Global and Regional Aerosol Modeling

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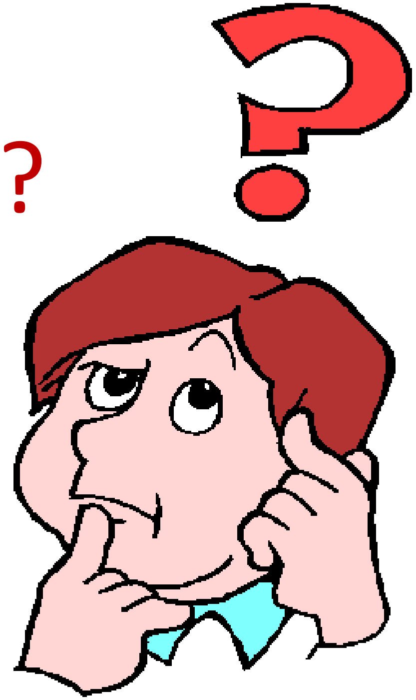
- Utility of models
- Modeling concepts
- Aerosol representation in models
- Some results from aerosol simulations

All model are wrong!
Why do we need them?



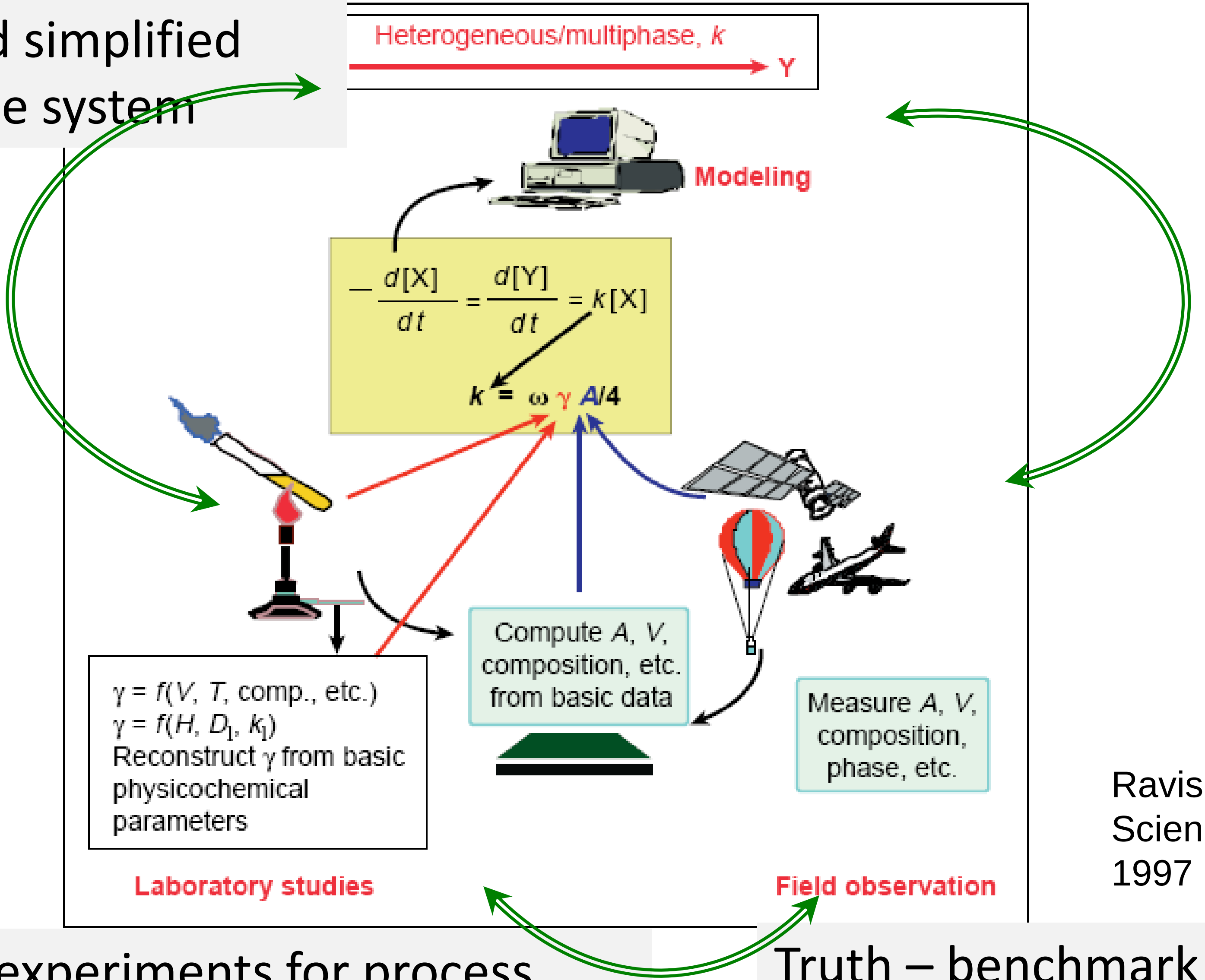
All model are wrong!
Why do we need them?

- understand mechanisms, confirm understanding, generalize theory, analyze observations, guide experiments, predict changes,
- tools of synthesis of knowledge
- simplify the description of a complex system
- Account for feedback mechanisms.
- use a limited number of representative compounds or mixtures to describe the system's behavior
- Relatively simple parameterizations of processes can be used in global models of chemistry and climate.
- The accuracy of the models is evaluated by comparison to observations
- The different properties of atmospheric constituents need to be considered in the models: volatility, solubility, chemical reactivity, physical and optical properties

Surprises help learning and improving models.

Continuous dialogue

Integrated simplified view of the system



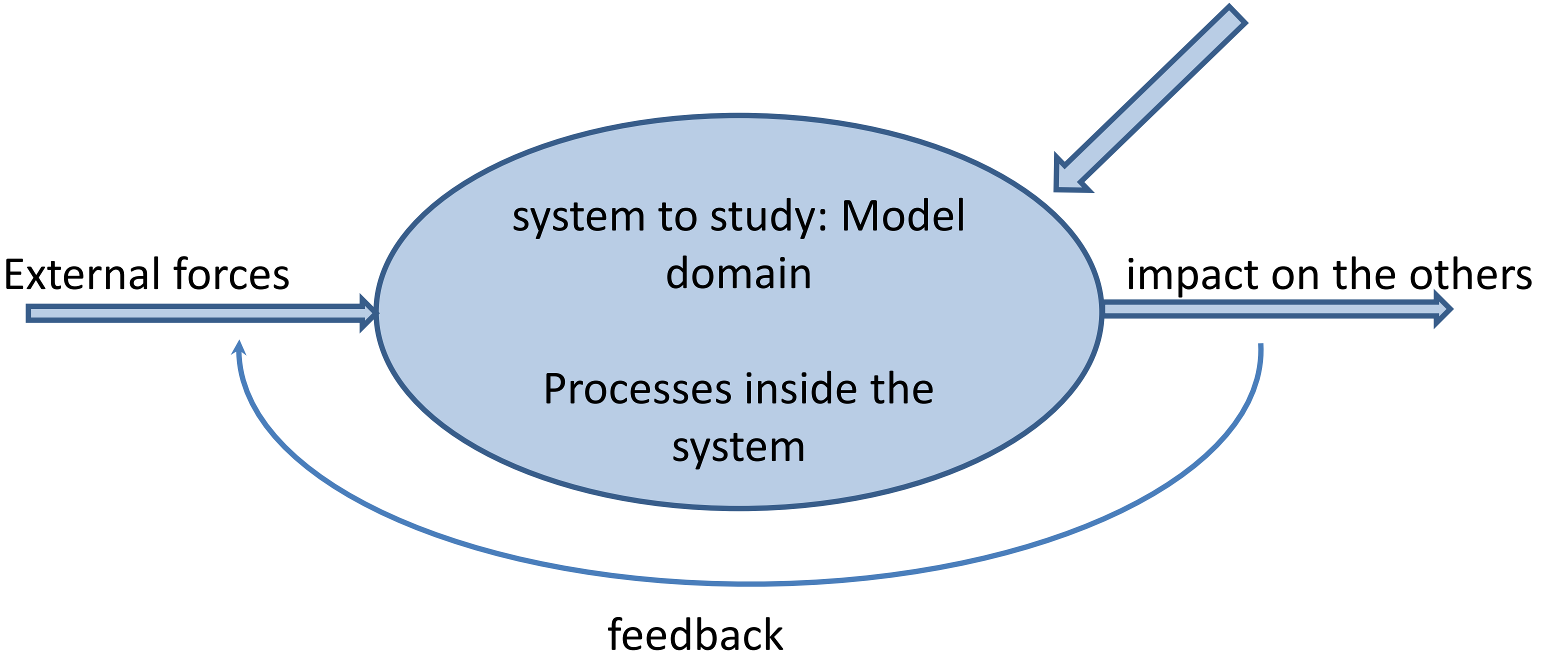
Controlled experiments for process understanding

Truth – benchmark for model results

Ravishankara
Science,
1997

To construct a model we need to:

Define the model domain and its boundaries



External forces

system to study: Model domain

Processes inside the system

impact on the others

feedback

Main rule to follow → do not loose mass !

Mass balance *(also element balance)*

$$\int^{\infty} \frac{dc}{dt} = \left(\frac{\partial c}{\partial t}\right)_{transp} + \left(\frac{\partial c}{\partial t}\right)_{chem} + \left(\frac{\partial c}{\partial t}\right)_{emiss} + \left(\frac{\partial c}{\partial t}\right)_{dep} = 0$$

Energy balance!

Terminology

Technical

- Dimensions, grid resolution, geometry, sigma layers, nudging, sub-grid scale
  - Tracers, aerosol microphysics, time-step, parameter splitting

Scientific

  - Chemistry-Transport Models (CTMs)
  - General Circulation Models (GCMs)
  - Coupled models –Earth System Models (ESMs)
    - Components (atmosphere, biosphere, lithosphere, cryosphere, etc)

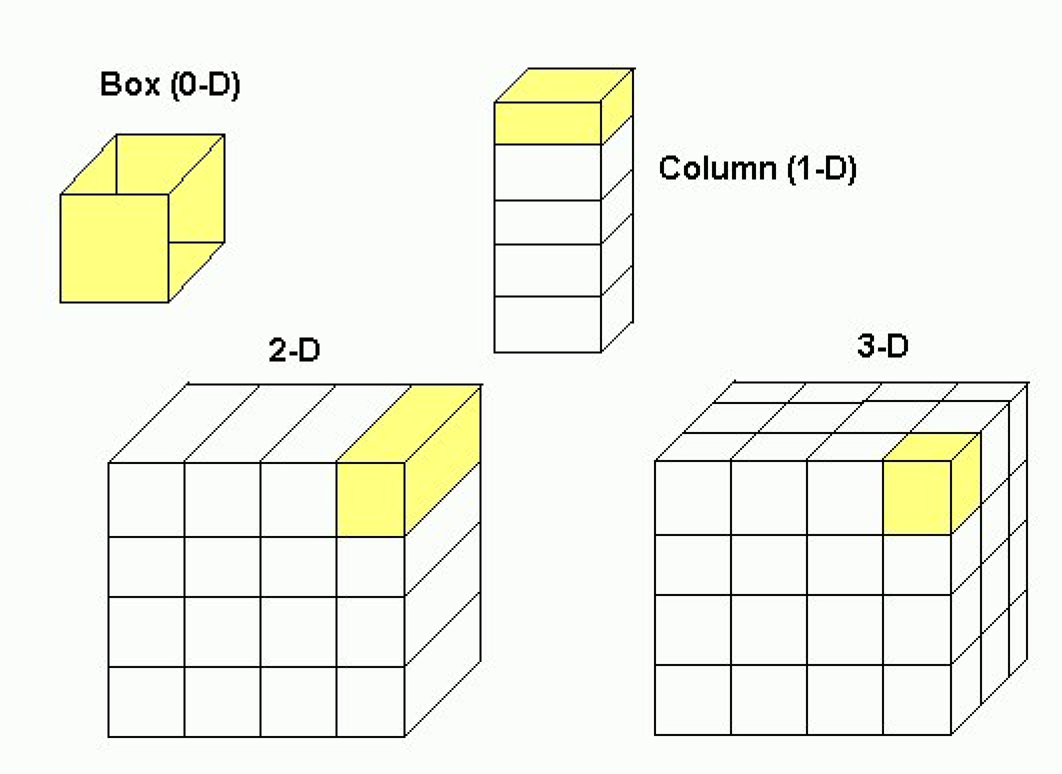
Processes

- emissions, transport, chemistry, radiation, deposition etc

Results

  - diagnostic and prognostic

Model dimensions

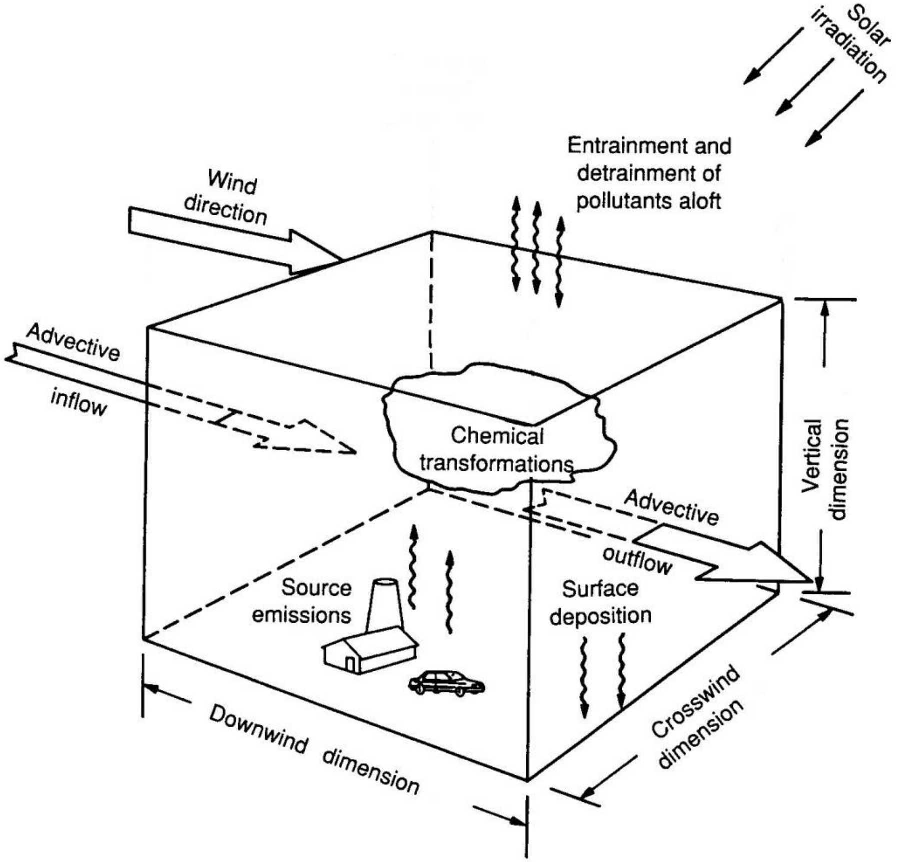


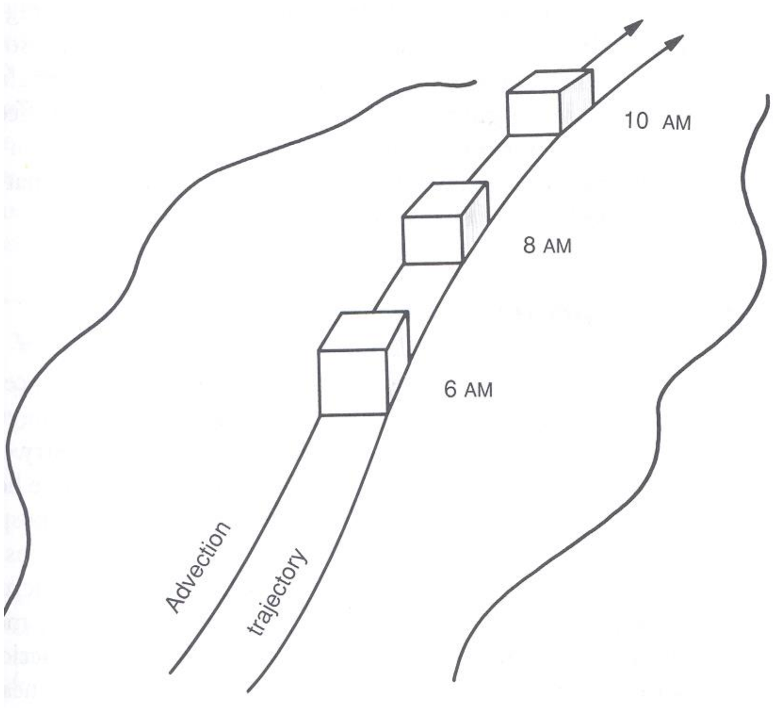
http://irina.eas.gatech.edu/lectures/Lec29.htm

Box (or 0D) models

Eulerian

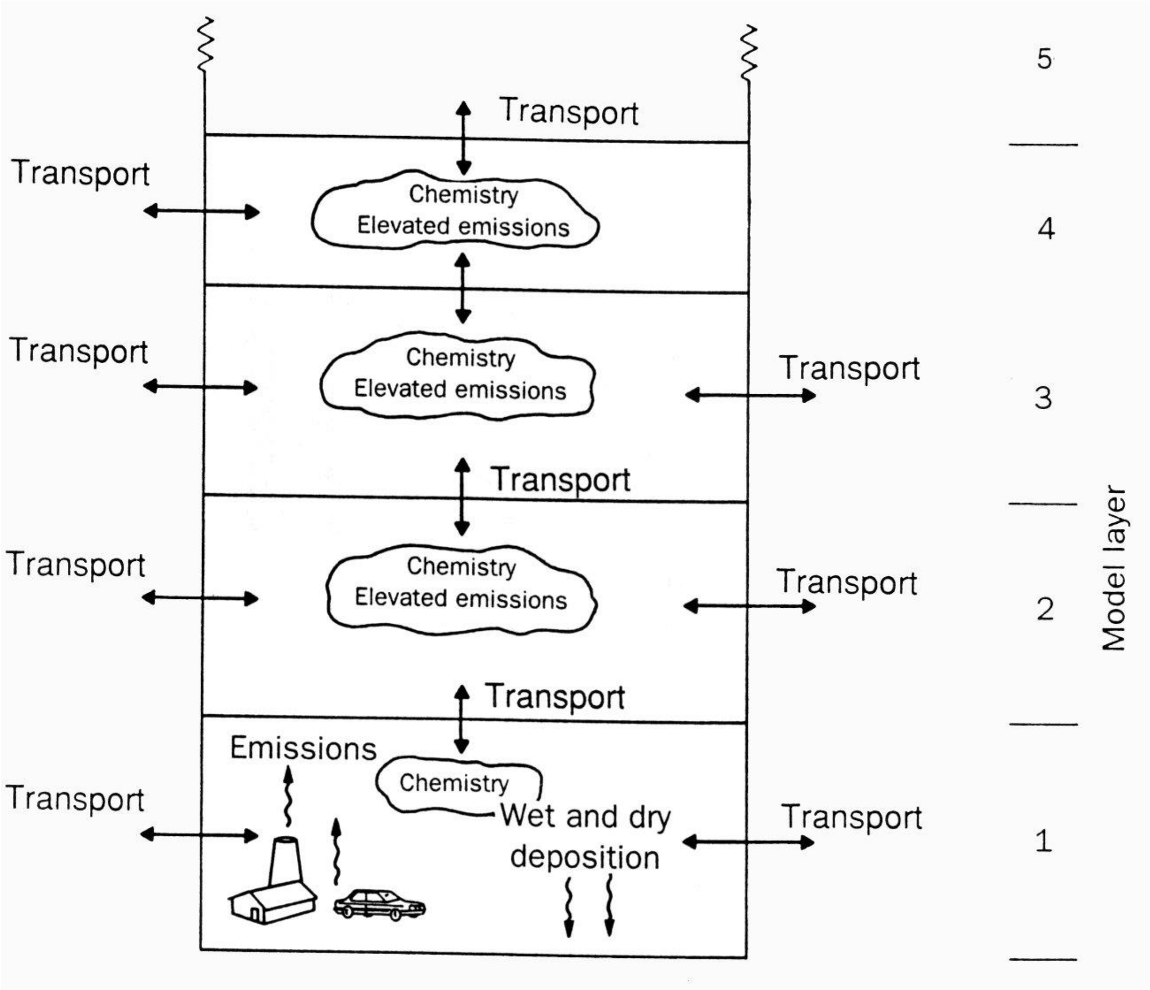
Lagrangian





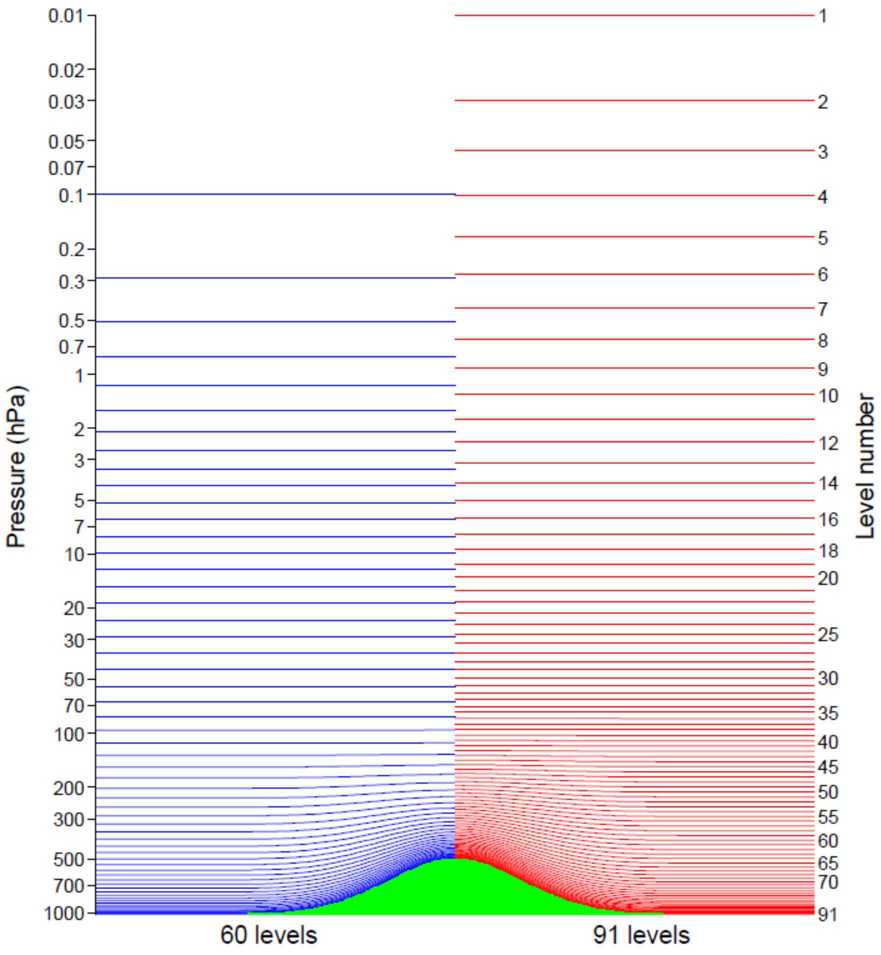
T.E. Graedel & P.J. Crutzen, Atmospheric Change: An Earth System Perspective, 1992

Column (or 1D) models



T.E. Graedel & P.J. Crutzen, Atmospheric Change: An Earth System Perspective, 1992

