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Lesson 2:

Aerosol Optical Depth
Radiative transfer equation
Deriving aerosol optical depth (AOD) from a single wavelength retrieval.
Adding information content means further constraining the retrieval.

MODIS, VIIRS and OMI aerosol products
Level 0, Level 1, Level 2, Level 3, Level 4

Retrieving aerosol characteristics vs. retrieving gases

Assimiliation data and MERRA-2

Brent Holben, Lorraine Remer Israel 1992

In remote sensing we measure radiation, after it has interacted with a target.

That interaction changes the radiation.

From those changes to the radiation, we can infer characteristics of that target.

Those characteristics are called retrievals.

Retrievals that have gone through a vetting process and offered to users by a data center are called products.

In aerosol remote sensing we measure radiation after it has interacted with aerosol particles in the atmosphere, and we infer aerosol characteristics from that interaction.

When radiation encounters a particle the scattered radiation has a

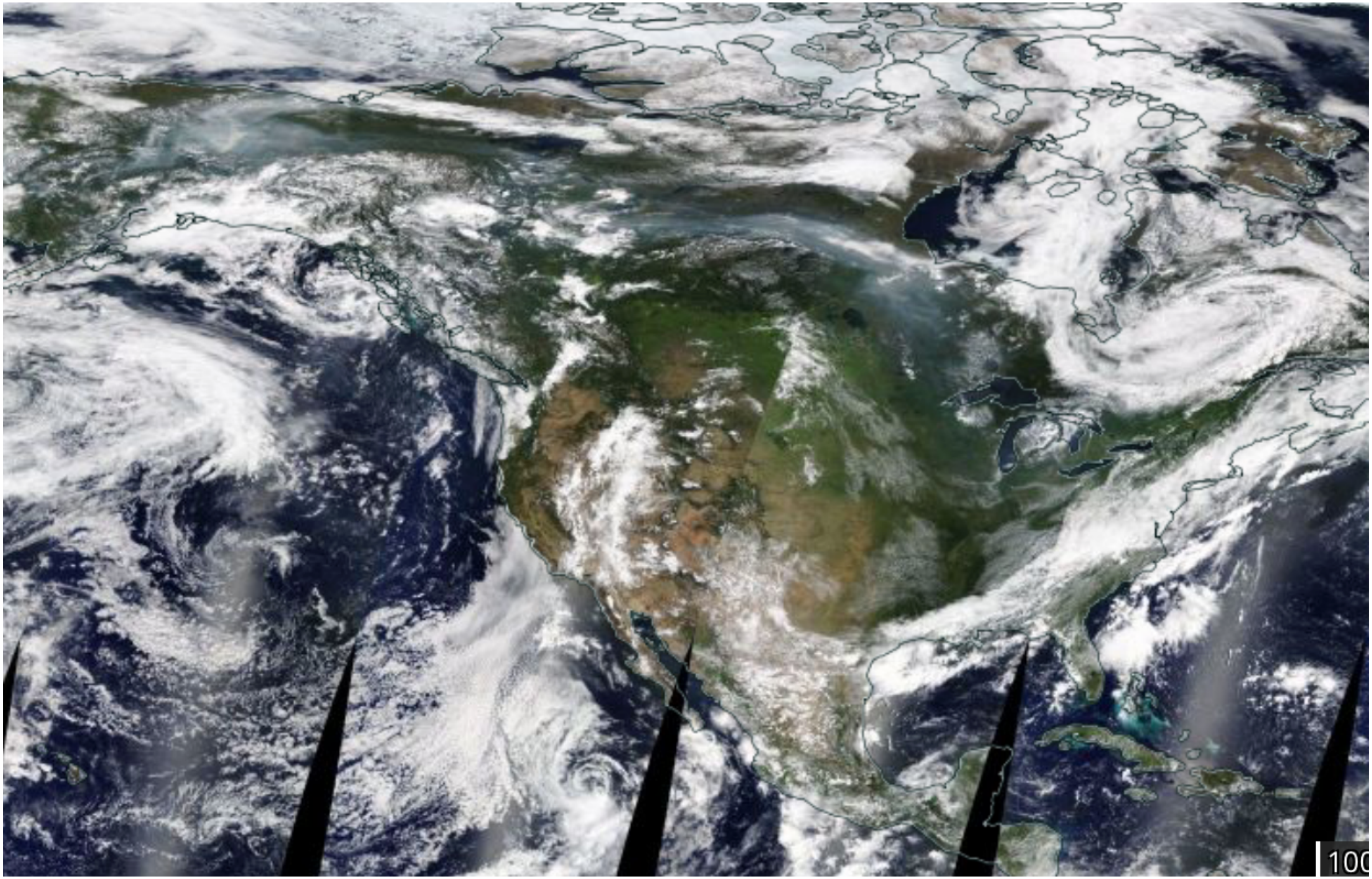
- Spectral (wavelength) signature
- Angular signature
- Polarization signature

These depend on the characteristics of the particles:

- Size
- Shape
- Composition

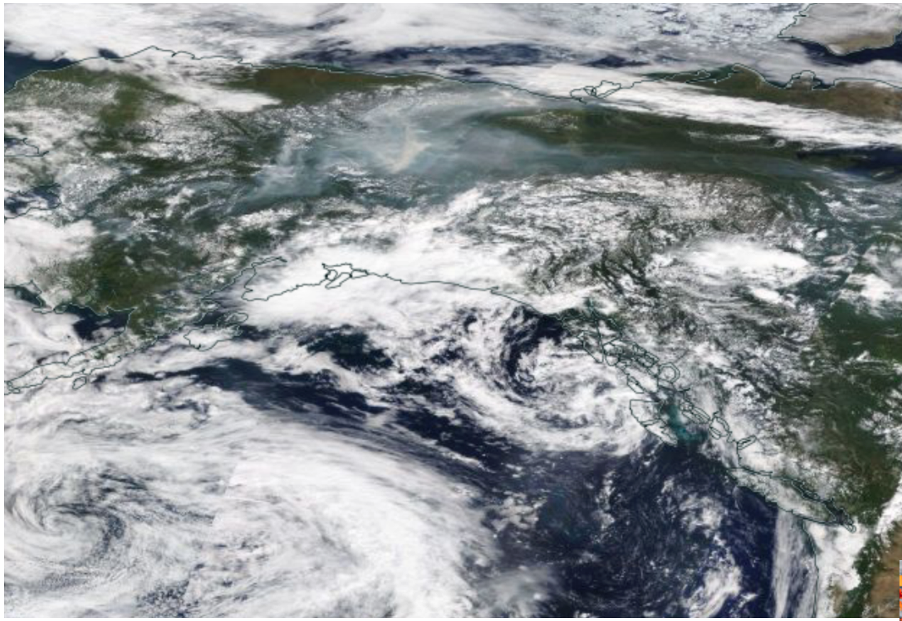
In aerosol remote sensing we measure the scattered radiation and try to reconstruct the characteristics of the particles that were involved in that encounter.

But we are missing something vital here….



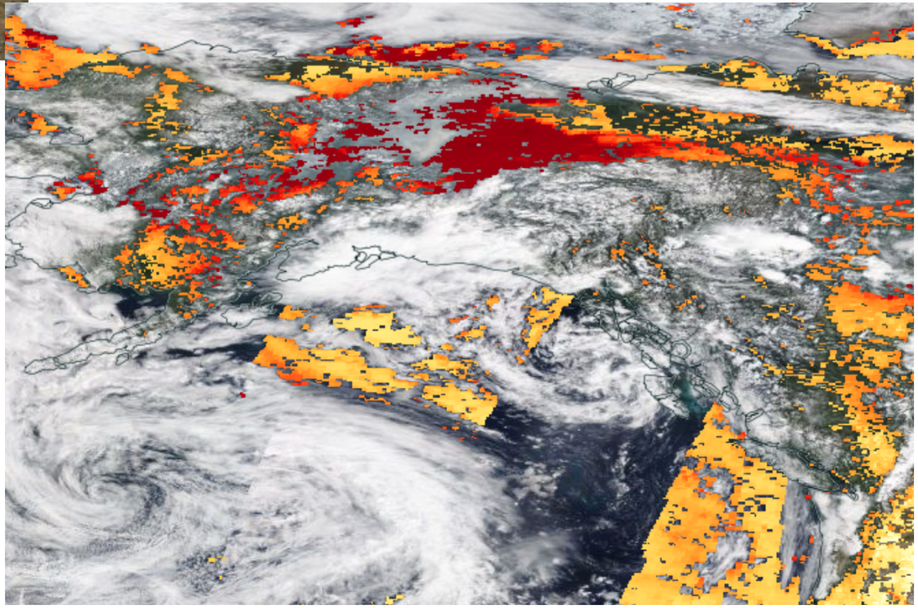
MODIS Terra image from yesterday (Worldview)

But we are missing something vital here …

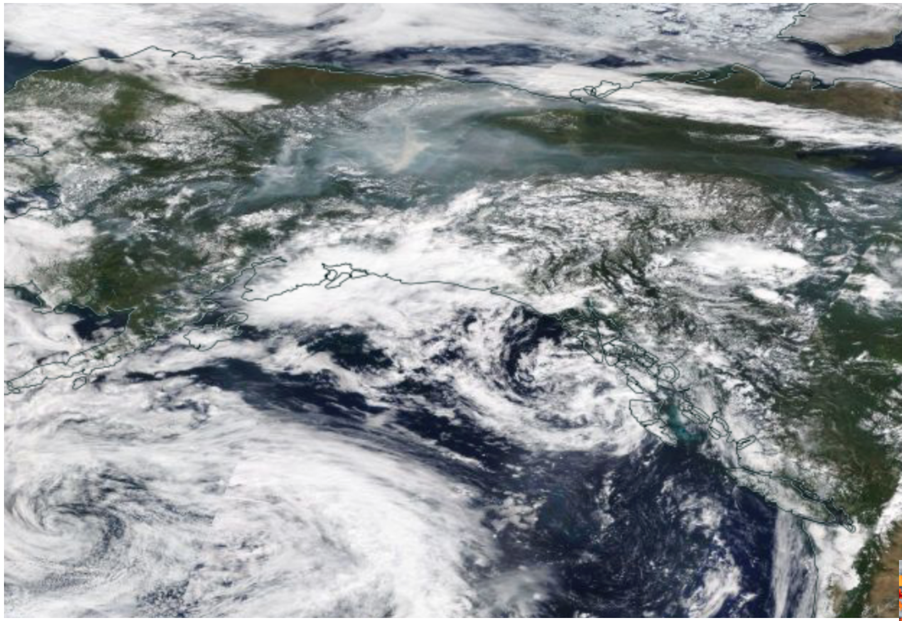


Smoke event in Alaska.
We would like to know the size, shape and composition of those particles.

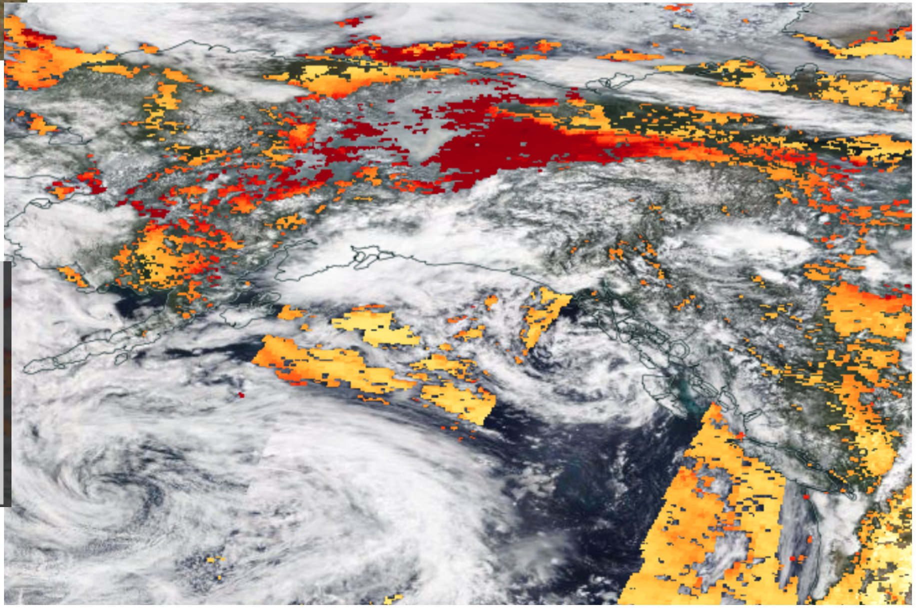
But what is even more basic?

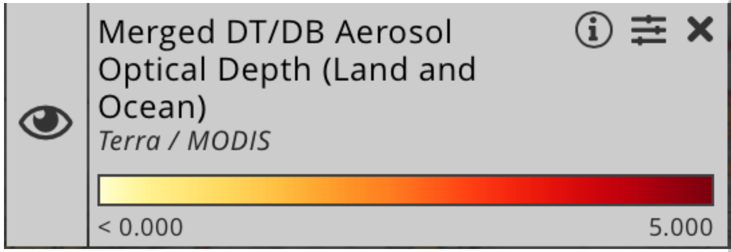


The basic parameters of an aerosol retrieval…



1) Qualitative detection of event.
2) Quantitative measure of the aerosol loading.





Merged DT/DB Aerosol Optical Depth (Land and Ocean)

Terra / MODIS

< 0.000

5.000

Aerosol Optical Depth (AOD or τ):

$$\tau_\lambda = \int_{sfc}^{toa} \sigma_{e\lambda} dz$$

$$\sigma_{e\lambda} = \sigma_{e\lambda} + \sigma_{e\lambda}$$

$\sigma_{e\lambda}$ is the extinction parameter
$\sigma_{a\lambda}$ is the absorption parameter
$\sigma_{s\lambda}$ is the scattering parameter

These parameters are intensive and depend on particle size, shape and composition, but when you integrate them through the atmospheric column they combine to give us a extensive measure of their total optical effect.

AOD depends on the aerosol loading, the amount of particles in the column, not just on their optical properties.

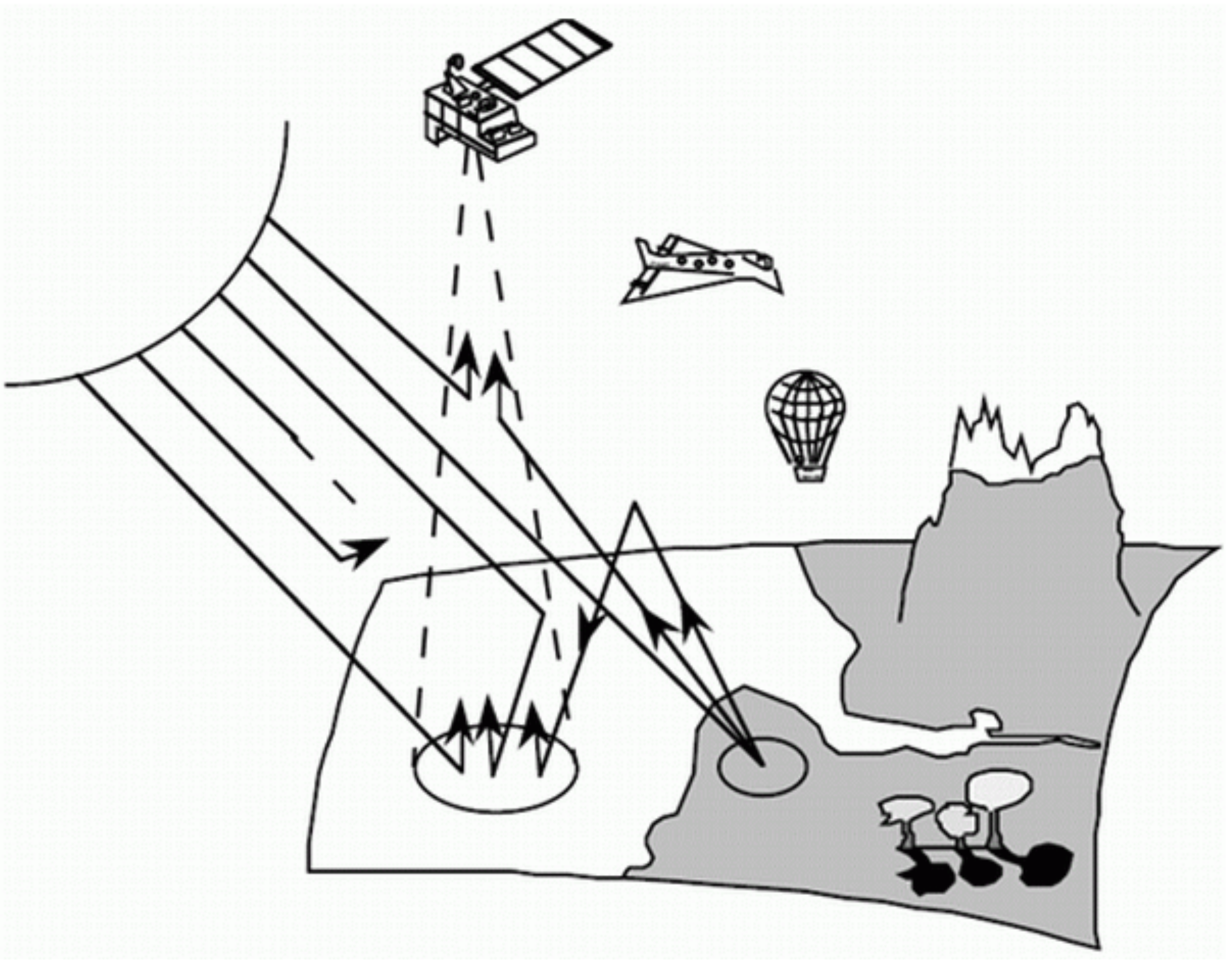
AOD and Aerosol Optical Thickness can be used interchangeably for our purposes.

The first order quantitative information that we want is the amount of particles in the column.

Because we work with radiation measurements in the optical regime, we satisfy this want by retrieving AOD.

Note that AOD is a function of size, shape and composition, which we don’t know, as well as amount.

