Modelling aerosol-cloud interations in GCMs

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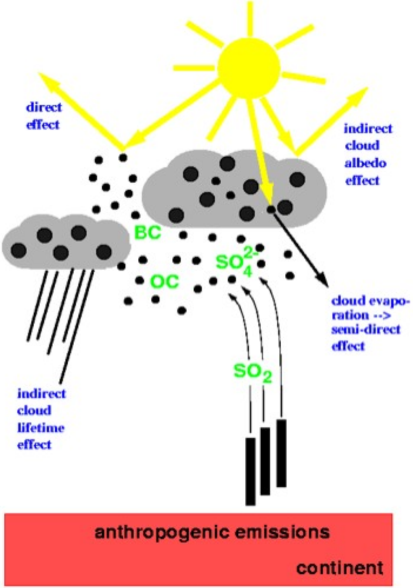
Aerosol radiative effects



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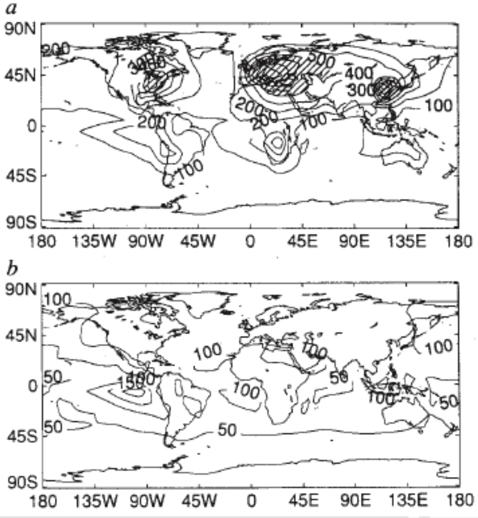
Model set-up in cloud-albedo effect studies

- Use monthly mean sulfate aerosol distributions
- Empirically relate the sulfate aerosol mass to the cloud droplet number concentration (N_d)
- Obtain the effective cloud droplet radius (r_e) from:

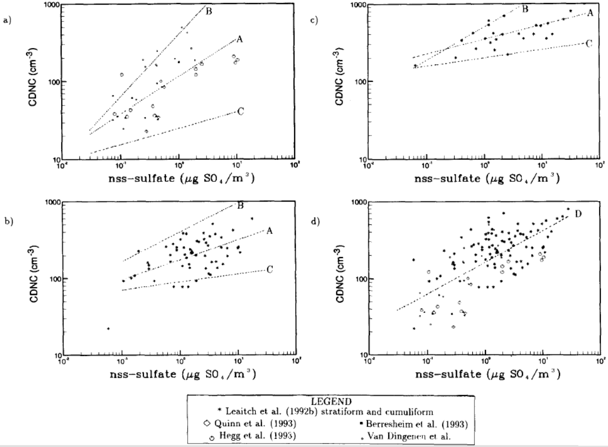
$$r_e = k \left(\frac{3\rho_\mathrm{a}\mathrm{LWC}}{4\pi N_d \rho_w} \right)^{1/3} \tag{1}$$

  with LWC=liquid water content, $k \sim 1.1$
- Call the radiation code twice each time-step:
  - Once with $r_e(N_d)$ obtained from present-day sulfate
  - Once with $r_e(N_d)$ obtained from pre-industrial sulfate
- The meteorology is not affected, i.e. these estimates are pure forcing estimates

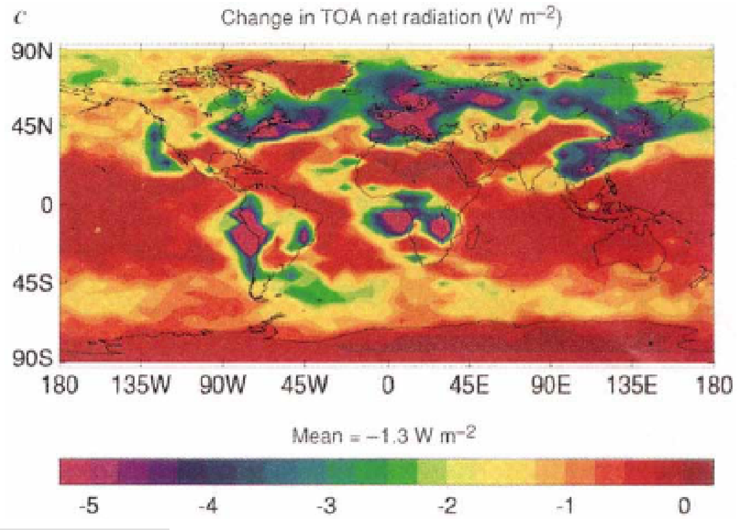
Sulfate aerosol input fields [Jones et al., Nature, 1994]



