Aerosol Modelling

"for measurement people"

AeroCom Workshop 2010

Oxford

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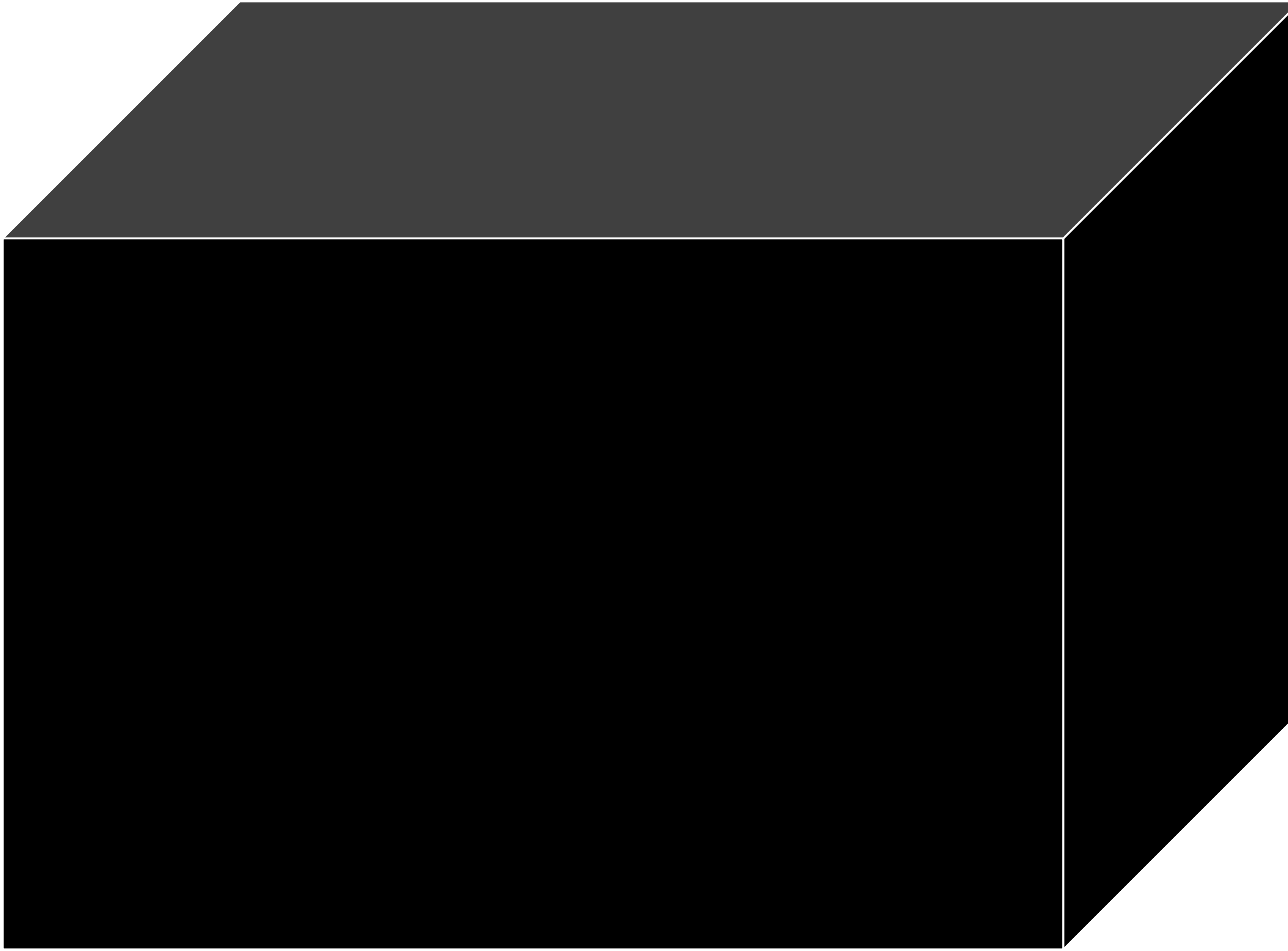
UNIVERSITY OF OXFORD

Aerosol Models – A Black Box



Aerosol Modelling

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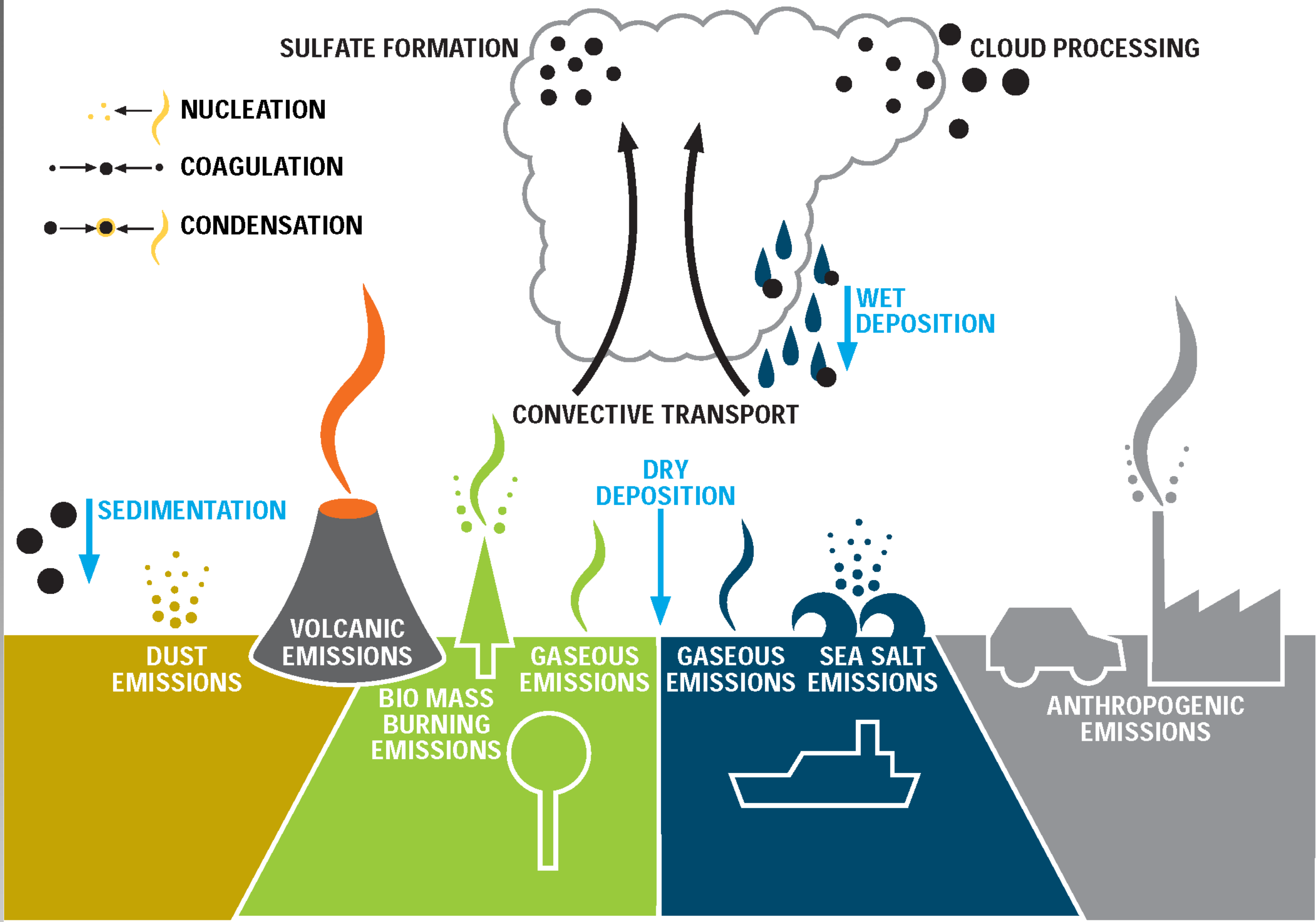
Questions (by François-Marie Bréon):

- What is the typical resolution of models?
- How do models handle variability within grid box?
- How do models handle size distributions?
- What happens in a cloud?
- How are defined the sources?
- What is the lifetime of aerosol in models.
  Is it significantly different among aerosol types?
- How do you estimate injection heights?
- Are the aerosol well mixed within "mixing" layer?
- Is the mixing layer height well reproduced by transport models?
- How are the aerosol optical properties computed?
- What are the main sources of errors?

Global Aerosol Cycles



Outline

Host Models

- Box-, Parcel-, Single Column-, Chemical Transport-, Regional Circulation-, Global Circulation Models
- Offline, Online, Nudged, AMIP, Climate Simulations
- Resolution, resolved and unresolved processes – parameterisations

Aerosol Models

- Bulk Models
- Moment-Based
- Sectional Models

Sources

- Primary emission
- Secondary formation

Transport

- Advection, Turbulence, Convection

Effects

- Radiative Properties
- Aerosol activation and ice nucleation
- Radiative “effect”, “forcing”, “feedback”

Removal

- Dry deposition & sedimentation
- Scavenging

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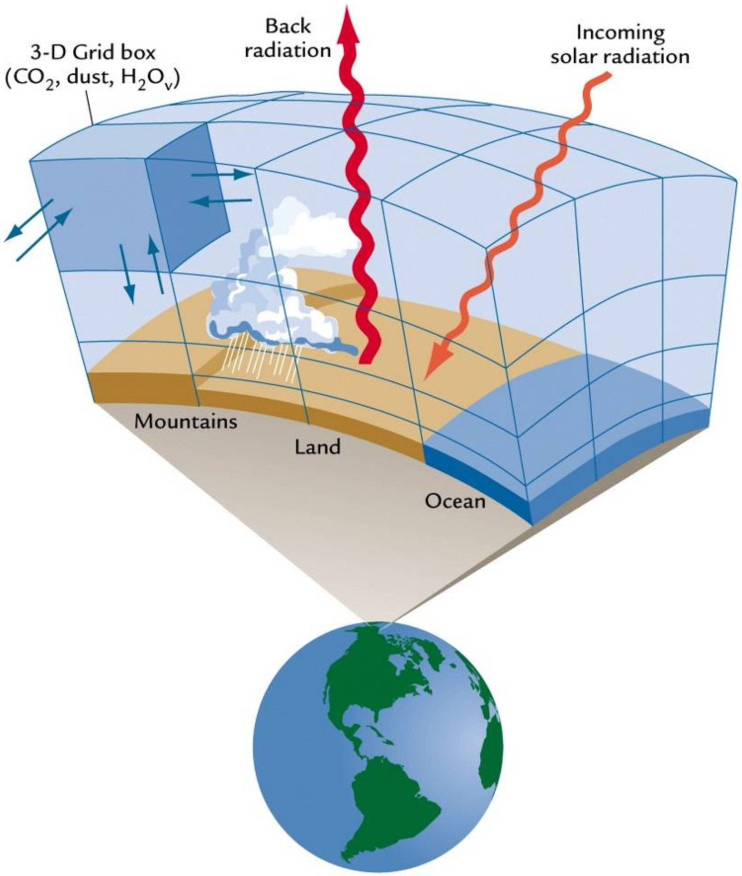
Atmospheric Models

Atmospheric circulation models of based on fundamental physics:



Numerical solution of fundamental physical equations:

- conservation of momentum
- conservation of mass
- conservation of energy
- equation of state

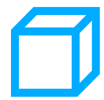
Additional sub-models for:

- **clouds cover**
- **cloud microphysics + precipitation**
- aerosols
- radiative transfer
- chemistry
- land surface processes
- vegetation
- carbon cycle
- cryosphere
- ….

