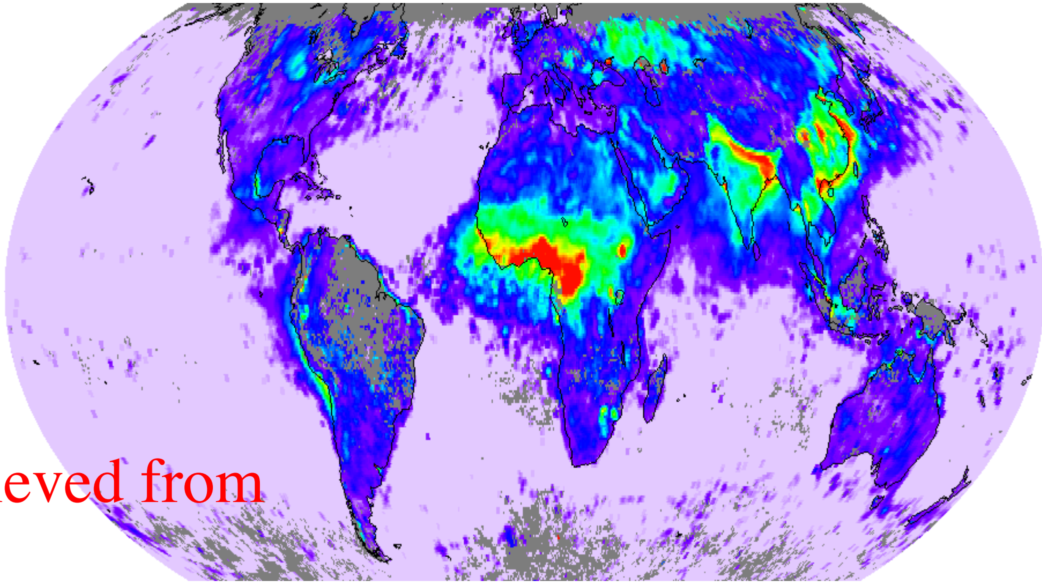




Polarized reflectances

- In total light, the surface contribution is generally much larger than that of aerosol
- The opposite is true in polarized light because surfaces are poor polarizers

POLDER result Jan. 1997



Optical thickness of aerosols retrieved from polarized reflectance at 865 nm.
Not sensitive to large particles (dust, sea salt)

Aerosol monitoring using thermal IR

Aerosol tend to cool the daytime apparent temperature

- Direct effect on IR radiance
- Surface cooling by reduction of solar incoming radiation

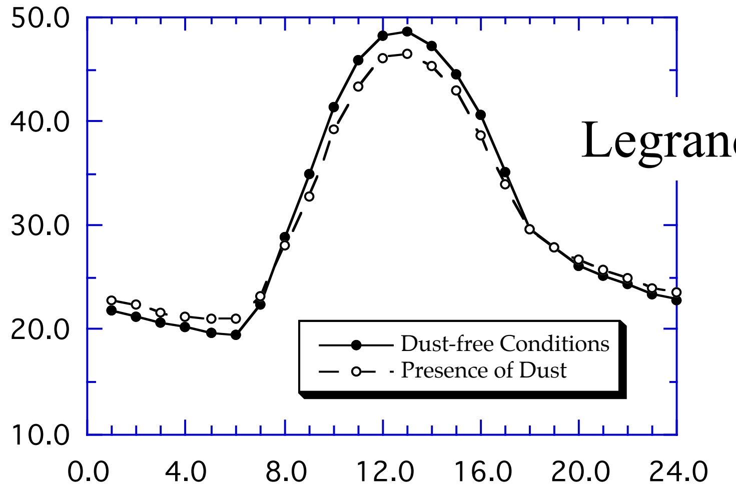
Monthly reference of apparent temperature T_{clear}

Dust Index based on $T_{clear}-T_{obs}$

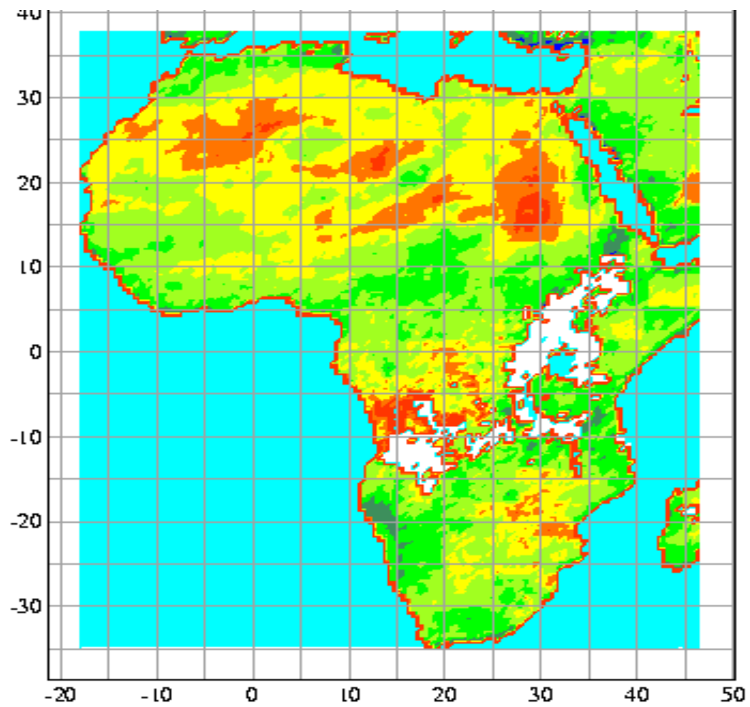
Sensitive to other atmospheric variables (humidity)

