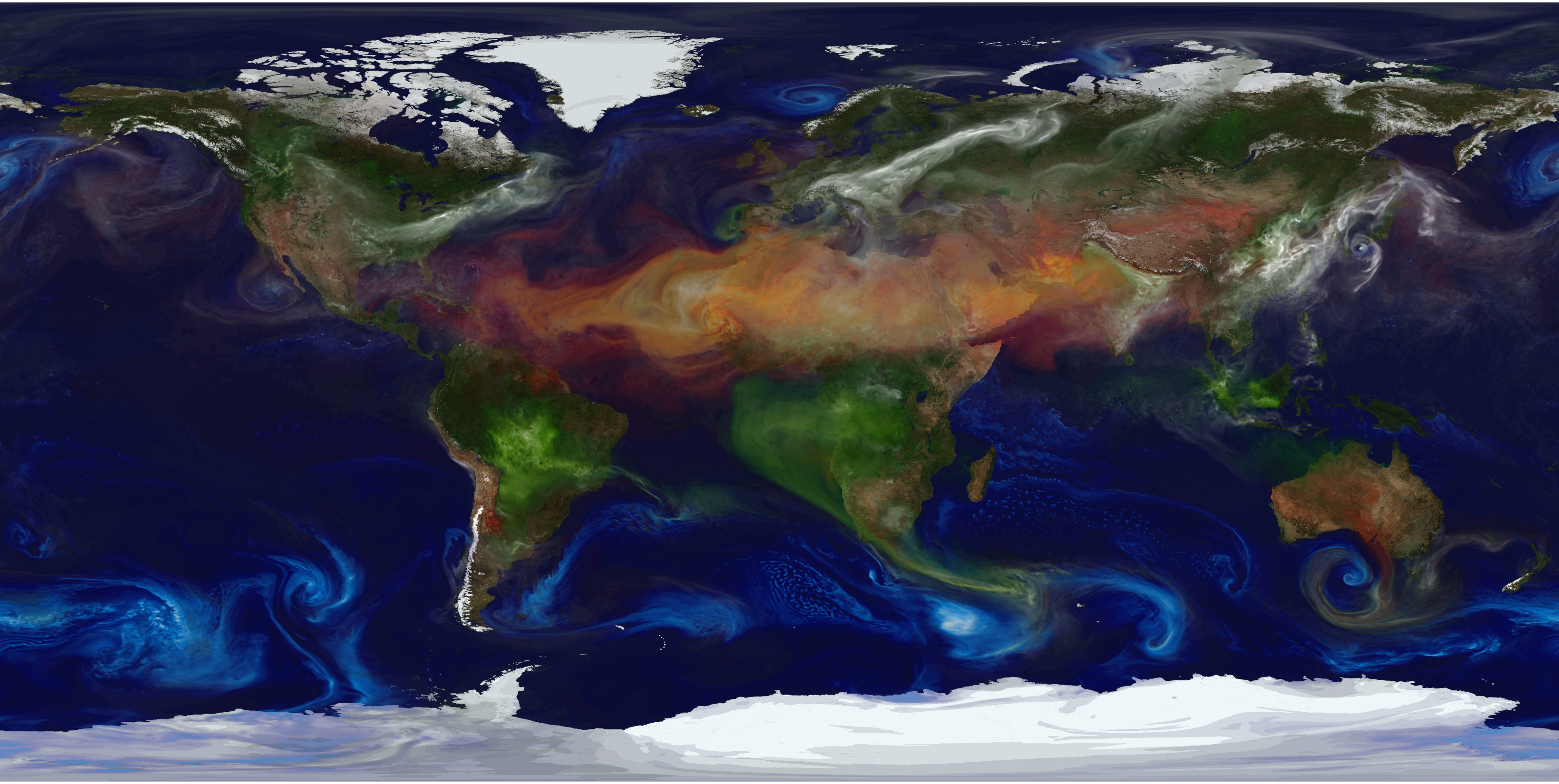
ARM Summer Training and Science Applications:

Aerosol Radiative Forcing in Clear and Cloudy Skies



Allison McComiskey, NOAA ESRL

ARM
CLIMATE RESEARCH FACILITY

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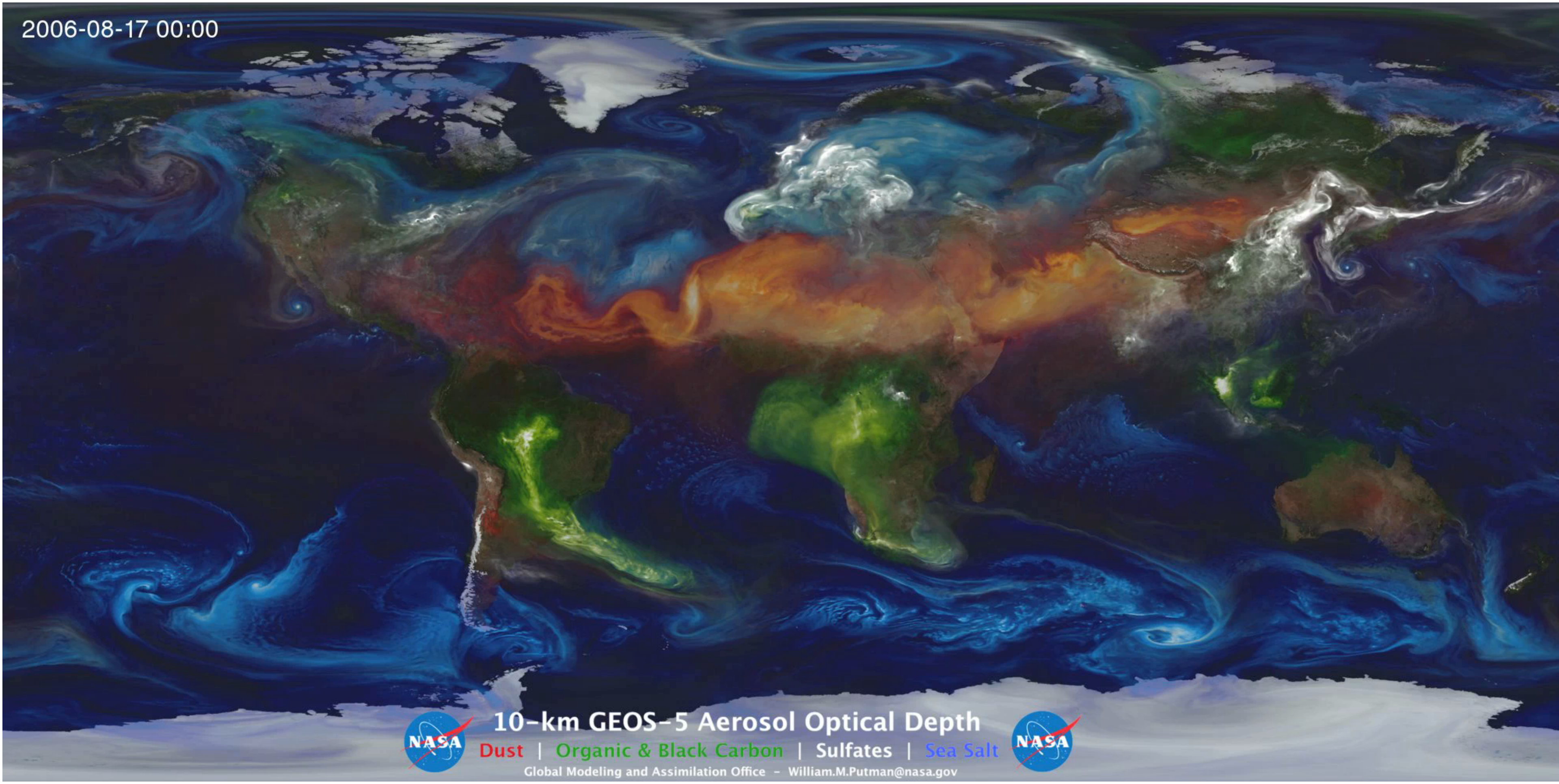
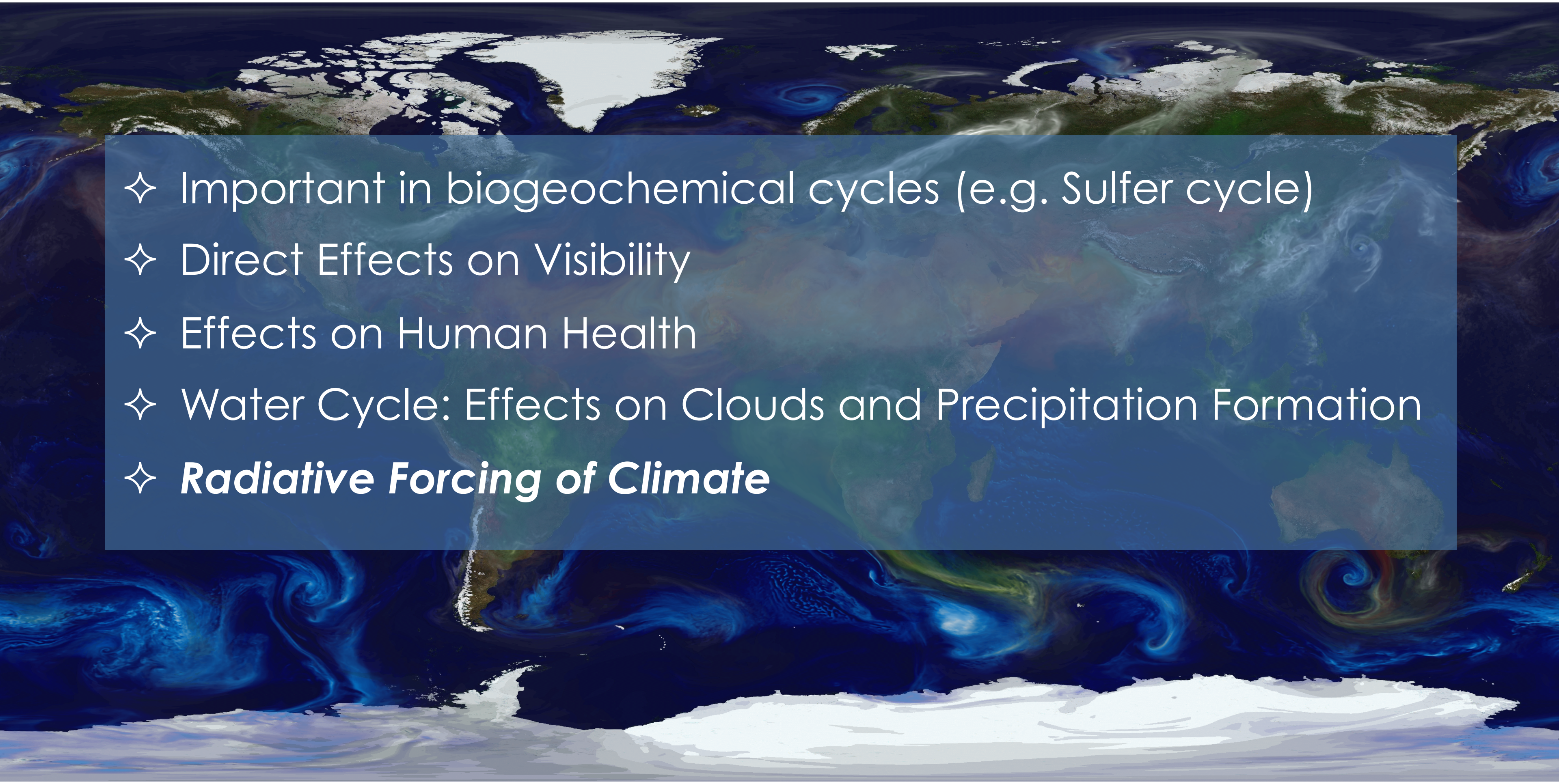
GEOS-Chem Aerosol Optical Depth by Type



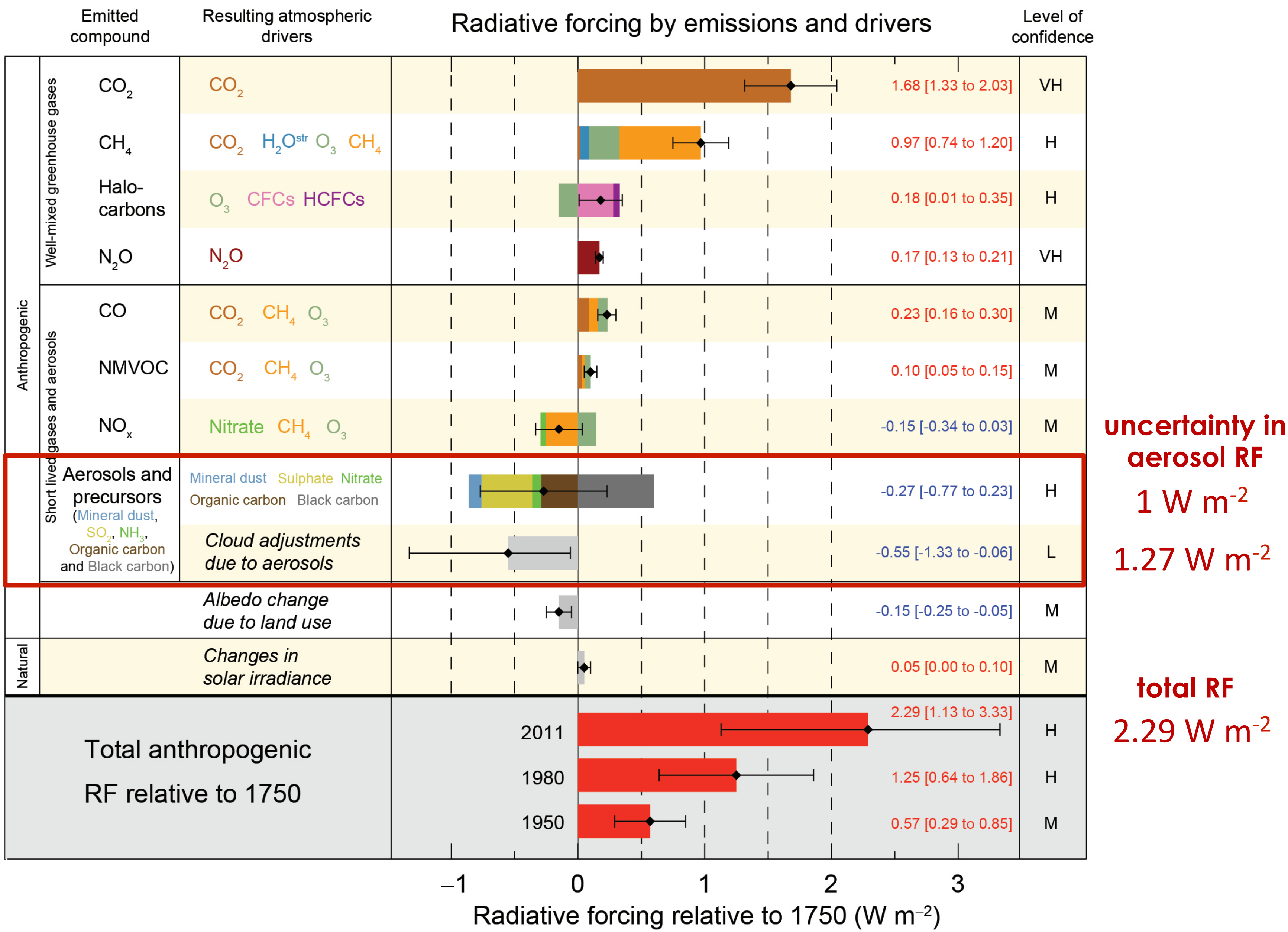
dust
organic & black carbon
sulfate
sea salt

Rationale for Studying Aerosol



- Important in biogeochemical cycles (e.g. Sulfer cycle)
- Direct Effects on Visibility
- Effects on Human Health
- Water Cycle: Effects on Clouds and Precipitation Formation
- ***Radiative Forcing of Climate***

IPCC AR5 Radiative Forcing



Aerosol Radiative Forcing

TOA forcing
global climate

$$\Delta T_S = \lambda F$$

net irradiance without anthro aerosol

$$RF = (f_a\downarrow - f_a\uparrow) - (f_0\downarrow - f_0\uparrow) \quad W\,m^{-2}$$

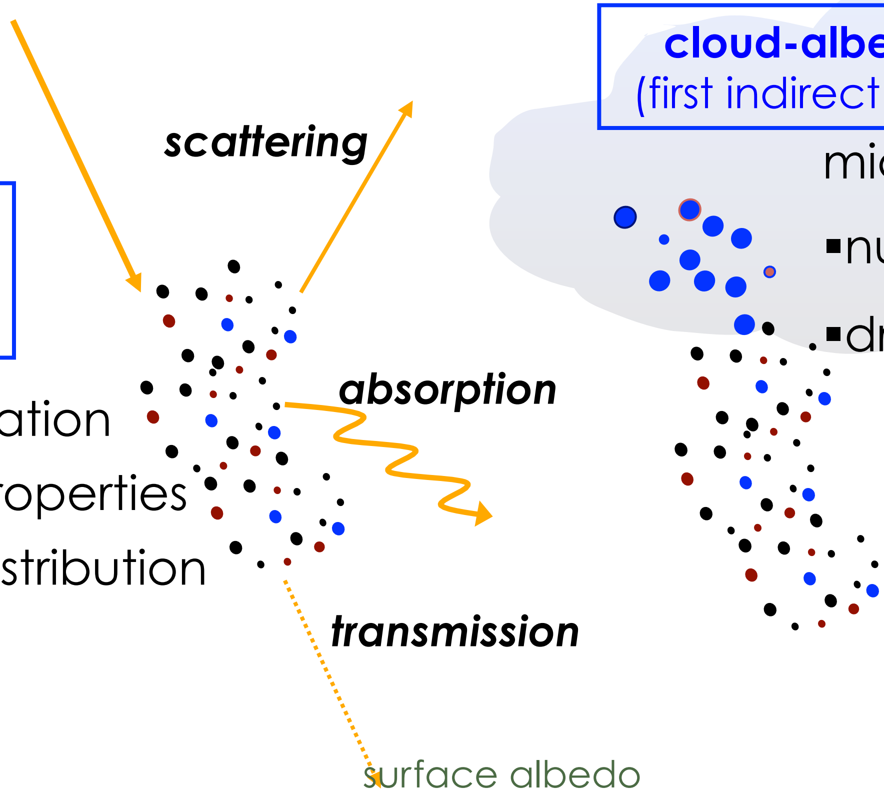
net irradiance with natural + anthro aerosol

