Aerosol Remote Sensing

ACAM Training School

Asian Institute of Technology, Bangkok 11-12 June 2015

Ritesh Gautam

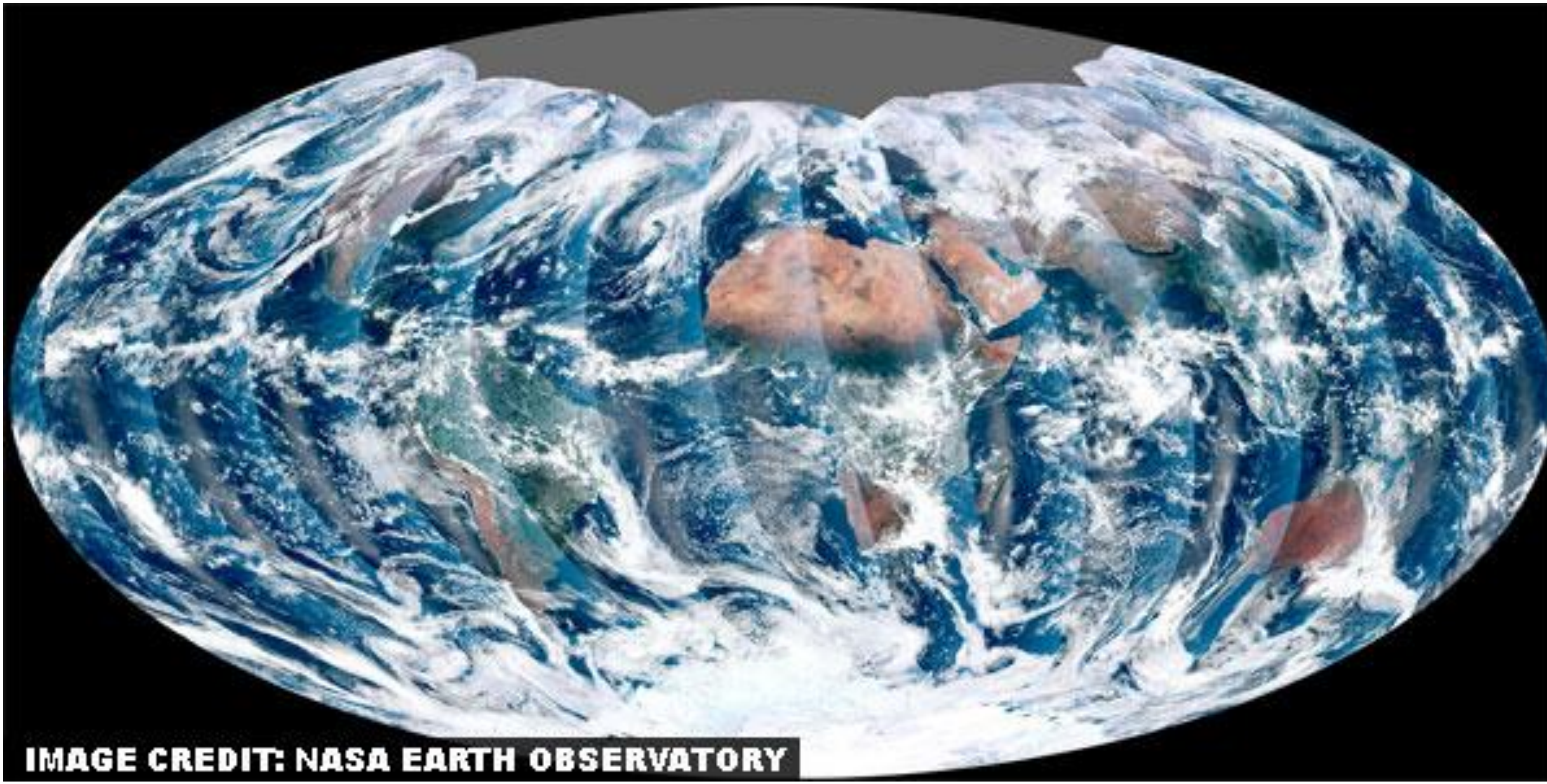
Centre of Studies in Resources Engineering

Interdisciplinary Program in Climate Studies

Indian Institute of Technology (IIT) Bombay

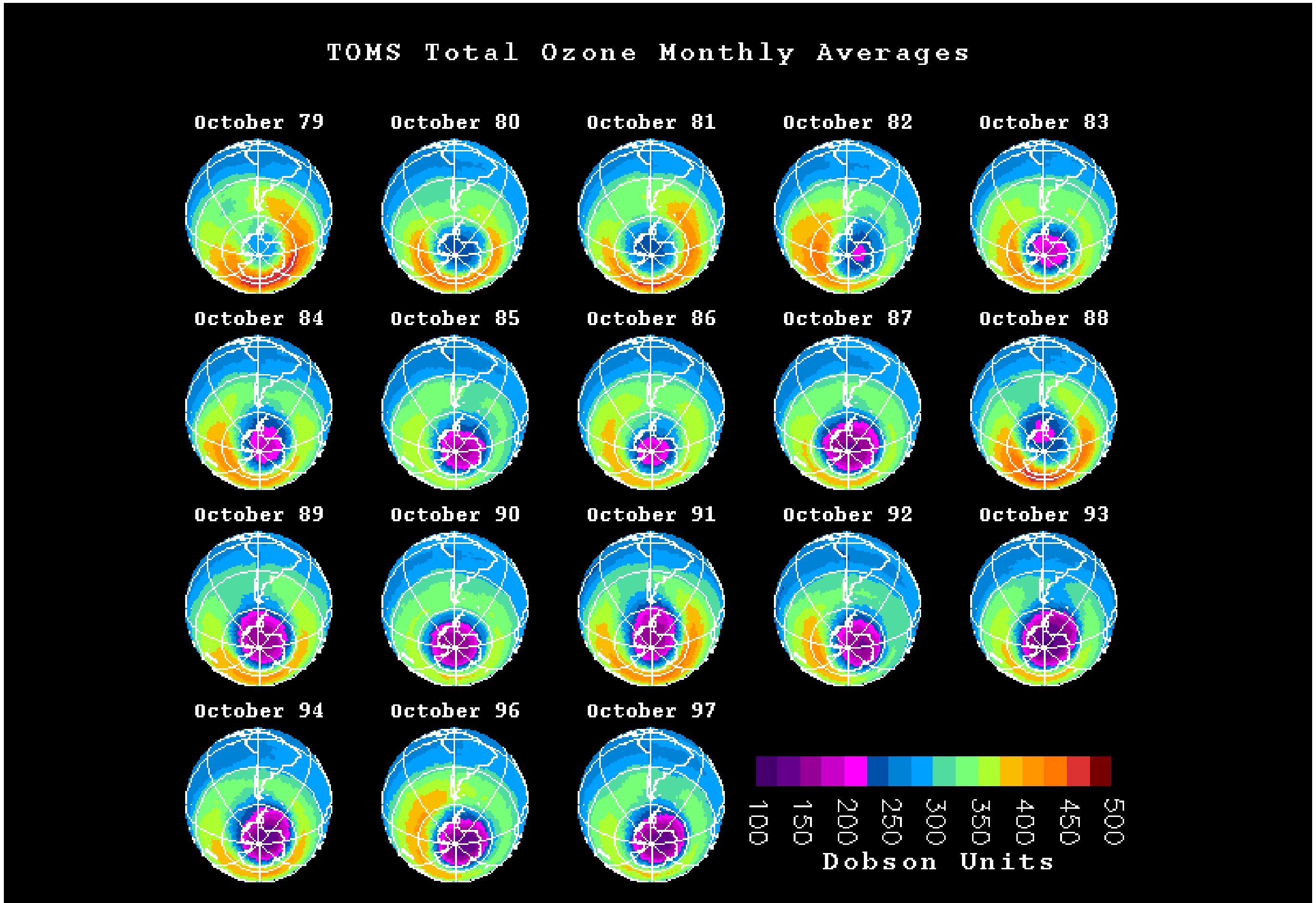
rgautam@iitb.ac.in

Trivia time….what season or month is this satellite image taken from??



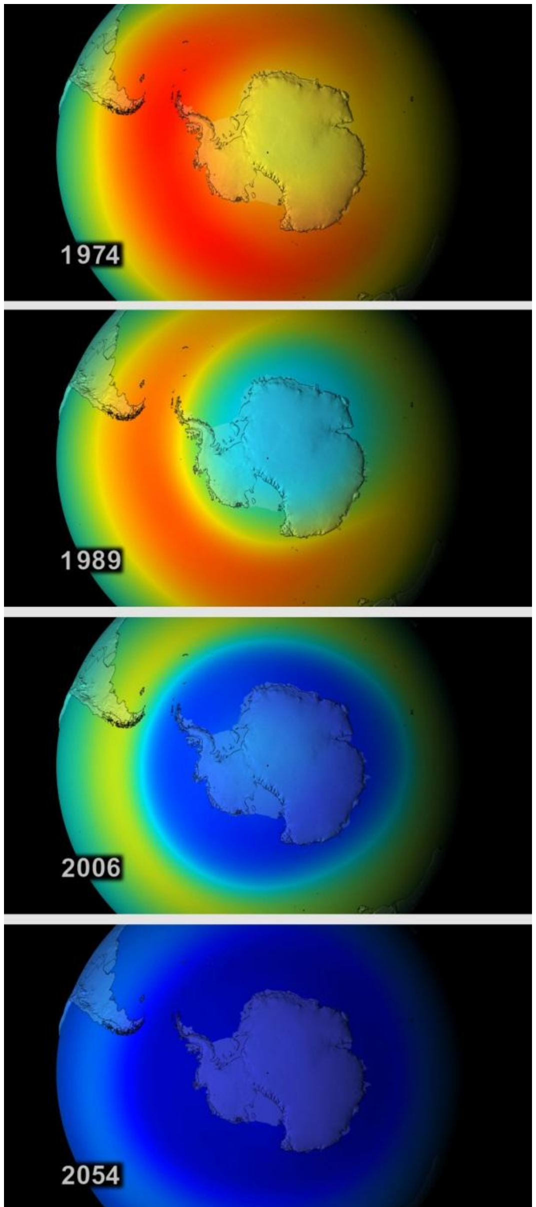
The (*accidental!*) discovery of the widespread Antarctic Ozone Hole.

(An Amazing account of how the NASA TOMS satellite team confirmed the ozone depletion….Controversial to say the very least)



Ozone Hole measured from NASA/TOMS)

What would have happened if Ozone Hole continued to develop & expand?



Climate model projections (images on left) of the development of the worldwide depletion of Ozone, if CFCs continued to increase in the atmosphere.

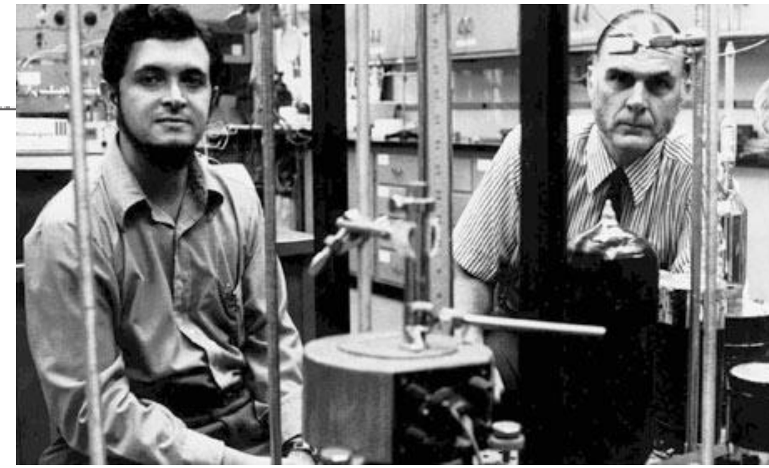
"The year is <u>2065</u>. Nearly two-thirds of Earth's ozone is gone -- not just over the poles, but everywhere.
The ultraviolet (UV) radiation falling on mid-latitude cities like Washington, D.C., is strong enough to cause sunburn in just five minutes. DNA-mutating UV radiation is up <u>650 percent</u>, with likely harmful effects on plants, animals and human skin cancer rates."

http://www.nasa.gov/topics/earth/features/world_avoided.html

Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone

Mario J. Molina & F. S. Rowland

Department of Chemistry, University of California, Irvine, California 92664



Chlorofluoromethanes are being added to the environment in steadily increasing amounts. These compounds are chemically inert and may remain in the atmosphere for 40–150 years, and concentrations can be expected to reach 10 to 30 times present levels. Photodissociation of the chlorofluoromethanes in the stratosphere produces significant amounts of chlorine atoms, and leads to the destruction of atmospheric ozone.

Nature (1974)

Quart. J. R. Met. Soc. (1970), **96**, pp. 320-325

551.510.41 : 551.510.534

The influence of nitrogen oxides on the atmospheric ozone content

By P. J. CRUTZEN*

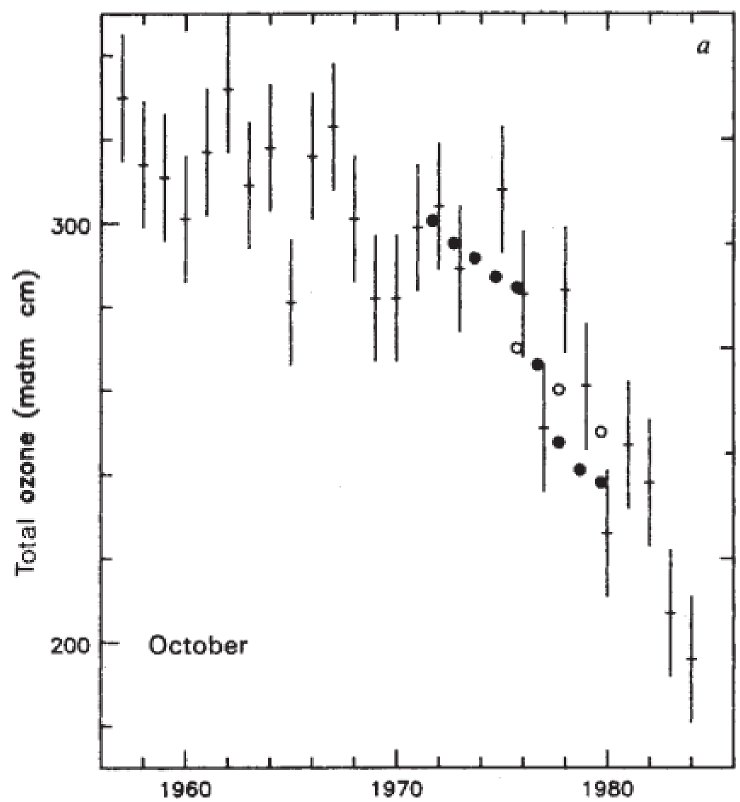
Clarendon Laboratory, Oxford University

(Manuscript received 5 November 1969, communicated by Dr. C. D. Walshaw)

Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction

J. C. Farman, B. G. Gardiner & J. D. Shanklin

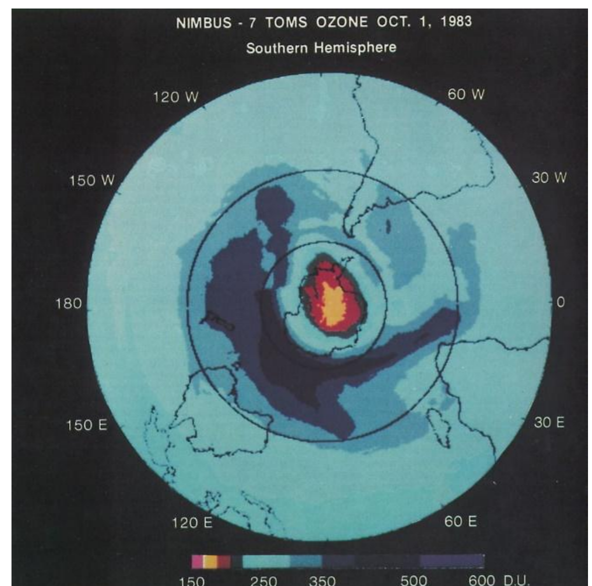
British Antarctic Survey, Natural Environment Research Council,
High Cross, Madingley Road, Cambridge CB3 0ET, UK



Nature (1985)

“It turns out that Dr. Bhartia and his colleagues did see very low ozone values from the TOMS instrument when they processed the data from October 1983; however the satellite algorithm flagged out the low Ozone retrievals!”

At an August 1985 meeting in Prague, Pawan Bhartia presented this satellite-based image that revealed for the first time the size and magnitude of the ozone hole.

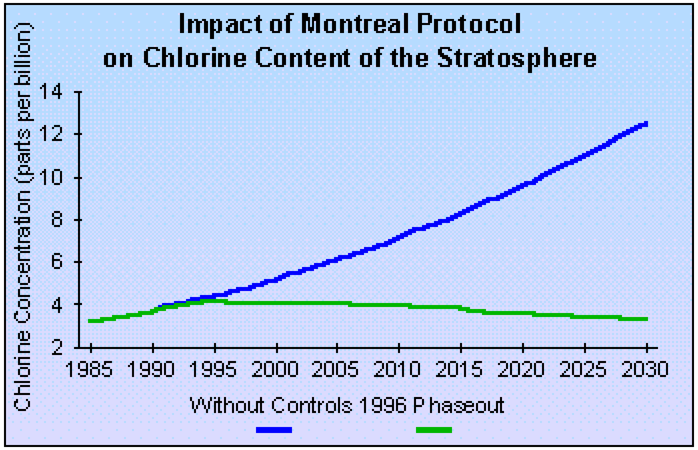


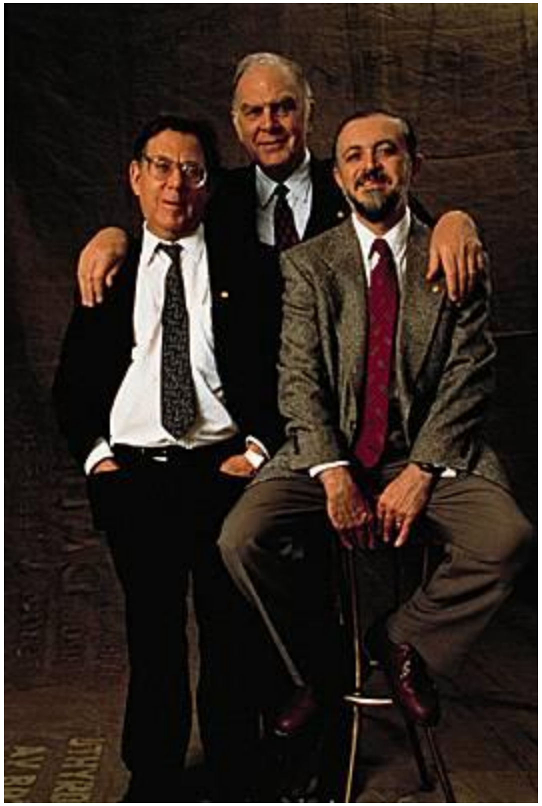
http://www.nasa.gov/topics/earth/features/bhartia-qa.html

Montreal Protocol (1987)

Nobel Prize in Chemistry (1995)

