What is the aerosol indirect effect in CAM-Oslo sensitive to and why?

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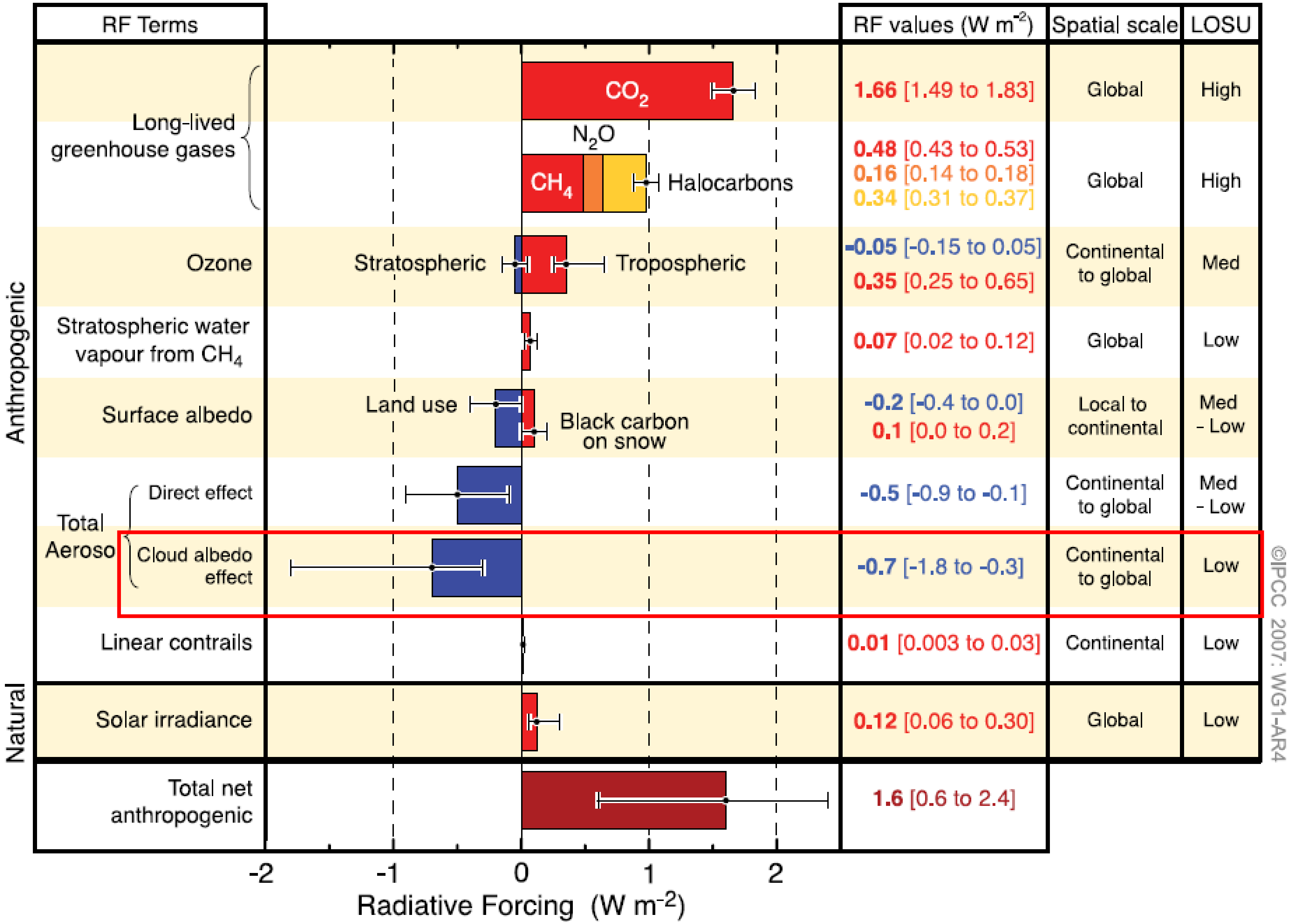
Overview of talk

- General comments
- Sensitivity to background aerosols
- Sensitivity to imposed constraints on cloud droplet number
- Sensitivity to treatment of anthropogenic ice nuclei

Figure from NASA

RADIATIVE FORCING COMPONENTS



	RF Terms	RF values (W m^{-2})	Spatial scale	LOSU
Anthropogenic	Long-lived greenhouse gases: CO$_2$	1.66 [1.49 to 1.83]	Global	High
	Long-lived greenhouse gases: CH$_4$, N$_2$O, Halocarbons	0.48 [0.43 to 0.53] 0.16 [0.14 to 0.18] 0.34 [0.31 to 0.37]	Global	High
	Ozone	-0.05 [-0.15 to 0.05] 0.35 [0.25 to 0.65]	Continental to global	Med
	Stratospheric water vapour from CH$_4$	0.07 [0.02 to 0.12]	Global	Low
	Surface albedo	-0.2 [-0.4 to 0.0] 0.1 [0.0 to 0.2]	Local to continental	Med - Low
	Total Aeroso: Direct effect	-0.5 [-0.9 to -0.1]	Continental to global	Med - Low
	Total Aeroso: 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]		

Aerosol Indirect Effect

- Definition: *Change in Radiative Forcing from Clouds due to Present-Day Aerosols minus Pre-Industrial Aerosols*

- *Model estimates vary greatly due to*:
- Sensitivity to Parameterizations of Aerosol-Cloud Interactions
- Sensitivity to Aerosol Scheme, in particular to the Treatment of Natural Aerosols: *Few natural CCN => Large Indirect Effect (strong cooling)*
- Sensitivity to the Atmospheric State in the host model, in particular to Cloud Properties: *Dense Clouds => Large Indirect Effect (strong cooling)*

Sensitivity to background aerosols

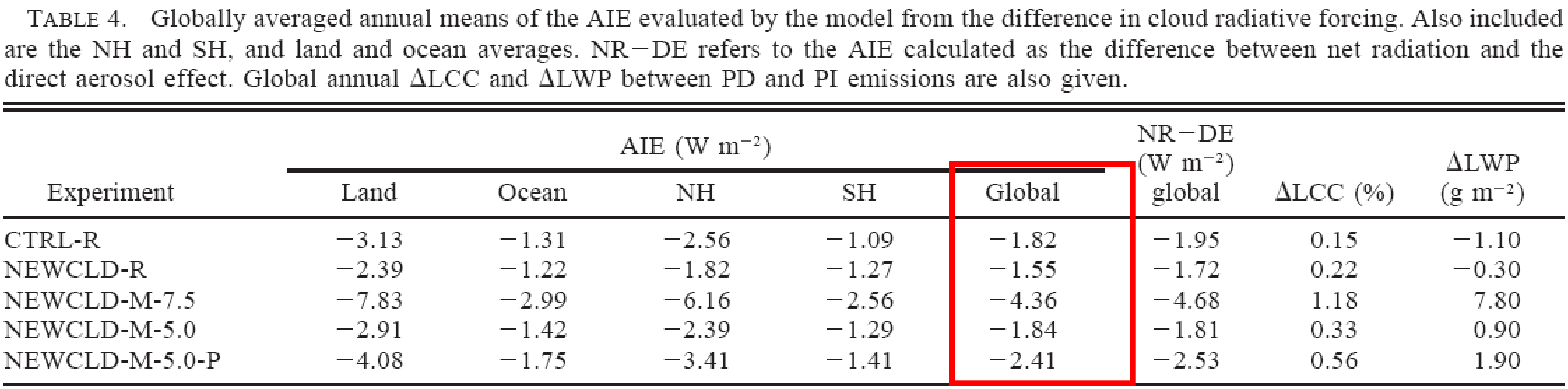


TABLE 4. Globally averaged annual means of the AIE evaluated by the model from the difference in cloud radiative forcing. Also included are the NH and SH, and land and ocean averages. NR−DE refers to the AIE calculated as the difference between net radiation and the direct aerosol effect. Global annual ΔLCC and ΔLWP between PD and PI emissions are also given.

Experiment	AIE (W m^{-2})					NR−DE (W m^{-2}) global	ΔLCC (%)	ΔLWP (g m^{-2})
	Land	Ocean	NH	SH	Global			
CTRL-R	−3.13	−1.31	−2.56	−1.09	−1.82	−1.95	0.15	−1.10
NEWCLD-R	−2.39	−1.22	−1.82	−1.27	−1.55	−1.72	0.22	−0.30
NEWCLD-M-7.5	−7.83	−2.99	−6.16	−2.56	−4.36	−4.68	1.18	7.80
NEWCLD-M-5.0	−2.91	−1.42	−2.39	−1.29	−1.84	−1.81	0.33	0.90
NEWCLD-M-5.0-P	−4.08	−1.75	−3.41	−1.41	−2.41	−2.53	0.56	1.90

Indirect Forcing varies between -1.55 W m^{-2} and -4.36 W m^{-2} depending on treatment of background aerosols

Menon et al. (2002: J.Atmos.Sci.)

Cloud Susceptibility

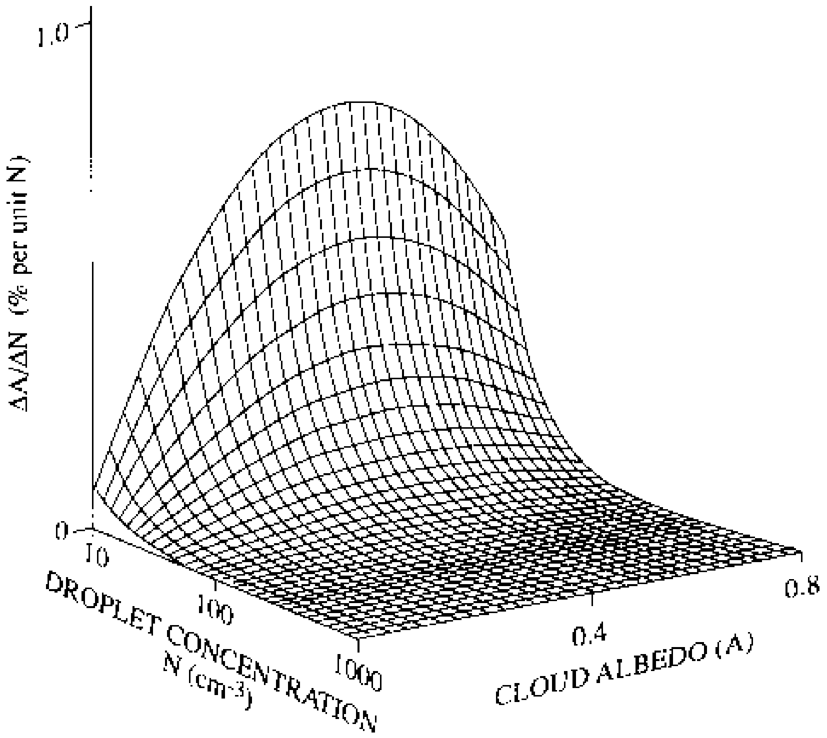


Figure 6 The change in the albedo of a cloud per unit change in the droplet concentration ($\Delta A/\Delta N$) as a function of the cloud albedo (A) and the droplet concentration (N), for a cloud with a constant liquid-water content. (Adapted from Twomey, 1991.)

Hobbs (1993: Academic Press)

Constraining CDNC influences the indirect effect

- In many models cloud droplet number concentration (CDNC) is not allowed to become smaller than e.g., 40 cm^{-3}
- How realistic is such a constraint?
- What is the implication of it?

Reports of low measured cloud droplet number values

- *Bower et al. (2006: Atm. Res.):* In-situ ship measurement from remote area SH ocean: 8 cm^{-3}
- *Yum and Hudson (2004: JGR):* Southern Hemisphere Oceans: 20-40 cm^{-3}
- *Bennartz (2007: JGR):* MODIS-based retrievals: Average values of 41±17 cm^{-3} in PBL clouds in South Pacific and South Indian Oceans
- *McFarquhar et al. (2007: JGR):* Arctic measurements in mixed-phase clouds (M-PACE) of between 23±10 cm^{-3} and 72±34 cm^{-3}

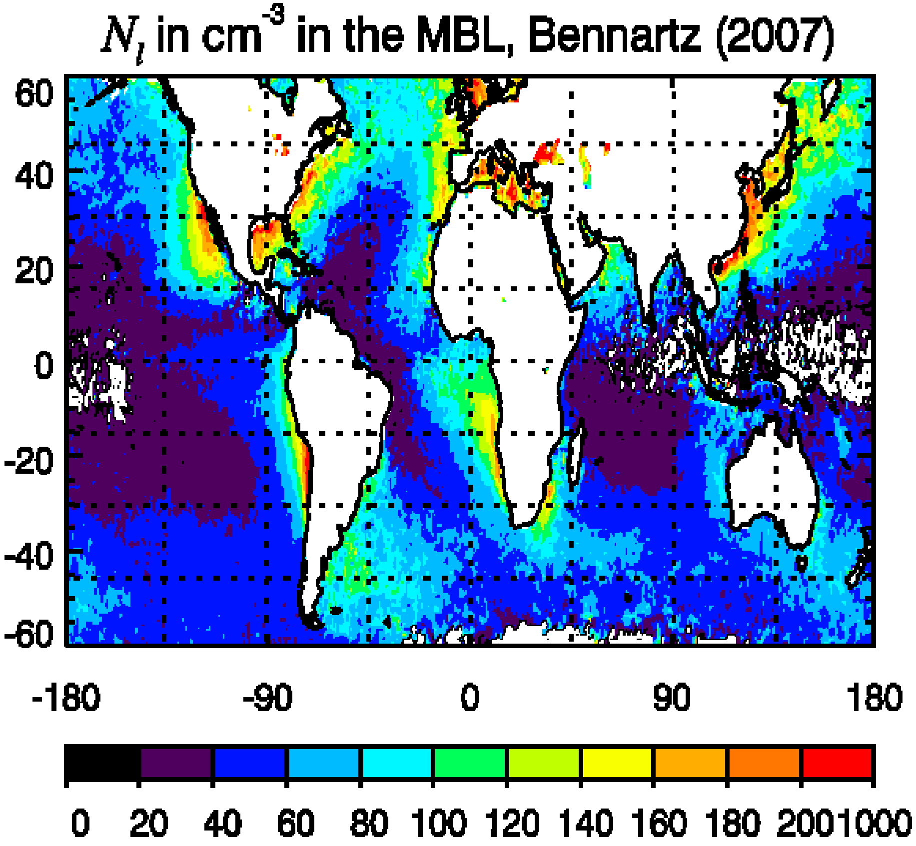
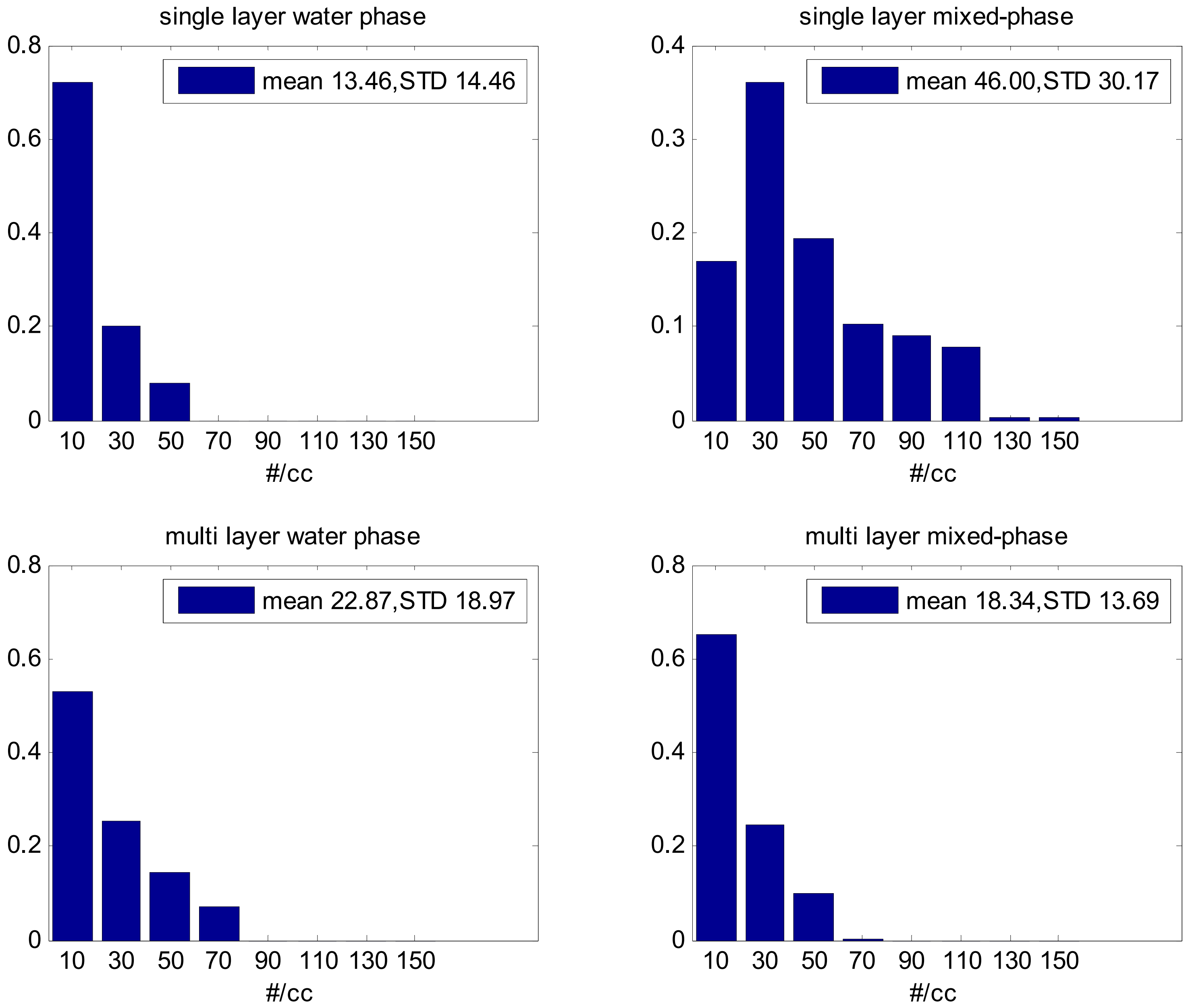


Table 2. Statistics of Cloud Droplet Number Concentration for Remote Ocean Areas With at Least 1500 km Distance to the Next Major Landmass[a]

Area	N All, cm^{-3}	N No Drizzle, cm^{-3}	N Drizzle, cm^{-3}	Fraction Drizzle, %
North Atlantic	89(99) ± 27	118(120) ± 23	50(56) ± 10	56(48) ± 20
South Atlantic	67(77) ± 29	93(96) ± 17	34(39) ± 7	64(59) ± 30
North Pacific	64(74) ± 22	84(88) ± 19	38(44) ± 9	57(49) ± 27
South Pacific	40(49) ± 16	69(74) ± 15	32(38) ± 7	86(82) ± 23
South Indian	42(51) ± 18	76(80) ± 14	32(38) ± 7	79(72) ± 21

[a] The values given are two and a half year mean value with one standard deviation. Results are presented for all stratiform boundary layer clouds and separated in clouds with high/low likelihood of drizzle. The values in parentheses give the estimates that are derived using the parameterization of k derived by *Lu and Seinfeld* [2006]. Standard deviations for the estimates using *Lu and Seinfeld* [2006] are almost identical to the standard deviations for $k = 0.8$ and are not reported.



