Constraining the aerosol indirect effect

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Many thanks to: Alf Kirkevåg (met.no), Corinna Hoose (Univ. Oslo), Leo Donner (GFDL)

Problem Definition

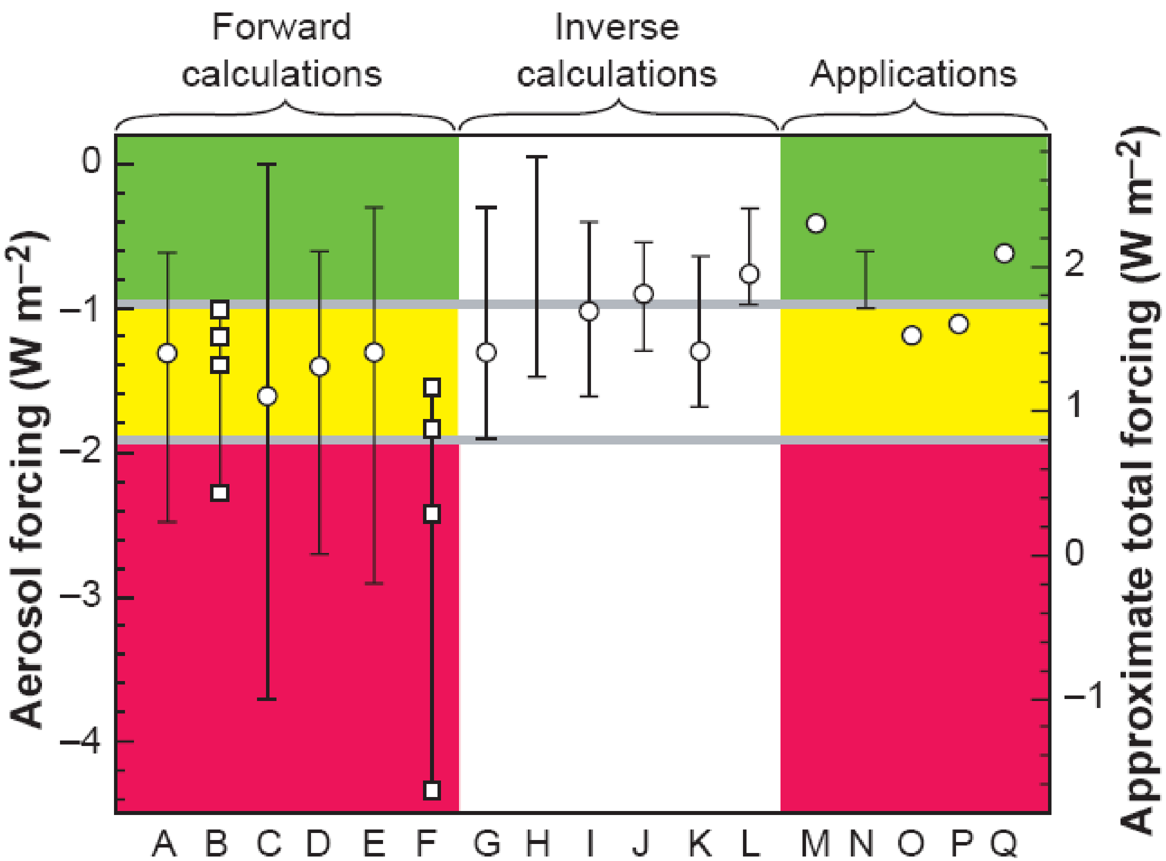
- Most GCMs give an aerosol indirect effect which is too high compared to results from residual calculations – Why?
- Many models have built in constraints on parameter values that keep the indirect effect within reasonable bounds – Is this justifiable?
- What can be done?

Aerosol Indirect Effect

- Definition: *Change in Cloud Radiative Forcing due to Anthropogenic Aerosols*

- *Model estimates of AIE are sensitive to:*
- The Aerosol Scheme, in particular the Treatment of Natural Aerosols
- Parameterizations of Aerosol-Cloud Interactions
- The Atmospheric State in the host model, in particular the Cloud Properties

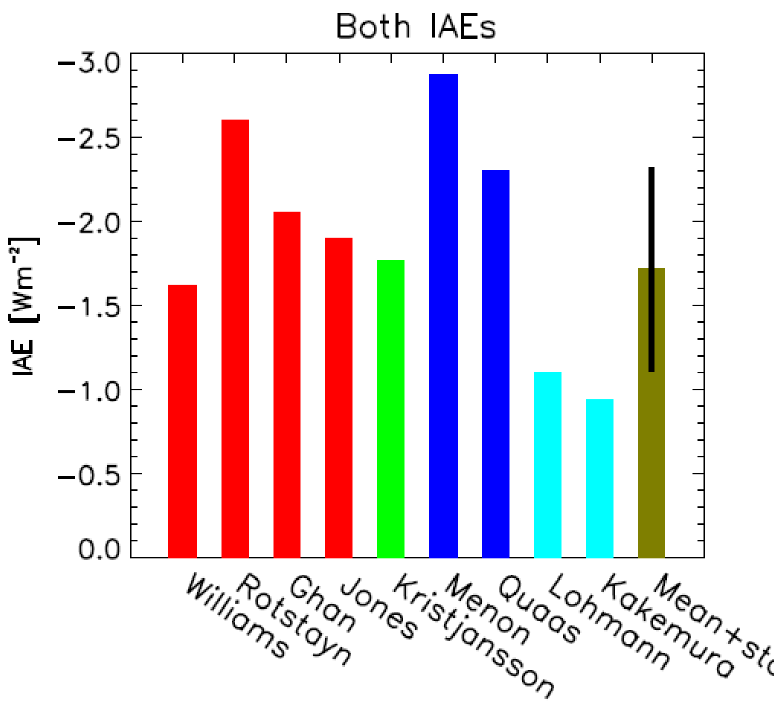
Models tend to overestimate the aerosol indirect effect



