Coupling of an advanced particle microphysics (APM) model with CAM5

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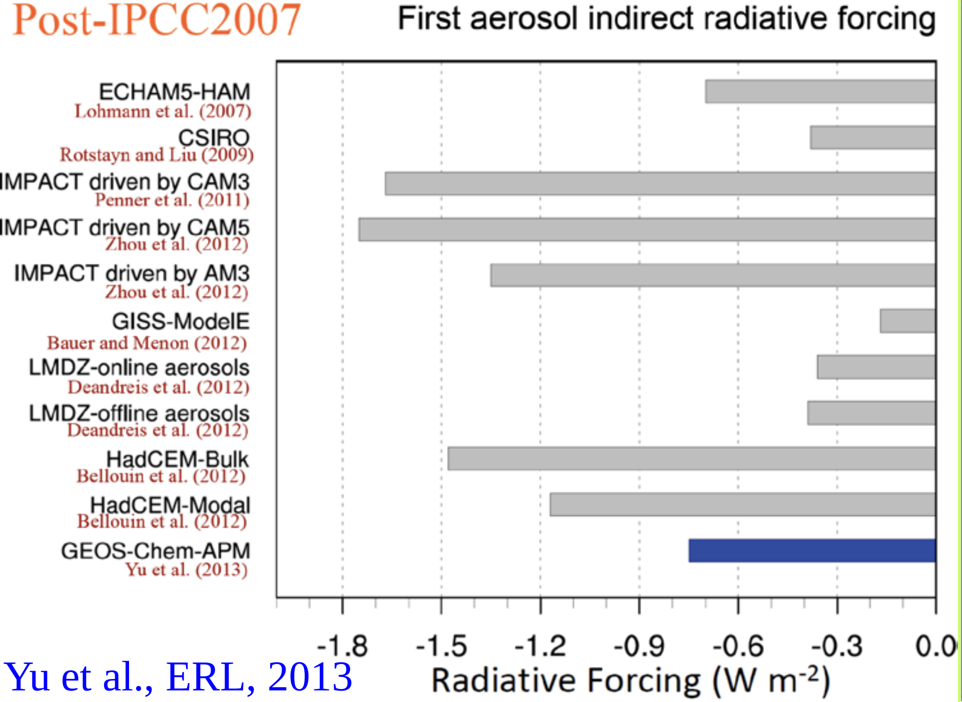
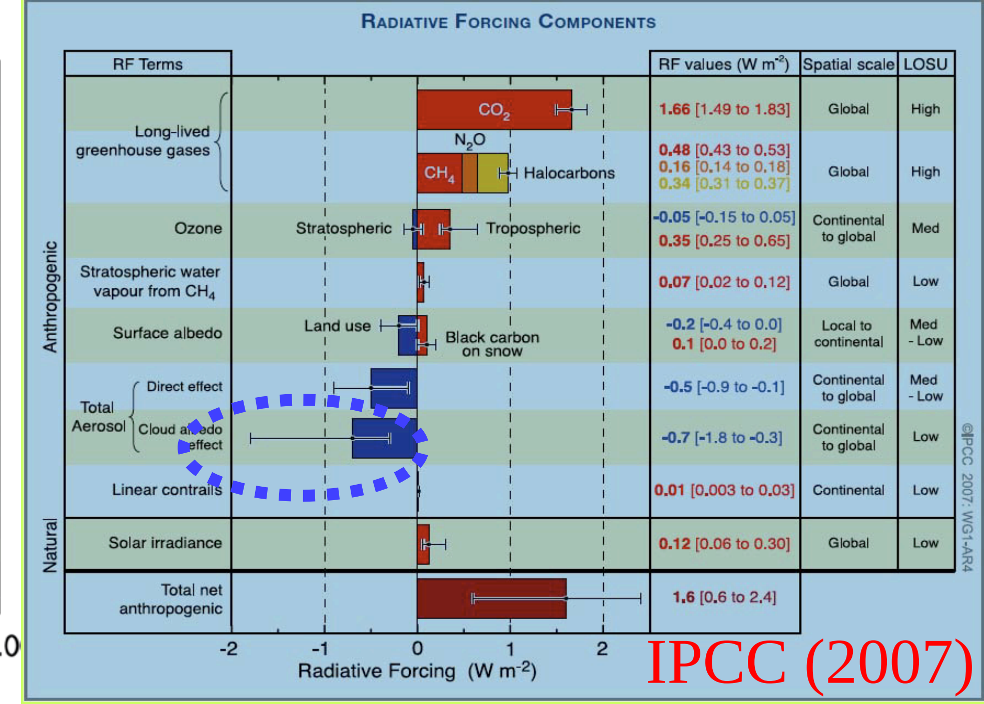
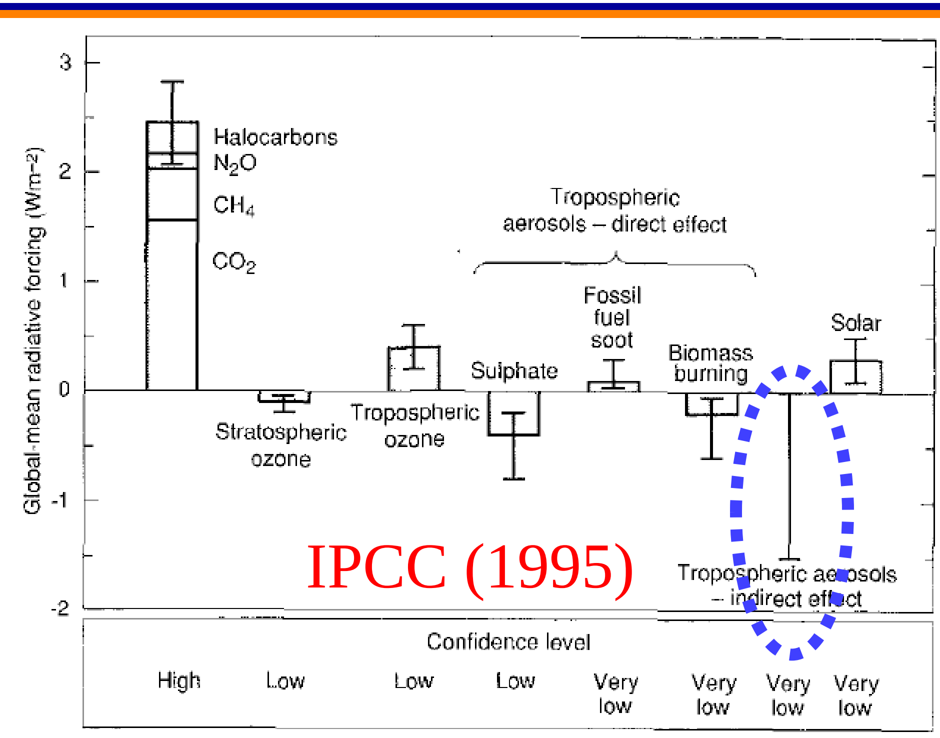
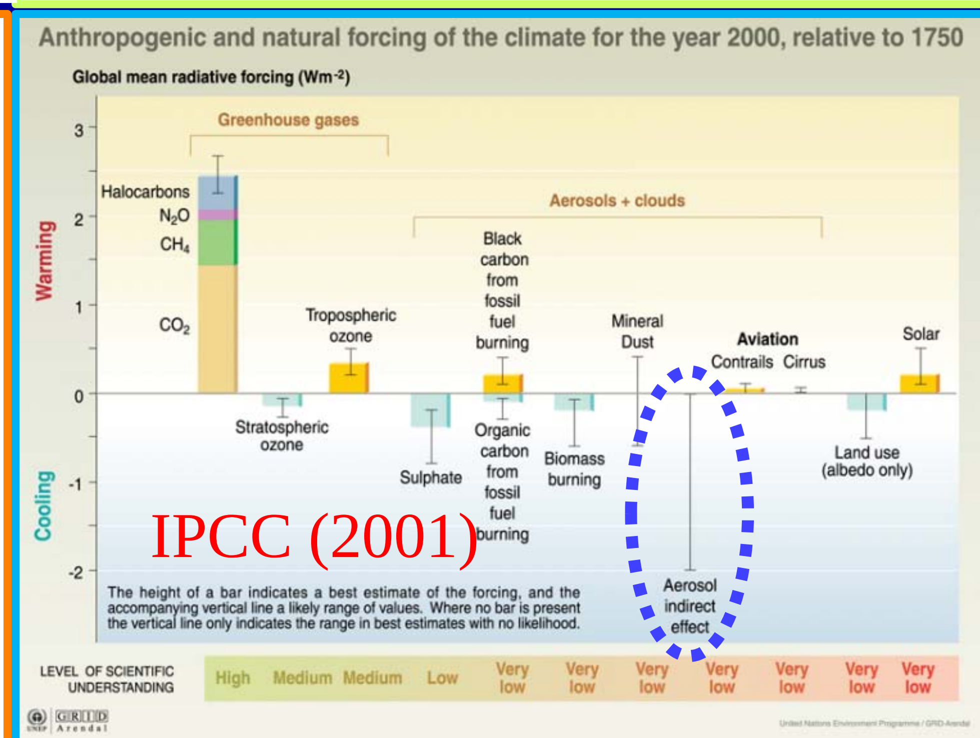

Post-IPCC2007
First aerosol indirect radiative forcing
ECHAM5-HAM
Lohmann et al. (2007)
CSIRO
Rotstayn and Liu (2009)
IMPACT driven by CAM3
Penner et al. (2011)
IMPACT driven by CAM5
Zhou et al. (2012)
IMPACT driven by AM3
Zhou et al. (2012)
GISS-ModelE
Bauer and Menon (2012)
LMDZ-online aerosols
Deandreis et al. (2012)
LMDZ-offline aerosols
Deandreis et al. (2012)
HadCEM-Bulk
Bellouin et al. (2012)
HadCEM-Modal
Bellouin et al. (2012)
GEOS-Chem-APM
Yu et al. (2013)
-1.8 -1.5 -1.2 -0.9 -0.6 -0.3 0.0
Radiative Forcing (W m-2)
Yu et al., ERL, 2013


Radiative Forcing Components
RF Terms
RF values (W m-2)
Spatial scale
LOSU
Anthropogenic
Long-lived greenhouse gases
CO2
N2O
CH4
Halocarbons
1.66 [1.49 to 1.83] Global High
0.48 [0.43 to 0.53]
0.16 [0.14 to 0.18]
0.34 [0.31 to 0.37] Global High
Ozone
Stratospheric
Tropospheric
-0.05 [-0.15 to 0.05]
0.35 [0.25 to 0.65] Continental to global Med
Stratospheric water vapour from CH4
0.07 [0.02 to 0.12] Global Low
Surface albedo
Land use
Black carbon on snow
-0.2 [-0.4 to 0.0]
0.1 [0.0 to 0.2] Local to continental Med - Low
Total Aerosol
Direct effect
-0.5 [-0.9 to -0.1] Continental to global Med - Low
Cloud albedo effect
-0.7 [-1.8 to -0.3] Continental to global Low
Linear contrails
0.01 [0.003 to 0.03] Continental Low
Natural
Solar irradiance
0.12 [0.06 to 0.30] Global Low
Total net anthropogenic
1.6 [0.6 to 2.4]
-2 -1 0 1 2
Radiative Forcing (W m-2)
©IPCC 2007: WG1-AR4
IPCC (2007)


Global-mean radiative forcing (Wm-2)
3 2 1 0 -1 -2
Halocarbons
N2O
CH4
CO2
Tropospheric aerosols – direct effect
Fossil fuel soot
Sulphate
Biomass burning
Solar
Stratospheric ozone
Tropospheric ozone
Tropospheric aerosols – indirect effect
IPCC (1995)
Confidence level
High Low Low Low Very low Very low Very low Very low


Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750
Global mean radiative forcing (Wm-2)
Warming
Cooling
3 2 1 0 -1 -2
Greenhouse gases
Halocarbons
N2O
CH4
CO2
Aerosols + clouds
Tropospheric ozone
Stratospheric ozone
Black carbon from fossil fuel burning
Organic carbon from fossil fuel burning
Sulphate
Biomass burning
Mineral Dust
Aerosol indirect effect
Aviation
Contrails
Cirrus
Land use (albedo only)
Solar
IPCC (2001)
The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.
LEVEL OF SCIENTIFIC UNDERSTANDING
High Medium Medium Low Very low Very low Very low Very low Very low Very low Very low
GRID Arendal

