Lecture 12. Satellite measurements cont'd

1. Recall from Lecture 11

The net aerosol contribution to the reflected shortwave solar irradiance F_0 is given by

$$L_{aer} \approx \frac{\omega P(\Theta)\pi F_0}{4\pi}\frac{\mu_0}{\mu_0+\mu}[1-e^{-\tau(1/\mu+1/\mu_0)}]+[\frac{(p_s-p_a)L_0}{p_s}+L_s][e^{-(1-w)\tau(1/\mu+1/\mu_0)}-1]$$

where μ_o, μ are the cosine of the solar (χ_0) and satellite (χ_s) zenith angle, respectively, and ω, $P(\Theta)$, τ, p_A is the single scattering albedo, scattering phase function for scattering angle Θ, optical thickness, and atmospheric pressure of the aerosol layer, respectively. The scattering angle is defined as

$$\Theta = \cos^{-1}(-\cos\chi_0\cos\chi + \sin\chi_0\sin\chi\cos\phi)$$

where $\phi = \phi_s - \phi_0$ is the relative azimuth angle

The normalization of L to the solar irradiance F_0, is defined by the path reflectance at TOA and is given by $\rho = \frac{L}{\pi F_0} m(\chi)$ where m is the air mass.

2. Satellite retrieval

Satellite instruments provide global data of aerosol properties daily for many years (up to 3 decades for AVHRR).

Their limitations are

- One snapshot per day
- Column integrated properties
- Sub-pixel cloud contamination
- Sensitivity to forward model parameters assumptions

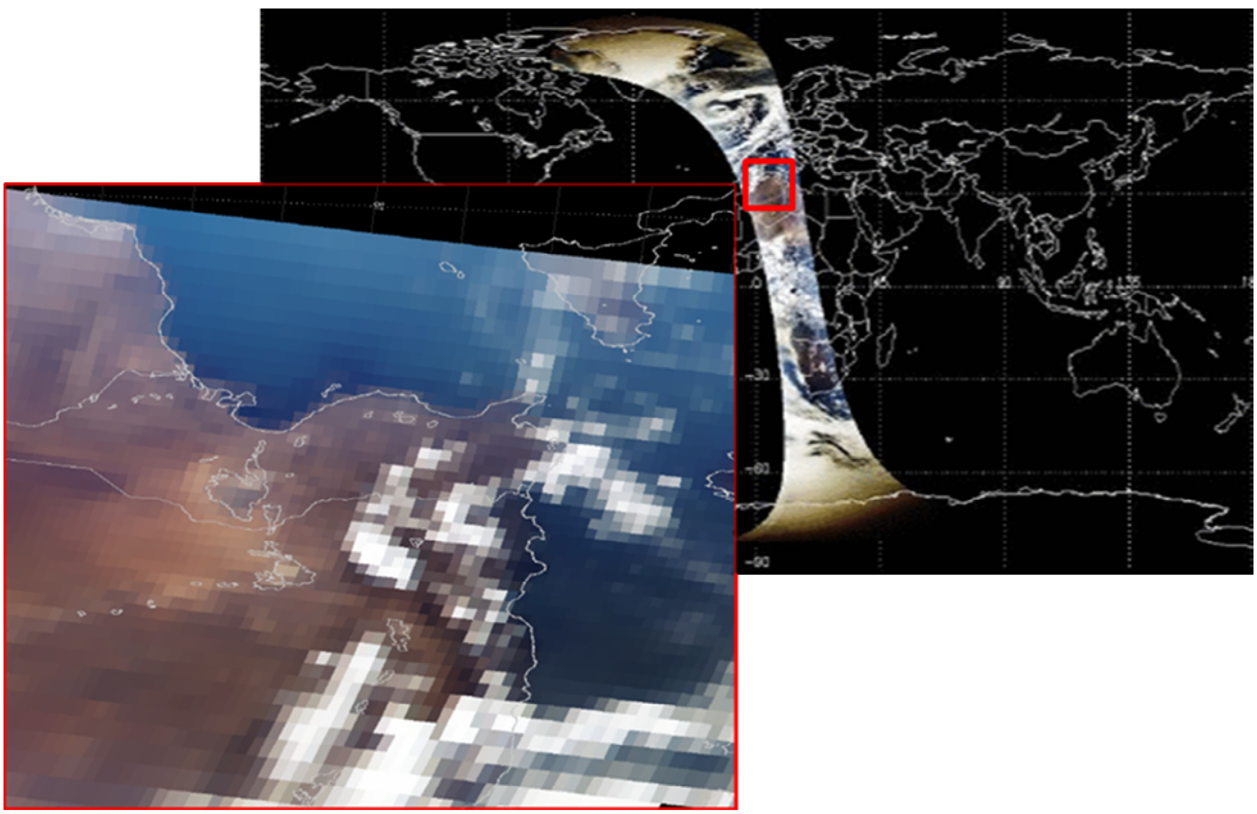
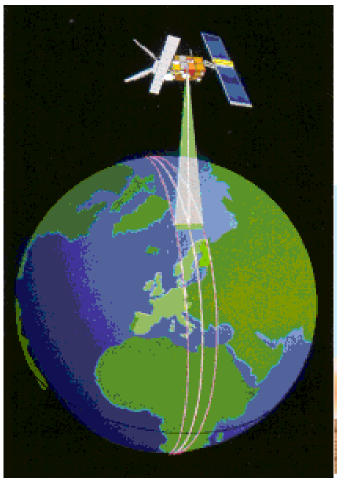
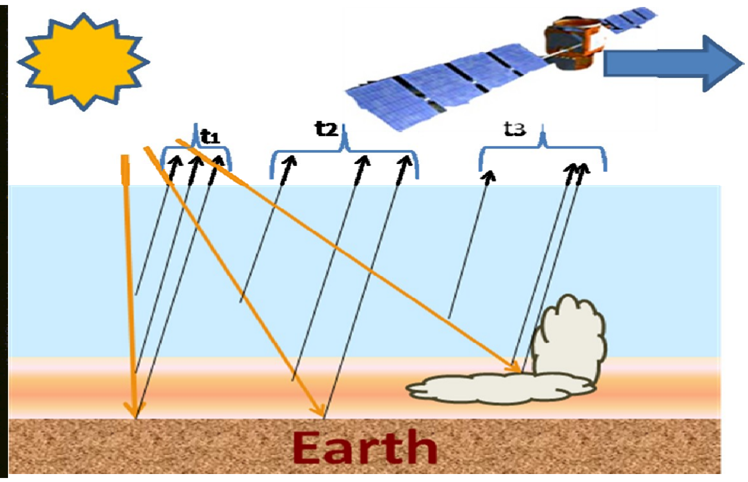


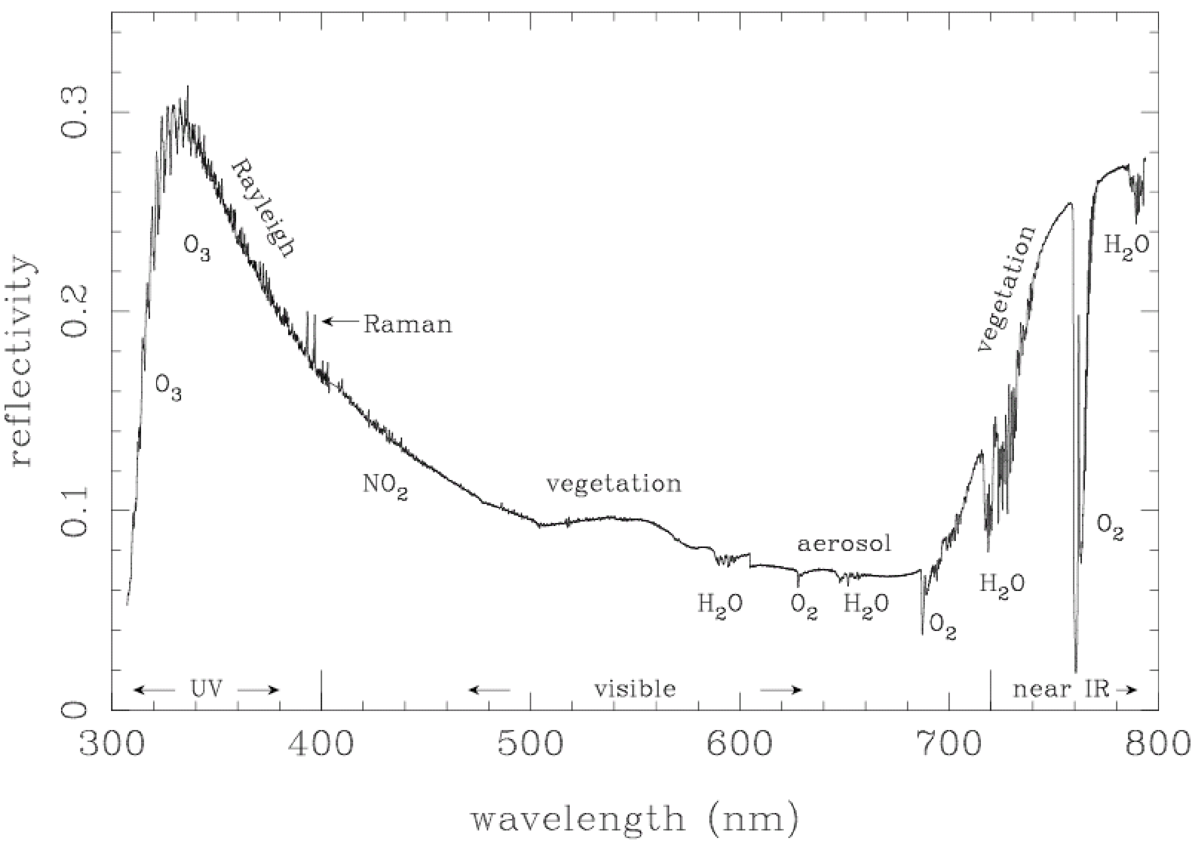
Figure 1 OMI swath and L1 granule over Tunisia (Africa).