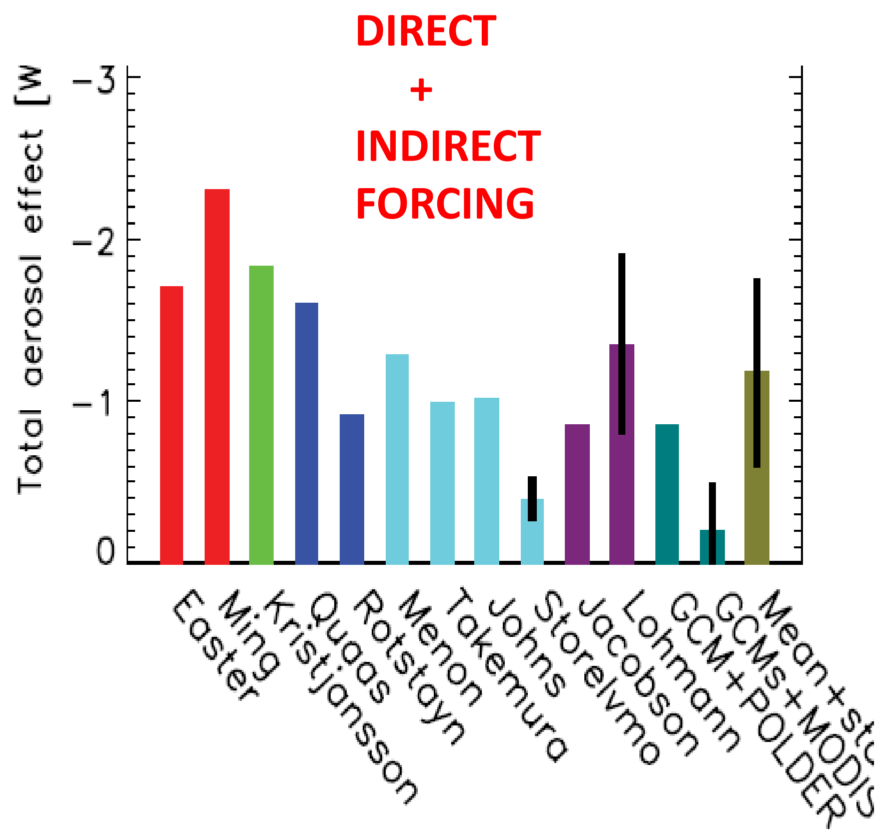
DIRECT + INDIRECT FORCING

Anderson et al. (2003: Science)

Models tend to overestimate the aerosol indirect effect?



Lohmann and Feichter (2005: ACP)



IPCC (2007)

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 ($W m^{-2}$) Land	Ocean	NH	SH	Global	NR−DE ($W m^{-2}$) global	ΔLCC (%)	ΔLWP ($g m^{-2}$)
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

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

Cloud Susceptibility

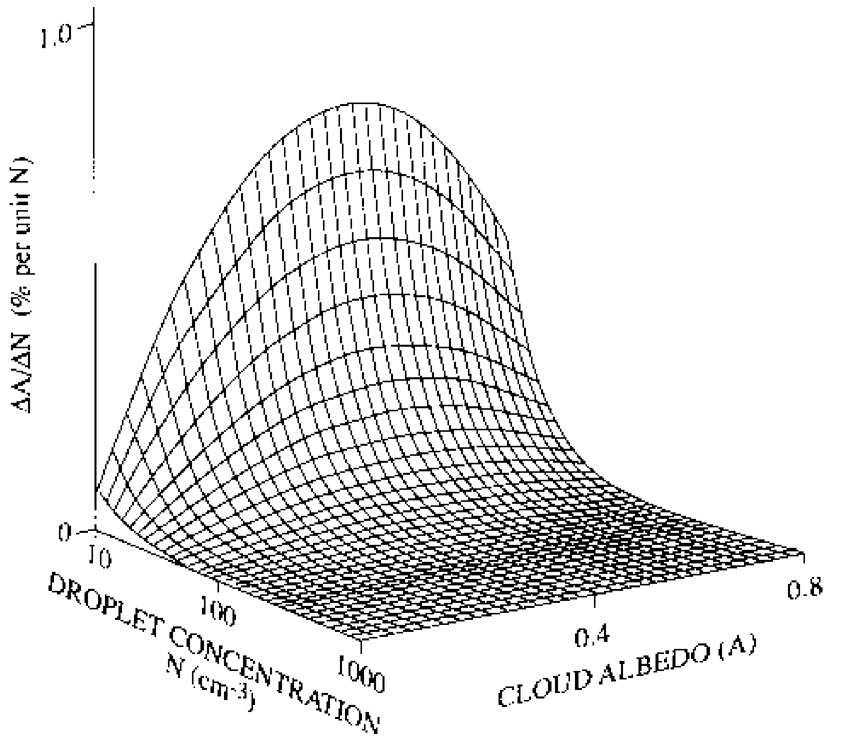
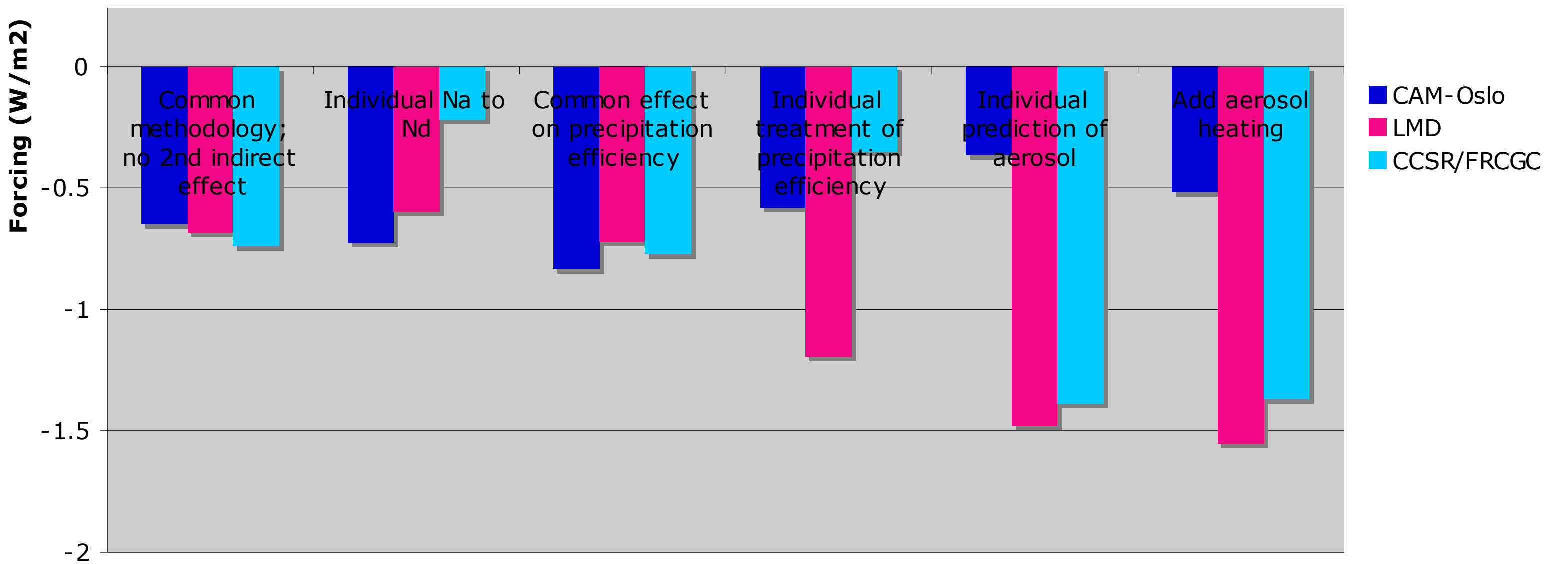