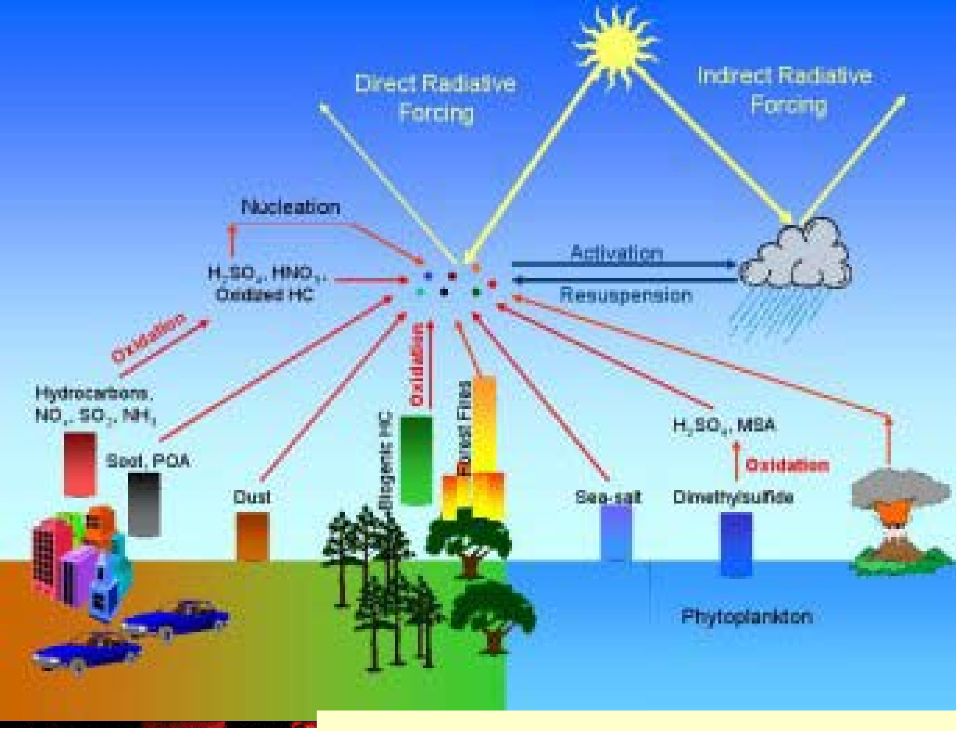
Studies of aerosol first IRF (in W m^{-2}) published after IPCC (2007)

Study	Model type [a]	Chemistry	Aerosols [b]		First IRF	
			size	Species	approach	Value
Lohmann et al. (20	ECHAM5-HAM	Sulfur cycle , with off-line monthly mean oxidants	Double-moment modal	SO_4,OC,BC, SS,D	Online	-0.7
Rotstayn (20		Sulfur cycle, with off-line monthly mean oxidants	bulk	SO_4,OC,BC, SS,D	Online	-0.38
Wang an (2009); Penner et al. (2011)	by CAM3 met	Sulfur cycle, with off-line monthly mean oxidants.	modal (two modes for sulfate)	SO_4,OC,BC, SS,D	Offline	-1.65 and -1.69
Zhou		Sulfur cycle, with off-line monthly mean oxidants	modal (3 modes for sulfate)	SO_4,OC,BC, SS,D	Offline	-1.74 to -1.77
						-1.26 to -1.44
Bauer and Menon (2	GISS-modelE	Sulfur cycle, with off-line oxidants and nitric acid concentrations.	modal (2 moment)	SO_4,OC,BC, SS, D, NIT, NH4	Online	-0.17
Deand (2		ulfur cycle , oxidants from n online chemistry model	bulk	SO_4	On-line	-0.36
					Offline	-0.39
Bellouin et al. (2012)	HadGEM	Sulfur cycle, oxidants from an online chemistry model	bulk	SO_4, NH4, OC,BC,SS, SOA	Online	-1.48
			modal			-1.17

Simplified chemistry

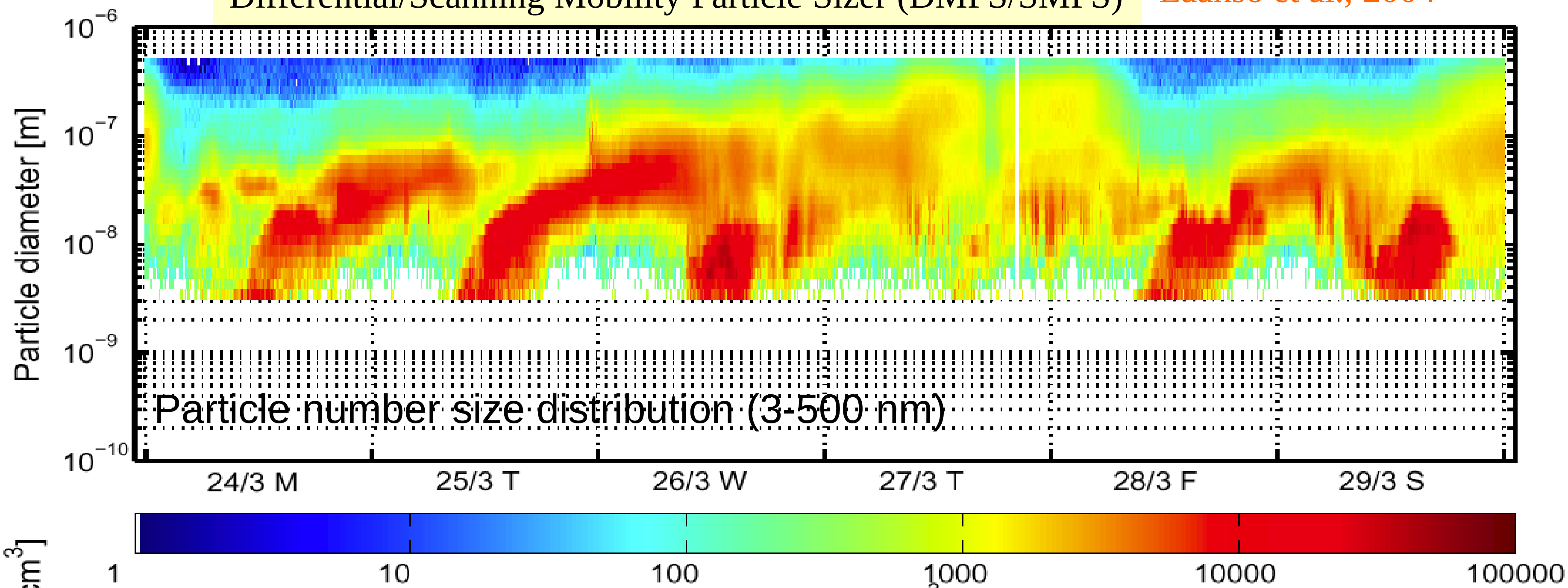
Simplified Microphysics

Not all major aerosols considered

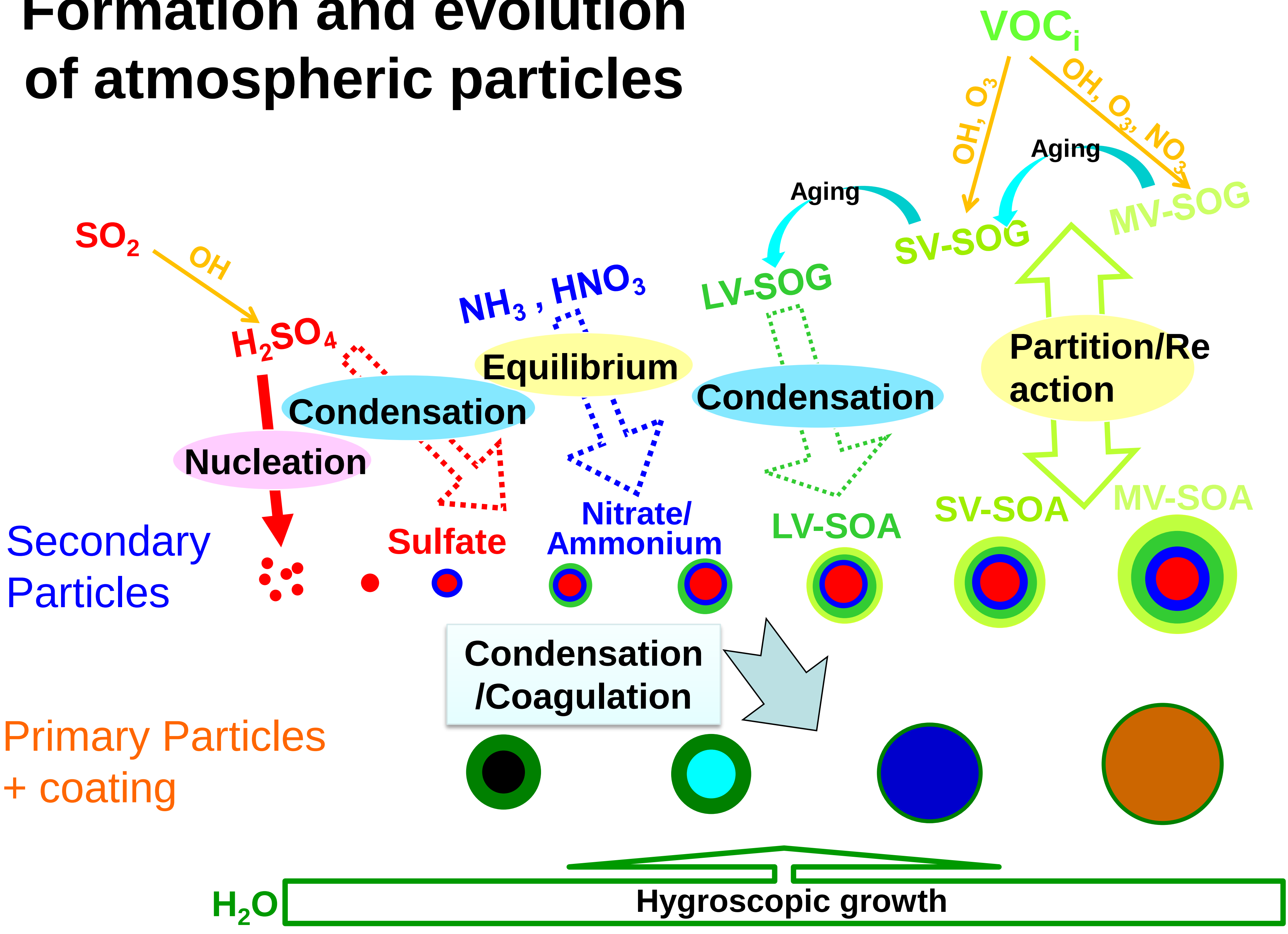


Differential/Scanning Mobility Particle Sizer (DMPS/SMPS)