Aerosol Retrieval approach

Polar orbiting satellite instrument measures the upwelling or top of the atmosphere (TOA) radiance $L(\lambda)$ at different wavelength in the near-ultraviolet (nUV), visible or near-infrared (nIR).







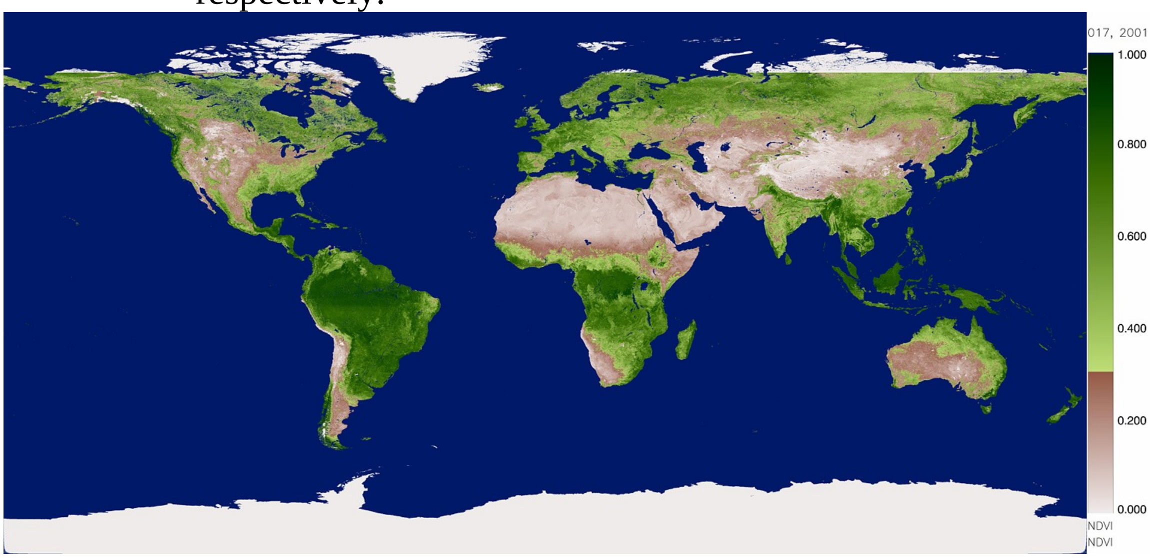
First, the cloudy scenes have to be discarded. This may be done by $L(\lambda) < L_{threshold}$. The retrieval of aerosol optical thickness is based on lookup tables (LUT) describing relationship between the measured $L(\lambda)$ and the aerosol optical thickness $\tau(\lambda)$. This requires an adequate set of Look-Up Table (LUT) taking into account all factors which influence the radiative transfer in the atmosphere:

Viewing angles: $\chi, \chi_0, \phi - \phi_0$

Rayleigh scattering: L_0

Surface reflectance for the different vegetation cover:

$L_s(NDVI)$ where the Normalized Difference Vegetation Index is calculated from the ratio: $NDVI = \frac{\rho_{NIR} - \rho_{VIS}}{\rho_{NIR} + \rho_{VIS}}$ where ρ_{NIR}, ρ_{VIS} are the path reflectance in the near infrared and visible, respectively.



Surface elevation with its surface pressure conditions:

$p(z) = p_0 \times \exp\left[\frac{-2.613\, g\, z}{(T_s - 0.75\, g\, z)}\right]$ where g=9.807 [m.s^{-2}] and z is the height above sea level in km.

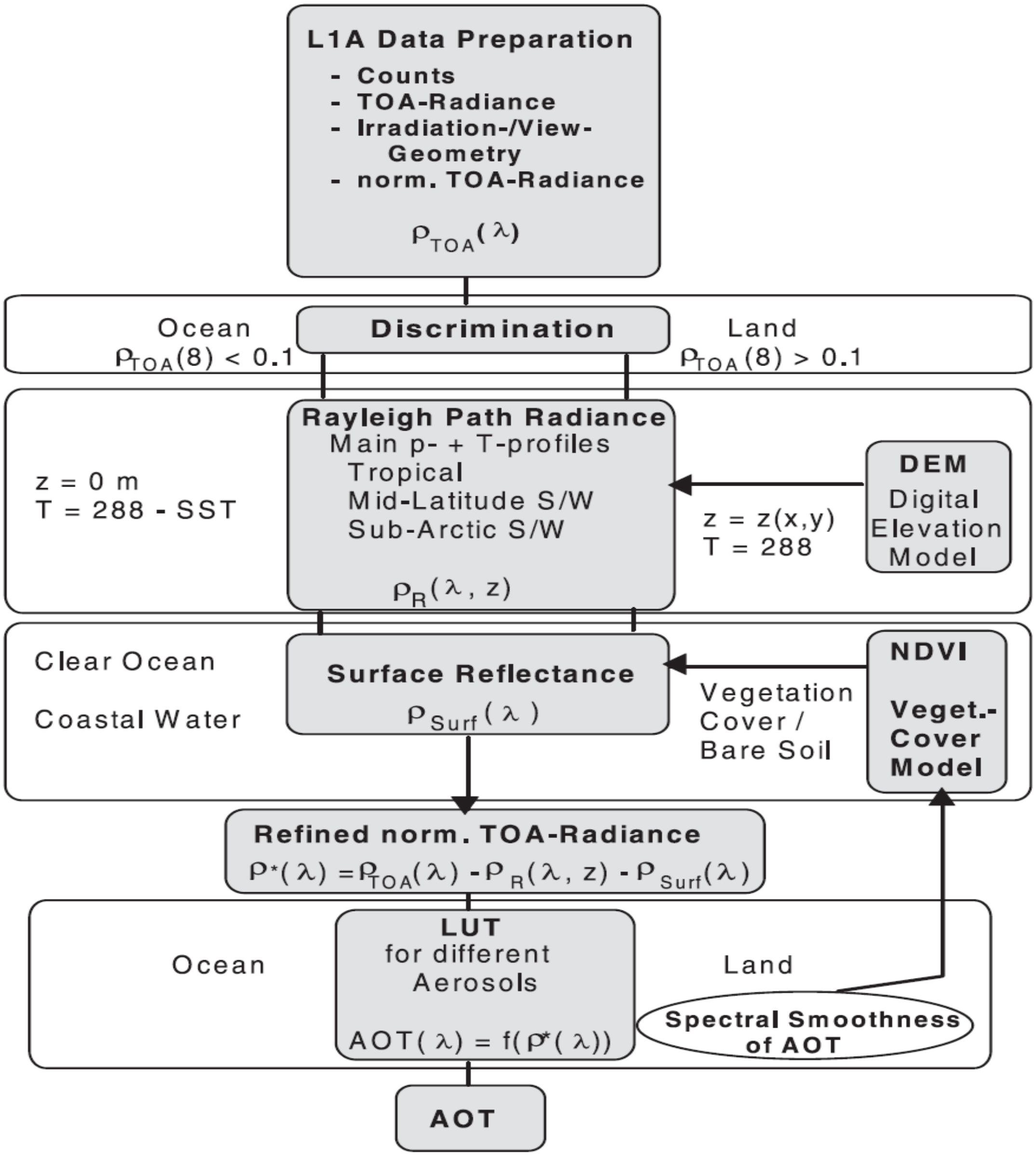
Aerosol parameters:

aerosol phase function: $P(\Theta)$

aerosol optical thickness: τ

aerosol single scattering albedo: ω

The logical flow and mathematical manipulation of the data within retrieval algorithm is described in the following figure:



3. Aerosol retrieval in nUV (TOMS)

In nUV wavelengths (300- 400 nm), the Rayleigh scattering component (L_0) is large and cannot be neglected. On the other hand, the surface reflectance is low and relatively constant with wavelength. Also, in nUV region there is significant sensitivity to aerosol absorption.

