Representing cloud-aerosol interactions in GCMs

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ECMWF,
Nov 6, 2012

Acknowledgements:
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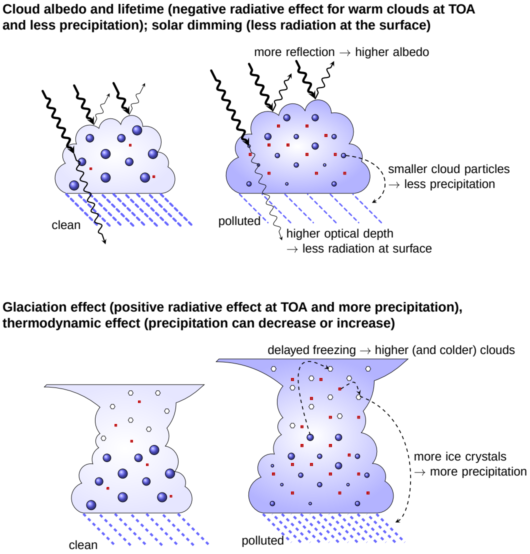
B. Stevens, T. Storelvmo

Aerosol effects on climate (IPCC, 2007)



Different indirect aerosol effects

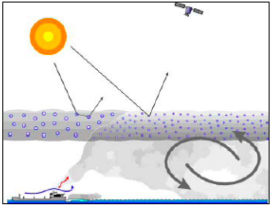
- Radiative forcing due to aerosol-cloud interactions (RFaci) (Twomey or first indirect effect): Included in IPCC AR4 forcing bar chart to be -0.7 W m^{-2} (-1.8 to -0.3 W m^{-2}) since pre-industrial times [Forster et al., 2007]
- Adjusted forcing due to aerosol-cloud and aerosol-radiation interactions (AFaci+ari) (includes fast adjustments): -1.2 W m^{-2} (-2.3 to -0.2 W m^{-2}) [IPCC, Denman et al., 2007]

Aspects discussed here:

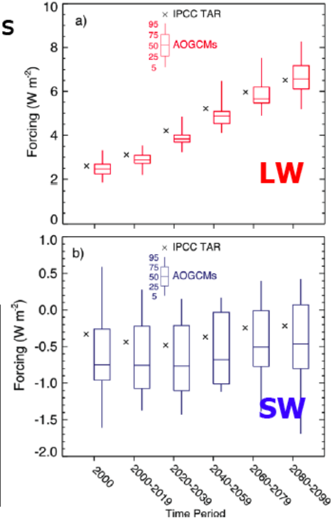
- Sources for uncertainty in RFaci
- Reasons for overestimating AFari+aci
- AFaci in cirrus clouds
- Necessary detail of representing aerosols: CCN climatology vs. 2-moment scheme

RFaci in the IPCC AR4 transient simulations

- ✓ Out of 23 models/model versions in Chapter 10 of IPCC AR4, 9 included aerosol indirect effects.
- ✓ 3 models included an online sulfur cycle
- ✓ All except one used empirical relationships to calculate cloud droplet number concentrations (CDNCs)
- ✓ Most models with AIE included 1st AIE only