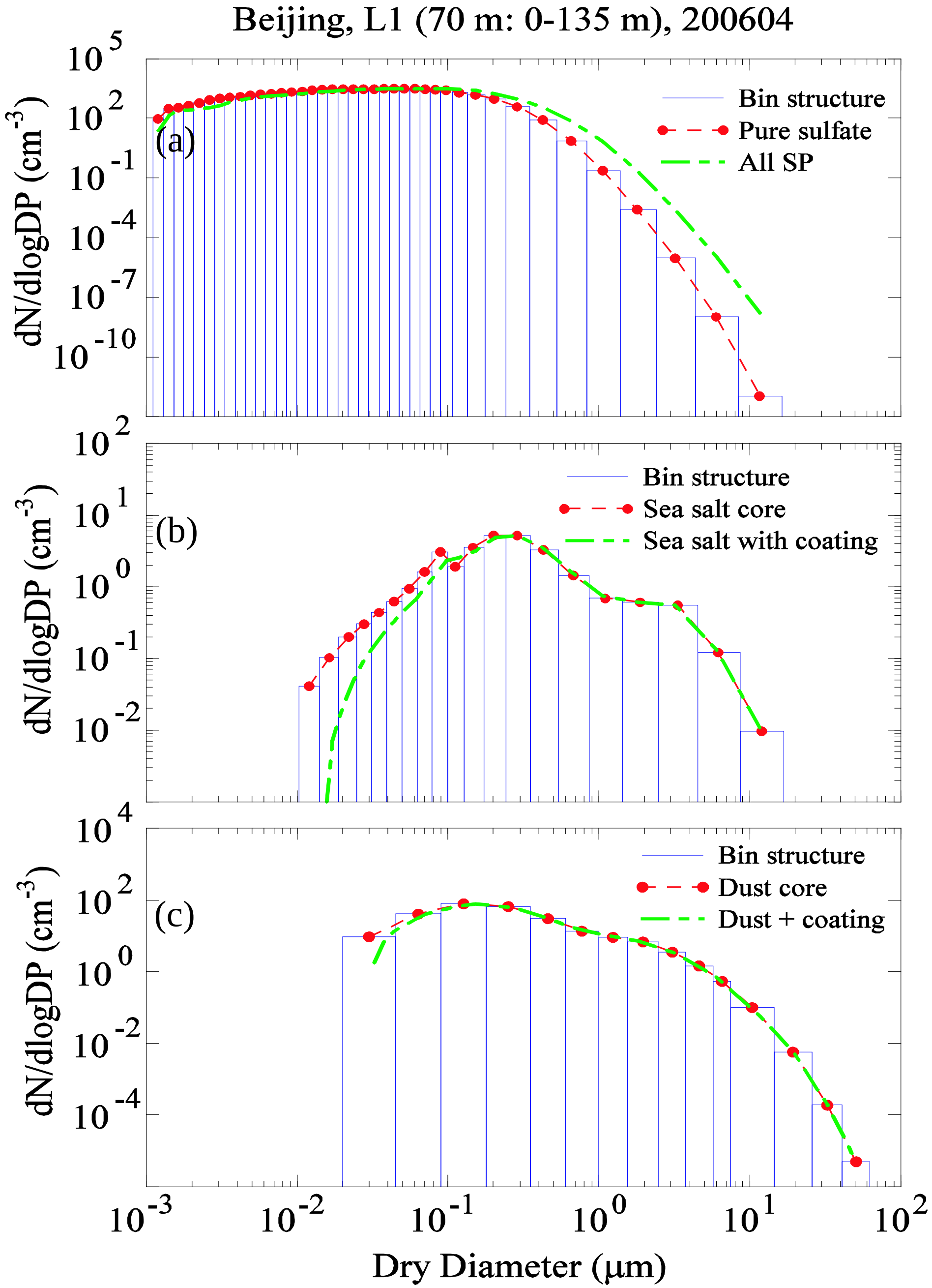
Laakso et al., 2004



Formation and evolution of atmospheric particles



Advanced Particle Microphysics (APM) model



APM aerosol representation

Secondary particles (SP): 40 bins

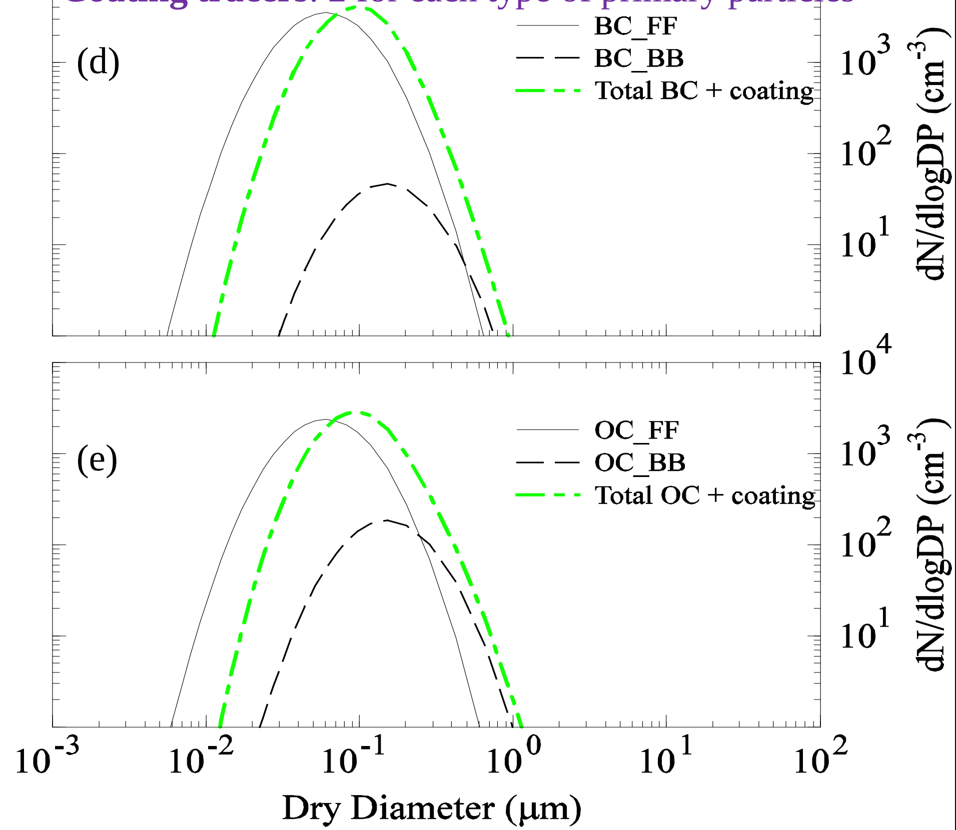
Sea salt: 20 bins

Dust: 15 bins

BC: 2 log-normal modes (one for fossil fuel, the other for biomass burning) for hydrophobic BC and 2 similar modes for hydrophilic BC.

Primary OC (POC): Similar to BC, 4 log-normal modes

Coating tracers: 2 for each type of primary particles



Key features of APM in GEOS-Chem and WRF-Chem

Ion-Mediated Nucleation (IMN): derived from a kinetic nucleation model constrained by multiple laboratory thermodynamic data and verified by field measurements (Yu and Turco, GRL1997, GRL 2000, JGR 2001, ACP 2008, 2011; Yu, JCP 2005, ACP 2006, JGR 2010)

Equilibrium uptake of NH_3, HNO_3, and H_2O: ISORROPIA II (Fountoukis and Nenes, ACP, 2007)

SOA formation: Extended 2-product method which considers successive oxidation aging and kinetic condensation (Yu, ACP, 2011)

Mixing state: Semi-externally mixed that tracks the amount of secondary species coated on primary particles (Yu and Luo, ACP, 2009; Yu et al., ACP, 2011)

Validation: Computationally efficient and simulations validated by a large number field measurements (Yu and Luo, 2009, 2010; Yu, 2010; Luo and Yu, 2011a, b; Yu et al., 2011, 2012; Ma et al., 2012a, b)

GEOS-Chem-APM (Yu and Luo, 2009)

- ✓ Full chemistry (NOx, SOx, VOCs, etc.)
- ✓ Full size-resolved microphysics
- ✓ Offline assimilated meteorology
- ✓ Suitable for studies of processes and global long-term simulations

Computing cost (24-core workstation)

GEOS-Chem (2^ox2.5^o , 47 layers, **1 yr**)

Original model	With APM
59 tracers	59+88= 147 tracers
~ 5 day	**~ 11** days

WRF-Chem-APM (Luo and Yu, 2011)

- ✓ Full chemistry (NOx, SOx, VOCs, etc.)
- ✓ Full size-resolved microphysics
- ✓ Online forecasted meteorology
- ✓ Suitable for regional short-term simulations and forecasting with high resolution

Computing cost (24-core workstation)

WRF-Chem (140x108x34 grid boxes, **1 day**)

8-bin MOSAIC	With APM
213 tracers	138 tracers
~ **6** hrs	~ **2** hrs

The same APM incorporated in GEOS-Chem and WRF-Chem has also been integrated into CESM-CAM5 in this study

- ✓ Full size-resolved (bin) microphysics;
- ✓ Coating of secondary species on primary particles tracked;
- ✓ Work with either simplified sulfur chemistry (offline oxidants) or full online chemistry (MOZART)
- ✓ Added ISORROPIA II (Fountoukis and Nenes, ACP, 2007) to CESM-CAM5-APM to calculate the uptake of HNO3, NH3, and H2O.
- ✓ Suitable for chemistry-aerosol-cloud-precipitation-climate study

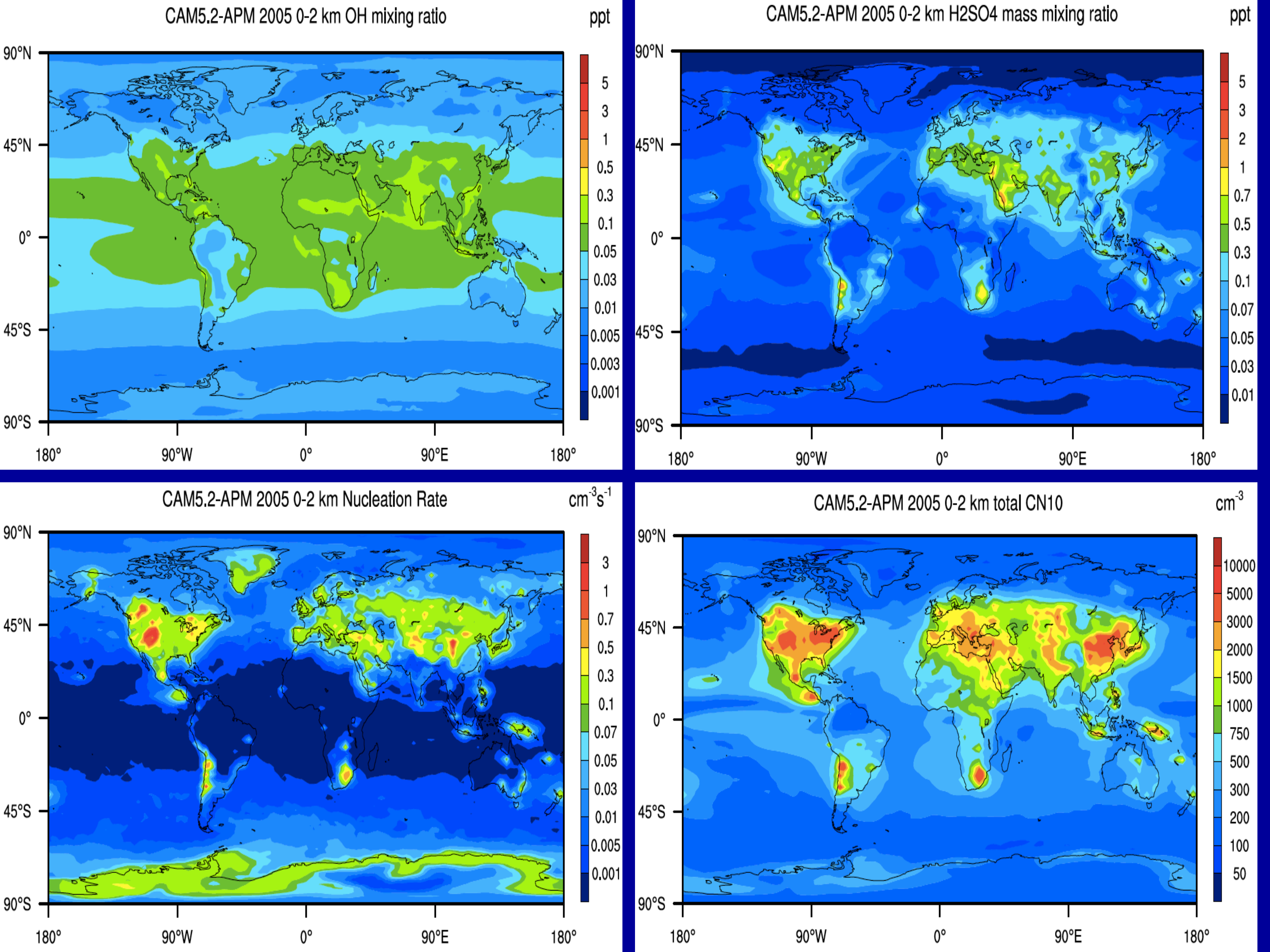
Computing cost (24-core workstation, 1.9°x2.5°, 30 layers, **1 yr**)