Radiative Transfer



From the 6SV manual

$$\underbrace{L(\tau^{*},\mu_o,\mu,\varphi)}_{\boxed{\text{Radiance measured at satellite}}} = \underbrace{L_o(\tau^{*},\mu_o,\mu,\varphi)}_{\boxed{\text{Radiance from atmosphere}}} + \underbrace{\frac{RE_oT_t(\tau^{*},\mu)}{1-RS}}_{\boxed{\text{Radiance from surface}}}$$

$$\underbrace{L(\tau^*,\mu_o,\mu,\varphi)}_{\text{Radiance measured at satellite}} = \underbrace{L_o(\tau^*,\mu_o,\mu,\varphi)}_{\text{Radiance from atmosphere}} + \underbrace{\frac{RE_oT_t(\tau^*,\mu)}{1-RS}}_{\text{Radiance from surface}}$$

μ_o = cos(solar zenith angle)
μ = cos(sensor zenith angle
φ = relative azimuth
τ^* = aerosol optical thickness

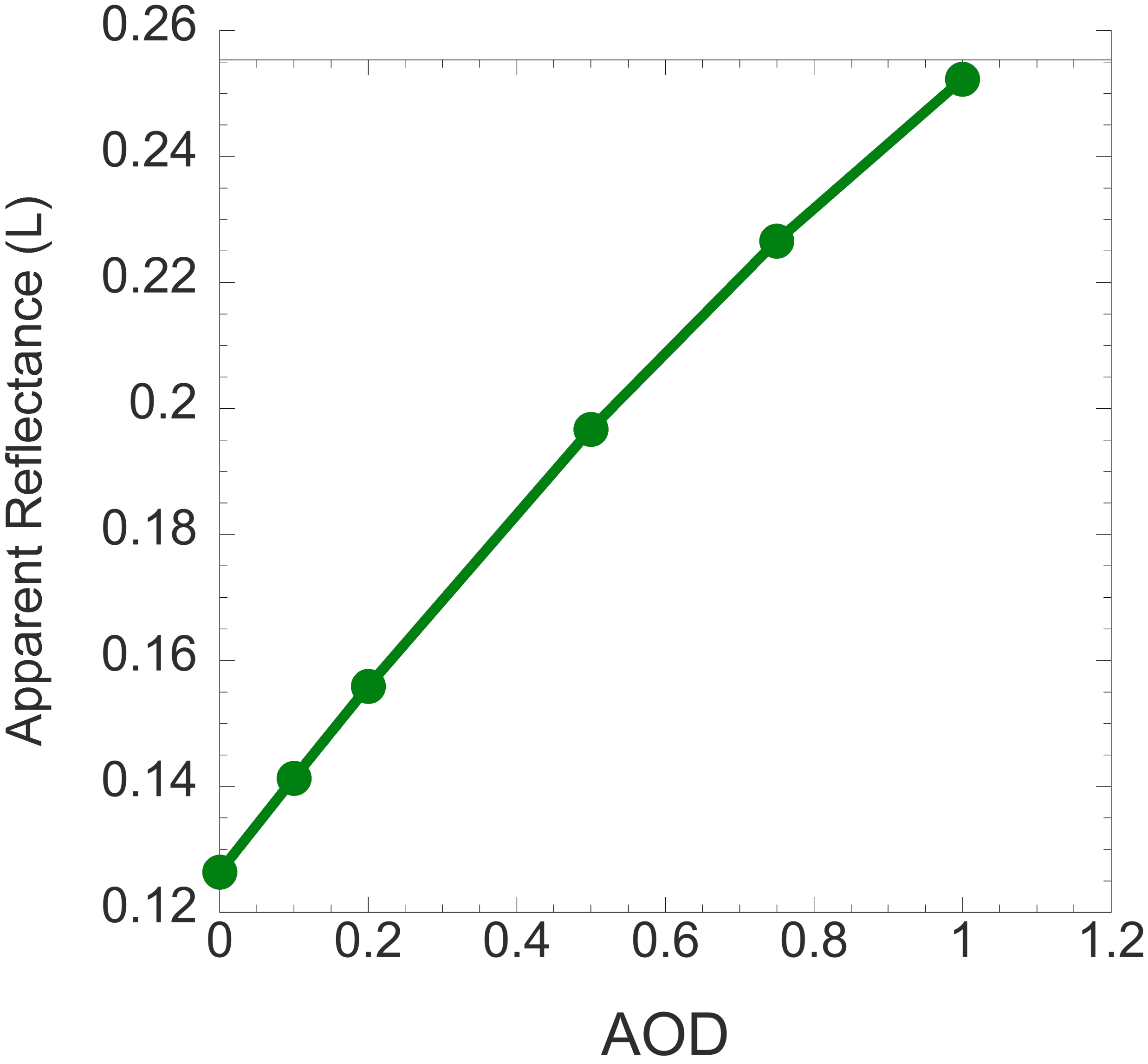
R = surface reflectance
E_o = extraterrestrial irradiance
T_t = total transmission
S = spherical albedo

$$L(\tau^*, \mu_o, \mu, \varphi) = L_o(\tau^*, \mu_o, \mu, \varphi) + \frac{RE_oT_t(\tau^*, \mu)}{1 - RS}$$

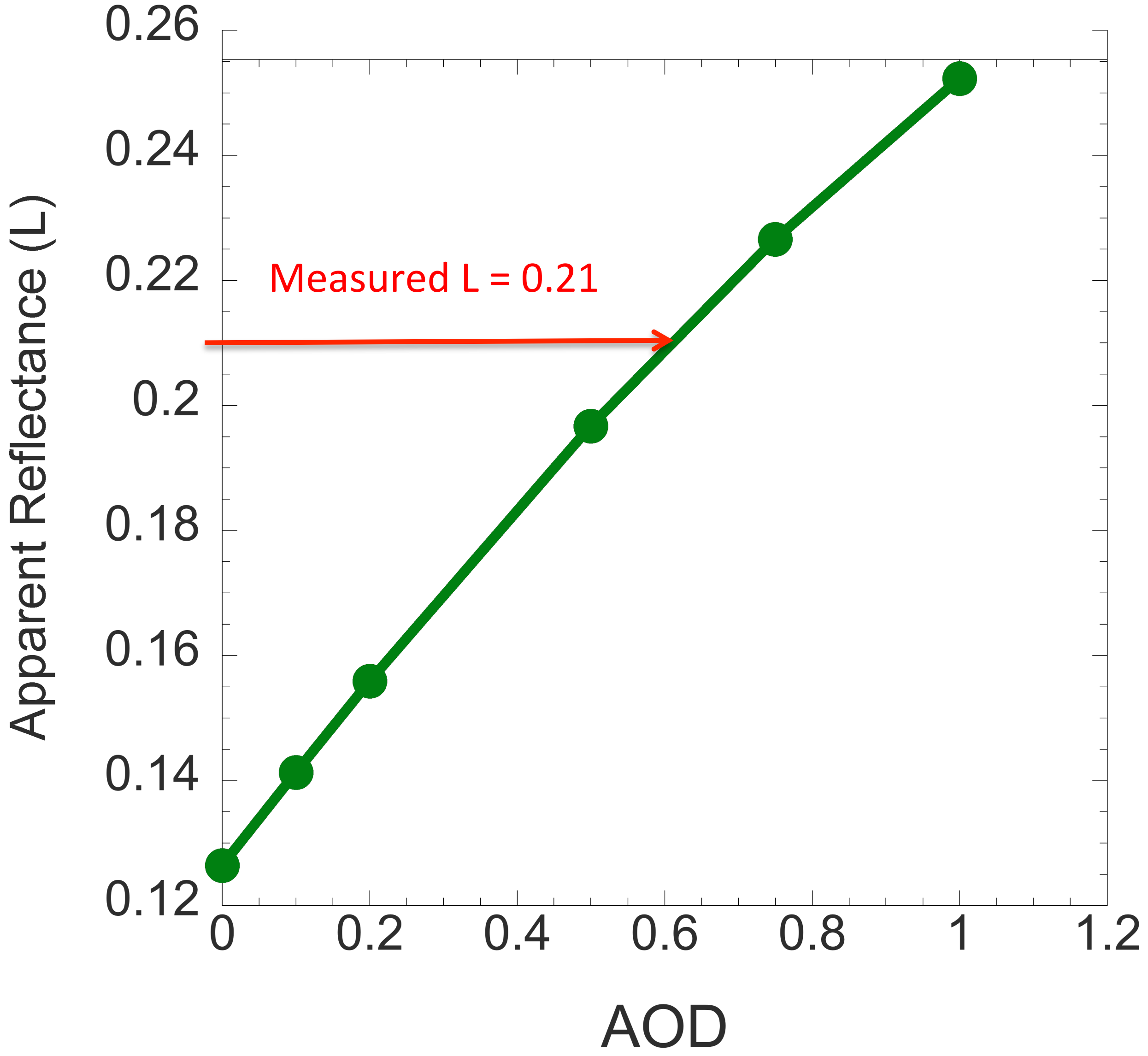
Calculate L_o, T_t and S for the particular geometry and several τ*

Then choose the τ* by matching the calculated right hand side of the equation to the measured *L*. Which τ* matches best?

Calculated L for a variety of AOD,
Assumed particle properties and surface reflectance
And for wavelength = 0.47 µm

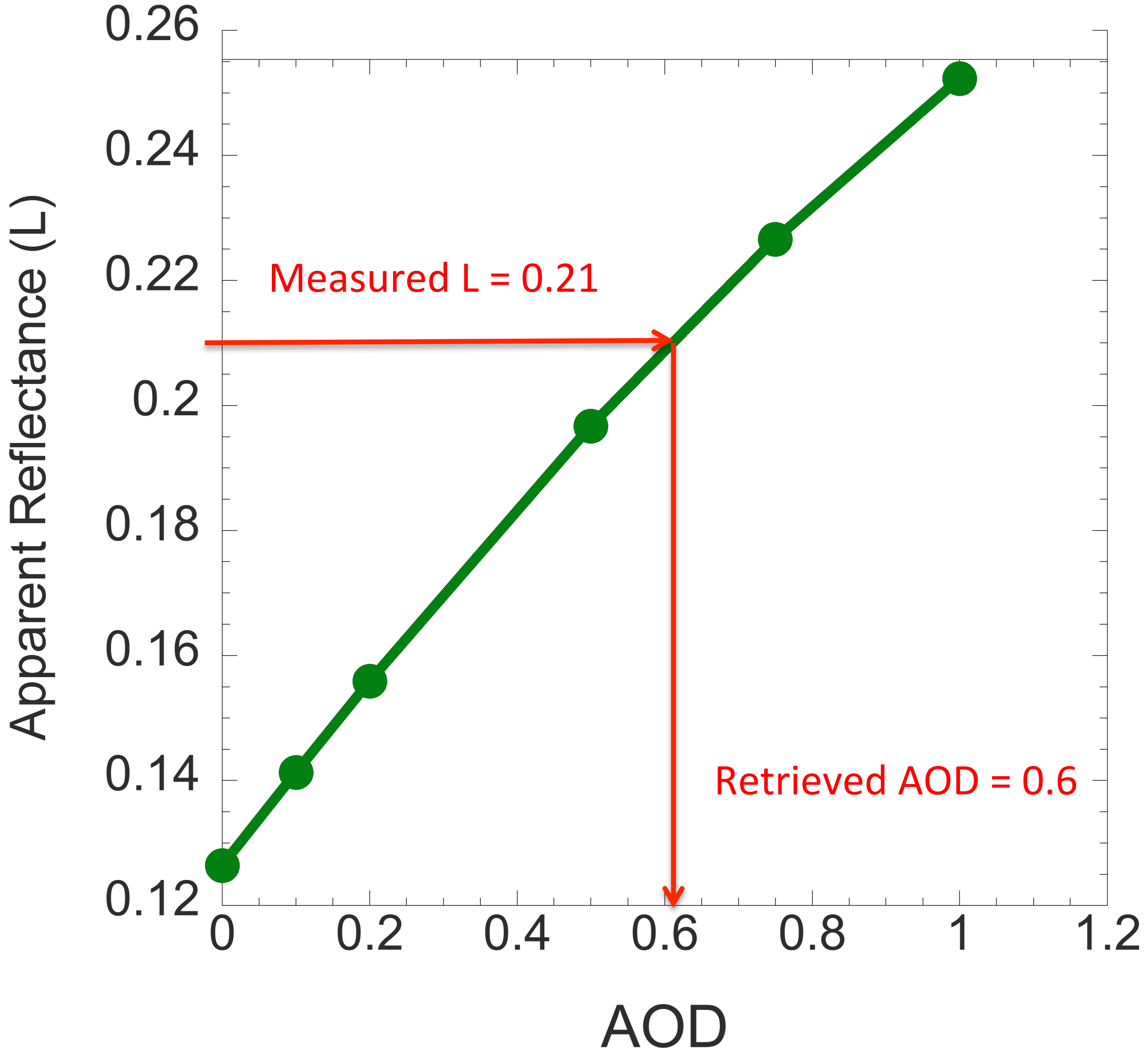


Calculated L for a variety of AOD,
Assumed particle properties and surface reflectance
And for wavelength = 0.47 µm



Measured L = 0.21

Calculated L for a variety of AOD,
Assumed particle properties and surface reflectance
And for wavelength = 0.47 µm



Measured L = 0.21

Retrieved AOD = 0.6

This is a single channel Dark Target retrieval.
(one wavelength at a time)

Requires assumptions of particle size, shape and composition (refractive index), as well as surface reflectance

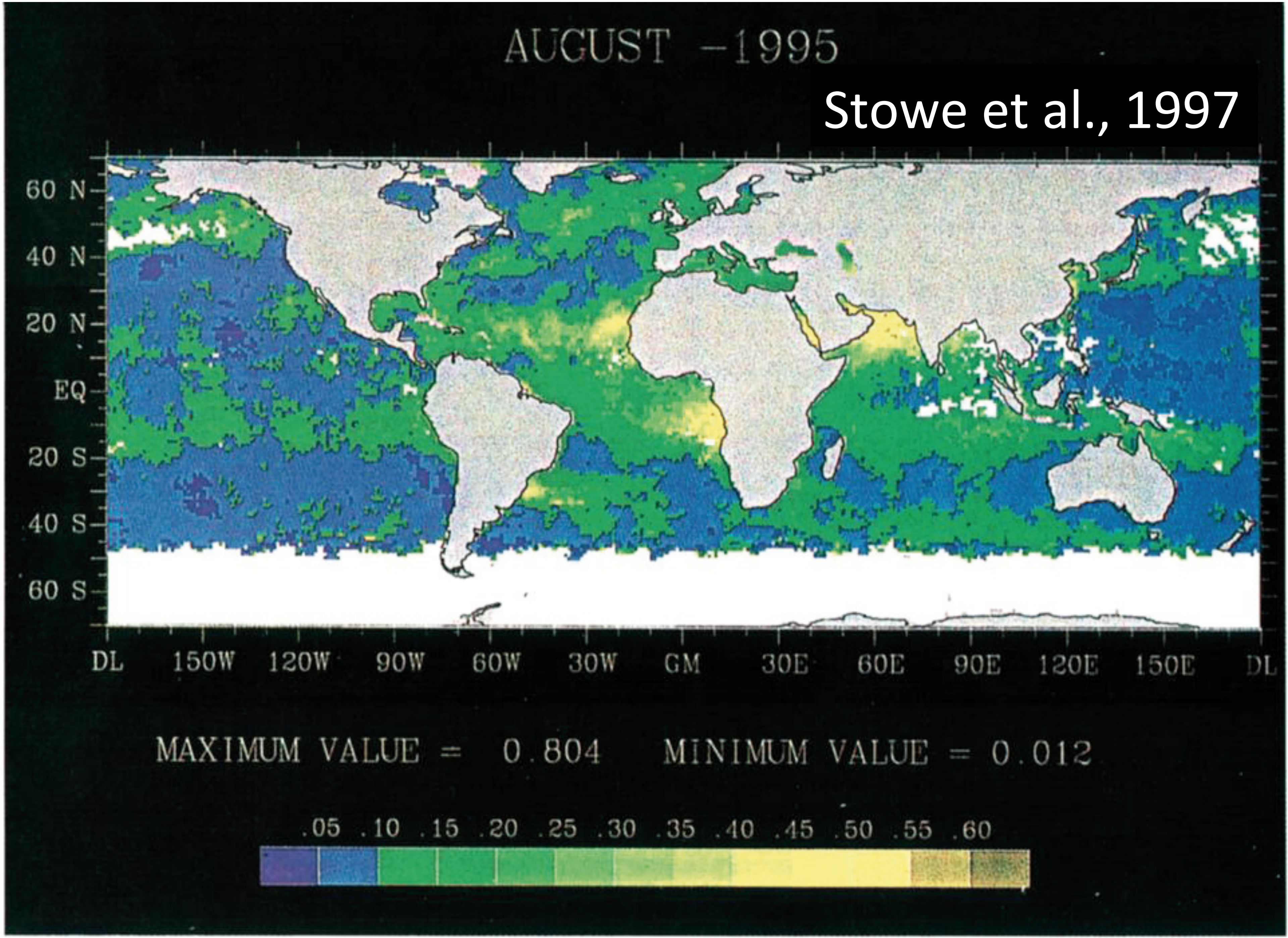
Returns 1 piece of information: AOD

Single channel Dark Target aerosol retrieval applied to AVHRR

AVHRR is a 5 channel instrument
(0.66, 0.87, 1.6 or 3.7, 11 and 12 μm)
moderate spatial resolution (1km at nadir)
with wide swath, producing images