Dictionary of Atmospheric Models

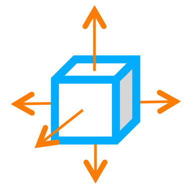
Box Model

0D, no transport,
no or external forcings



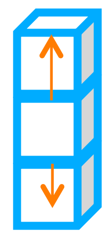
Parcel Model

0D, moved by prescribed
external forcings



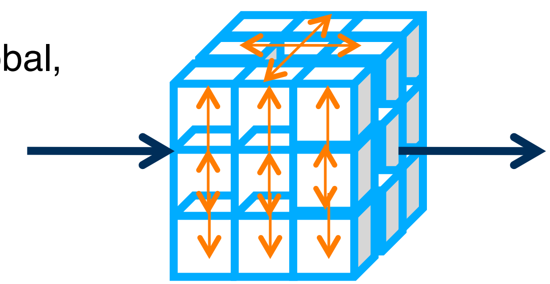
Single Column Model (SCM)

1D, vertical transport
no or external forcings (e.g. campaign)



Chemical Transport Model (CTM)

3D transport, regional (boundary conditions) or global,
met-fields diagnostic from GCM

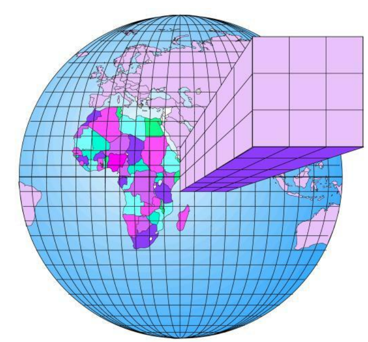


Regional Circulation Model

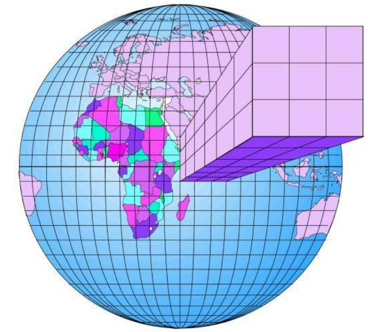
3D transport, regional,
met-fields prognostic but with boundary conditions from GCM

Global Circulation Model (GCM)

3D transport, global, **met-fields prognostic**, potentially assimilated
or “nudged” to assimilated meteorological analysis data

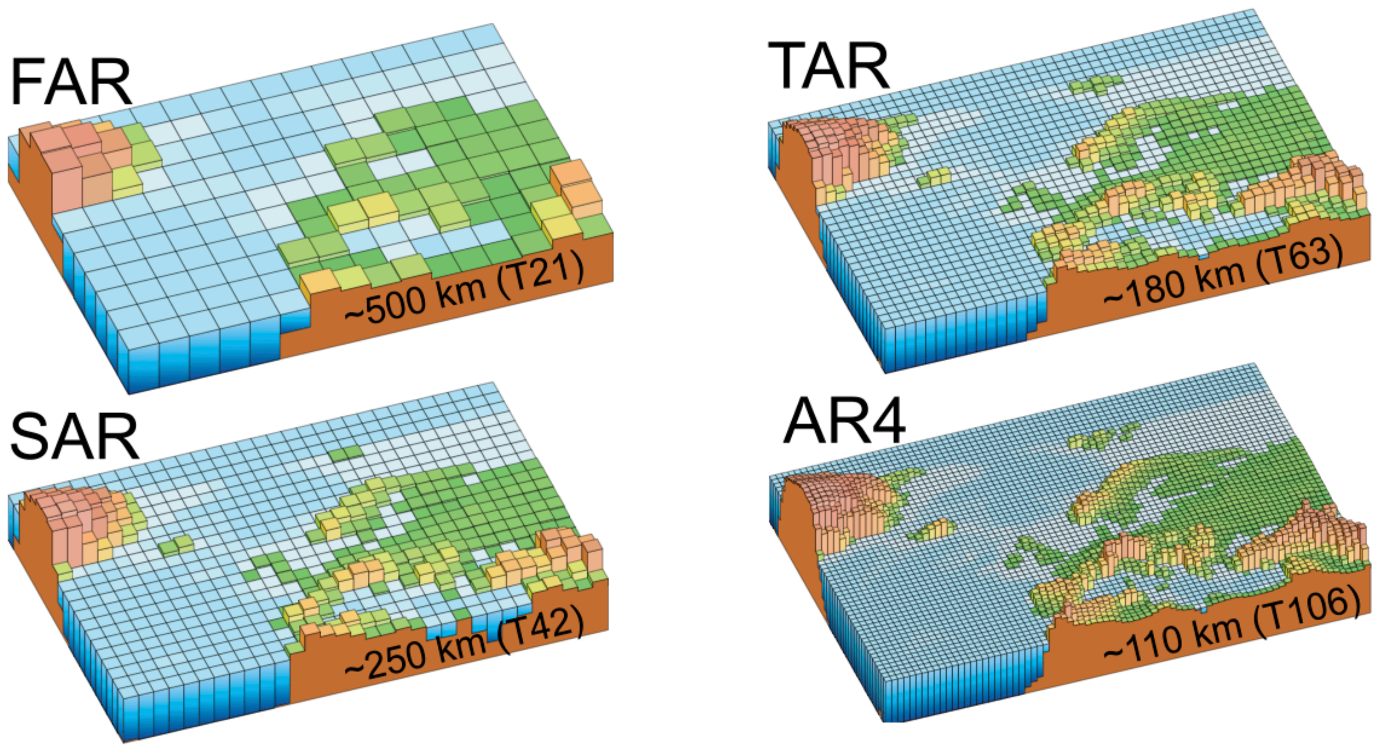


Resolution of Atmospheric Models



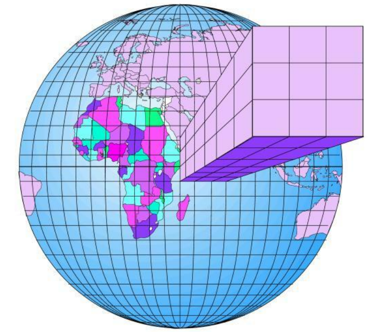
Global Circulation Model (GCM)

Climate model resolution since IPCC FAR:



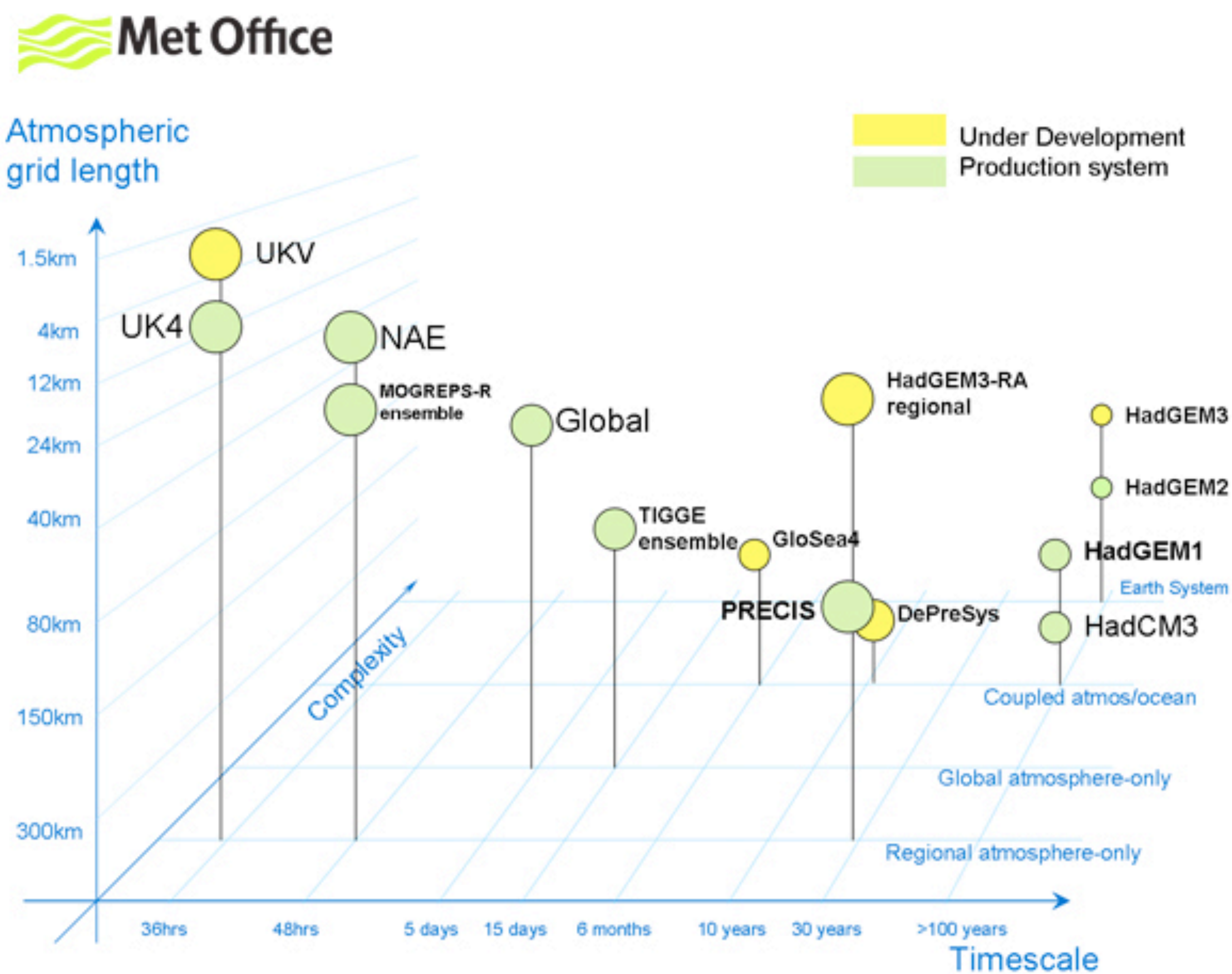
Typical AeroCom
Aerosol Model Resolution

Resolution of Atmospheric Models



Model Hierarchy

Resolution depends on complexity and temporal scales



Aerosol Modelling: Host Models

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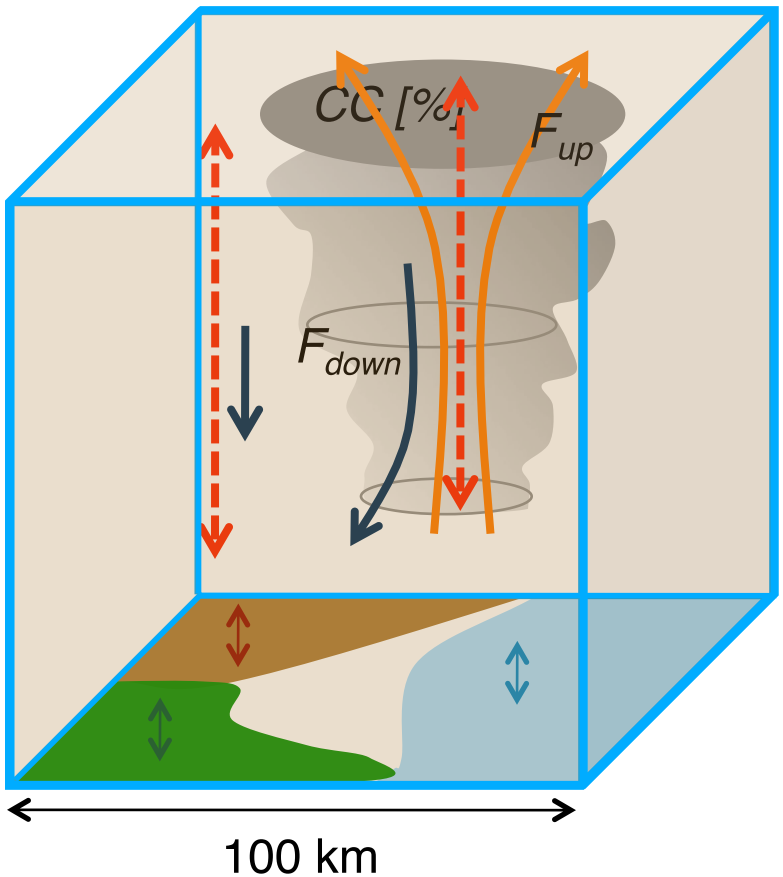
Caveat: Unresolved Scales

Within one model grid box:

Tracers (mass or number) assumed homogeneously mixed



Parameterised fractional cloud cover

Mean In-cloud liquid-, ice-water (or sub-grid scale pdf)

Mean up- and down-drafts

Mean clear-sky and cloudy-sky radiative fluxes

Mosaic approach: Fractional surface cover

Dictionary of Simulation Types

Offline (CTM)

- Transport using prescribed met-fields from GCM or RCM

Online (GCM)

- Transport solving the fundamental equations of motion

Nudged (GCM)

- Transport solving the fundamental equations of motion
- Large scale prognostic variables relaxed to assimilated analysis data
- Sub-grid scales (e.g. clouds) not constrained

"AMIP" (Atmospheric Model Intercomparison Project)

- Standardised simulation protocol
- Prescribed SST ("fixed SST run), Ozone, CO_2, topography,…

Climate

- Transport solving the fundamental equations of motion
- Simple ocean models ("slap", "q-flux", "mixed layer") or
- Complex ocean general circulation models AtmosphereOceanGCMs

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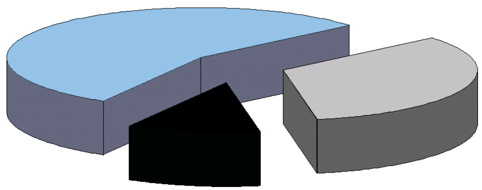
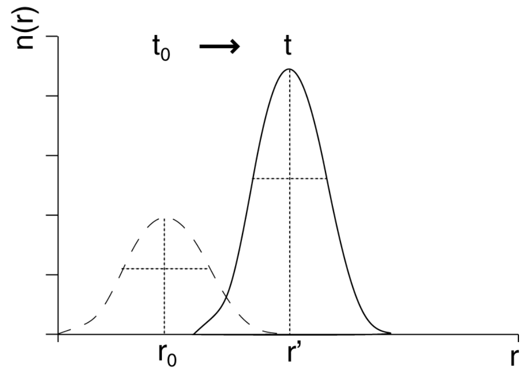
Aerosol Representation in Atmospheric Models

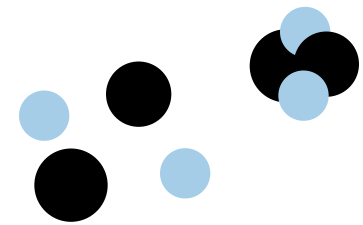
Aerosol microphysical state determined by:



composition



size distribution



mixing state

Caveat: models generally ignore the effects of non-spherical shapes…

Electron-microscopic image of black carbon aerosol (From Heintzenberg et al., 2003)

Aerosol Representation in Atmospheric Models

Key Model Types

1) **Bulk** ("mass based")

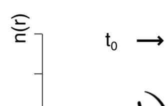
Component masses only prognostic variable. Size and mixing assumed.