Well adapted to desert dust ==>

Complementary to other techniques



Legrand et al., 1989



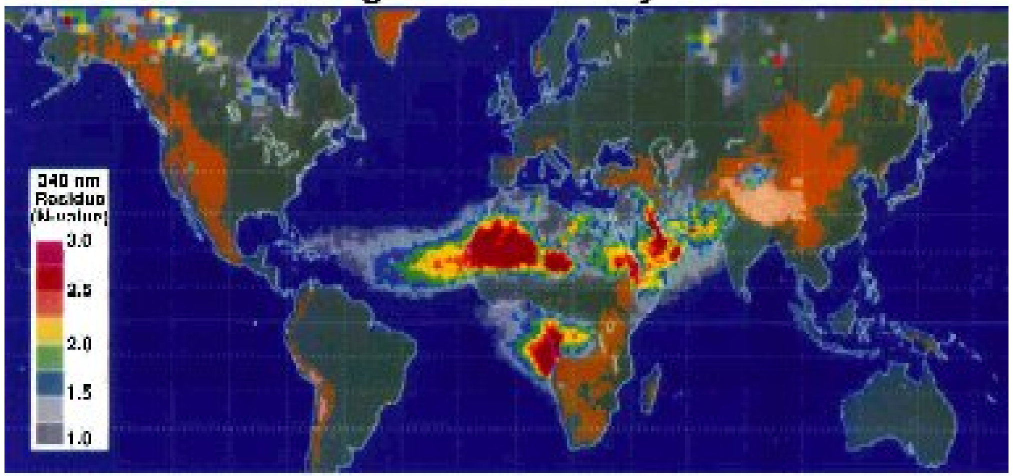
March climatology

UV measurements (TOMS, OMI…)

Making good use of an Ozone monitoring instrument…

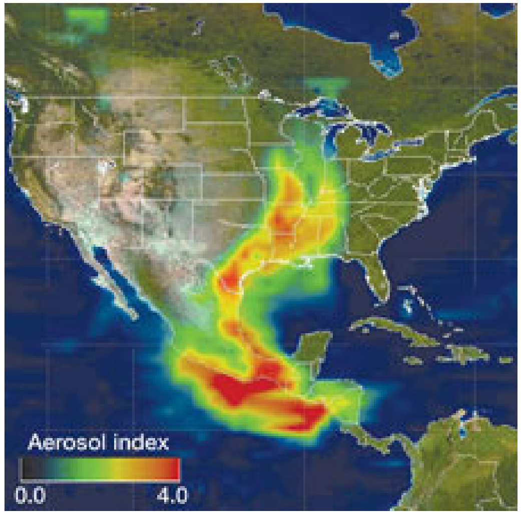
$$AerIndex = Ln\left[\frac{R_{340}}{R_{380}}\right]_{mes} - Ln\left[\frac{R_{340}}{R_{380}}\right]_{mol}$$

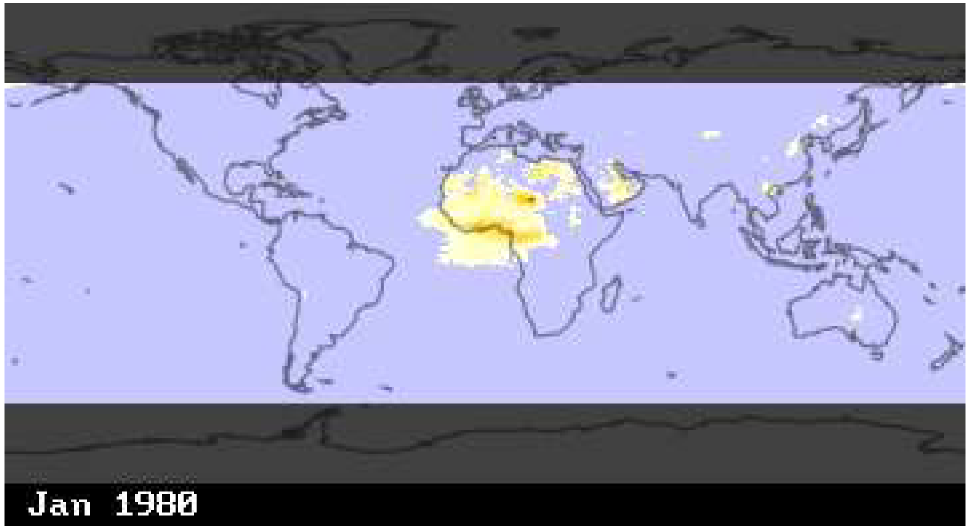
TOMS Absorbing Aerosols - July 1989 and 1990