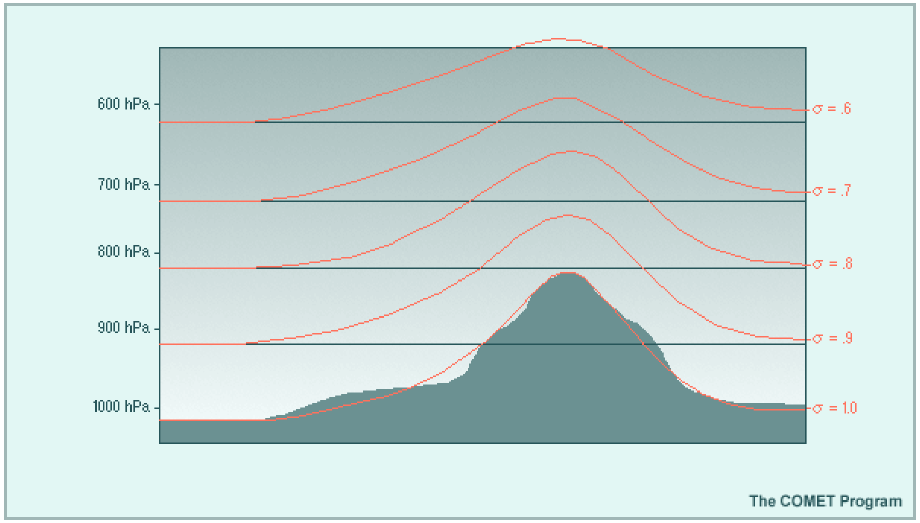
Vertical resolution – sigma levels



ECMWF

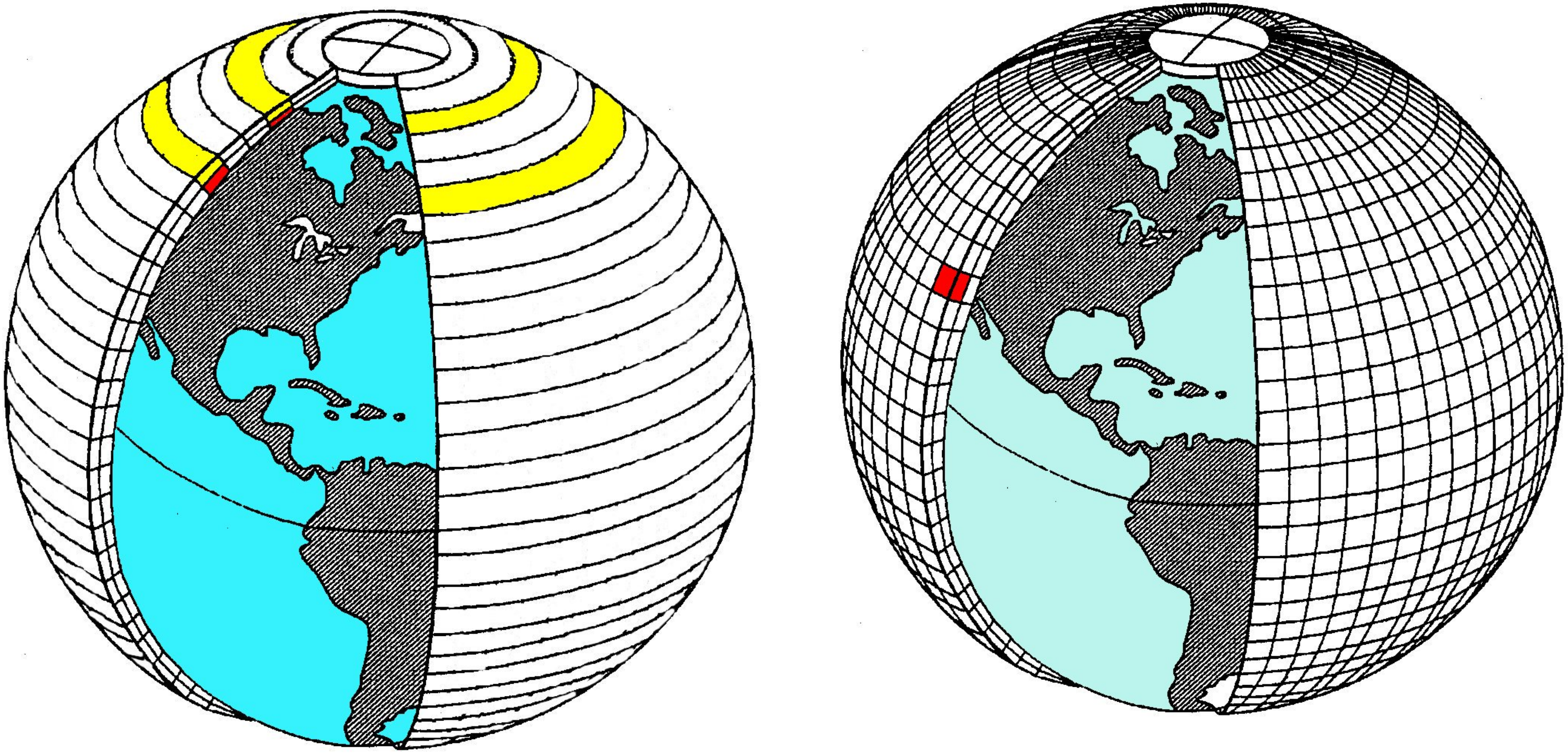
$$p_{k+1/2} = A_{k+1/2} + B_{k+1/2}p_{\text{surf}} \qquad 0 \le k \le NLEV$$

$$p_k = \frac{1}{2}(p_{k-1/2} + p_{k+1/2}) \qquad 1 \le k \le NLEV$$



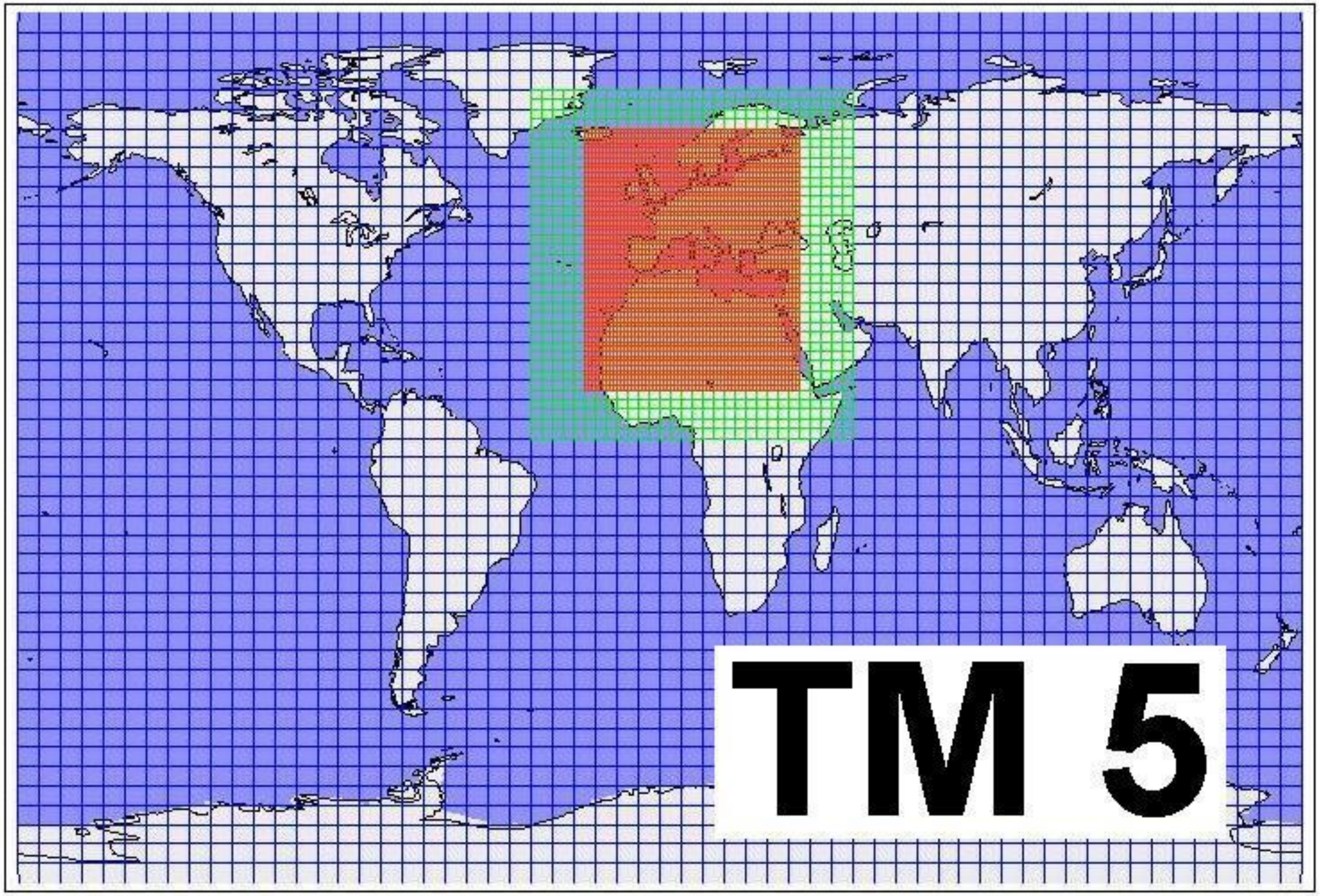
http://atmo.tamu.edu/class/metr452/models/2001/sigma.png

2D Global models 3D



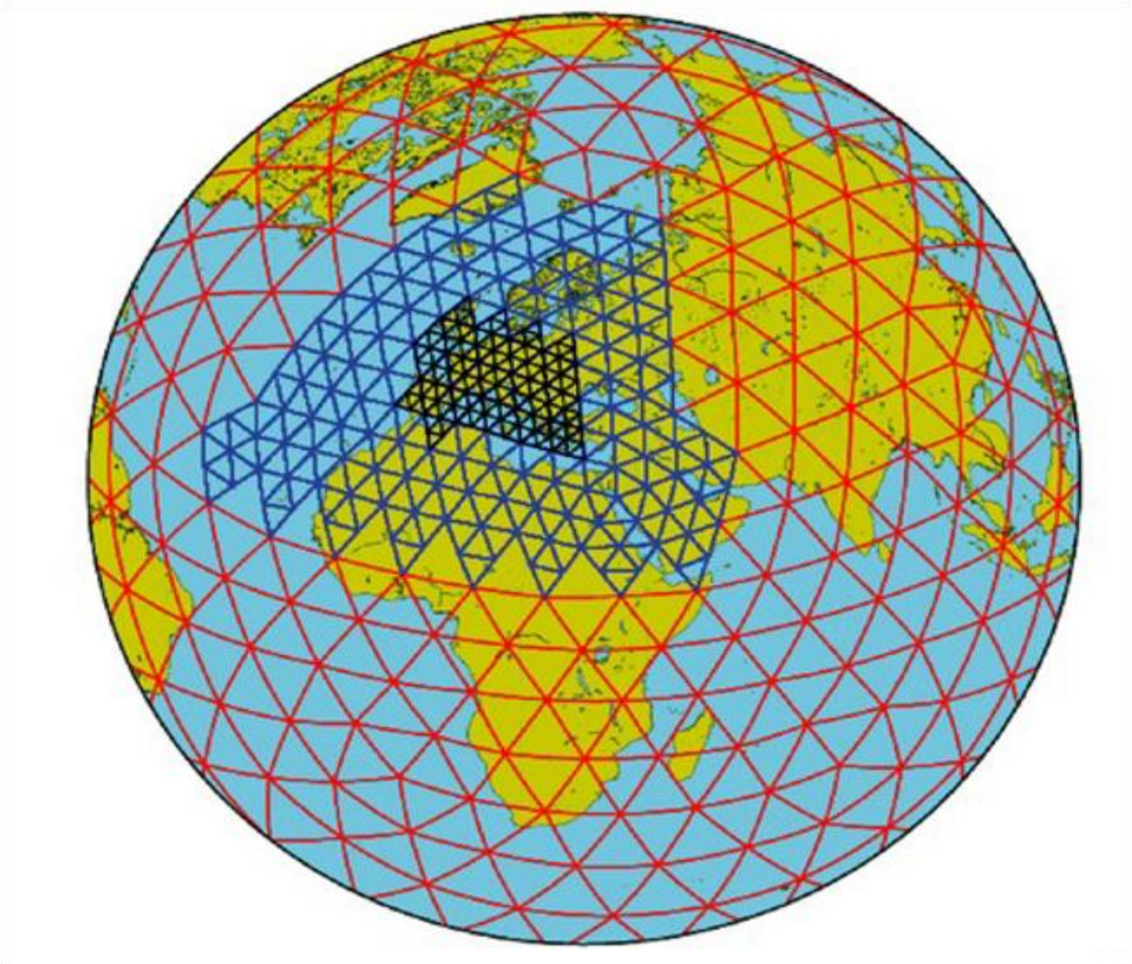
http://irina.eas.gatech.edu/lectures/Lec29.htm

Nested global models



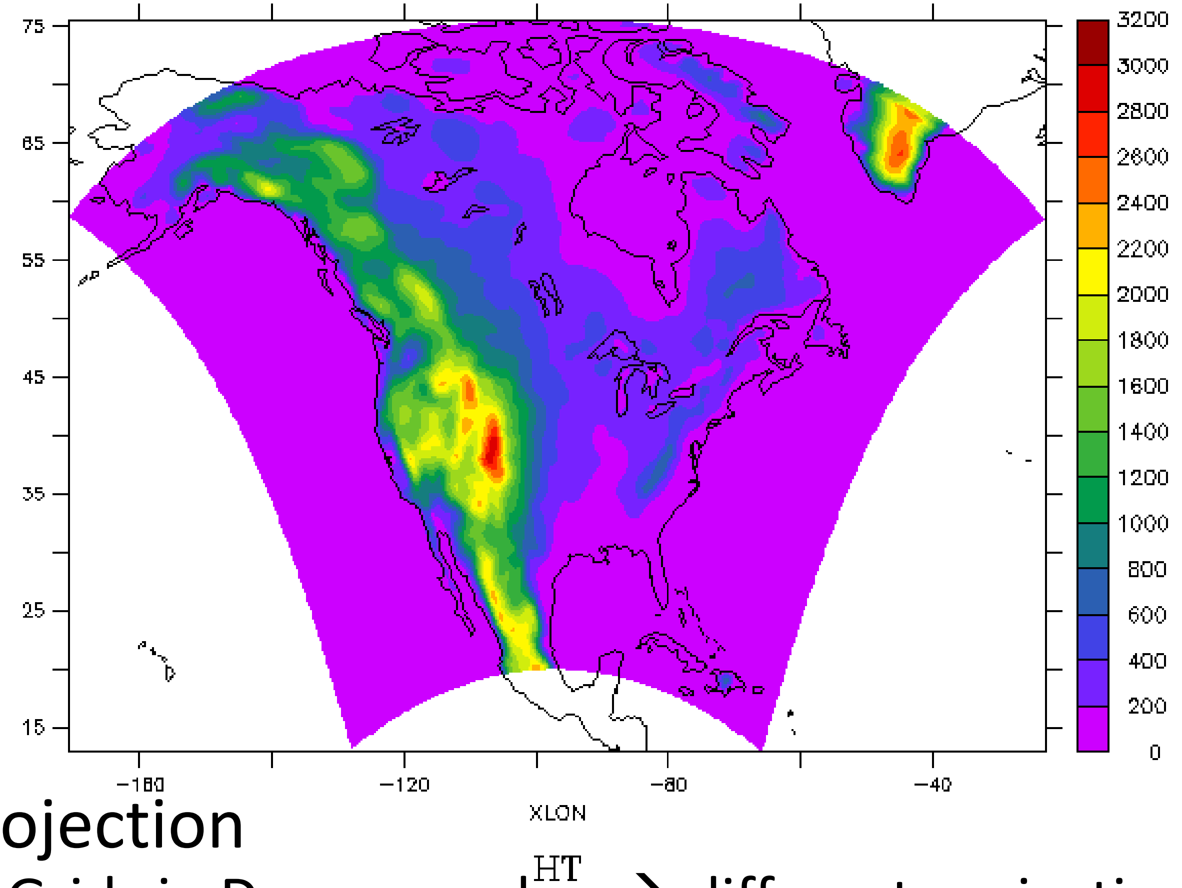
http://www.phys.uu.nl/~tm5/

Emerging geometries
ICON (Icosahedral Nonhydrostatic) Model



https://www.meteo.physik.uni-muenchen.de/methoden/numerische_simulationen/index.html

Regional models

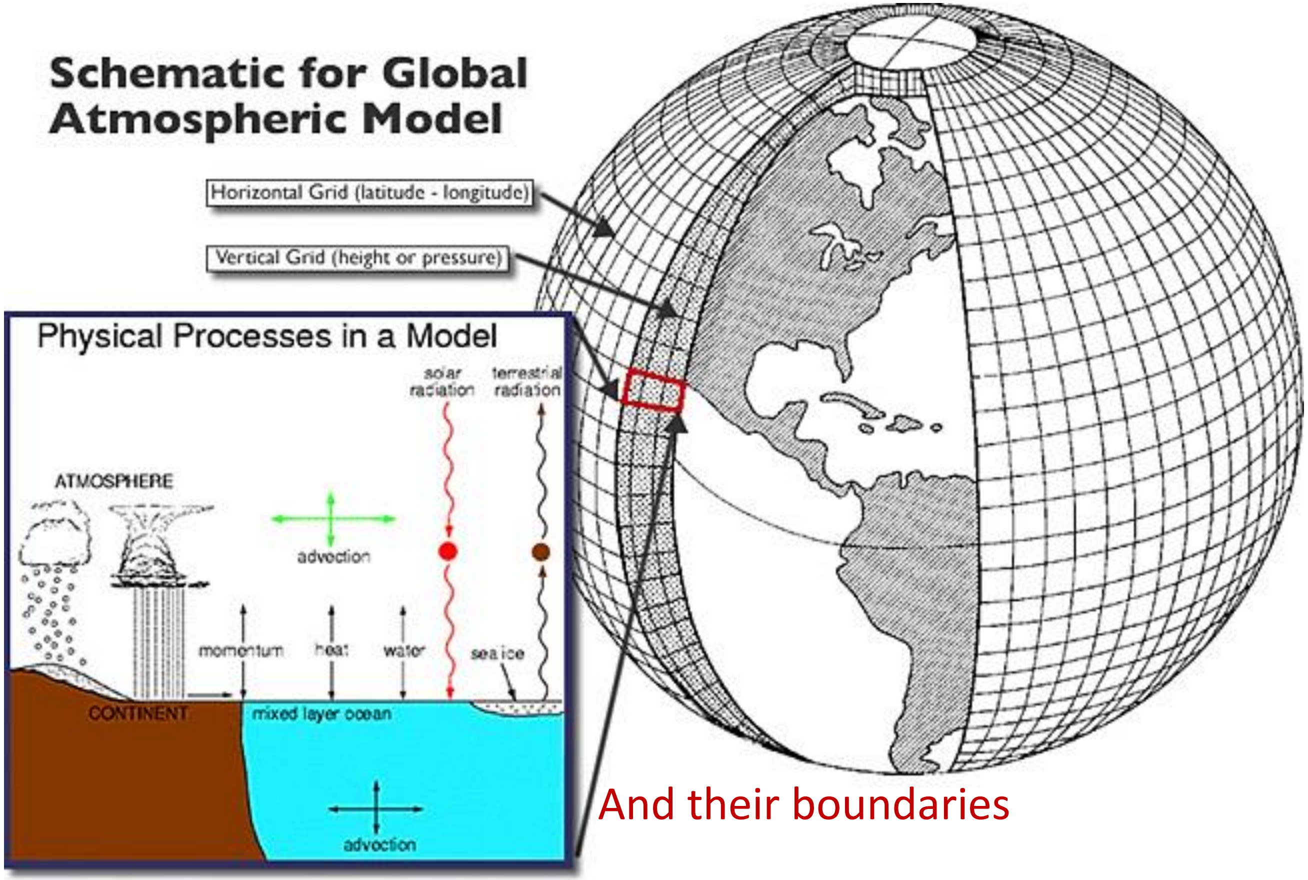


Lambert projection

Grids in Degrees or km → different projections

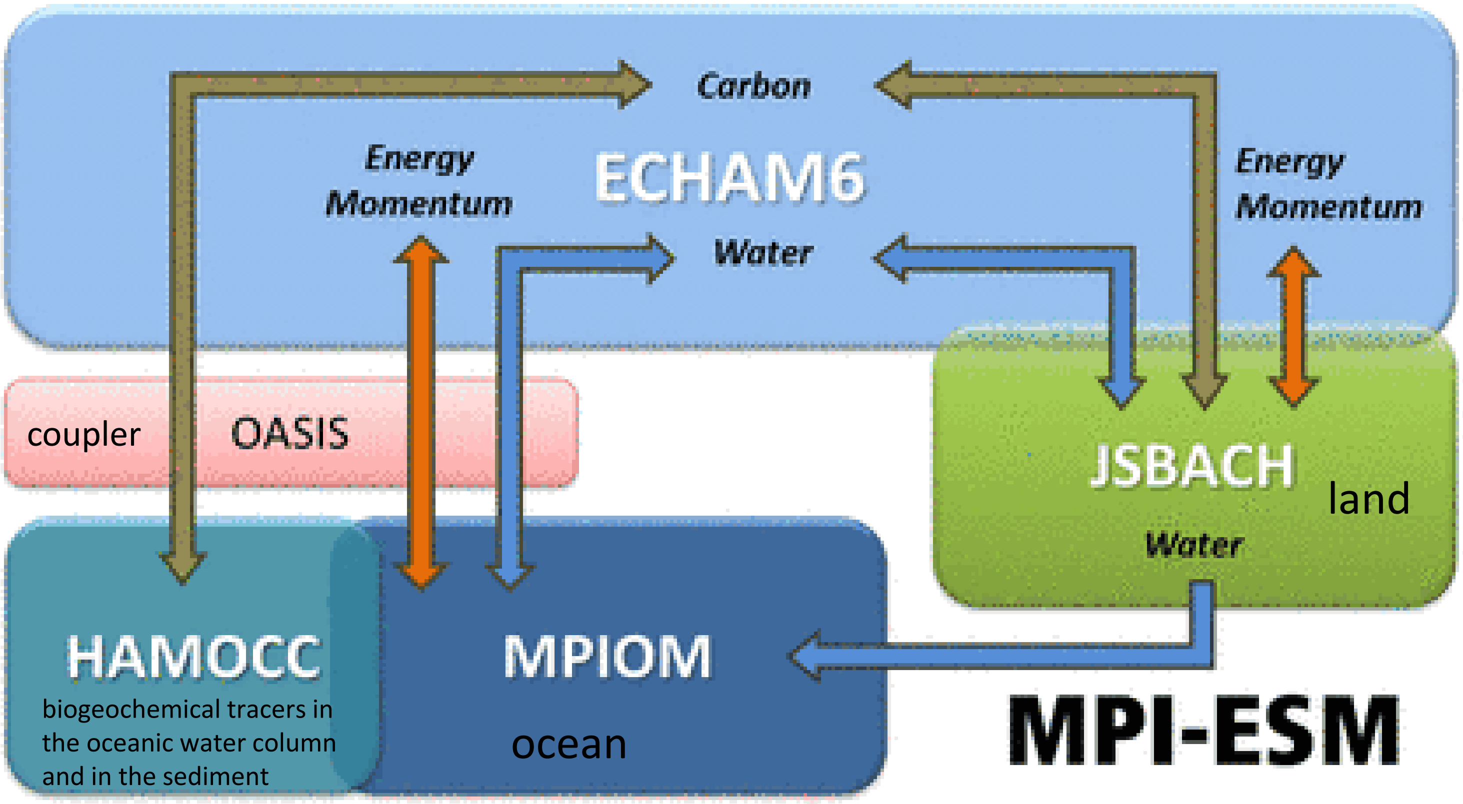
WRF – http://www.unidata.ucar.edu/newsletter/2006nov/Domain_narccap.gif

Global atmospheric models



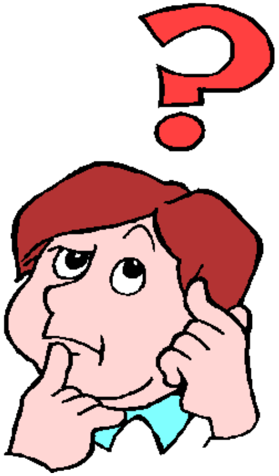
And their boundaries

http://upload.wikimedia.org/wikipedia/commons/4/4a/Global_Atmospheric_Model.jpg



http://www.mpimet.mpg.de/en/science/models/mpi-esm/

Which is the best model to use?