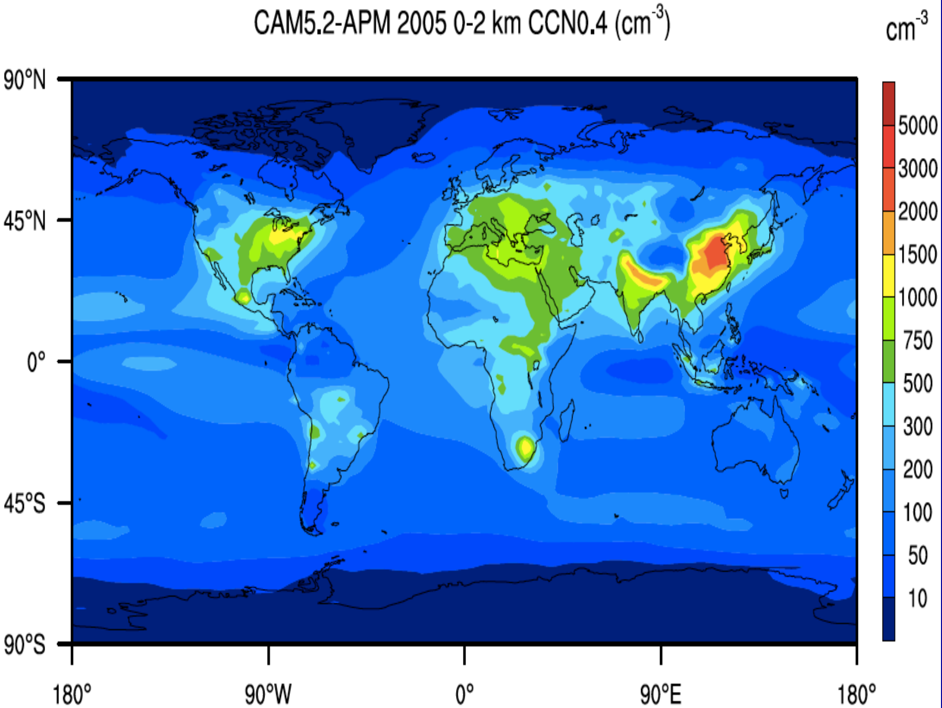
CAM5 (Simplified sulfur chemistry)		CAM5-MOZART-APM (full chemistry)
MAM3	With APM	
20 tracers	20+96= 116 tracers	20+96+87= 203 tracers
~ 2 day	**~ 4** days	**~ 6** days

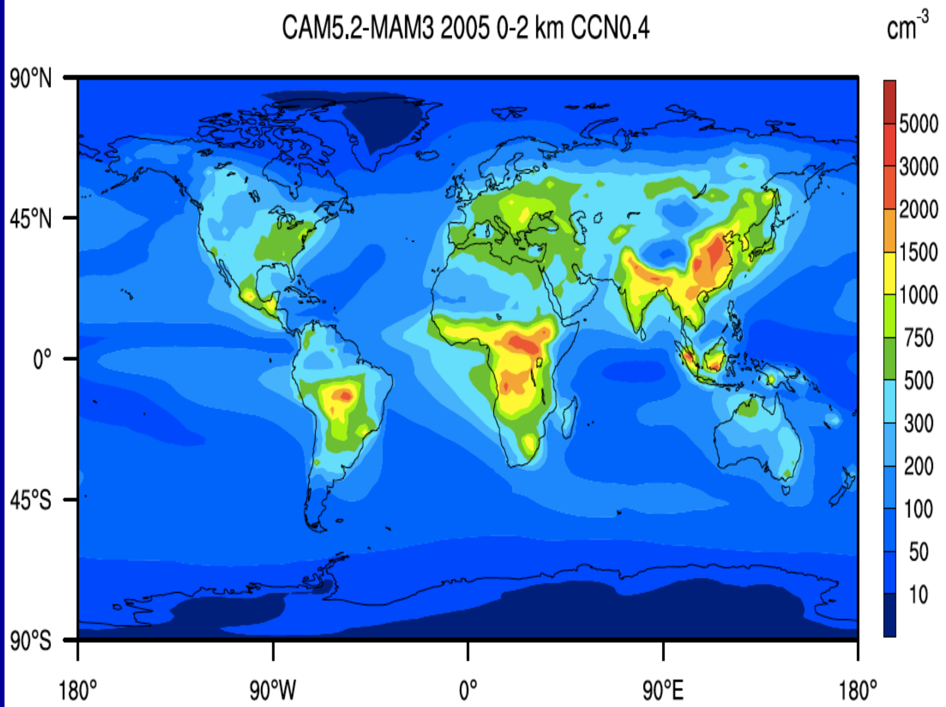
CAM5-MOZART-MAM3-APM simulations

Preliminary results

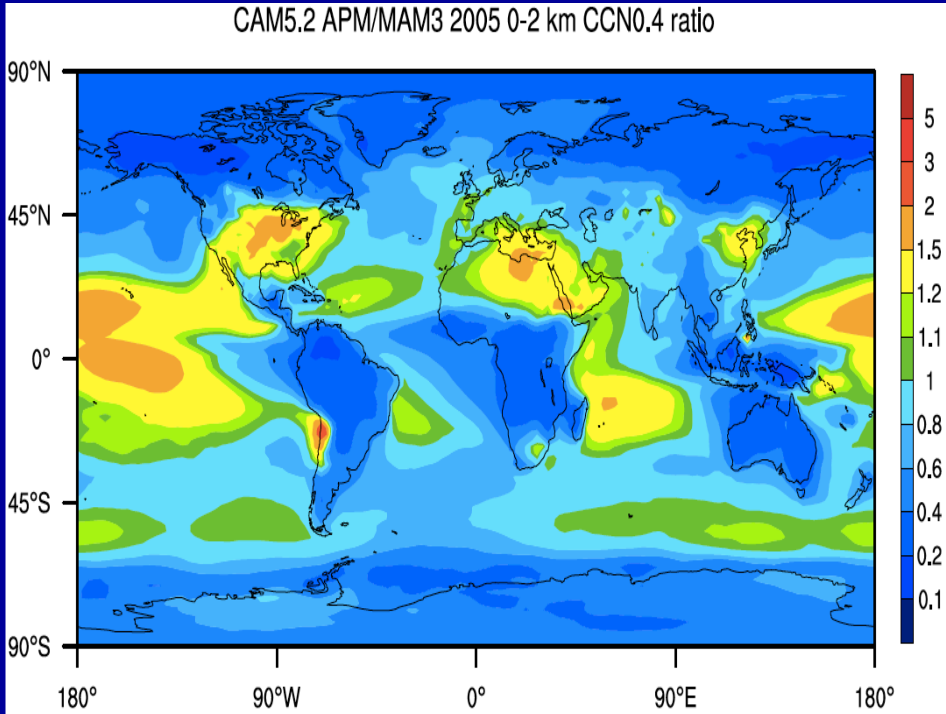
(Oxidation aging and SOA not considered yet)

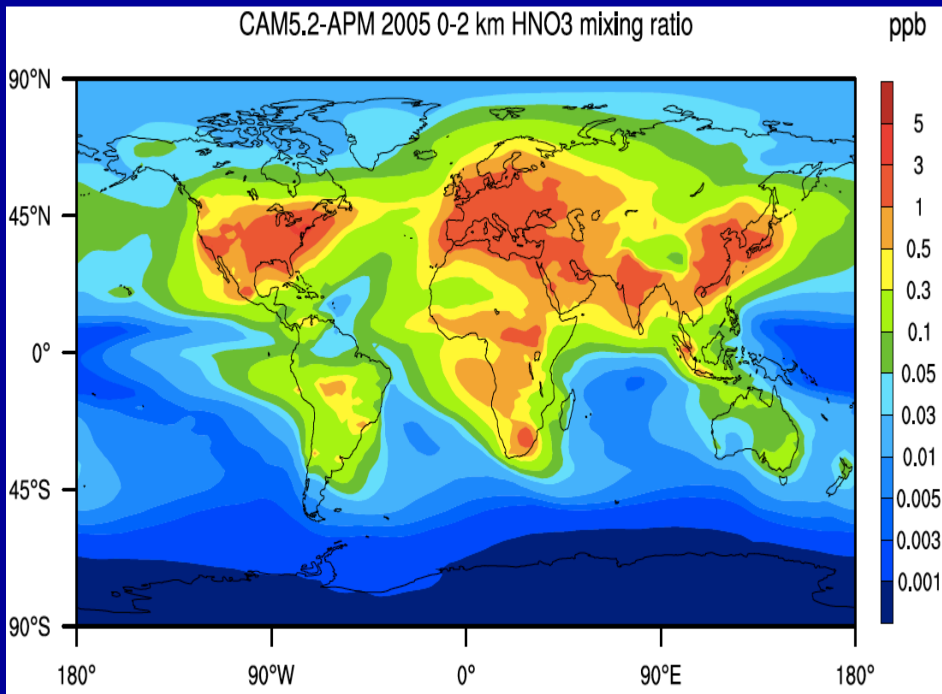

CAM5.2-APM 2005 0-2 km OH mixing ratio
ppt
5
3
1
0.5
0.3
0.1
0.05
0.03
0.01
0.005
0.003
0.001
CAM5.2-APM 2005 0-2 km H2SO4 mass mixing ratio
ppt
5
3
2
1
0.7
0.5
0.3
0.1
0.07
0.05
0.03
0.01
CAM5.2-APM 2005 0-2 km Nucleation Rate
cm-3s-1
3
1
0.7
0.5
0.3
0.1
0.07
0.05
0.03
0.01
0.005
0.001
CAM5.2-APM 2005 0-2 km total CN10
cm-3
10000
5000
3000
2000
1500
1000
750
500
300
200
100
50
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°