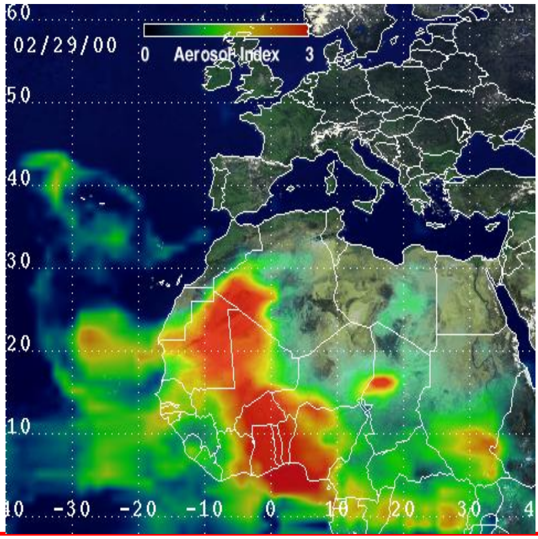
- Spectral signature of reflected radiance in the near-UV (340-380 nm)
- Sensitive to absorbing aerosols (dust, biomass burning)
- Both over ocean and land
- Little constrain on cloud cover => near daily global coverage
- Sensitive to aerosol height and absorption

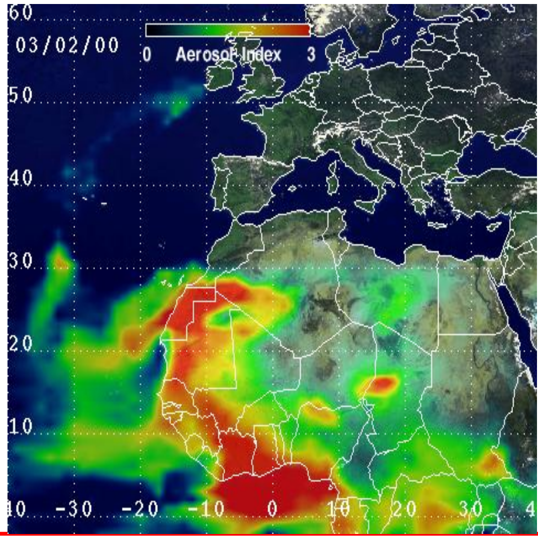
Mid 90s: TOMS (Herman, Hsu, Torres…)

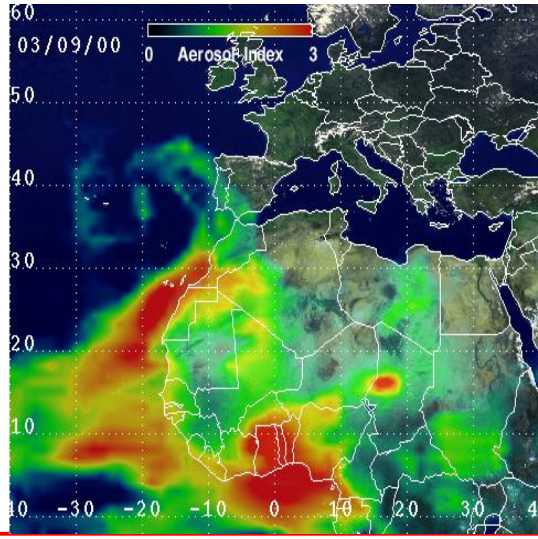




Long time series
Very consistent record



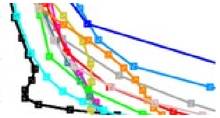




Summary

Technique	Works well for…	Drawback
UV	High aerosol	Insensitive to low aerosol Sens. to aerosol absorption
Spectral signature	Vegetated surfaces	Not over bright surf.
Polarization	Small particles	Large particles
Thermal IR	Dust over desert	Surface variability Atmospheric variability
Multi-Views	All aerosols	Surface BRDF

Characterization, what is lacking ?



Optical thickness and size speciation information of sufficient quality
to validate/constrain transport models

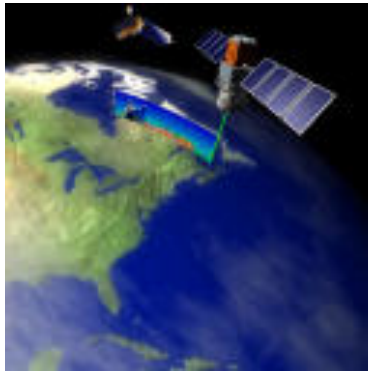
Satellite provide a near direct measurement of the direct radiative
effect at the TOA (over the oceans)