Figure 6 The change in the albedo of a cloud per unit change in the droplet concentration ($\Delta A/\Delta N$) as a function of the cloud albedo (A) and the droplet concentration (N), for a cloud with a constant liquid-water content. (Adapted from Twomey, 1991.)

Hobbs (1993: Academic Press)

Indirect forcing in 3 GCMs:
Model estimates differ mainly due to different parameterizations and different emissions

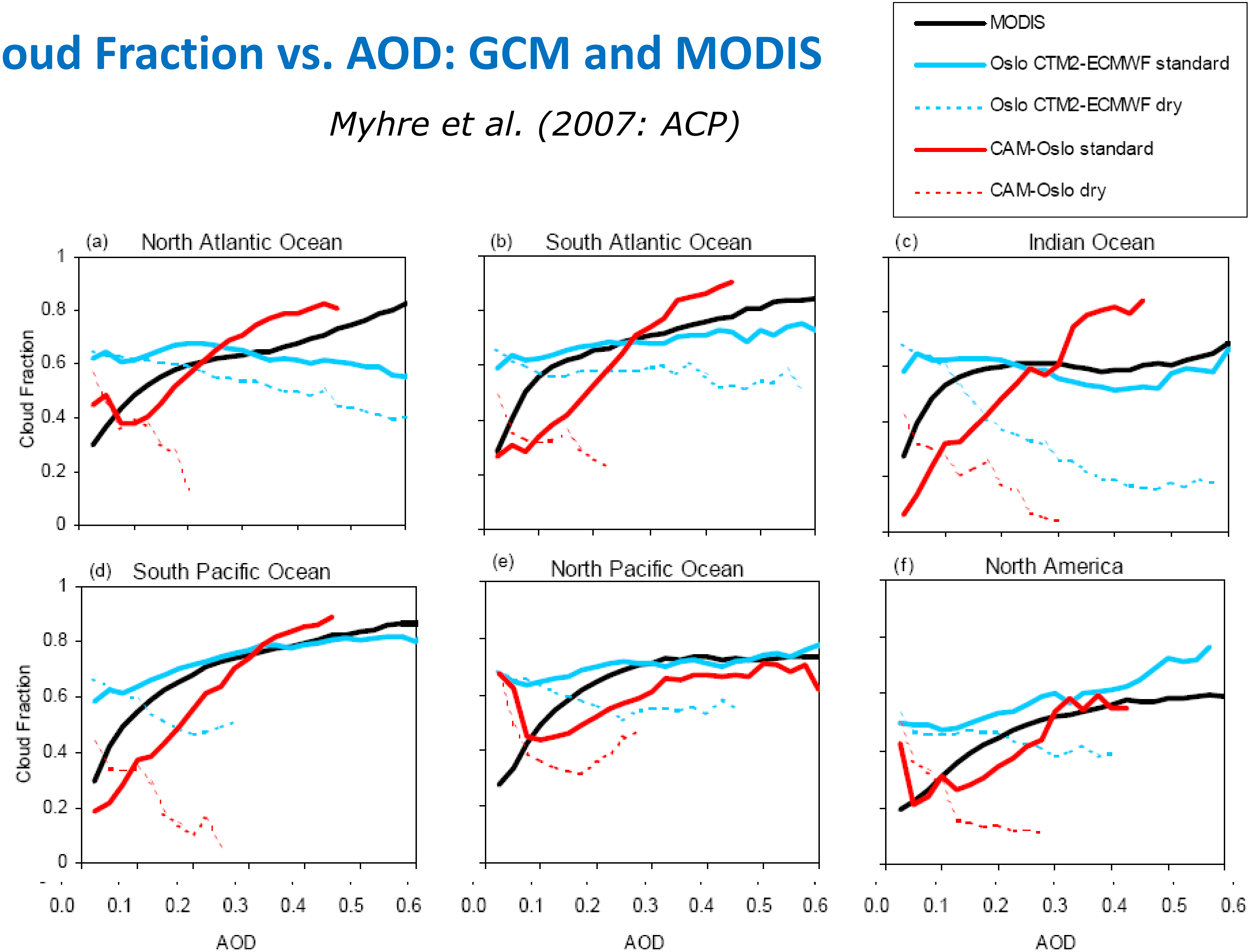
experiment	1	2	3	4	5	6
Purpose: to examine influence of:	Cloud variability	CDNC parameterization	Cloud lifetime effect	Autoconversion scheme	Aerosol distribution	Direct effect
Aerosol distributions	prescribed	prescribed	prescribed	prescribed	model's own	model's own
CDNC parameterization	BL95 "A"	model's own	model's own	model's own	model's own	model's own
Autoconversion parameterization	S78	S78	KK00	model's own	model's own	model's own
Direct radiative effect of aerosols	no	no	no	no	no	yes

