Aerosols and Climate

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Alpbach Summer School, 2010

Outline

1. What is an aerosol
2. Why are aerosols important climate variables
3. Future climate
4. Observing aerosol from space

1. What is an aerosol

Definition:

An aerosol is a suspension of liquid droplets or solid particles in air

Characteristics:

Large variability in origin, size, shape and concentration

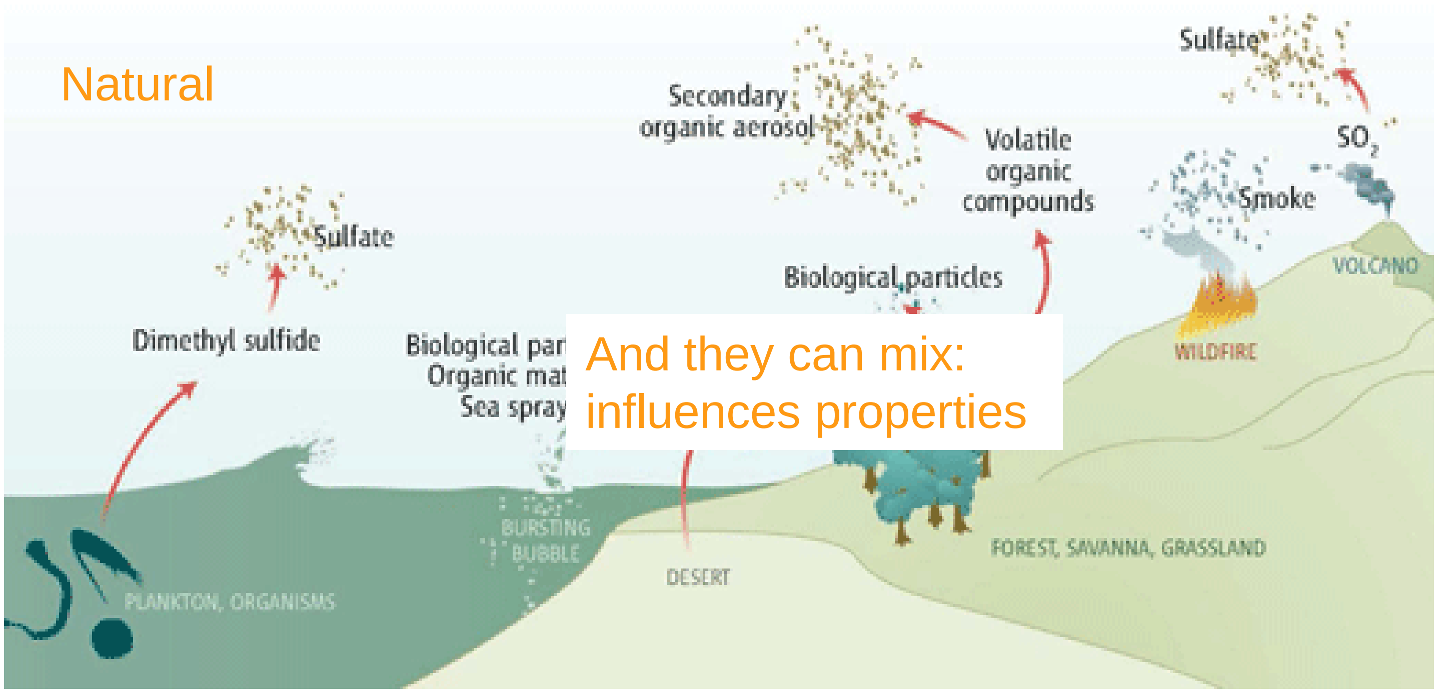
Diverse climate impacts

From space, often considered as ‘noise’ when retrieving other climate variables but very important in their own right

I: Origin

Primary and secondary

Natural

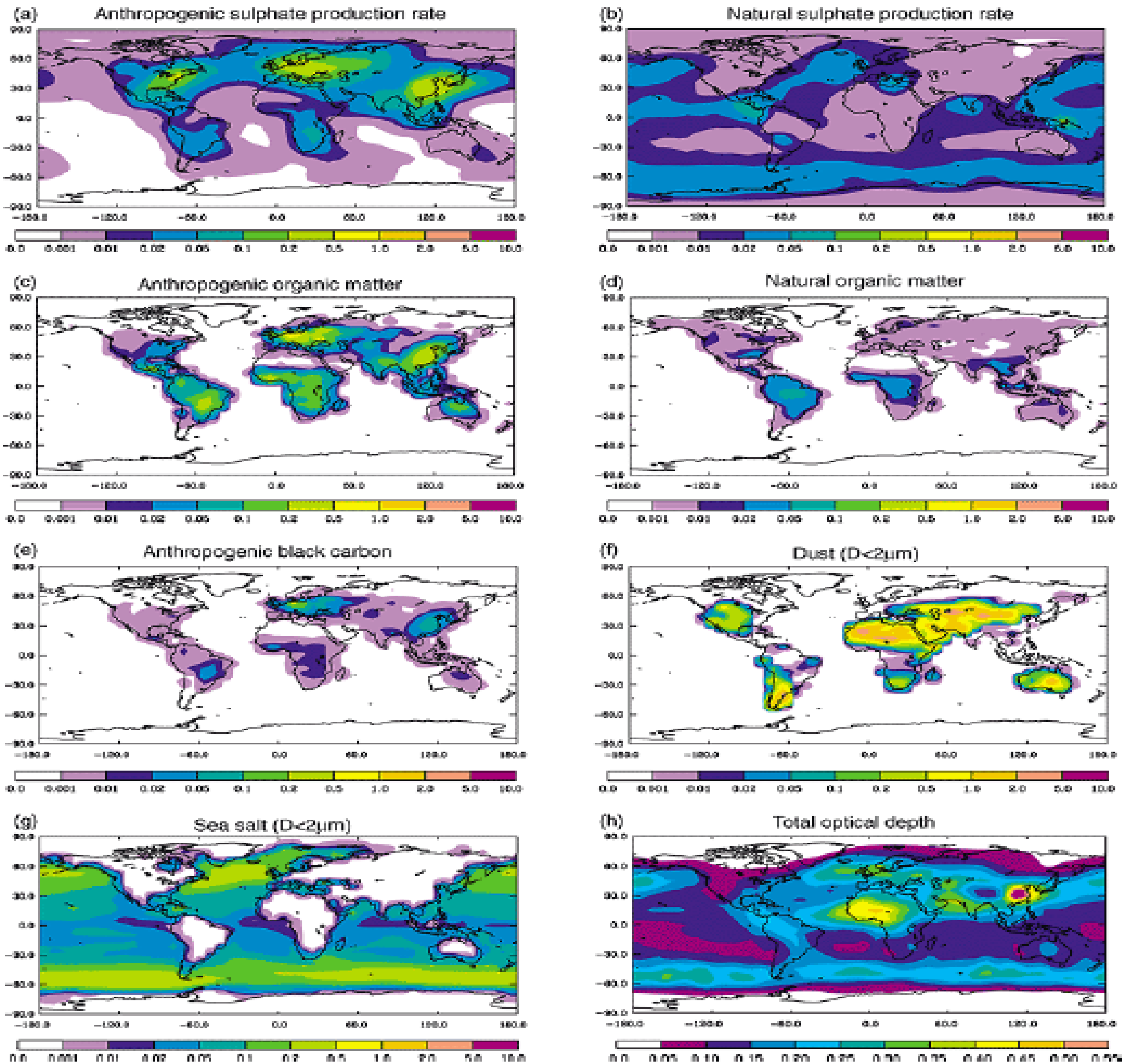


And they can mix: influences properties

Same aerosol type can be produced both naturally and anthropogenically

Anthropogenic

1. What is an aerosol

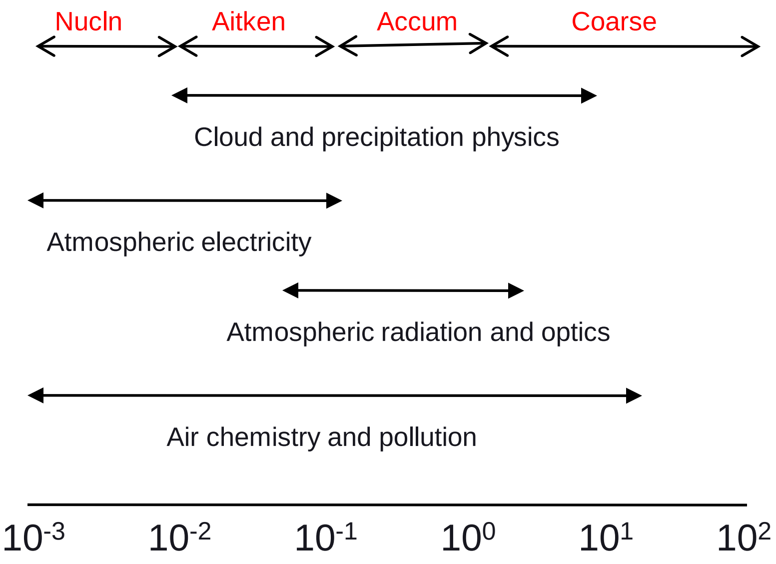


Sources in kg km^{-2} hr^{-1}

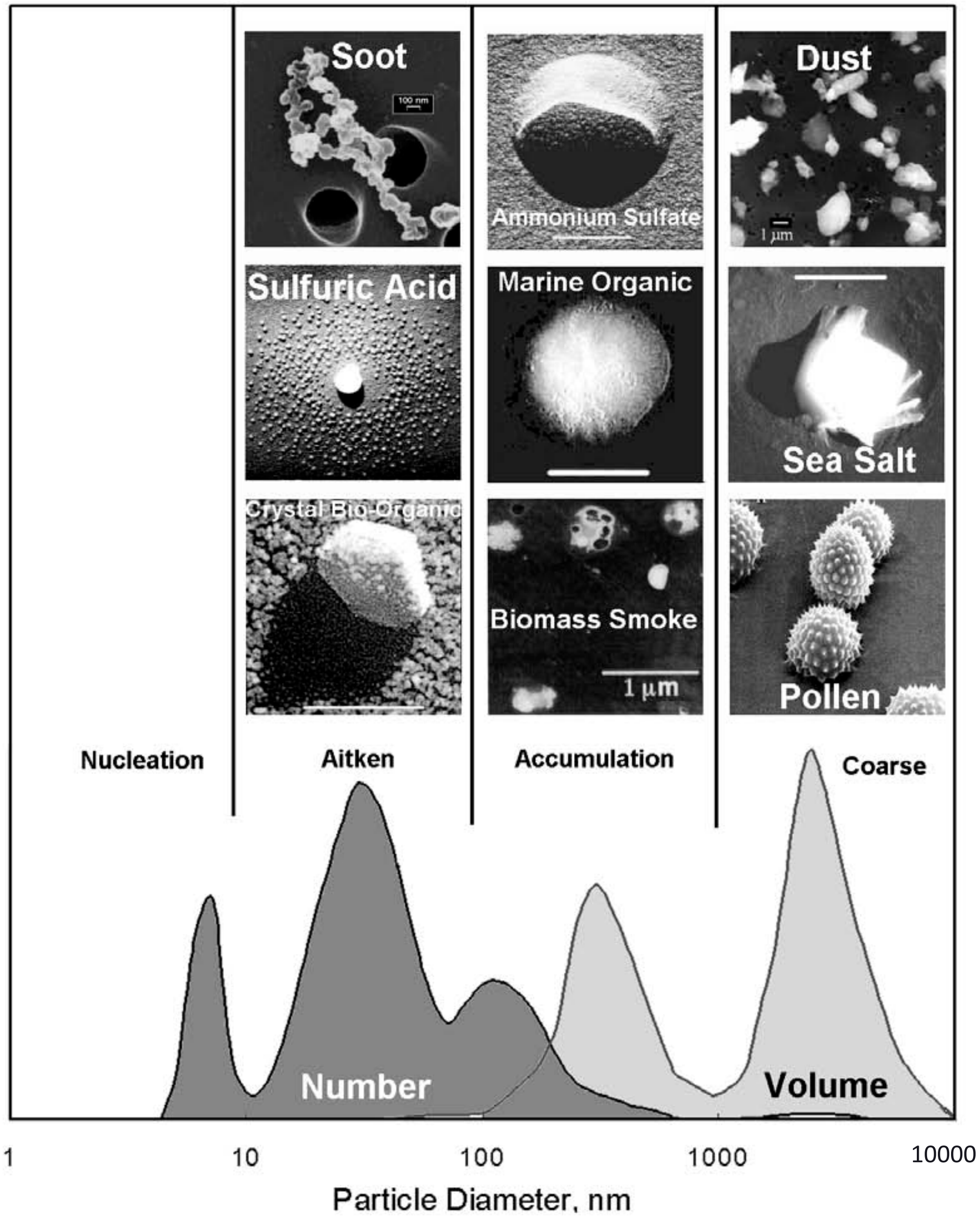
IPCC, 2001

II: Size and shape

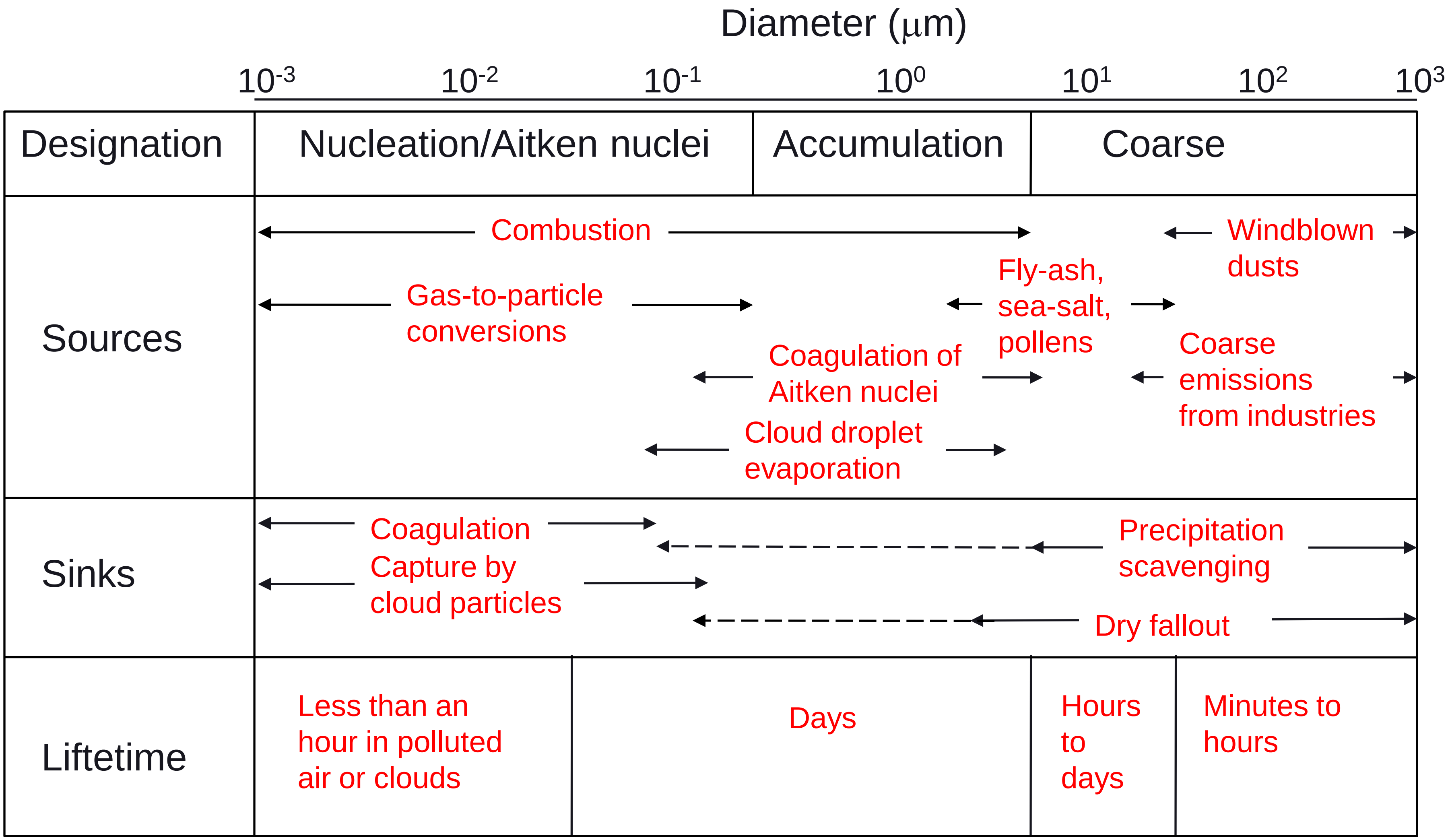
Different representations of size distribution mean different emphasis: most mass is in coarse mode but these may not be the most climatologically important aerosols…



Aerosol diameter (µm)



III: Lifetime



Diameter (µm)

10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}

Designation: Nucleation/Aitken nuclei | Accumulation | Coarse

Sources

Combustion

Windblown dusts

Gas-to-particle conversions

Fly-ash, sea-salt, pollens

Coagulation of Aitken nuclei

Coarse emissions from industries

Cloud droplet evaporation

Sinks

Coagulation

Capture by cloud particles

Precipitation scavenging

Dry fallout

Liftetime

Less than an hour in polluted air or clouds

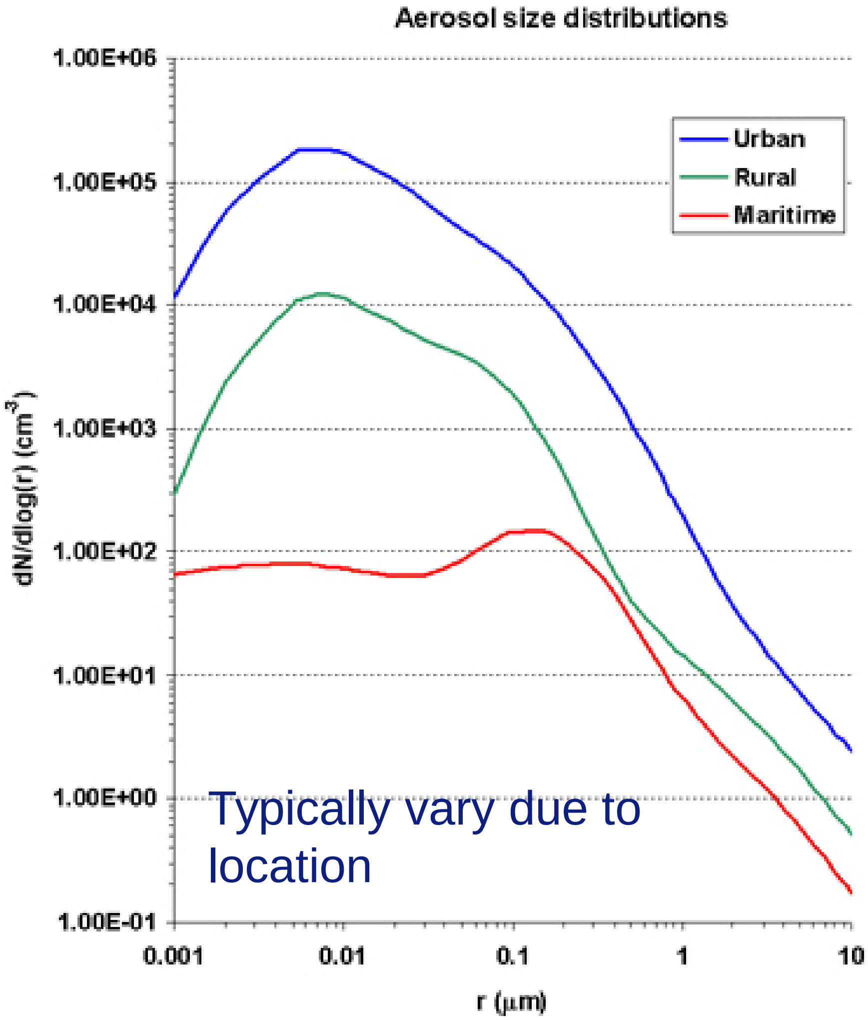
Days

Hours to days

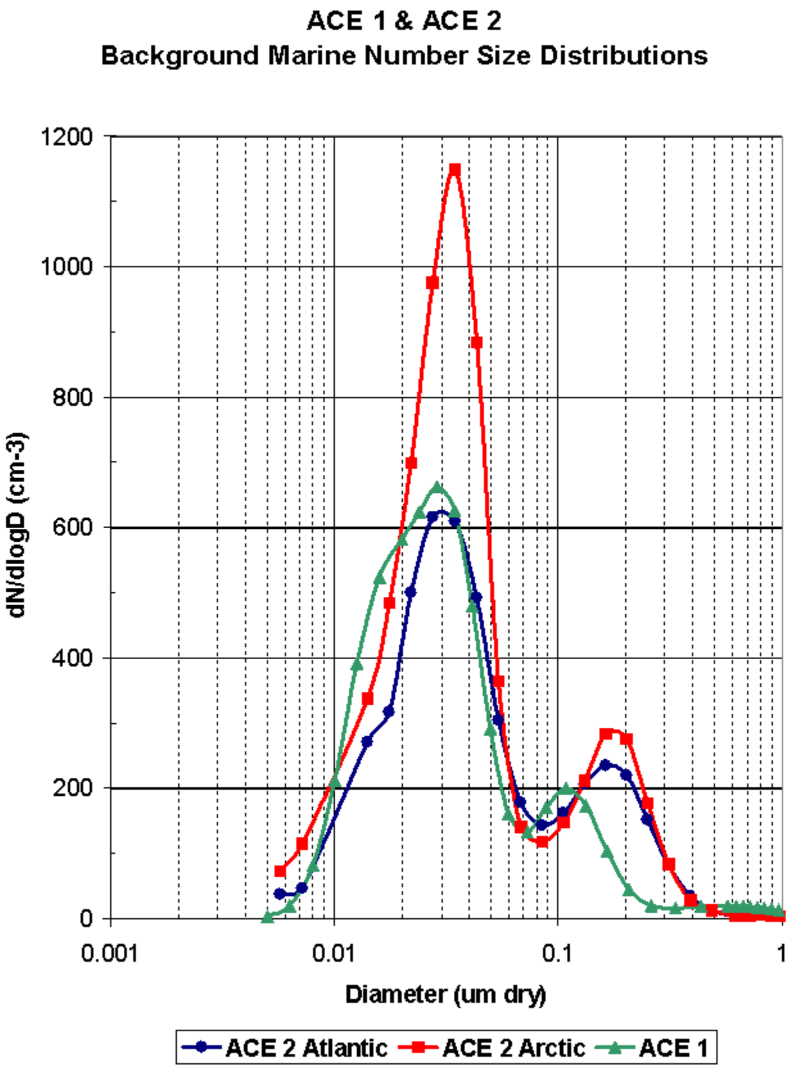
Minutes to hours

IV: Concentrations

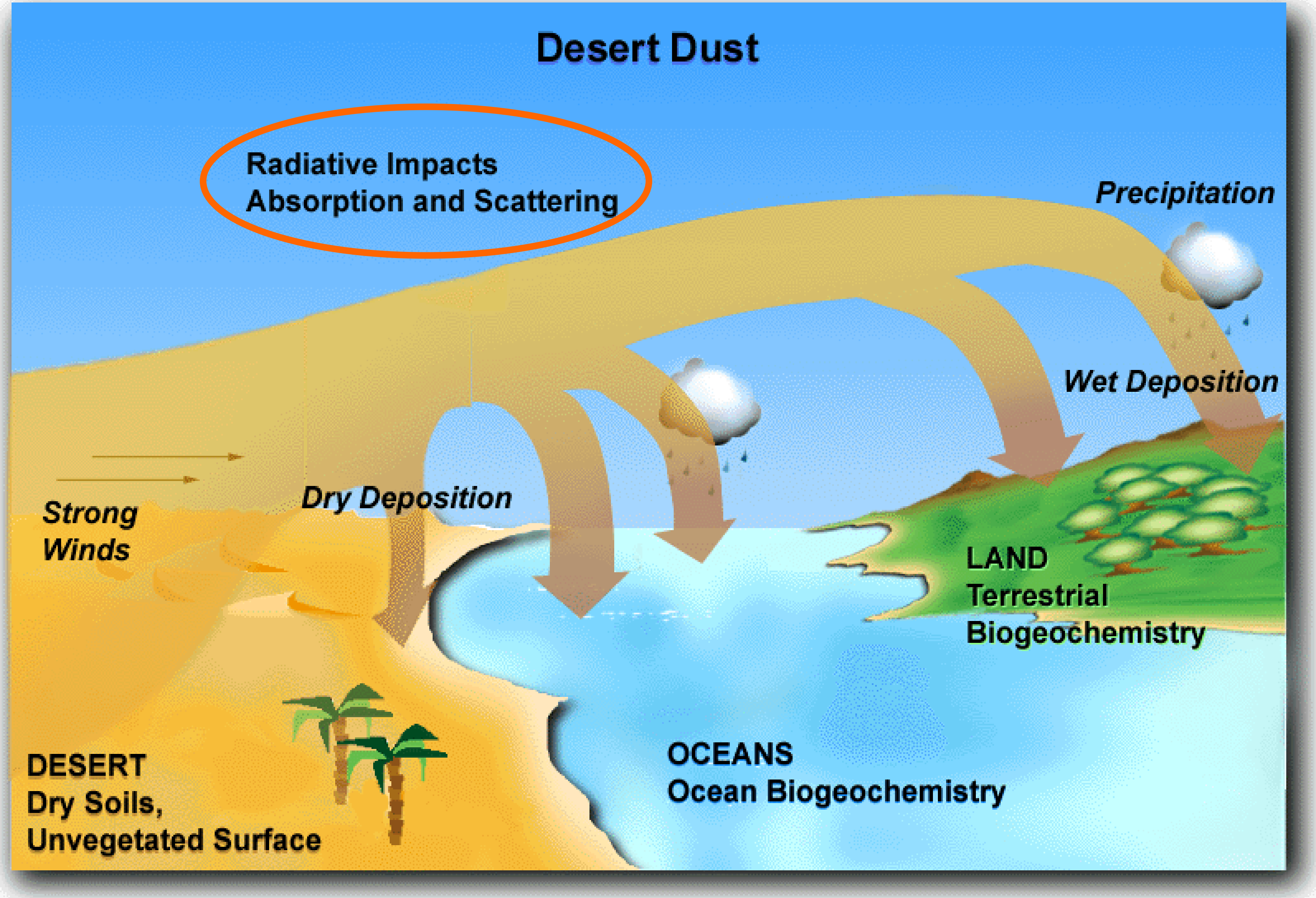
But also vary for same generic aerosol 'type' due to meteorological conditions