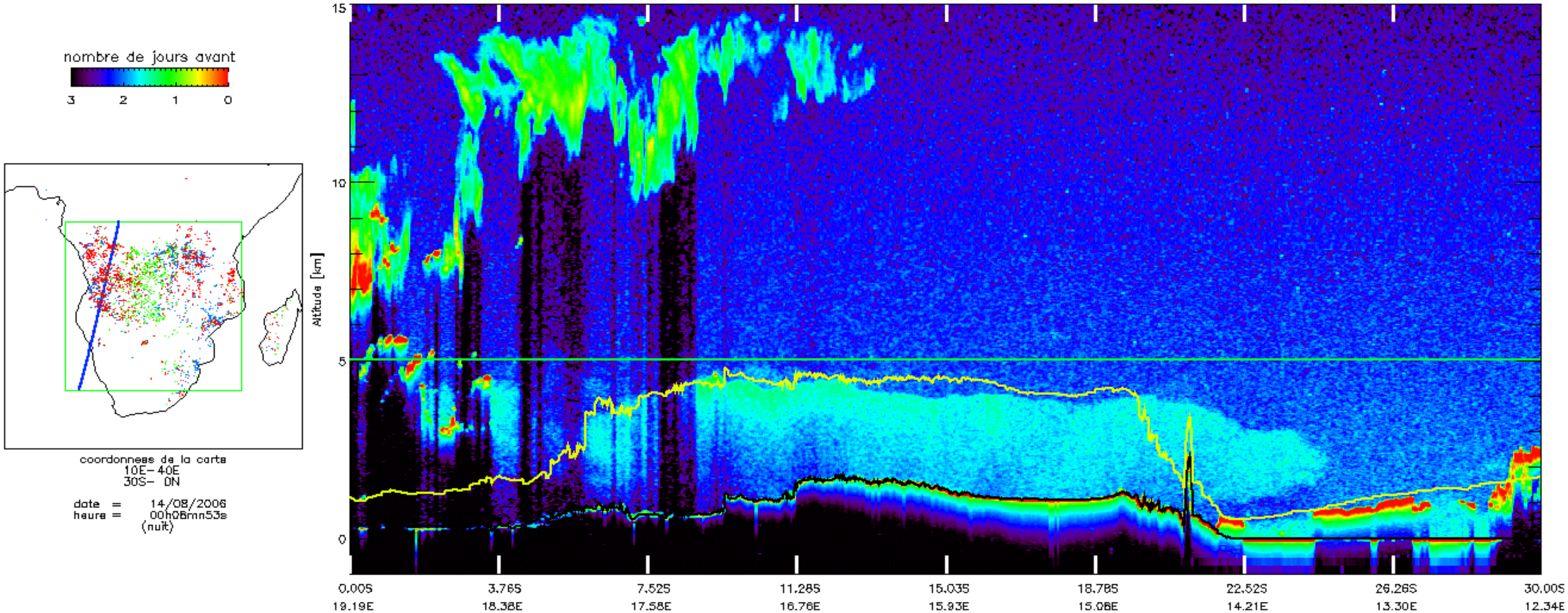
Aerosol absorption (ω_0): Still a matter of debate
Difficult to measure from satellite (a few specific analysis)
Dust absorbs in the blue/UV
Black carbon shows a large absorption at all wavelengths

Aerosol vertical distribution: Almost impossible from passive satellites
but a great asset of active sensing

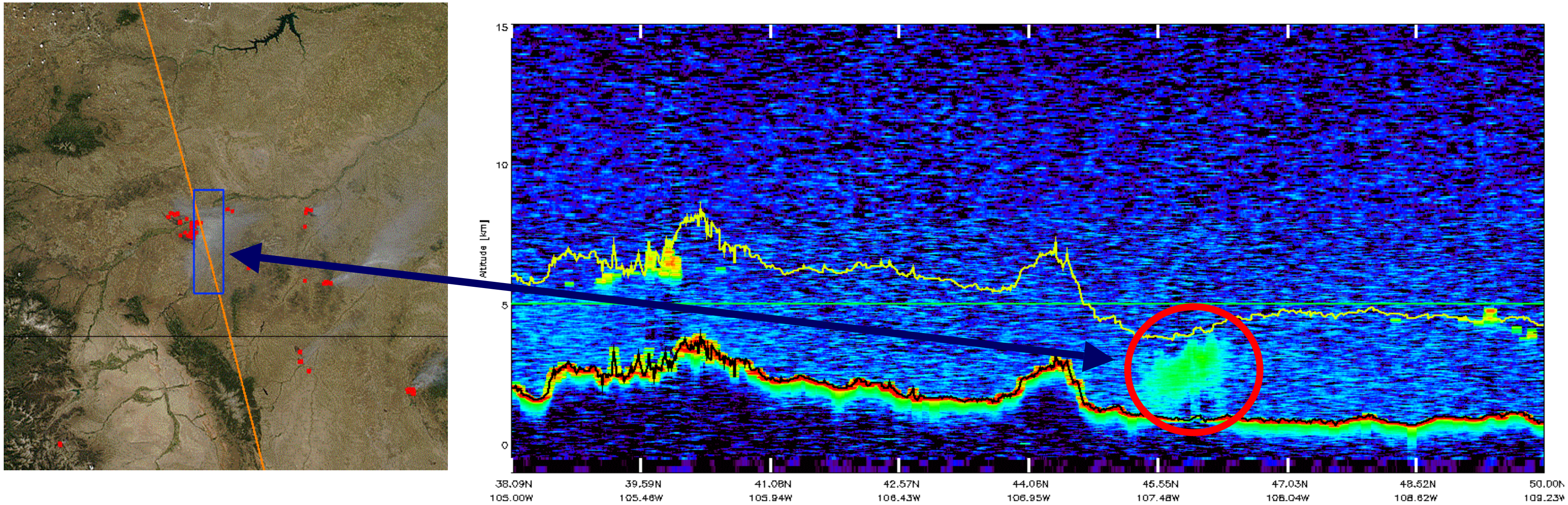
Active Sensing

Active Sensing provide the expected information on aerosol vertical distribution
Calipso (NASA/CNES) was launched in 2006



