NASA AMES Sunphotometer - Satellite Team

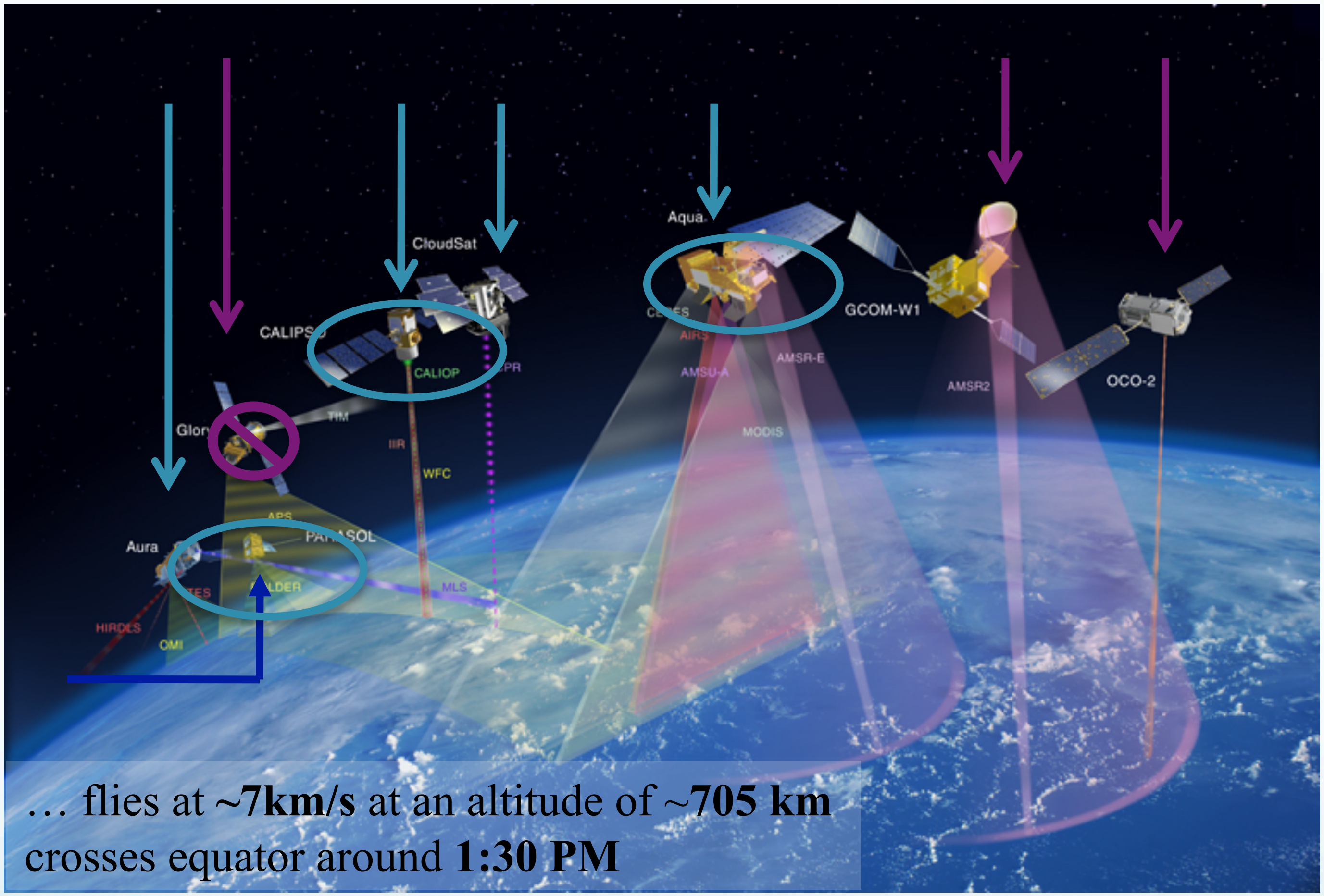
NASA Postdoctoral Program
administered by Oak Ridge Associated Universities

Satellite aerosol remote sensing, air quality and climate

Meloë Kacenelenbogen
Jens Redemann
Phil Russell
SJSU CA 05/04

View from cockpit: Lake Athabasca fires, CA, 28 Jun 2008

The “A-train”



… flies at **~7km/s** at an altitude of ~**705 km**
crosses equator around **1:30 PM**

Currently flying: Aura (Jul. 04), CALIPSO and CloudSat (Apr. 06) and Aqua (May 02)

Lowered under A-Train (decay of orbit): PARASOL (Dec. 04-09)

Scheduled to join: Glory (2011, launch failure caused satellite destruction), GCOM-W1 (2012), OCO-2 (2013)

Atmosphere composition
1. Gas

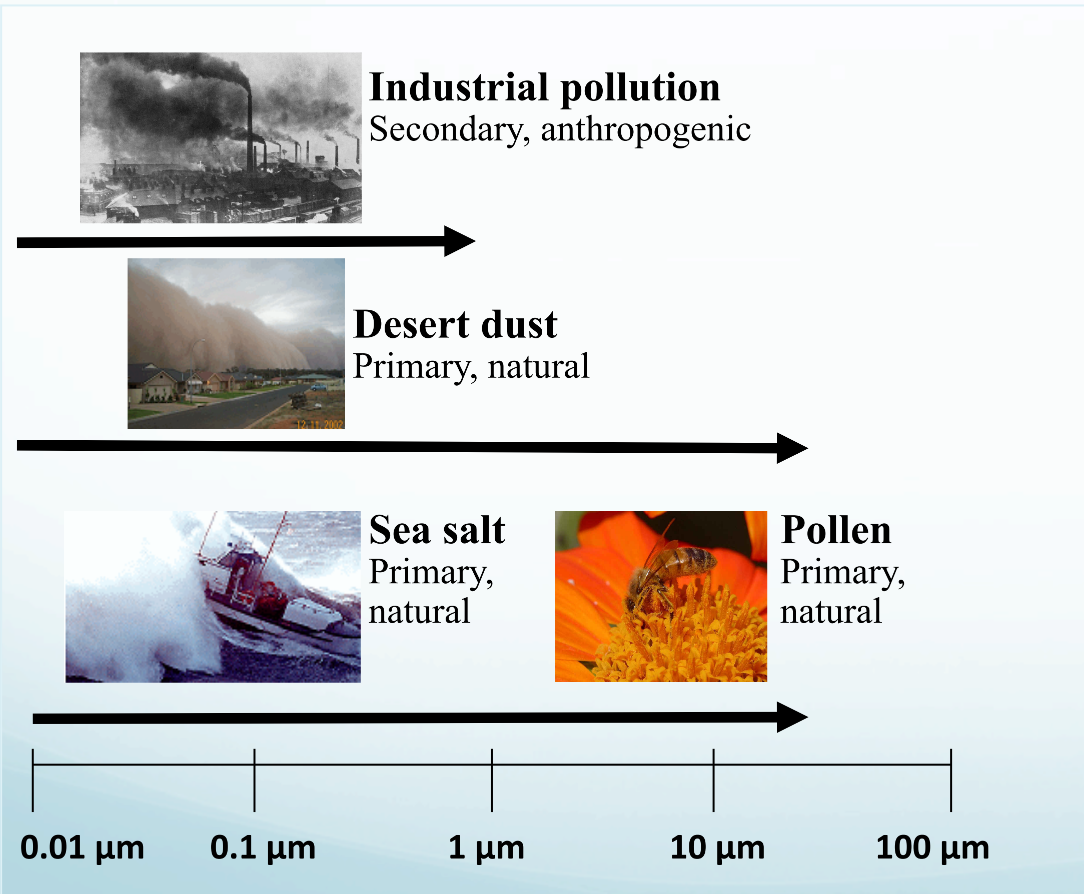
Gases	Gas Volume
Nitrogen (N_2)	78.084%
Oxygen (O_2)	20.946%
Argon (Ar)	0.9340%
Carbon Dioxide (CO_2)	0.0383%
Methane (CH_4)	0.0001745%
Water Vapor (H_2O)	0.40%

- Green house gases

And many other gases…

Atmosphere composition
2. Aerosols

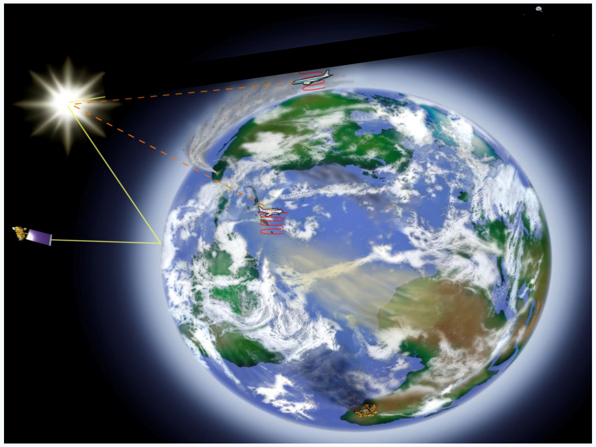
Fine suspended particles in the atmosphere



- Primary (emitted directly) or Secondary (gas to particle) aerosols
- Stay a few days to a week in the atmosphere
- Generally, coarse particles are natural and fine particles are anthropogenic (industrial pollution)

Exception: Wildfire smoke

Passive satellite sensor



"MODerate resolution Imaging Spectroradiometer"
"POLarization and Directionality of Earth's Reflectance"

	MODIS-AQUA	**POLDER-PARASOL**
Resolution for aerosols	Horizontal 10 x 10km	Horizontal 20 x 20km
Channels for aerosols over land	7 λ and 1 viewing direction 466, 553, 644, 855, 1243, 1632 and 2119nm	3 λ, 16 viewing direction 490, 670 and 865nm
Main asset	High spectral/ spatial resolution	Directional and polarized properties of reflected solar radiation

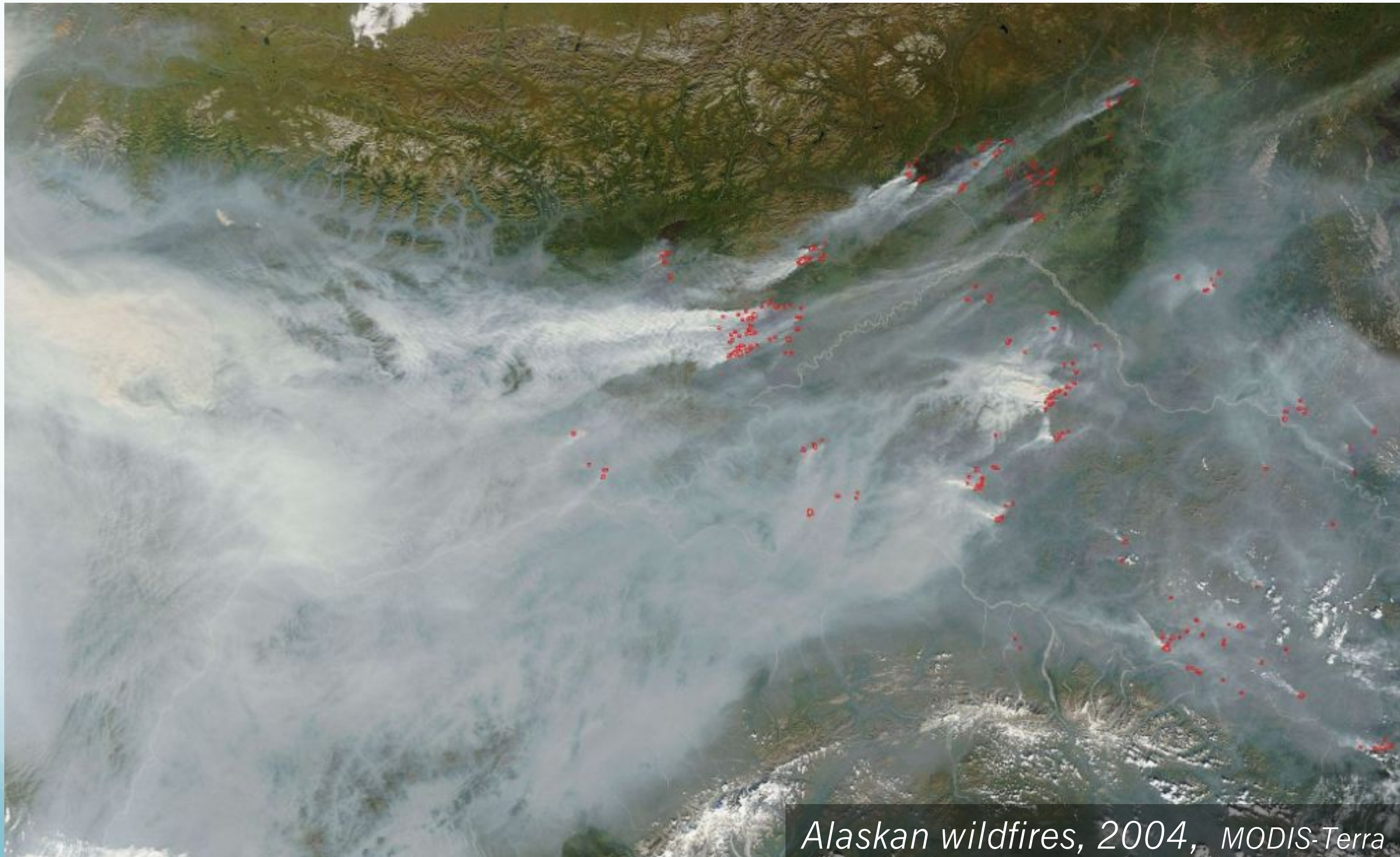
MODIS **measures** total radiances
POLDER **measures** polarized radiances; sensitive to fine particules over land ($r \leq 0.3$ μm)