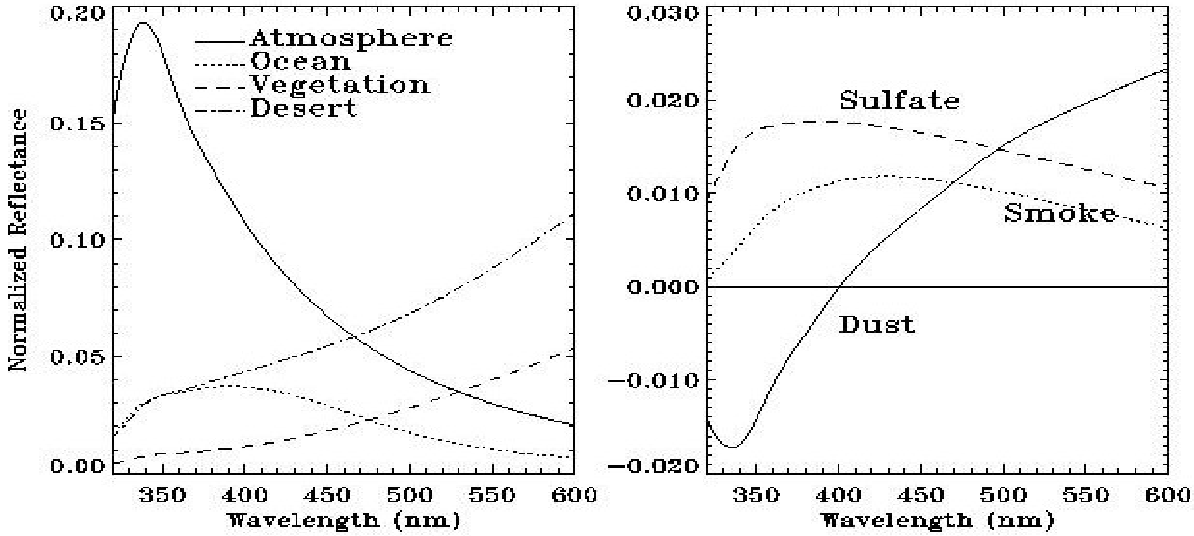


Figure 2 Normalized reflectances

Example of instrument: TOMS (Total Ozone Mapping Spectrometer)

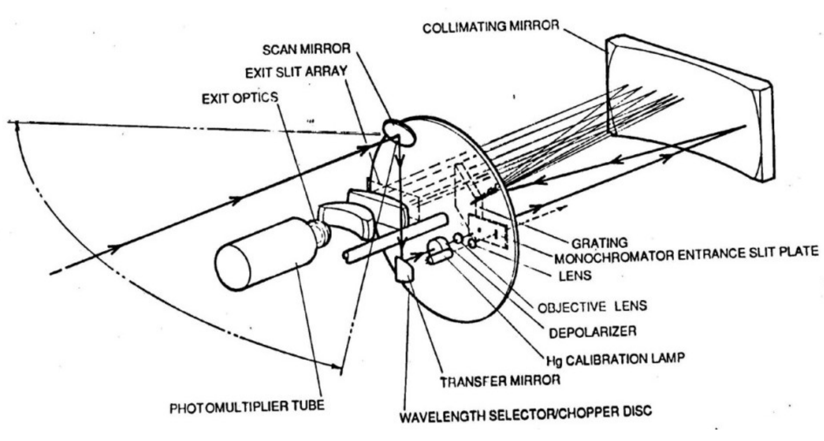


Figure 3 TOMS instrument

INSTRUMENT: Measures backscattered near UV radiation at six 1 nm bands between 312 and 380nm. It was designed to measure the atmospheric ozone content, but because of its characteristics is also well suited to measure column SO_2 and absorbing aerosols.

PLATFORMS: The TOMS instrument has been launched five times and operated on 4 platforms (+1 project has operated four instruments:

1. Nimbus7, October 1978 - April 1993
2. Meteor3, August 1991 - December 1994
3. Earth-Probe, June 1996 - present
4. ADEOS, September 1996 – June1997
5. QuikTOMS, lost during ascension to orbit in 2001

ORBIT: Polar orbit (11:30 AM equator crossing time)

SCANNING: Cross-track scanning capability, 2400 km swath

RESOLUTION: Nominal nadir ground resolution is 50km

TOMS retrieval algorithmof aerosol optical thickness and single scattering albedo.

- The aerosol backscattered radiances at two wavelength are used to retrieve aerosol optical thickness and single scattering albedo at one wavelength for cloud free pixels (L_s<25%).
- The average properties of eight aerosol models (1 sulfate, 3 carbonaceous, 4 dust) are fed into a Mie code, resulting in values of extinction efficiency and single scattering albedo at 380nm.
- LUT: a radiative transfer code is used to fill up a LUT with pre-calculated radiances at TOA as a function of
    - Aerosol models =8
    - ω_{380}=0.79, 0.82, 0.86, 0.9, 0.945, 0.7
    - A_g=0, 2, 4, 8, 12, 20, 40, 60, 80 %
    - τ_{380} = 0, 0.1, 0.5, 1, 2.5, 4 (7 values)
    - χ_0=0, 20,40,60,80 (5 values)
    - χ_s = 0 to 70 (16 values)
    - $\phi - \phi_0$ =0, 30, 60, 90, 120, 150, 180 (12 values)
    - Z_a=1.5, 3, 6 km (3 values)
- For one aerosol model and surface reflectivity (based on location of pixel over the globe), one viewing geometry, extract from LUT the single scattering albedo and optical thickness for the set of I_{380} and I_{340}/I_{380} values. The altitude of the aerosol layer as to be determined from independent dataset (generally transport model)

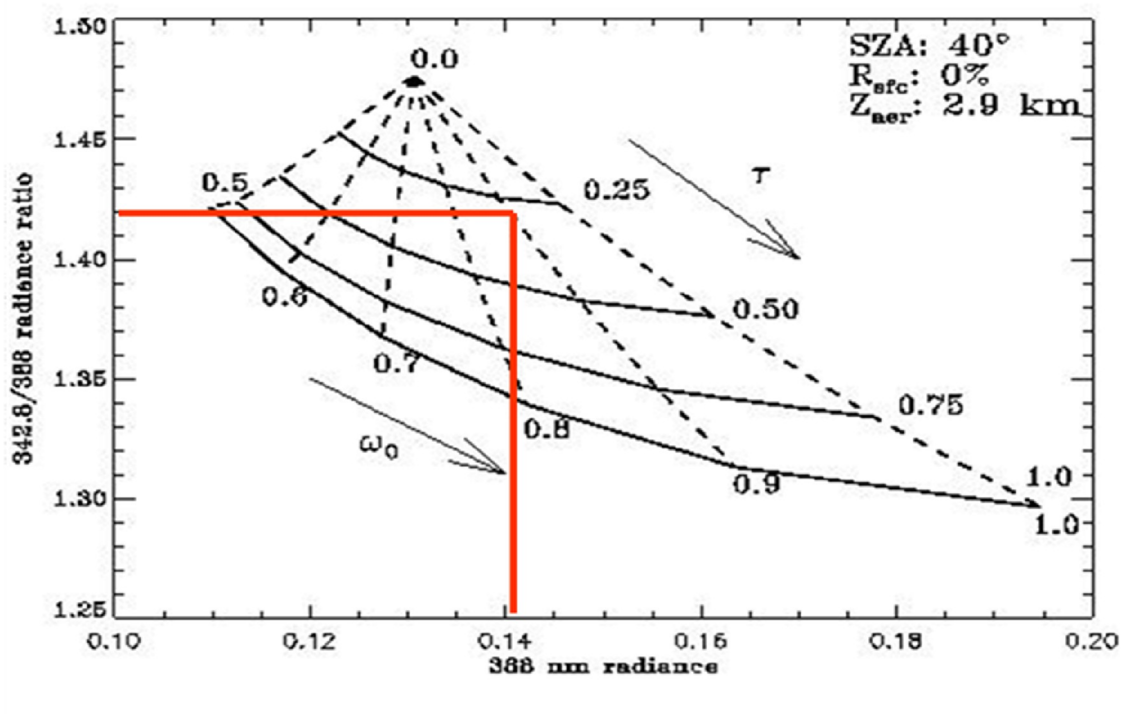


Figure 4 Example of retrieval of single scattering albedo and optical depth at 380 nm from measured radiances at 340 and 380 nm.