Lifetime of studied pollutant and space-geographic extent of the model

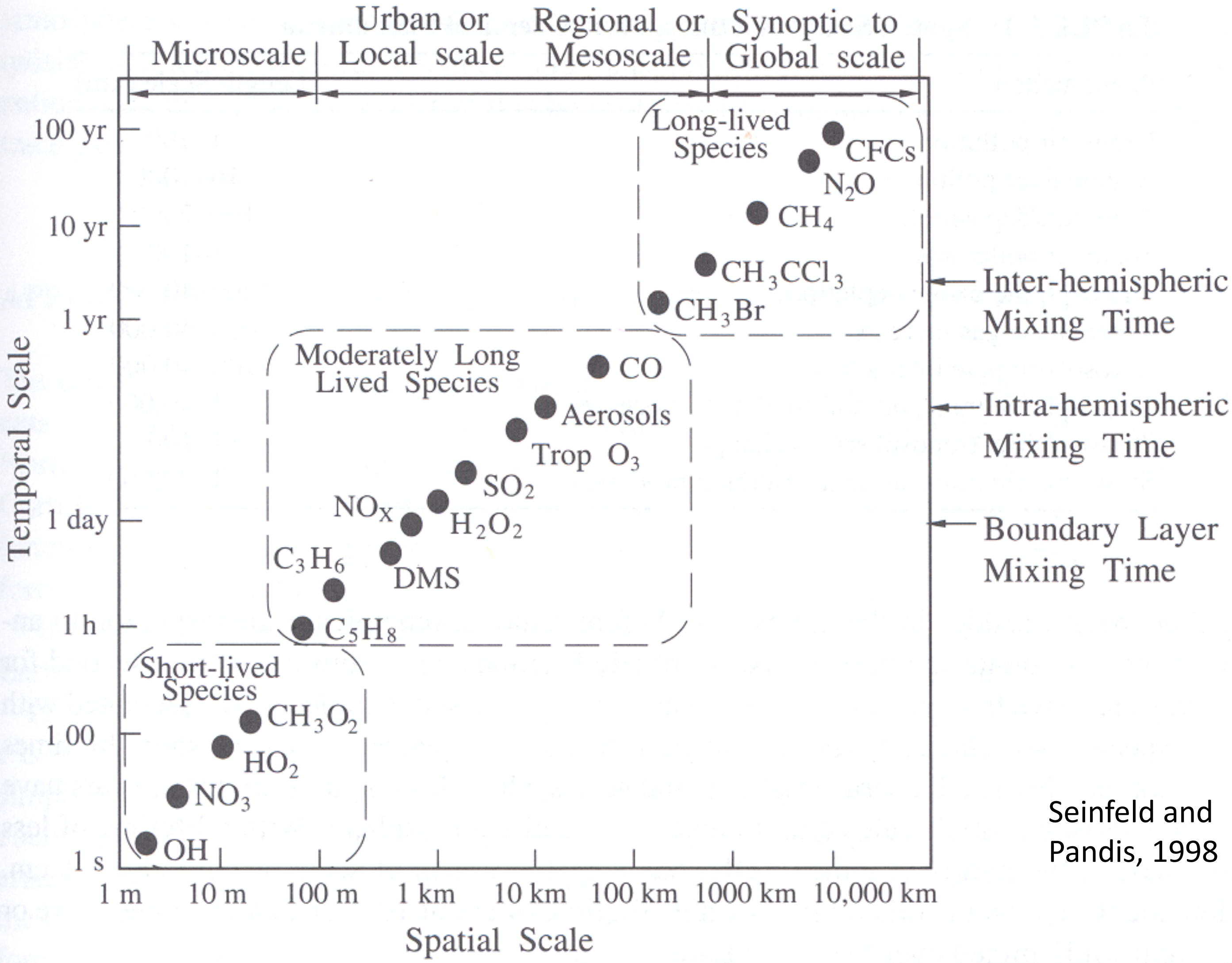
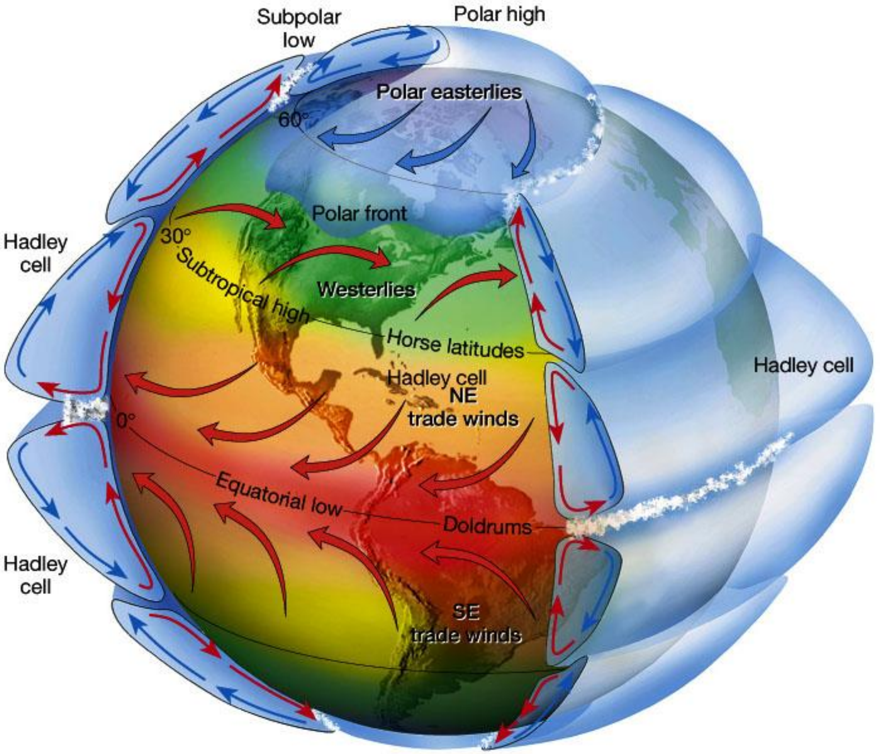


FIGURE 1.17 Spatial and temporal scales of variability for atmospheric constituents.

Seinfeld and Pandis, 1998

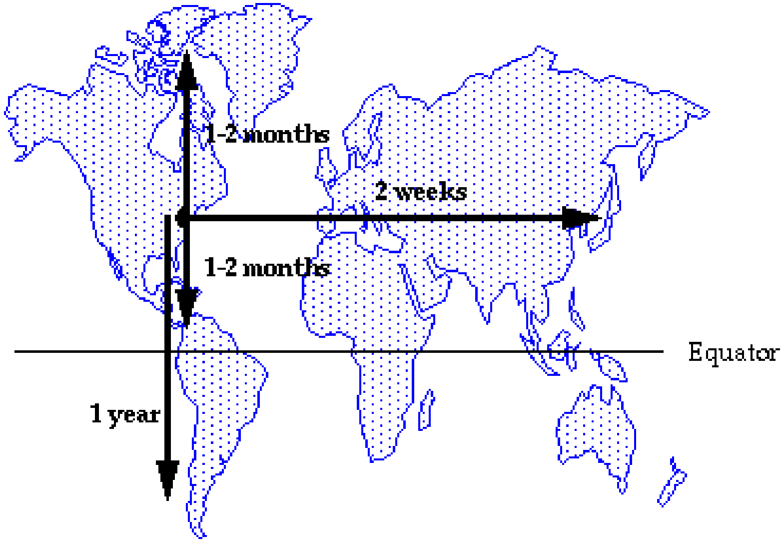
Atmospheric transport

Advection, deep and shallow convection



http://www.ux1.eiu.edu/~cfjps/1400/FIG07_006.jpg

transport time scales for advection



Jacob, 1999

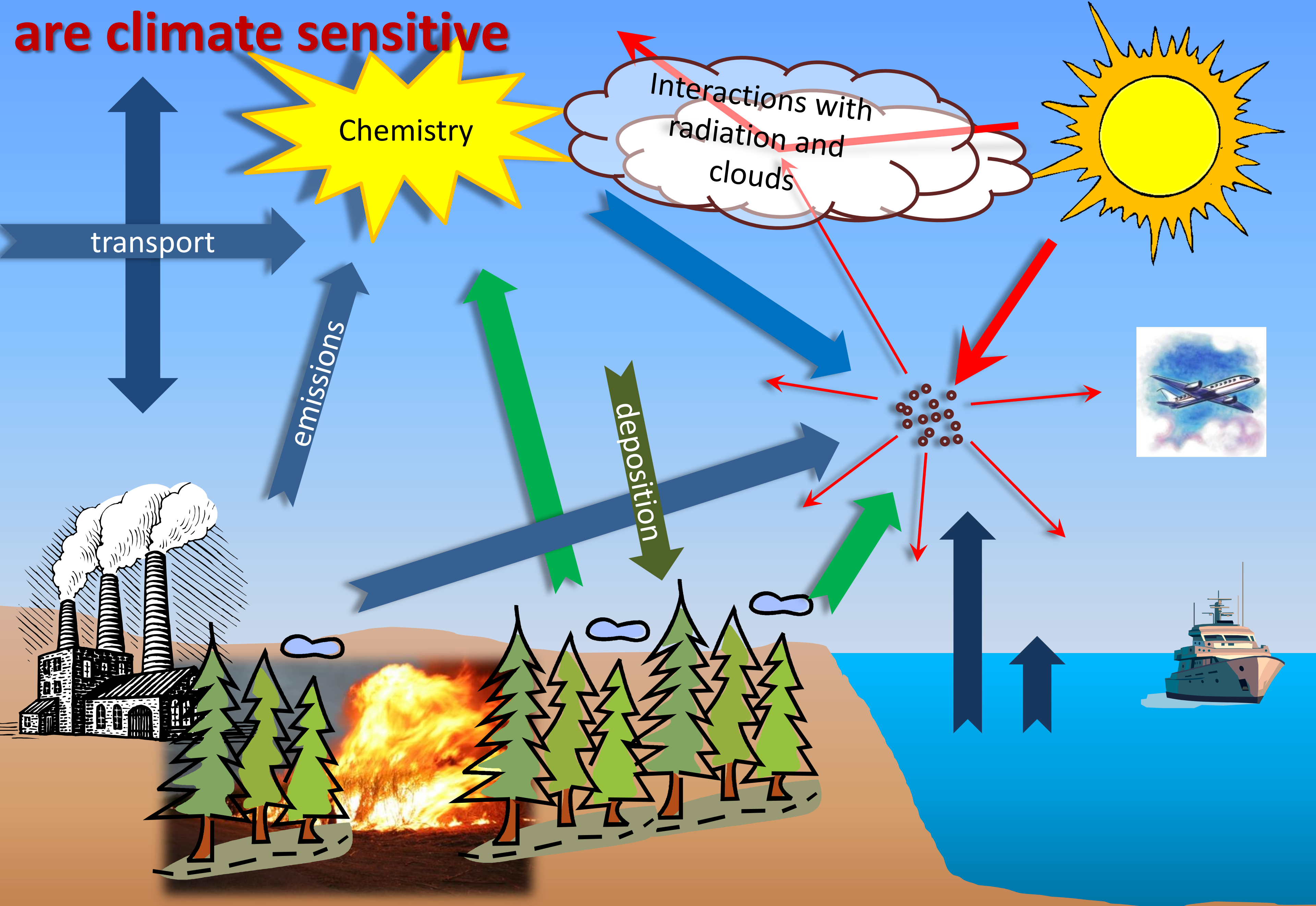
Issues with mesoscale modeling

- Upper boundary conditions
- Lateral conditions
- Influx & outflux

(to represent sources or sinks that are not in the model domain)

- Time resolution

Processes affecting atmospheric composition – some are climate sensitive



AEROSOL SOURCES

- Emissions (primary aerosols)

	Over land	Over ocean
Anthropogenic*	Fossil Fuel (FF), Bio Fuel (BF), Biomass Burning (BB), dust (resuspension)	Shipping
Natural	BB, bioaerosols, dust, volcanoes	Sea-spray

- Chemistry (secondary aerosols, precursor emissions)

	Over land	Over ocean
Anthropogenic*	NO_x, SO_2, NH_3, Aromatics, Alkanes, etc. From FF, BF, BB, agricult.	NO_x, SO_2, NH_3, Aromatics, Alkanes, etc Shipping
Natural	Isoprene, Terpenes, OVOC From vegetation, soils	DMS, Isoprene, Terpenes OVOC

* Main activity sectors transport, energy, agriculture, industry

AEROSOL SOURCES

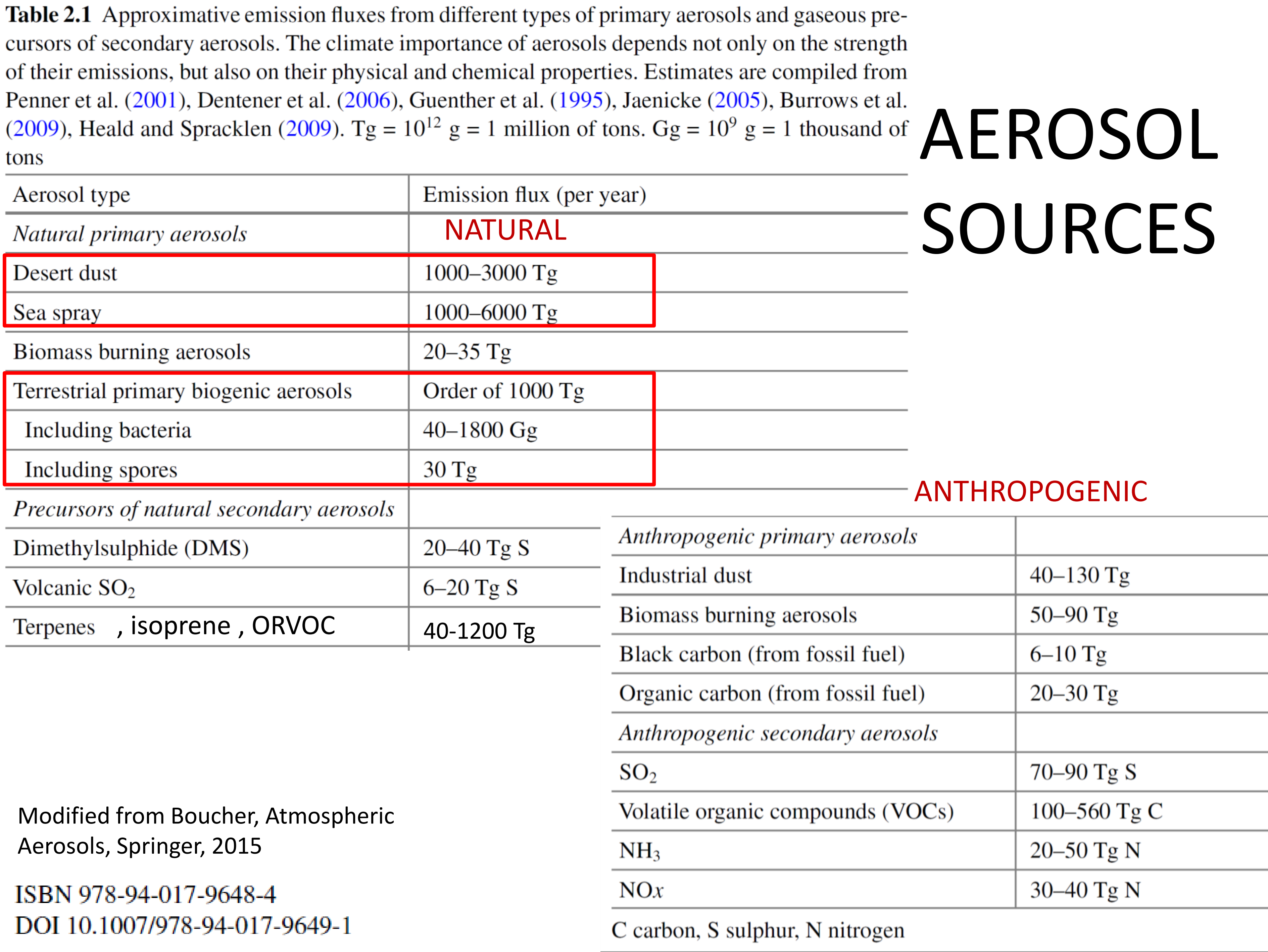


Table 2.1 Approximative emission fluxes from different types of primary aerosols and gaseous precursors of secondary aerosols. The climate importance of aerosols depends not only on the strength of their emissions, but also on their physical and chemical properties. Estimates are compiled from Penner et al. (2001), Dentener et al. (2006), Guenther et al. (1995), Jaenicke (2005), Burrows et al. (2009), Heald and Spracklen (2009). Tg = 10^{12} g = 1 million of tons. Gg = 10^9 g = 1 thousand of tons

NATURAL

Aerosol type	Emission flux (per year)
Natural primary aerosols	
Desert dust	1000–3000 Tg
Sea spray	1000–6000 Tg
Biomass burning aerosols	20–35 Tg
Terrestrial primary biogenic aerosols	Order of 1000 Tg
Including bacteria	40–1800 Gg
Including spores	30 Tg
Precursors of natural secondary aerosols	
Dimethylsulphide (DMS)	20–40 Tg S
Volcanic SO_2	6–20 Tg S
Terpenes , isoprene , ORVOC	40-1200 Tg

ANTHROPOGENIC

Anthropogenic primary aerosols	
Industrial dust	40–130 Tg
Biomass burning aerosols	50–90 Tg
Black carbon (from fossil fuel)	6–10 Tg
Organic carbon (from fossil fuel)	20–30 Tg
Anthropogenic secondary aerosols	
SO_2	70–90 Tg S
Volatile organic compounds (VOCs)	100–560 Tg C
NH_3	20–50 Tg N
NO_x	30–40 Tg N

C carbon, S sulphur, N nitrogen

Modified from Boucher, Atmospheric Aerosols, Springer, 2015

ISBN 978-94-017-9648-4
DOI 10.1007/978-94-017-9649-1

Which emissions can be calculated on line by a chemistry-climate model?

Interactive emissions

- Dust
- Sea-spray (sea-salt and organics)
- Fires
- Bioaerosols
- Biogenic VOC (MEGAN model)

databases

- Anthropogenic emissions
- Emissions from soils
- Volcanoes

1. Selection of emissions inventories
2. Time resolution typically very poor
3. Seldom updates

Aerosol emissions from arid soils

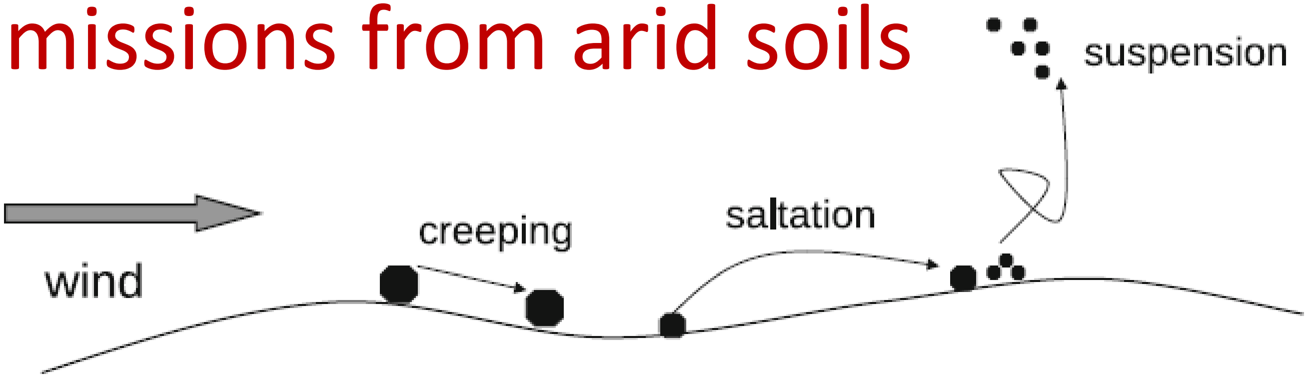


Fig. 4.2 Schematic description of the source mechanism for desert dust particles: creeping of the bigger particles which are rolling along the ground, saltation of the particles small enough to be lifted by the wind before falling, bouncing against and breaking up some of the soil aggregates into smaller particles, and suspension of the smallest particles (Boucher 2015)

Controlled by

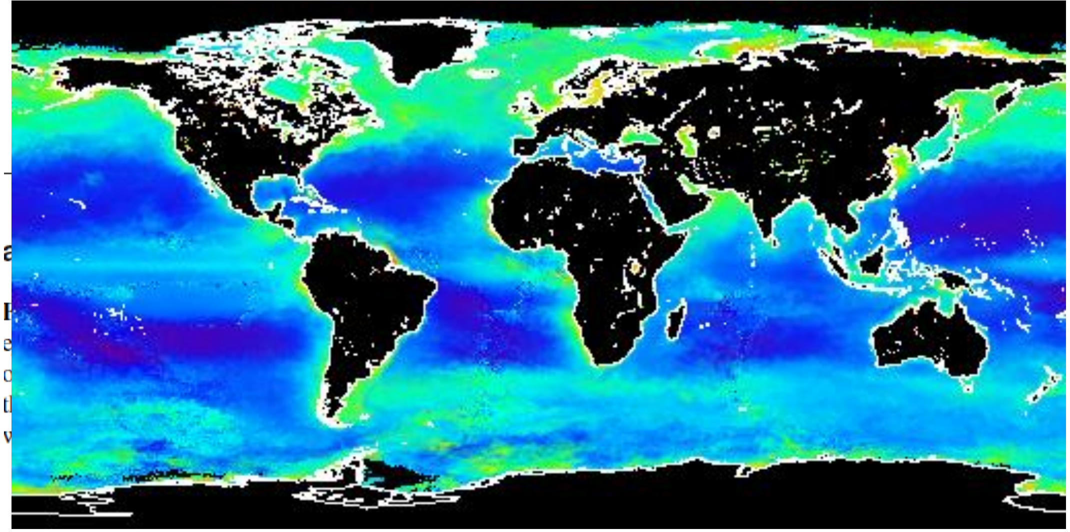
- quality of the soil (minerals, size of grains, soil moisture)
- wind speed (above friction velocity)

Examples in : Tegen et al, 2009 & Astitha et al. Atmos. Chem. Phys., 12, 11057–11083, 2012

http://bitethedust.com.au/bitingthedust/2009/03/22/dust-storm

Sea-spray organic enrichment

Chl, SeaWiFS, 2000



O’Dowd et al., Nature, 2008

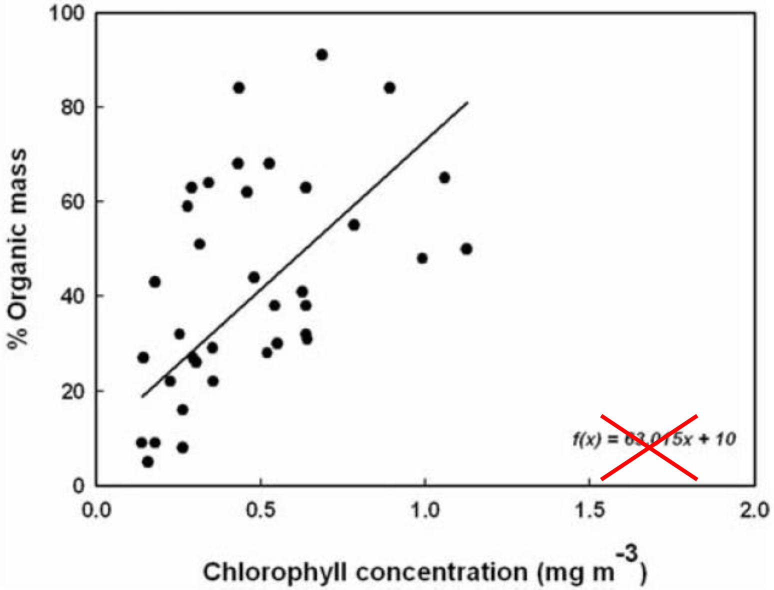
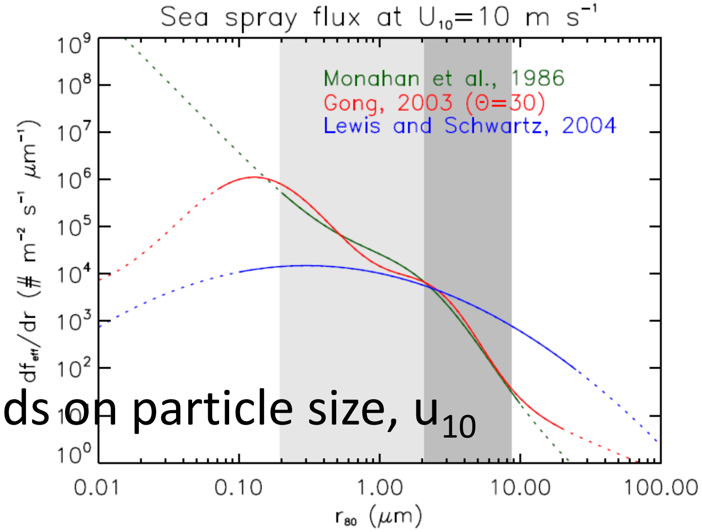


Figure 2. Correlation between fractional WIOC component of sea-spray as a function of grid-average chlorophyll-a concentration.



depends on particle size, u_{10}

Vignati et al., AE, 2010

$$\boxed{\begin{gathered}\%\ \text{organic mass} = 43.5{*}\text{Chl}\ [\text{mg m}^{-3}] + 13.805, \\ \text{Chl} < 1.43\ \mu\text{g m}^{-3}\end{gathered}}$$

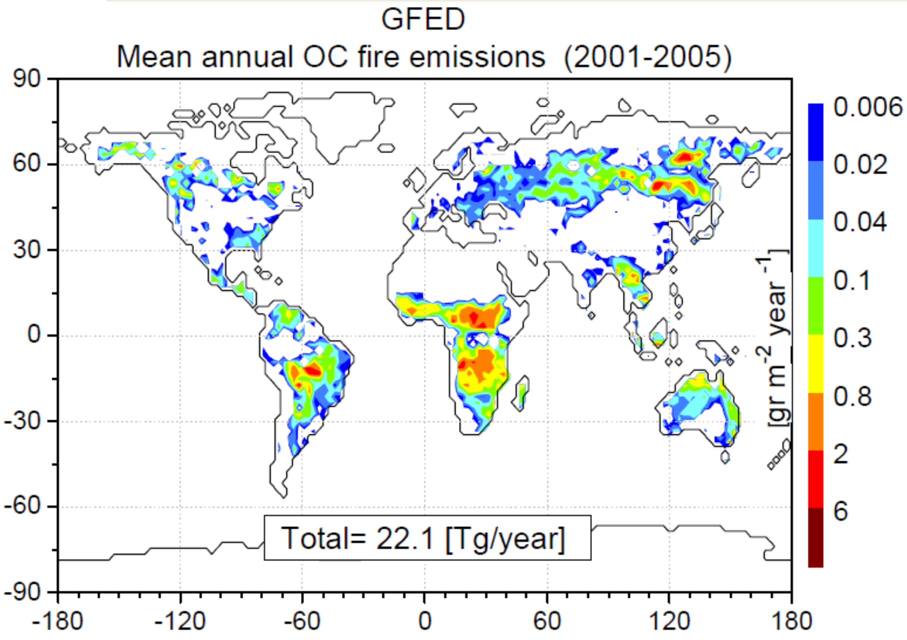
Fire sources

$$E_i = A(x,t) \times B(x) \times \mathrm{FB} \times \mathrm{ef}_i \qquad (1)$$

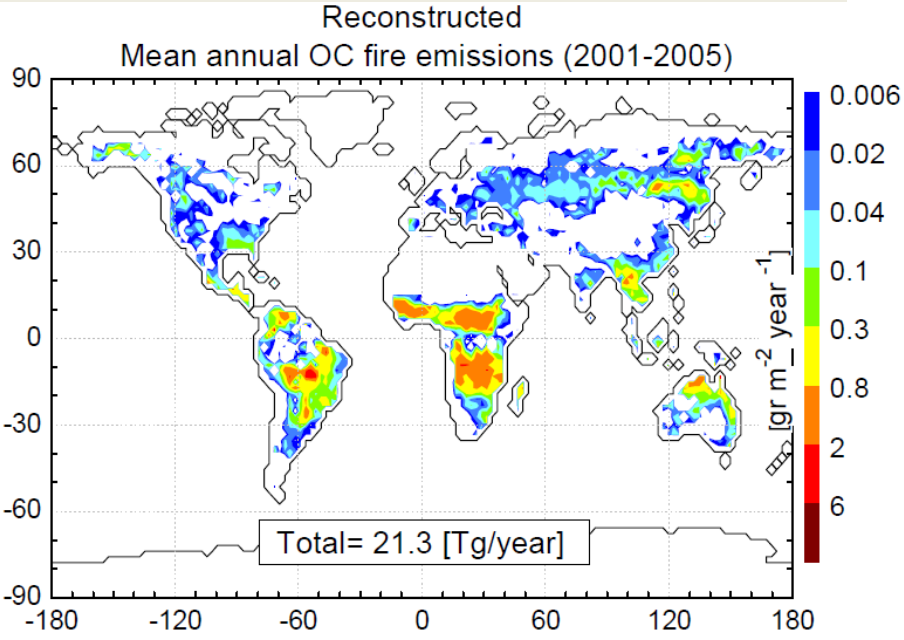
Where the emission of species i (E_i, mass of i emitted) is equal to the area burned at time t and location $x[(A(x,t)]$ multiplied by the biomass loading at location x [$B(x)$], the fraction of that biomass that is burned in the fire (FB), and the emission factor of species i (ef_i, mass of i emitted/mass of biomass burned). All biomass terms are on a dry weight basis.