McFarquhar and Zhang, U. Illinois

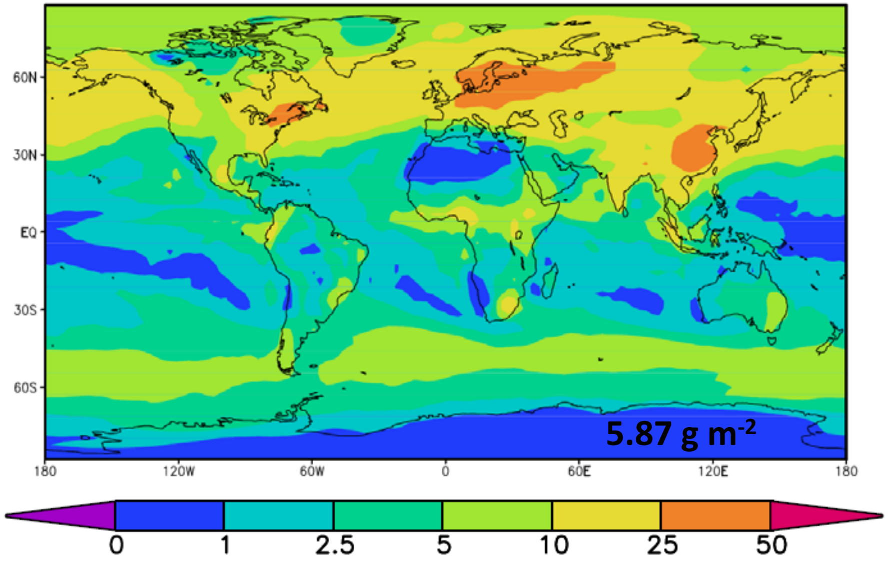
Model tool: CAM-Oslo

- CAM-Oslo = NCAR CAM3 atmospheric climate model + Oslo aerosol schemes
- Prognostic SO4, BC, OM, SS, DU
- Prognostic CDNC, (ICNC)
- T42 horizontal resolution, 26 vertical levels
- SST prescribed

Seland et al. (2008: Tellus), Storelvmo et al. (2008: JAS, in press)

standard CDNC treatment (no lower cut-off)

Change in cloud liquid water path



Present day:

LWP = 133.1 g m^{-2}

Reff = 12.93 µm

CDNCint = 3.95e6 cm^{-2}

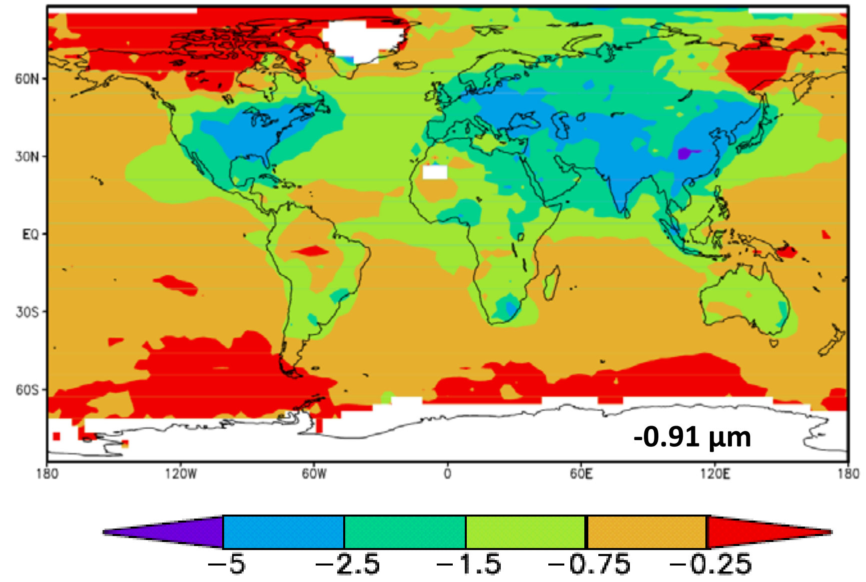
Pre-industrial:

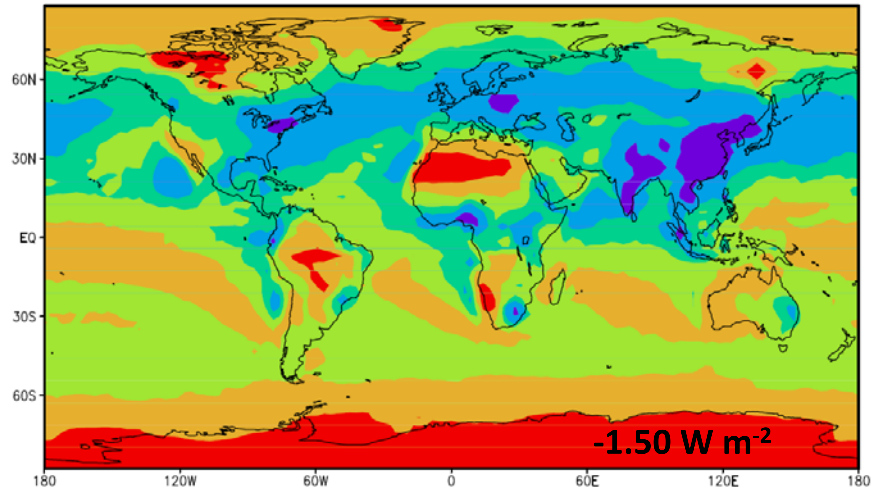
LWP = 127.2 g m^{-2}

Reff = 13.85 µm

CDNCint = 2.57e6 cm^{-2}

Change in effective radius as seen from satellite

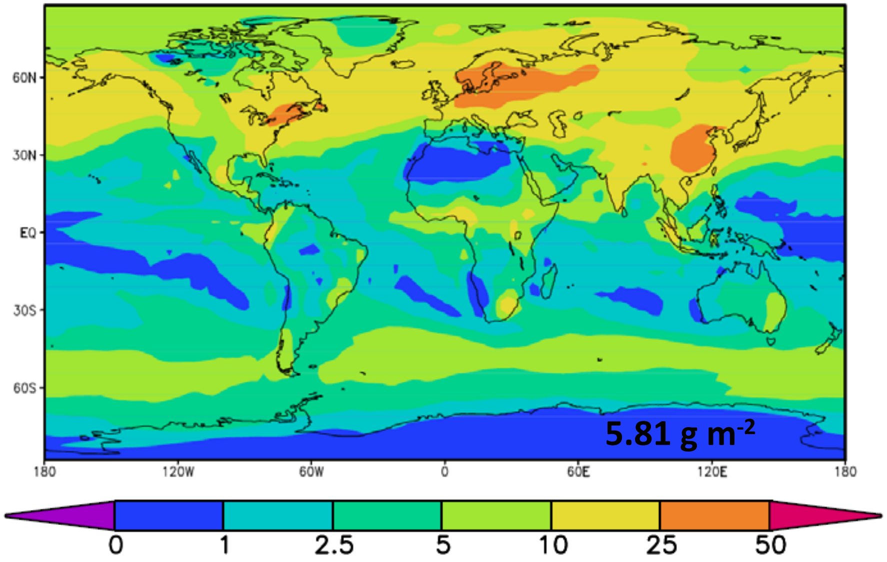




1+2. indirect radiative forcing

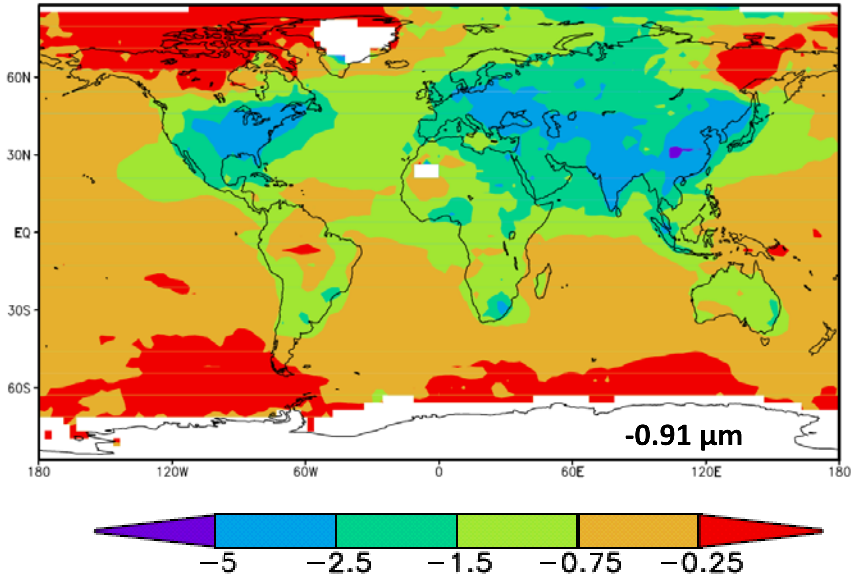
$CDNC_{min}$ = 1 cm^{-3}

Change in cloud liquid water path

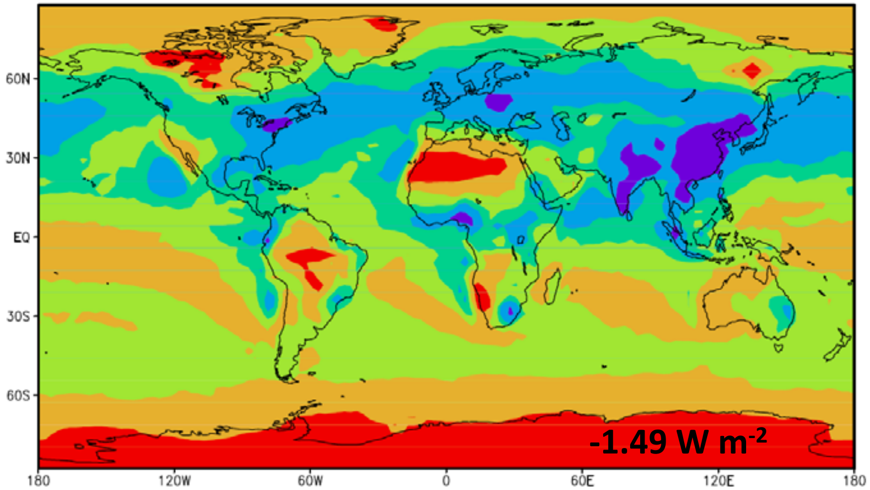


5.81 g m^{-2}

Change in effective radius as seen from satellite



-0.91 µm



-1.49 W m^{-2}

1+2. indirect radiative forcing

Present day:

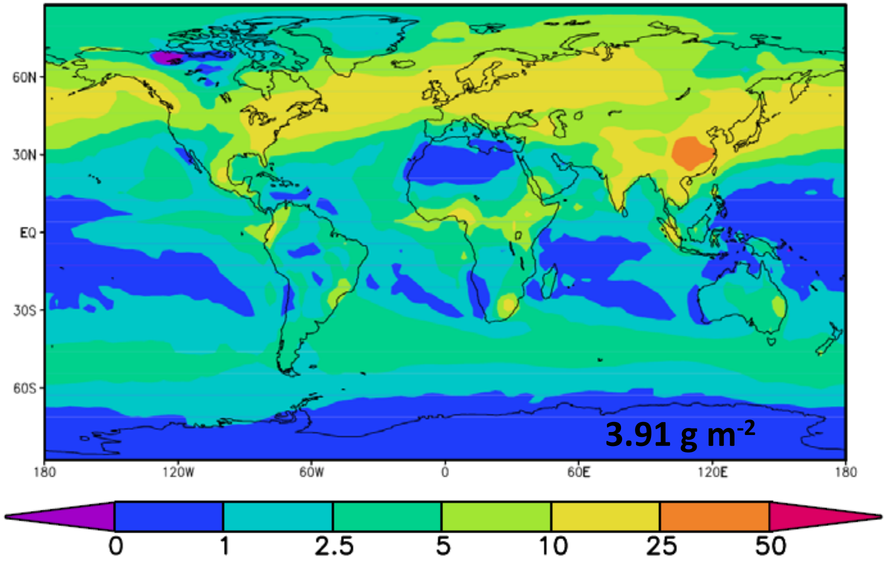
LWP = 133.6 g m^{-2}
Reff = 12.95 µm
CDNCint = 3.95e6 cm^{-2}

Pre-industrial:

LWP = 127.8 g m^{-2}
Reff = 13.87 µm
CDNCint = 2.57e6 cm^{-2}

$CDNC_{min}$ = 10 cm^{-3}

Change in cloud liquid water path



3.91 g m^{-2}

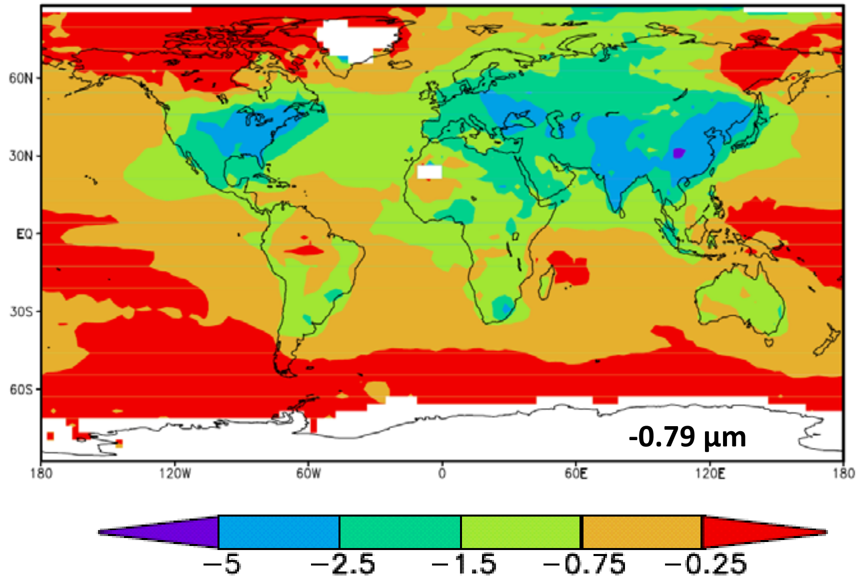
Present day:

LWP = 136.3 g m^{-2}
Reff = 12.64 µm
CDNCint = 3.95e6 cm^{-2}

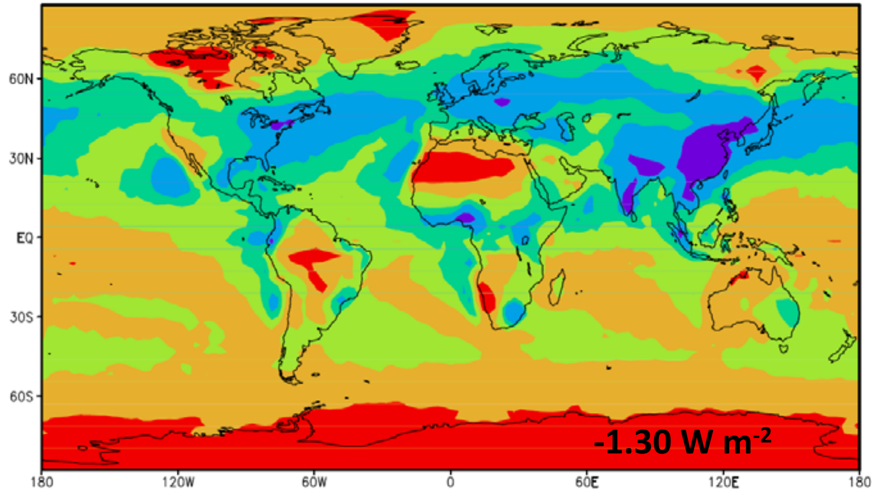
Pre-industrial:

LWP = 132.4 g m^{-2}
Reff = 13.44 µm
CDNCint = 2.57e6 cm^{-2}

Change in effective radius as seen from satellite



-0.79 µm

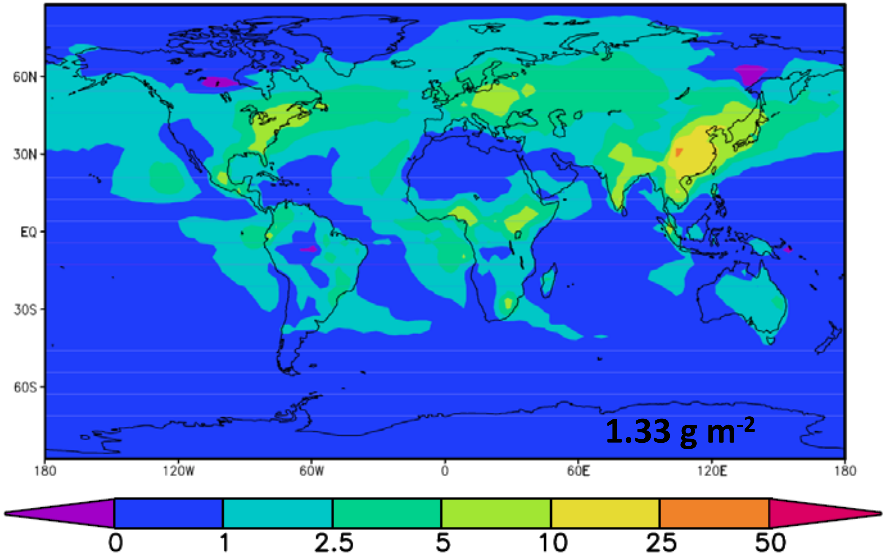


-1.30 W m^{-2}

1+2. indirect radiative forcing

$CDNC_{min}$ = 40 cm^{-3}

Change in cloud liquid water path



Present day:

LWP = 149.4 g m^{-2}

Reff = 10.99 μm

CDNCint = 3.95e6 cm^{-2}

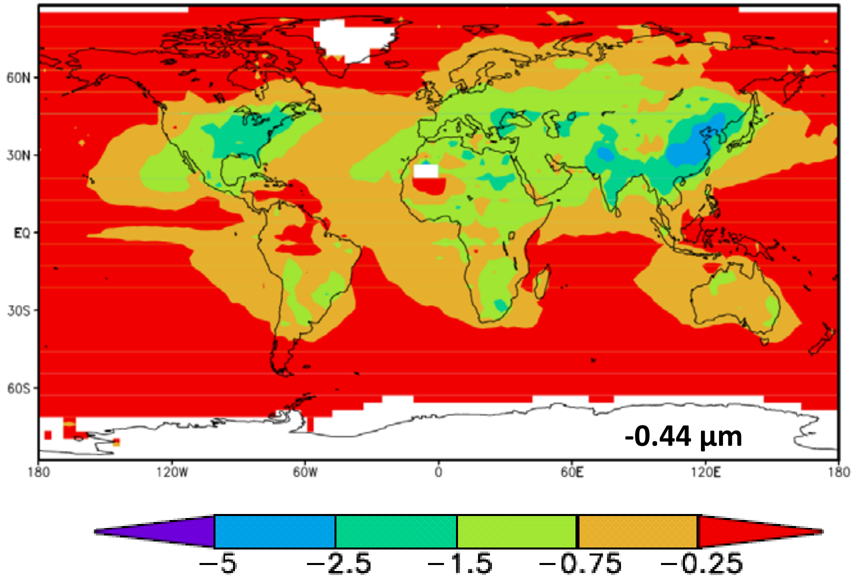
Pre-industrial:

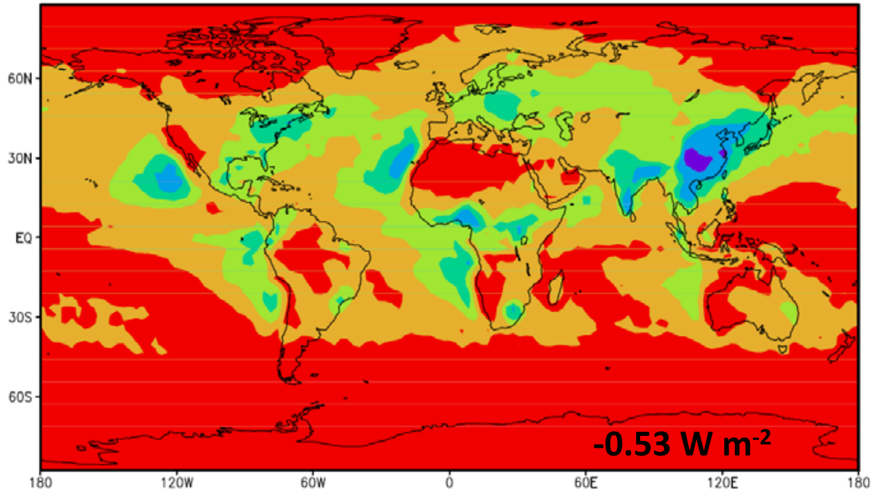
LWP = 148.1 g m^{-2}

Reff = 11.43 μm

CDNCint = 2.57e6 cm^{-2}

Change in effective radius as seen from satellite





1+2. indirect radiative forcing

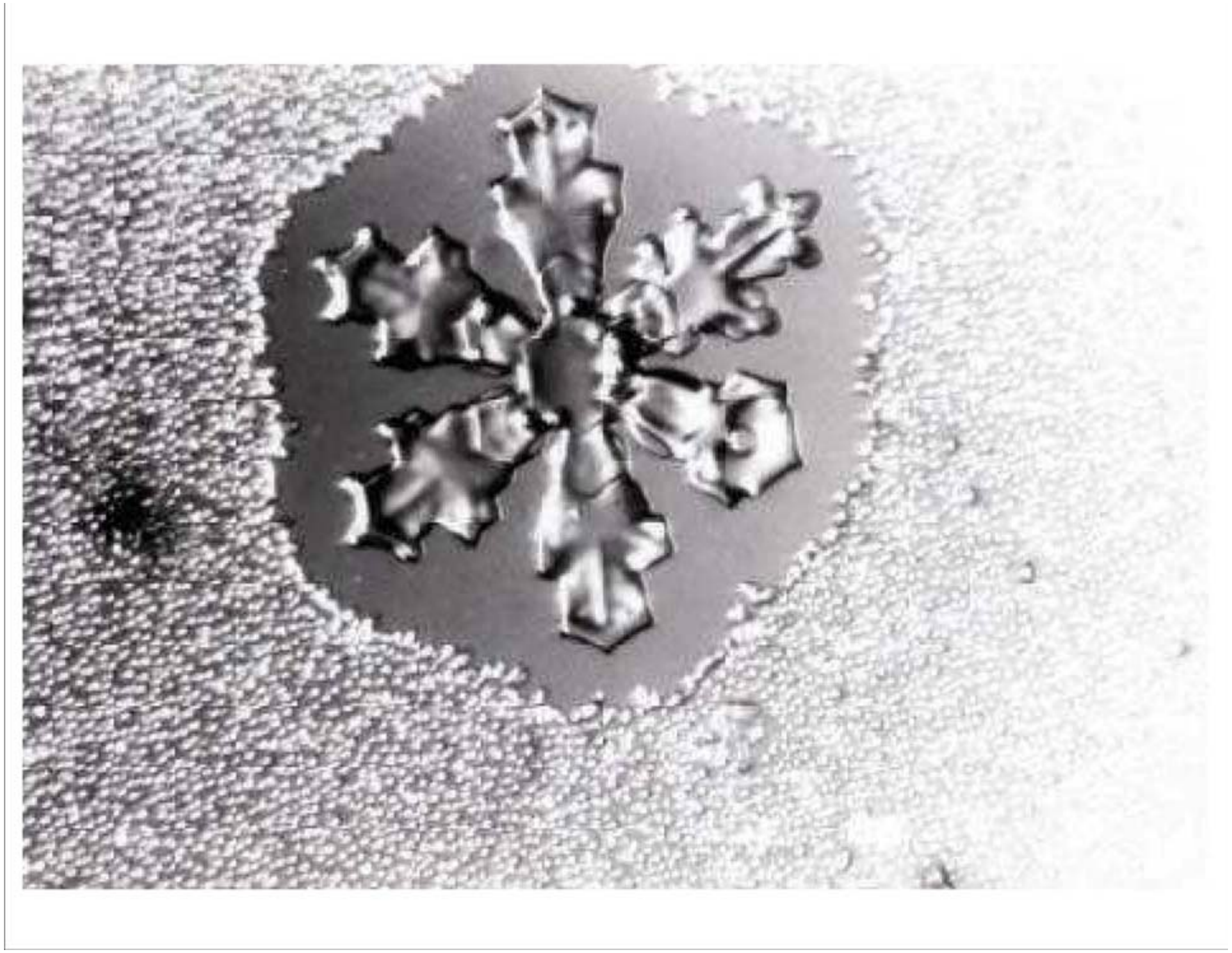
Anthropogenic Ice Nuclei

Picture from Daniel Rosenfeld

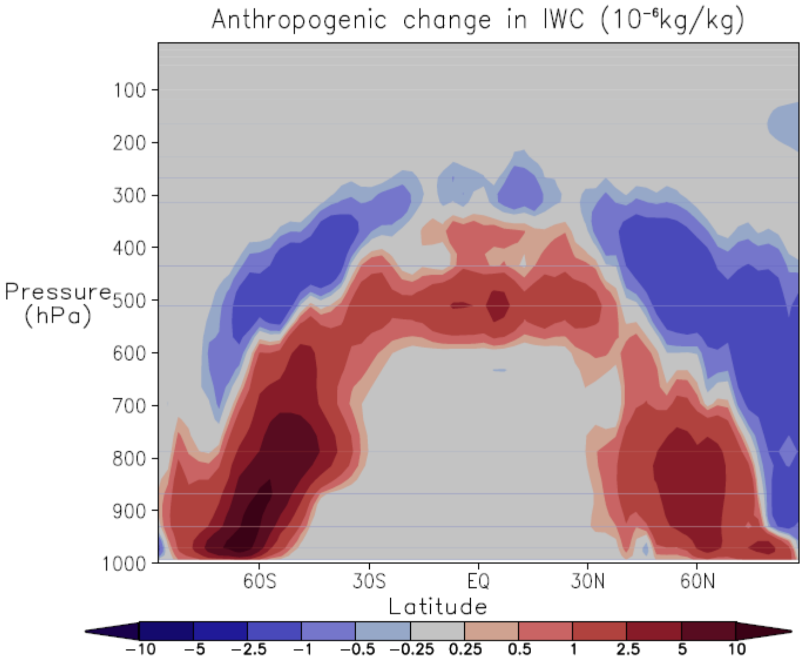
Anthropogenic Ice Nuclei

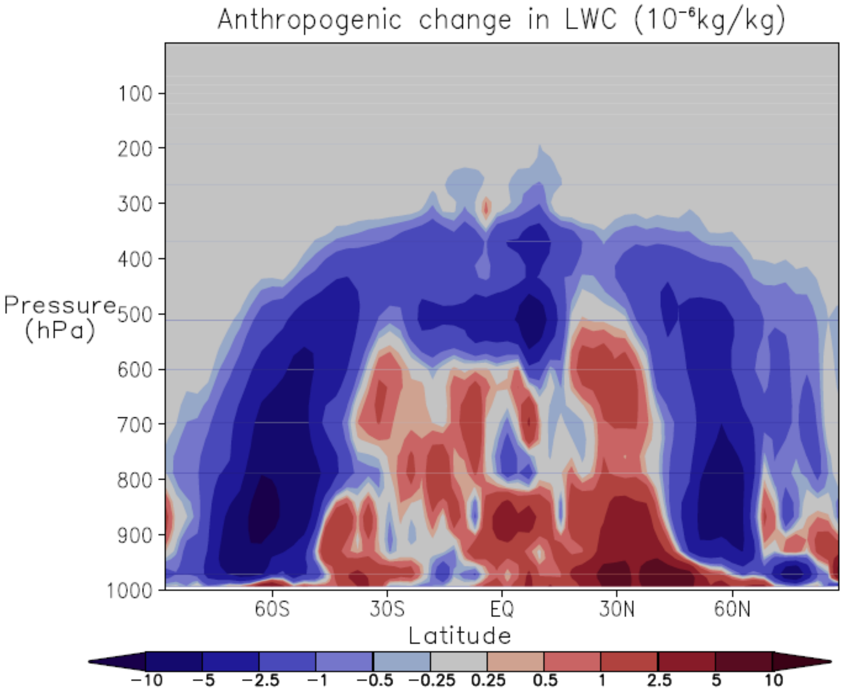
- BC and DU assumed to be both contact nuclei and immersion nuclei; DU less numerous, but operate at higher temperatures than BC
- Parameterization of ice nucleation based on Lohmann and Diehl (2006: JAS)
- Storelvmo et al. (2008: ERL, accepted) introduced a new treatment of the Wegener-Bergeron-Findeisen mechanism, based on Korolev (2007): a gradual transition from supercooled water to ice, rather than an artificial threshold value of IWC