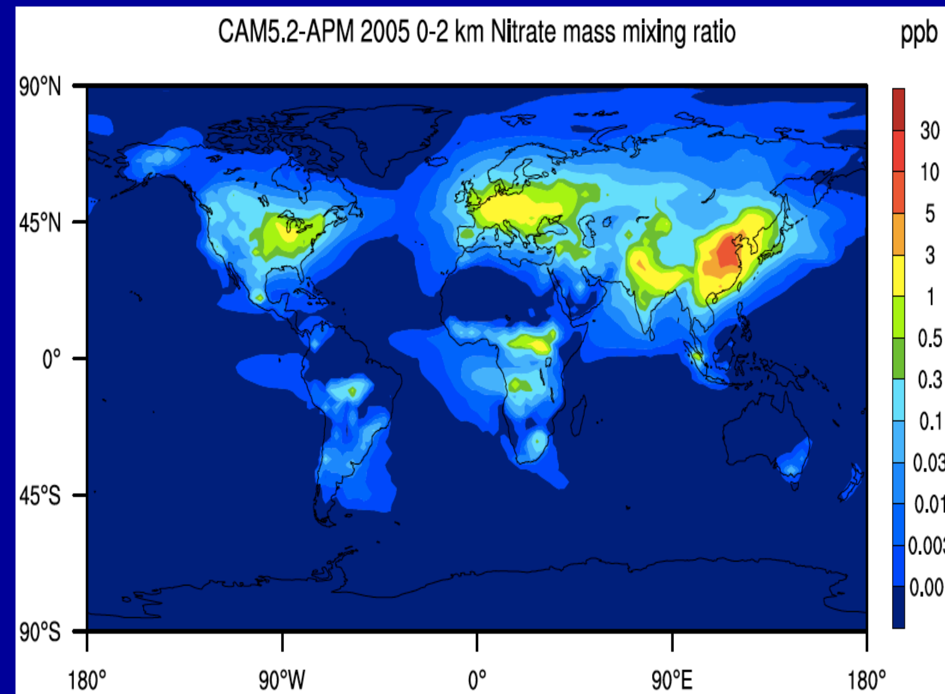


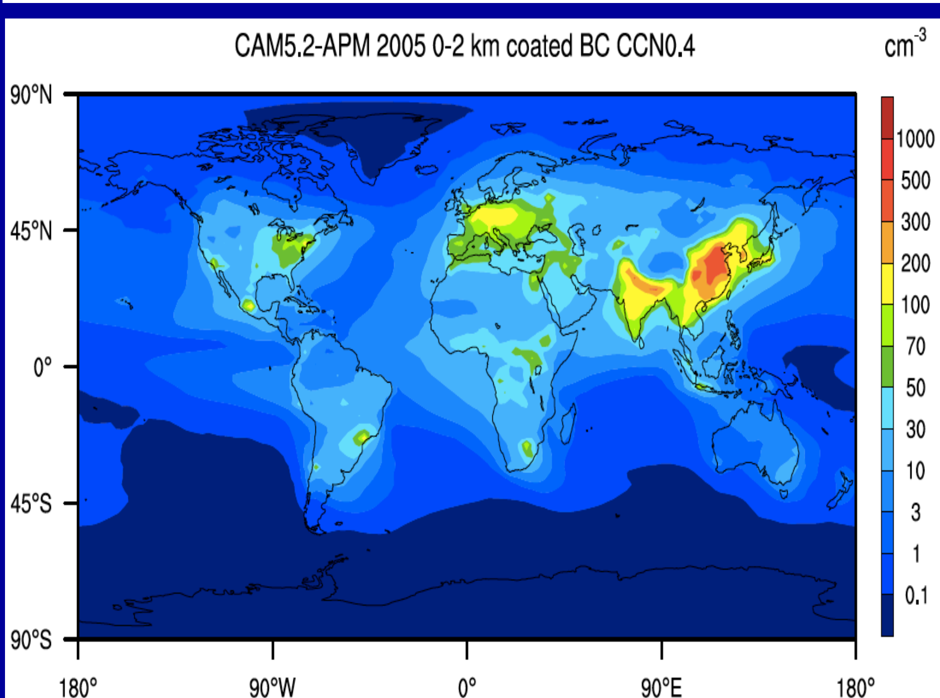


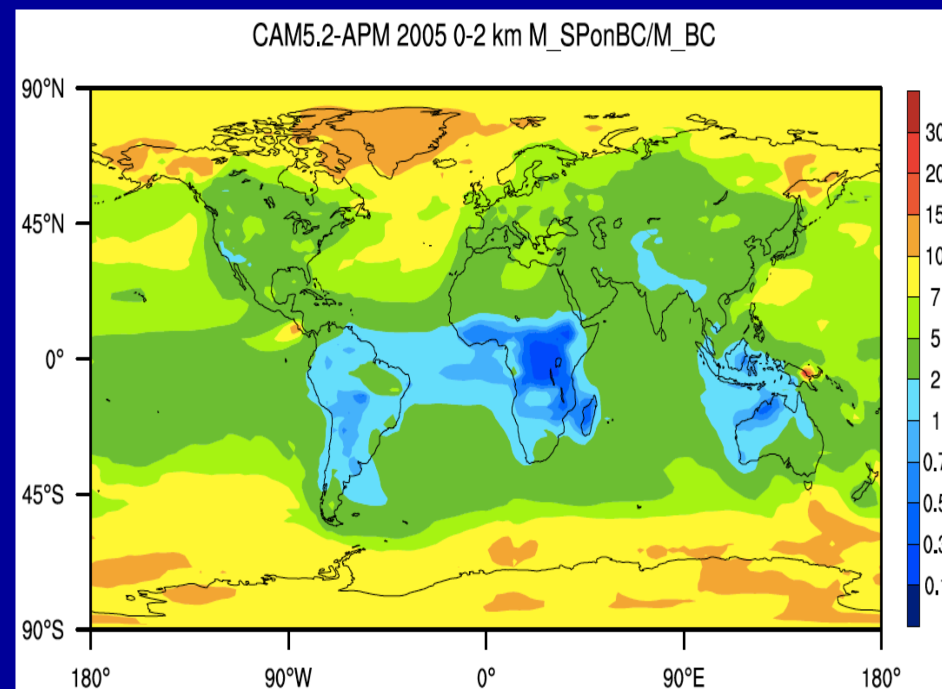
CCN at S=0.4% (CCN0.4)



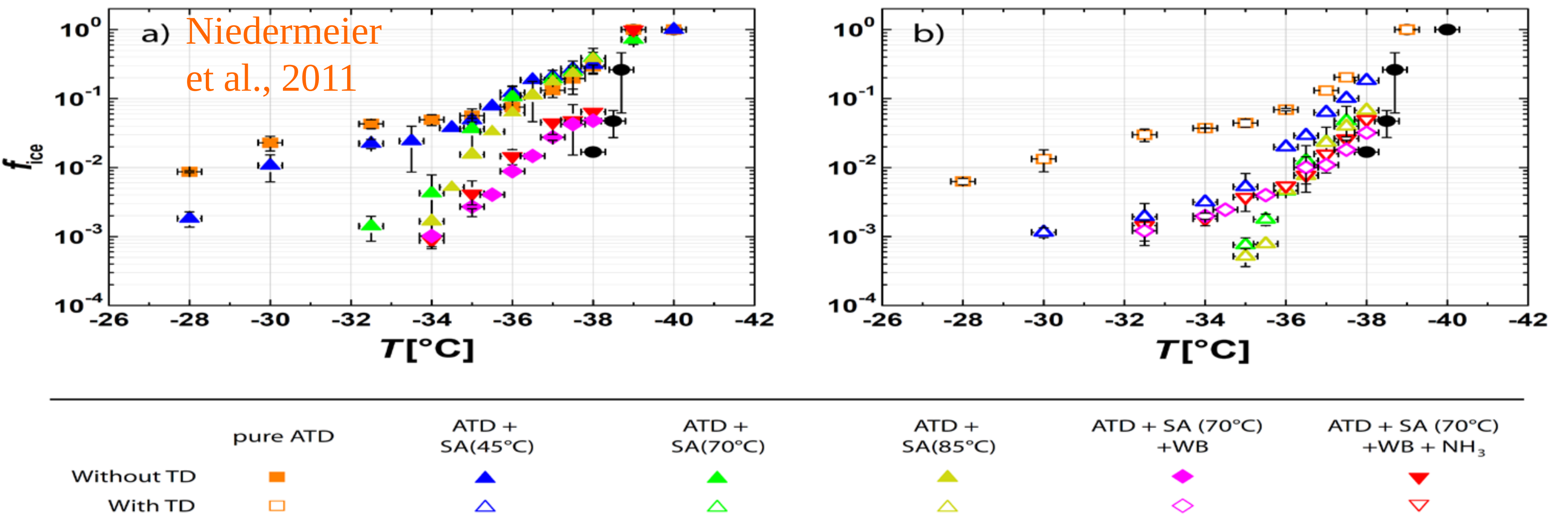

CAM5.2-APM 2005 0-2 km HNO3 mixing ratio
ppb
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°
5
3
1
0.5
0.3
0.1
0.05
0.03
0.01
0.005
0.003
0.001

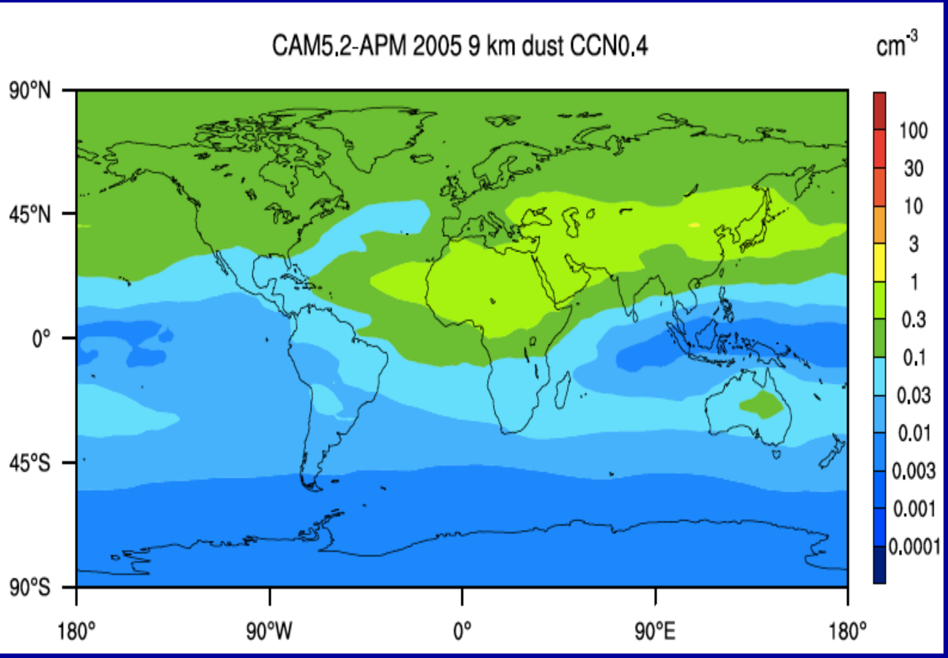

CAM5.2-APM 2005 0-2 km Nitrate mass mixing ratio
ppb
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°
30
10
5
3
1
0.5
0.3
0.1
0.03
0.01
0.003
0.001

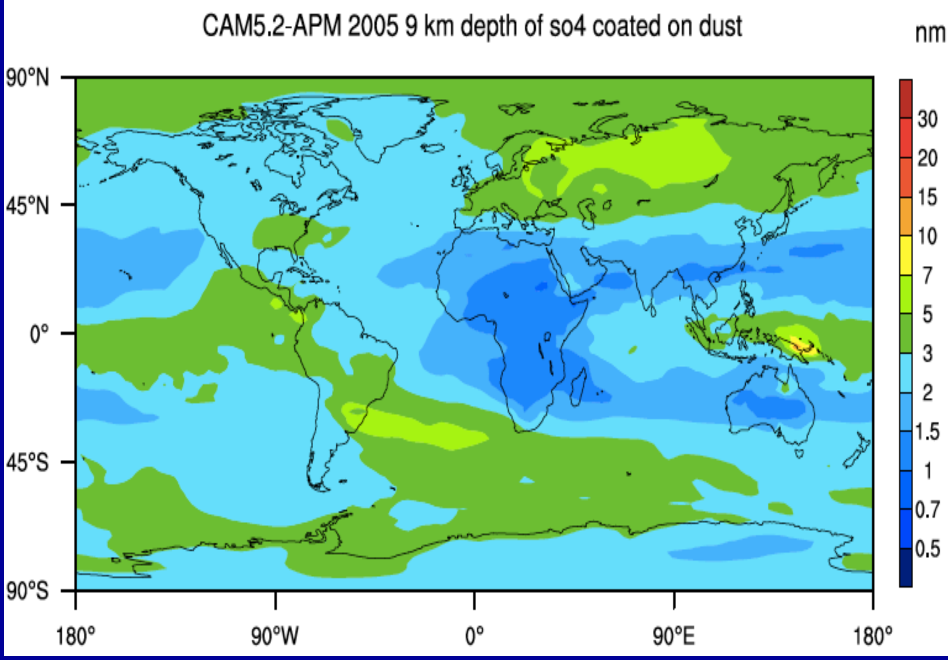

CAM5.2-APM 2005 0-2 km coated BC CCN0.4
cm-3
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°
1000
500
300
200
100
70
50
30
10
3
1
0.1


CAM5.2-APM 2005 0-2 km M_SPonBC/M_BC
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°
30
20
15
10
7
5
2
1
0.7
0.5
0.3
0.1

Coating of sulfate on dust







Summary

A computationally efficient advanced particle microphysics (APM) model, same as the one in GEOS-Chem-APM and WRF-Chem-APM, has been integrated into CAM5. In addition to full size-resolved (bin) microphysics, coating of secondary species on primary particles is explicitly tracked. We have also added ISORROPIA II to calculate the uptake of HNO_3, NH_3, and H_2O.

CAM5-APM works with either simplified sulfur chemistry (offline oxidants) or full online chemistry (MOZART).

Preliminary CAM5-MOZART-MAM3-APM simulations indicate large difference of CCN predicted by MAM3 and APM.

APM provides a large amount of additional information about aerosol properties that may be important for chemistry-aerosol-cloud-precipitation-climate interactions processes.