Empirical relationship between sulfate aerosols and the cloud droplet number concentration (CDNC) [Boucher and Lohmann, Tellus, 1995]



Indirect aerosol effect [Jones et al., Nature, 1994]



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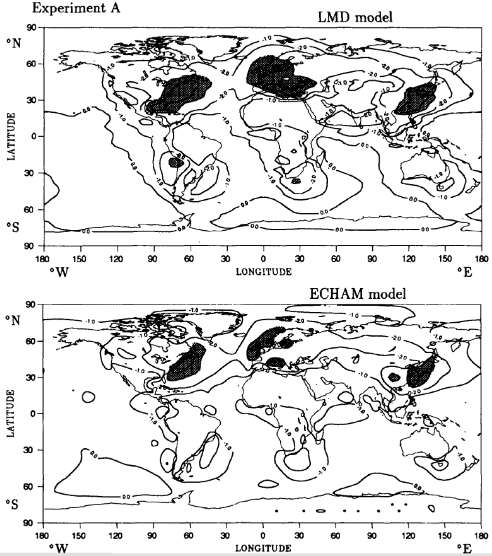
Indirect aerosol effect [Boucher and Lohmann, Tellus, 1995]



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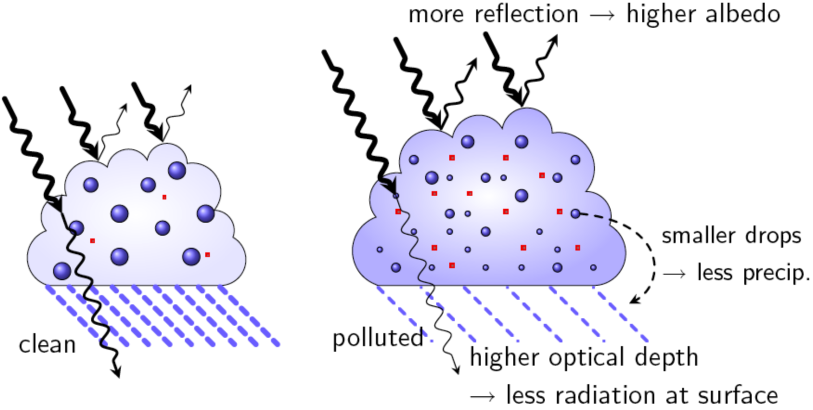
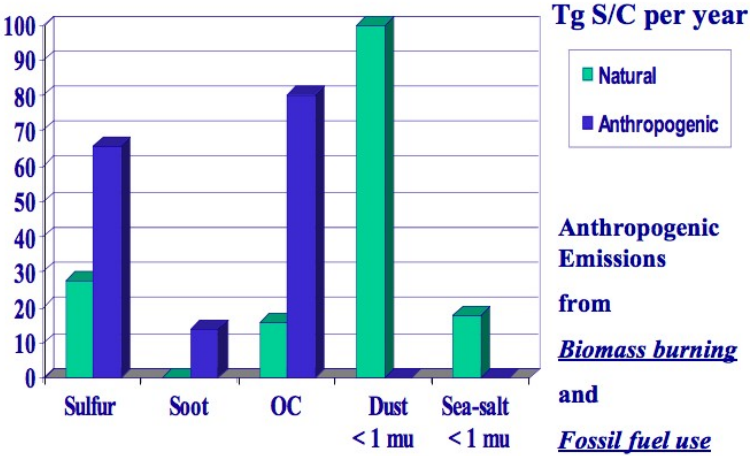
Cloud albedo and lifetime effect

(more aerosols → more and smaller cloud droplets per given cloud liquid water content → more reflection of solar radiation to space; → less precipitation)