(Wegener-)Bergeron-Findeisen effect: Ice Crystal growth at the expense of water droplets



Changes due to anthropogenic IN and CCN





IWC is increased due to more numerous IN
LWC is decreased at relatively low temperatures due to more IN => - lifetime effect
LWC is increased at relatively high temperature due to more CCN => + lifetime effect

Storelvmo et al. (2008: ERL, accepted)

Aerosol Indirect Effect Estimates with CAM3-Oslo

- Aerosol → cloud interactions for warm clouds only: – 1.8 W m^{-2}, due to decreased Droplet Size, increased Liquid Water Path
- Aerosol → cloud interactions for warm and mixed-phase clouds: Between – 1.7 W m^{-2} and + 0.05 W m^{-2}, depending on assumptions on coating; mineral dust treatment, treatment of WBF process, etc.
- This reduction in AIE is caused by a reduced cloud life-time of the clouds due to enhanced glaciation
- In mixed-phase clouds there is a significant contribution from changes in longwave radiative forcing

Summary and Conclusions

- The Aerosol Indirect Effect (AIE) is Highly Sensitive to Treatment of Background Aerosols: Thin Background => Large AIE
- Constraining AIE with imposed thresholds on cloud properties is problematic
- AIE for Warm Clouds => Cooling due to larger cloud albedo and positive lifetime effect
- AIE for Mixed-Phase Clouds => considerable cancellation of the cooling because of a negative lifetime effect

The End

http://www.uio.no/~jegill

Photo: Michael Gauss

Continuity equation for cloud droplet number concentration

$$\frac{dN_l}{dt} = A_{N_l} + \underbrace{Nucl}_{\textit{Ghan/Abdul-Razzak (2000)}} - \frac{N_l}{q_l}\underbrace{(AC + Coll + Accr - E)}_{\textit{Rasch/Kristjánsson (1998)}} - Self + Mlt - Frz$$

N_l = Cloud droplet number concentration (#/cm^3)

A_{Nl}= Transport (advection, convection & turbulence) of cloud droplets.

q_l= Mixing ratio for cloud water (liquid phase)

Nucl = Nucleation of cloud droplets

AC = Loss of cloud droplets due to auto-conversion of cloud droplets

Coll = Loss of cloud droplets due to collection of cloud droplets by rain

Accr = Loss of cloud droplets due to collection of cloud droplets by snow

E = Evaporation of cloud droplets

Self = Self-collection of cloud droplets

Mlt = Melting of ice crystals

Frz = Freezing of cloud droplets

Storelvmo et al. (2006): JGR

Continuity equation for ICNC

$$\frac{dN_i}{dt} = A_{N_i} - \frac{N_i}{q_i}(AC_{ice} + Agg + Subl) - Dep + Frz - Mlt + Multi$$

N_i = Ice crystal number concentration (#/cm^3).

A_{Ni}= Transport (advection, convection & turbulence) of ice crystals.

q_i= Mixing ratio for ice crystals (inside cloud).

AC_{ice} = Loss of ice crystal number due to “auto-conversion” of ice crystals.

Agg = Loss of ice crystal number due to collection of ice crystals by snow.

Subl = Sublimation of ice crystals.

Dep = Deposition of water vapor onto ice crystals

Frz = Freezing of cloud droplets

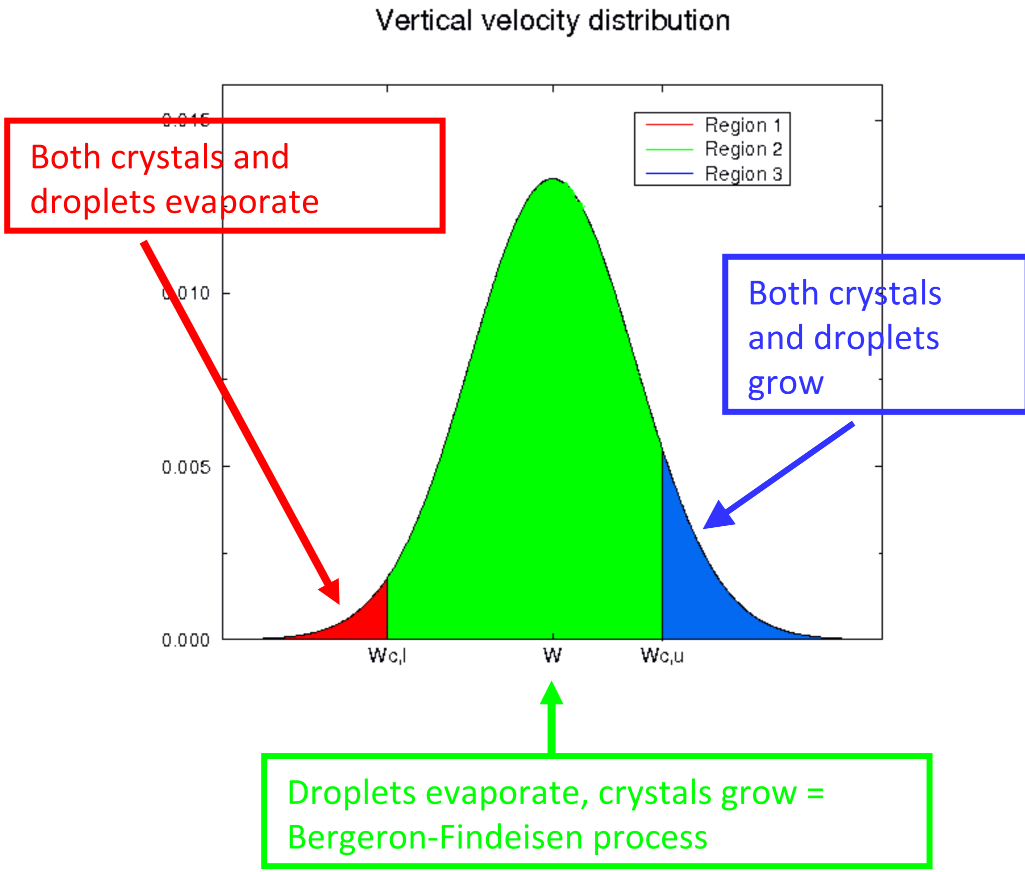
Mlt = Melting of ice crystals

Multi = Ice multiplication (Hallett-Mossop)

Storelvmo et al. (2008: JAS, in press)

Improved treatment of Bergeron-Findeisen mechanism

- *Korolev (2007: JAS):* B-F mechanism only effective if $e_i < e < e_s$
- Criterion can be reformulated in terms of updraft speed
- Condition for B-F can be determined from (resolved) environmental conditions



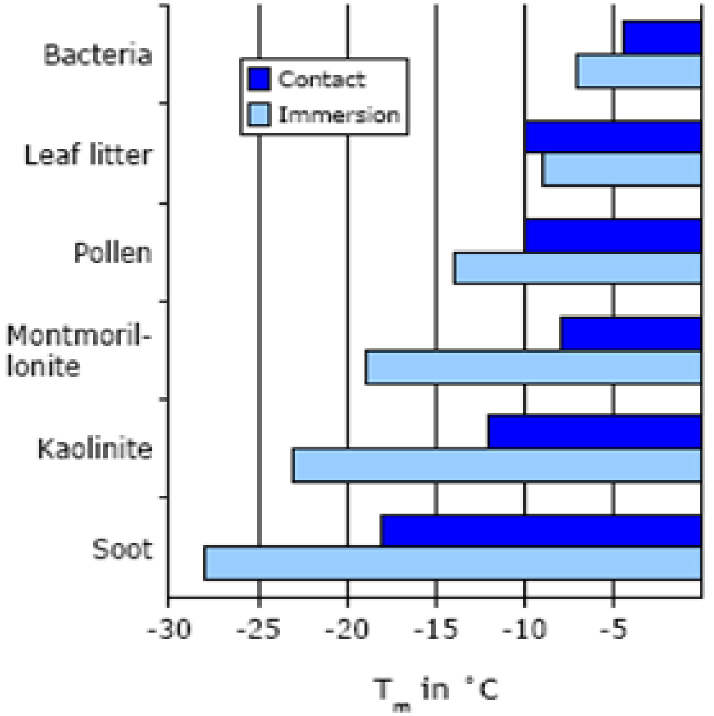
Both crystals and droplets evaporate

Both crystals and droplets grow

Droplets evaporate, crystals grow = Bergeron-Findeisen process

Storelvmo et al. (2008: ERL, accepted)

Heterogeneous Nucleation



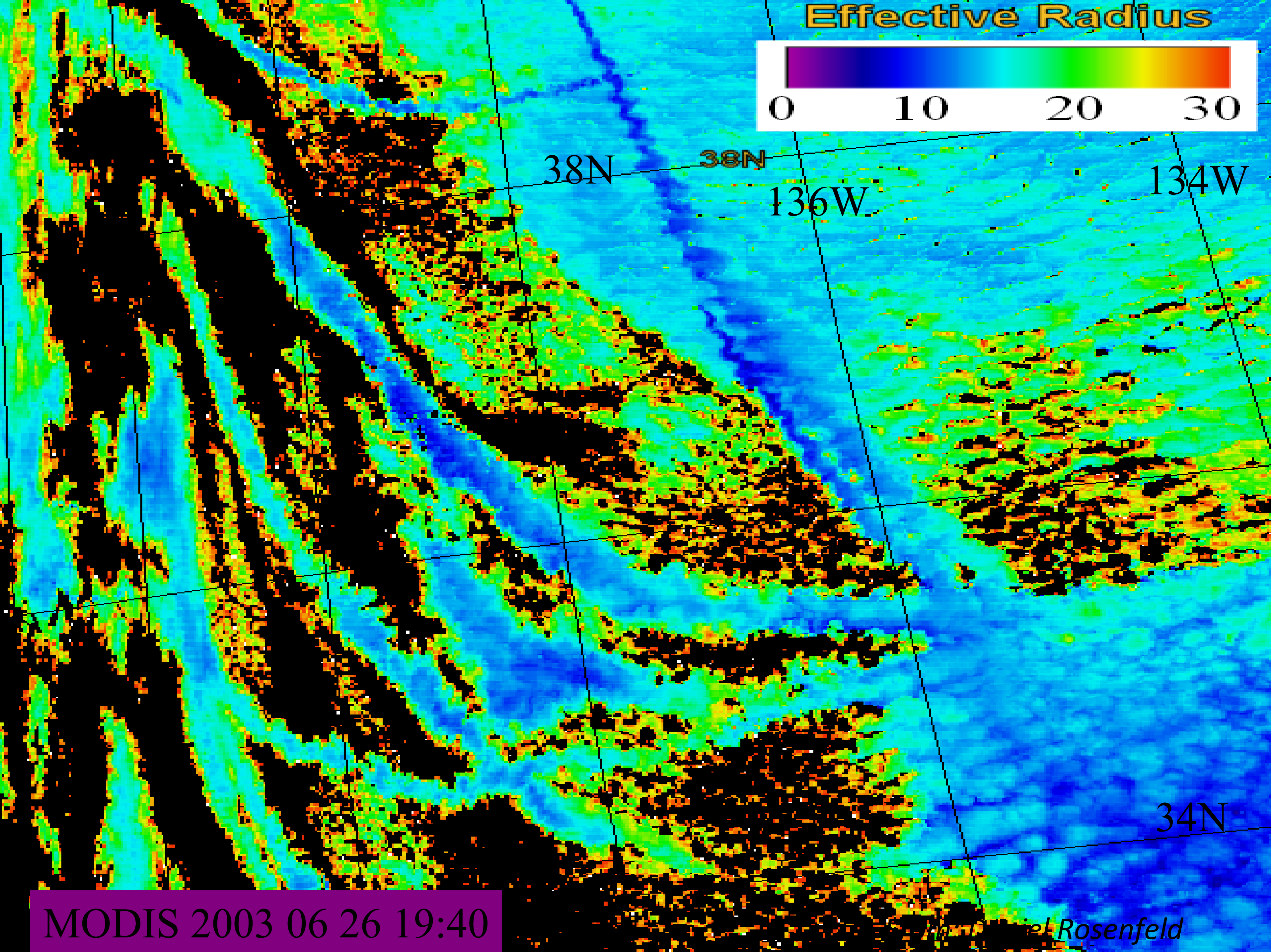
Median freezing temperatures for different IN from lab experiments. Drop radii 250-350 µm. Adapted from *Diehl et al. (subm.)*.

- The activation temperature, T_m, varies between different nuclei
- T_m higher for contact freezing than for immersion freezing

From: Corinna Hoose

Problem Definition

- Most GCMs give an aerosol indirect effect which is too high compared to results from residual calculations – Why?
- Many models have built in constraints on parameter values that keep the indirect effect within reasonable bounds – Is this justifiable?
- What can be done?



MODIS 2003 06 26 19:40

From: Daniel Rosenfeld

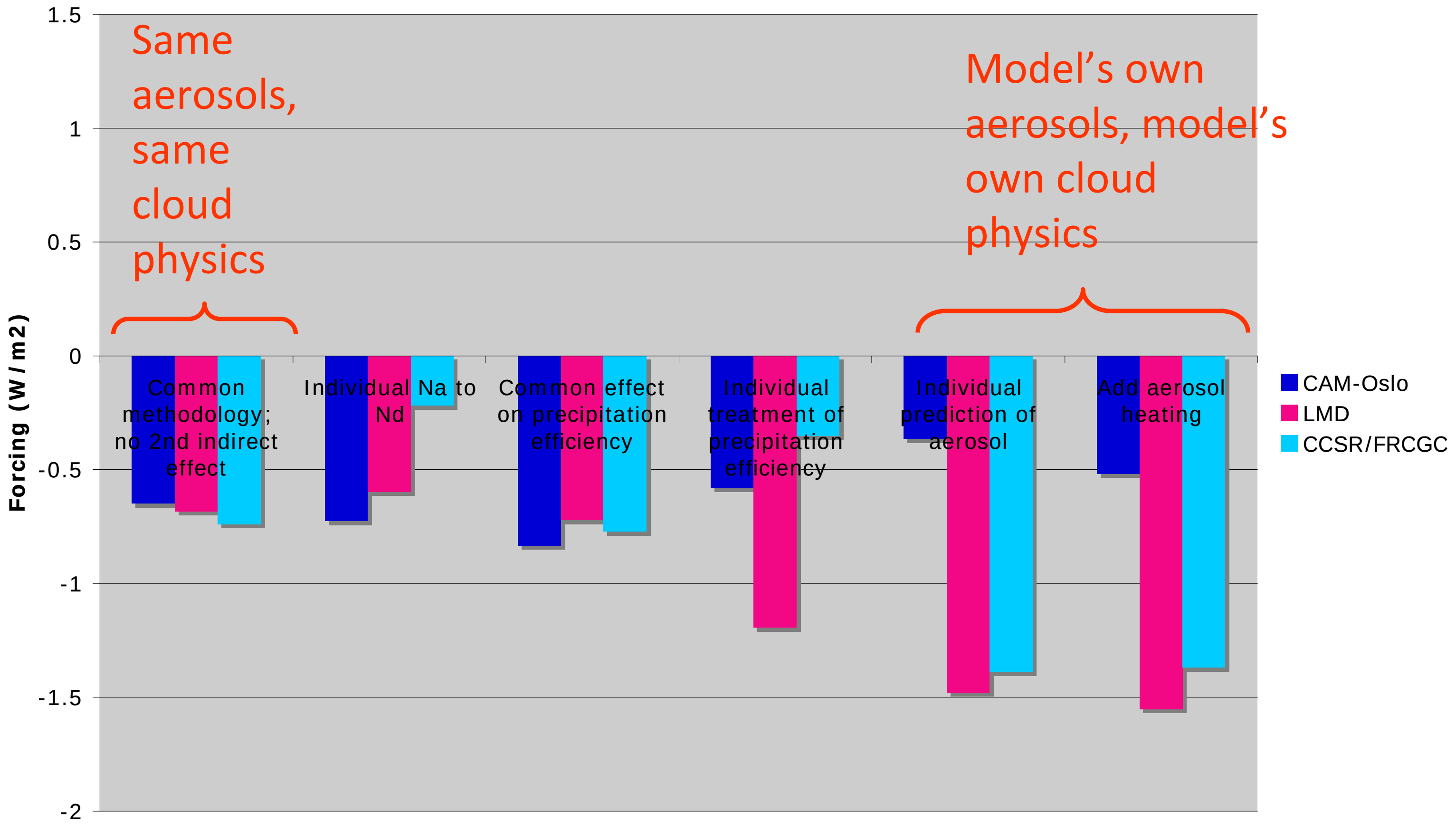
Aerosol -> cloud interactions

- CCN: Hygroscopic particles (Sea Salt, Sulfate)
- More CCN: Warm clouds more reflective to solar radiation (*Albedo Effect, Lifetime Effect*)
- More CCN: Delayed freezing and enhanced vertical extent of mixed-phase clouds (*Thermodynamic Effect*)

- IN are non-hygroscopic, crystalline aerosols (Min. Dust, Black Carbon)
- More IN: Enhanced precipitation release from mixed-phase clouds (*Glaciation Effect*)

- Suggestions that coating may in extreme cases lead to de-activation of IN (*Girard et al., 2005: Atm.Res.*)

Indirect forcing in 3 GCMs



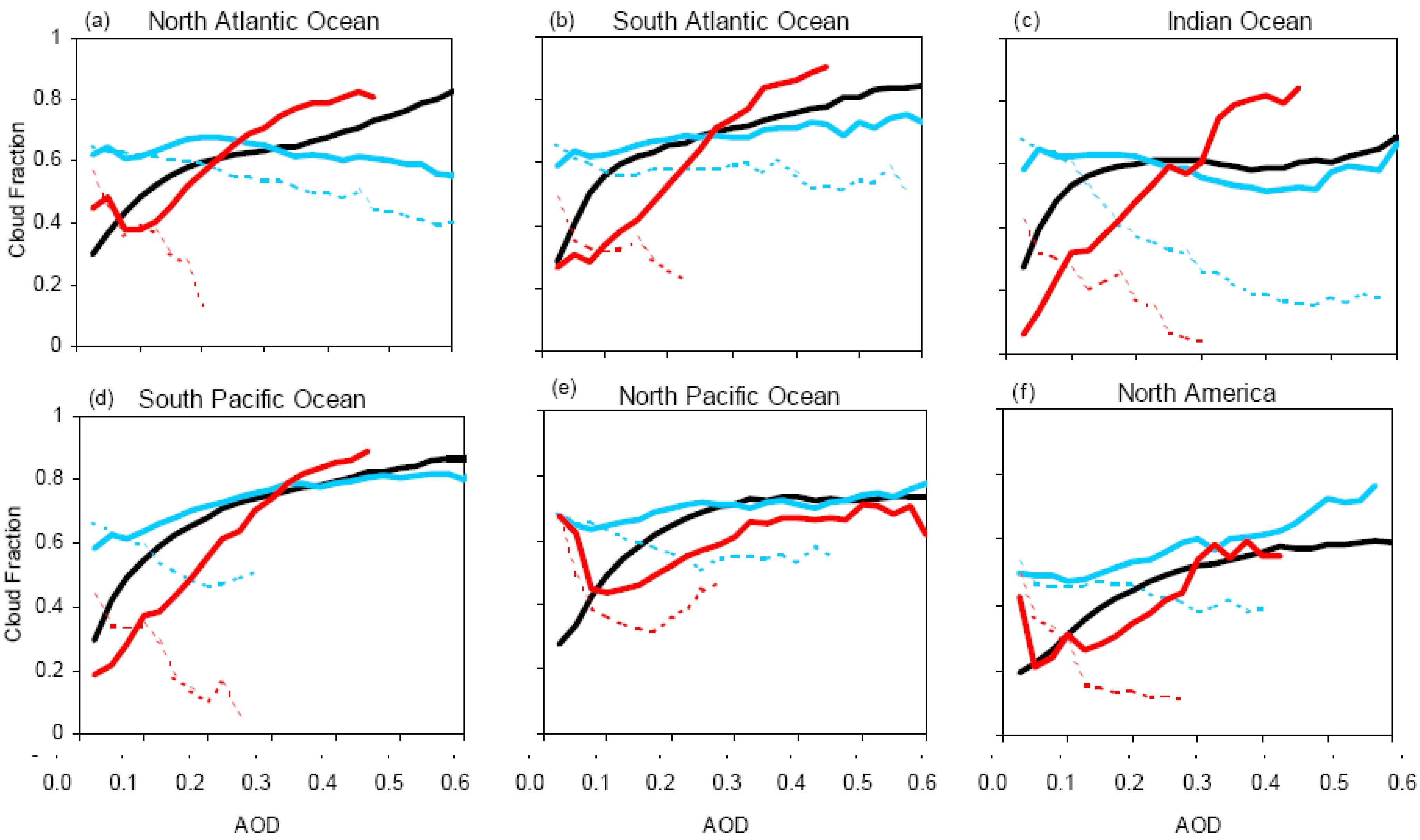
Penner et al. (2006: ACP)