Future Research

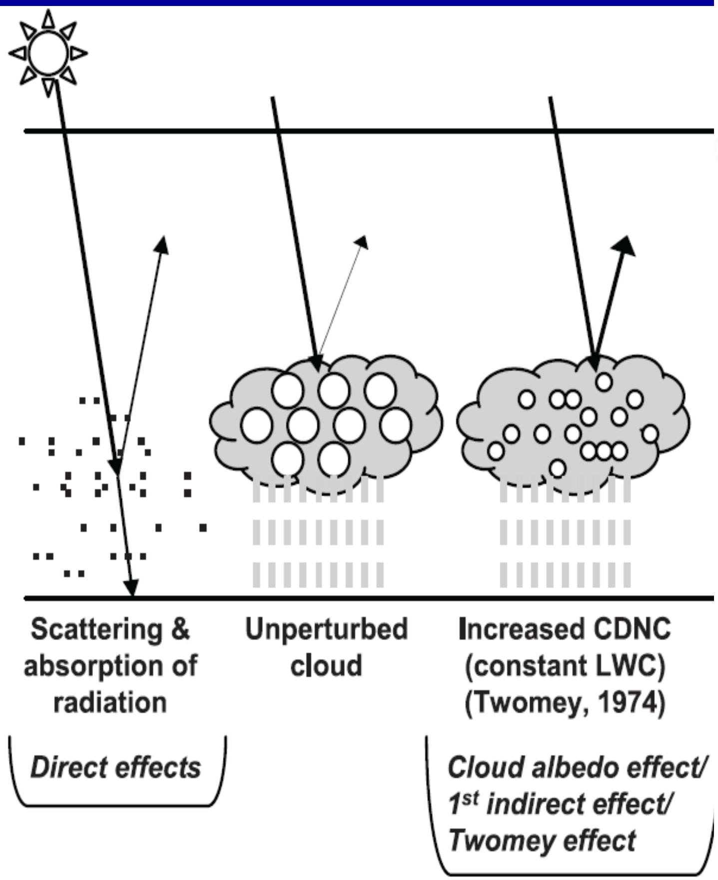
Refine APM schemes in CAM5, especially SOA formation and size-dependent wet-scavenging., and then fully evaluate the CAM5-APM simulations with various observations (total number concentration, CCN, AOD, size distribution, composition, etc.). Compare CAM5-APM results with simulations of other models (including CAM5-MAM, GEOS-Chem-APM, etc.).

Connect APM aerosol with cloud activation scheme to study aerosol-cloud-precipitation interactions. Investigate the impacts of various aerosol related chemical and microphysical processes.

Use CAM5-MOZART-APM simulations as a benchmark to develop schemes to improve the computationally more efficient CAM5-MAM and CAM5-APM versions of the model for long-term climate change simulations.

Thank you !

Aerosol Direct and Indirect Climate Effects



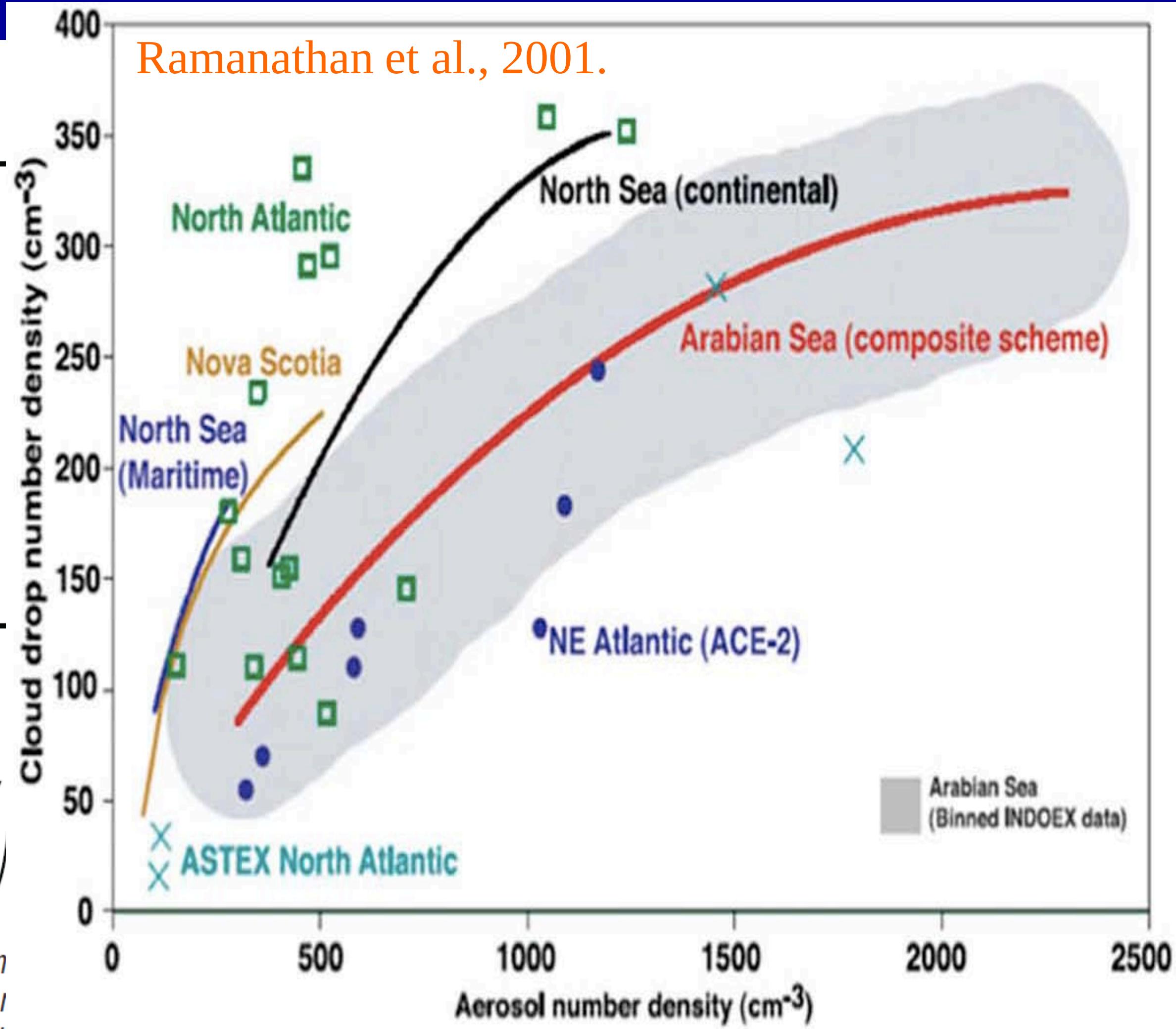


Figure 2.10. *Schematic diagram showing the various radiative m (modified from Haywood and Boucher, 2000). The small black dots r reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content.*

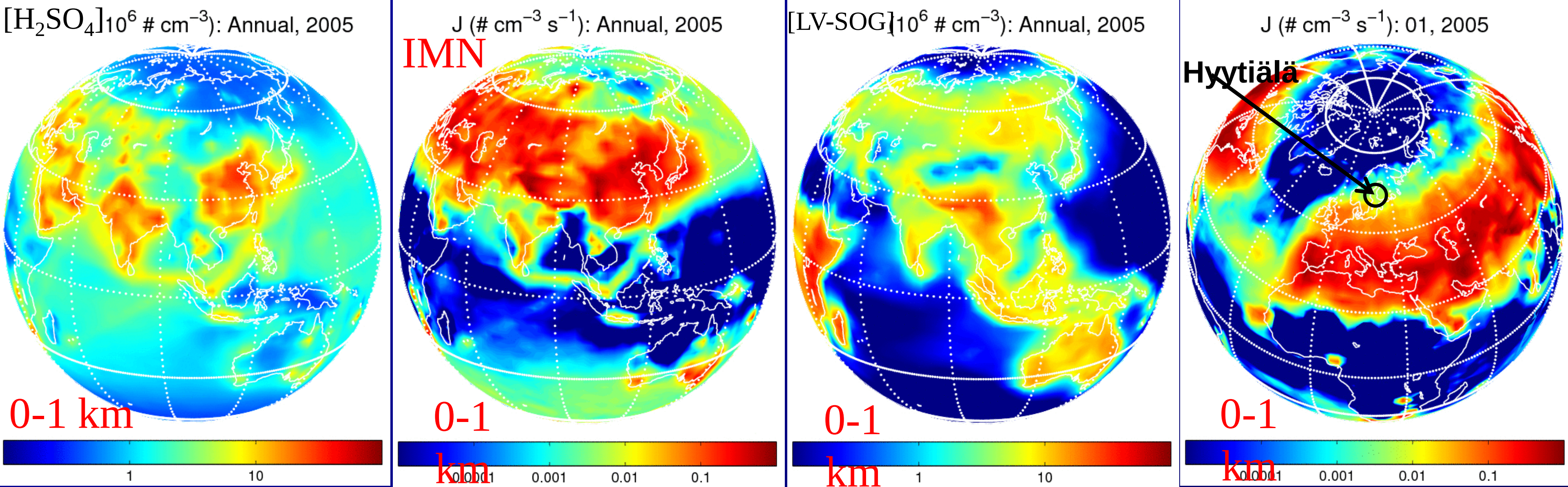
IPCC, 2007

Aerosol radiative forcing uncertainty

Aerosol radiative forcing remains the largest uncertainty among the various climate forcing factors (IPCC, 2007).

The uncertainties can be attributed to a number of issues, such as the emissions of precursor gases and primary particles, parameterizations of physical and chemical processes, meteorological conditions, aerosol properties, etc..

According to aerosol model inter-comparison (AeroCom) project, model diversity was not greatly reduced by unifying emissions, indicating that the greatest model differences are due to features such as meteorology and aerosol treatments rather than from emissions.



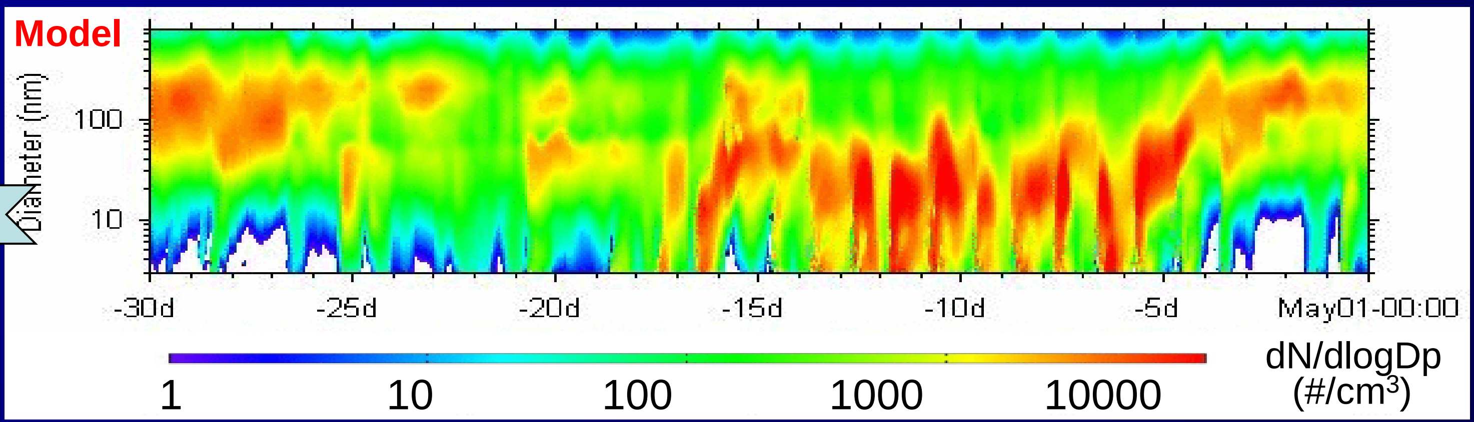
CN

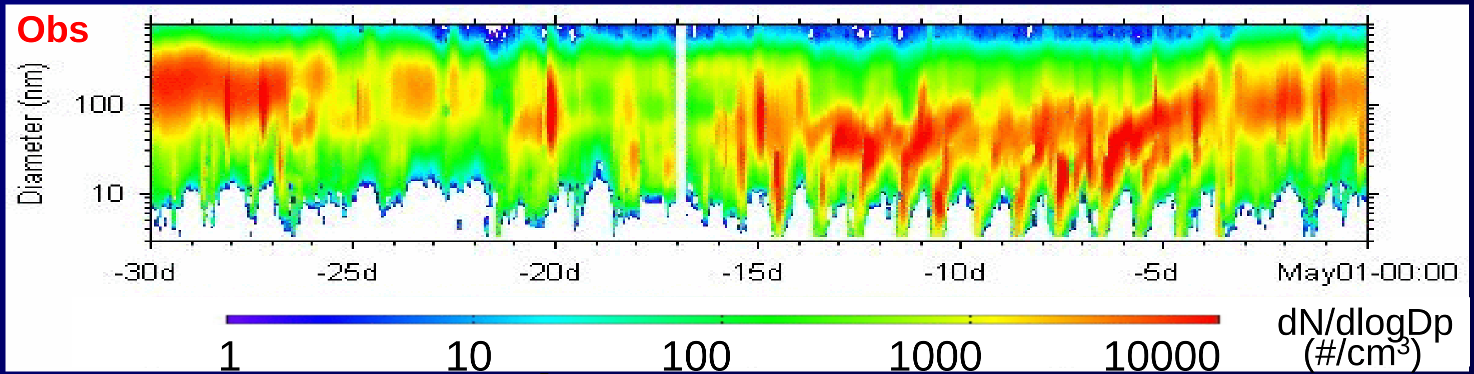
Simulated and observed particle size distribution at Hyytiälä