Typically vary due to location



Role in the climate system: one example

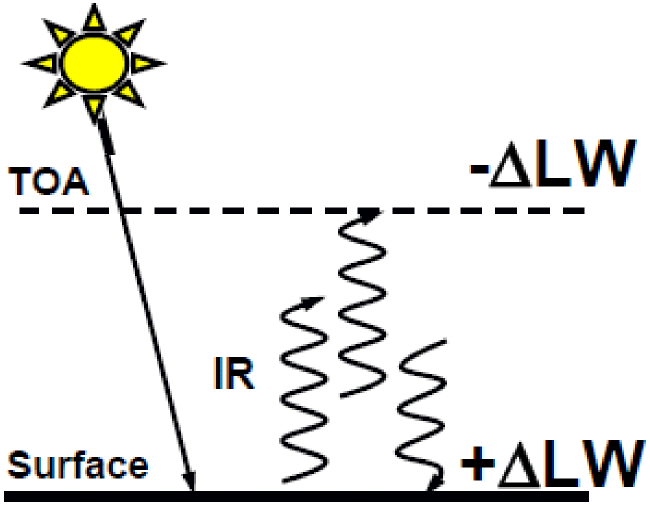


Direct Radiative forcing

Radiative forcing (RF): ‘the net change in total irradiance at the tropopause to an applied perturbation after allowing for stratospheric temperatures to readjust to radiative equilibrium but holding all other atmospheric variables fixed’

Here net total irradiance (SW + LW) has the convention down – up

For WMGG, $\Delta T_s \sim \lambda$ RF where λ is the climate sensitivity parameter



CO_2 increase

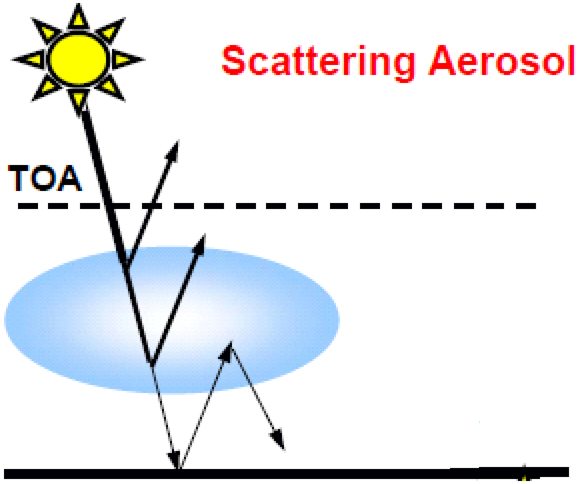
Surface and troposphere warms

Stratosphere cools

Positive forcing

For aerosol it is more complicated: depends on aerosol properties plus characteristics of underlying surface

Case I: Scattering aerosol over dark surface



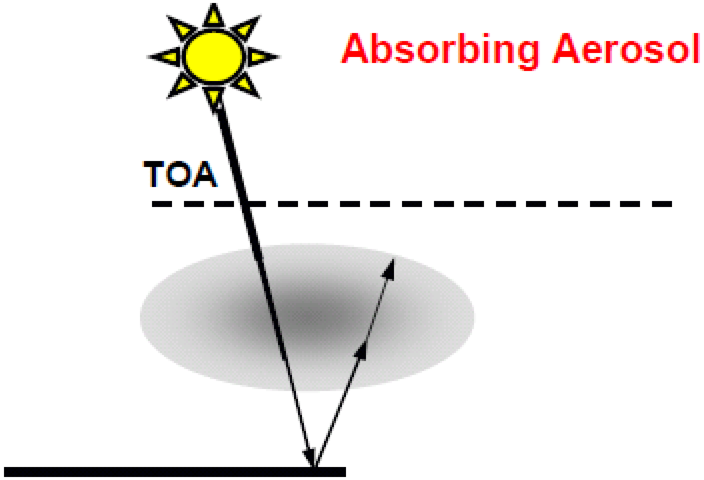
Reduced SW radiation at surface, more SW radiation reflected to space

Negative forcing

Local surface and atmospheric cooling

For aerosol it is more complicated: depends on aerosol properties plus characteristics of underlying surface

Case II: Absorbing aerosol over bright surface



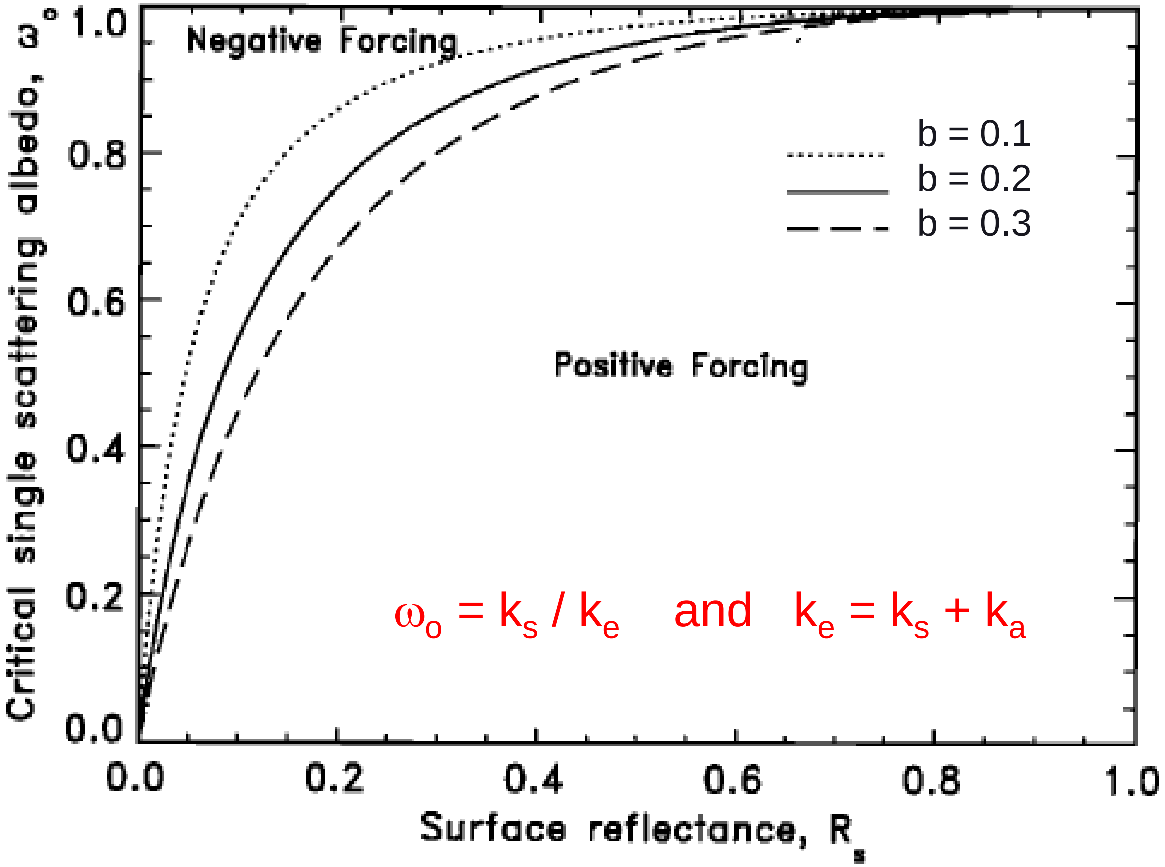
Less SW radiation reaches surface, more absorbed in atmosphere, less reflected to space

Positive forcing

Local surface cooling and atmospheric warming – Oops!

How can we estimate whether forcing is positive or negative for a given set of conditions: concept of ***critical single scattering albedo***

Increasing aerosol absorption



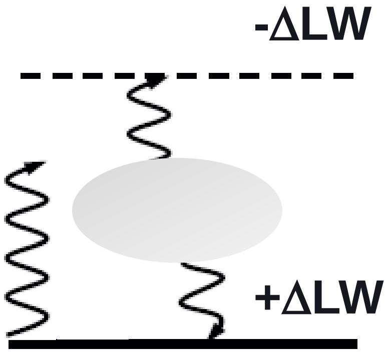
$\omega_o = k_s / k_e$ and $k_e = k_s + k_a$

Haywood and Boucher, 1999

What about LW?

Only really an issue for aerosol types with large coarse mode population: most interest on mineral dust from anthropogenic activity…

…but some work suggests urban pollution, pollen outbreaks etc. also directly affect LW



Reduction in OLR

Positive forcing

Local surface and atmospheric heating

NB1: Forcing magnitude strongly dependent on surface/atmospheric temperature contrast: sign can change

NB2: Natural emissions of mineral dust and volcanic material also affect the LW: impact on radiation field generally termed ‘Direct Effect’ as not strictly a forcing; ditto for impact of natural aerosols in SW

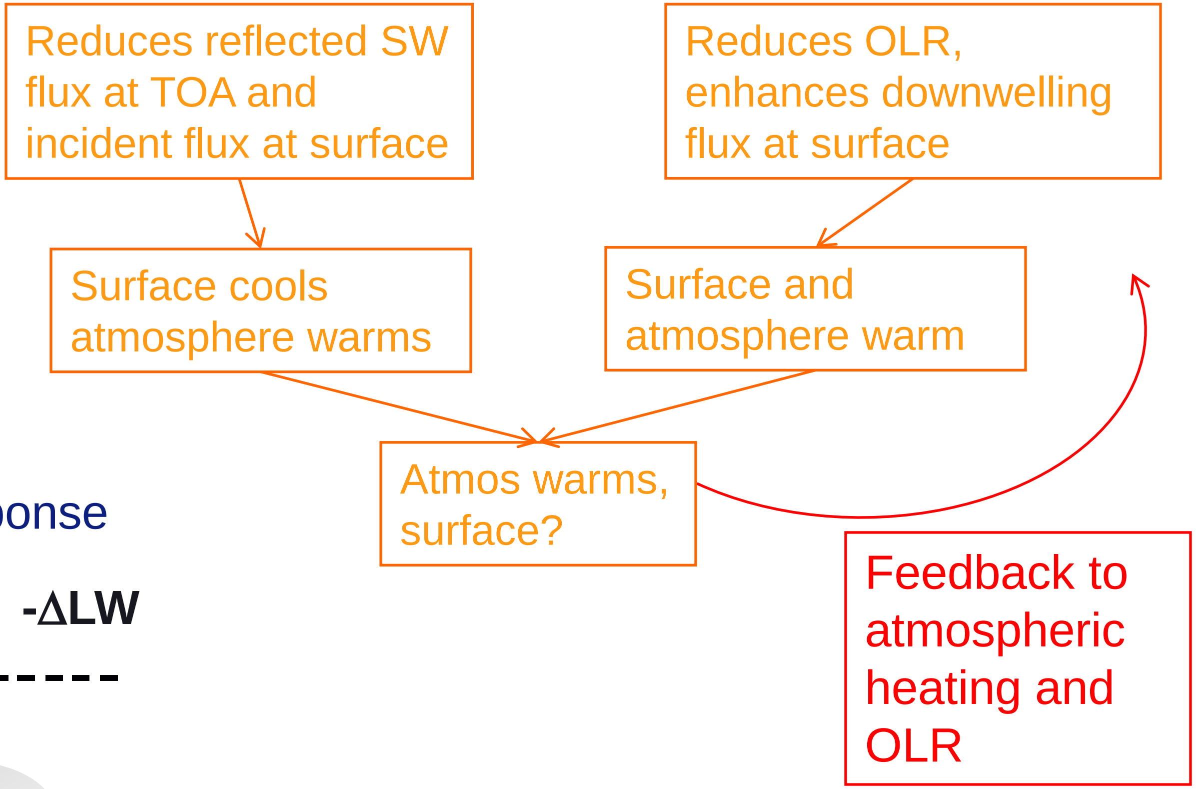
And Radiative Feedbacks…

A ‘simple’ example: absorbing dust over desert in daytime

Instantaneous

Individual response

Combined response



Reduces reflected SW flux at TOA and incident flux at surface

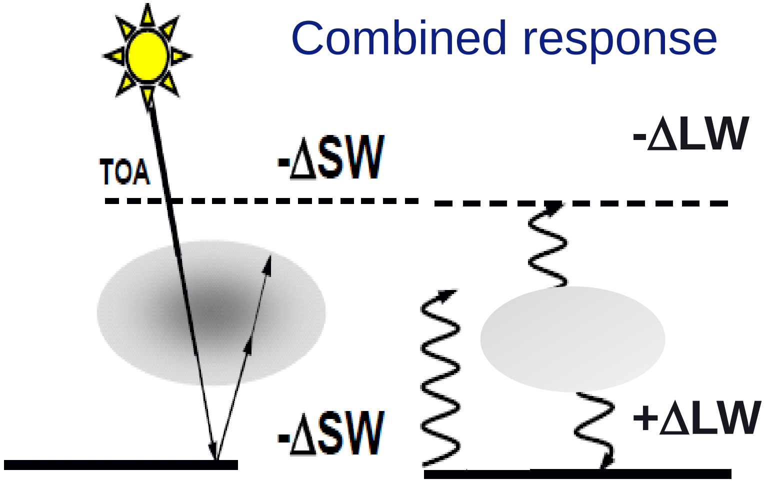
Reduces OLR, enhances downwelling flux at surface

Surface cools atmosphere warms

Surface and atmosphere warm

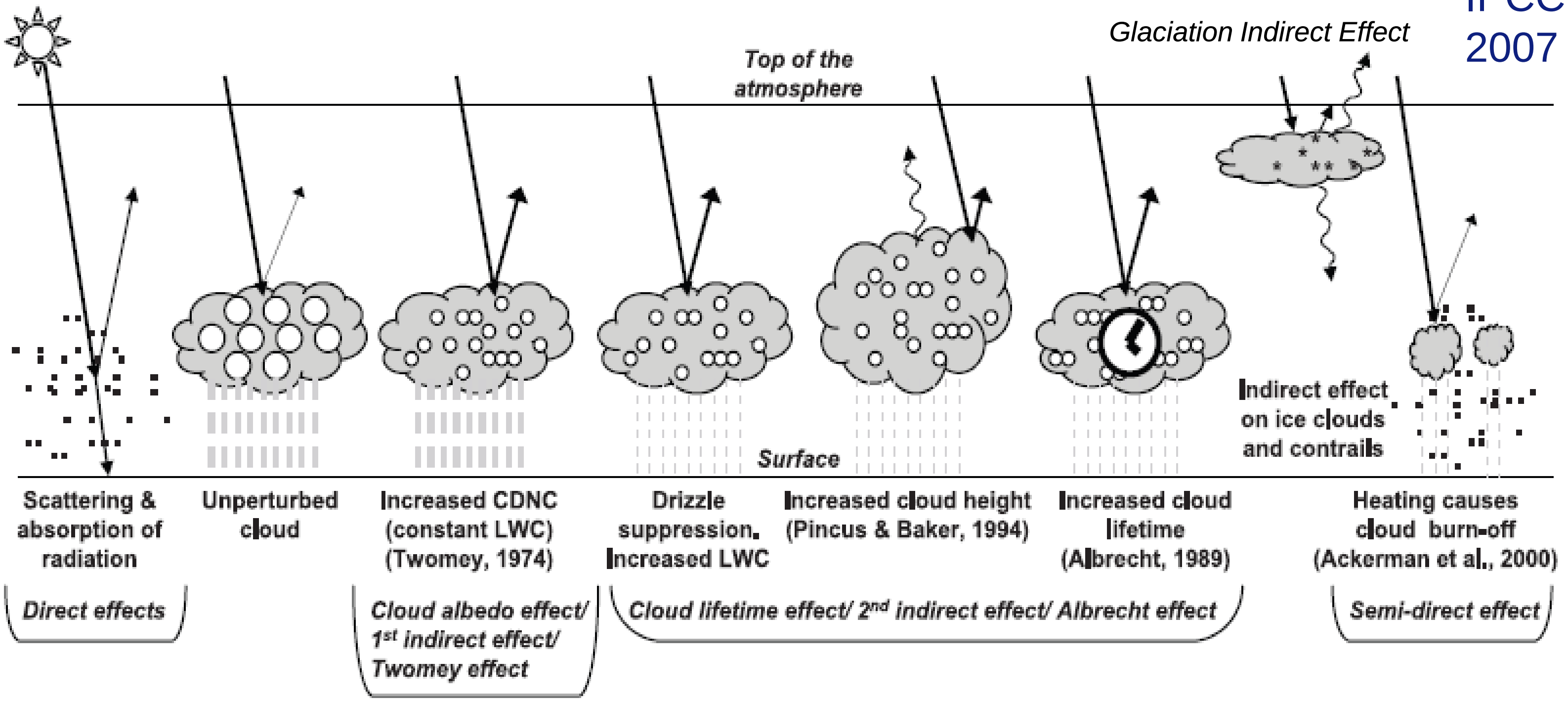
Atmos warms, surface?

Feedback to atmospheric heating and OLR

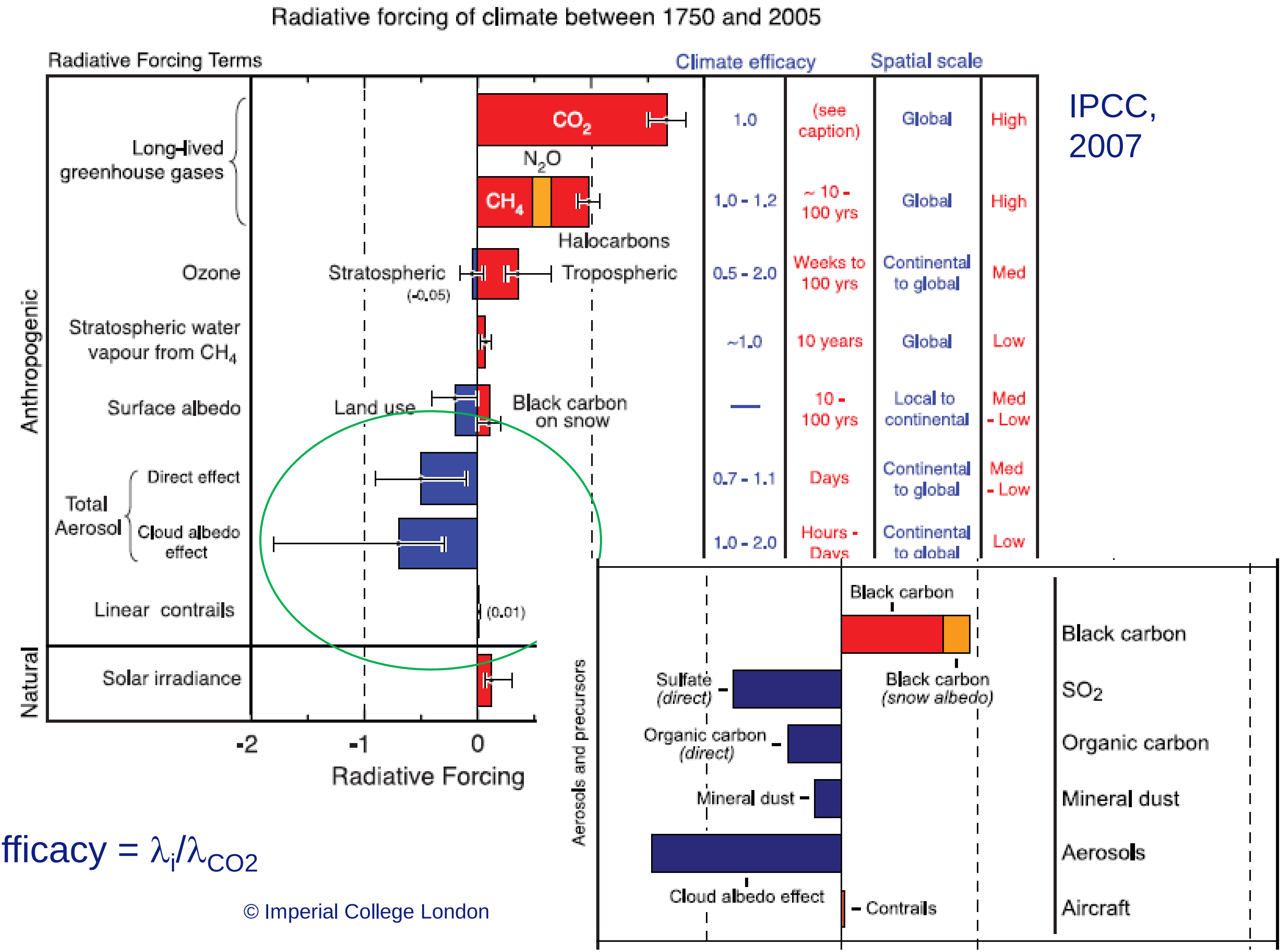


Cloud-aerosol effects

IPCC, 2007



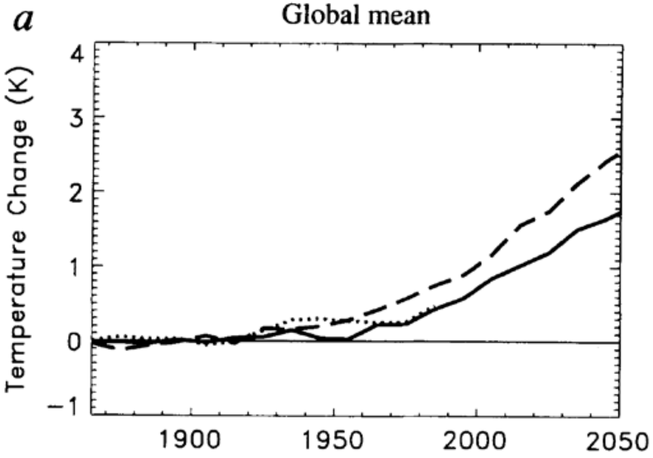
(Still) Highly uncertain in terms of climate impact



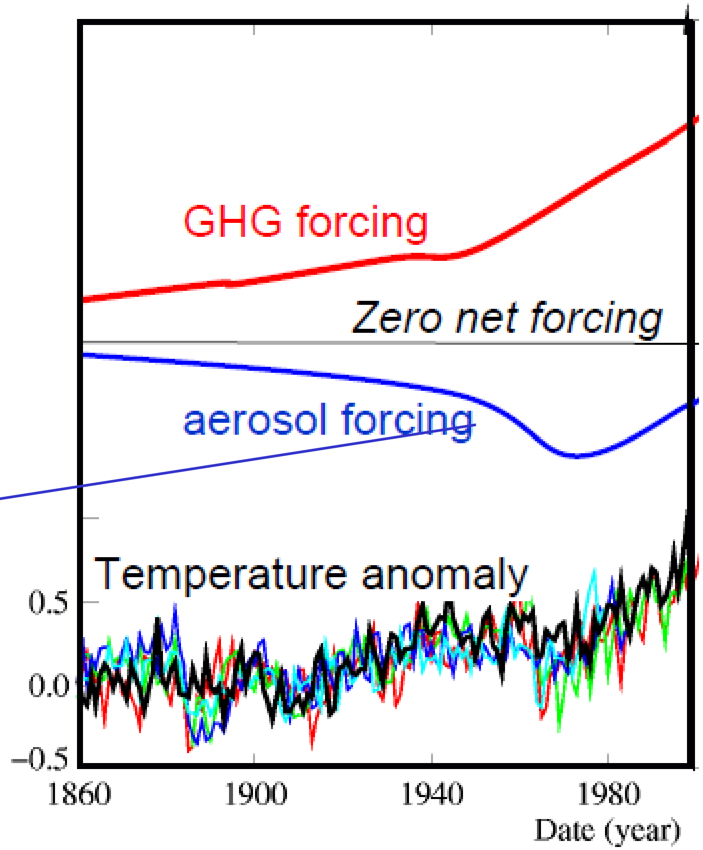
IPCC, 2007

Efficacy = λ_i/λ_{CO2}

Aerosol impact on future climate?