Direct

-0.27 [-0.77 to 0.23] W m^{-2}

direct radiative forcing

- concentration
- optical properties
- spatial distribution



surface albedo

sign and magnitude dependent on coupled surface-atmosphere system

SRF forcing
regional cooling

Indirect

-0.55 [-1.33 to -0.06] W m^{-2}

cloud-albedo effect
(first indirect / Twomey)

microphysical processes

- number concentration
- drop size

Secondary: *fraction*

- **precipitation (second indirect)**
- **evaporation (semi-direct)**
- **lifetime**

hydrological processes

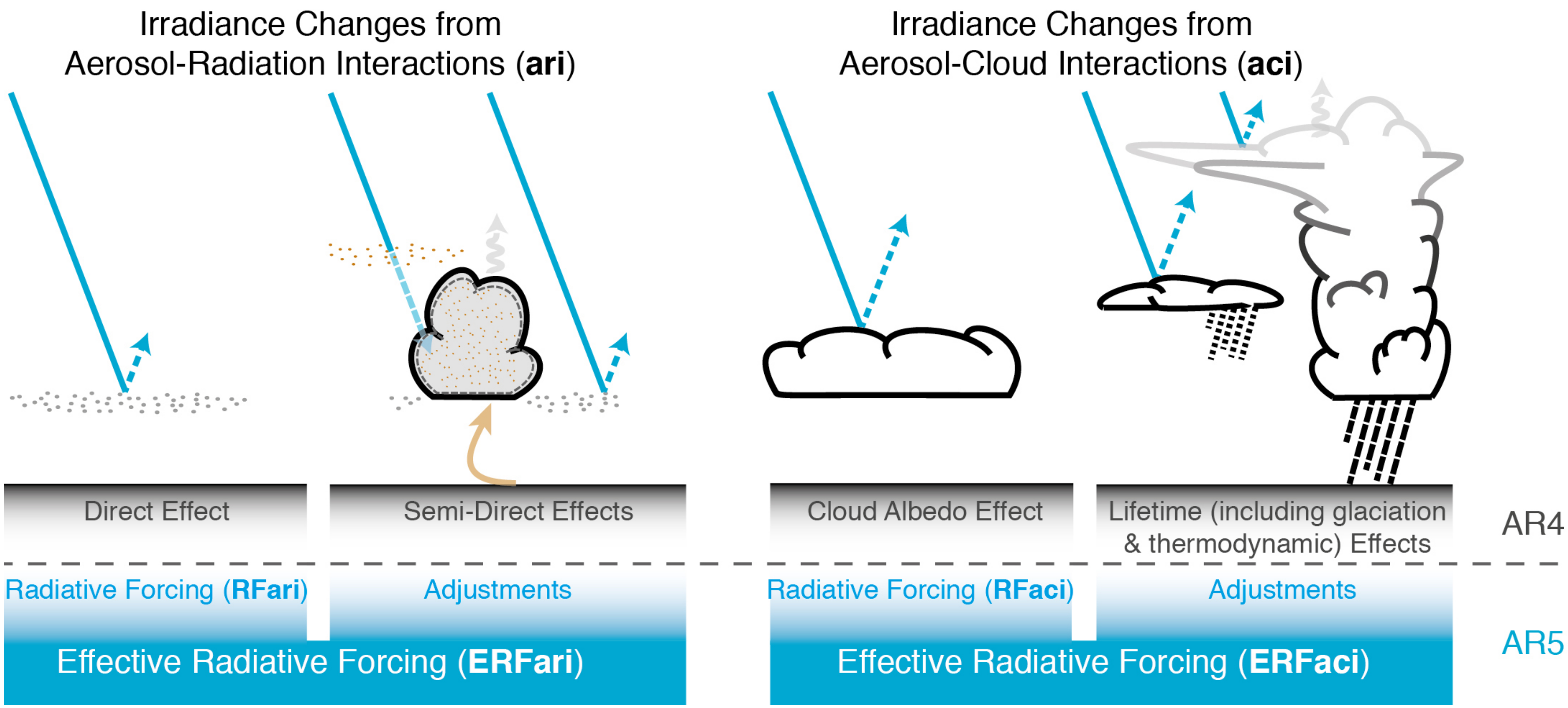
water budget

eco-systems

Aerosol Radiative Forcing according to IPCC AR5

Aerosol Direct Effect – aerosol radiative forcing in clear skies

Aerosol Indirect Effect – aerosol radiative forcing in cloudy skies



What role does aerosol play in the climate system?

Aerosol Direct Effect – aerosol radiative forcing in clear skies

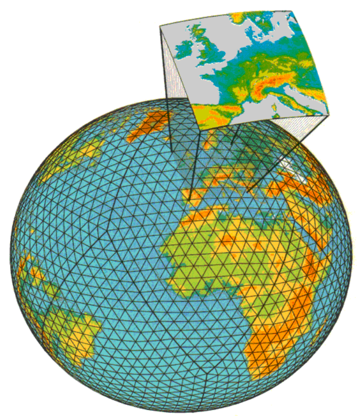
Aerosol Indirect Effect – aerosol radiative forcing in cloudy skies

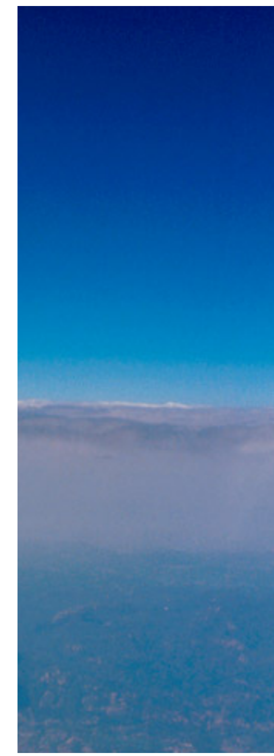
What about 'transition zones'?
the integrated aerosol cloud system?
ERF ARI+ACI

Top of the Atmosphere RF

Atmospheric RF

Surface RF



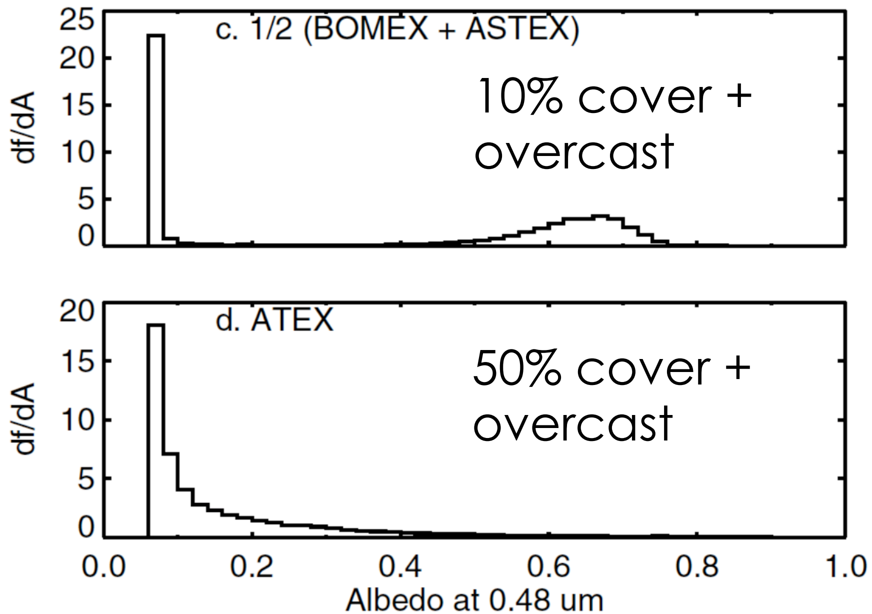


Global – Regional – Local
Annual – Diurnal - Instantaneous

TOA Global Annual Average does not tell the whole aerosol story!

The cloudy-clear transition zone (a.k.a.'twilight zone', 'halos')

LES

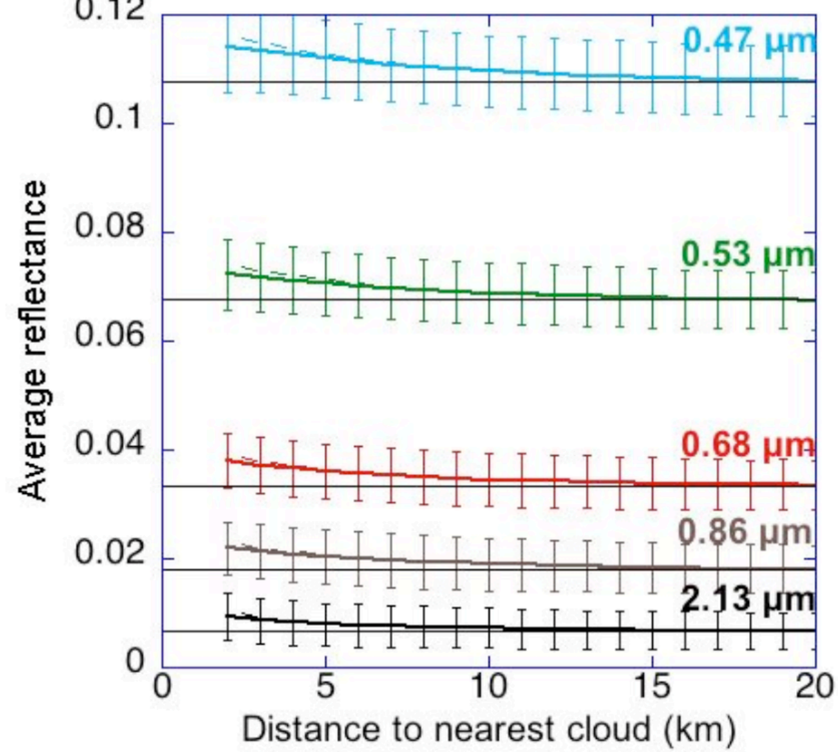


Charlson et al 2007

humidified aerosol between clouds

What is a cloud anyway?

MODIS



Varnai and Marshak 2009

Aerosol Direct Radiative Forcing

TOA forcing
global climate

solar geometry

$$RF = (f_a \downarrow - f_a \uparrow) - (f_0 \downarrow - f_0 \uparrow) \quad W\ m^{-2}$$

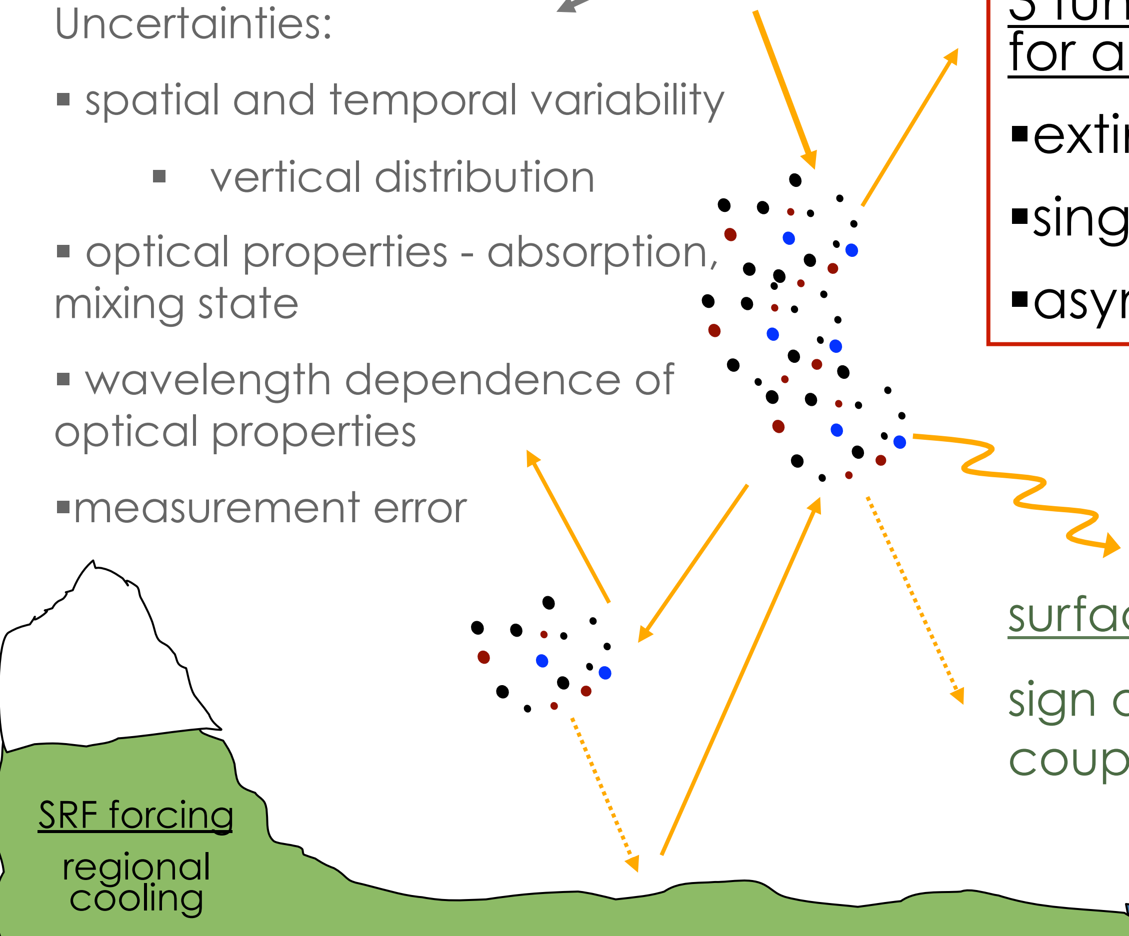
-0.27 [-0.77 to 0.23] W m^{-2}

Uncertainties:

- spatial and temporal variability
    - vertical distribution
- optical properties - absorption, mixing state
- wavelength dependence of optical properties
- measurement error

3 fundamental optical properties for aerosol radiative forcing

- extinction/optical depth
- single scattering albedo
- asymmetry parameter



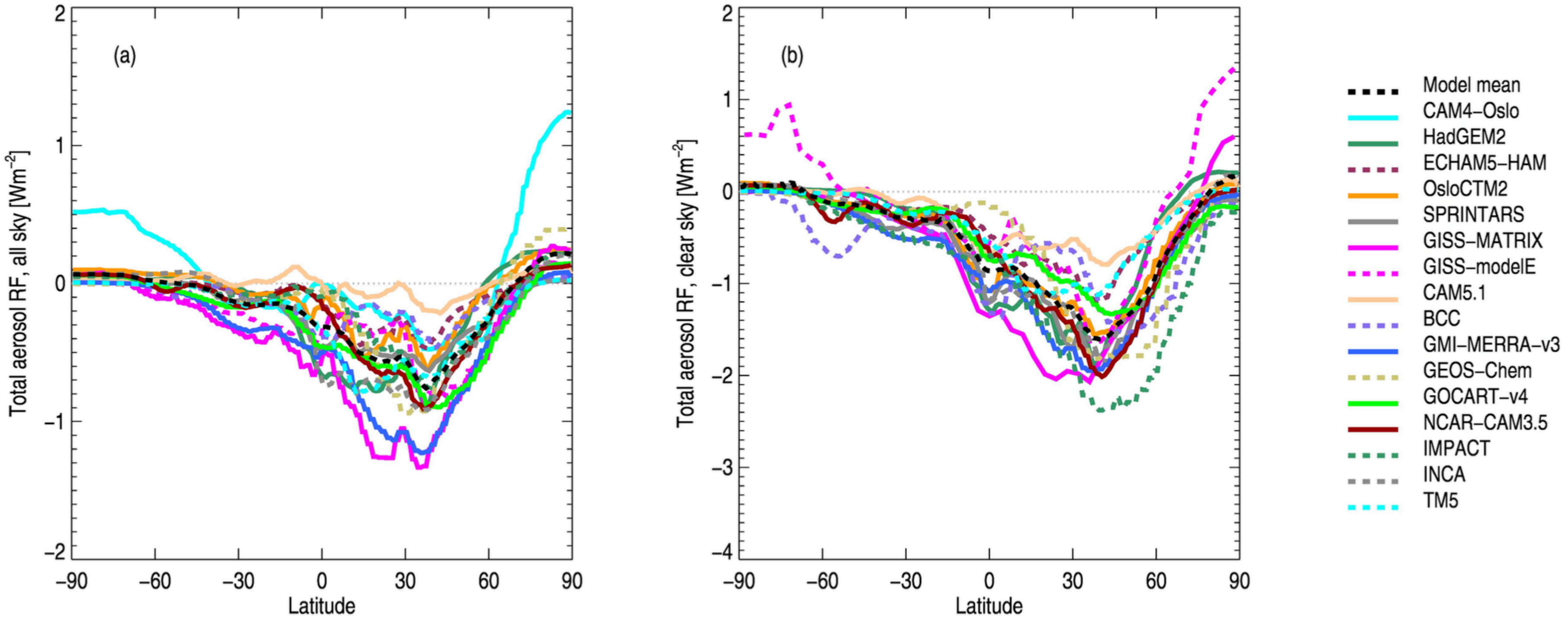
surface albedo

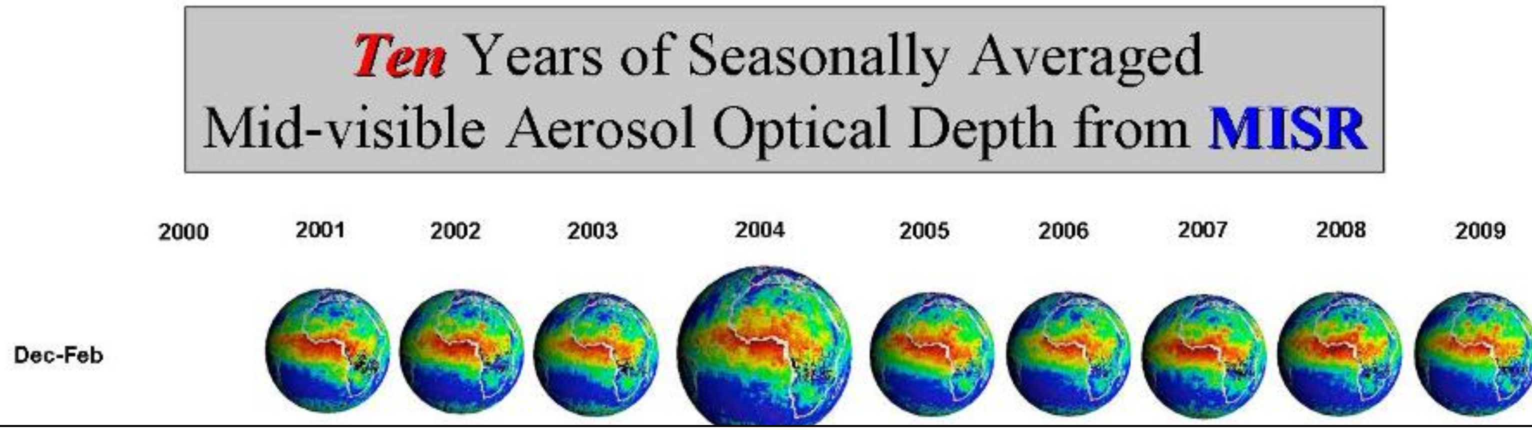
sign and magnitude dependent on coupled surface-atmosphere system

What are uncertainties for estimating aerosol radiative forcing?