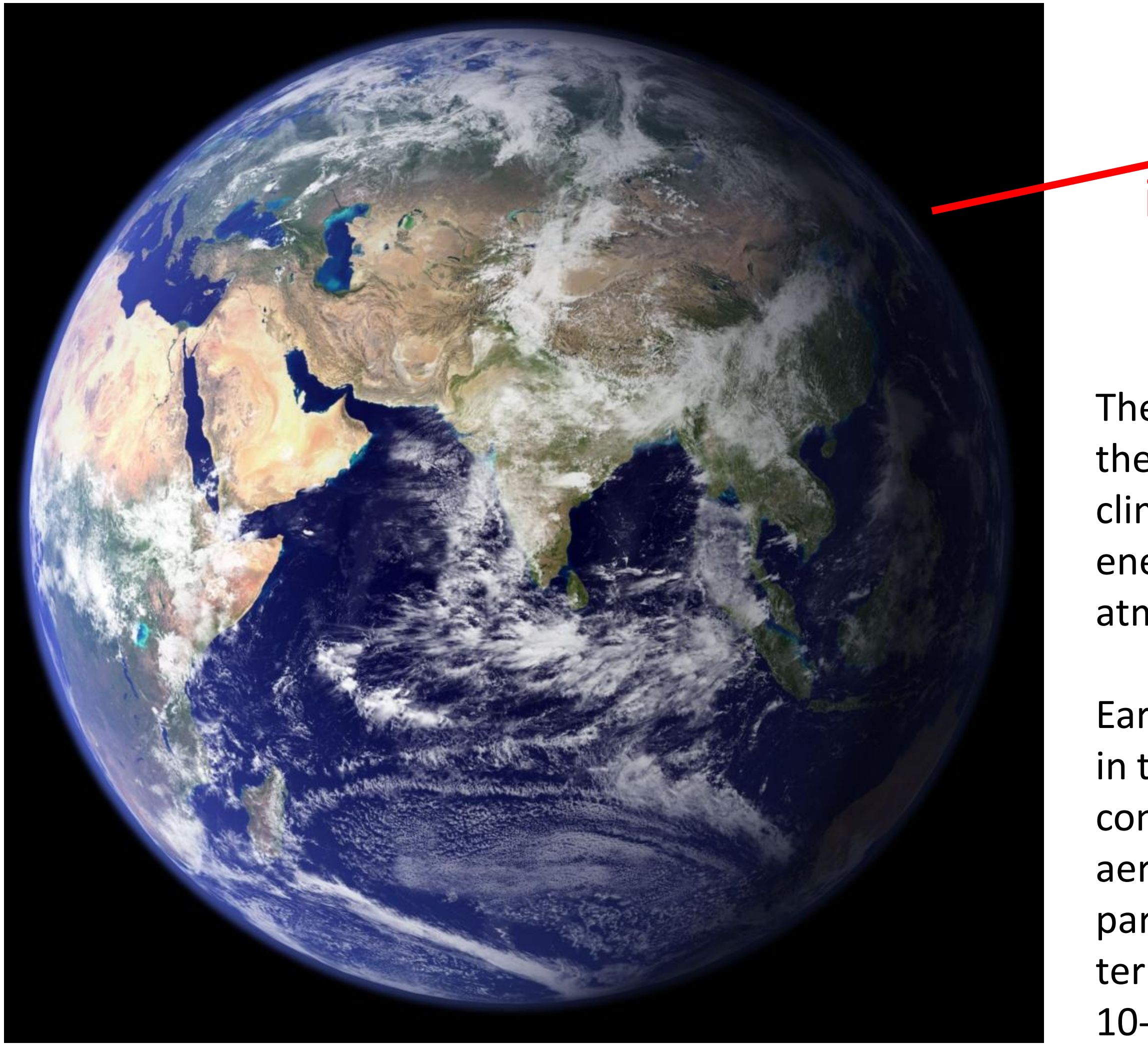
Kofi Annan quoted as saying that "perhaps the single most successful international agreement to date has been the Montreal Protocol"





Moral of the Story

Don't throw away your valuable measurements/data!!



The atmosphere is like a blanket covering the Earth and regulates the balance of the climate system, and is responsible for the energy exchange between land, ocean and atmosphere.

Earth’s atmosphere is a very thin shell; and in this thin shell, there are large concentrations of chemicals, gases, aerosols or simply referred to as pollution particles. Most of the atmosphere (in terms of its density) is contained within 10-15km from the Earth’s surface (referred to as the troposphere).

Why Atmospheric Remote Sensing?

- **Why Remote Sensing?**
- The main advantage of satellite RS is to monitor the whole globe with a good spatial and temporal frequency.
- This is unlike ground measurements which only sample over a given location.
- Satellites have the ability to routinely monitor the whole globe systematically.
- RS is used to monitor the Earth, and retrieve various geophysical variables over land, ocean, atmosphere and cryosphere.

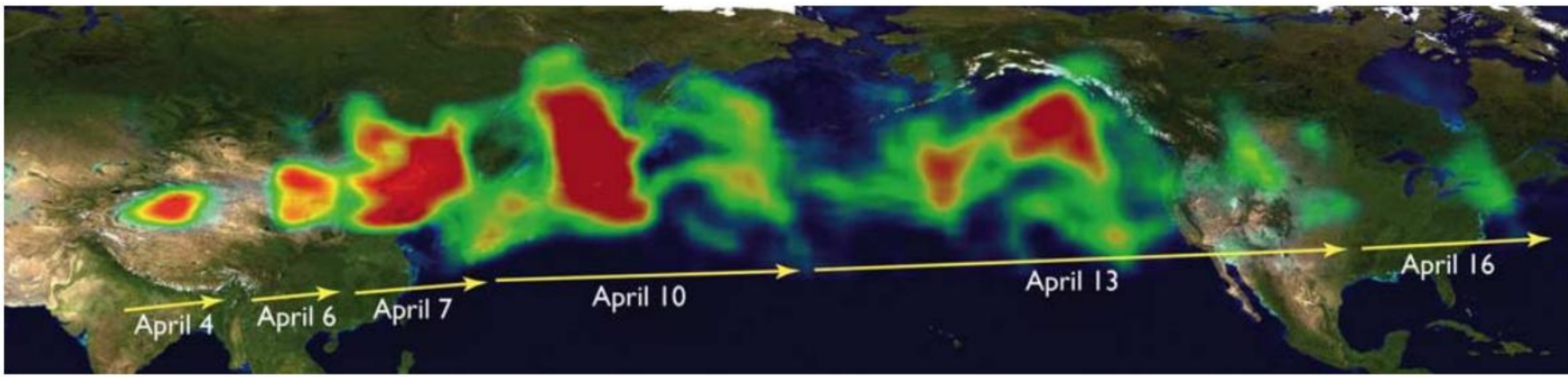
Why Atmospheric RS (continued)

- Because there is a global need/concern to understand more about atmosphere, its contents, various processes.
- Monitoring & Retrieval of aerosols, clouds, water vapor, rainfall and so on.
- Atmospheric Correction in satellite/airborne imagery
- Atmospheric data is used for weather forecasting and climate prediction
- Air Quality characterization
- Studying Global & Regional Environmental/Climate Change

Aerosols

[Atmosphere Has No Boundaries]

TOMS Aerosol Index



A Global Portrayal of Aerosols

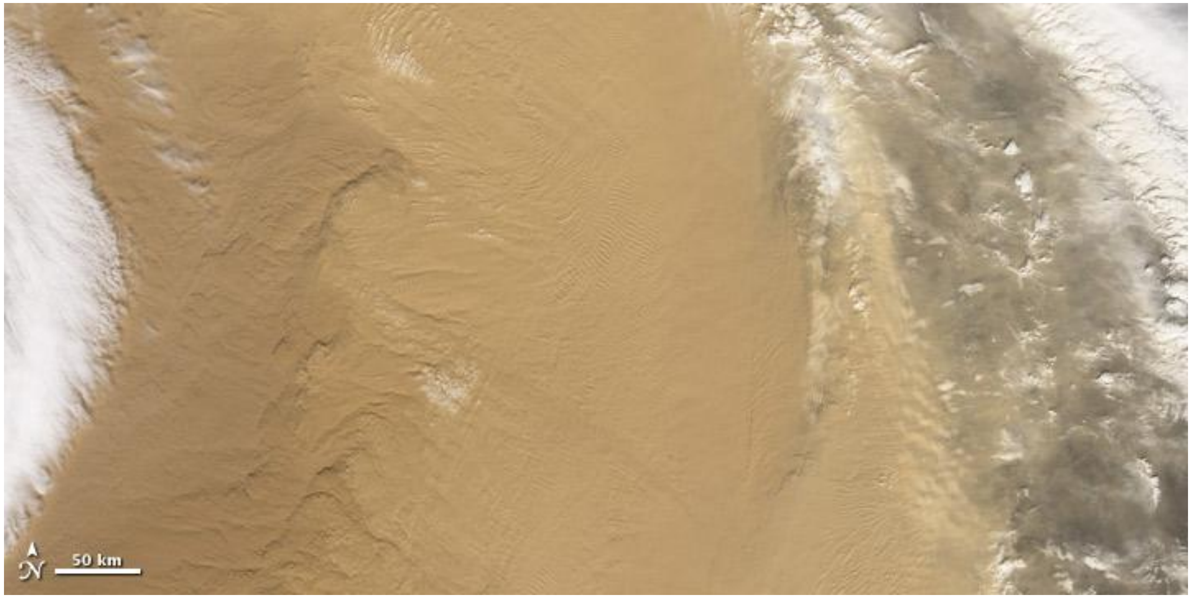
https://www.youtube.com/watch?v=t9GgIIOtbHA

- Atmospheric aerosols are particles or both suspended in air with diameters between about 0.002 μm to about 100 μm.

- Aerosol particles vary greatly in size, source, chemical composition, amount and distribution in space and time, and how long they survive in the atmosphere.

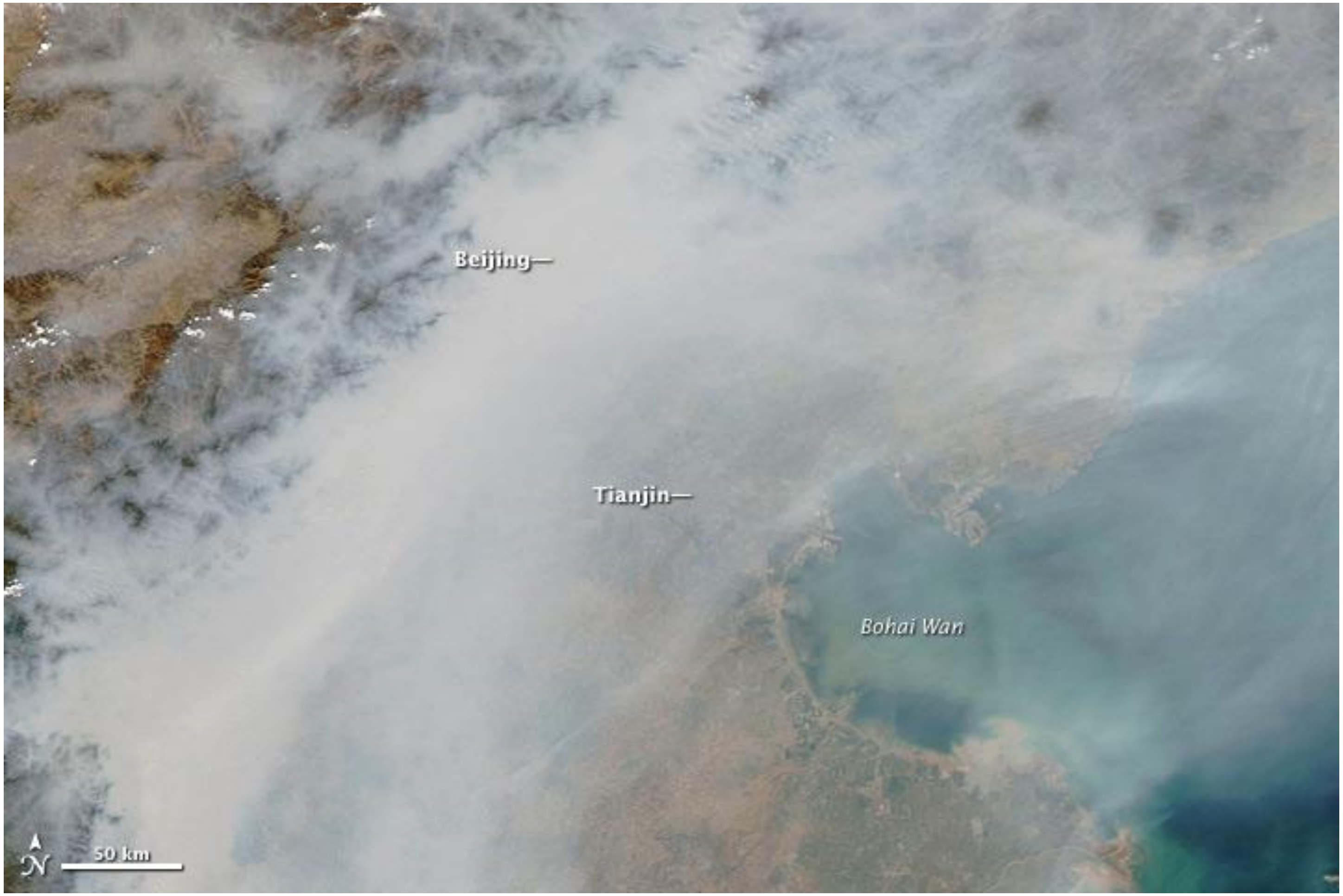
These aerosol particles are released in large concentrations, and therefore affect large areas, in the form of dust storms, haze, smoke plumes.

Mineral Dust



Biomass burning Smoke

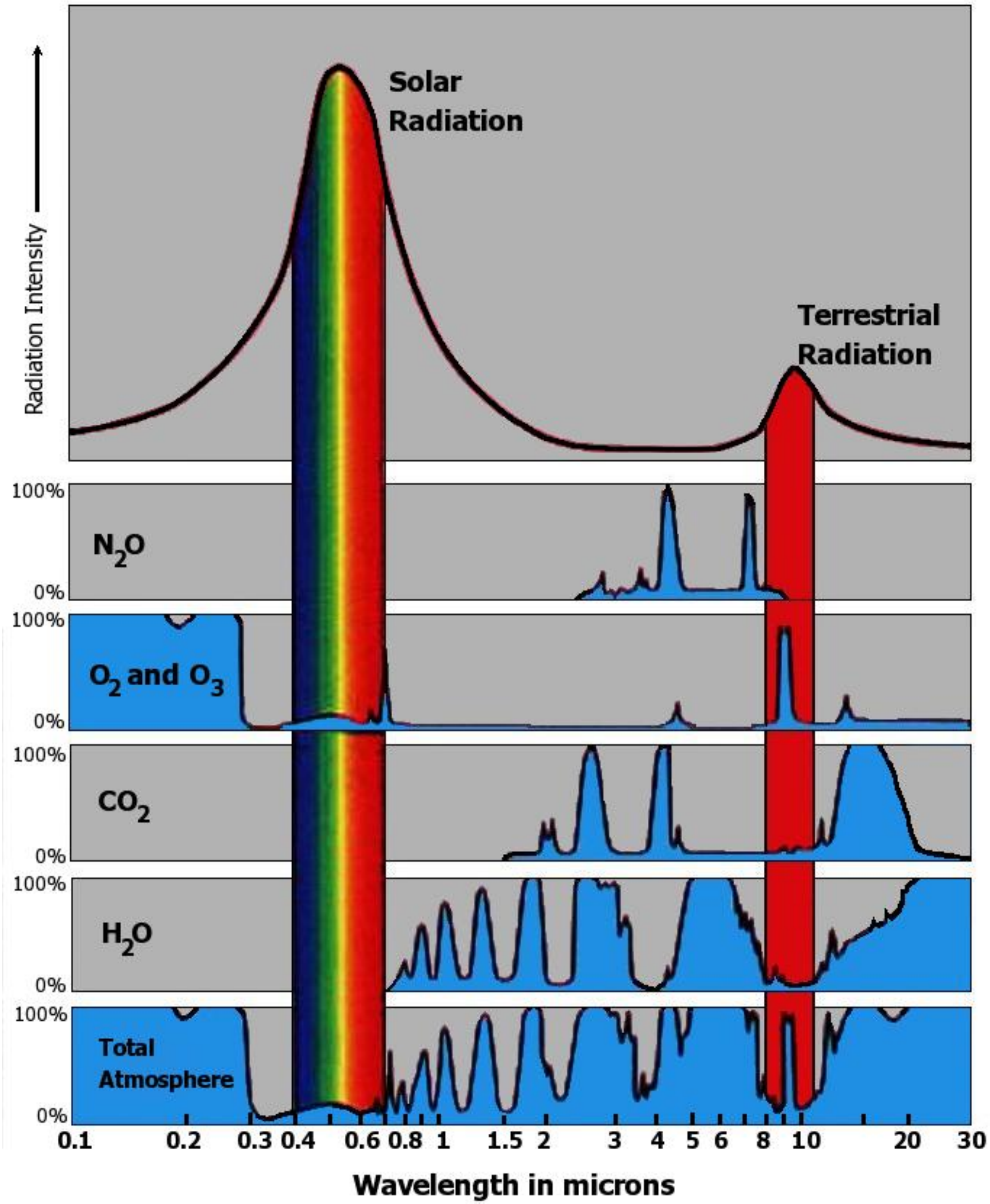
Urban Pollution



Various types of Aerosols

- Sea Salt (Ocean/Sea Spray) -- NATURAL
- Mineral Dust (soil, desert dust) -- NATURAL
- Sulfate (industrial/urban emissions) -- ANTHROPOGENIC
- Carbonaceous (soot/black carbon, source: industrial/urban) -- ANTHROPGENIC
- Volcanic Ash -- NATURAL

Earth Observatory



Visible part of Solar Radiation is largely unaffected atmospheric gases, but it is influenced by particle scattering (due to aerosols and clouds).

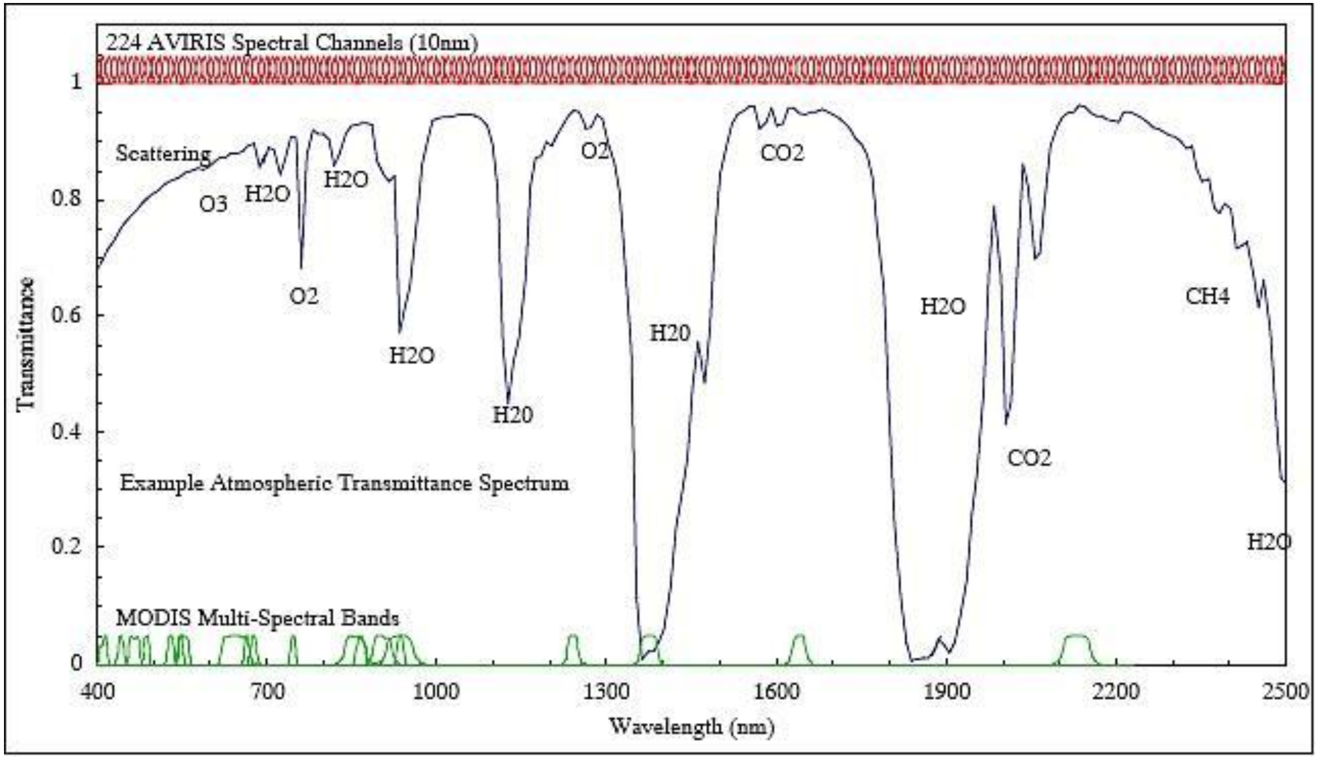
Longwave radiation is influenced by absorption due to gases present in the atmosphere such as CO2, water vapour, methane, etc.