Aerosol sources

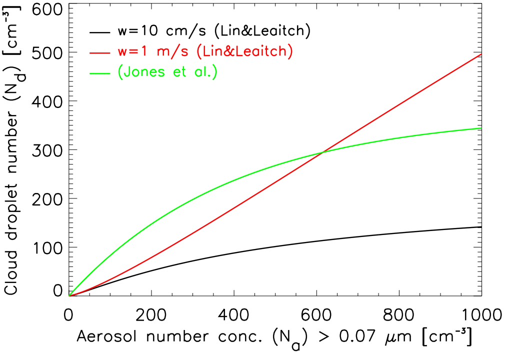


Aerosol activation

$$N_d = 375(1 - exp[-0.00035 N_a]) \quad \text{(Jones et al., 1994)}$$

$$N_d = 0.1 \left(\frac{N_a \cdot w}{w + 0.0023 N_a} \right)^{1.27} \quad \text{(Lin \& Leaitch, 1997)}$$

where $w = \overline{w} + 1.33\sqrt{TKE}$, and TKE = turbulent kinetic energy (Lohmann, JAS, 2002)



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Autoconversion rates (→ cloud lifetime effect)

$$\mathrm{AUT} = \alpha \mathrm{LWC}^{4.7} N_d^{-3.3} \quad \text{(Beheng, 1994)}$$

$$\mathrm{AUT} = \beta \mathrm{LWC}^{2.5} N_d^{-1.8} \quad \text{(Khairoutdinov \& Kogan, 2000)}$$

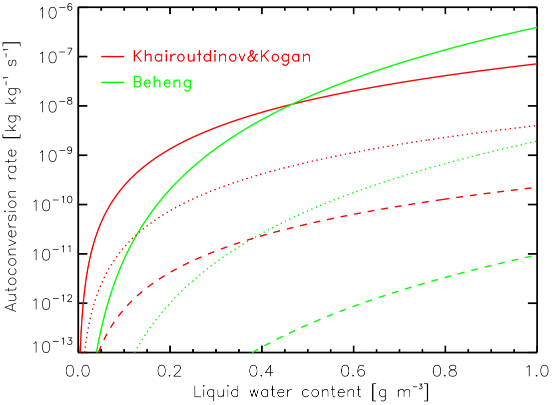

Figure: Cloud droplet number conc.= 40, 200, 1000 cm^{-3}

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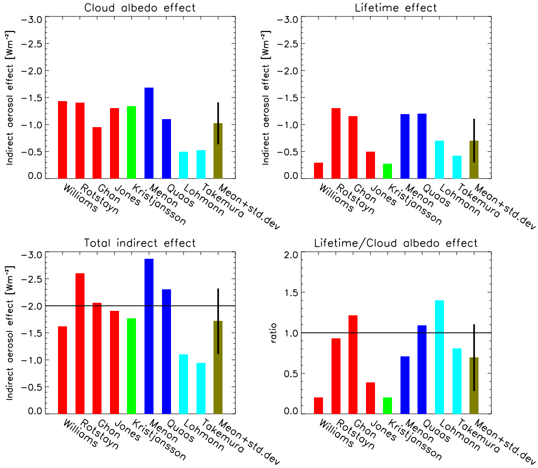
Cloud albedo versus cloud lifetime effect



- Sulfate
- Black carbon (BC) and sulfate
- Organic aerosols (OC) and sulfate
- BC, OC and sulfate

Figure: Lohmann and Feichter, ACP, 2005

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Summary of aerosol forcing estimates

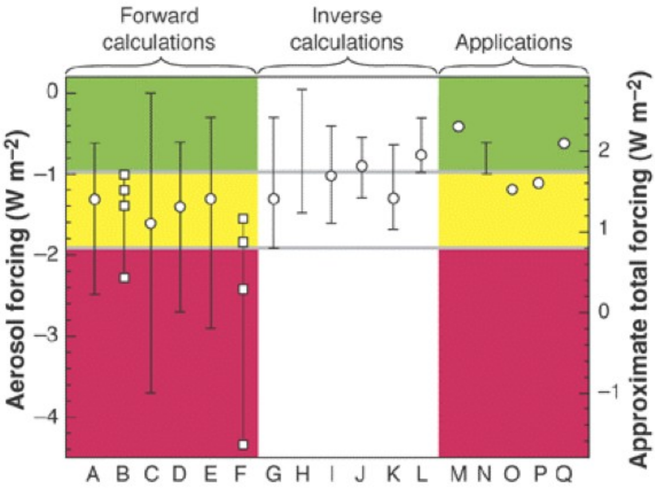
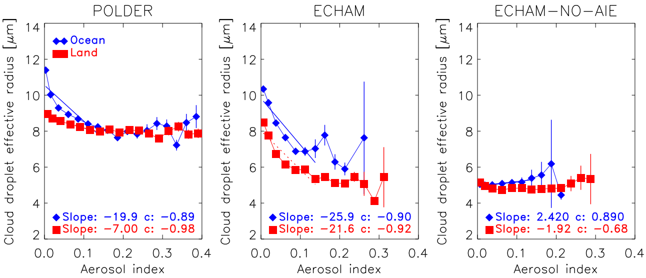