MODIS/ POLDER mainly **retrieves** the **Aerosol Optical Depth (AOD):**
Extinction of solar light by total column of particles (no unit)

MODIS RGB image (1/3)

Southern California Wildfires, 26 Oct 2003, MODIS-Terra

MODIS image (2/3)

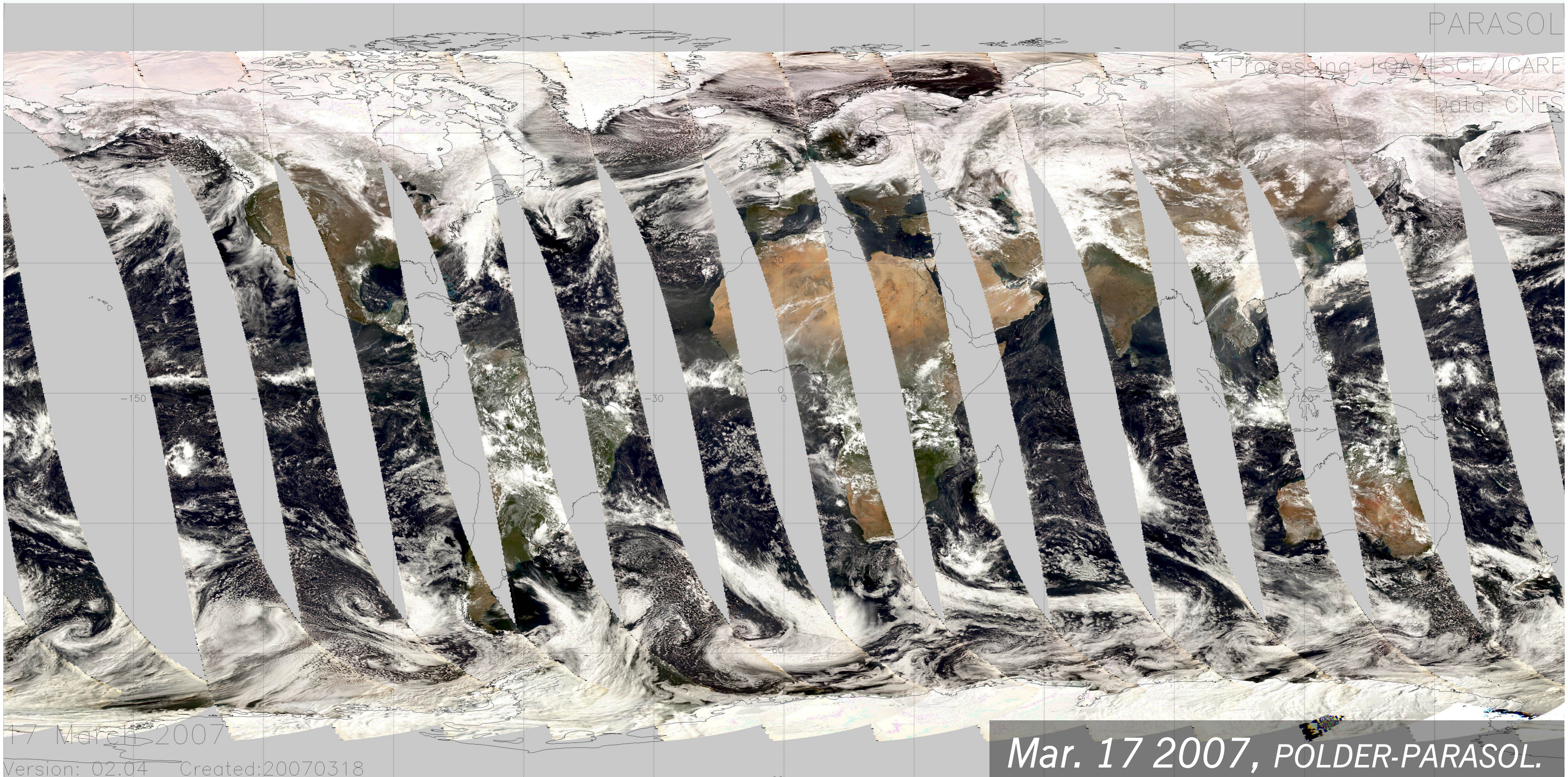


Alaskan wildfires, 2004, MODIS-Terra

MODIS image (3/3)

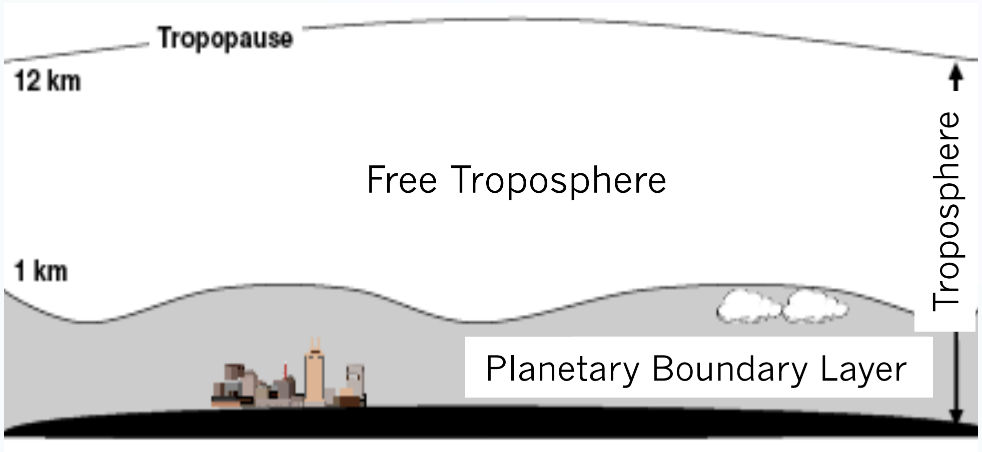
Smoke from Alaska wildfires, 21 Jul 2004, MODIS-Aqua.

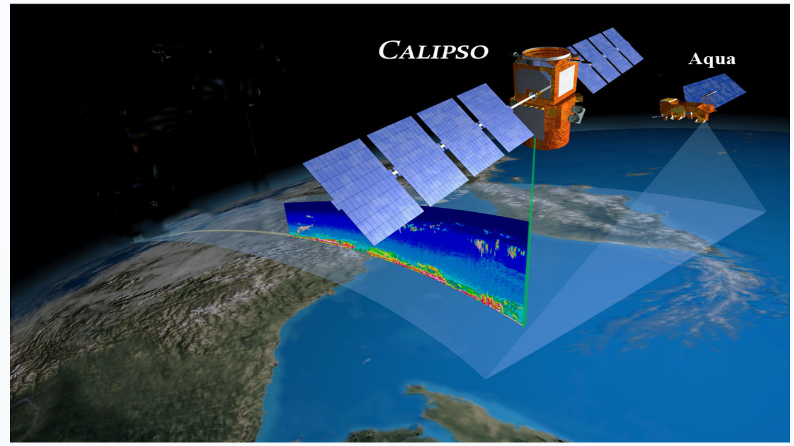
POLDER image

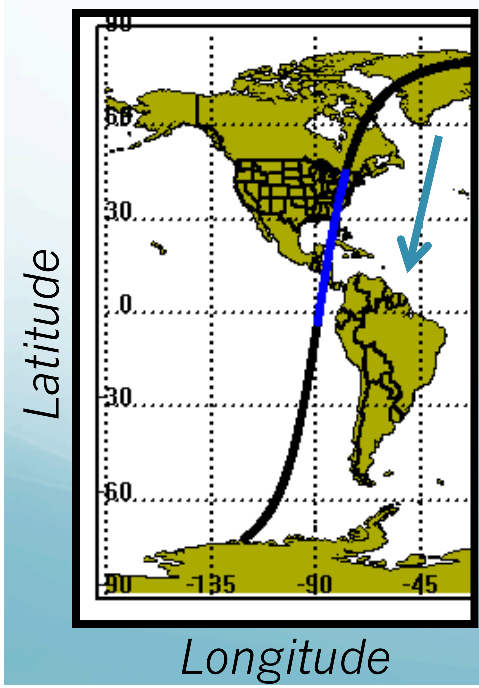


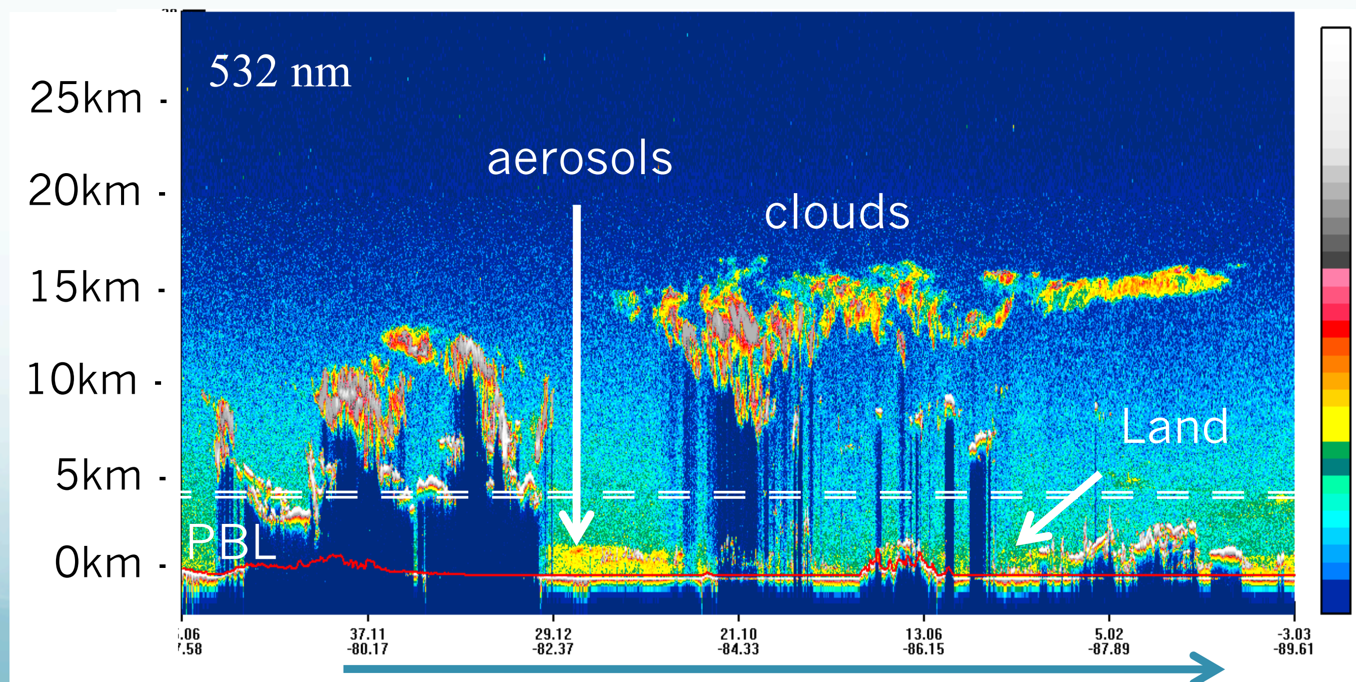
Mar. 17 2007, POLDER-PARASOL.