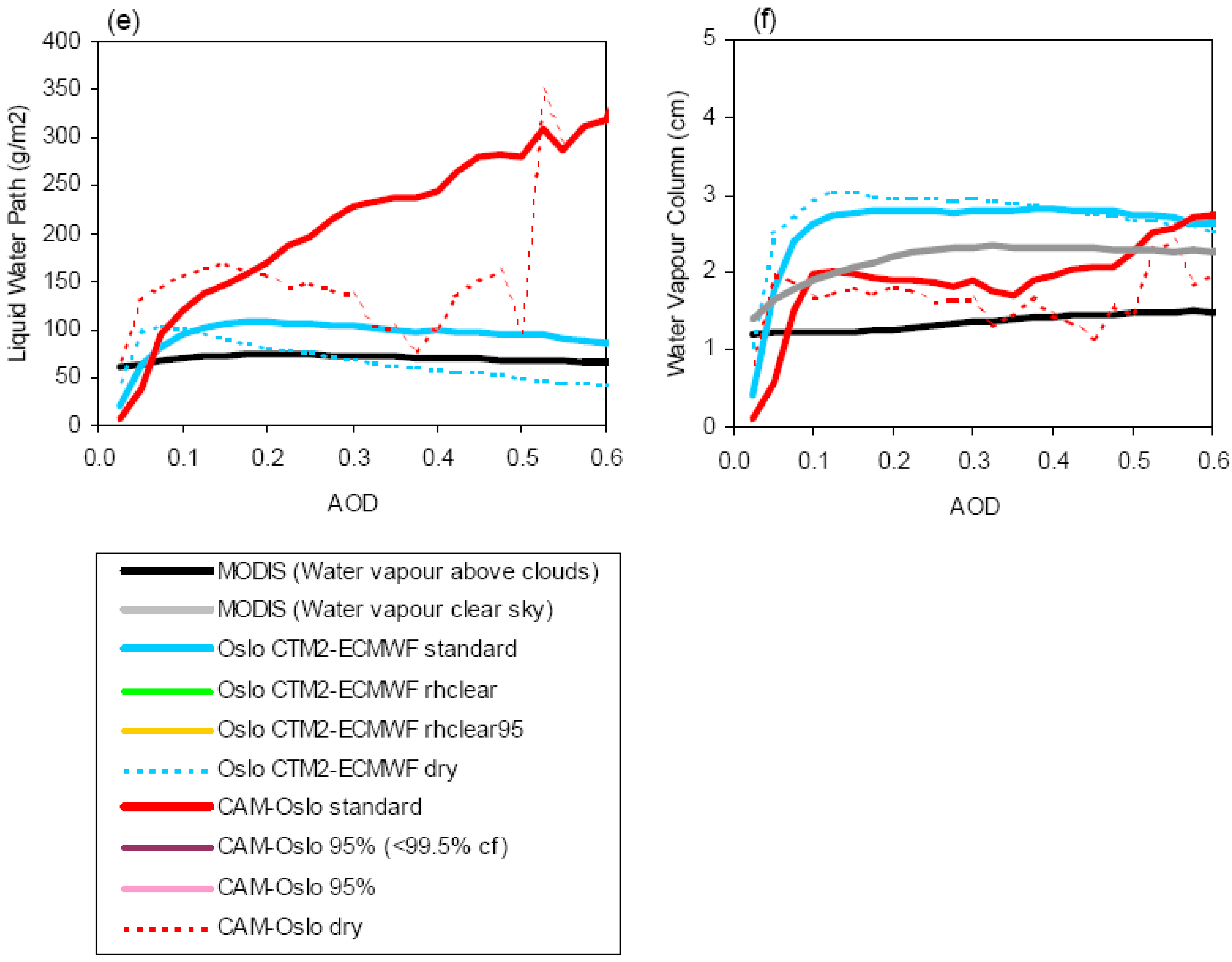


Penner et al. (2006: ACP)