Long-term record on aerosol optical depth

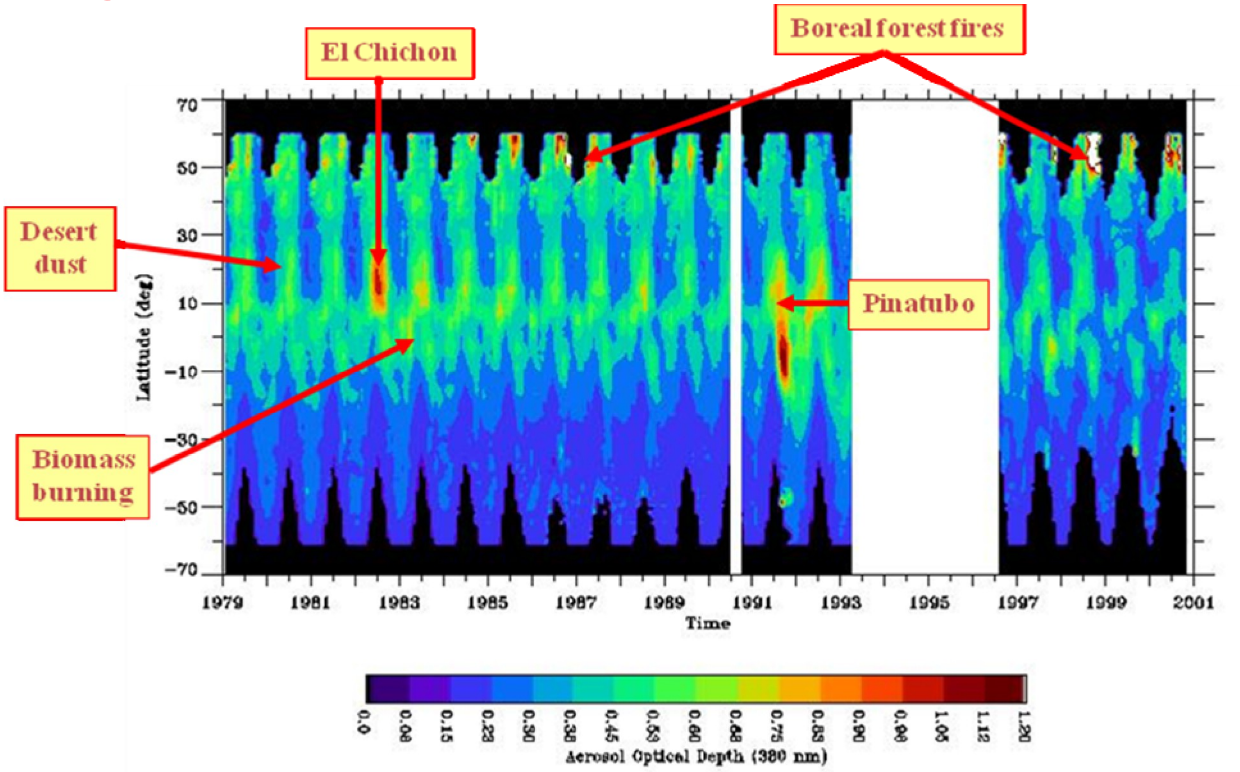


Figure 5. Zonal mean monthly aerosol optical depth at 380nm retrieved from TOMS radiances.

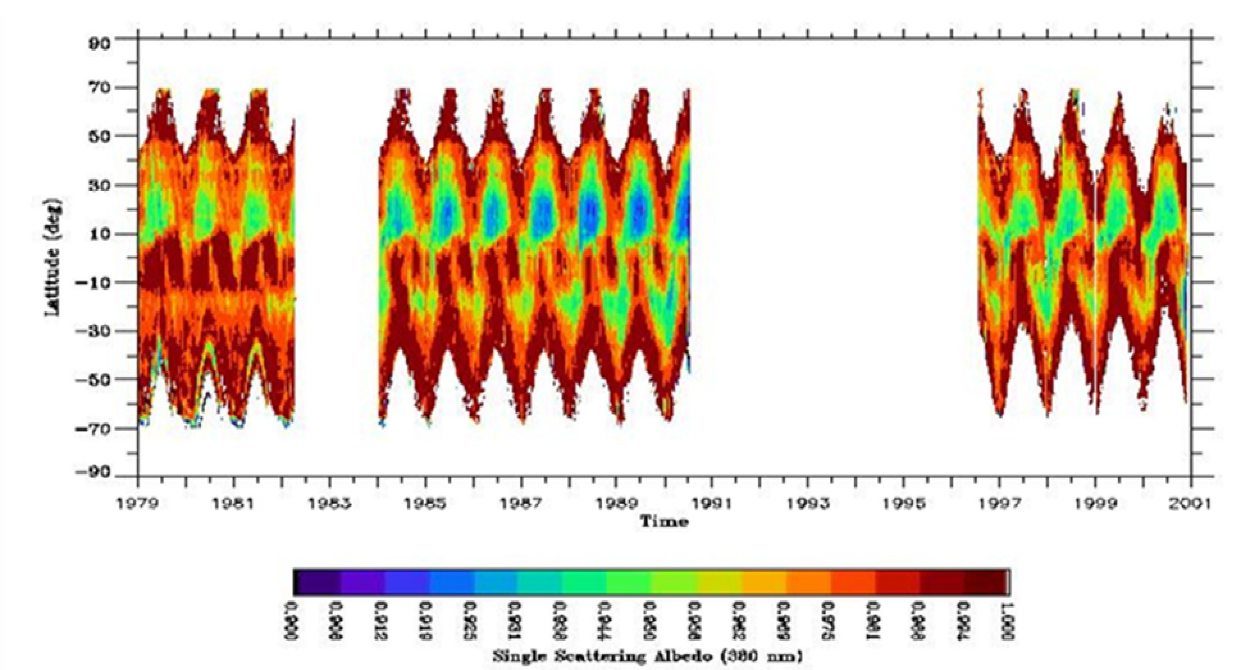
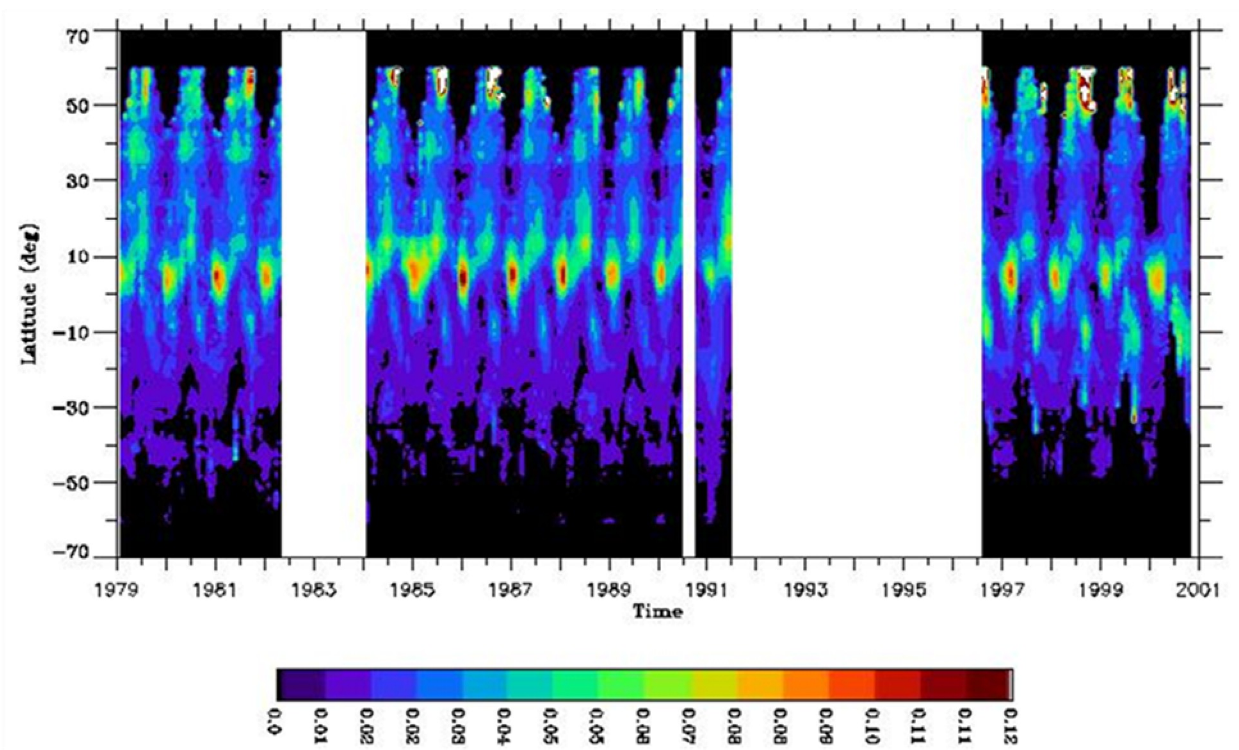


Figure 6. Zonal mean monthly single scattering albedo at 380 nm retrieved from TOMS radiances.

