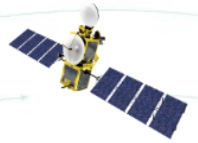
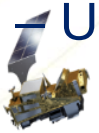


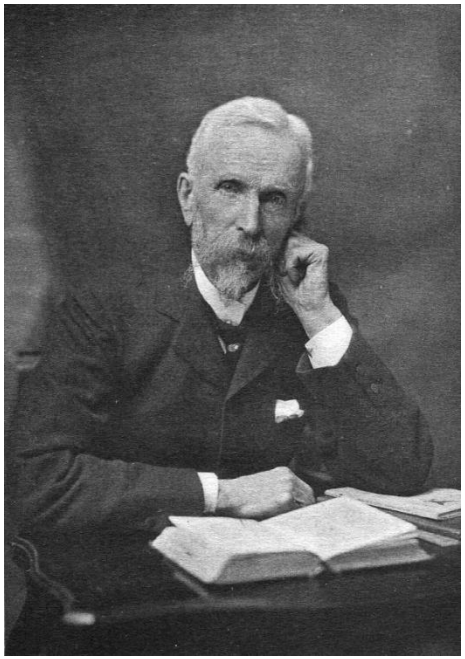
Observing aerosols

Federico Fierli

Contribution from many colleagues and co-workers

Acknowledge the teaching material from D. Jacob – U-Harvard – S. Massie NCAR





John Aitken (1839-1919)

“We have in this fine dust [aerosols] a most beautiful illustration of how the little things in the world work great effects by virtue of their numbers.”

-John Aitken, 1880

Why should we care about aerosol and dust ?

Human health

Air quality

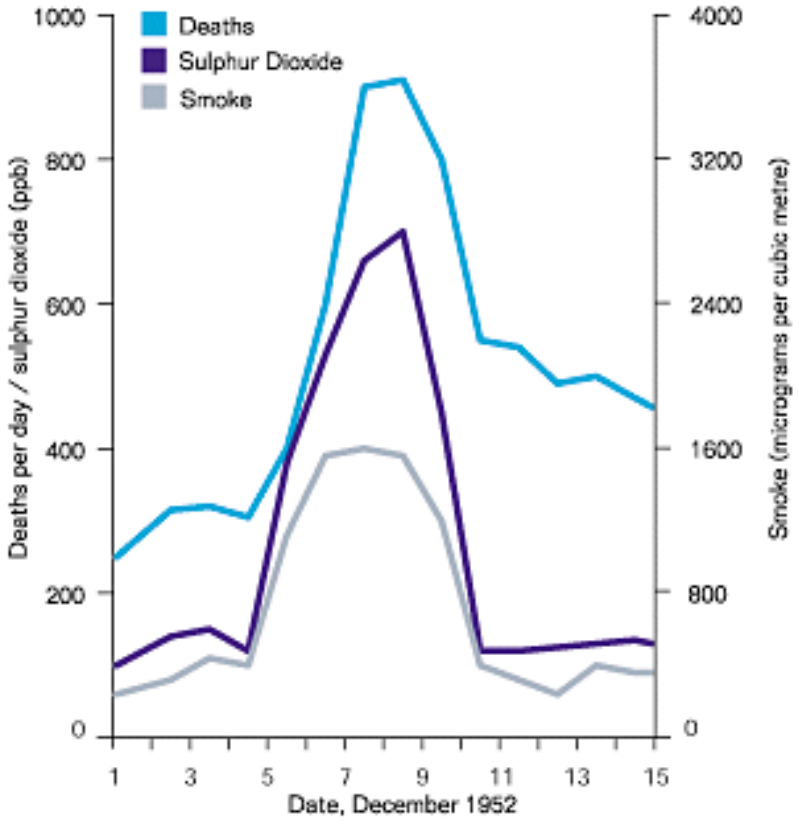
Global Climate

Radiation, Chemistry, Rainfall

Aerosols are important from the molecular to the global scale

Aerosols and human health

1952: the “London smog disaster”



Air pollution

O_3, CO, NO_2, SO_2

aerosol

Aerosols are the principle component of what we perceive as “smog”

Submicron aerosols are primarily responsible for visibility reduction.

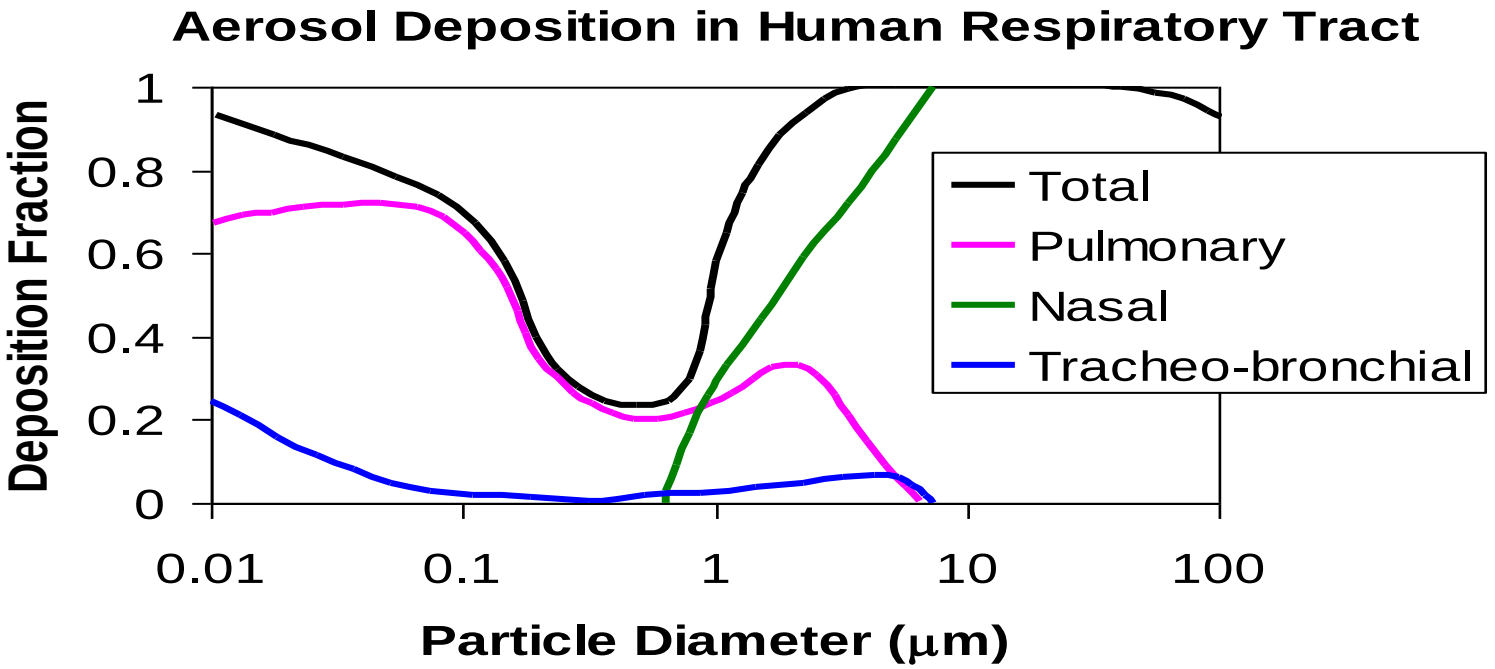
Pasadena, CA, on a clear day (hills are 7 km away)

Environmental Protection Agency (EPA)
$PM_{2.5}$ 15 μg /m^3 (annual average)
PM_{10} 150 μg /m^3 (24 hour)
regulations.

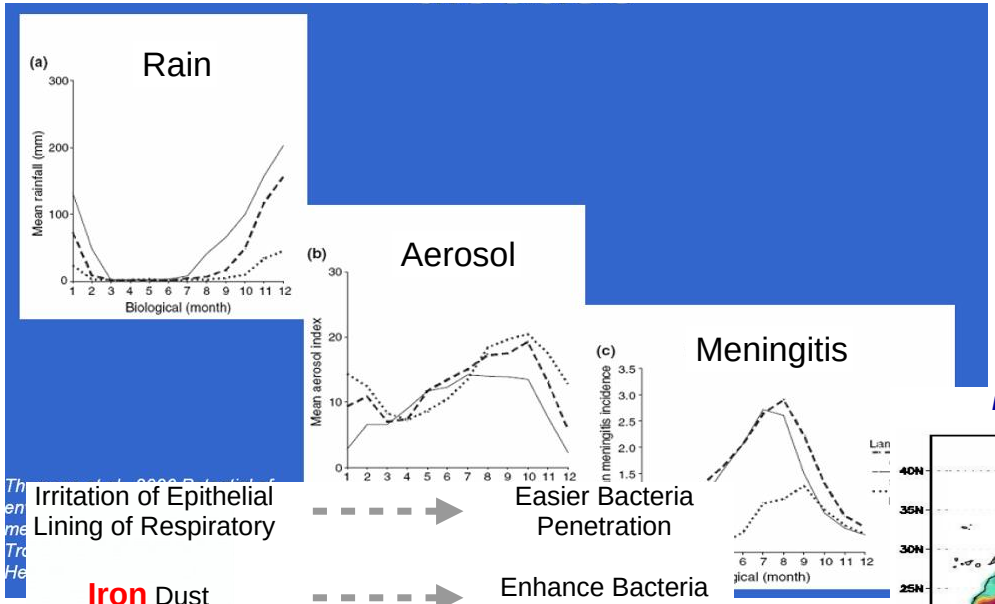
Pasadena, CA, on a bad smog day

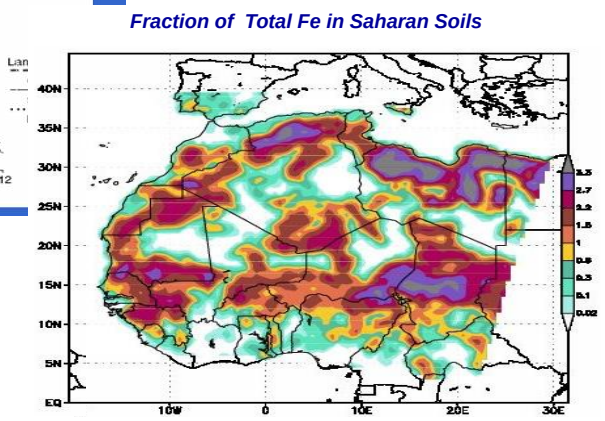
Aerosols and human health

Submicron aerosols can penetrate to the deepest parts of the lung whereupon they can affect the pulmonary part of the respiratory system. For this reason many, including the EPA, consider them dangerous air pollutants.



The role of atmospheric aerosol on meningitis spread





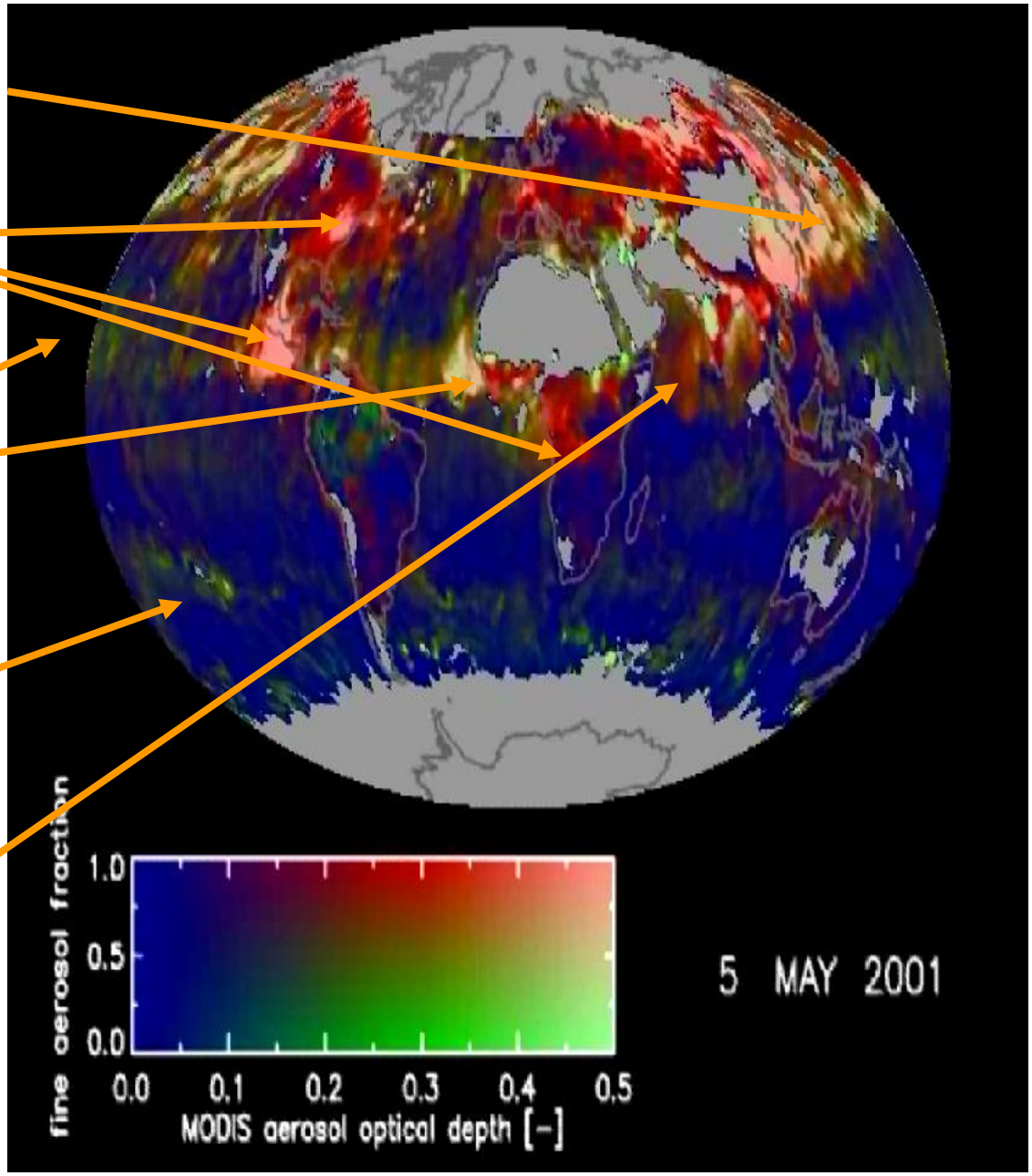
Pollution/dust in China

Smoke
Pollution?

Saharan dust

Sea Salt

Pollution/dust in India



Dust and smoke are Transported to the North-East Atlantic. From MODIS

TABLE 2.19 Global Emission Estimates for Major Aerosol Types in the 1980s

Source	Estimated Flux (Tg yr^{-1}) Low	High	Best	Particle Size Category[a]
NATURAL				
Primary				
Soil dust (mineral aerosol)	1000	3000	1500	Mainly coarse
Sea salt	1000	10000	1300	Coarse
Volcanic dust	4	10000	30	Coarse
Biological debris	26	80	50	Coarse
Secondary				
Sulfates from biogenic gases	80	150	130	Fine
Sulfates from volcanic SO_2	5	60	20	Fine
Organic matter from biogenic VOC	40	200	60	Fine
Nitrates from NO_x	15	50	30	Fine and coarse
Total natural	2200	23500	3100	
ANTHROPOGENIC				
Primary				
Industrial dust, etc. (except soot)	40	130	100	Fine and coarse
Soot	5	20	10	Mainly fine
Secondary				
Sulfates from SO_2	170	250	190	Fine
Biomass burning	60	150	90	Fine
Nitrates from NO_x	25	65	50	Mainly coarse
Organics from anthropogenic VOC	5	25	10	Fine
Total anthropogenic	300	650	450	
Total	2500	24000	3600	

[a]Coarse and fine size categories refer to mean particle diameter above and below 1 μm, respectively.

Note: Sulfates and nitrates are assumed to occur as ammonium salts. Flux unit: Tg yr^{-1} (dry mass).

Source: Kiehl and Rodhe (1995).

450 / 3100 = 15%

Seinfeld and Pandis

Aerosols : solid and liquid particles suspended in the air

Size: nm to 100 microns (range of 10^5)

Lifetime: Troposphere (days to weeks) Stratosphere (year)

Primary aerosol: emitted directly into the air

Secondary aerosol: gas to particle conversion

Composition: sulfate, ammonium, nitrate, sodium,

trace metals, carbonaceous, crustal, water

Carbonaceous

elemental: emitted directly into the air (e.g. diesel soot)

organic: a) directly by sources (e.g combustion, plant leaf)

b) condensation of low volatile organic gases

“fine” diameters D < 2.5 microns

sulfate, ammonium, organic carbon, elemental carbon

Nuclei mode 0.005 to 0.01 microns

condensation of vapors

Accumulation mode

0.1 to 2.5 microns coagulation

“coarse” diameters D > 2.5 microns

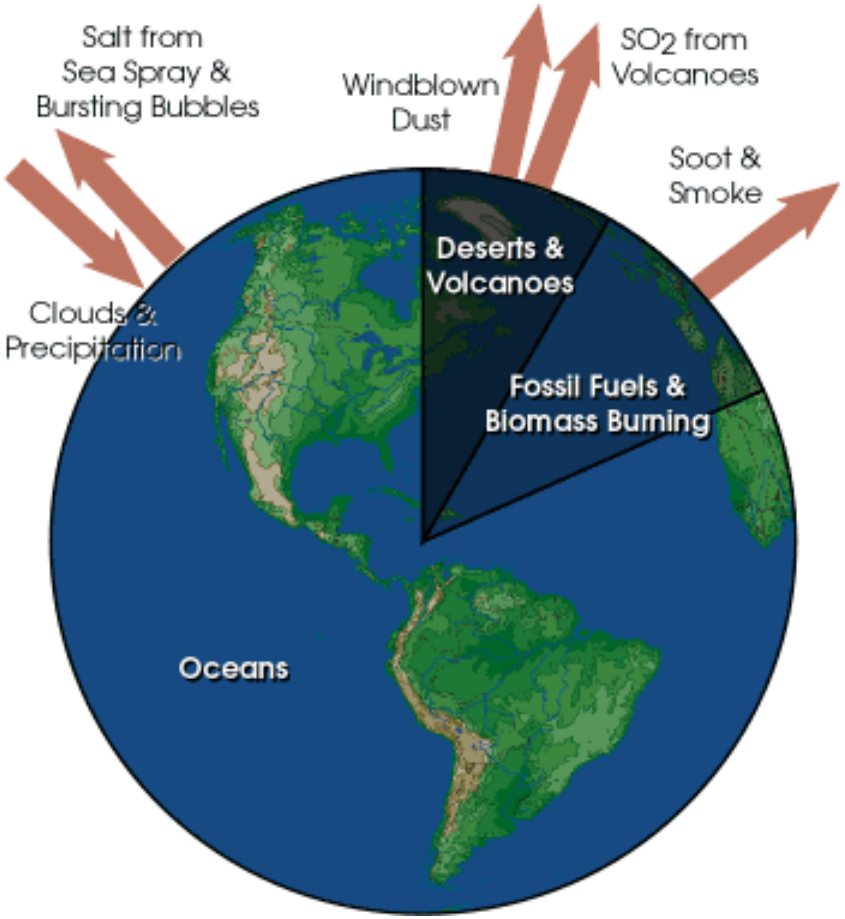
natural dust (e.g. desert)

mechanical processes

crustal materials

biogenic (pollen, plant fragmets)

Aerosol Types and Origin



- Aerosol particles larger than about 1 μm in size are produced by windblown dust and sea salt from sea spray and bursting bubbles.
- Aerosols smaller than 1 μm are mostly formed by condensation processes such as conversion of sulfur dioxide (SO_2) gas (released from volcanic eruptions) to sulfate particles and by formation of soot and smoke during burning processes.
- After formation, the aerosols are mixed and transported by atmospheric motions and are primarily removed by cloud and precipitation processes.