Impact of Atmospheric Gases Absorption on Transmittance Spectrum

For example, Oxygen is strongly absorbing at 760nm, while water vapour is absorbing at multiple wavelength bands in nearIR (940nm, 1380nm, etc.)

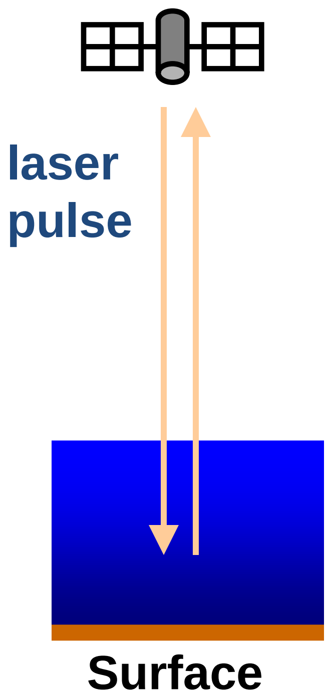
Transmission = 1 (100%), indicates atmosphere is totally transparent (no extinction of light either from absorption or scattering)

Transmission = 0, indicates atmosphere is totally opaque.

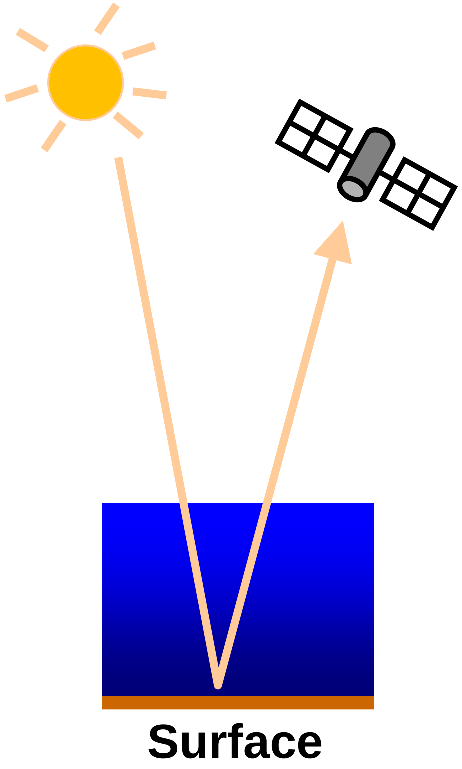


Active vs. Passive Remote Sensing

Active system
(sensor has its own source of light)
(Radar, CALIOP/CALIPSO)



Solar/Terrestrial back-scatter
(sensor depends on backscattered shortwave/longwave radiation)
(Landsat, MODIS, MISR, SeaWiFS, etc.)

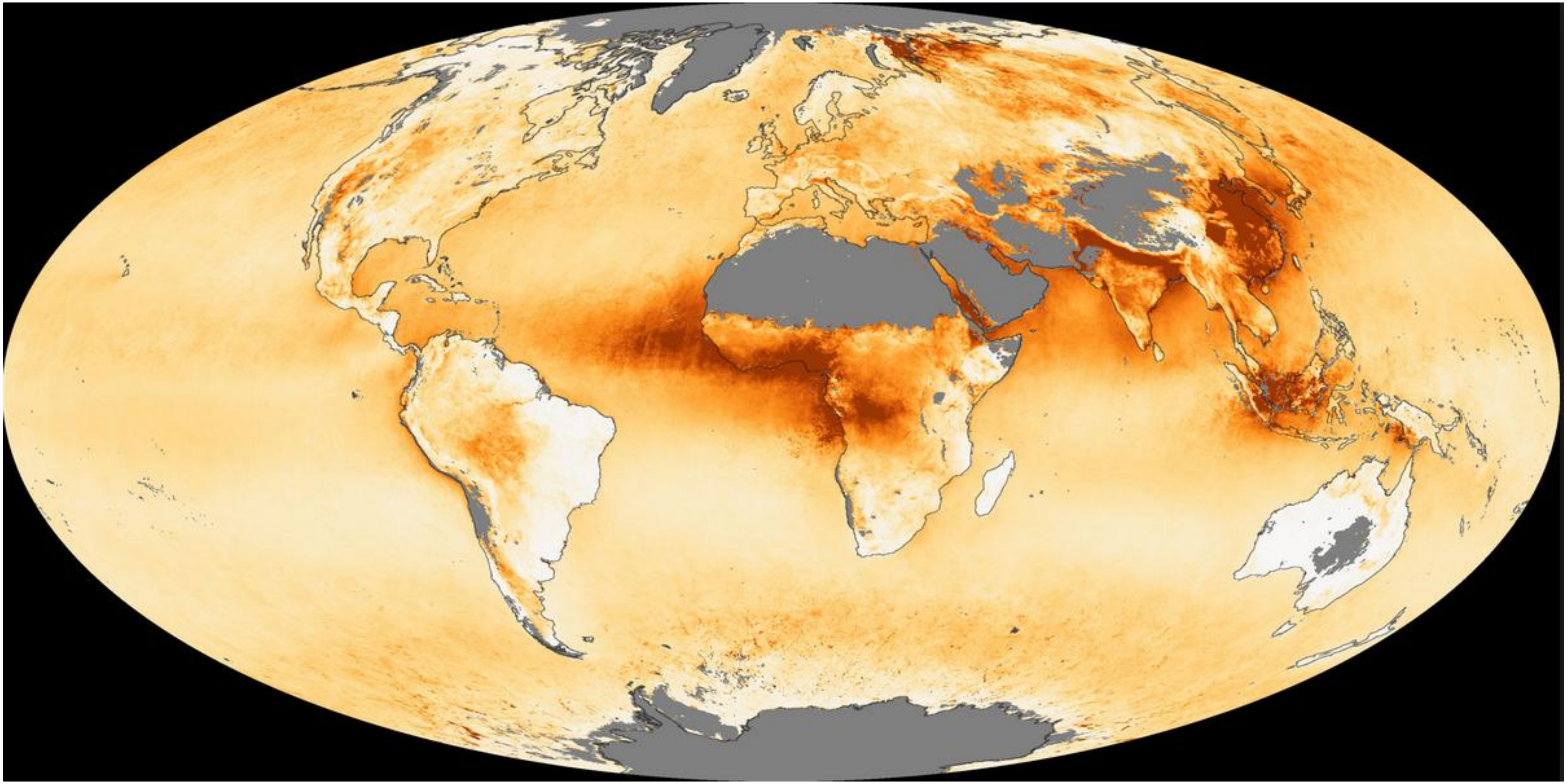


Slide by Rich Kleidman/GSFC

Pros: vertical profiling
Cons: sparse sampling, low S/N

Pros: horiz. resolution
Cons: daytime only, no vertical resolution

MODIS Dark-Target
Aerosol Optical Depth

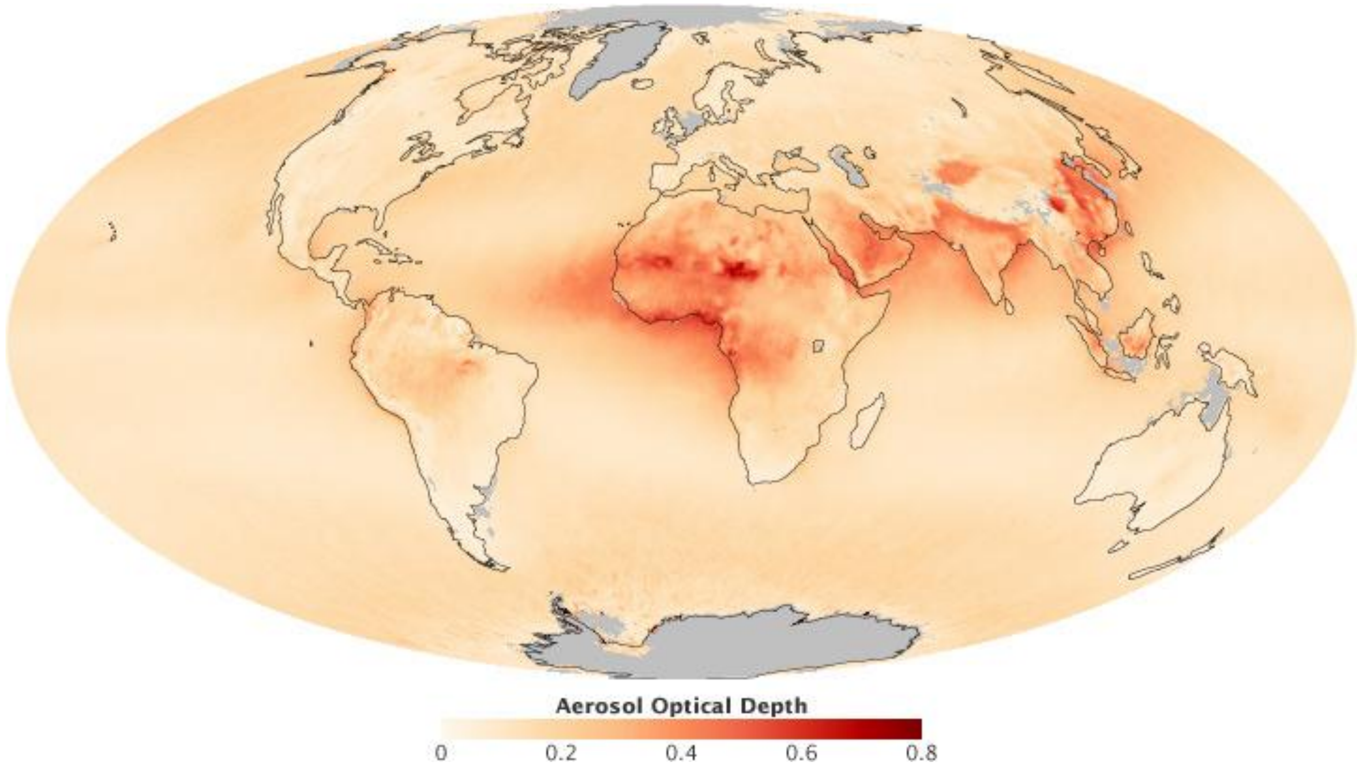


Example of Aerosol Optical Depth retrieved by MISR (multi-angular measurements)

Red color indicates where aerosol optical depth (AOD) is high associated with high air pollution (India, China, Sahara desert, etc.) . Light colors indicate where pollution is low, e.g. over oceans.

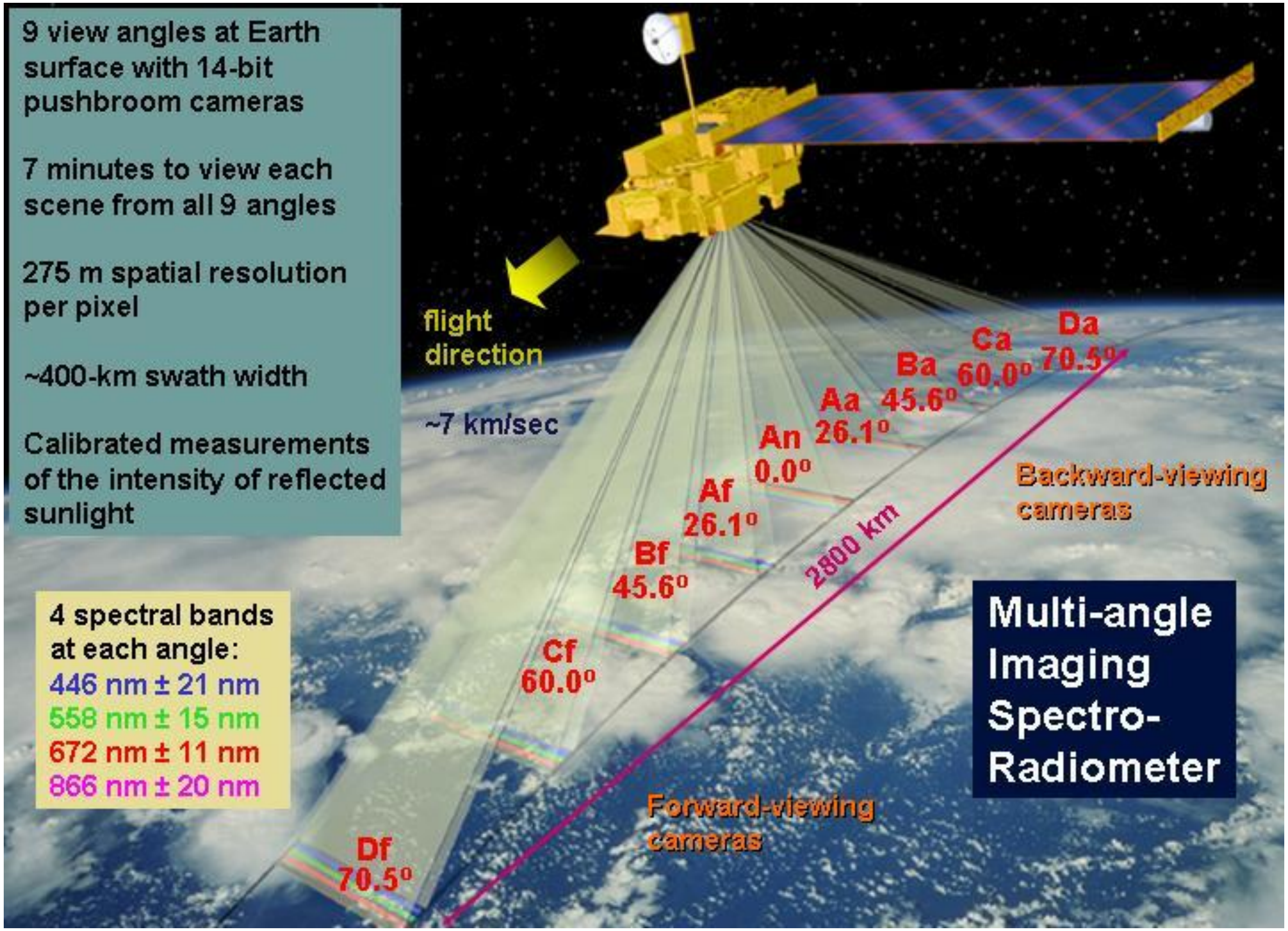
The typical range of AOD is from 0 to 2, with higher values indicating larger aerosol concentration in atmosphere. Missing values (shown in gray) indicate where AOD is not retrieve over snow-covered regions including polar regions, Greenland, parts of Himalaya, Tibetan Plateau.

Note: aerosols can only be observed from satellites when there are no clouds present in the same pixel. For persistently cloudy regions, e.g. areas around Indonesia, there are hardly any aerosols retrieved by satellites because of the frequent cloud-cover. This does not mean there are no aerosols present in the atmosphere, but only suggests that aerosol observations from space can be made in cloud-free conditions.



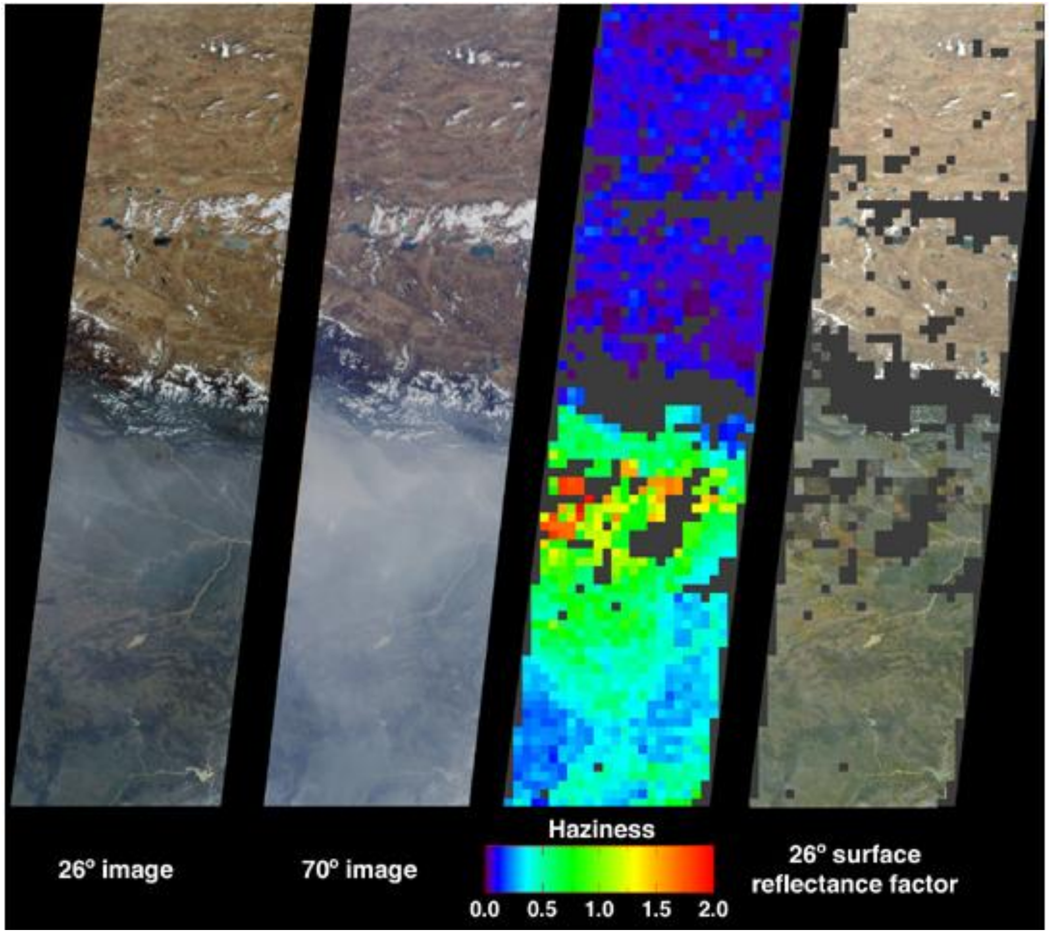
Multi-angle Imaging SpectroRadiometer (MISR)

