Impact of new parameterizations on aerosol microphysics and cloud forcing in ECHAM5-HAM

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4. ETH, Zürich

Outline

1. Introduction
2. New features in ECHAM5-HAM
3. Change of aerosol properties
4. Effect of aerosols on clouds & feedback of clouds on aerosols
5. Summary

The ECHAM5-HAM Model (Original)

Meteorology: Roeckner et al., 2005

Spectral model with modified ECMWF physics:

- Advection: FFSL (Lin & Rood, 1996)
- Convection: Tiedke, 1989 & Nordeng (1994)
- Prognostic cloud cover (Tompkins, 2001)

Aerosol: Stier et al. 2005

M7 microphysics (Vignati et al. 2004) , modal approach

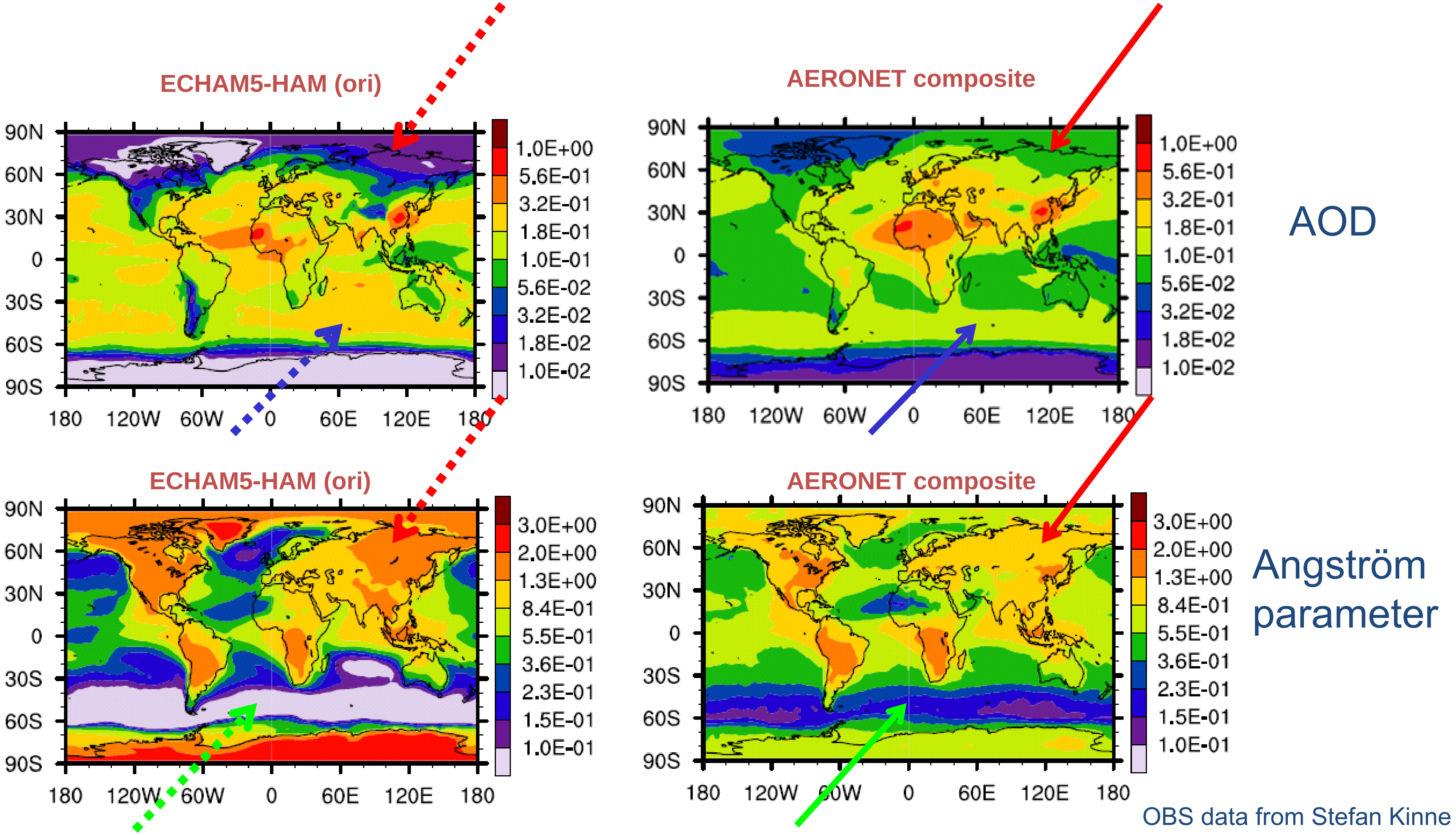
aerosol mass and number predicted, mode width prescribed

Sulfate, BC, POM, dust, sea salt
External or internal mixing

Cloud microphysics: Lohmann and Roeckner, 1996

Mass of cloud liquid and cloud ice predicted
Cloud droplet number conc. ***prescribed***

Problems in the previous model



OBS data from Stefan Kinne

New features

1. Nucleation scheme which considers the charged nucleation induced by cosmic ray (J. Kazil)

2. New below-cloud scavenging scheme (B. Croft)

3. κ-Köhler theory based water-uptake scheme (D. O'Donnell)

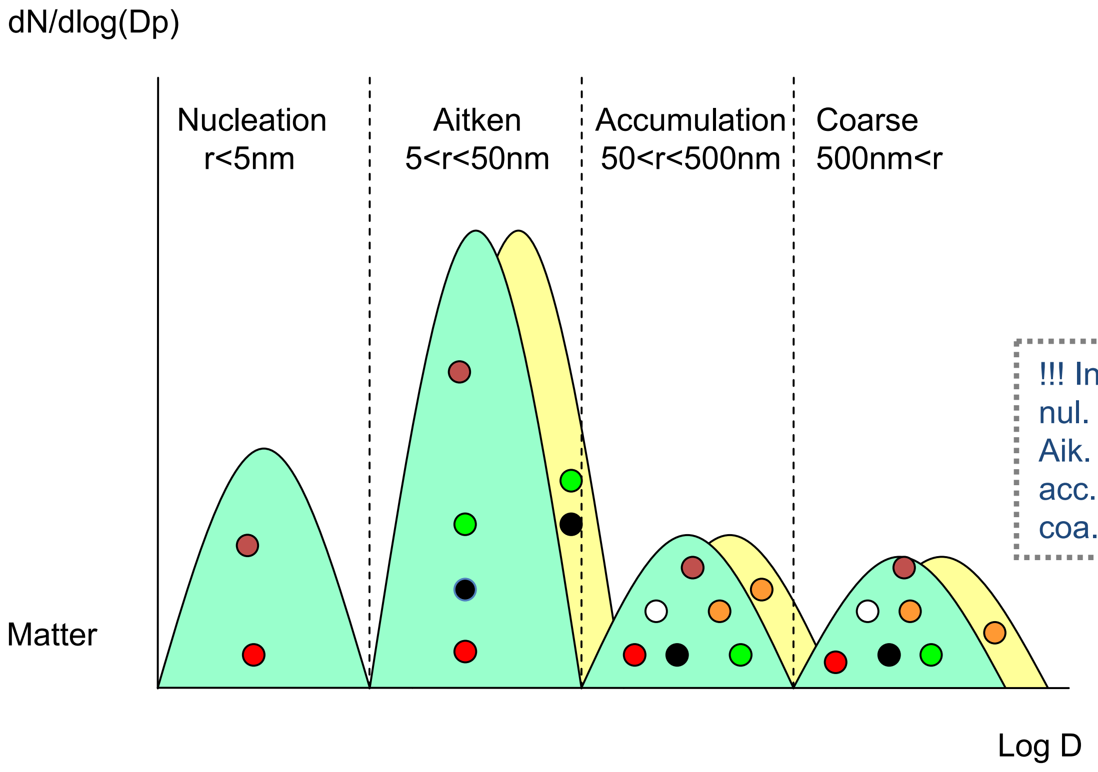
4. New explicit treatment of SOA (D. O'Donnell)

5. Two-moment cloud microphysics, CDNC predicted, allow modeling the interaction between aerosol and cloud in a more consistent way (U. Lohmann, S. Ferrachat)

Question:

How will these changes affect aerosol size, number?
How does the changed aerosol microphysics interact with cloud?
Can these changes give better prediction of AOD and size of aeosols?