Aerosol time series 1978 to present

Stowe et al. 1997



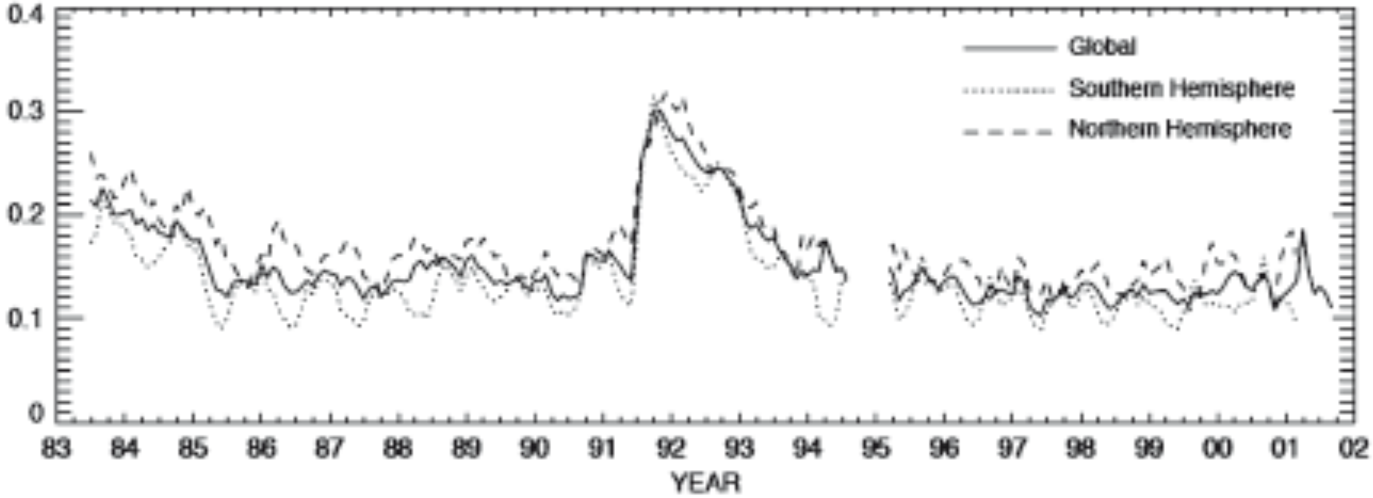
AUGUST -1995

Stowe et al., 1997

MAXIMUM VALUE = 0.804 MINIMUM VALUE = 0.012

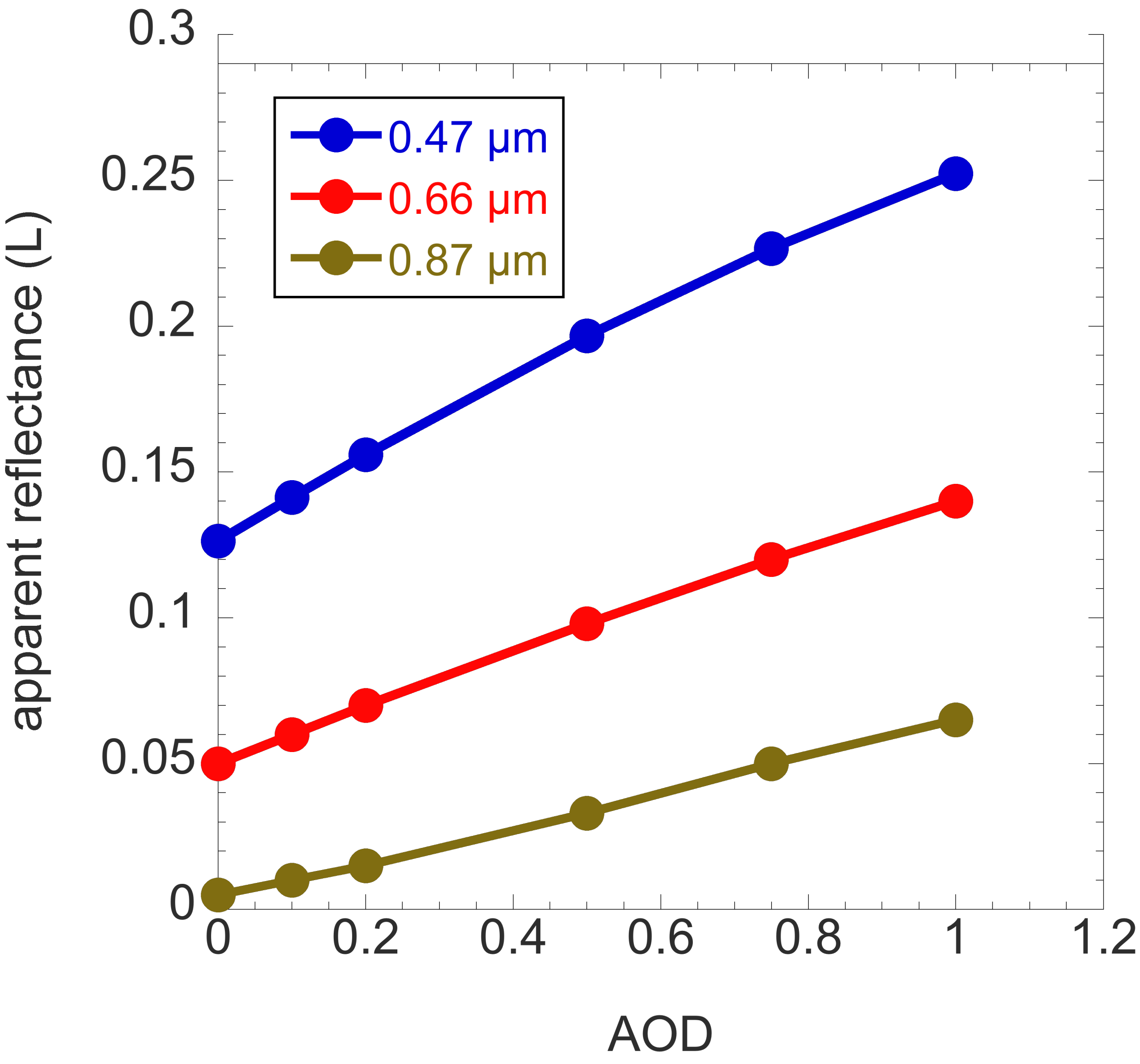
AVHRR aerosol optical thickness

Optical thickness



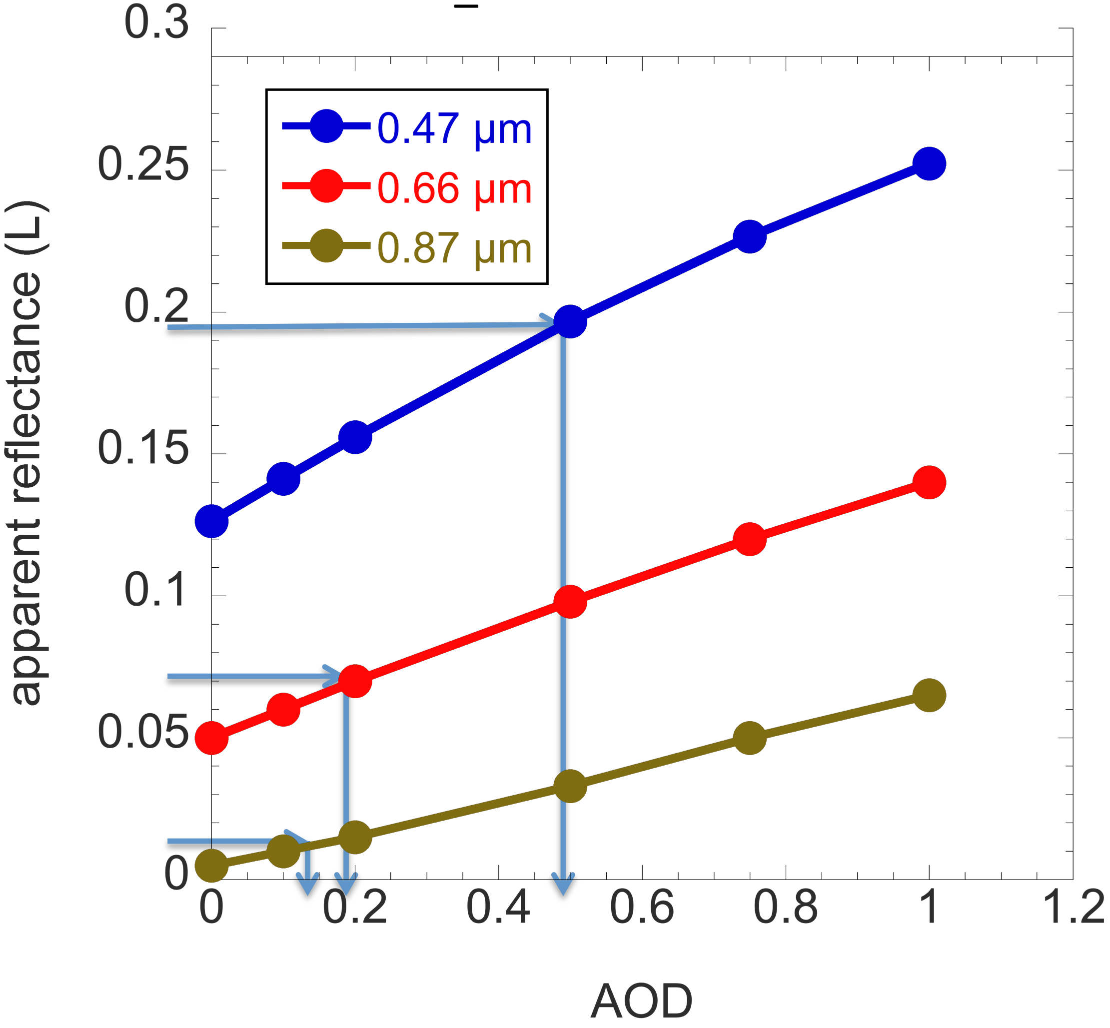
Geogdzhayev et al., 2004

What if we were measuring radiation in more than one wavelength?

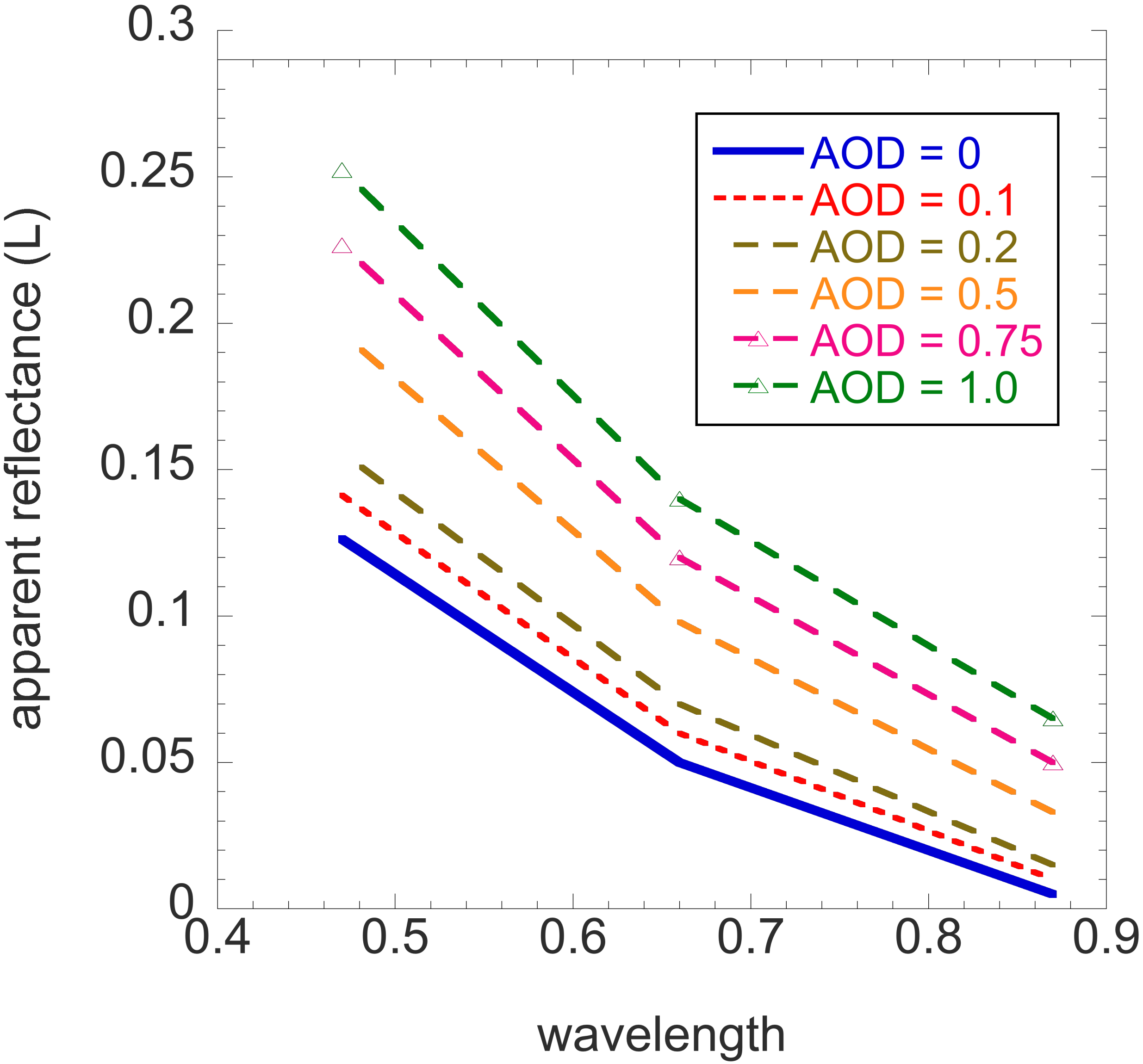


What if we were measuring radiation in more than one wavelength?

AOD_470 = 0.5
AOD_660 = 0.2
AOD_870 = 0.08



But we don’t do 3 individual wavelength retrievals. Instead we approach the problem in wavelength space.



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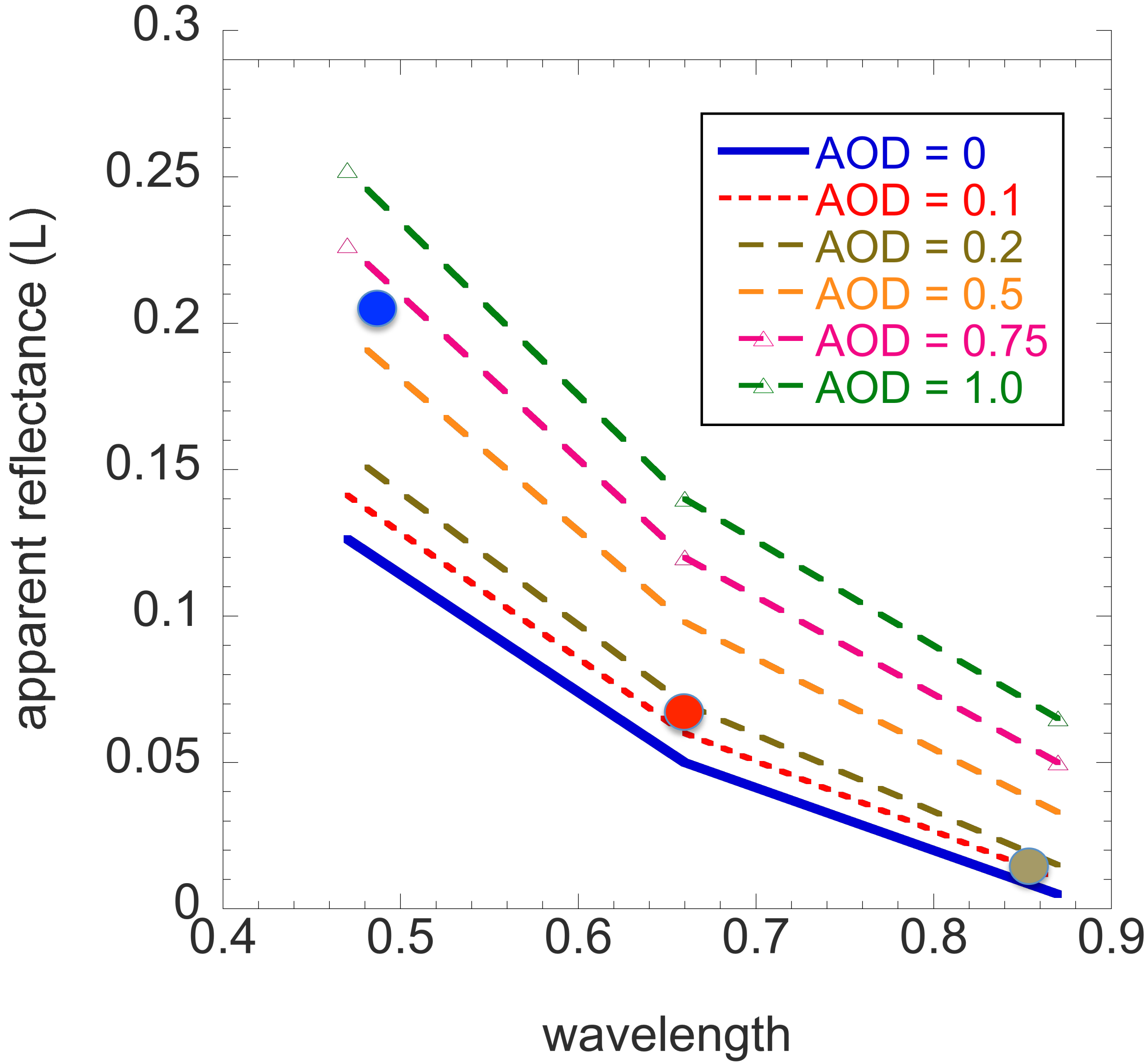
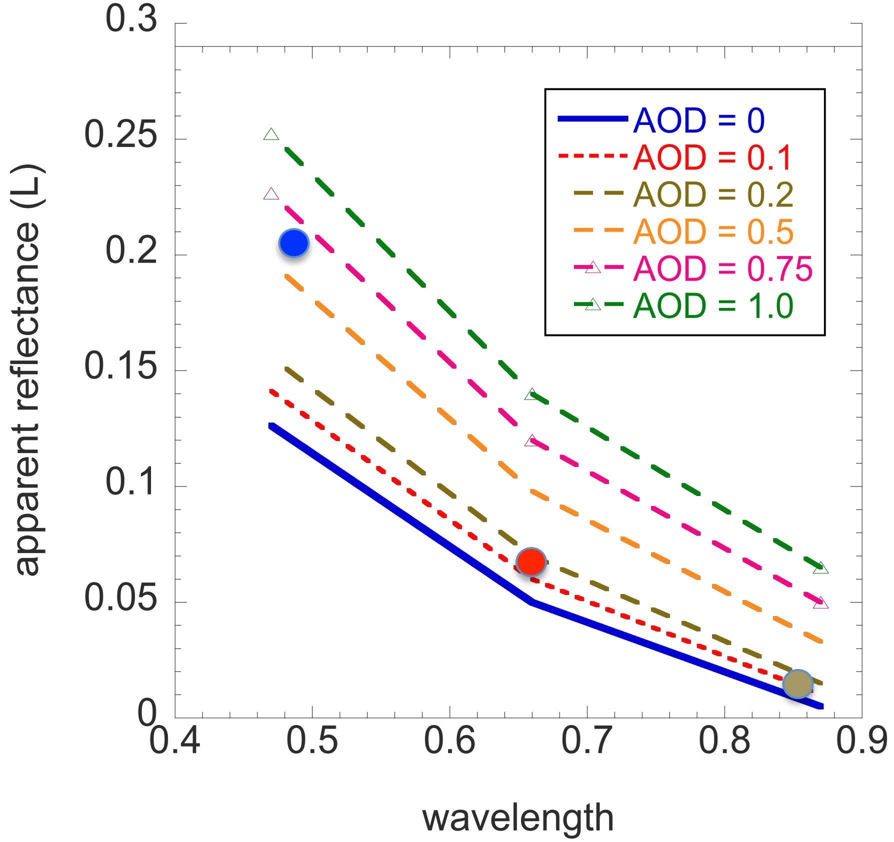
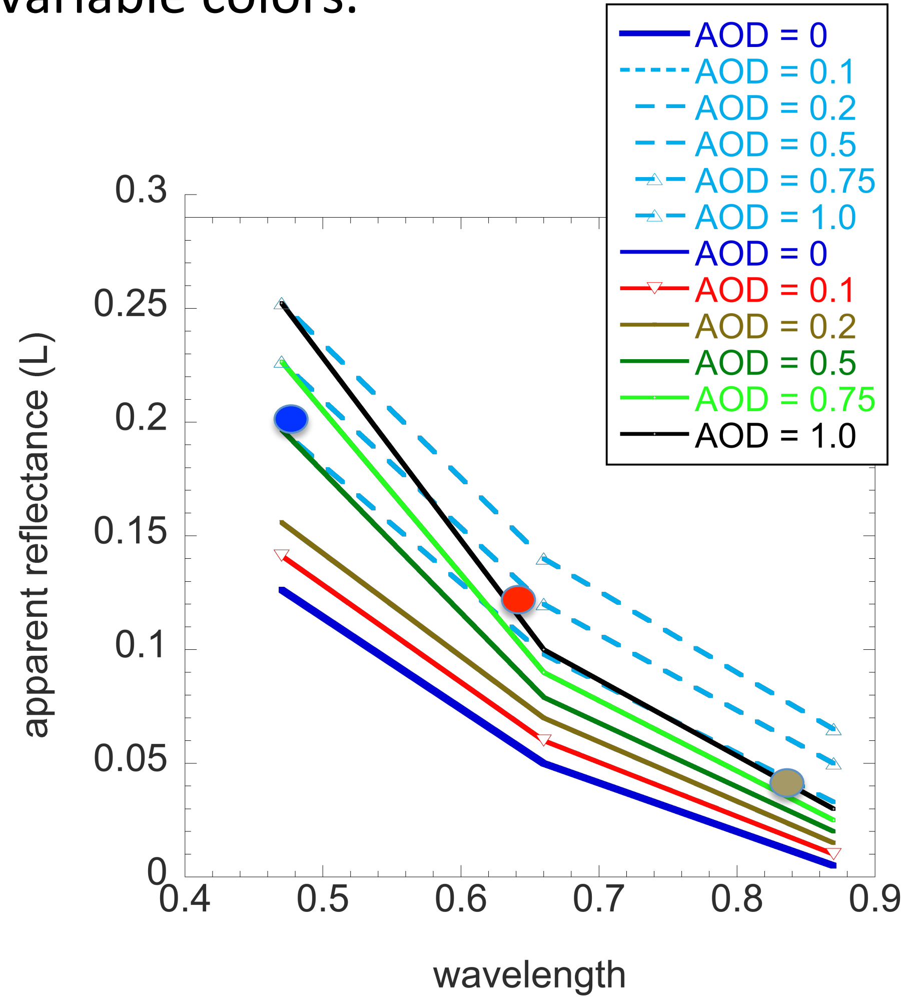