Figure: Anderson et al., Science, 2003

Combination of satellite data and GCM results

[Lohmann and Lesins, Science, 2002]



Indirect aerosol effect [W m^{-2}]	Original	Constrained
Ocean	-1.28	-0.98
Land	-1.62	-0.53
Global	-1.4	-0.85

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Combination of satellite data and GCM results

[Quaas, Boucher, Lohmann, ACP, 2006]

- Compute cloud droplet number concentration (N_d) from MODIS retrievals of cloud optical depth (τ_c) and cloud droplet effective radius (r_e) for those pixels, where the retrieval is most reliable (4 μm $\leq r_e \leq$ 30 μm and 4 $\leq \tau_c \leq$ 70)
- LMDZ: $N_d = exp(a_0 + a_1 \; ln \; m_{aer})$
  where m_{aer} = mass of all potential CCN
- ECHAM4: $N_d = 0.1 \left(\frac{N_a \; w}{w + b_0 \; N_a} \right)^{b_1}$
  where $w = \overline{w} + b_2 \sqrt{TKE}$;
  N_a = aerosol number concentration; TKE = turbulent kinetic energy
- $a_0, a_1, b_0 - b_2$ are adjusted in order to match the MODIS fine mode aerosol optical depth - cloud droplet number relationship

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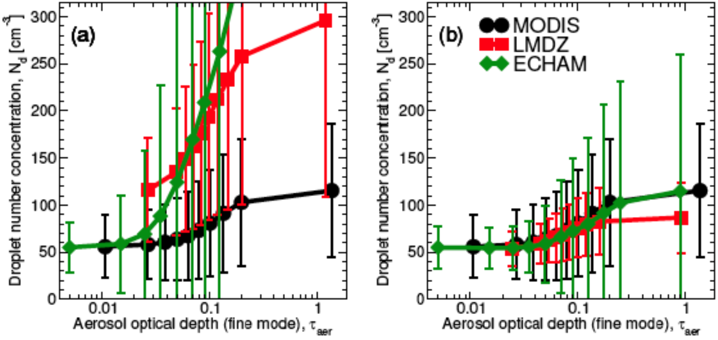
Combination of satellite data and GCM results

[Quaas, Boucher, Lohmann, ACP, 2006]



Indirect aerosol effect [W m^{-2}]	Original	Constrained
LMDZ	-0.84	-0.53
ECHAM	-1.54	-0.29

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Glaciation indirect aerosol effect

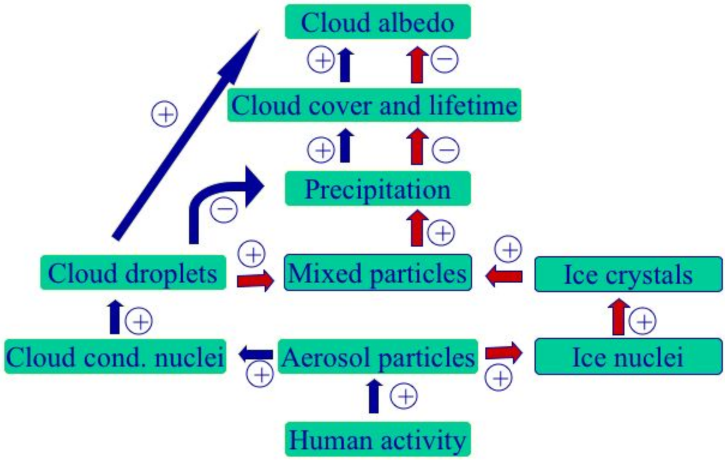
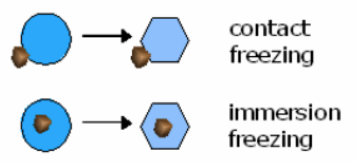