7 lognormal modes – M7 module



🟩 Soluble

🟨 Insoluble

!!! In the following slides:
nul. ~ nucleation mode
Aik. ~ Aitken mode
acc. ~ accumulation mode
coa. ~ coarse mode

- 🔴 Sulphate
- ⚫ Black Carbon
- 🟢 Particulate Organic Matter
- ⚪ Sea Salt
- 🟠 Dust
- 🟤 SOA

Predicted variables per mode:

One number concentration

mass mixing ratios of each chemical compound

Courtecy of Declan O'Donnell

Simulations

- T63L31 resolution (~1.9ºx1.9º)
- Nudged with year-2000 ERA40 re-analysis data
- Two types of experiments:
  - Group A: standard cloud scheme, CDNC prescribed
  - Group B: two-moment cloud scheme, CDNC predicted

Group A (aerosol microphysics, optical properties)
Group B (cloud forcing)

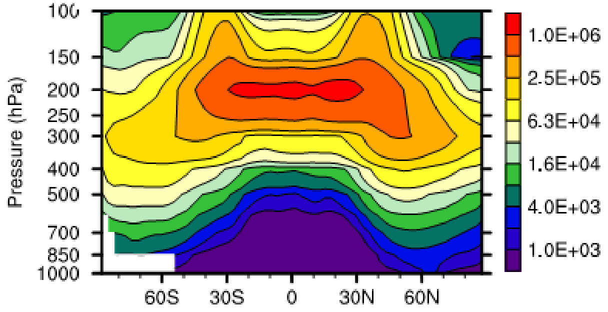
Stier et al. (2005) → nucleation → below-cloud scavenging →
K- Köhler water-uptake → SOA → two-moment cloud scheme | new model

new model → old nucleation
new model → old water-uptake scheme

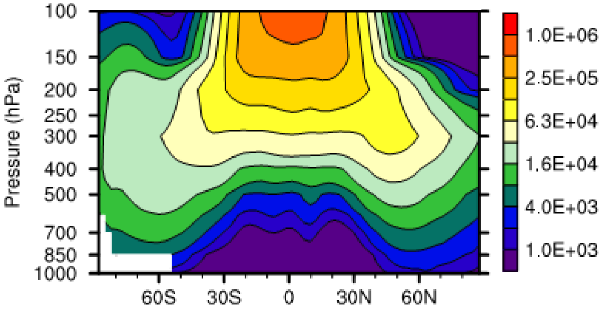
Effect of new nucleation scheme

number concentration of soluble nucl. mode particles (r<5nm, N cm^{-3} STP)

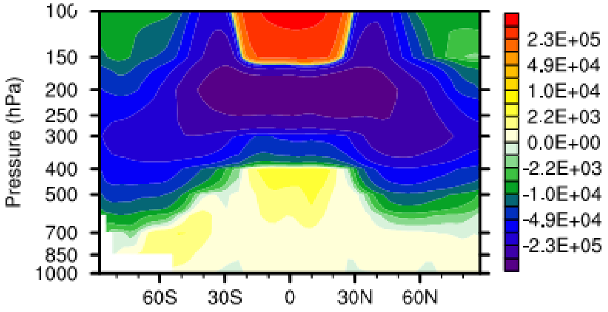
***V**ehkamaeki et al.*



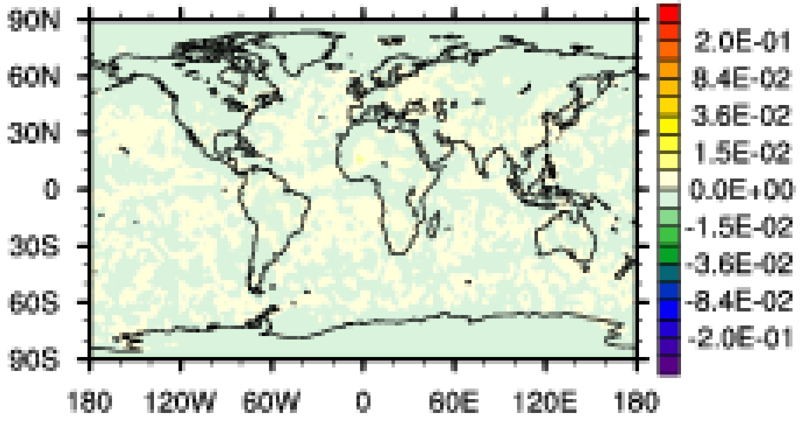
***K**azil et al.*



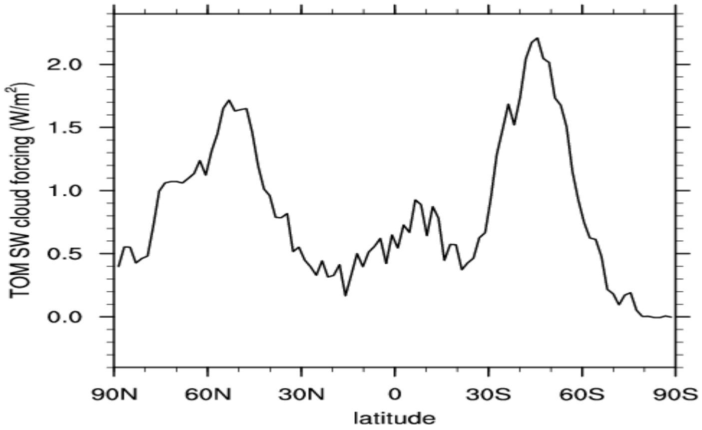
Difference (K - V)



Difference in the simulated AOD (K-V)



Difference in the simulated SWCF (V-K)



SWCF: Net shortwave flux at TOA: total sky – clear sky

Kappa-Köhler theory based water-uptake scheme

Original: ZSR based scheme

- take aerosol as a solution of mixed electrolytes
- extremely sensitive to higher RH

Jacobson et al. JGR-1996

New: Kappa-Köhler theory based scheme

- can easily be applied for non-electrolytes (e.g. organic specie)
- a hygroscopicity parameter κ for each chemical component

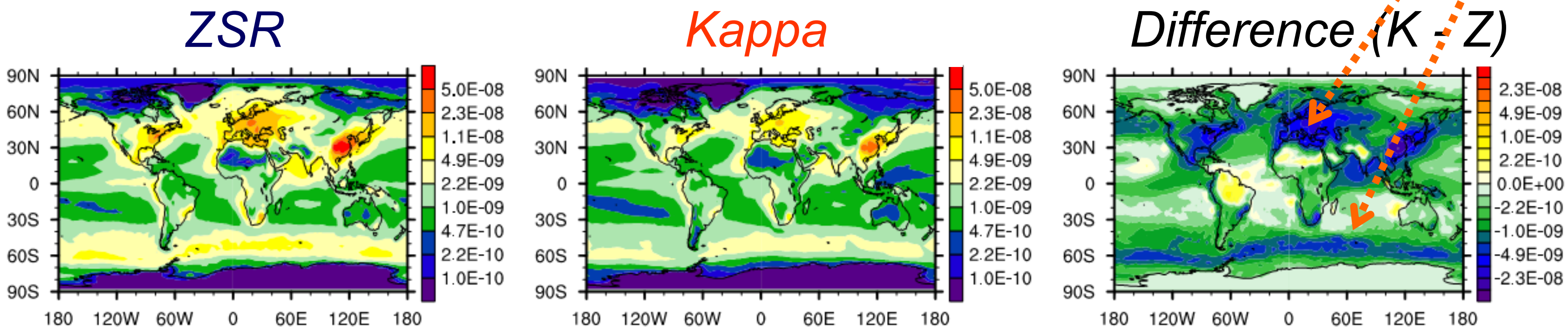
Petters and Kreidenweis ACP-2007

Growth factor of an aerosol particle can be expressed as a function of temperature, relative humidity, aerosol dry diameter and kappa

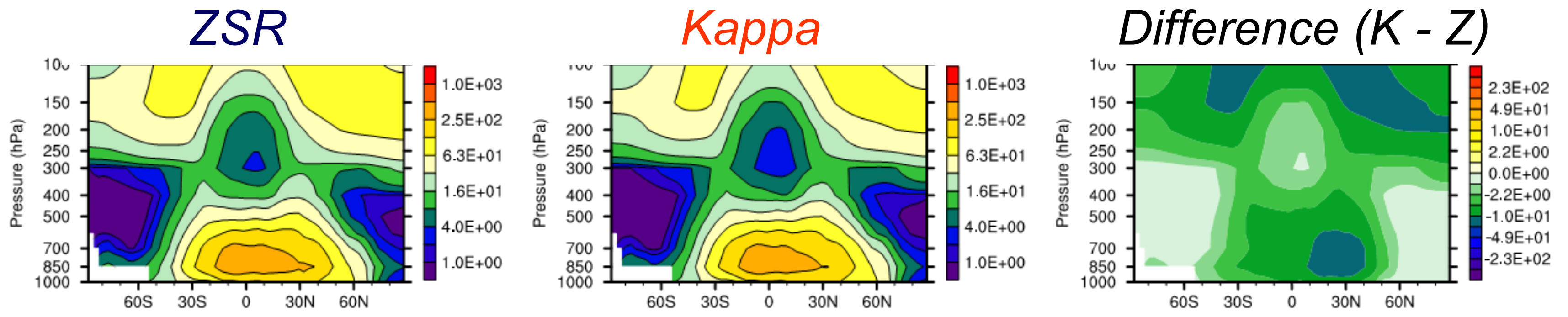
Implemented by D. O'Donnell

Effect of new water-uptake scheme

Surf. aerosol water in the soluble acc. mode particles (50<r<500nm, kg kg^{-1})
→ Less acc. aerosol water


ZSR
Kappa
Difference (K - Z)

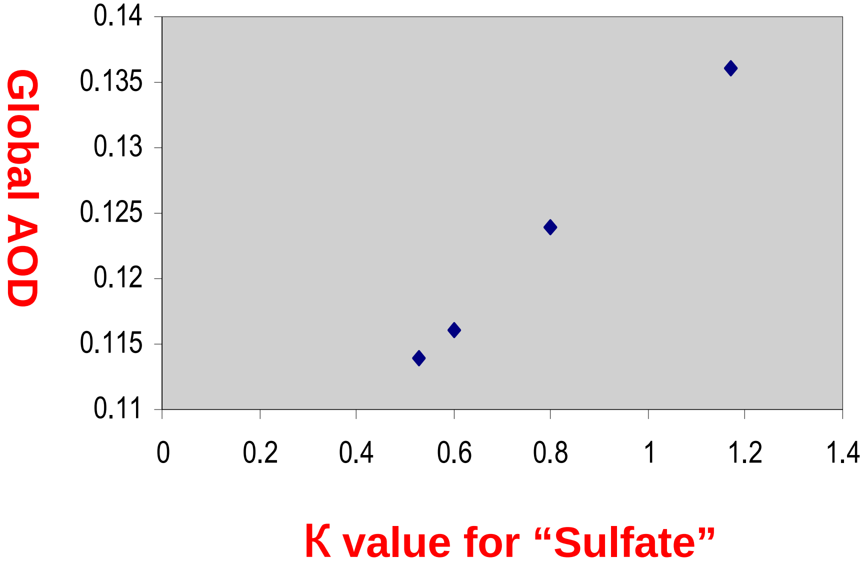
Zonal mean number concentration of soluble acc. mode particles (50<r<500nm, N cm^{-3} STP) → Less acc. particles, more smaller particles (nul. Ait.)