CCN/IN

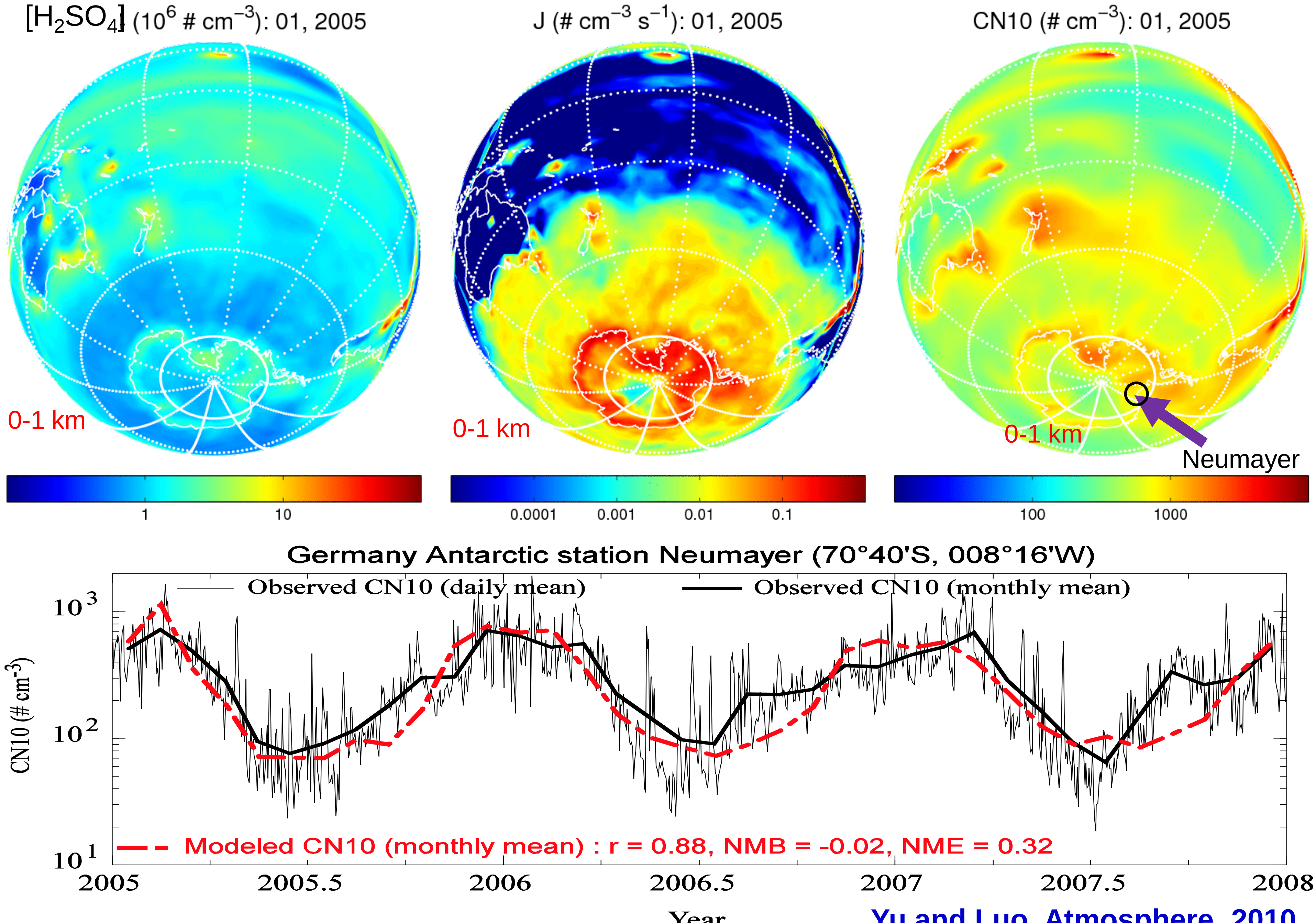
Ext Coef.

AOD



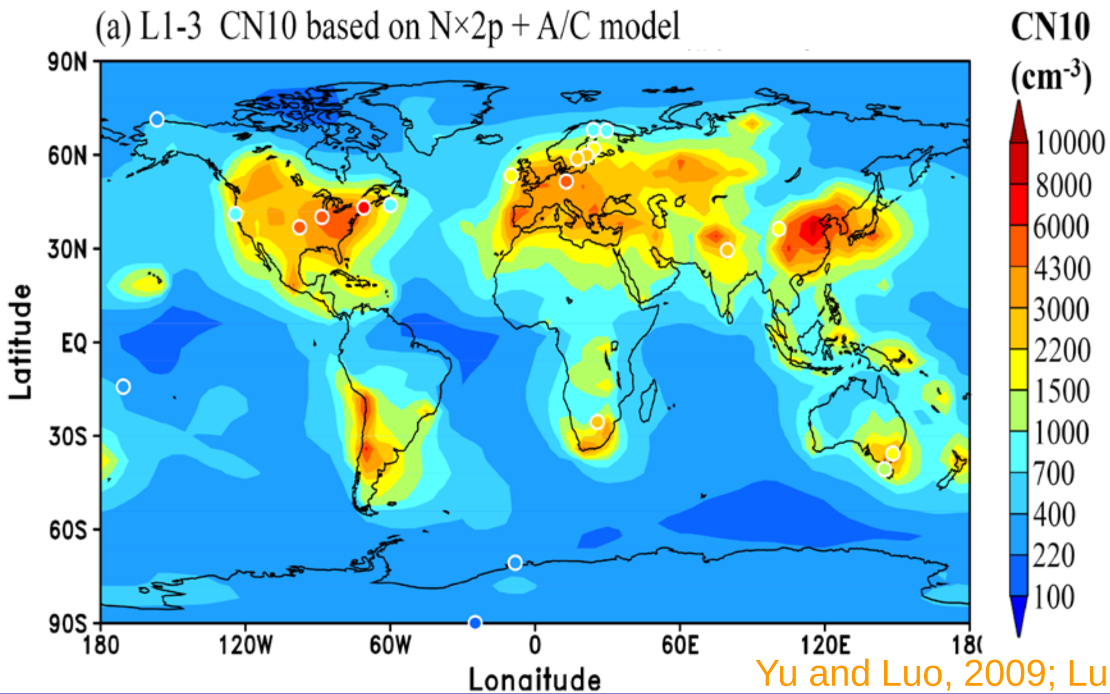


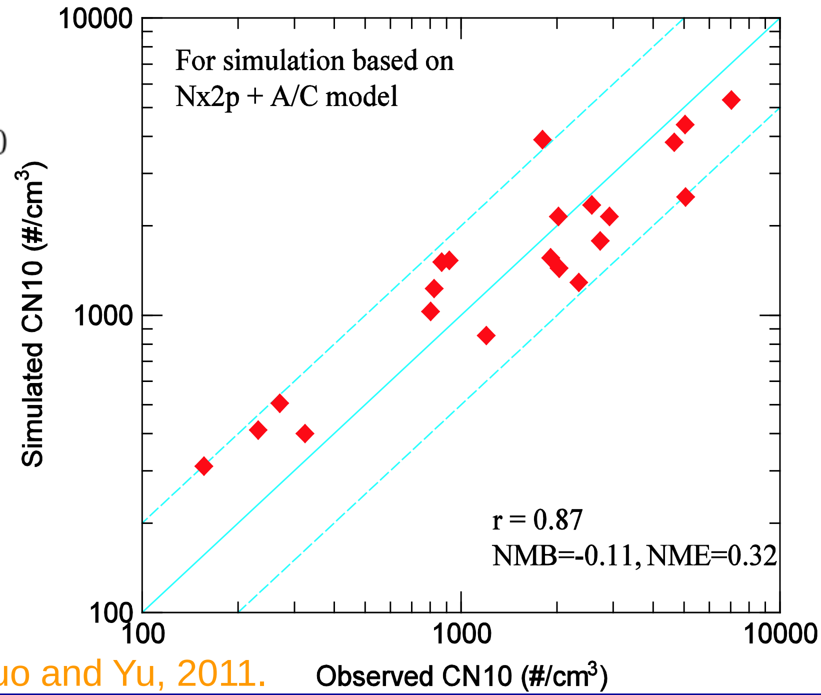
Data acknowledgements: Prof Markku Kulmala, CREATE and EUSSAR data base.