FINN: Wiedinmyer et al., GMD, 2011
GFED: van der Werf et al ACP 2006,
2010
Online: *Pechony and Shindell, J Geophys Res 2009*

Flammability =f(RH, precipitation, vapor pressure deficit, vegetation density)
Fire counts = f(Flammability, Ignition by lightning + humans, fraction of non suppressed fires)



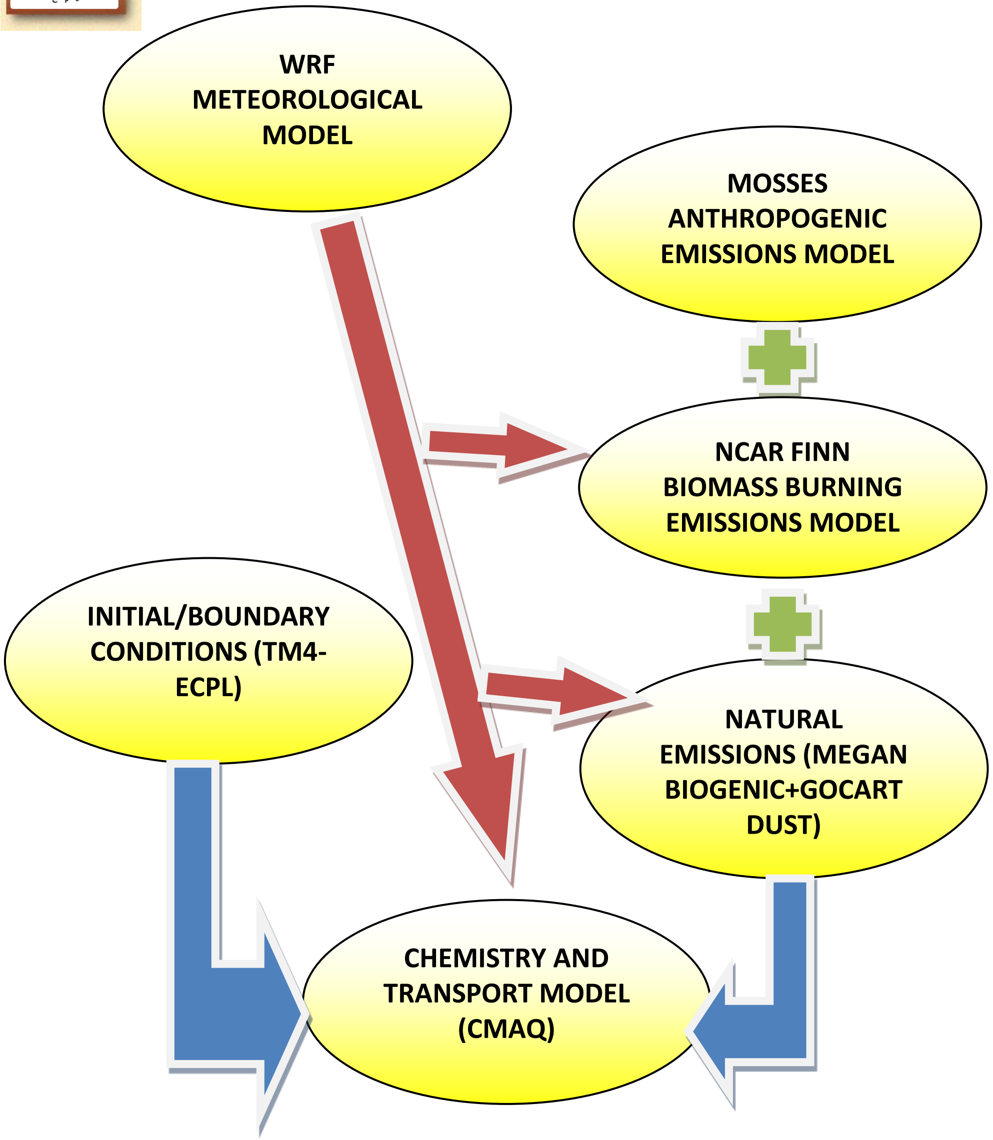
GFED
Mean annual OC fire emissions (2001-2005)



Reconstructed
Mean annual OC fire emissions (2001-2005)

Pechony and Shindell, unpublished & PNAS 2010, JGR 2009

Methods – Model Configuration



WRF METEOROLOGICAL MODEL

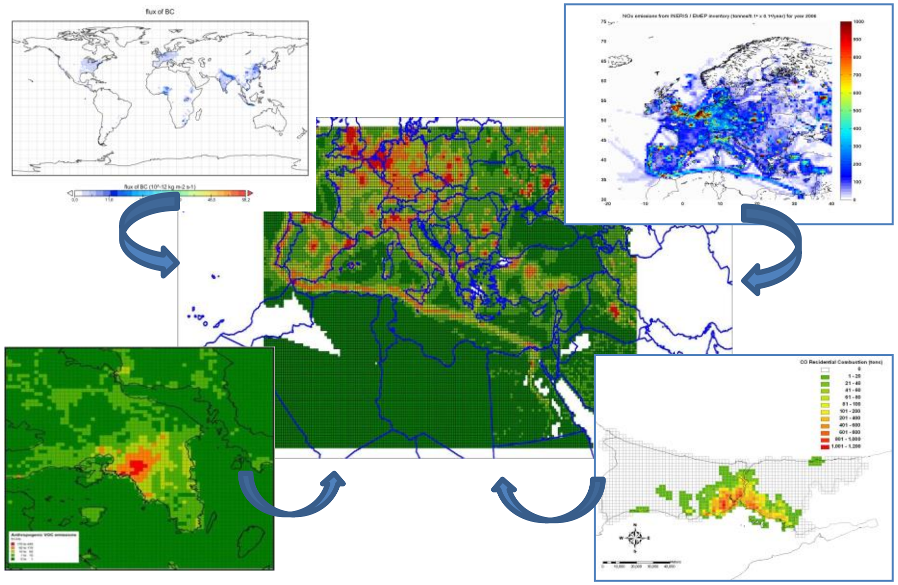
MOSSES ANTHROPOGENIC EMISSIONS MODEL

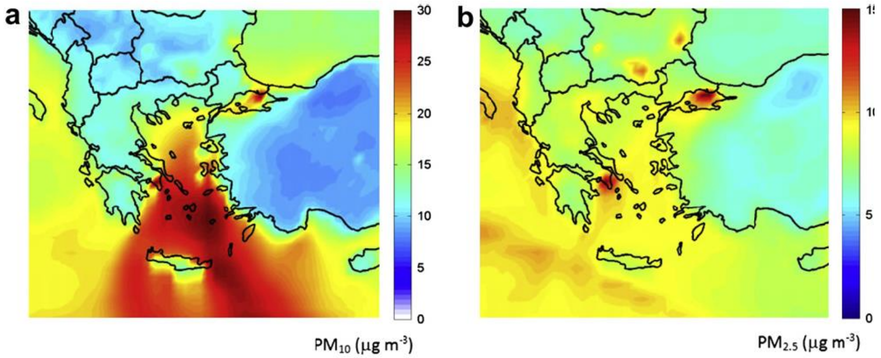
NCAR FINN BIOMASS BURNING EMISSIONS MODEL

INITIAL/BOUNDARY CONDITIONS (TM4-ECPL)

NATURAL EMISSIONS (MEGAN BIOGENIC+GOCART DUST)

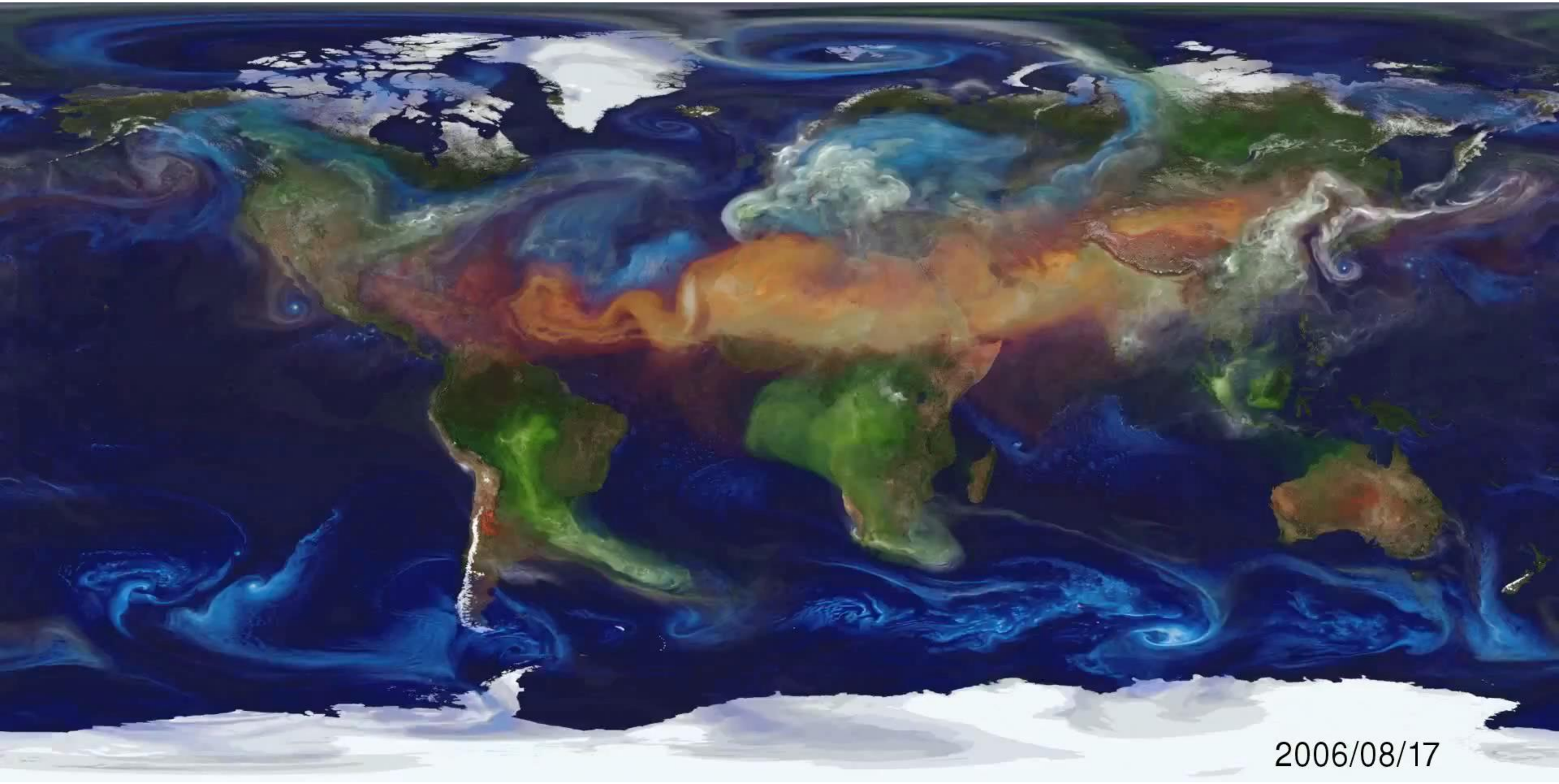
CHEMISTRY AND TRANSPORT MODEL (CMAQ)





Im at al., AE,2012

Aerosols up to 10 km



2006/08/17

NASA GEOS 5

Desert dust

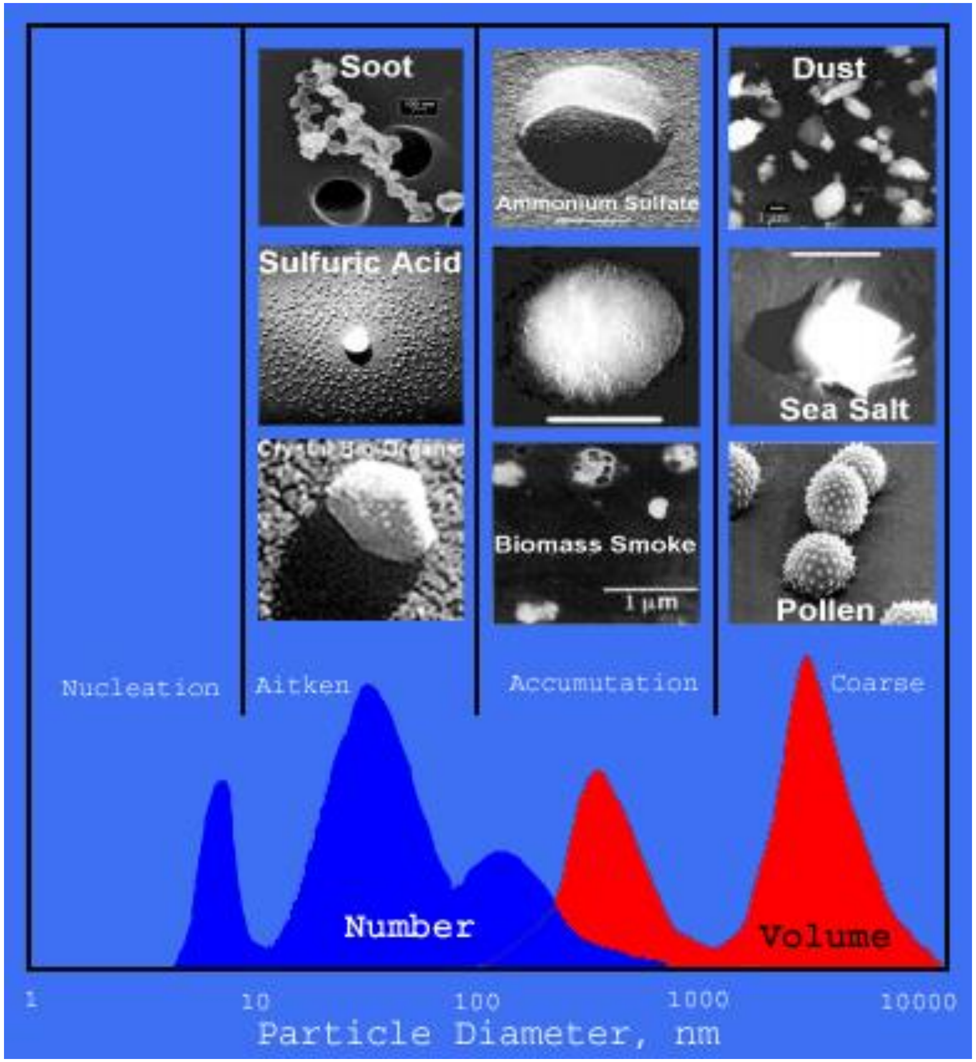
Sea-salt

Black and organic carbon

Sulfate aerosol

AEROSOL REPRESENTATION IN MODELS

Size distribution and shape



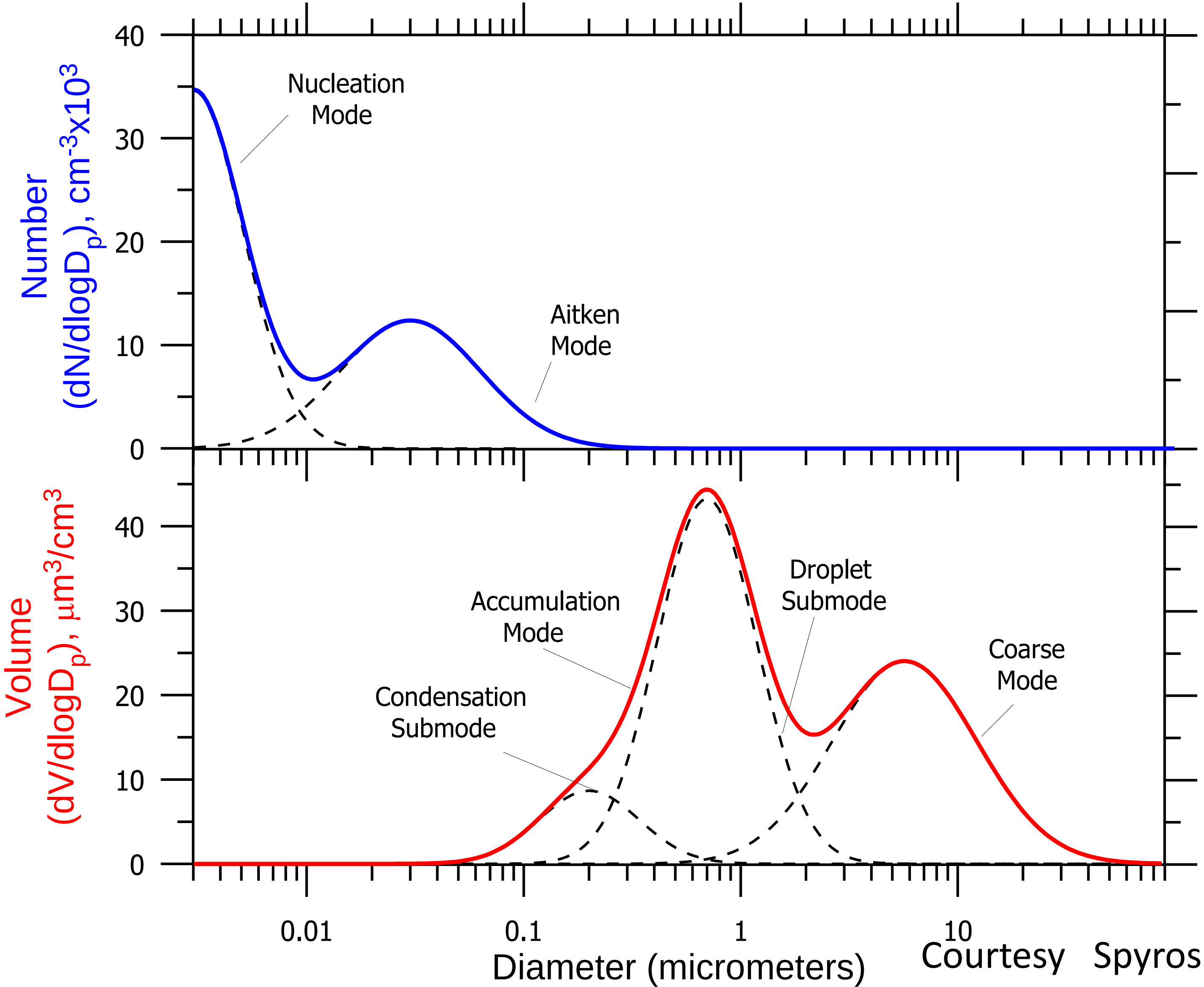
Models assume all aerosols are spherical

From the IGAC first 10 year synthesis book, edited by Brasseur et al. (2002)

Do we need to resolve aerosol size ?

Is only one way to do this?

Atmospheric Aerosol Size Distribution



Courtesy Spyros Pandis

Size distribution –not resolved (bulk)

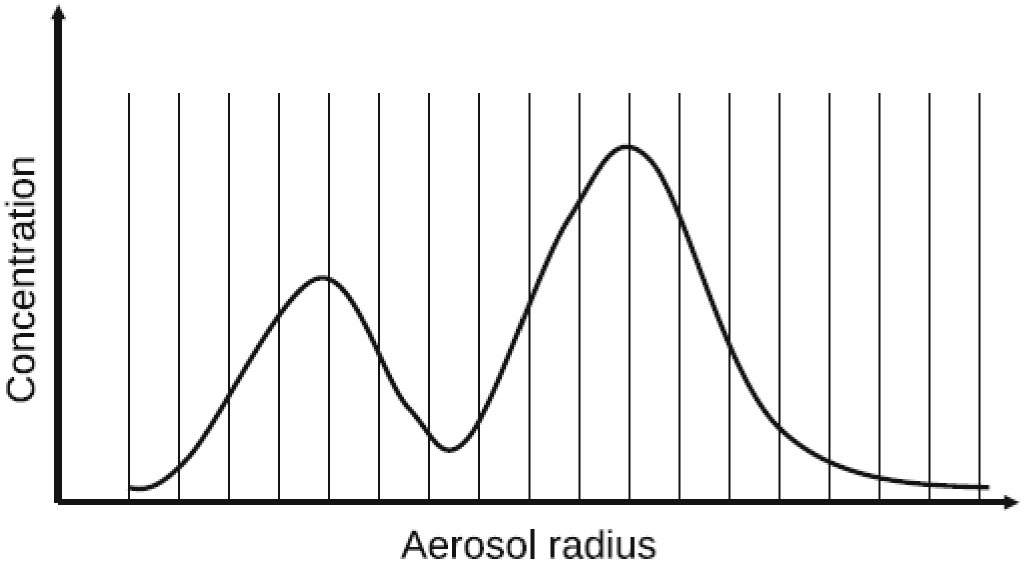
- Aerosols in models have a characteristic prescribed constant dry size, almost always lognormally distributed, with a constant width (sigma).