Note: The slope of these curves in wavelength space are specific for a particular choice of aerosol size, shape and composition. Also for a known geometry and surface reflectance.



Imagine the ability to calculate a set of these curves for other choices of size, shape and composition.

Here we have two sets of curves. The original in dashed light blue.
A new set for a different choice of size, shape and composition in solid variable colors.



We can minimize the difference between calculated (curves) and measured (dots) reflectance to find the best AOD AND also the best curve that fits the measurements. Together. All at once.

$$\varepsilon = \sqrt{\frac{\sum_{\lambda=1}^{6} N_\lambda \left(\frac{\rho_\lambda^m - \rho_\lambda^{LUT}}{\rho_\lambda^m - \rho_\lambda^{ray} + 0.01} \right)^2}{\sum_{\lambda=1}^{6} N_\lambda}}$$

https://darktarget.gsfc.nasa.gov/atbd/overview

Dark Target aerosol retrieval applied to MODIS

AVHRR is a 36 channel instrument
(0.41, 0.47, 0.55, 0.66, 0.86, 1.24, 1.63, 2.13 μm)
moderate spatial resolution (0.5 km at nadir)
with wide swath, producing images

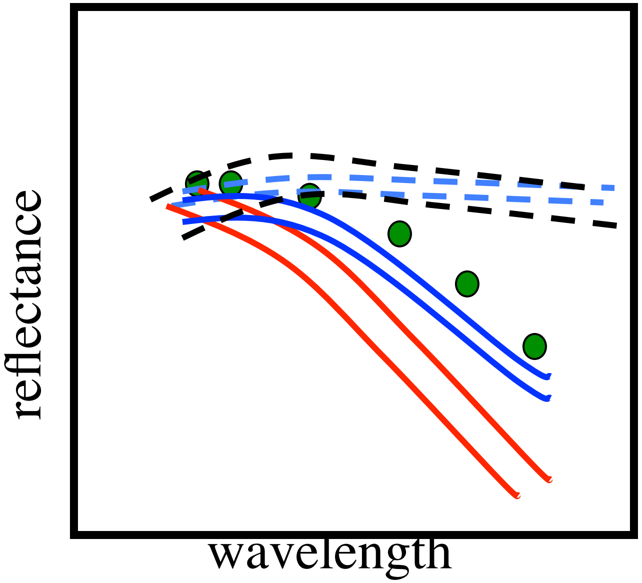
Aerosol time series 2000 to present

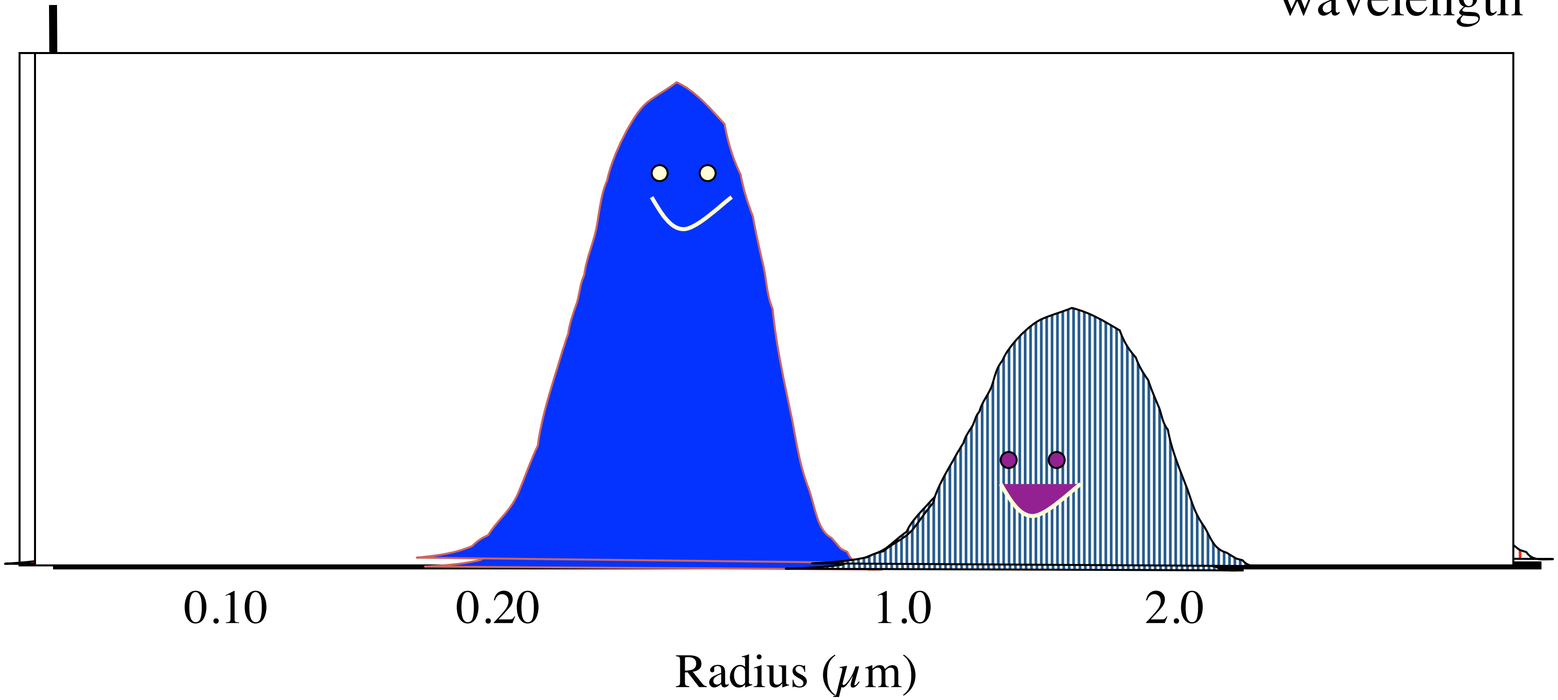
Because of extend wavelength range:

1. retrievals over land
2. 2 pieces of information over ocean (τ^* and size)

MODIS aerosol retrieval over ocean

Find one coarse mode and
one fine mode
that combine to match the
observed spectral reflectances





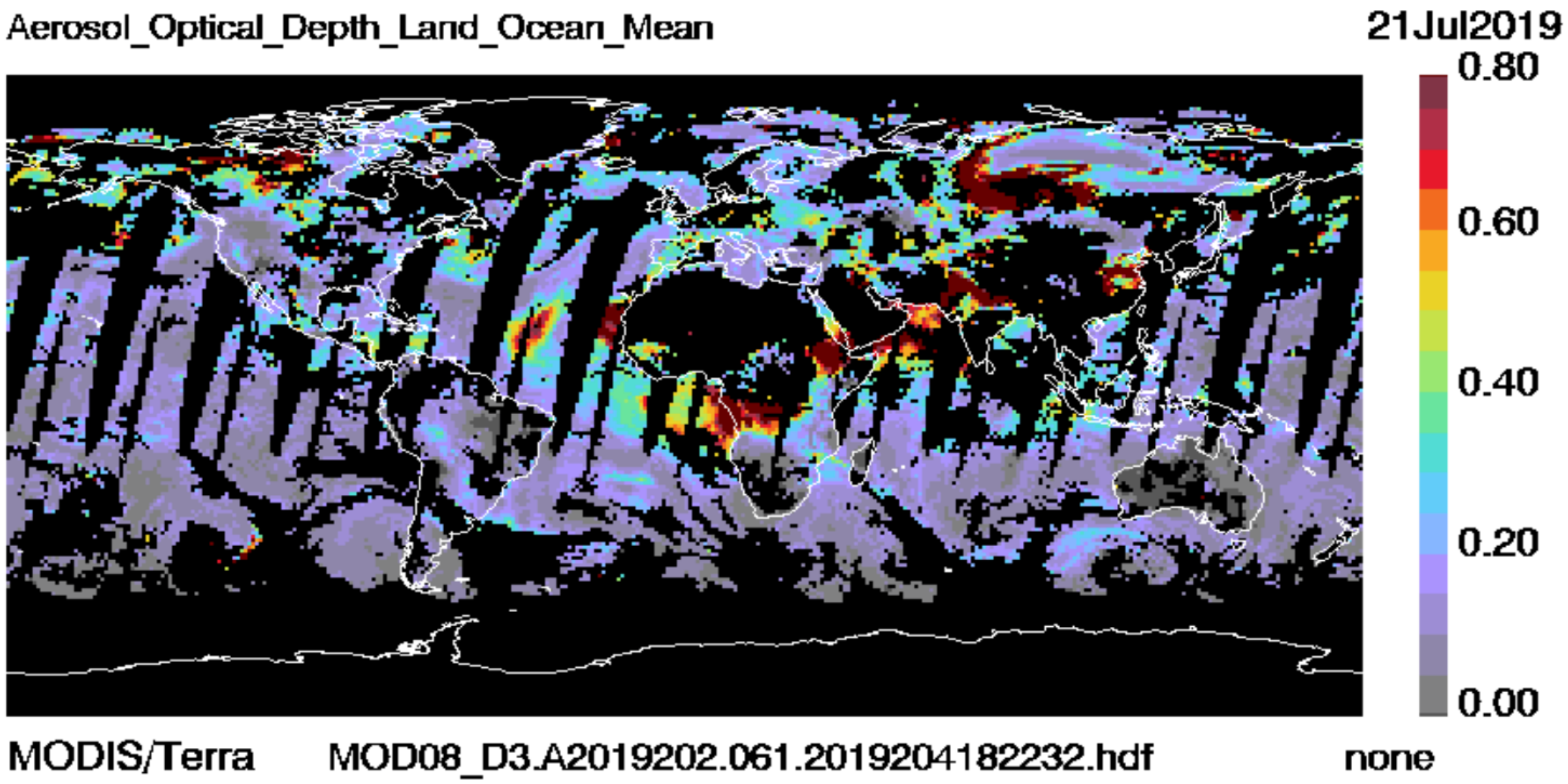
Over land, the challenge is the variability of land surface.
R is not well known.

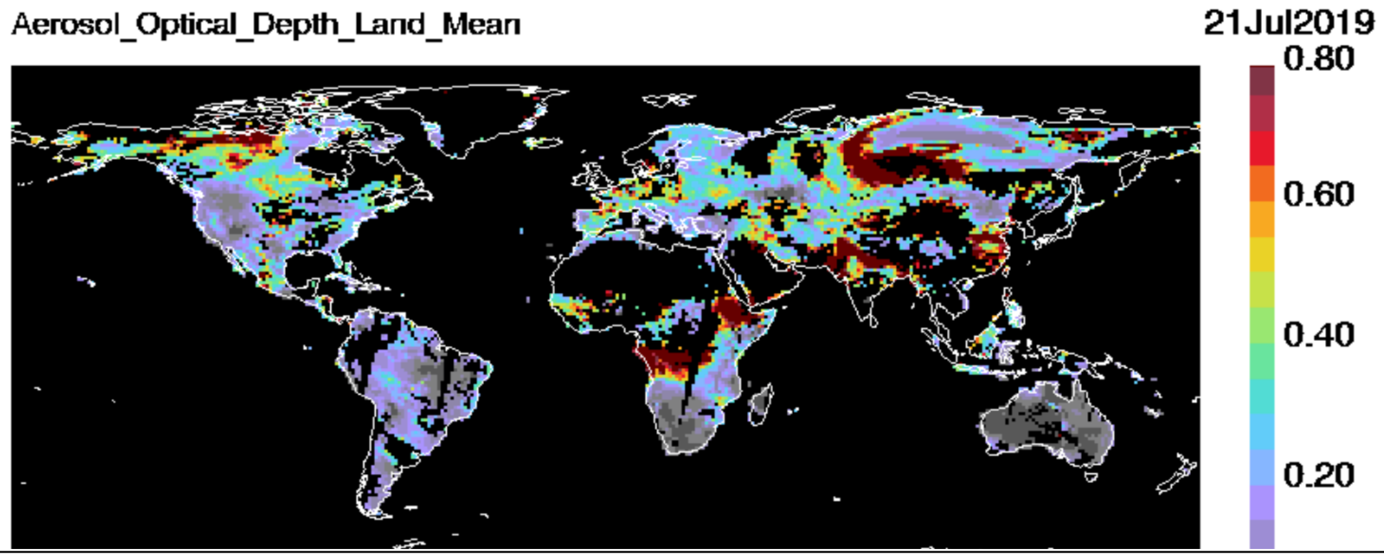
$$L(\boldsymbol{\tau}^*,\mu_o,\mu,\varphi) = L_o(\boldsymbol{\tau}^*,\mu_o,\mu,\varphi) + \frac{RE_oT_t(\boldsymbol{\tau}^*,\mu)}{1-RS}$$

Different methods:

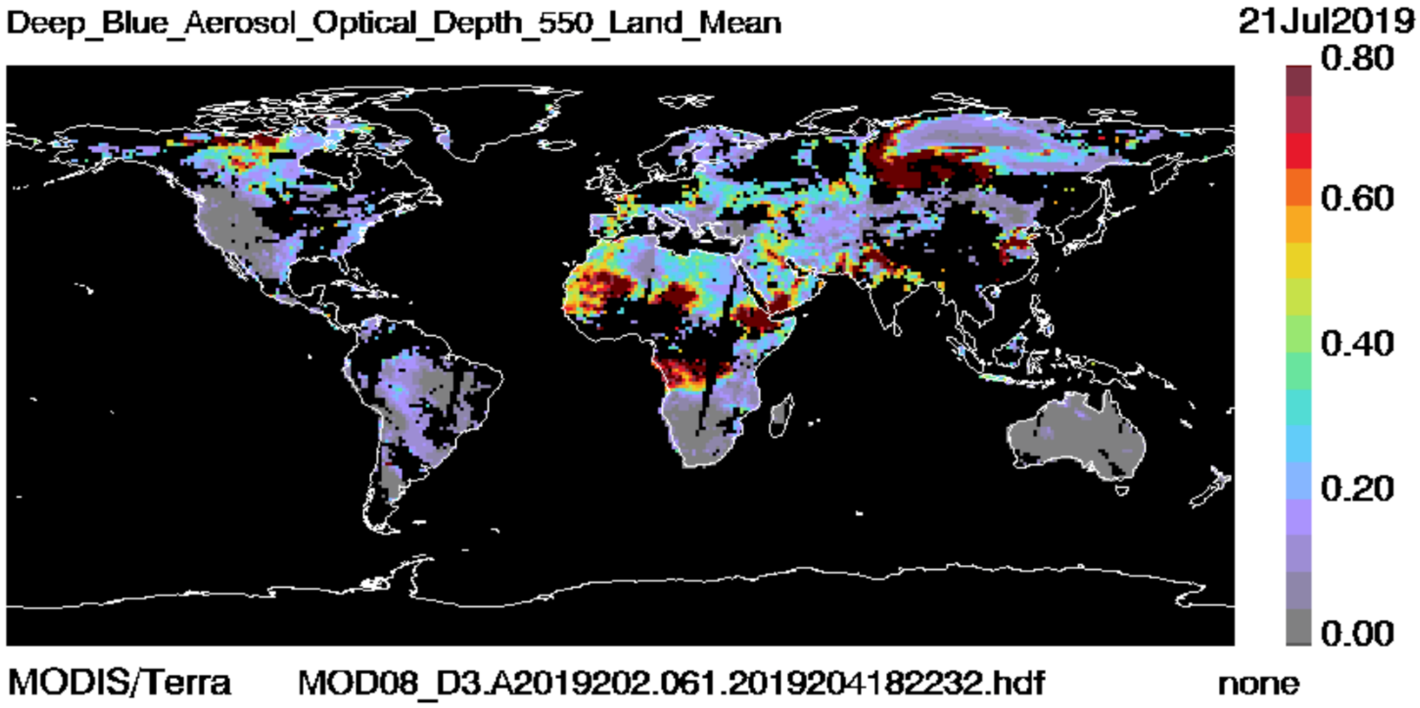
1. Dark Target: Use only situations where R is small. Apply an empirical relationship between wavelengths to constrain the surface.
2. Deep Blue: Use the near UV wavelength (410 nm) where the surface is always dark, even when the visible is bright, and accumulate a global data base of retrieved R so that R is known in the above equation.
3. NOAA EPS: Combines similar techniques of Dark Target and Deep Blue, using each in appropriate places.
4. MAIAC: Introduce temporal information, assuming that aerosol is variable in time but constant in space, while land surface is constant in time (over 8 days) and variable in space.