Active satellite sensor



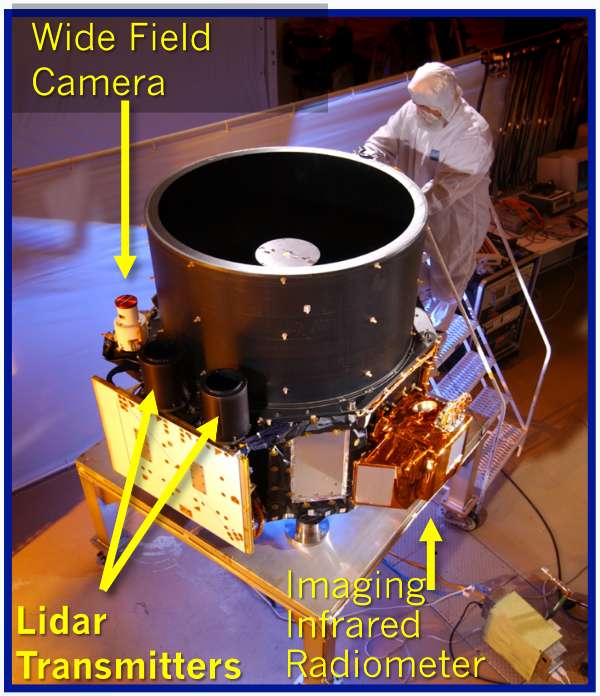






CALIOP

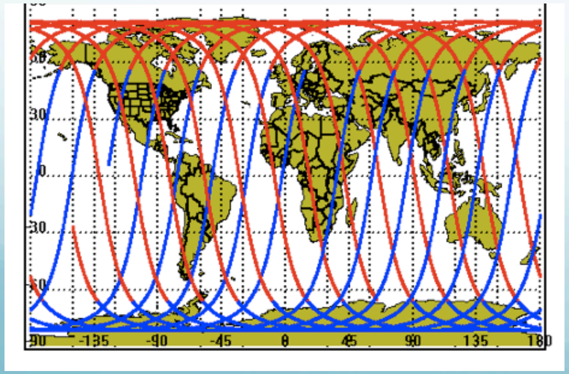
"Cloud-Aerosol Lidar with Orthogonal Polarization"



Resolution for aerosols	90m foot print x 333m horizontal x 30m vertical up to 8km
Channels for aerosols	532 (perp. and total) and 1064nm
Main asset	Vertical distribution, shape and size of aerosols

CALIOP **measures** β' (z, $km^{-1}.sr^{-1}$):
Attenuated backscatter coefficient profile

CALIOP **retrieves** β (z, $km^{-1}.sr^{-1}$) and α (z,km^{-1}):
Backscatter and extinction coefficient profile



day/ night

- No daily global coverage
- Flies over given region (±10km) every 16 days

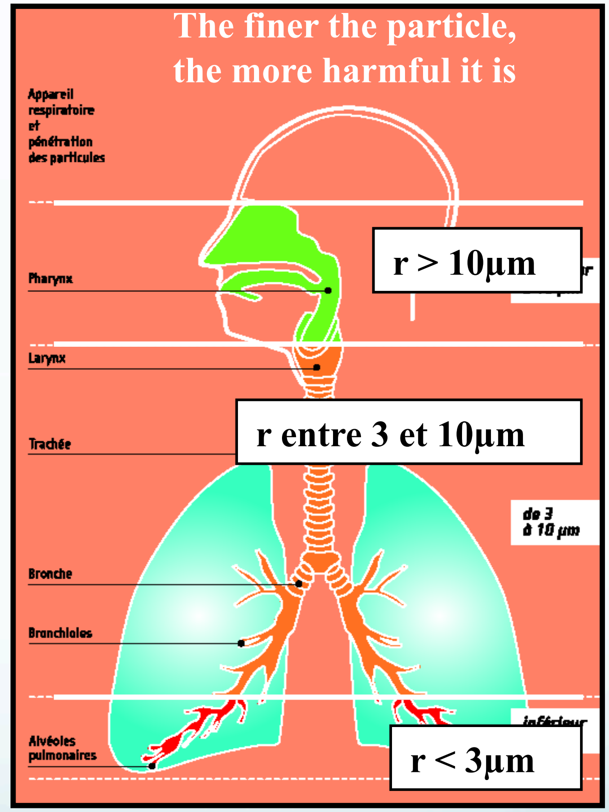
$$AOD = \int_0^\infty \alpha(z)dz$$

1. Aerosol and air quality

Air quality

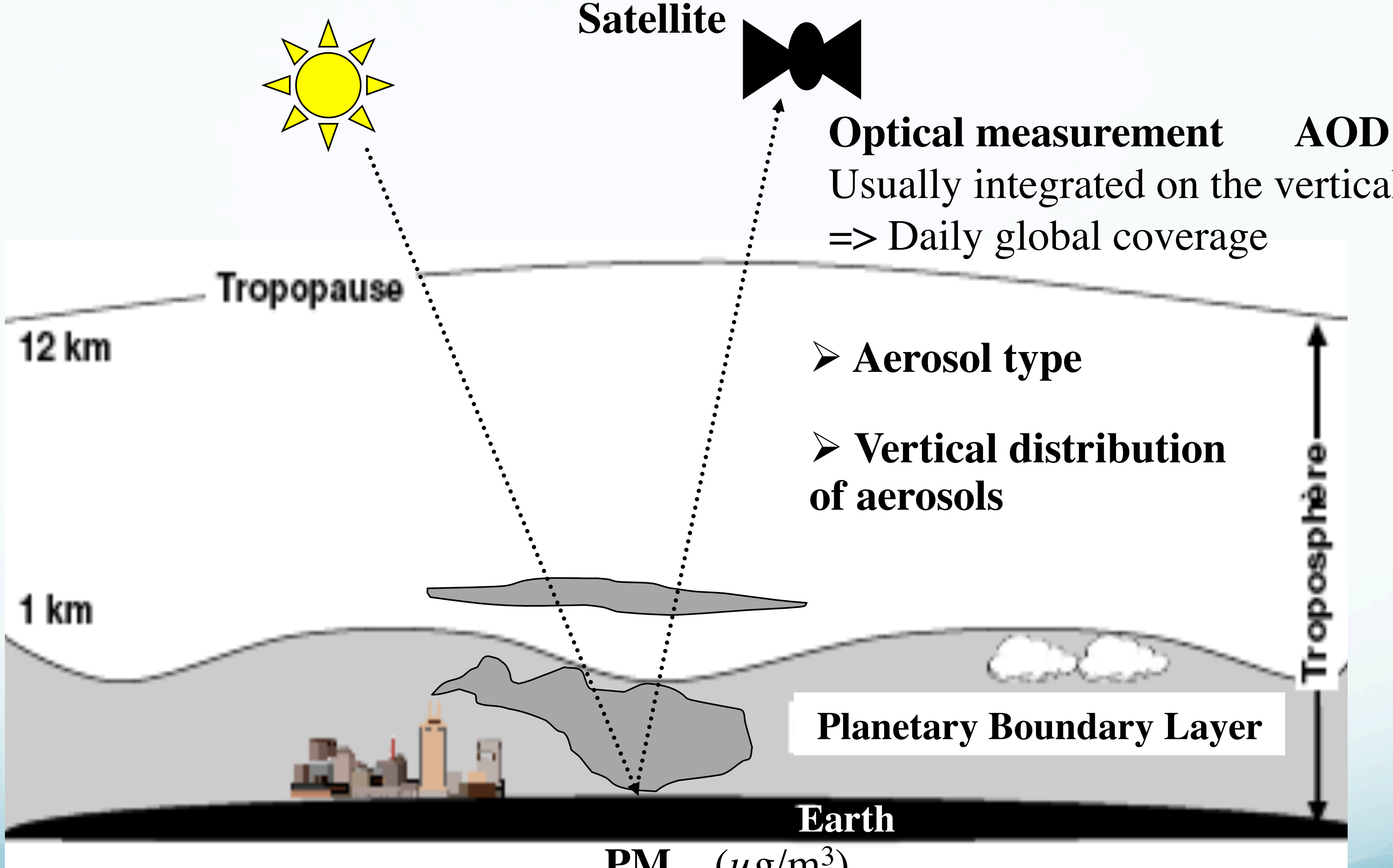
=> Among others, some lung and respiratory diseases and even premature death [*Thurston et al.*, 1994; *Schwartz et al.*, 1996; *Pope,* 2000]

In the US, 8-year study in 6 different cities show that an increase in particle mass concentration is associated with an increase in the death rates [*Dockery et al.*, 1993]



PM_X (µg/m^3): Mass concentration of particles with aerodynamic diameter < x µm

Satellite and air quality



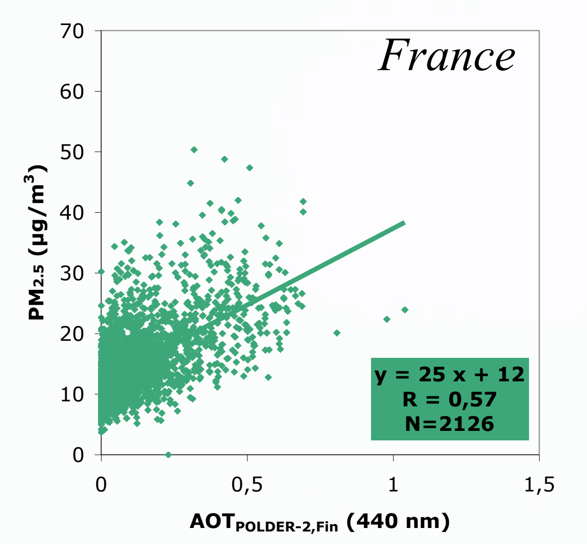
$PM_{2.5}$ ($\mu g/m^3$)

Large areas left without any operational data

$PM_{2.5}$(24h, μg/m³)	0-15.4	15.5-35.4	35.5-55.4	55.5-140.4	140.5-210.4	>210.5
AQC	Good	Moderate	Unhealthy*	Unhealthy	Very Unhealthy	Hazardous

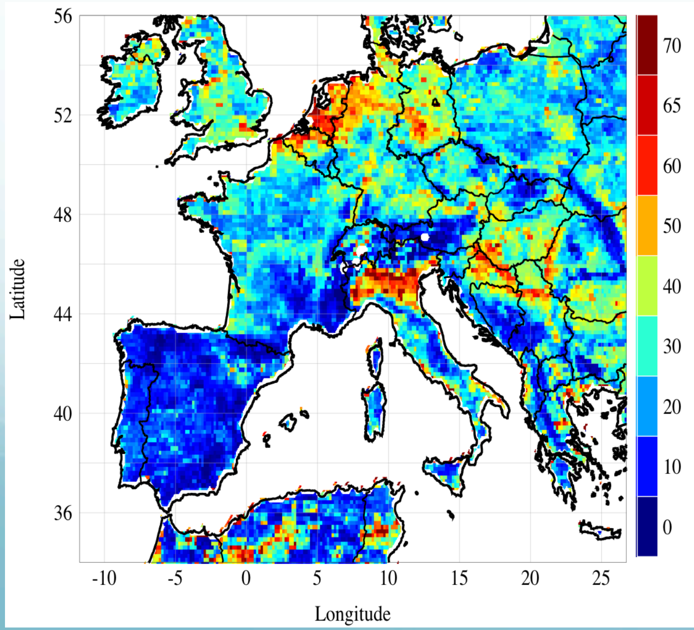
Direct satellite-ground comparison

[*Kacenelenbogen et al.*, 2006]