Multi-angular sensors refer to multiple viewing cameras associated with an instrument. In the case of the MISR instrument, there are 9 viewing cameras (4 in forward direction, 4 in backward direction and one at nadir. Having multiple views of the same region of the earth better characterize the scattering due to atmospheric constituents (e.g. aerosols, clouds) and also better characterize the underlying surface in terms of its directional reflectance)



https://eosweb.larc.nasa.gov/faq-page/misr-faq

Multi-angle Imaging SpectroRadiometer (MISR) observation of Aerosols

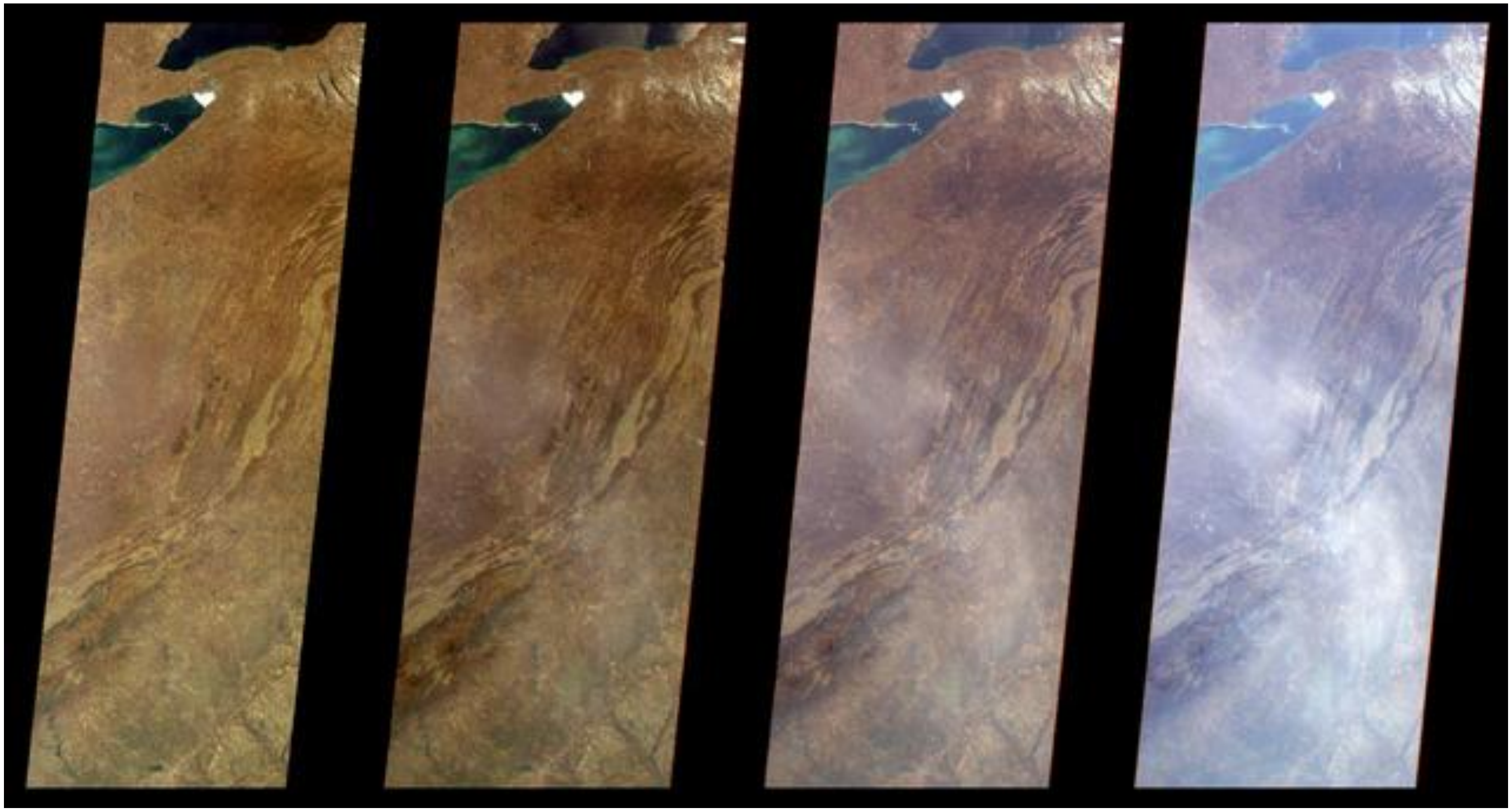


The two images on left show the scene from MISR's 26-degree and 70-degree forward viewing angles, respectively. The high levels of aerosols are enhanced in the 70-degree forward image, due to the longer atmospheric path length associated with the more oblique viewing angle.

http://earthobservatory.nasa.gov/IOTD/view.php?id=1880

MISR Provides enhanced information about aerosols at different angles

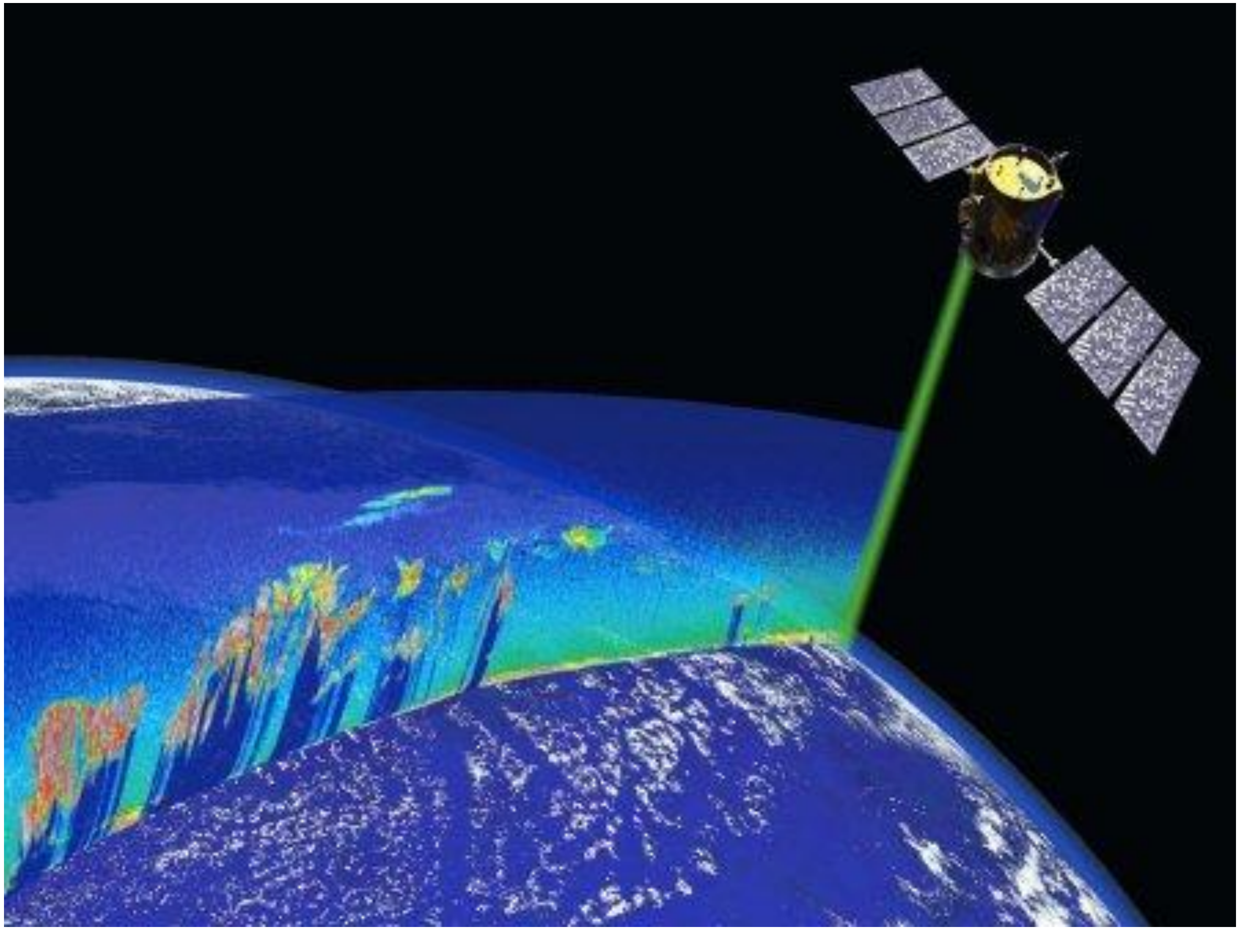
September 7, 2000



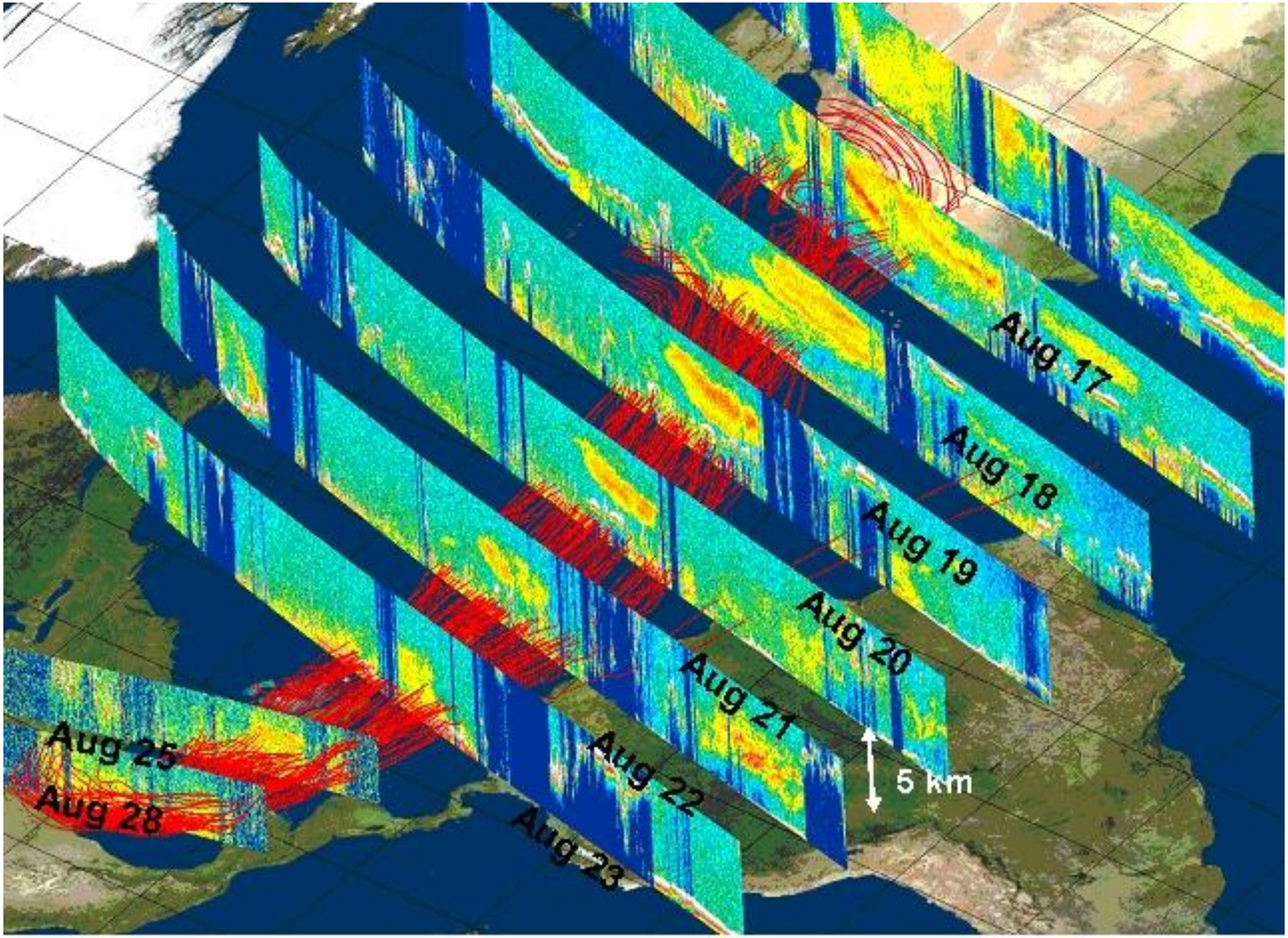
Nadir *46°* *60°* *70°*

Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)

(CALIPSO is an example of a Lidar-based active remote sensing instrument which sends a laser pulse from the sensor and then measures the backscattered signal received at the sensor. It has strong capability to profile the scattering/absorption due to aerosols/clouds in the atmosphere (especially aerosols).



CALIPSO tracking a dust storm across the Atlantic (providing the vertical distribution of scattering due to dust aerosols)



Credit: C. Trepte/NASA

The extinction coefficient (b_{ext}) represents the sum of the extinctions from gases and particles, each of which can in turn be divided into extinction due to absorption or scattering.

$b_{ext} = b_{gas} + b_{particles}$ (extinction due to gases and particles)
$b_{ext} = b_{abs} + b_{scatt}$ (extinction refers to attenuation of light due to absorption and scattering)

b_{abs} (gases) = Beer's Law absorption
b_{scatt} (gases) = Rayleigh Scattering
b_{abs} (particles) = Usually < 10% of extinction
b_{scatt} (particles) = Mie Scattering = (b_{sp})

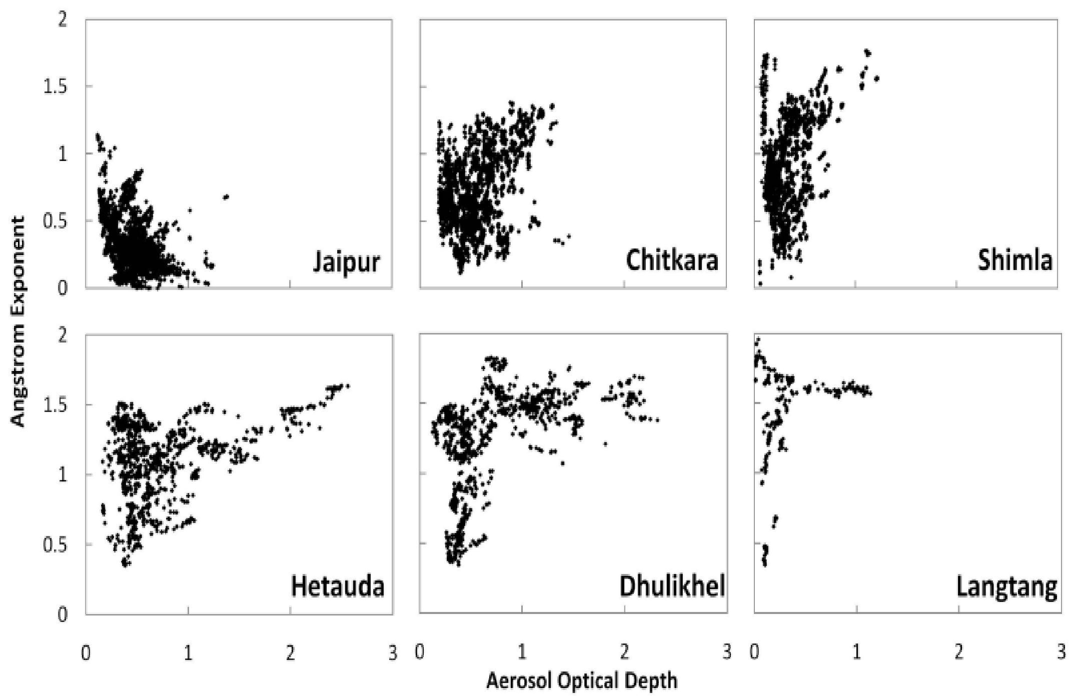
Aerosol optical depth (AOD), τ is a measure of the extinction caused by scattering and absorption, where 'z' is the altitude (typically z ranges from surface to top of atmosphere):

$$\tau = \int b_{ext}(z)\, dz \text{ (unitless)}$$

AOD is unitless. The integral is from surface to top of atmosphere.

Angstrom exponent, α, is a measure of the size distribution, describes the dependency of the aerosol optical thickness on wavelength. For urban aerosols (fine particles) α > 1.0, for dust storms (coarse particles) α << 1.0.

$$\frac{\tau_\lambda}{\tau_{\lambda_0}} = \left(\frac{\lambda}{\lambda_0}\right)^{-\alpha} \qquad \alpha = -\frac{\ln \frac{\tau_{\lambda_1}}{\tau_{\lambda_2}}}{\ln \frac{\lambda_1}{\lambda_2}}$$



From the scatter plots, shown on left, between Aerosol Optical Depth, or AOD (x-axis) and Angstrom Exponent (y-axis):

For Jaipur, majority of the AOD data is associated with Angstrom Exponent less than 1, while most of the AOD data over Dhulikhel (near Kathmandu) is associated with values greater than 1.

Jaipur is close to the Thar desert in Rajasthan, and therefore is subjected to frequent dust storms, while Dhulikhel (Kathmandu) is far from the desert and is mostly affected by urban (fine) aerosols.

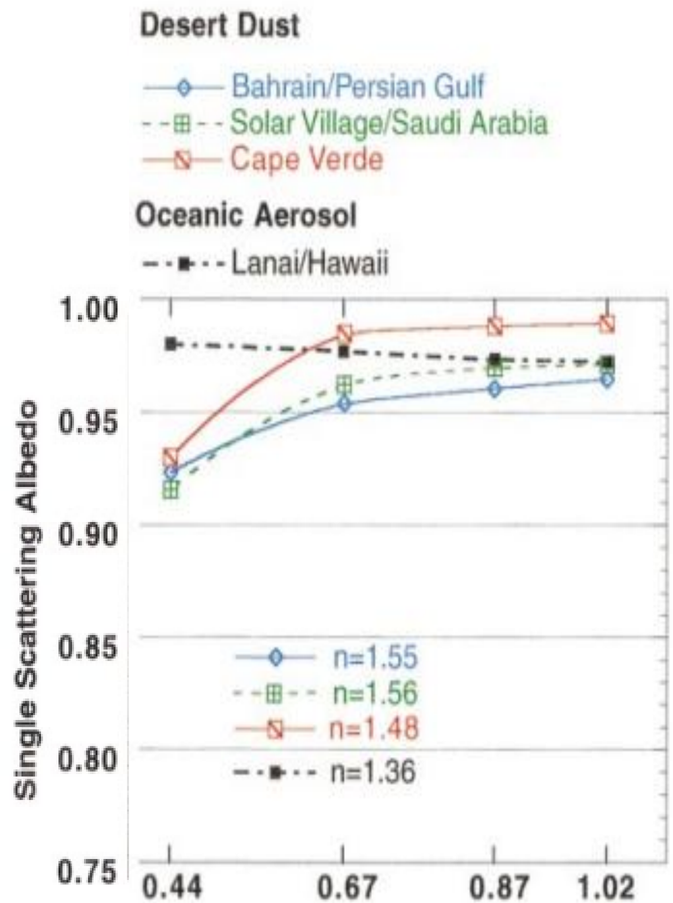
Gautam et al. 2011, ACP

Single scattering albedo, ω, is a measure of the fraction of aerosol extinction caused by scattering:

$$\omega = b_{sp}/(b_{sp} + b_{ap})$$

b_{sp} is scattering coefficient and b_{ap} is absorption coefficient

More Light-absorbing aerosol

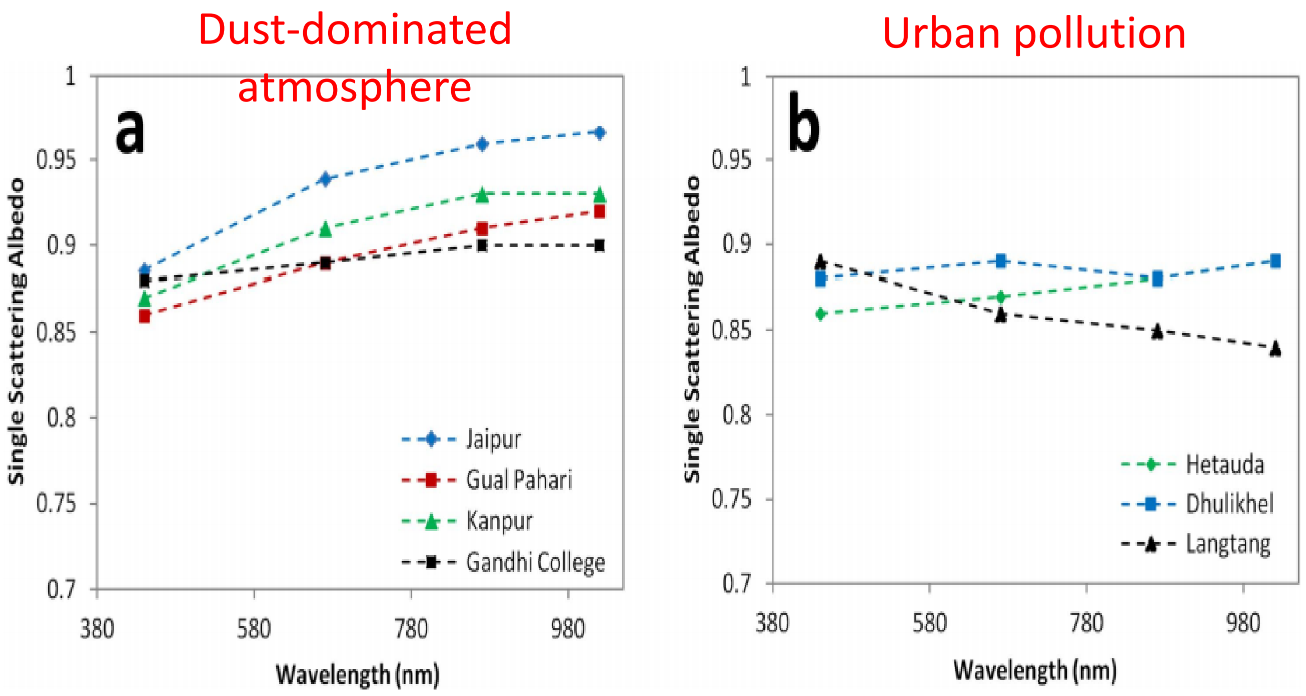


Single Scattering Albedo (SSA) value of aerosols ranges from 0 to 1. SSA=1 means 100% scattering aerosol (with no absorption).