- Mixing is typically external, but can be internal as well, typically homogeneously mixed, but other mixing states are possible

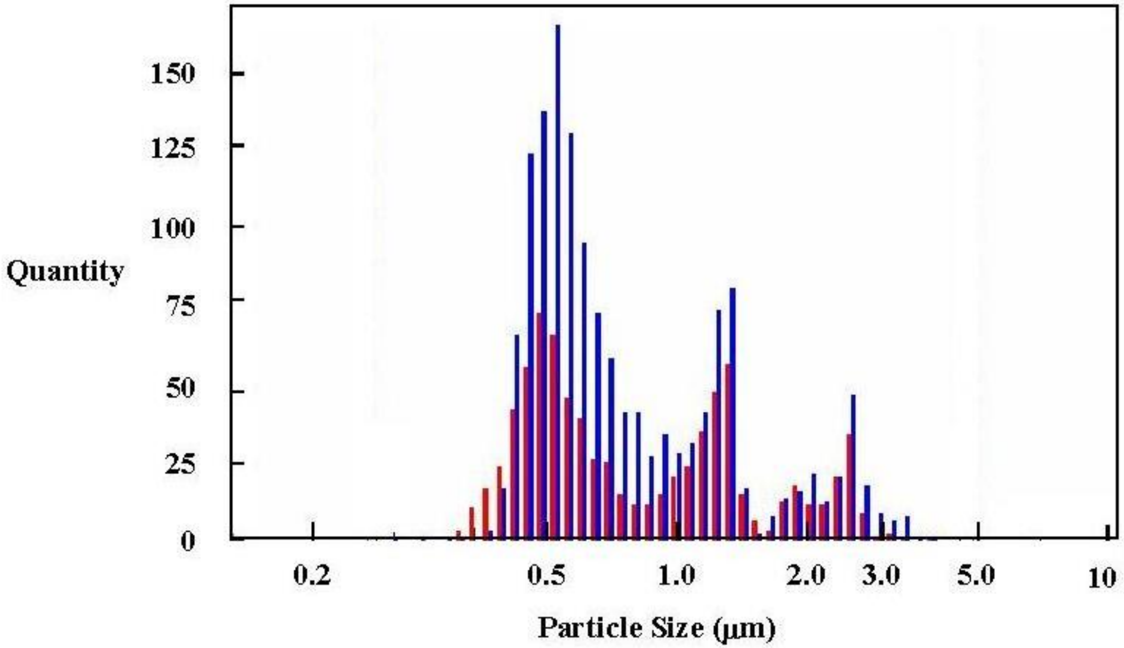
- Aerosol total mass is calculated, out from which the aerosol number can be derived

- Very simple with very few tracers, but very fast

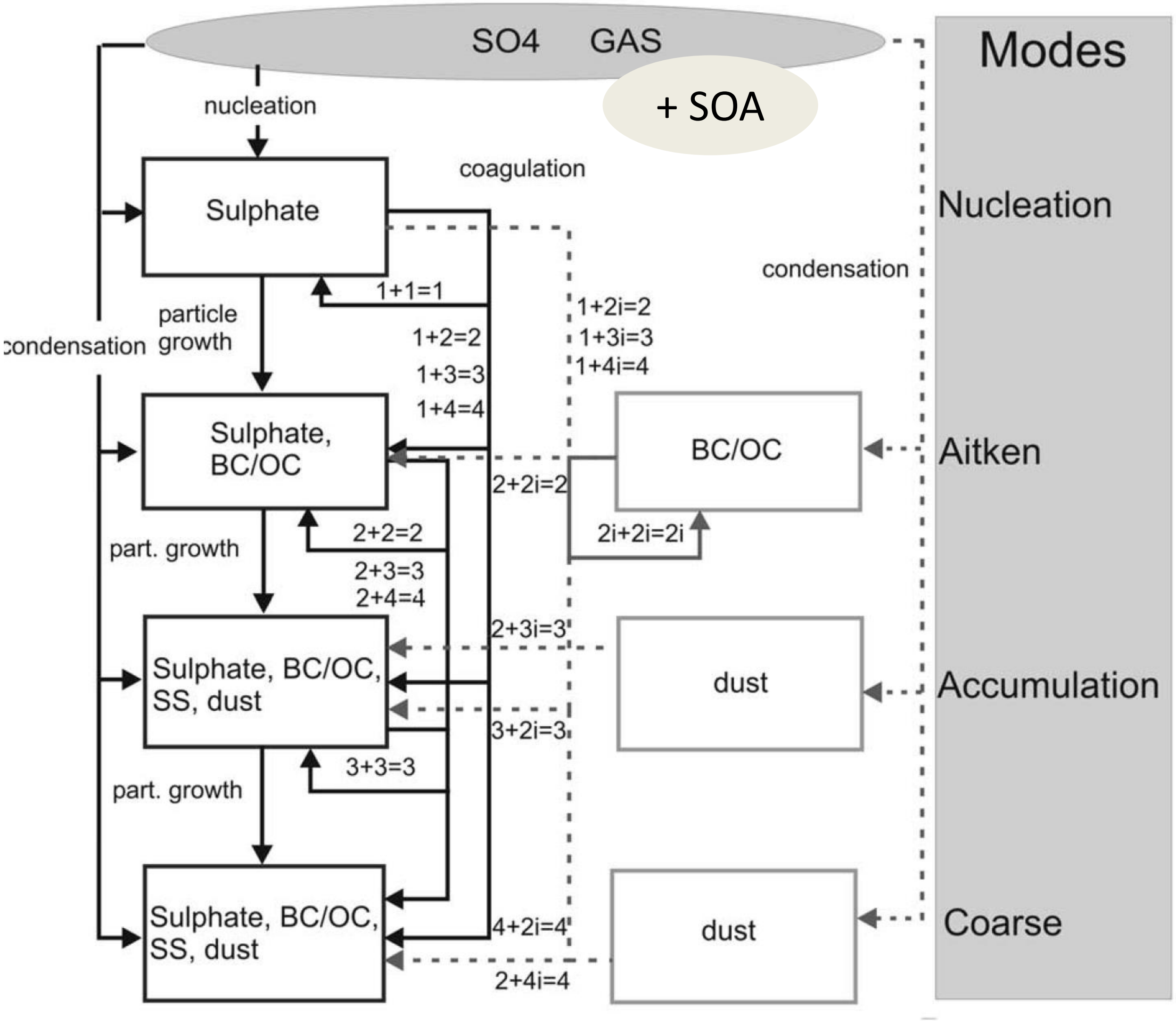
Size distribution modal vs sectional/bin approach



Boucher (text book) 2015



Modal approach & mixing of aerosols



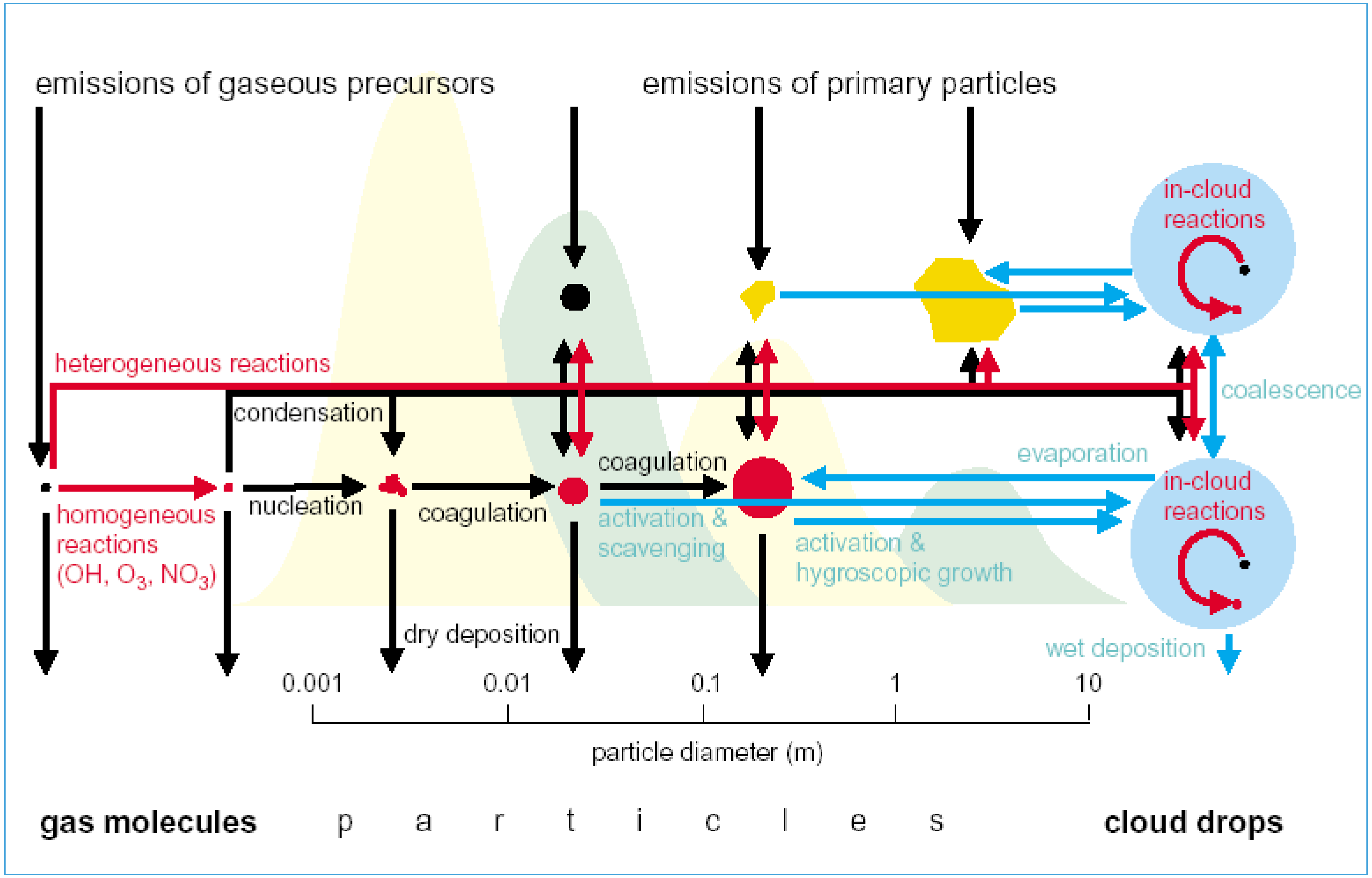
Aerosol microphysics model M7

soluble

In soluble

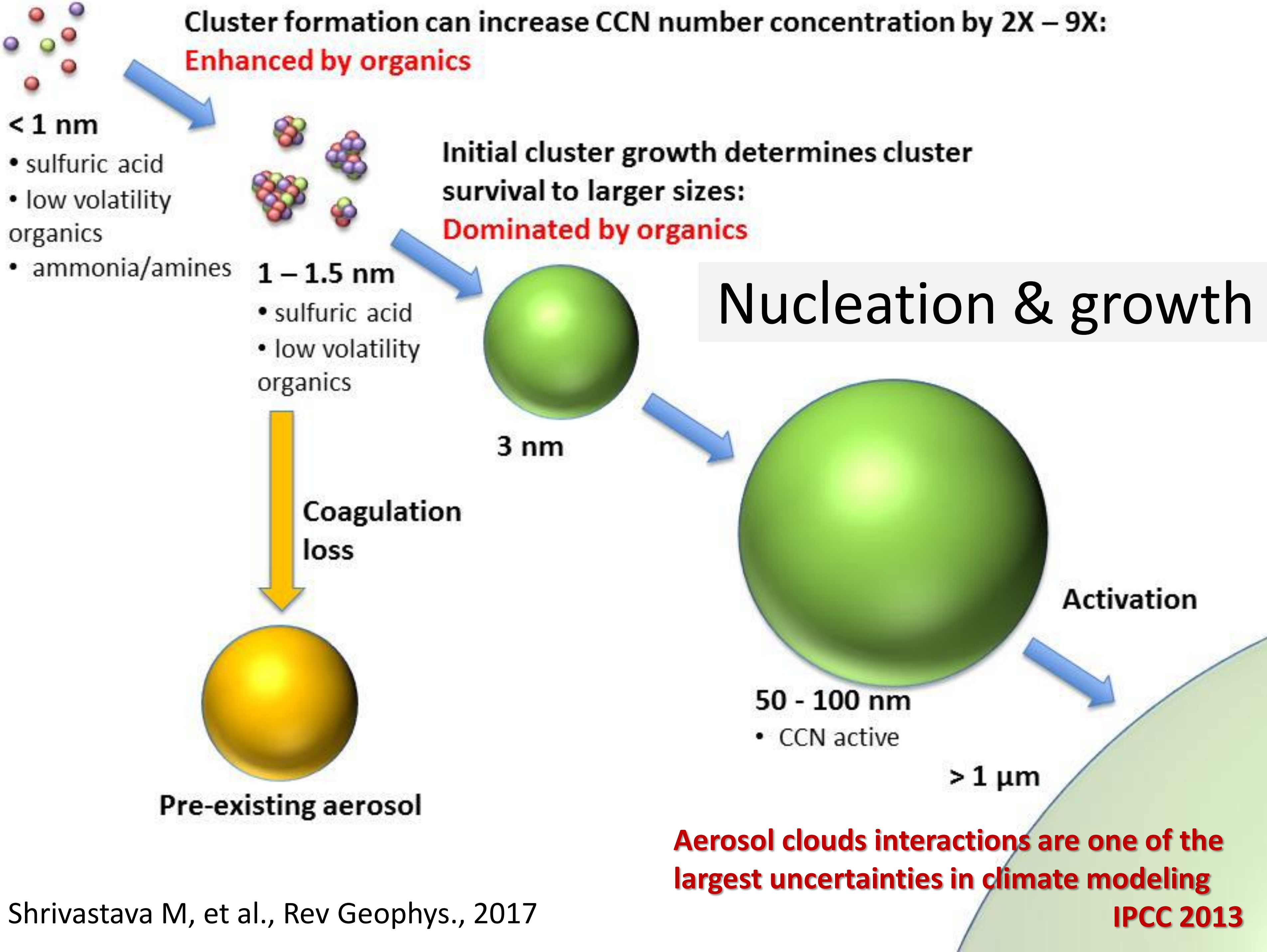
Vignati et al., JGR 2004

Processes affecting aerosols



Raes et al., 2000

Nucleation & growth



Cluster formation can increase CCN number concentration by 2X – 9X:
Enhanced by organics

< 1 nm
- sulfuric acid
- low volatility organics
- ammonia/amines

1 – 1.5 nm
- sulfuric acid
- low volatility organics

Initial cluster growth determines cluster survival to larger sizes:
Dominated by organics

3 nm

Coagulation loss

Pre-existing aerosol

50 - 100 nm
- CCN active

Activation

> 1 µm

Aerosol clouds interactions are one of the largest uncertainties in climate modeling
IPCC 2013

Shrivastava M, et al., Rev Geophys., 2017

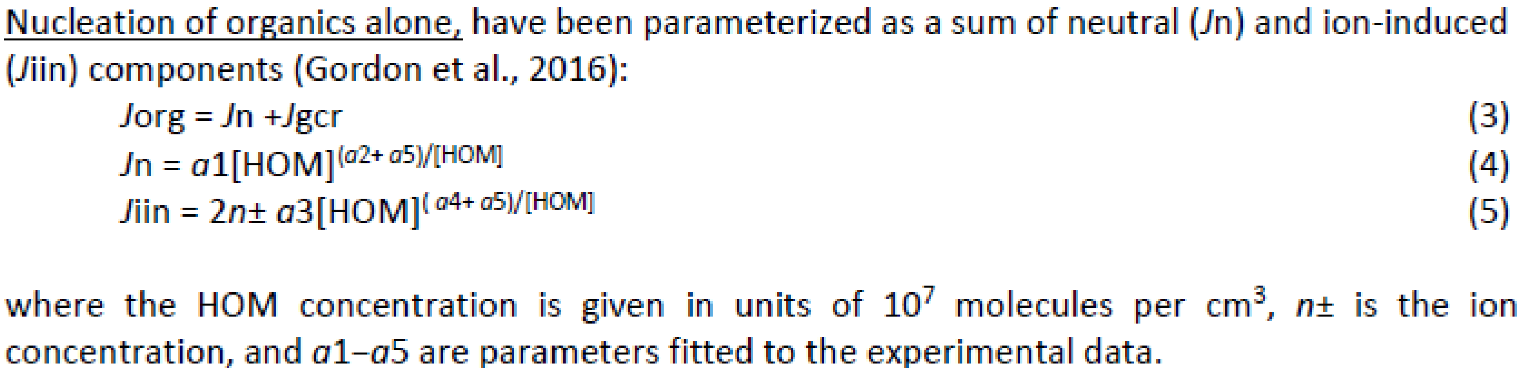
Nucleation mechanisms

1. **Binary – sulfuric acid and water**
2. **Ternary- sulfuric acid – water – ammonia**
3. Organics (HOM/ELVOC) contribute to the fast growth of the cluster. (Ehn et al., 2012)

   $JR = k_R\, [H_2SO_4]^2\, 0.5\, [BioOxOrg]$ (Jöniken et al 2015)

   $GR = 7.3\times10^{-8}\, [H_2SO_4] + 1.41\times10^{-7}\, [HOM]$ (Gordon et al., JGR, 2017)

4. Ion induced nucleation by organics Kirkby et al., Nature 2016
5. Organics (amines, ELVOC) involved from the first step of nucleation



Nucleation of organics alone, have been parameterized as a sum of neutral (*J*n) and ion-induced (*J*iin) components (Gordon et al., 2016):

$$Jorg = Jn + Jgcr \quad (3)$$

$$Jn = a1[HOM]^{(a2+a5)/[HOM]} \quad (4)$$

$$Jiin = 2n\pm\, a3[HOM]^{(a4+a5)/[HOM]} \quad (5)$$

where the HOM concentration is given in units of 10^7 molecules per cm^3, $n\pm$ is the ion concentration, and $a1$–$a5$ are parameters fitted to the experimental data.

Currently in models:
(1), (2) where NH_3 levels are high, (3) consider organics for growth of clusters

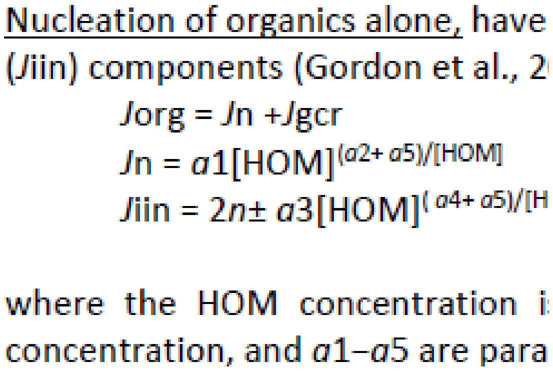
Nucleation mechanisms

1. **Binary – sulfuric acid and water**
2. **Ternary- sulfuric acid – water – ammonia**
3. Organics (HOM/ELVOC) contribute to the fast growth of the cluster. (Ehn et al., 2012)

$JR = k_R\,[H_2SO_4]^2$ 0.

GR = 7.3×10^{-8} [H_2SO_4] + 1.

4. Ion induced nucleation by
5. Organics (amines, ELVOC)



Nucleation of organics alone, have

(Jiin) components (Gordon et al., 2

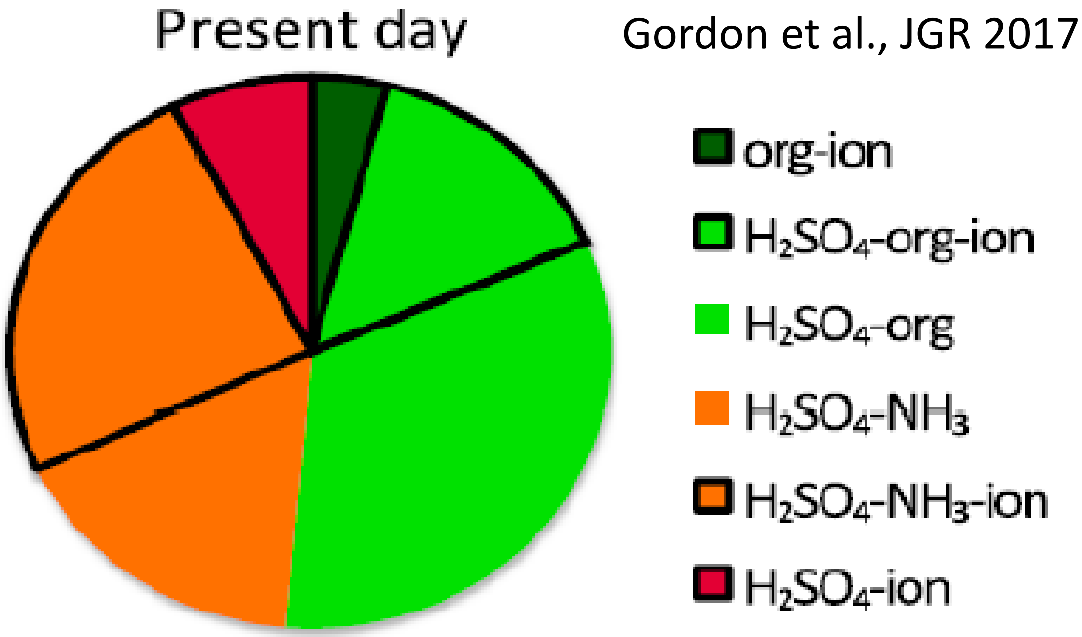
$Jorg = Jn + Jgcr$

$Jn = a1[HOM]^{(a2+a5)/[HOM]}$

$Jiin = 2n\pm\, a3[HOM]^{(a4+a5)/[H}$

where the HOM concentration i

concentration, and a1–a5 are para



Present day

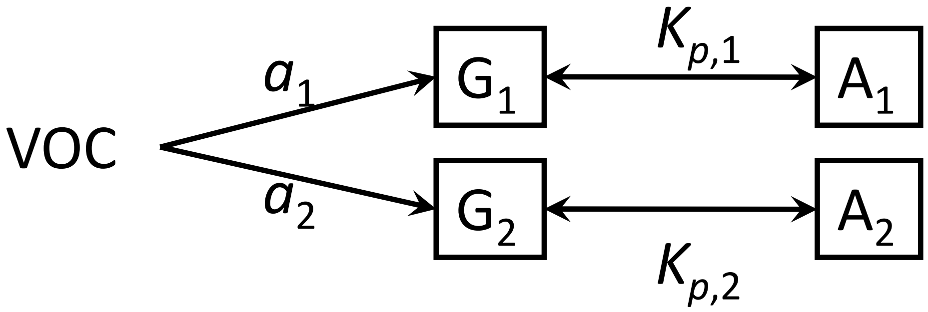
Gordon et al., JGR 2017

Currently in models:

(1), (2) where NH_3 levels are high, (3) consider organics for growth of clusters

How SOA is parameterized in the models?