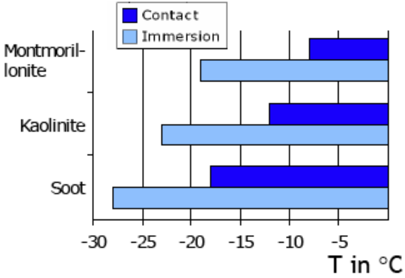
Figure: Lohmann, GRL, 2002

Heterogeneous freezing

- Mixed-phase clouds (-38°C<T<0°C)
- In ECHAM5-HAM: only contact and immersion freezing, dust and black carbon



- IN efficiencies depend on material and drop volume



Median freezing temperatures for different IN from lab experiments. Drop radii 250-350 µm. Adapted from *Diehl et al. (2005)*.

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Sensitivity Simulations [Lohmann and Diehl, JAS, 2006]

- 10 year simulations with ECHAM4 in T30 horizontal resolution with 19 vertical levels after 3 months spin-up
- Double moment cloud microphysics scheme
- Dust and soot act as contact and immersion nuclei

Simulation	Description
MON	Assuming dust to be composed of montmorillonite (better freezing nuclei)
KAO	Assuming dust to be composed of kaolinite (worse freezing nuclei)
CTL	Reference simulation, in which both contact and immersion freezing are independent of the chemical composition of the ice nuclei

Number concentration of different aerosols

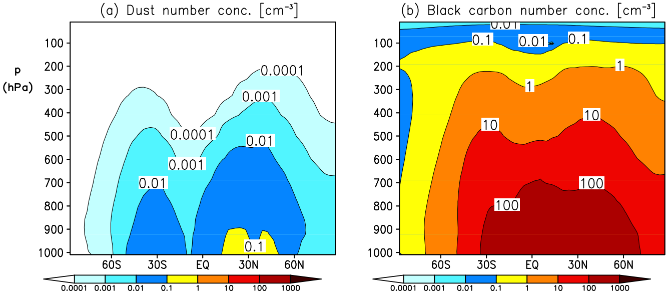
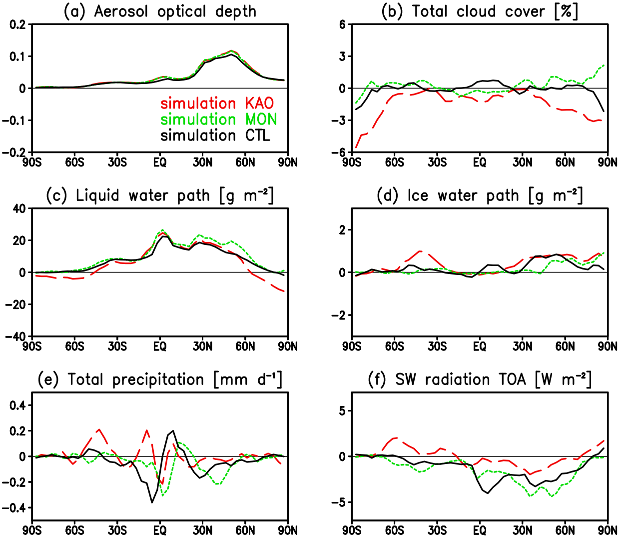


Figure: Annual zonal mean latitude-height cross-sections

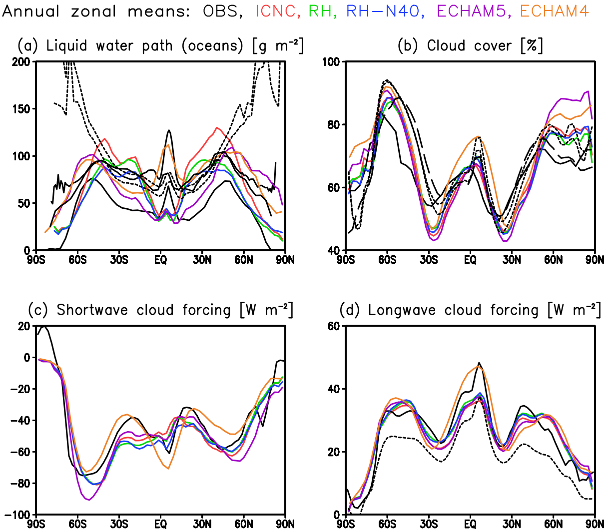
Annual zonal mean indirect aerosol effect