The AeroCom Project:

Aerosol comparisons between observations and models

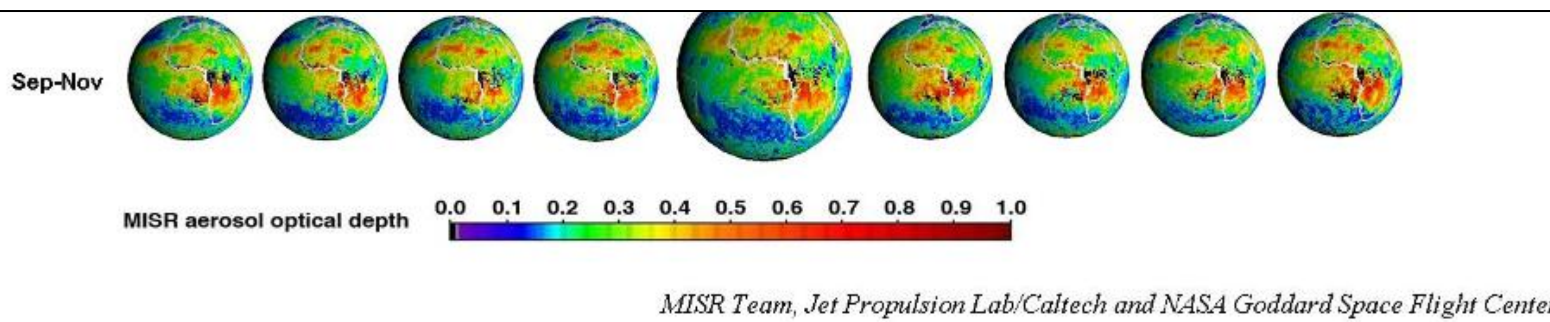




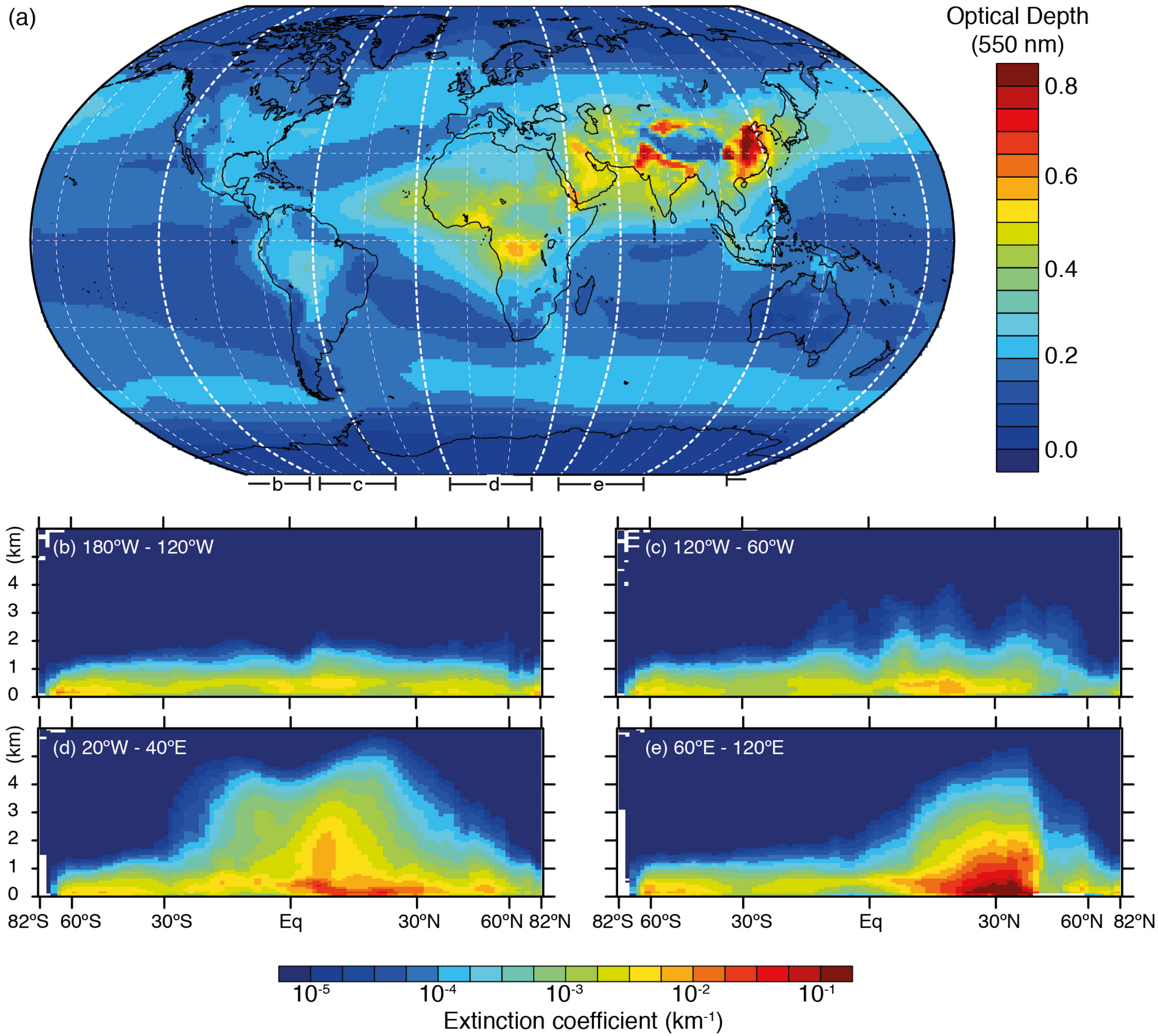
concentrations and distributions are remarkably seasonally consistent at a given location – why?

emissions and transport (meteorology) patterns are seasonally consistent

but what happens if emissions and circulation patterns change?



Aerosol optical depth horizontal and vertical distribution 8-year average: IPCC AR5



What are uncertainties for estimating aerosol radiative forcing?

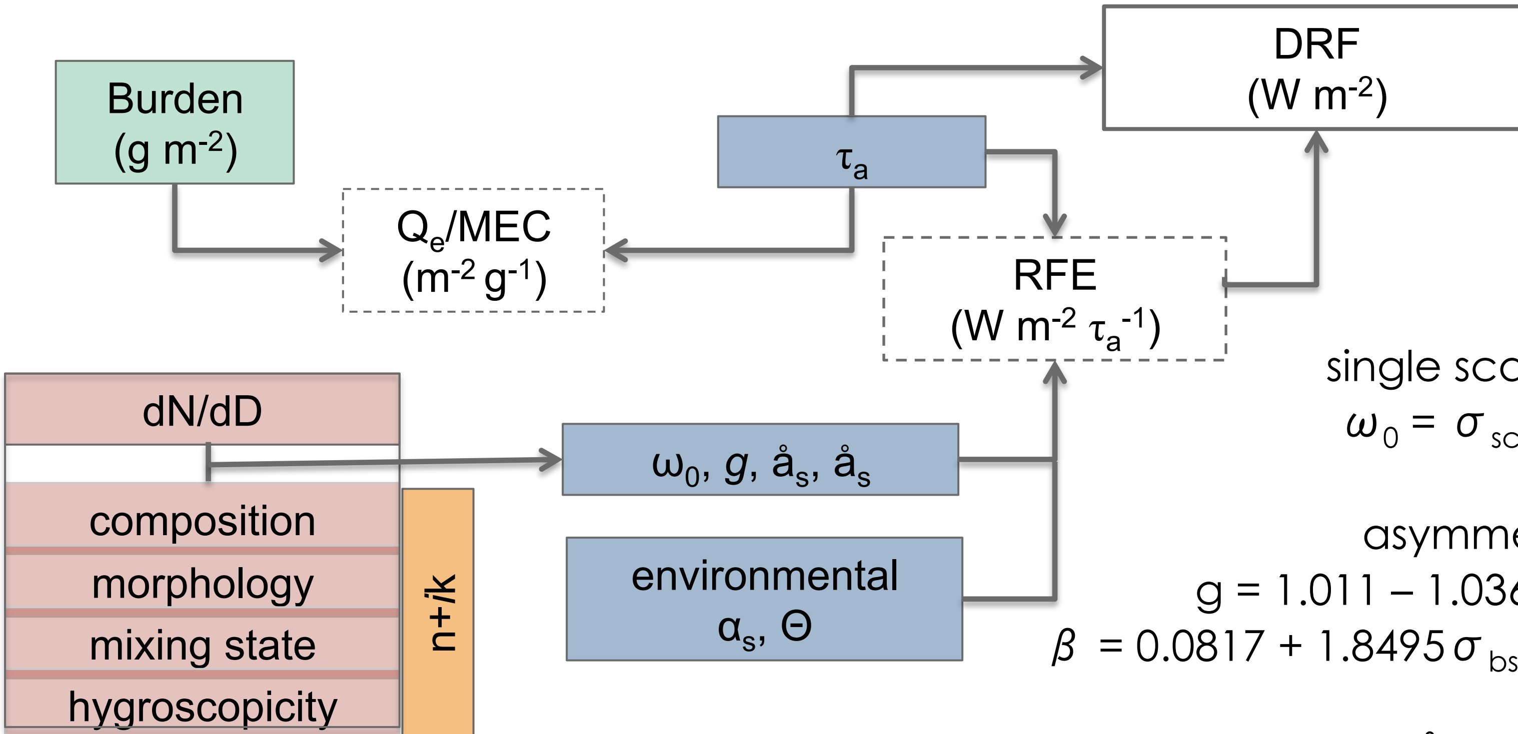
spatial distribution (horizontal and vertical) of aerosol amount and properties

- aerosol formation processes: emissions to burden
- composition & size distribution to optical properties
- optical properties to radiative fluxes

feedbacks

- aerosol heating and cooling effects on circulation, cloud development, temperature

Pathways to Calculating Aerosol Direct Radiative Forcing



single scattering albedo:
$\omega_0 = \sigma_{sca}/(\sigma_{sca} + \sigma_{abs})$

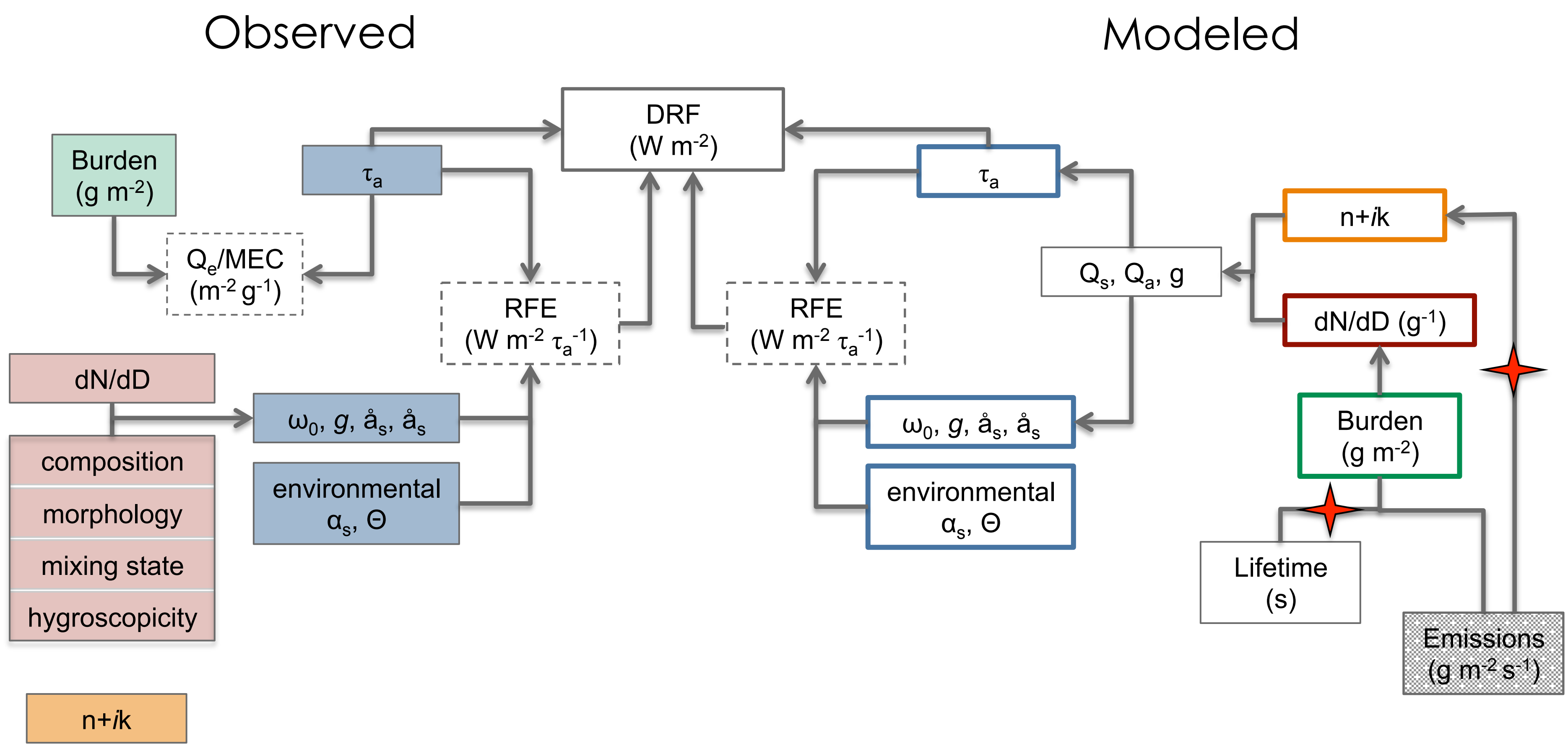
asymmetry parameter:
$g = 1.011 - 1.036\beta + 2.0059\beta^2$,
$\beta = 0.0817 + 1.8495\sigma_{bsca} - 2.9682\sigma_{bsca}^2$

scattering Ångström exponent:
$\alpha_{sca} = \log(\sigma_{sca\ 450\ nm}/\sigma_{sca\ 700\ nm})/\log(450/700)$

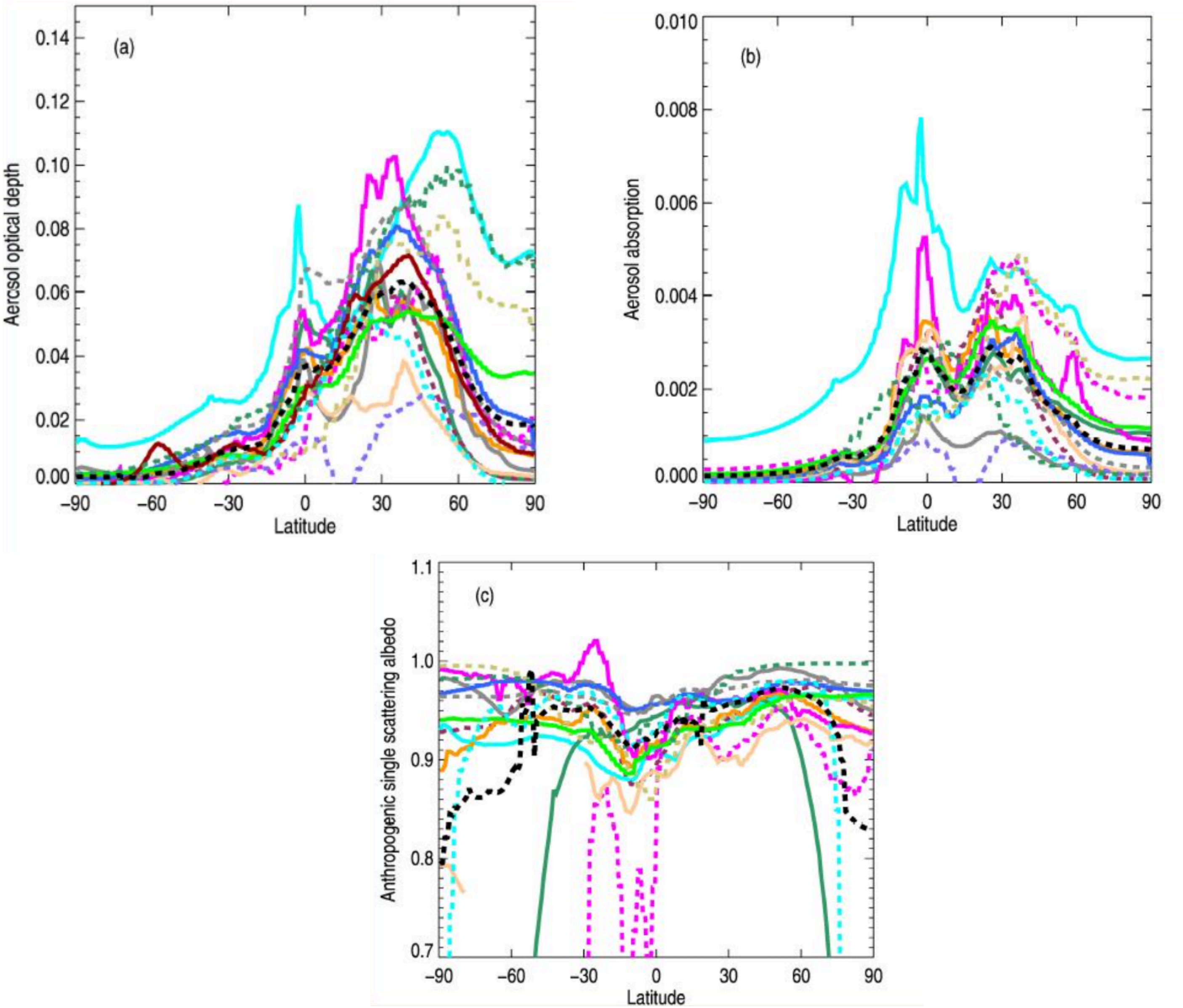
absorption Ångström exponent:
$\alpha_{abs} = \log(\sigma_{abs\ 450\ nm}/\sigma_{abs\ 700\ nm})/\log(450/700)$

extinction efficiency:
$Q_e = \text{total mass}/(\sigma_{sca} + \sigma_{abs})\ m^2\ g^{-1}$

Pathways to Aerosol Direct Radiative Forcing: Observed and Modeled



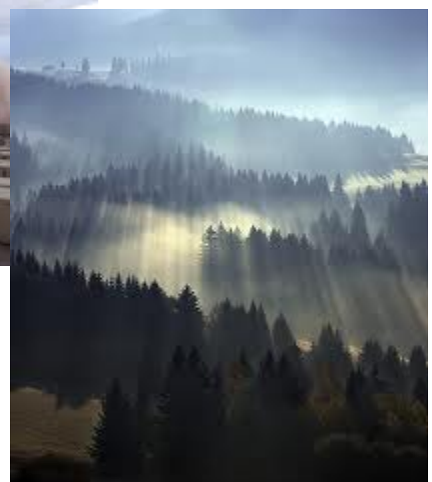
AeroCom Diversity in optical properties



What is an aerosol?