$PM_{2.5} \approx 25 \times AOD_{POLDER} + 12$

Overall Data set…
helps define a POLDER satellite AOD threshold to characterize « moderate » pollution event
= 0.17 at 440 nm from April to October



Days (%) above « Moderate » POLDER AOD threshold (/ total number of observations)

Stationary aerosol emission sources:

1) Ireland, UK
2) N. France, Belgium, Netherlands, N. Germany
3) Northern Italy
4) Eastern countries
5) Northern Africa

Western Europe
Apr. - Oct. 2003-05-06-07

Direct satellite-ground comparison

[Hoff et al., 2009]

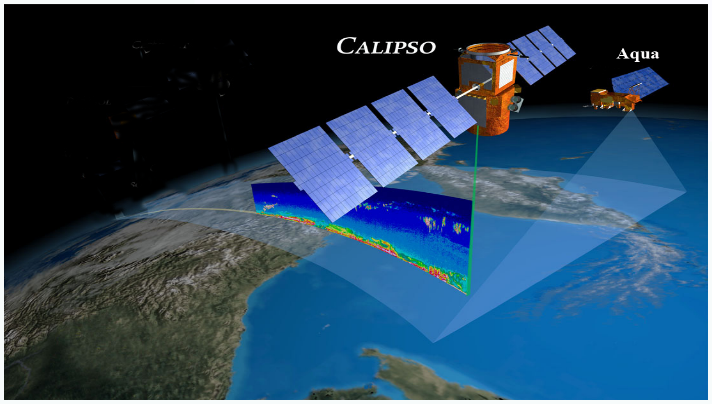
Author	Sensor	Date	Region	Number of Ground Monitors	$PM_{2.5}/PM_{10}$	Linear Regression	R
Wang[154]	MODIS (Terra)	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$77.0\tau - 0.23$	0.67
	MODIS (Aqua)	2002	Alabama	7	$PM_{2.5}$ (24 hr)[a]	$68.6\tau + 1.93$	0.76

Too much dispersion between PM and satellite AOD…

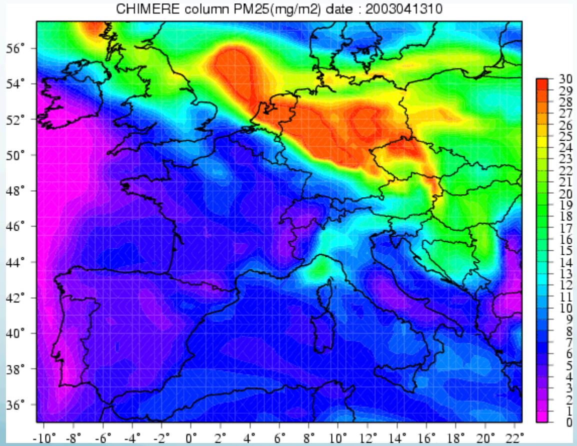
Author	Sensor	Date	Region	Number of Ground Monitors	$PM_{2.5}/PM_{10}$	Linear Regression	R
Engel-Cox[161]	MODIS	April–September 2002	United States	1338	$PM_{2.5}$	$22.6\tau + 6.4$	0.4
					$PM_{2.5}$ (24 hr)	$18.7\tau + 7.5$	0.43
Liu[208]	MISR	2003	St. Louis	22	$PM_{2.5}$	NA	0.8
Engel-Cox[163]	MODIS	July 1 to August 30, 2004	Baltimore	4	$PM_{2.5}$	$31.1\tau + 5.2$	0.65
					$PM_{2.5}$ (<PBL)	$48.5\tau + 6.2$	0.65
						$25.3\tau + 11.1$	0.57
					<	$64.8\tau + 1.76$	0.76
							–
						62.0τ	NA
						$141.0\ \tau$	0.96
						NA	0.63
					PM_{10}[a]	$214.0\tau - 42.3$	0.58
Kacenelenbogen[118]	POLDER	April–October 2003	France	28	$PM_{2.5}$	$26.6\tau + 13.2$	0.7
Gupta[173]	MODIS	February 2000 to December 2005	Southeastern United States	38	$PM_{2.5}$	$29.4\tau + 8.8$	0.62
					$PM_{2.5}$ (24 hr)	$27.5\tau + 15.8$	0.52
Hutchison[158]	MODIS	August–November 2003 and 2004	Texas	28	$PM_{2.5}$ (August)[a]	$68.8\tau - 39.9$	0.47
					$PM_{2.5}$ (September)[a]	$59.7\tau - 17.2$	0.98
Paciorek[177]	GOES-12	2004	United States	Not given	$PM_{2.5}$ (24 hr)	NA	0.5
					$PM_{2.5}$ (yearly)	NA	0.75
An[179]	MODIS	April 3–7, 2005	Beijing	6	PM_{10}[a]	$21.7\tau + 6.1$	0.92
					$PM_{2.5}$[a]	$31.1\tau + 5.1$	0.92
Schaap[180]	MODIS	August 2006 to May 2007	Cabauw, Netherlands	1	$PM_{2.5}$	$120\tau + 5.1$	0.72

Need additional information on:
vertical distribution and type of aerosols…

Aerosol vertical distribution



Inferred by space-borne lidar CALIOP-CALIPSO



Inferred by 3-D Chemistry Transport Model (CTM)

Infer ground mass with active and passive satellites

Estimated mass at the ground

Passive satellite

POLDER AOD

Active satellite

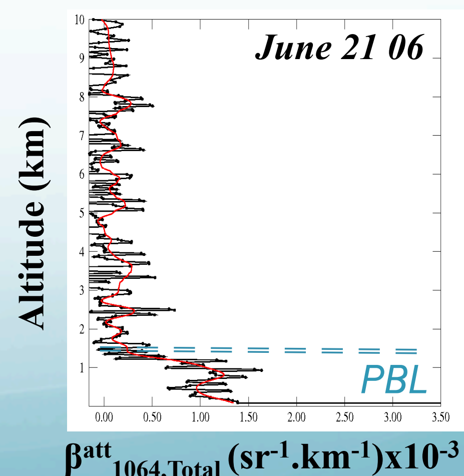
Ratio of aerosol content in PBL/ column – **CALIOP-**

$$M_{POL}(H_1) = \frac{AOD_{POL} \times R_C}{s_1 \times H_1}$$

Specific mass extinction cross section at the ground –**met. station-**

Active satellite

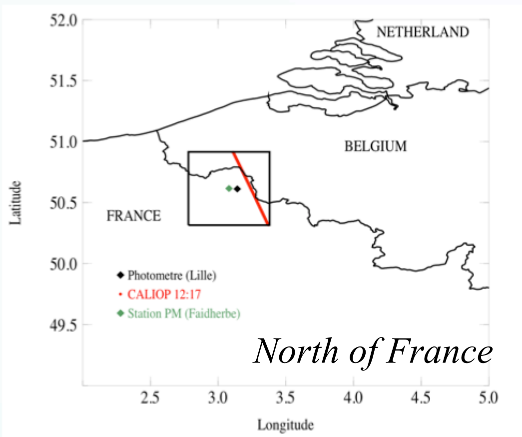
Height of PBL **-CALIOP-**



R_c = 100%
H_1 = 1,21 km

Infer ground mass with active and passive satellites

Four case studies



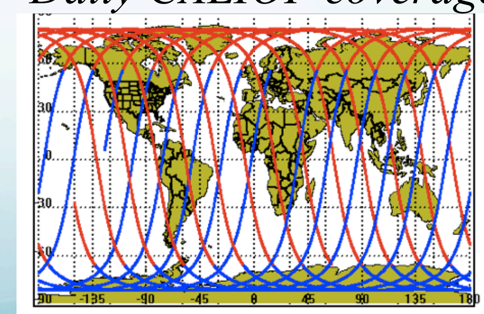
	06/13/06	06/29/06	03/12/07	04/29/07
POLDER AOD (440 nm)	0.39	0.21	0.12	0.78
Measured $PM_{2.5}$ ($\mu g/m^3$)	19	19	15	21
Estimated M_{POL} ($\mu g/m^3$): Combining POLDER and CALIPSO	19	16	16	17

For all 4 cases, estimated M_{POL} similar to measured $PM_{2.5}$ ($\pm$ 4 $\mu g/m^3$)

Next step is apply this method to broader area and longer time period

But CALIOP has insufficient coverage…

Daily CALIOP coverage

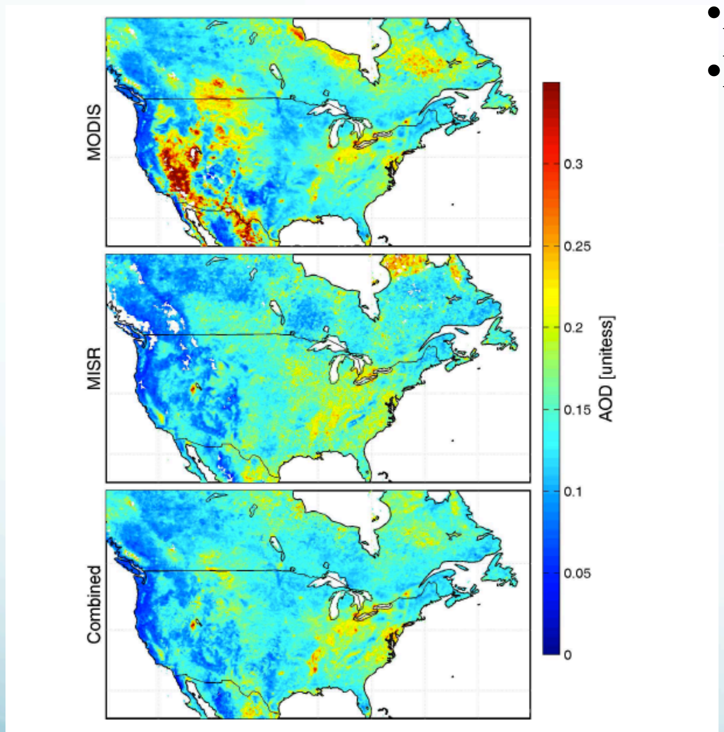


Another option is to use a CTM estimate of aerosol vertical distribution…

Infer ground mass with passive satellites and CTM

[*Aaron Van Donkelaar et al.*, 2010]

1.Combine two passive satellite sensors (MODIS and MISR)



6-yr mean AOD (2001-2006)

•MODIS high spectral/ spatial resolution
•MISR lower spectral/ spatial res but reduced retrieval bias

Combined MODIS-MISR map:
dominated by MODIS in the East (more data)
dominated by MISR in the West (more accuracy)