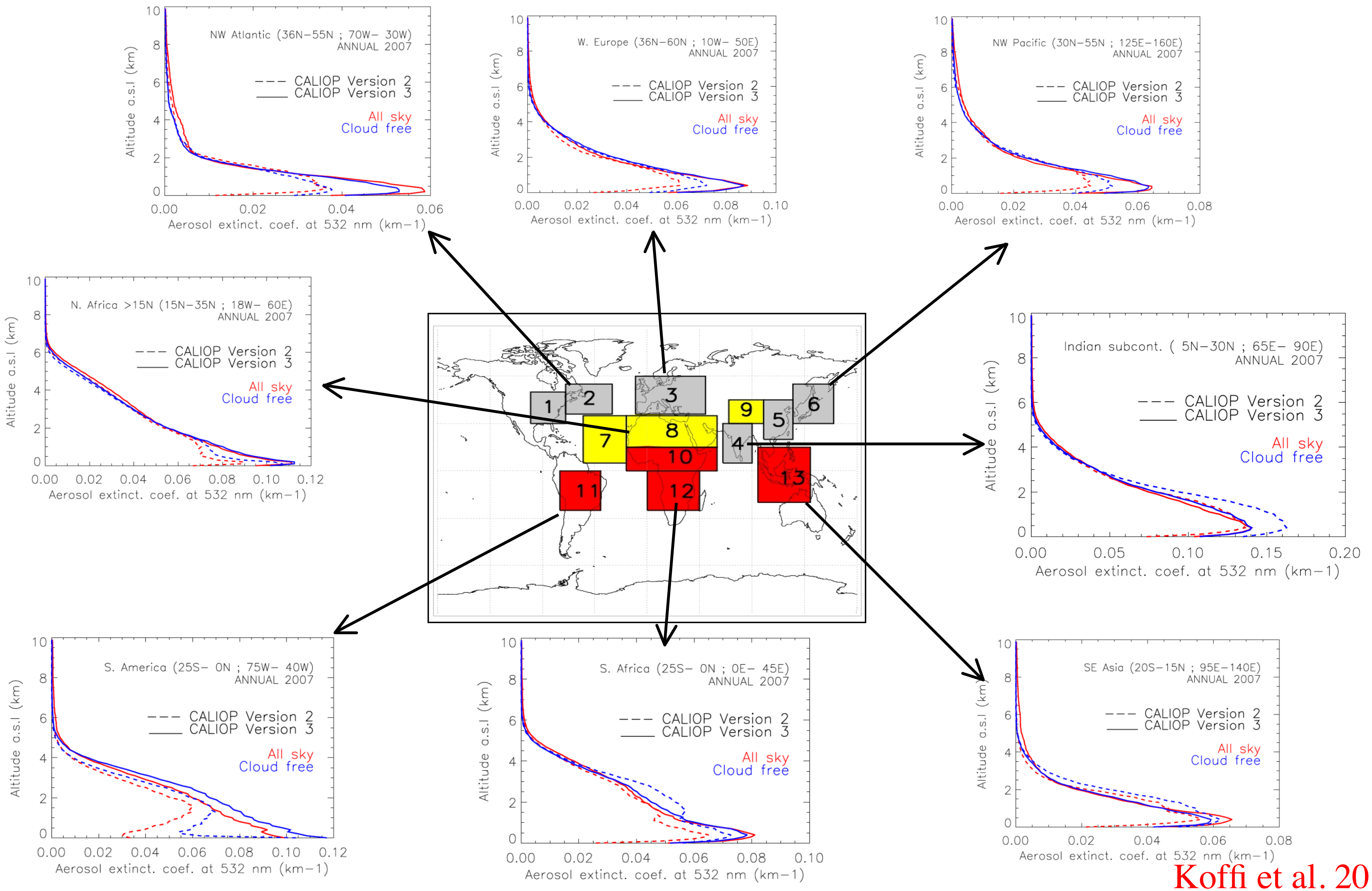


Biomass burning plumes



Calipso is a great tool to observe dense aerosol plumes
Useful in particular for injection height analysis

Mean Vertical Profiles



Koffi et al. 2010

Calipso : pros and cons

Pros

- Only instrument that provides reliable vertical profiles
- Can observe aerosol layers, even in the presence of thick clouds below, and/or thin clouds above
- Provide measurements both day and night

Cons

- Limited information on aerosol model => Uncertainty on extinction to backscatter ratio => Large uncertainty on extinction/optical depth
- Noisy measurements, in particular during daytime
- Some confusion between aerosol and cloud layers
- Limited spatial coverage

Sunphotometer measurements

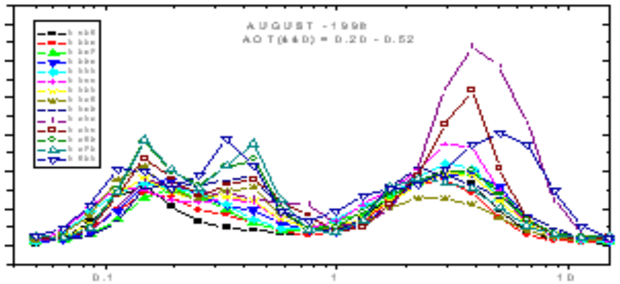
Sunphotometer provide a near-direct measurement of the AOD $\tau(\lambda)$

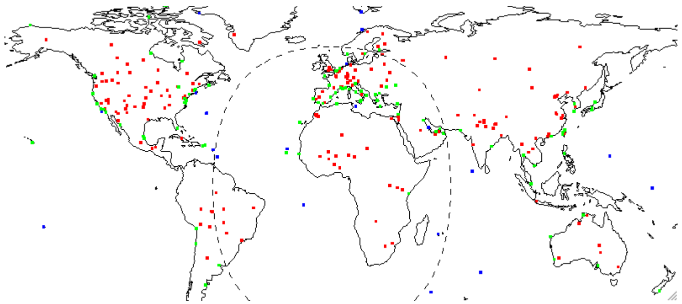
The spectral variation of $\tau(\lambda)$ can be used to derive a Fine Mode and a total AOD with little uncertainty

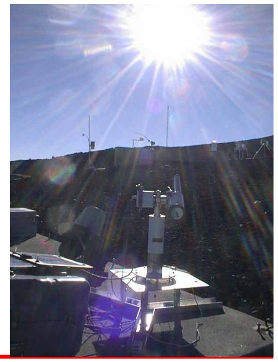
Sky radiance measurements are needed to estimate the size distribution.