Cloud Fraction vs. AOD: GCM and MODIS

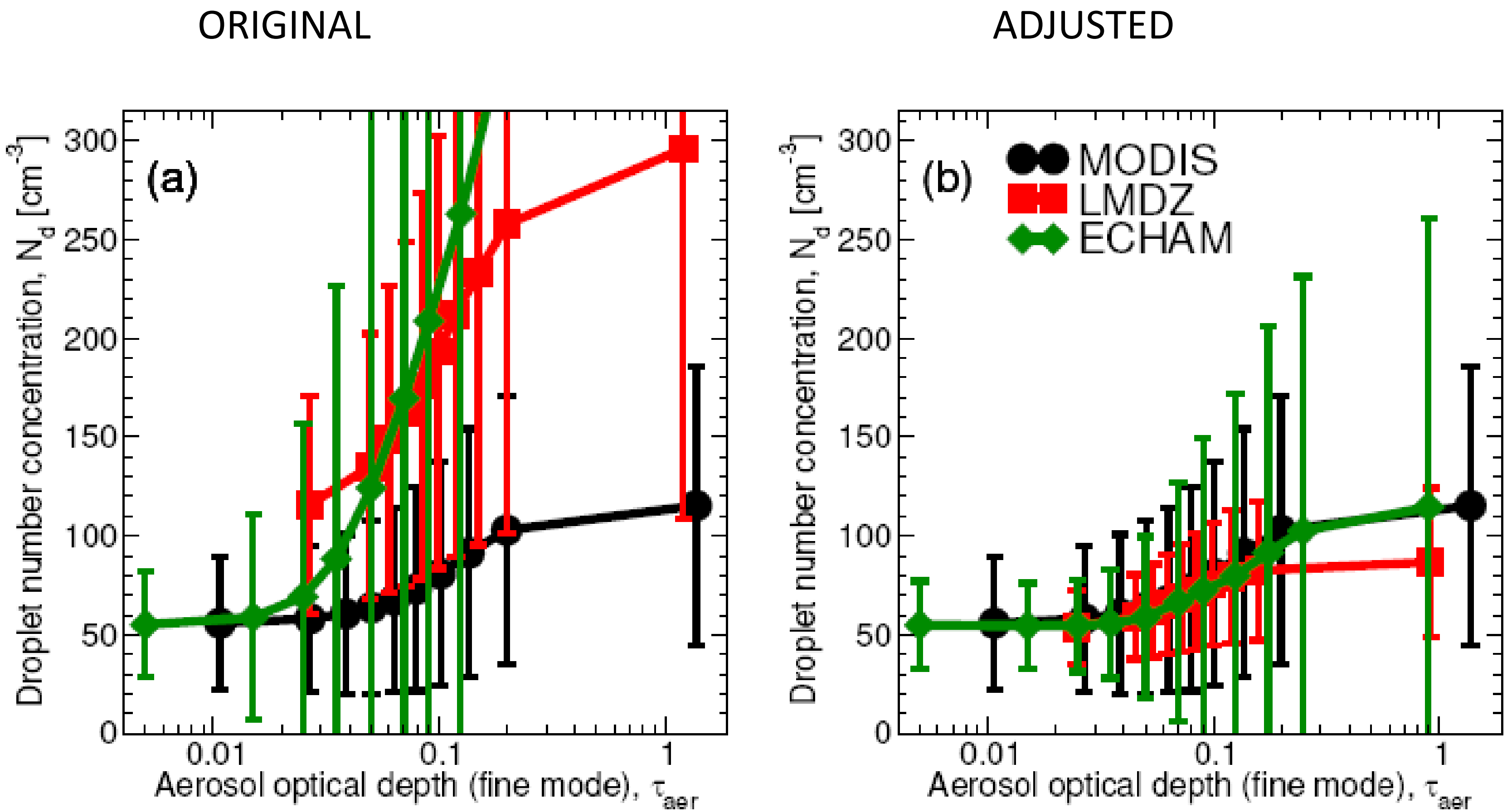
Myhre et al. (2007: ACP)





Myhre et al. (2007: ACP)

Constraining the indirect effect with observations



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)

Constraining CDNC reduces the indirect effect

- ECHAM does not allow CDNC < 40 cm^{-3}
- How realistic is this constraint?
- What is the implication of it?

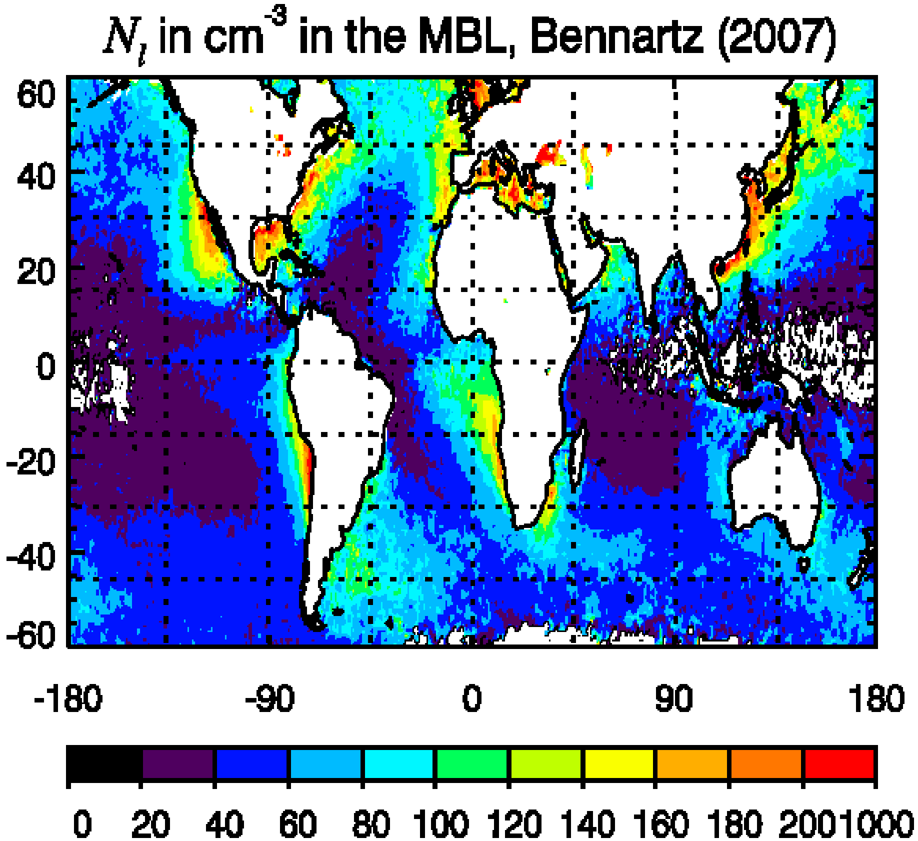


Table 2. Statistics of Cloud Droplet Number Concentration for Remote Ocean Areas With at Least 1500 km Distance to the Next Major Landmass[a]