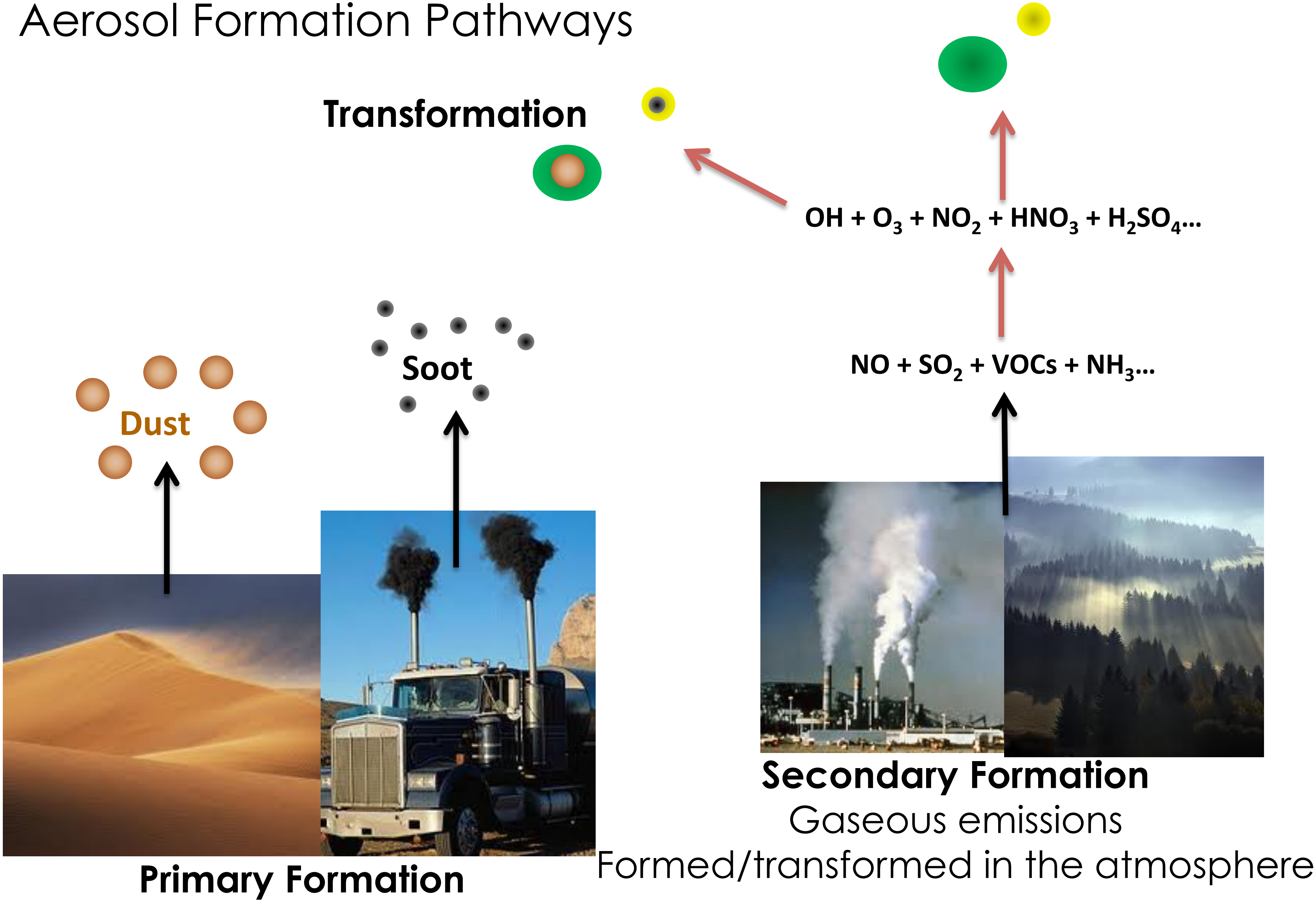
A liquid or solid particle suspended in a gas

Originate from natural and anthropogenic sources



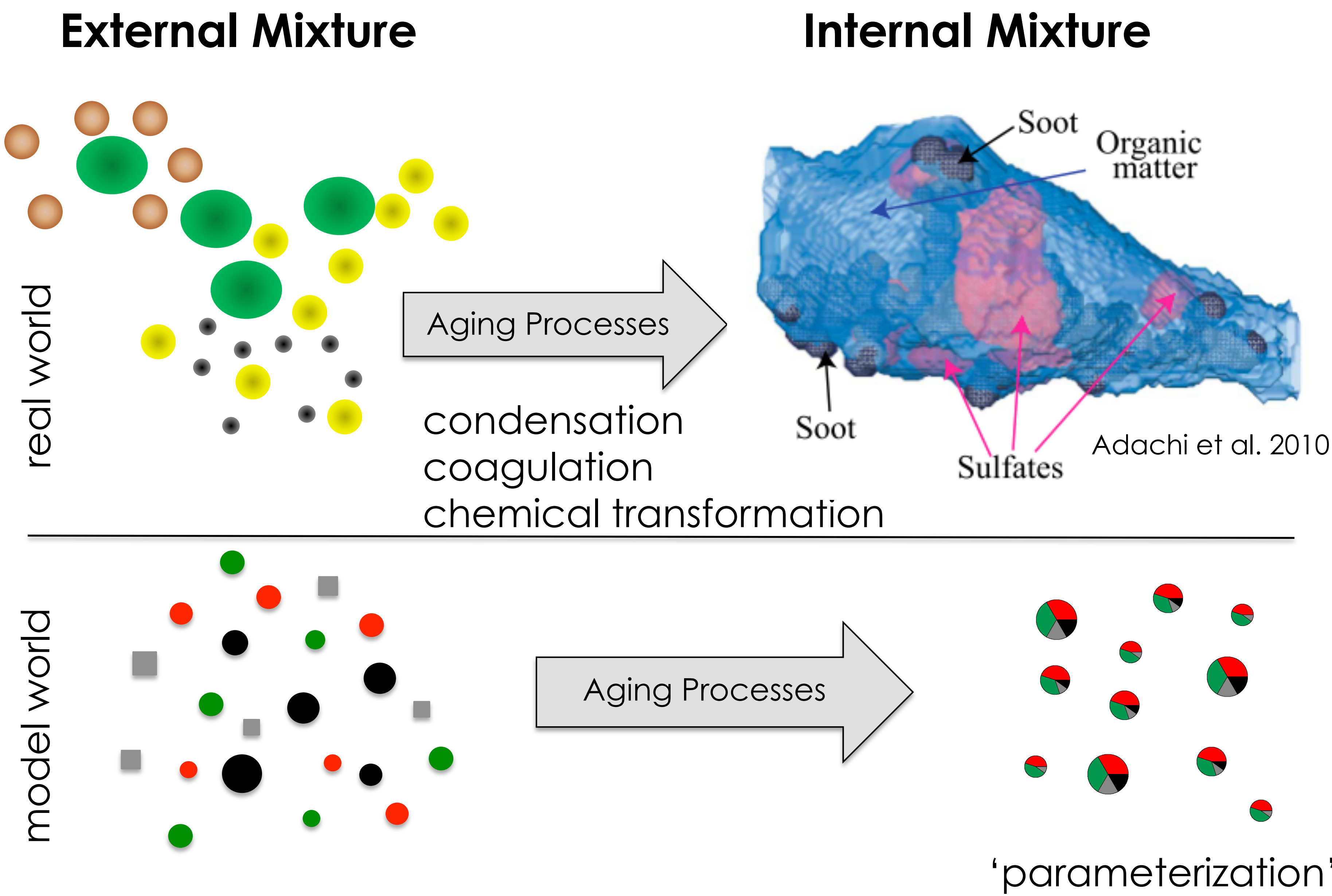
courtesy Jessie Creamean

Aerosol Formation Pathways



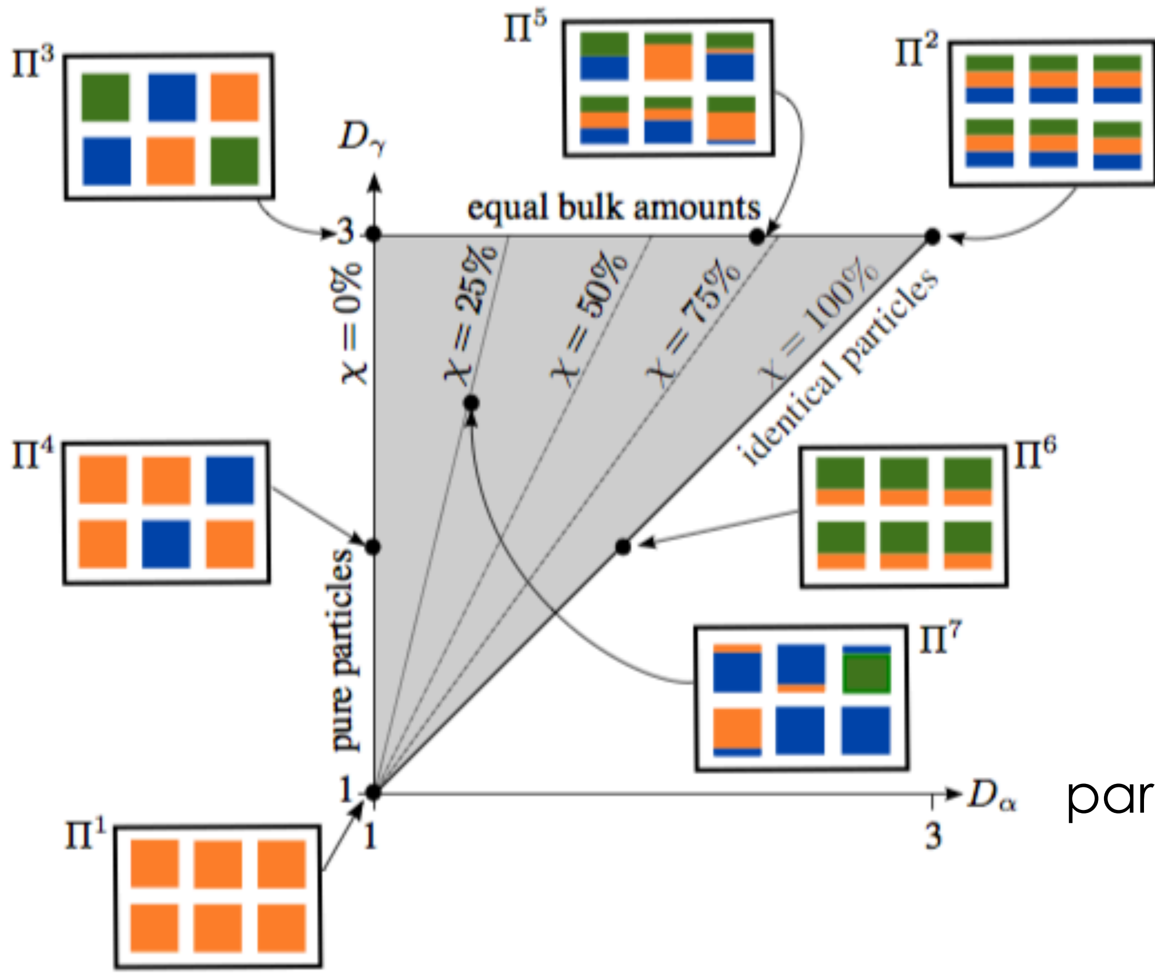
courtesy Jessie Creamean

Aerosol Mixing State



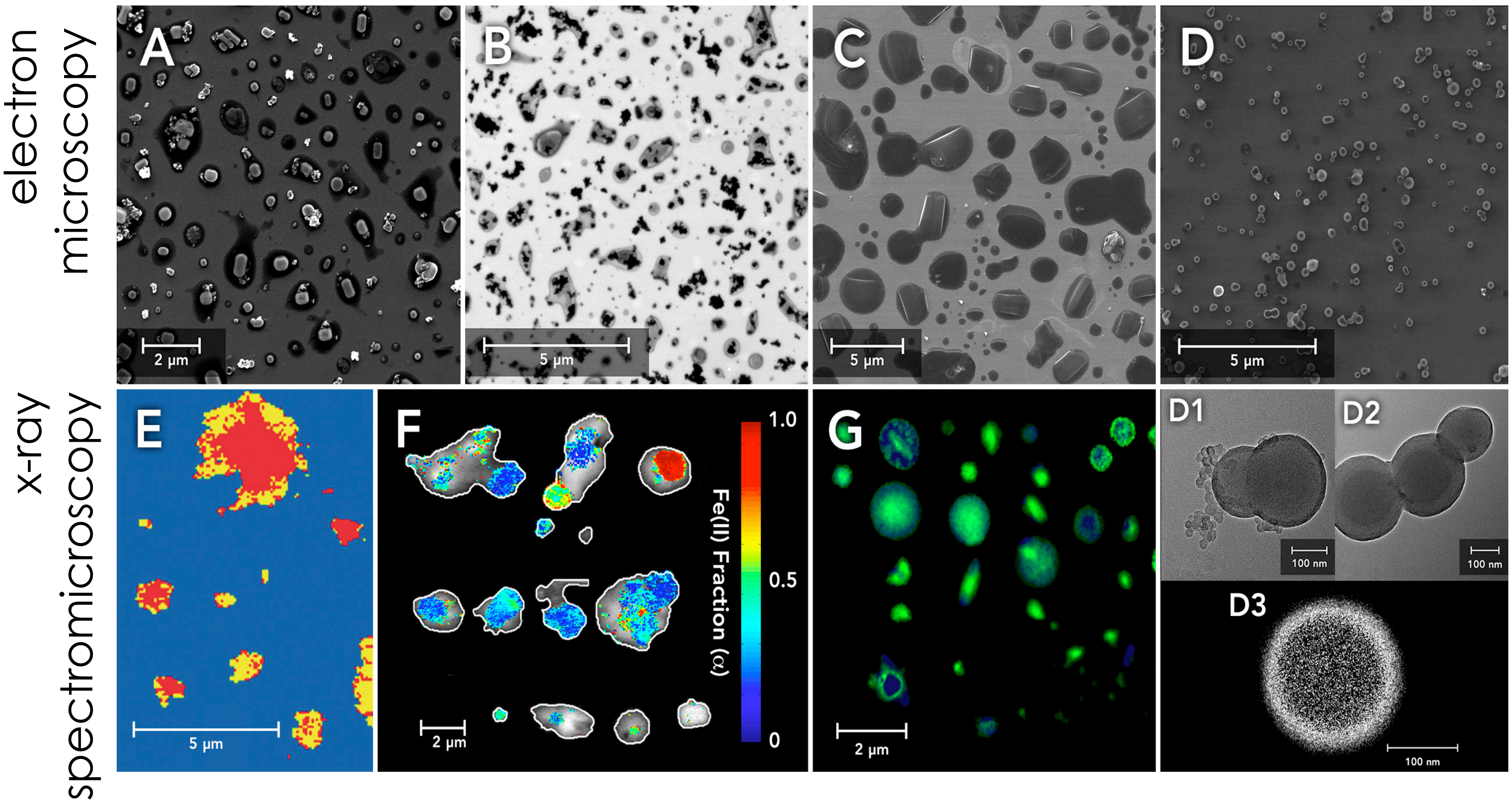
the Mixing State Index χ

bulk diversity



particle diversity

Riemer and West 2013

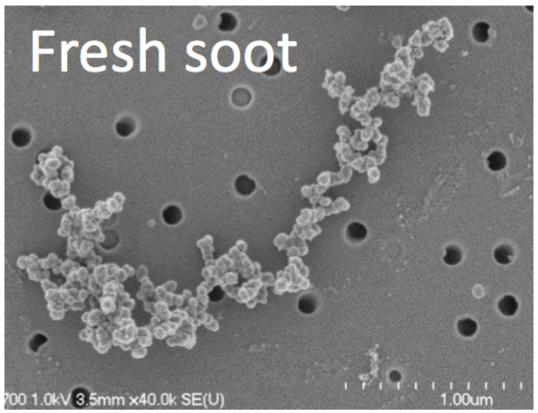


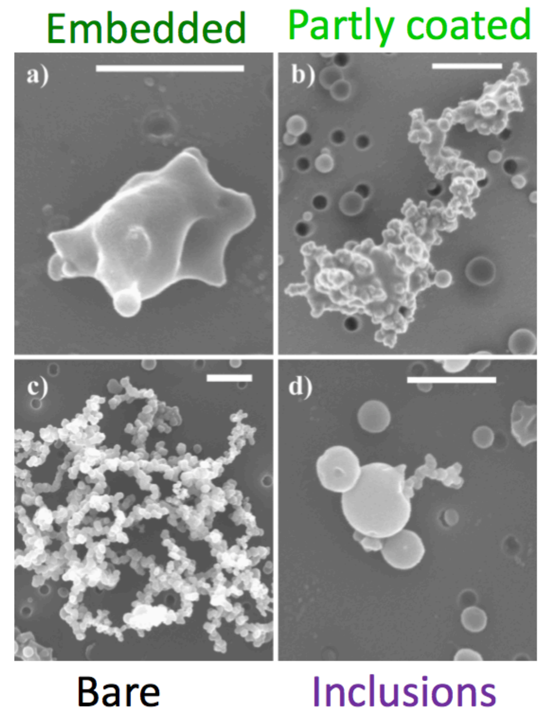
E - Marine particles collected at Pt. Reyes National Shore Park, California. Red and yellow colors indicate the internal distribution of two different oxidation states of sulfur (S(IV) and S(VI)) inside individual particles (Liu et al. 2011b)

F - Atmospheric dust particles collected on Okinawa Island, Japan. Color scale indicates fraction of Fe(II) present in individual particles (Moffet et al. 2012)