Dubovik et al. 2002

Single Scattering Albedo (SSA) over northern India and Nepal (April-May)

Dust aerosols contain haematite/iron oxide, which has strong absorption bands in the UV-blue spectrum. As a result, there is enhanced absorption at shorter visible (blue) wavelengths and thus decrease in SSA for dust-dominated atmosphere.

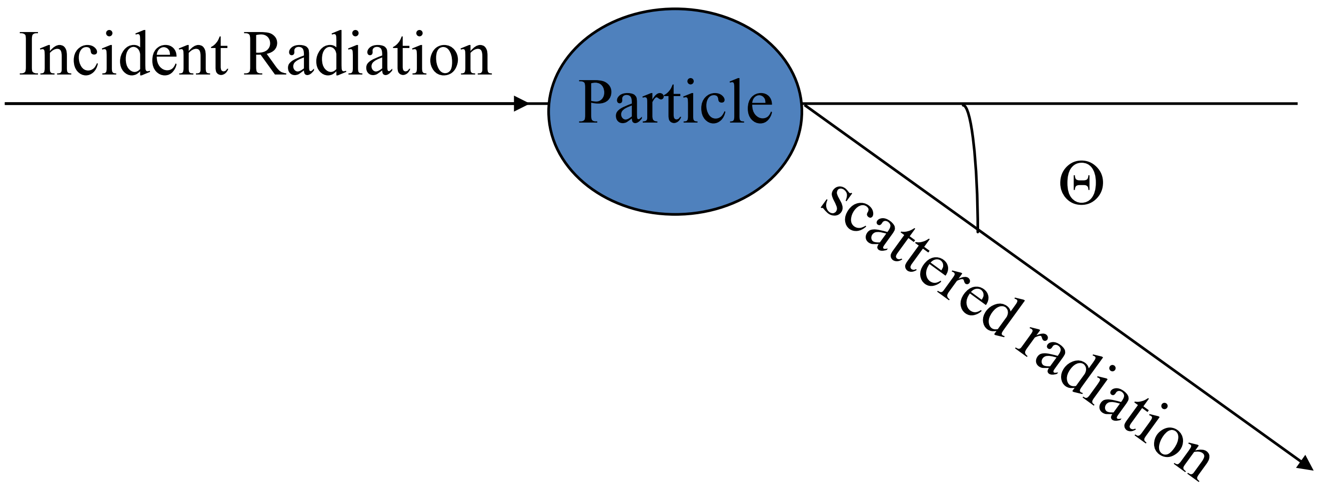


SSA from AERONET sunphotometers at (a) Jaipur, Gual Pahari, Kanpur and Gandhi College in Northern India, and (b) at Hetauda, Dhulikhel and Langtang of Himalayan foothill/slope regions Nepal. The SSA from AERONET is retrieved at four wavelengths – 440 nm, 670 nm, 870 nm and 1020 nm. Values shown are mean SSA for the 2009 pre-monsoon measurement period.

Gautam et al. 2011, ACP

Scattering angle

The scattering angle, Θ, is the relative angle between the incident and the scattered radiation



Phase function

The phase function, P(Θ), describes the distribution of scattered radiation for one or a set of particles. It is normalized such as:

$$\int_0^{2\pi}\int_0^{\pi} P(\Theta)\,d\omega = 4\pi$$

since $$\int_0^{2\pi}\int_0^{\pi} P(\Theta)\,sin(\theta)\,d\theta\,d\phi = 2\pi\int_0^{\pi} P(\theta)\,sin(\theta)\,d\theta$$

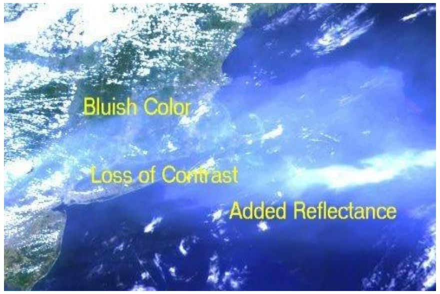
we have $$\int_0^{\pi} P(\theta)\,sin(\theta)\,d\theta = 2$$

Aerosol Impact on At-sensor Reflectance (Top-of-Atmosphere)

At-sensor reflectance, Apparent Reflectance and Top-of-Atmosphere (TOA) Reflectance imply the same quantity!!

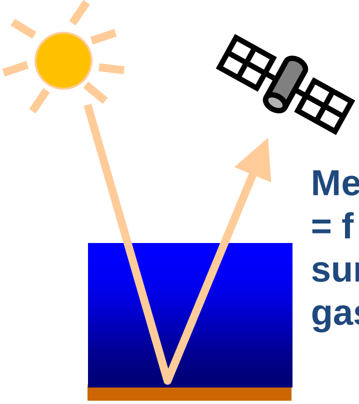
California fire plumes

Pollution off U.S. east coast



Dust off West Africa

$I_\lambda(o)=I_\lambda \exp[-AOD]$



Measured top-of-atmosphere reflectance = f (AOD, aerosol properties, surface reflectance, air scattering, gas absorption, Sun-satellite geometry)

Slide by Rich Kleidman/GSFC

Aerosol scattering/absorption signal at Top-of-Atmosphere

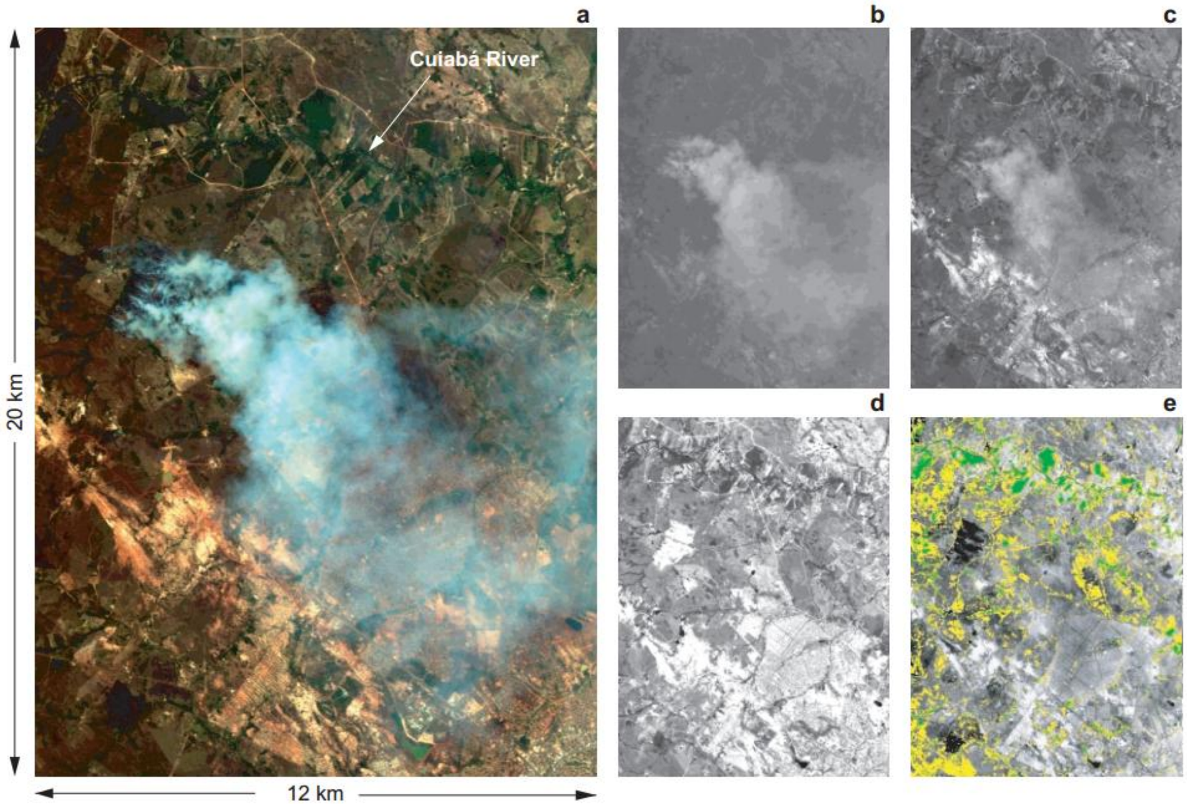


FIG. 4. AVIRIS images acquired near Cuiabá, Brazil, on 25 Aug 1995. (a) A red–green–blue composite of 0.66, 0.55, and 0.46 μm bands; (b)–(d) images for individual bands. Panel (b) applies to 0.46 μm, which is especially sensitive to smoke, (c) to 0.66 μm, also sensitive to smoke but with brighter surface reflectance, and (d) to 2.13 μm, which shows both hot ground and bright land. (e) Location of all dense dark vegetation within this scene, defined as pixels for which the surface reflectance $A_g(2.13\ \mu m) \leq 0.10$ (green pixels) or $0.10 < A_g(2.13\ \mu m) \leq 0.15$ (yellow pixels). The background image on which the dark vegetation pixels are overlaid is the AVIRIS image at 0.86 μm, for which vegetation is bright and burn scars dark.

A sequence of figures (a-e) shows the different images as a function of wavelength. Note, how the reflectance changes as one approaches the absorption bands and the surface disappears.

The reflection from the vegetated surface increases after 0.66 micron and surface features become evident (recall vegetation is more reflective in near-IR and shortwave-IR, e.g. 2.13micron- figure d). At the same time, smoke particles are small in size and interact efficiently with the light at shorter wavelengths (<0.66micron), causing enhanced scattering.

Above 0.66 micron the low level smoke becomes less opaque and more transparent, and we are able to see the underlying more clearly at longer wavelengths. The fire on the ground becomes evident at the longer wavelengths as thermal emission supplements solar reflection.

Kaufman et al.

Principles of Aerosol Remote Sensing from Space

$$R(\mu, \mu_0, \phi) = \frac{\pi I(\mu, \mu_0, \phi)}{\mu_0 \, F_0}$$

where *R* is the normalized radiance (or apparent reflectance), F_o is the extraterrestrial solar flux, *I* is the radiance at the top of the atmosphere, μ is the cosine of the view zenith angle, μ_o is the cosine of the solar zenith angle, and *φ* is the relative azimuth angle between the direction of propagation of scattered radiation and the incident solar direction

Purely Atmosphere

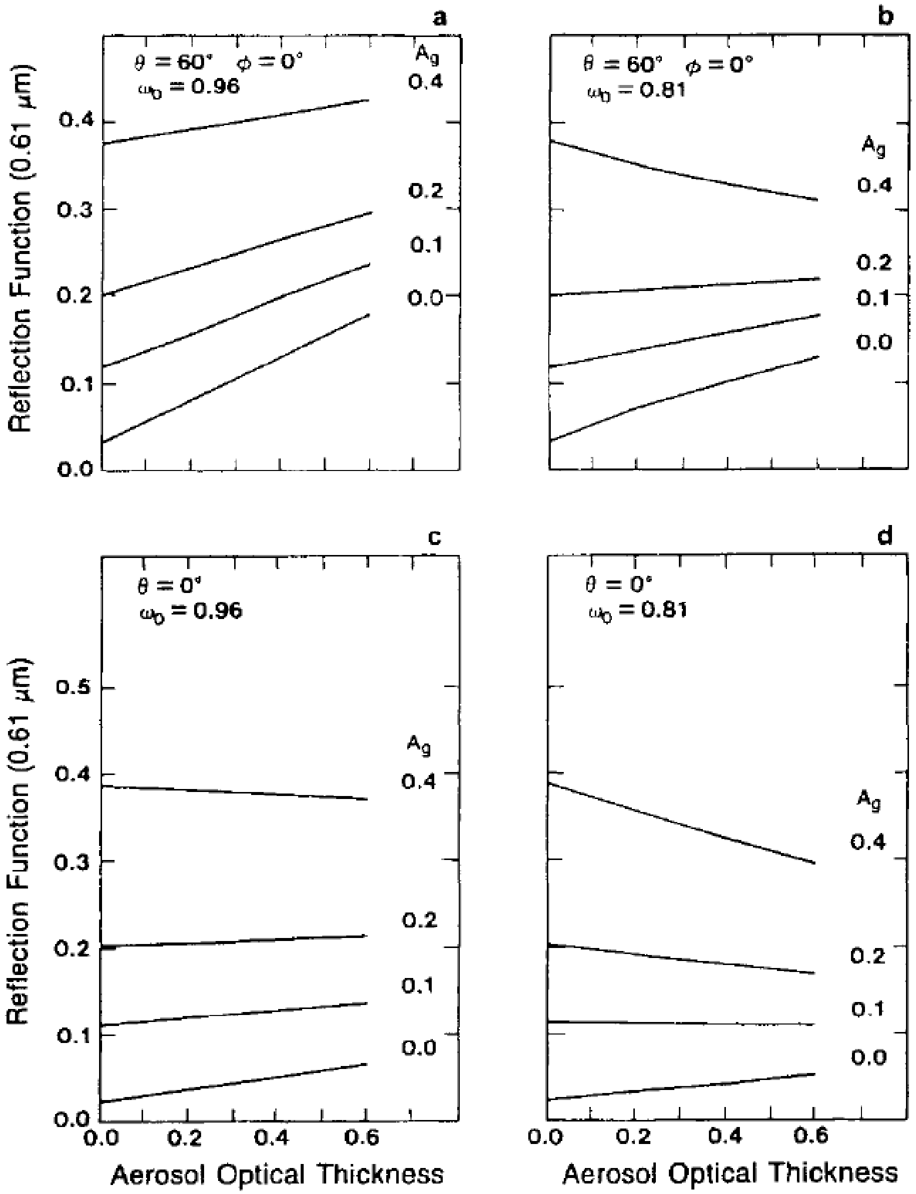
Surface Contribution

$$R(\mu, \mu_0, \phi) = R_0(\mu, \mu_0, \phi) + \frac{T \, A_s}{1 - s \, A_s}$$

where $R_0(\mu, \mu_0, \phi)$ represents the path radiance, T is the transmission function describing the atmospheric effect on upward and downward radiance, A_s is the Lambertian reflectance, and s is the spherical albedo of the atmosphere for illumination from below.

's' is the fraction of the upward flux reflected back to the surface by the atmosphere

Kaufman, 1987



Figures in the two columns show changes in Top-of-Atmosphere Reflectance (Reflection Function), on y-axis, as a function of Aerosol Optical Thickness (or depth), on x-axis, as well as due to changes in surface reflectance (A_g)

These plots are based on the following equation:

$$R(\mu, \mu_0, \phi) = R_0(\mu, \mu_0, \phi) + \frac{T\ A_s}{1 - s\ A_s}$$

The reflection function or reflectance as a function of aerosol optical thickness and surface reflectance. The changing slope of each line depends on variations in surface reflectance

King et al. 1999

Principles of Aerosol Remote Sensing from Space

Two Key assumptions:

- Reliable Atmospheric Aerosol Model/Type

  … AOD, SSA, Phase Function, etc.

- Parameterization of Surface Characteristics

  … Primarily Surface Reflectance

Surface Parameterization for Dark Target Algorithm

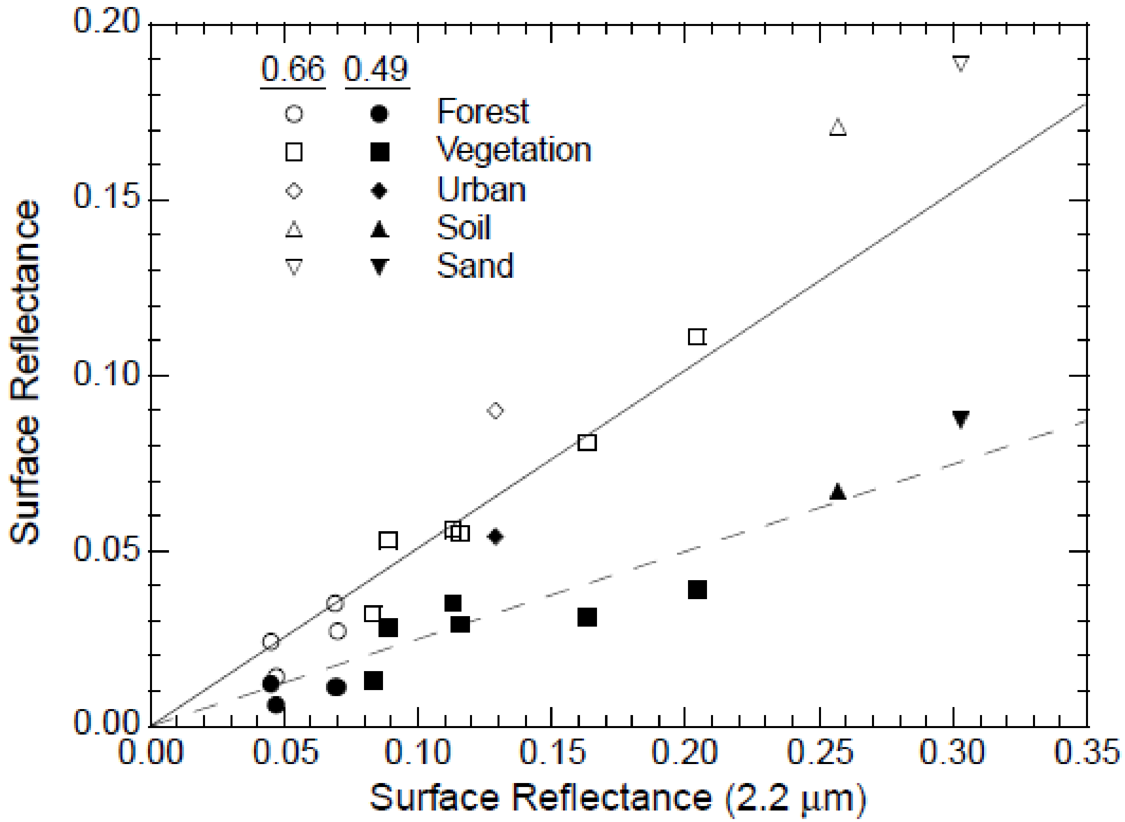


FIG. 3. Scatter diagram between the surface reflectance at 0.49 μm (solid symbols) and 0.66 μm (open symbols) to that at 2.2 μm, for several surface types. The average relationships $A_{0.49}/A_{2.2} = 0.25$ and $A_{0.66}/A_{2.2} = 0.5$ are also plotted (dashed and solid lines, respectively) (adapted from Kaufman et al. 1997b).

First, with the exception of dust, the aerosol optical thickness typically decreases with wavelength. Therefore aerosol optical thickness is 3–30 times smaller in the shortwave-infrared region than in the visible.