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

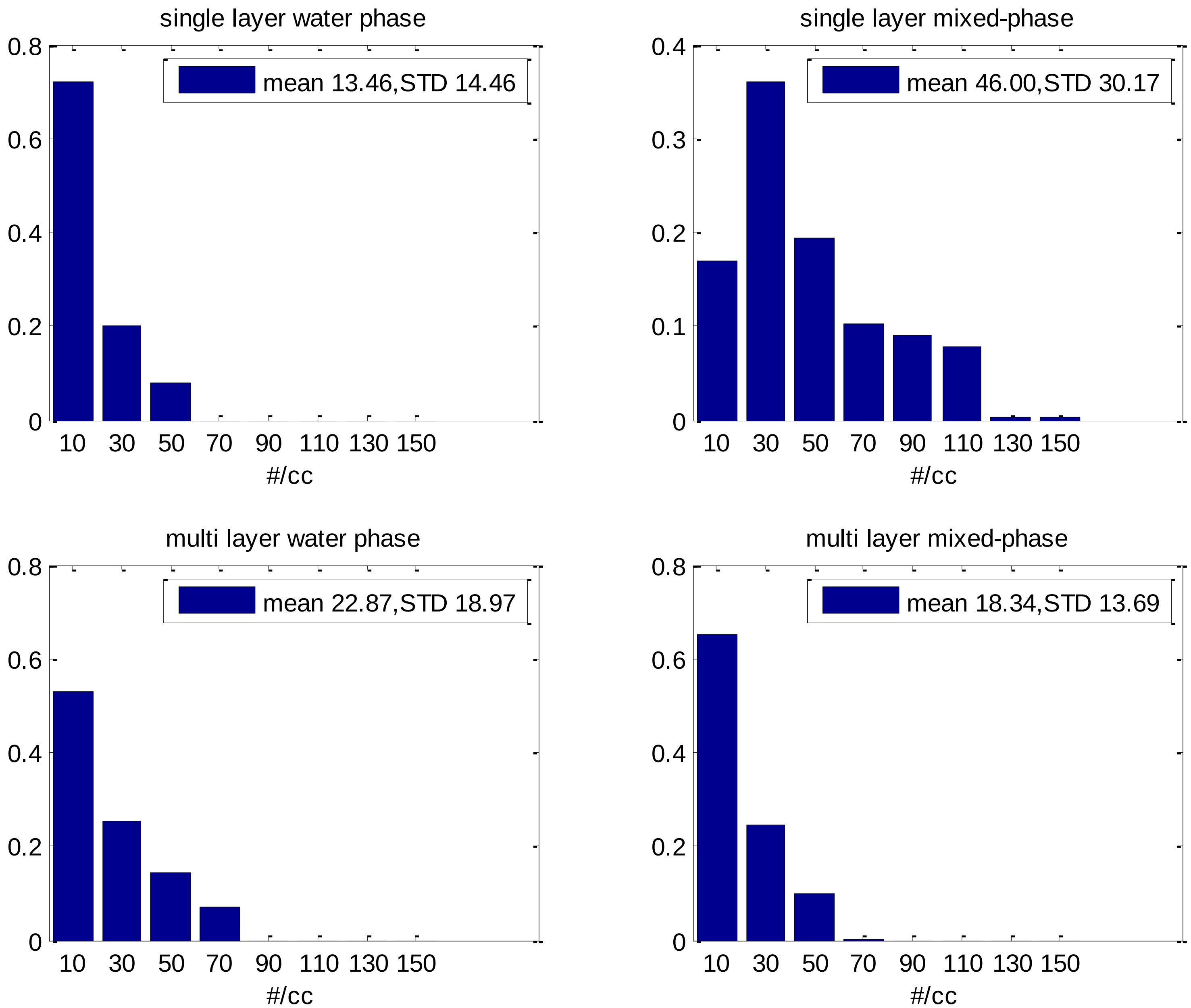
[a]The values given are two and a half year mean value with one standard deviation. Results are presented for all stratiform boundary layer clouds and separated in clouds with high/low likelihood of drizzle. The values in parentheses give the estimates that are derived using the parameterization of k 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.

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.

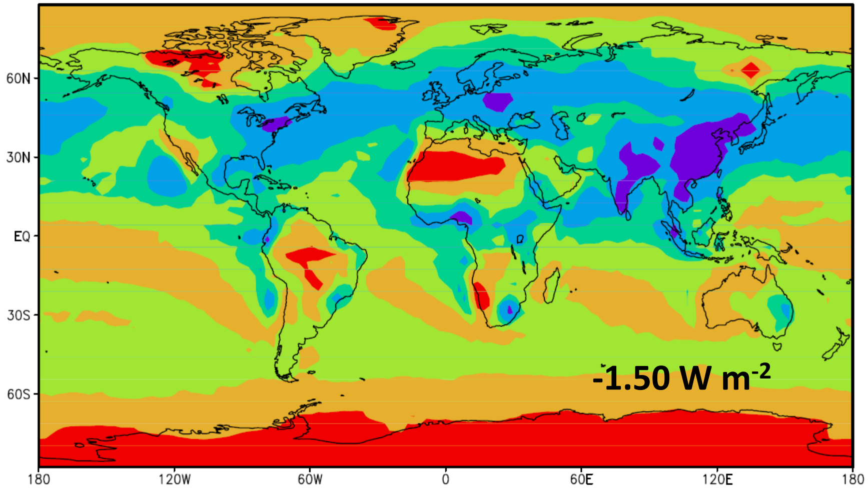
McFarquhar et al. (2007: JGR)