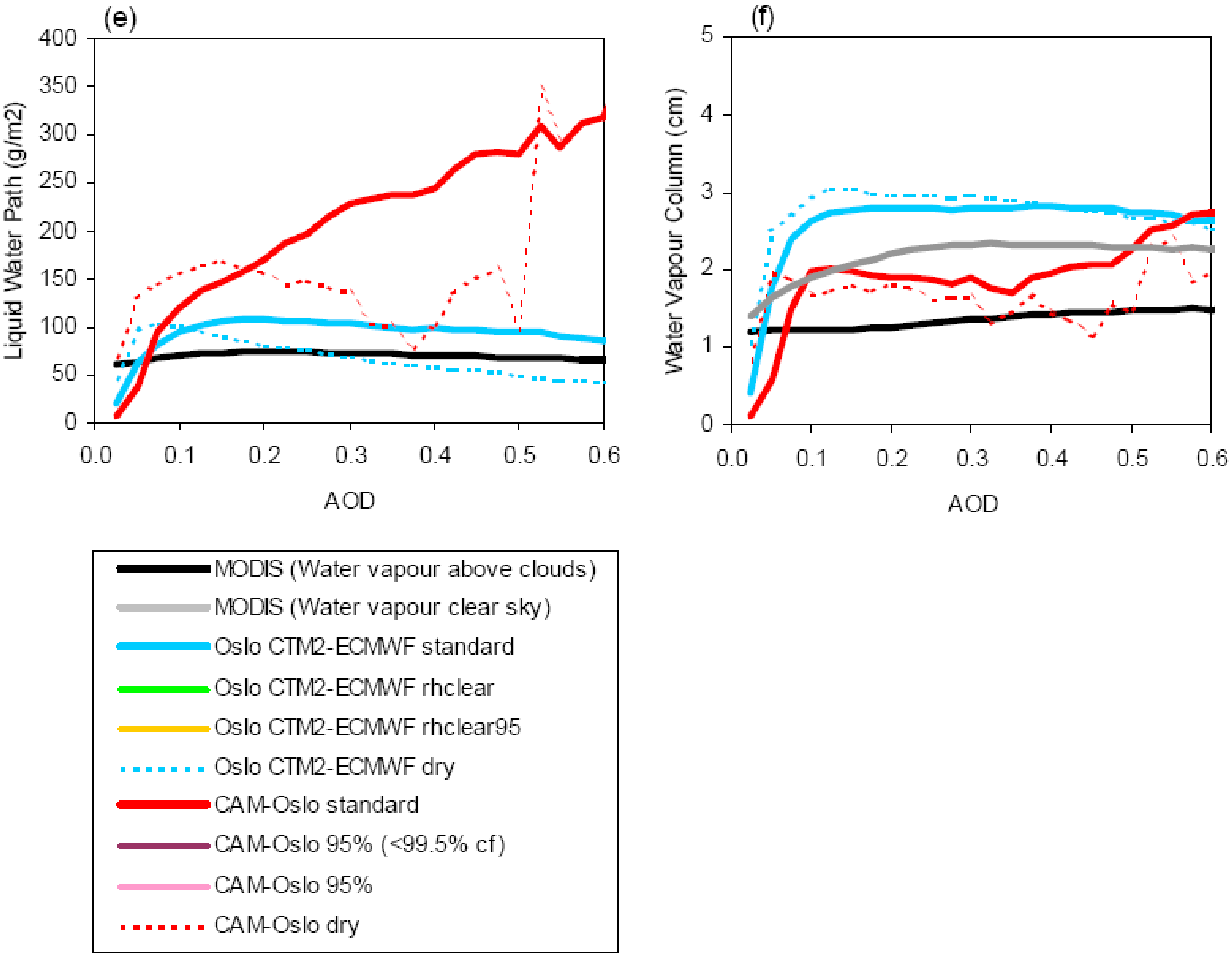
Aerosol Indirect Effect Estimates with CAM2-Oslo

- Aerosol → cloud interactions for warm clouds only: - 0.49 Wm^{-2}, due to decreased Droplet Size, increased Liquid Water Path
- Aerosol → cloud interactions for warm and mixed-phase clouds: Between - 0.07 Wm^{-2} and - 0.27 Wm^{-2}, depending on assumptions on coating; significant changes in Ice Water Path and Liquid Water Path
- This reduction in AIE is caused by: a) a reduced cloud life-time of the clouds due to glaciation; b) longwave radiative forcing

Cloud Fraction vs. AOD: GCM and MODIS

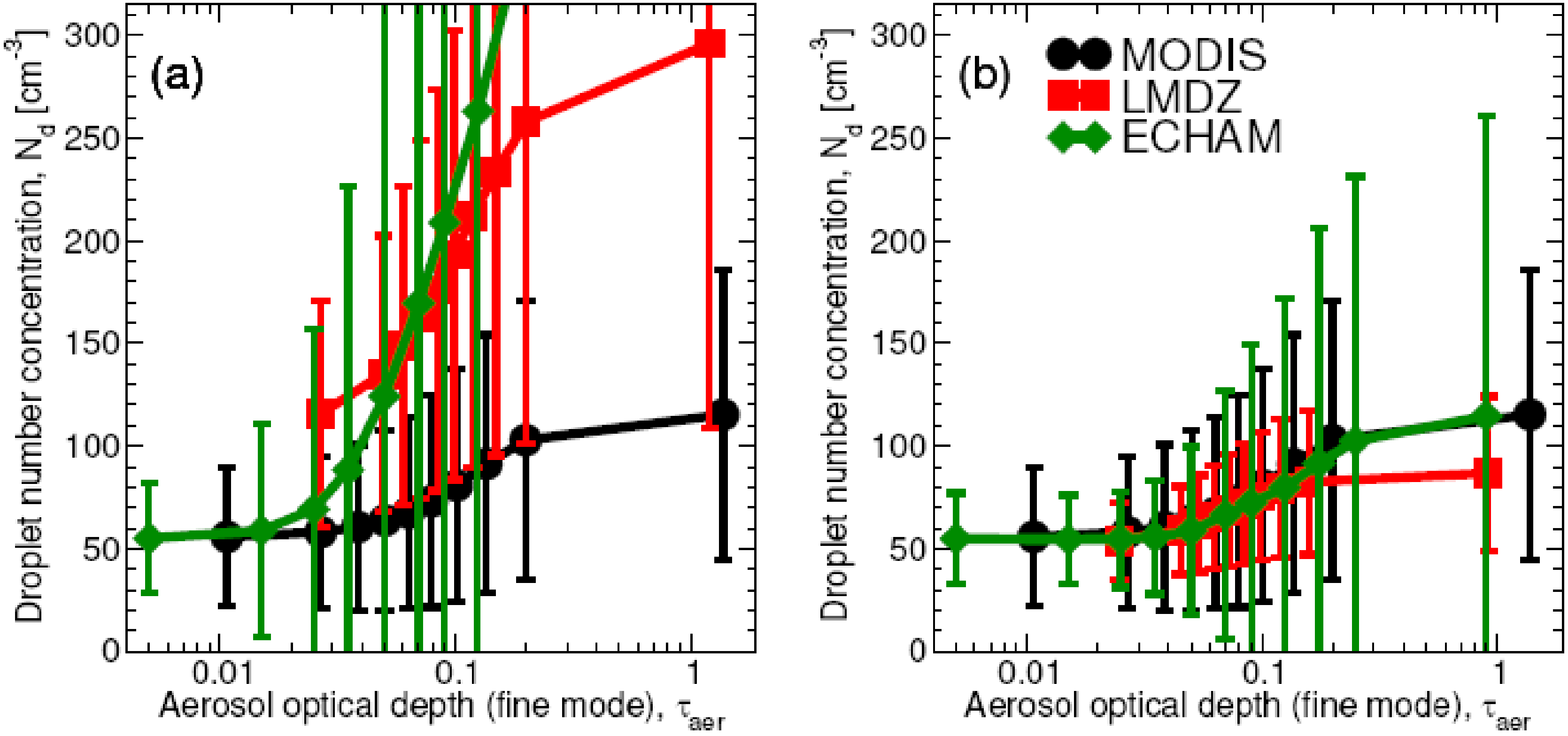
Myhre et al. (2007: ACP)





Myhre et al. (2007: ACP)

Constraining the indirect effect with observations


ORIGINAL

ADJUSTED

Quaas et al. (2006: ACP)

Constraining the indirect effect with observations

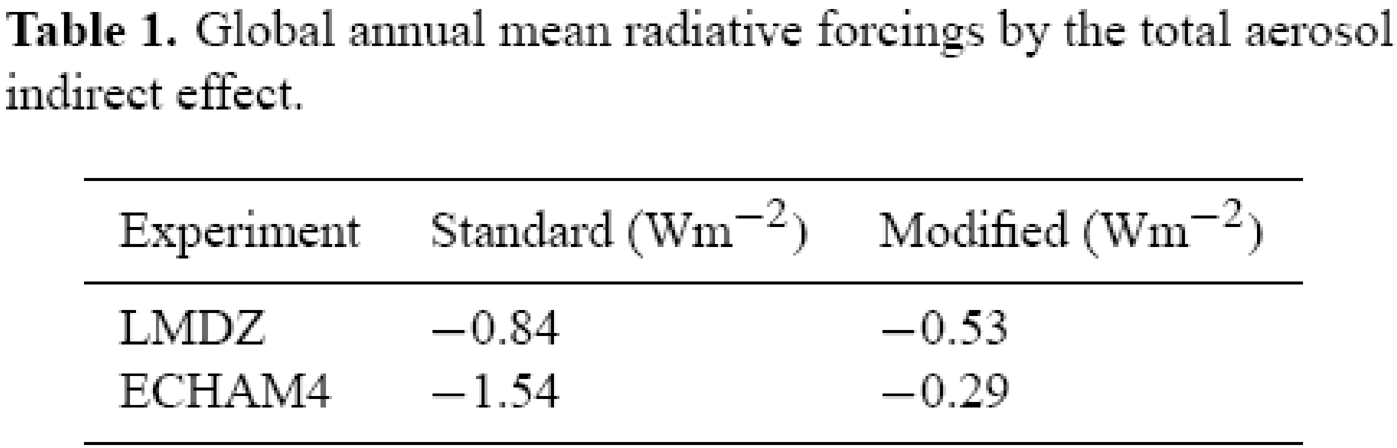
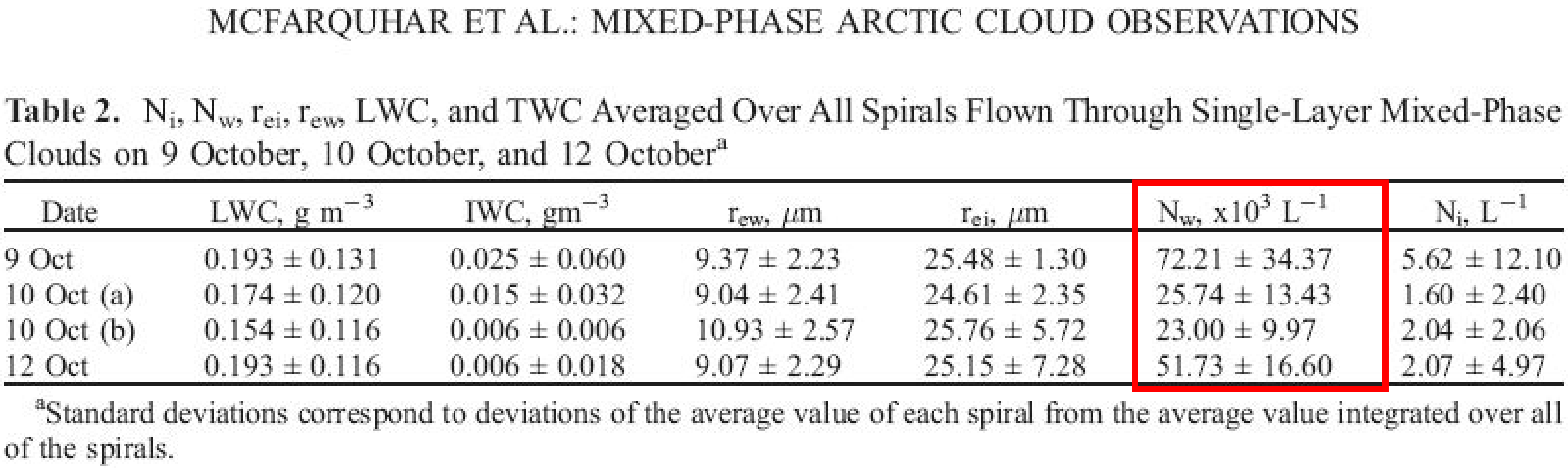


Table 1. Global annual mean radiative forcings by the total aerosol indirect effect.

Experiment	Standard (Wm^{-2})	Modified (Wm^{-2})
LMDZ	−0.84	−0.53
ECHAM4	−1.54	−0.29

Quaas et al. (2006: ACP)



MCFARQUHAR ET AL.: MIXED-PHASE ARCTIC CLOUD OBSERVATIONS

Table 2. N_i, N_w, r_{ei}, r_{ew}, LWC, and TWC Averaged Over All Spirals Flown Through Single-Layer Mixed-Phase Clouds on 9 October, 10 October, and 12 October[a]

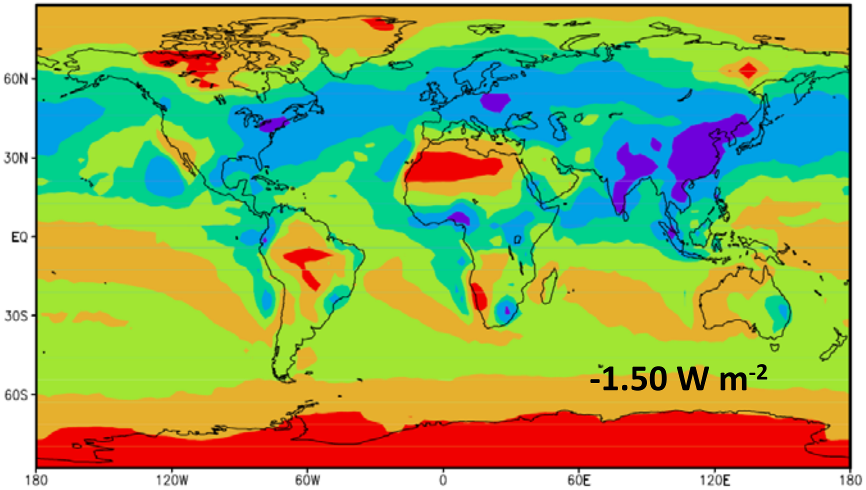
Date	LWC, g m^{-3}	IWC, gm^{-3}	r_{ew}, μm	r_{ei}, μm	N_w, x10^3 L^{-1}	N_i, L^{-1}
9 Oct	0.193 ± 0.131	0.025 ± 0.060	9.37 ± 2.23	25.48 ± 1.30	72.21 ± 34.37	5.62 ± 12.10
10 Oct (a)	0.174 ± 0.120	0.015 ± 0.032	9.04 ± 2.41	24.61 ± 2.35	25.74 ± 13.43	1.60 ± 2.40
10 Oct (b)	0.154 ± 0.116	0.006 ± 0.006	10.93 ± 2.57	25.76 ± 5.72	23.00 ± 9.97	2.04 ± 2.06
12 Oct	0.193 ± 0.116	0.006 ± 0.018	9.07 ± 2.29	25.15 ± 7.28	51.73 ± 16.60	2.07 ± 4.97

[a] Standard deviations correspond to deviations of the average value of each spiral from the average value integrated over all of the spirals.

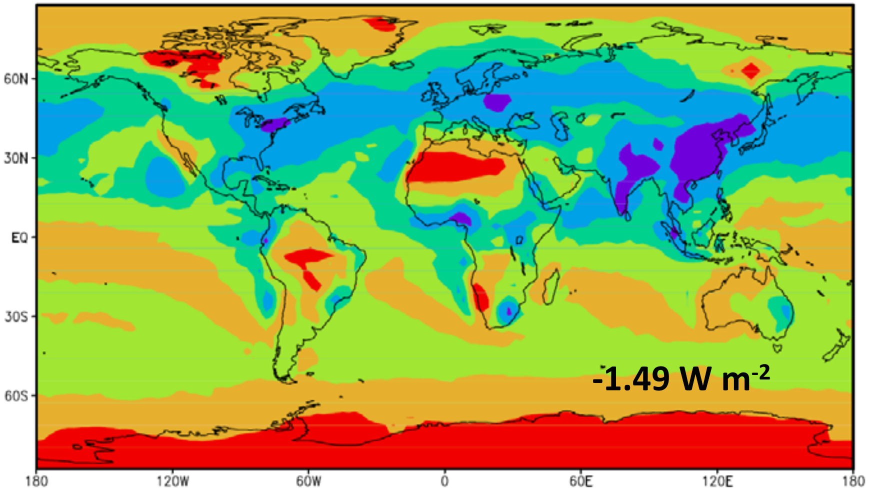
McFarquhar et al. (2007: JGR)

Tests with CAM3-Oslo (1-year runs)

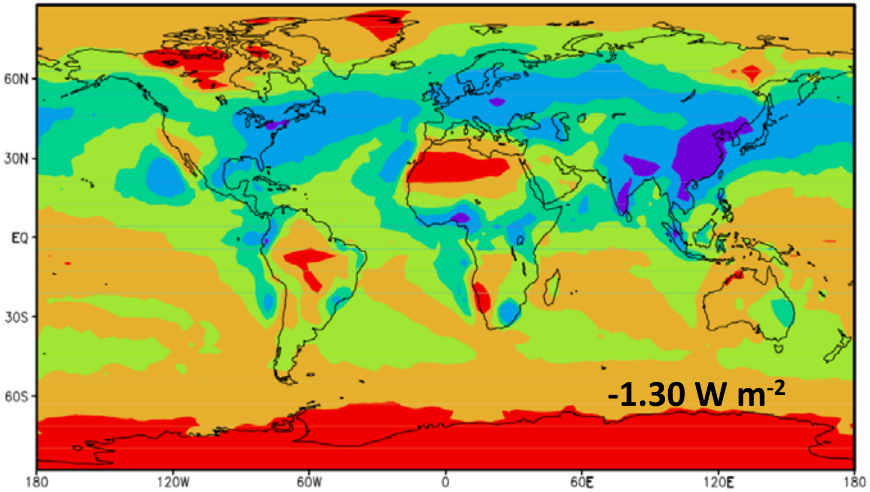
no cut-off on CDNC



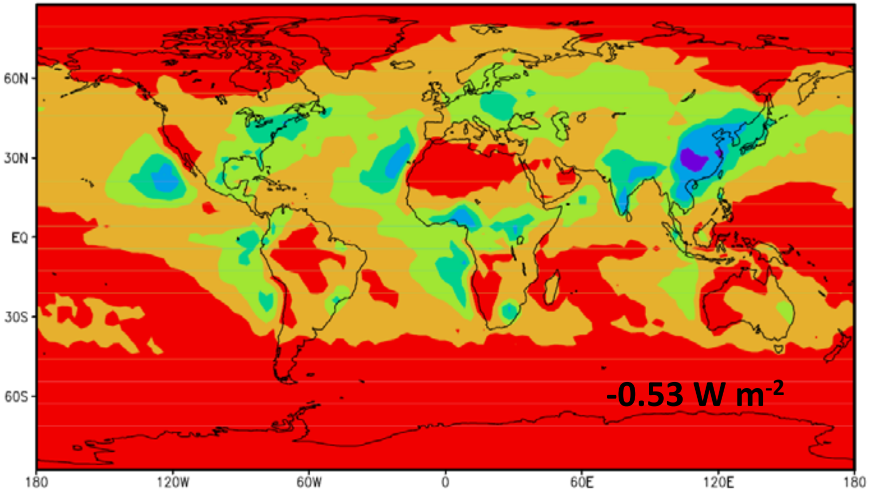
$CDNC_{min}$ = 1 cm^{-3}



$CDNC_{min}$ = 10 cm^{-3}



$CDNC_{min}$ = 40 cm^{-3}



Anthropogenic Ice Nuclei Weaken Cloud Lifetime Effect

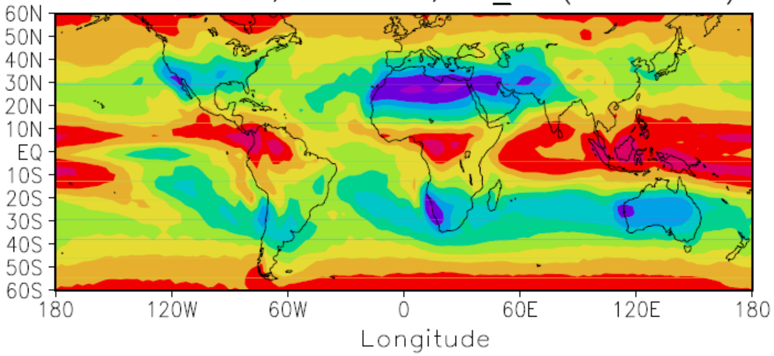
Exp. →	LIQUID	CONTROL	KAOLINITE	LESS DUST	COATING
ΔLWP (g m^{-2})	+ 0.87	- 0.07	- 0.32	+ 0.68	+ 0.64
ΔIWP (g m^{-2})	- 0.04	+ 0.20	+ 0.36	+ 0.52	- 0.46
ΔR_{eff} (μm)	- 0.44	- 0.33	- 0.32	- 0.41	- 0.43
INDIR (W m^{-2})	- 0.49	- 0.07	- 0.10	- 0.18	- 0.27

Storelvmo et al. (2008: J.Atm.Sci., in press)

Cloud Amount

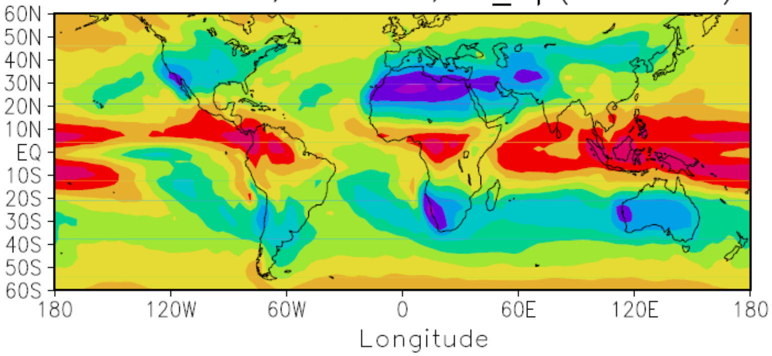
CONTROL: With mixed-phase param.