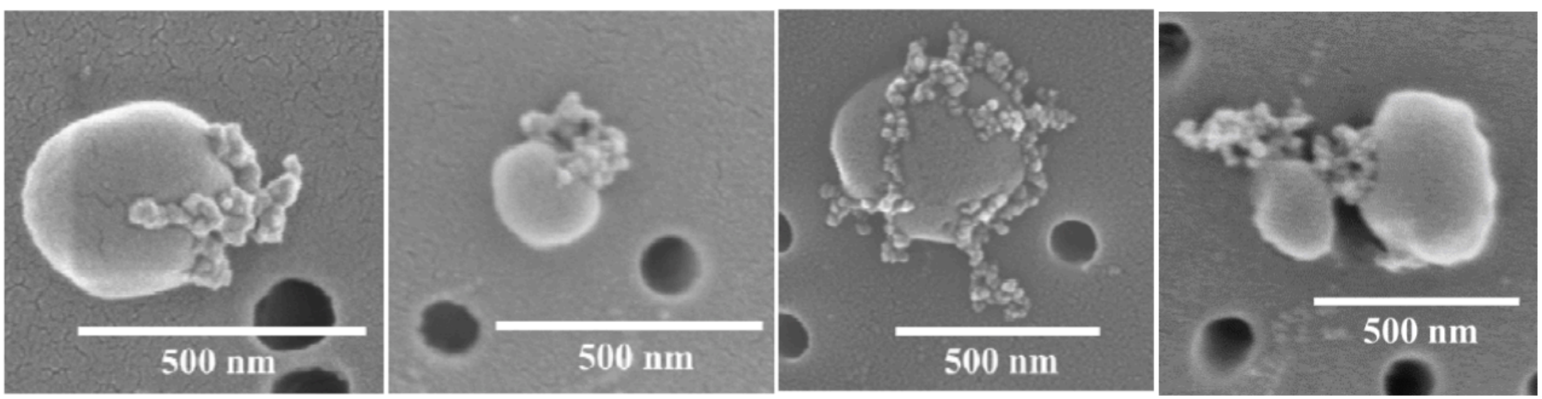
G - Marine particles (blue) internally mixed with anthropogenic organic material (green) collected in vicinity of Sacramento, California (Laskin et al. 2012b)

Aerosol Morphology



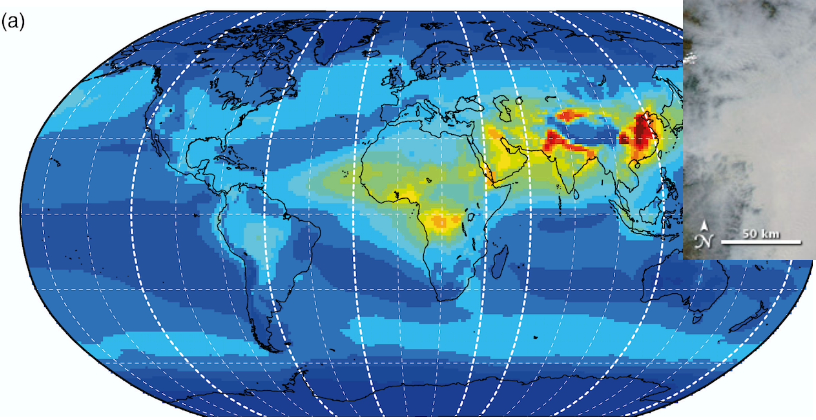


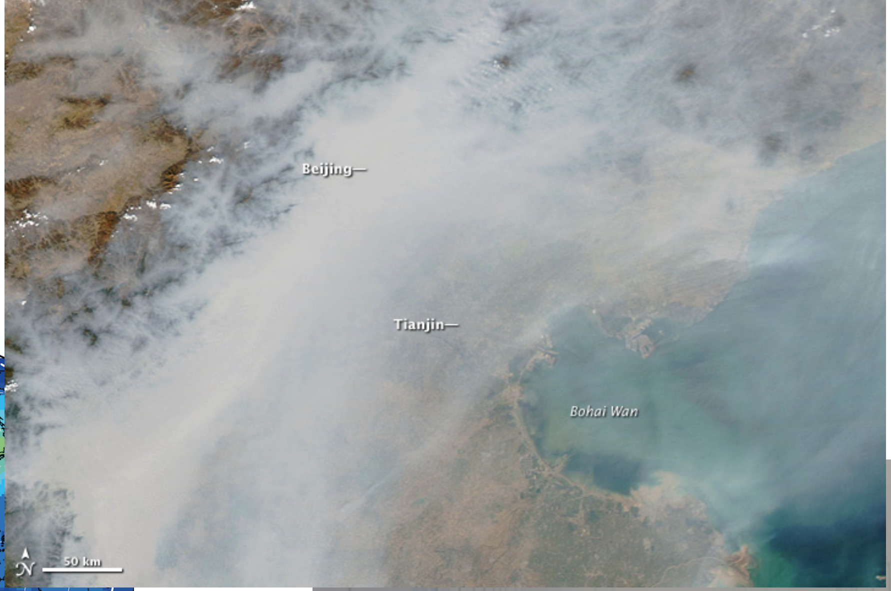
[China et al., 2013]