Global multi-year record of aerosol absorption optical depth



TOMS V7 Residue Definition

By taking the difference between the measured and calculated radiances for a purely molecular atmosphere, Herman et al. [1997] defined the TOMS Aerosol Index (TOMS AI) as follow

$$AI = -100\left\{\log_{10}\left(\frac{I_m(\lambda)}{I_m(380nm)}\right) - \log_{10}\left(\frac{I_c(\lambda)}{I_c(380nm)}\right)\right\}$$

where I_m is the backscattering radiance measured by TOMS at the wavelength λ and I_c is the calculated radiance using a radiative transfer model for a pure Rayleigh atmosphere.

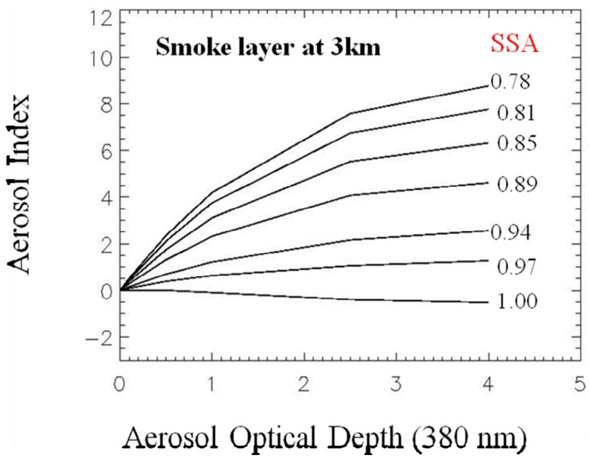
1.1. Aerosol Index Properties

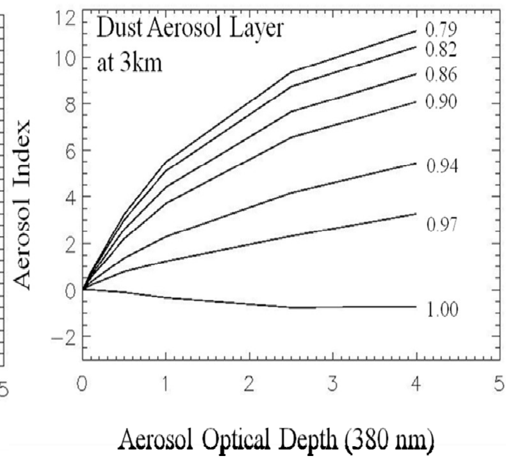
- Clearly separates between absorbing (smoke, desert dust, and ash) and non-absorbing aerosols.
- Insensitive to clouds.
- Detects absorbing aerosols over all terrestrial surfaces including ice and snow.

- Detects absorbing aerosols above cloud decks.
- AI magnitude depends on aerosol height, aerosol optical depth and microphysical properties

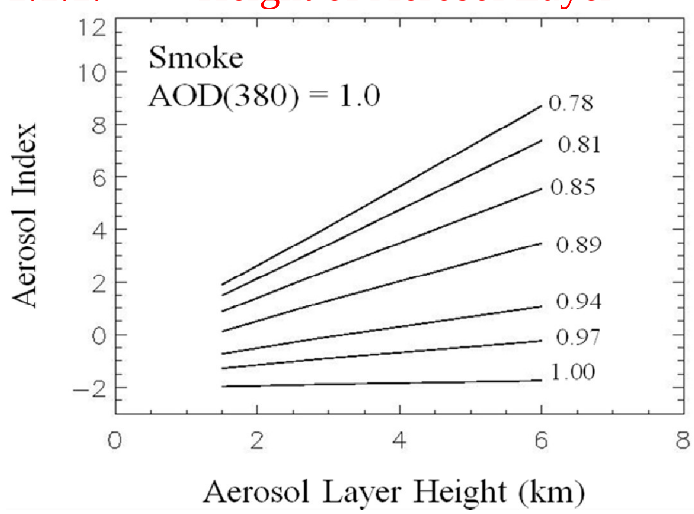
1.1. Sensitivity of TOMS AI

1.1.1. Aerosol Optical Depth and Single Scattering Albedo





1.1.1. Height of Aerosol Layer

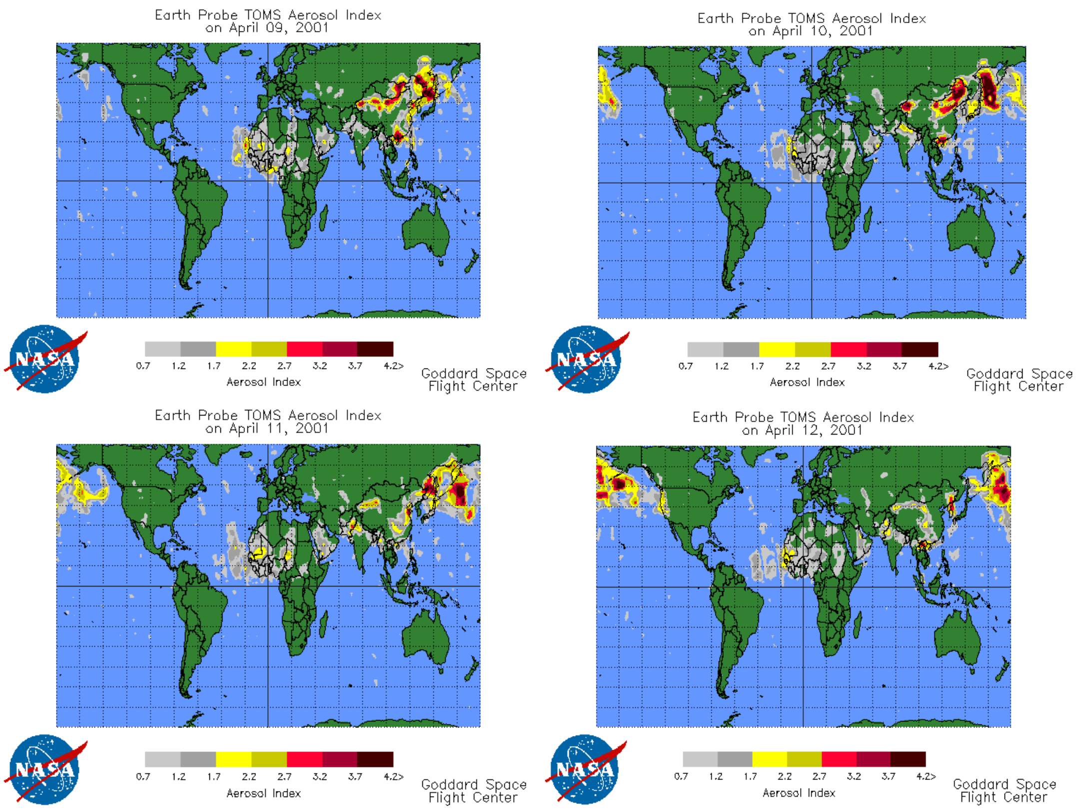


1.1. Parameterization of TOMS AI

$$AI \approx \{1 - 0.2\log_{10}(p_s)\}[1.25 + 5(1 - \omega_{380})h](\tau_{380})^{\omega_{380}}$$