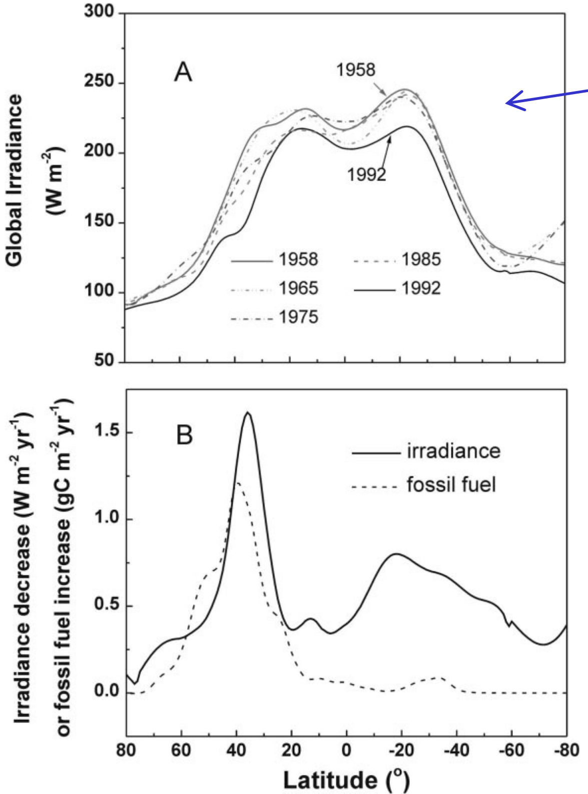


Mitchell *et al.*, 1995



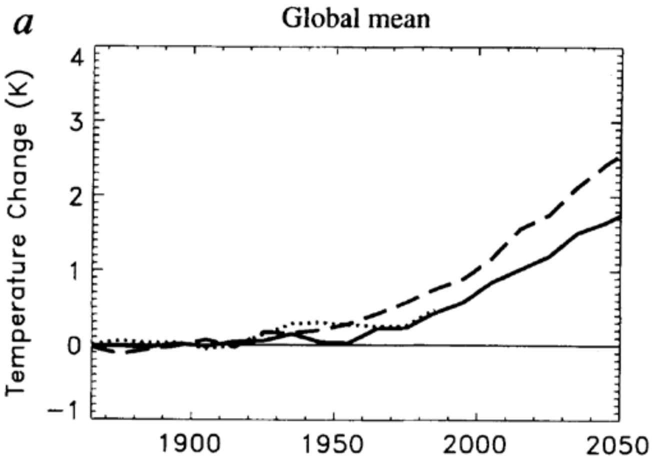
Consistent with:

(a) Global Dimming



Courtesy K. Carslaw

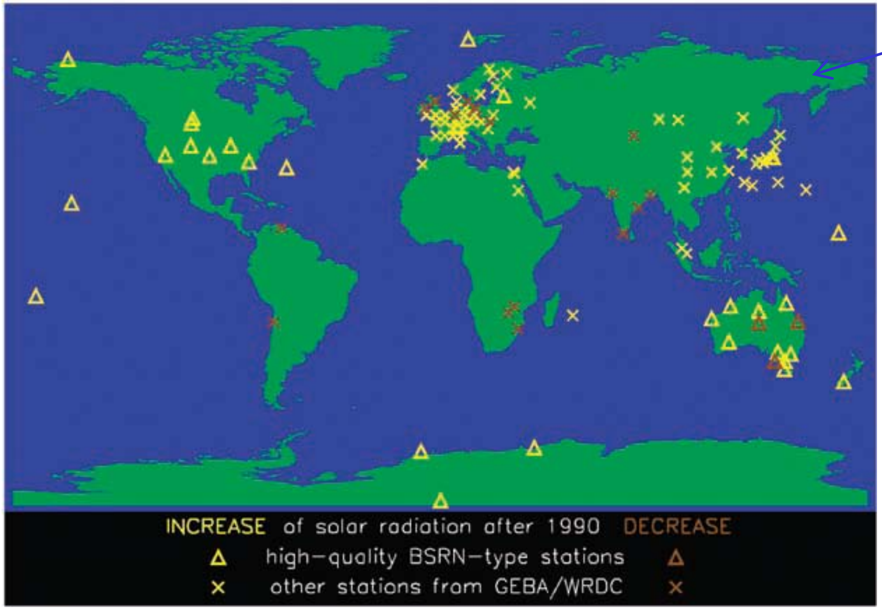
Stanhill and Cohen, 2001



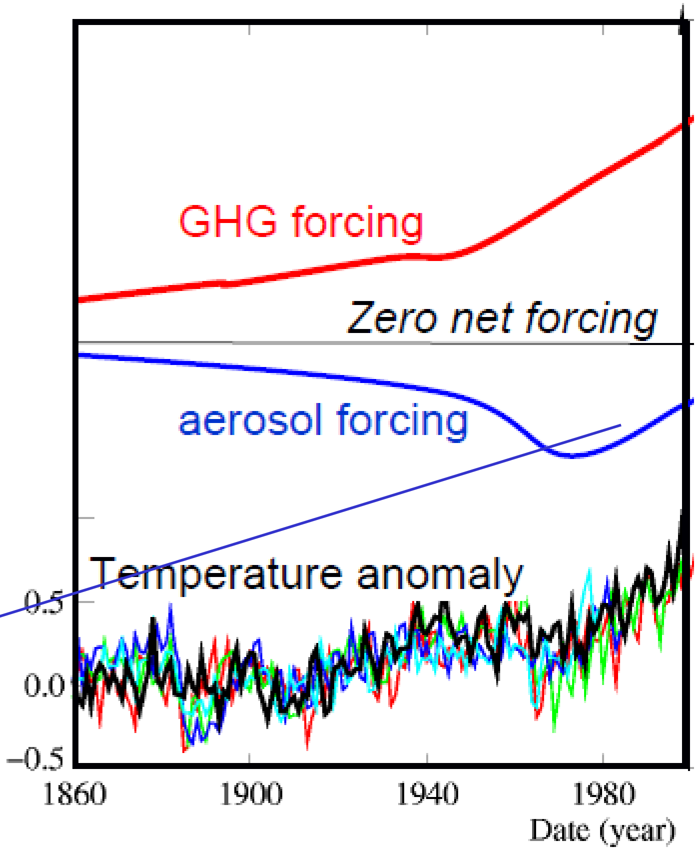
Mitchell *et al.*, 1995

Consistent with:

(b) Global Brightening

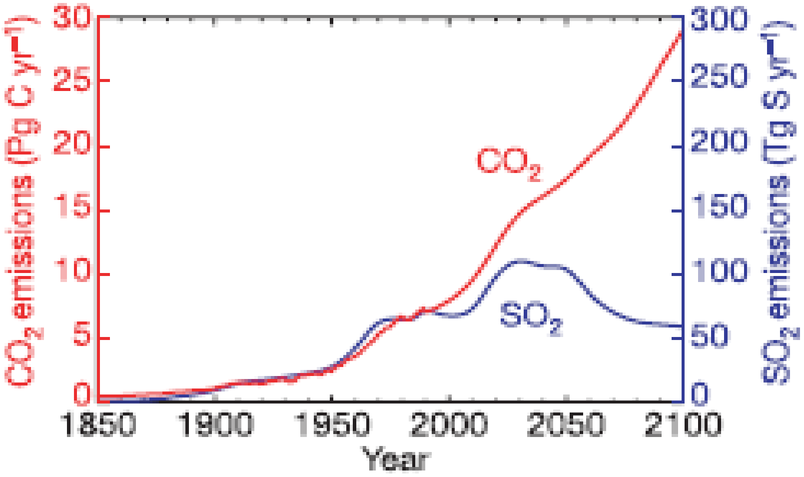


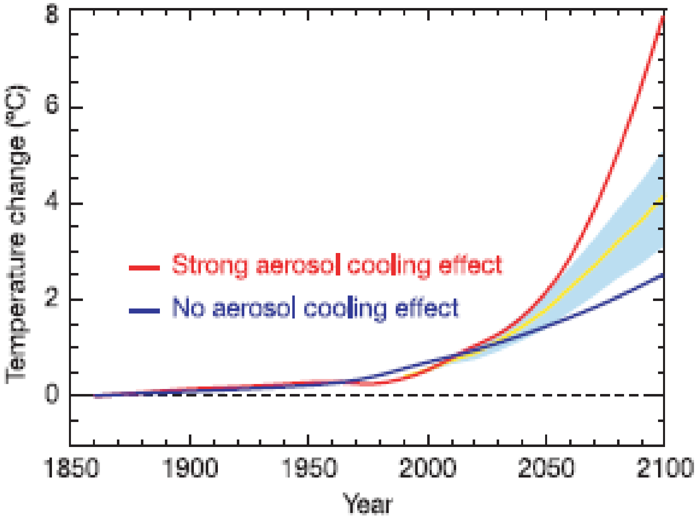
Wild *et al.*, 2005



Courtesy K. Carslaw

Projected changes will exacerbate GHG effects





IPCC TAR prediction

Andreae *et al.*, 2005

Key: understanding present day forcing and sensitivity of climate to aerosols…

Observing aerosol from space

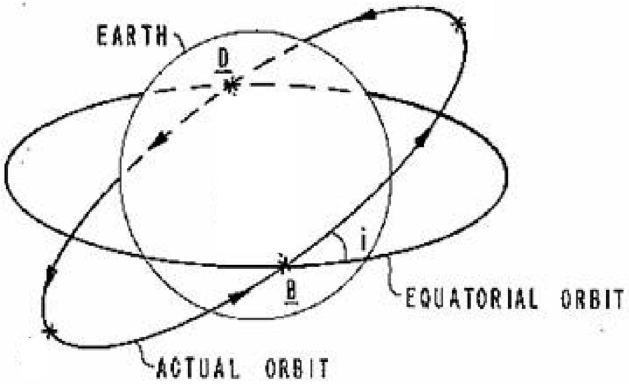
2 types of 'basic' orbit…

GEO

Geostationary: rotates with Earth. Limited view but excellent time resolution

LEO

(i) Sun-synchronous: Provides coverage of whole globe within ~ 6 days dependent on inclination. Always crosses given latitude band at same local times



(ii) Inclined or Precessing: Generally a low angle of inclination. Limits latitude regions sampled but allows sampling of all local times at a given location

Most (but not all) 'aerosol' instruments in LEO

…and two basic methods of sensing

PASSIVE

Using measured radiances/reflectances (+ polarisation, angular distribution,…)

Longest available records tend to focus on aerosol optical depth, τ, but if enough independent information is contained in the signal can attempt to retrieve more parameters (e.g. α, τ_c, τ_f, r_e, ω_o, n,...)

ACTIVE

Via LIDAR backscatter

Provides vertical profile and aerosol type information as long as signal is not completely attenuated

4. Observing aerosol from space

Surface representation

Atmospheric profile

Aerosol representation

Set of geometries and τs →

Radiative Transfer code

LUT GENERATION

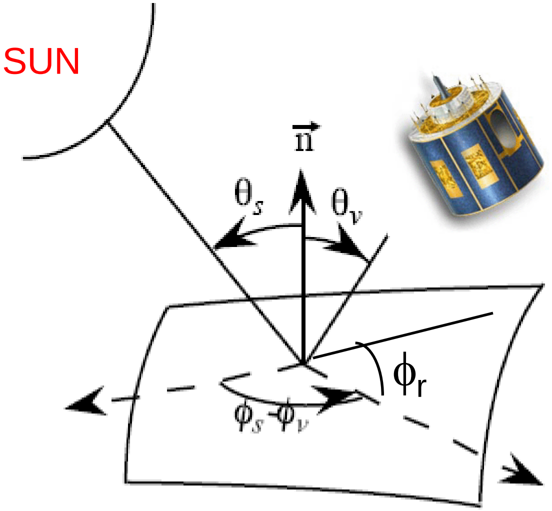
Channel filter functions

Simulated quantity, $\chi(\theta_s,\theta_v,\phi_r,\tau_\lambda)$

geometrical restrictions →

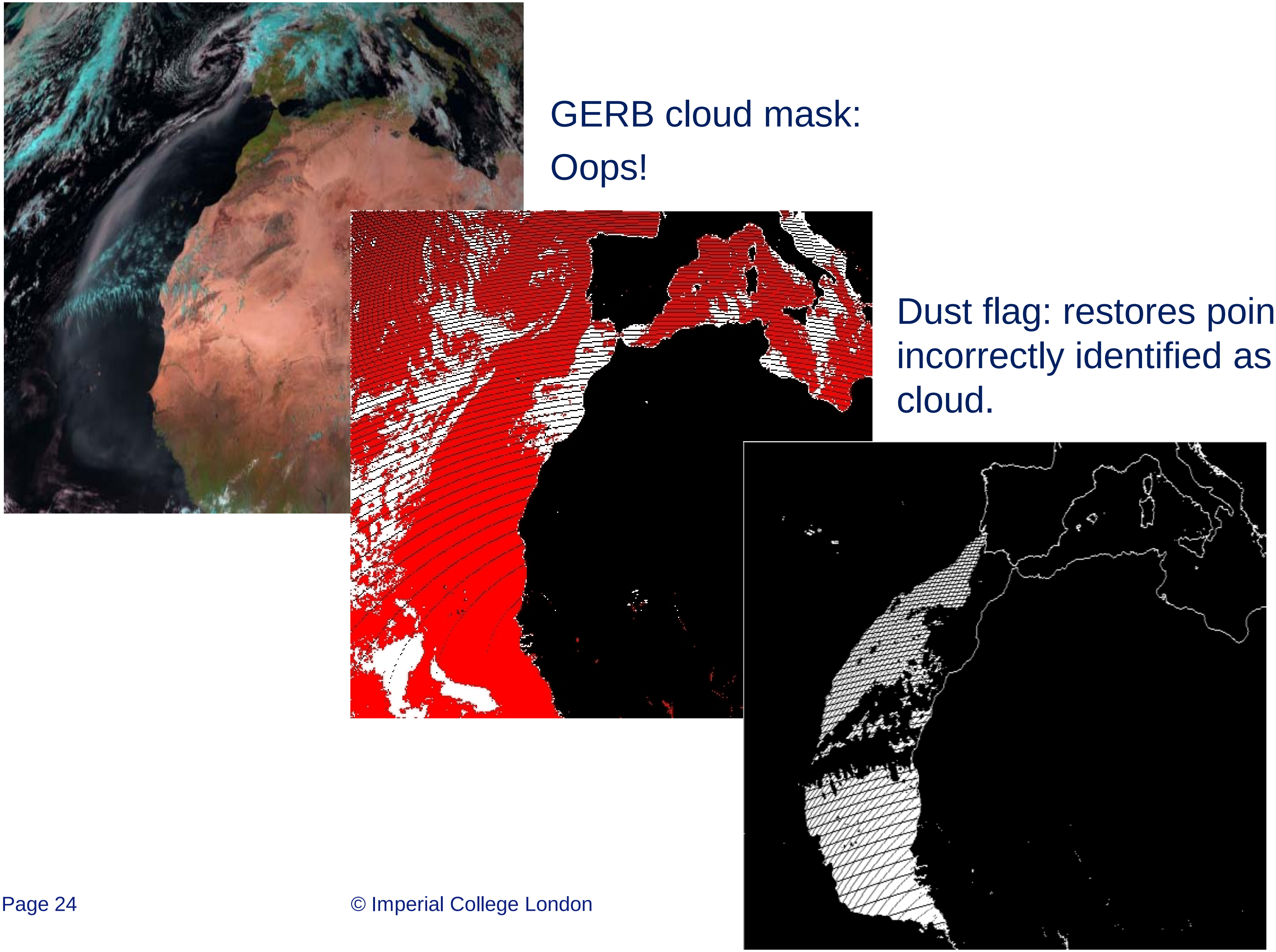
Retrieved τ_λ

Observed quantity, $\chi(\theta_s,\theta_v,\phi_r)$



But which points to perform retrieval on?

5th March, 2004, 14:00 UTC



GERB cloud mask:

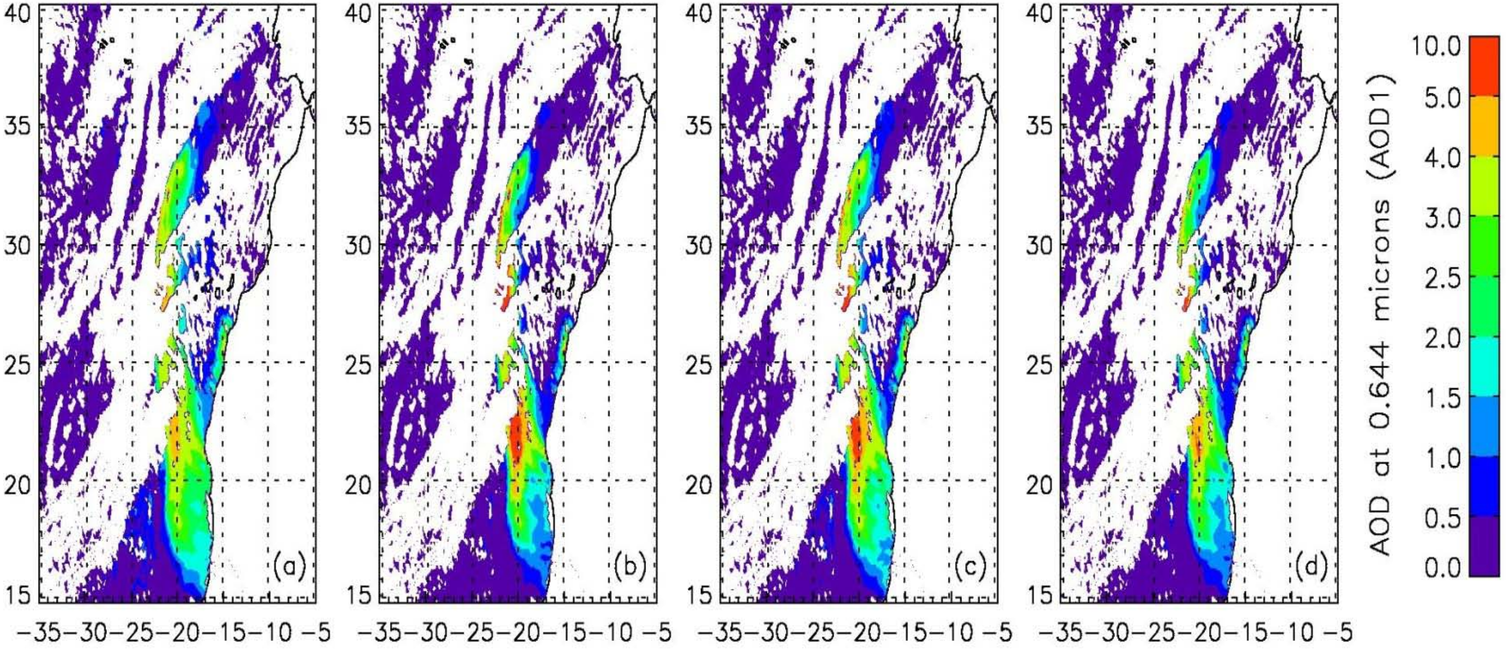
Oops!

Dust flag: restores points incorrectly identified as cloud.

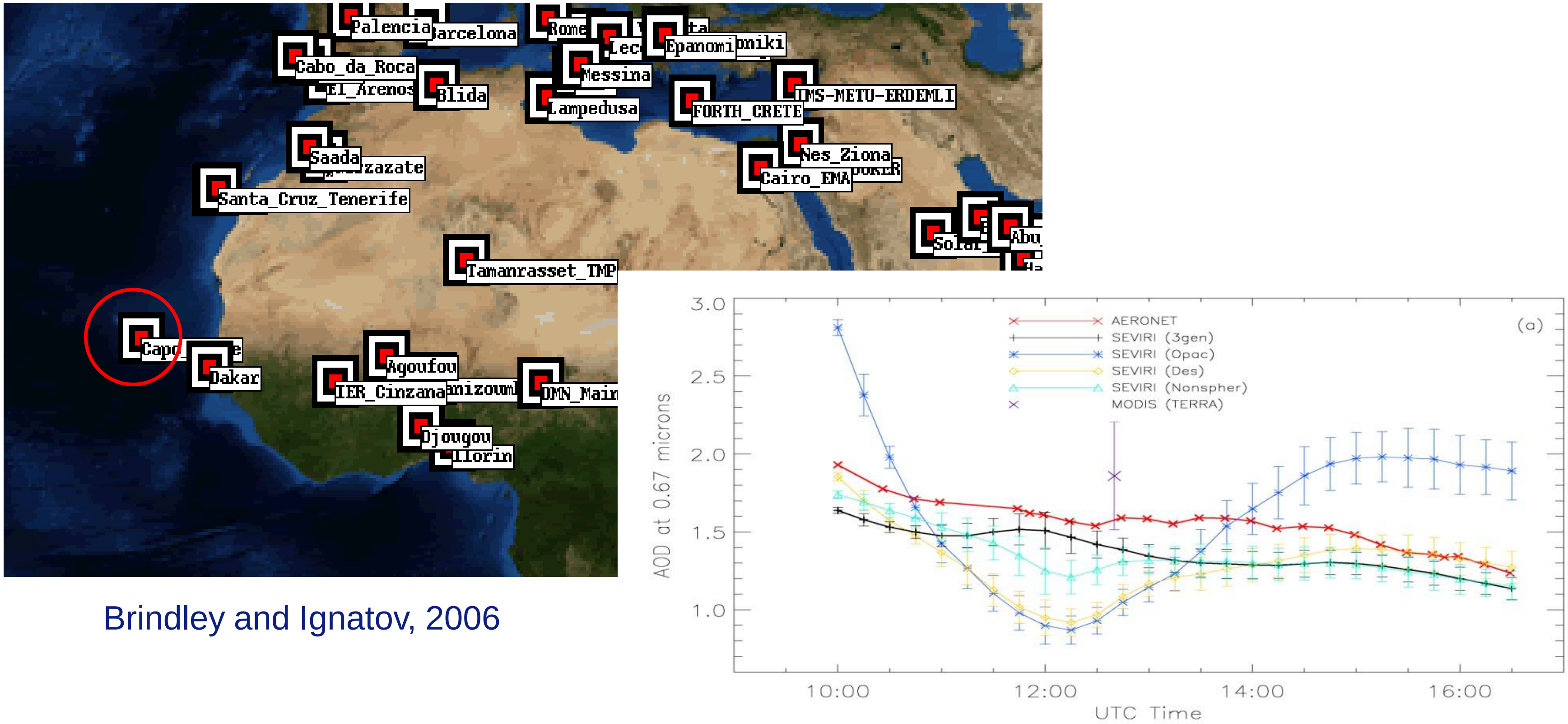
12:00 UTC 04/03/04

SEVIRI

3gen OPAC Nonspher Des



4. Observing aerosol from space



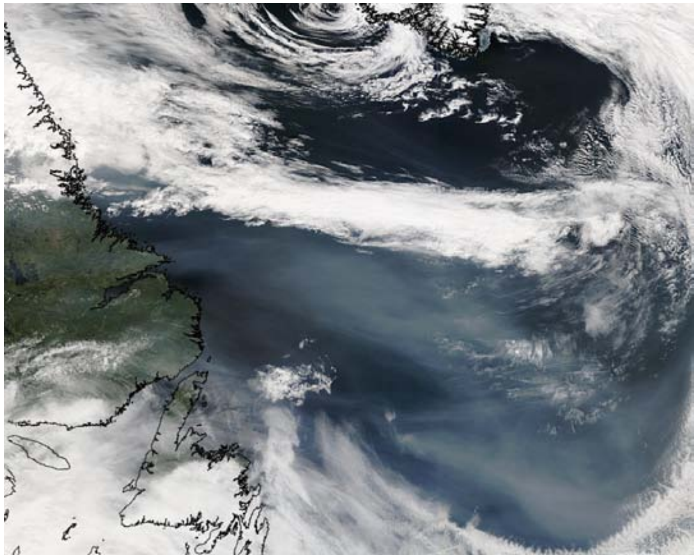
Brindley and Ignatov, 2006

Longest established method: Narrow band radiometers

Different spectral regions exploited for different purposes

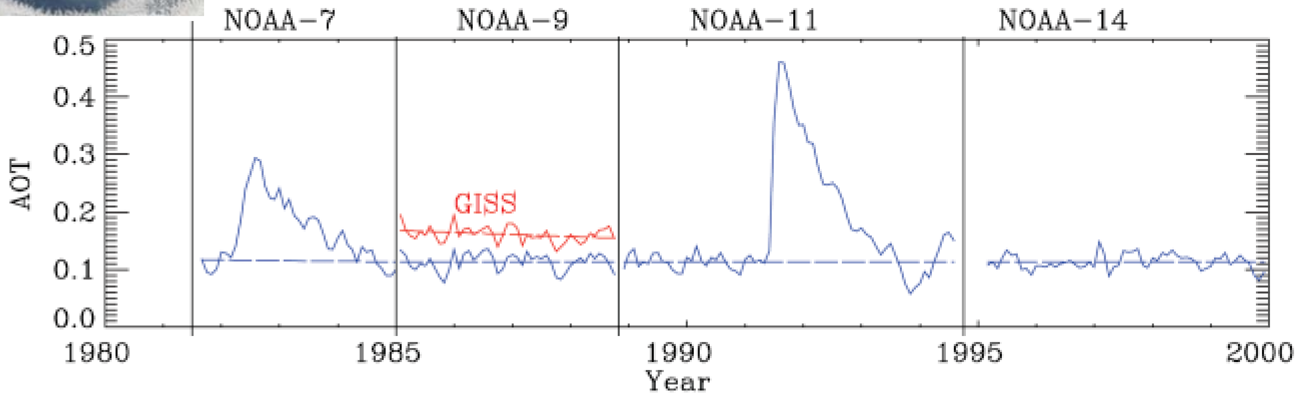
(i) Visible reflectances

$$\rho_{ch} = \frac{\pi \times L_{ch}}{F_{och}}$$



Requires a large contrast between surface and aerosol reflectance, and surface bi-directional reflectance function (BDRF) to be well known: good for ocean