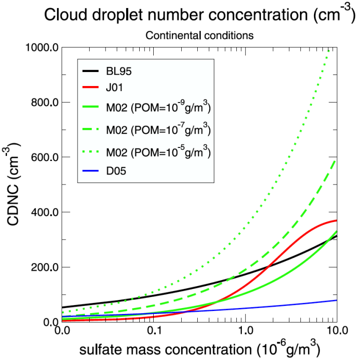


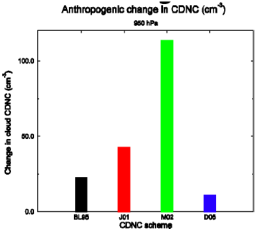
Courtesy of D. Rosenfeld

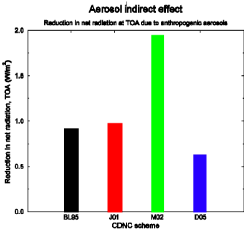


Storelvmo et al., GRL, 2009

RFaci in the IPCC AR4 transient simulations



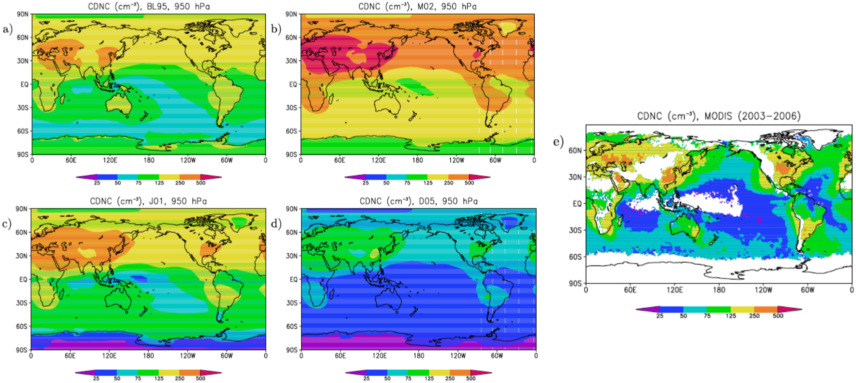




1.3 W m^{-2} of the 2.2 W m^{-2} spread in present-day shortwave forcing can be explained by these different methods to predict cloud droplet number from sulfate aerosols

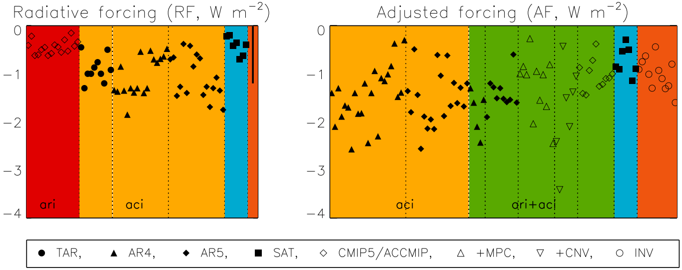
Storelvmo et al., GRL, 2009

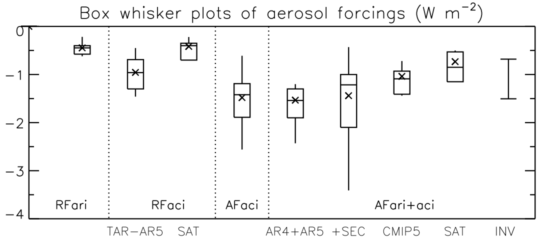
Comparison with observations



Storelvmo et al., GRL, 2009

Classification of RFaci and AFaci

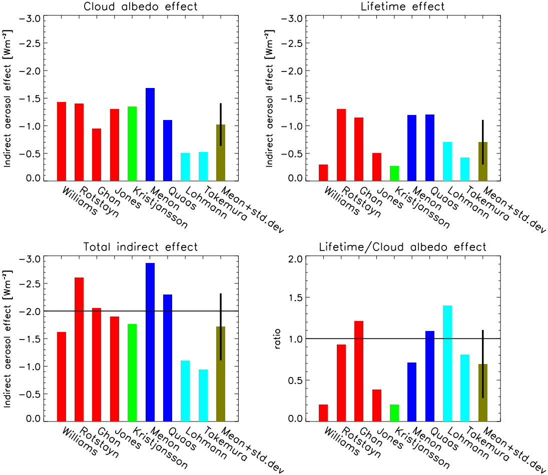




Reasons for overestimating AFari+aci

- GCMs tend to include only primary aerosol-cloud-interactions (via autoconversion) and thus their mean AFari+aci is -1.5 W m^{-2}
- Whereas no lifetime effect is found in LES studies (Jiang et al., 2006), all GCMs with an autoconversion depending on N_c have a build-in lifetime effect
- If convection is resolved as in the MMF approach (Wang et al., 2011), AFari+aci is: -1.1 W m^{-2}
- GCMs constrained by satellite data yield AFari+aci of -0.7 W m^{-2}
- The inverse estimate from an energy balance perspective (Murphy et al., 2009) yields AFari+aci between -0.7 and -1.5 W m^{-2}
- New CMIP5/ACCMIP models give AFari+aci: -1 W m^{-2}