2. Use global 3-D CTM (GEOS-Chem) to find the daily global distribution of η:

$PM_{2.5} = \eta \times AOD$

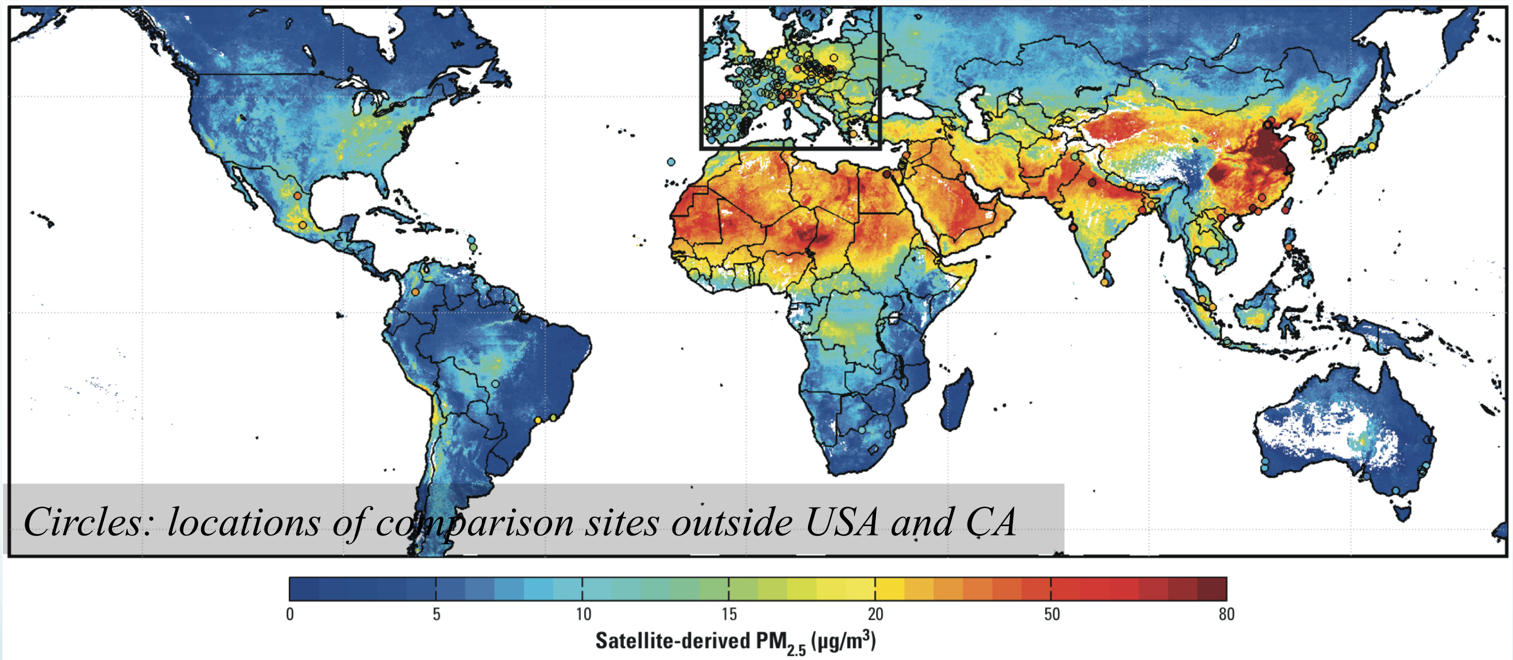
η function of aerosol size, type, diurnal variation, relative humidity, and the extinction vertical profile

3. Apply η to combined MODIS-MISR AOD map…

Infer ground mass with passive satellites and CTM model

[*Aaron Van Donkelaar et al.*, 2010]

Global satellite-derived $PM_{2.5}$ averaged map over 6 years



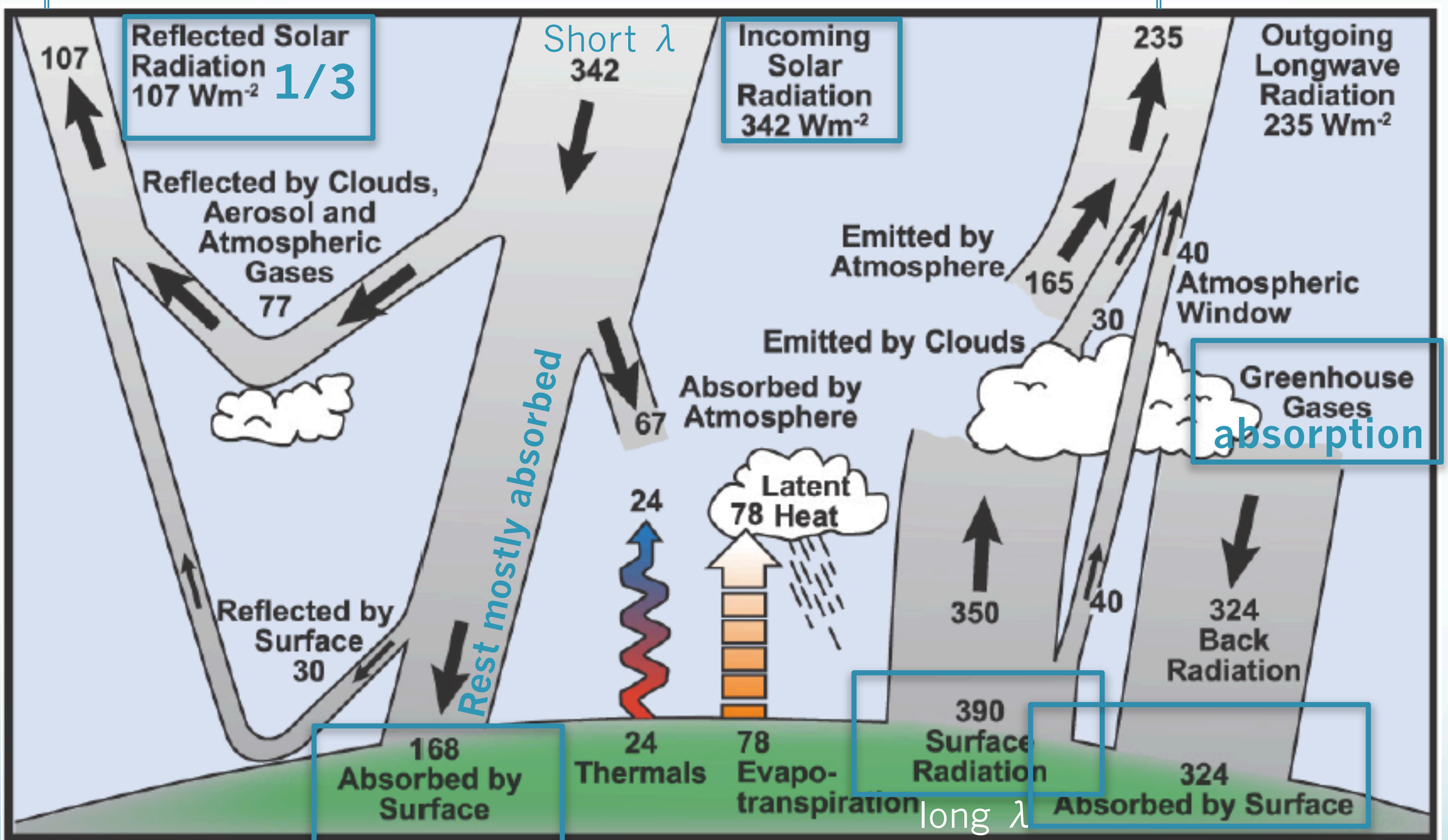
Satellite-derived vs. measured $PM_{2.5}$: significant overall global agreement
r = 0.83; slope = 0.86; intercept = 1.15 μg/m^3; n = 244

2. Aerosol and climate

Earth energy's balance

[Kiehl and Trenberth, 1997]

Net input/ output must be balanced

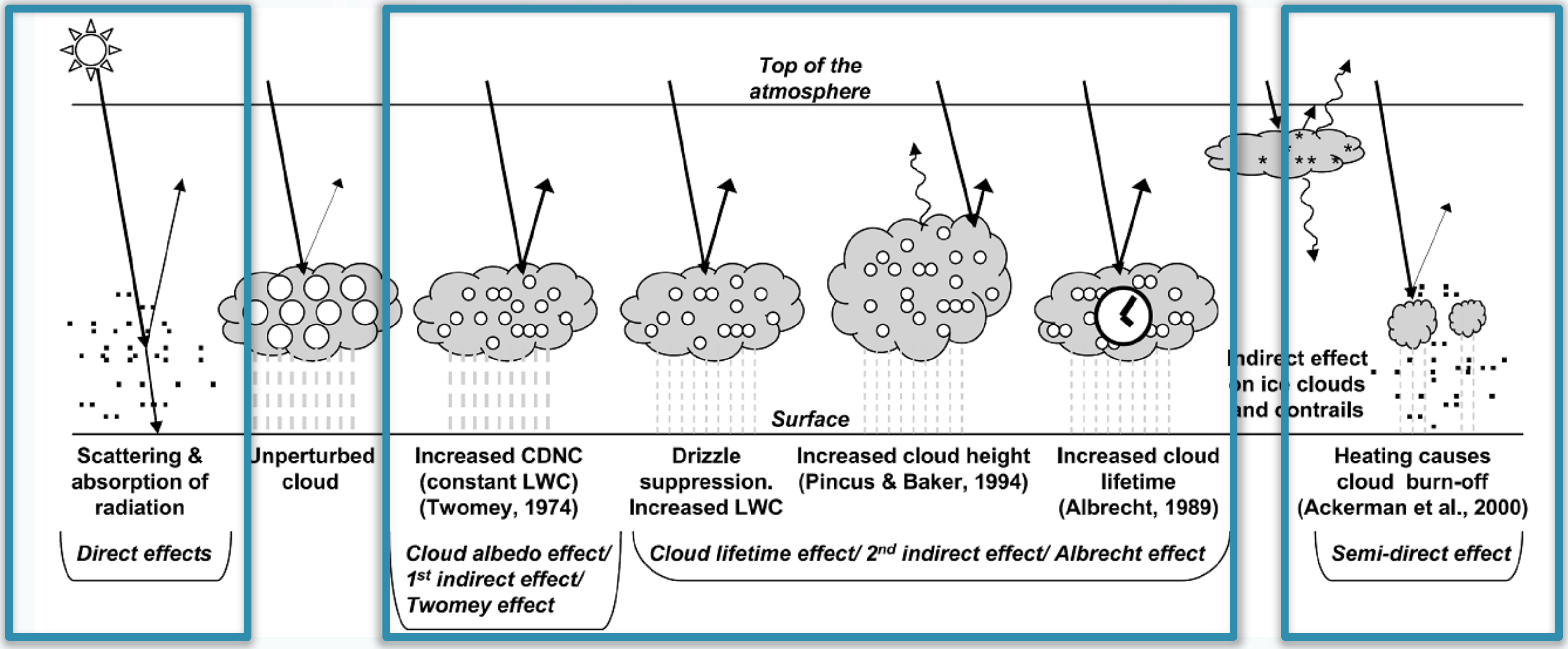


Carbon Dioxide
Methane
Water Vapor
etc…

Absorption, radiation and surface heat: natural green house effect

"Radiative forcing":
Rate of energy change per unit area of the globe as measured at the top of the atmosphere (change in net down minus up irradiance $W.m^{-2}$)

Aerosol radiative effects



Direct aerosol effect:

scattering and absorption of solar and infrared radiation

Direct Aerosol Radiative Forcing = DARF

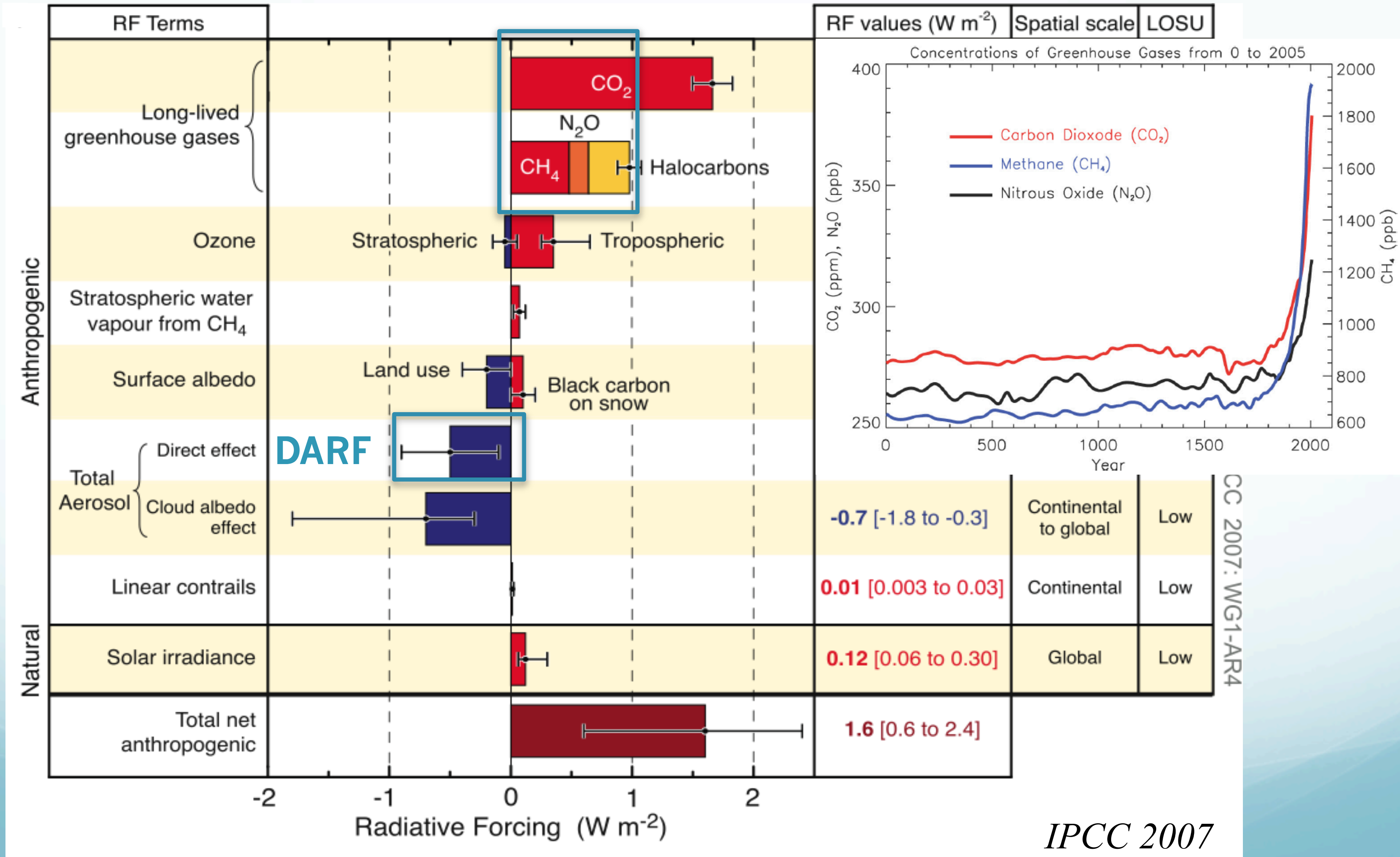
Semi-direct aerosol effect:

Change in cumulus cloud formation influenced by absorbing aerosols (black carbon)

Indirect aerosol effect:

Change in cloud formation, lifetime and radiative properties due to chemical and microphysical properties of aerosols

Principal factors affecting climate

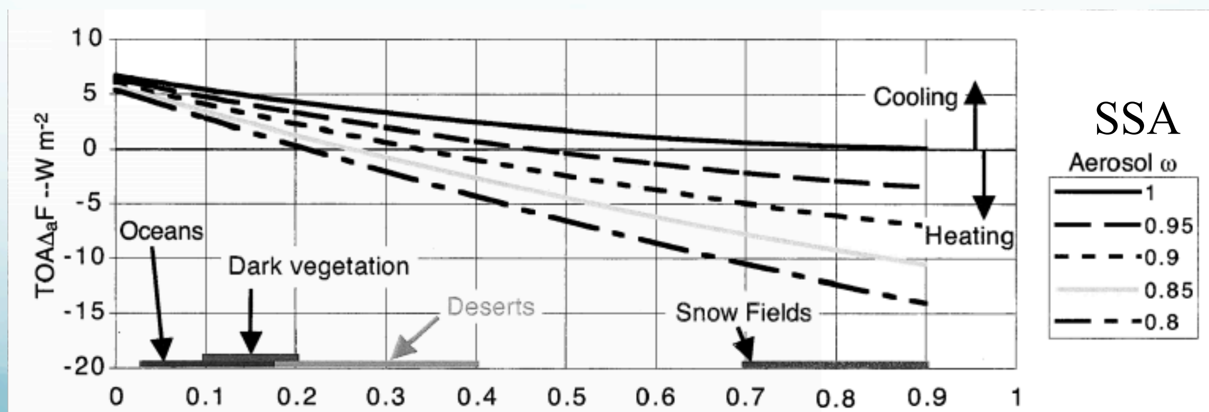


IPCC 2007

To compute DARF

- •Solar constant and zenith angle
- •Cloud fraction
- •**Surface albedo** (% solar energy reflected back to space)
- •Gas/ molecular extinction profile
- •**Aerosol radiative properties:**
  1. Extinction: light absorption and scattering by particle
  2. Scatter asymmetry parameter (z): direction of scattered light
  3. Single scattering albedo: ratio of scattering to total extinction

DARF



[*Russell et al.*, 2002]

Satellite and DARF calculation

[Sun-Sat group at AMES]

Each satellite sensor insufficient to constrain a set of aerosol radiative properties

• Combination of 3 satellite sensors:
CALIOP aerosol backscatter
MODIS aerosol optical depth
OMI aerosol absorption optical depth AOD (1-SSA)

• Find particle model (size distribution and refractive index) that best matches satellite observations

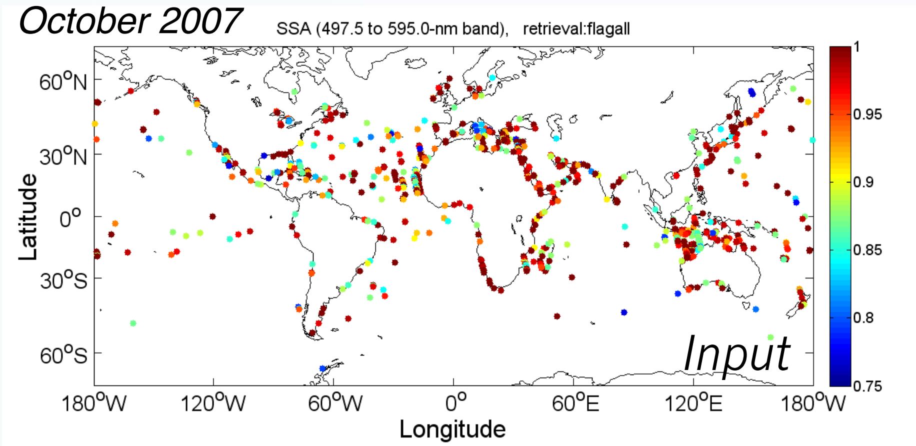
• Retrieval of aerosol radiative properties: ext(λ,z), SSA(λ,z) and g(λ,z)

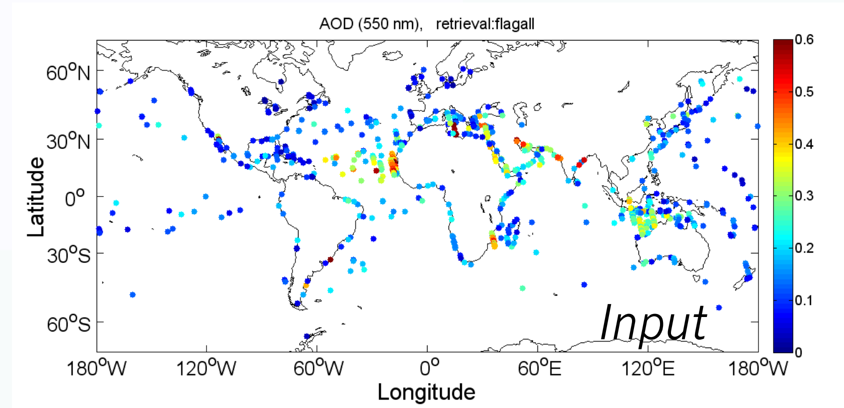
• DARF computation using Fu-Liou radiative transfer model

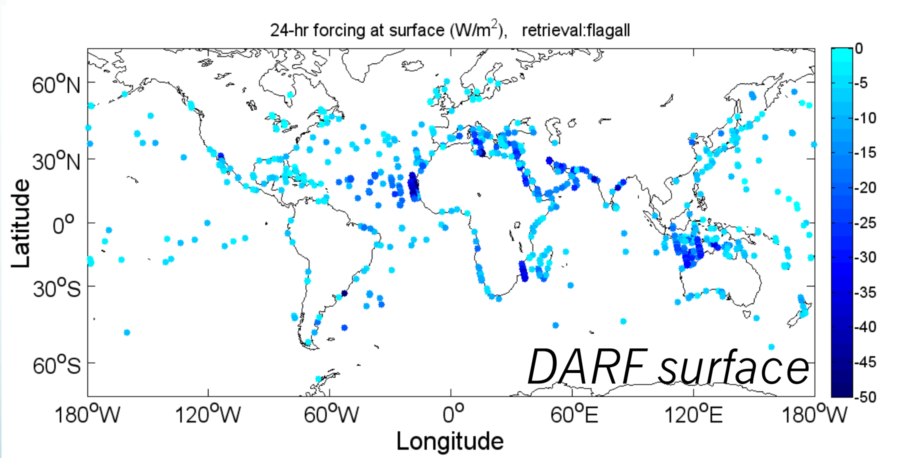
• Airborne validation (combining sunphotometer and Solar Spectral Flux Radiometer)

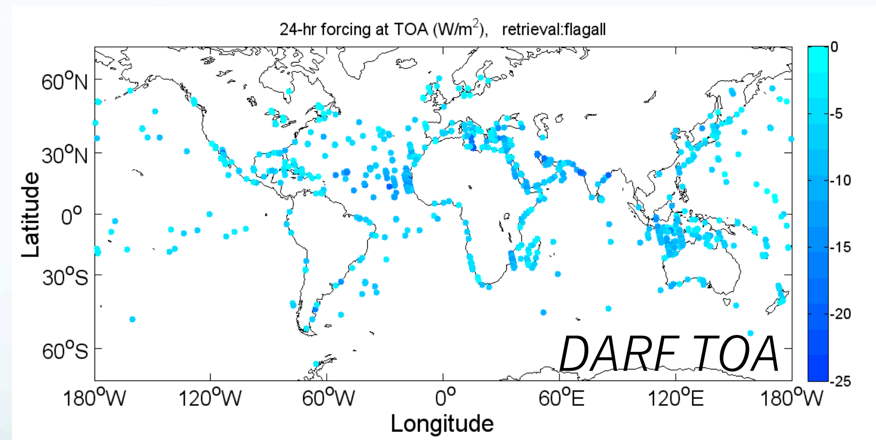
Satellite and climate

[Redemann et al., 2011]









Data density driven by overlap OMI (mostly land) and MODIS over ocean

High SSA (low absorption near coast)

Here natural and anthropogenic aerosols, no distinction yet

Majority of global DARF TOA between 0 and -5 $W.m^{-2}$

Satellite and climate

Remaining difficulties in DARF computation with satellites:

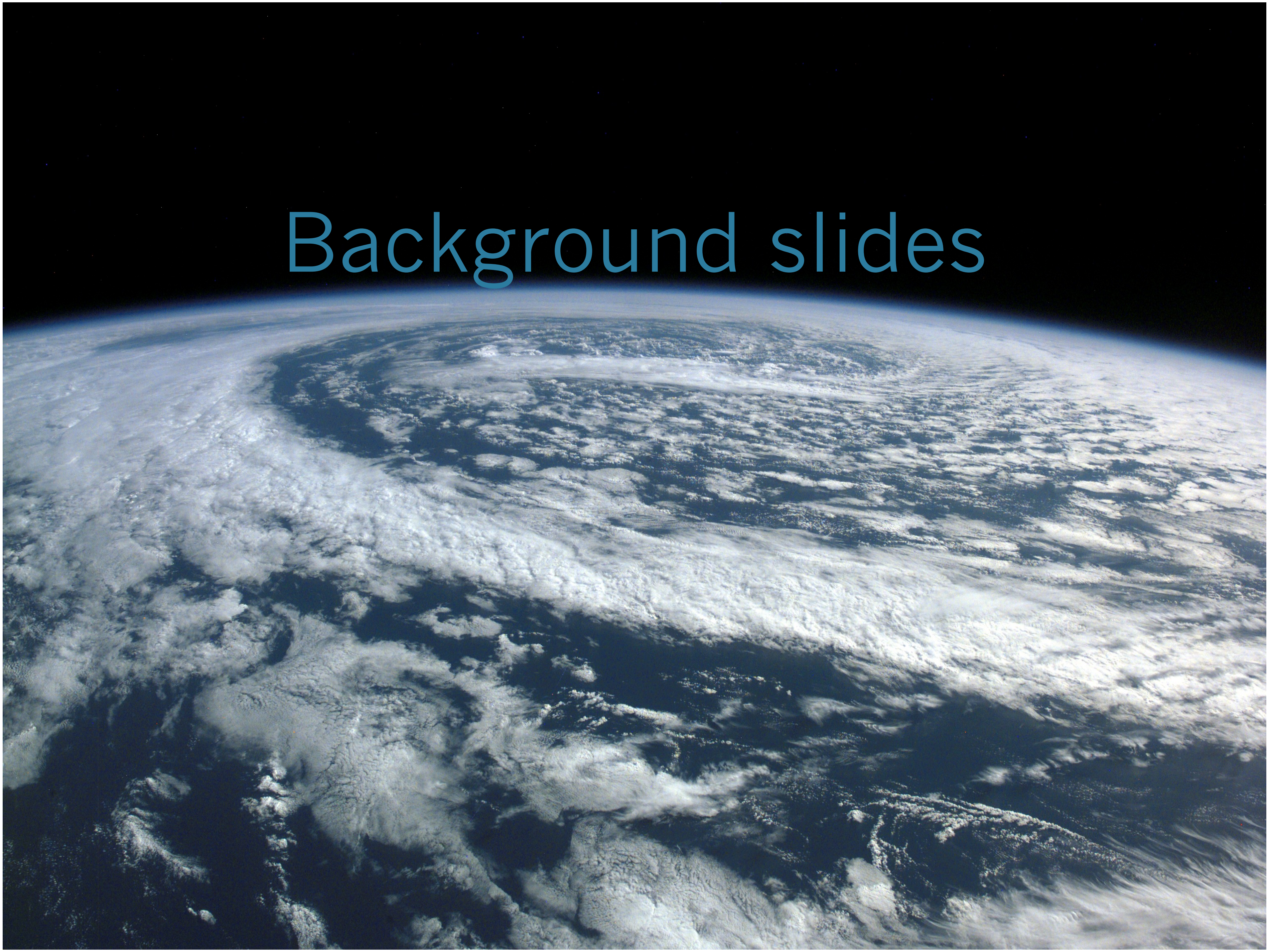
- Separation anthropogenic/ natural aerosol
- Spatial coverage of aerosol vertical profile
- Global aerosol absorption measurements
- Satellite aerosol retrieval over land
- Satellite observations with cloudy sky

Conclusion

- Combination of satellite aerosol remote sensors currently used for air quality and climate studies
- Still many satellite retrieval uncertainties (especially over land). We need suborbital airborne validation to help algorithm improvements
- Major main difficulty for air quality and climate: accurate global measurement of aerosol vertical distribution


Thanks!

Background slides



MODIS over land

Measures total radiance in one direction and 7 wavelengths (466, 553, 644, 855, 1243, 1632 and 2119 nm)

MODIS main asset: High spectral/ spatial resolution (10 x 10 Km compared to 20 x 20 Km for POLDER)

Surface radiance:

1. Atmospheric signal (molecules and aerosols) supposed neglectable at 2119 nm (short wave infrared) => we got surface radiance directly
2. We suppose linear relationship between surface reflectance in the 3 bands
3. Detection of dark surfaces (vegetation) at 466 and 644 nm
4. Note: forest dark in visible (except at 550 nm, green)

Aerosol radiance:

1. AOD derived over those dark pixels with a continental model
2. Path radiance for each wavelength is SSA x AOD x phase function
3. Ratio of path radiance at different wavelength informs on non dust, dust or mixe

POLDER over land

Measures polarized radiances in different viewing directions and 2 wavelengths

$$L_p = L_p^{mol} + L_p^{surf} \exp(-m_a(c_{aer}\tau_{aer} + c_{mol}\tau_{mol}) + L_p^{aer} \exp(-m_a c_{mol}\tau_{mol})$$

Surface radiance:

1. the contribution of the solar reflected beam on the surface is lower in polarization than the total radiance. The surface is way less polarizing (one chosen direction) than the molecules and particles.

2. More over, the polarization of the surfaces is spectrally neutral from the visible to the near infrared (0.44-0.8 µm). POLDER uses the strong spectral dependance of the polarized contribution of the fine mode aerosols compared to the low spectral effect of the surfaces to detect them.

3. We don't neglect the contribution of the surface though… We use a semi-empirical bidiretional polarized modeled surface (viewing geometry, surface type and NDVI) [Nadal and Breon, 1995]

Molecular radiance:

Simulated (Pressure and Temperature)

Aerosol radiance:

10 lognormal monomodal models of small spherical aerosols for LUT. The inversion is to find the aerosol model that minimizes the most the difference between simualted and observed polarized radiances in the 14 (or 16) viewing directions and the two wavelength

CALIPSO algorithm

1. **Attenuated backscatter data** (function of backscatter and extinction coefficient and directly proportional to the LIDAR signal, covering 80 Km)

2. **Selective Iterated Boundary Locator (SIBYL)**
   - Averaging engine
   - Profile scanner locating feature boundaries
   - Removing features previously detected from profiles and correct all data beneath for the attenuation

3. **Scene classification algorithm (SCA)**
   - Classification of features in clouds (ice/ water) or aerosols (5 types)
   - Selects initial LIDAR ratios from LUT (location, depolarization ratio, mean attenuated back scatter)

4. **Hybrid Extinction Retrieval Algorithm (HERA)**

=> particle backscatter and extinction profiles

New data release (version 2 to version 3):

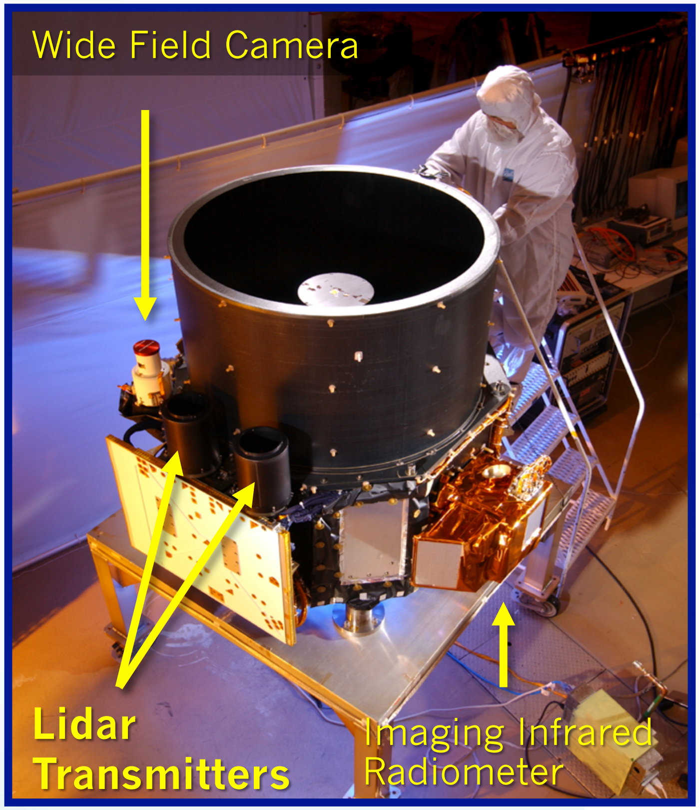
a) Correction of bug in cloud clearing code

b) Aerosol profile products will be reported at the same spatial resolution as the aerosol layer products,

c) Elimination of horizontal smearing/mixing of different aerosol types (e.g., dust, smoke, etc.) within individual profile altitude resolution element,

d) Extinction coefficients from high quality retrievals will no longer be averaged with those from low quality retrievals.

CALIOP on board CALIPSO



Wide Field Camera	
Wavelength	645 nm
Spectral bandwidth	50 nm
IFOV / Swath	125 m / 61 km

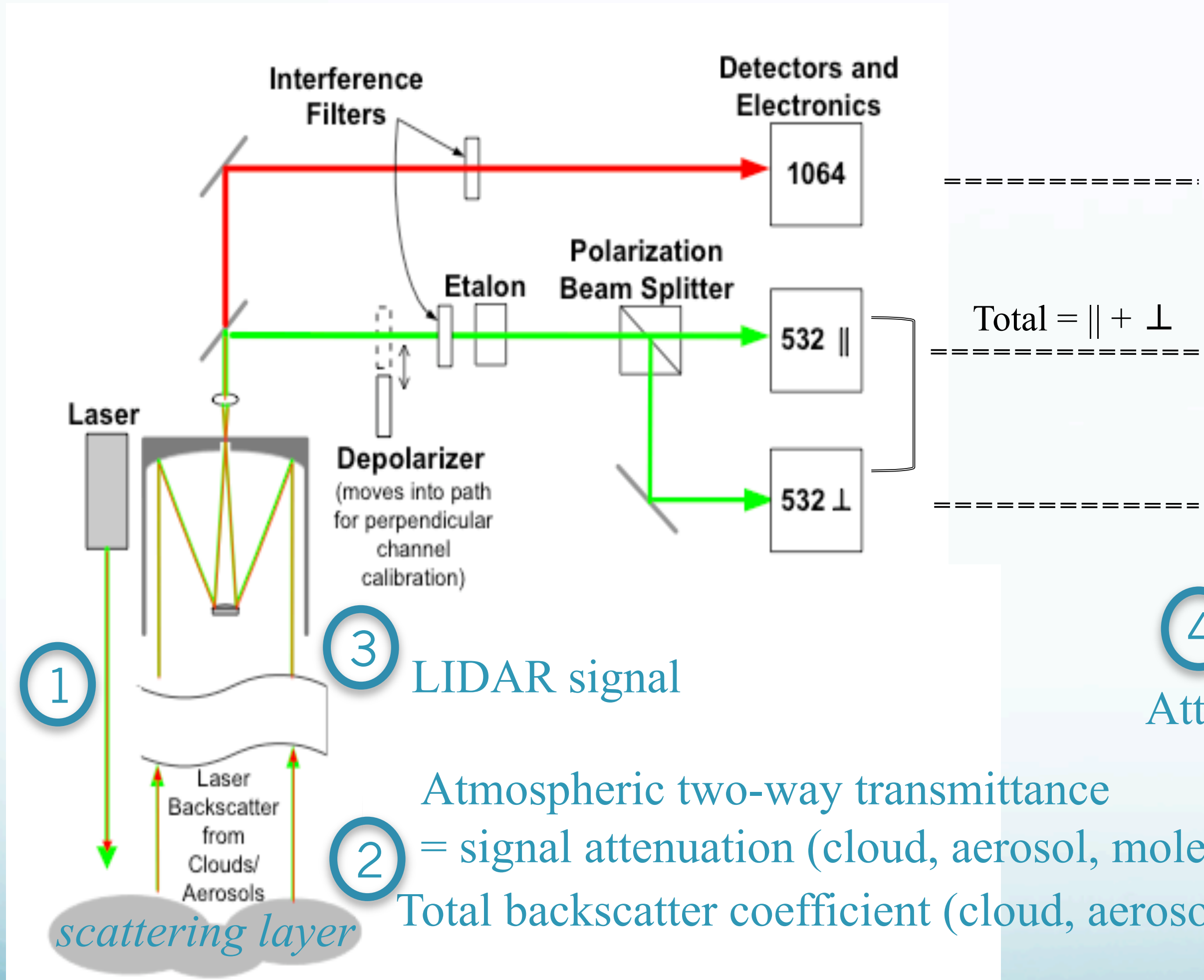
Imaging Infrared Radiometer	
Wavelength	8.65, 10.6,12.05 µm
Spectral resolution	0.6-1.0 µm
IFOV / Swath	1 km / 64 km
NETD @ 210K	0.3 K
Calibration	±1 K

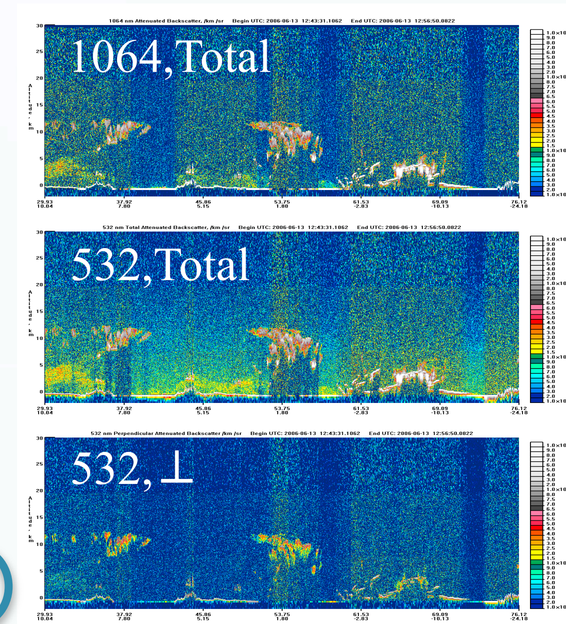
Cloud-Aerosol LIDAR with Orthogonal Polarization (CALIOP)	
Laser	Nd: YAG, 2x110 mJ
Wavelength	532 nm, 1064 nm
Repetition rate	20.25 Hz
Receiver telescope	1.0 m diameter
Polarization	532 || and ⊥
Footprint/FOV	100 m / 130 µrad
Lin. dynamic range	22 bits

CALIOP:

- Active downward pointing elastic backscatter LIDAR (LIght Detection And Ranging)
- Two wavelengths: 532 and 1064 nm with 532 nm polarized
- 90 m diameter foot print every 333m; No daily global coverage (given region every 16 days)

How does CALIOP work?