Longest record (1978+) from AVHRR

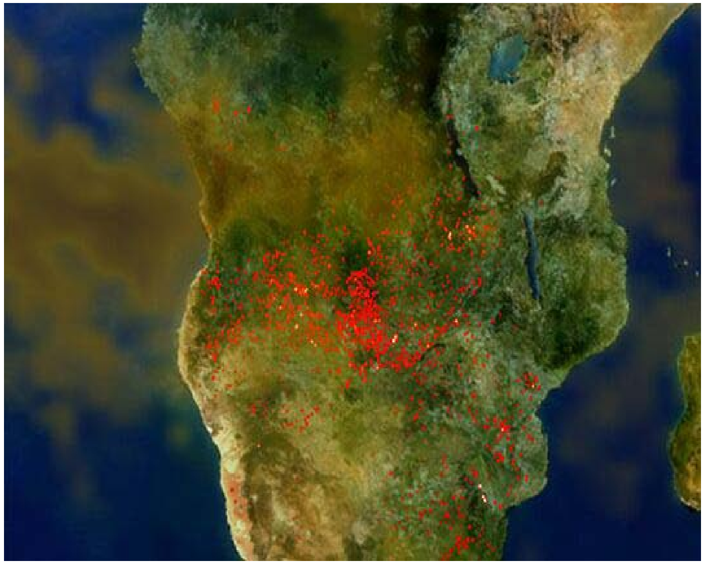


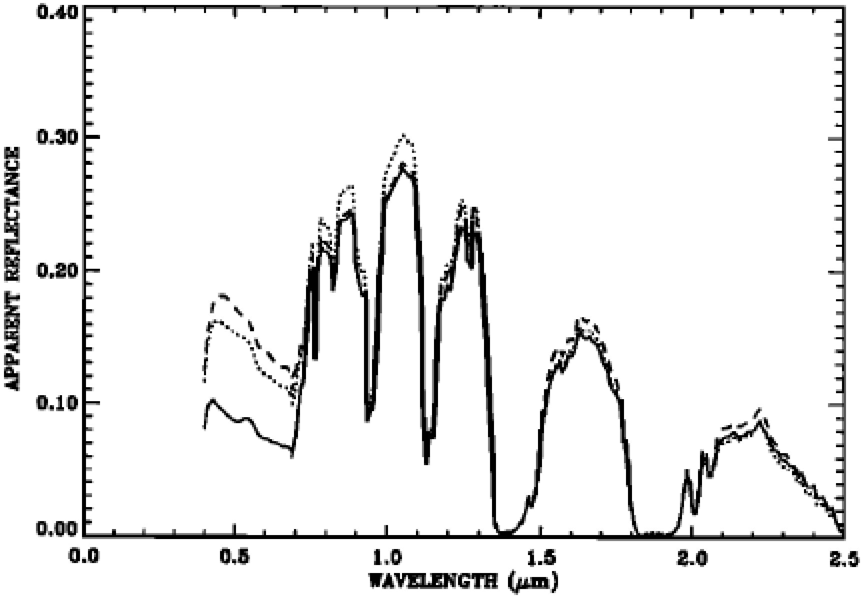
Jacobowitz *et al*., 2003

Longest established method: Narrow band radiometers

Different spectral regions exploited for different purposes

(ii) Visible reflectances may also be used over other dark targets but extra information is required





Kaufman *et al*., 1997

Relies on relationship between ρ_s in different spectral channels

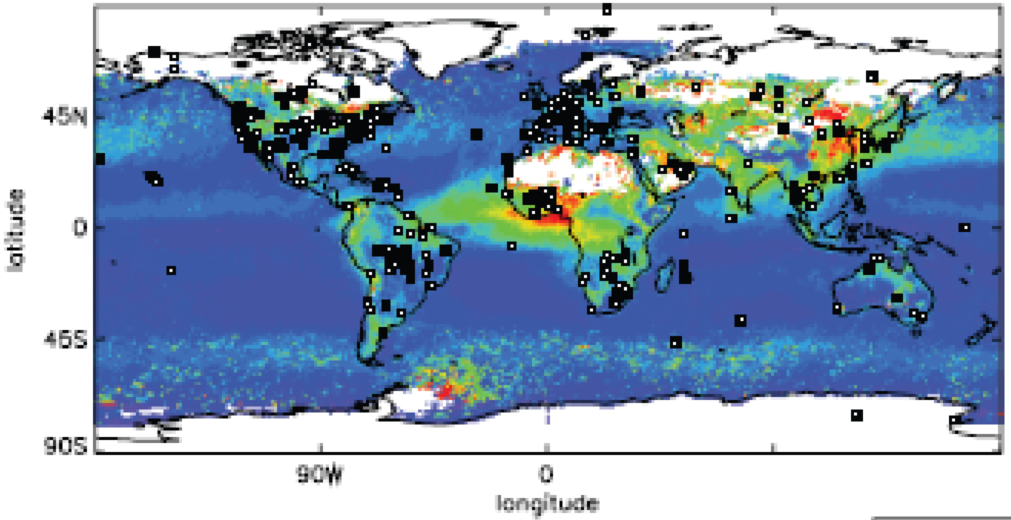
4. Observing aerosol from space

MODerate Imaging Spectroradiometer (MODIS)

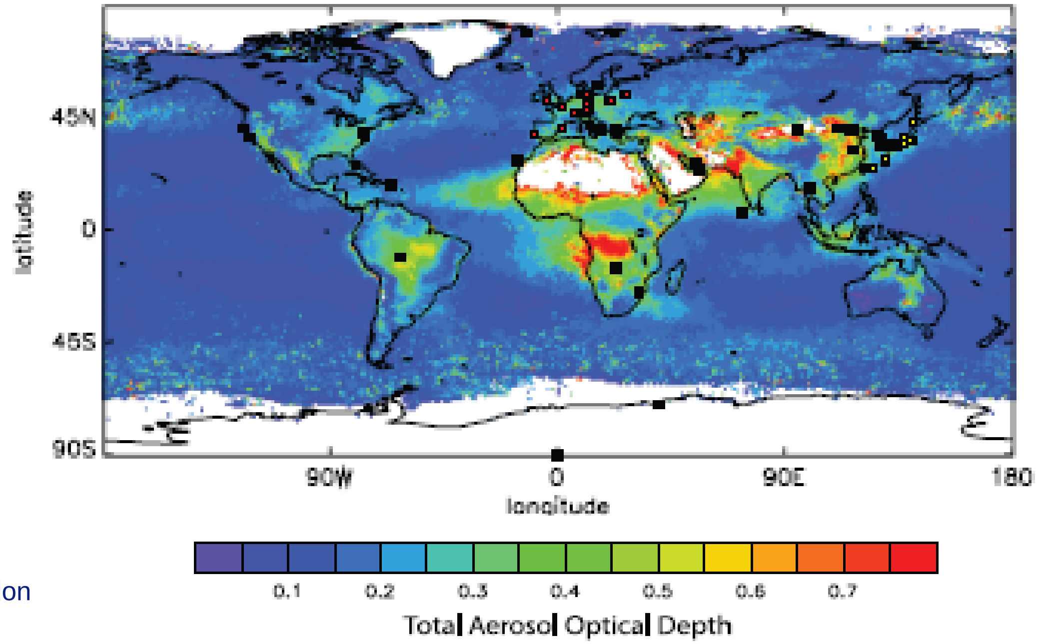
-standard algorithm

(Remer et al., 2007)

January to March 2001



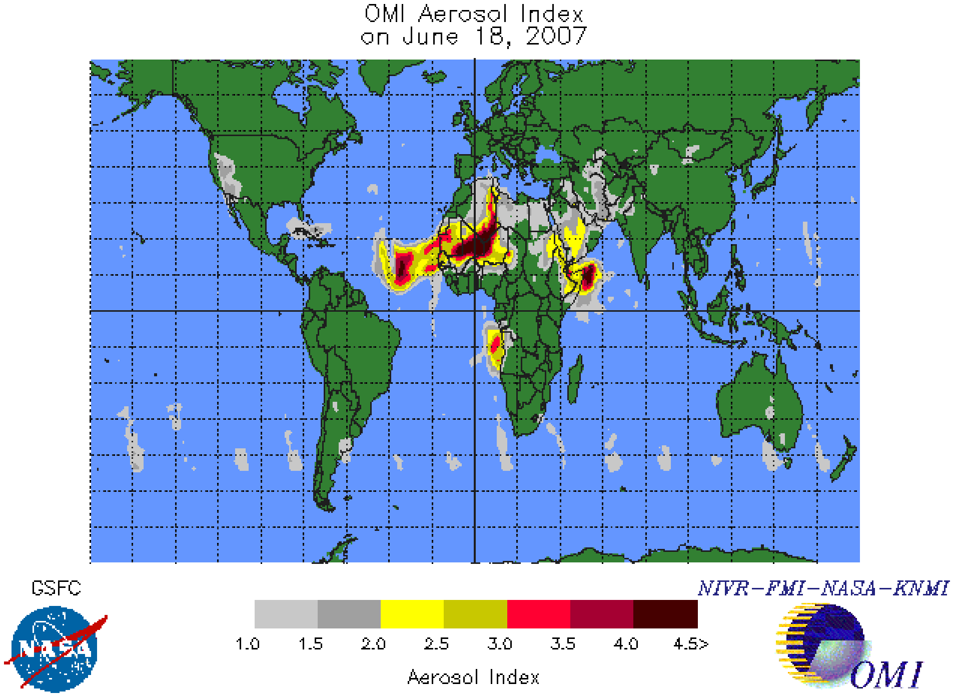
August to October 2001



Longest established method: Narrow band radiometers

Different spectral regions exploited for different purposes

(iii) UV radiances: exploit low surface reflectance in this regime (bar snow)



Herman et al., 1997, Torres et al., 2007, Hsu et al., 2004

Development of UV aerosol index, UVAI

$$\mathrm{UVAI} = -100\log\left[\frac{I_{354}^{obs}}{I_{354}^{calc}(R_{354}^{*})}\right]$$

An ‘error’ caused by presence of aerosol

Positive for absorbing aerosols

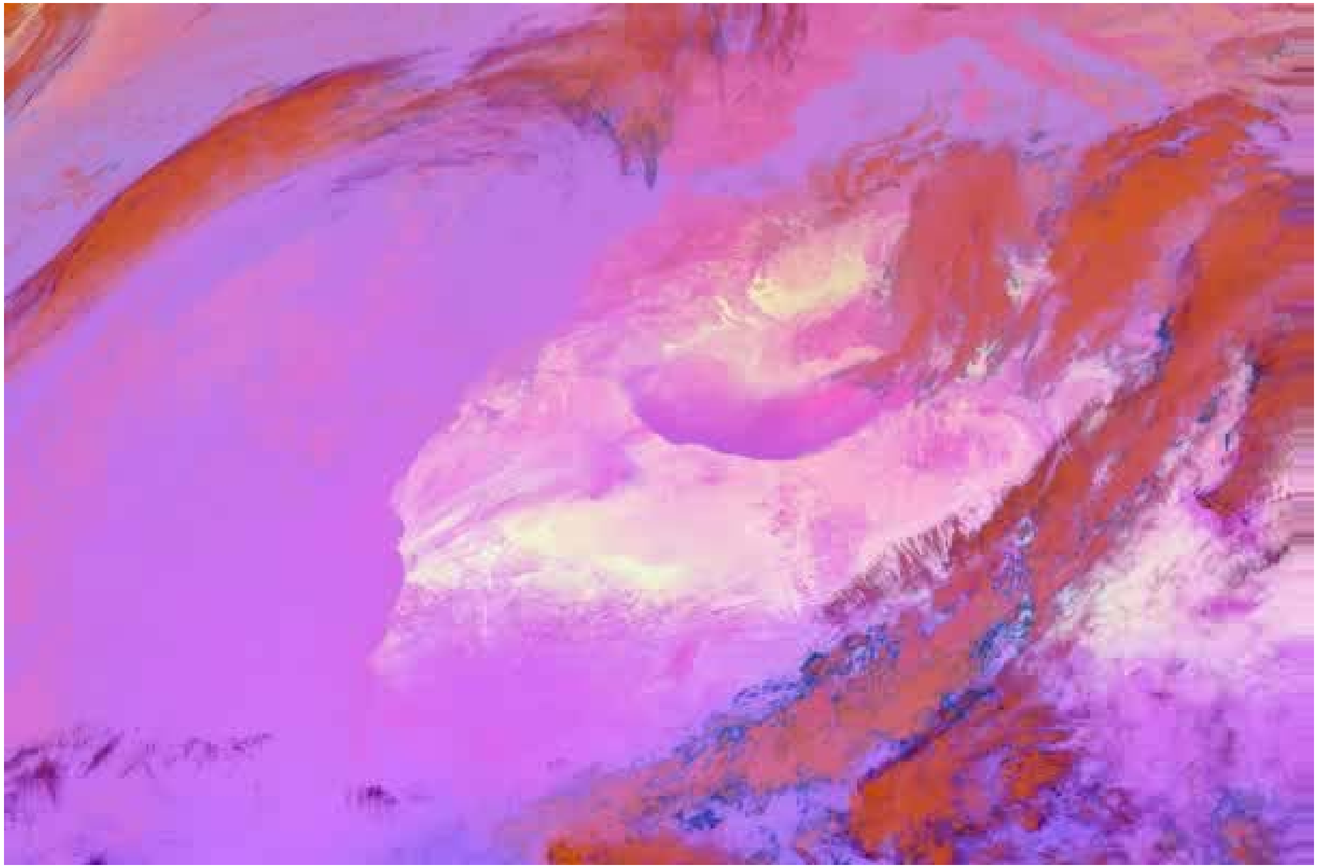
Qualitative, but correlated to aerosol optical depth, and ***a long-term record***

UV and ‘Deep Blue’ now being exploited for quantitative optical depth estimates (OMI, MODIS)

Longest established method: Narrow band radiometers

Different spectral regions exploited for different purposes

(iv) IR radiances: avoids reflectance issue, exploits contrast between T_{sfc} and T_{dust}. Sensitive to dust height, atmospheric profile and surface emissivity



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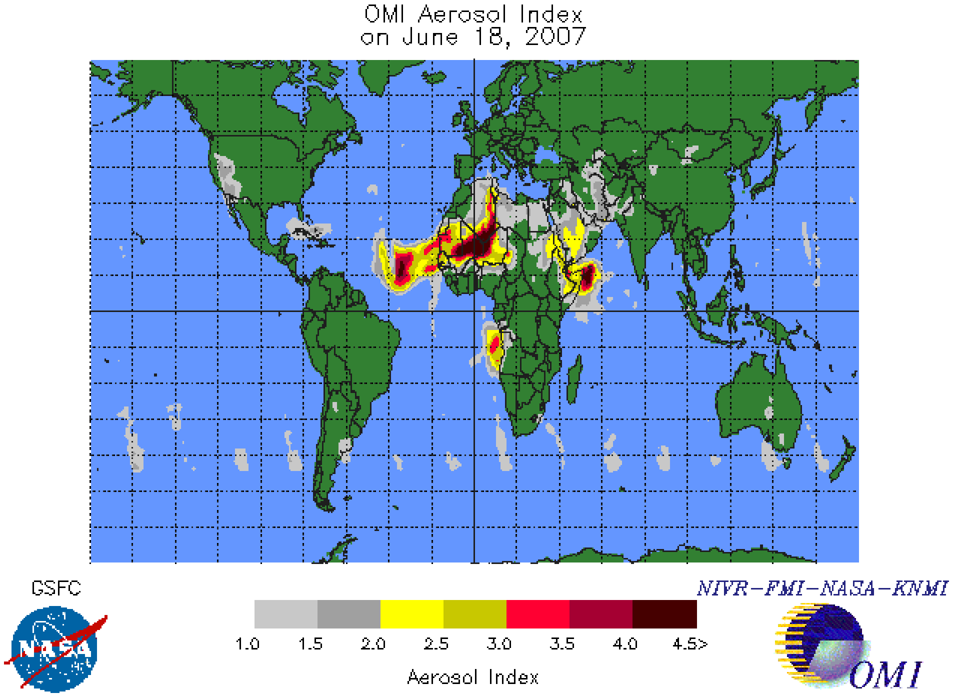
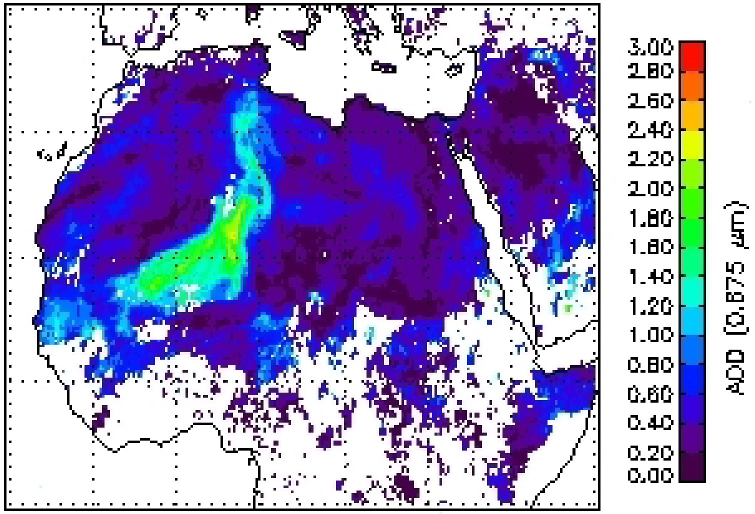


e.g. Legrand *et al.*, 2001,
Brindley and Russell, 2009



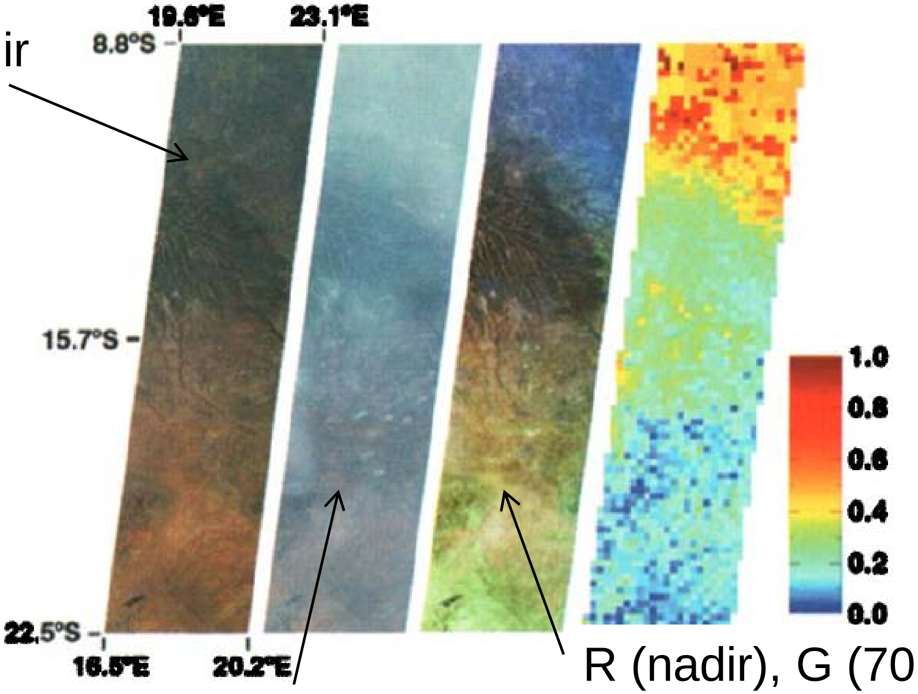
AOD from SEVIRI, 1200 UTC, 18th June, 2007

Alternatives:

(v) Exploit directional behaviour of aerosol scattering: viewing different angles allows differentiation between surface structure and different aerosol types