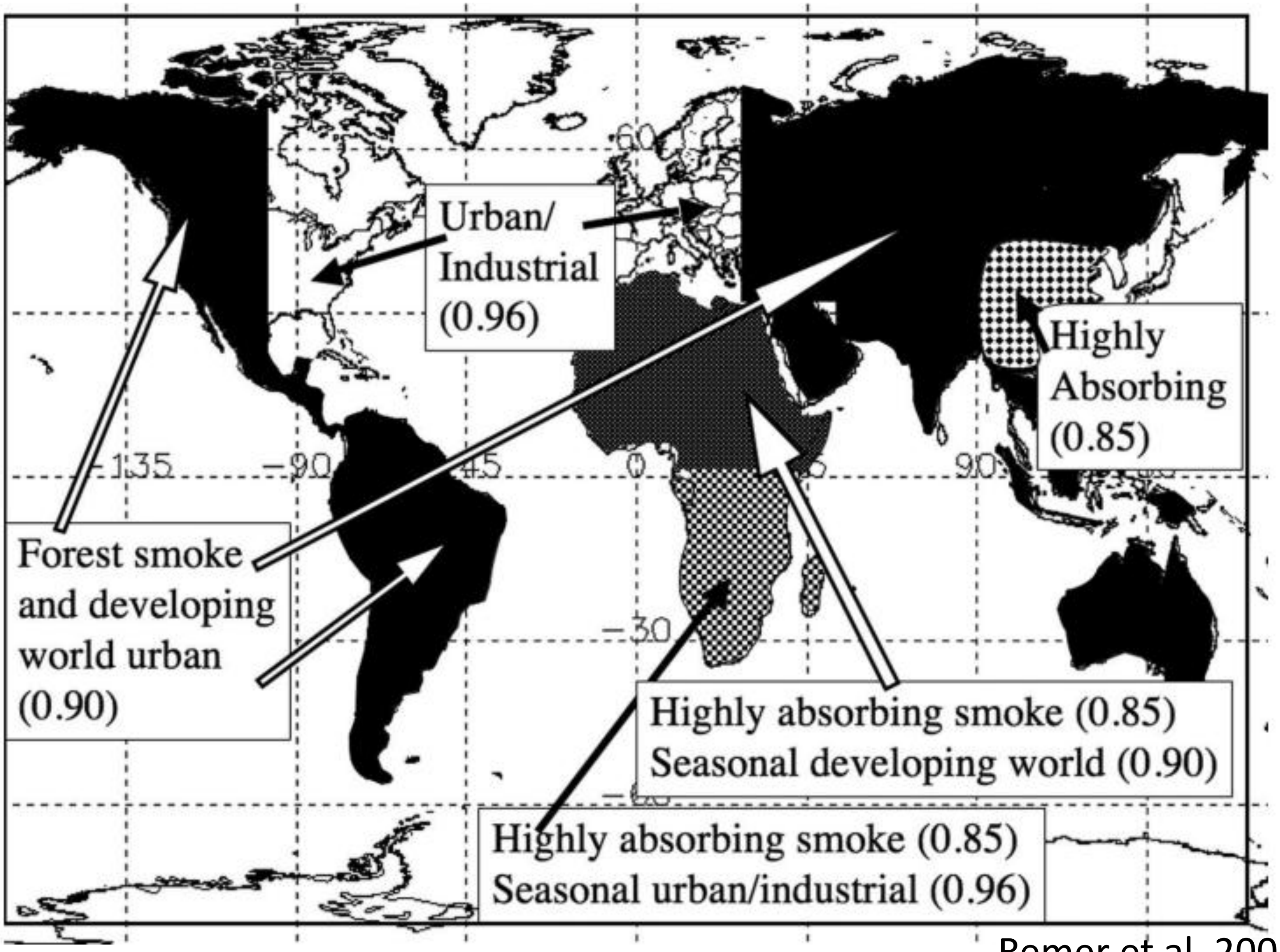
Second, surface reflectance across the solar spectrum is well correlated. Soils usually have a reflectance that increases as a function of wavelength, with a correlation that slowly decreases as the wavelength span increases.

Surface Reflectance at longer wavelengths (e.g. 2.2 micron, shown on x-axis) is used as a reference value, which is then linearly transformed to estimate the surface reflectance in the visible bands (e.g. 0.49 and 0.66 micron).

Remer et al. 2005

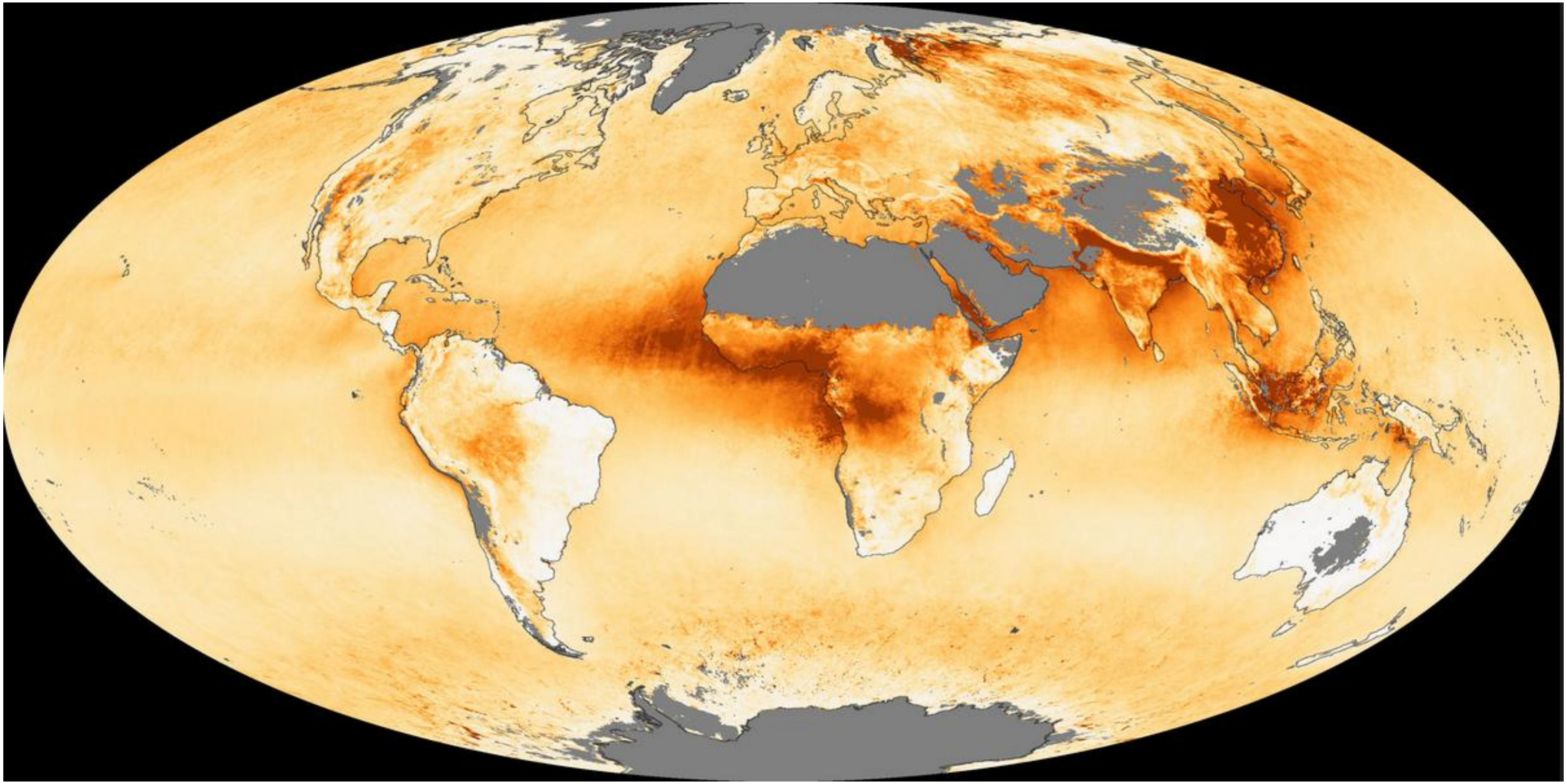
Aerosol Model Parameterization in Dark-Target Algorithm

Values in below figure indicate different Single Scattering Albedo for various regions, suggesting varying aerosol absorption



Remer et al. 2005

MODIS Dark-Target AOD



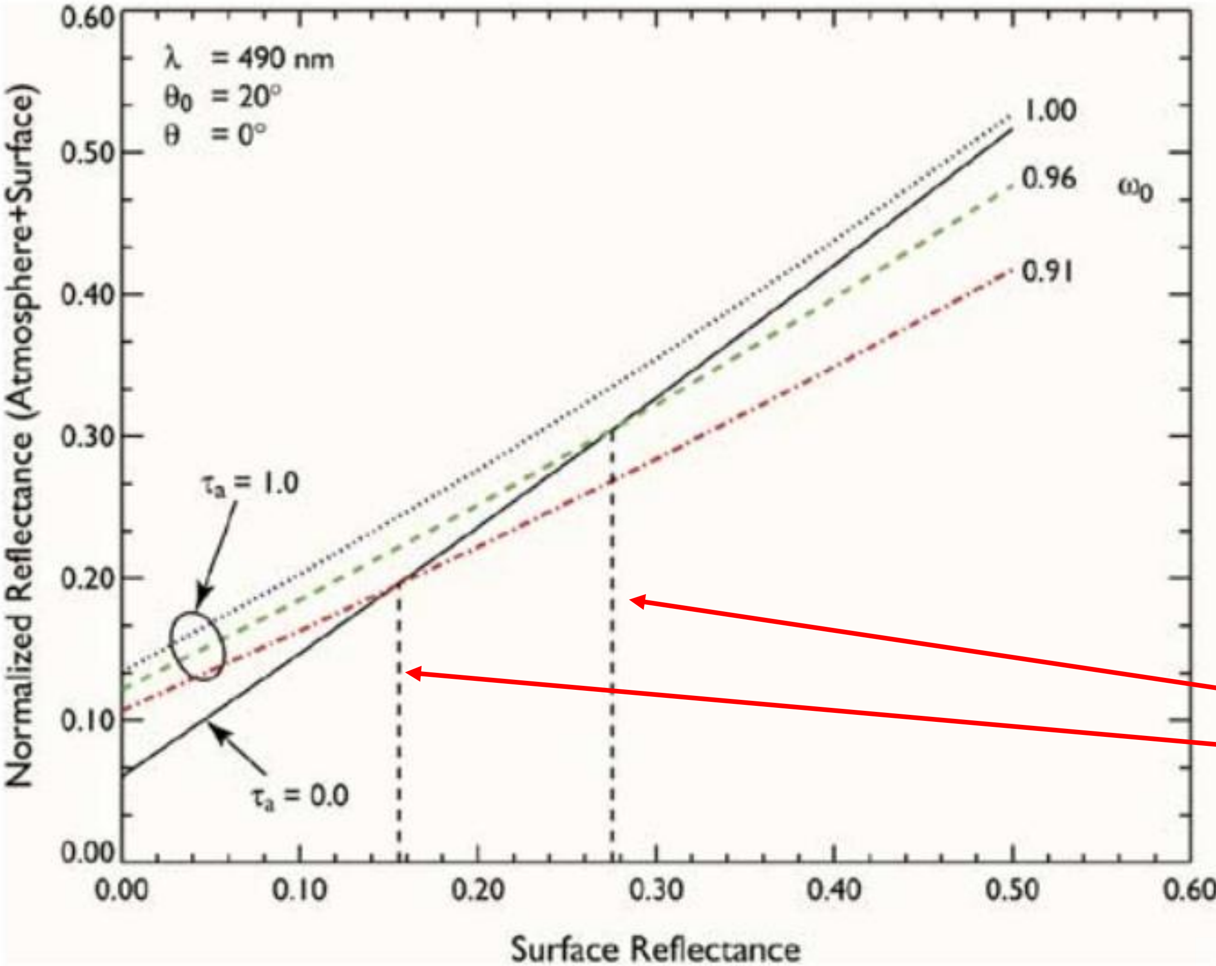


Fig. 1. Simulated apparent reflectance (atmosphere + surface) at the top of the atmosphere at 490 nm, as a function of surface reflectance for various values of the aerosol optical thickness τ_a and single-scattering albedo ω_0. The black solid line represents the apparent reflectance without aerosol, and the black dotted, green, and red lines represent the apparent reflectance with $\tau_a = 1.0$. The vertical lines denote the critical values of surface reflectance where the presence of aerosol cannot be detected by satellite for selected values of ω_0.

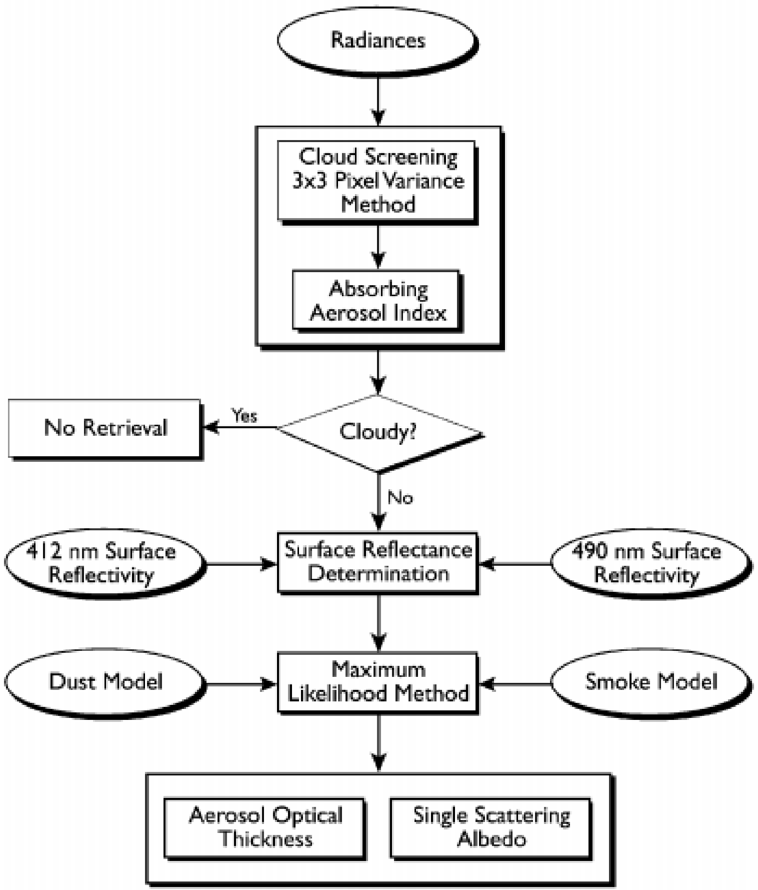
Basis for MODIS Aerosol Dark Target Retrieval Algorithm

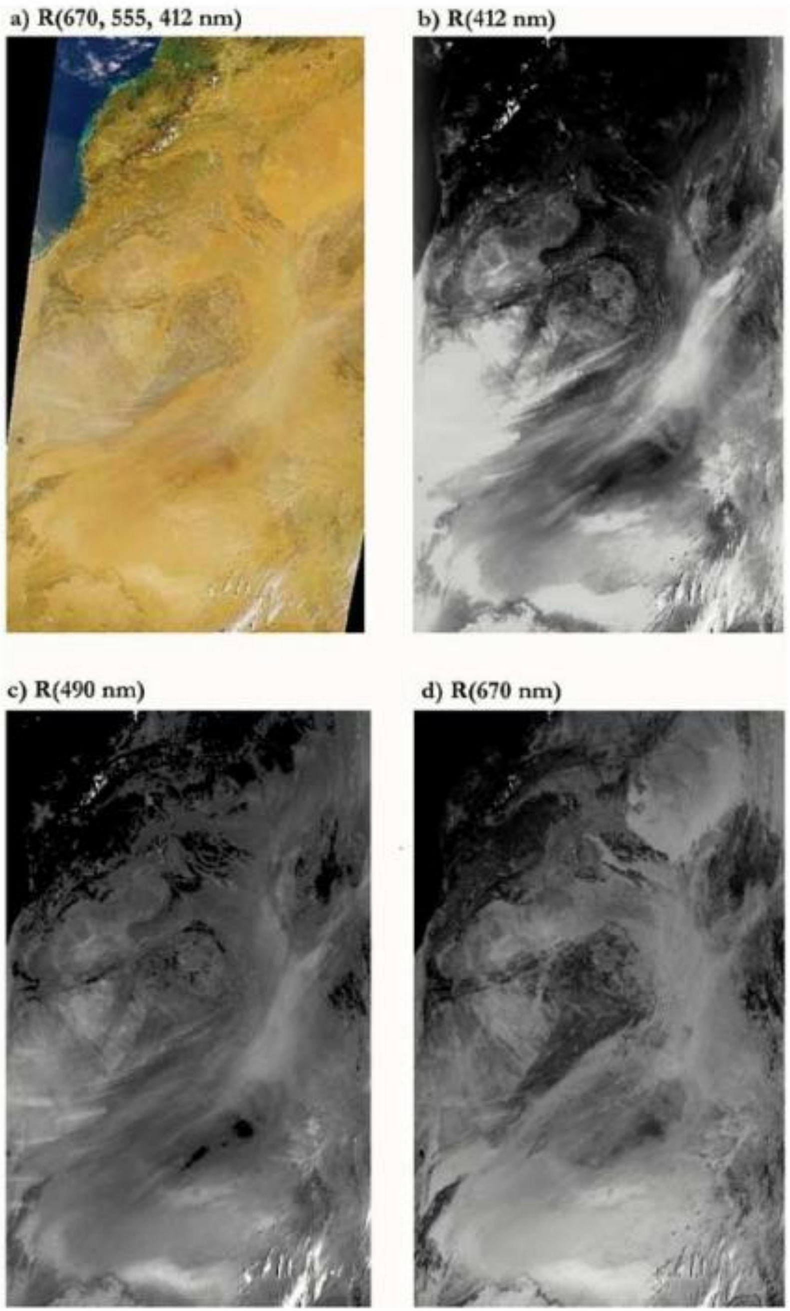
The vertical lines denote where detection of aerosols is difficult from satellite. This is because at higher surface reflectance values, it is difficult to distinguish between the underlying surface and overlying aerosol, from TOA.

Hsu et al. 2004

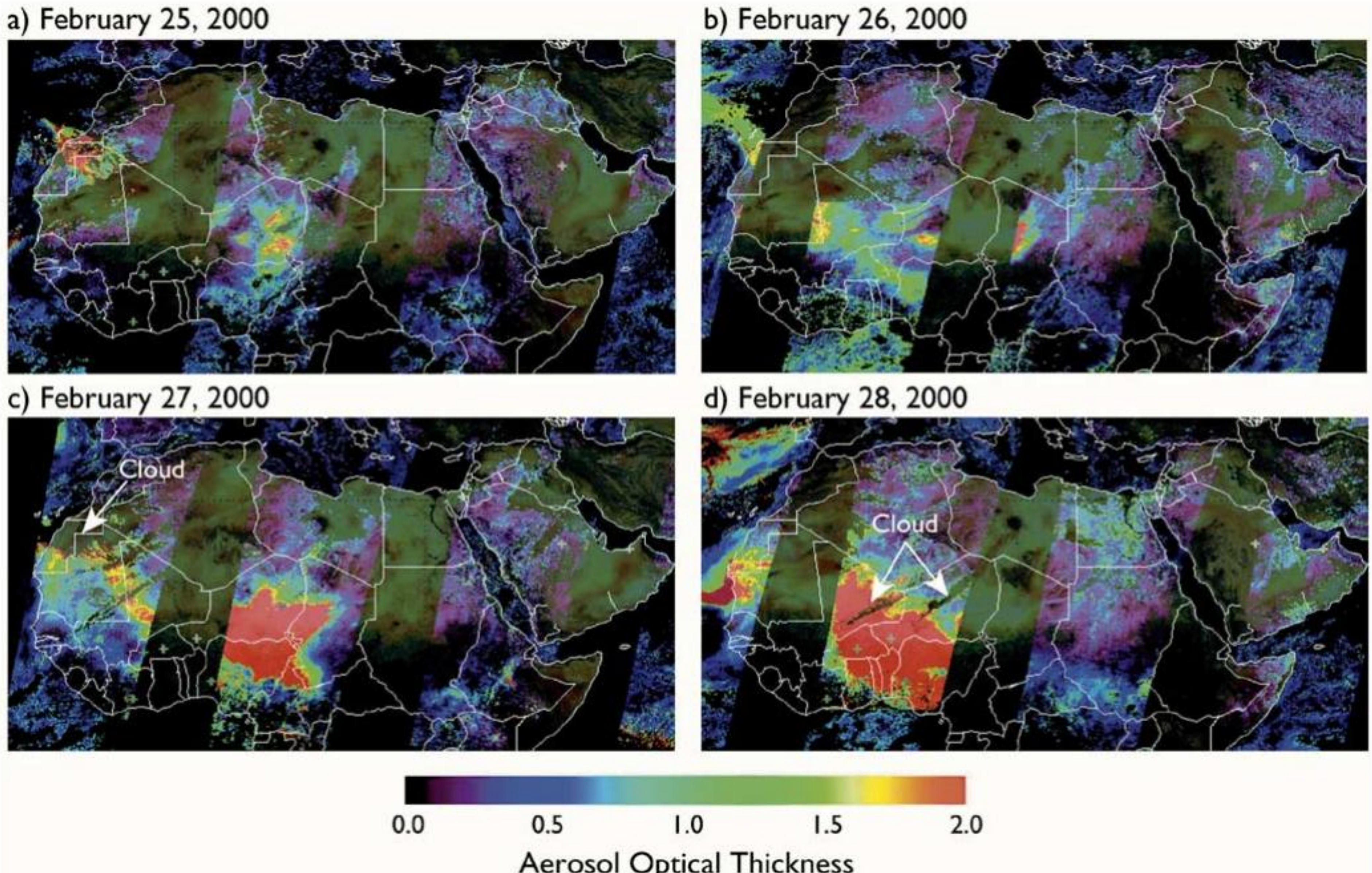
Basic Principle of MODIS Deep Blue Aerosol Algorithm over bright desert surfaces:

→ Instead of using reflectance at 490nm and 670nm, the deep blue algorithm uses the 412nm band where desert surface appears darker. As a result, it is easier to detect aerosols over desert at deep blue band (e.g. 412nm band).