Cloud Fraction, CAM–Oslo, AIE_ctl (ave. 64.8%)



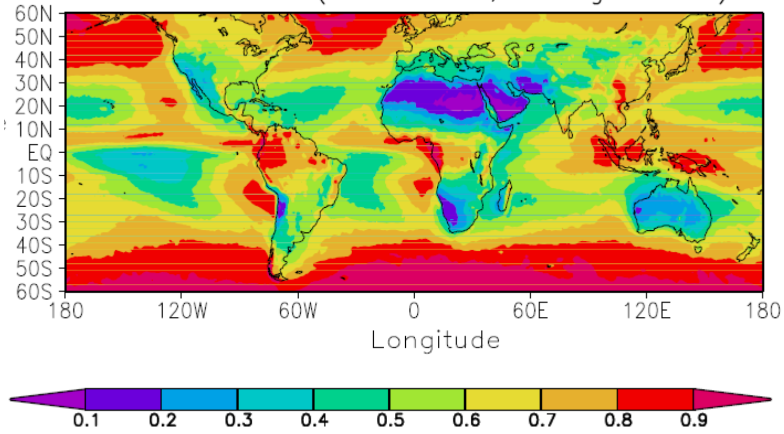
LIQUID: Without mixed-phase param.

Cloud Fraction, CAM–Oslo, AIE_liq (ave. 60.5%)



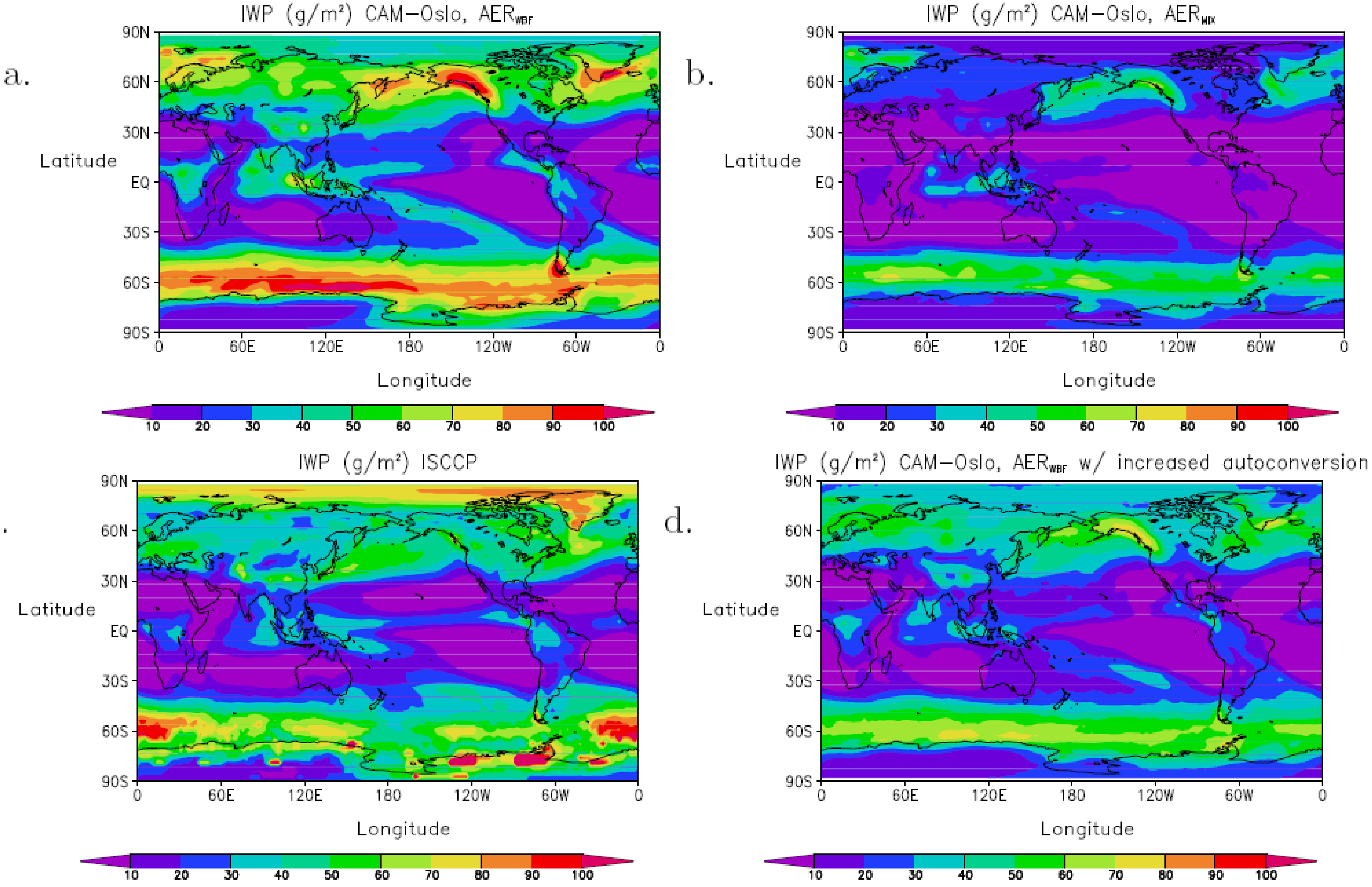
Observed by MODIS

Cloud Fraction (2001–2003, average 65.0%)



Storelvmo et al. (2008: JAS, in press)

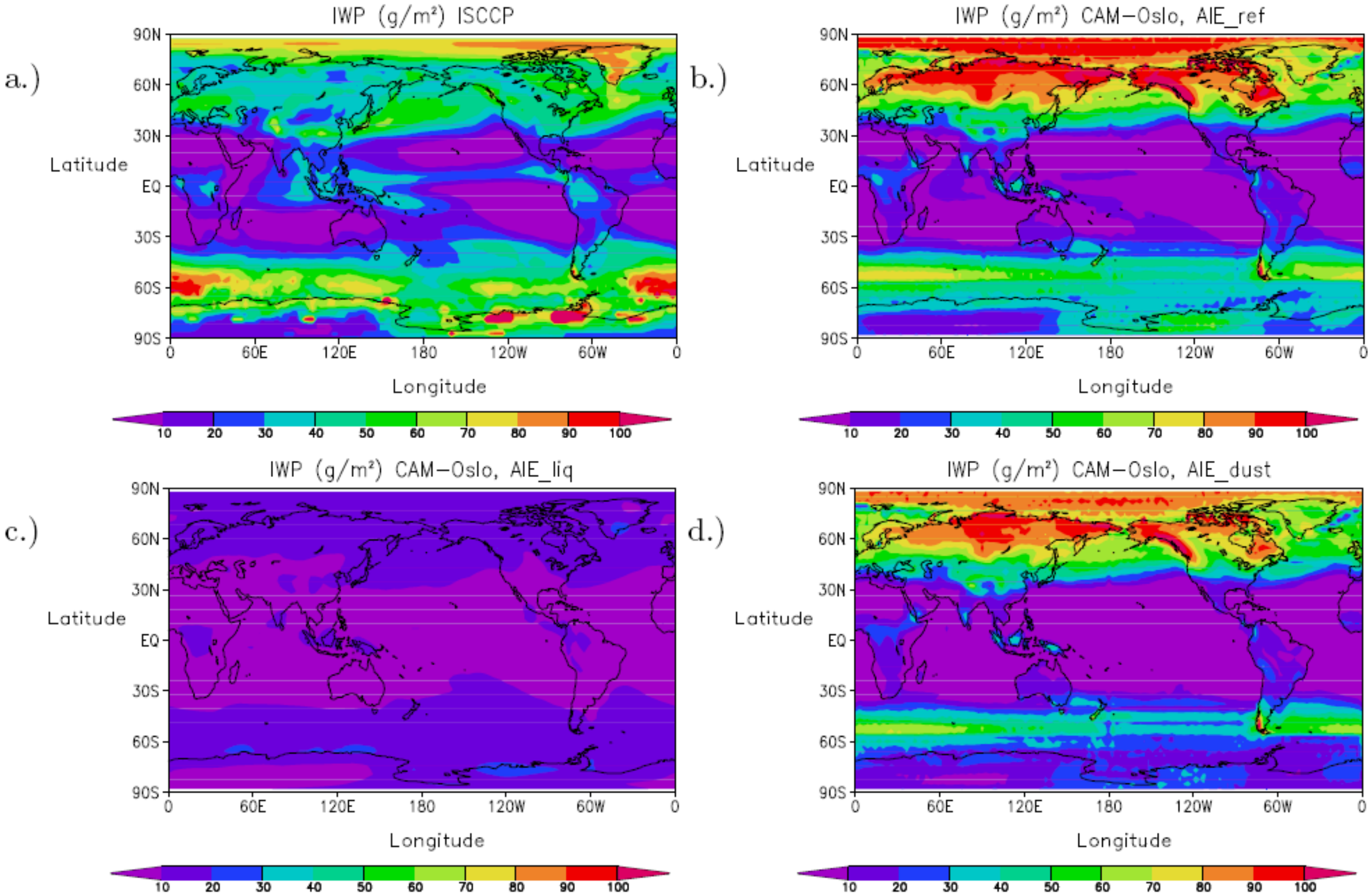
Ice Water Path (CAM3-Oslo)



Ice Water Path simulations improved due to new B-F formulation

Storelvmo et al. (2008: ERL, accepted)

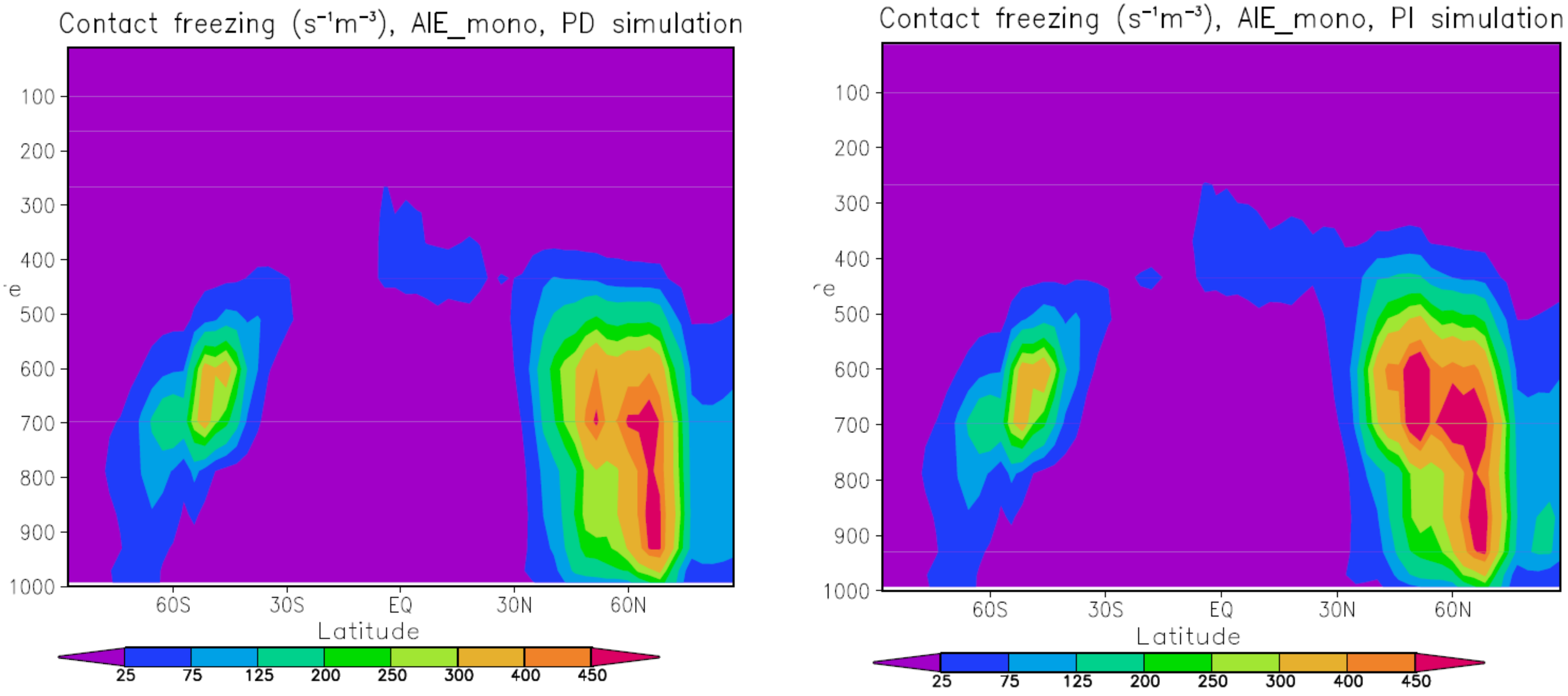
Ice Water Path (CAM2-Oslo)



Ice Water Path simulations improved, but overestimated in the Arctic

Storelvmo et al. (2008: JAS, in press)

Sensitivity to coating by ammonium sulfate



Present-day aerosols

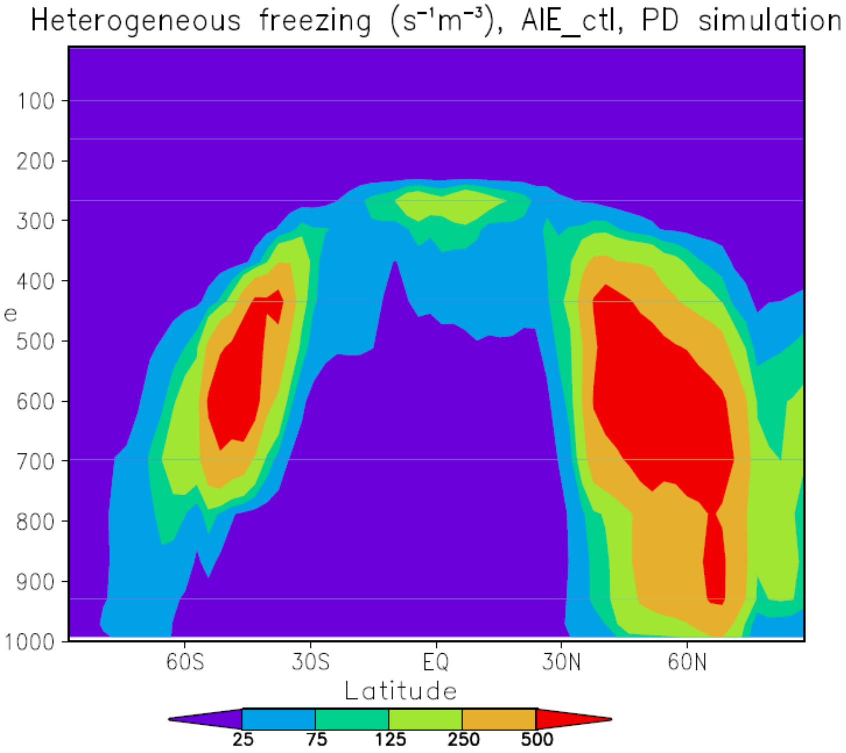
Pre-industrial aerosols

Reduced freezing rate in polluted conditions, due to enhanced sulfate coating

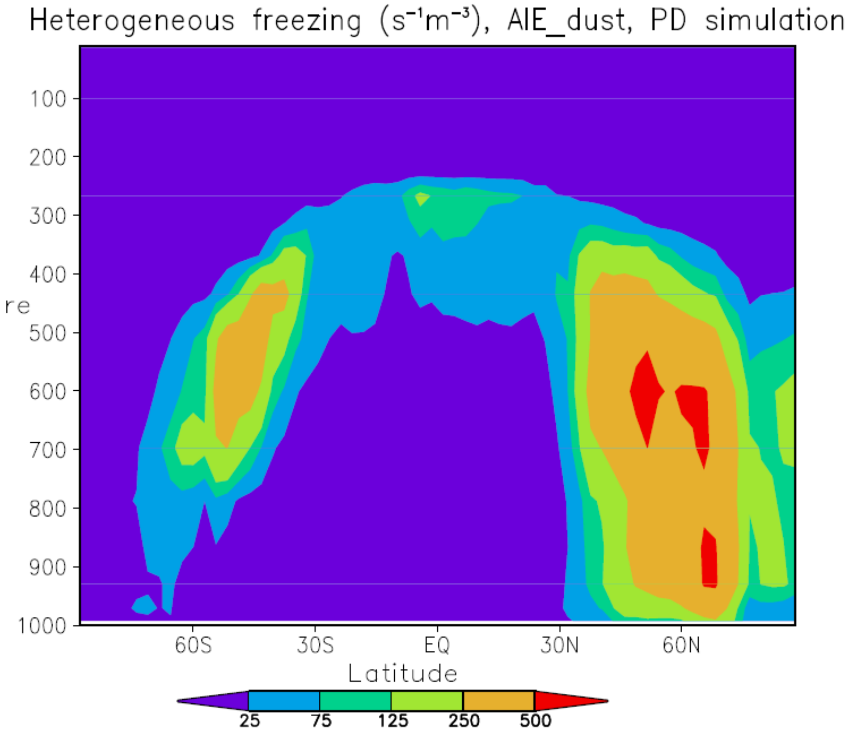
Storelvmo et al. (2008: JAS, in press)

Sensitivity of heterogeneous freezing to mineral dust

CONTROL



DUST: Min. dust concentrations reduced

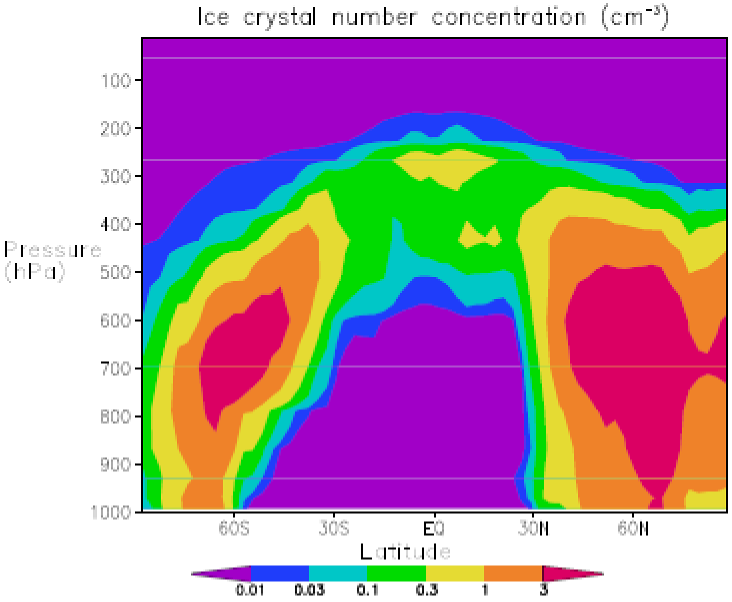


Reduced mineral dust concentrations => Reduced freezing => Larger indirect forcing

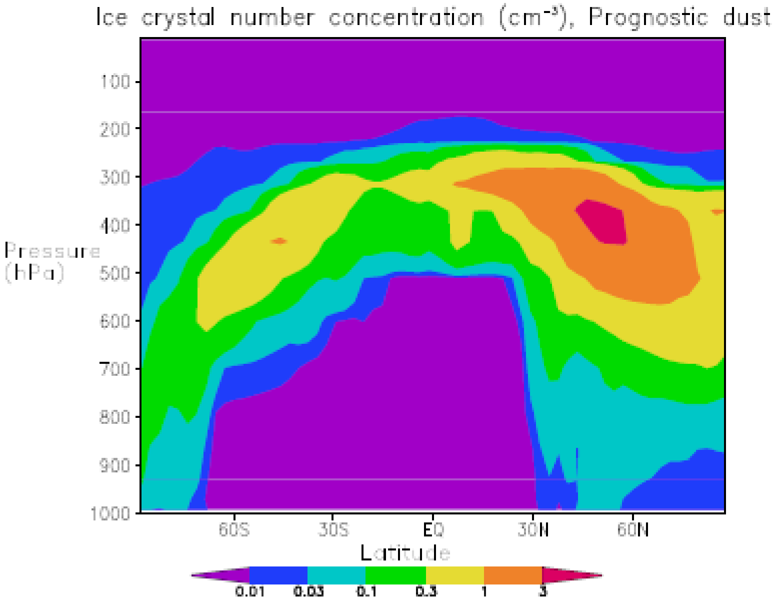
Storelvmo et al. (2008: J.Atm.Sci., in press)

Ice Crystal Number Concentrations

CONTROL (CAM2-Oslo)



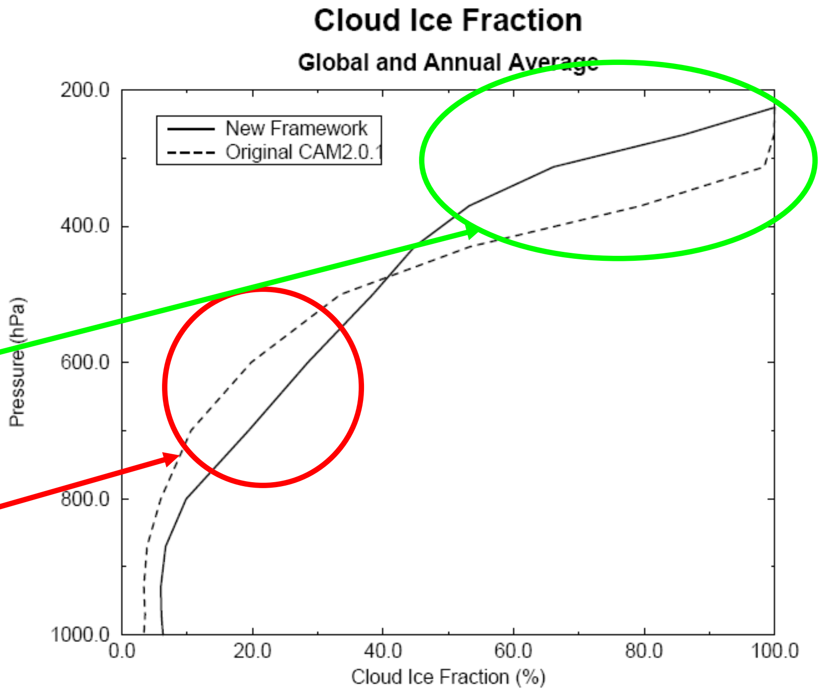
CAM3-Oslo with prognostic dust



Storelvmo et al. (2008: J.Atm.Sci., in press)