Cloud albedo versus cloud lifetime effect

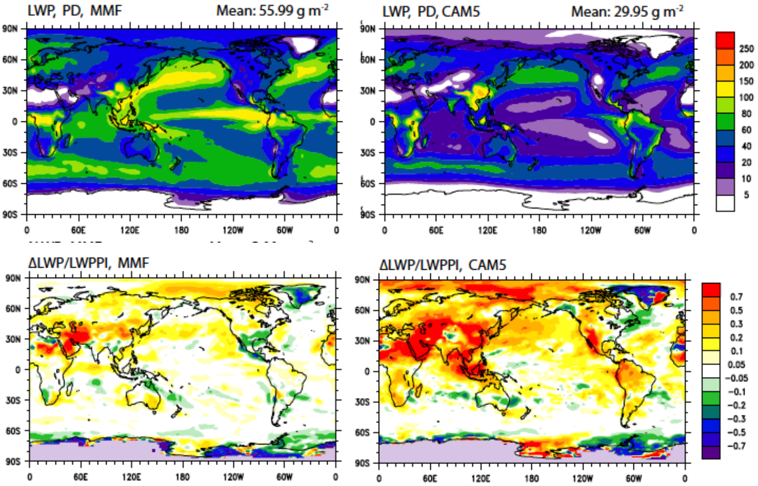


- Sulfate
- Black carbon (BC) and sulfate
- Organic aerosols (OC) and sulfate
- BC, OC and sulfate

Lifetime effect: -0.7 W m^{-2} in GCMs, but 0 in LES (Jiang et al., 2006)

Lohmann and Feichter, ACP, 2005

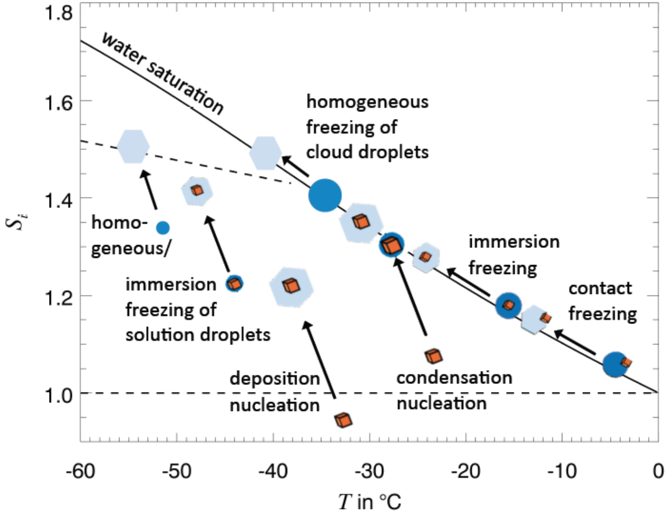
Multi-Modelling Framework (MMF) approach