Aerosol Size Distribution

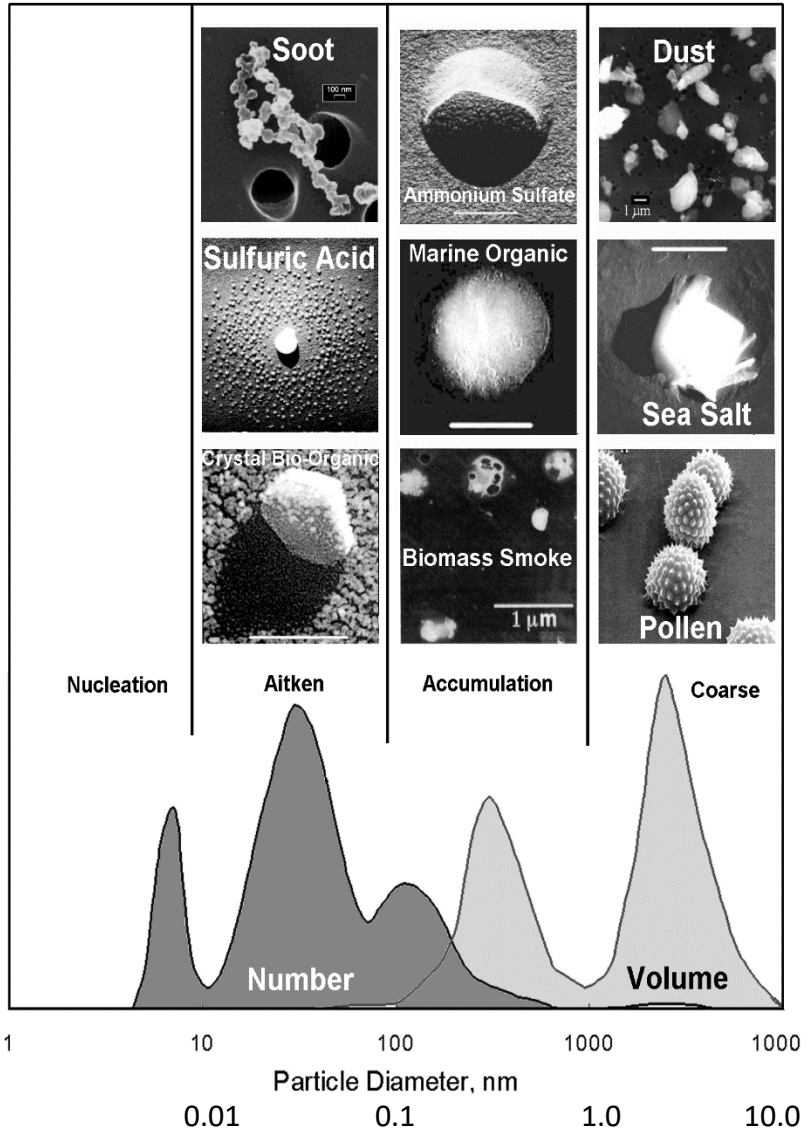
It presents 3 modes :

- « **nucleation** »: radius is between 0.002 and 0.05 mm. They result from combustion processes, photo-chemical reactions, etc.

- « **accumulation** »: radius is between 0.05 mm and 0.5 mm. Coagulation processes.

- « **coarse** »: larger than 1 mm. From mechanical processes like aeolian erosion.

« fine » particles (nucleation and accumulation) result from anthropogenic activities, coarse particles come from natural processes.



Size Distribution

Log-normal particle size distribution

$$dN/dr = \Sigma \ (N_i / (2\pi)^{1/2} \ r \ln\sigma) \ \exp\{- (\ln r/\ln r_0)^2/2\ln^2\sigma)$$

Units: number per cm^{-3} per microns

i=1,2 2 modes

N_i, total number of particles for mode i (cm^{-3})

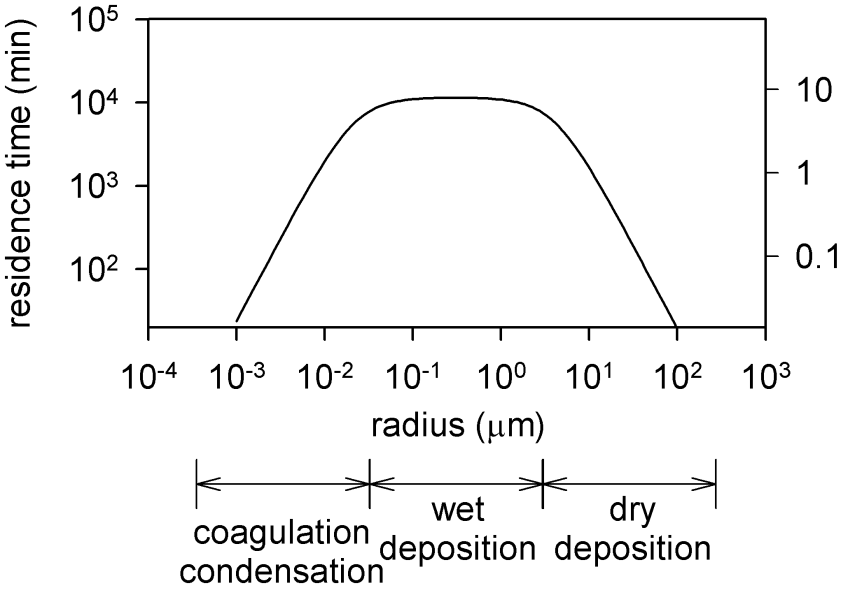
r, radii (microns)

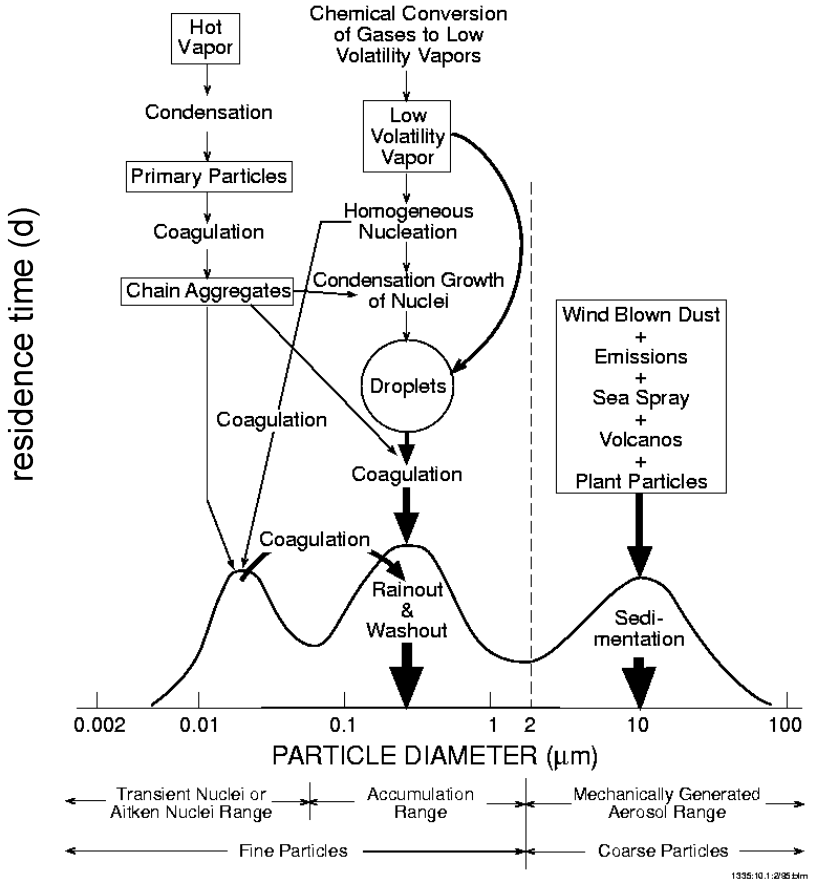
σ, mode width (dimensionless)

r_0, modal radii (microns)

Aerosols come from a variety of sources, and reside in the atmosphere for weeks

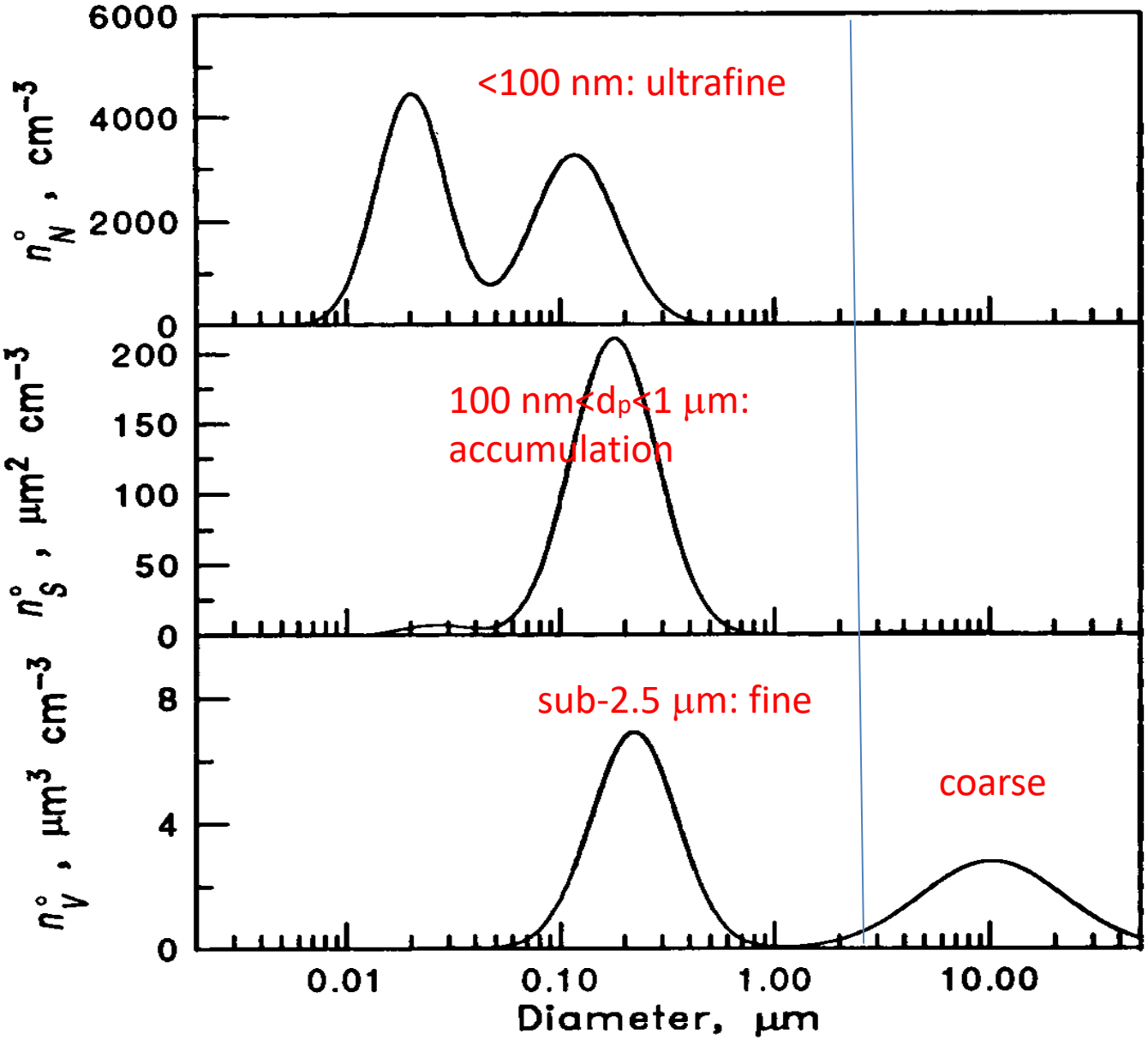
aerosols = particles suspended in a gas





Seinfeld and Pandis

Size Distribution



"remote continental air"

Number Density n

Surface Area ($n \pi r^2$)

Volume Density ($n\ 4/3\ \pi r^3$)

Seinfeld and Pandis

Key aerosol microphysical parameters

Particle size and size distribution
Aerosol particles > 1 mm in size are produced by windblown dust and sea salt from sea spray and bursting bubbles. Aerosols smaller than 1 mm are mostly formed by condensation processes such as conversion of sulfur dioxide (SO_2) gas to sulfate particles and by formation of soot and smoke during burning processes

Effective radius
Moment of size distribution weighted by particle area and number density distribution

Complex refractive index
The real part mainly affects scattering and the imaginary part mainly affects absorption

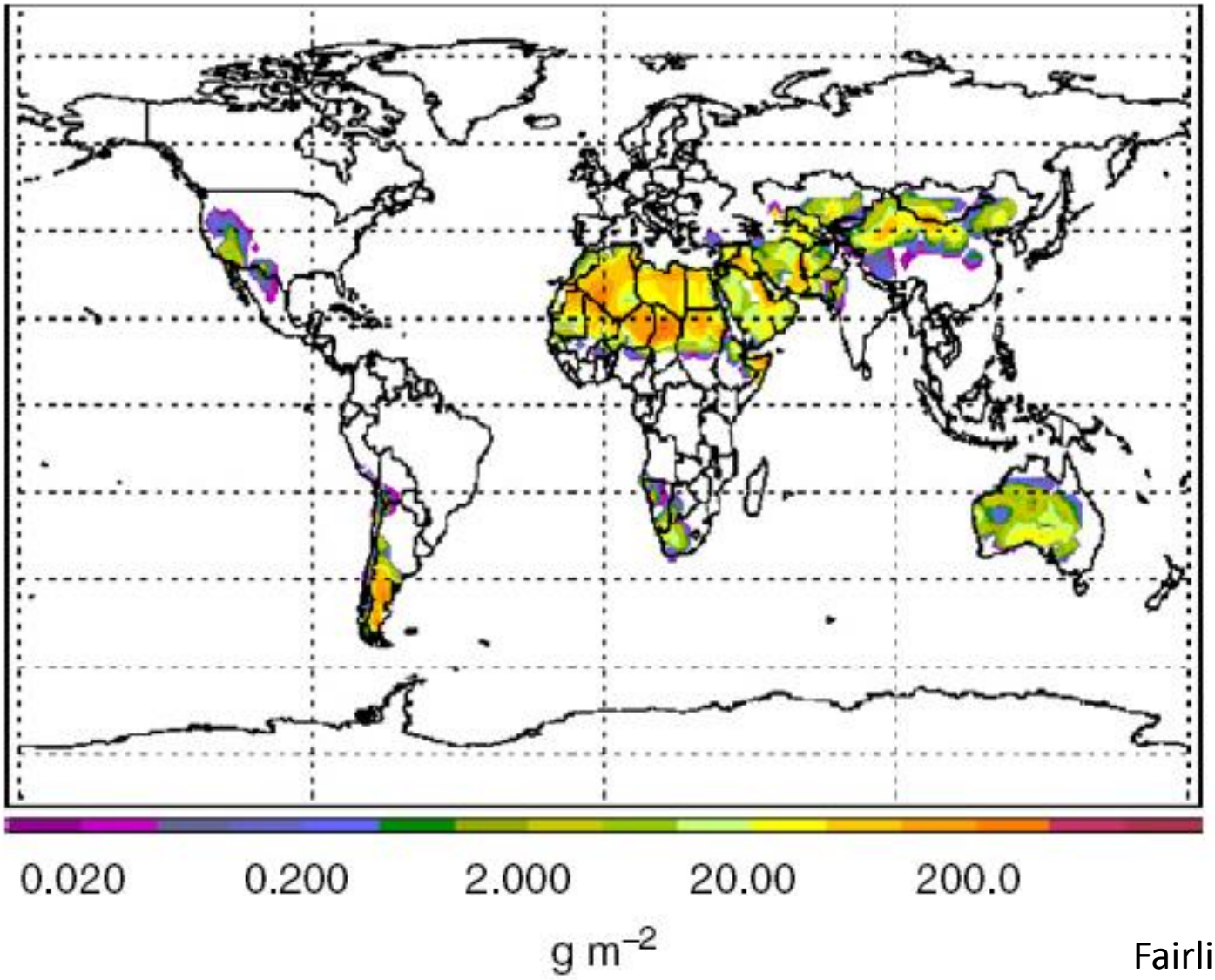
Particle shape
Aerosol particles can be liquid or solid, and therefore spherical or nonspherical.
The most common nonspherical particles are dust and cirrus

The bimodal nature of the size-number distribution of atmospheric particles suggests at least two distinct mechanisms of formation, and the chemical composition of the particles reflects their origins.

Fine particles have a diameter smaller than about 2.5 mm, and are produced by the condensation of vapors, accumulation, and coagulation. They have a chemical composition that reflects the condensable trace gases in the atmosphere: SO_2, NH_3, HNO_3, VOC′s, and H_2O. The chemical composition is water with SO_4^{-2}, NO_3^-, NH_4^+, Pb, Cl^-, Br^-, C(soot), and organic matter; where biomass burning is prevalent, K^+.

Coarse Particles have a diameter greater than about 2.5 mm, are produced by mechanical weathering of surface materials. Their lifetimes, controlled by fallout and washout, are generally short. The composition of particles in this size range reflects that of the earth's surface - silicate (SiO_2), iron and aluminum oxides, $CaCO_3$ and $MgCO_3$, over the oceans , NaCl.

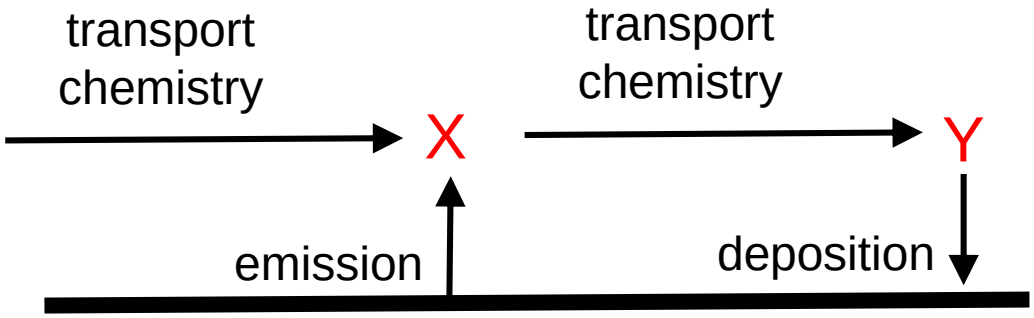
Global dust emissions (modeled)

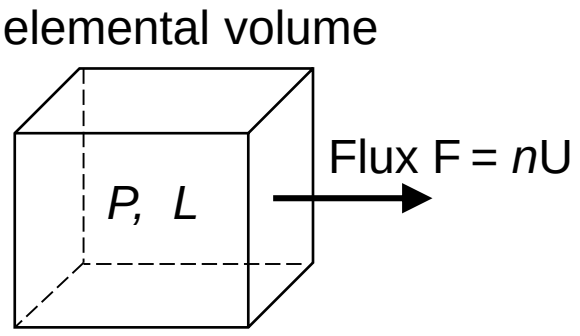


1 cent coin
= 2.5 g

Fairlie et al. [2007]

Physical modeling: solve continuity equation for chemical species





Eulerian form of continuity equation: fixed frame of reference:

$$\frac{\partial n}{\partial t} = -\nabla \cdot (n\mathbf{U}) + P - L$$

local trend in number density

transport (flux divergence)

emission, deposition, chemistry

Alternative Eulerian form in terms of mixing ratio *C:*

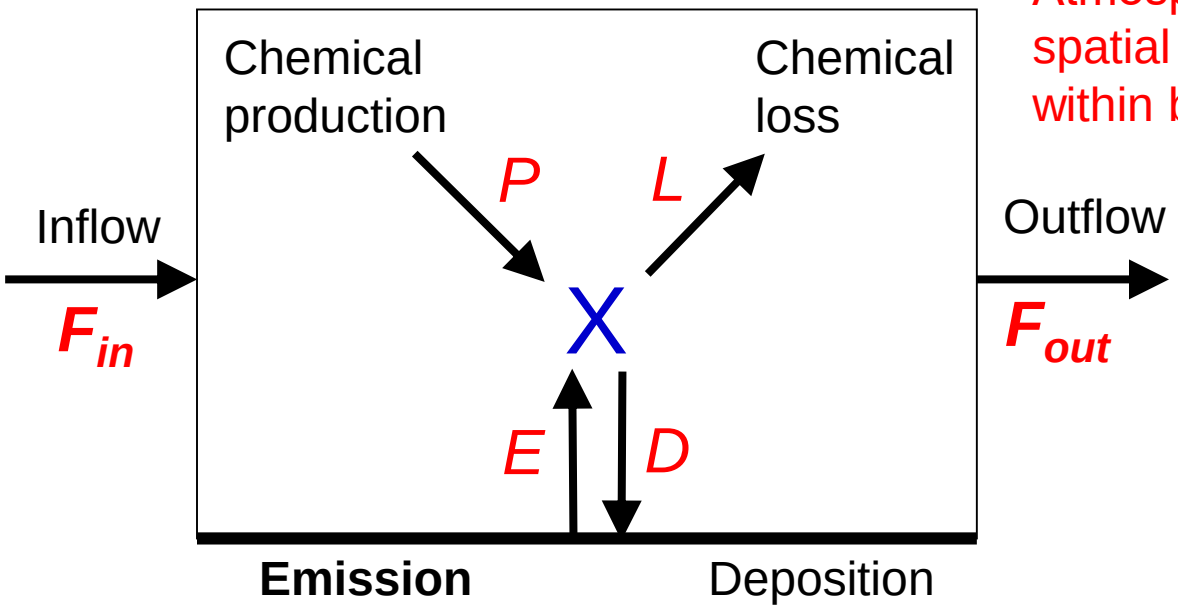
$$\frac{\partial C}{\partial t} = -\mathbf{U} \cdot \nabla C + P - L$$

Lagrangian form (moving frame of reference):

$$\frac{dC}{dt} = P - L$$

where $\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{U} \cdot \nabla$

One-box model



Atmospheric "box"; spatial distribution of X within box is not resolved

Mass balance equation: $\frac{dm}{dt} = \sum \text{sources} - \sum \text{sinks} = F_{in} + E + P - F_{out} - L - D$

Atmospheric lifetime: $\tau = \frac{m}{F_{\text{out}} + L + D}$

Loss rate constant: $k = \frac{1}{\tau} = \frac{F_{out} + L + D}{m}$

Lifetimes add in parallel: $\frac{1}{\tau} = \frac{F_{out}}{m} + \frac{L}{m} + \frac{D}{m} = \frac{1}{\tau_{\text{out}}} + \frac{1}{\tau_{\text{chem}}} + \frac{1}{\tau_{\text{dep}}}$

Loss rate constants add in series: $k = \frac{1}{\tau} = k_{\text{out}} + k_{\text{chem}} + k_{\text{dep}}$

Dust event – how it works ?