ZSR
Kappa
Difference (K - Z)

kappa=0.53 for sulfate

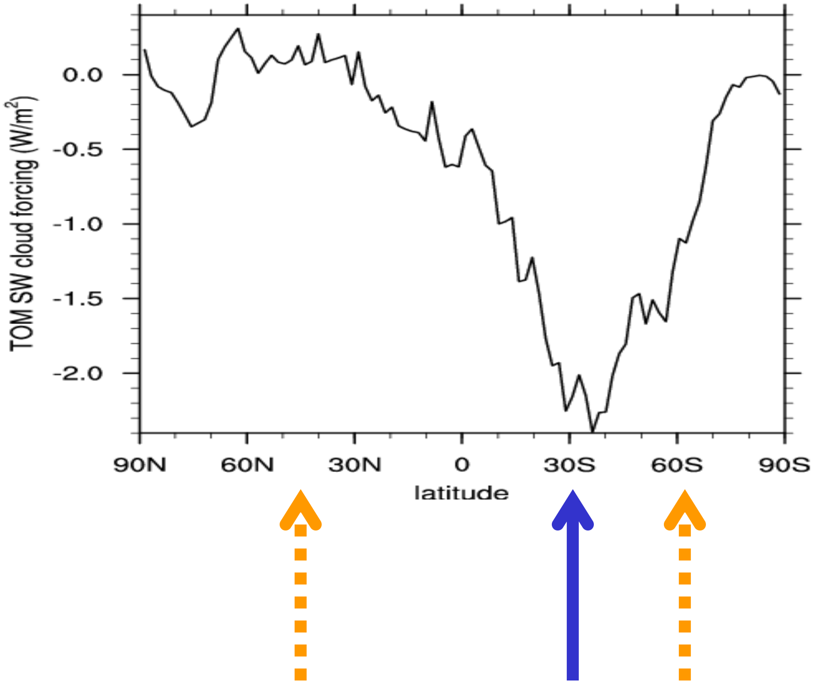
Effect of new water-uptake scheme (II)

Sensitivity of global AOD to κ



$\kappa_{\text{ammonium bisulphate}} \rightarrow \kappa_{\text{sulfuric acid}}$

Difference in SWCF (Z – K)



Cloud microphysics

Two-moment cloud microphysics:

Lohmann et al. (2007), Lohmann (2008)

Activation: Lin & Leaitch, 1997

$$Q_{\text{nucl}} = \max\left[\frac{1}{\Delta t}\left(0.1\left(\frac{\underline{N_a} w}{w + \alpha \underline{N_a}}\right)^{1.27} - N_{l,\text{old}}\right), 0\right]$$

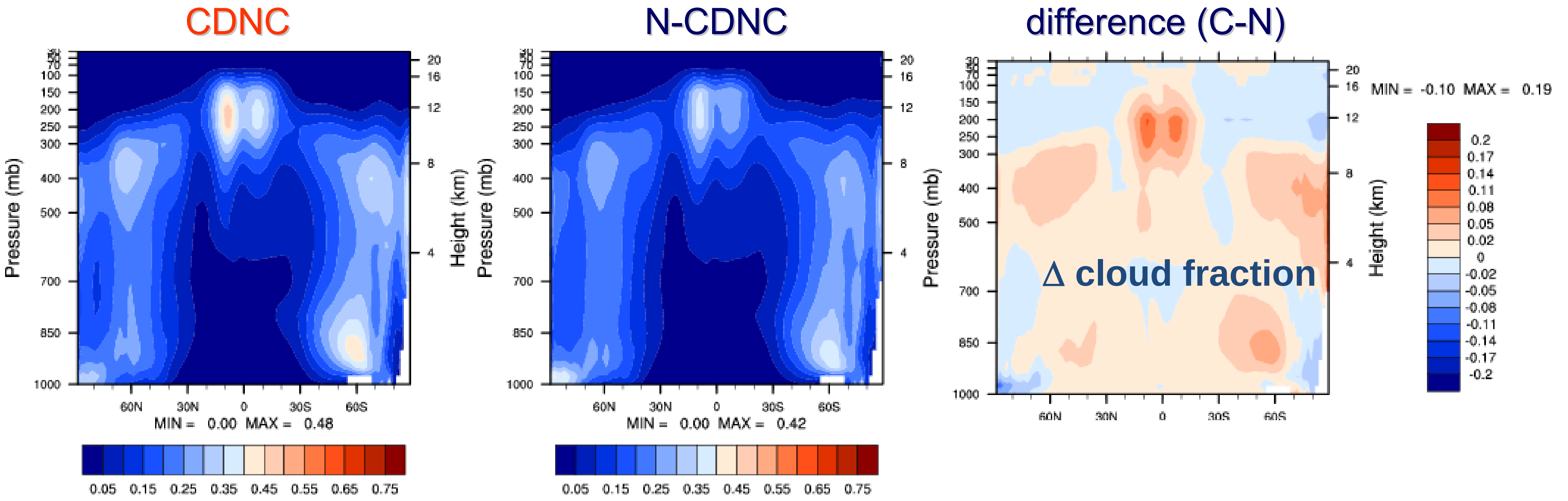
Auto-conversion: Khairoutdinov & Kogan, 2000

$$Q_{\text{aut}} = 1350 \times q_l^{2.47} \underline{N_l}^{-1.79}$$

Processes that not considered in current simulations:

1. Cloud processing of aerosols
currently smaller particles in cloud droplets can be "re-evaporated" again
2. Microphysics of convective cloud
… …

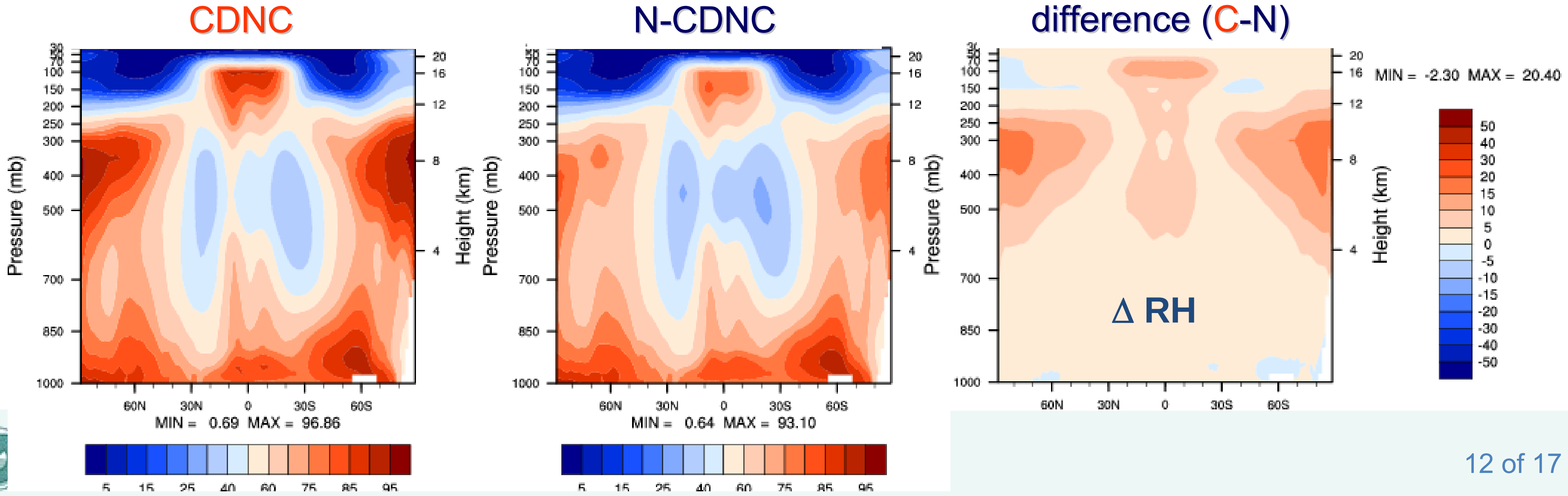
Effect of prognostic CDNC calculation on cloud and water vapor


CDNC

N-CDNC

difference (C-N)

Δ cloud fraction


CDNC

N-CDNC

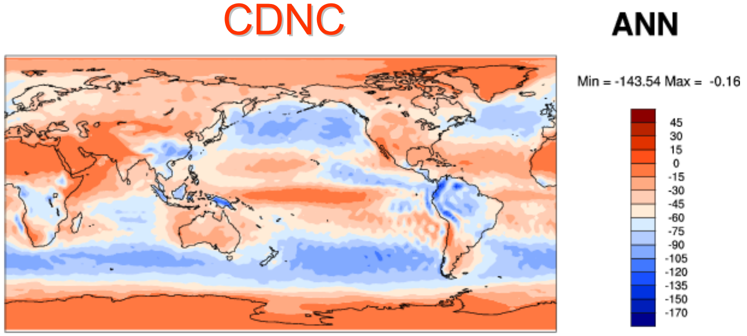
difference (C-N)