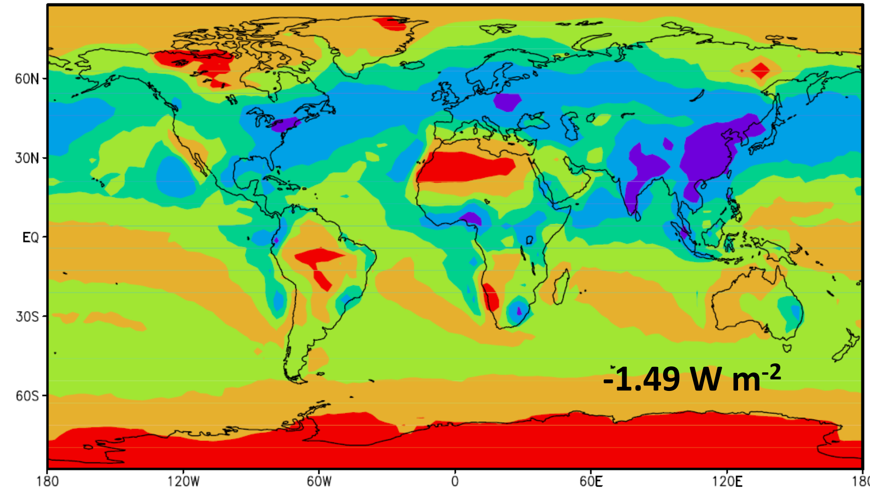
McFarquhar and Zhang, U. Illinois

Tests with CAM3-Oslo (1-year runs)

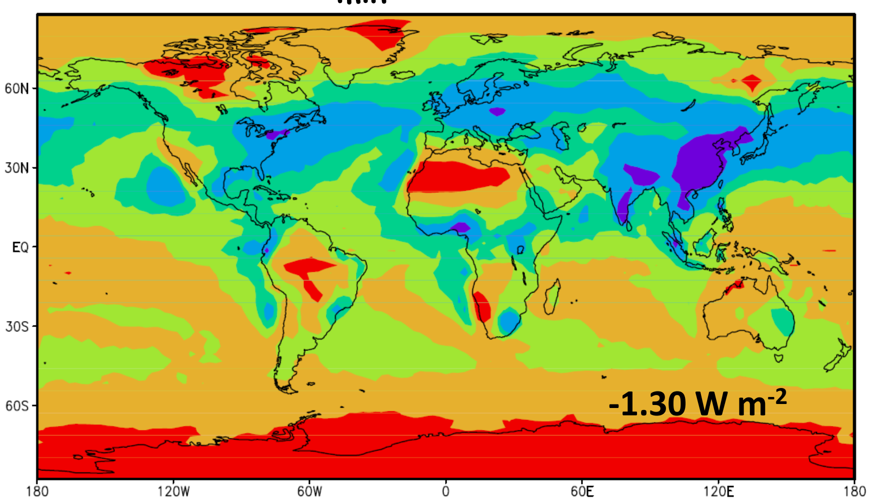
no cut-off on CDNC



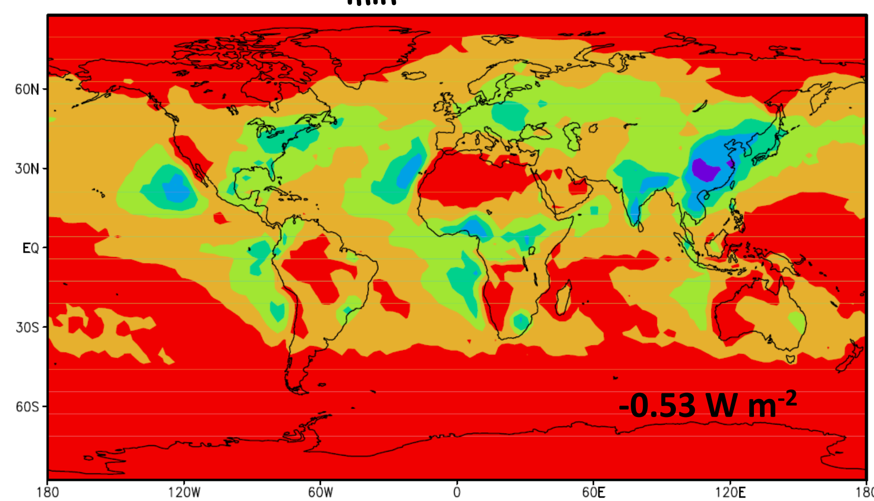
$CDNC_{min}$ = 1 cm^{-3}



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



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



Anthropogenic Ice Nuclei

Exp. →	LIQ-UID	CON-TROL	KAO-LINITE	LESS DUST	COAT-ING
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)

Summary and Conclusions

PROBLEM

- Most GCMs struggle to keep the aerosol indirect forcing low enough to yield realistic climate simulations (~ -1 W m^{-2})
- The AIE is very sensitive to background (pre-industrial) aerosols
- Comparisons to observations indicate too large sensitivity of cloud parameterizations to aerosol burdens

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POSSIBLE SOLUTIONS

- Constraining with satellite data yields significantly suppressed indirect effect
- Constraining with prescribed bounds on CDNC reduces AIE, but violates observations in remote regions
- Indications that AIE of mixed-phase clouds may reduce the overall indirect forcing
- Enhanced evaporation may lead to a positive indirect effect in trade wind cumuli (Feingold)
- Competition effect reduces AIE (Ghan)

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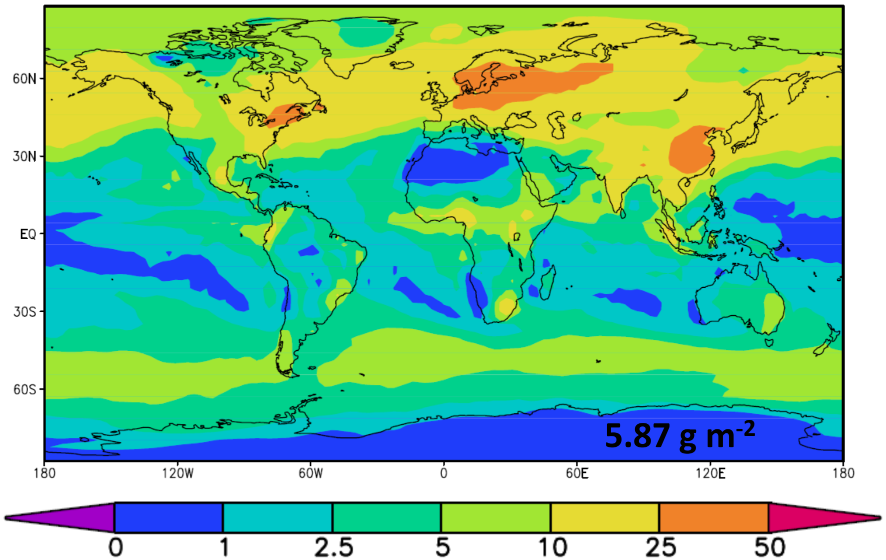
MODIS image