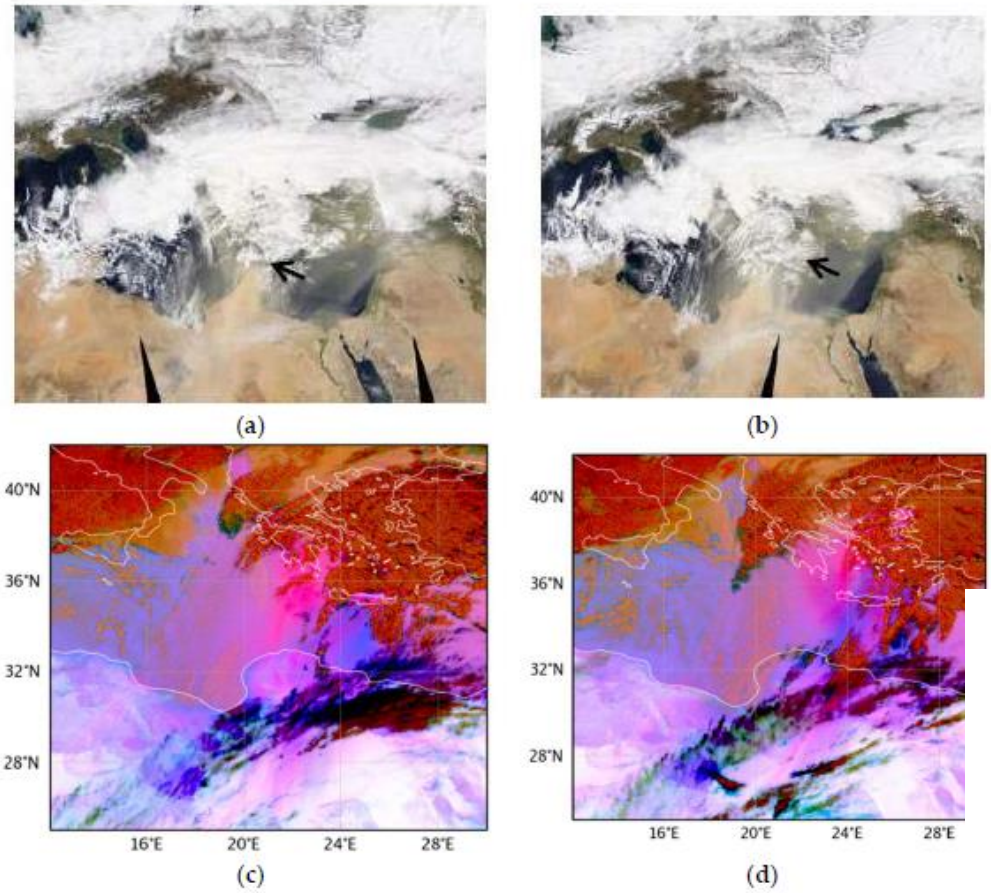


Figure 1. Up (**a**,**b**) True color images from MODIS-Terra (left) and MODIS-Aqua (right) on 22 Ma 2018. The arrows indicate the location of Crete; Down (**c**,**d**) MSG-SEVIRI dust RGB images on 1200 U (left) and 1500 UTC (right), 22 March 2018.

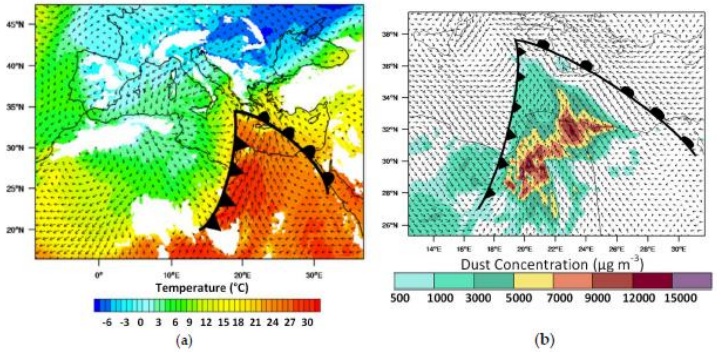
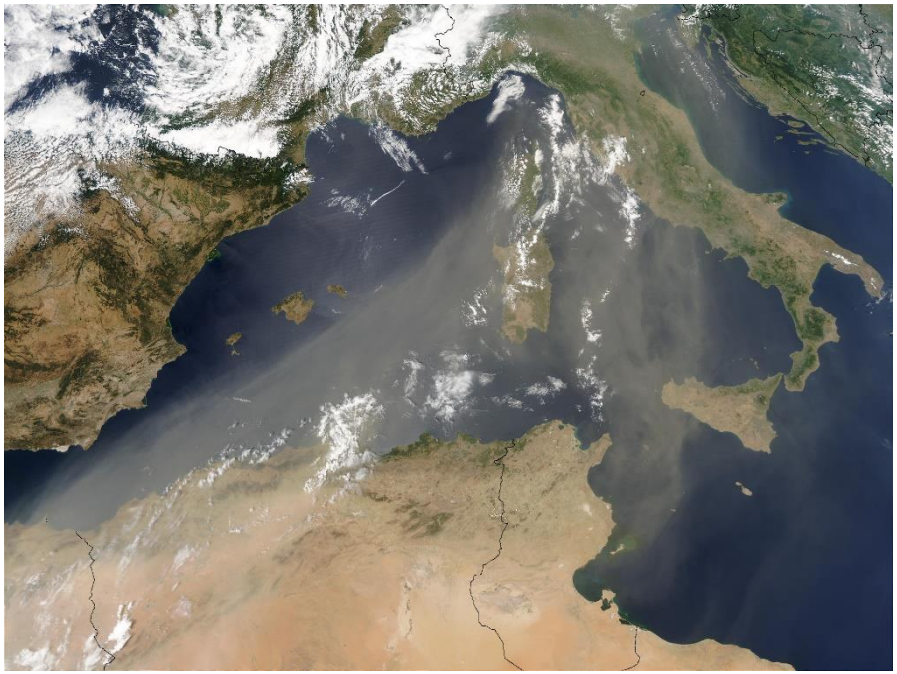


Figure 5. (**a**) Frontal activity, temperature (°C) and wind vectors at 925 hPa and (**b**) Near-surface dust concentration (μg m^{-3}) and wind vectors at 10 m (zoom from the external 12 × 12 km domain), on 22 March 2018 0600 UTC.

Dust event – how frequent is it ?



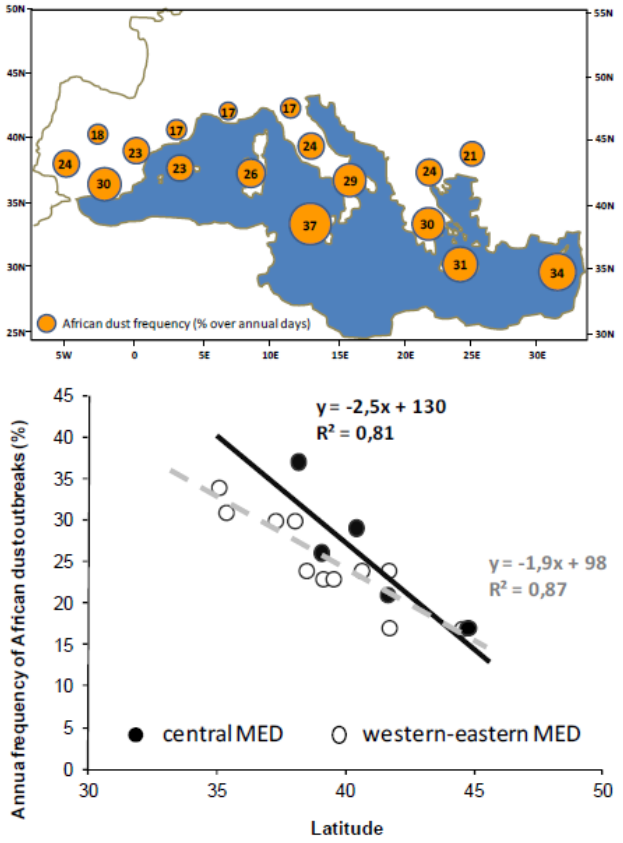
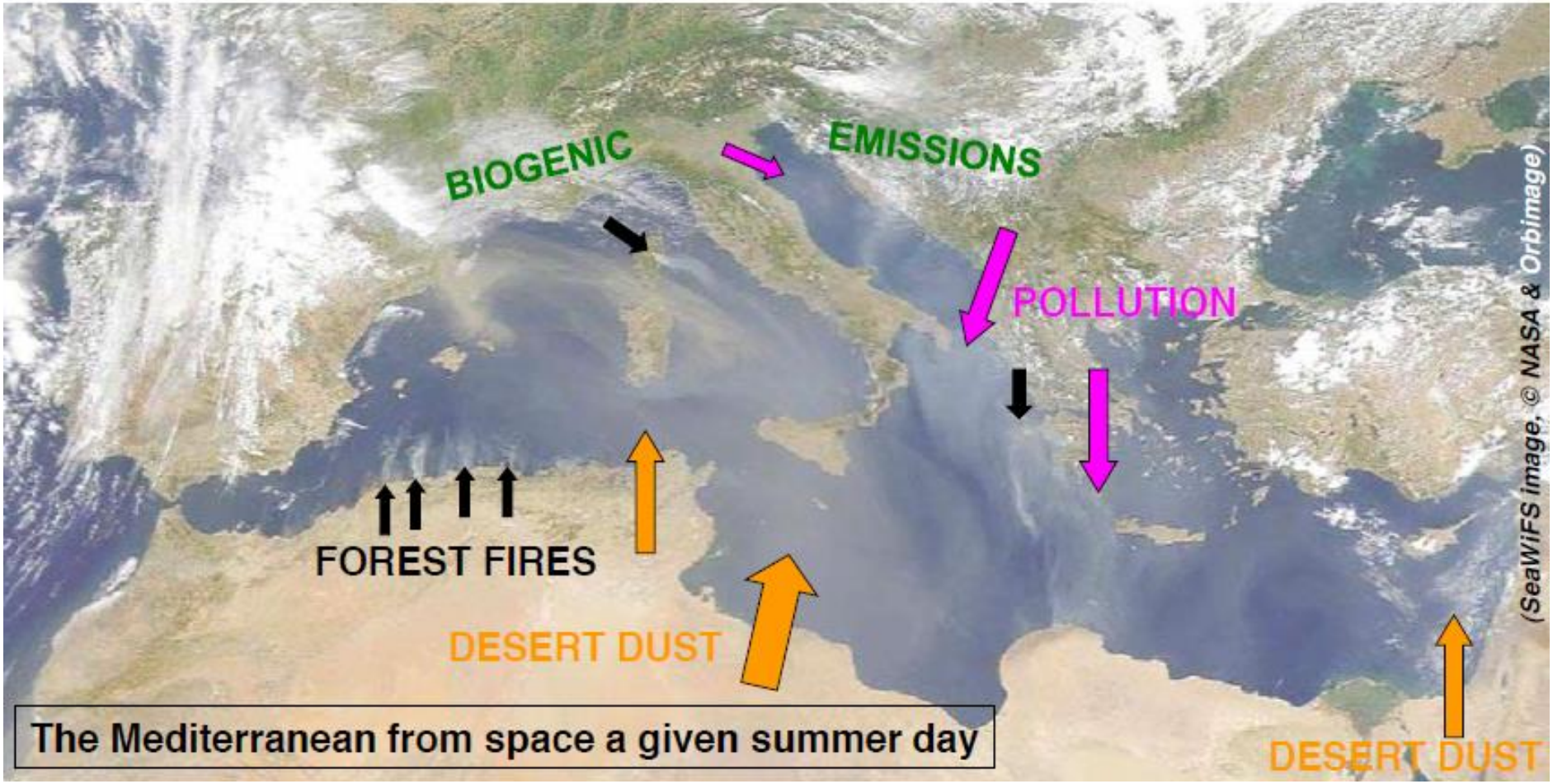


Fig. 4. **(a)** Top: mean frequency of African dust outbreaks (%) across the Mediterranean Basin during the period 2001–2011; **(b)** bottom: mean frequency of African dust outbreaks (%) versus latitude across the Mediterranean Basin during the period 2001–2011.

⇨ A natural laboratory to study

(i) the contribution of long-range transport,
(ii) the ageing of continental air masses over the basin,
(iii) the impact of aerosol on the regional climate,
(iv) the impact of atmos. deposition on low-Chl, low-nutrient surface waters



The Mediterranean from space a given summer day

Dust event – impacts on Particulate Matter

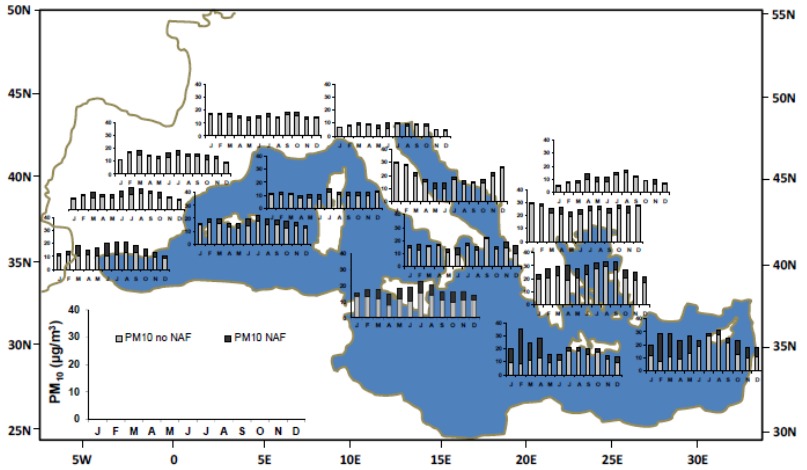


Fig. 7. Seasonal partitioning of PM_{10} (in $\mu g\,m^{-3}$), considering the influence of African dust (average values for the periods v available, in most cases from 2001–2010) across the Mediterranean Basin. NAF: African dust outbreaks.

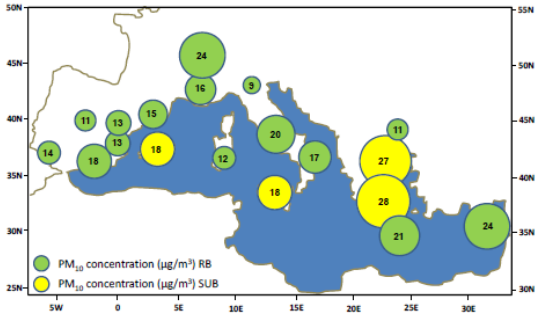


Fig. 2. Annual PM_{10} levels ($\mu g\,m^{-3}$) at regional (RB) and suburban (SUB) background sites across the Mediterranean for the period 2001–2011.

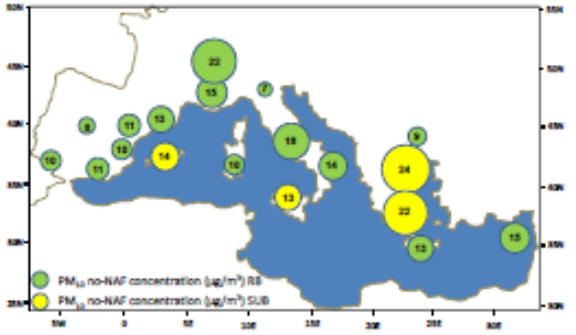
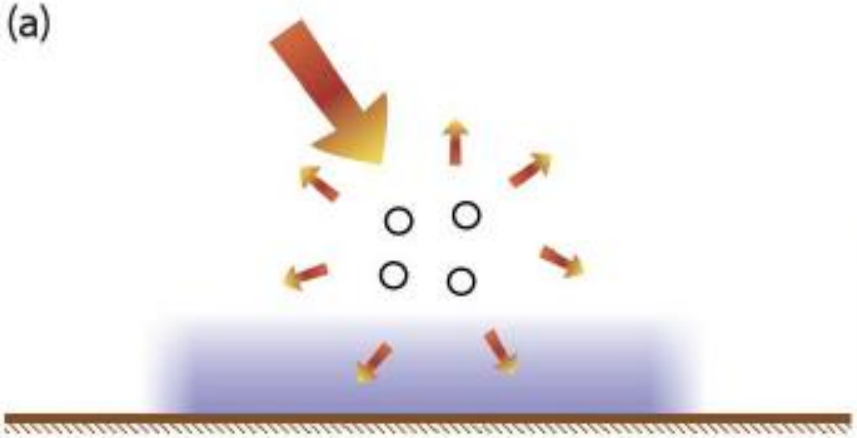


Fig. A1. Annual PM_{10} levels ($\mu g\,m^{-3}$), without African dust, at regional (RB) and suburban (SUB) background sites across the Mediterranean for the period 2001–2011. NAF: African dust outbreaks.

Aerosol-radiation interactions

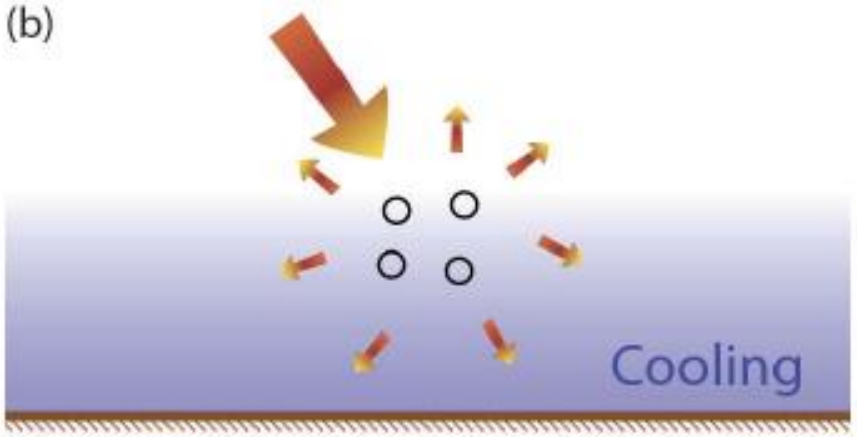
Scattering aerosols

(a)



Aerosols scatter solar radiation. Less solar radiation reaches the surface, which leads to a localised cooling.

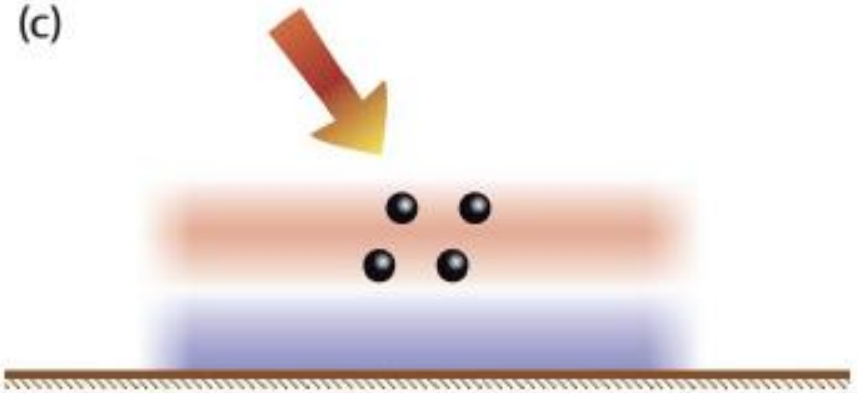
(b)



The atmospheric circulation and mixing processes spread the cooling regionally and in the vertical.