Dark Target AOD at 0.55 µm.



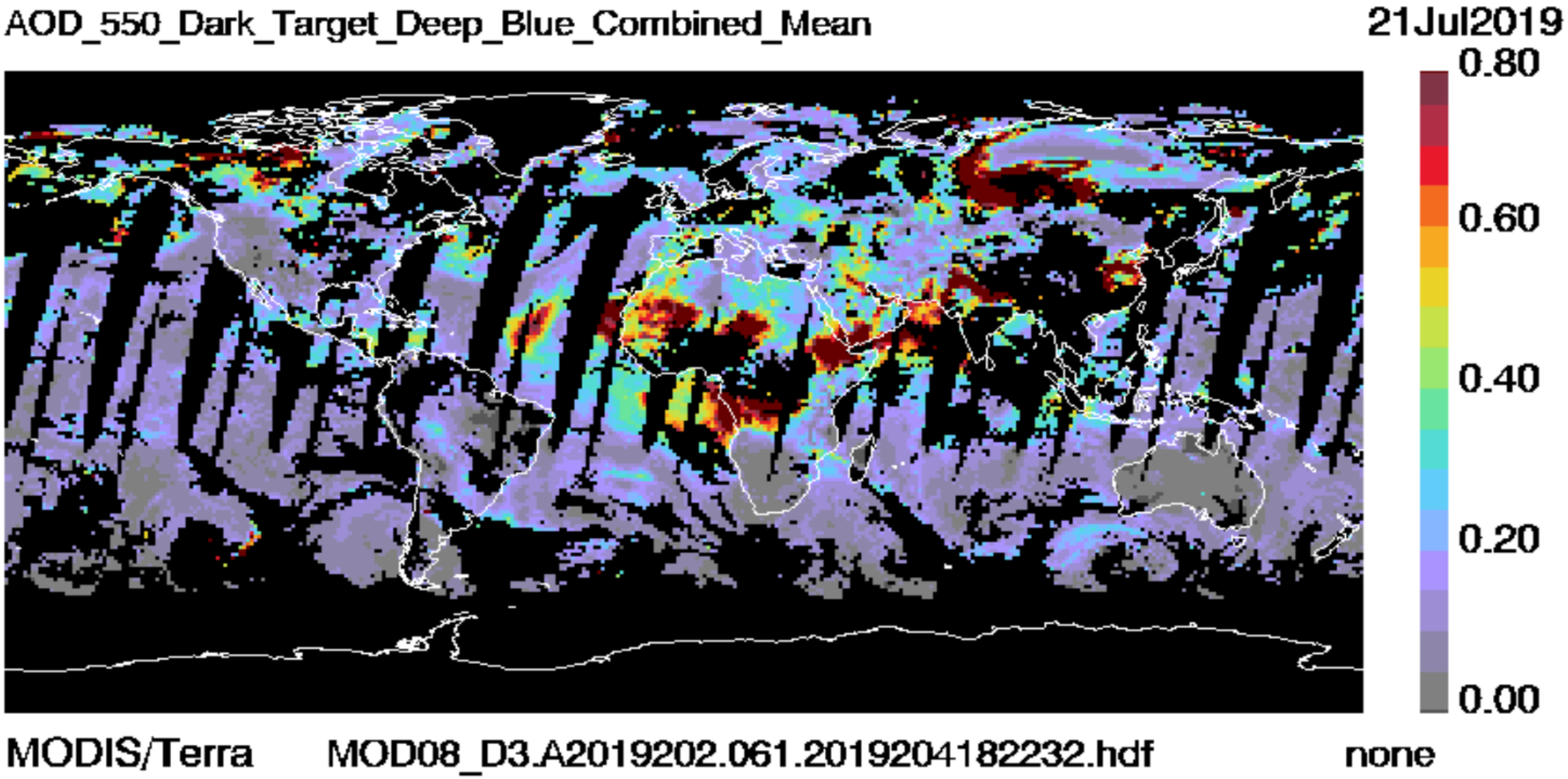


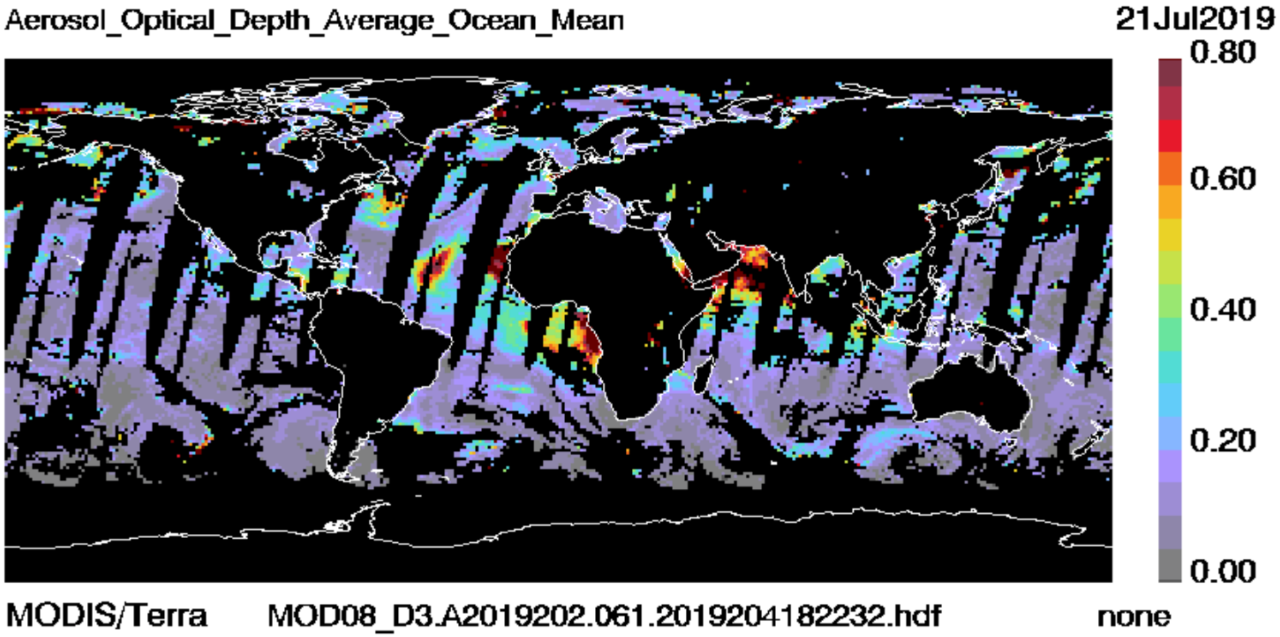
Dark Target



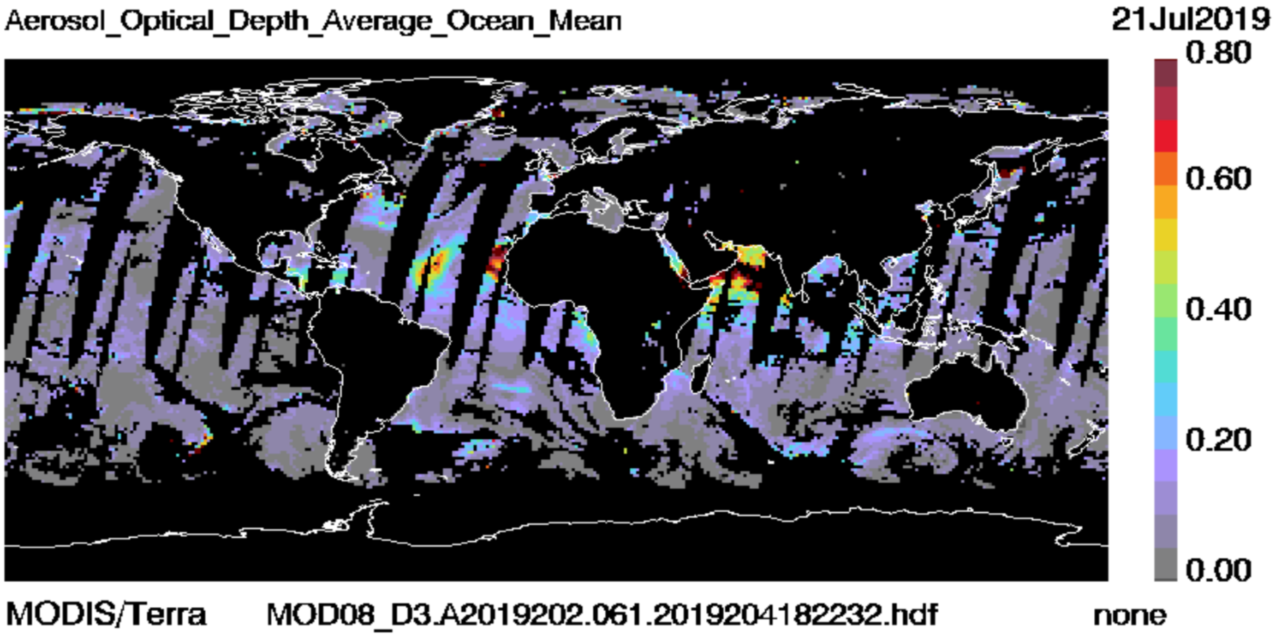
Deep Blue

Combined Dark Target Deep Blue



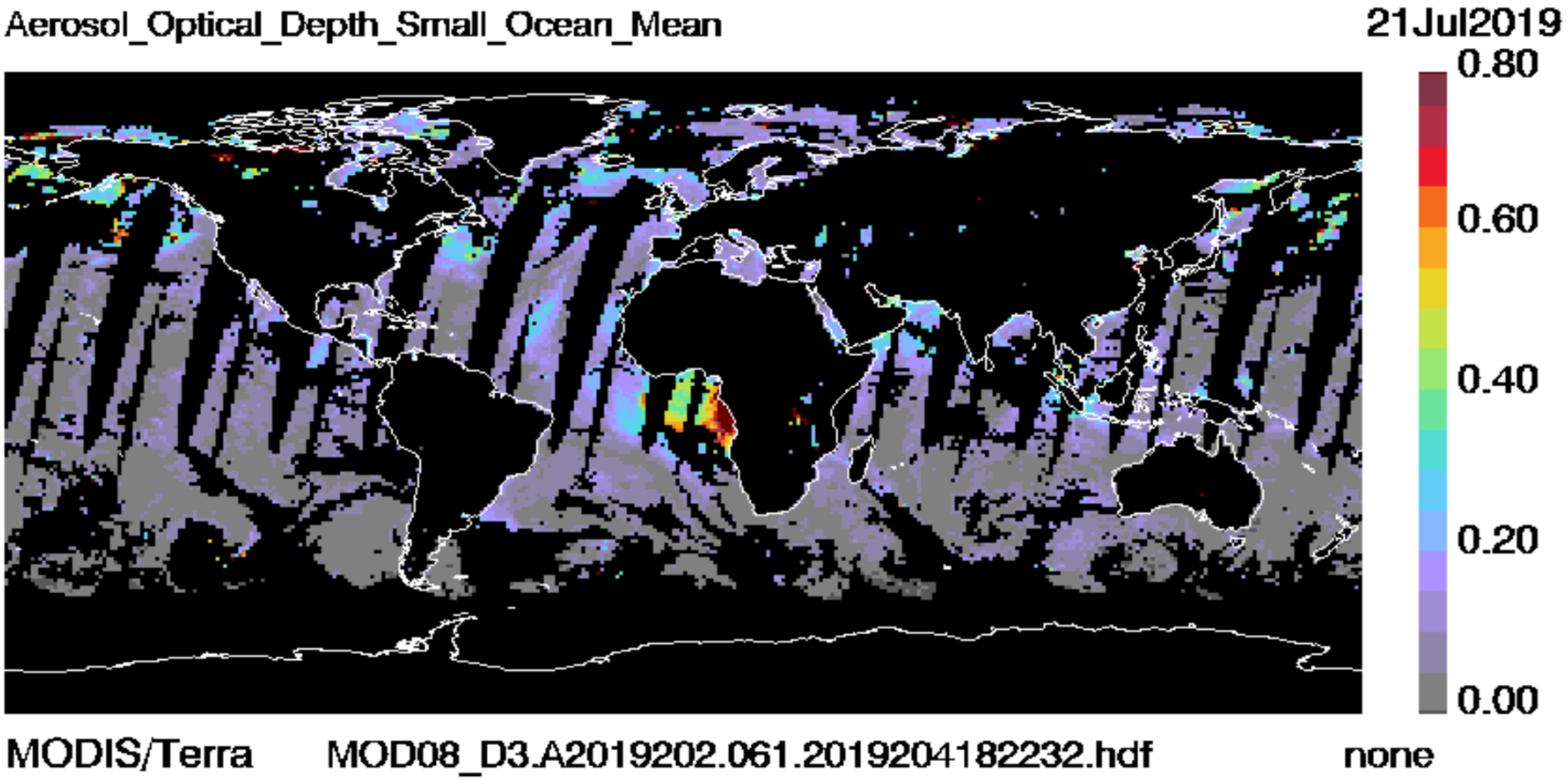

Aerosol_Optical_Depth_Average_Ocean_Mean
21Jul2019
0.80
0.60
0.40
0.20
0.00
MODIS/Terra
MOD08_D3.A2019202.061.2019204182232.hdf
none

0.55 µm


Aerosol_Optical_Depth_Average_Ocean_Mean
21Jul2019
0.80
0.60
0.40
0.20
0.00
MODIS/Terra
MOD08_D3.A2019202.061.2019204182232.hdf
none

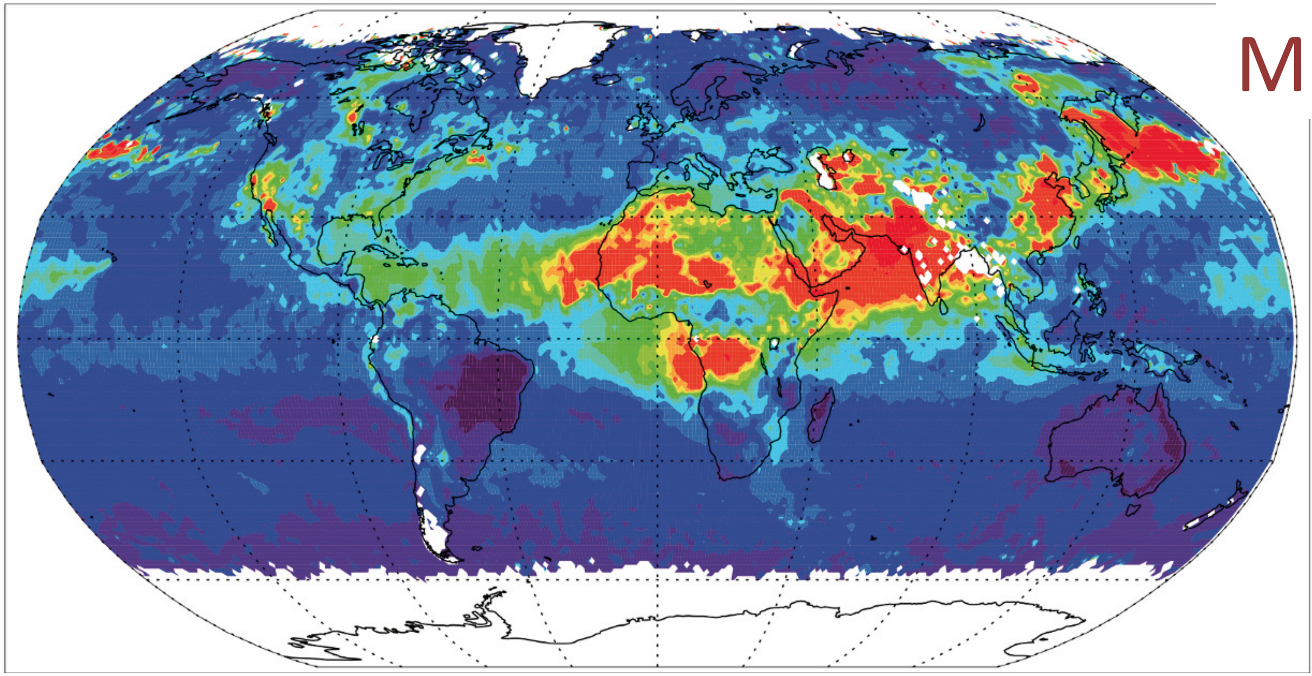
1.24 µm

AOD contributed by fine mode (radius < 0.5 μm)