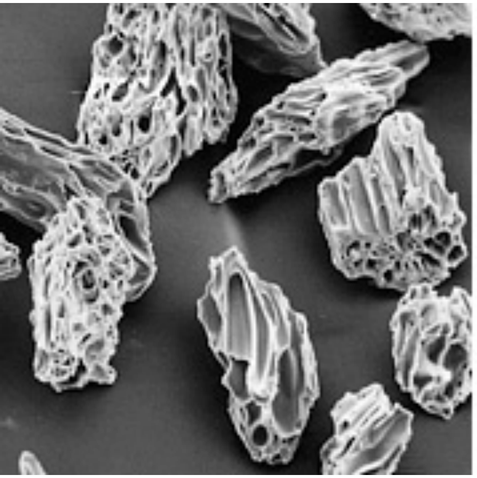


Soot morphology and mixing: Sacramento 2010

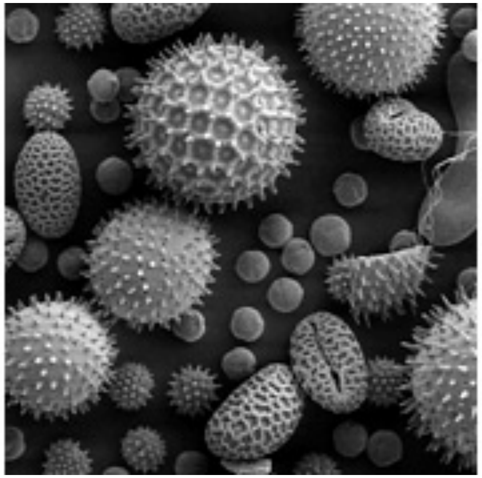
courtesy Claudio Mazzoleni



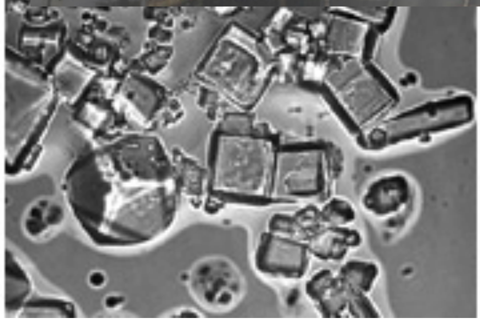




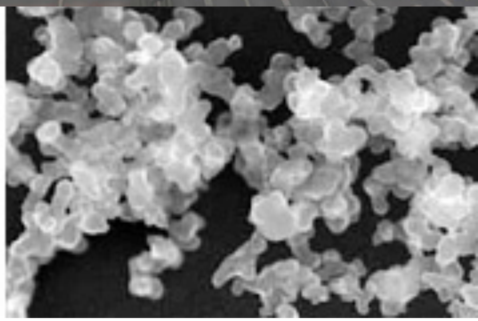
volcanic ash



pollen

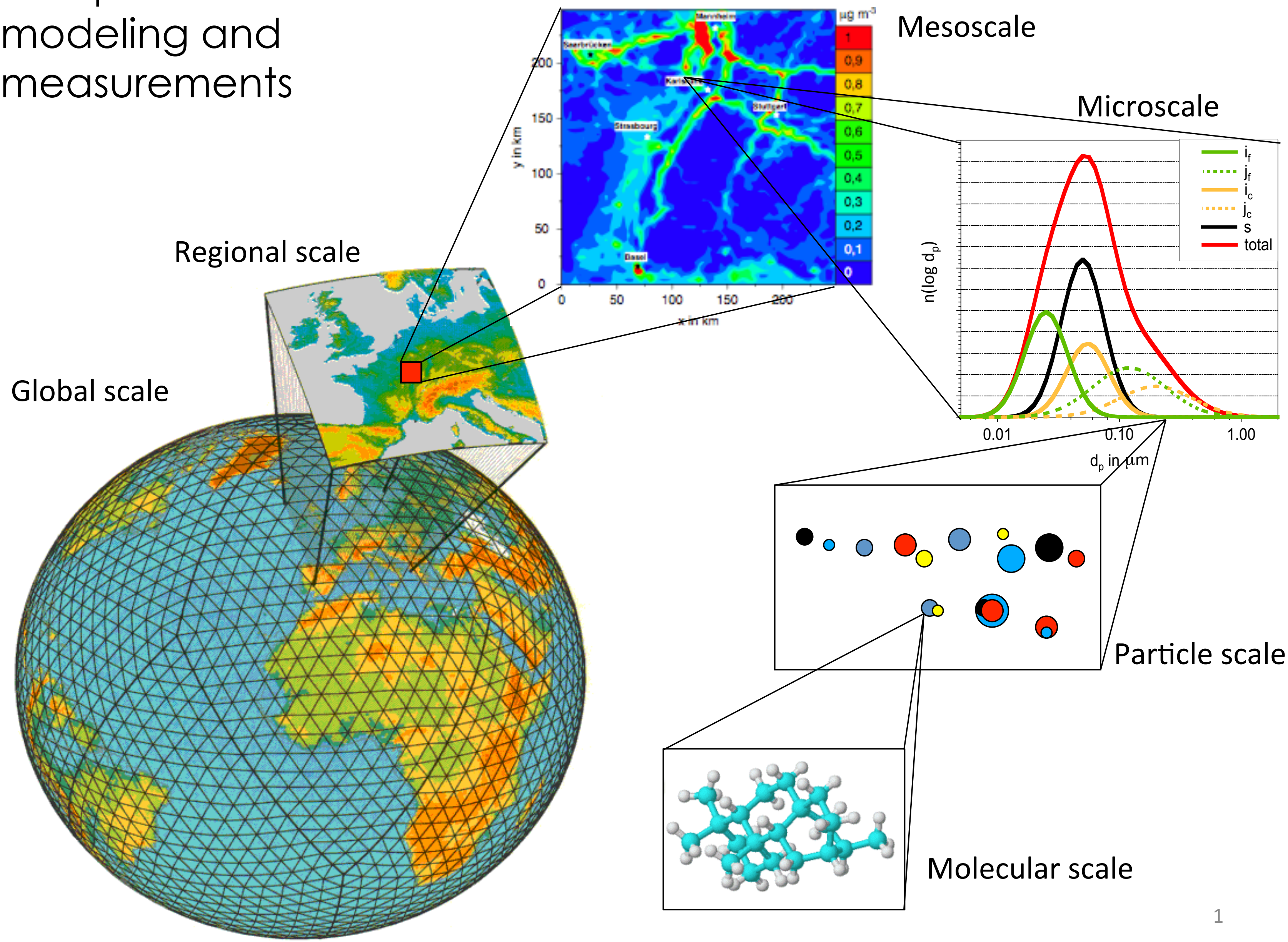


sea salt



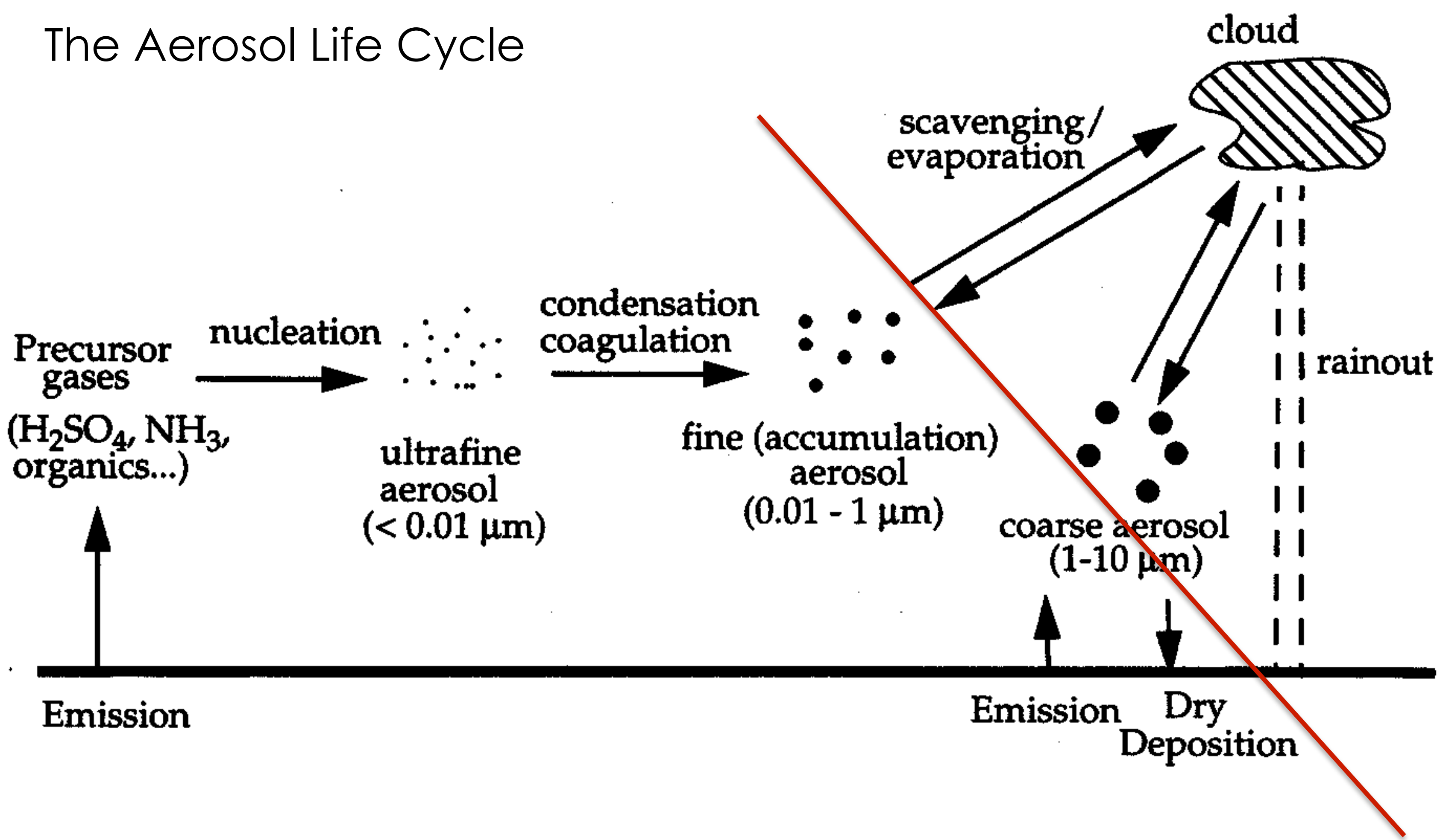
soot

Multiple scales for modeling and measurements

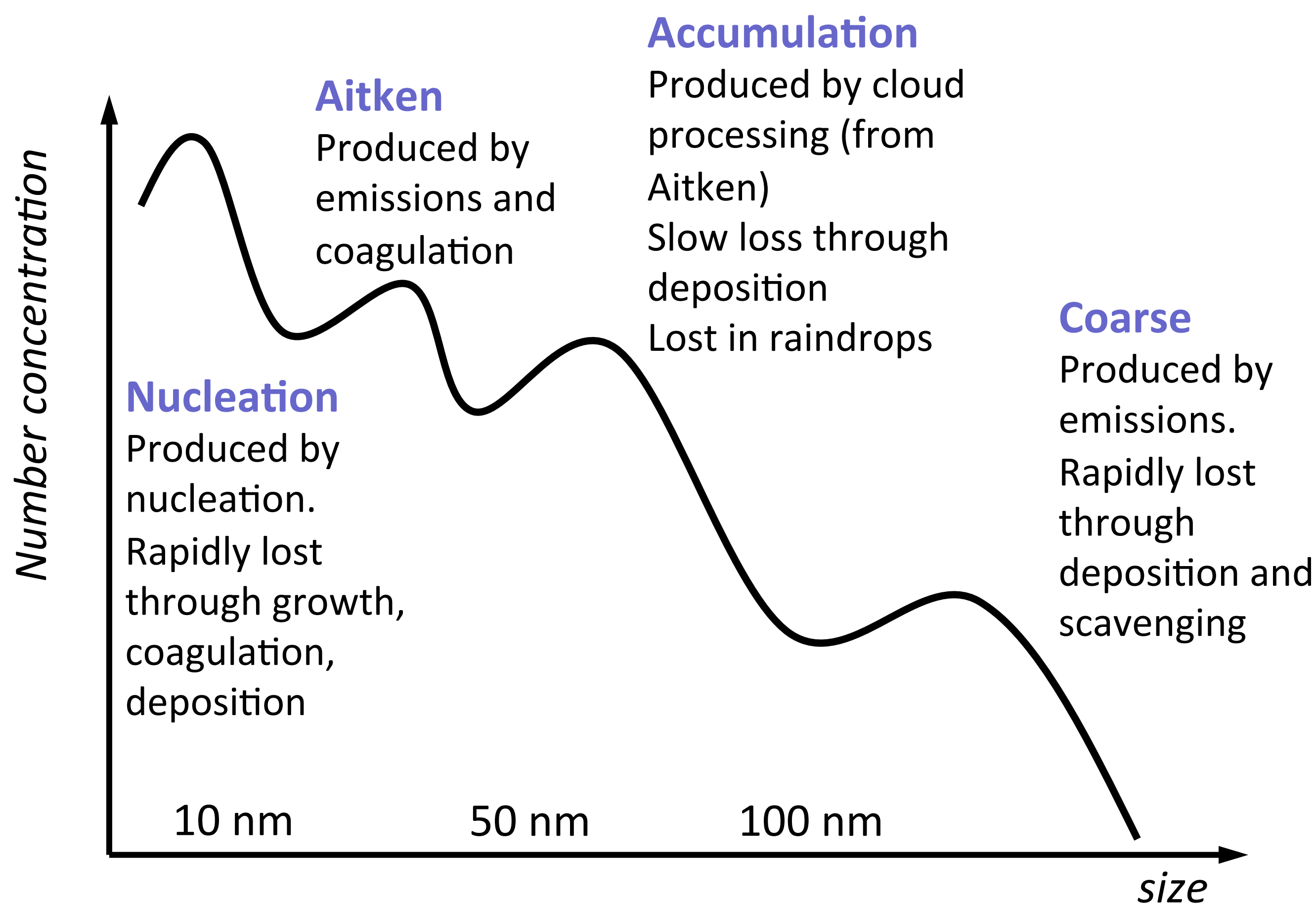


courtesy N. Riemer

The Aerosol Life Cycle

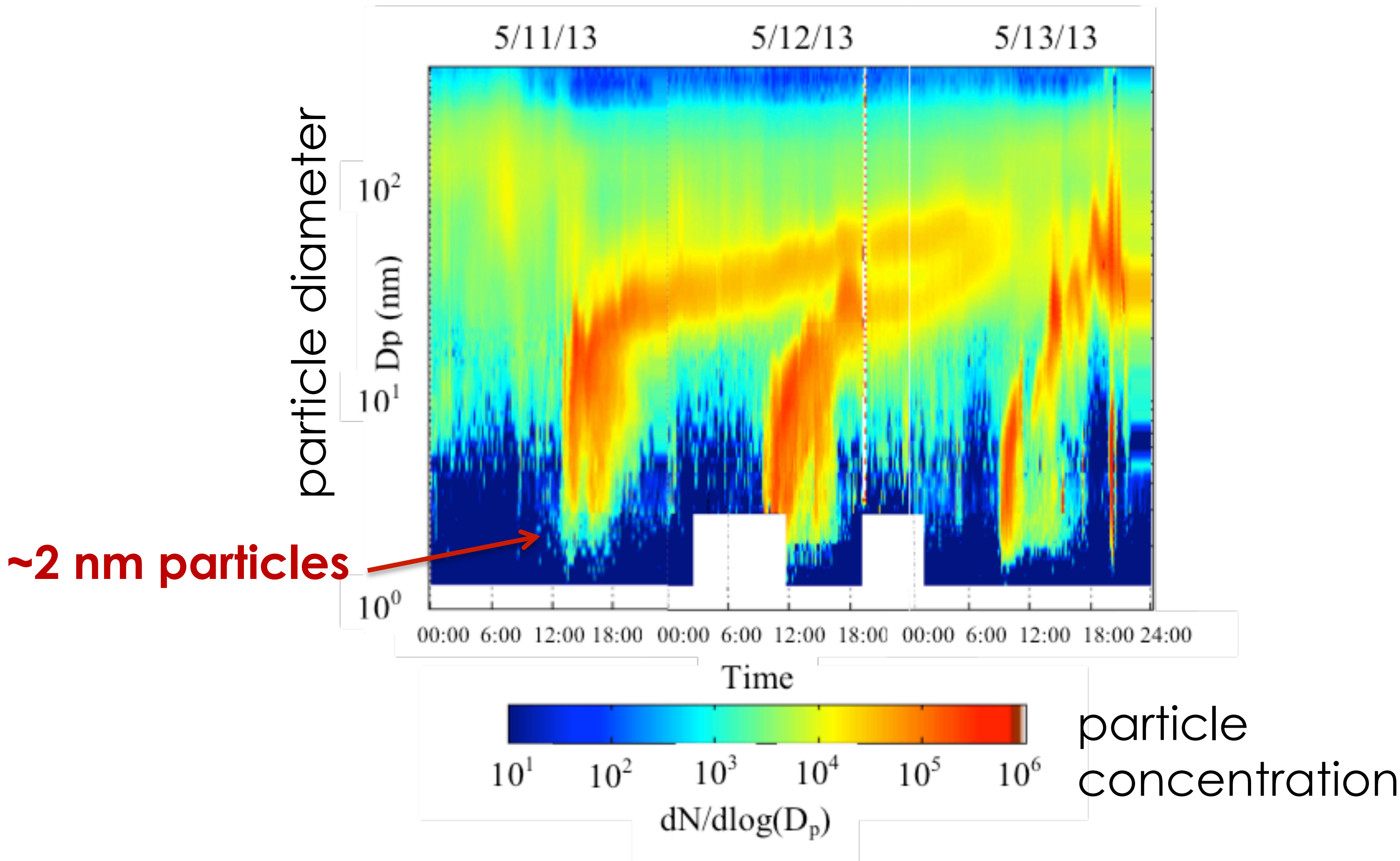


Aerosol size distributions:
function of emissions, formation, and processing



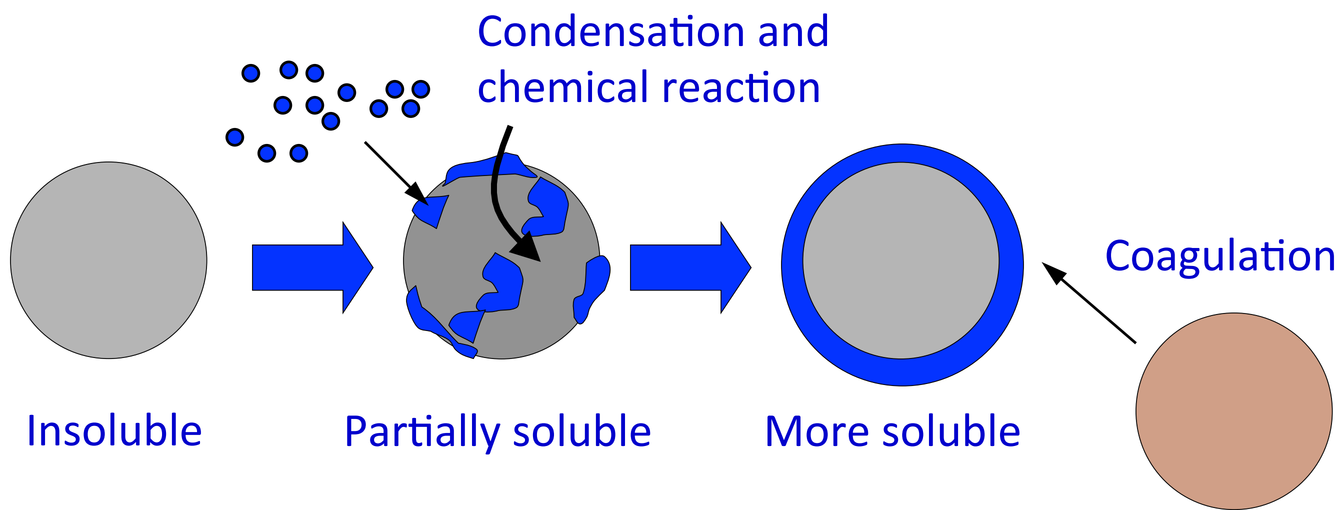
Size is the most fundamental parameter for determining aerosol optical properties and radiative effects.

Aerosol Nucleation
New Particle Formations events at SGP



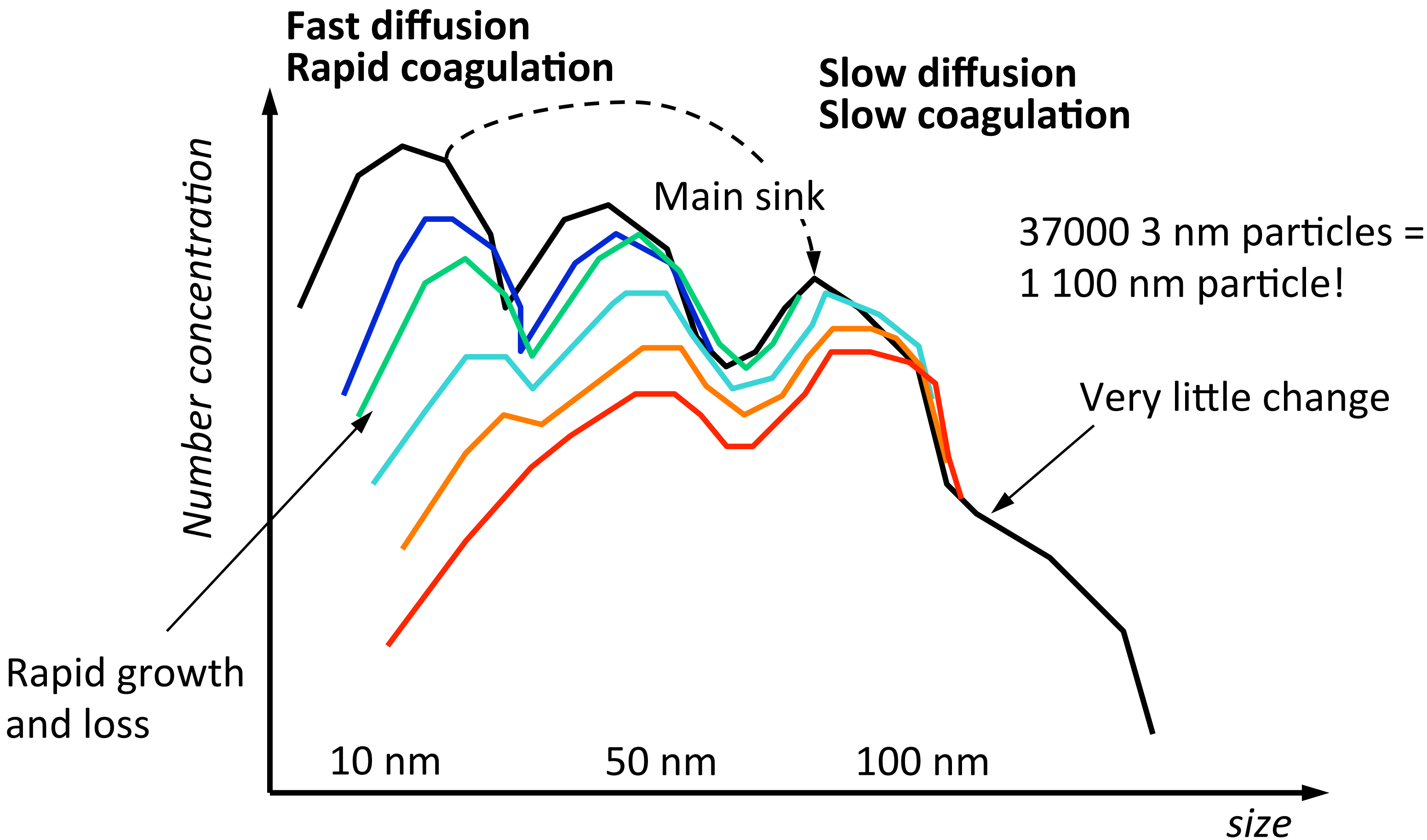
courtesy Peter McMurry and Jim Smith

Aging Processes

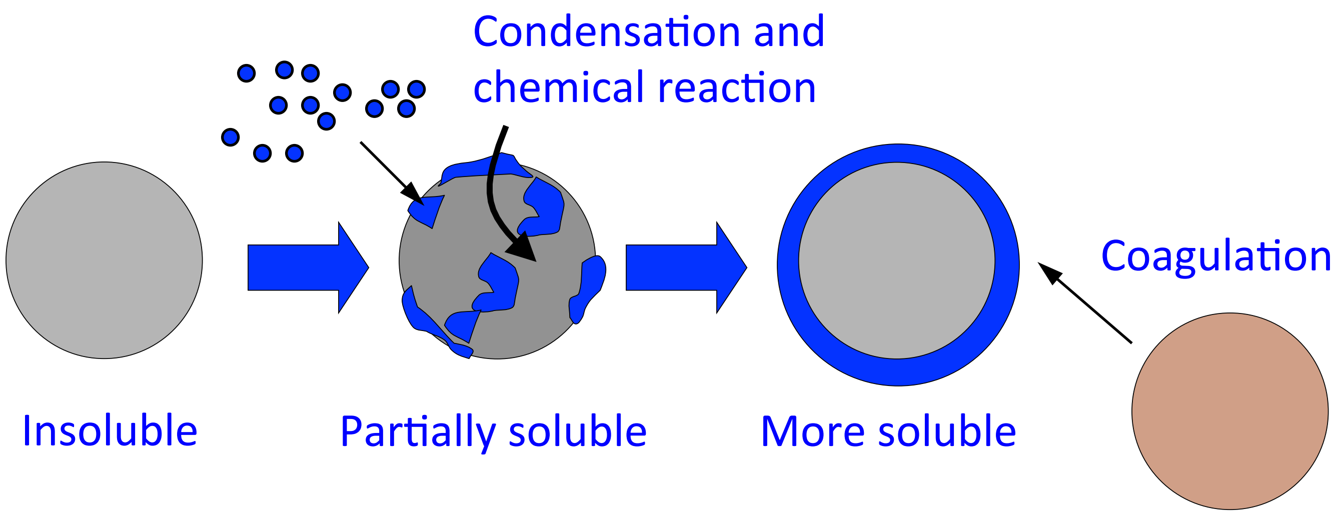


- some primary particles are initially insoluble
- can become partly soluble through
  - coagulation
  - chemical transformation
  - condensation
- results in
  - varied optical properties
  - greater CCN activity

Growth and coagulation



Aging Processes



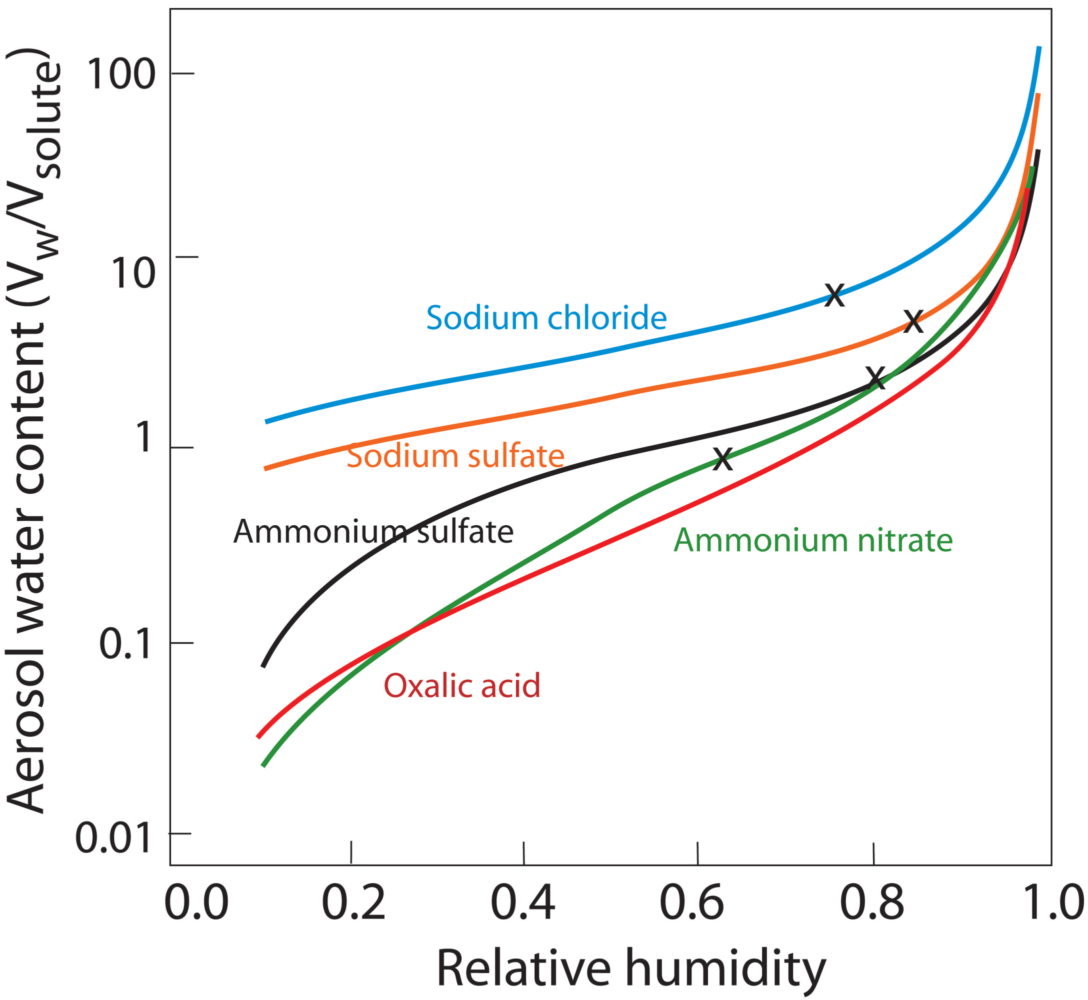
Rate of ageing: time to form 1 monolayer (~10^{19} molec m^{-2}) of H_2SO_4 on a 100 nm particle

- **~10^4s (3 h)** in <u>polluted conditions</u> (H_2SO_4 = 10^7 cm^{-3})
- **~10^5 – 10^6 s (1-10 days)** in <u>clean conditions</u>
- Factor >10 longer for coarse particles

these processes coupled with meteorology determine the spatial distribution of aerosol and their radiative properties