- Pseudo-emissions (~18% on terpenes emissions or terpenes oxidized amounts)
- 2-product model
  - VOC reactivity
  - SOA yield
    - Chemical dependence (e.g. NO_x levels) – a_i
    - Physical dependence (e.g. temperature) – $K_{p,i}$

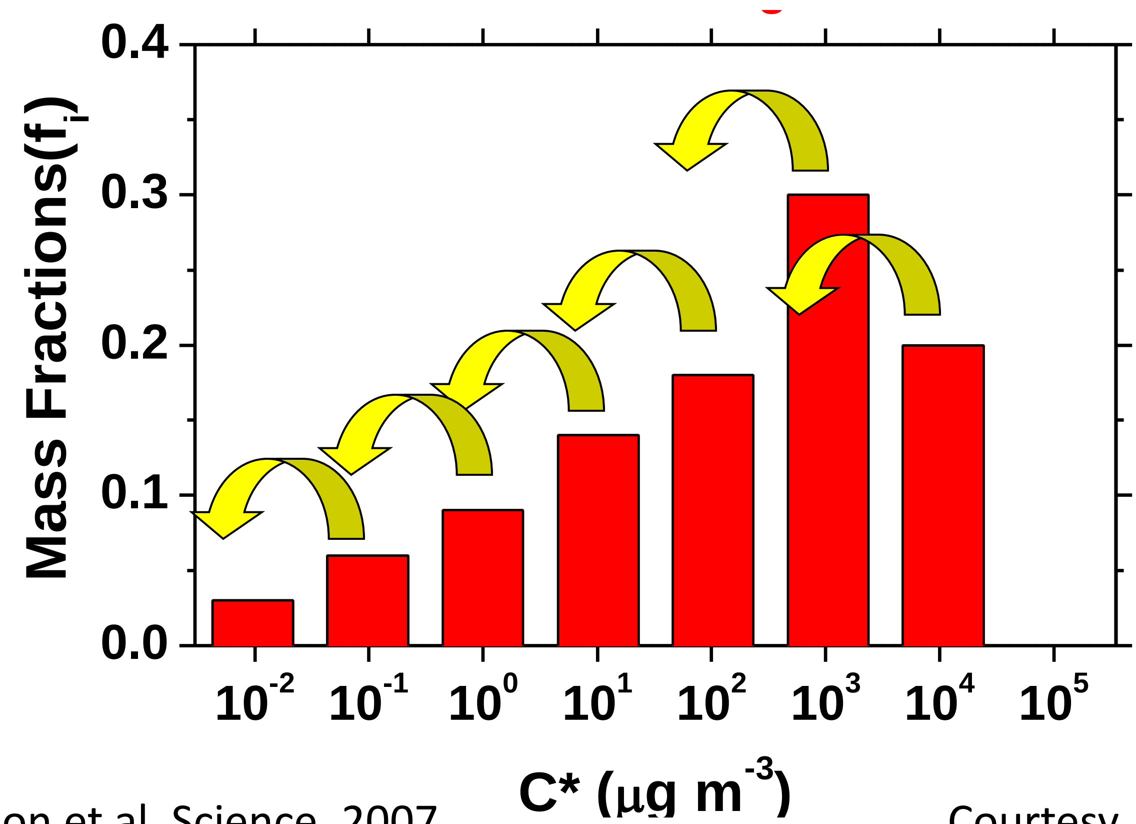


Odum et al., GRL, 2007;
Kanakidou et al., JGR, 2000

- Volatility bases set (VBS)

Organic Aerosol and its Chemical Aging

- Primary and secondary organics in the atmosphere also cover a wide range of volatilities
- Compounds react in the gas phase with OH producing material with lower volatility . Formation of very low volatility material (10^{-5} µg m^3 from aging of semivolatile material assumed)

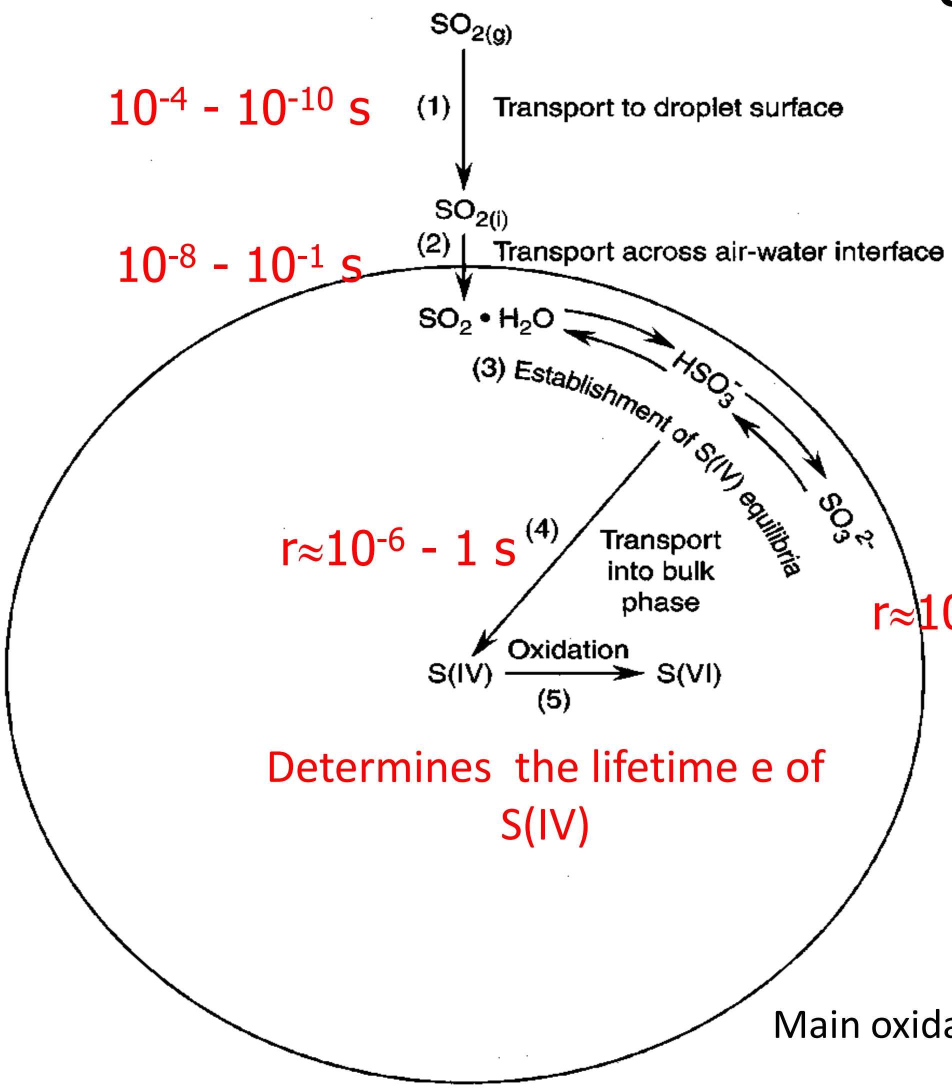


Concept in Robinson et al, Science, 2007

Courtesy Spyros Pandis

Oxidation in droplets/ aqueous phase chemistry

Characteristic times for the steps:



10^{-4} - 10^{-10} s

10^{-8} - 10^{-1} s

r≈10^{-6} - 1 s

r≈10^{-6} s

Determines the lifetime e of S(IV)

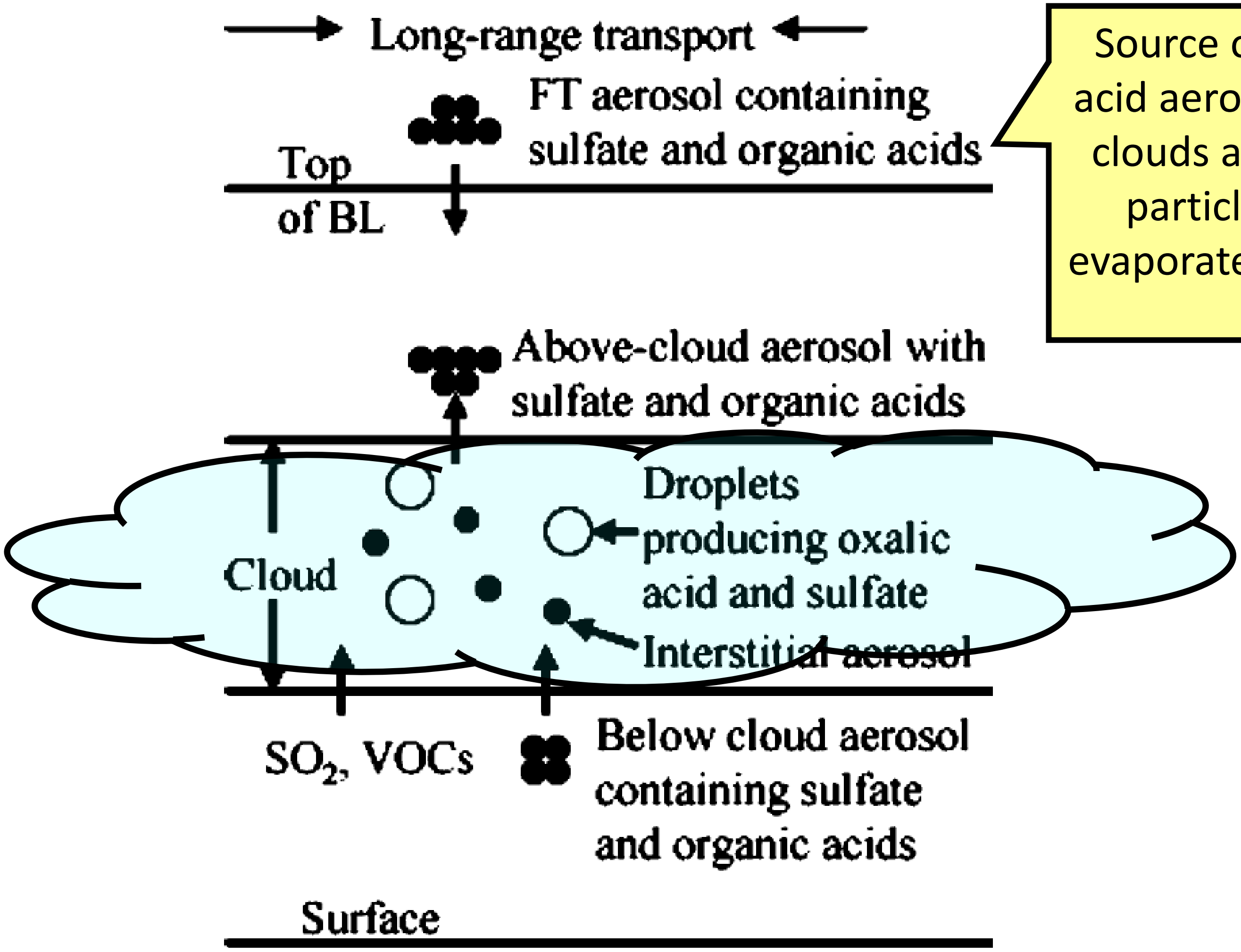
Typical products of interest inside the droplet
SO_4^{2-}, organic acids

Main oxidants are O_2, O_3, H_2O_2, •OH, HO_2•, NO_x

Importance of Fenton reactions Fe^{2+}/Fe^{3+} & Cu^+/Cu^{2+}

Modified from IGAC newsletter

Cloud processing



Source of organic acid aerosols above clouds as residual particles from evaporated droplets

Sorooshian et al., EST, 2007

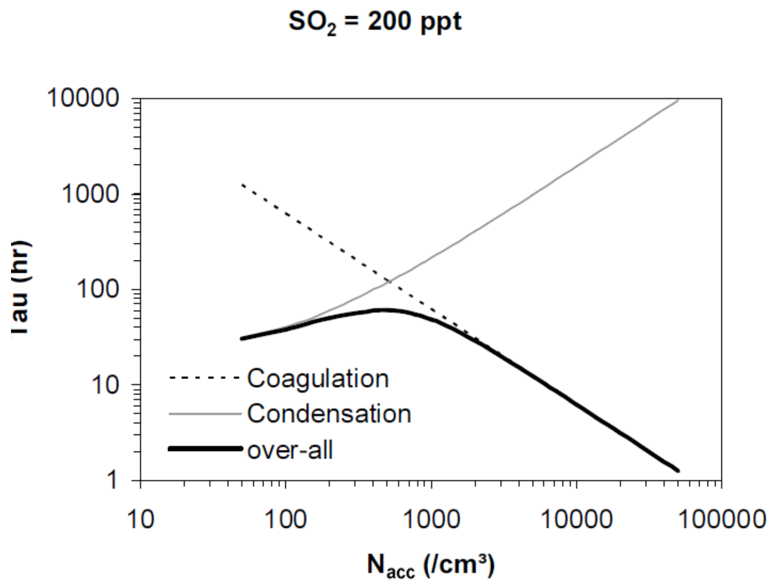
AEROSOL PROCESSING

Coagulation

- reduces the number of aerosols
- leads to larger sizes
- modifies size distribution
- does not remove mass from the atmosphere
- Important to consider when studying fine aerosol number concentrations.

Importance of coagulation vs condensation for conversion of hydrophobic to hydrophilic particles. (turn overtime)
for SO_2=200 ppt

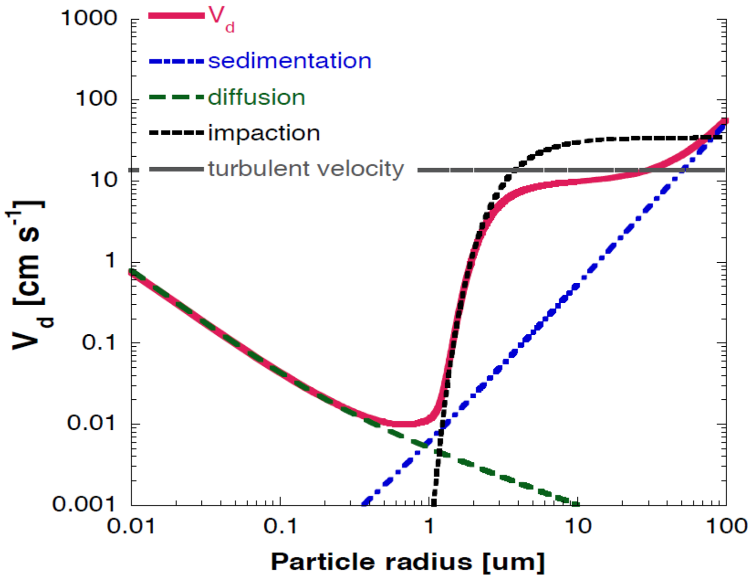
Kanakidou et al., ACP 2005

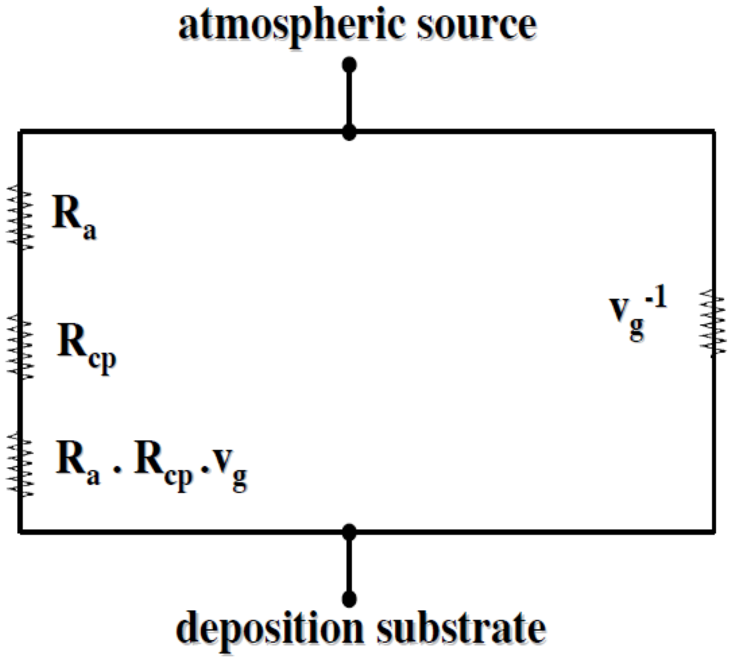


Removal

Aerosol dry deposition and sedimentation

$$V_d = \frac{1}{(R_a + R_{cp} + R_a R_{cp} v_g)} + v_g$$





R_a = aerodynamic resistance
R_{cp}: quasi-laminar boundary layer resistance
R_{surf}: surface resistance (all types of surface - soil, plant, buildings etc), becomes zero (if a particle reaches the ground, it has been deposited)

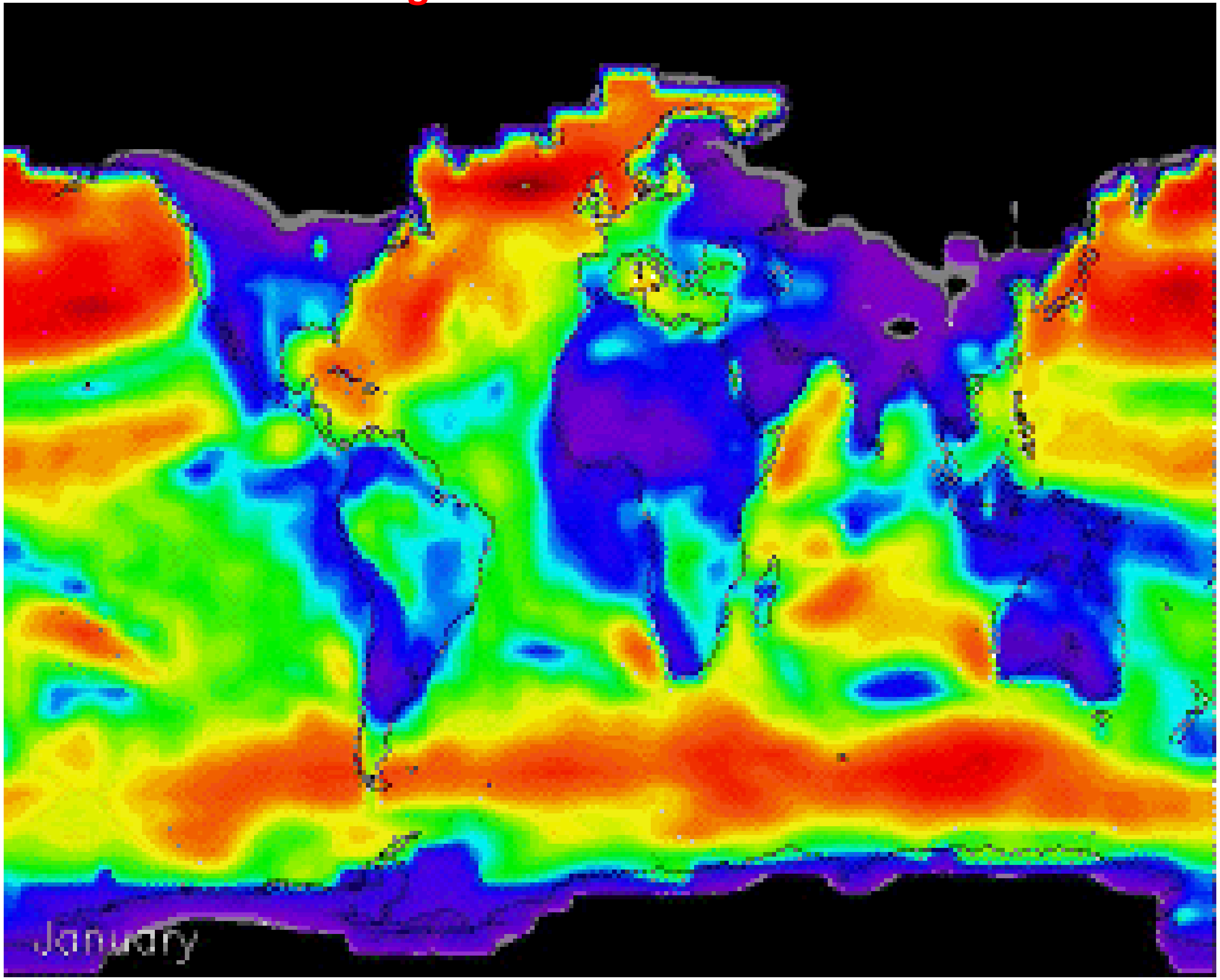
v_g: sedimentation velocity
V_d = deposition velocity

Ganzeveld, JGR 1998

Monthly variation of SO_2 deposition as computed by ECHAM4 – Gazenveld Laurens

http://www.atmosphere.mpg.de/enid/aaf662be6cd123f4c54c4d90d24b1373,0/hr.html

Blue low red high



A dry deposition parameterization for sulfur oxides in a chemistry and general circulation model, Ganzeveld, Lelieveld, and Roelofs, J. Geophys. Res., 103. 1998, 5679-5694

Annual cycle in global SO_2 dry deposition velocity constructed by using 2-week average global distributions.

Over the oceans V_{dSO2} reflects the **turbulence intensity** ➔large removal rates over the **stormtracks** over the higher latitudes in the SH throughout the year and in the NH winter over the Atlantic & Pacific.

Over land **near-zero values (black areas),** due to a large surface resistance for surface temperatures < -10 ^oC, reflecting the **snow/ice** cover.

Relative large values **over Europe in winter due to the presence of a large fraction of wetted surfaces** due to rainfall interception and dewfall.

Wet deposition

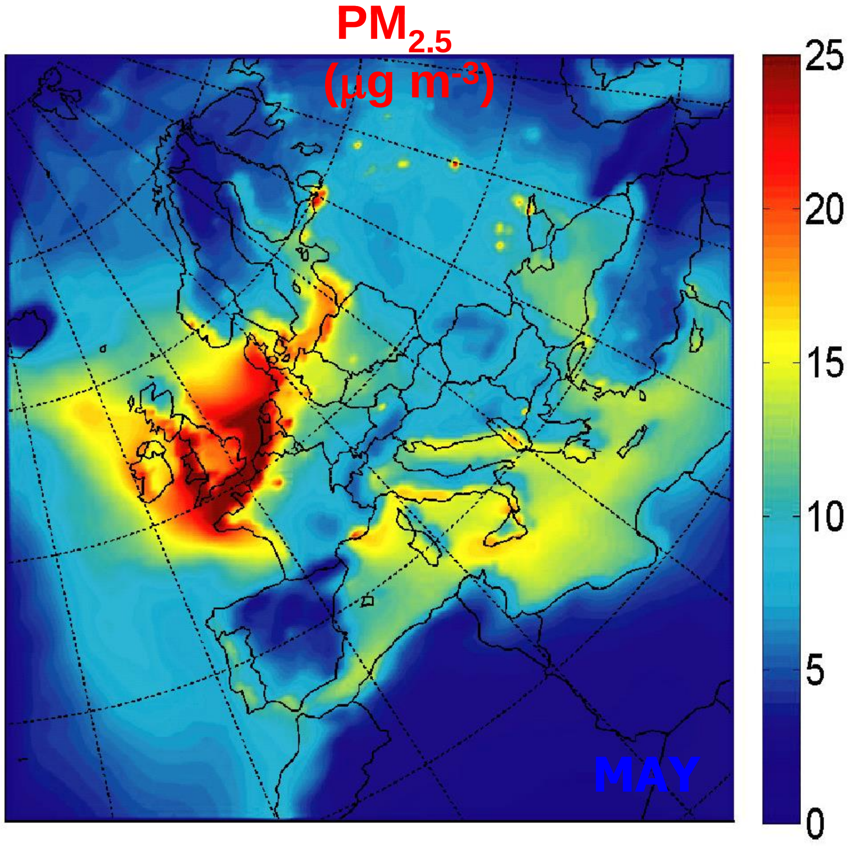
- In-cloud removal
  - By dissolution followed by precipitation
- Below-cloud removal
  - By falling droplets

- Function of size, both aerosol's and cloud droplet's

- Not all wet-removed aerosols reach the ground, due to rain-droplet evaporation, a process serving as a lower level source of cloud processed aerosols

PMCAMx-UF

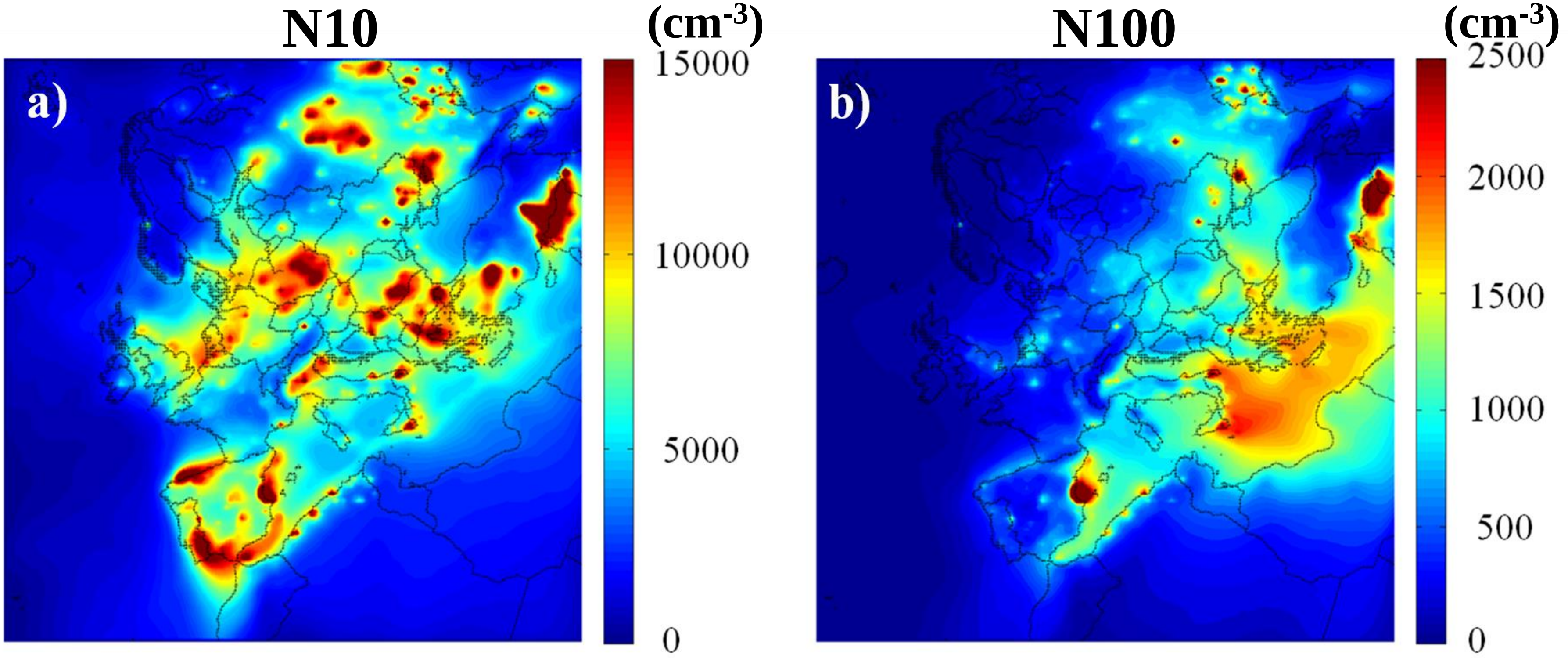
- Ultrafine PM-focused version of PMCAMx.
- Simulates both aerosol number and composition using the TOMAS algorithm
  - 43 size sections (1 nm-10 μm)
  - 13 aerosol species
  - H_2SO_4 in pseudo-steady state
- Grid nesting (down to a 3x3 km)
  - 3492x3240 km region
  - 36x36 km grid
  - 14 levels up to 6 km
- Carbon Bond-IV gas-phase chemistry
  - 34 gas species
- WRF Meteorology