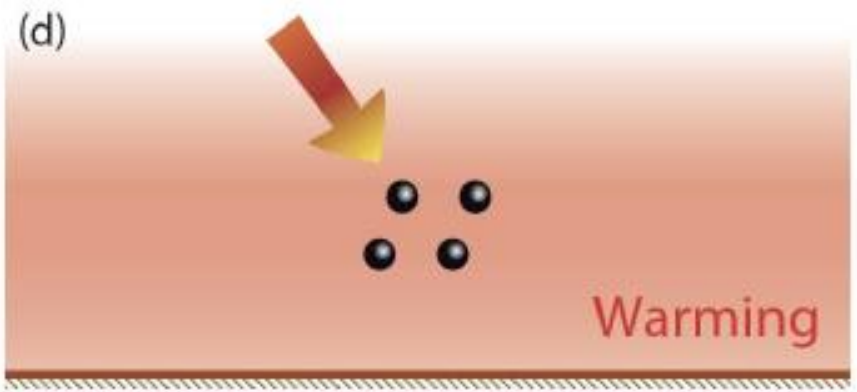
Absorbing aerosols

(c)



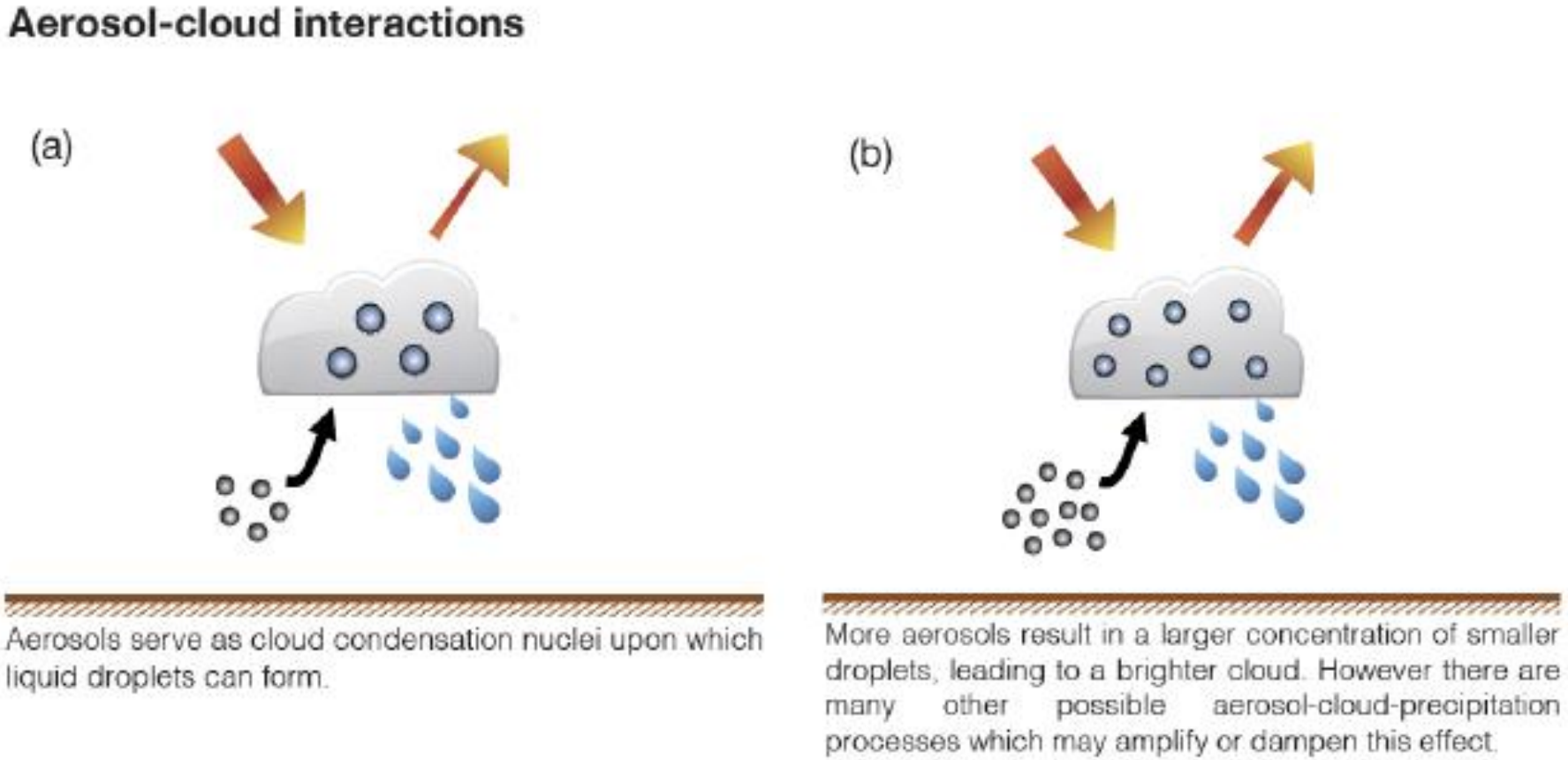
Aerosols absorb solar radiation. This heats the aerosol layer but the surface, which receives less solar radiation, can cool locally.

(d)



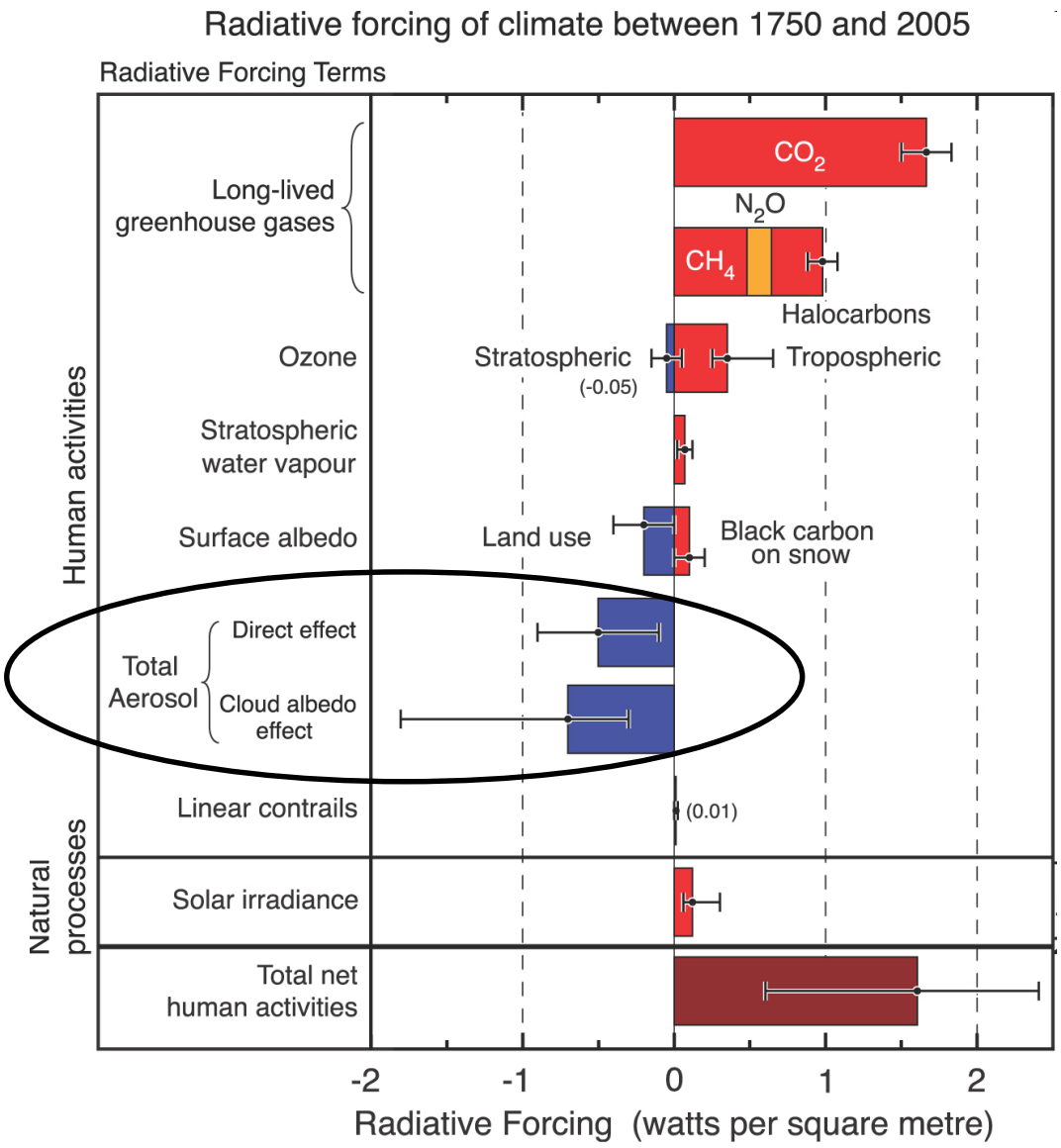
At the larger scale there is a net warming of the surface and atmosphere because the atmospheric circulation and mixing processes redistribute the thermal energy.

Aerosol-cloud interactions



IPCC AR5, Chapter 7, 2013

Aerosols and climate

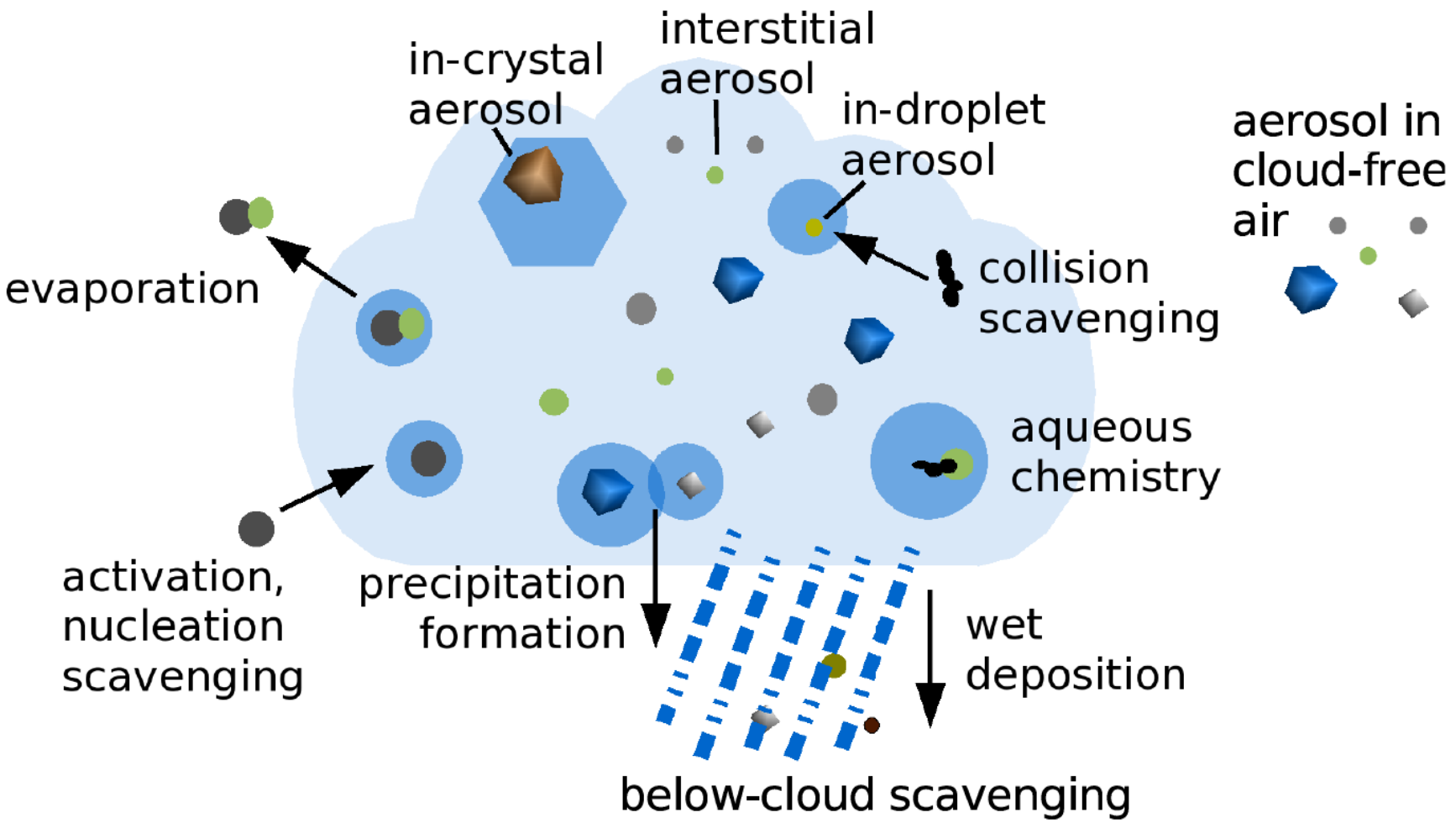


← **Drives Global Warming**

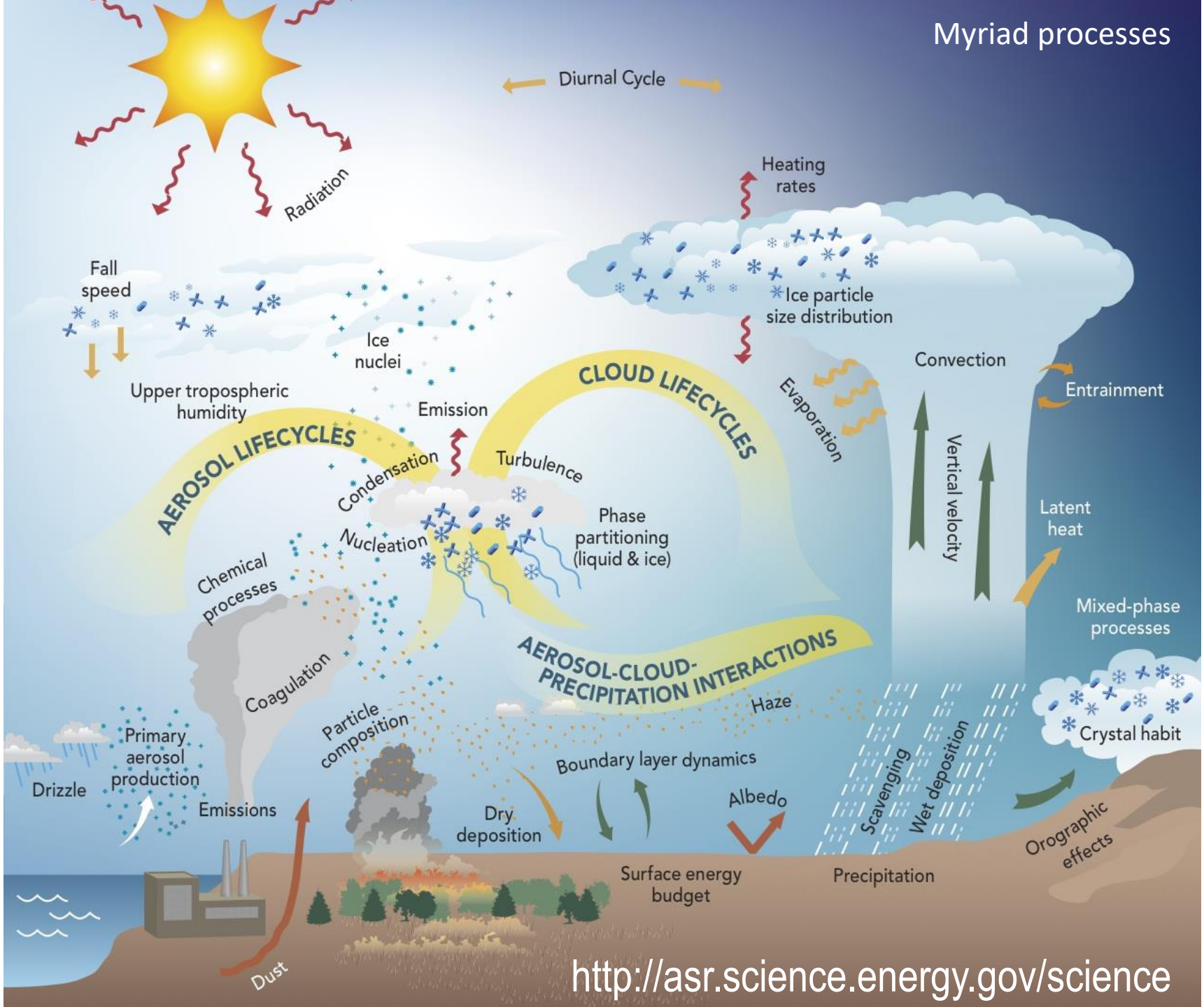
Direct effect – Light is scattered and absorbed

IPCC, AR4

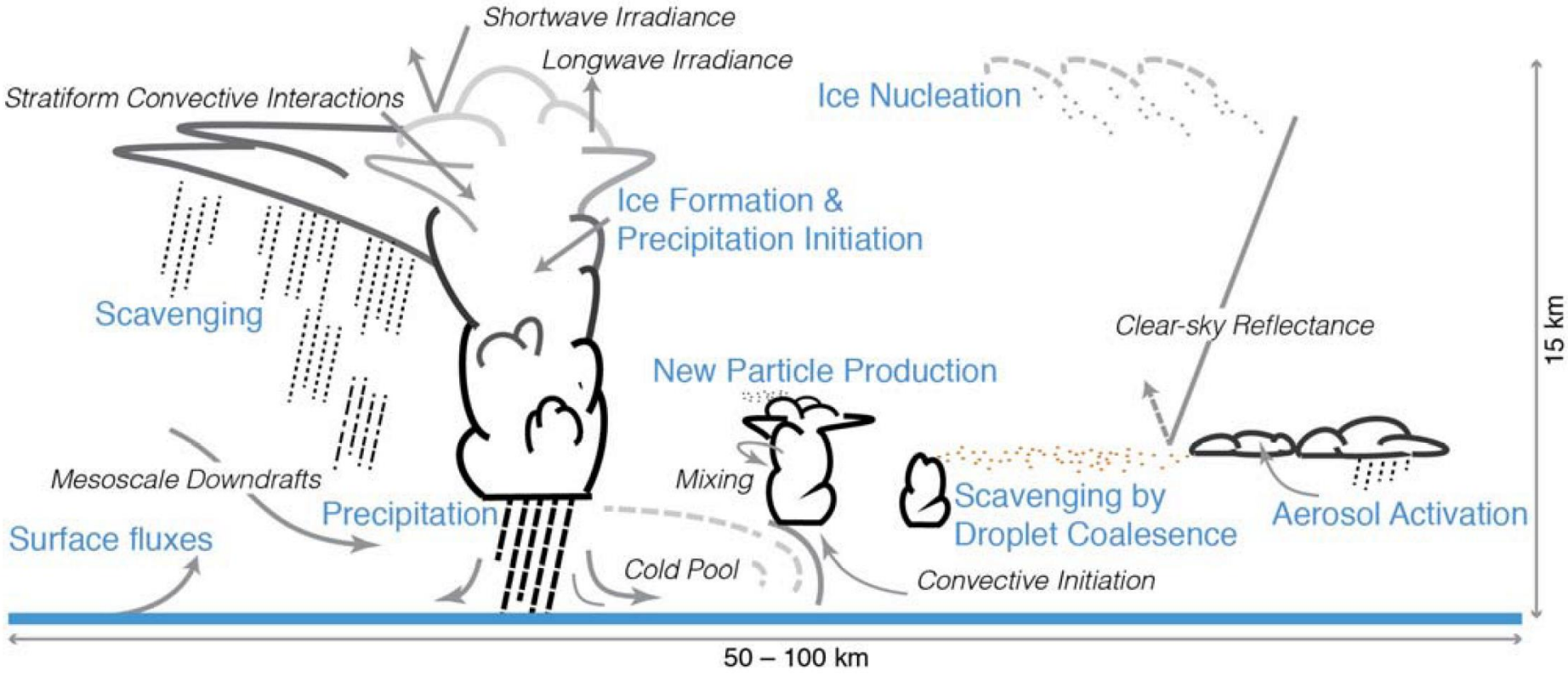
Cloud impacts on aerosols



Hoose et al., ACP, 2008


Myriad processes
Diurnal Cycle
Radiation
Heating rates
Ice particle size distribution
Fall speed
Ice nuclei
Upper tropospheric humidity
Emission
CLOUD LIFECYCLES
AEROSOL LIFECYCLES
Condensation
Turbulence
Nucleation
Phase partitioning (liquid & ice)
Evaporation
Convection
Entrainment
Vertical velocity
Latent heat
Chemical processes
Coagulation
AEROSOL-CLOUD-PRECIPITATION INTERACTIONS
Haze
Mixed-phase processes
Crystal habit
Particle composition
Primary aerosol production
Drizzle
Emissions
Boundary layer dynamics
Albedo
Dry deposition
Scavenging
Wet deposition
Orographic effects
Surface energy budget
Precipitation
Dust
http://asr.science.energy.gov/science

Myriad aerosol-cloud-precipitation processes occurring within a climate model gridbox (or not)



IPCC AR5, Chapter 7, Fig 7.16

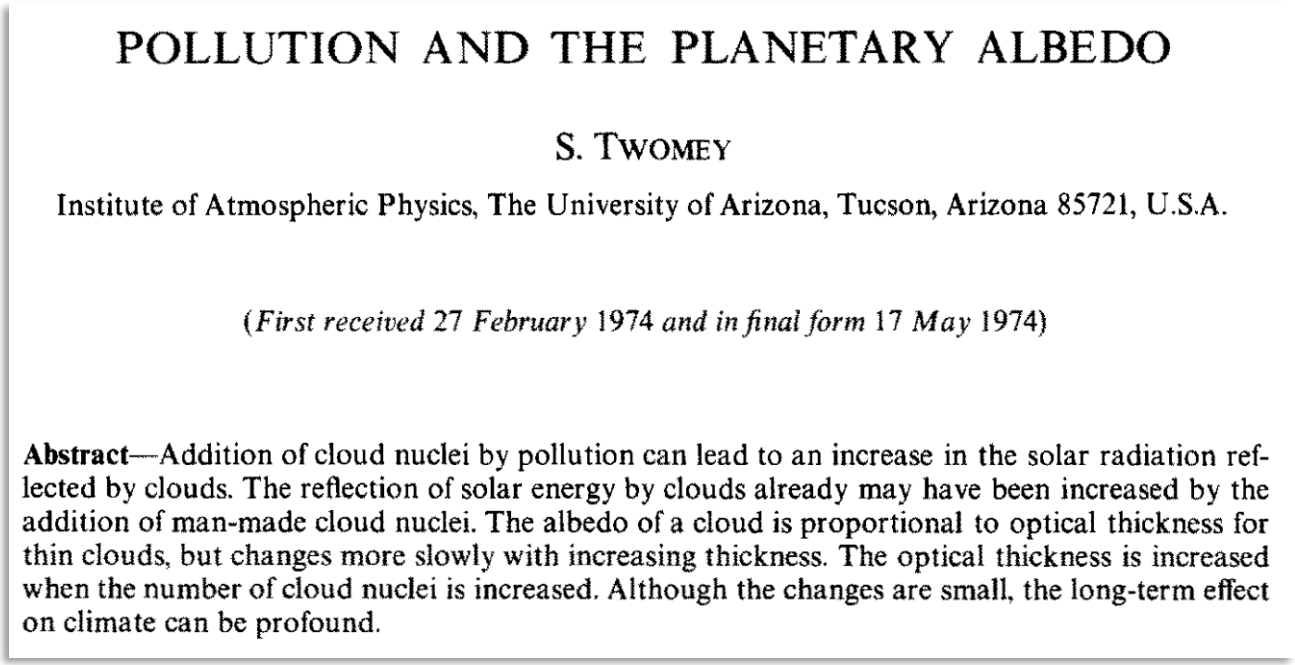
Aerosols and climate: indirect effect

“Ship Tracks” off the coast of Washington

- aerosols are the “seeds” upon which water vapor condenses to form a cloud (these are called “cloud condensation nuclei, or CCN).
- If people make more aerosols, we make more cloud droplets, but because there is a fixed amount of water vapor in the air these droplets will be smaller.
- smaller droplets scatter light more efficiently!
- smaller cloud droplets may also impact rain from these clouds.
- very difficult effect to observe and model!