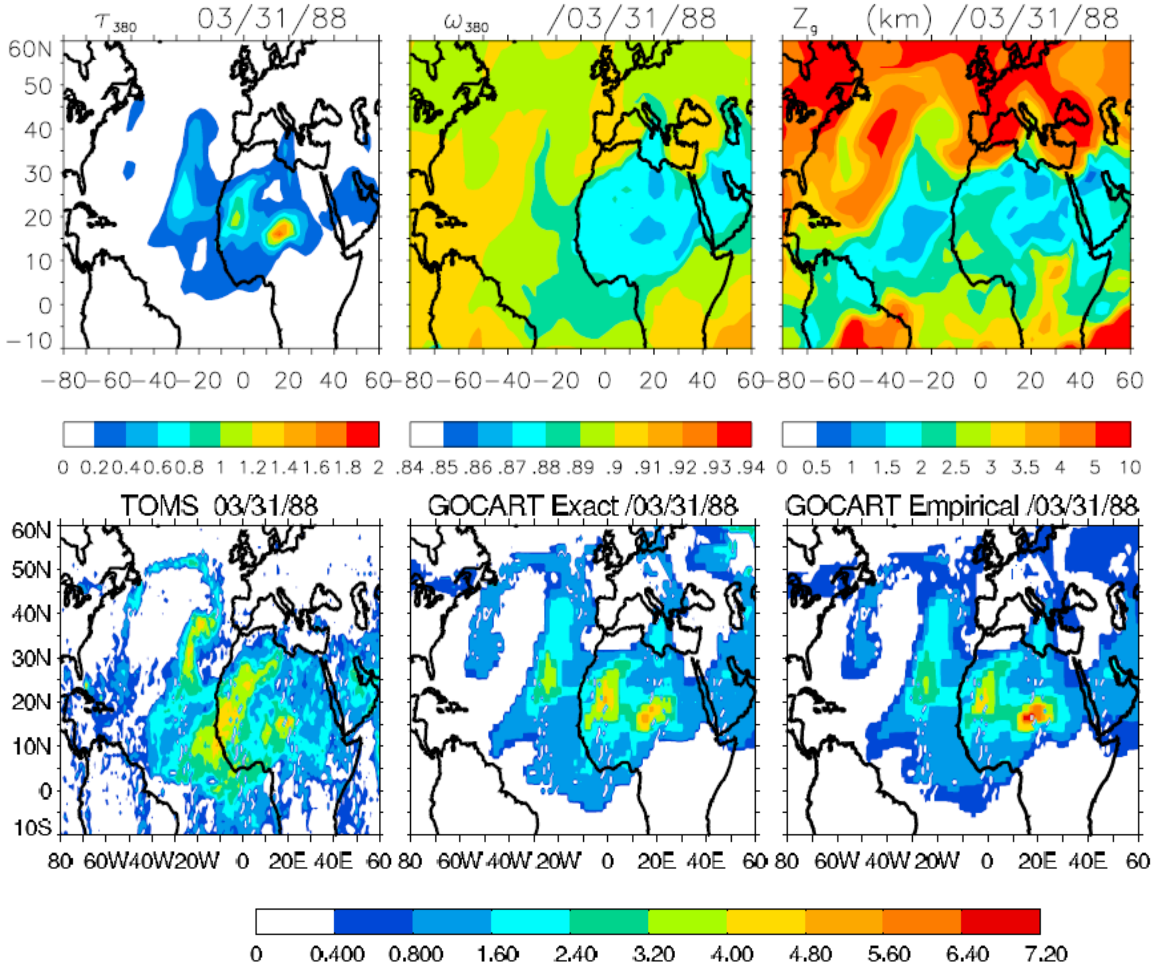
where p_s is the surface pressure [atm], ω_{380} is the single scattering albedo at 380 nm, τ_{380} is the optical thickness at 380 nm, and h is the altitude of the aerosol layer.

1.2. Application 1: Following the evolution of a dust plume out of East Asia



2. **Figure 7 Daily evolution of dust plume moving from East Asia to North America during ACE-Asia field campaign (April 2001), as seen by TOMS AI.**

2.1. Application 2: Model evaluation



http://www.gfdl.noaa.gov/reference/bibliography/2003/pag0301.pdf

1.3. New definition for V8

TOMS aerosol detection capability was discovered when the ‘residue’ concept was introduced in the Total Ozone Algorithm

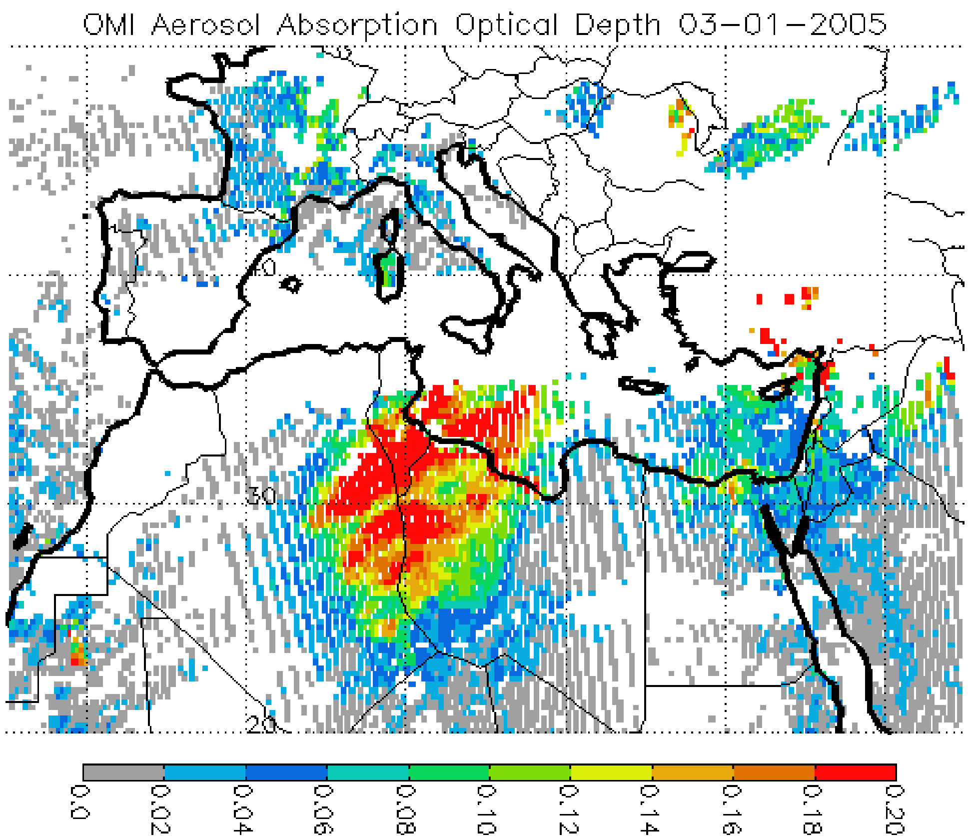
$$r_\lambda = -100\ [\log\ (\frac{L_\lambda}{L_{331}})_{meas} - \log\ (\frac{L_\lambda}{L_{331}})_{calc}]$$

1.4. OMI: New TOMS-like instrument with higher spectral and spatial resolution

Developed by the Netherlands Space Agency (NIVR) and the Finnish Meteorological Institute (FNMI)

Hyper-spectral Sensor: UV1 270-314 nm, UV2 306-380 nm, VIS 350-500 nm

Data Products: Total Ozone, Aerosol Optical Depth, Aerosol single scattering albedo, NO_2, SO_2, Tropospheric Ozone, Other trace gases.