Courtesy Spyros Pandis

Particle number concentration fields

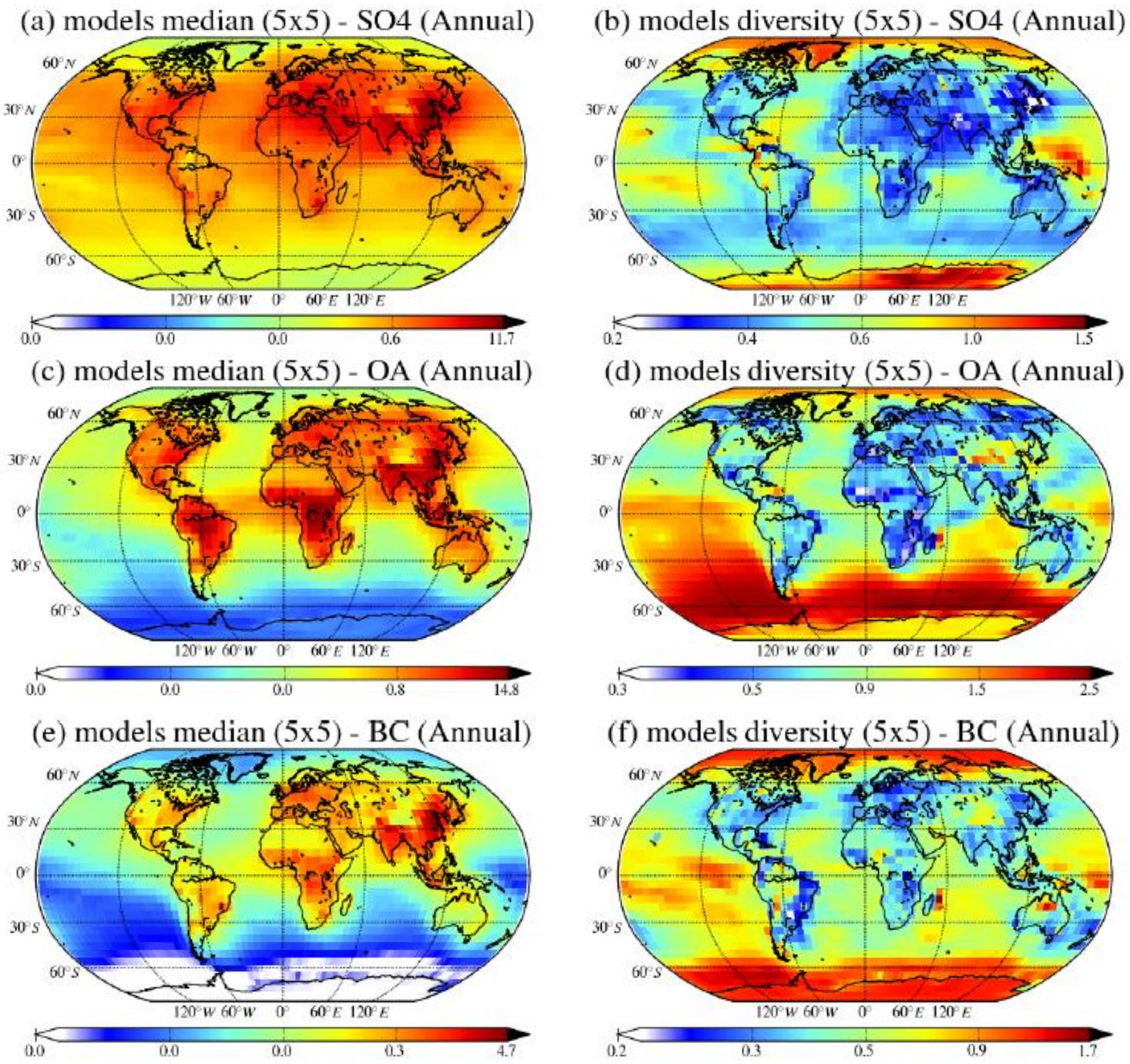
(June 2012)



Courtesy Spyros Pandis

Video that shows how NPF are formed in Europe in July 2012

PM_1 multi-model median chemical composition- surface



median

diversity

sulfate

Organic aerosol

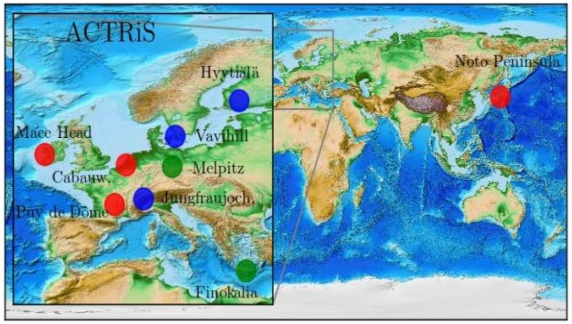
Black carbon

Fanourgakis et al., Atmos. Chem. Phys., 19, 8591–8617, 2019

BACCHUS
Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic UnderStanding

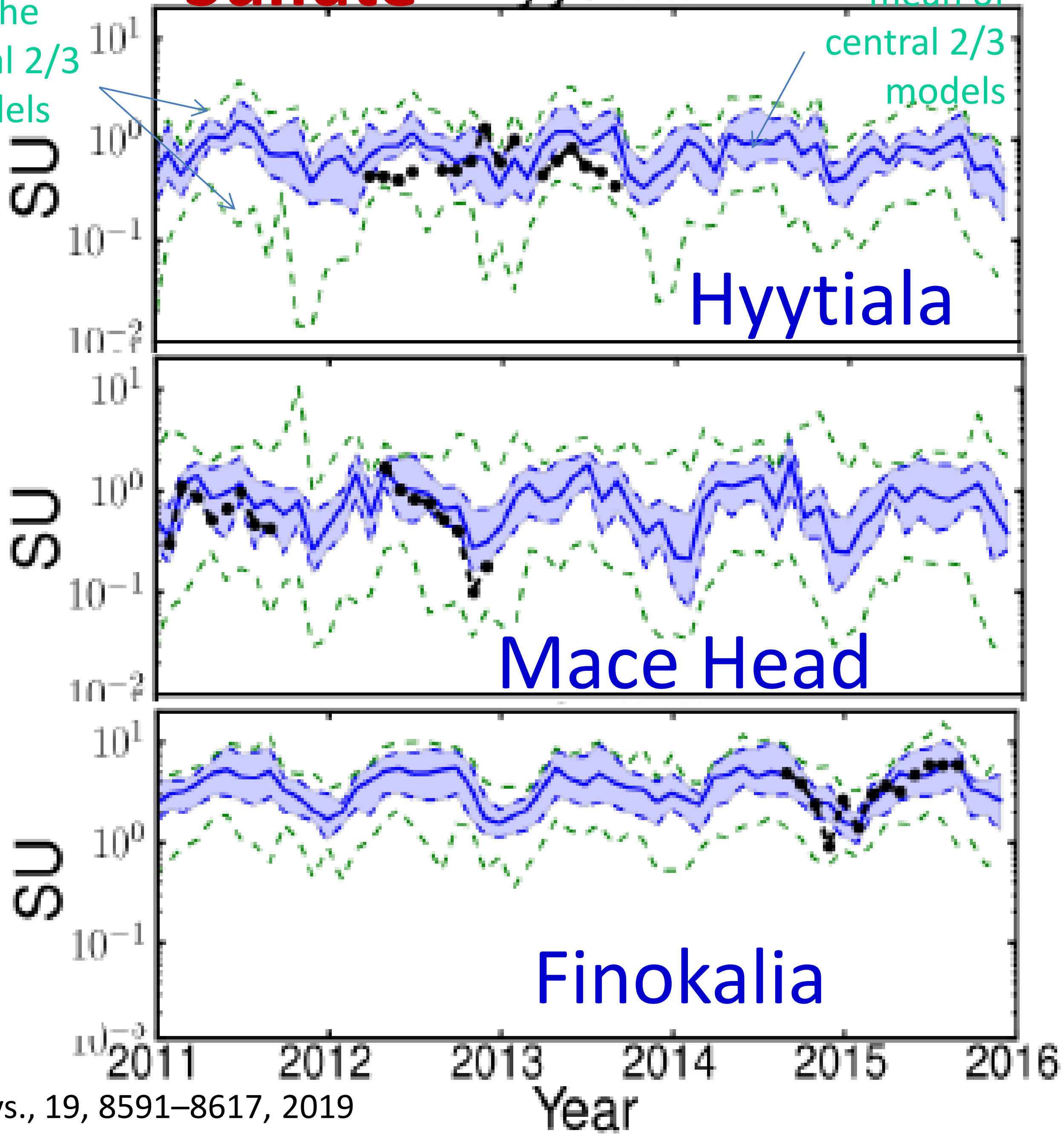
Sulfate

BACCHUS model intercomparison 15 models vs AMS- organics



Data (black dots) from ACTRIS - Schmale et al. Scientific Reports, 2017

MMM – blue line
min, max model green dashed



Min max of the central 2/3 models

Geometric mean of central 2/3 models

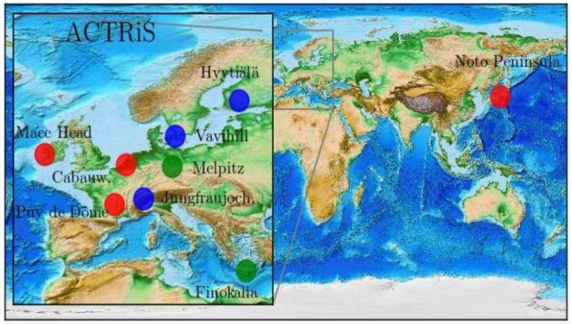
Fanourgakis et al., Atmos. Chem. Phys., 19, 8591–8617, 2019

BACCHUS

Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic UnderStanding

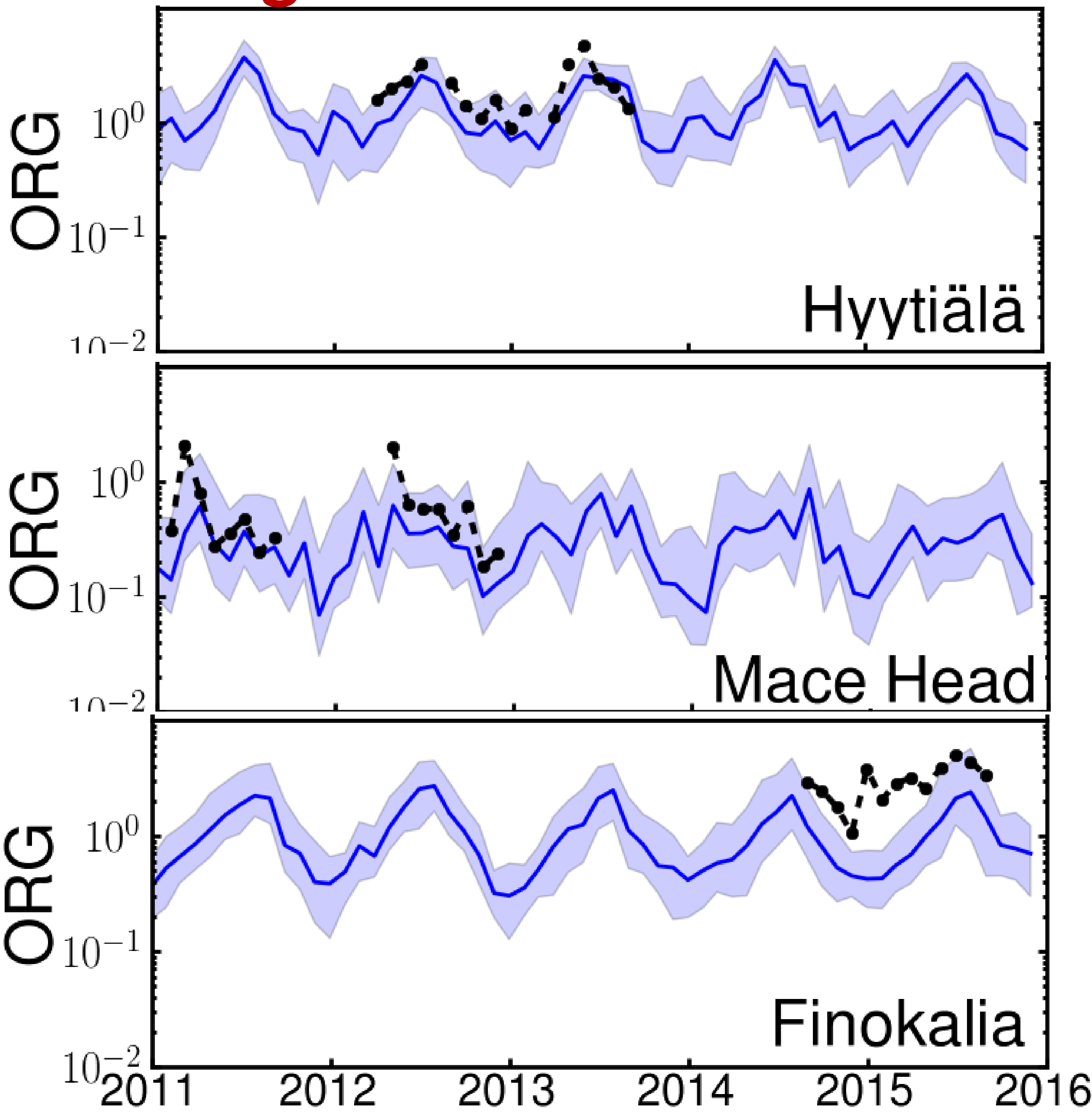
Organics

BACCHUS model intercomparison 15 models vs AMS- organics



Data from ACTRIS - Schmale et al. Scientific Reports, 2017

Fanourgakis et al., Atmos. Chem. Phys., 19, 8591–8617, 2019



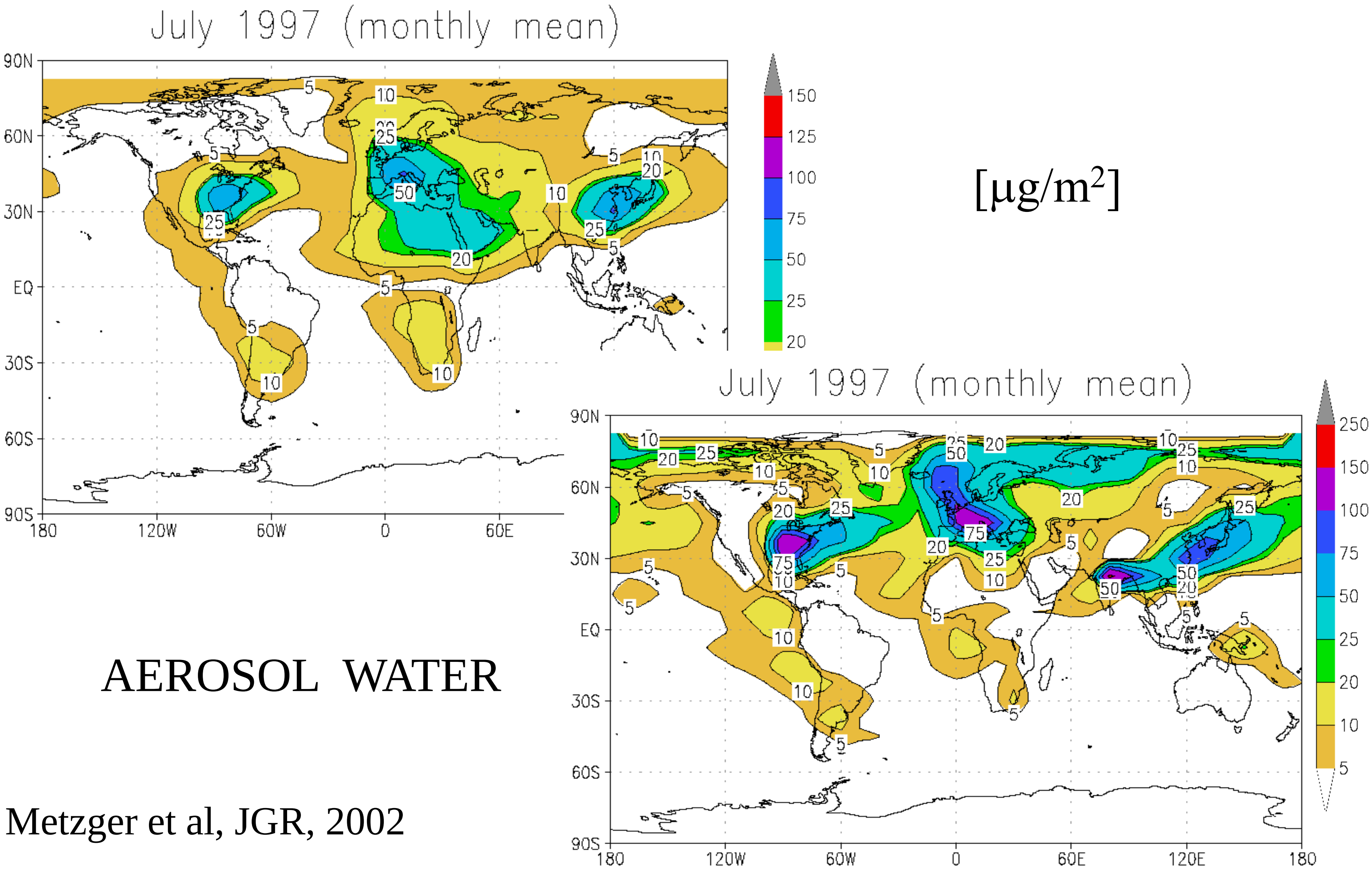
AEROSOL WATER

sum of water associated with the inorganic and organic components of the aerosols –
in most models only the inorganic aerosol is taken into account for this calculation

AEROSOL ACIDITY

Important for aerosol reactions, for NO_3^- partitioning to aerosol phase, for nutrients solubilisation

TOTAL DRY AEROSOL MASS (SO4, NO3, NH4)

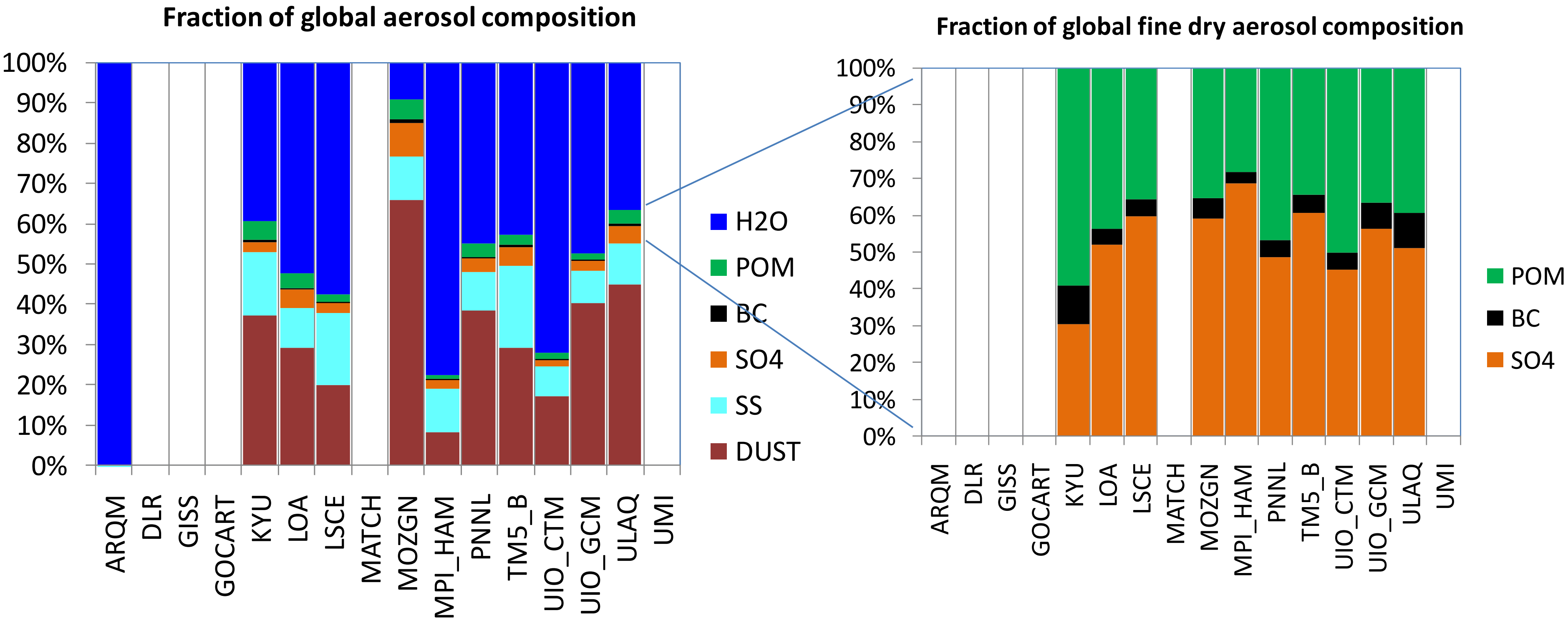


[µg/m^2]

AEROSOL WATER

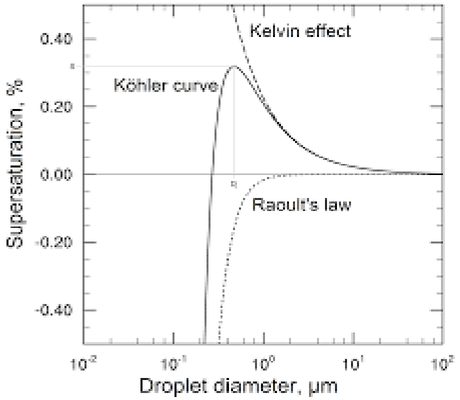
Metzger et al, JGR, 2002

Aerosol composition



Modified from Textor et al., 2006

AEROSOL HYGROSCOPICITY (κ)



$$\kappa = \sum_i \varepsilon_i \kappa_i$$

$$\frac{1}{a_w} = 1 + \kappa \frac{V_s}{V_w},$$

$$S = a_w \exp\left(\frac{4\sigma_{s/a} M_w}{RT\rho_w D}\right)$$

$$S(D) = \frac{D^3 - D_d^3}{D^3 - D_d^3(1-\kappa)} \exp\left(\frac{4\sigma_{s/a} M_w}{RT\rho_w D}\right)$$

α_w activity of water in solution

V_s dry volume

V_w volume of water

S saturation ratio

$\sigma_{s/\alpha}$ surface tension

Mw, ρw molecular weight and density of water

D particle diameter

D_d dry particle diameter

M. D. Petters and S. M. Kreidenweis
Atmos. Chem. Phys., 7, 1961–1971, 2007

$$d_{\mathrm{c}} = \left(\frac{4A^3}{27\kappa s_c^2} \right)^{1/3}$$

s_c supersaturation
d_c critical diameter

above which the particle acts as CCN

CCN at a specific supersaturation : number of particles of diameter ≥ d_c

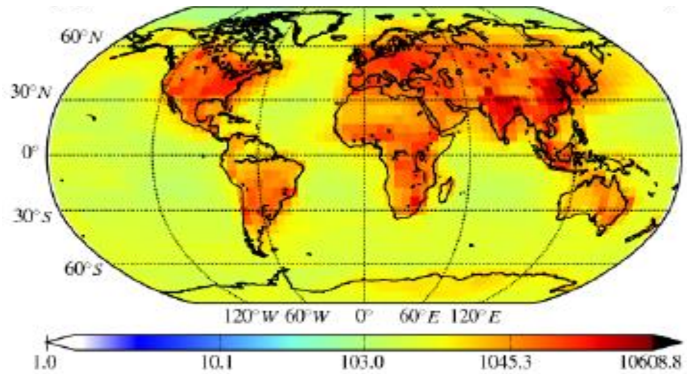
$$\mathrm{CCN}(d_{\mathrm{c}}) = \int_{d_{\mathrm{c}}}^{\infty} n(d_p)\mathrm{d}d_p$$

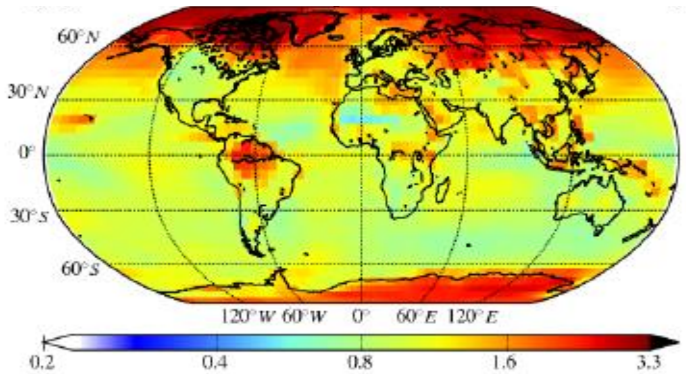
P. Kalkavouras et al.:
Atmos. Chem. Phys., 19, 6185–6203, 2019

multi-model results at surface

Annual Multi-model median

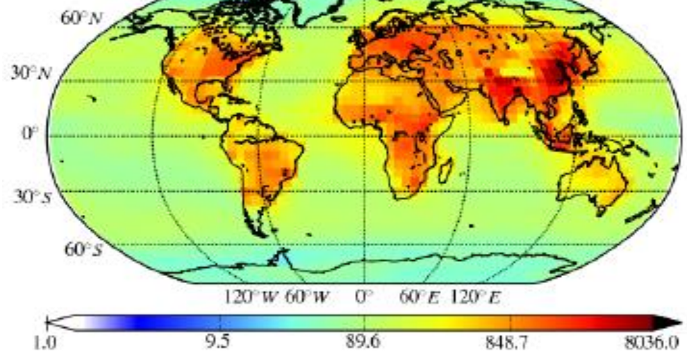
Model diversity (stdev/mean)