Twomey effect

- The paper(s) that "started it all"
  - Actually, Twomey (1974) was the first paper suggesting anthropogenic aerosol impacts on cloud albedo:



POLLUTION AND THE PLANETARY ALBEDO

S. TWOMEY

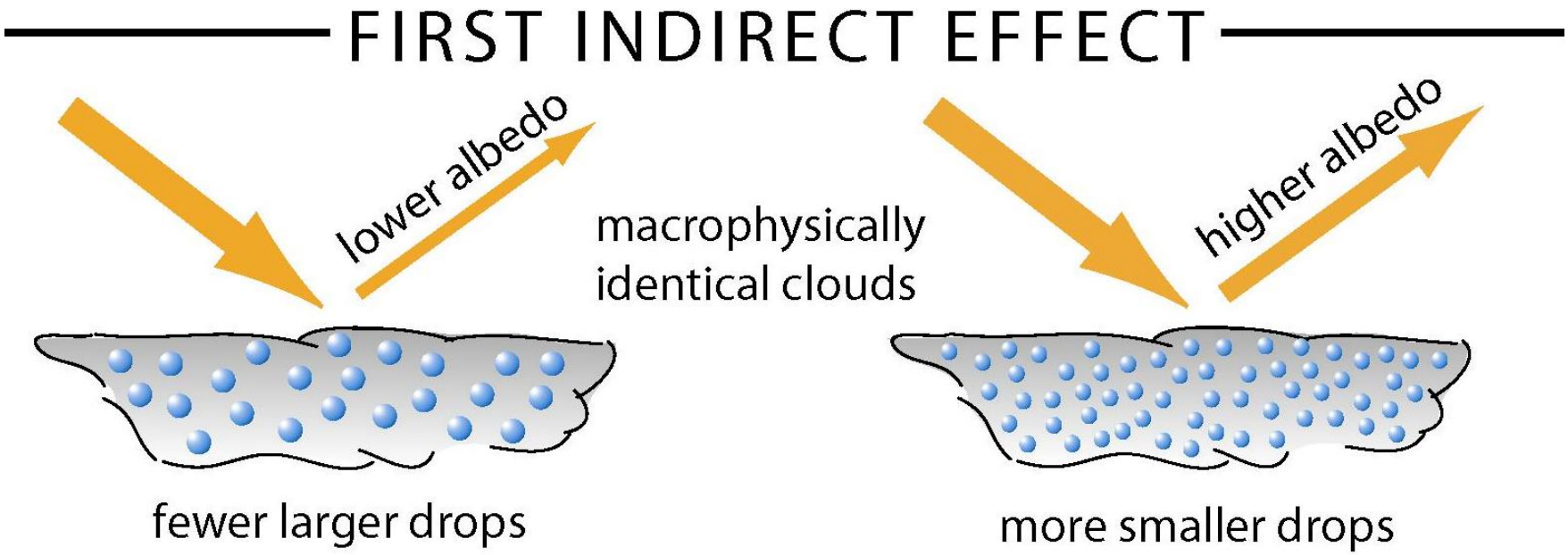
Institute of Atmospheric Physics, The University of Arizona, Tucson, Arizona 85721, U.S.A.

(*First received* 27 *February* 1974 *and in final form* 17 *May* 1974)

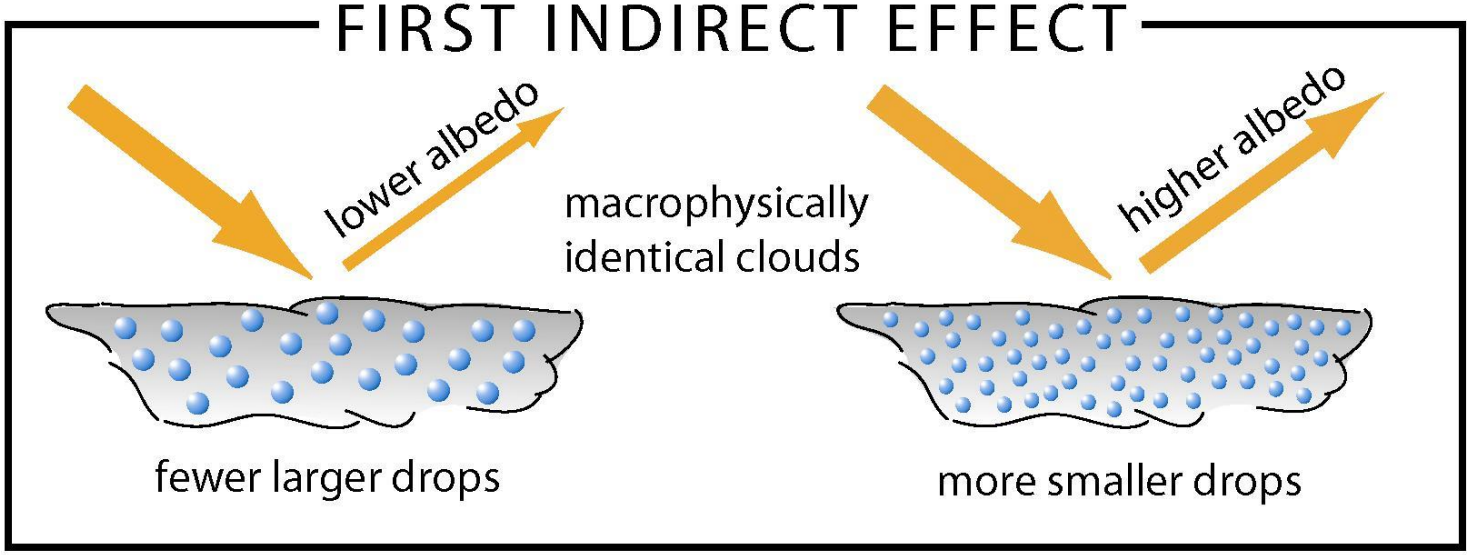
Abstract—Addition of cloud nuclei by pollution can lead to an increase in the solar radiation reflected by clouds. The reflection of solar energy by clouds already may have been increased by the addition of man-made cloud nuclei. The albedo of a cloud is proportional to optical thickness for thin clouds, but changes more slowly with increasing thickness. The optical thickness is increased when the number of cloud nuclei is increased. Although the changes are small, the long-term effect on climate can be profound.

Twomey, S., 1974: Pollution and the Planetary Albedo. *Atmospheric Environment,* 8, 1251–56.

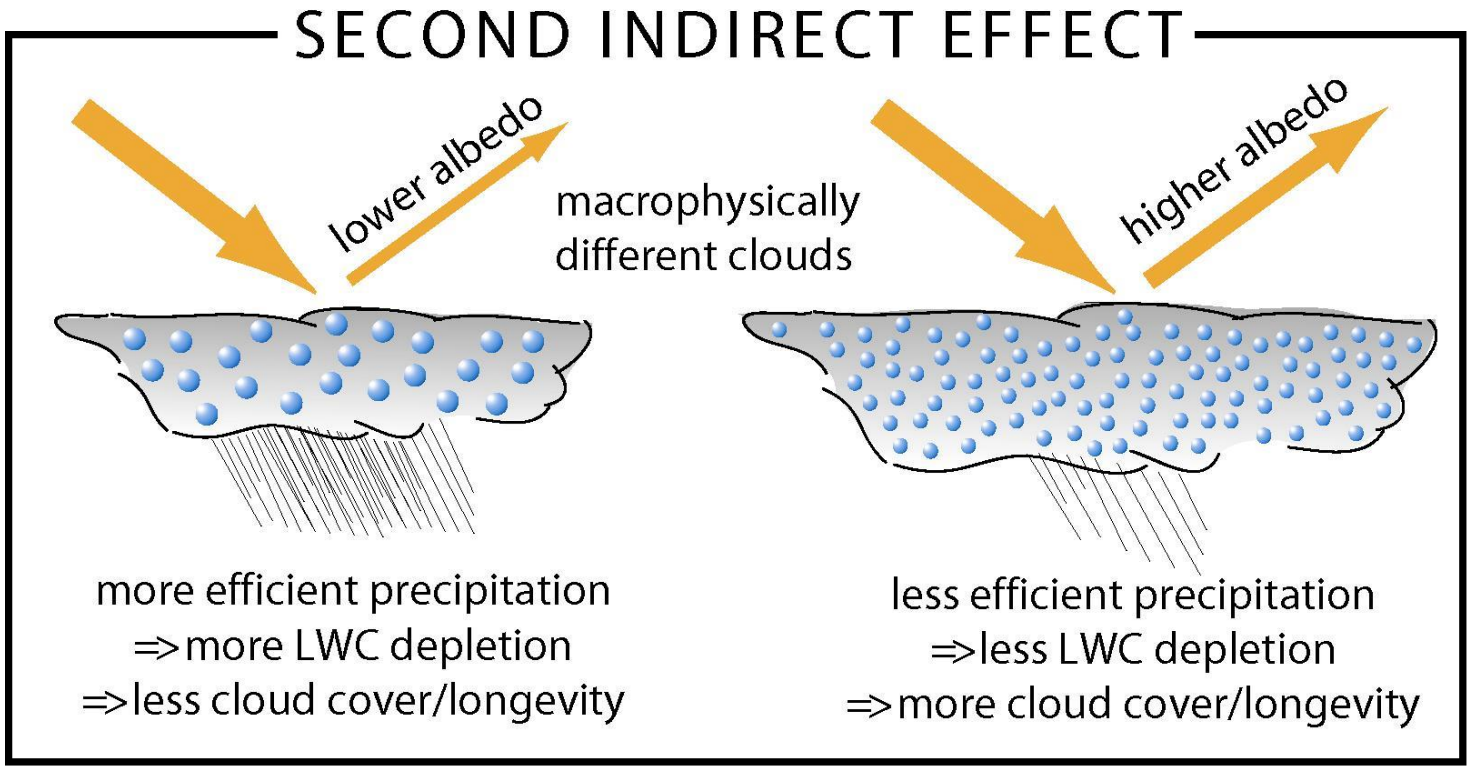
Twomey effect
a.k.a. the *first aerosol indirect effect*



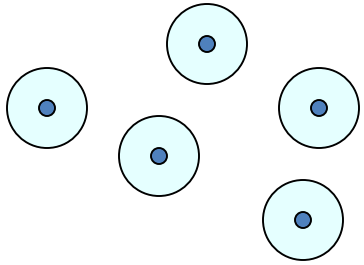
Twomey



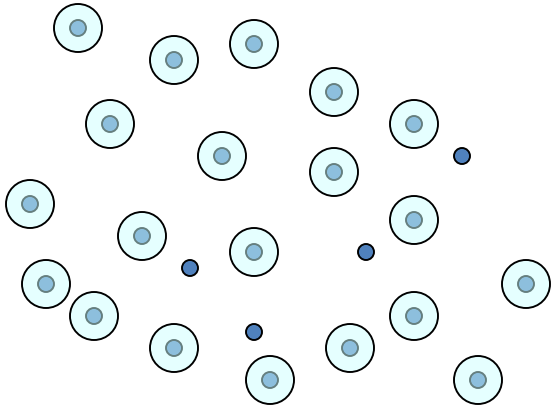
Albrecht



Aerosol “indirect effect” on climate



clean cloud (few particles):
large cloud droplets
- low albedo
- efficient precipitation



polluted cloud (many particles):
small cloud droplets
- high albedo
- suppressed precipitation
  (very controversial)

Table 1. Overview of the different aerosol indirect effects.[3]

Effect	Cloud Type	Description	Sign of the Radiative Forcing
First indirect aerosol effect (cloud albedo or Twomey effect)	All clouds	For the same cloud water or ice content more but smaller cloud particles reflect more solar radiation	Negative
Second indirect aerosol effect (cloud lifetime or Albrecht effect)	Warm clouds	Smaller cloud droplets decrease the precipitation efficiency thereby prolonging cloud lifetime	Negative
Semi-direct effect	Warm clouds	Absorption of solar radiation by soot leads to an evaporation of cloud droplets	Positive
Glaciation indirect effect	Mixed-phase clouds	An increase in ice nuclei increases the precipitation efficiency	Positive
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets inhibit freezing causing supercooled droplets to extend to colder temperatures	Unknown
Surface energy budget effect	All clouds	The aerosol induced increase in cloud optical thickness decreases the amount of solar radiation reaching the surface, changing the surface energy budget	Negative

“Warm clouds” clouds with liquid droplets
“Mixed phase clouds” clouds with liquid and ice

Observational needs

If your concern is …

Mass transported through the air for biogeochemical cycles, then you want to know the mean diameter of the particles with the mass or volume. In other words, "What size particles carry the most mass?”

loss of visibility then you want to know the diameter of the particles that have the largest cross section or surface area. In other words, "What size particles cover the largest surface area?"

Cloud formation or microphysics then you want to know the range of diameters with the largest number of particles. In other words, "What is the size of the most abundant particles?"

Observational needs

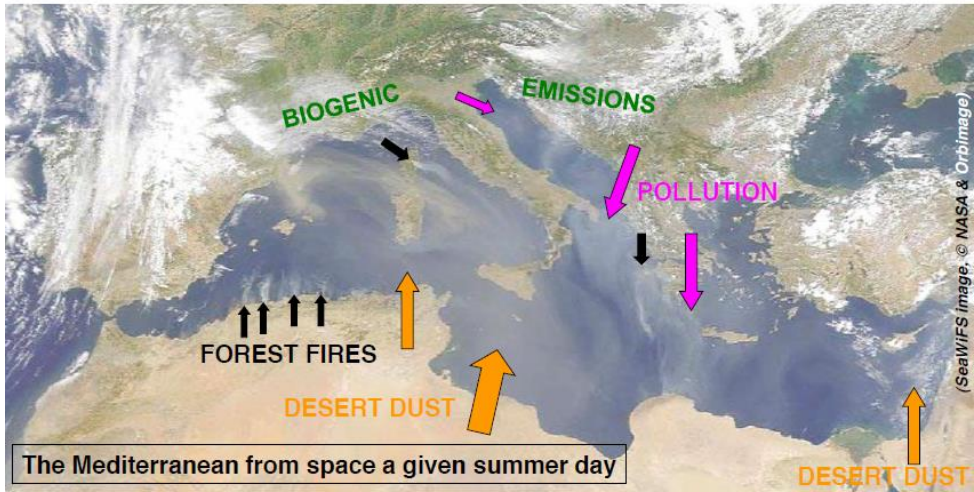
If your concern is…

human health then you need to know about both the mass and number of the particles, because only a certain size particle can enter the lungs.

climate effect then you need to know about global distribution and impact on radiative budget

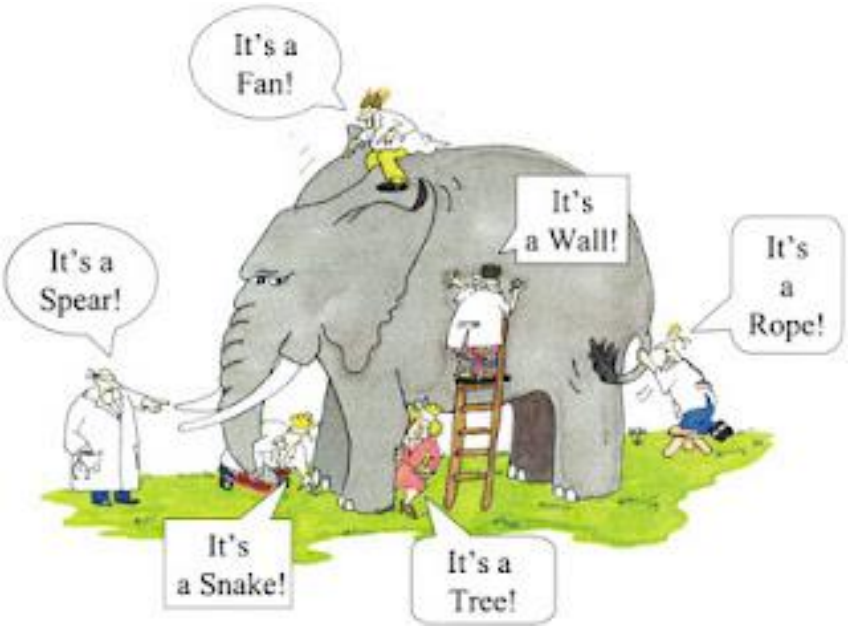
… discern among different aerosol

⇨ A natural laboratory to study
(i) the contribution of long-range transport,
(ii) the ageing of continental air masses over the basin,
(iii) the impact of aerosol on the regional climate,
(iv) the impact of atmos. deposition on low-Chl, low-nutrient surface waters



The Mediterranean from space a given summer day

Observational needs



There is no perfect instrument – they observe a specific aspect at a different time and spatial scale …

In situ – reference stations

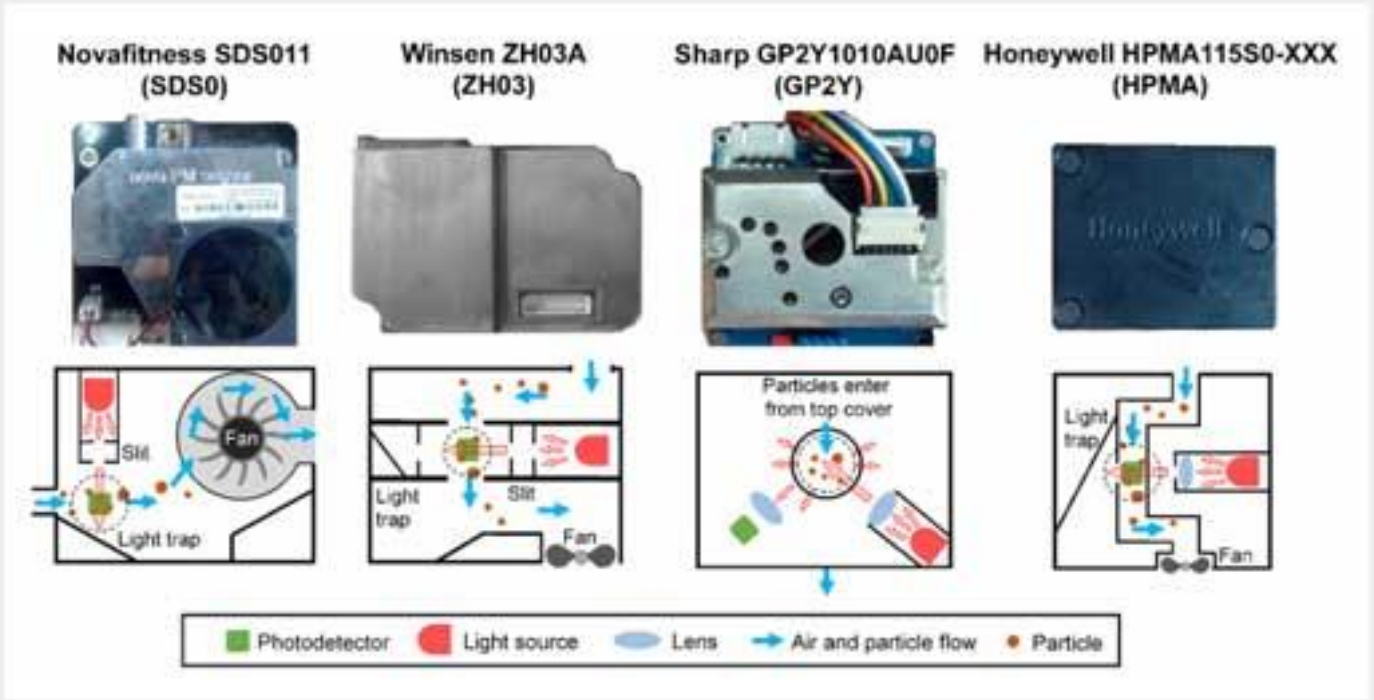
Gravimetric method – reference for air quality monitoring