AFaci: -1.05 W m^{-2} MMF vs. -1.66 W m^{-2} CAM5

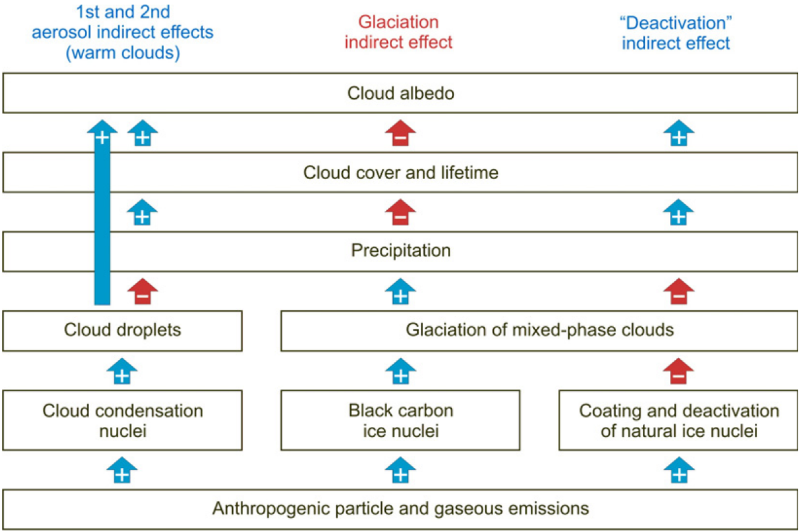
Wang et al., ACP, 2011

Heterogeneous freezing



Hoose and Möhler, 2012

De-activation vs. glaciation effect



Hoose et al., ERL, 2008

Prognostic rain

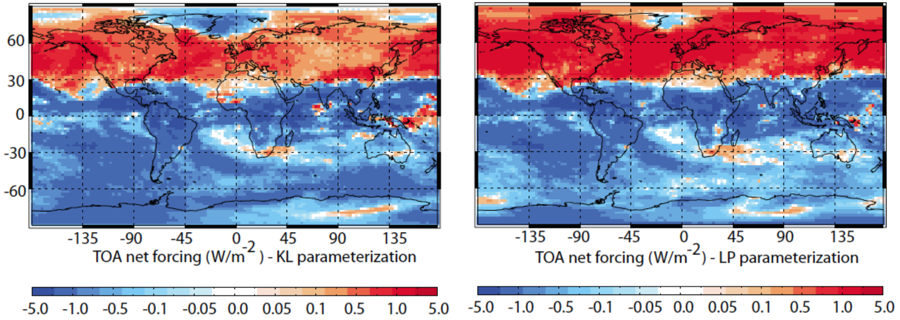
Table 3. Annual Global Means of the Vertically Integrated Autoconversion Rate (AUT), Accretion Rate (ACC) and the Fraction of the Autoconversion Rate to the Total Conversion Rate (AUT+ACC) for the Model Simulations Described in Table 1

		MU-1	MU-1m	MU-10	MU-PARA	DIAG
AUT	kg m^{-2} s^{-1}	0.52	0.64	0.43	0.42	3.2
ACC	kg m^{-2} s^{-1}	6.95	6.65	7.52	7.58	4.93
AUT/(AUT+ACC)	%	7.0	8.8	5.4	5.2	39.3

AFari+aci reduced by 0.5-0.9 W m^{-2}

Posselt and Lohmann, 2009

Anthropogenic aerosol forcing of cirrus clouds

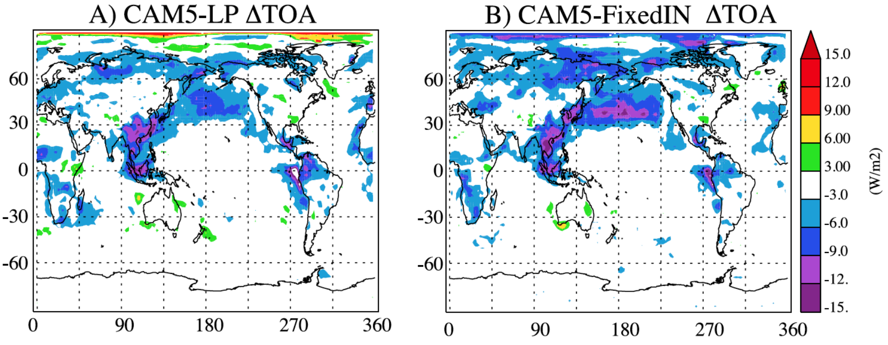


Global mean effect: -0.67 W m^{-2} KL (Kärcher and Lohmann param.)
-0.53 W m^{-2} LP (Liu and Penner param.)

SW cooling by more ice crystals on NH is offset by LW heating. SW warming due to fewer crystals on SH causes more LW cooling.

Penner et al., ACP, 2009

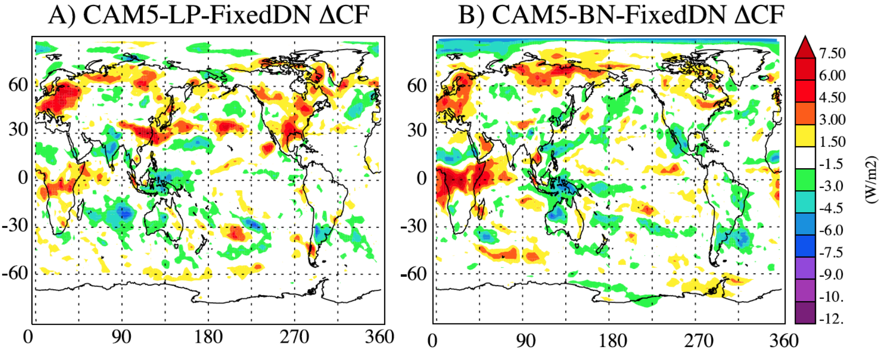
Anthropogenic aerosol forcing with and without cirrus clouds



Global mean effect: -1.58 W m^{-2} (water clouds only)
-1.36 W m^{-2} (all clouds) $\rightarrow$ +0.22 W m^{-2} (cirrus clouds)