Model set-up in ECHAM5 studies

- ECHAM5 global climate model (Roeckner et al., 2003)
- Multi-year simulations in T42 resolution (2.8° x 2.8°) after a 3-month spin-up
- 2-moment aerosol scheme ECHAM5-HAM (Stier et al., 2005)
- 4 pairs of simulations:
    - ECHAM4: Reference simulation with ECHAM4
    - ECHAM5-ICNC: Reference simulation with ECHAM5 (2-moment cloud microphysics scheme, Tompkins cloud cover, $N_{d,min} = 1\ \mathrm{cm}^{-3}$)
    - ECHAM5-RH: Using the ECHAM4 cloud cover scheme (Sundqvist et al., 1989)
    - ECHAM5-RH-N40: Using $N_{d,min} = 40\ \mathrm{cm}^{-3}$ together with the Sundqvist cloud cover scheme
    - Each simulation pair is run with present-day and pre-industrial (1750) aerosol emissions

Climate model validation



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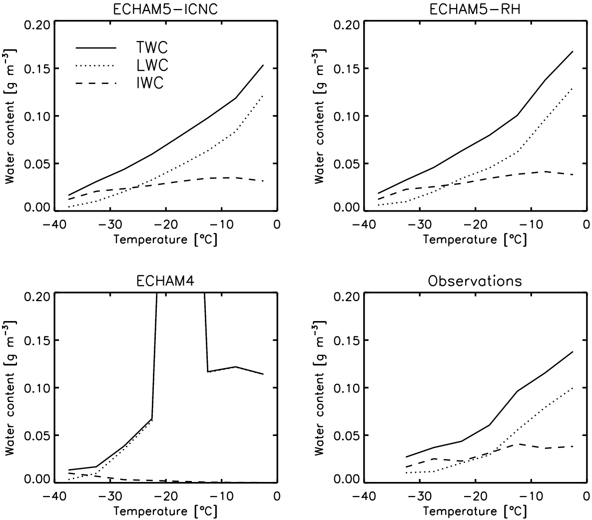
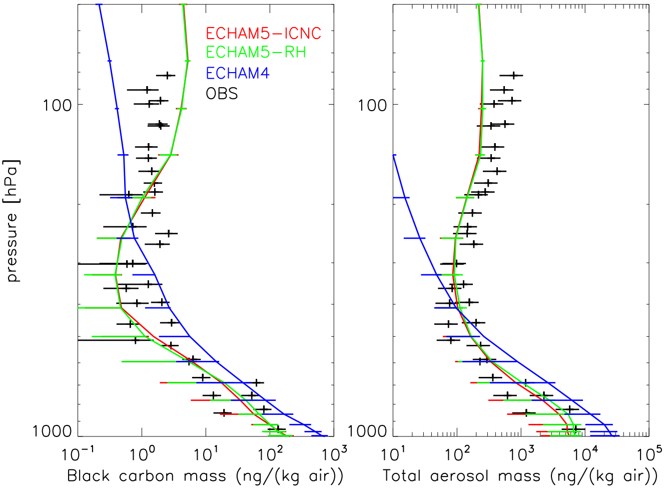
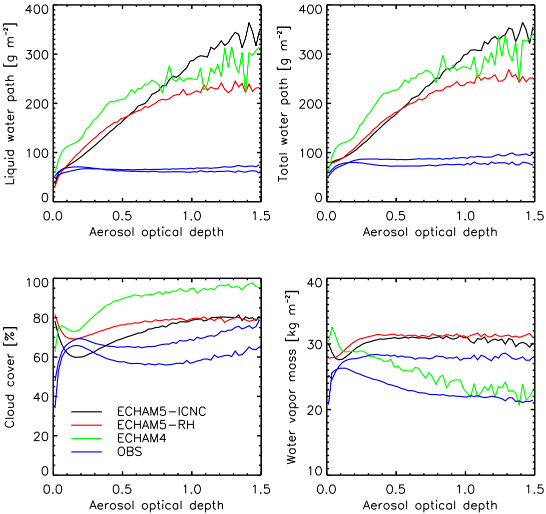
Liquid (LWC), ice (IWC) and total water content (TWC) in mixed-phase clouds [Observations from Korolev et al., QJ, 2003]



Vertical distribution of black carbon and total aerosol mass in Texas [Obs. from Schwarz et al., JGR, 2006]