Δ RH

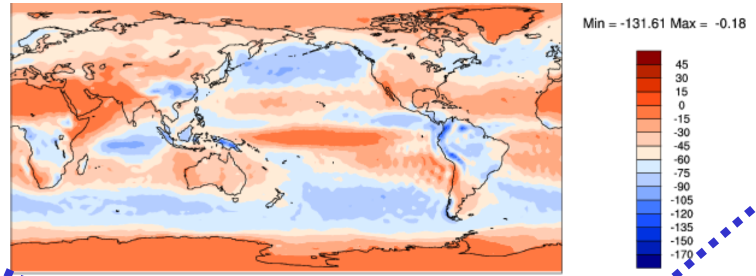
Shortwave cloud forcing

Net shortwave flux at TOA: total sky – clear sky

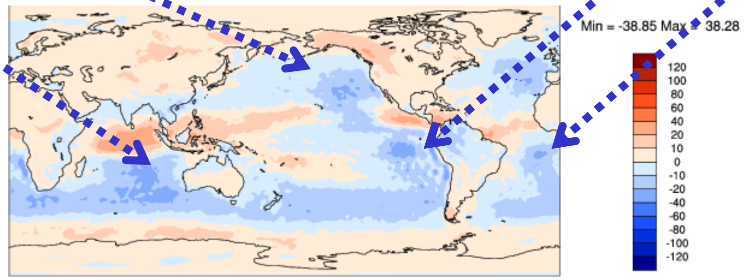
CDNC

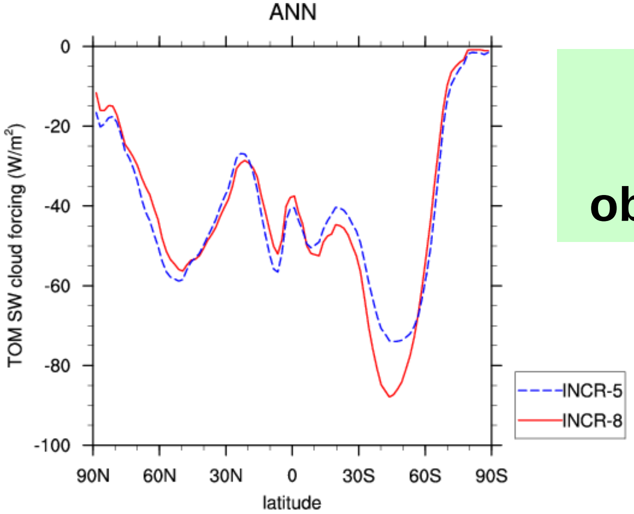


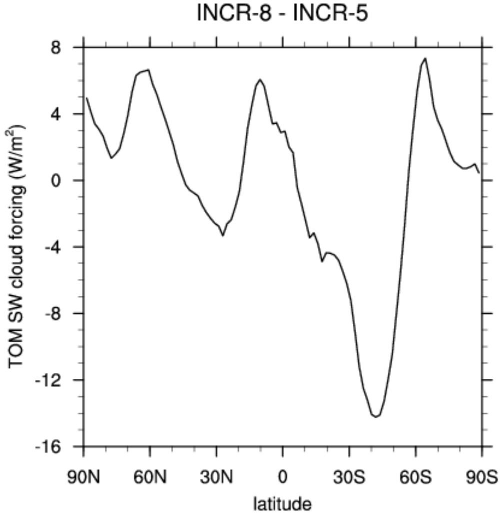
N-CDNC



Difference (C-N)







-47.9
-46.6
obs: ~ 50

Longwave cloud forcing

Net longwave flux at TOA: total sky – clear sky

CDNC

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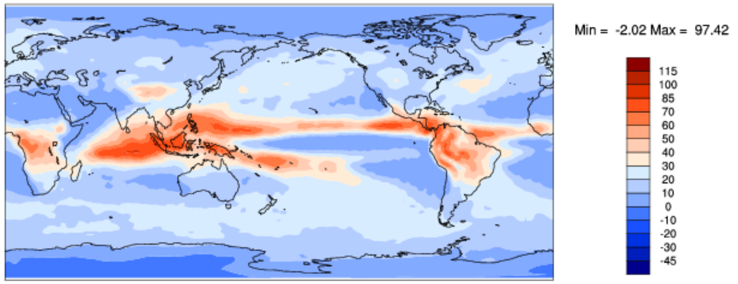
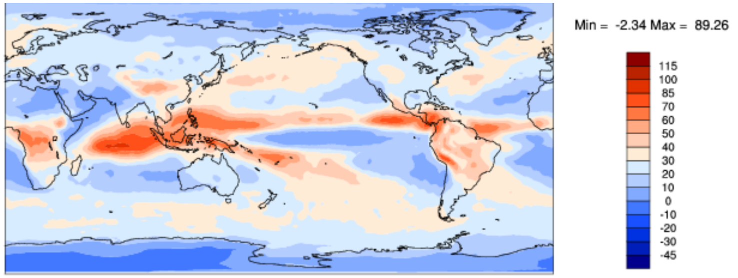
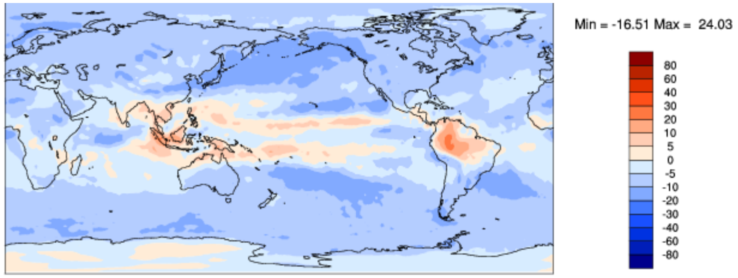
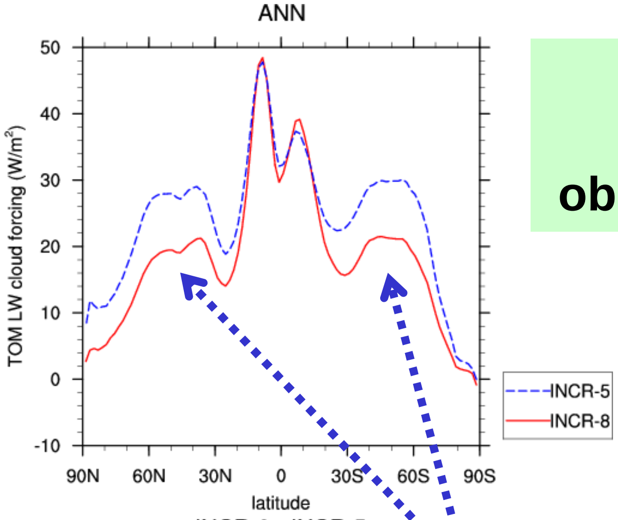


N-CDNC



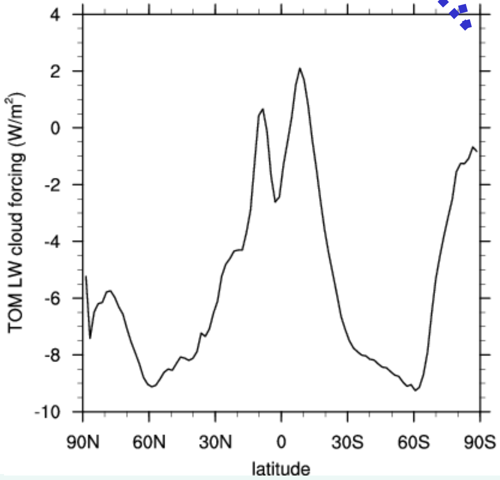
Difference (C-N)





22.8
27.9
obs: 22~30

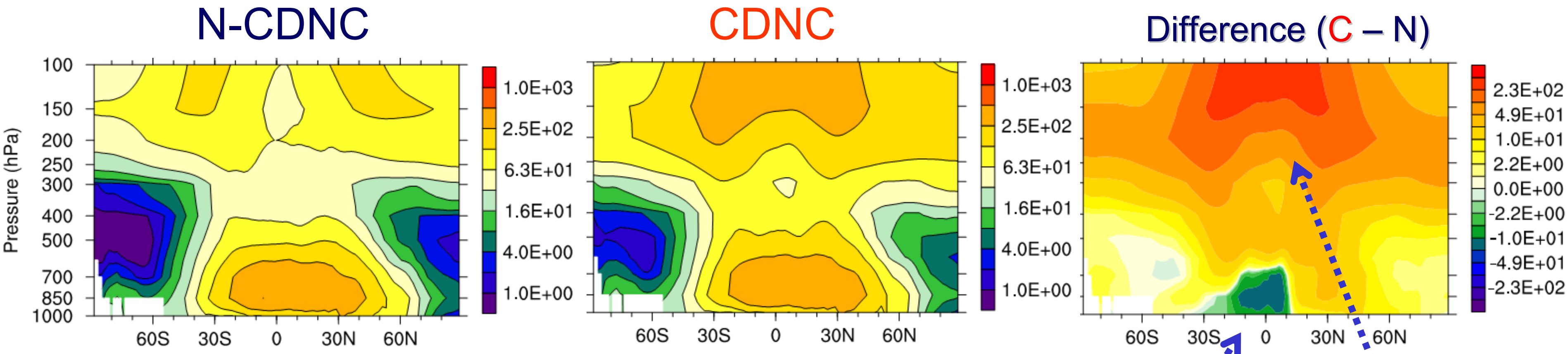
INCR-8 - INCR-5



Due to smaller cloud ice content in the upper troposphere

Feedbacks of clouds on aerosols in prognostic CDNC calculation

Number conc. of soluble acc. mode particles (50<r_p<500nm, N cm-3 STP)
More aerosol particles in the upper troposphere
Less aerosol particles over tropical forest below 700 hPa