2) **Moment** based ("Modal", "Log-Normal", Quadrature of Mom…

Assume functional form of size distribution, predict evolution…

Prognostic size, external mixing through several "mo…

Applied with/without microphysics, with various…



3) **Sectional** ("bin"…

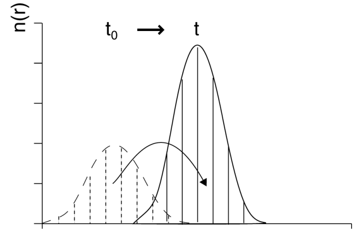
Split aero… …bins and predict their evolution.

Pro… …mptions, external mixing "expensive".

…ysics (e.g. dust models).

General Aerosol Dynamic Equation…

$$\frac{\partial n(v,t)}{\partial t} = \frac{1}{2}\int_0^v K(v-q,q)\,n(v-q,t)\,n(q,t)\,dq - n(v,t)\int_0^\infty K(q,v)\,n(q,t)\,dq - \frac{\partial}{\partial v}[I(v)n(v,t)] + J_0(v)\delta(v-v_0) + S(v) - R(v)$$



Computational cost

Aerosol Modelling: Aerosol Models

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Aerosol R

Aerosol Modelling: Aerosol Models

Microphysics

Bin models

Modal models

Model	Global model	Horizont. Resolution (#lon #lat) (lon lat)	Vertical Resolution (# levels) (type)	References for global model	Type of scheme	Number of bins or modes	Aerosol mixing	Aerosol dynamics*	References for aerosol module
ARQM	GCM Canadian GCMIII	128x64 2.81°x2.81°	32 sigma-p	Zhang and McFarlane (1995b)	bin	12 all internally mixed	int	nucl, coag, cond, thermodyn, cloud processing	Zhang et al. (2001); Gong et al. (2003)
DLR	GCM ECHAM4	96x48 3.75°x3.75°	19 sigma	Roeckner et al. (1996)	modal MN	2 nuclm+accm	int	nucl, cond, coag, thermodyn, aging BC POM	Ackermann et al. (1998)
GISS	GCM modelE	46x72 5°x4°	20 sigma	Schmidt et al. (2006)	bin	13 2 SS, 4 DU, 1 BC, 1 POM, 1 SO_4, 4 DU/SO_4	ext	aging BC POM, hetero DU-SO_4	Koch et al. (1999, 2006); Koch (2001); Bauer and Koch (2006)[5]; Cakmur et al. (2006); Koch and Hansen (2005); Miller et al. (2006)
GOCART	CTM GOCART 3.15b	144x91 2.5°x2.0°	30 sigma	Atlas and Lucchesi (2000)	modal M	17 8 DU, 4 SS, 2 BC, 2 POM, 1 SO_4	ext	aging BC POM	Chin et al. (2000, 2002); Ginoux et al. (2001)
KYU (SPRINT)	GCM CCSR/NIES/FRCGC GCM / SPRINTARS 5.7b	320x160 1.1°x1.1°	20 sigma	Numaguti et al. (1995); Hasumi and Emori (2004)	bin, modal M for aerosol dyn**	17 bins 10 DU, 4 SS, 1 BC, 1 BCPOM, 1 SO_4 (5 modes for aerosol dyn)	ext partly int for BC/ POM	none	Takemura et al. (2000, 2002, 2005)
LSCE	GCM LMDzT 3.3	96x72 3.75°x2.5°	19 sigma	Sadourny and Laval (1984); Hourdin and Armengaud (1999)	modal MN	5 accm: sol+insol, coam: sol+insol, supcoam: sol	ext mix of int modes[3]	aging BC POM	Claquin et al. (1998, 1999); Guelle et al. (1998a, b, 2000); Smith and Harrison (1998); Balkanski et al. (2003); Bauer et al. (2004); Schulz et al. (2006)[4]
LOA	GCM LMDzT 3.3	96x72 3.75°x2.5°	19 sigma	Sadourny and Laval (1984); Hourdin and Armengaud (1999)	bin	16 2 DU, 11 SS, 1 BC (sol+insol), 1 POM (sol+insol), 1 SO_4	ext	aging BC POM	Boucher and Anderson (1995); Boucher et al. (2002); Reddy and Boucher (2004); Guibert et al. (2005)
MATCH	CTM MATCH v 4.2	192x94 1.9°x1.9°	28 sigma-p	Zhang and McFarlane (1995a); Rasch et al. (1997); Rasch and Kristjansson (1998)	bin	8 4 DU, 1 SS,1 BC, 1 POM, 1 SO_4	ext	aging BC POM	Barth et al. (2000); Rasch et al. (2000, 2001)
MPI_HAM	GCM ECHAM5	192x96 1.8°x1.8°	31 sigma-p	Roeckner et al. (2003, 2004); Stier et al. (2005)	modal MN	7	ext mix of int modes	nucl, cond, coag, thermodyn	Stier et al. (2005)
MOZGN	CTM MOZART v2.5	192x96 1.9°x1.9°	28 sigma-p	Brasseur et al. (1998); Tie et al. (2001, 2005); Horowitz et al. (2003)	bin	12 1 SO_4, 1 POM, 1 BC, 5 DU, 4 SS	ext	aging BC POM	Tie et al. (2001, 2005)
PNNL	GCM MIRAGE 2 / derived from NCAR CAM2.0	144x91 2.5°x2.0°	24 sigma-p	Kiehl and Gent (2004)	modal MN	8 aitm accm coam DU+SO_4 coam SS+SO_4, interstit+act each	ext mix of int modes***	nucl, cond, coag, thermodyn, cloud processing	Easter et al. (2004)
TM5	CTM TM5	global 60x45 6°x4° Europe+North America: 1°x1°	25 sigma-p	Krol et al. (2005)	modal MN	8 3 SS, 2 DU, 1 SOA-POM, 1BC, 1 SO_4-NO_3	ext	aging BC	Metzger et al. (2002a, b)
UIO_CTM	CTM OsloCTM2	128x64 2.81°x2.81°	40 sigma	Berglen et al. (2004)	bin	25 8 DU, 8 SS, 4 BC, 4 POM, 1 SO_4	ext except bioburn	aging BC POM	Grini et al. (2002b, 2005); Myhre et al. (2003); Berglen et al. (2004); Berntsen et al. (2006)
UIO_GCM	GCM CCM3.2	128x64 2.81°x2.81°	18 sigma-p	Hack (1994); Kiehl et al. (1998)	modal, M/MN bin for aerosol dyn**	12 modes aerosol dyn: 43 bins from 8 int modes DU + SS fix**	4 ext 8 int: mixed from 4 prog + 8 fix****	nucl, cond, coag, thermodyn, cloud processing	Iversen and Seland (2002); Kirkevåg and Iversen (2002); Kirkevåg et al. (2005)
ULAQ	CTM ULAQ	16x19 22.5°x10°	26 log-p	Pitari et al. (2002)	bin	41 7 DU, 9 SS, 5 BC, 5 POM, 15 SO_4	ext	aging BC POM (Koch, 2001), SO_4microphysics	Pitari et al. (1993, 2002)
UMI	CTM IMPACT	144x91 2.5°x2°	30 sigma-p	Schubert et al. (1993); Rotman et al. (2004)	bin	13 3 SO_4, 1 POM, 1 BC, 4 DU, 4 SS	ext	none	Liu and Penner (2002)

AeroCom I Modells
Textor et al. (2006)

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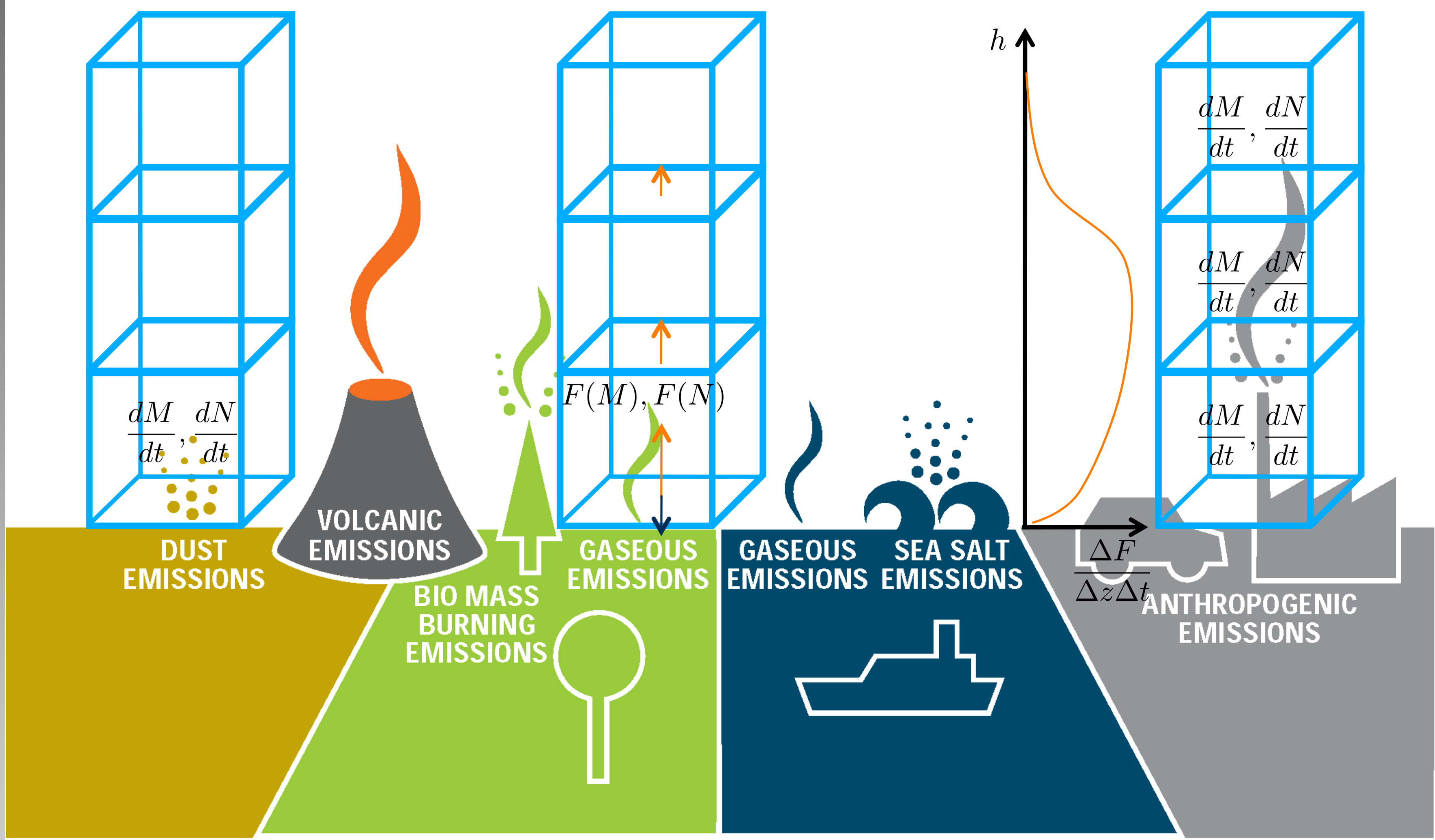
Aerosol Sources in Modells