Although these size distributions are widely accepted, they are difficult to validate.

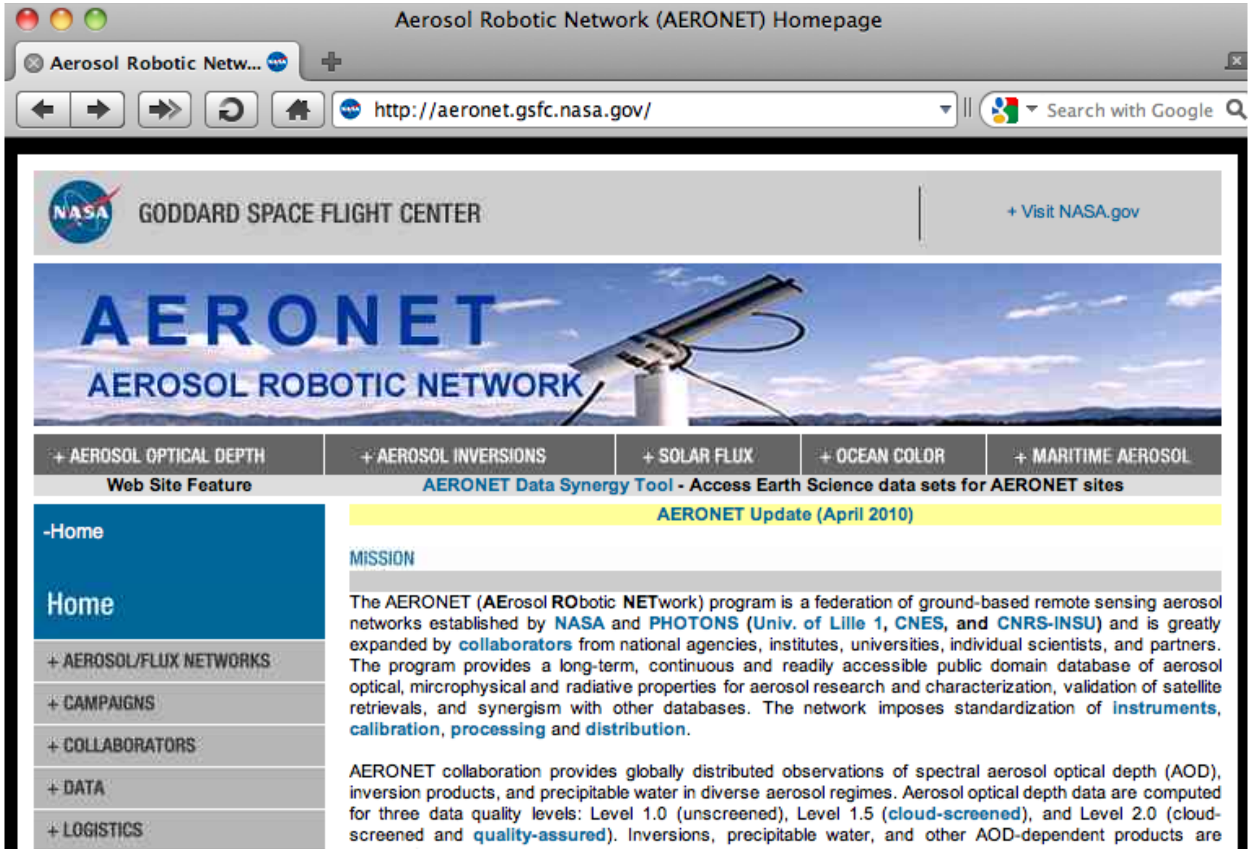
No doubt that the sunphotometer measurements are much more accurate than their satellite-derived counterparts. They can therefore be used for validation







Aeronet

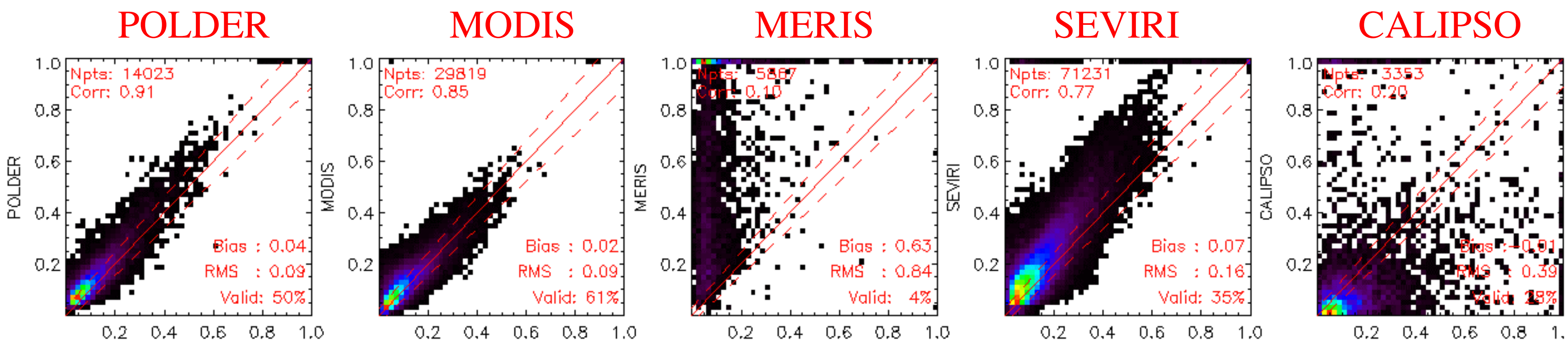


Sunphotomer measurements are standardized and freely accessible through AERONET.