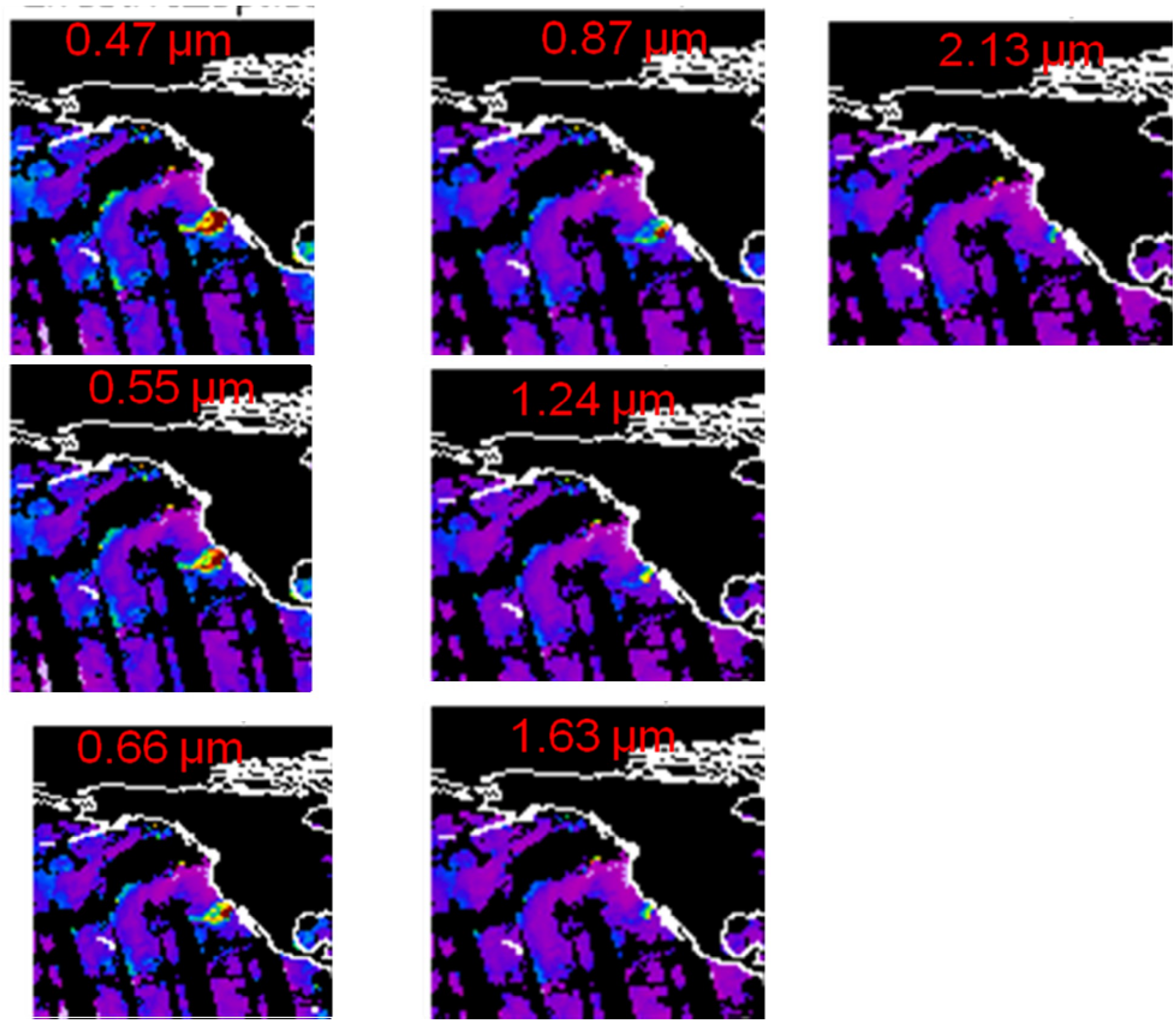
4. Aerosol retrieval in visible (MODIS)

In the visible, the surface component of the measured reflectance is as large as the aerosol part.

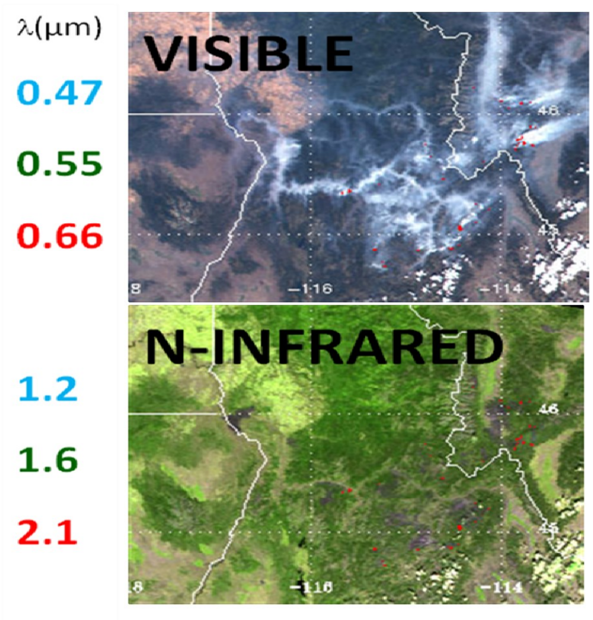
Band	Bandwith (μm)	Central Wavelength (μm)	Spatial Resolution (m)	Rayleigh Optical depth
1	0.620-0.670	0.646	250	0.0520
2	0.841-0.876	0.855	250	0.0165
3	0.459-0.479	0.466	500	0.1948
4	0.545-0.565	0.553	500	0.0963
5	1.230-1.250	1.243	500	0.0037
6	1.628-1.652	1.632	500	0.0012
7	2.105-2.155	2.119	500	0.0004

Removing Rayleigh scattering

Observed reflectance at 7 wavelengths over Ocean



Observed reflectances at 6 wavelength over land



MODIS V5.1 (Collection 4) APPROXIMATION OVER LAND:

- Aerosols are almost transparent in the near-infrared $\tau_{aer}(2.2\mu m) \approx 0$ (Are they?!)
- The surface reflection is brighter at 2.2 μm than in the visible, therefore the aerosol effect is negligible at 2.2 μm. Constant ratio between $\rho_{2.2}$ and ρ_{550}, ρ_{670} are established: $\rho_{670} = 0.5\rho_{2200}$ and $\rho = 0.25\rho_{2200}$ for pixels where $\rho_{2.2}$<0.25

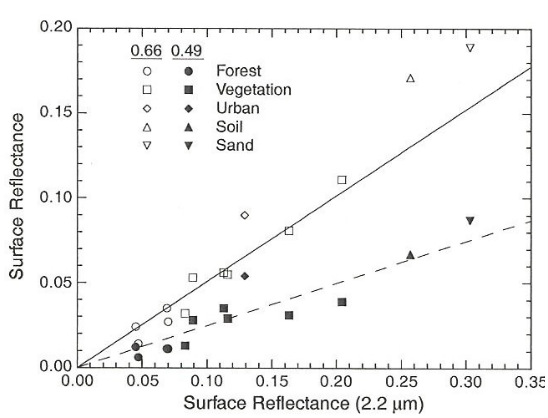
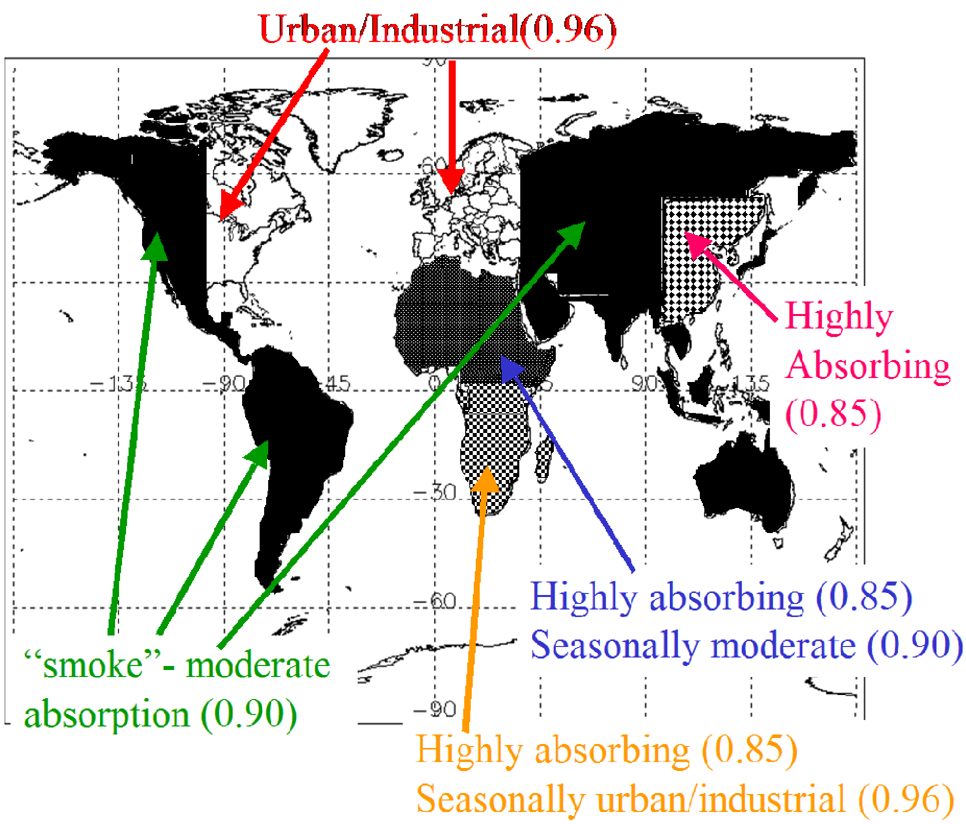


Figure 8 Surface reflectances at 670 nm and 500 nm as a function of the reflectance at 2200nm.