Advantage: direct measure of mass – reliable

Disadvantage: relatively expensive, need for operator, not global coverage

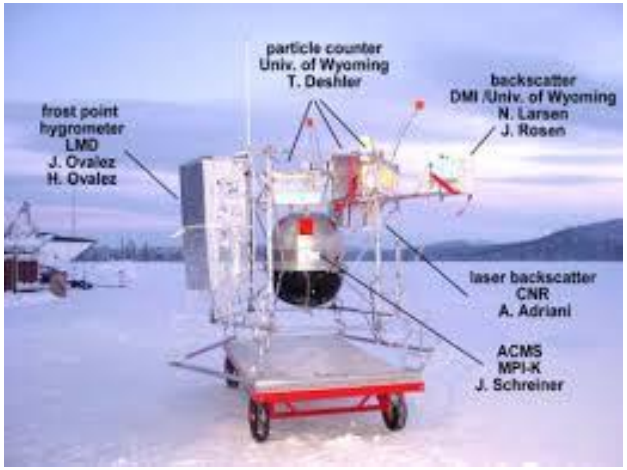
https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etcacm_tp_2011_21_pm10equivalence

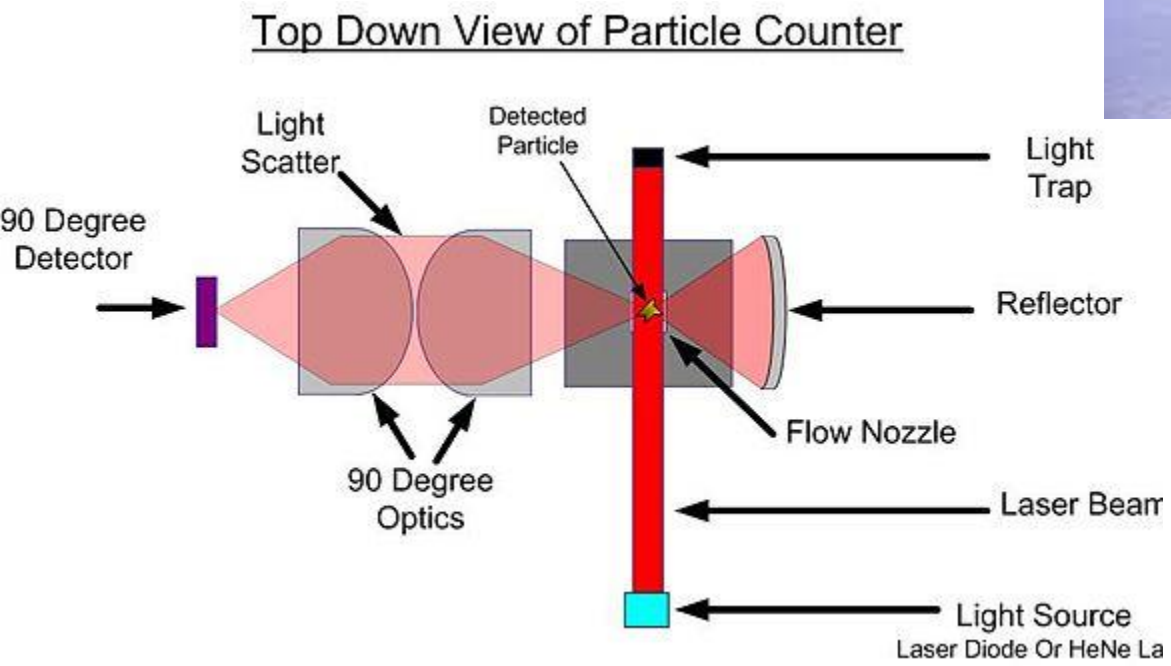
In-situ – optical instruments

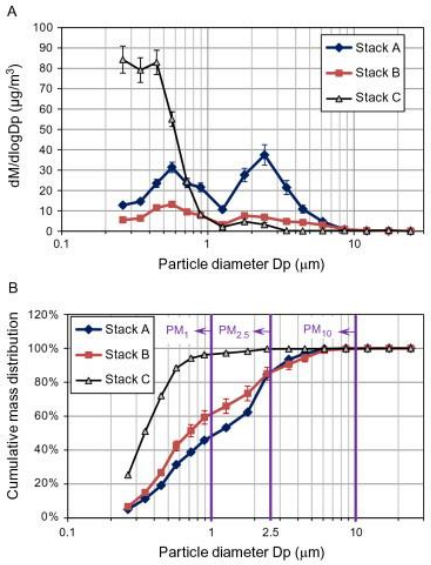


https://doi.org/10.4209/aaqr.2017.12.0611

In-situ – Optical Counter





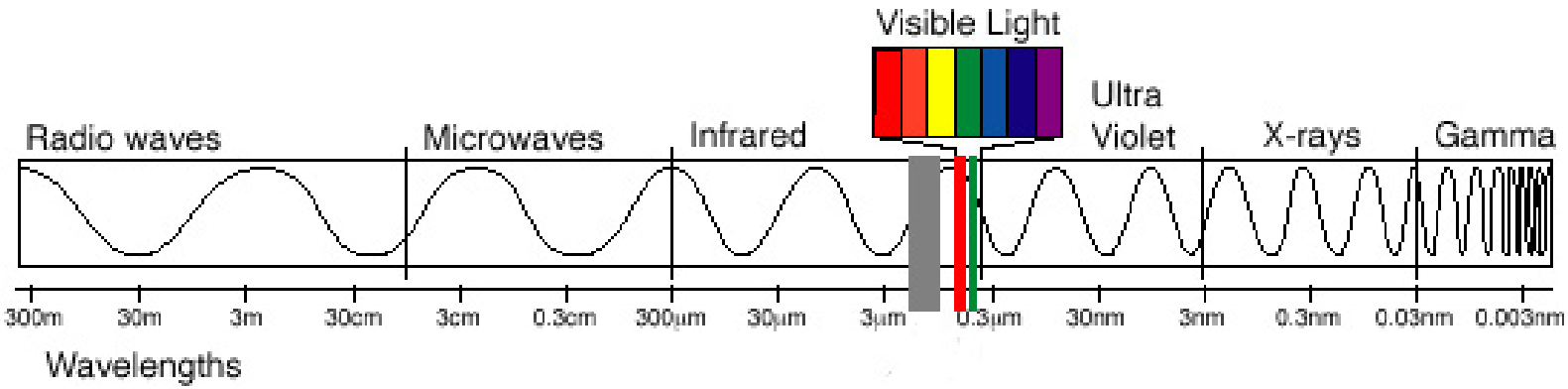


https://doi.org/10.4209/aaqr.2017.12.0611

Remote Sensing Overview

- What is “remote sensing”?
  - Using artificial devices, rather than our eyes, to observe or measure things from a distance without disturbing the intervening medium
    - It enables us to observe & measure things on spatial, spectral, & temporal scales that otherwise would not be possible
    - It allows us to observe our environment using a consistent set of measurements throughout the globe, without prejudice associated with national boundaries and accuracy of datasets or timeliness of reporting
- How is remote sensing done?
  - Electromagnetic spectrum
    - Passive sensors from the ultraviolet to the microwave
    - Active sensors such as radars and lidars
  - Satellite, airborne, and surface sensors
  - Training and validation sites

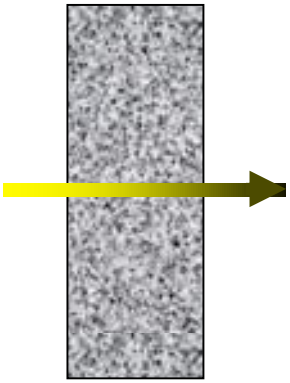
The Electromagnetic Spectrum



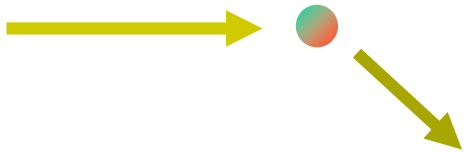
- Remote sensing uses the radiant energy that is reflected and emitted from Earth at various “wavelengths” of the electromagnetic spectrum
- Our eyes are only sensitive to the “visible light” portion of the EM spectrum
- Why do we use nonvisible wavelengths?

Key aerosol optical parameters

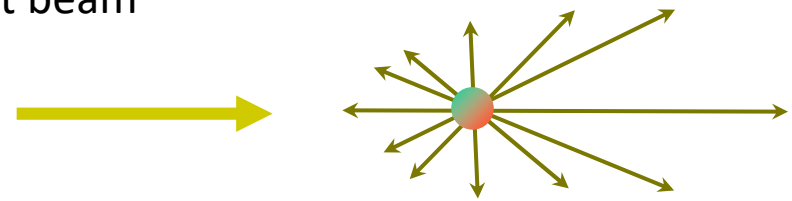
Optical depth
negative logarithm of the direct-beam transmittance
column integrated measure of the amount of extinction
(absorption + scattering)



Single-scattering albedo v_0
given an interaction between a photon and a particle, the probability that the photon is scattered in some direction, rather than absorbed



Scattering phase function
probability per unit solid angle that a photon is scattered into a particular direction relative to the direction of the incident beam



Angstrom exponent a
exponent of power law representation of extinction vs. wavelength

Optical Depth

$I = I_0 \exp [-(\sigma_{scattering} + \sigma_{absorption}) (n L)]$ Beer's Law

I_0 original intensity of light that goes into the cell

I observed intensity of light after it travels through the cell

L, path length of cell (cm)

n, number density of particles (cm^{-3})

$\sigma_{scattering}$ scattering cross section (cm^2)

$\sigma_{absorption}$ absorption cross section (cm^2)

$\tau = (\sigma_{scattering} + \sigma_{absorption}) (n L)$ Optical depth (unitless)

$a = (\sigma_{scattering}) / (\sigma_{scattering} + \sigma_{absorption})$ Single scattering albedo

$K = (\sigma_{scattering} + \sigma_{absorption}) n$ Extinction coefficient (1 / km)

Optical Properties

$\beta_{ext}(\lambda) = 10^3 \int Q_{ext}(r,\lambda)\, \pi r^2\, dN/dr\, dr$ extinction (units km^{-1})

r particle radius (μm)

dn / dr particle size distribution (# cm^{-3} μm^{-1})

$Q_{ext}(r, \lambda)$ extinction efficiency (from Mie theory)

$Q_{ext} = Q_{sca} + Q_{abs}$ (sca=scattering, abs = absorption)

Q is a function of the complex index of refraction
i.e. composition

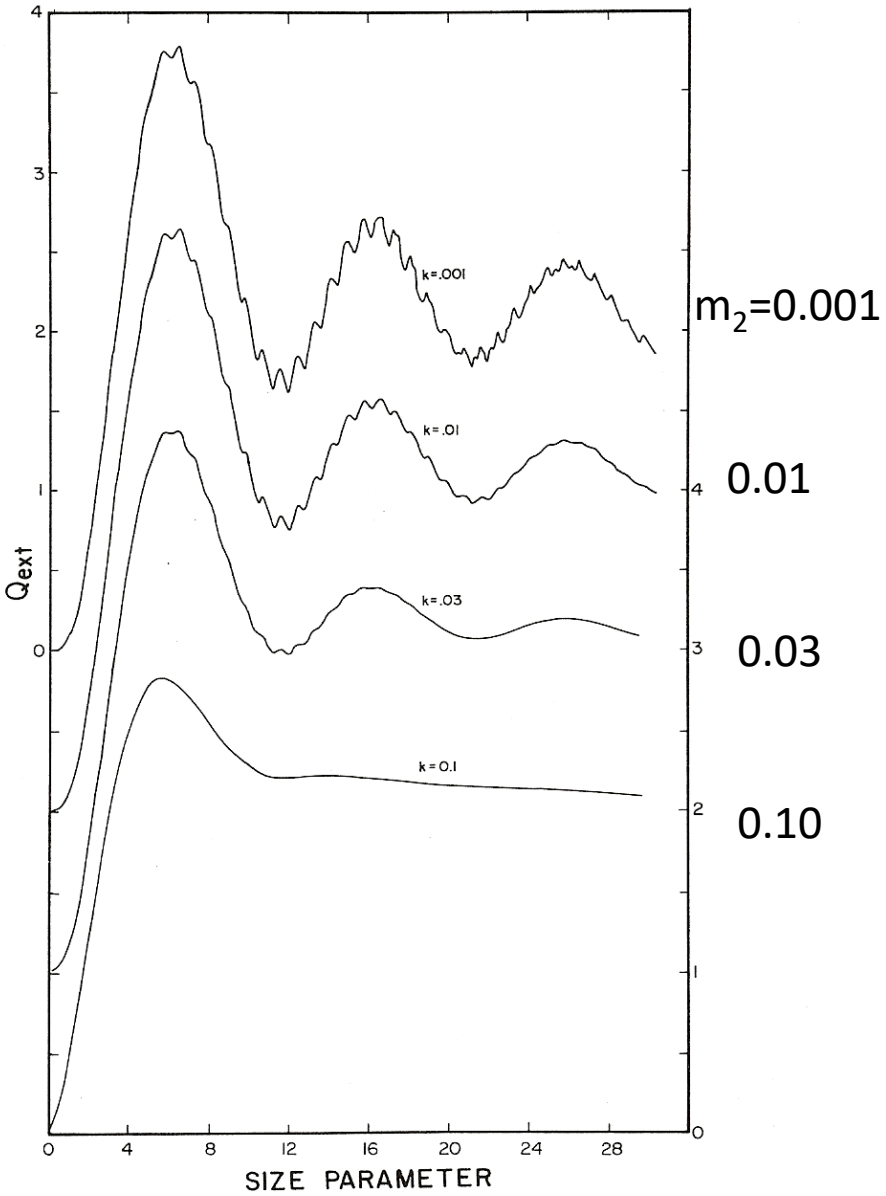
Size parameter $x = 2 \pi r / \lambda$

Optical depth contribution in path length ds is $\beta(\lambda)\, ds$

Mie Scattering

Each curve is offset by 1

Q_{ext}



Mie scattering (spherical particles)

Sensitivity to m_2

m, complex index of refraction

Increase absorption, m_2
$m = 1.33 + i\, m_2$

The fine details become smoother

Note as particle size becomes large,
Q_{ext} -> 2

Bohren and Huffman

General Results

Size parameter $x = 2 \pi r / \lambda$ for λ = wavelength

For very small particles $x << 1$ (Rayleigh scattering)

scattering $\propto 1 / \lambda^4$ The sky is Blue

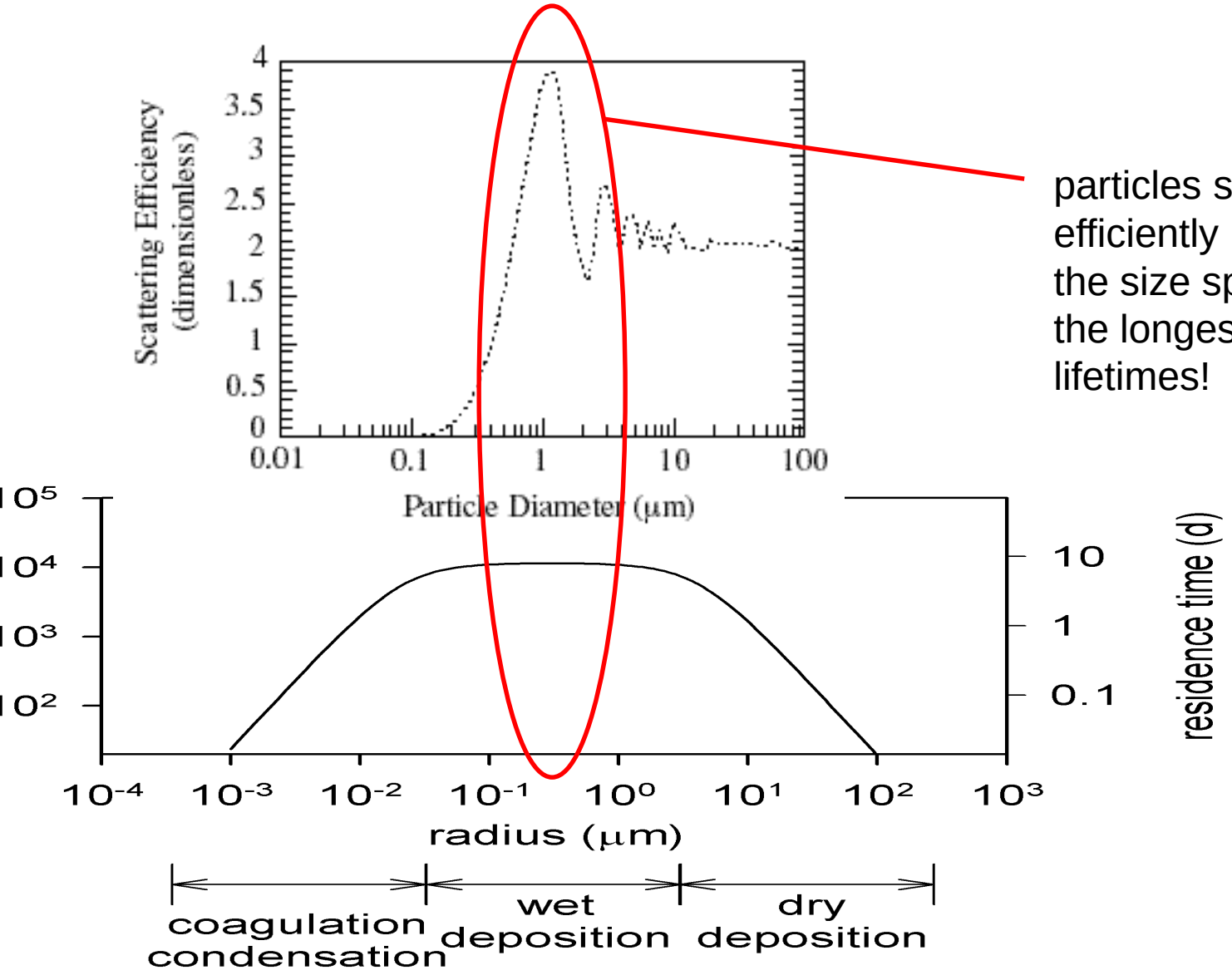
For medium size particles (aerosols), x ~1 (Mie scattering)

scattering ~ $1/ \lambda$ The sky is grey

For big size particles (cloud droplets, cirrus) $x >> 1$

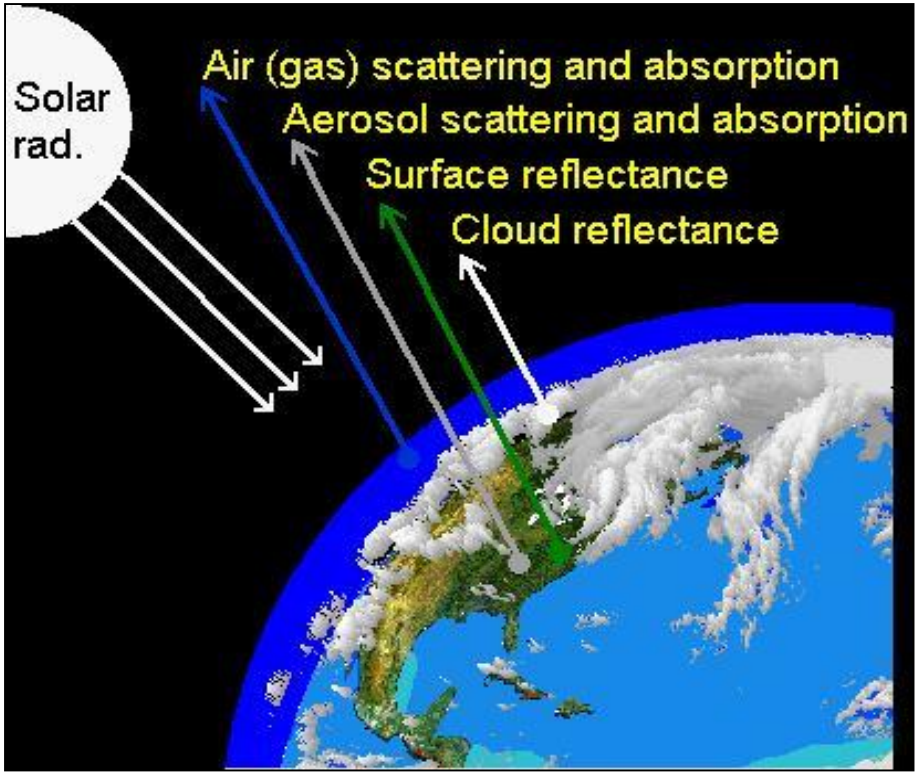
Q_{ext} -> 2 independent of λ Clouds are white

Aerosol optics



particles scatter most efficiently in the part of the size spectrum with the longest atmospheric lifetimes!