Implementation of Primary Emissions

Apply tendency to mixing ratios in lowest grid box

Apply (net) emission fluxes as boundary of vertical diffusion

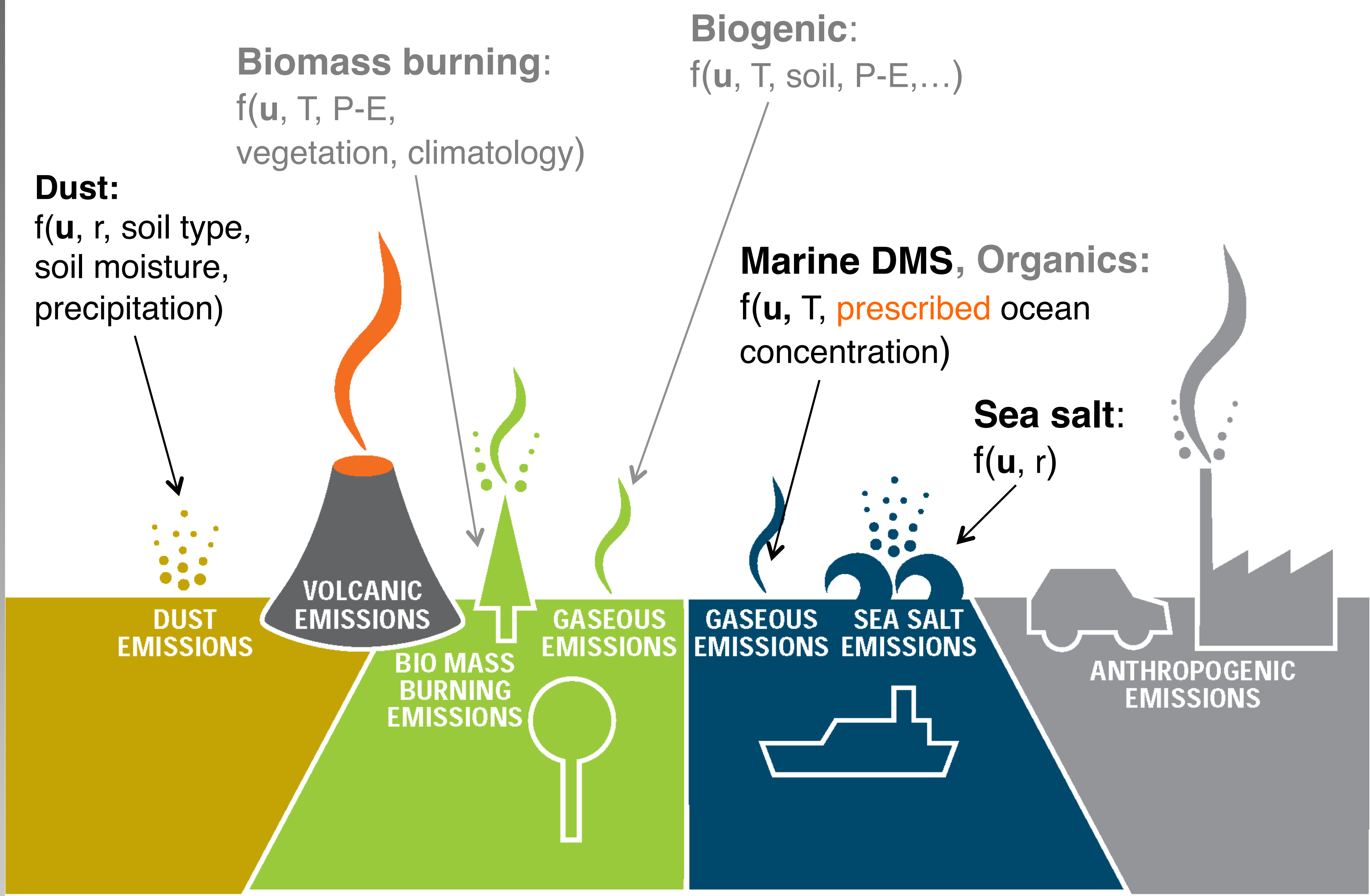
Apply prescribed injection height profile (or injection model)



Aerosol Sources in Modells

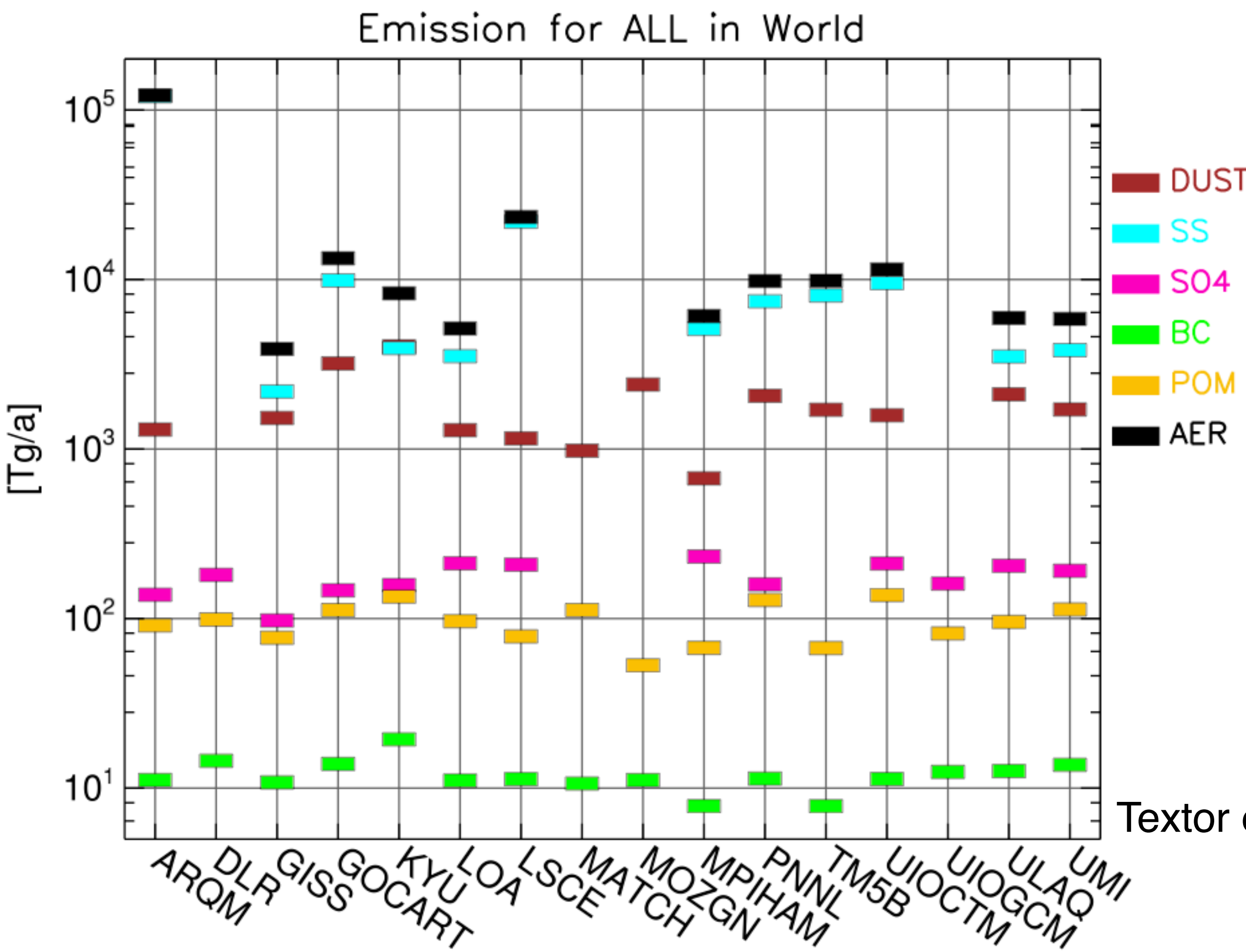
Prognostic Emission Sub-Models

(Other emissions are generally prescribed from inventories)



Aerosol Sources in Modells

Emissions in AeroCom Phase I Experiment A:



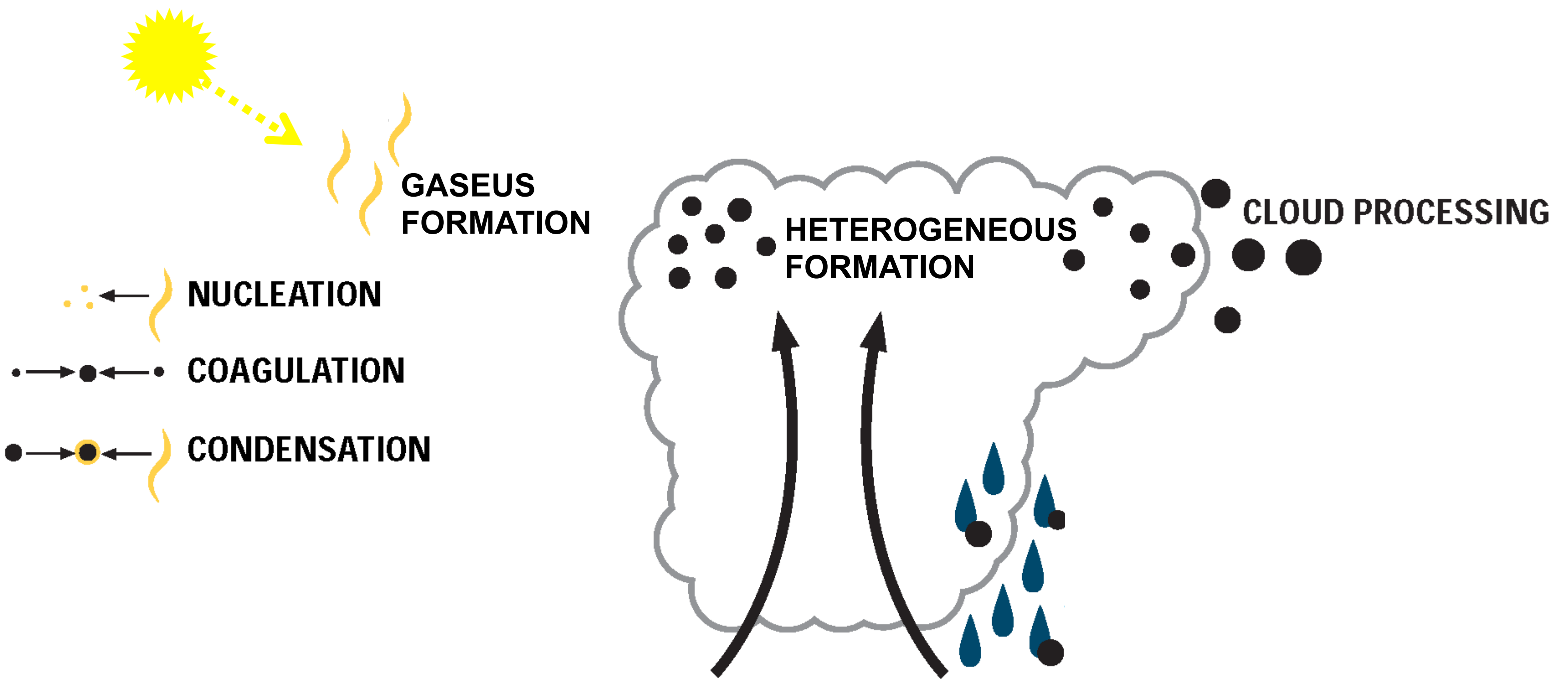
Textor et al. (2006)

Caveat: Emission inventories currently provide only mass fluxes. Effective emission size distributions (at model scale) remain uncertain.