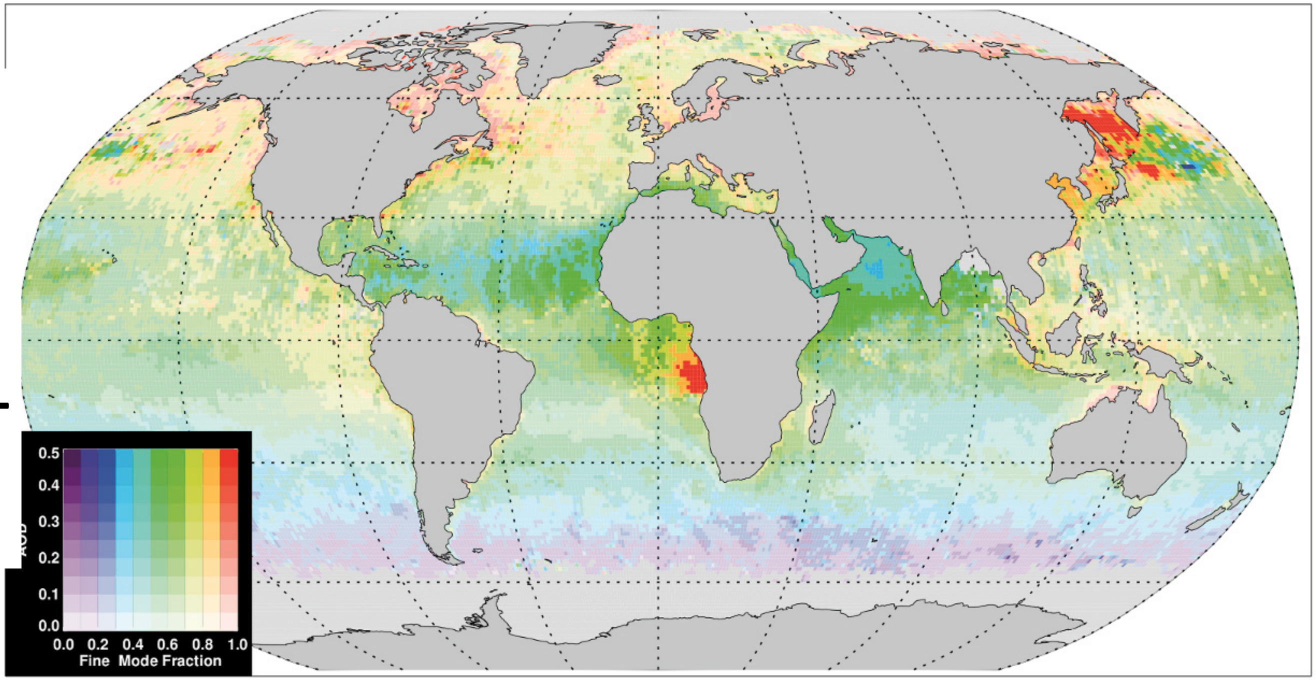


MODIS

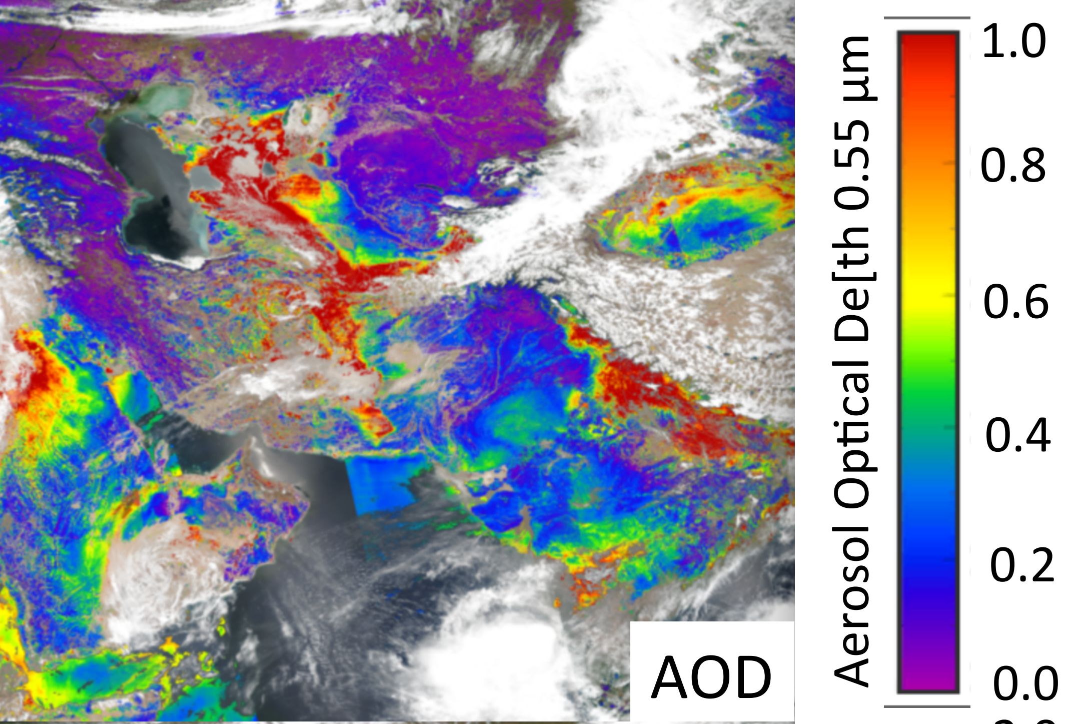
Optical thickness

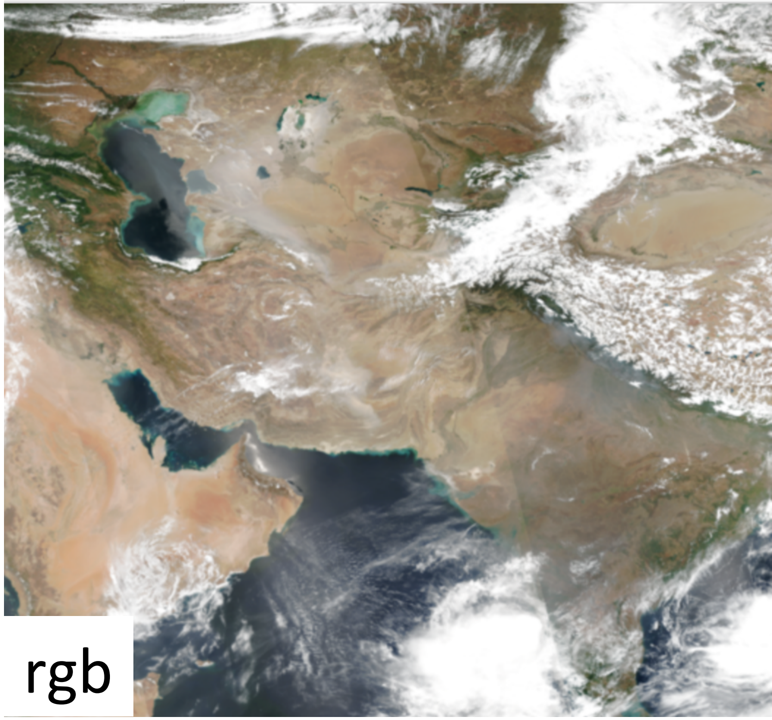


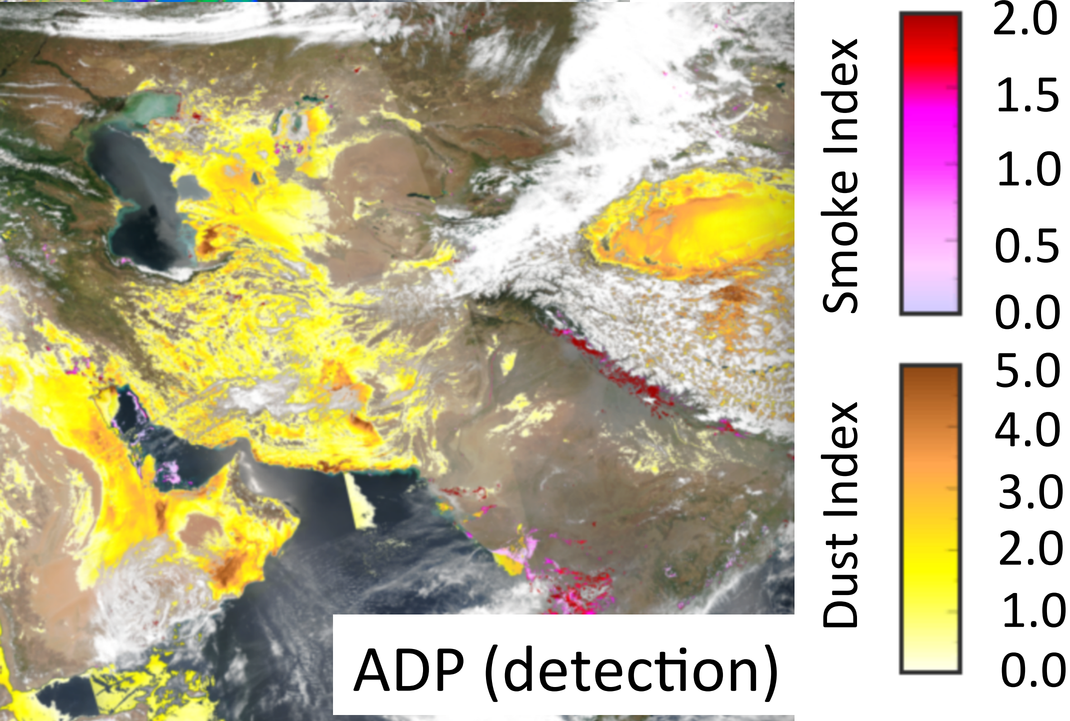
Size parameter



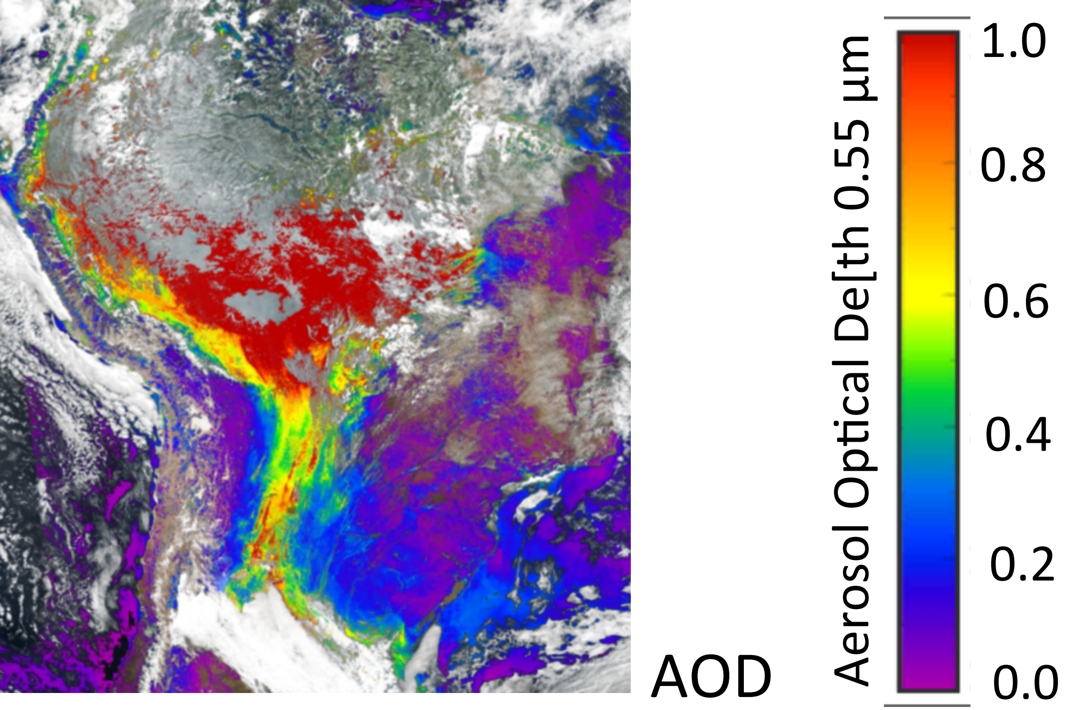
Fraction of AOD at 550 nm contributed by the fine mode

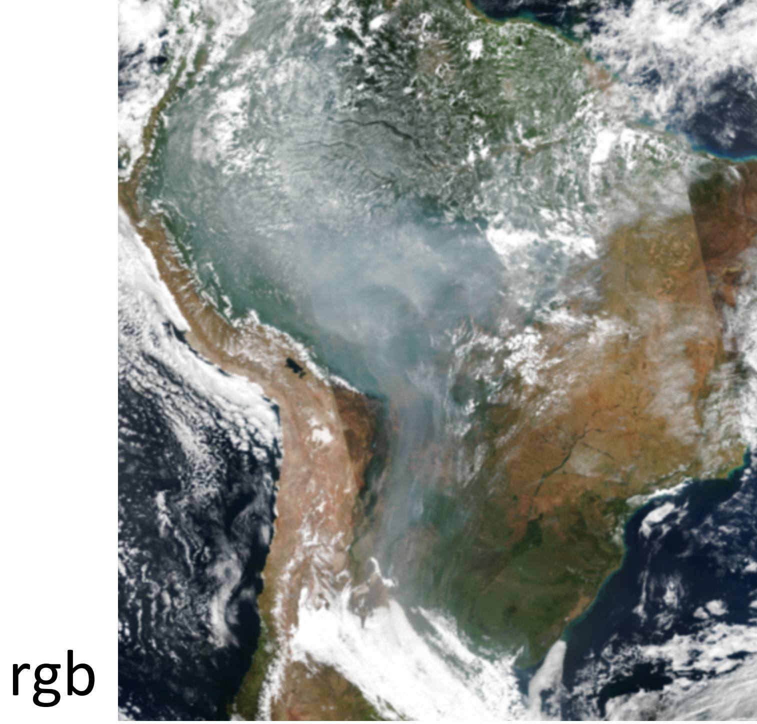

AOD
Aerosol Optical De[th 0.55 µm
1.0
0.8
0.6
0.4
0.2
0.0

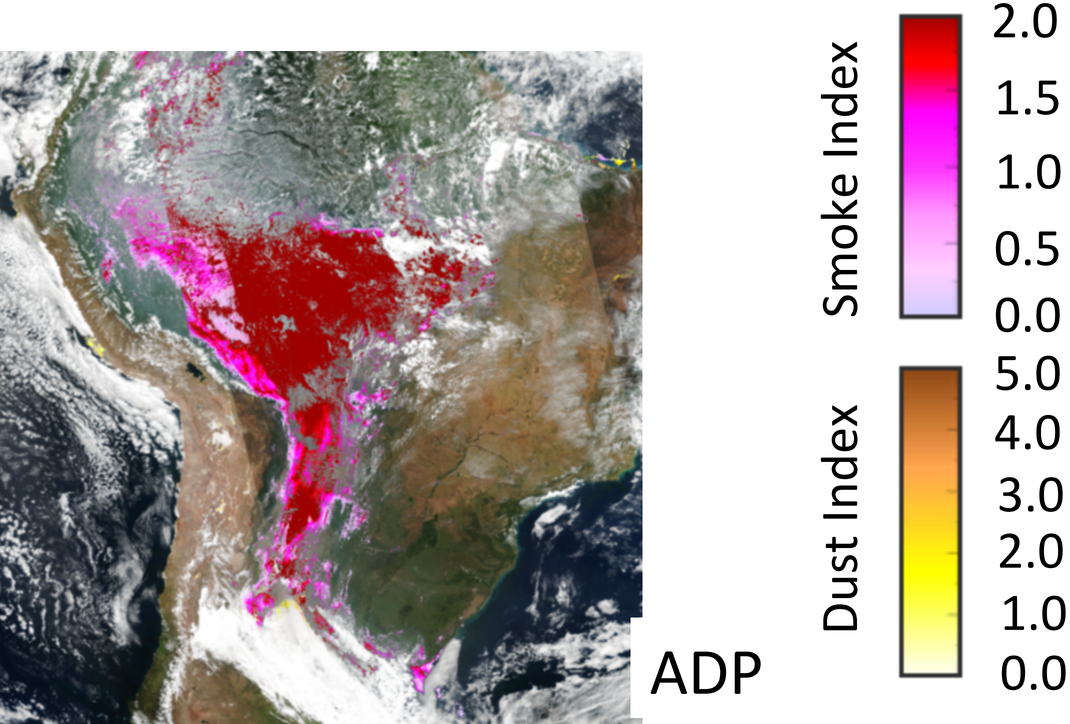

rgb


ADP (detection)
Smoke Index
2.0
1.5
1.0
0.5
0.0
Dust Index
5.0
4.0
3.0
2.0
1.0
0.0