Gettelman et al., JGR, 2012

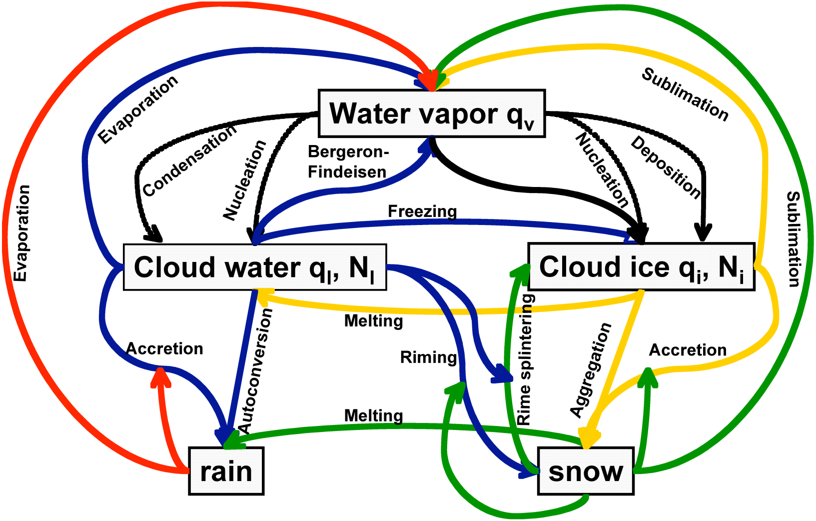
Anthropogenic aerosol forcing of cirrus clouds



Global mean effect: 0.31 W m^{-2} (Liu and Penner param.)
0.19 W m^{-2} (Barahona and Nenes param.)
0.39 W m^{-2} (Kärcher and Lohmann param. in ECHAM)

Gettelman et al., JGR, 2012

2-moment cloud microphysics in ECHAM5



based on Lohmann et al. (2008); figure from S. Jess

Predict N_l and parameterize cloud droplet activation

Simple param. derived from Köhler theory and obs. (Lin & Leaitch, 1997)

$$N_l^t = 0.1 \left(\frac{N_a \cdot w}{w + 0.0023 N_a} \right)^{1.27} ; Q_{nucl} = max \left(\frac{N_l^t - N_l^{t-1}}{\Delta t}, 0 \right)$$

When using CCN climatology, N_a is replaced by CCN

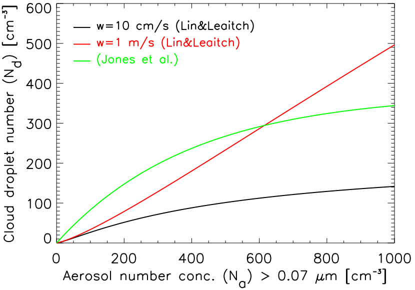
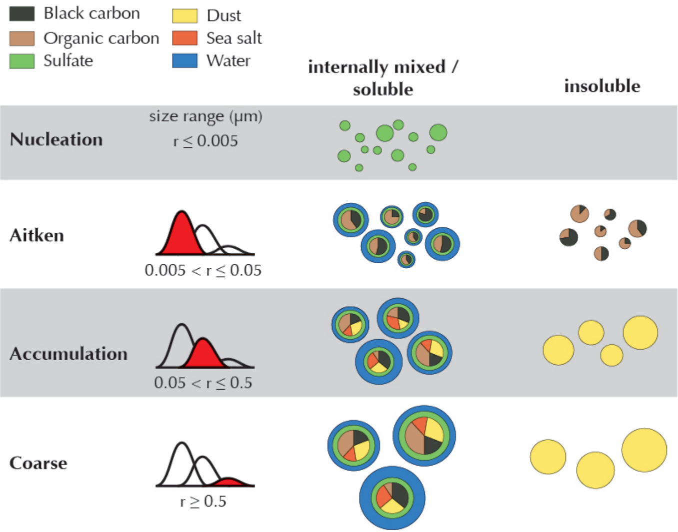