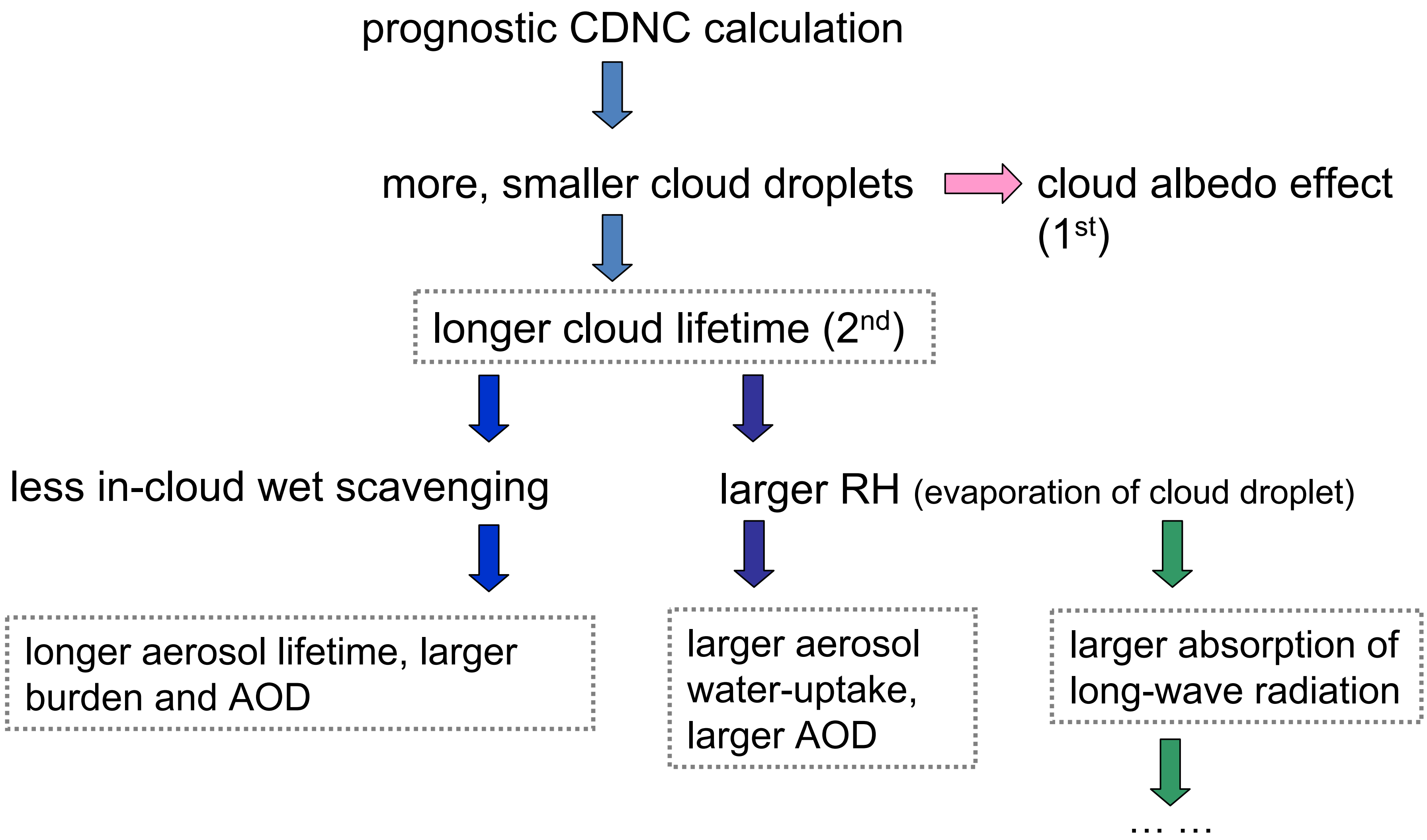


Sulfate burden (Tg)	0.98	1.20
Sulfate lifetime (day)	3.7	4.5
Total AOD	0.11	0.13

Larger rainfall over tropical forest

Less in-cloud scavenging and more vertical transport

Why longer aerosol lifetime & larger AOD?



prognostic CDNC calculation

more, smaller cloud droplets

cloud albedo effect (1st)

longer cloud lifetime (2nd)

less in-cloud wet scavenging

larger RH (evaporation of cloud droplet)

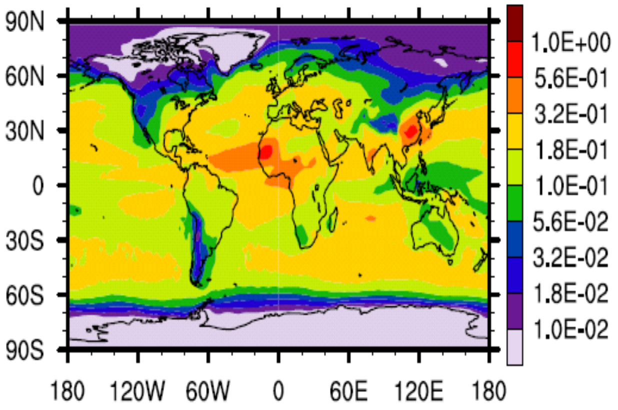
longer aerosol lifetime, larger burden and AOD

larger aerosol water-uptake, larger AOD

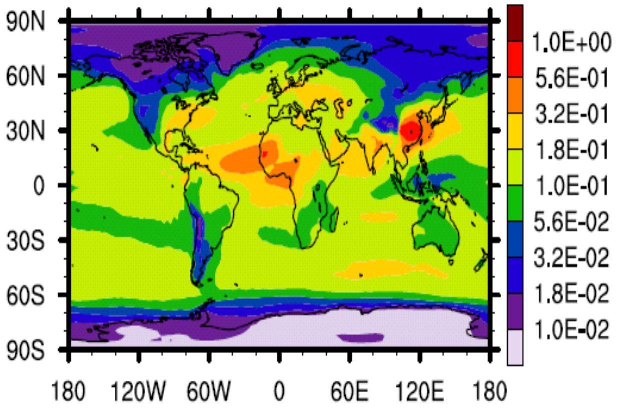
larger absorption of long-wave radiation

… …

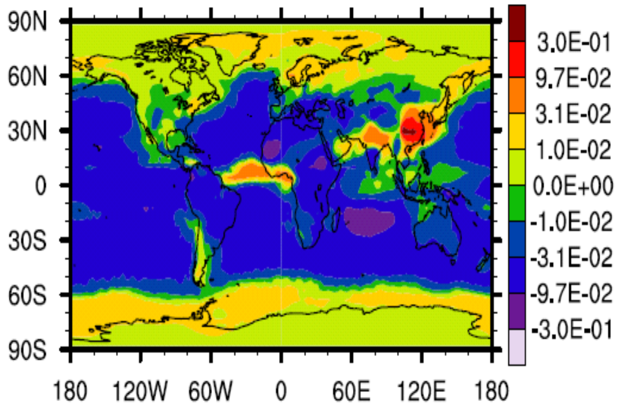
Aerosol optical depth (AOD)