Aerosol Sources in Modells

Secondary formation in the atmosphere

Chemical formation of low-volatility products



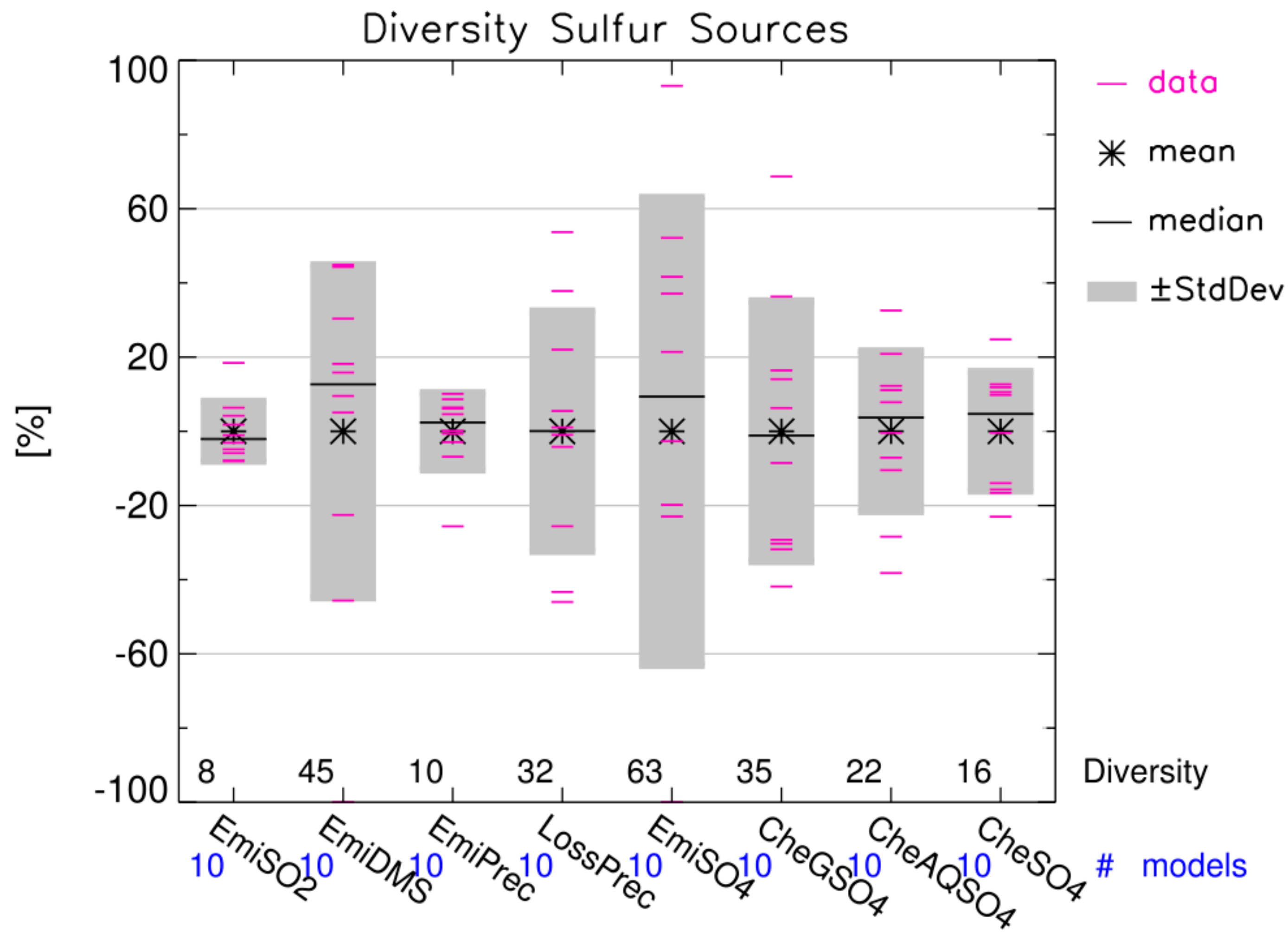
All models: sulfur cycle with homogeneous and heterogeneous chemistry

Some models: detailed inorganic chemistry, ammonium / nitrate system

Few models: secondary organic aerosol formation

Aerosol Sources in Modells

Sulfur cycle in AeroCom Phase I Experiment A:



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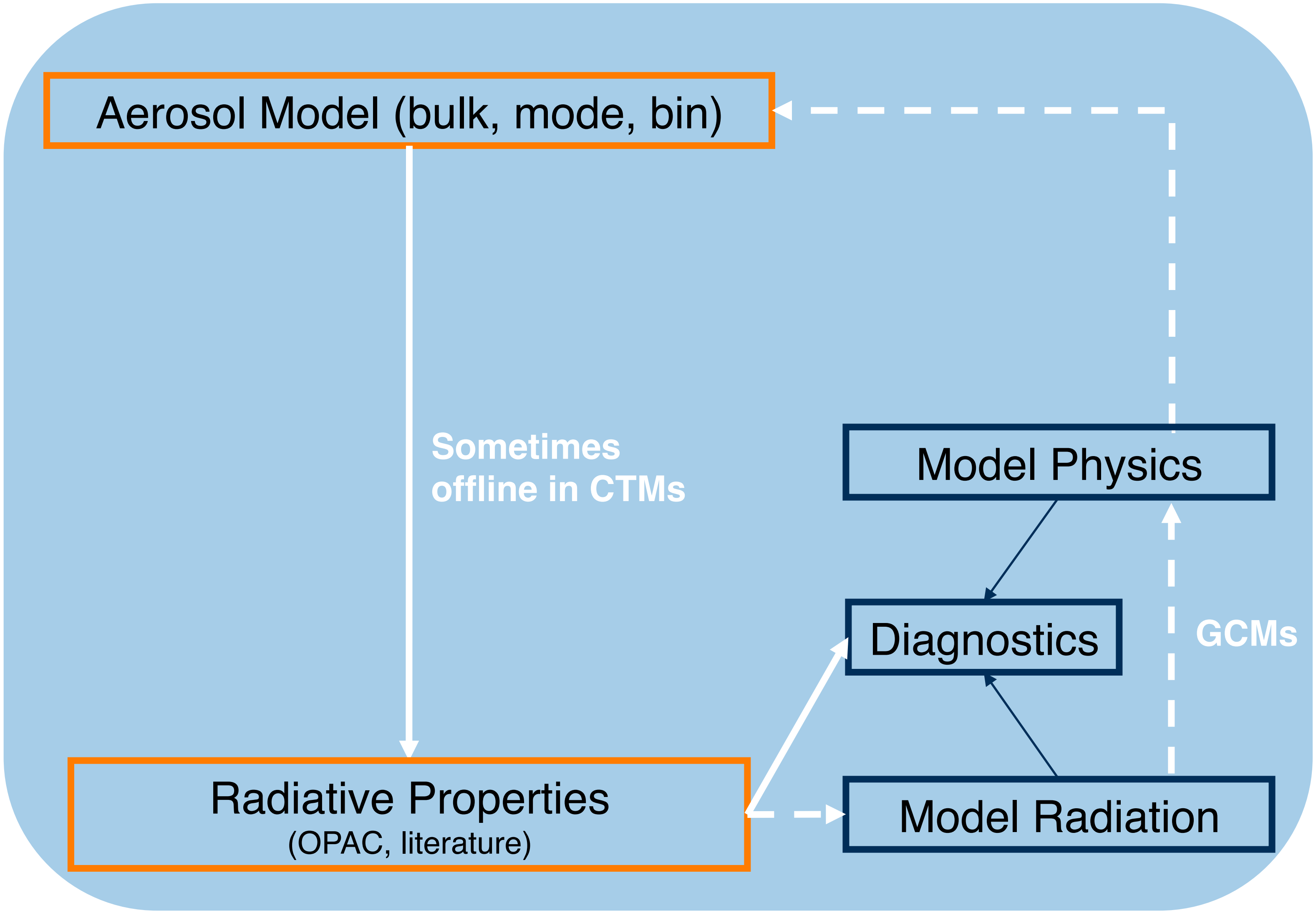
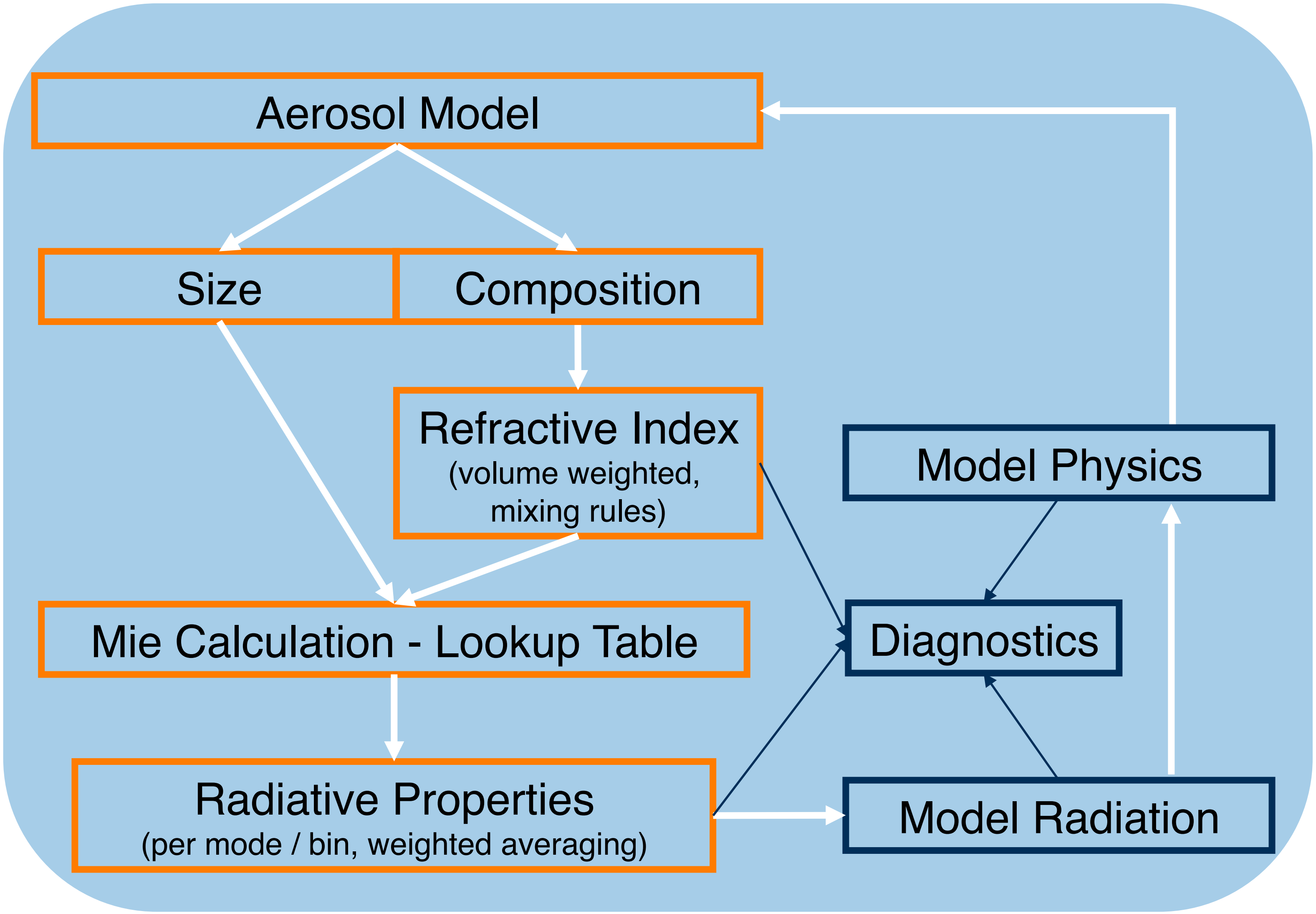
Aerosol Radiative Properties

Simple implementation (not uncommon in CTMs and some GCMs):



Aerosol Radiative Properties

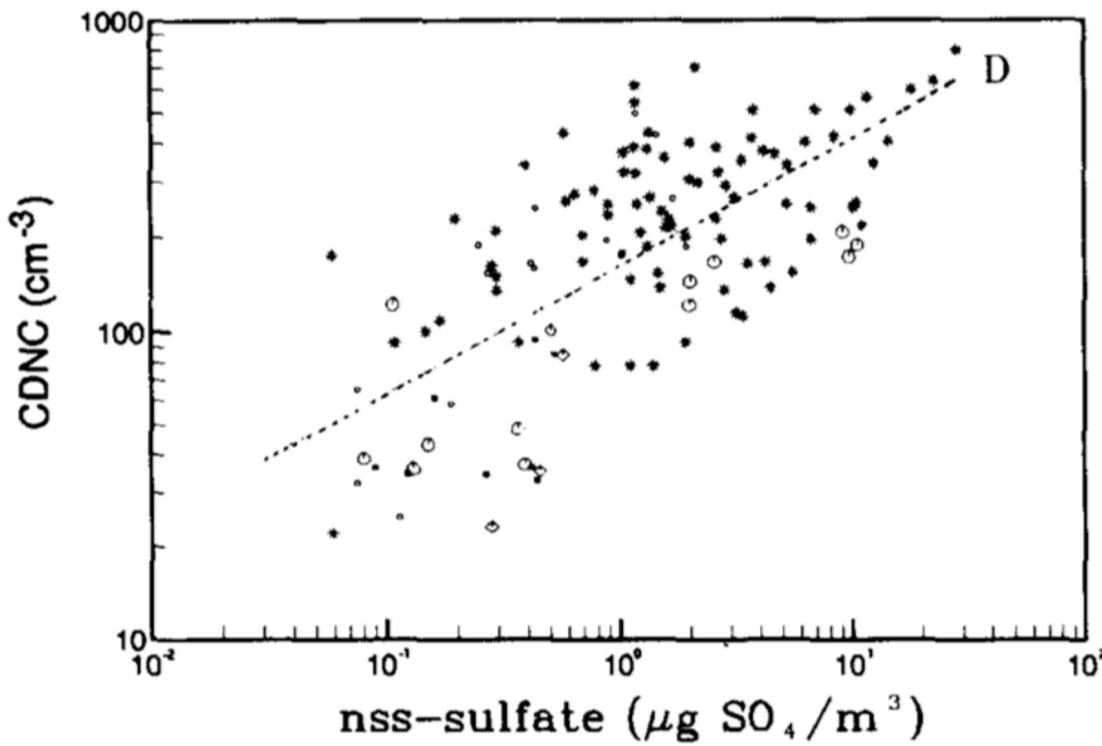
Complex implementation (or simplifications thereof):