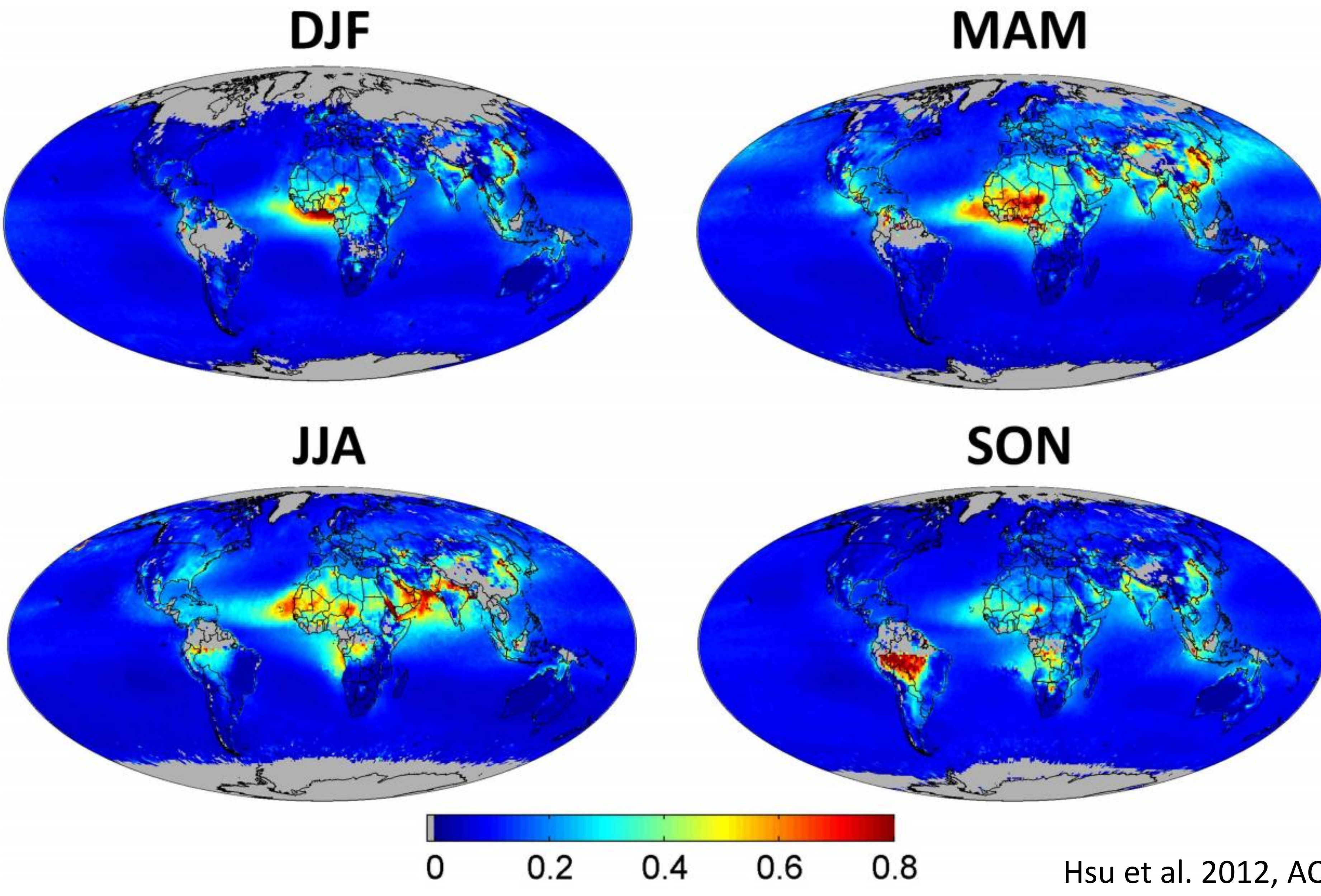




MODIS Deep Blue AOD



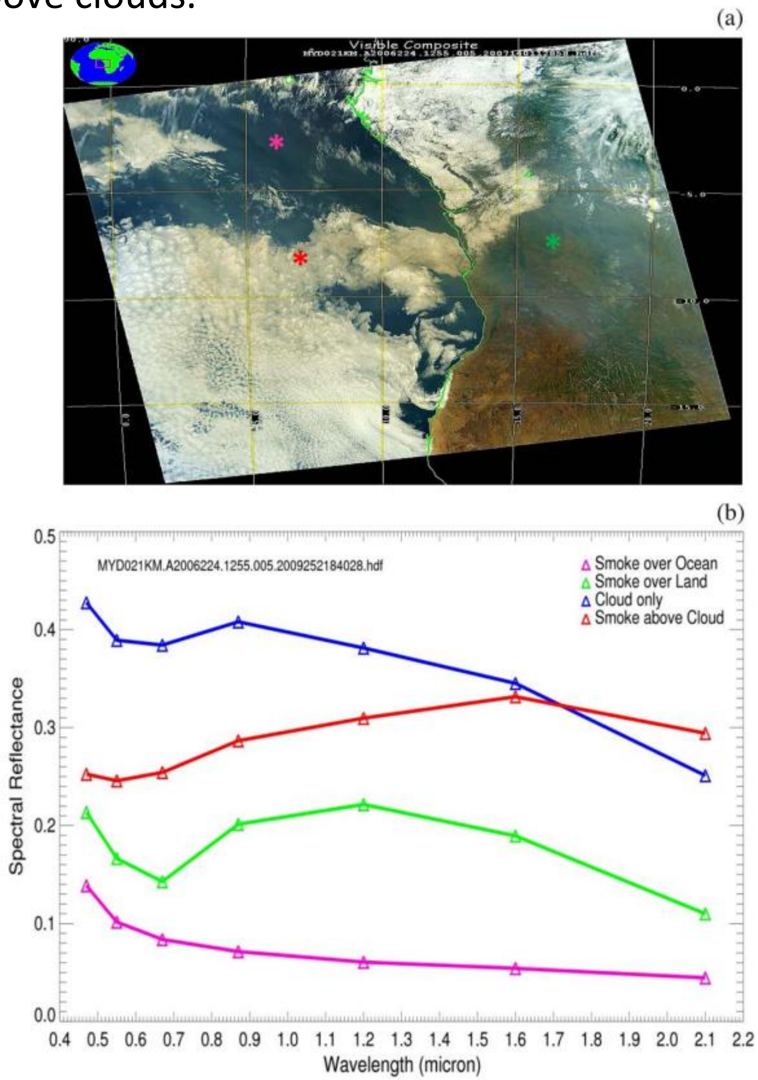
SeaWiFS Deep Blue AOD

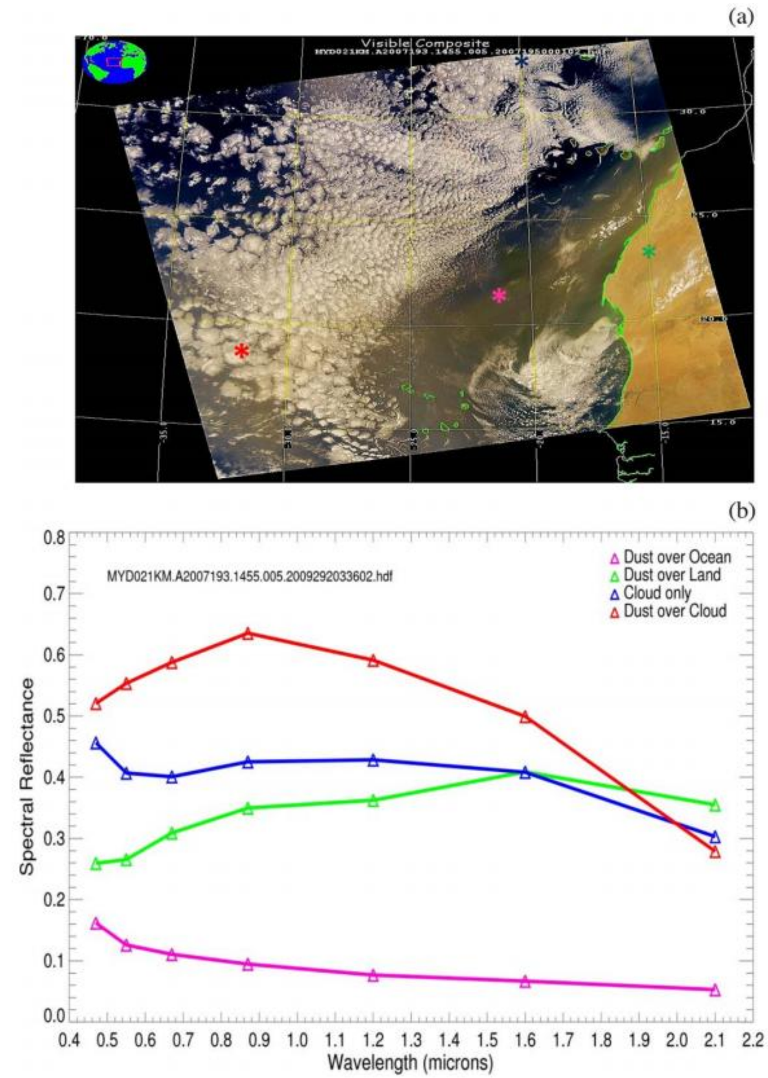


Hsu et al. 2012, ACP

Aerosol Remote Sensing over bright regions (e.g. Clouds)

In the case of aerosols above clouds, clouds appear darker due to multiple orders of reflections taking place between a bright surface such as the top of the cloud and the overlying aerosol layer. Refer to the red curves in the two plots below when smoke is above clouds and dust is above clouds.





Jethva et al. 2013

Aerosol Remote Sensing over bright regions (e.g. Clouds)

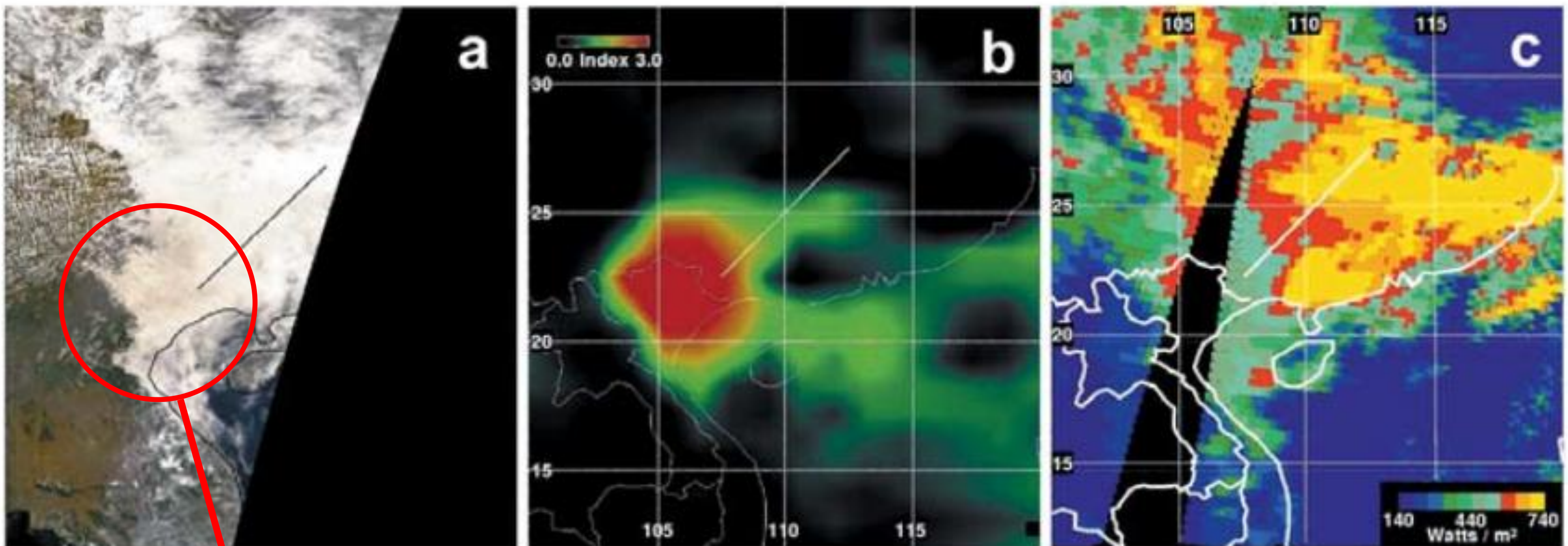


Figure 1. SeaWiFS true color image for Southeast Asia on 17 March 2000 is shown in (a), the corresponding TOMS AI in (b), and the CERES TOA upwelling shortwave flux in (c).

Hsu et al. 2013

This area of the clouds appears to be darker than the rest of the cloudy region. It is also evident, in the figure on the right (panel c), that the upward reflected flux (in Wm^{-2}) is lower for the same region when aerosols are above cloud. The reflected flux values are significantly higher when there is not much aerosols above clouds (>600 Wm^{-2})

Aerosol Remote Sensing over bright regions (e.g. Clouds)

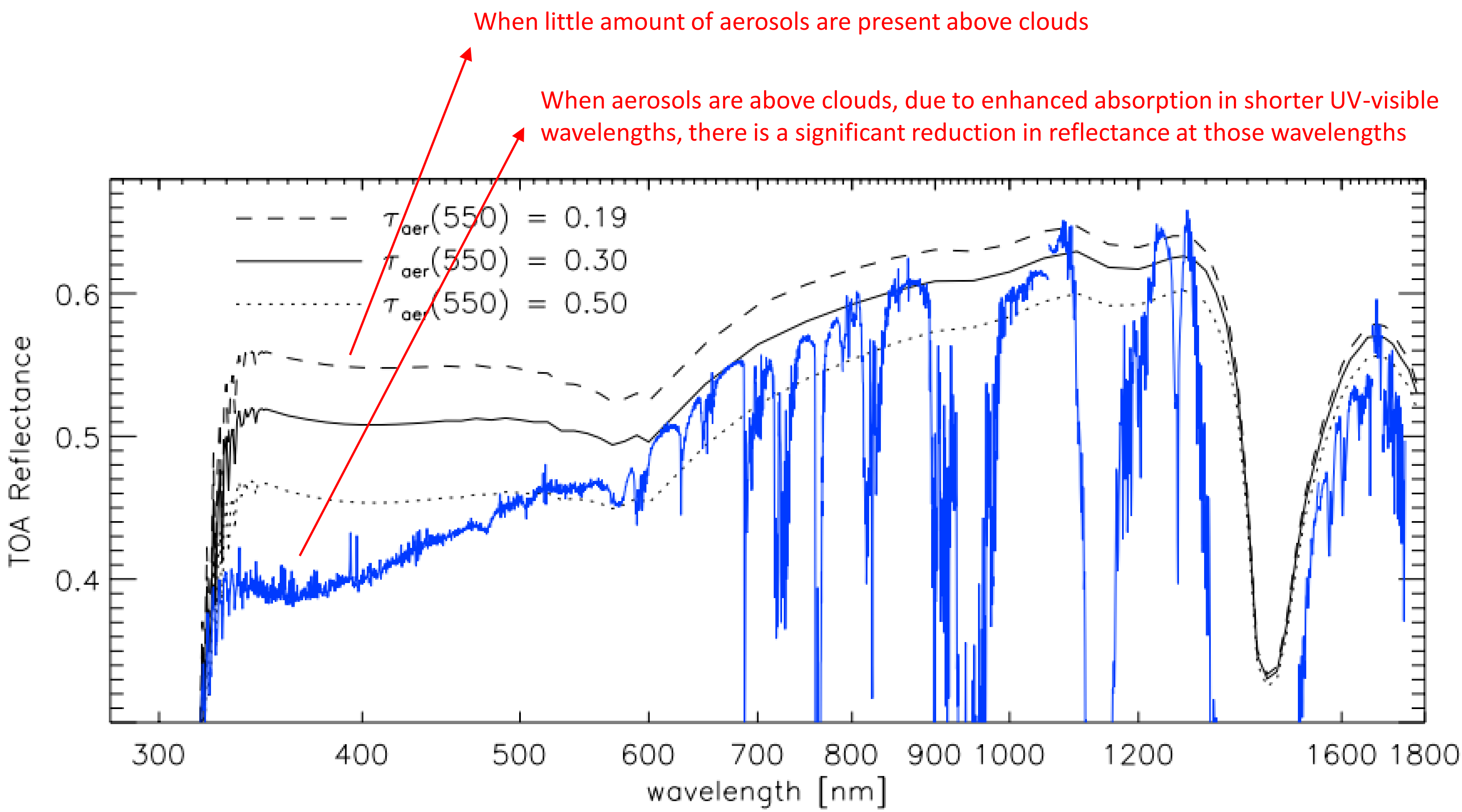
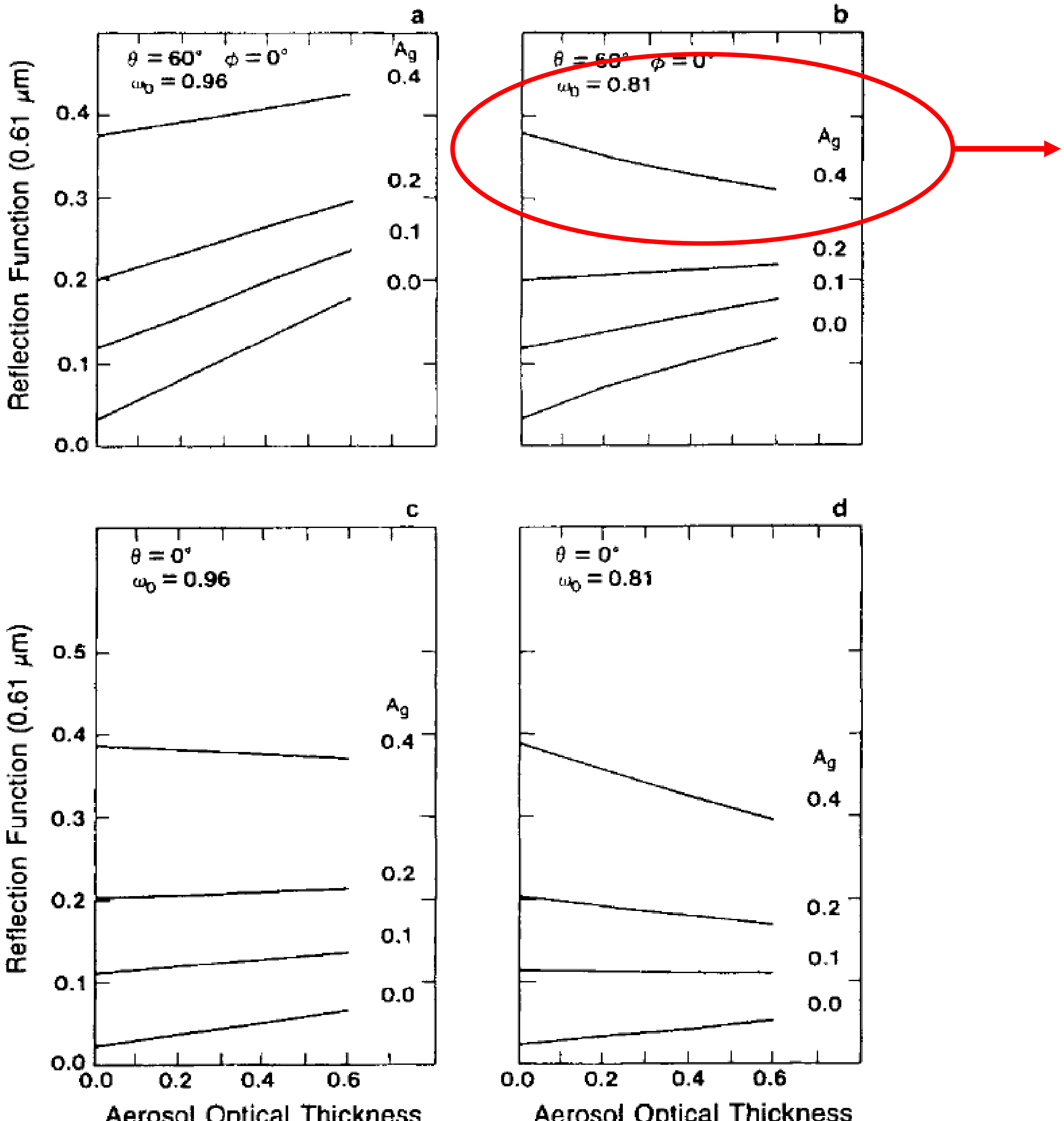