Liquid / ice phase in clouds predicted, not prescribed

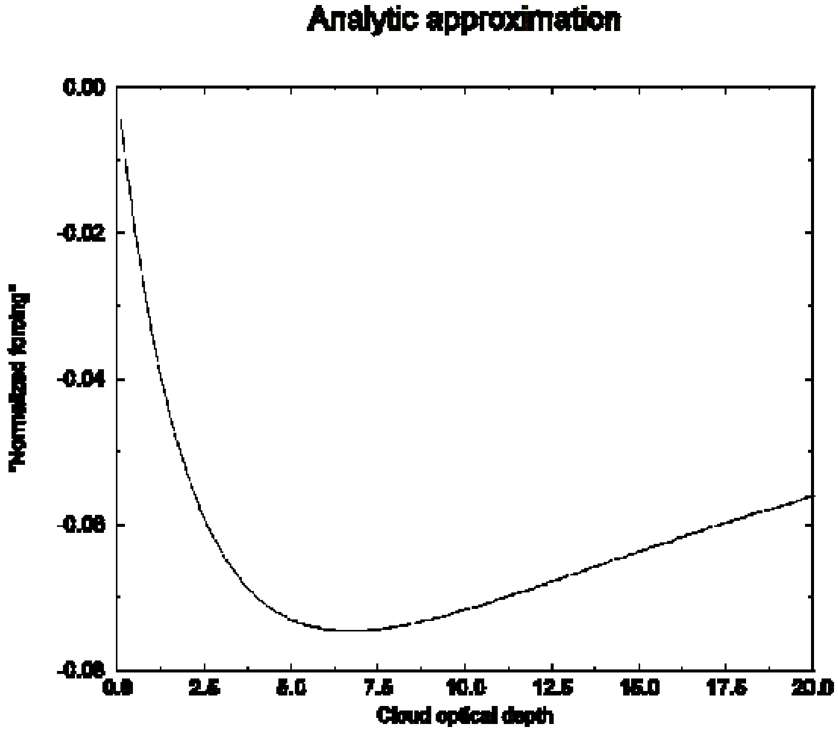
- Previously, cloud liquid / ice distinction was a prescribed function of temperature (dashed)
- Now it is computed, based on sources and sinks of condensate (solid)
- Low T: More supercooled water than before
- High T: More cloud ice than before



Storelvmo et al. (2008: J. Atm. Sci., in press)

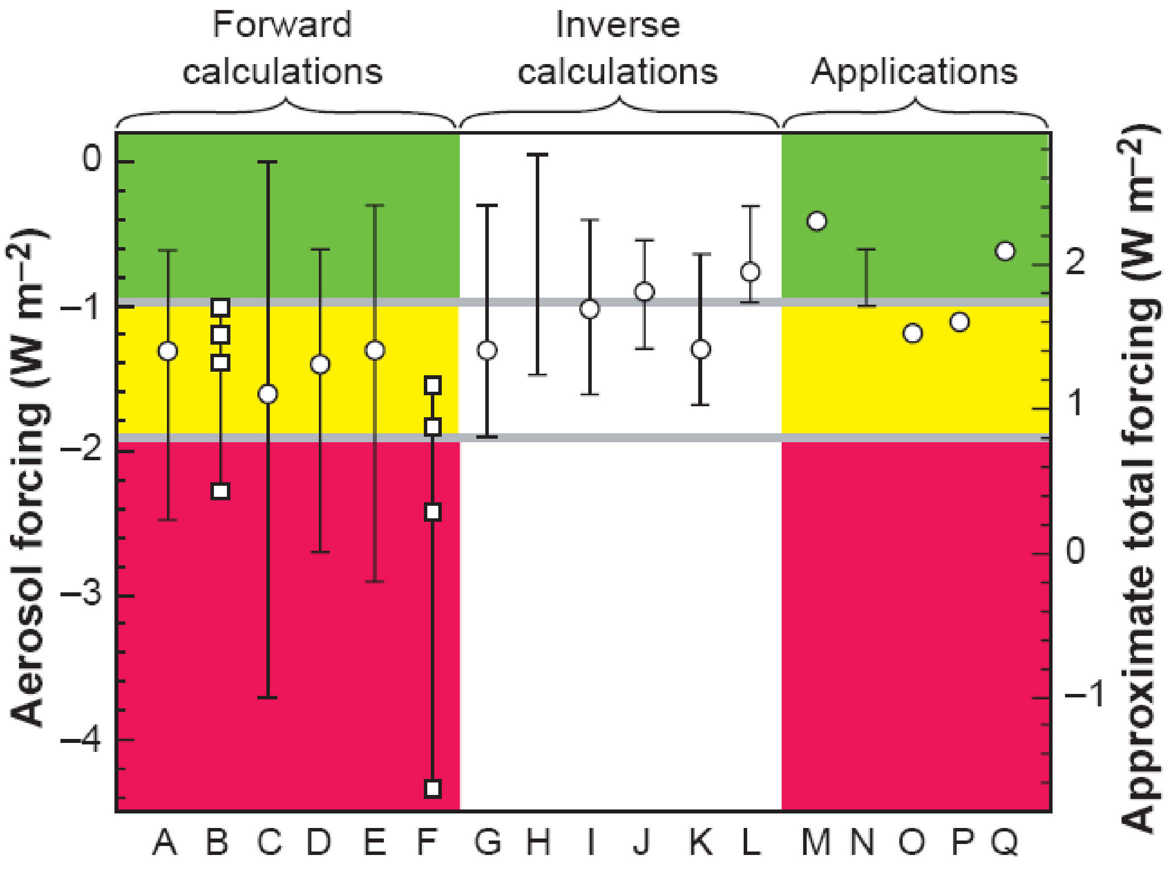
Indirect forcing vs. optical depth

$$\Delta F_{indirect} \propto -\frac{\tau}{(\tau+6.7)^2}$$



Kiehl et al. (2000: JGR) / Storelvmo et al. (2006: JGR)

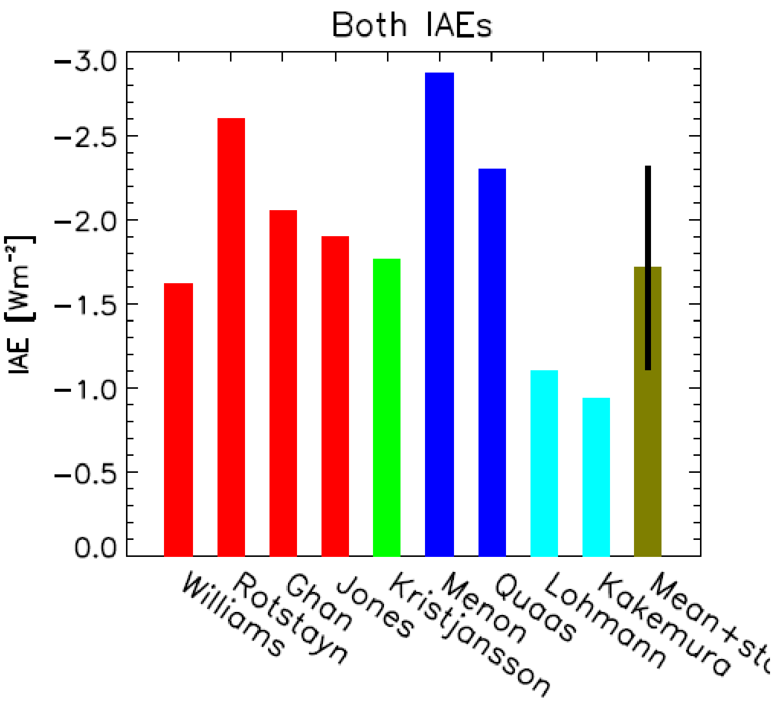
Models tend to overestimate the aerosol indirect effect



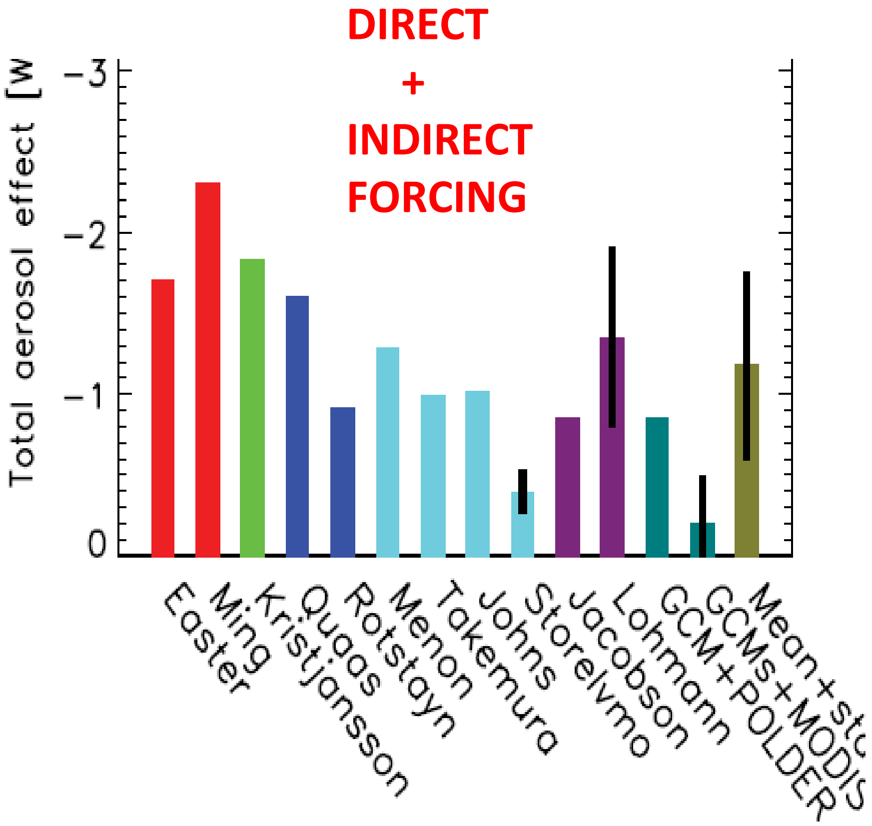
DIRECT
+
INDIRECT
FORCING

Anderson et al. (2003: Science)

Models tend to overestimate the aerosol indirect effect?



Lohmann and Feichter (2005: ACP)


DIRECT
+
INDIRECT
FORCING

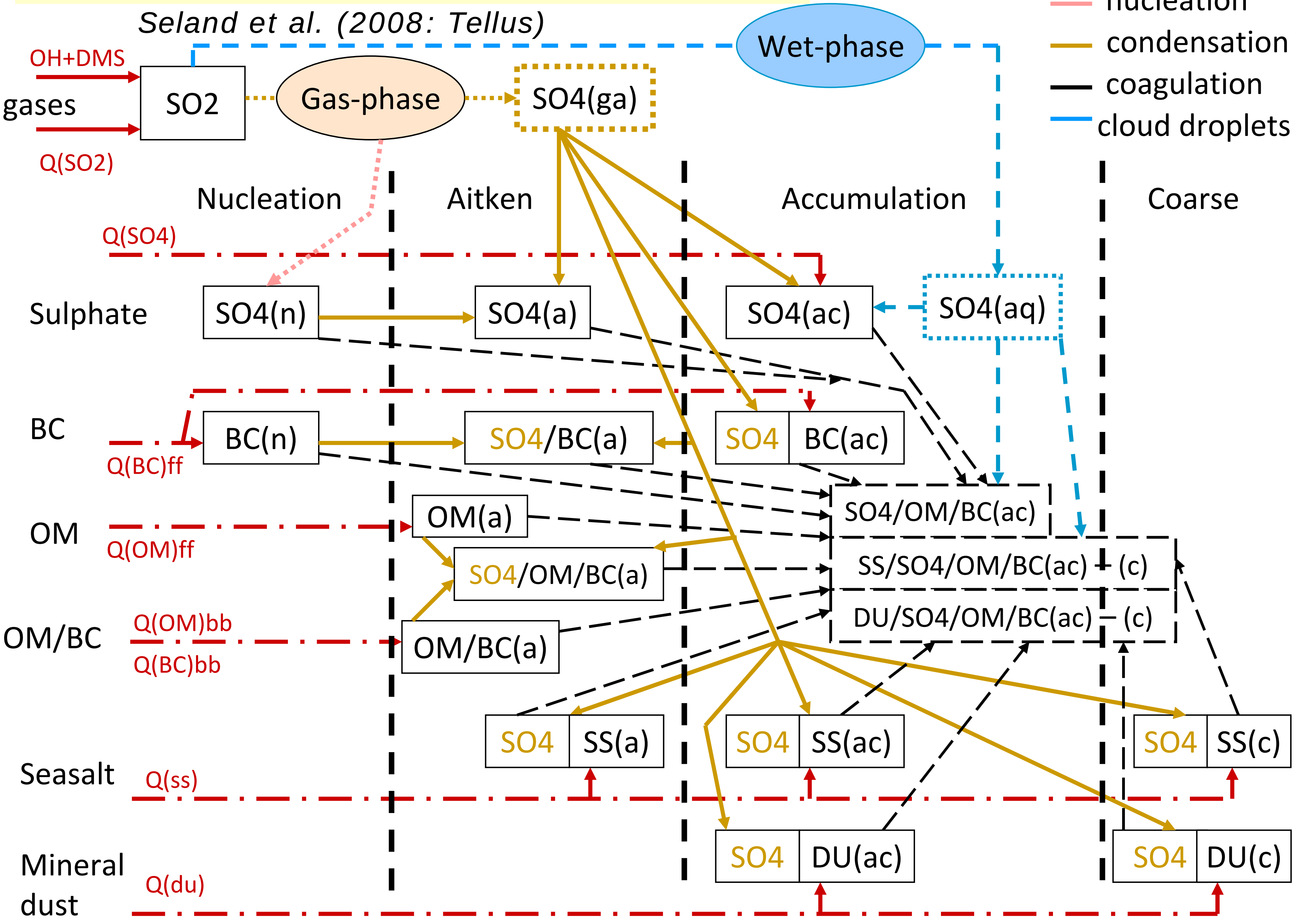
IPCC (2007)

Major extensions to NCAR CAM3:

- Aerosol lifecycling and physical properties
  - Sea-Salt, Dust, SO_4, OM, BC
  - Size-modes of emitted primary particles are presumed
  - Concentrations are tagged to production and size mode
  - Process-specific mixing state
  - Tables for size, optical, and physical properties
- Aerosol interactions with radiation
  - Refractive index according to mixing state and size
  - Optical Mie scattering and absorption
- Aerosol interaction with clouds
  - CCN activation by prescribed vs. realized super-saturations
  - Cloud droplet aging and auto-conversion

CAM-Oslo - Aerosol lifecycle schematic

Seland et al. (2008: Tellus)



emission
nucleation
condensation
coagulation
cloud droplets

OH+DMS
gases
Q(SO2)
SO2
Gas-phase
SO4(ga)
Wet-phase

Nucleation
Aitken
Accumulation
Coarse

Q(SO4)
Sulphate
SO4(n)
SO4(a)
SO4(ac)
SO4(aq)

BC
Q(BC)ff
BC(n)
SO4/BC(a)
SO4 | BC(ac)

OM
Q(OM)ff
OM(a)
SO4/OM/BC(a)
SO4/OM/BC(ac)
SS/SO4/OM/BC(ac) – (c)
DU/SO4/OM/BC(ac) – (c)

OM/BC
Q(OM)bb
Q(BC)bb
OM/BC(a)

Seasalt
Q(ss)
SO4 | SS(a)
SO4 | SS(ac)
SO4 | SS(c)

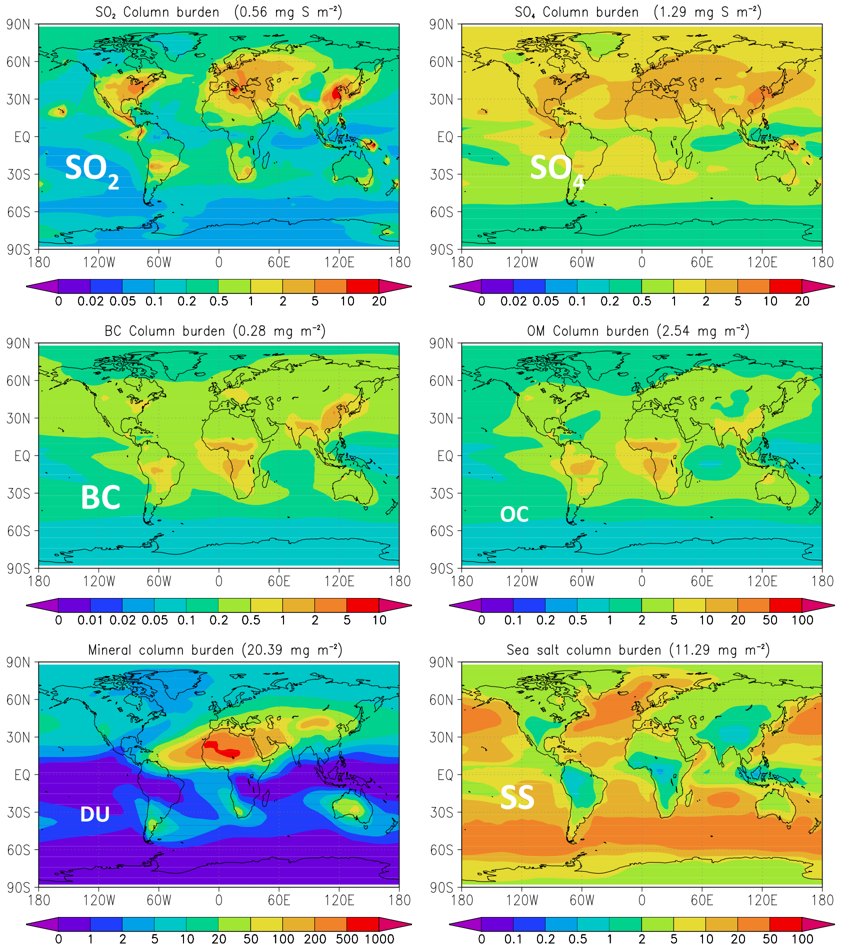
Mineral dust
Q(du)
SO4 | DU(ac)
SO4 | DU(c)

Prescribed lognormal externally mixed modes (before growth)

modes	modal median radius (μm)
SO_4(n/a), BC(n/a)	0.0118
BC(ac)	0.1
OC(a)	0.04
OC&BC(a)	0.04
SO4(ac)	0.075
MINERAL	0.22, 0.63
SEA-SALT	0.022, 0.13, 0.74

Seland et al. (2008: Tellus)

Aerosol Column burdens in CAM3-Oslo

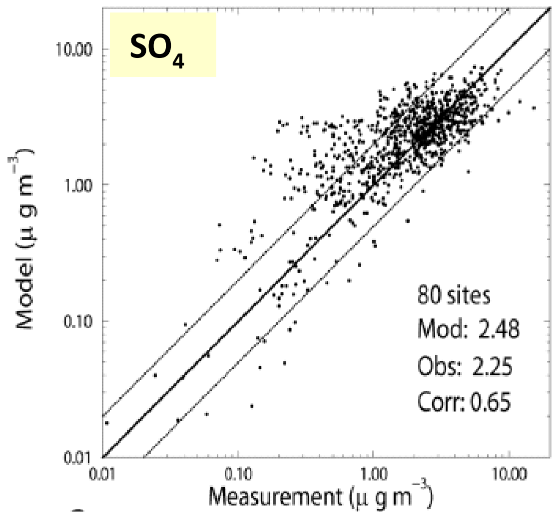


Seland et al. (2008: Tellus)

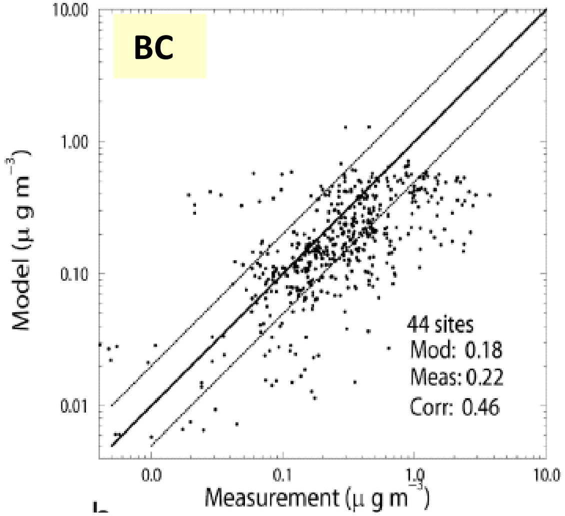
Seland et al. (2008: Tellus)

Regular Surface Measurement verification: Modeled vs. Measured annual concentrations