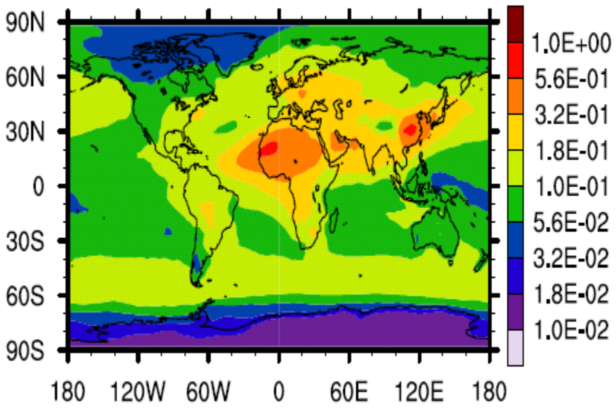
A: ECHAM5-HAM-rev42



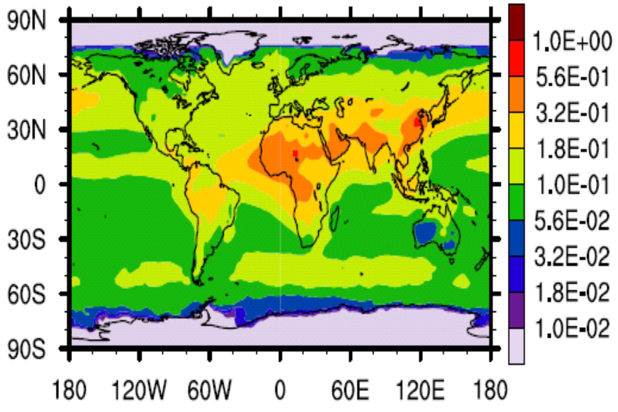
B: ECHAM5-HAM-CDNC



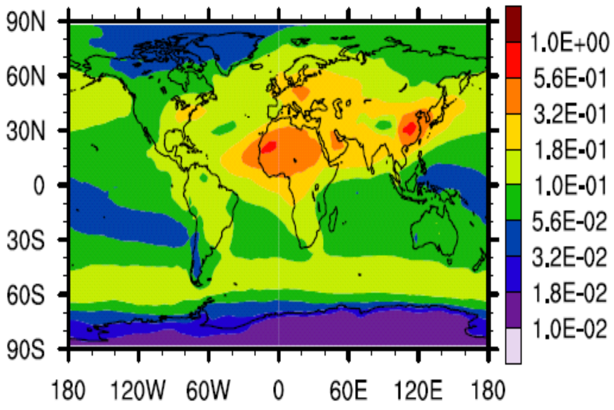
B - A



C: AERONET-2000 composite



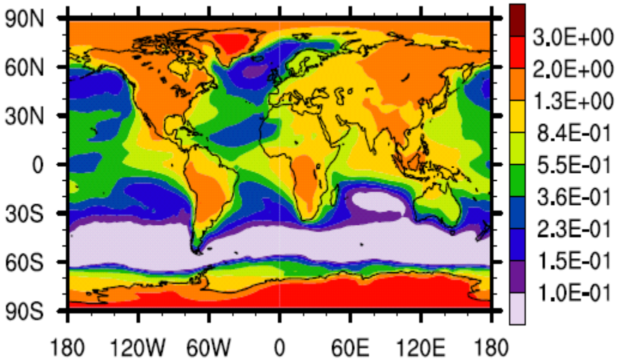
D: satellite composite



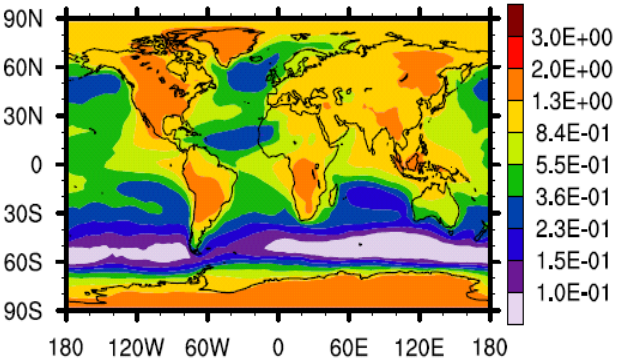
E: AEROCOM median

Angstroem parameter

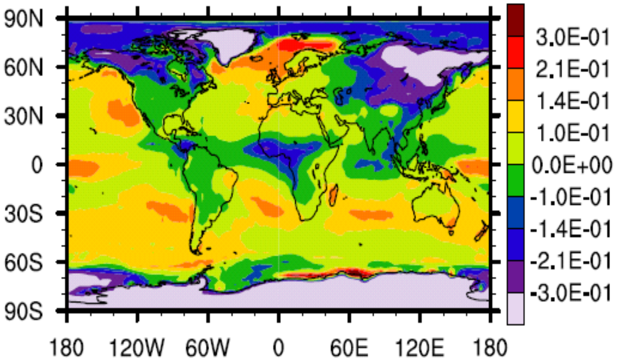
A: ECHAM5-HAM-rev42



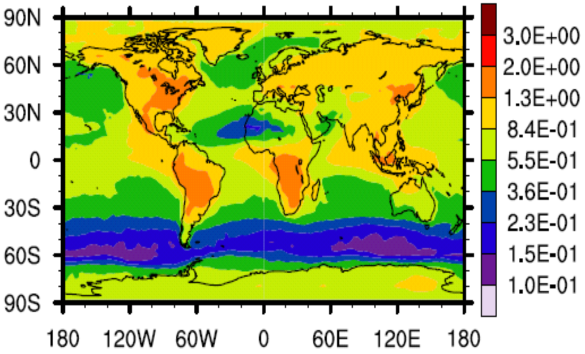
B: ECHAM5-HAM-CDNC



B - A



C: AERONET composite



Summary

1. Modification in the parameterizations in the model leads to significant changes of aerosol properties. In terms of AOD and aerosol size distribution, new model version performs better.

2. Aerosol-cloud-climate interaction has been considered in a more consistent way. The CDNC version predicts more cloud and higher RH in the free troposphere than standard ECHAM5.

3. New nucleation scheme enhances SW cloud forcing, while the new water-uptake scheme

4. Due to the slower auto-conversion process, prognostic CDNC calculation increases the lifetime of aerosol. For example, sulfate lifetime increases by about 1 day.

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Thanks !

ECHAM5-HAM AEROCOM-A2 simulation

Experiment	expected ready-time
A2-CTRL	31.10.2009
A2-SIZ1	30.11.2009
A2-SIZ2	30.11.2009
A2-SIZ3	30.11.2009
A2-SIZ4	30.11.2009

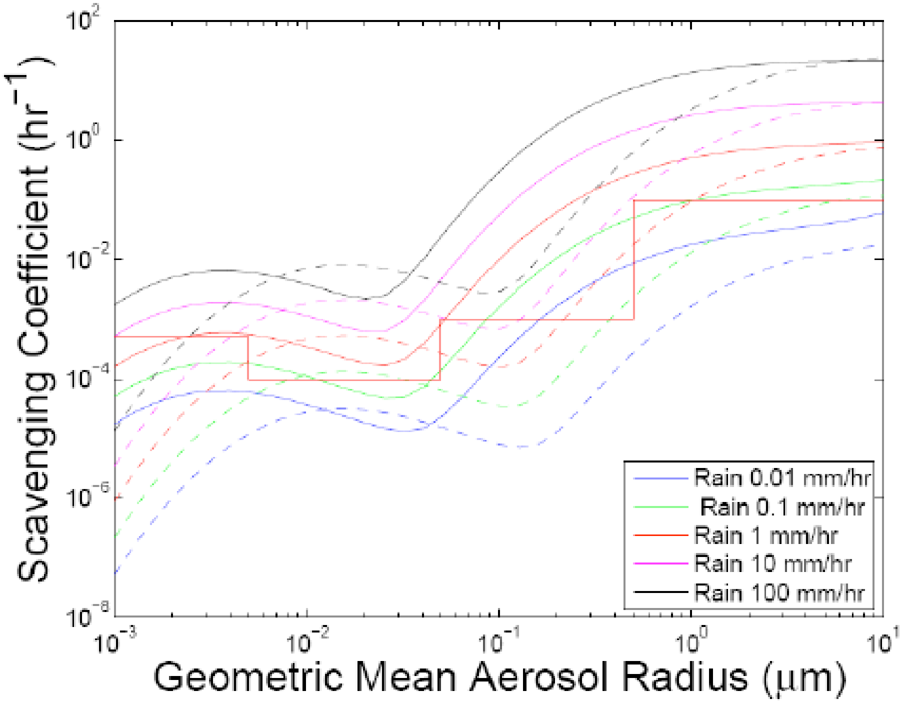
Hindcast simulations (and others?) will be taken over by Univ. Oxford (Stier)

END

New below-cloud scavenging scheme

Collection of aerosol particles by rain drops

look-up table: 60 aerosol radii and 10 rainfall rates



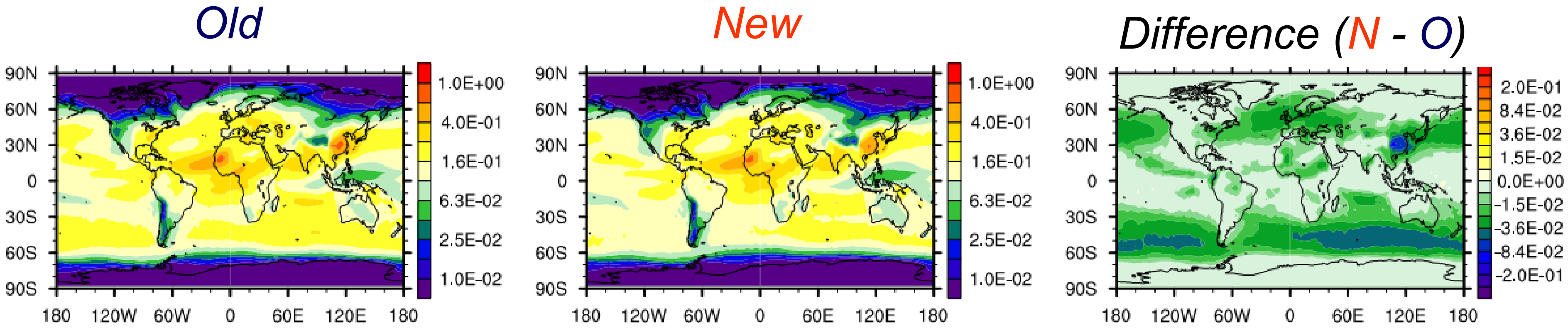
solid line - mass

dashed line - number

Croft et al. (2009)

Effect of new wet scavenging scheme

10% smaller global average AOD



Old

New

Difference (N - O)