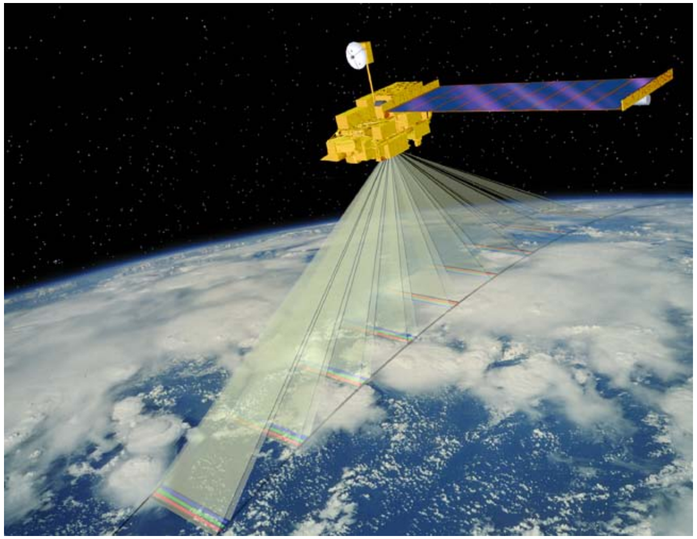
Example: Multi-angle Imaging SpectroRadiometer (MISR) – currently ‘gold-standard’ over land, but limited swath width and repeat cycle

nadir



70.5° backward view

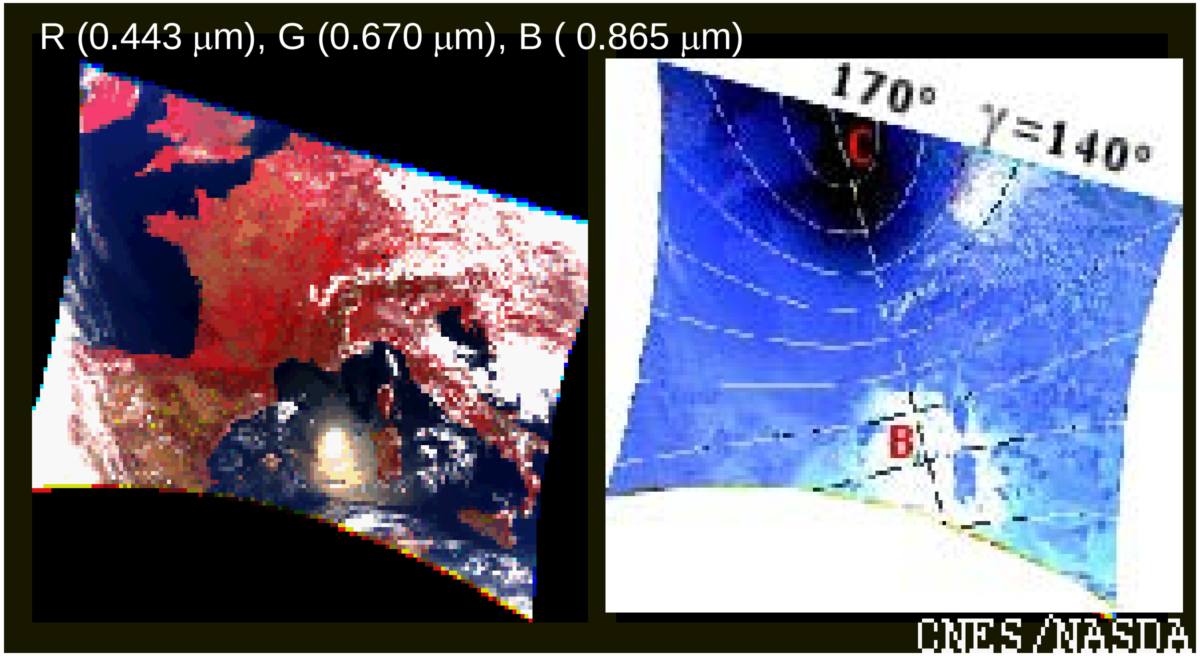
R (nadir), G (70.5 ° forward), B(70.5 ° back)



Diner *et al*., 2001

Alternatives:

(vi) Exploit directional behaviour plus change in polarisation caused by aerosols
Example: POLarisation and Directionality of the Earth's Reflectances (POLDER)



'Natural' light

Polarised light

Polarisation affected by shape of aerosol so can indicate non-sphericity

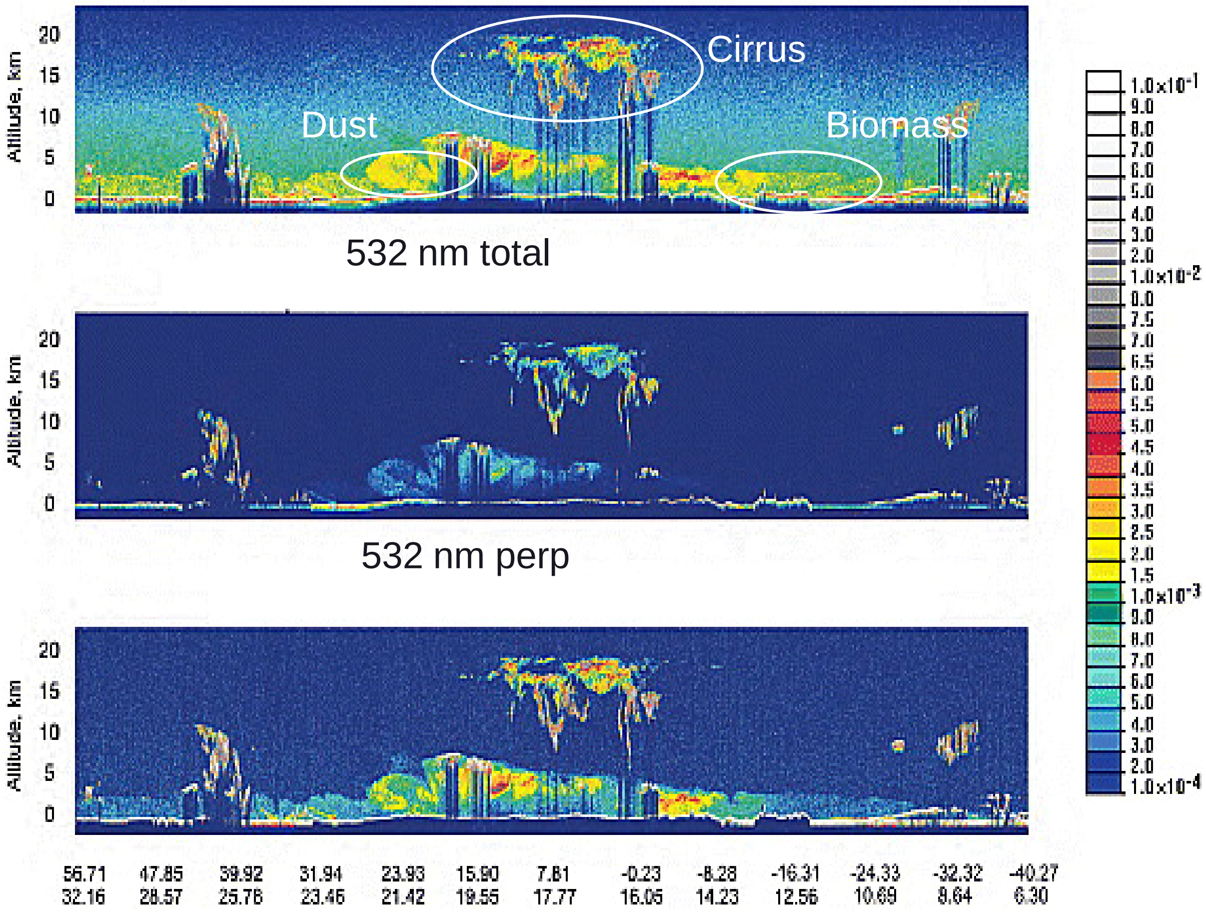
Over land, better performance for low surface/high aerosol polarisation: more sensitive to small sizes

e.g. Deuzé *et al*., 2001, 2002

Alternatives:

(vii) LIDAR

Example: Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)



532 nm total

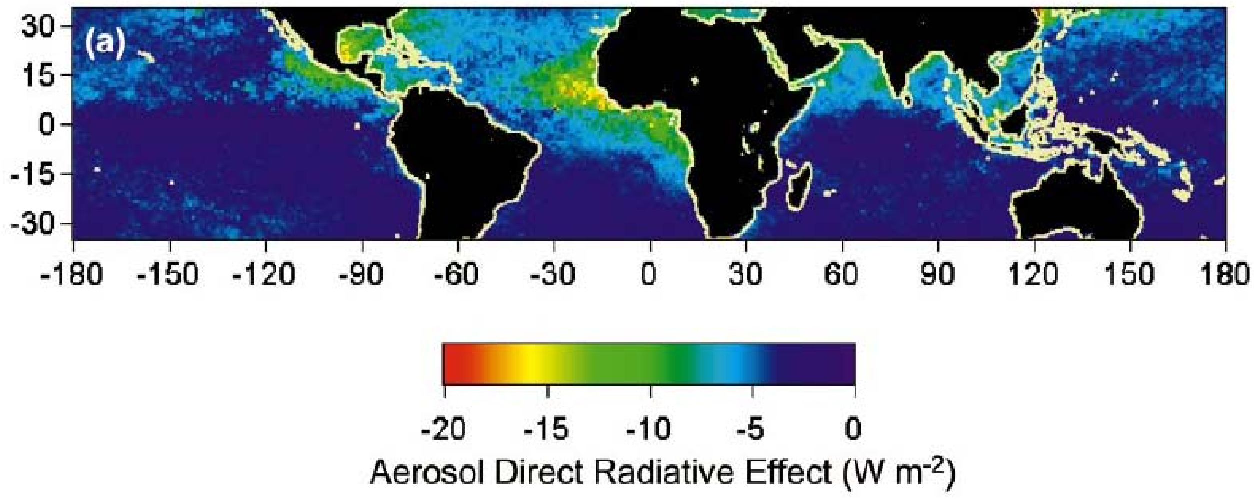
532 nm perp

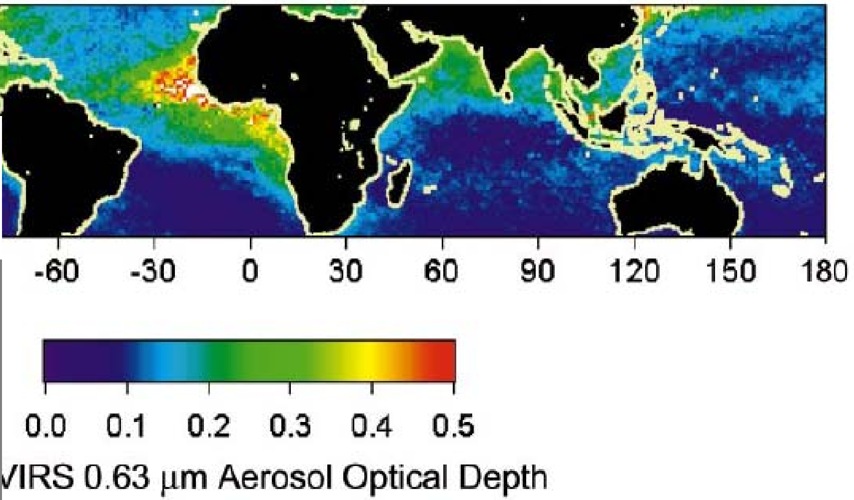
1064 nm total

- Measures backscatter.
- LIDAR ratio, η = extinction/backscatter
- Requires modelling of expected η for different atmospheric components
- Limited horizontal coverage

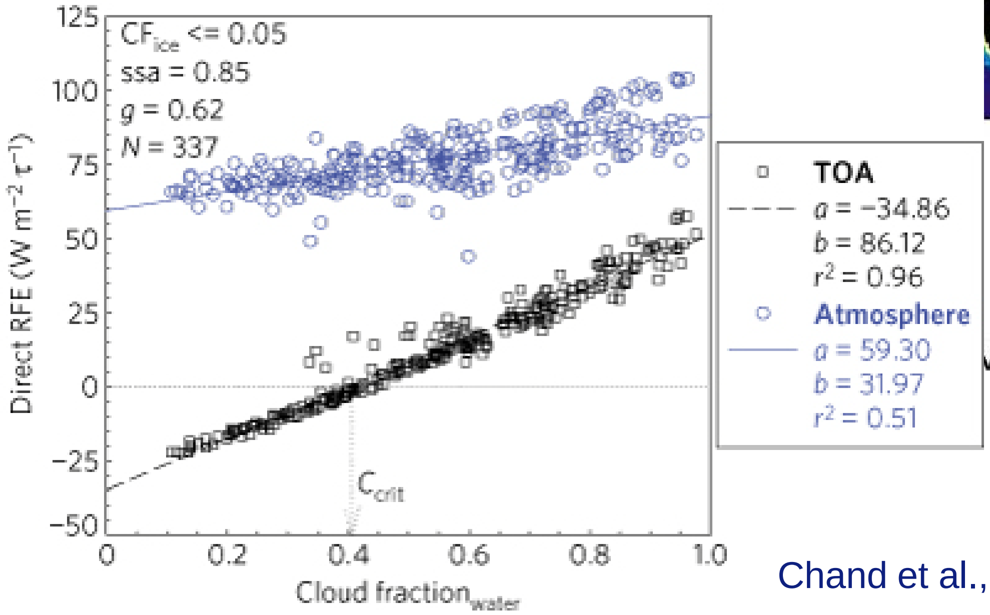
4. Observing aerosol from space

Can be used to probe direct effects…



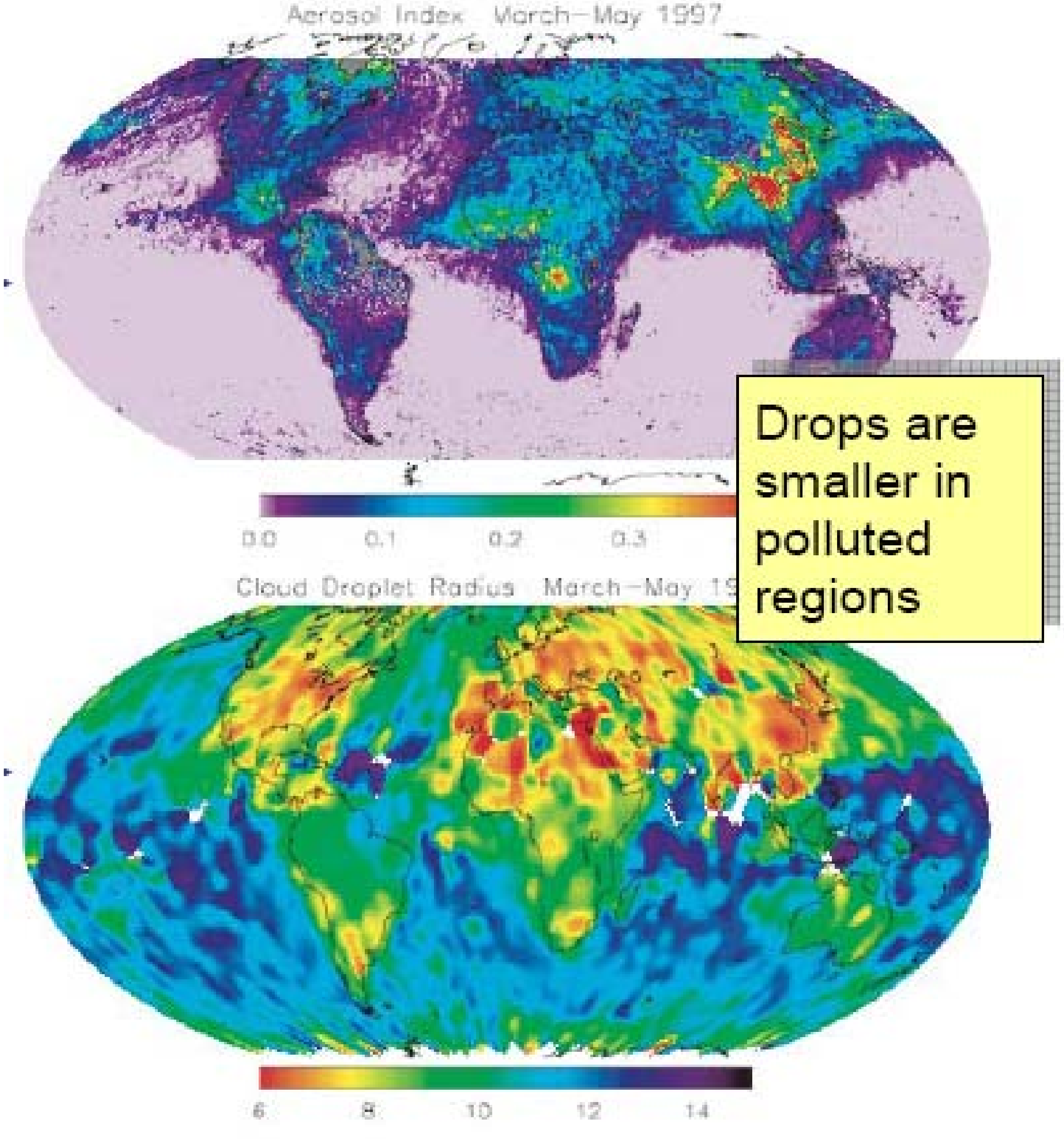


Loeb and Kato, 2002



Chand et al., 2009

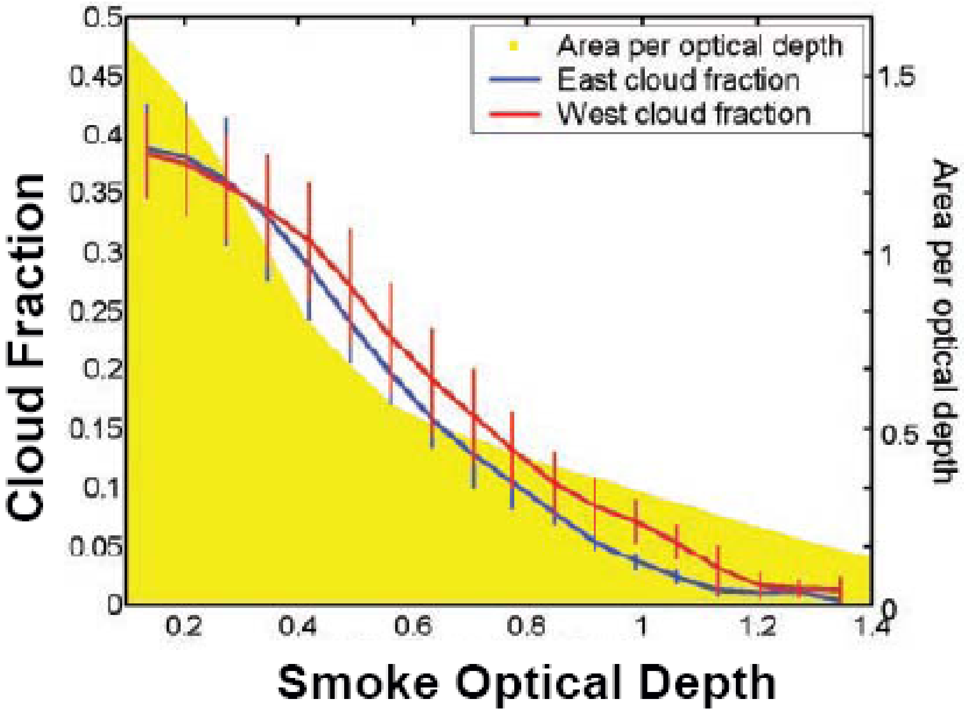
+ possibility to investigate indirect effects…



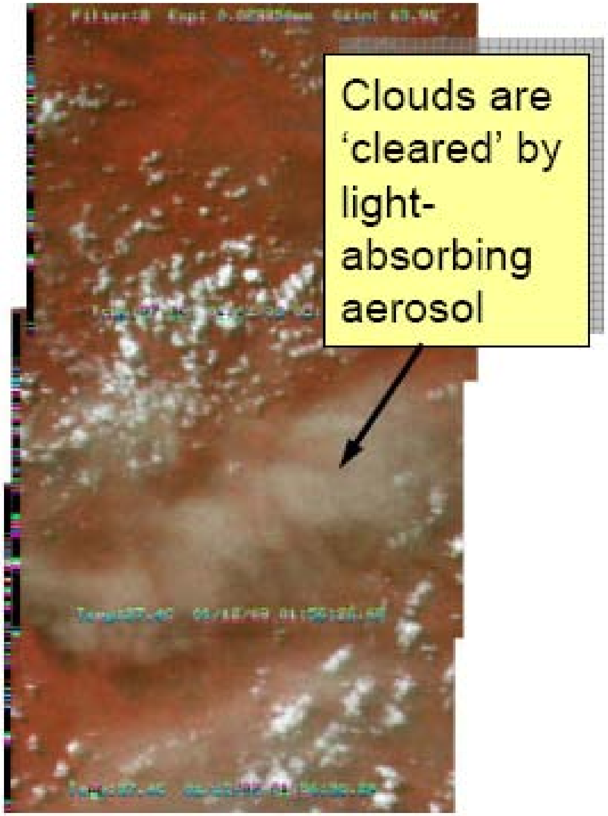
Drops are smaller in polluted regions

Breon *et al*., 2002

…and semi-direct effects reducing cloud…



From Koren et al., Science 2004

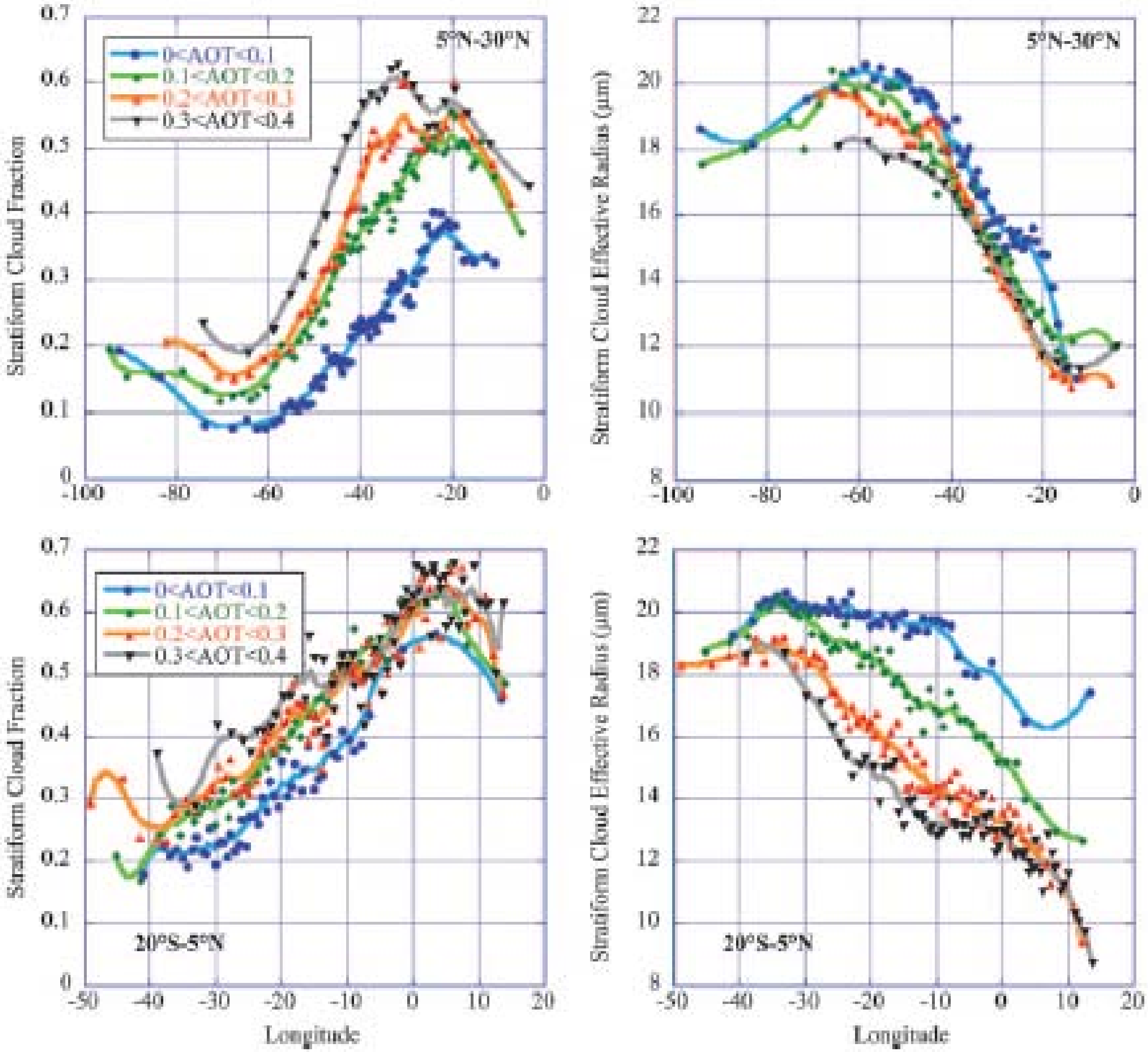


Clouds are 'cleared' by light-absorbing aerosol

Columbia Shuttle image
MEIDEX, January 2003

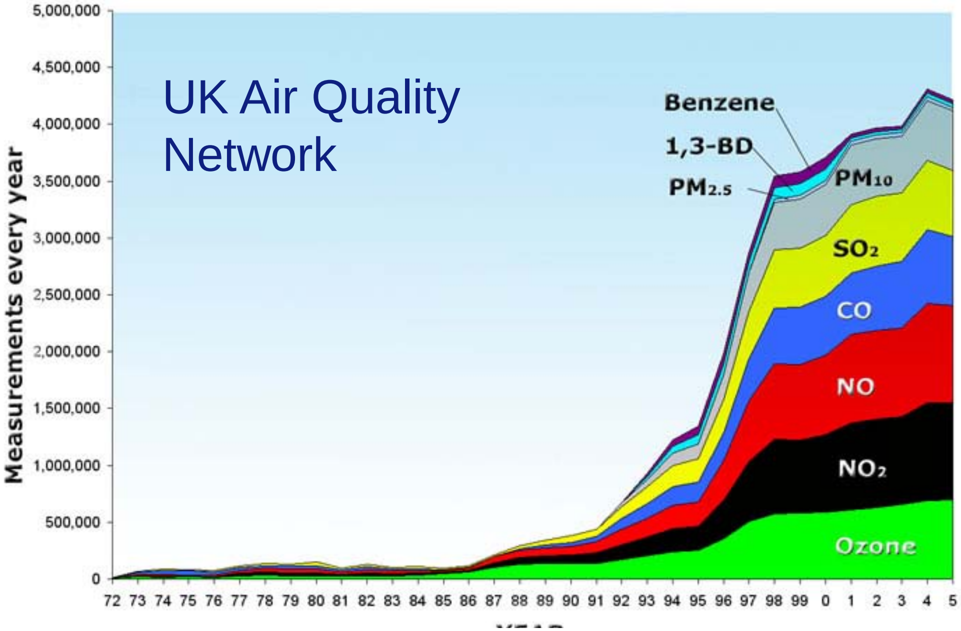
…or not!