200+ sites

It is an impressive achievement of international collaboration among researchers with the help of funding agencies

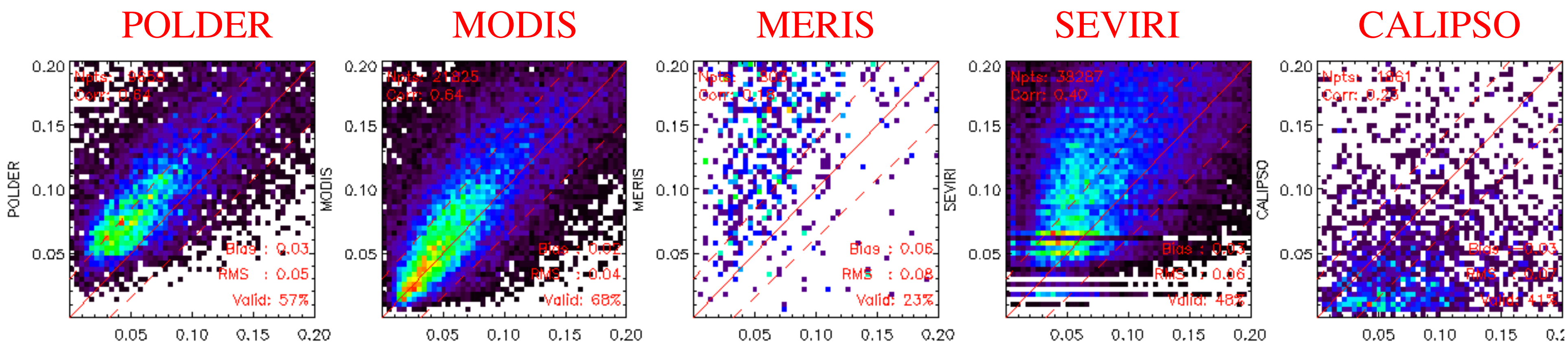
Evaluation. Ocean; Total AOD



POLDER and MODIS provide the best AOD estimates
SEVIRI rather good, with the advantage of much higher temporal resolution
MERIS and CALIPSO AOD of doubtfull value

Correlation ≈ 0.9; RMS ≈ 0.09
≈60% of retrievals within 0.03+0.08 τ
Small (high) bias for POLDER retrievals

Focus on "clean atmospheres"



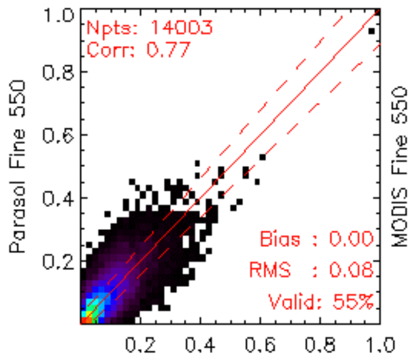
There is clearly a high bias on POLDER/Parasol products for "clean3 atmospheres (τ≈0.05)

Probably a problem in the calibration

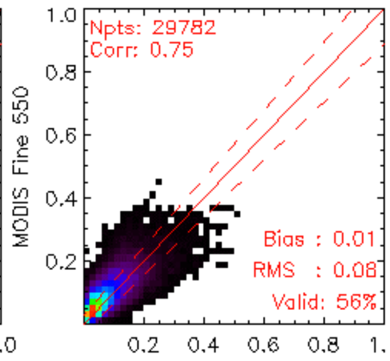
MODIS does not show such bias.