Aerosol-Cloud Coupling

Aerosol activation

i) Highly empirical:

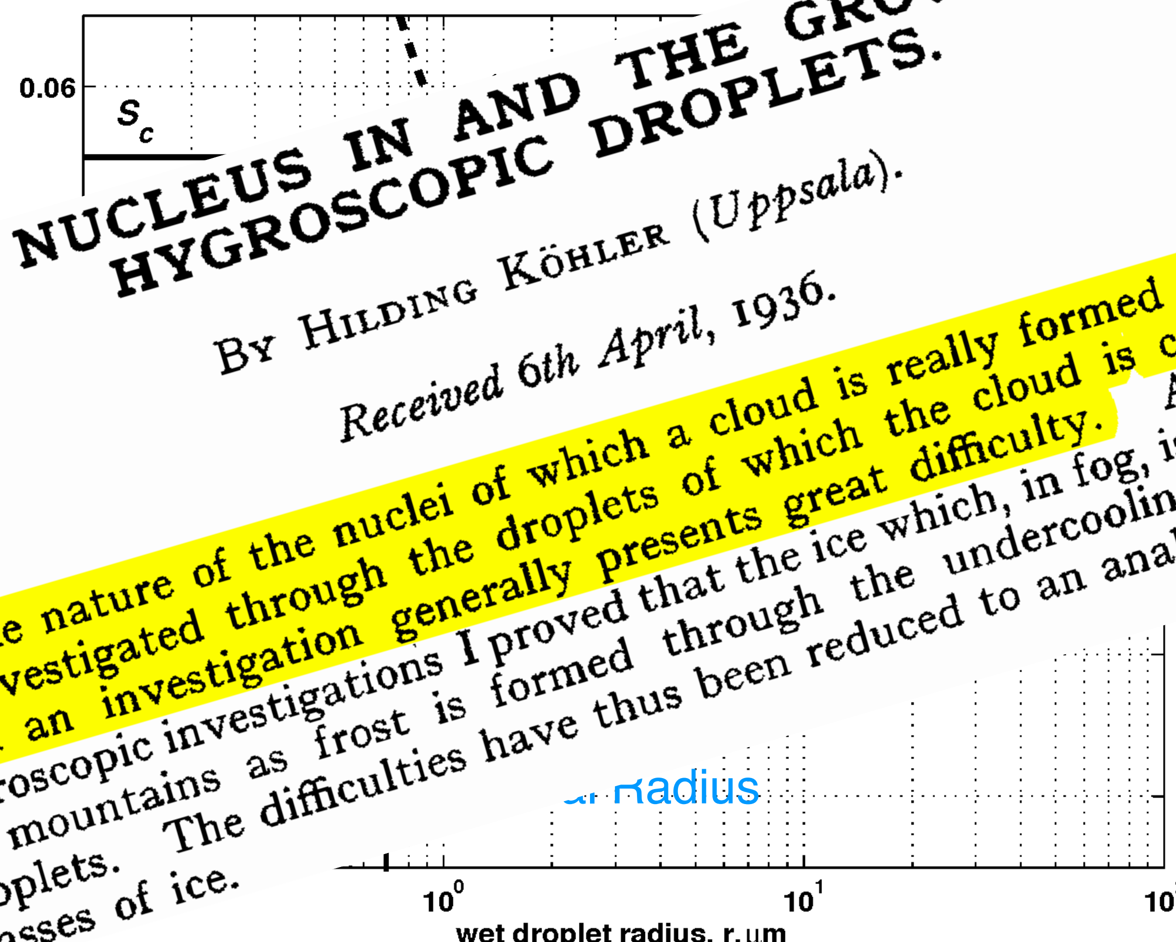


Boucher and Lohmann (1995)

Aerosol-Cloud Coupling

ii) Köhler (1936) based – Combining Raoult's Law and Kelvin Equation:

$$e_S^{sol}(r) = e_S(\infty)\left(1 - \frac{B}{r^3}\right)\left(e^{\frac{A}{r}}\right)$$



THE NUCLEUS IN AND THE GROWTH OF HYGROSCOPIC DROPLETS.

By HILDING KÖHLER (*Uppsala*).

Received 6th April, 1936.

The nature of the nuclei of which a cloud is really formed can best be investigated through the droplets of which the cloud is composed. Such an investigation generally presents great difficulty. After long microscopic investigations I proved that the ice which, in fog, is deposited on mountains as frost is formed through the undercooling of water droplets. The difficulties have thus been reduced to an analysis of such masses of ice.

Aerosol-Cloud Coupling

Difficulty?

Caveat: Estimation of maximum supersaturation

$$\frac{dS}{dt} = \alpha V - \gamma \frac{dW}{dt} \quad \text{where}$$

$$\frac{dW}{dt} = 4\pi\rho_w G S \int \left(r^2(\tau) + 2G \int_\tau^{t_{max}} S(t)dt \right)^{1/2} n(S')dS'$$

Solutions to supersaturation balance equation:

i) Empirical fit to detailed parcel model (Abdul-Razzak and Ghan, 2000)

ii) Population splitting allows to minimise empirical contributions: (Nenes & Seinfeld, 2003; Barahona et al., 2010)

Caveats: updraft velocity is sub-grid scale and not prognostic in mass-flux based convection schemes. Diagnosed from prognostic variables e.g. via TKE.

Interested? Posters by Rosalind West and Steve Ghan

Aerosol-Cloud Coupling

Coupling to cloud microphysics:

i) Two moment cloud microphysics schemes:

$$\frac{\partial N}{\partial t} = \frac{DN^{act}}{Dt} + \left(\frac{\partial N}{\partial t}\right)^{Transport} + \left(\frac{\partial N}{\partial t}\right)^{Sources} + \left(\frac{\partial N}{\partial t}\right)^{Sinks}$$

$$\frac{\partial M}{\partial t} = \frac{DM^{cond}}{Dt} + \left(\frac{\partial M}{\partial t}\right)^{Transport} + \left(\frac{\partial M}{\partial t}\right)^{Sources} + \left(\frac{\partial M}{\partial t}\right)^{Sinks}$$

directly coupled to cloud radiative properties and precipitation scheme

ii) Single moment (bulk) cloud microphysics schemes

Caveat: Diagnostic calculation of r_{eff} from N^{act} and M

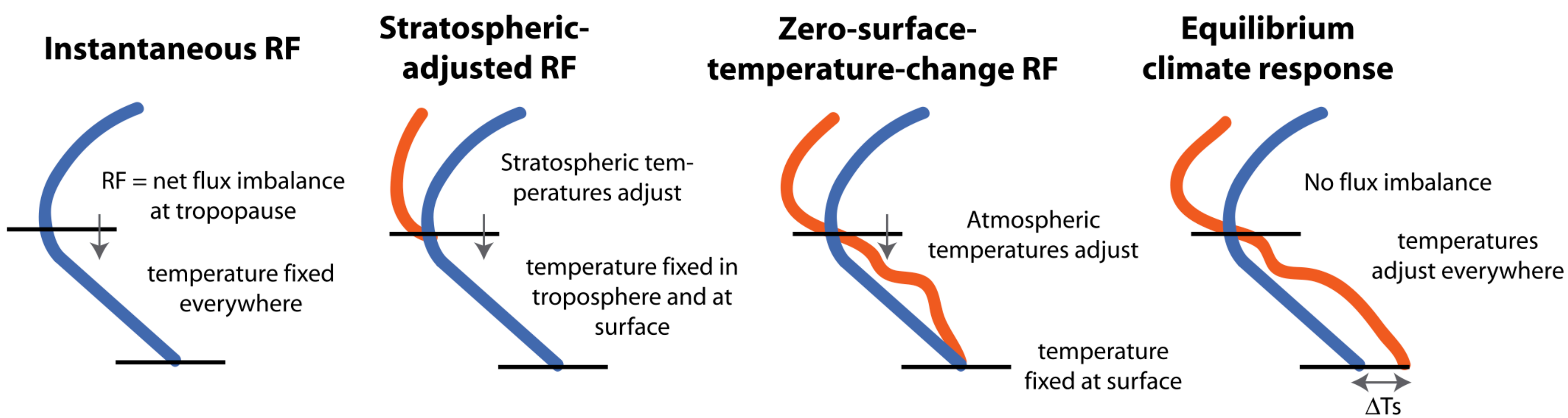
No or highly parameterised effects on precipitation

Lack of reliable evaluation data…

Aerosol Radiative Effects

Radiative Forcing

"the change in net (down minus up) irradiance (solar plus longwave; in W m−2) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values"



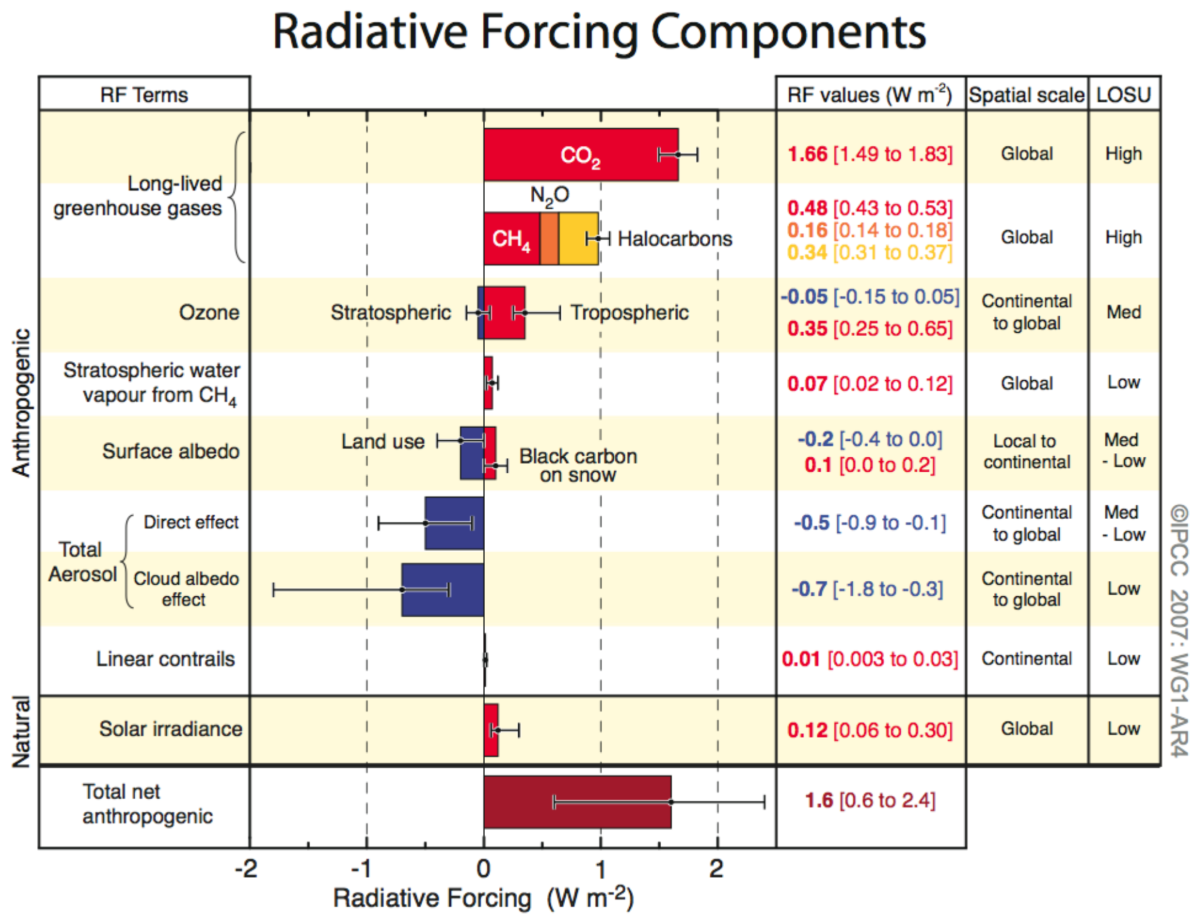
(IPCC, Forster et al., 2007)