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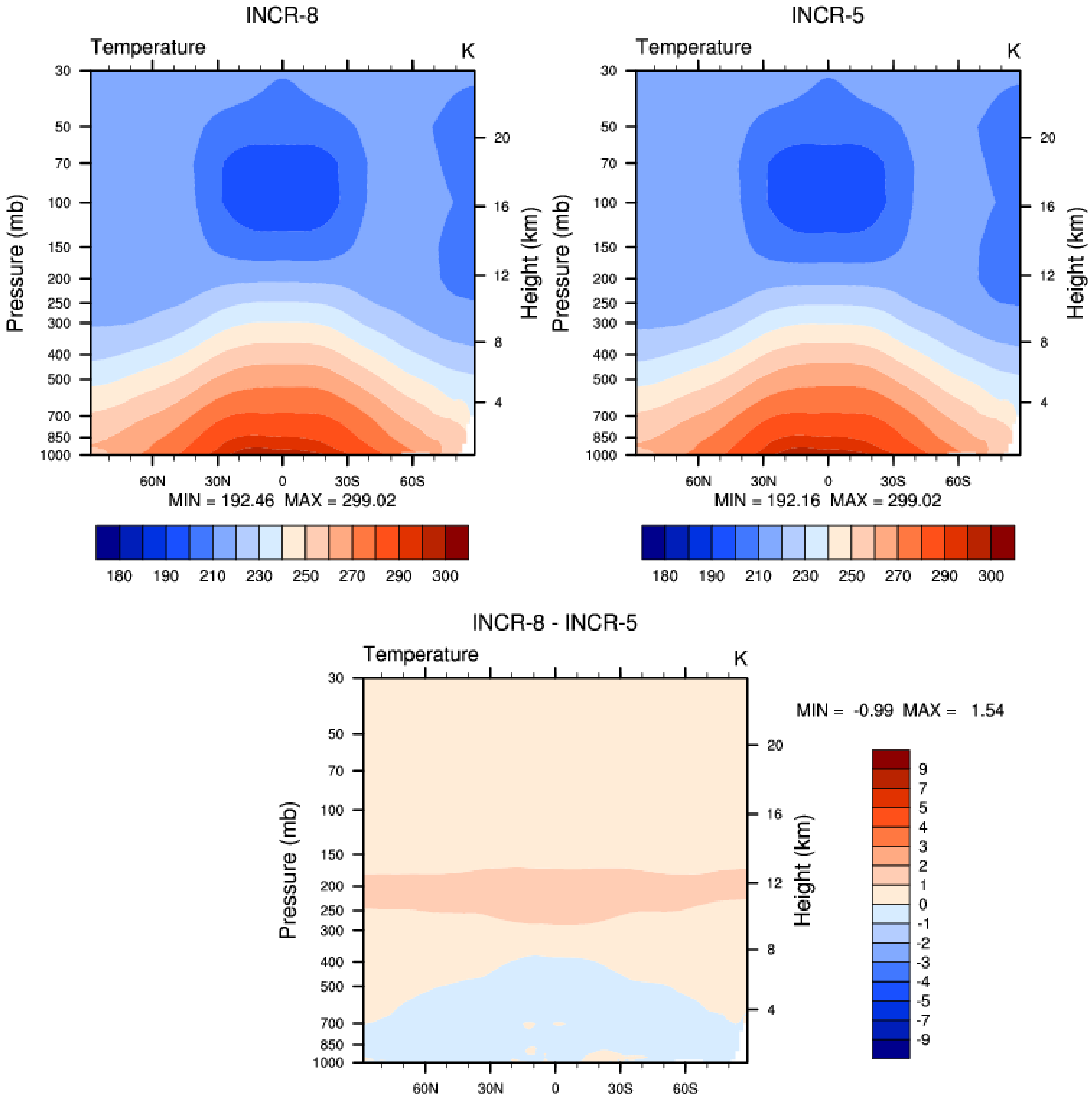
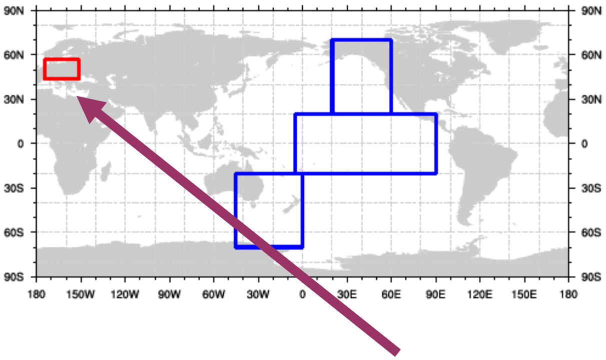
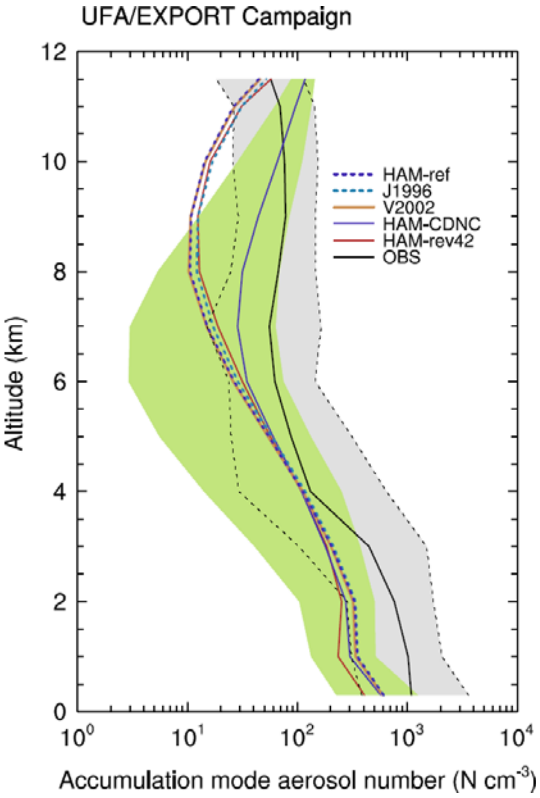

INCR-8
Temperature
K
Pressure (mb)
Height (km)
30
50
70
100
150
200
250
300
400
500
700
850
1000
20
16
12
8
4
60N
30N
0
30S
60S
MIN = 192.46 MAX = 299.02
180
190
210
230
250
270
290
300
INCR-5
Temperature
K
Pressure (mb)
Height (km)
MIN = 192.16 MAX = 299.02
INCR-8 - INCR-5
Temperature
K
Pressure (mb)
Height (km)
MIN = -0.99 MAX = 1.54
9
7
5
4
3
2
1
0
-1
-2
-3
-4
-5
-7
-9

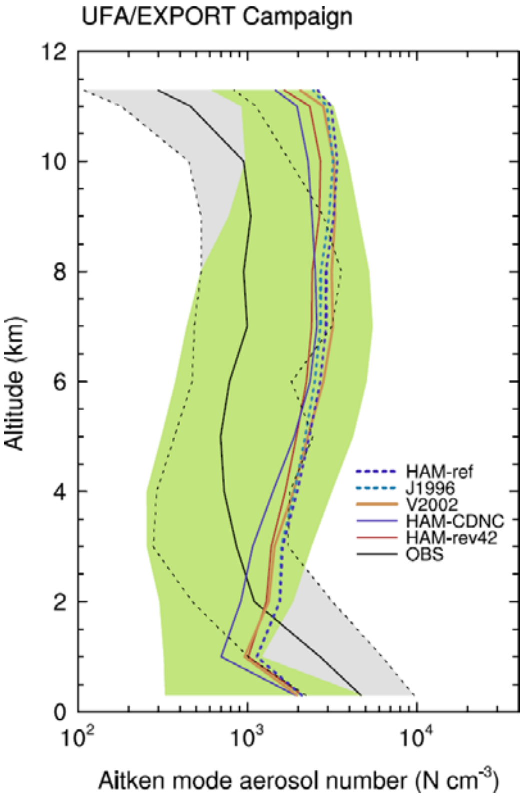
Vertical profile of fine mode particles



Comparison between the simulated and observed Aitken and accumulation mode number concentrations over Europe.



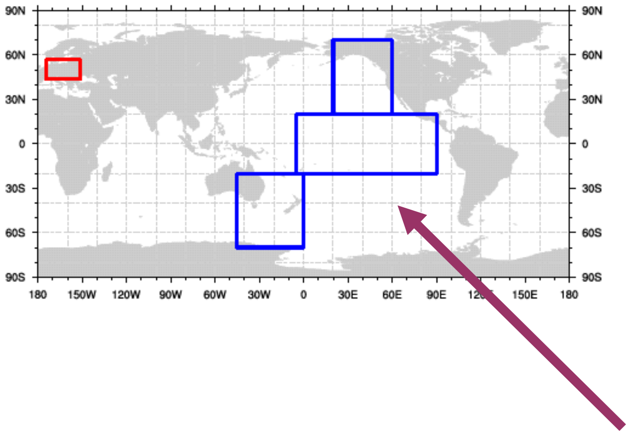
accumulation mode (0.1–3 μm)



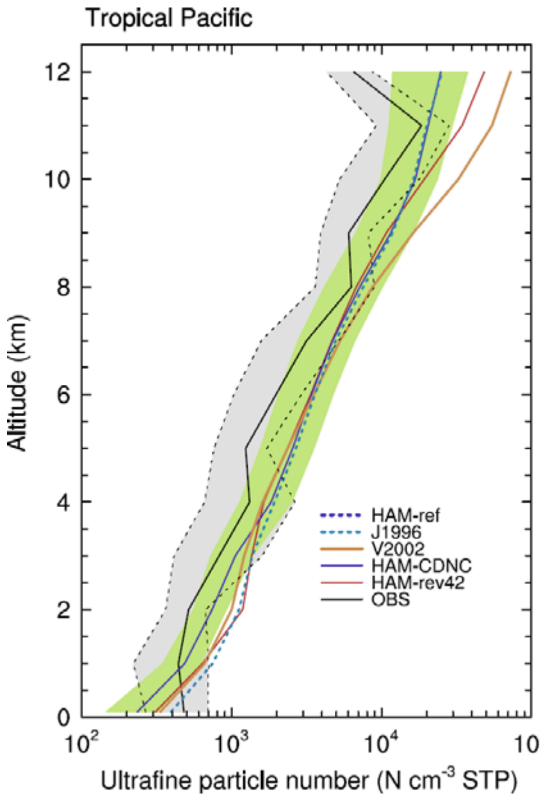
Aitken mode (0.014–0.1 μm)