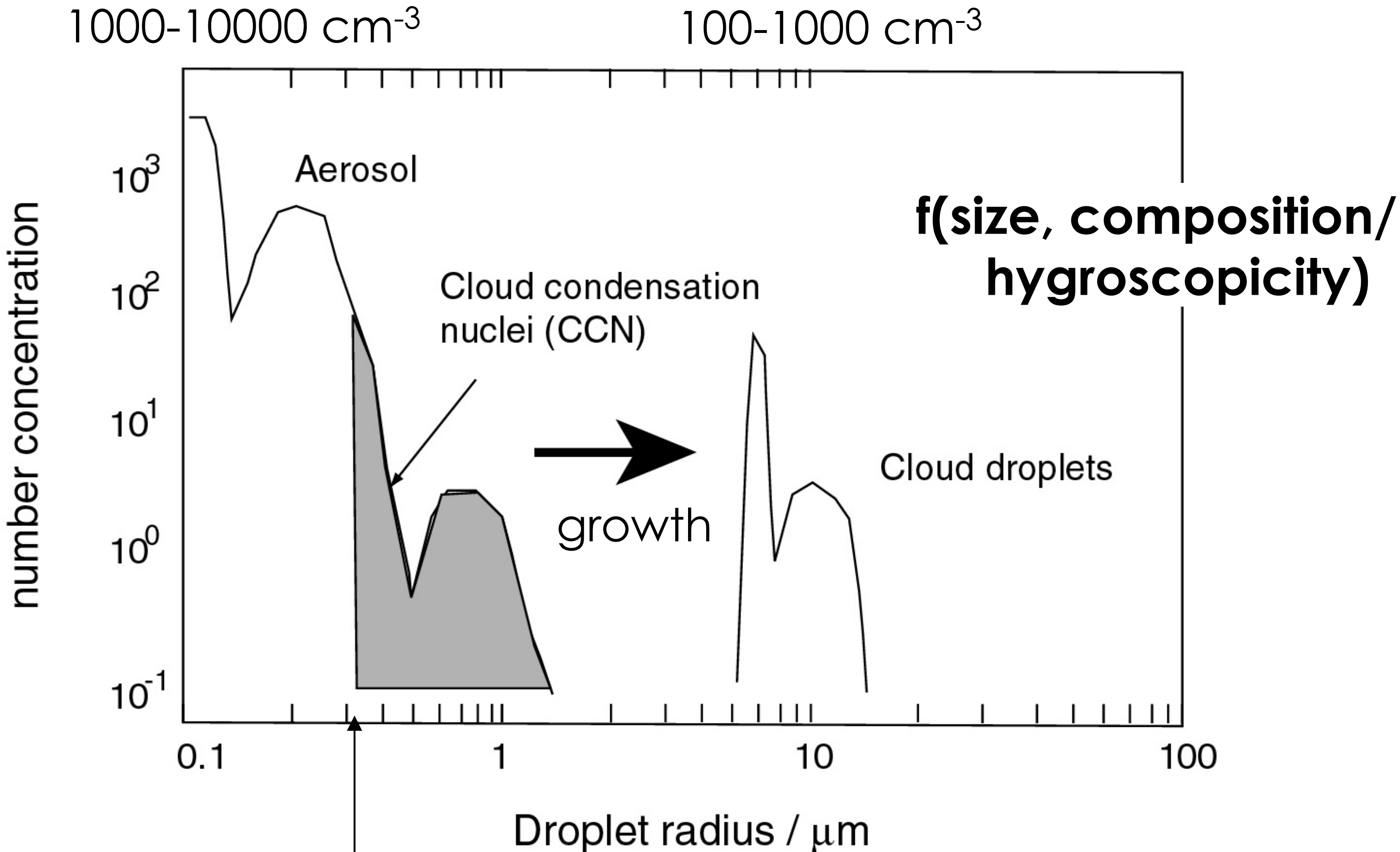
Hygroscopicity
measure of water uptake by soluble particles

- Reversible process (deliquescence, effloresence)
- f(RH, composition)
- Timescale for water equilibration ~ seconds



Petters and Kreidenweis, 2007

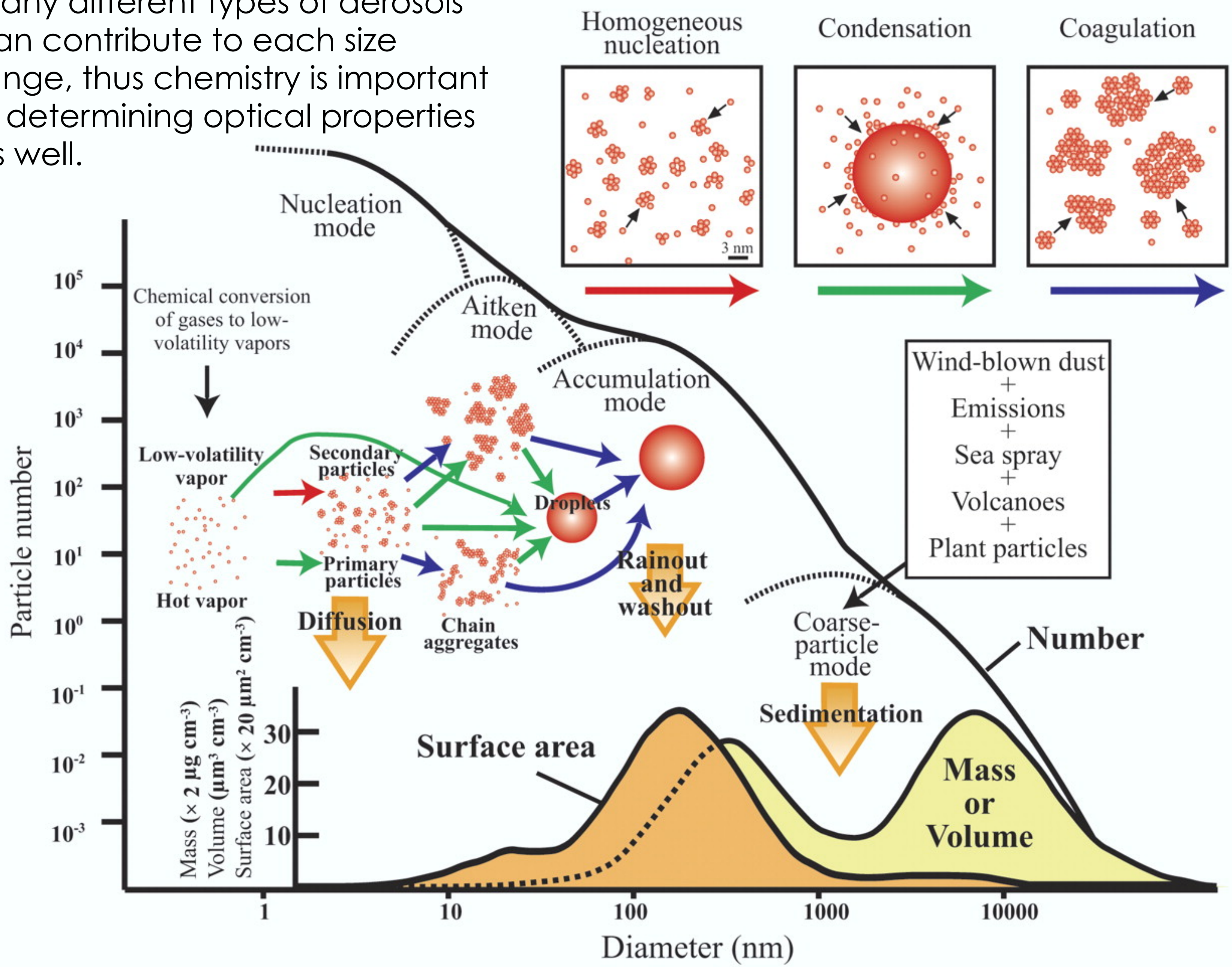
Particle activation in clouds



maximum supersaturation in cloud
equates to minimum radius of activation

Size is the most fundamental parameter for aerosol radiative effects.

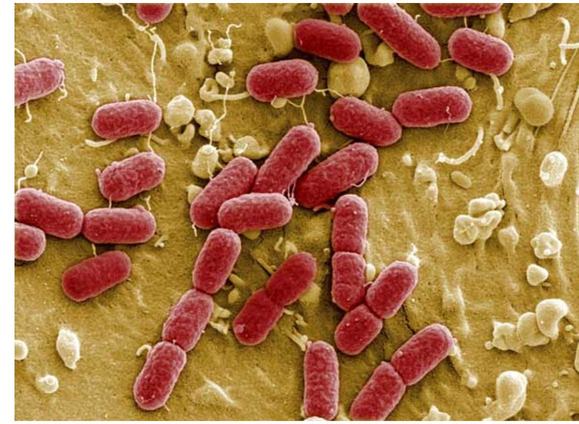
Many different types of aerosols can contribute to each size range, thus chemistry is important in determining optical properties as well.



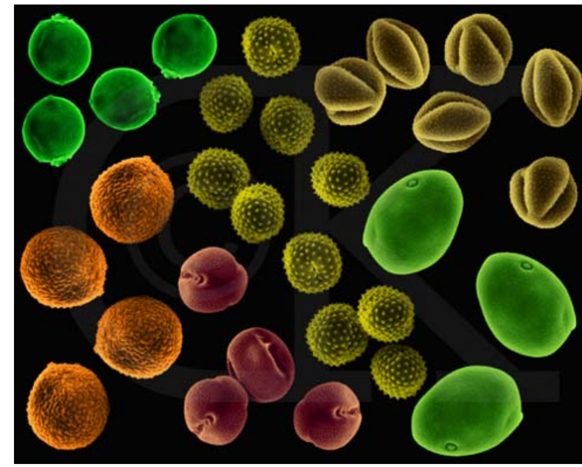
Bioaerosol sources

- "Bioaerosol" comprises particles from viruses (10's of nm) to pollen and leaf fragments (100's of um)
- Some are emitted actively and some passively

Bacteria ~1 um



Pollen > ~10 um



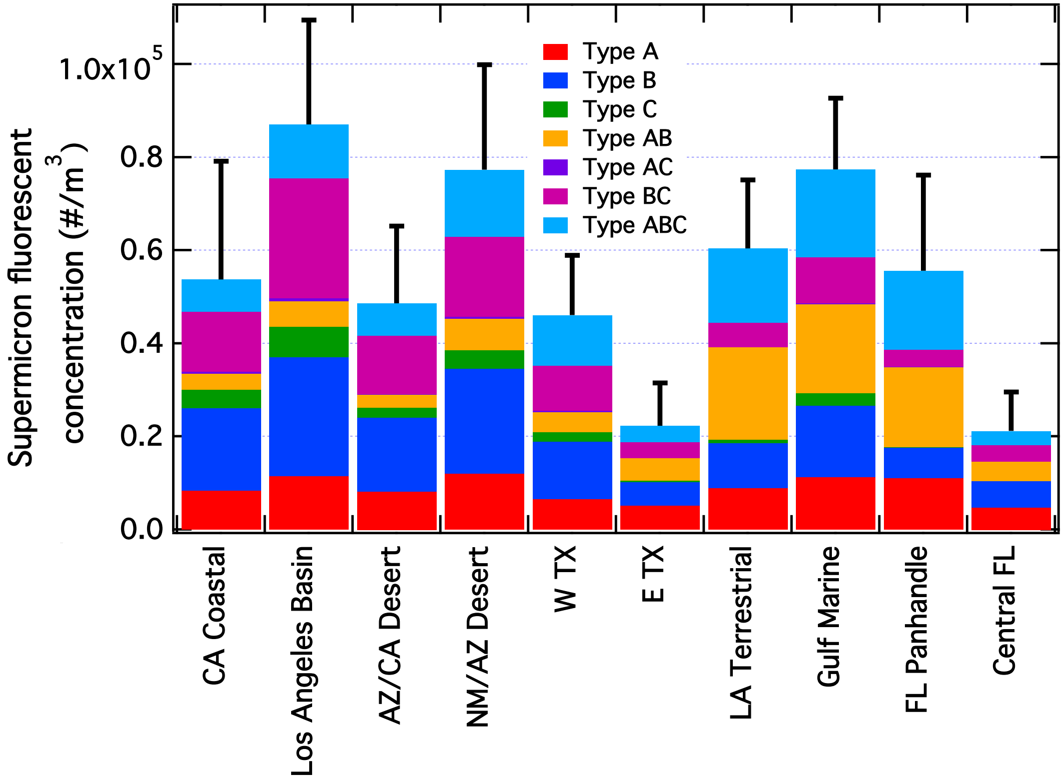
Fungal spores: 2-10 um

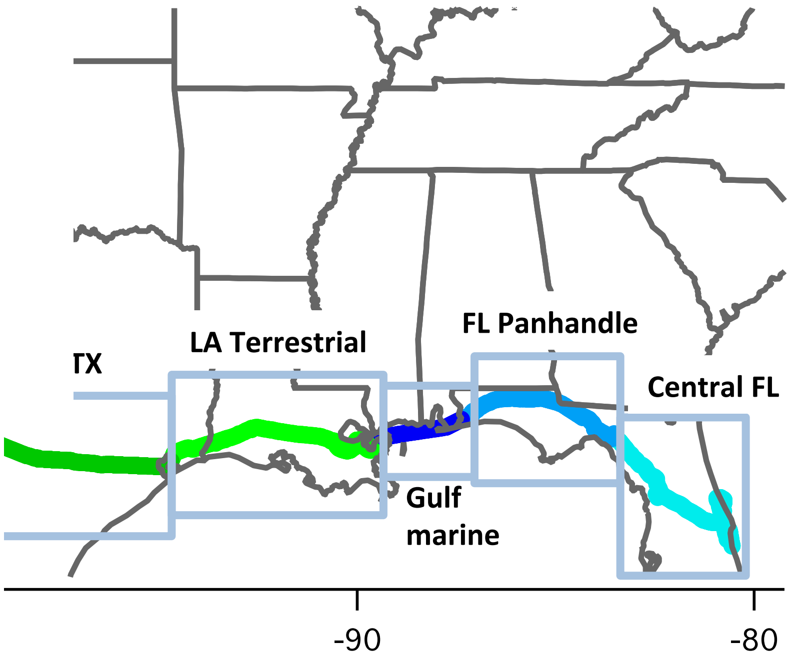
courtesy Anne Perring

Yafetto et al, 2008

CloudLab

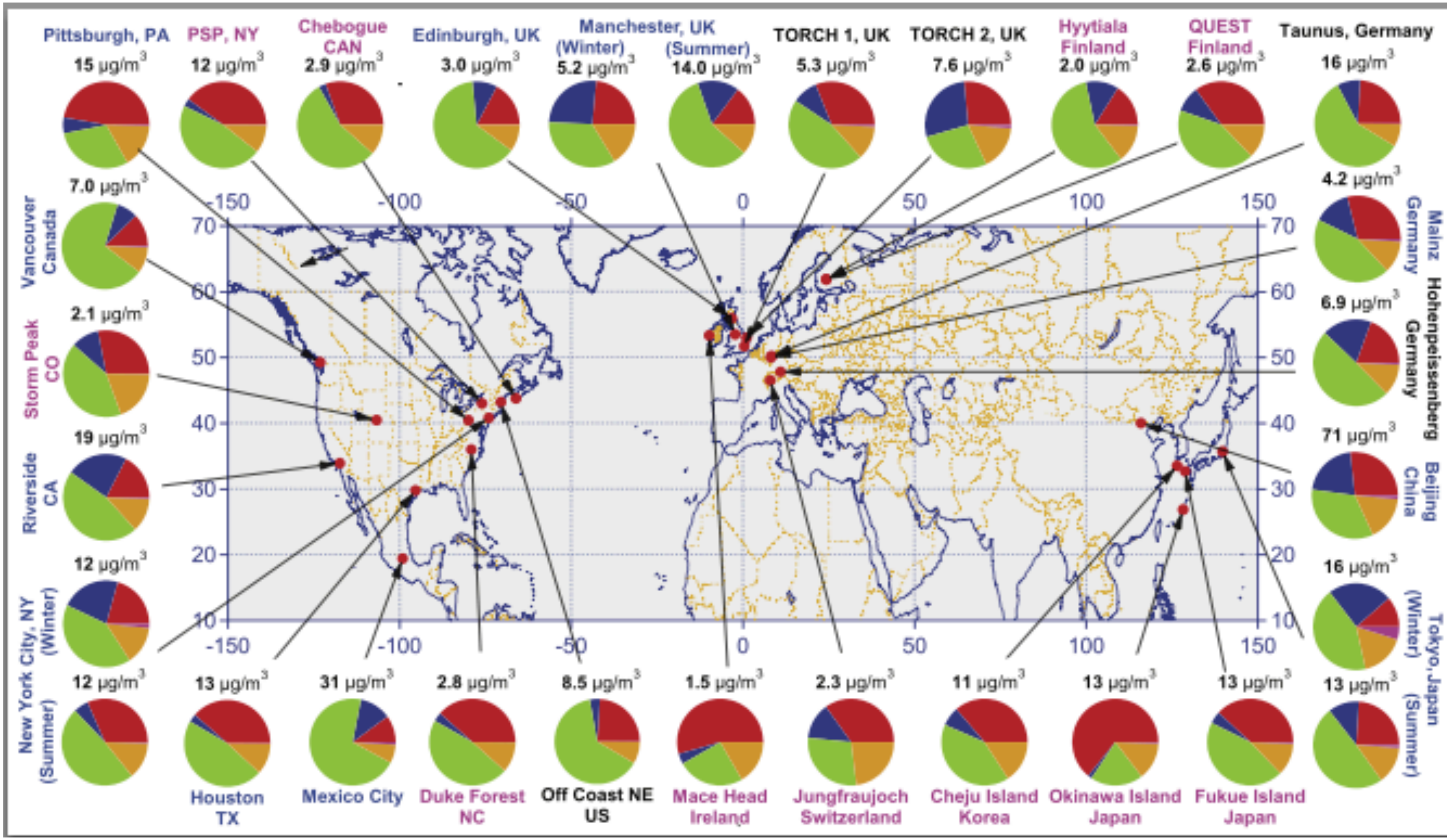
- ~1 month study from Sept – Oct 2013
- Most sampling at 300m, some excursions up to 1 km.
- In addition to the WIBS, the blimp was equipped with:
  - SP2 (Black carbon)