Caveat:

Instantaneous definition excludes (fast) cloud-lifetime and dynamical effects

Anthropogenic Perturbations to the Climate System

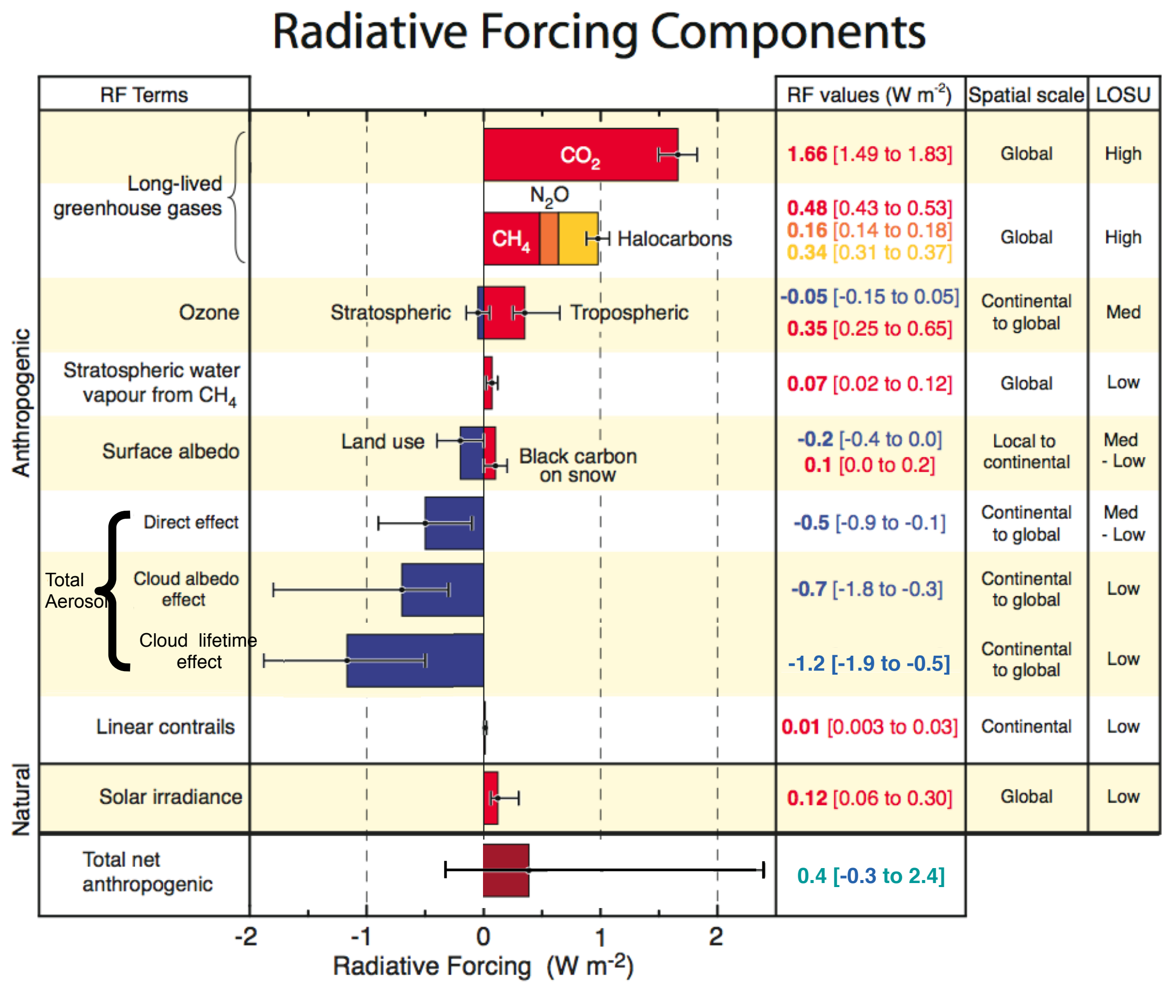
Current best estimate of anthropogenic radiative forcing:



Intergovernmental Panel on Climate Change estimate of present day global annual mean anthropogenic radiative forcings (Solomon et al., 2007)

Anthropogenic Perturbations to the Climate System

Including (fast) cloud-lifetime effect:



Lohmann & Feichter (2005)

Outline

Host Models

- Box-, Parcel-, Single Column-, Chemical Transport-, Regional Circulation-, Global Circulation Models
- Offline, Online, Nudged, AMIP, Climate Simulations
- Resolution, resolved and unresolved processes – parameterisations

Aerosol Models

- Bulk Models
- Moment-Based
- Sectional Models

Sources

- Primary emission
- Secondary formation

Transport

- Advection, Turbulence, Convection

Effects

- Radiative Properties
- Aerosol activation and ice nucleation
- Radiative “effect”, “forcing”, “feedback”

Removal

- Dry deposition & sedimentation
- Scavenging

Aerosol Removal Processes

Dry Deposition

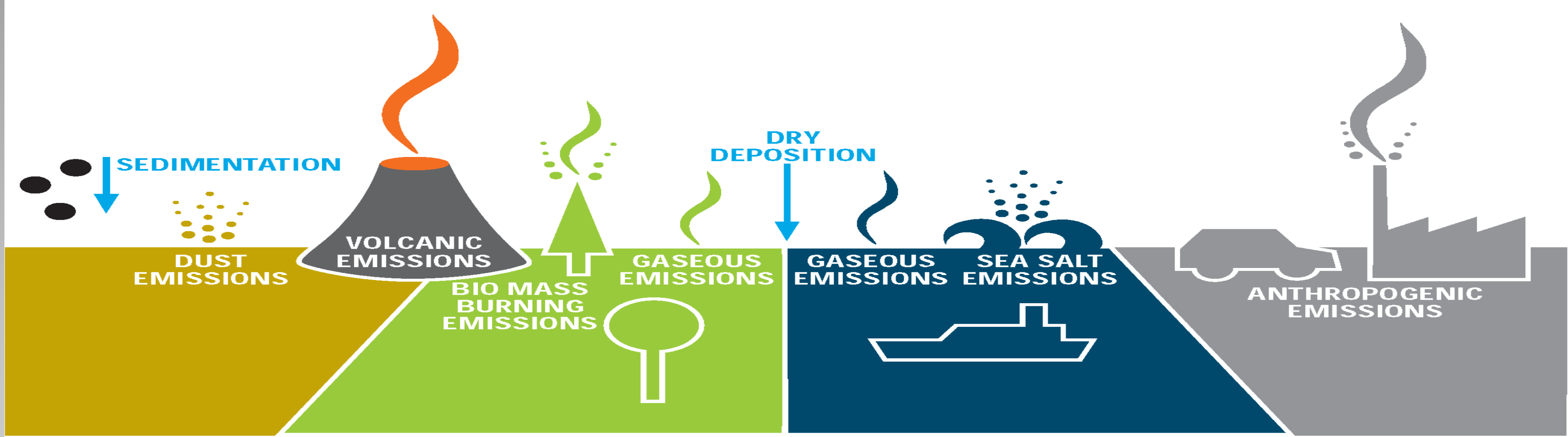
Most models use classical serial resistance approach:

$$F_d = C\rho_{air} v_d \qquad v_d = v_g + \frac{1}{(r_a + r_s)}$$

Caveats:

i) Surface resistance terms are uncertain and land-type specific. Only few models consider explicit mosaic approach.

ii) Aerodynamic resistance is dependent on turbulent transport in the boundary layer – difficult to simulate with few layers, expensive with many layers



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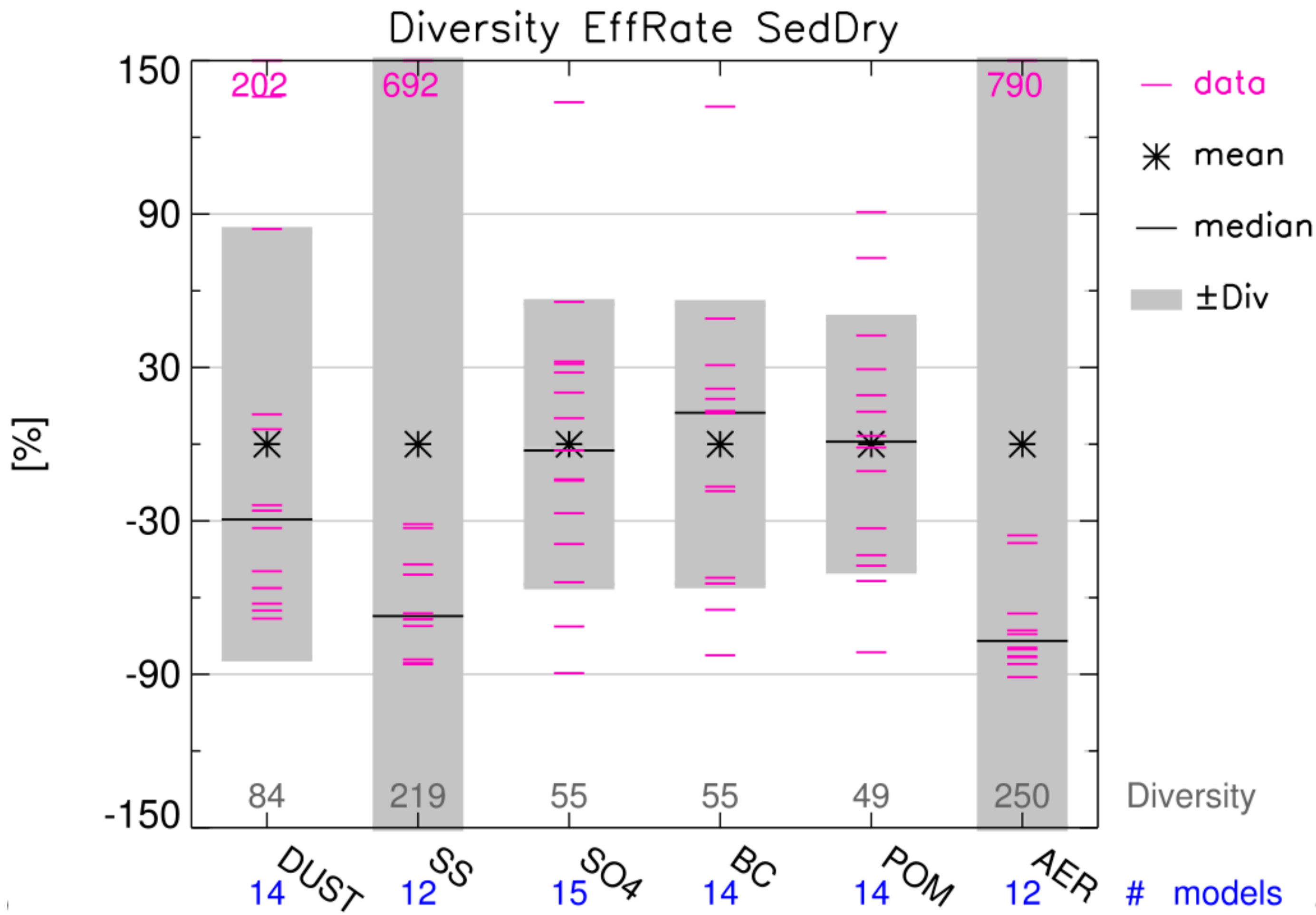
Aerosol Removal Processes

Dry Deposition

Diversity of effective total dry deposition rate coefficients in AeroCom Phase I:



Textor et al. (2006)