LIDAR signal

Attenuated backscatter coefficient

Atmospheric two-way transmittance
= signal attenuation (cloud, aerosol, molecule, gas)

Total backscatter coefficient (cloud, aerosol, molecule)

From lidar signal to extinction profile? -Theory-

Lidar signal => **calibration => Attenuated backscatter coefficient β'**

In a cloud-free atmosphere:

$$\beta' = (\beta_a + \beta_m) T_a^2 \, T_m^2 \, T_{O_3}^2$$

Aerosol and molecular backscatter: $(\beta_a + \beta_m)$

Atmospheric two-way transmittance = signal attenuation: $T_a^2 \, T_m^2 \, T_{O_3}^2$
Aerosols, Molecules, Ozone

For aerosols:

$$T_a^2 = \exp\left(-2\int \alpha_a(z)\,dz\right)$$

Aerosol extinction coefficient: $\alpha_a(z)$

Molecular backscatter and attenuation can be computed
=> **β' function of β_a and α_a**

One measurement (β') — **Two unknowns** (β_a and α_a)

If we assume an aerosol extinction-to-backscatter LIDAR ratio $S_a = \alpha_a/\beta_a$
function of particle size and shape and β' in 3 channels

=> Retrieval of β_a and α_a

CALIPSO products

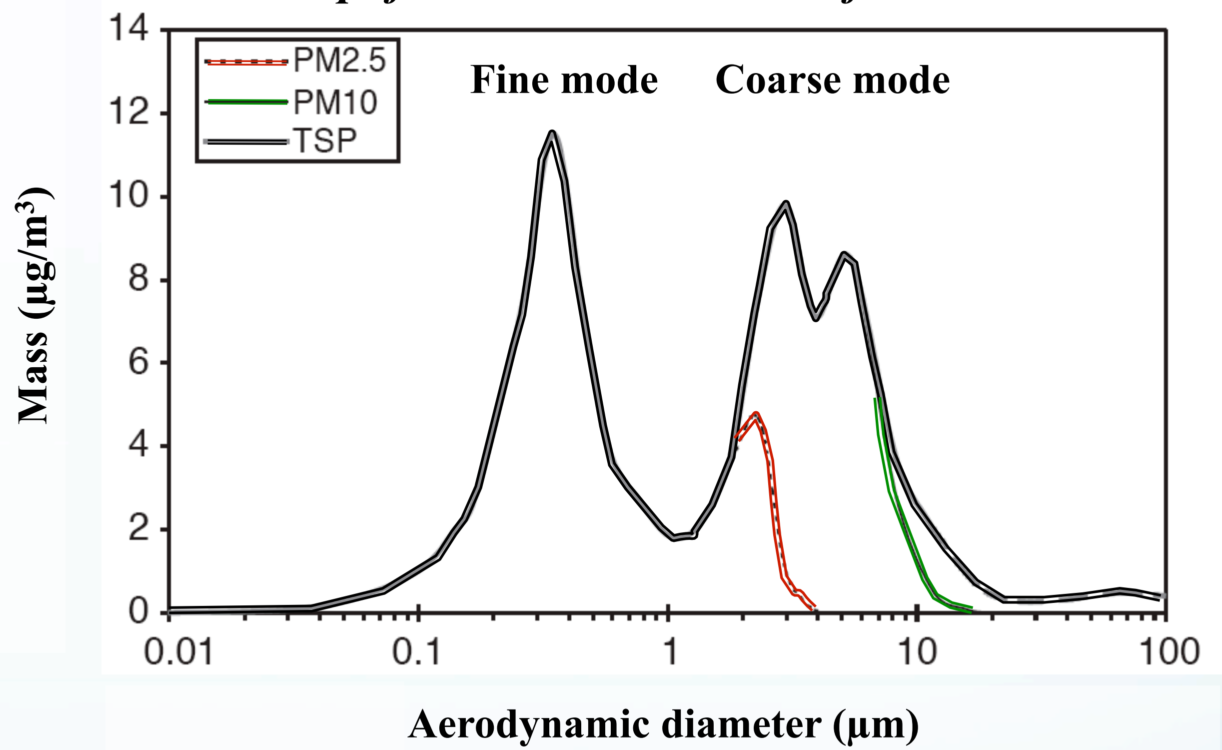
Version 3 Product	Primary Parameter	Resolution due to averaging	
		Horizontal	Vertical (<8km)
Level 1 **Measured**	Total_Attenuated_Backscatter_532 Perpendicular_Attenuated_Backscatter_532 Total_Attenuated_Backscatter_1064	1/3km	30m
Level 2 **LAYER** **Retrieved**	Cloud Layer_Top/ Base_Altitude Aerosol Layer_Top/ Base_Altitude	1/3, 1, 5km 5km	30m 30m
Level 2 **PROFILE** **Retrieved**	Cloud and Aerosol Total_Backscatter_Coefficient_532 Extinction_Coefficient_532	5km	60m
Level 2 **Vertical Feature Mask** **Retrieved**	Feature_Classification_Flags	5km	30m

PM2.5 Definition

PM_X (µg/m^3):

Mass concentration of particles with aerodynamic diameter < x µm

Simplified mass distribution of aerosols



E.P.A.'s standards:

$PM_{2.5}$(24h, µg/m^3)	0-15.4	15.5-35.4	35.5-55.4	55.5-140.4	140.5-210.4	>210.5
AQC	Good	Moderate	Unhealthy*	Unhealthy	Very Unhealthy	Hazardous

(*) for sensitive groups

Satellite AOD – PM

$$\text{Satellite} \quad AOD(\lambda) = \int_0^\infty s_{ext}^{mass}(z,\lambda) \times PM(z)\,dz$$

with s^{ext}_{mass}: mass extinction cross section ($m^2/\mu g$) at altitude z and wavelength λ
And for a single particle,

$$s_{ext}^{mass}(z,\lambda) = \pi r^2 Q_{ext} / \rho \times \frac{4}{3}\pi r^3$$

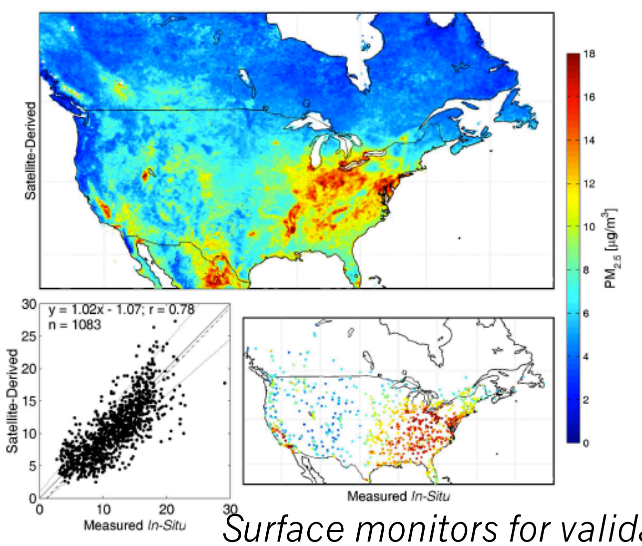
with r: particle radius,
ρ: particle density,
Q_{ext}: extinction efficiency factor (refractive index, particle size, wavelength)

⇒ AOD-PM depends on:

- particle size
- particle chemical composition
- particle vertical distribution

[Aaron Van Donkelaar *et al.*, 2010]

Find conversion factor between MODIS-MISR AOD and PM2.5 using CTM
Apply this factor to combined MODIS-MISR AOD to get PM2.5
=> satellite-based estimate of surface $PM_{2.5}$ (0.1° × 0.1° ~11 x 11km)



Surface monitors for validation

Figure 3: Satellite-derived PM2.5 and comparison with surface measurements. The top panel shows overall mean satellite-derived PM2.5 between 2001-2006. White space denotes water or fewer than 5 AOD measurements per year for at least 3 of 6 years. The bottom right panel shows positions and mean values of coincidently measured surface sites. The bottom left panel compares average coincident values of both measured and satellite-estimated PM2.5 in μg/m3. The solid black line denotes unity. Thin dotted lines show measured uncertainty of ±(1 μg/m3 + 15%). The line of best fit (Hirsh and Golroy 1984) is dashed.
203x177mm (300 x 300 DPI)

•6-year mean of 24-hr average satellite-derived surface $PM_{2.5}$

•Increase of spatial contrast relative to only satellite: reflects ground-level aerosol sources in the east and aerosols aloft in the north and west

•*Satellite derived-measured PM:*
r = 0.77; slope = 1.07; bias = –1.75 μg/m^3

[*Aaron Van Donkelaar et al.*, 2010]

Table 1: Comparison of coincidently sampled six-year mean measurements[a] of daily 24h average $PM_{2.5}$ with AOD and satellite-derived $PM_{2.5}$.

	slope[b]	intercept	r	n
MODIS AOD	0.020	0.10	0.40	1134
MISR AOD	0.011	0.09	0.54	841
Average AOD	0.017	0.10	0.45	1139
Combined AOD	0.014	0.06	0.63	1083
Satellite-derived $PM_{2.5}$	1.016	-1.07	0.78	1083

[a] A minimum of 5 measurements, 3 years out of 6 are required for each point.
[b] calculated with reduced major-axis linear regression (Hirsh and Golroy 1984)

Direct Aerosol Radiative Forcing

= aerosol-induced change in the net flux $\Delta_a(F\uparrow - F\downarrow)$ at a given altitude

At the top of the atmosphere, $\Delta_a F\downarrow = 0$ and above an aerosol layer, $\Delta_a F\downarrow \ll \Delta_a F\uparrow$
Aerosol radiative forcing ~ aerosol-induced change in upwelling flux at TOA: $\Delta_a F\uparrow$

$$\Delta_a F \uparrow = \frac{1}{2} F_T T^2 (1 - A_C) \left[\omega \overline{\beta_a} (1 - \overline{R_S})^2 - 2(1 - \omega) \overline{R_S} \right] AOD$$

[Haywood and Shine, 1995; Chylek and Wong, 1995 and Russell et al., 1997]

Auxiliary parameter:

- F_T: solar constant (1360 $W.m^{-2}$)
- A_c: cloud fraction; $1-A_c$=clear sky fraction
- R_s: surface albedo

Surface	Typical Albedo
Fresh asphalt	0.04[1]
Conifer forest (Summer)	0.08,[2] 0.09 to 0.15[3]
Worn asphalt	0.12[1]
Deciduous trees	0.15 to 0.18[3]
Bare soil	0.17[4]
Green grass	0.25[4]
Desert sand	0.40[5]
New concrete	0.55[4]
Ocean Ice	0.5–0.7[4]
Fresh snow	0.80–0.90[4]

Function of aerosol radiative properties (ext(z), ω(z) and g(z)):

- β_a:aerosol upscatter fraction (ext(z),g(z))
- T: Atmospheric transmission (ext(z) for aerosol, H2O & O3 vert. prof.)
- AOD: Aerosol Optical Depth from satellite for ex.
- ω: Single scattering albedo (fraction of intercepted light that is scattered, rather than absorbed)

Obs./ model based DARF