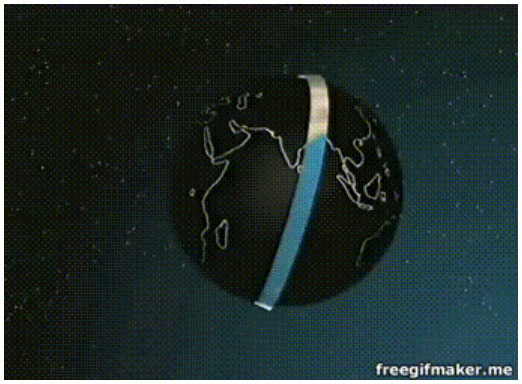
Radiation detected by satellites



- Air scattering depends on geometry and can be calculated (Rayleigh scattering)
- Clouds completely obscure the surface and have to be masked out
- Aerosols redirect incoming radiation by scattering and also absorb a fraction
- Surface reflectance is a property of the surface

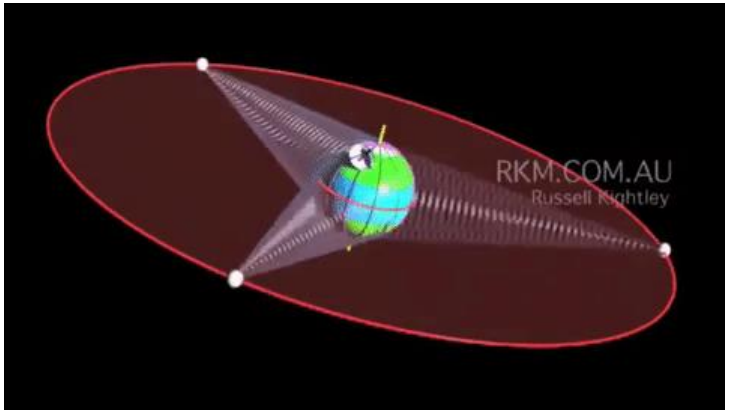
Satellite orbits

Advantages:
More near to Earth -> Higher spatial resolution
Used also for Active Obs.(Radar/Lidar) and PMW
Disadvantages:
Poorer time resolution -> needs of constellation



Advantages:
Better time resolution

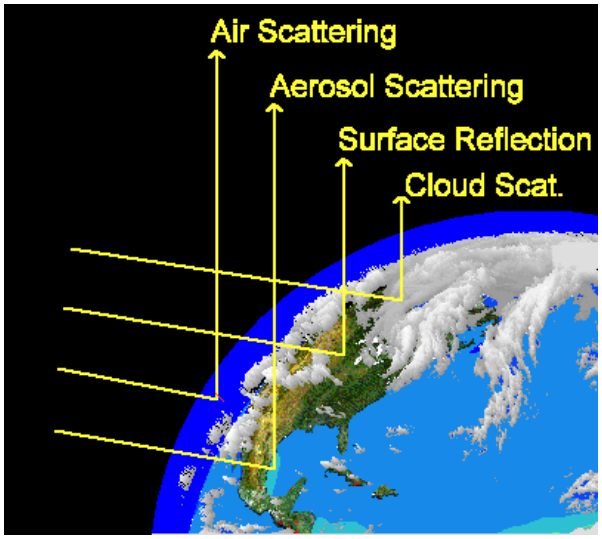
Disadvantages:
One side of the Earth -> needs of constellations
large viewing angles at the borders -> geometrical distorsions
Only VIS/IR and passive Obs.



Satellite Detection of Aerosols

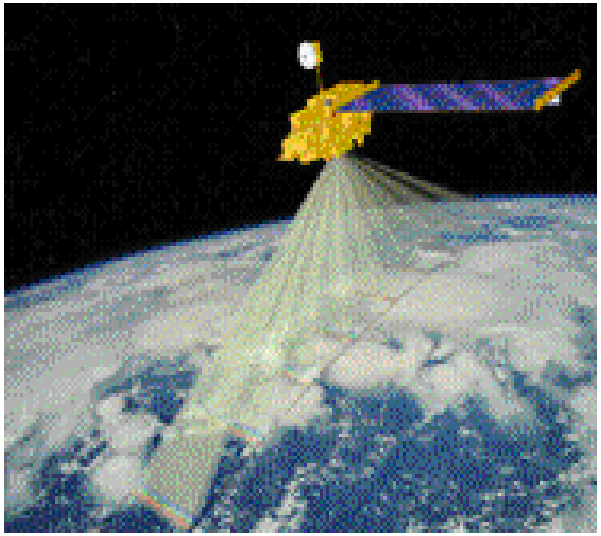
Just like the human eye, satellite sensors detect the total amount of solar radiation that is reflected from the earth's surface (R_o) and backscattered by the atmosphere from aerosol, pure air, and clouds. A simplified expression for the relative radiation detected by a satellite sensor (I/I_o) is:

$$I = \int_{Height}\int_{Type}\int_{Size}\int_{Angle}\int_{Shape} H \bullet C \bullet D \bullet P \bullet S \; dHdCdDdPdS$$



$$I / I_o = R_o e^{-\tau} + (1 - e^{-\tau}) P$$

where τ is the aerosol optical thickness and P the angular light scattering probability.

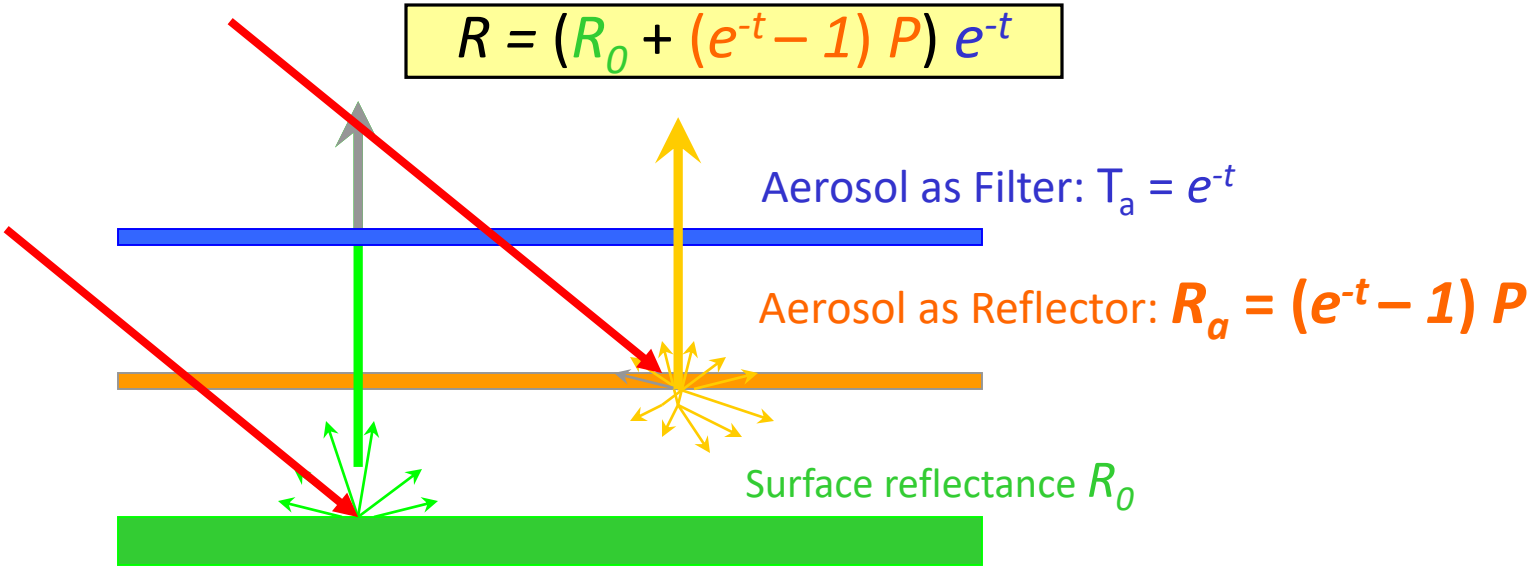


Today, geo-synchronous and polar orbiting satellites can detect different aspects of aerosols over the globe daily.

Apparent Surface Reflectance, R

- The surface reflectance R_0 is obscured by aerosol scattering and absorption before it reaches the sensor
- Aerosol acts as a ***filter*** of surface reflectance and as a ***reflector*** solar radiation

$$R = (R_0 + (e^{-t} - 1)\,P)\,e^{-t}$$



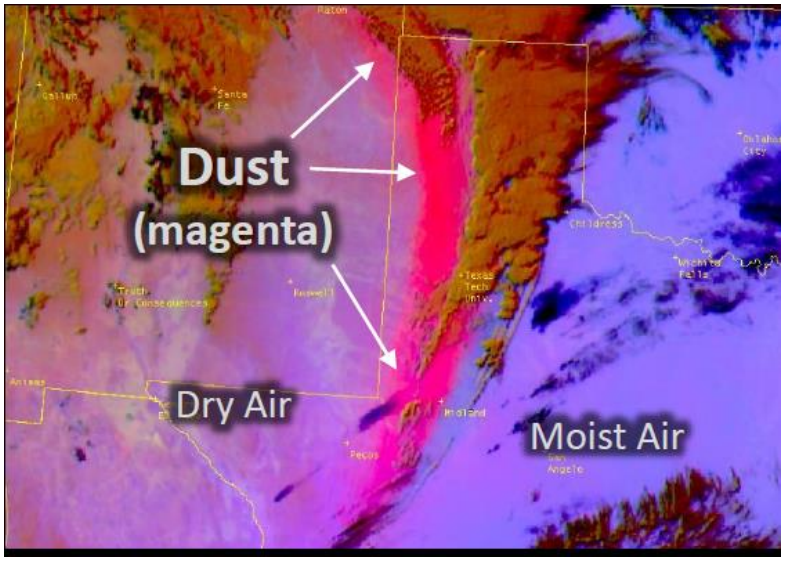
- The **apparent reflectance , *R*,** detected by the sensor is: $R = (R_0 + R_a)\,T_a$
- Under cloud-free conditions, the sensor receives the reflected radiation from ***surface*** and ***aerosols***
- Both surface and aerosol signal varies independently in time and space
- Challenge: Separate the total received radiation into surface and aerosol components

Aerosol Effect on Surface Color and Surface Effect

- Aerosols **add** to the reflectance and sometimes **reduce** the reflectance of surface objects
- Aerosols always **diminish** the **contrast** between dark a bright surface objects
- **Haze** and smoke aerosols **change the color** of surface objects to bluish while **dust** adds a yellowish tint.

- **Dark** surfaces like ocean and dark vegetation makes the aerosol appear **bright**.
- **Bright** surfaces like sand and clouds makes the aerosol **invisible**.

Dust measured on visible channels (RGB)



Limitations

High clouds obscure dust: High cloud cover can obscure dust plumes beneath them and make spatial analysis of the dust more difficult.

Dust thickness typically unknown: Magenta/pink variations in daytime are not indicators of thickness, but rather density. However, very thick dust plumes are purple in both day and night scenes.

Low clouds look like dust over oceans: Marine stratus over the ocean in the tropics appear light purple and can look similar in color to dust, particularly at night.

Dust RGB Recipe (GOES/ABI, H8/AHI)

Color	Band / Band Diff. (µm)	Physically Relates to…	Small contribution to pixel indicates…	Large Contribution to pixel indicates…
Red	12.3-10.3	Optical depth / cloud thickness	Thin clouds	Thick clouds or dust
Green	11.2-8.4	Particle phase	Ice and particles of uniform shape (dust)	Water particles or thin cirrus over deserts
Blue	10.3	Surface temperature	Cold surface	Warm surface

Contributor: Kevin Fuell NASA SPoRT https://weather.msfc.nasa.gov/sport/

Apparent Surface Reflectance, R

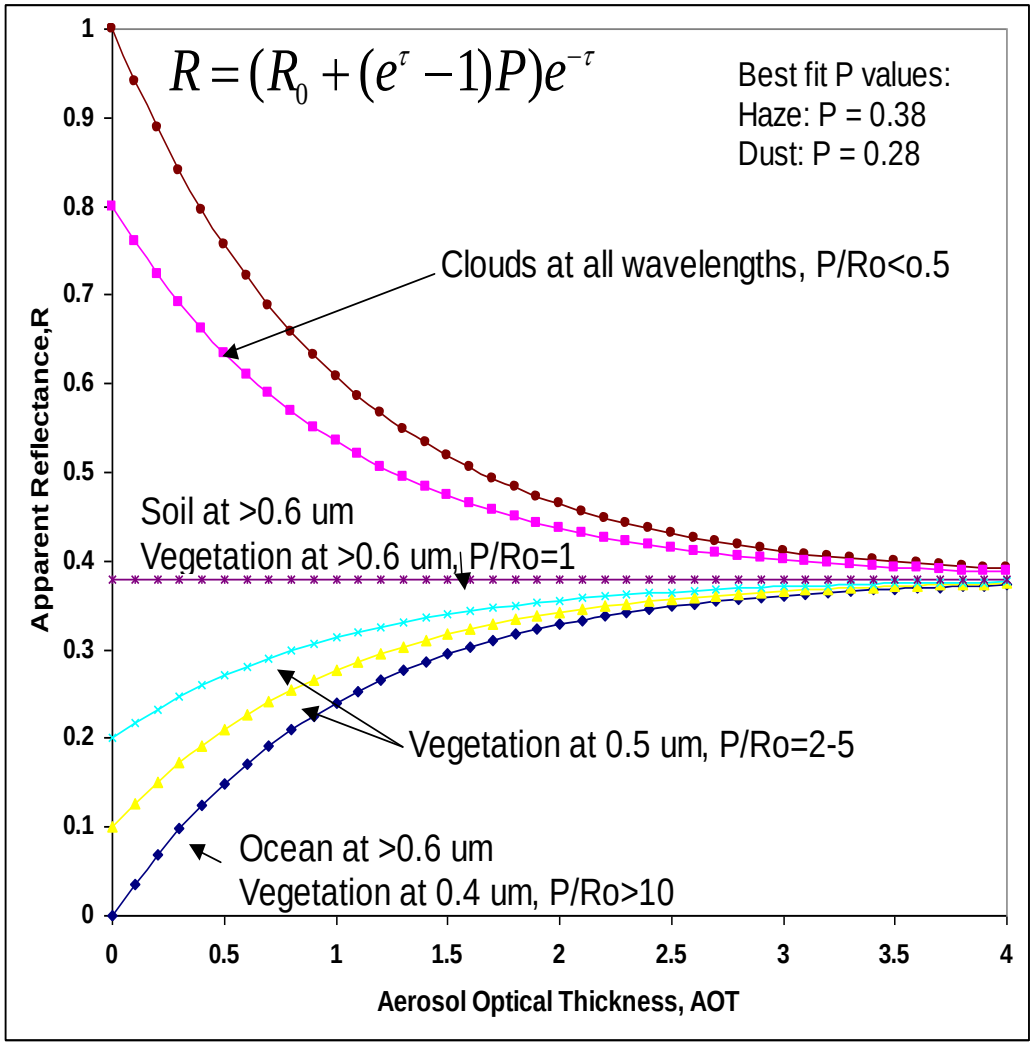
The critical parameter whether aerosols will increase or decrease the apparent reflectance, R, is the ratio of aerosol angular reflectance, **P,** to bi-directional surface reflectance, $\mathbf{R_0}$, $\mathbf{P/R_0}$

Aerosols will increase the apparent surface reflectance, R, if $\mathbf{P/R_0 < 1.}$ For this reason, the reflectance of ocean and dark vegetation increases with τ.

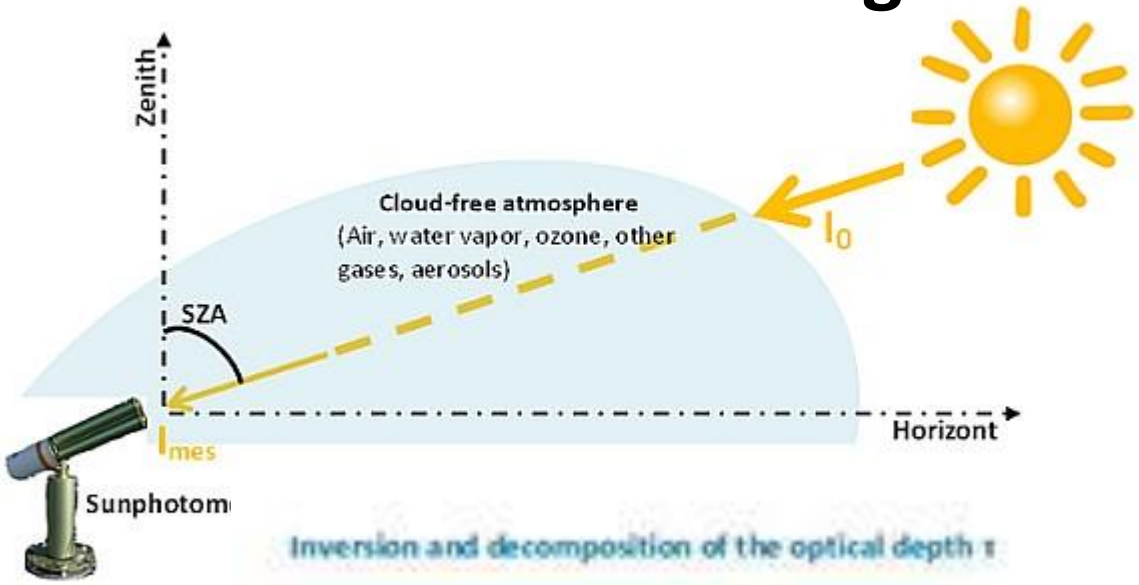
When $\mathbf{P/R_0 > 1,}$ aerosols will decrease the surface reflectance. Accordingly, the brightness of clouds is reduced by overlying aerosols.

At $\mathbf{P \sim R_0}$ the reflectance is unchanged by haze aerosols (e.g. soil and vegetation at 0.8 um).

At large τ (radiation equilibrium), both dark and bright surfaces asymptotically approach the 'aerosol reflectance', P



Photometers – ground-based



Inversion and decomposition of the optical depth τ

The Beer's law can be expressed in a logarithmic form:

$$\tau = \frac{1}{m_0} \cdot \ln \frac{I_0}{I_{meas}}$$

- This is valuable at a given wavelength λ
- I_{meas} is measured, I_0 und m_0 are known.

This shows that the measurement of I_{meas} is sufficient to invert the Optical Depth (τ).

The Optical Depth τ quantifies the turbidity of the atmosphere. The optical depth of the atmosphere is the sum of the optical depth of all atmospheric components separately:

$$\tau = \tau_R + \tau_{aer} + \tau_{H_2O} + \tau_{O_3} + \tau_{a.g.}$$

Photometers – ground-based

Methodology for the inversion of AOD, PWV und O_3DU

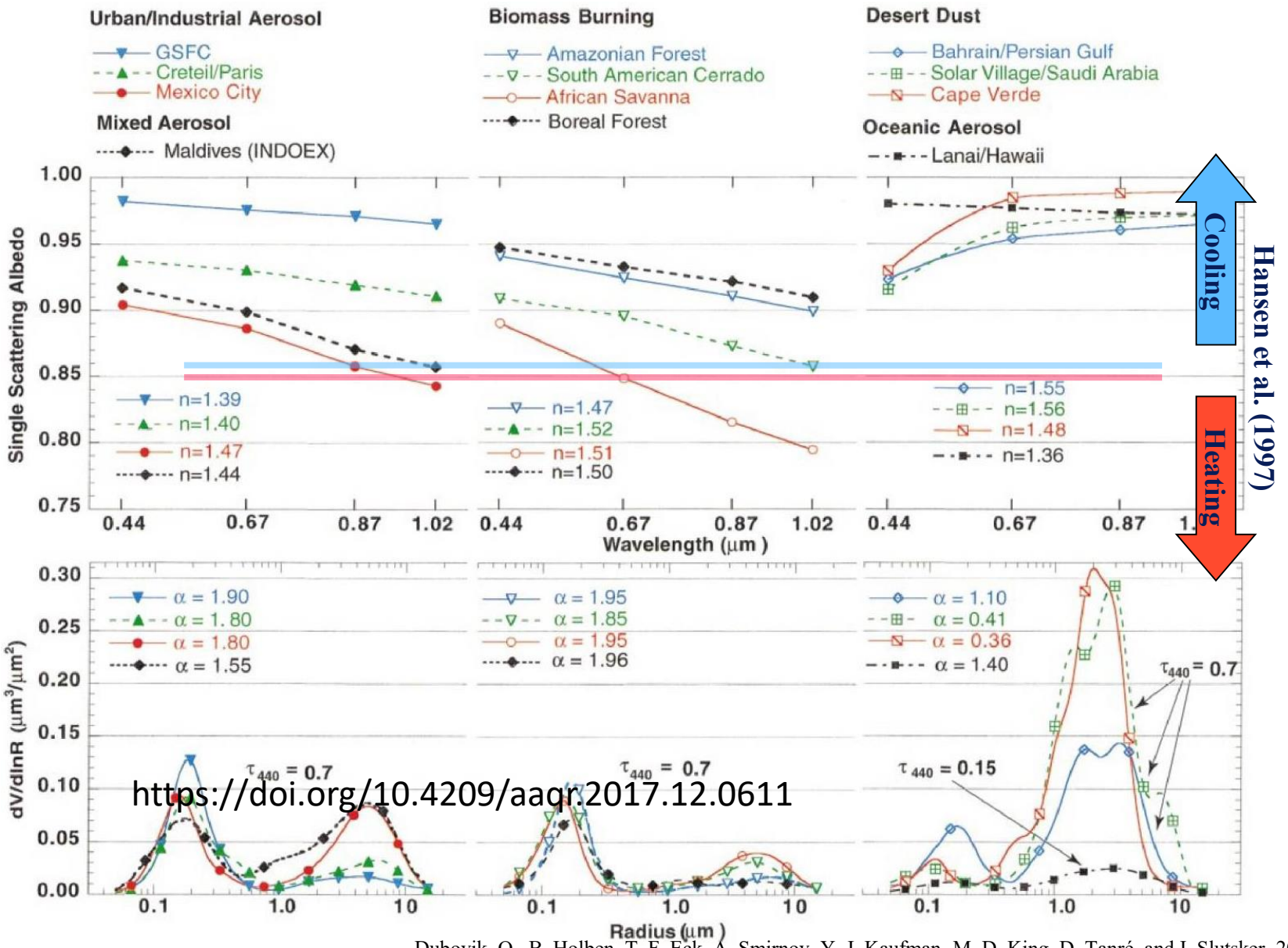
The values of $\tau_{a,g}$, τ_{H_2O} and τ_{O_3} are 0 for all wavelength λ, for which there are no line of gas absorption (see section "Spectroscopy and UV radiation"). It is easy to invert the AOD (τ_{aer}) throw a photometrical measurement in a spectral channel where the values of $\tau_{a,g}$, τ_{H_2O} and τ_{O_3} are 0. The AOD is therefore estimated with a measurement at these wavelengths, and then the AOD values for other wavelengths are extrapolated using the law of Ångström.