Aerosol Removal Processes

Caveat: Wet Deposition

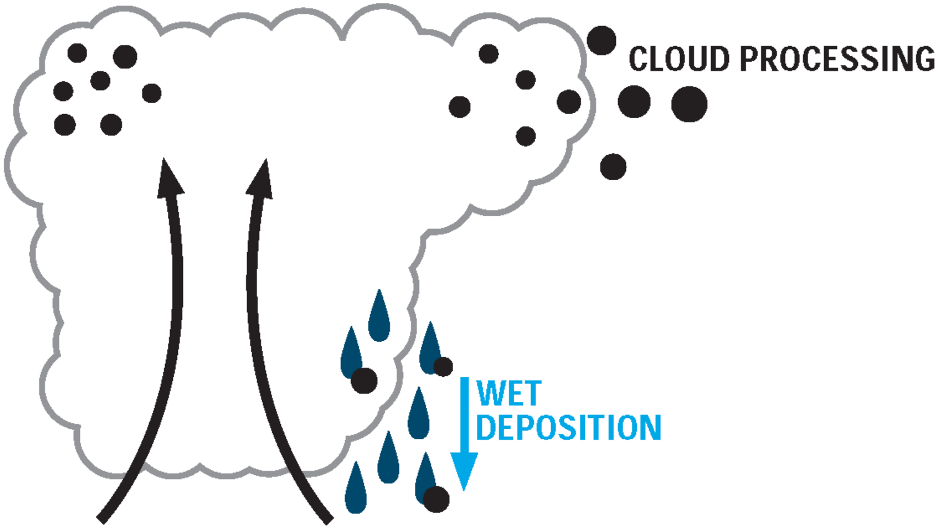
Convolution of difficult (sub-grid scale) processes:

i) Cloud microphysics not existent (CTMs) or of limited complexity (GCMs)

ii) Simulated precipitation in GCMs is imperfect

iii) Uptake processes are difficult (water) or insufficiently (ice) understood

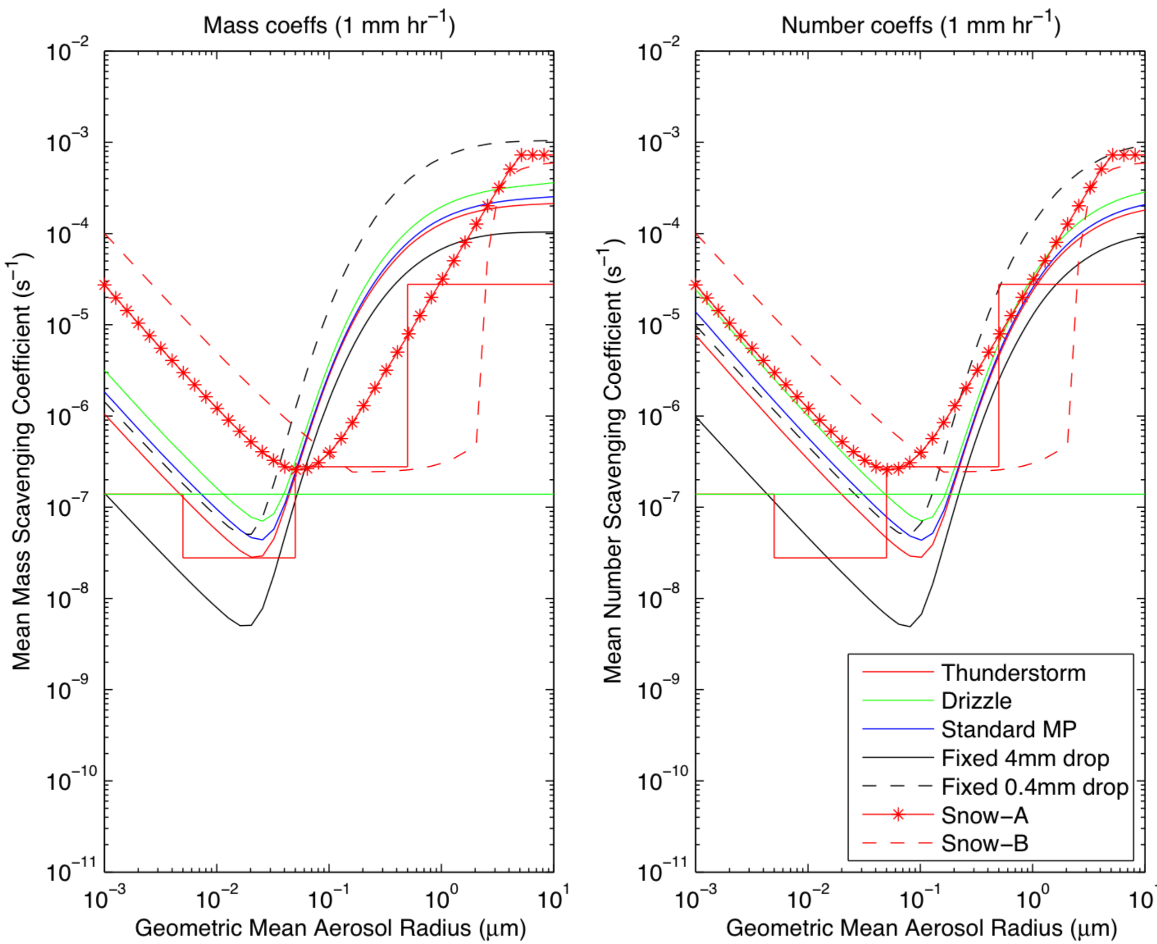
iv) Cloud cycling and evaporation often ignored



Aerosol Removal Processes

Caveat: Wet Deposition

Impaction scavenging coefficients from explicit calculation

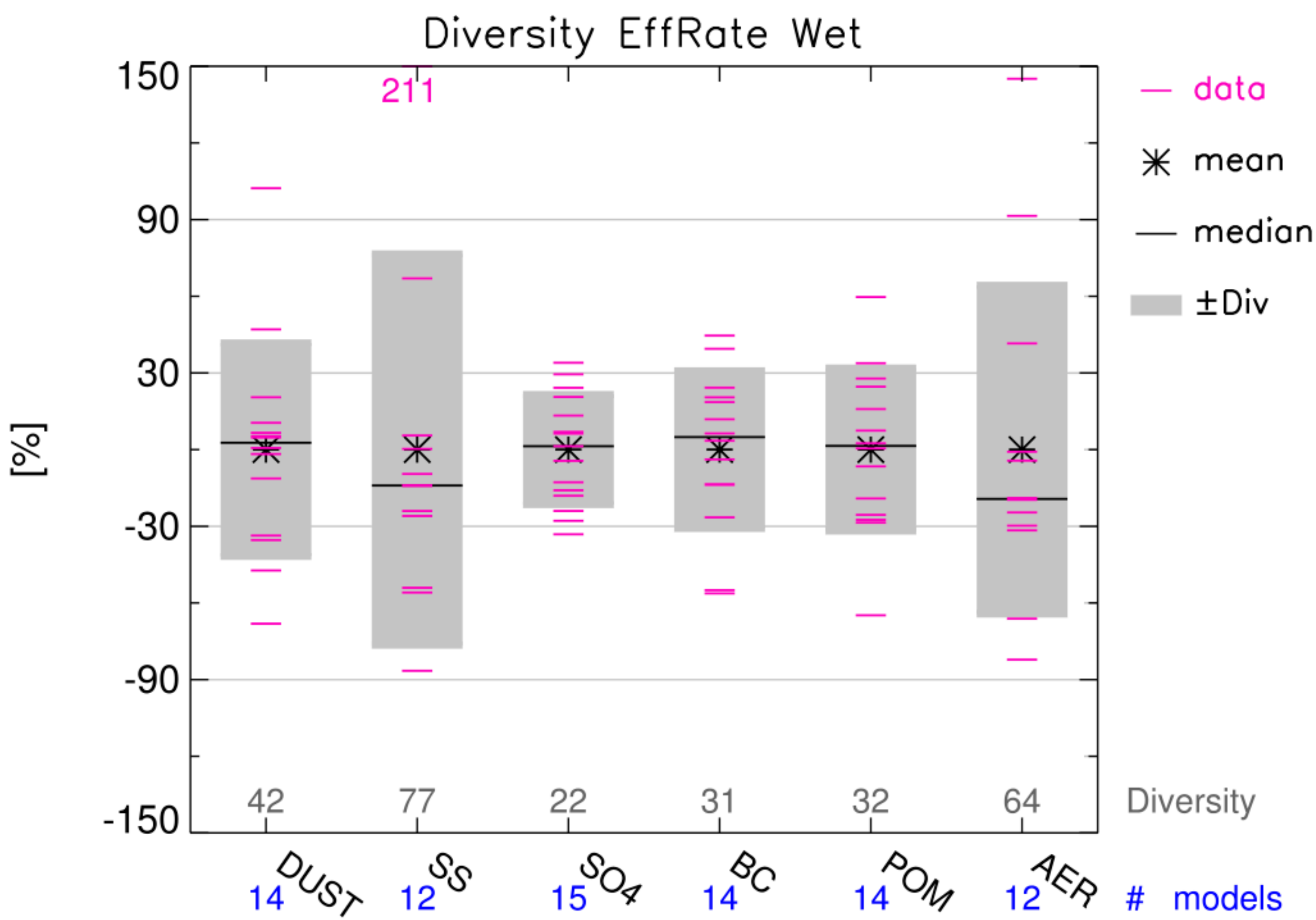


Croft et al, (2009)

Difficult to approximate with simple aerosol representations

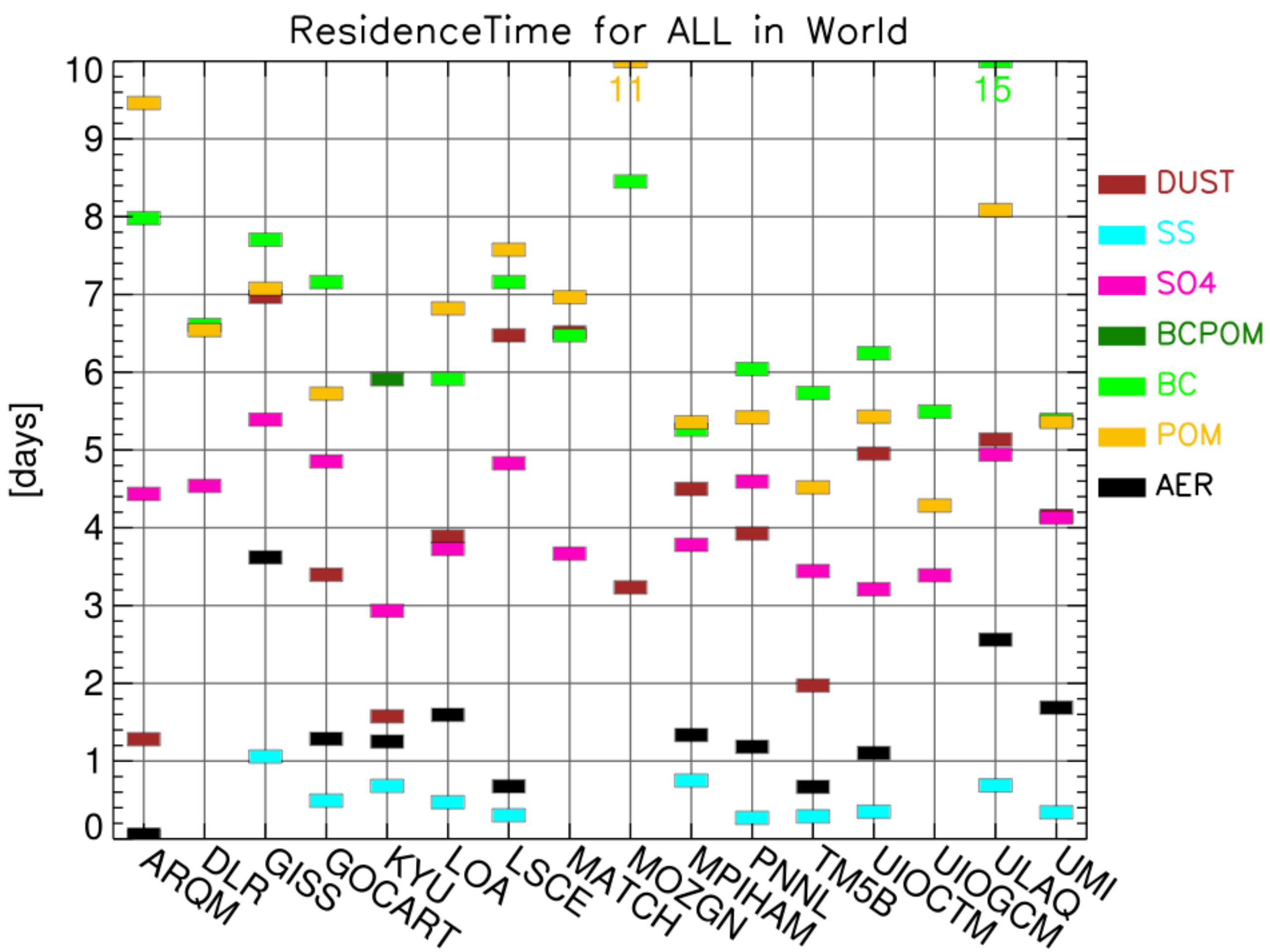
Aerosol Removal Processes

Caveat: Wet Deposition



Textor et al. (2006)

Aerosol Residence Time



Textor et al. (2006)

Summary

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