Cloud properties vs. AOD [Obs. from MODIS following Myhre et al., ACPD, 2006]



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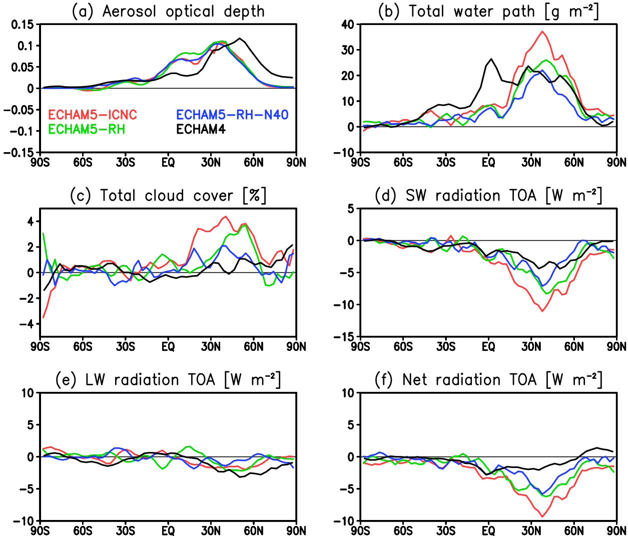
Preliminary annual zonal mean changes present - 1750



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Preliminary global annual mean changes present-day - 1750

Simulation	ECH5 -ICNC	ECH5 -RH	ECH5 -RH-N40	ECH4
Liquid water path, g m^{-2}	11.8	8.7	6.8	12.7
Total cloud cover, %	1.4	0.7	0.4	0.1
SW radiation, W m^{-2}	-3.7	-2.5	-2.0	-1.7
LW radiation, W m^{-2}	0.4	0.3	0.2	0.7
Net radiation, $\mathrm{W\ m^{-2}}$	-3.3	-2.2	-1.8	-1.0

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Conclusions

- The indirect cloud albedo effect on warm clouds from GCMs amounts to -0.5 to -1.9 W m^{-2}
- The indirect cloud lifetime effect varies between -0.3 and -1.4 W m^{-2}
- These estimates are larger than combined satellite+GCM estimates
- One possible reason for large indirect effects is the neglect of the ice phase
- The vertical distribution of aerosols and the dependency of cloud condensate with temperature in mixed-phase clouds are much better captured in ECHAM5-ICNC than in ECHAM4
- Preliminary results show that the indirect aerosol effect in ECHAM5-ICNC is much larger than in ECHAM4