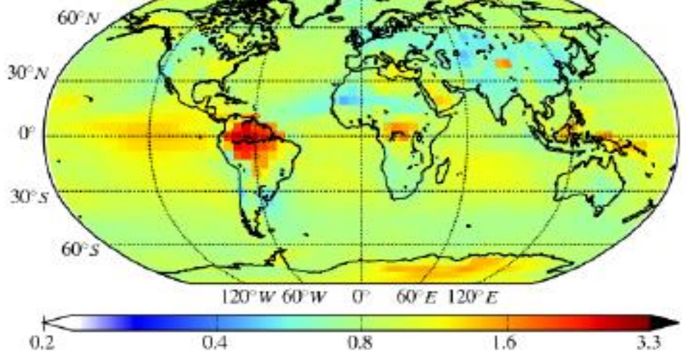


N3

(c) models median (5x5) - N50 (Annual)

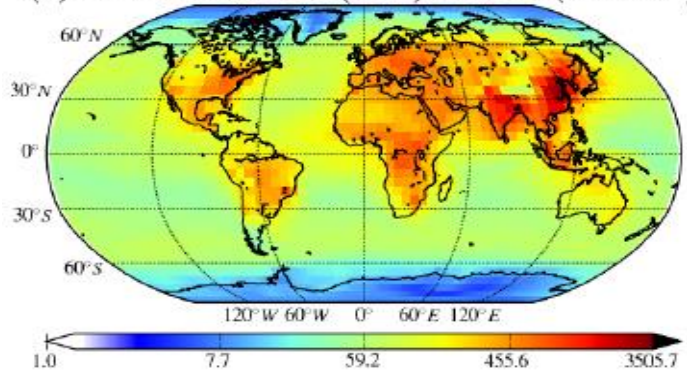


(d) models diversity (5x5) - N50 (Annual)

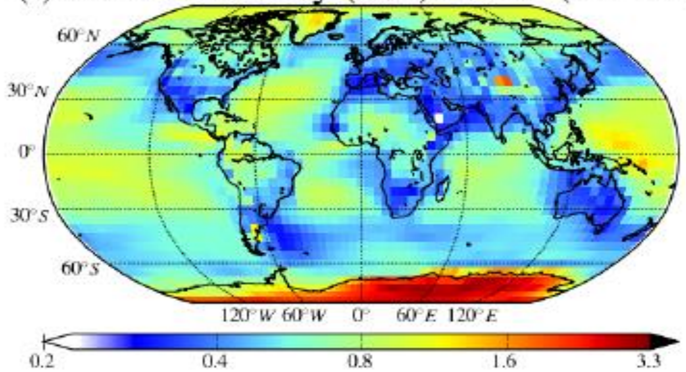


N50

(e) models median (5x5) - CCN (Annual)



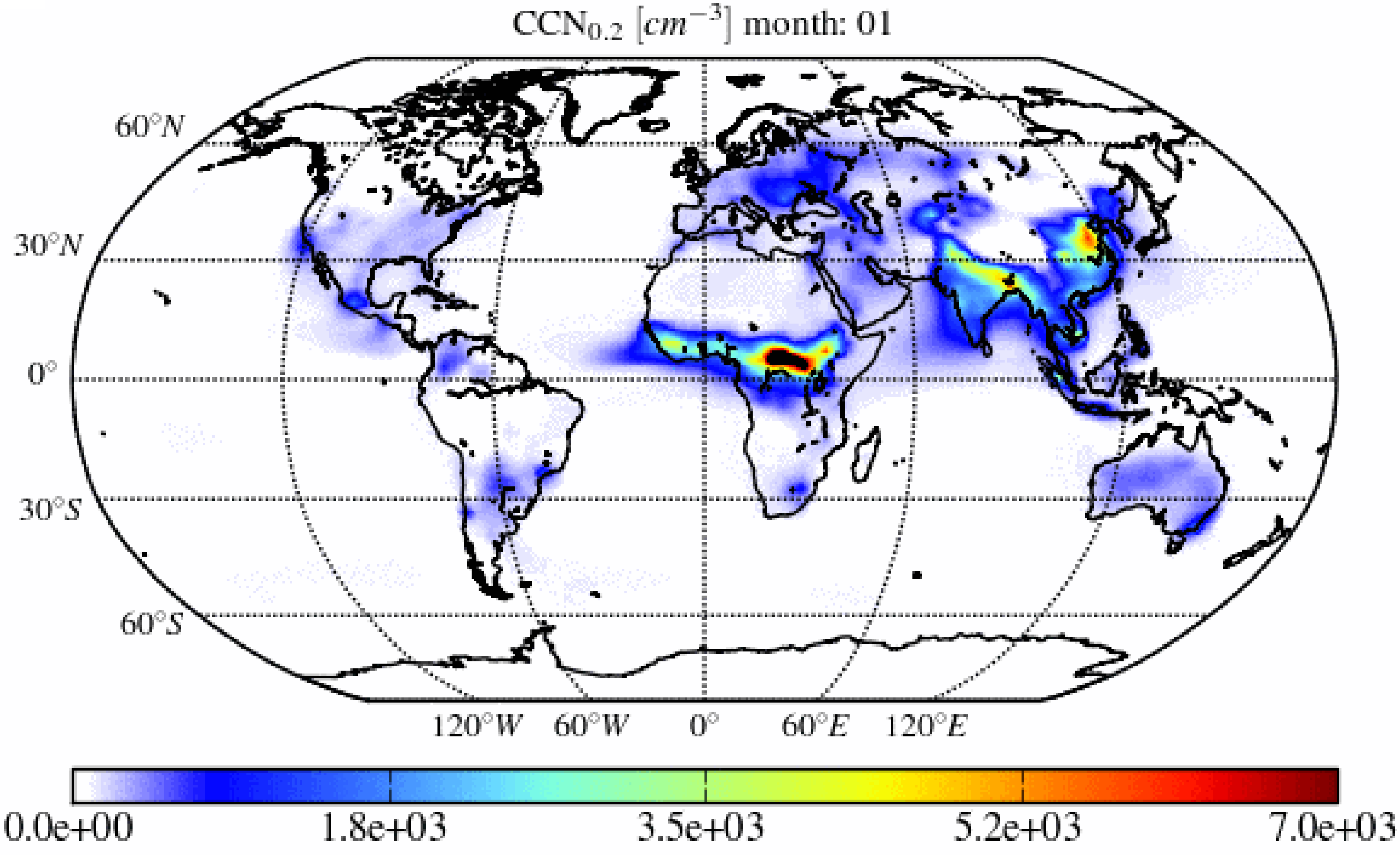
(f) models diversity (5x5) - CCN (Annual)



CCN

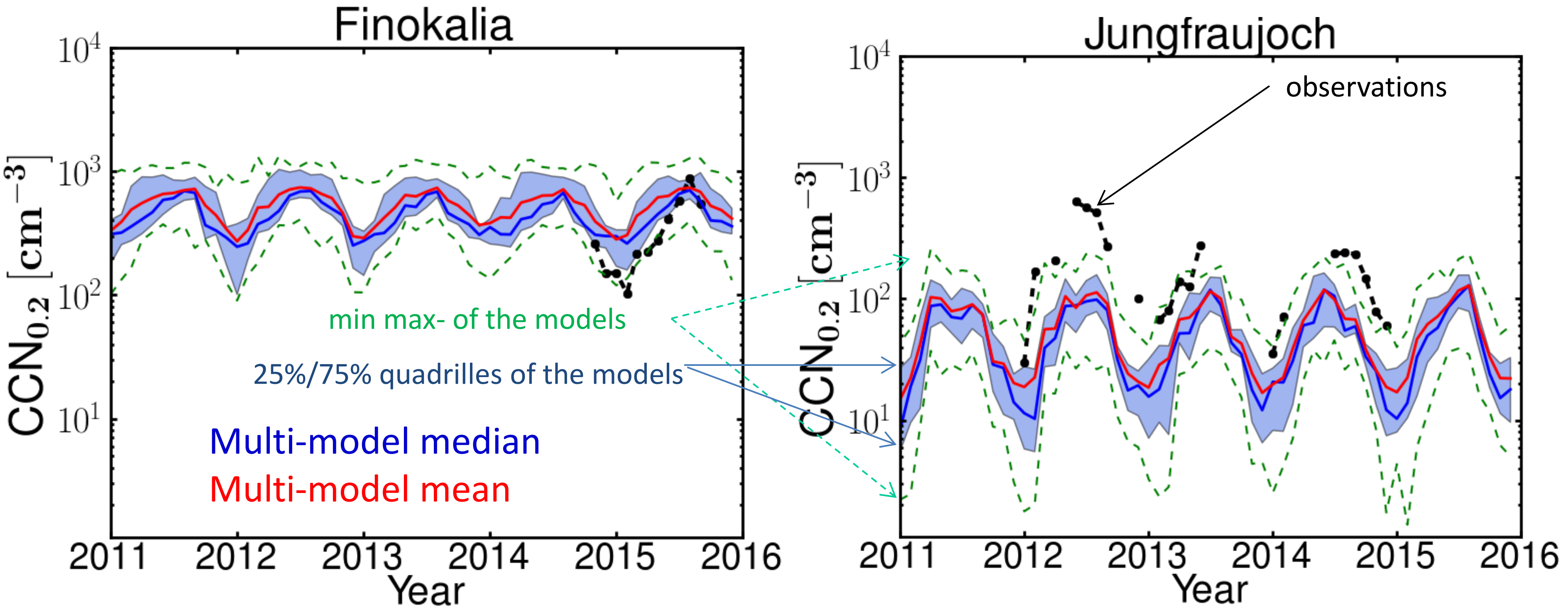
Fanourgakis et al., Atmos. Chem. Phys., 19, 8591–8617, 2019

Seasonal variability of CCN at 0.2% ss



Near the surface

CCN at 0.2% supersaturation



observations

min max- of the models

25%/75% quadrilles of the models

Multi-model median

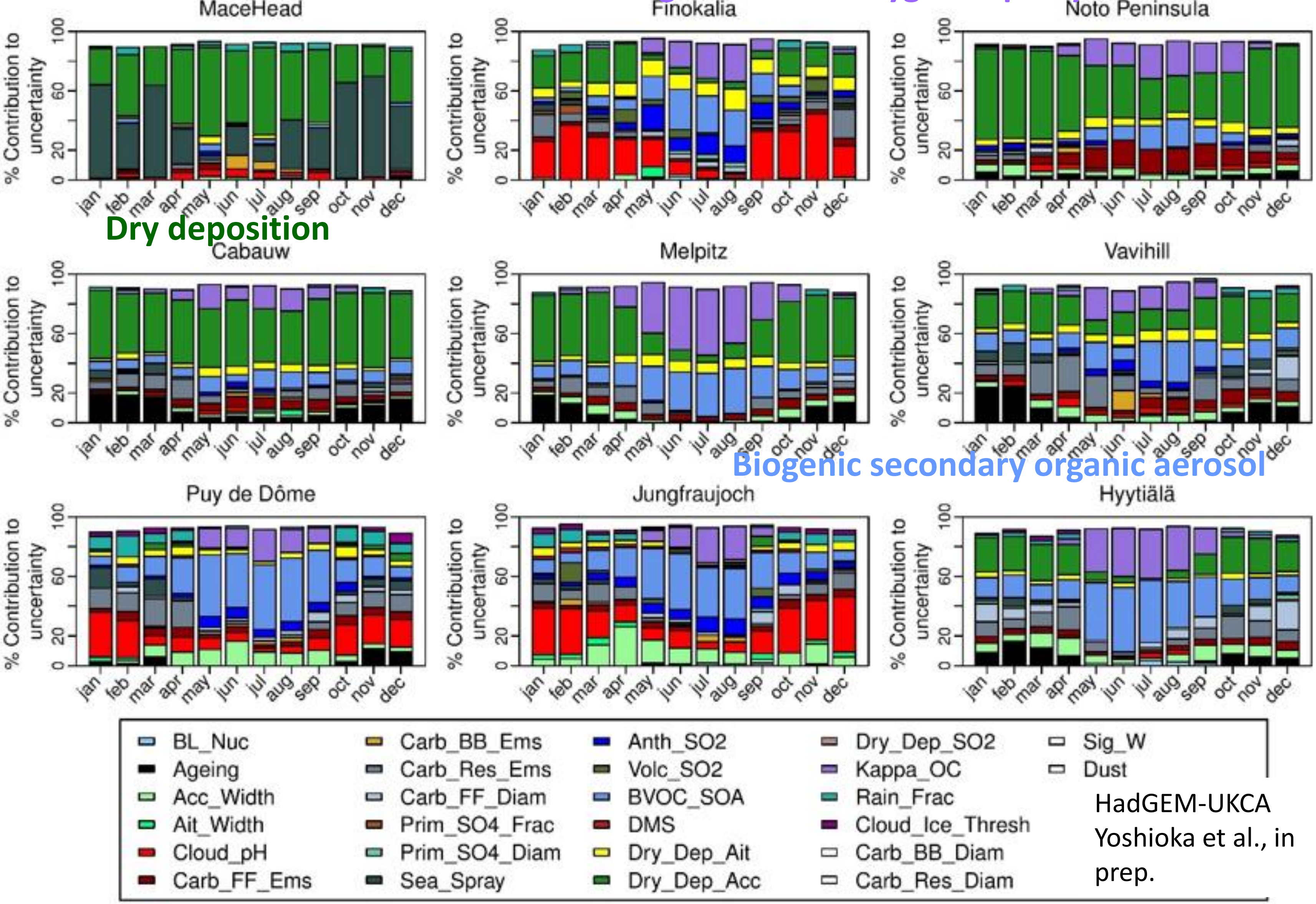
Multi-model mean

Overall NMB -37%

Fanourgakis et al., Atmos. Chem. Phys., 19, 8591–8617, 2019

Major contributors to model uncertainty – perturbed parameter ensemble

Fanourgakis et al., ACP, 2019



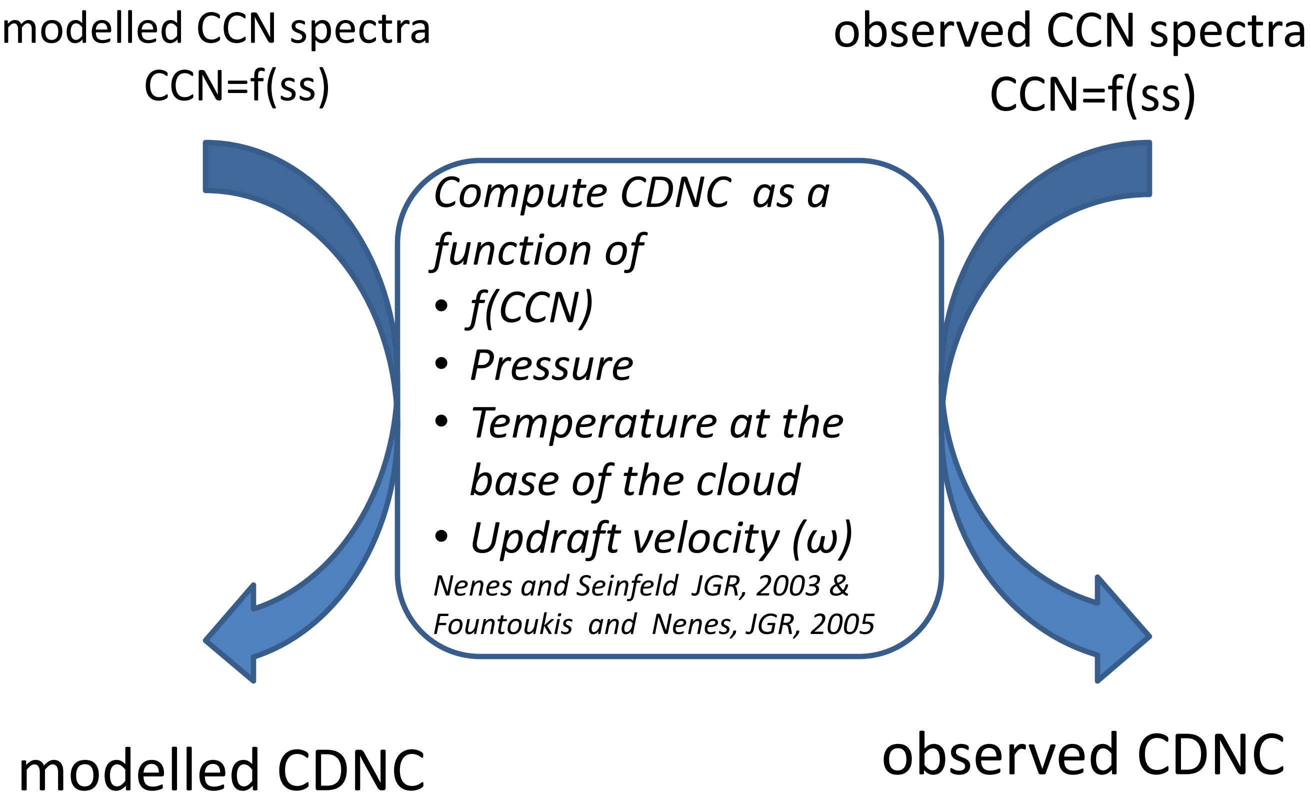
Organic aerosol hygroscopicity

Dry deposition

Biogenic secondary organic aerosol

HadGEM-UKCA
Yoshioka et al., in prep.

How the CCN uncertainty reflects in CDNC calculations?



modelled CCN spectra
CCN=f(ss)

observed CCN spectra
CCN=f(ss)

Compute CDNC as a function of

- *f(CCN)*
- *Pressure*
- *Temperature at the base of the cloud*
- *Updraft velocity (ω)*

Nenes and Seinfeld JGR, 2003 &
Fountoukis and Nenes, JGR, 2005

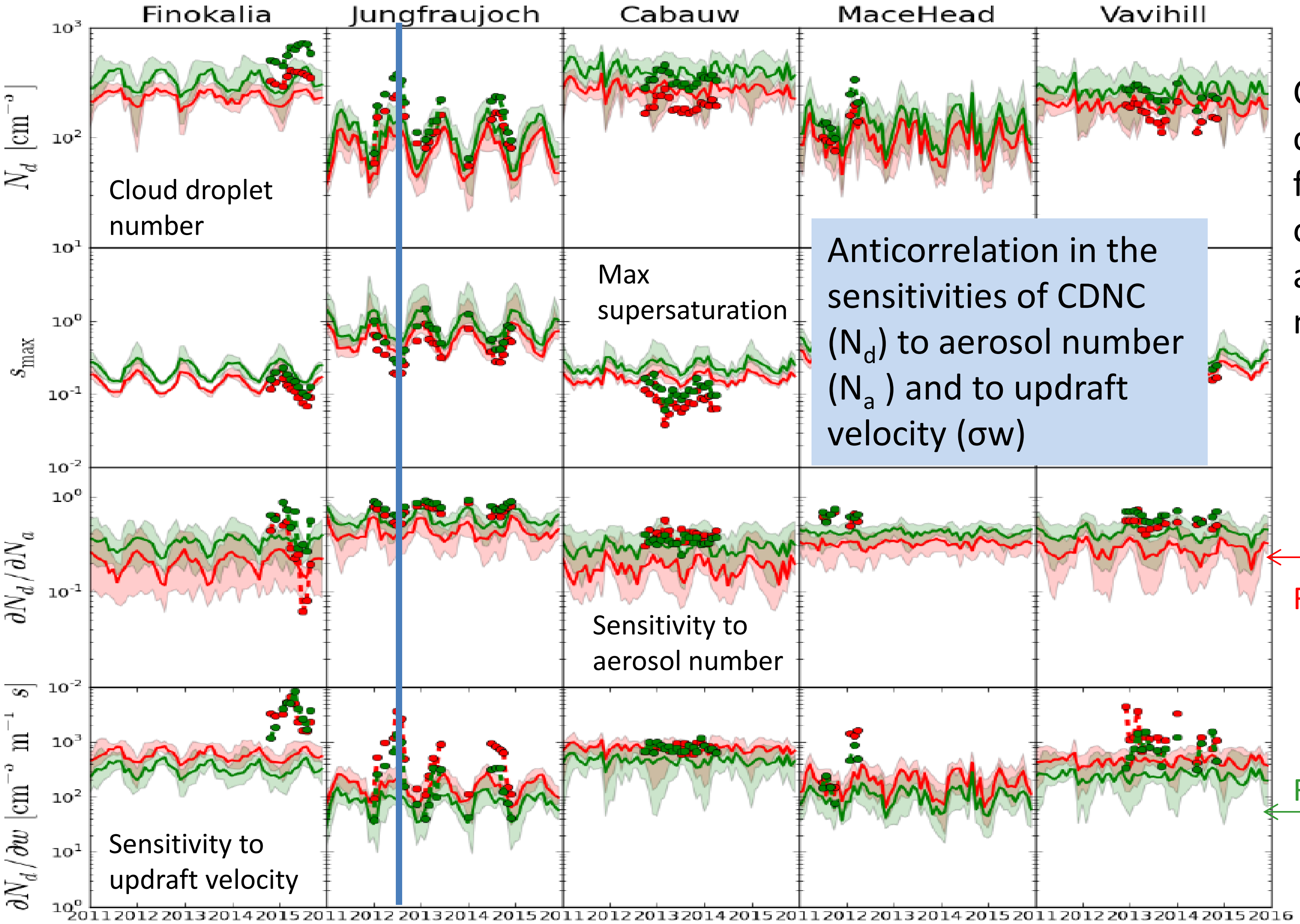
modelled CDNC

observed CDNC

σ_ω = 0.3ms^{-1} typical for stratiform clouds

σ_ω = 0.6ms^{-1} typical for cumulus clouds

Cloud droplet number and its sensitivity to aerosol number and updraft velocity



Cloud droplet number

Max supersaturation

Sensitivity to aerosol number

Sensitivity to updraft velocity

Anticorrelation in the sensitivities of CDNC (N_d) to aerosol number (N_a) and to updraft velocity (σw)

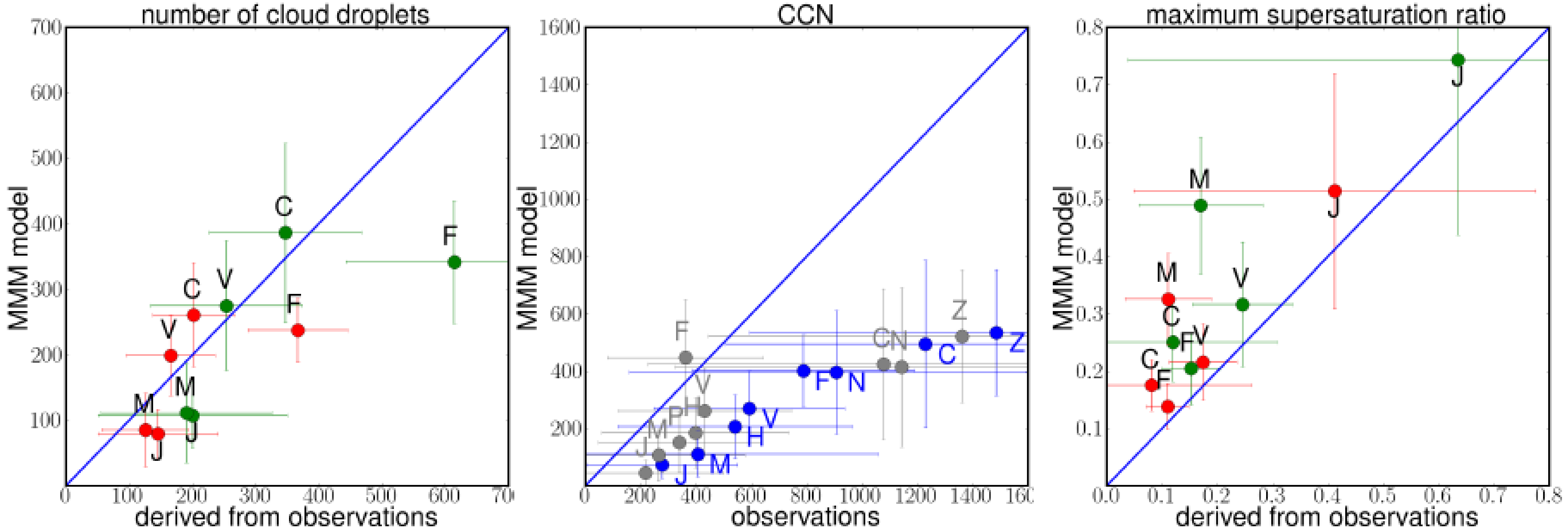
CDNC calculated from observations and from models

Nenes and Seinfeld JGR, 2003 & Fountoukis and Nenes, JGR, 2005

For ω = 0.3ms^{-1}

For ω = 0.6ms^{-1}

Cloud droplet number and its sensitivity to aerosol number and updraft velocity



σ_w 0.6 m s^{-1}

σ_w 0.3 m s^{-1}

CCN at supersaturation 0.2%

CCN at max measured supersaturation (0.8%-1.0%

σ_w 0.6 m s^{-1}

σ_w 0.3 m s^{-1}

The number of CCN at a prescribed supersaturation cannot be used as indicator of CDNC, as supersaturation is dynamically determined and can vary considerably for a given site

Fanourgakis et al., Atmos. Chem. Phys., 19, 8591–8617, 2019

ευχαριστώ

Thank you!