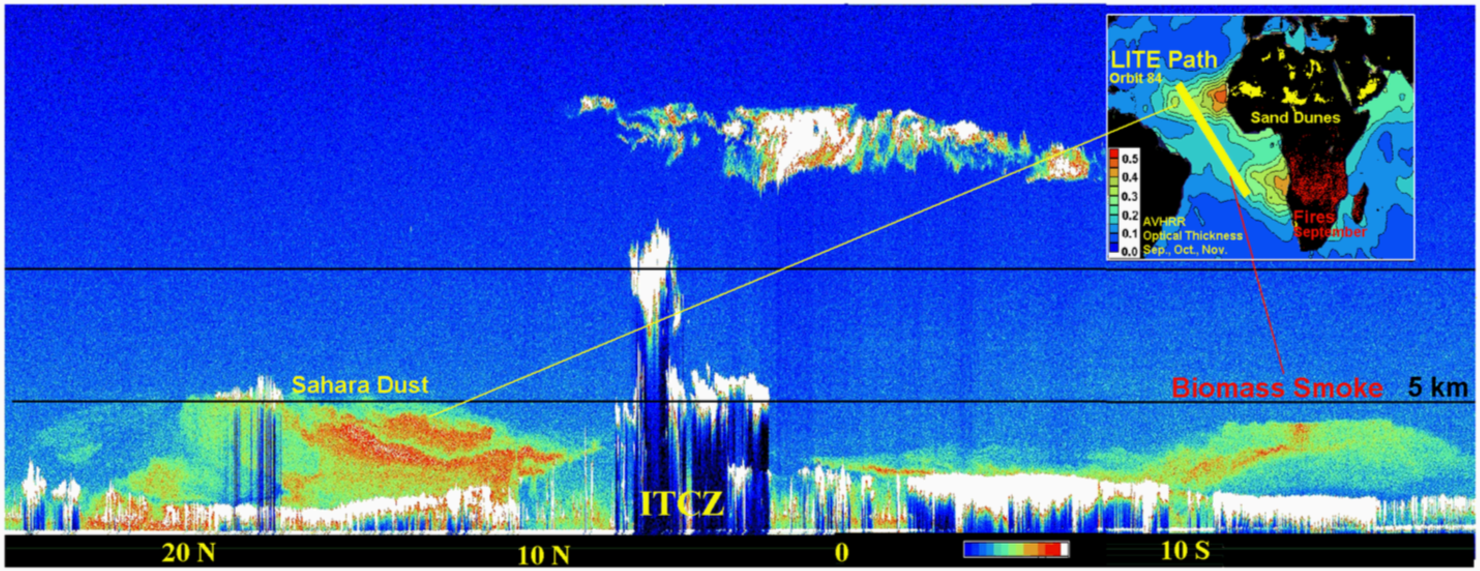
Perring et al, JGR, 2015

Global distribution of aerosol chemical composition

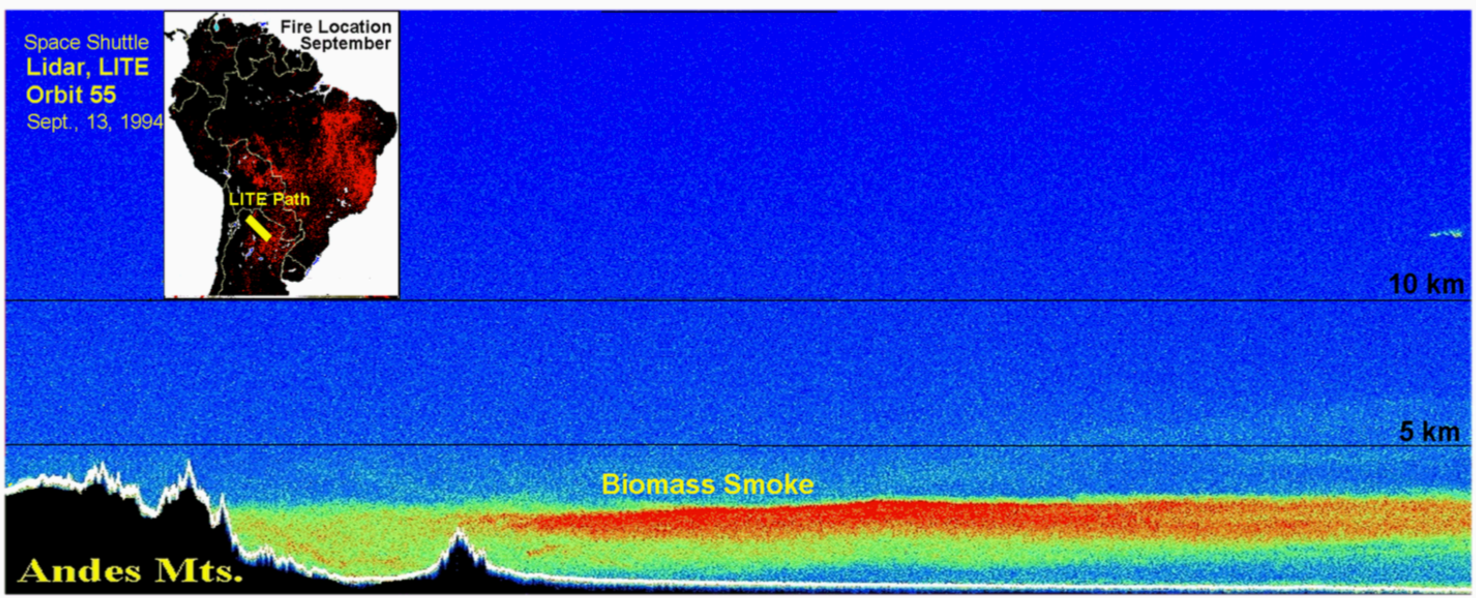


Zhang et al. 2007

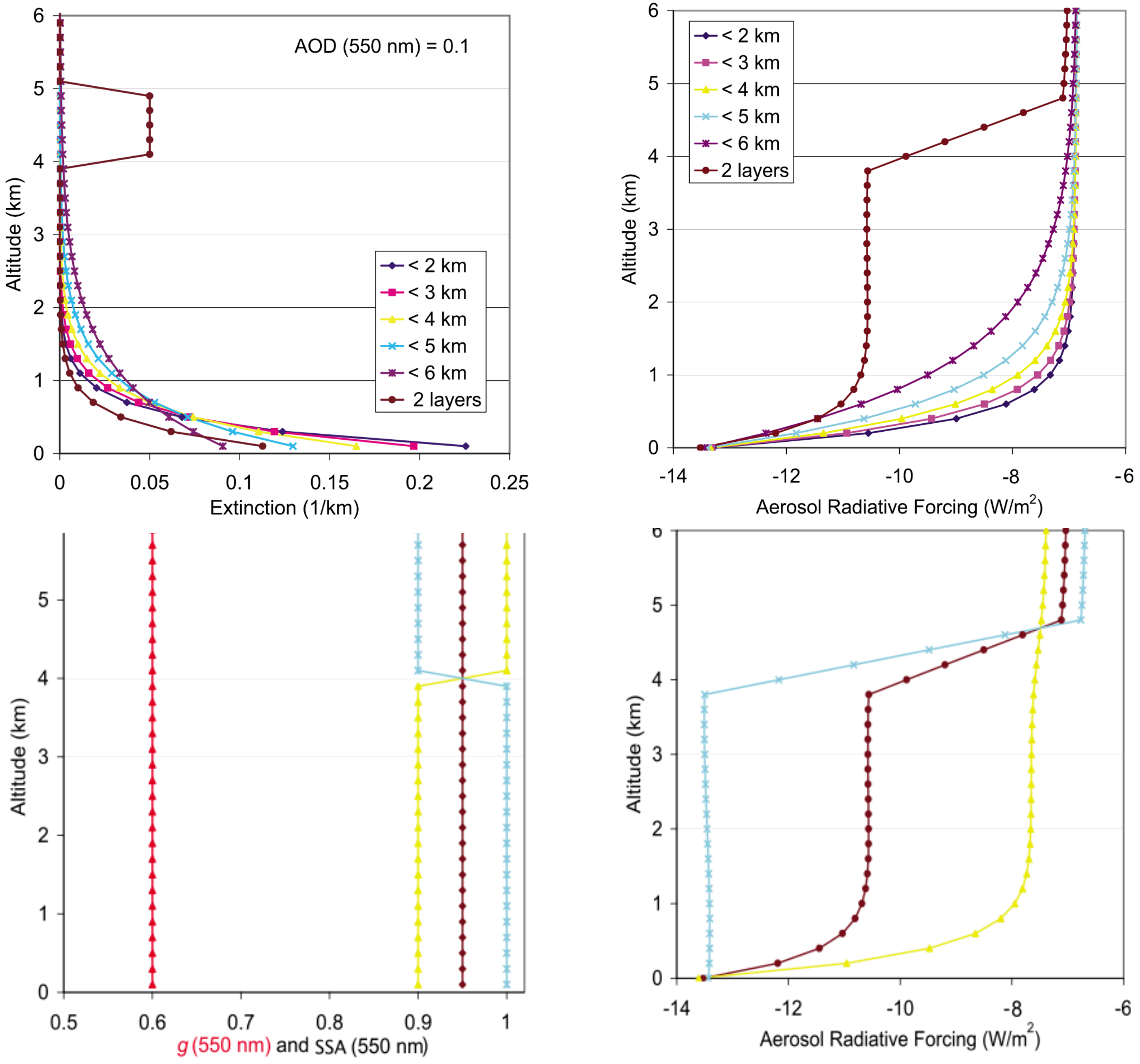
Sahara Dust and Biomass Smoke over the Atlantic



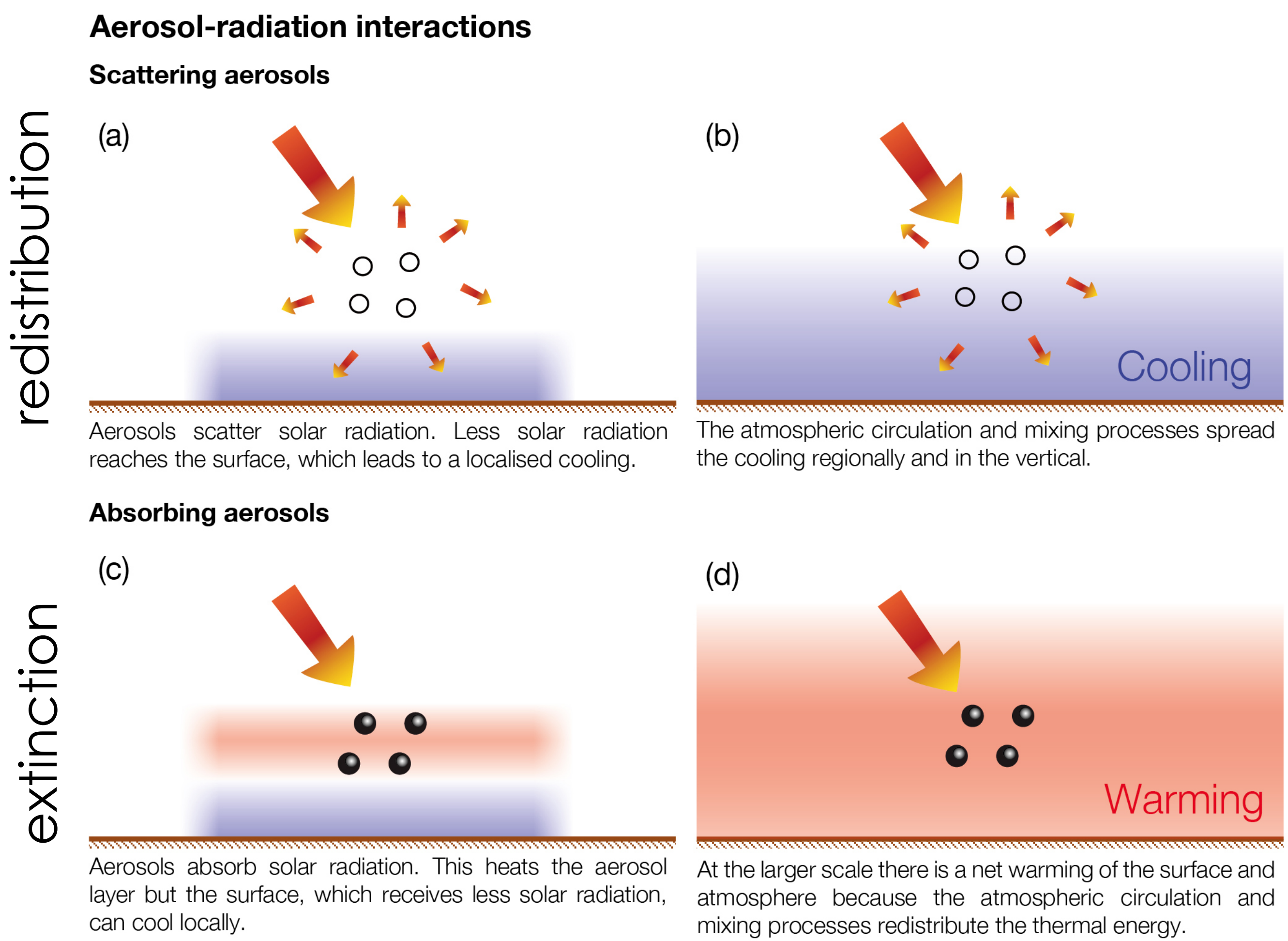
Biomass Smoke over South America



Vertical Distribution of Aerosol: Impacts on Radiative Forcing



Guan et al. 2010


Aerosol-radiation interactions
Scattering aerosols
redistribution
(a)
Aerosols scatter solar radiation. Less solar radiation reaches the surface, which leads to a localised cooling.
(b)
Cooling
The atmospheric circulation and mixing processes spread the cooling regionally and in the vertical.
Absorbing aerosols
extinction
(c)
Aerosols absorb solar radiation. This heats the aerosol layer but the surface, which receives less solar radiation, can cool locally.
(d)
Warming
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.

Optical and Radiative Properties: Standard Long-Term Products

Measured quantities

σ_{sca} = scattering coefficient Mm^{-1}

σ_{abs} absorption coefficient Mm^{-1}

σ_{bsca} = backscattering coefficient Mm^{-1}

aerosol mass concentration (total/ speciated) $\mu g\ m^{-3}$

surface radiative fluxes $W\ m^{-2}$

Radiative Forcing

$RF = (f_a \downarrow - f_a \uparrow) - (f_0 \downarrow - f_0 \uparrow)$ $W\ m^{-2}$

$(f \downarrow - f \uparrow)$ = net irradiance (upwelling minus downwelling flux)

f_a = flux with aerosol
f_0 = flux without aerosol

$RFE = RF / \tau_a$ $W\ m^{-2}$

$\tau_a \sim Q_e$

Derived quantities

extinction efficiency:
Q_e = total mass/$(\sigma_{sca} + \sigma_{abs})$ $m^2\ g^{-1}$

single scattering albedo:
$\omega_0 = \sigma_{sca}/(\sigma_{sca} + \sigma_{abs})$

asymmetry parameter:
$g = 1.011 - 1.036\beta + 2.0059\beta^2$,
$\beta = 0.0817 + 1.8495\sigma_{bsca} - 2.9682\sigma_{bsca}^2$

scattering Ångström exponent:
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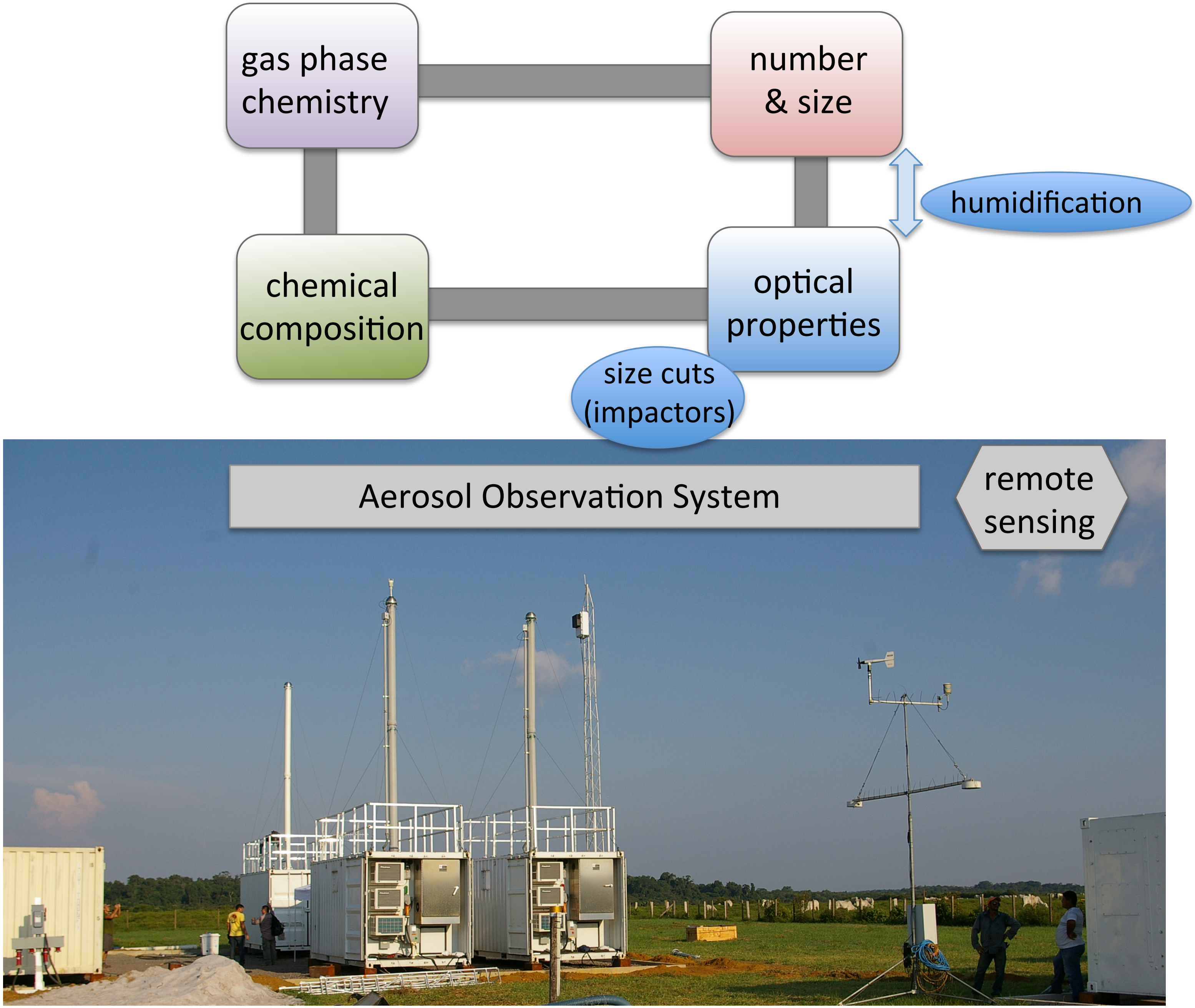
absorption Ångström exponent:
$\alpha_{abs} = \log(\sigma_{abs\ 450\ nm}/\sigma_{abs\ 700\ nm})/\log(450/700)$

humidification factor:
$fRH = \sigma_{sca\ 85\%RH}/\sigma_{sca\ 40\%\ RH}$

sub-micron scattering fraction:
$R_{sca} = \sigma_{sca\ 1\ \mu m}/\sigma_{sca\ 10\ \mu m}$

ARM Aerosol Measurements



number & size

number conc
CPC 3772 (> 10 nm)
CPC 3776 (> 2.5 nm)

size distribution
50 nm – 1 µm
UHSAS

size distribution
400 nm – 15 µm
APS

CCN number conc. spectrum with S
CCN-2

growth factor
HTDMA

optical properties

dry
light extinction
CAPS 3λ

light scattering
nephelometer 3λ

light absorption
PSAP (CLAP) 3λ

humidified
light scattering
nephelometer + humidograph 3λ

aerosol chemical composition

non-refractory mass concentration
(ToF-)ACSM

gas phase chemistry

CO
Los Gatos

CH_4, CO_2
Picarro

SO_2
ThermoScientific

NO_x/NO_y
NO_x Analyzer

O_3
Ozone Analyzer