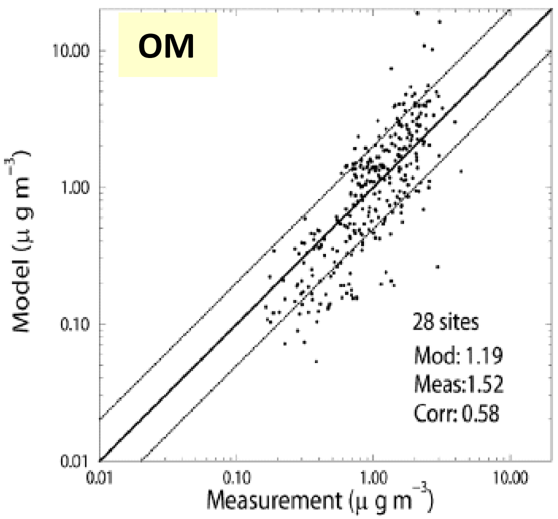
Modelled vs. measured SO_4



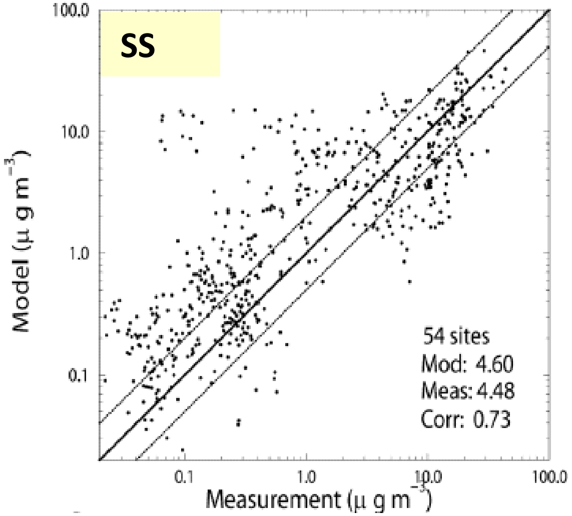
Modelled vs. measured BC



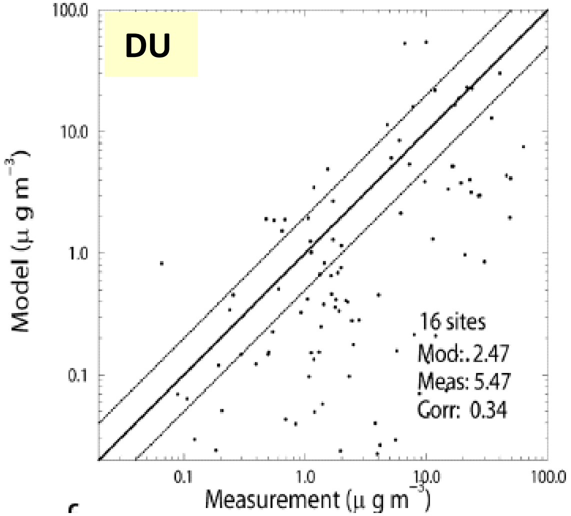
Modelled vs. measured OM AeroCom



Modelled vs. measured sea salt



Modelled vs. measured mineral dust



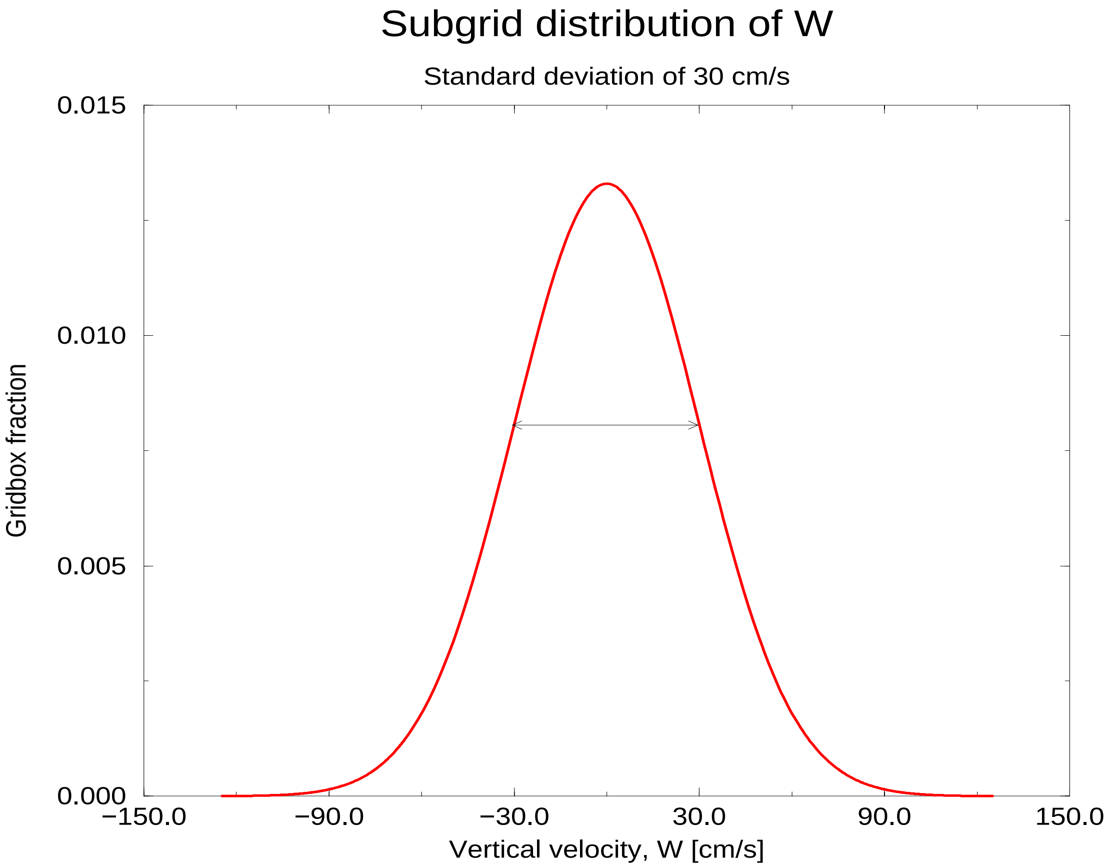
SO4: over-estimated remotely
BC: under-estimated
SS: wide scatter
DU: under-estimated

Parameterization of vertical velocity

$\sigma_w \propto K / \Delta Z$,

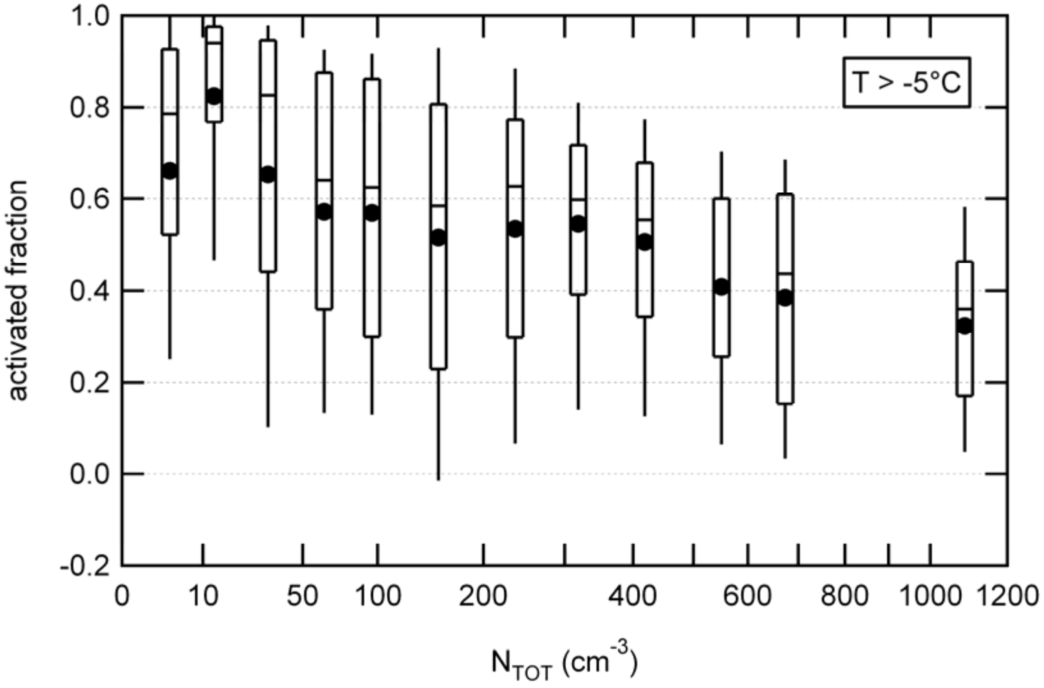
where K is the eddy diffusion coefficient and ΔZ is the thickness of the model layer.

Due to coarse vertical resolution in the GCMs it is necessary to apply a lower limit for σ_w, e.g., 0.3 m s^{-1}



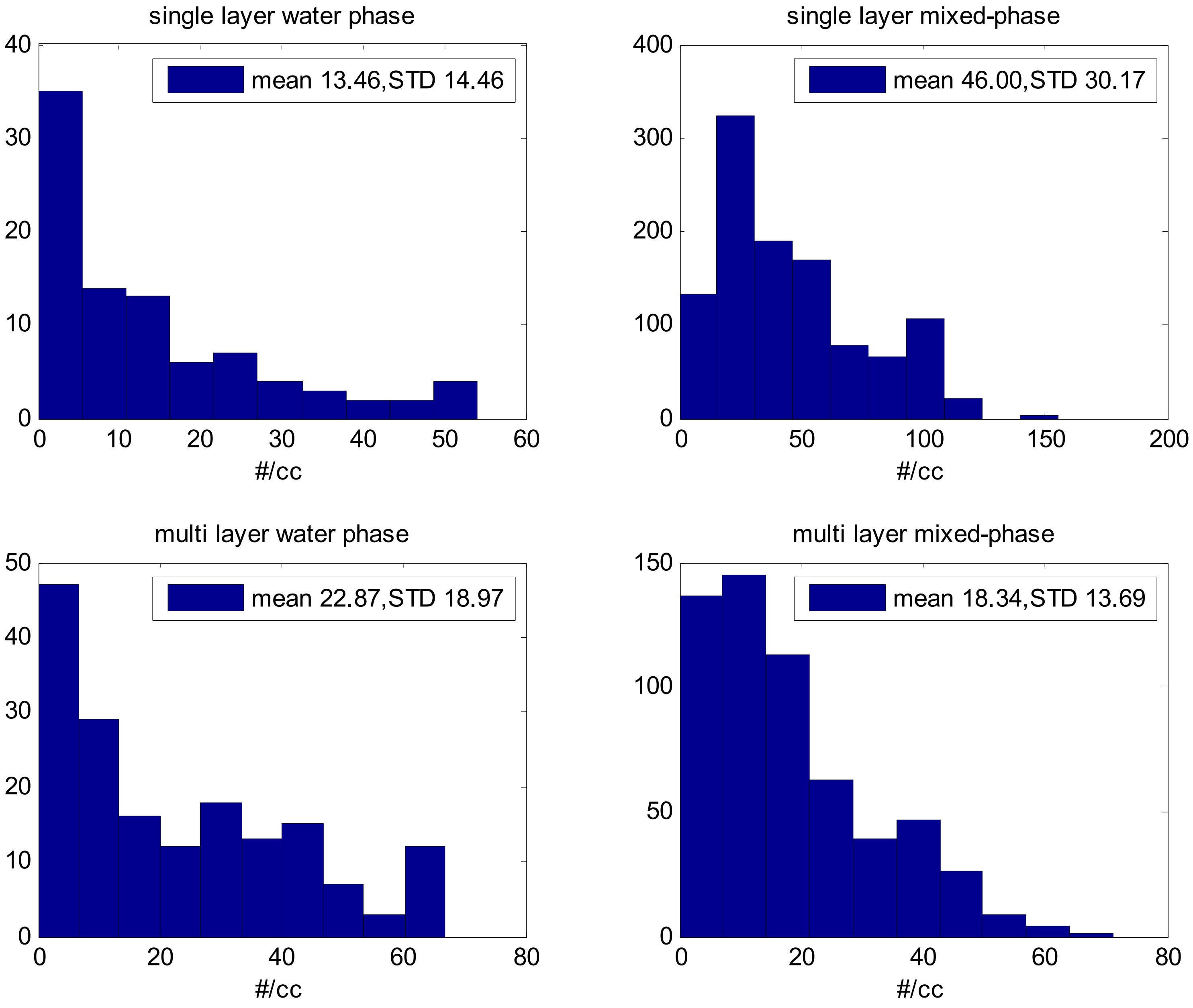
Ghan et al. (1997): JGR

Observational evidence of the competition effect



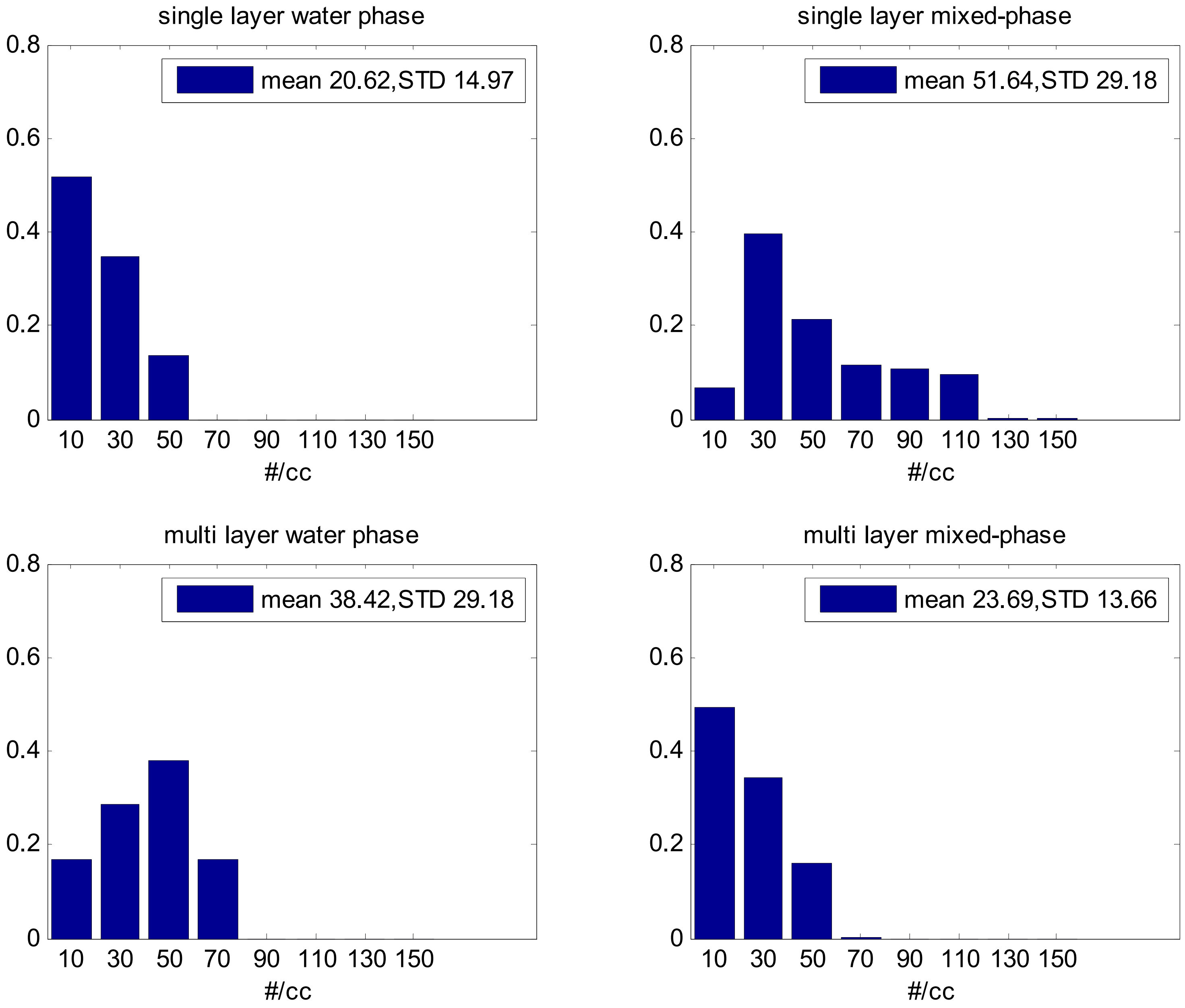
Verheggen et al. (2007)

- Measurements in warm clouds at Jungfraujoch, Switzerland
- Aerosol fraction activated to form cloud droplets decreases with increasing aerosol concentration



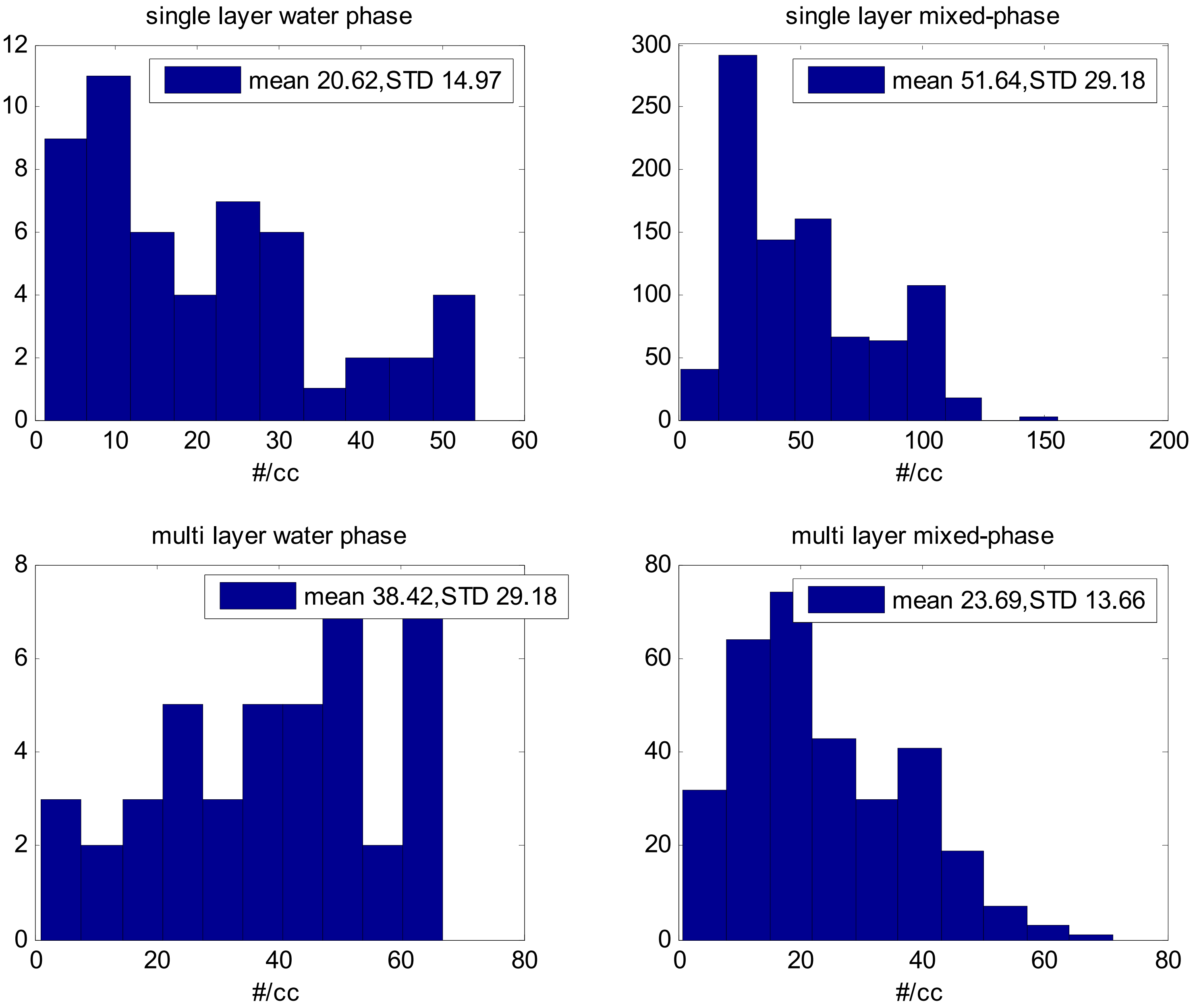
McFarquhar and Zhang, U. Illinois

LWC>0.05g/m^3



McFarquhar and Zhang, U. Illinois

LWC>0.05g/m^3



McFarquhar and Zhang, U. Illinois

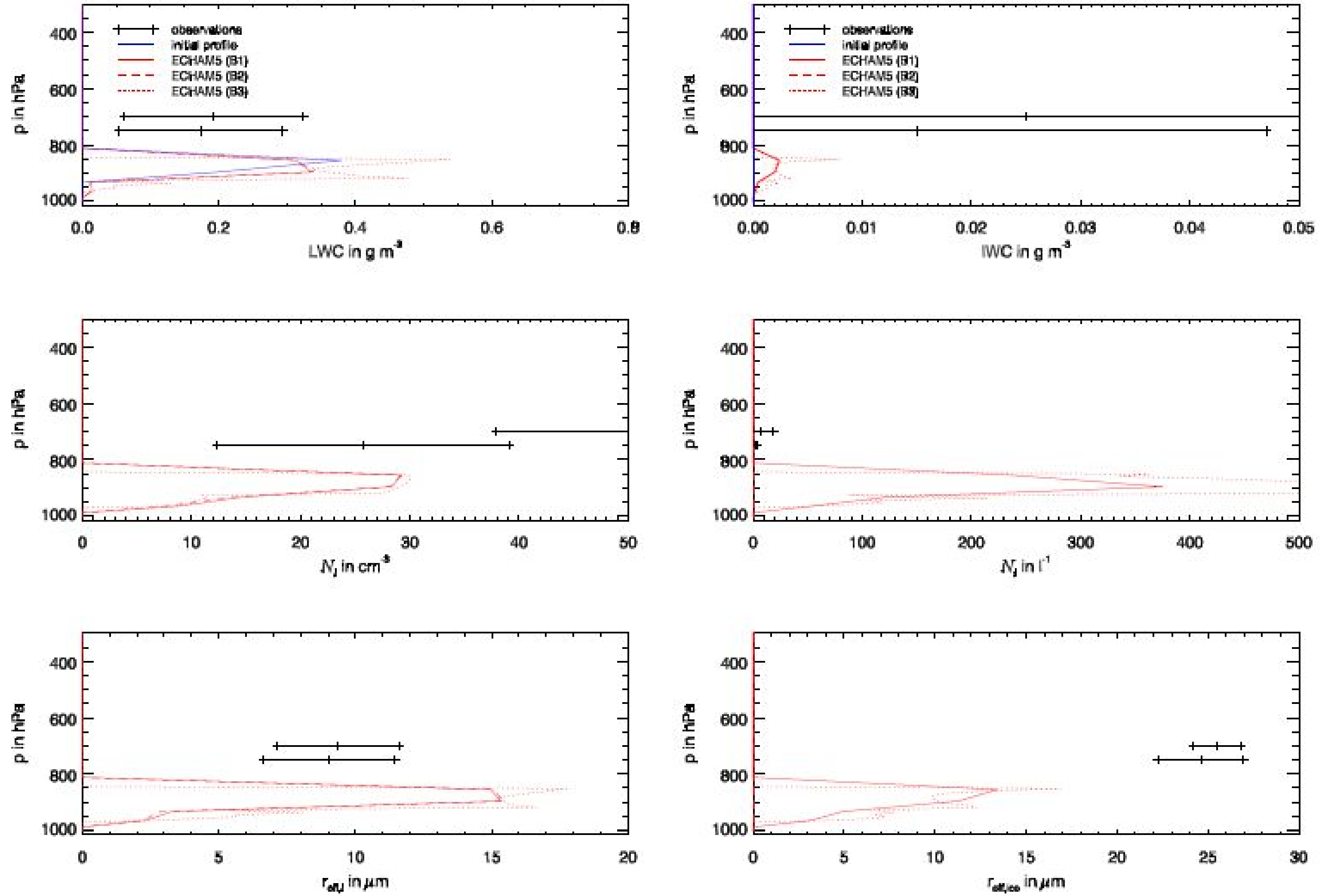
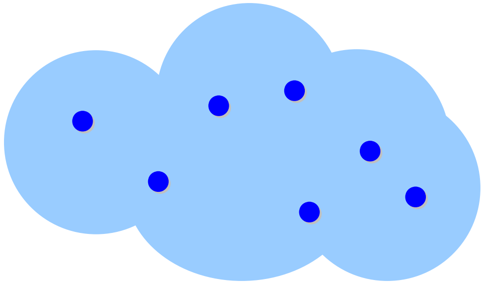


Figure 4.7: Model results for M-PACE period B, averaged over the 12h simulation period. Simulations B1 and B2 lie close together. Observations are aircraft data from McFarquhar et al. (2007), averaged over several vertical spirals for two flights during period B. The standard deviations correspond to deviations of the vertically averaged value of each spiral to the average value over all spirals per flight.