Freezing of kaolinite vs. soot

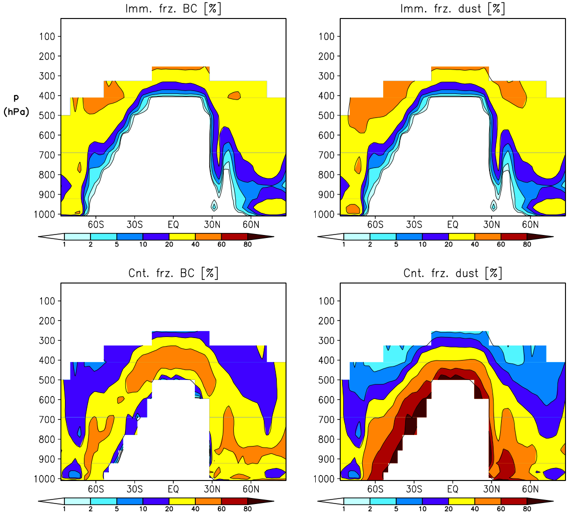

Figure: Lohmann and Diehl, JAS, 2006

Freezing of montmorillonite vs. soot

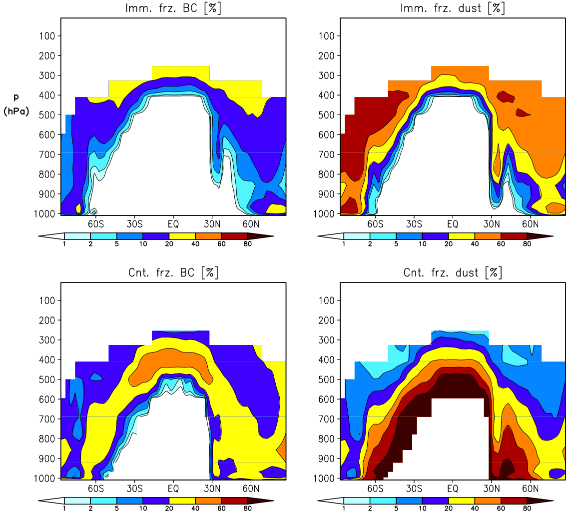

Figure: Lohmann and Diehl, JAS, 2006

Table: Global annual mean changes ± interannual standard deviations of aerosol optical depth ($\Delta\tau$), liquid water path (ΔLWP, g m^{-2}), ice water path (ΔIWP, g m^{-2}), total cloud cover (ΔTCC, %), precipitation (ΔPR, mm d^{-1}), shortwave (ΔF_{SW}, W m^{-2}), longwave (ΔF_{LW}, W m^{-2}) and net TOA radiation (ΔF_{net}, W m^{-2}) between pre-industrial and present-day.

Simulation	CTL	KAO	MON
$\Delta\tau$	0.04±0.001	0.04±0.001	0.04±0.001
ΔLWP	10.5±0.69	9.83±0.61	12.73±0.39
ΔIWP	0.20±0.09	0.35±0.04	0.10±0.03
ΔTCC	0.07±0.38	-1.00±0.26	0.12±0.16
ΔPR	-0.051±0.008	0.005±0.007	-0.052±0.008
ΔF_{SW}	-1.63±0.39	-0.22±0.24	-1.77±0.14

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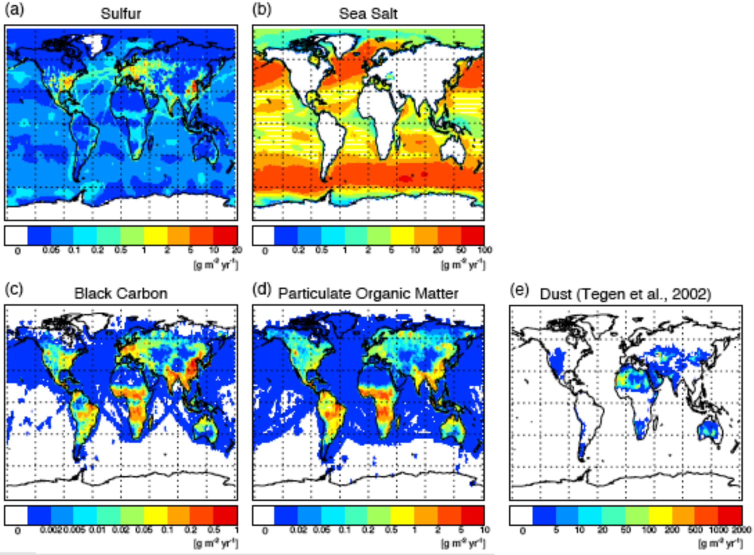
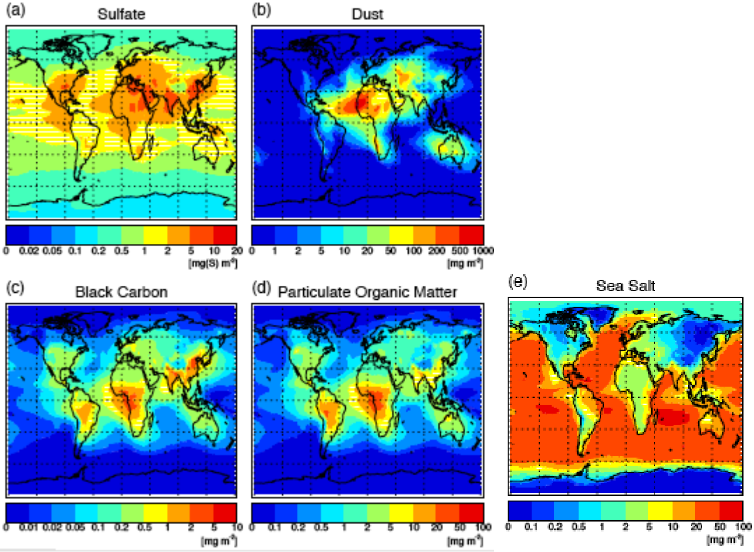
Global aerosol sources [Stier et al., ACP, 2005]



Vertically integrated aerosol burden [Stier, ACP, 2005]



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