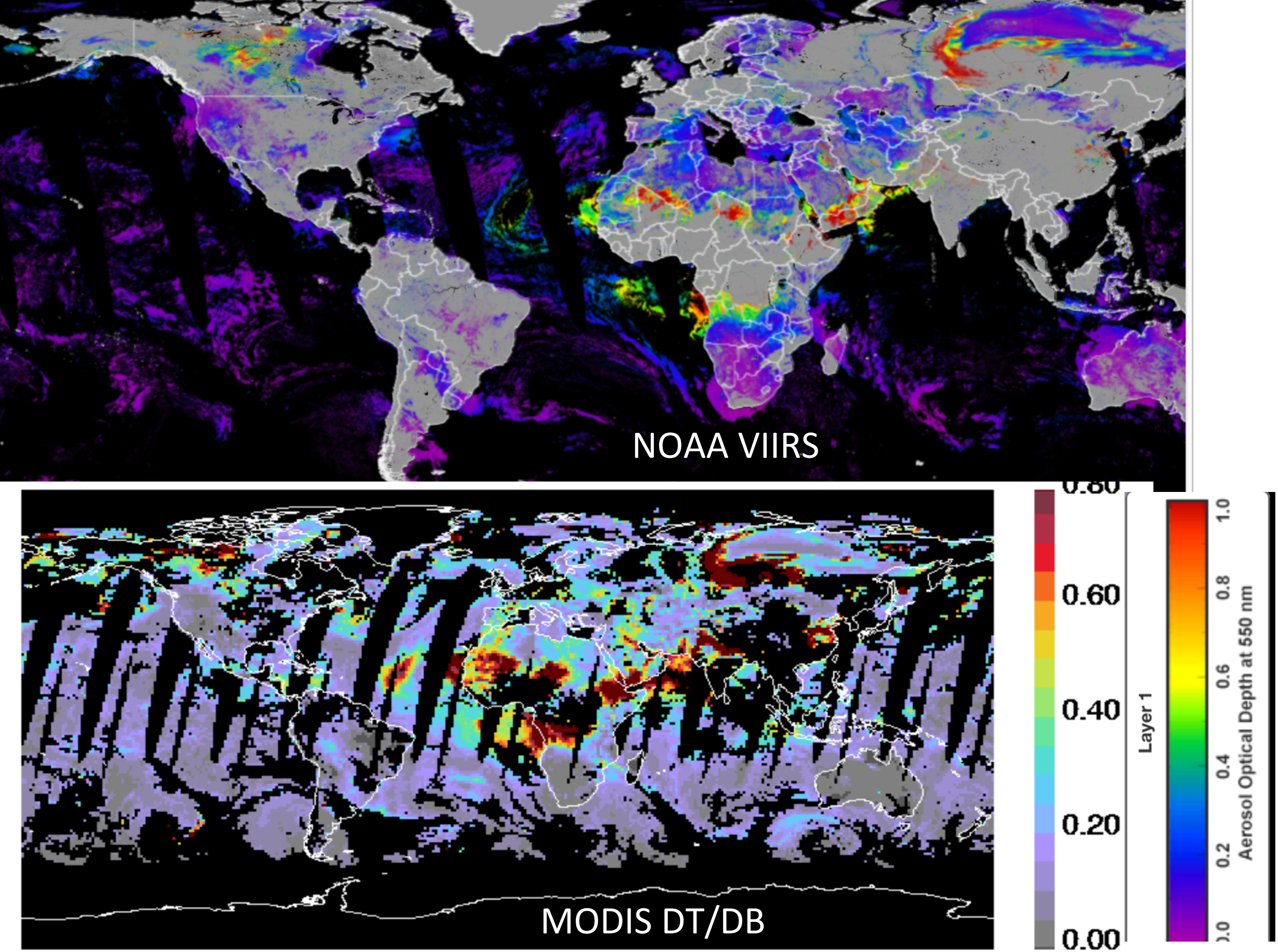
28 May 2018

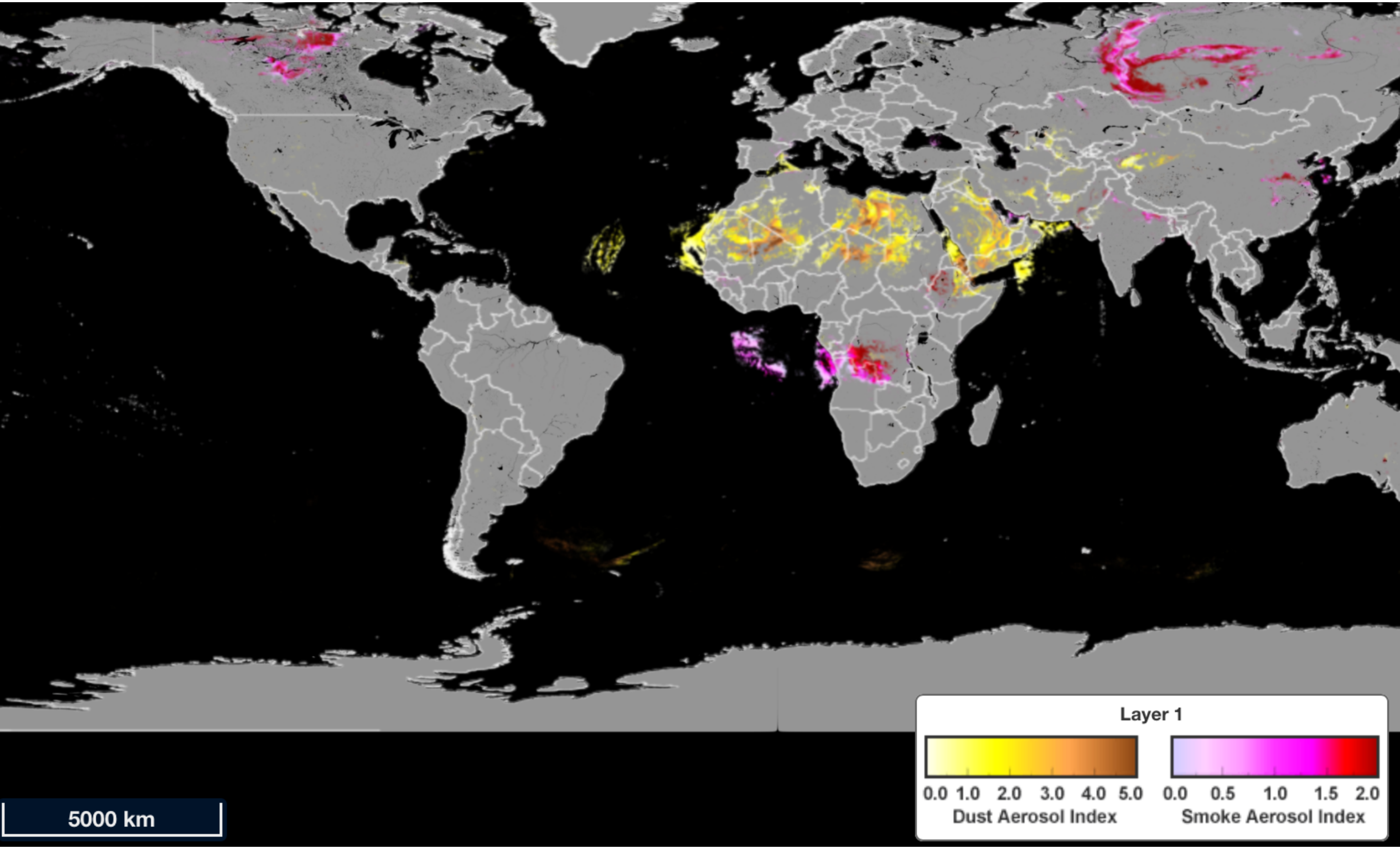






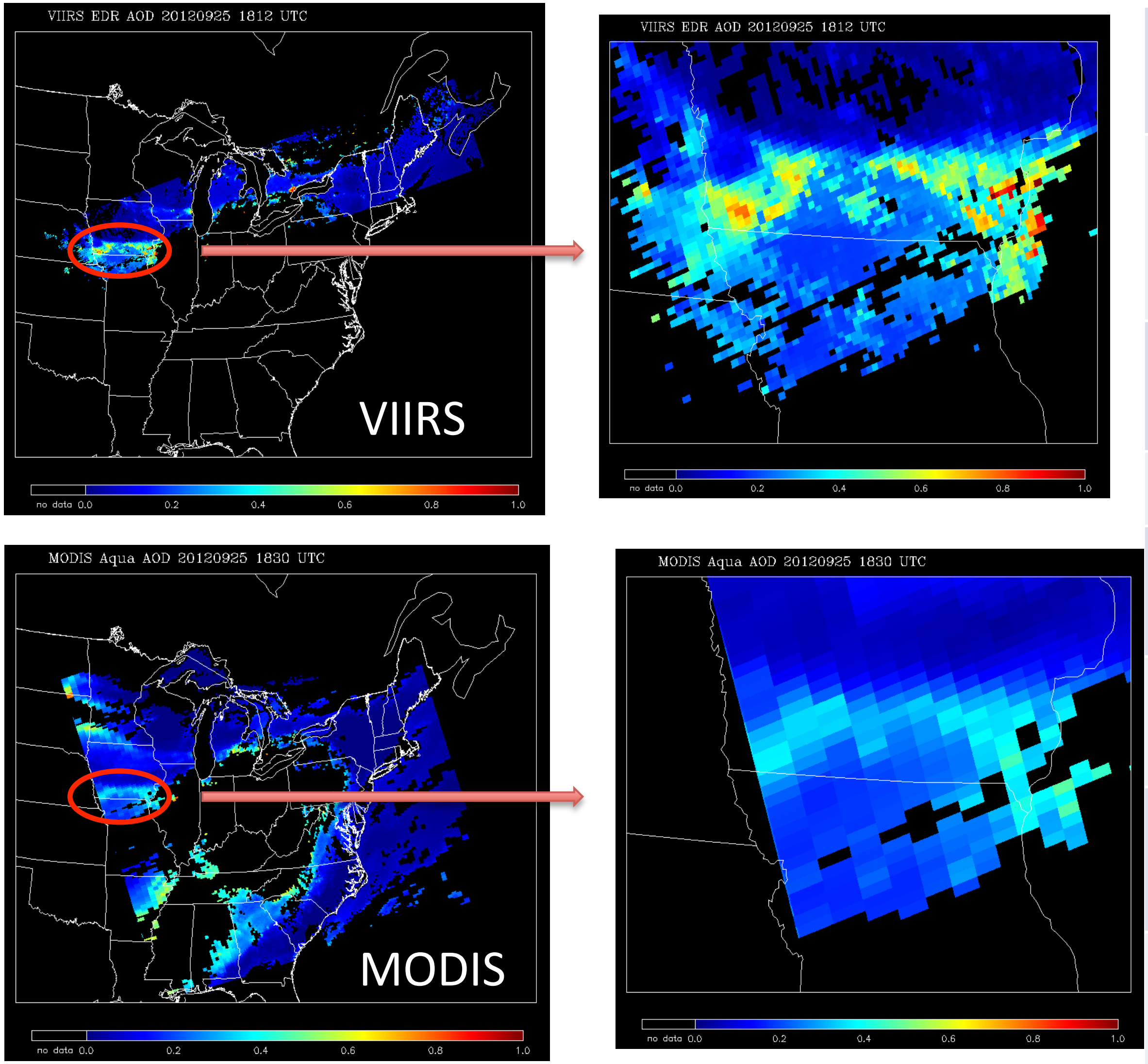
20 September 2017


NOAA VIIRS
MODIS DT/DB
0.80
0.60
0.40
0.20
0.00
Layer 1
Aerosol Optical Depth at 550 nm
1.0
0.8
0.6
0.4
0.2
0.0


Layer 1
0.0 1.0 2.0 3.0 4.0 5.0
Dust Aerosol Index
0.0 0.5 1.0 1.5 2.0
Smoke Aerosol Index
5000 km

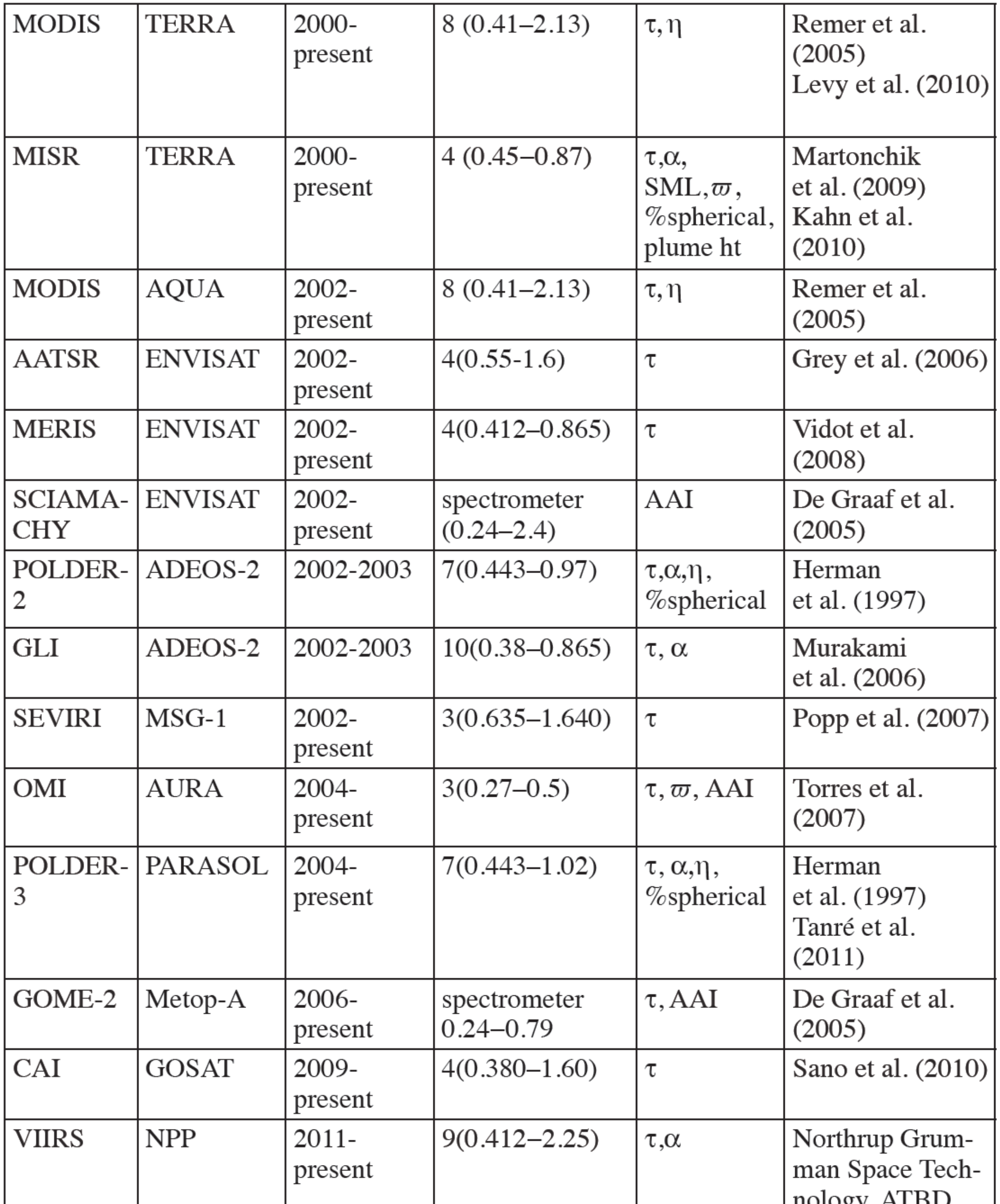
NOAA VIIRS aerosol detection product (ADP) is a stand-alone product, in its own file, and completely independent of the AOD product

The VIIRS instrument has interesting properties



	Aqua MODIS	**S-NPP VIIRS**
Orbit altitude	690 km	824 km
Equator crossing time	13:30 LT	13:30 LT
Granule size	5 min	86 sec
swath	2330 km	3040 km
Pixel nadir	0.5 km	0.75 km
Pixel at edge	2 km	1.5 km
AOD nadir	3 km/ 10 km	0.75 km
AOD at edge	12 km/ 40 km	1.5 km

Slide from Shobha Kondragunta (NOAA)

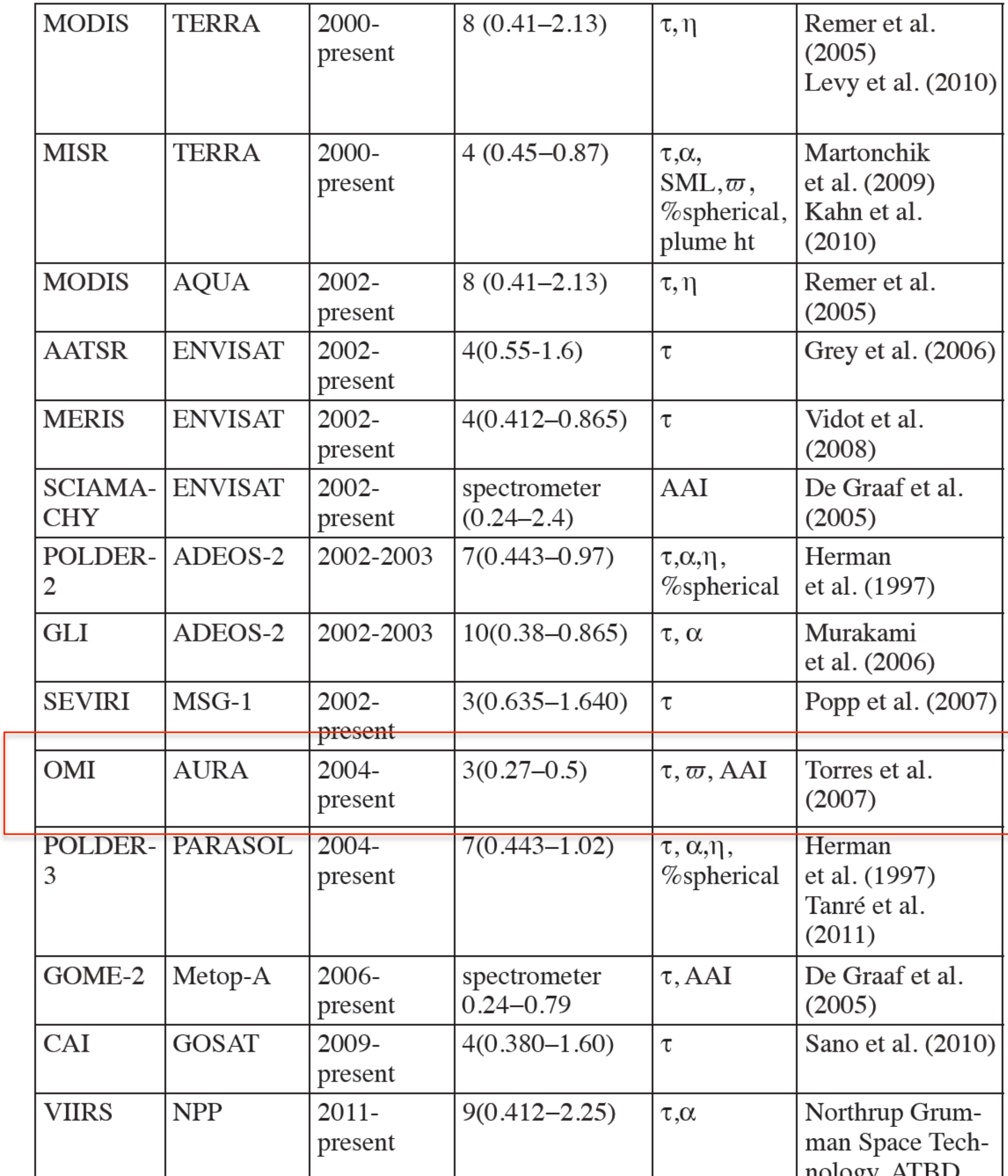


MODIS	TERRA	2000-present	8 (0.41–2.13)	τ, η	Remer et al. (2005) Levy et al. (2010)
MISR	TERRA	2000-present	4 (0.45–0.87)	τ,α, SML,ϖ, %spherical, plume ht	Martonchik et al. (2009) Kahn et al. (2010)
MODIS	AQUA	2002-present	8 (0.41–2.13)	τ, η	Remer et al. (2005)
AATSR	ENVISAT	2002-present	4(0.55-1.6)	τ	Grey et al. (2006)
MERIS	ENVISAT	2002-present	4(0.412–0.865)	τ	Vidot et al. (2008)
SCIAMACHY	ENVISAT	2002-present	spectrometer (0.24–2.4)	AAI	De Graaf et al. (2005)
POLDER-2	ADEOS-2	2002-2003	7(0.443–0.97)	τ,α,η, %spherical	Herman et al. (1997)
GLI	ADEOS-2	2002-2003	10(0.38–0.865)	τ, α	Murakami et al. (2006)
SEVIRI	MSG-1	2002-present	3(0.635–1.640)	τ	Popp et al. (2007)
OMI	AURA	2004-present	3(0.27–0.5)	τ, ϖ, AAI	Torres et al. (2007)
POLDER-3	PARASOL	2004-present	7(0.443–1.02)	τ, α,η, %spherical	Herman et al. (1997) Tanré et al. (2011)
GOME-2	Metop-A	2006-present	spectrometer 0.24–0.79	τ, AAI	De Graaf et al. (2005)
CAI	GOSAT	2009-present	4(0.380–1.60)	τ	Sano et al. (2010)
VIIRS	NPP	2011-present	9(0.412–2.25)	τ,α	Northrup Grumman Space Technology ATBD

From Chapter 11.
Passive shortwave Earth-viewing sensors and their platforms used in aerosol measurements
from space, providing total column measurements.