We invert τ_{O_3} thanks a photometrical measurement in ultraviolet (UV), where the values of all optical depths are 0 except the Rayleigh one, the ozone one and the AOD (this is possible for several wavelength λ).

We invert τ_{H_2O} thanks to a photometrical measurement in near infrared (NIR), at wavelengths where the values of all optical depths are 0, except the Rayleigh one, the one of water vapor and the AOD.

The water vapor column PWV (in mm) and the ozone column (in Dobson Unit: DU) are inverted from the values of τ_{H_2O} and τ_{O_3} respectively thanks to the tabulated values of the absorption coefficient of these gases.

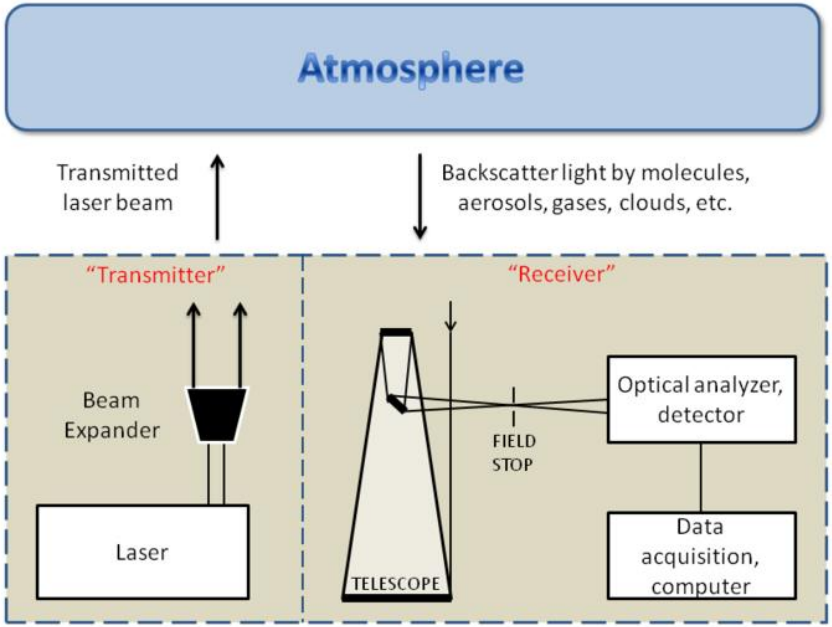
Climatology from AERONET

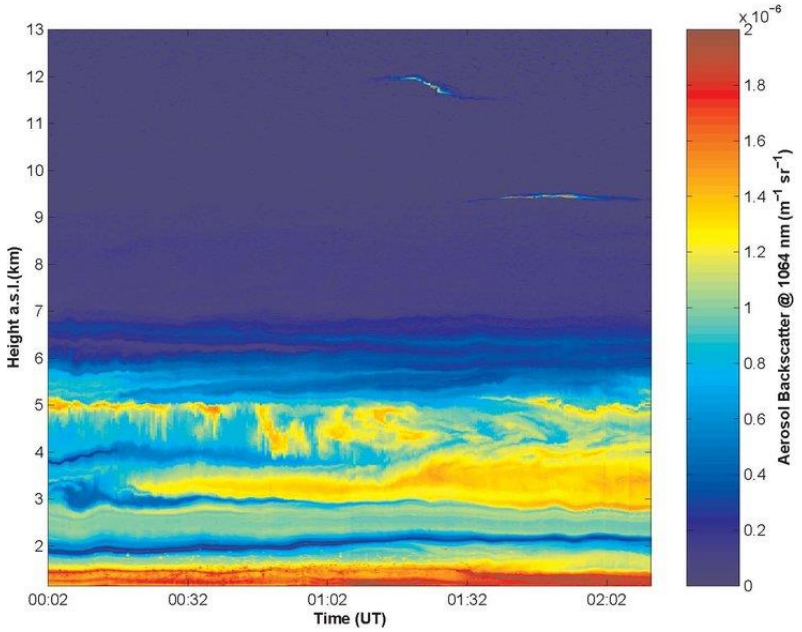


https://doi.org/10.4209/aaqr.2017.12.0611

Dubovik, O., B. Holben, T. F. Eck, A. Smirnov, Y. J. Kaufman, M. D. King, D. Tanré, and I. Slutsker, 2002: Variability of absorption and optical properties of key aerosol types observed in worldwide locations. *J. Atmos. Sci.*, 59, 590–608.

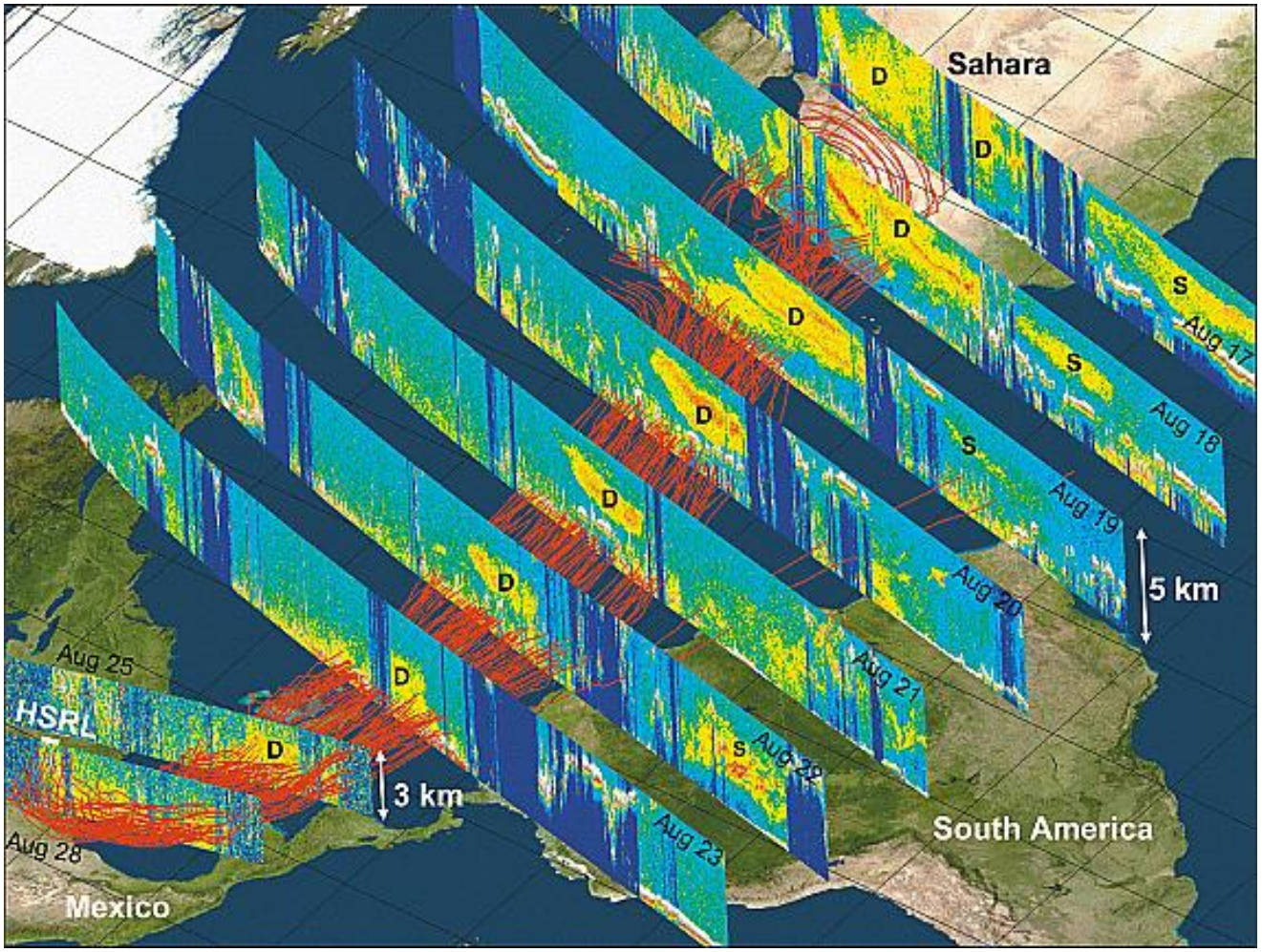
Active Remote Sensing - Lidar





$$P(r) = \frac{EL}{r^2} O(r) \left[\beta_{\mathrm{aer}}(r) + \beta_{\mathrm{mol}}(r)\right] e^{-2\int_0^r \alpha_{\mathrm{aer}}(s)+\alpha_{\mathrm{mol}}(s)\,ds},$$

Active Remote Sensing – Lidar Satellite



Multiple instruments – how to characterize dust ?

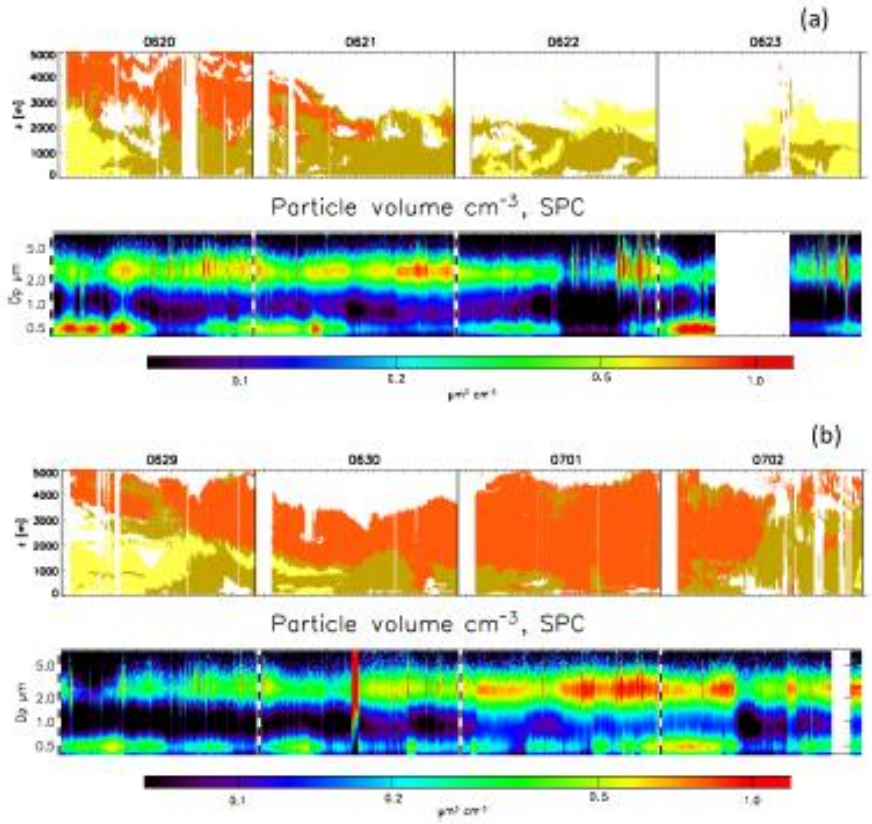


Figure 5. Vertical profiles of aerosol particle types (upper panels), as in Fig. 2, and APSS aerosol time series of the volume size distribution of aerosol particles (lower panels), as in Fig. 4, for the first (a) and the second (b) dust event.

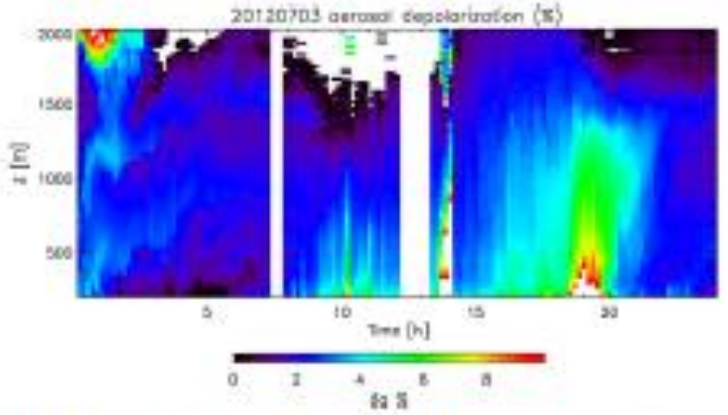
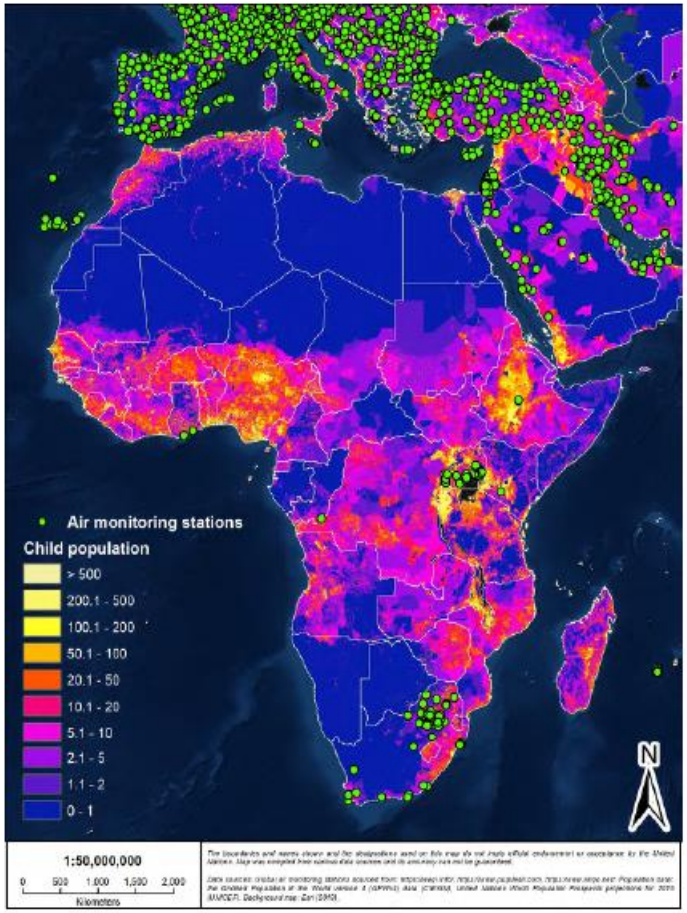
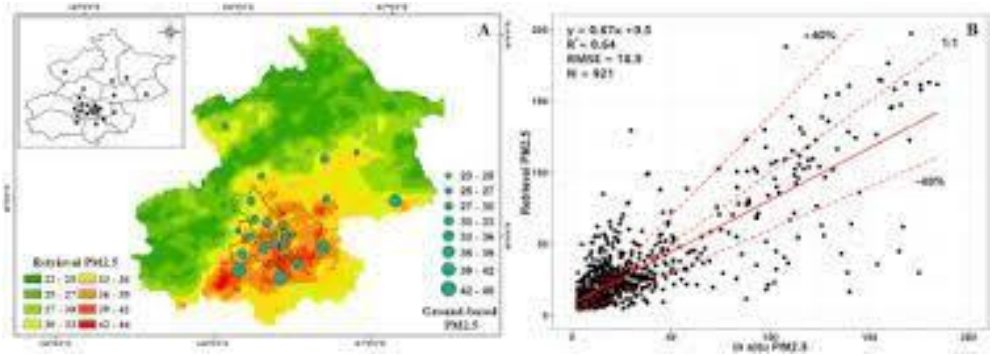


Figure 9. Vertical profiles of lidar aerosol linear depolarization ratio on 3 July 2012.

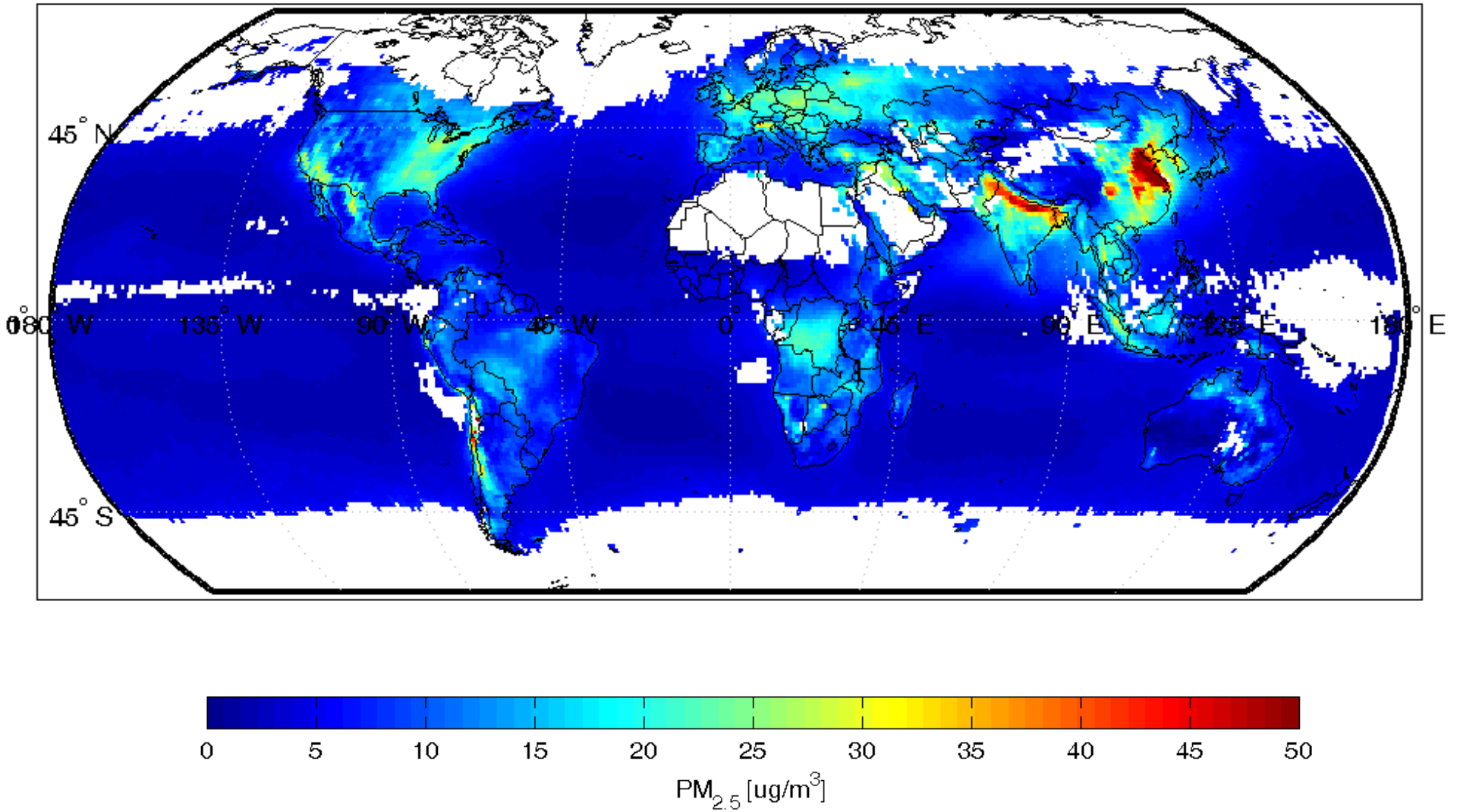
Advantages and drawbacks – my personal view

Figure 3: Air pollution monitoring in Africa





Annual mean $PM_{2.5}$ concentration (2002) derived from MODIS satellite instrument data



Advantages and drawbacks – my personal view

In-situ gravimetric	**Measurements of mass – accurate**	**Local coverage – no over sea – relatively expensive – no aerosol types**
In-situ optical	**Cheaper, potentially pervasive**	**Not direct, less accurate, calibration needed**
Remote Sensing satellite	**Global, cover long time range**	**Optical parameters, difficult to derive aerosol type – no info on vertical**
Ground-based	**Dense networks, calibrated, insights on aerosol size**	**Not global, no info on vertical**
Lidar	**Information on vertical structure, insights on aerosol size and optical properties**	**Not global, expensive**

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