C. Hoose (2008: Ph.D. thesis)

Warm and cold clouds

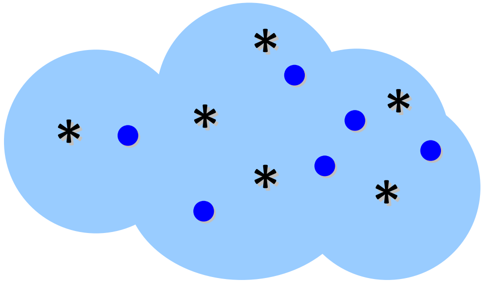
Warm clouds → clouds with $T > 0^{o}C$



Cold clouds

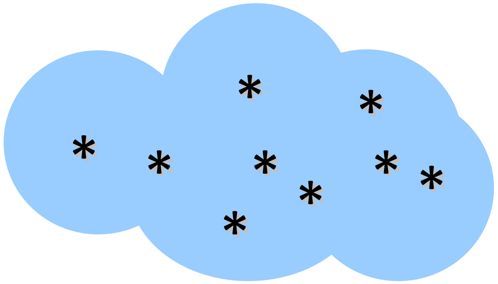
→ mixed-phase clouds

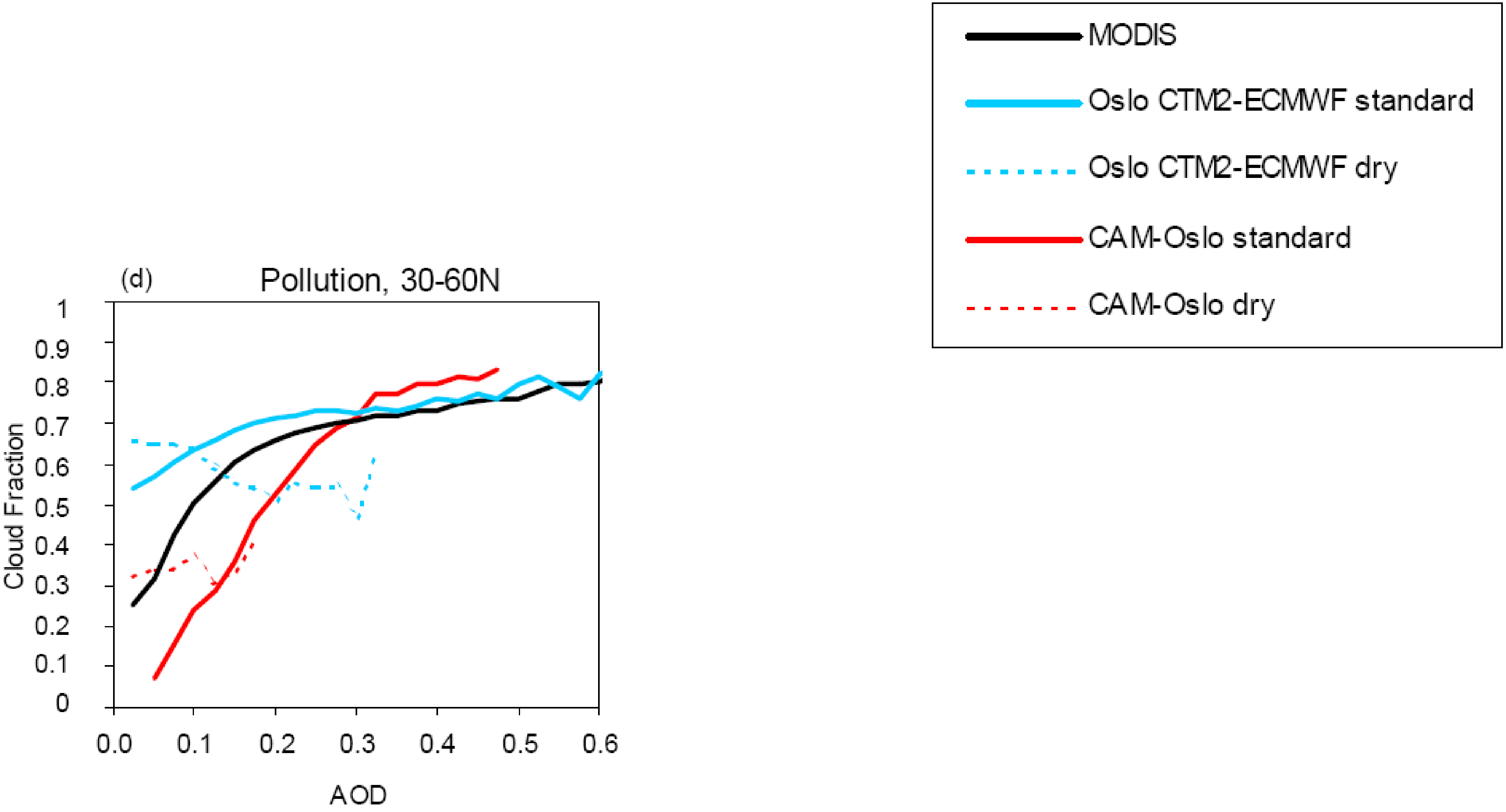
$(\sim -35^{o}C < T < 0^{o}C)$



→ ice clouds (cirrus)

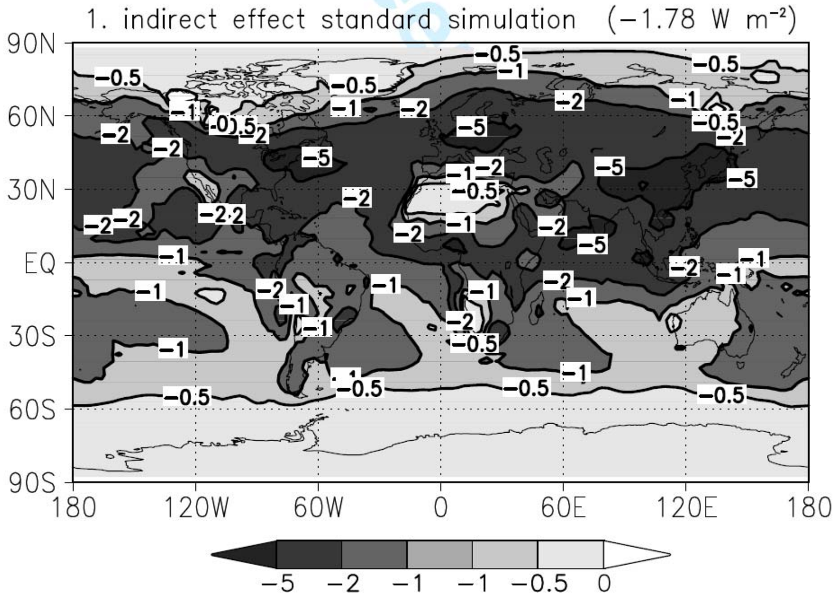
$(T < \sim -35^{o}C)$



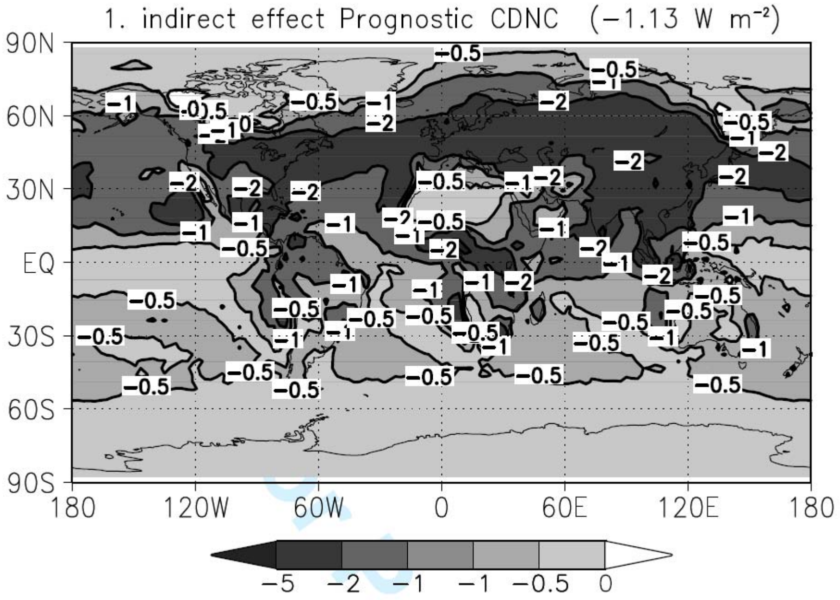

(d)
Pollution, 30-60N
Cloud Fraction
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
AOD
MODIS
Oslo CTM2-ECMWF standard
Oslo CTM2-ECMWF dry
CAM-Oslo standard
CAM-Oslo dry

Aerosol Indirect Forcing in CAM3-Oslo

Diagnostic CDNC



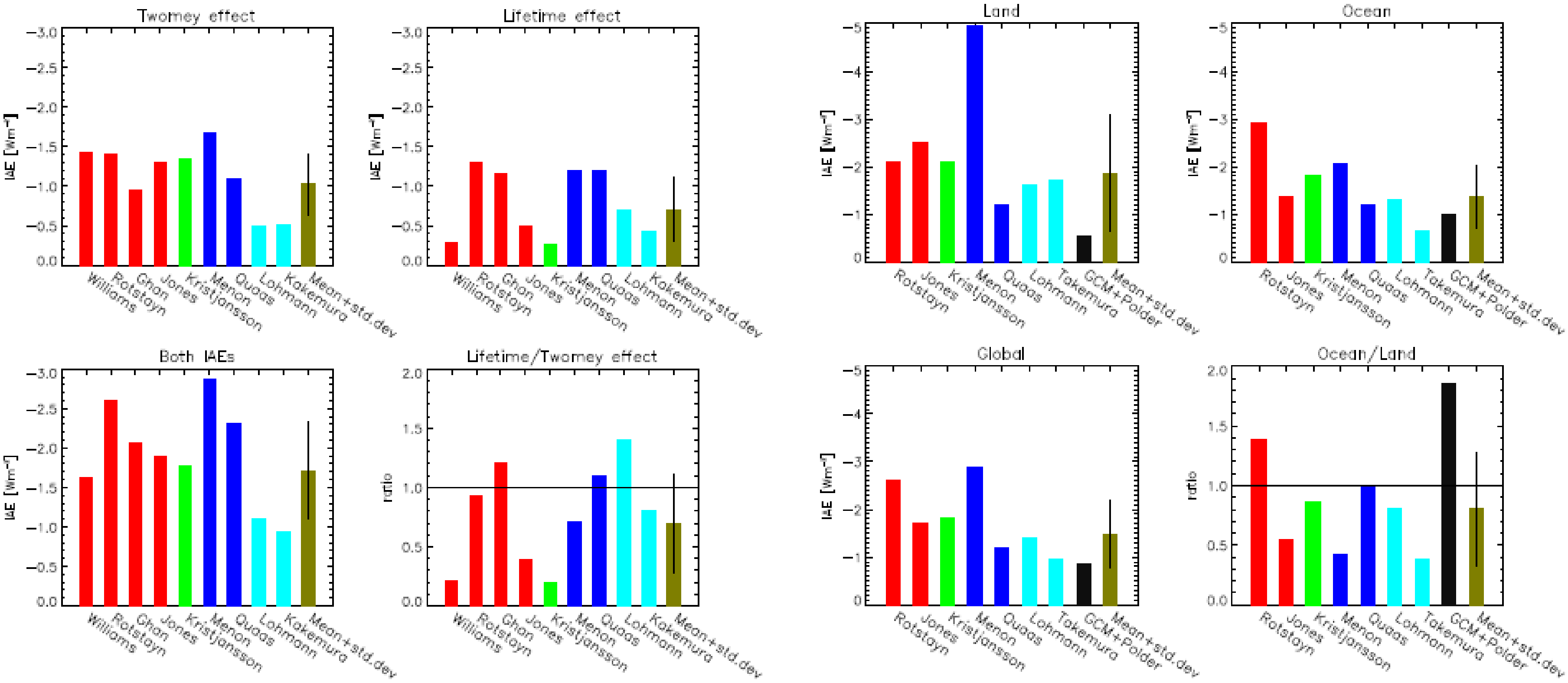
Prognostic CDNC



Indirect forcing reduced by 35%, largely due to competition effect!

Seland et al. (2008: Tellus A)

Model Estimates of the Aerosol Indirect Effect



Lohmann & Feichter (2005: ACP)

Cloud Feedback

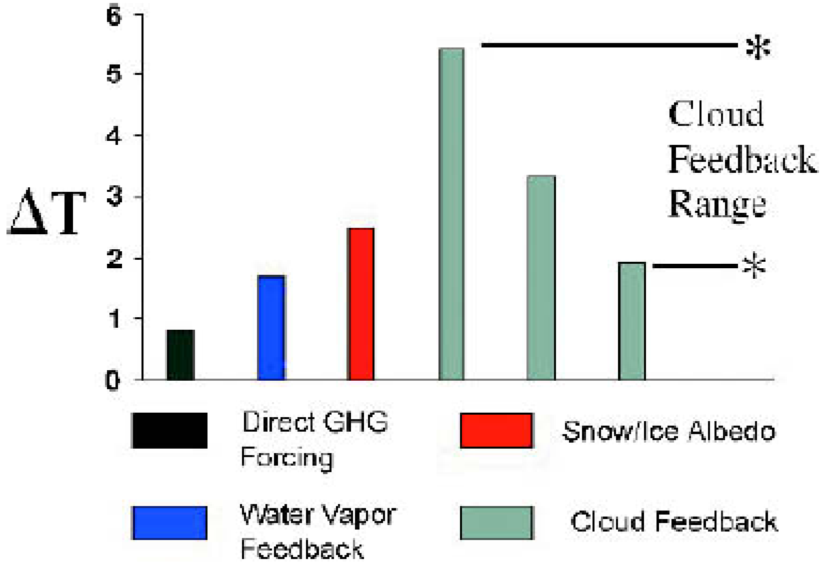


Fig. 13. The response of a single climate model to an imposed doubling of CO$_2$ as different feedbacks are systematically added in the model (adapted from Senior and Mitchell 1993). Different treatments of cloud processes in the model produce a large spread in predicted surface temperature due to CO$_2$ doubling.

- Sensitivity to the treatment of clouds and cloud-radiative processes

Stephens (2005: J. Climate)

Log-normal fits to aerosol size distributions: Influence on number of activated CCN

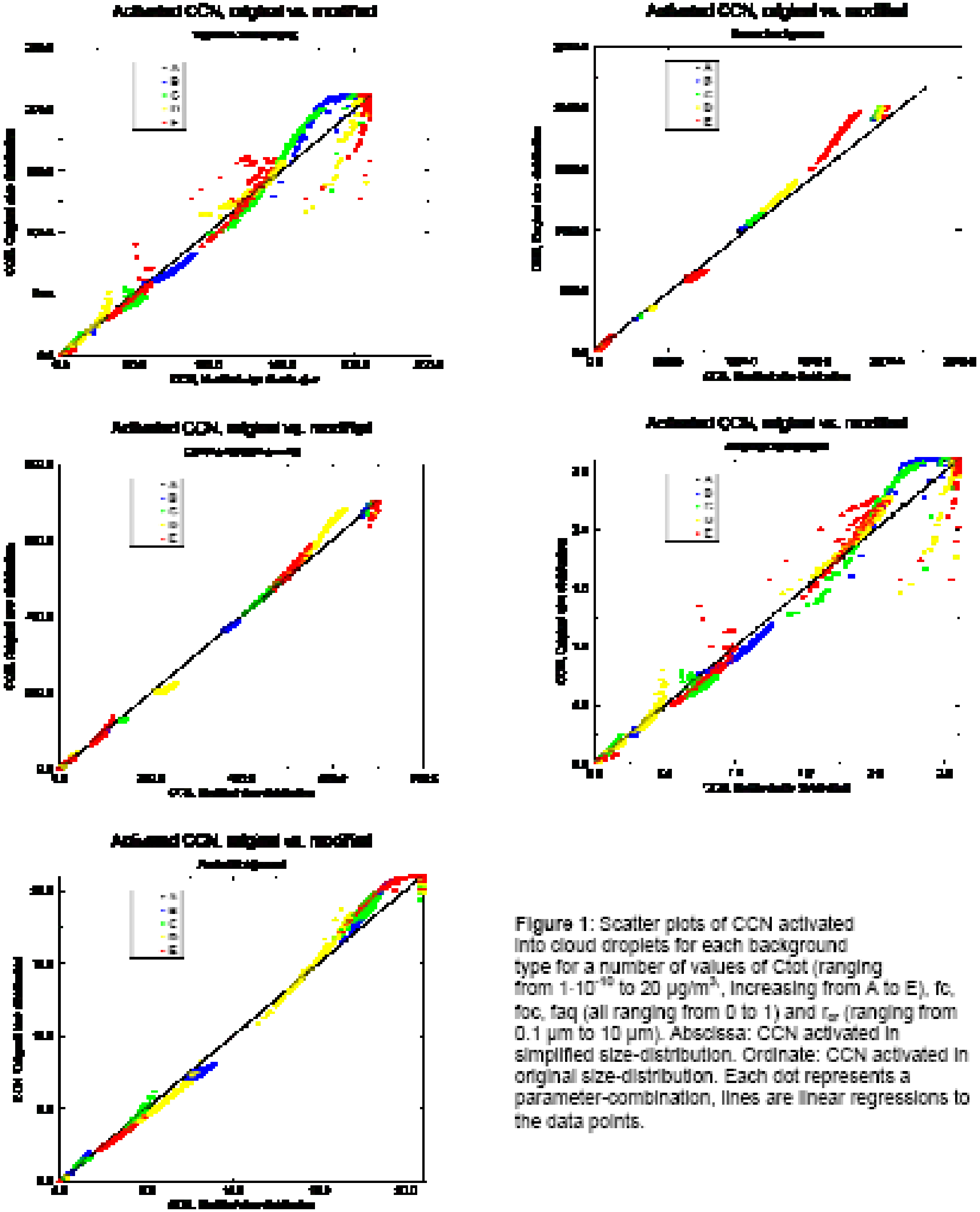


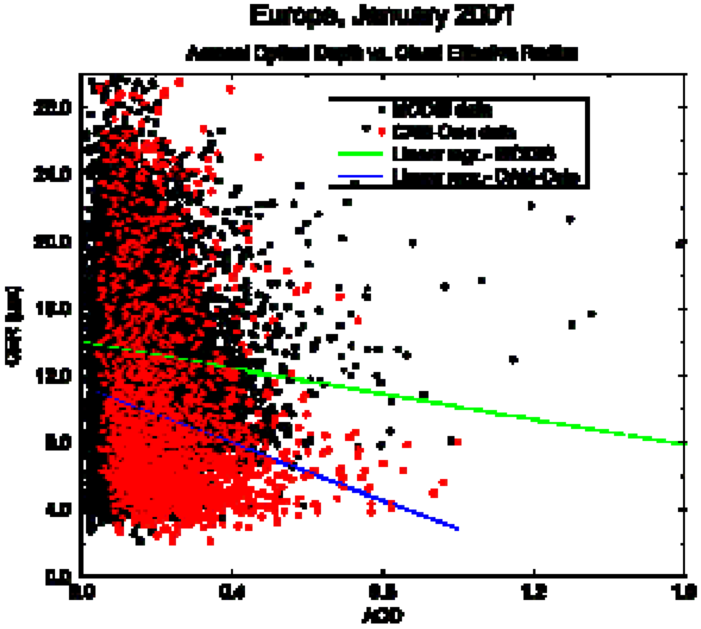
Figure 1: Scatter plots of CCN activated into cloud droplets for each background type for a number of values of Ctot (ranging from $1 \cdot 10^{-10}$ to 20 $\mu g/m^3$, increasing from A to E), fc, foc, faq (all ranging from 0 to 1) and r_{gr} (ranging from 0.1 μm to 10 μm). Abscissa: CCN activated in simplified size-distribution. Ordinate: CCN activated in original size-distribution. Each dot represents a parameter-combination, lines are linear regressions to the data points.

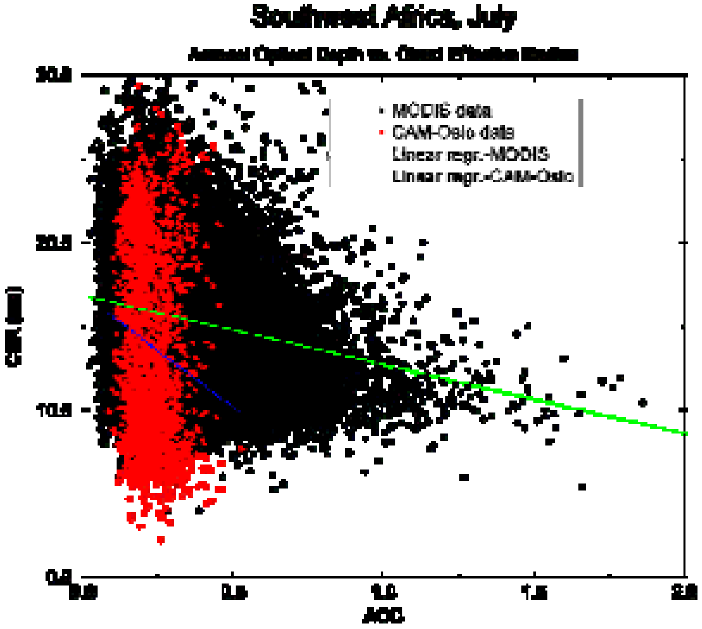
Storelvmo et al. (2006:JGR)

Aerosol Optical Depth vs. Cloud Droplet Size

Red dots: Model

Black dots: MODIS





Storelvmo et al. (2006: ACP)