- The average properties of nine aerosol models (4 fine modes and 5 coarse modes) are fed into a Mie code, resulting in scattering/extinction properties. From these properties, the spectral dependence of τ and $P(\Theta)$ are calculated
- LUT: a radiative transfer code is used to fill up a LUT with pre-calculated radiances at TOA as a function of
  - Aerosol models = 9
  - τ = 0, 0.25, 0.5, 1, 2, 3, 5 (7 values)
  - χ_0=0, 6, 12, 24, 36, 48, 54, 60, 66 (9 values)
  - χ_s = 0 to 66 (16 values)
  - $\phi - \phi_0$ =0 to 180 (12 values)
- Choice of 4 fine modes and 5 coarse modes are used to minimize $\varepsilon = (\rho_{meas} - \rho_{LUT})$ over 6 wavelengths as function of location



INVERSION PROCEDURE:

The technique consists to find the aerosol model which provides the best fit between the measured 6 reflectance and the calculated values given the viewing angles.

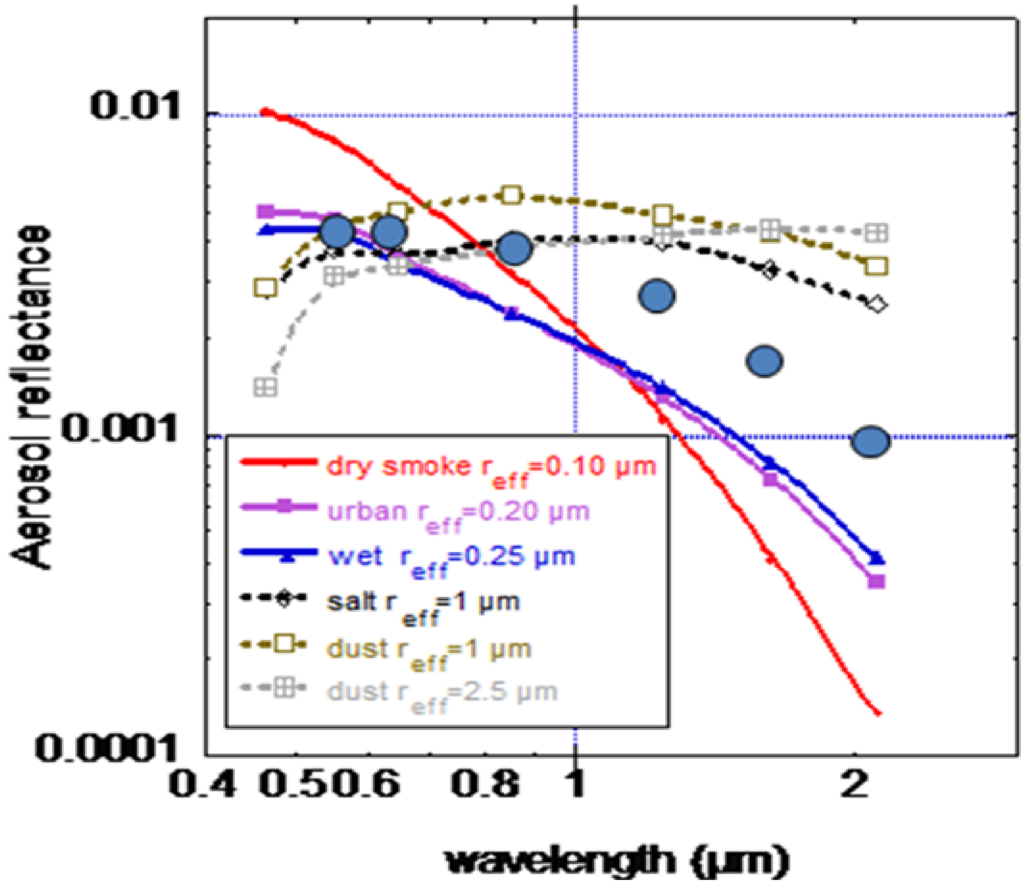


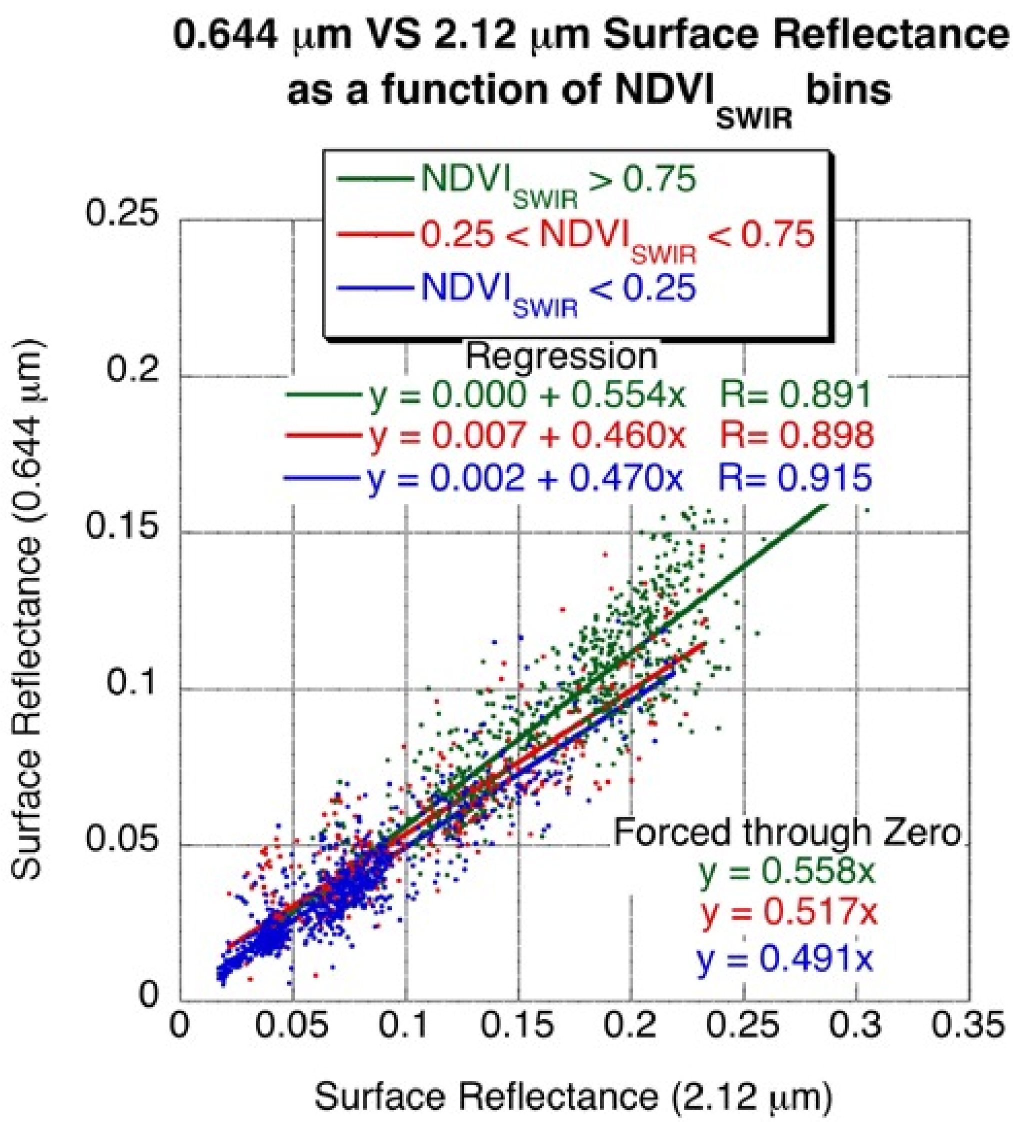
Figure 9 Example of inversion of 6 reflectances measured by MODIS with different values calculated for different aerosol models.

MODIS V5.2 (C005) APPROXIMATION

There are many improvements between V5.1 and V5.2 which are presented in great details by Levy et al., *Second generation operational algorithm: Retrieve of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance, J.Geophys. Res., v 112,* D13211, doi:10.1029/2006JD007811, 2007.

Improvements:

- Observed reflectance at 2.2 μm contains information of both surface and aerosol
- Surface reflectance as a function of NDVI



COMPARISON WITH AERONET