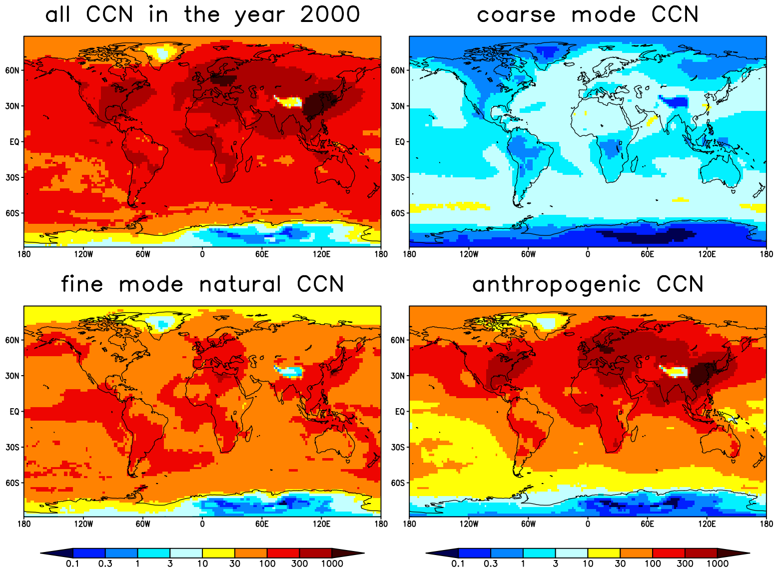
Figure: Green line: $N_l = 375(1 - exp[-0.00035 N_a])$

M7 aerosol scheme (Vignati et al., 2004)

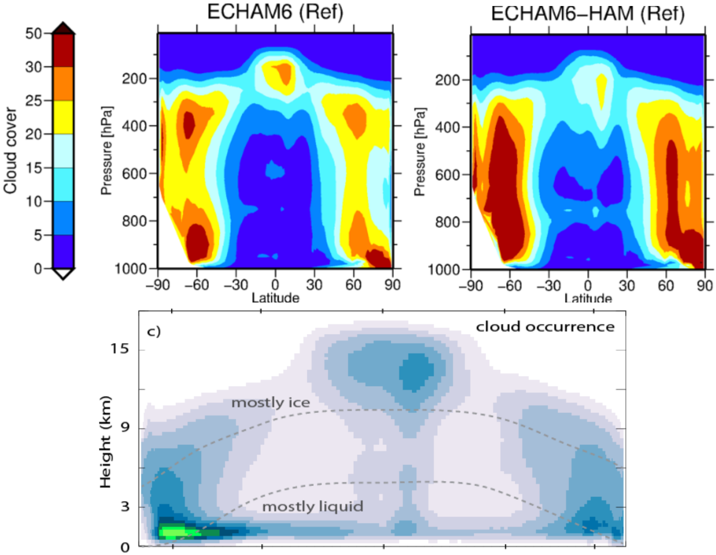


Courtesy Elias Zubler, adapted from Stier et al., ACP, 2005

CCN (cm^{-3}) in 1km at 0.1% supersat.

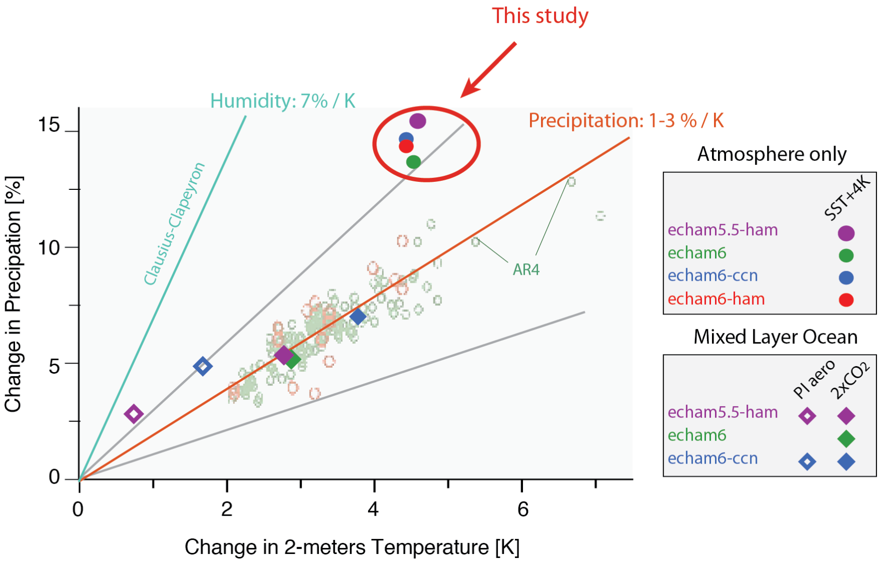


Comparison with observations



CloudSat observations (Courtesy M. Lebsock and B. Stevens)