Evaluation. Ocean; Fine Mode AOD

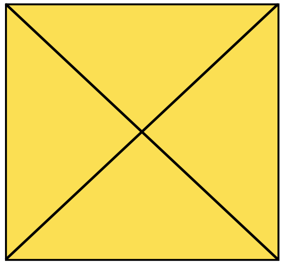
POLDER



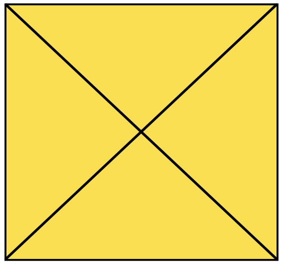
MODIS



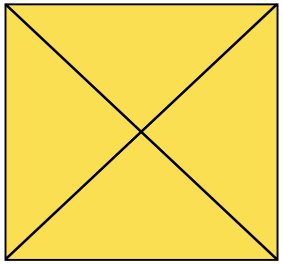
MERIS



SEVIRI



CALIPSO



Only POLDER and MODIS provide this estimate

No bias

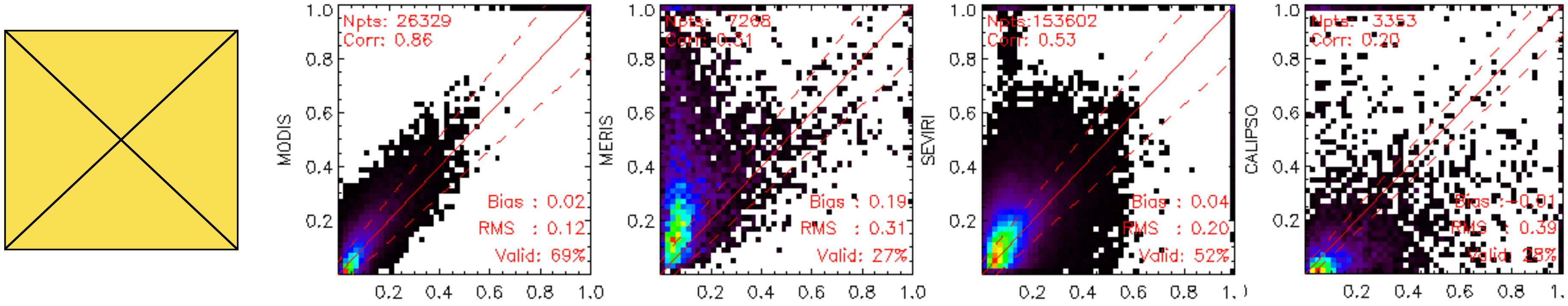
Correlation ≈ 0.75; RMS ≈ 0.08

≈55% of retrievals within 0.03+0.08 τ

There is clearly some information on the distinction between Fine and total AOD

Evaluation. Land; Total AOD

POLDER MODIS MERIS SEVIRI CALIPSO

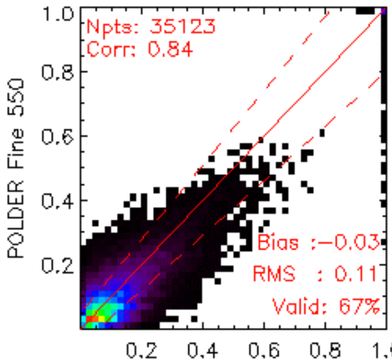


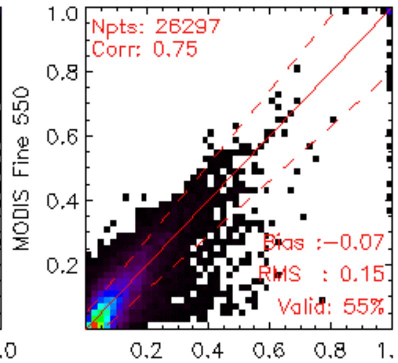
POLDER does not attempt a total AOD estimate
MODIS estimates are clearly better than the others

Correlation ≈ 0.85; RMS ≈ 0.12
≈69% of retrievals within 0.05+0.15 τ

Evaluation. Land; Fine Mode AOD

POLDER | MODIS | MERIS | SEVIRI | CALIPSO





Only POLDER and MODIS provide this estimate

POLDER estimate of the Fine Mode AOD better than that of MODIS
Recent studies have shown that MODIS size discrimination has little value

Correlation ≈ 0.84; RMS ≈ 0.11
≈67% of retrievals within 0.05+0.15 τ

Results suggest to use total AOD from MODIS and Fine Mode AOD from POLDER/Parasol

The importance of Quality Indices

	Land	Ocean
QAC=0	20871/0.808/0.202/45.8	260/0.701/0.587/44.6
QAC=1	17403/0.821/0.191/49.1	19749/0.792/**0.116**/**53.5**
QAC=2	16120/0.843/0.174/53.0	0
QAC=3	23047/**0.903**/**0.126**/**67.9**	5510/**0.829**/0.151/42.5

MODIS

Nobs / Corr / RMS / %good

	Land	Ocean
0≤Q≤0.2	1567/0.112/0.154/52.5	1180/0.508/0.307/29.2
0.2≤Q≤0.4	1736/0.272/0.119/55.5	952/**0.915**/0.110/36.9
0.4≤Q≤0.6	5228/0.370/**0.114**/59.5	2764/0.875/0.115/45.6
0.6≤Q≤0.8	17766/0.678/**0.114**/63.7	6410/0.879/**0.105**/50.3
0.8≤Q≤1.0	18846/**0.882**/0.121/**71.3**	1222/0.886/0.106/**51.6**

POLDER

Analysis of the results indicate that

- Over land, only the “best” QA retrievals should be retained
- Over the oceans, only the “worst” QA retrievals should be removed

Level-2 vs Level-3

Level-2 are aerosol estimates derived from individual satellite passes. Coverage is sparse and irregular

Level-3 are spatial/temporal means. They are generally easier to use.

Can they be trusted ?

To generate significant monthly means, a good temporal coverage is needed, which requires a large swath. This excludes instruments such as ATSR, MISR, or Calipso

In some regions, cloud cover leads to very few measurements during the month.

Bias is possible if cloud cover is correlated with aerosol load.

Choice of Level-2 or Level-3 depends on application, but must consider potential biases

Conclusions

- Not all satellite aerosol products are born equal…
- Over the oceans, I recommend MODIS products, although Parasol could become very compatitive if the bias problem is solved
- Over land, I recommend MODIS product for the total AOD, and Parasol product for the Fine Mode AOD
- Seviri provide usefull estimates over the oceans, with a temporal resolution that can be precious for specific applications
- There is a need to use quality indices as discussed
- Some regions are sampled infrequently [cloud cover] so that the monthly mean may not be representative