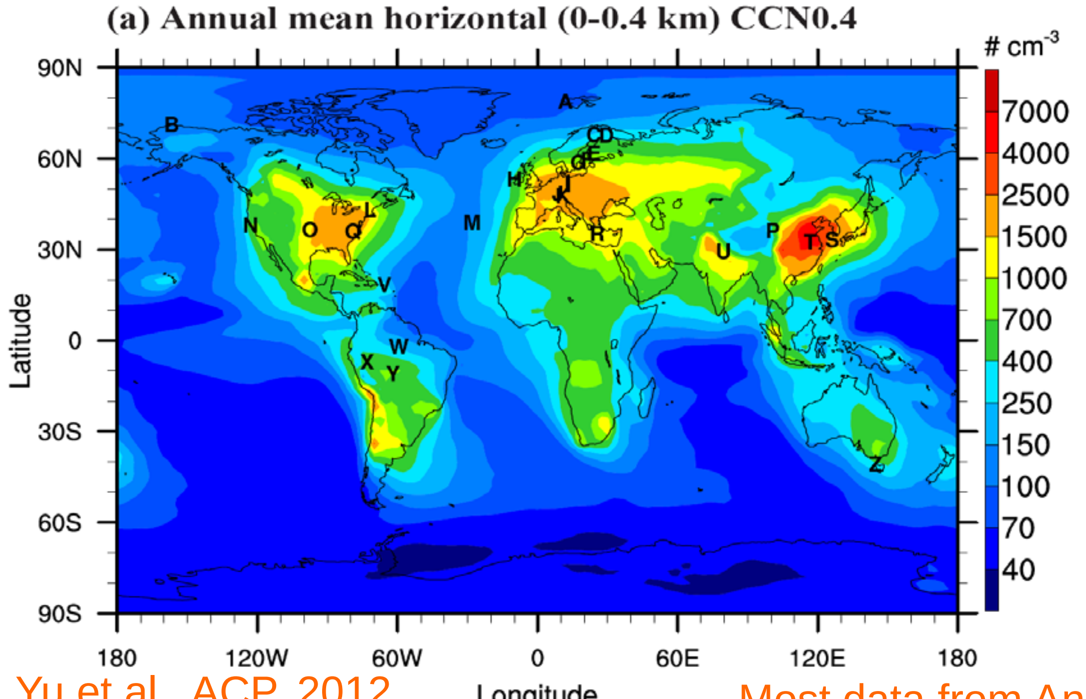
Yu and Luo, Atmosphere, 2010

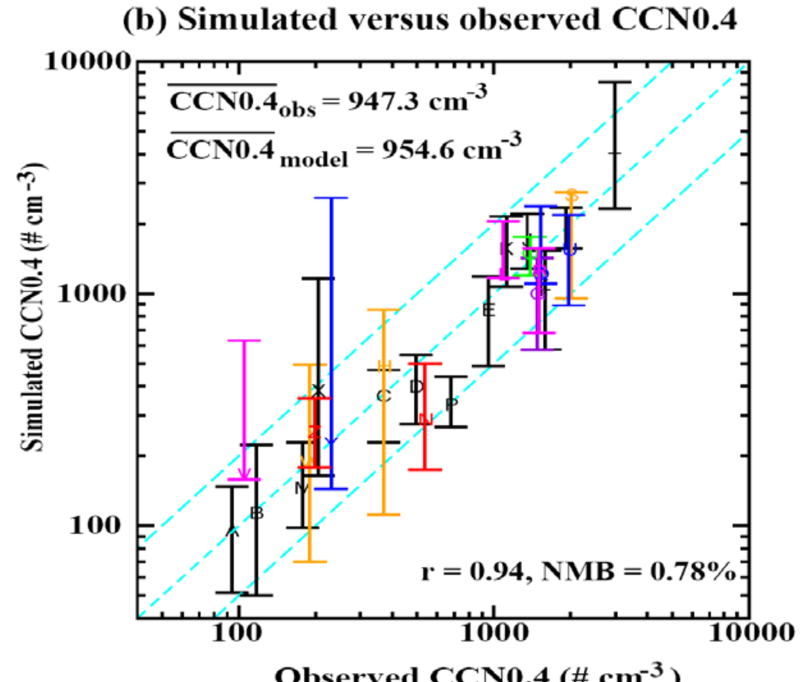
Modeling results are for surface layer





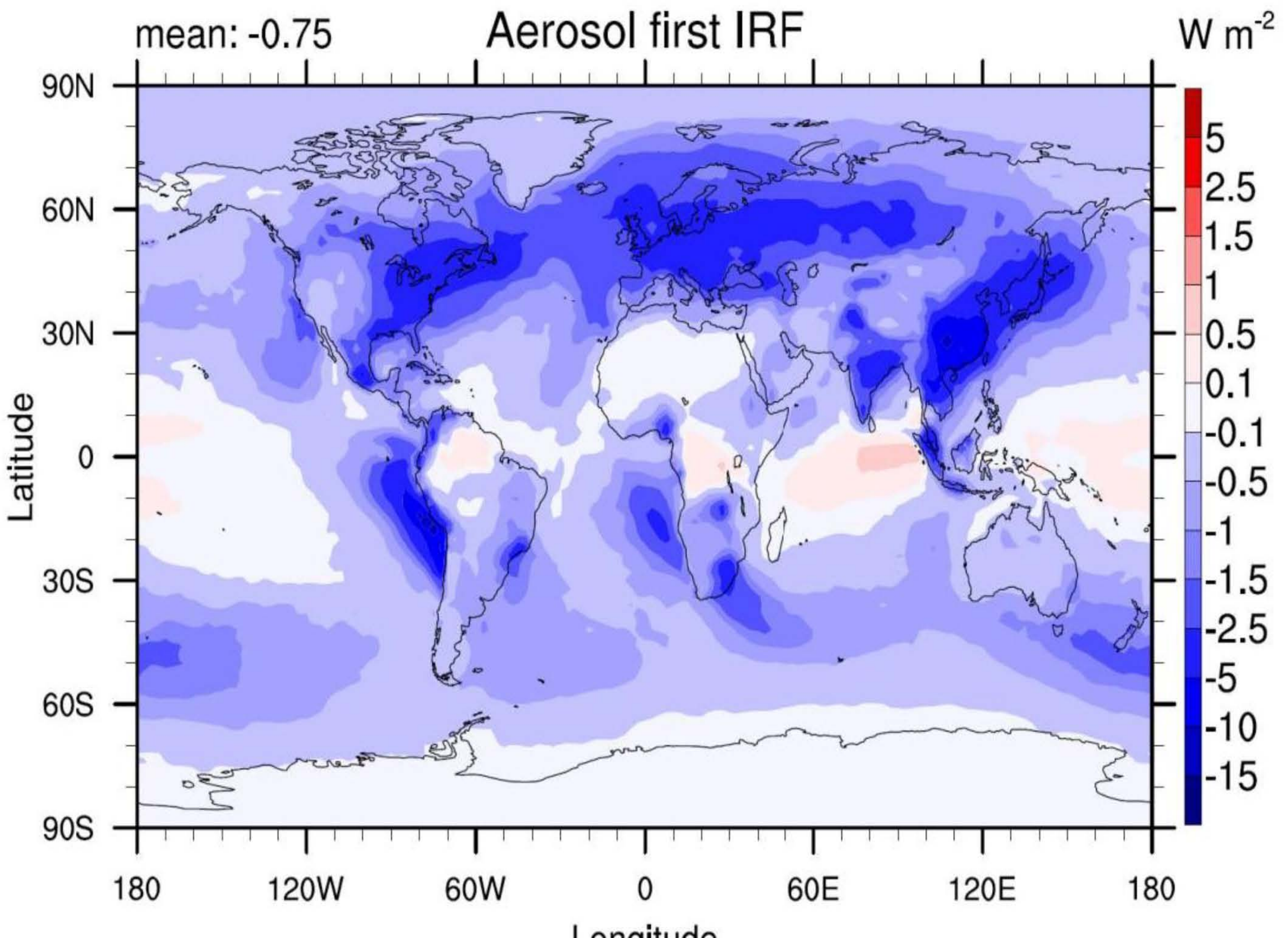
Yu and Luo, 2009; Luo and Yu, 2011.





Yu et al., ACP, 2012.

Most data from Andreae, ACP, 2009.



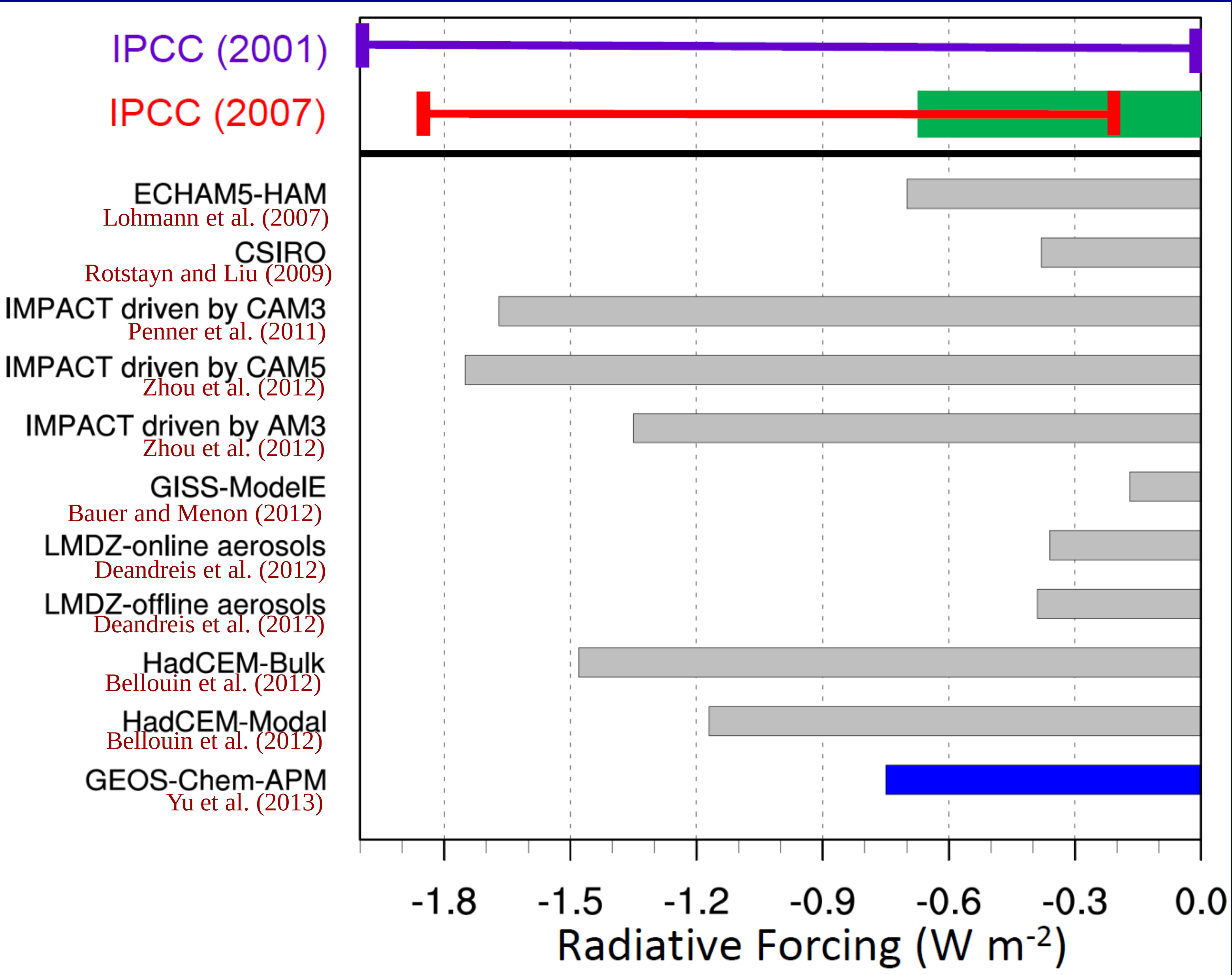
Yu et al., ERL, 2013

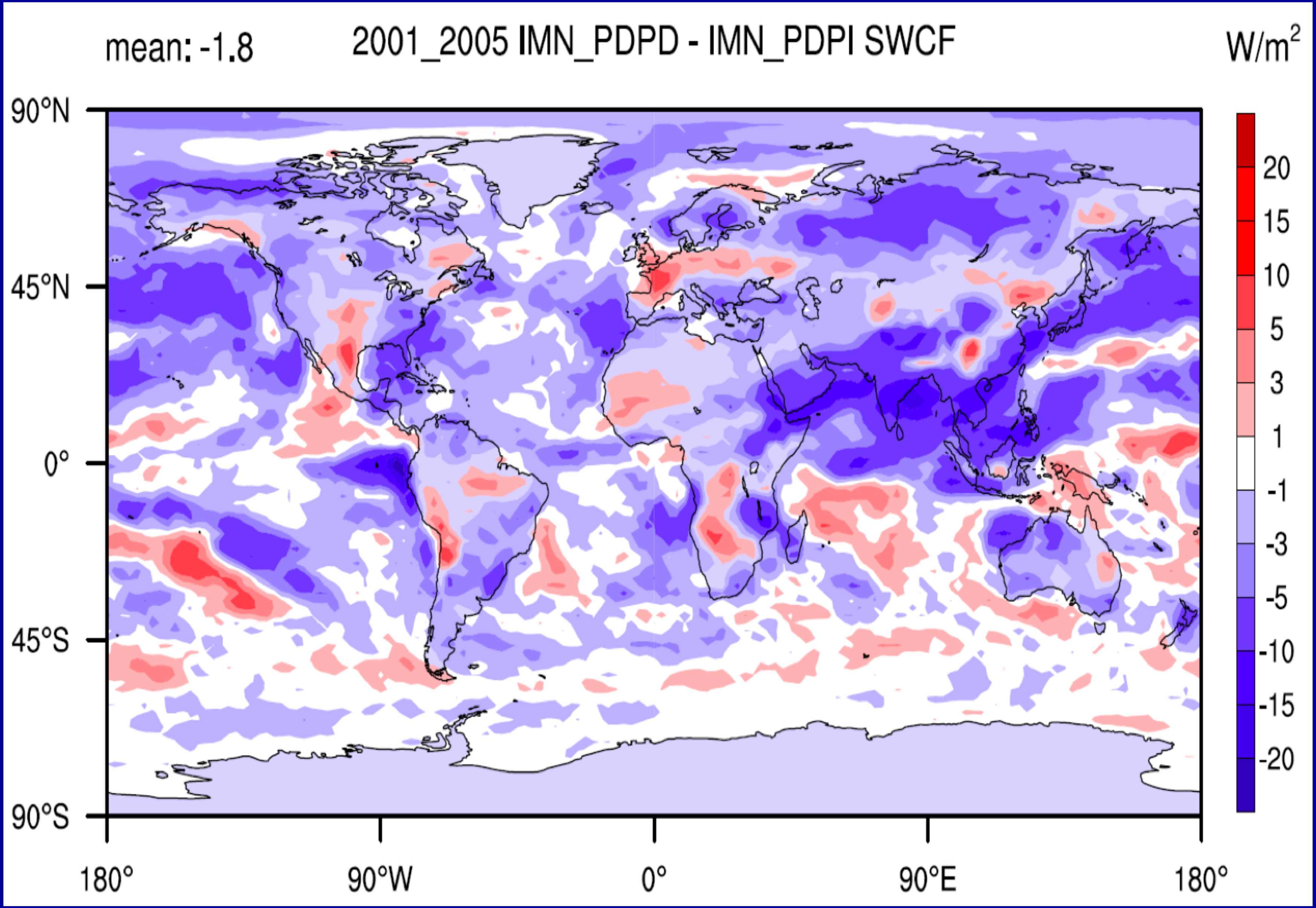
First aerosol indirect radiative forcing

Post-

IPCC2007

studies




mean: -1.8
2001_2005 IMN_PDPD - IMN_PDPI SWCF
W/m2
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°
20
15
10
5
3
1
-1
-3
-5
-10
-15
-20