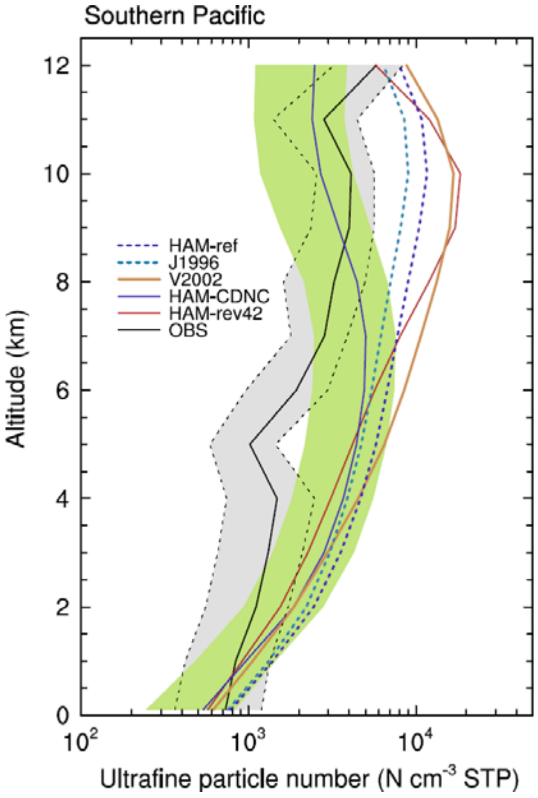
The simulated profiles are July and August averages. Observations were compiled by Minikin et al. (2003) using the measurements obtained in July and August 2000 during the UFA/EXPORT campaign. The boundaries of the shaded areas indicate the 10- and 90-percentiles of the observational data

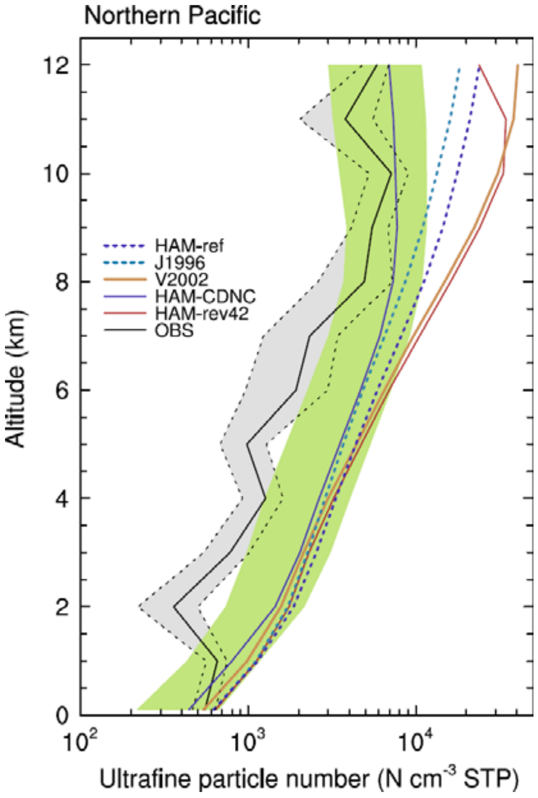
Vertical profile of ultra-fine particles (Dp>3nm)



Data from Clarke and Kapustin (2002)

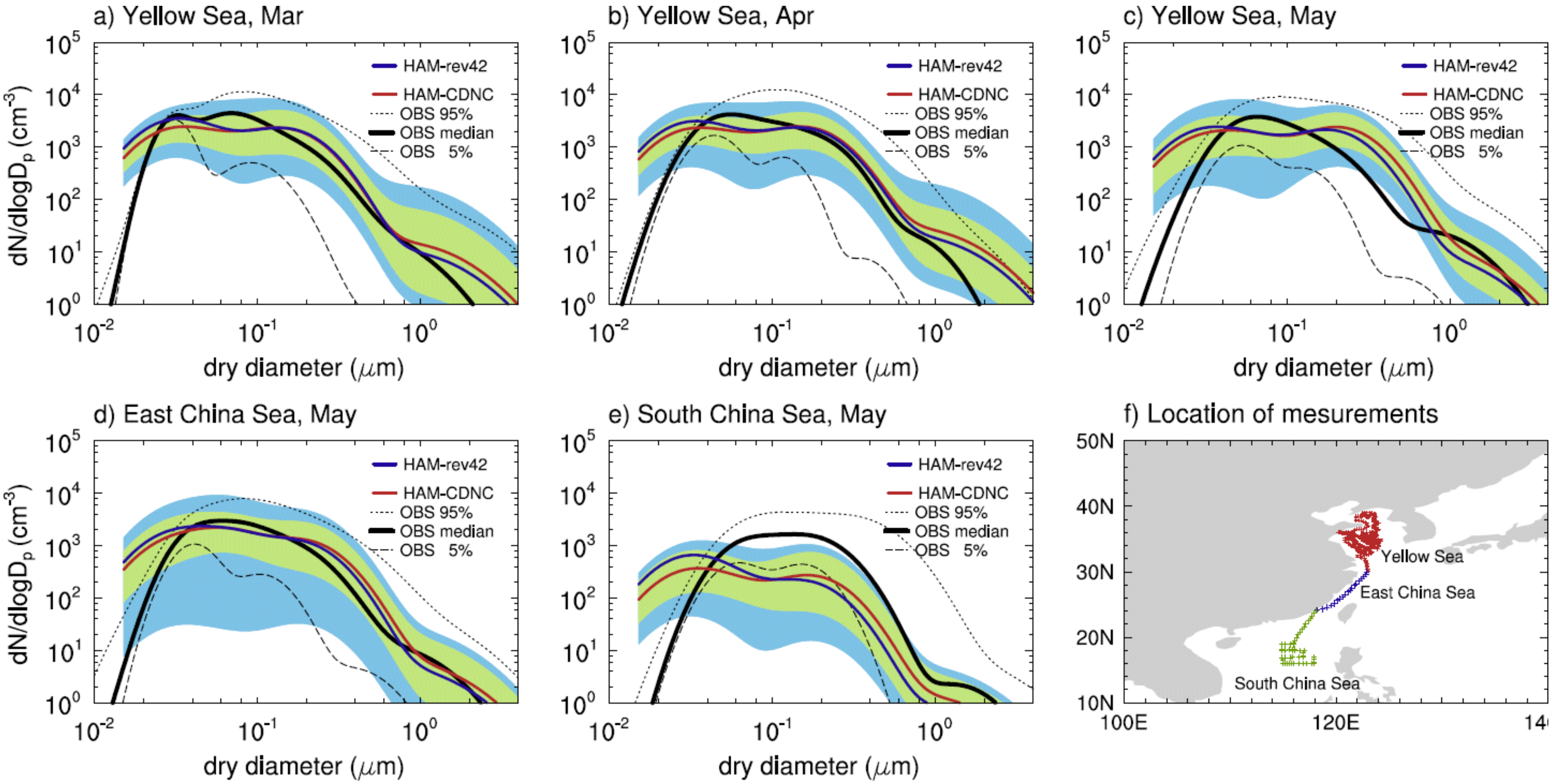






Aerosol size distribution

in the offshore regions of polluted area



Kappa-Köhler theory based water-uptake scheme

$$\frac{gf^3-1}{gf^3-\left(1-\kappa\right)}=RH\exp\left[-\left(\frac{4\sigma_{s/a}M_w}{RT\rho_w}\right)/D_d\,gf\right]$$

This is solved offline for *gf* using T, RH, κ and D_d of atmospheric relevance and the results stored in a lookup table. In runtime, we first calculate the dry diameter D_d and the κ value for each soluble mode, then simply look up the growth factor to get the wet diameter

Activation of particles

Cloud droplet nucleation Lin & Leaitch, 1997

$$Q_{\mathrm{nucl}} = \max\left[\frac{1}{\Delta t}\left(0.1\left(\frac{N_a w}{w + \alpha N_a}\right)^{1.27} - N_{l,\mathrm{old}}\right), 0\right]$$

Updraft velocity Lohmann et al. 2007

$$w = \begin{cases} \overline{w} + 1.33\sqrt{\mathrm{TKE}} & \text{stratiform clouds} \\ \overline{w} + \sqrt{\mathrm{CAPE}} + 1.33\sqrt{\mathrm{TKE}} & \text{convective clouds} \end{cases}$$

Activation of particles (2)

N_a = number concentration of aerosol particles with wet radii > 0.035 µm

$N_{l,old}$ = the cloud droplet number concentration from the previous time step

$\alpha = 0.023\ \mathrm{cm}^4\ \mathrm{s}^{-1}$ from observation

Aerosol size dominates aerosol activation in the first instance (Dusek et al. 2006)

Cloud Microphysics – Two-Moment Scheme

Predicts both the mass mixing ratios and number concentrations of cloud droplets and ice crystals

Heterogeneous freezing in large-scale mixed-phase clouds:

immersion freezing and contact freezing by dust and soot aerosols

Homogeneous freezing in cirrus clouds

Lohmann et al., 2007

Autoconversion rate

Autoconversion rate Q_{aut} (kg $kg^{-1}s^{-1}$)

(Khairoutdinov & Kogan, 2000)

$$Q_{\mathrm{aut}} = 1350 \times q_l^{2.47} N_l^{-1.79}$$

The autoconversion rate is a key process for the formation of precipitation in warm clouds and therefore is important for the cloud lifetime effect of aerosols

Vehkamaeki et al. *Kazil et al.*

As temperature goes down, neutral H2SO4/H2O nucleation becomes increasingly efficient, and at temperatures below about 230 K it is the dominant aerosol nucleation process (stronger than charged nucleation of H2SO4/H2O and of H2SO4 and organics). Once neutral nucleation takes over, the slope of the increase is controlled by the dG for the H2SO4(H2O)x + H2SO4(H2O)x process. In the new nucleation scheme, the dG comes from lab measurements; in the old nucleation scheme it derives from the classical liquid drop model plus some modifications.