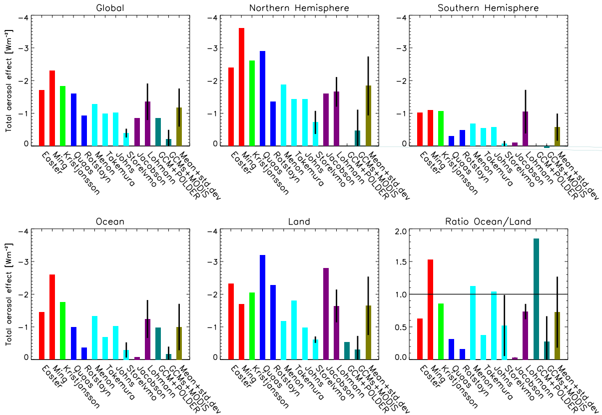
Hydrological sensitivity



Take-home messages

- The adjusted forcing due to aerosol-cloud-interactions (AFaci) remains uncertain
- GCMs tend to overpredict AFaci if secondary processes (mixed-phase, accretion instead of autoconversion, entrainment) are missing
- The sign of aerosol effects on cirrus clouds is not yet known
- The degree of aerosol detail that is necessary depends on the question asked. For ECHAM6, so far the simulations with the CCN climatology instead of the full aerosol scheme do not give reliable results

Total anthropogenic aerosol effect at TOA

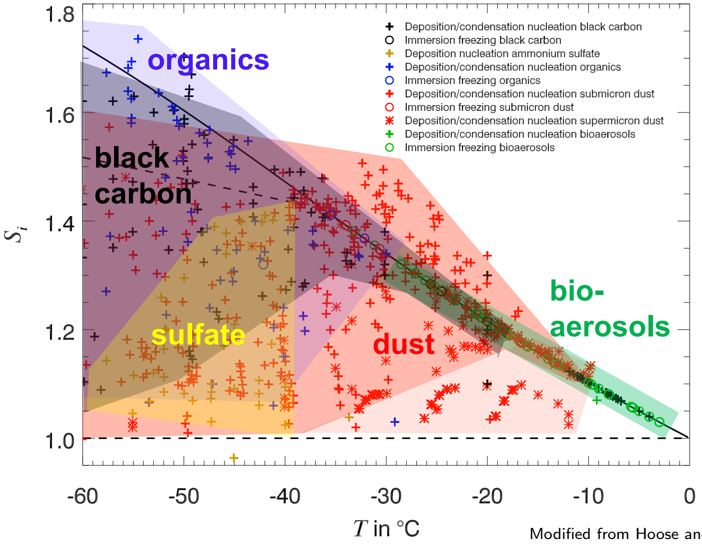


- Sulfate
- Sulfate, BC
- Sulfate, OC
- Sulfate, BC, OC
- Water+ice clouds
- GCM+satellites

Figure: Results from different global models: average: -1.2 W m^{-2} [-0.2 to -2.3 W m^{-2}]

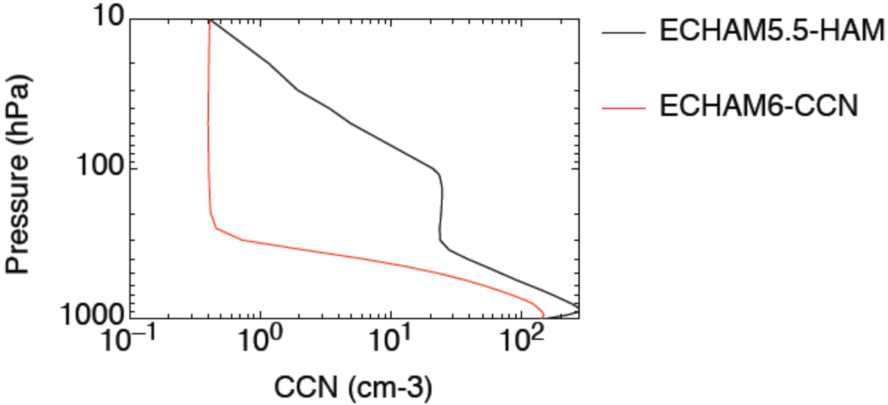
IPCC, 2007, Fig. 7.21

Compilation of all freezing data: imm (o), dep (+)



Modified from Hoose and Möhler, 2012

CCN climatology vs. HAM



Comparison with observations