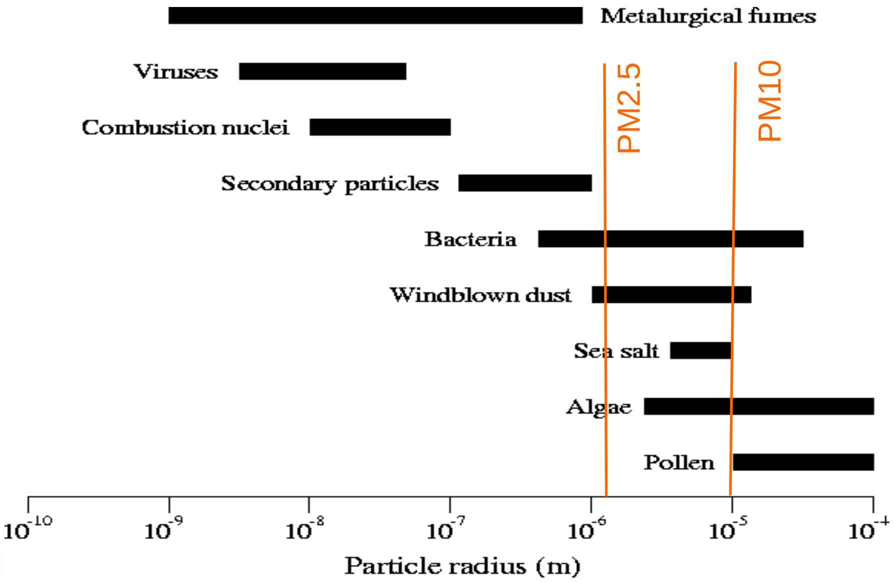
But note that aerosol presence above cloud may affect retrieval quality!

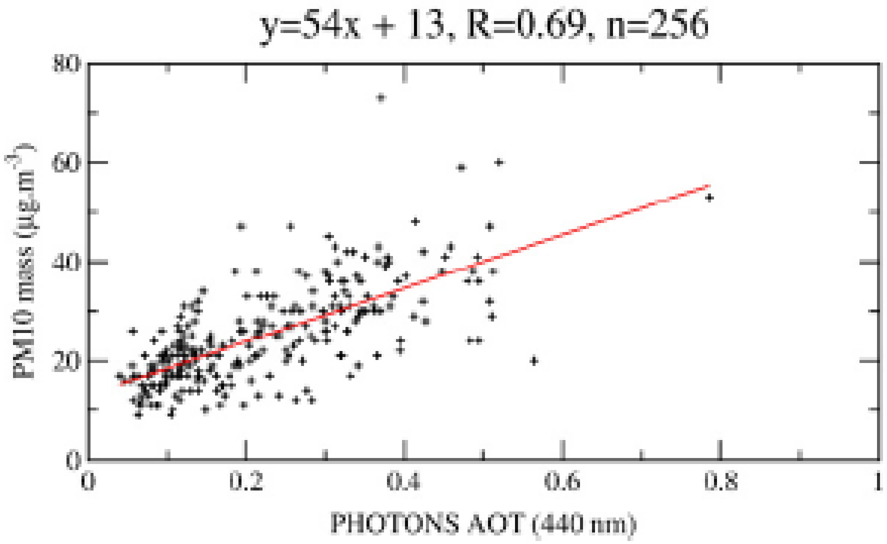


Kaufman *et al.*, 2005

Potential relationship to air quality…


UK Air Quality Network

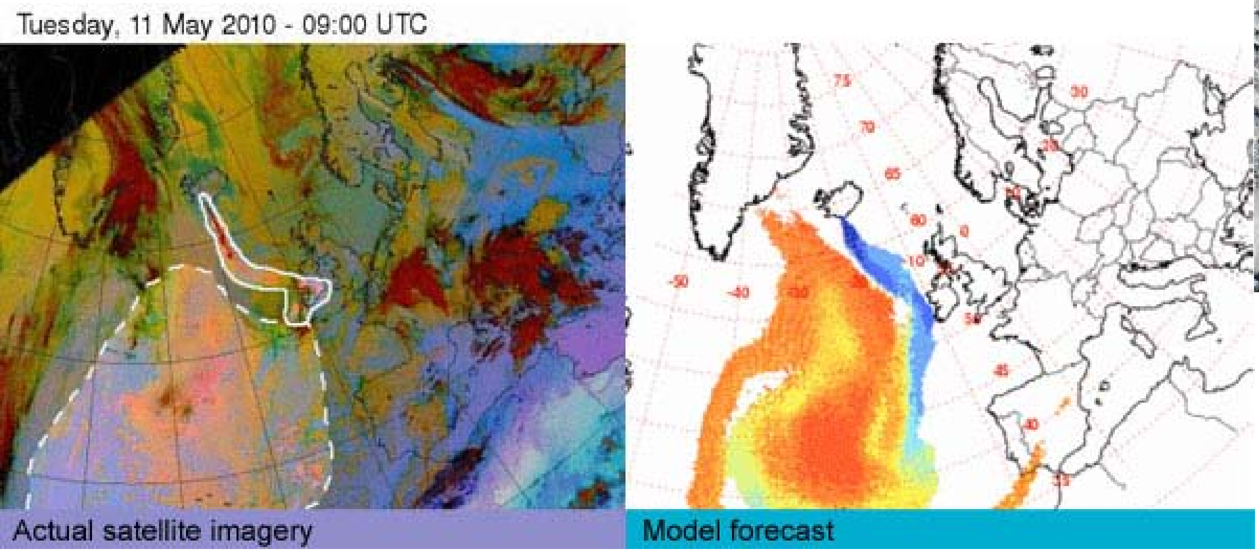




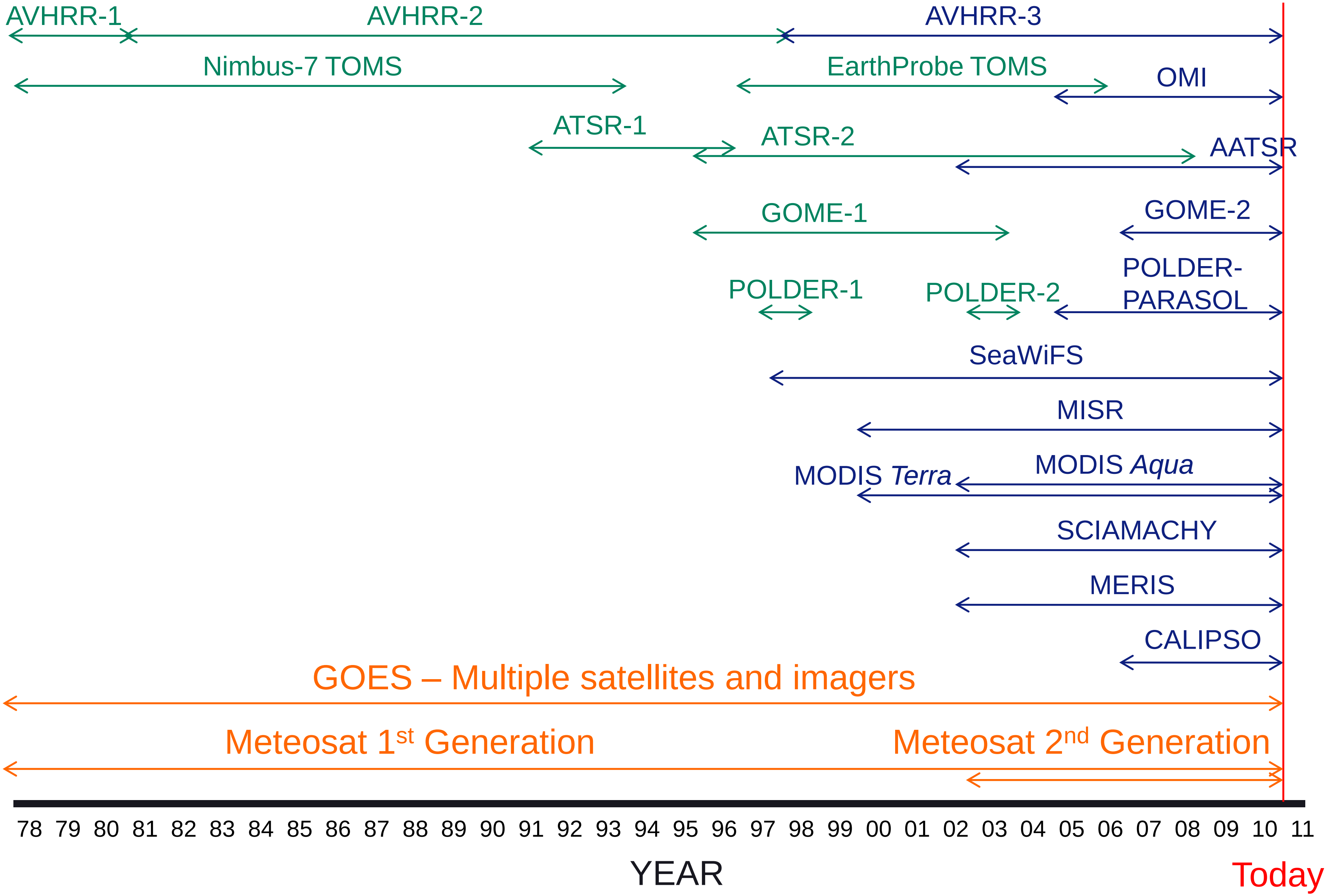
Attempts to relate PM measurements to AOT

e.g. Pere *et al*., 2009

And with air travel!

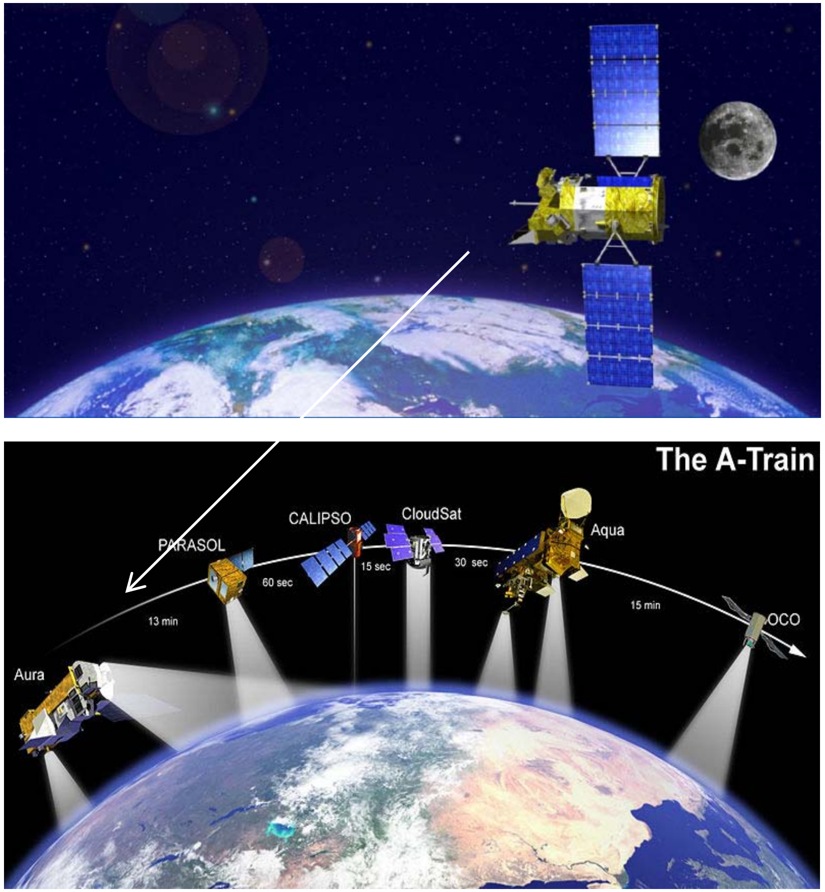


Past/Current (LEO/GEO) instruments



Coming Soon…

GLORY: aims to measure total solar irradiance (TIM) and aerosol/cloud properties (APS). Scheduled launch date: 22/11/10, Lifetime: minimum 3 years



Data product	Range	Uncertainty
AOD	0-5	0.02 (ocean) 0.04 (land)
Effective radius	0.05-5 μm	10 %
Effective variance	0-3	40 %
Real Refractive index	1.3-1.7	0.02
Single-scattering albedo	0-1	0.03
Morphology	Spherical, irregular dust, soot clusters	N/A

Mishchenko *et al*., 2007

Coming Soon…

EarthCare: aims to quantify cloud-aerosol-radiation interactions.

Scheduled launch date: 2013, Lifetime: minimum 2 years

Instrument suite includes:

Polarising LIDAR for aerosol vertical profile, shape information

RADAR for cloud profiles, phase, microphysics, vertical velocity, rain rates

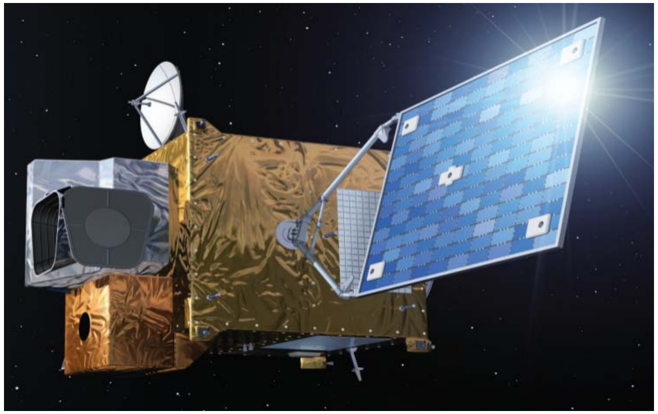
Multi-spectral imager for scene identification

Broad-band radiometer for radiative impact

http://www.esa.int/esaLP/ASESMYNW9SC_LPearthcare_0.html

And further ahead

GMES: specifically Sentinels 4 and 5, designed for operational atmospheric chemistry monitoring, including aerosol/air quality



Sentinel 4: on MTG

High res UVN spectrometer: total range 305-775 nm in 3 channels (non-continuous)

At least 60 min repeat cycle: Europe/N. Africa

Scheduled launch: 2018

Sentinel 5/precursor: in LEO

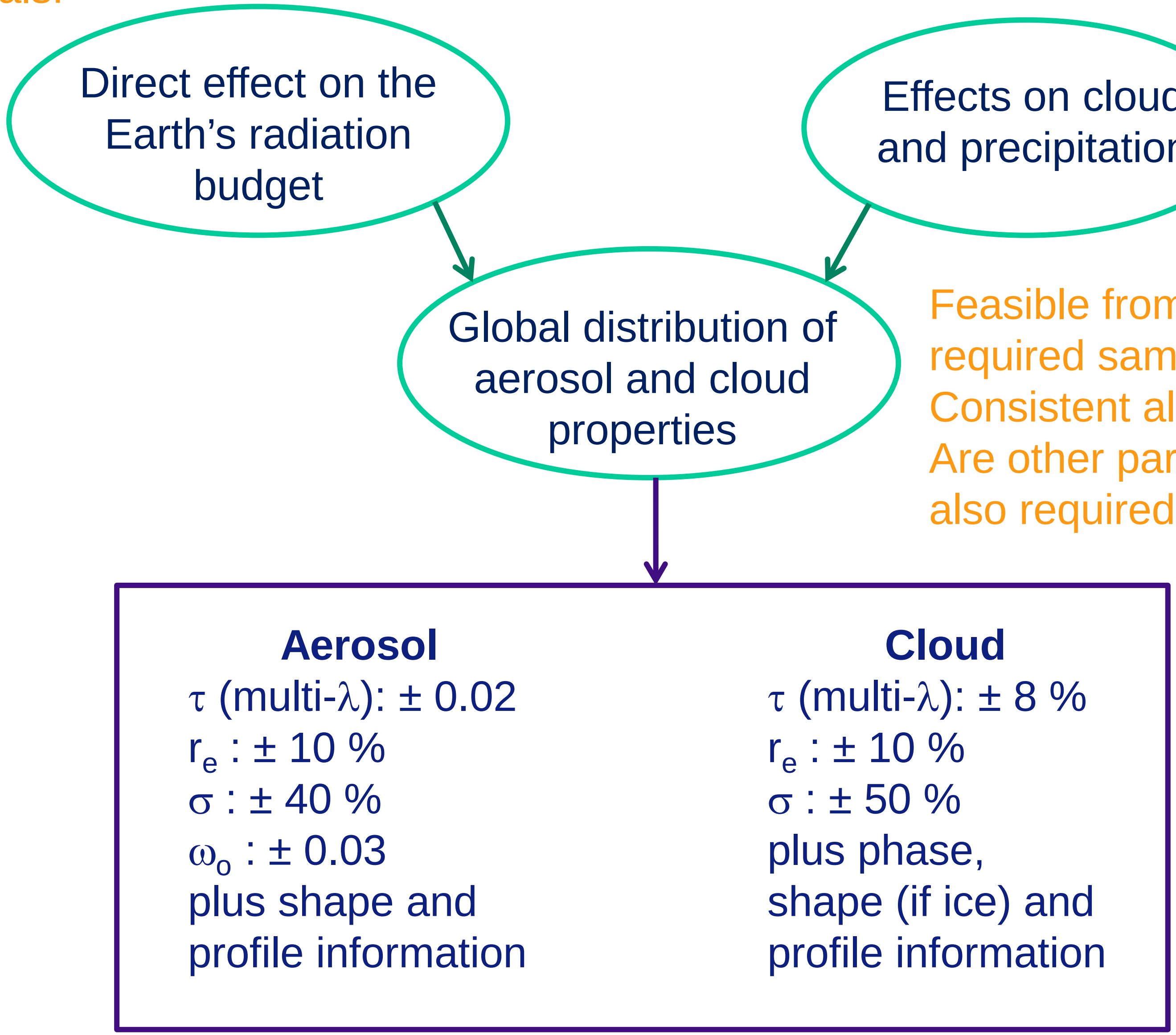
High res spectrometer: total range 270-2382 nm in 5 channels (non-continuous) - TROPOMI

Global daily coverage, nadir view

Scheduled launch: 2014 (precursor) 2019 (sentinel 5)

Mission design review at: http://esamultimedia.esa.int/docs/GMES/Sentinel4and5MRDissue1rev0signed.pdf

Science Goals:



Direct effect on the Earth's radiation budget

Effects on cloud and precipitation

Requires:

Global distribution of aerosol and cloud properties

Feasible from space with required sampling?
Consistent algorithms?
Are other parameters also required?

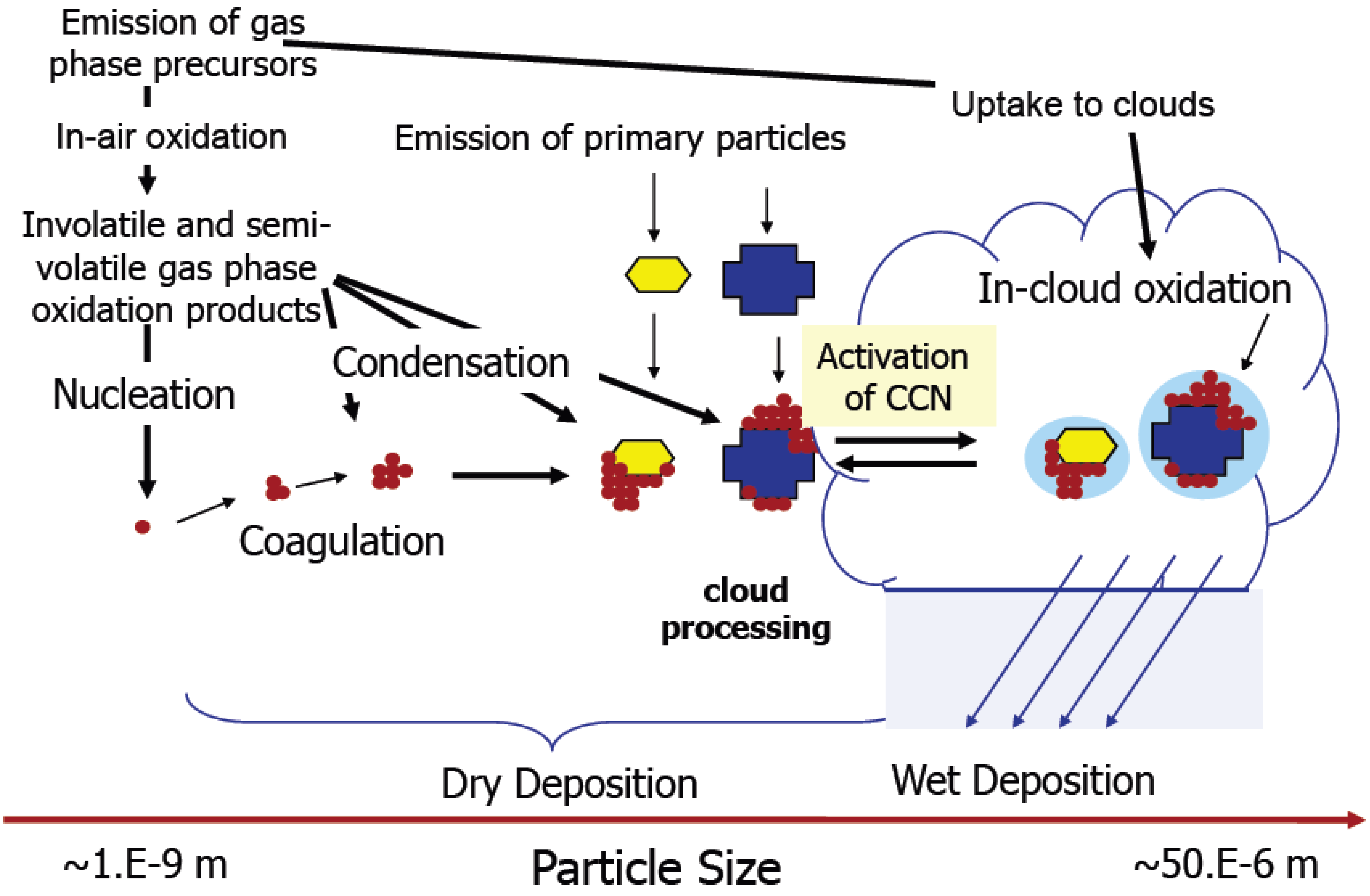
With a suggested accuracy:

Aerosol

τ (multi-λ): ± 0.02
r_e : ± 10 %
σ : ± 40 %
ω_o : ± 0.03
plus shape and profile information

Cloud

τ (multi-λ): ± 8 %
r_e : ± 10 %
σ : ± 50 %
plus phase, shape (if ice) and profile information



Courtesy G. Mann

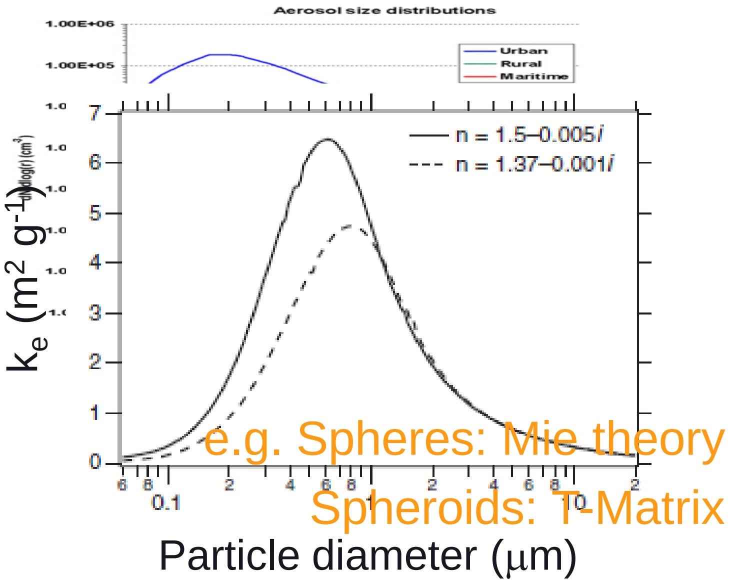
Direct Radiative forcing

What about a scattering aerosol over a bright surface?! How can we estimate whether forcing is positive or negative for a given set of conditions?