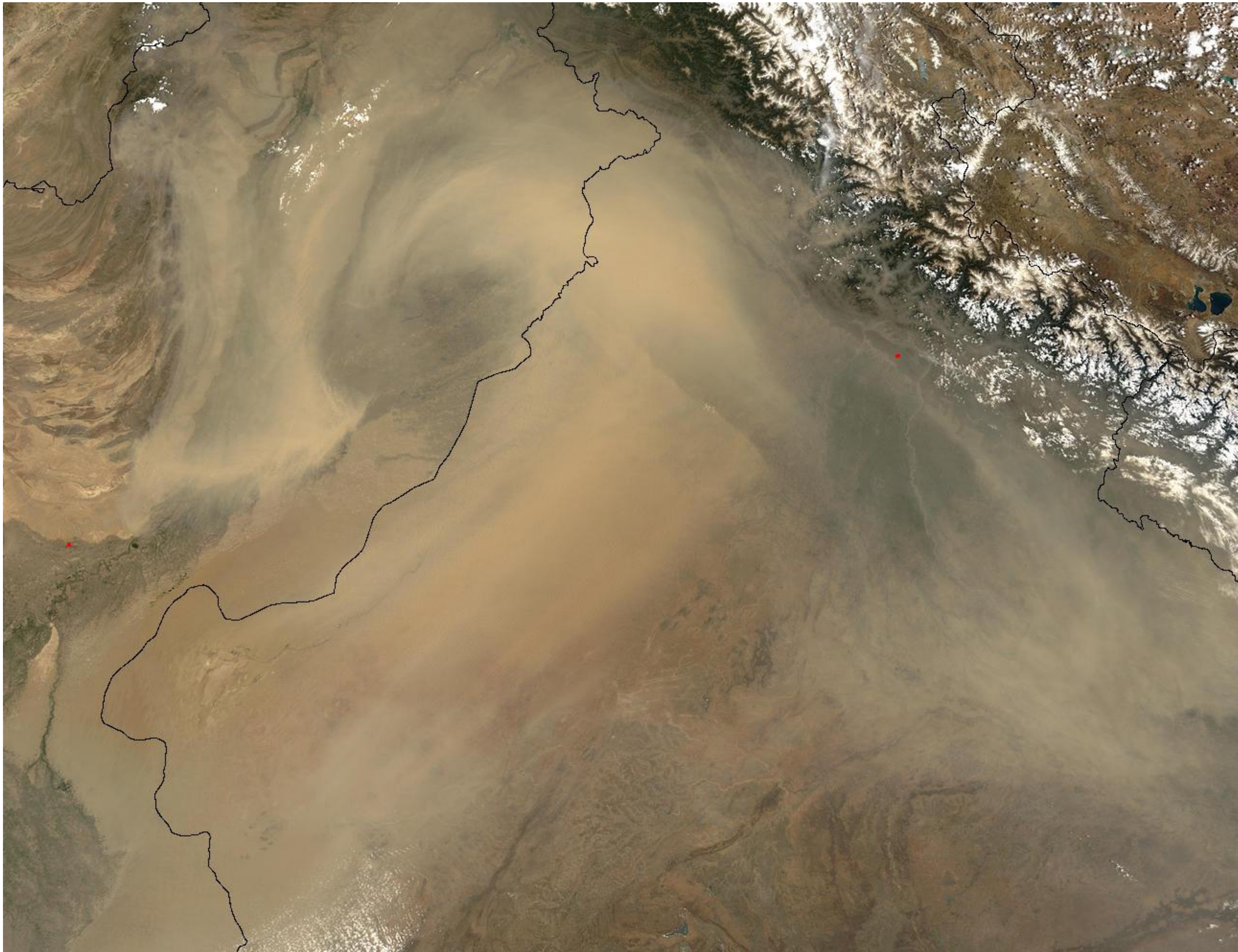
Figure 8. Multiple simulations of a smoke scene using model 3 (black lines), compared to the measured BBA scene (blue). The solid black line shows a fit to the measured reflectance spectrum, using a mixture of 99.5% aerosols in number density, corresponding to an aerosol optical thickness at 550 nm of 0.30, which is the same as the AOT of model 1. The reflectance spectra of layers with an AOT of 0.19 and 0.50 are shown for comparison by the dashed and the dotted line, respectively.

De Graaf et al. 2007



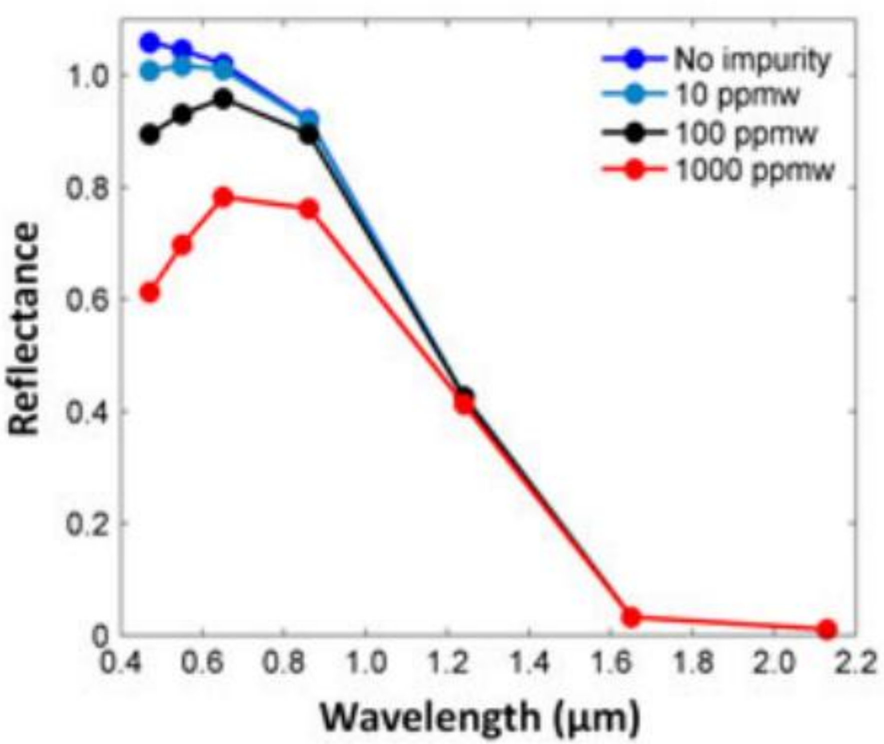
This reduction in reflectance for bright areas (higher surface reflectance value) is the basis for the apparent darkening of clouds, observed by satellites, when aerosols are present above clouds or snow.

Aerosol Remote Sensing over bright regions (e.g. SNOW)

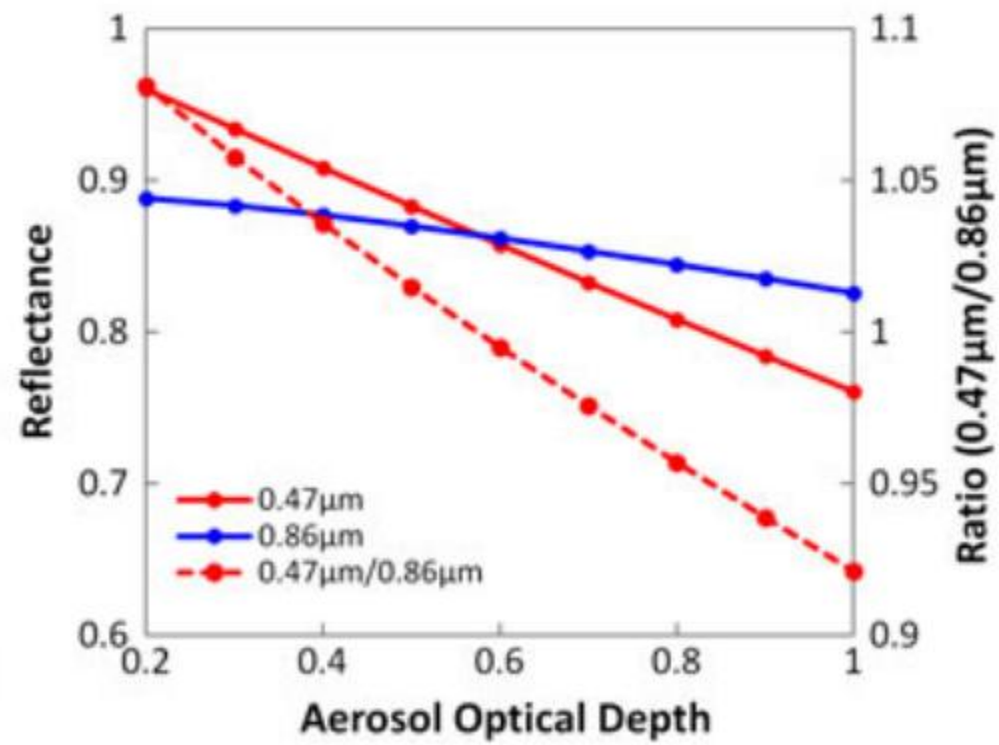


Model sensitivity study of Snow Reflectance

Snow surface reflectance (with dust impurity)



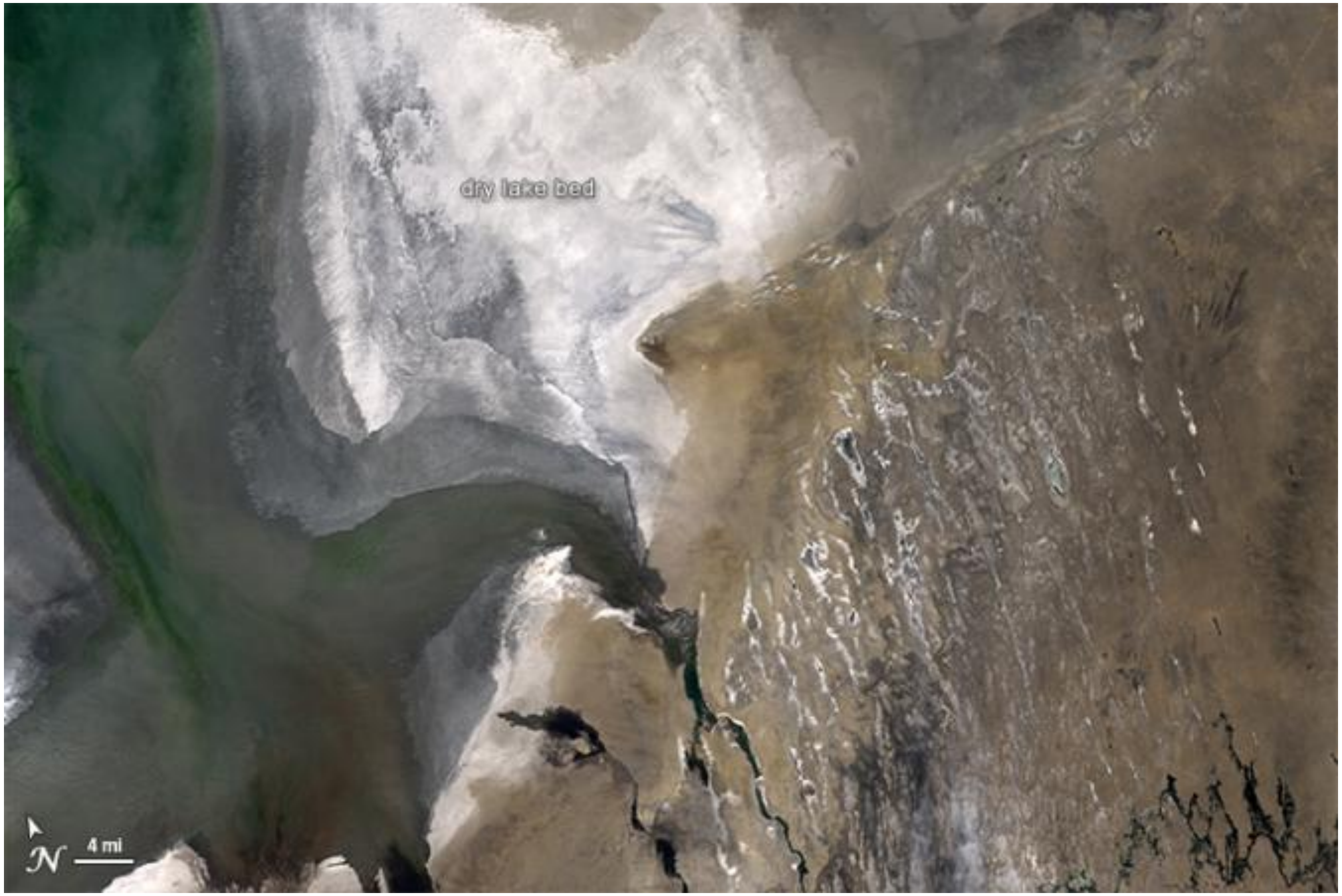
TOA reflectance (with dust above snow)



→ *Snow Bidirectional Reflectance Distribution Function (BRDF) model (Kokhanovsky et al. 2011)*
→ *Enhanced solar absorption at shorter visible wavelengths (e.g. 0.47µm), VIS-NIR gradient*
→ *SZA=30°, VZA=20°*

Gautam et al. *Geophys. Res. Lett.* (2013)

True-color Image from Landsat



http://earthobservatory.nasa.gov/IOTD/view.php?id=81210

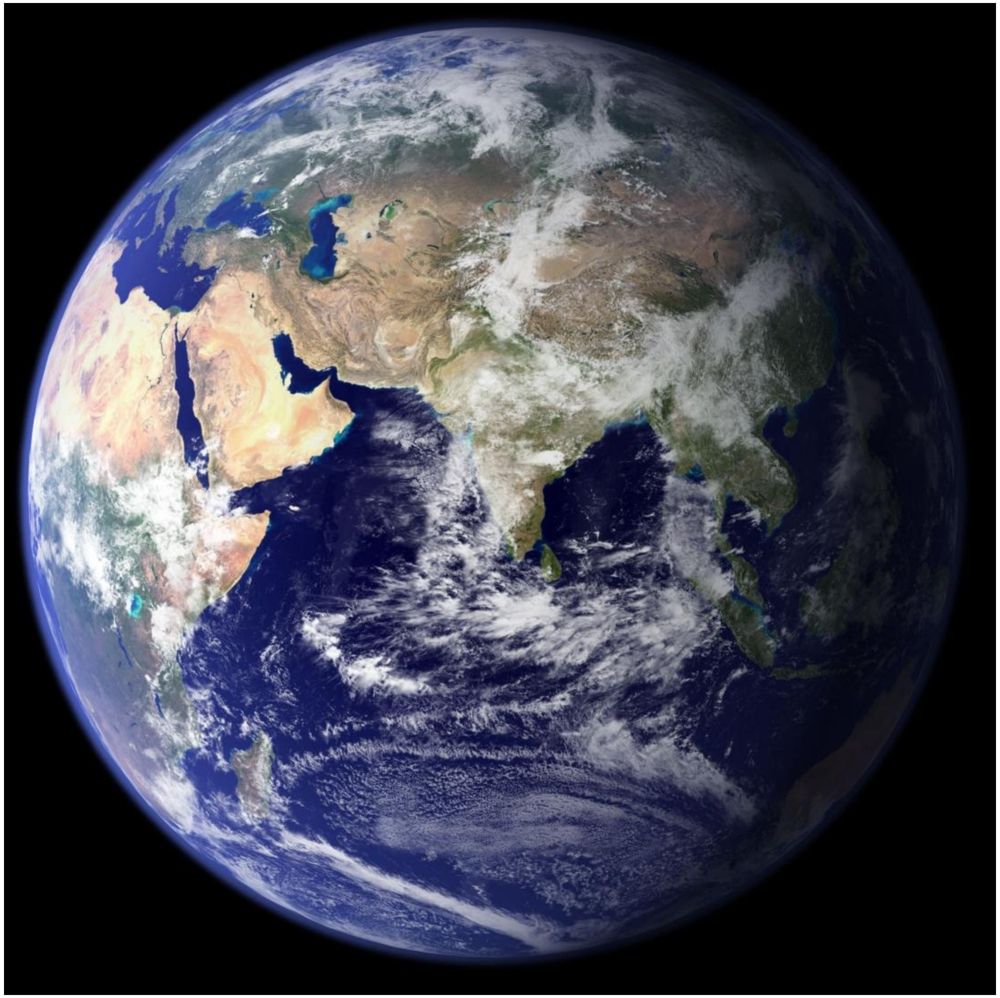
This true-color image (made from R, G, B bands) from the Landsat satellite is an excellent example of a case when apparently there are sub-visible thin cirrus clouds present in the scene, but are barely visible in the R, G, B bands. However, they are evident in the near-IR wavelength at 1.38 micron which is used to detect the presence of cirrus clouds (refer to next slide).

Reflectance at 1.38micron

http://www.nasa.gov/mission_pages/landsat/news/cloud-free-aral.html

“Man must rise above the Earth -- to the top of atmosphere and beyond – for only thus will he fully understand the world in which he lives”

– Socrates



Remote Sensing of Aerosols

- Remote Sensing of Tropospheric Aerosols from Space: past, present and future
- Authors- King, Kaufman, Tanre, Nakajima
- Paper is available at:

http://repository.dl.itc.u-tokyo.ac.jp/dspace/bitstream/2261/51855/1/Nakajima1999BAMS_H24P51.pdf

Long-term trend analysis of aerosols using satellite data

- Global and Regional trends in Aerosol Optical Depth over land and ocean using SeaWiFS measurements from 1997 to 2010
- Authors: Hsu et al.
- Paper is available at:

http://www.atmos-chem-phys.net/12/8037/2012/acp-12-8037-2012.pdf