From Lenoble, Remer, Tanré Aerosol Remote Sensing. Springer

https://www.springer.com/gp/book/9783642177248



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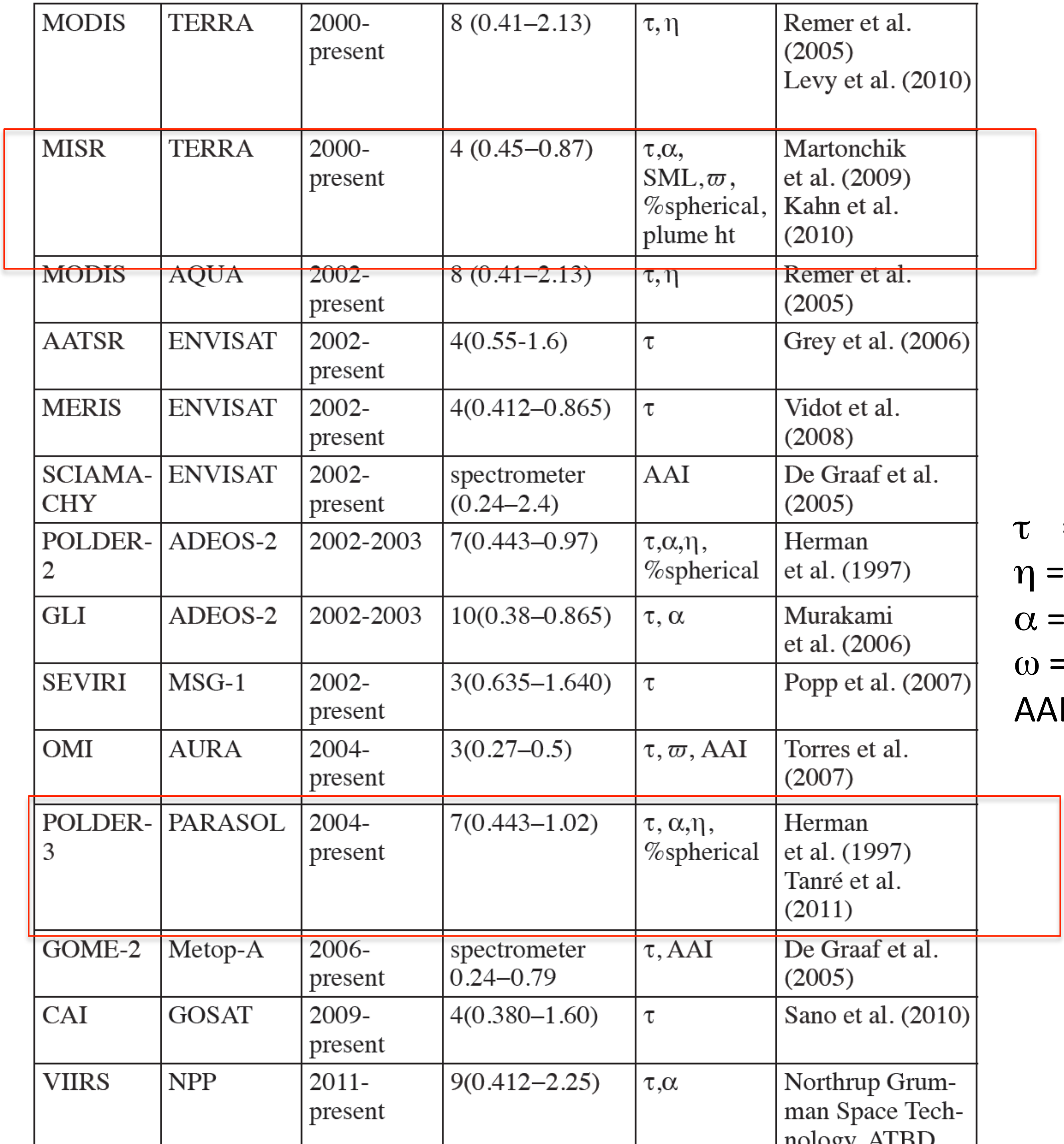
OMI	AURA	2004-present	3(0.27–0.5)	τ, ϖ, AAI	Torres et al. (2007)
POLDER-3	PARASOL	2004-present	7(0.443–1.02)	τ, α,η, %spherical	Herman et al. (1997) Tanré et al. (2011)
GOME-2	Metop-A	2006-present	spectrometer 0.24–0.79	τ, AAI	De Graaf et al. (2005)
CAI	GOSAT	2009-present	4(0.380–1.60)	τ	Sano et al. (2010)
VIIRS	NPP	2011-present	9(0.412–2.25)	τ,α	Northrup Grumman Space Technology ATBD

https://darktarget.gsfc.nasa.gov
https://deepblue.gsfc.nasa.gov

https://darktarget.gsfc.nasa.gov
https://deepblue.gsfc.nasa.gov

τ = AOD
η = fine mode fraction
α = Angstrom Exponent
ω = single scattering albedo
AAI = Aerosol absorption index



MODIS	TERRA	2000-present	8 (0.41–2.13)	τ,η	Remer et al. (2005) Levy et al. (2010)
MISR	TERRA	2000-present	4 (0.45–0.87)	τ,α, SML, ϖ, %spherical, plume ht	Martonchik et al. (2009) Kahn et al. (2010)
MODIS	AQUA	2002-present	8 (0.41–2.13)	τ,η	Remer et al. (2005)
AATSR	ENVISAT	2002-present	4(0.55-1.6)	τ	Grey et al. (2006)
MERIS	ENVISAT	2002-present	4(0.412–0.865)	τ	Vidot et al. (2008)
SCIAMACHY	ENVISAT	2002-present	spectrometer (0.24–2.4)	AAI	De Graaf et al. (2005)
POLDER-2	ADEOS-2	2002-2003	7(0.443–0.97)	τ,α,η, %spherical	Herman et al. (1997)
GLI	ADEOS-2	2002-2003	10(0.38–0.865)	τ, α	Murakami et al. (2006)
SEVIRI	MSG-1	2002-present	3(0.635–1.640)	τ	Popp et al. (2007)
OMI	AURA	2004-present	3(0.27–0.5)	τ, ϖ, AAI	Torres et al. (2007)
POLDER-3	PARASOL	2004-present	7(0.443–1.02)	τ, α,η, %spherical	Herman et al. (1997) Tanré et al. (2011)
GOME-2	Metop-A	2006-present	spectrometer 0.24–0.79	τ, AAI	De Graaf et al. (2005)
CAI	GOSAT	2009-present	4(0.380–1.60)	τ	Sano et al. (2010)
VIIRS	NPP	2011-present	9(0.412–2.25)	τ,α	Northrup Grumman Space Technology ATBD

These bring angular information to the table

τ = AOD

η = fine mode fraction

α = Angstrom Exponent

ω = single scattering albedo

AAI = Aerosol absorption index

These bring angular information to the table

But remember….

AOD quantifies aerosol loading in an optical sense. To get from optical AOD to mass concentration, you need to know the bulk optical effect of size, shape and composition (Mass Extinction Efficiency MEE).

Spectral (wavelength) measurements in the visible can only give you one piece of information (AOD), and only if you can constrain optical effects of size, shape, composition and surface reflectance within reasonable uncertainties.

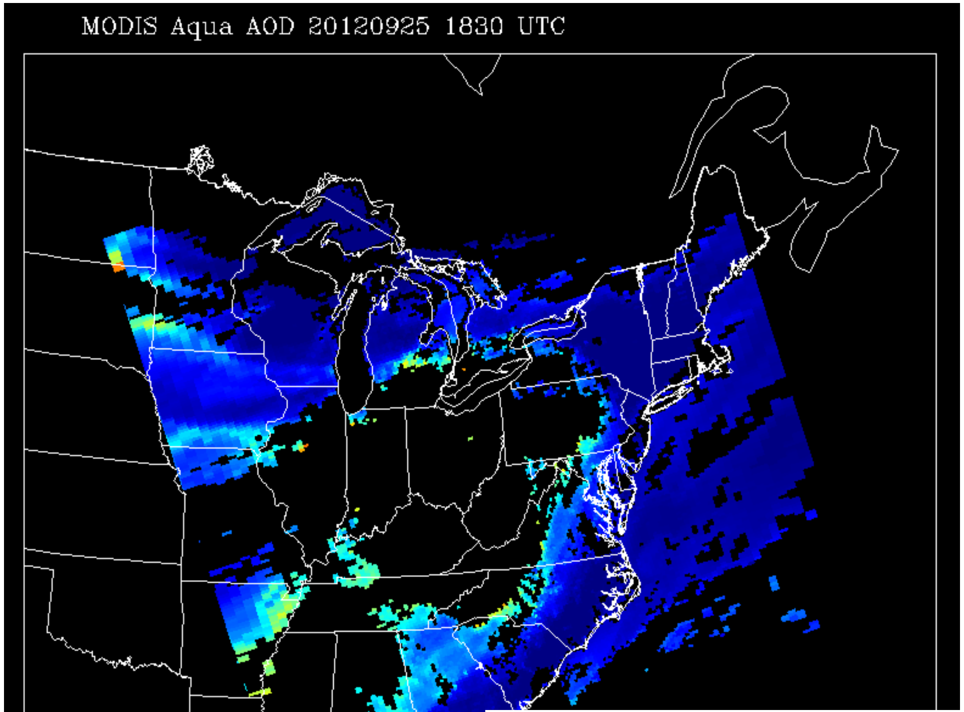
Extending from visible into the shortwave infrared that is sensitive to differences in fine and coarse particles, allows a measure of particle size, but not characterization of the full size distribution, and only when surface reflectance is well constrained like over ocean.

The ultraviolet (UV) spectral range is sensitive particle absorption in a way that visible and shortwave infrared is not. But retrieval of aerosol absorption requires constraint of aerosol layer height, some times not easy to do.

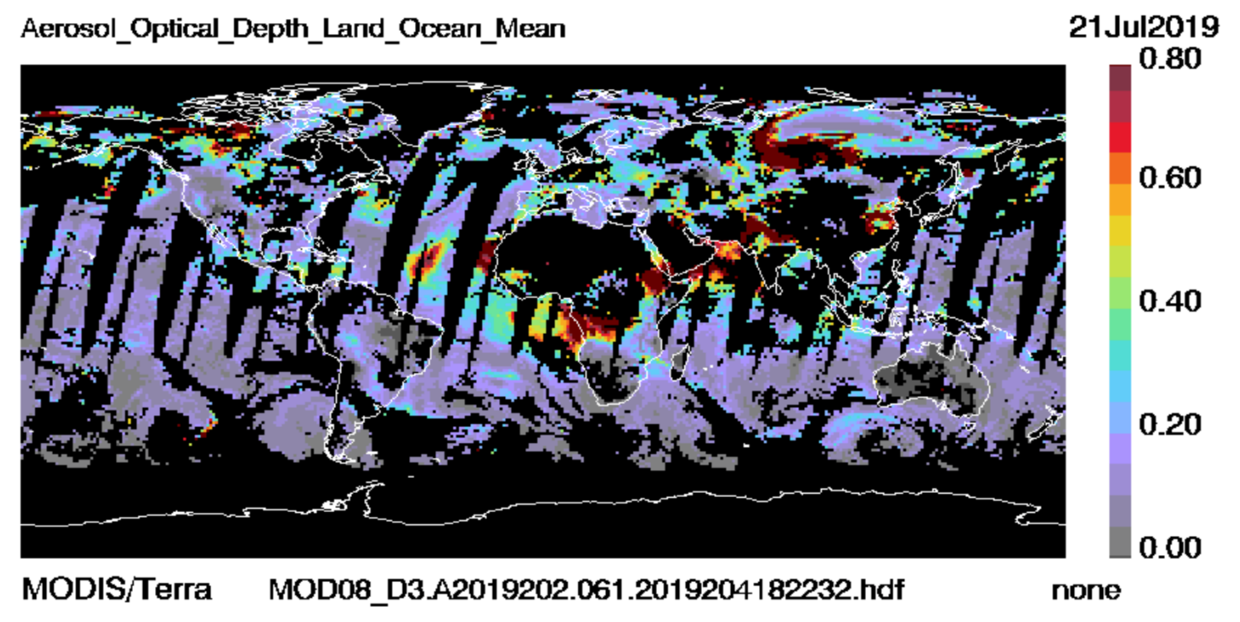
OMI

Once you add angular information (MISR) and polarization (POLDER), your ability to constrain size, shape and composition increases a lot. You are able to retrieve even more information from the aerosol.

Level 0	Digital count.
Level 1	Calibrated radiances
Level 1b	Calibrated radiances with identified geolocation
Level 2	Granule level
Level 3	Gridded



Level 2



Level 3

MOD	MODIS Terra
MYD	MODIS Aqua
MOD04/MYD04	Dark Target and Deep Blue 10 km product
MOD04_3K/MYD04_3K	Dark Target 3 km product

Inside the MOD/MYD files, if it doesn't specify, the product is Dark Target.
If the product is Deep Blue, it will be labeled as such.

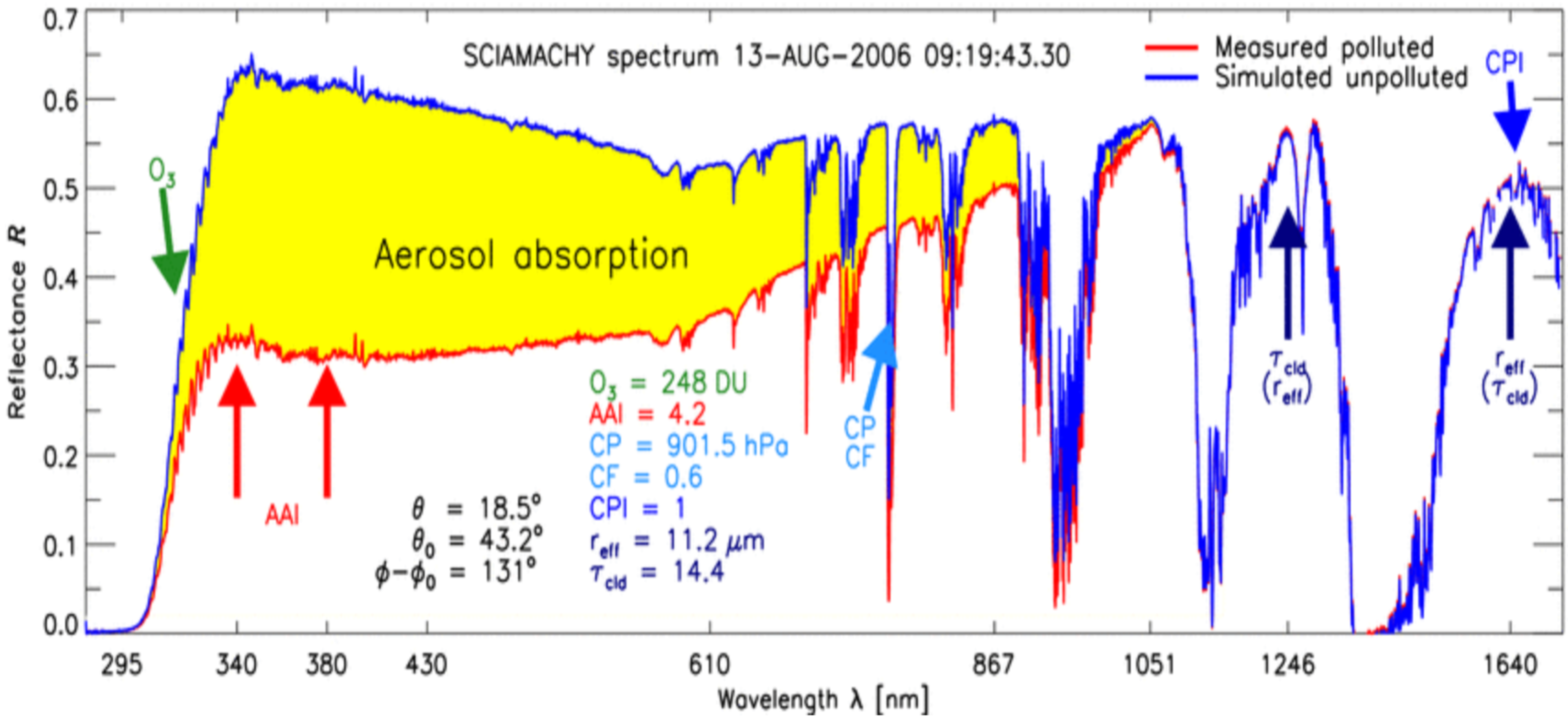
Collection 6.1 is the most modern up-to-date version of the products.

MAIAC is new. Links to learn about and obtain MAIAC are on the last page of my lesson 1 slides.

NOAA VIIRS products are difficult to navigate, as compared to NASA's, but they are worth the effort. I have a tutorial for accessing those products, if you want them. I may also give a webinar specifically on the NOAA products next month.

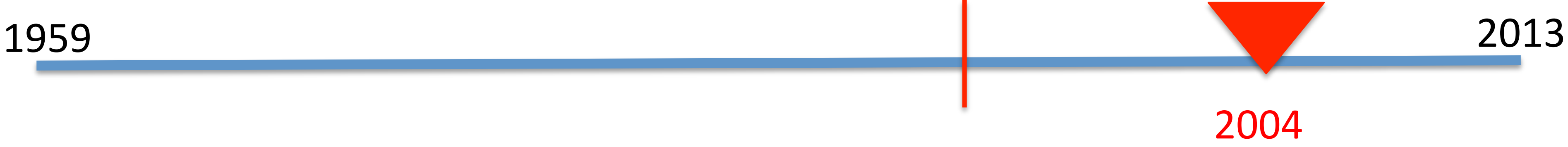
A note on retrieving gases versus retrieving aerosol.

(yellow). This spectral reflectance difference can be converted into aerosol DRE directly.



Aerosol effects are spectrally smooth. Gaseous absorption happens on very fine spectral scales and are species specific.

Vanderlei Martins Mount Evans Colorado



1959

2013

2004

Lorraine Danny Rosenfeld Rich Vanderlei Ilan


t Aid
ZEE

The last time we were Brazil together