Concept of **critical single-scattering albedo**

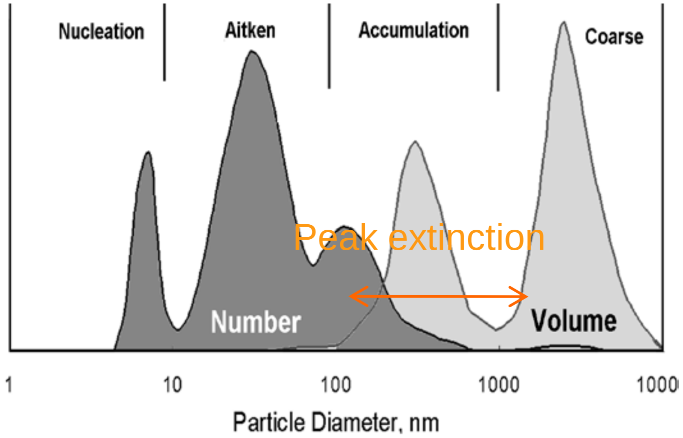
First we need to back-track slightly and introduce some key aerosol parameters…

Calculating key aerosol optical properties



e.g. Spheres: Mie theory

Spheroids: T-Matrix



Peak extinction

Size distribution

Chemical composition (complex refractive index)

INPUTS

PROCESSING

Assumption of particle shape + appropriate scattering code

NB size parameter: $2\pi r/\lambda$

OUTPUTS

Mass extinction coefficient, k_e

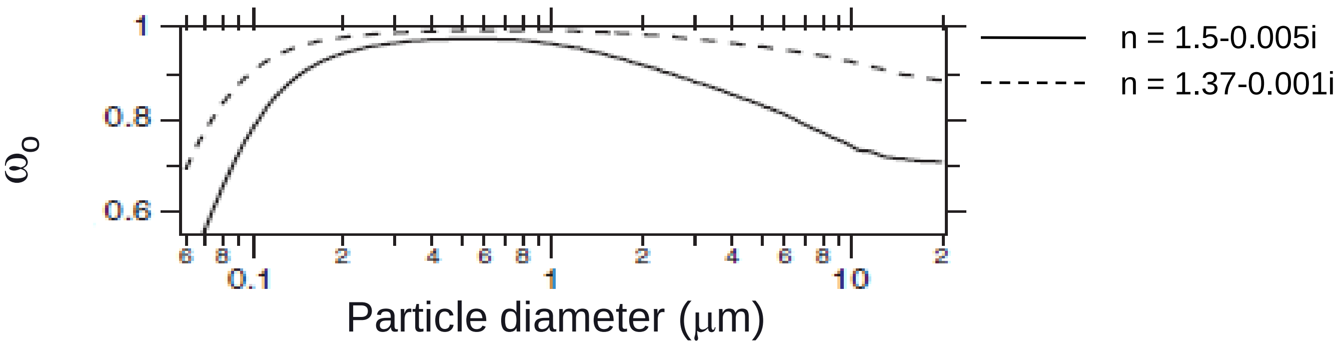
Single-scattering albedo, ω_o

Scattering phase function

Single scattering albedo

$\omega_o = k_s / k_e$ and $k_e = k_s + k_a$

where k_s is the mass scattering coefficient and k_a is the mass absorption coefficient



NB: Instead of k_e (k_s, k_a) can also use:

Extinction coefficient, β_e = attenuation of radiation per unit path length (m^{-1})

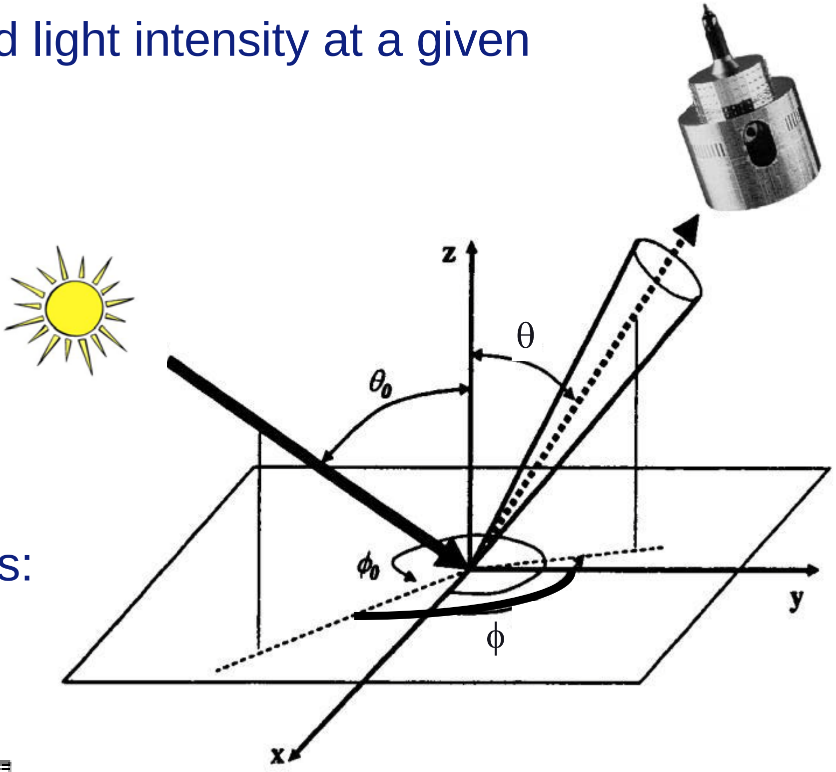
Extinction cross section, $A_e = Q_e$ x geometric area of particle (m^2)

where Q_e is extinction efficiency

The phase function

Definition: ‘The angular distribution of scattered light intensity at a given wavelength’

$$\frac{1}{4\pi}\int_{4\pi} \mathrm{P}(\Theta,\lambda,\mathrm{m})\,\mathrm{d}A = 1$$

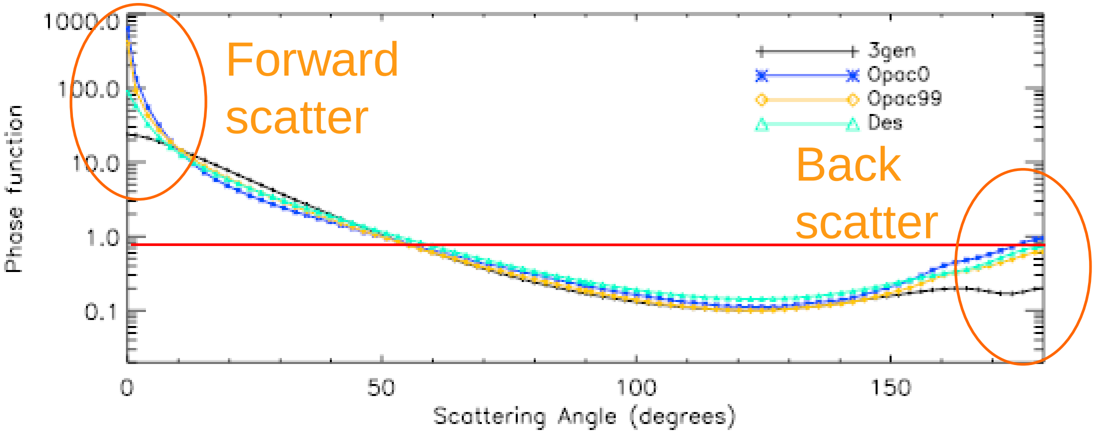


where Θ is the scattering angle, m is the complex refractive index and dA is an element of area

$$\cos\Theta = \cos\theta_o\cos\theta + \sin\theta_o\sin\theta\cos\phi$$

Taking $\theta_o = 0$ and assuming spherical scatterers:

$$\frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} \mathrm{P}(\theta)\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi = 1$$



Forward scatter

Back scatter

Isotropic scattering, P(Θ,λ,m) = 1

The phase function

Definition: 'The angular distribution of scattered light intensity at a given wavelength'

Related terms:

Asymmetry Parameter, g

$$g(\lambda, m) = \frac{1}{2}\int_0^{\pi} P(\theta, \lambda, m)\sin\theta\cos\theta\, d\theta$$

Gives idea of scatter direction

+ve: forward scatter

0: isotropic

-ve: back scatter

Backscatter ratio, b

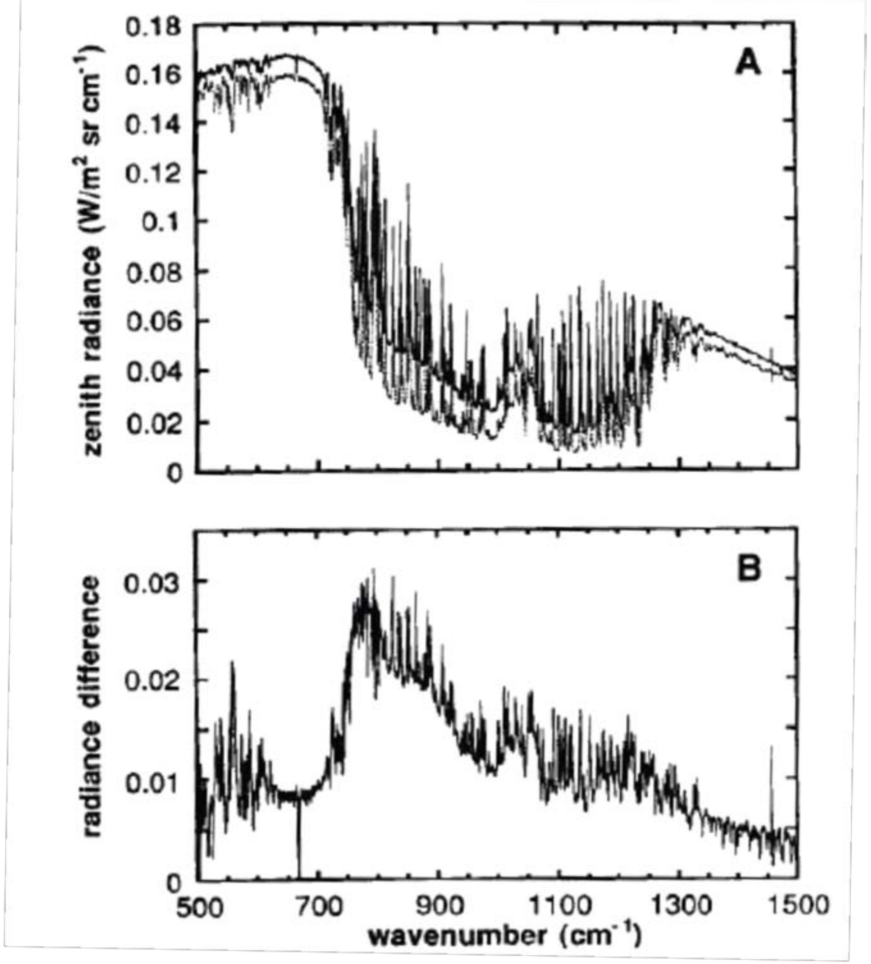
$$b(\lambda, m) = \frac{\int_{\frac{\pi}{2}}^{\pi} P(\theta, \lambda, m)\sin\theta\, d\theta}{\int_0^{\pi} P(\theta, \lambda, m)\sin\theta\, d\theta}$$

Proportion of radiation scattered into backwards hemisphere

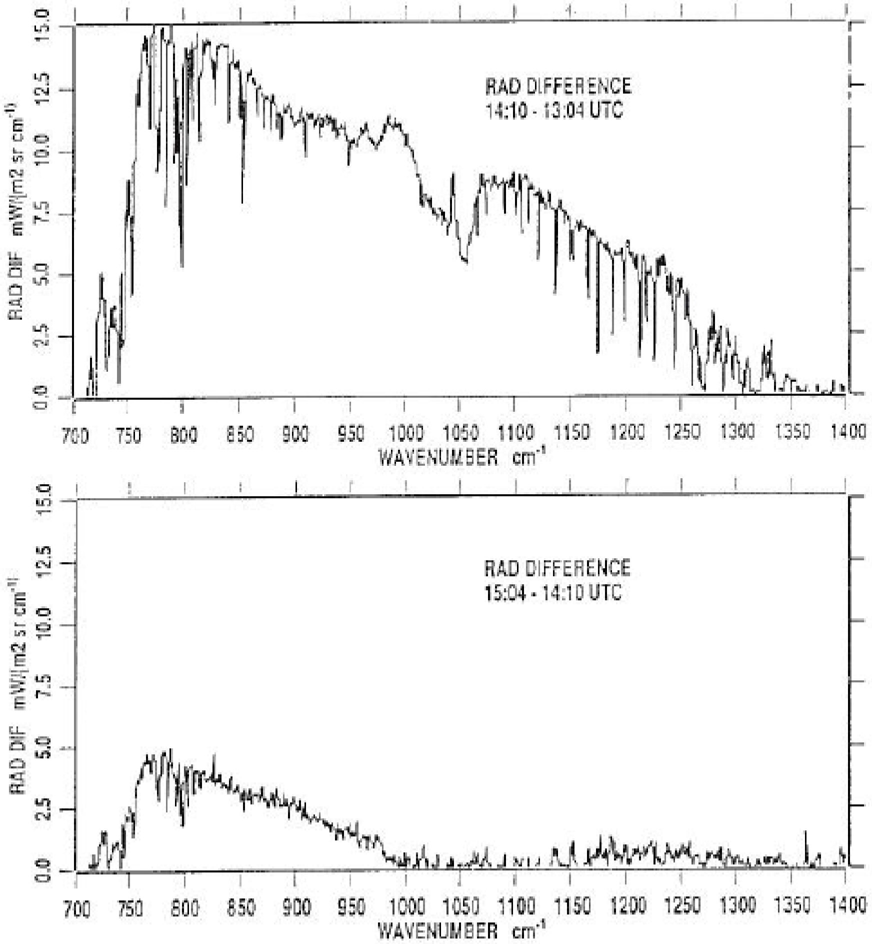
Direct Radiative forcing

…but some work suggests urban pollution, pollen outbreaks etc. also directly affect LW

Lubin *et al*., 1994

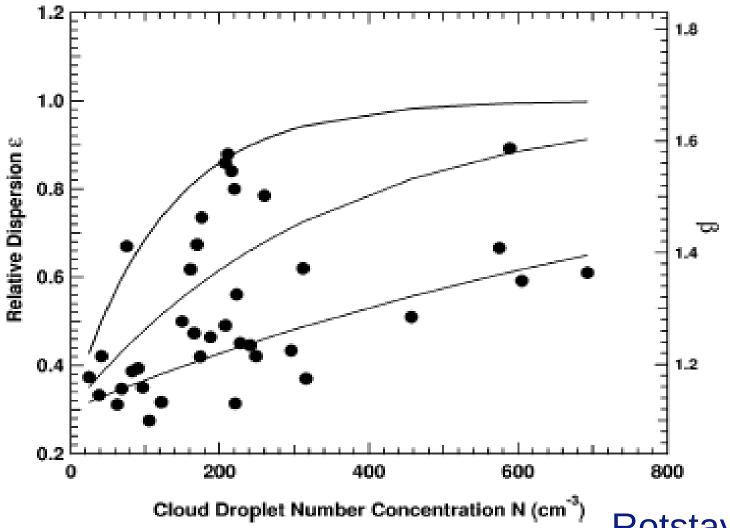


Spankuch *et al*., 2000



More tenuous perhaps:

Observations: no of droplets does increase but concurrent widening of cloud droplet spectrum:
‘First Dispersion Effect’



Rotstayn and Liu, 2003

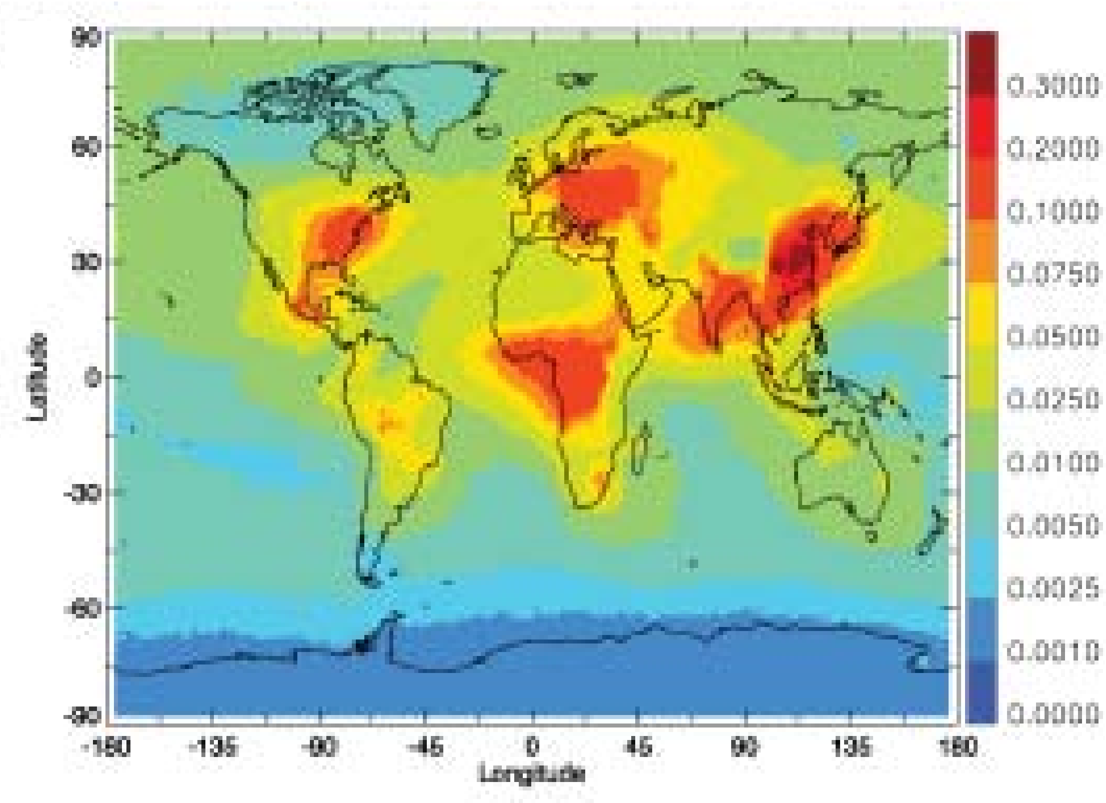
Simulations suggest an associated increased precipitation amount:

‘Second dispersion Effect’

(e.g. Roelofs and Jongen, 2004)

Could partially offset 1^{st} indirect effect but countered by Lu and Seinfeld, 2006

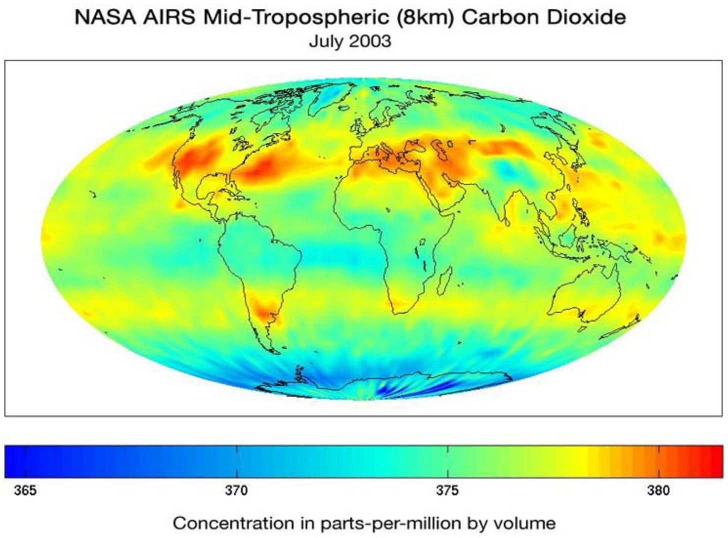
Observing aerosol from space



$$\tau_{055} = \int_{dz} k_{e055} \rho \, dz$$

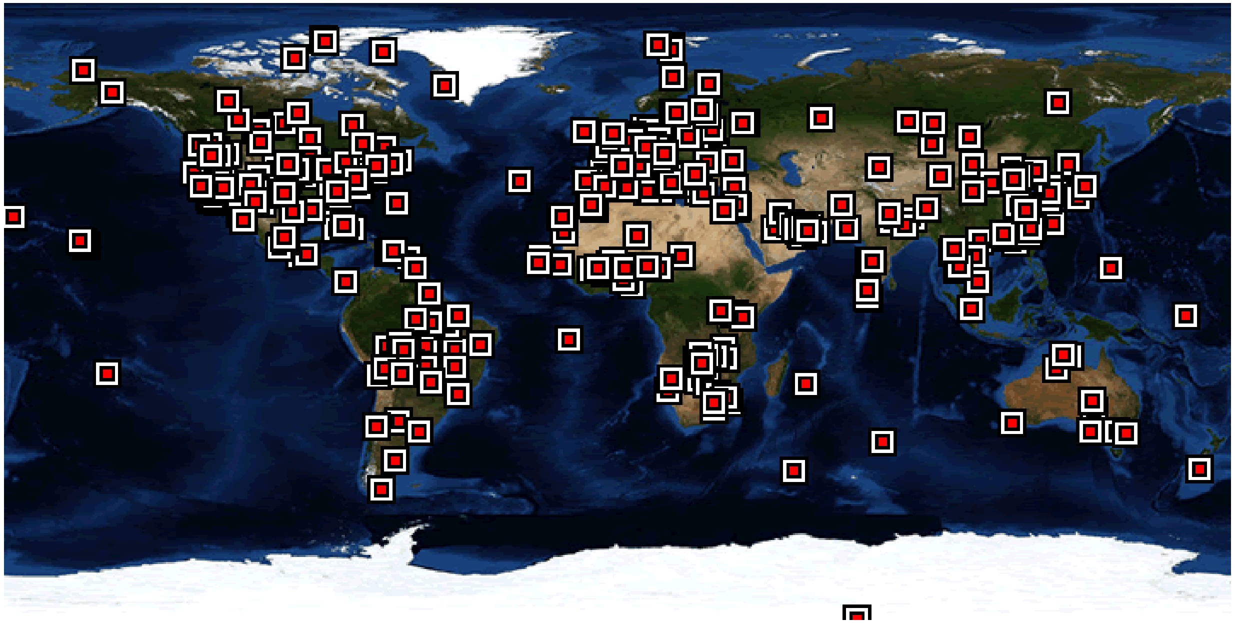
τ_{055}

Average of nine model predictions


NASA AIRS Mid-Tropospheric (8km) Carbon Dioxide

July 2003

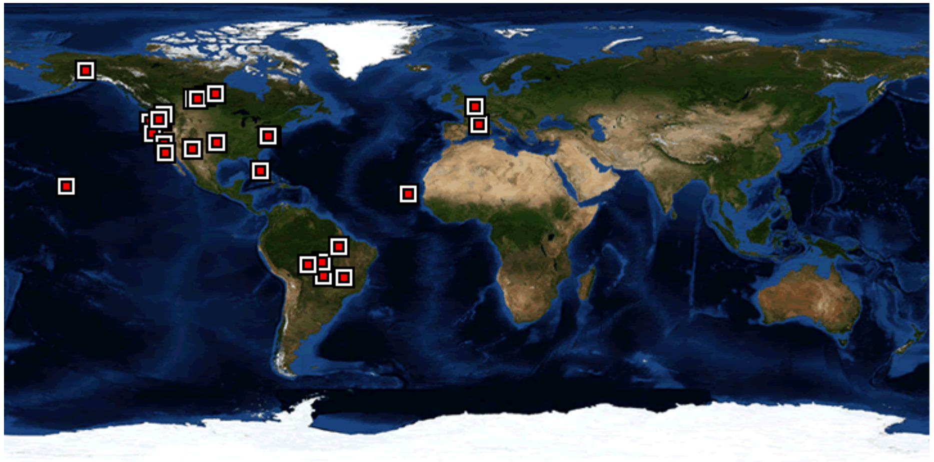
Observing aerosol – Ground based



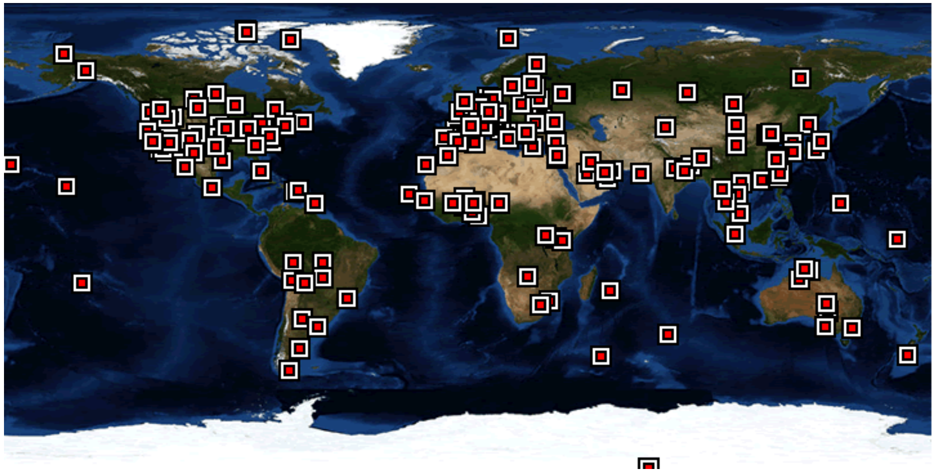
AErosol ROBotic NETwork (AERONET)

http://aeronet.gsfc.nasa.gov/

1994



2007



Observing aerosol – Ground based

AERONET measurements directly provide:

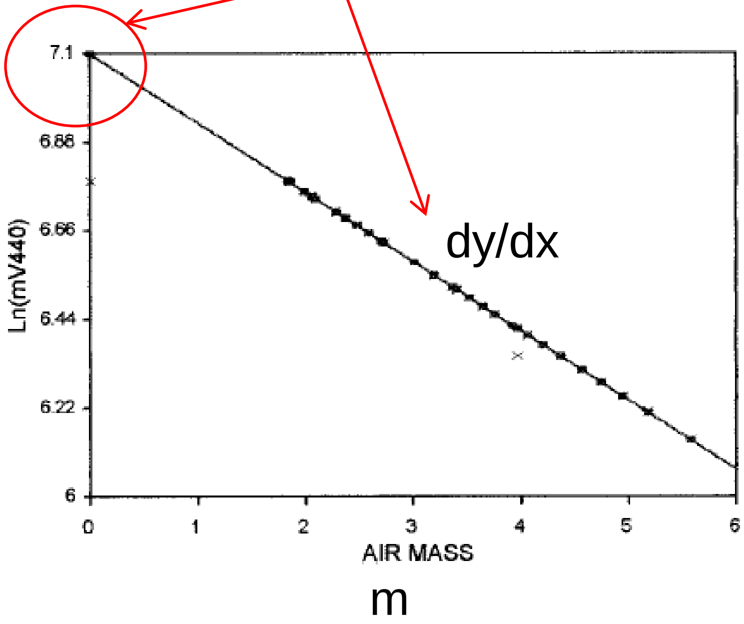
$\tau(\lambda)$: $I(\lambda) \propto V(\lambda)$ and, Beer-Lambert:

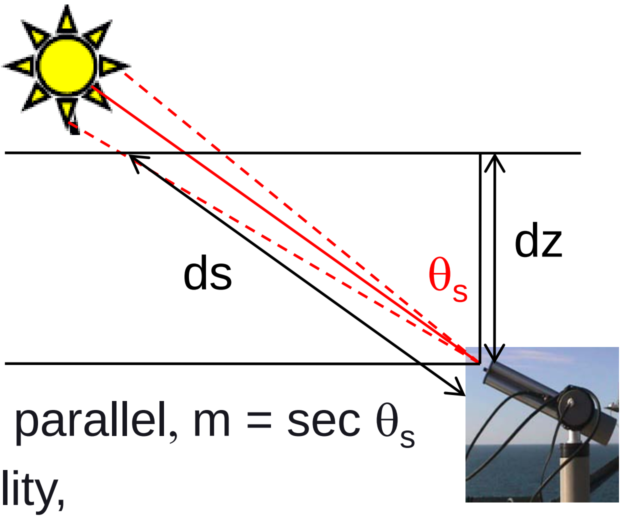
$$V(\lambda) = V_o(\lambda)\left(\frac{R_m}{R}\right)^2 \exp(-\tau(\lambda)_{TOT} \times m)$$

Leads to

$$\ln V(\lambda) = -m(\tau(\lambda)_{TOT}) + \ln V'_o(\lambda)$$

Langley plots:





Plane parallel, m = sec θ_s

In reality,

$\theta_s < 60°$, m ~ sec θ_s

And

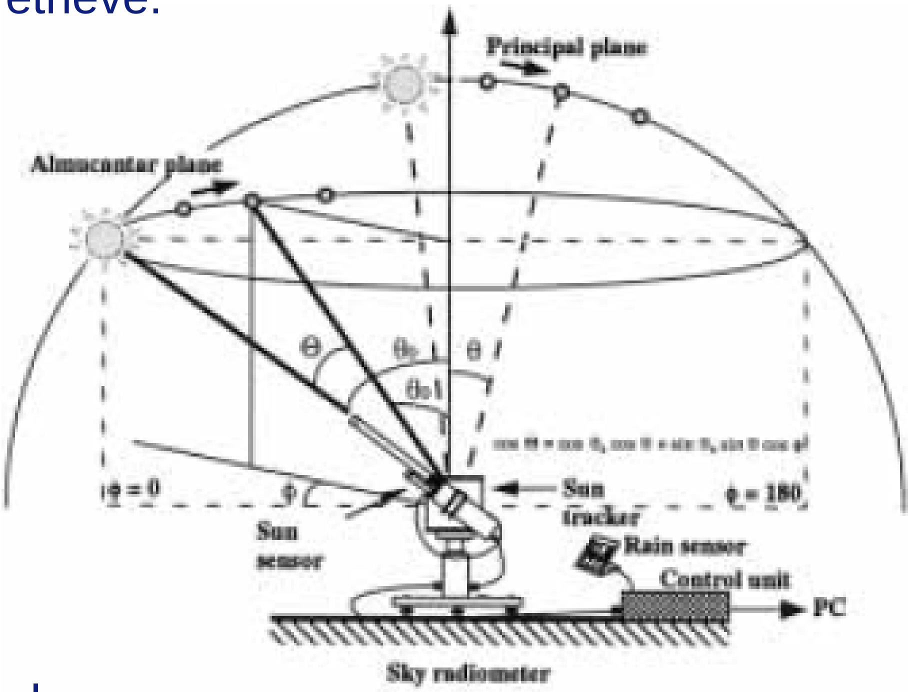
$\tau(\lambda)_a = \tau(\lambda)_{TOT} - \tau(\lambda)_t - \tau(\lambda)_r$

Measurements at several λs, so also provides Ångström coefficient, α

$$\alpha = -\frac{d \ln \tau(\lambda)_a}{d \ln \lambda} \sim -\frac{\ln \frac{\tau(\lambda_i)_a}{\tau(\lambda_j)_a}}{\ln \frac{\lambda_i}{\lambda_j}}$$

Observing aerosol – Ground based

AERONET measurements also used to retrieve:



size distribution, single scattering albedo, phase function and complex index of refraction

Idea: simultaneously invert radiances measured at a number of wavelengths and scattering angles so uses diffuse and direct beam measurements

Then: variability in clear-sky downward solar radiance assumed dominated by aerosol

$$I(\Theta,\lambda) = I(\tau_a(\lambda);\omega_{oa}(\lambda);P_a(\Theta,\lambda)) \qquad \text{or} \qquad I(\Theta,\lambda) = I(N_a(r), m_a(\lambda))$$

Observations of aerosol – in situ

Balloon or aircraft based instrumentation

One example: FAAM BAE-146

Type of measurement	Instrument	Size range, wavelengths etc
Aerosol microphysics	PMS PCASP SID-1/SID-2 FFSSP	0.05-1.5 μm 1-30 μm 1.5-20 μm
Aerosol optical properties	TSI Nephelometer Radiance research PSAP	λ = 0.45,0.55,0.7 μm λ = 0.568 μm
Aerosol chemical comp	Filters	2 ranges for inorganics and carbon
Broadband irradiance	BBRs	0.3-3 or 0.7-3 μm
Spectral radiances	SWS ARIES	303.4-1706.5 nm 3.33-18.18 μm
Spectral irradiances	SHIMS	303.4-1706.5 nm

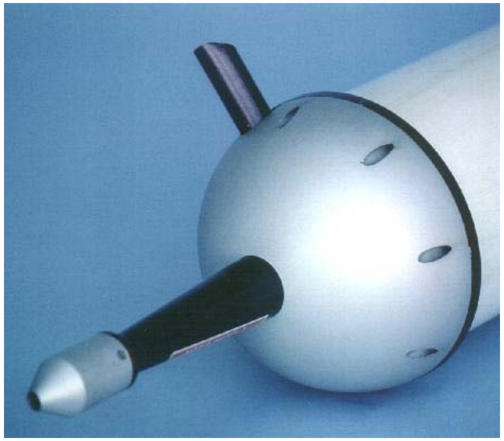
Plus other ‘standard’ meteorological measurements…

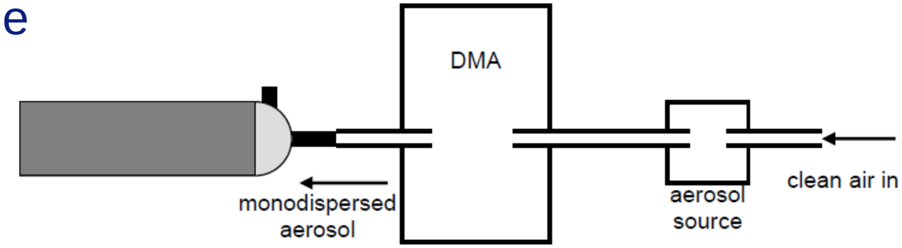
In situ size (and shape)

PCASP: Passive Cavity Aerosol Spectrometer Probe

Measures angular distribution of light scattered out of HeNe beam focussed on particle laden air stream

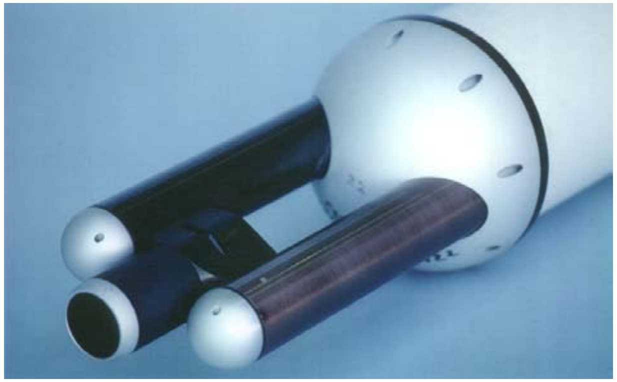
Uses Mie theory to relate scattering pattern to particle size





FFSSP: Fast Forward Scattering Spectrometer Probe

As above, but only considers ‘forward’ scattered light

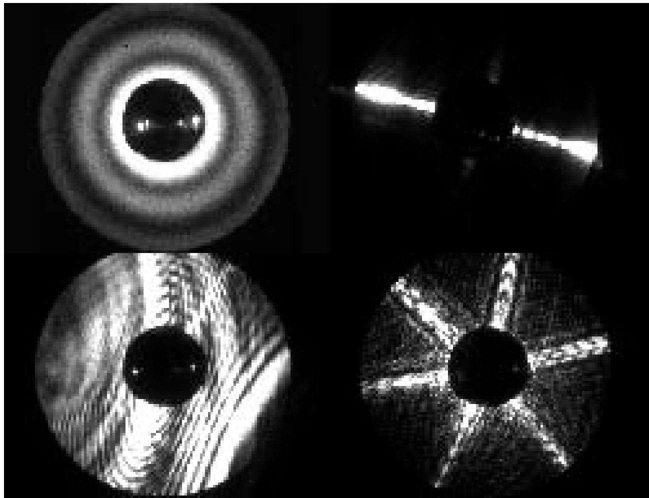


SID1/2: Small Ice Detector

Similar idea to above

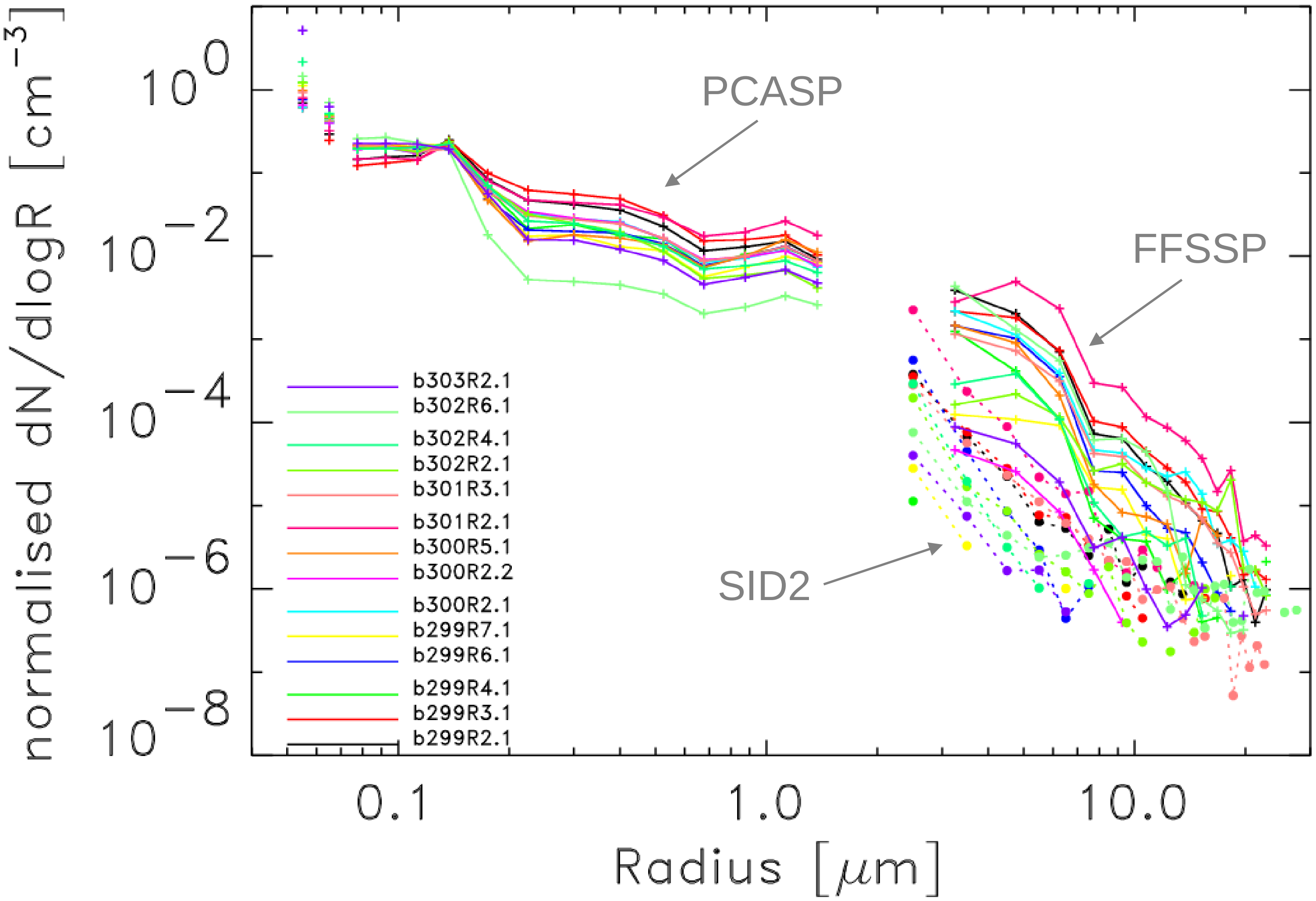
Isolates single particles and measures angular scattering using array of detectors

Variation in detector response cf mean value provides particle shape information



In situ size

GERBILS campaign, June 2007



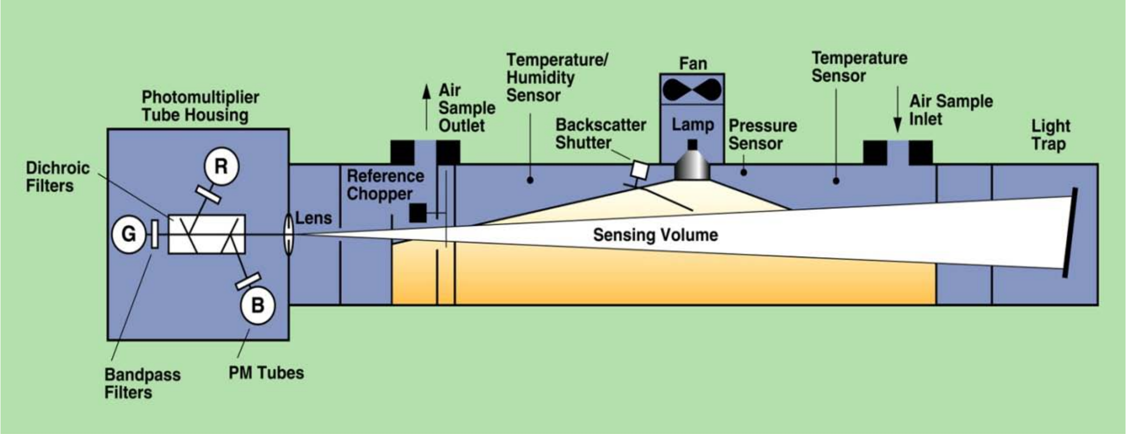
Courtesy S. Osborne

In situ optical properties

Nephelometer

Measures total scatter and hemispheric backscatter

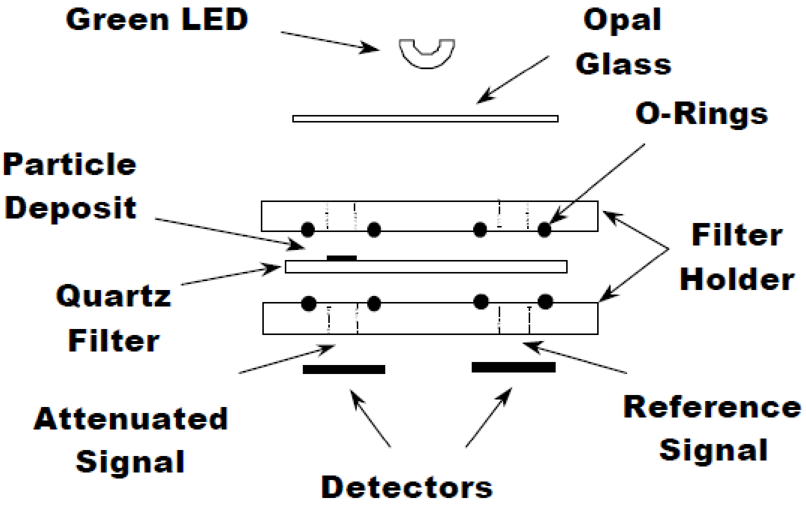
Known light source, known path length: obtain scattering coefficient



Particle soot absorption photometer (PSAP)

Measures absorptance through a filter

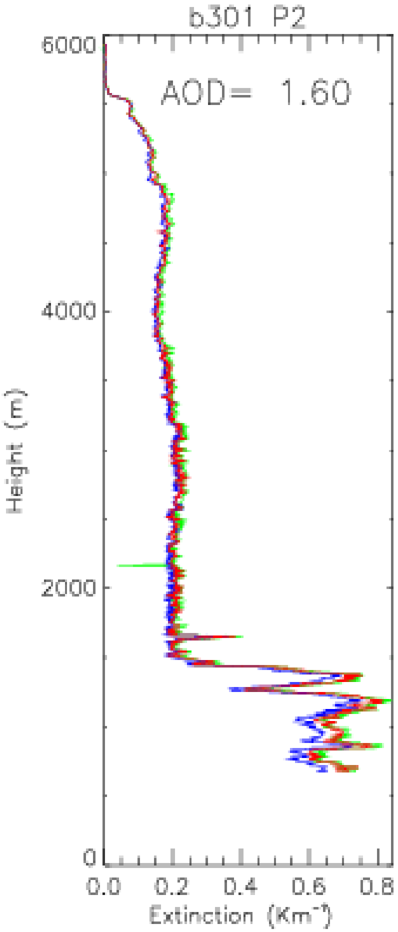
Provides absorption coefficient

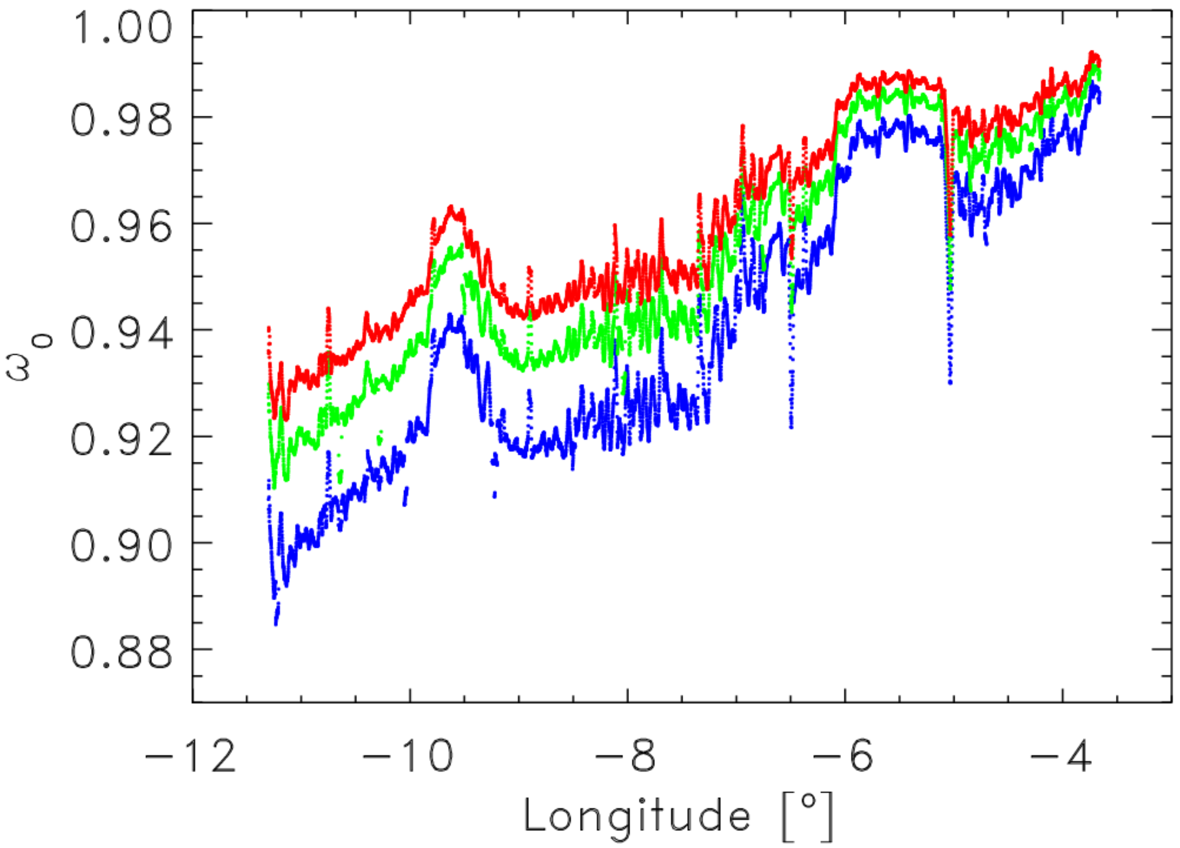


Combination of two allows derivation of extinction coefficient

In situ optical properties

Courtesy S. Osborne and
B. Johnson





Excellent detail and opportunity to study aerosol case studies but ‘snapshot’ in nature