Reports of low CDNC measurements

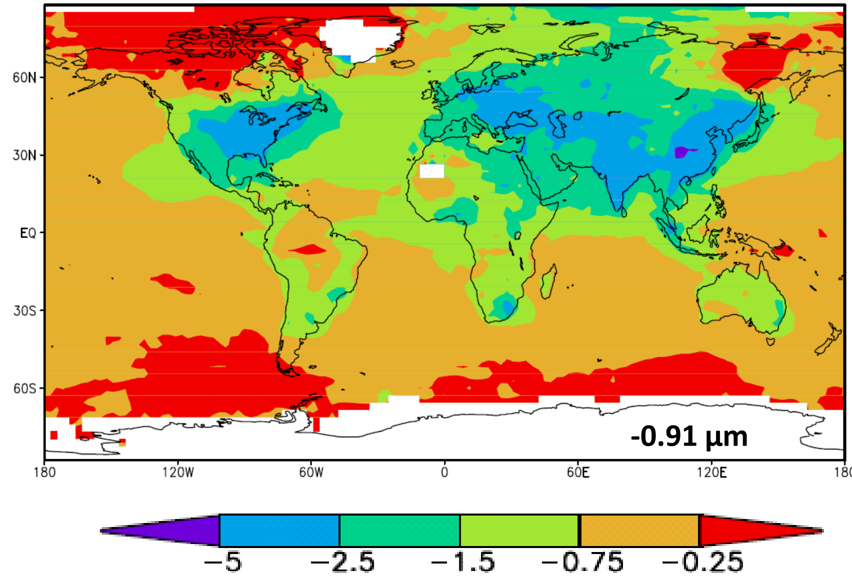
- *Bower et al. (2006: Atm. Res.):* In-situ ship measurement from remote area SH ocean: 8 cm^{-3}
- *Yum and Hudson (2004: JGR):* Southern Hemisphere Oceans: 20-40 cm^{-3}
- *Bennartz (2007: JGR):* MODIS-based retrievals: Average values of 41±17 cm^{-3} in PBL clouds in South Pacific and South Indian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

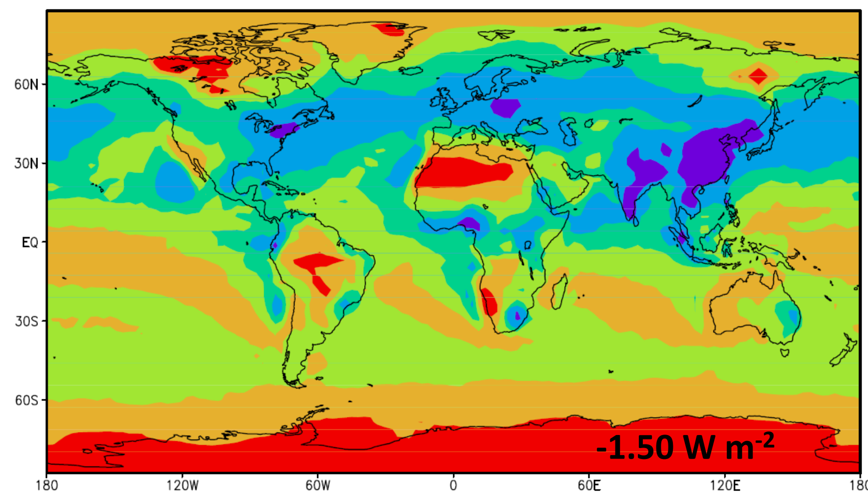
standard CDNC treatment (no lower cut-off)

Change in cloud liquid water path



Change in effective radius as seen from satellite





1+2. indirect radiative forcing

Present day:

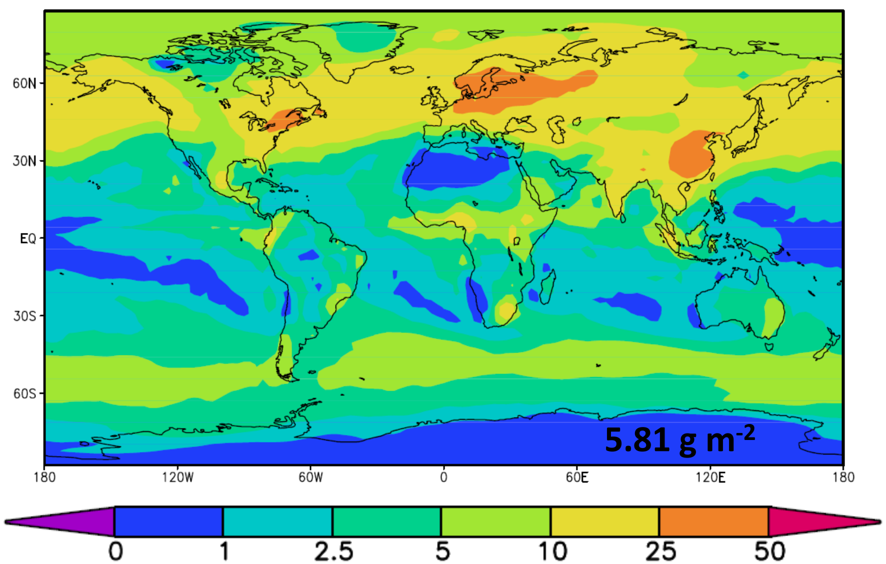
LWP = 133.1 g m^{-2}
Reff = 12.93 µm
CDNCint = 3.95e6 cm^{-2}

Pre-industrial:

LWP = 127.2 g m^{-2}
Reff = 13.85 µm
CDNCint = 2.57e6 cm^{-2}

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

Change in cloud liquid water path



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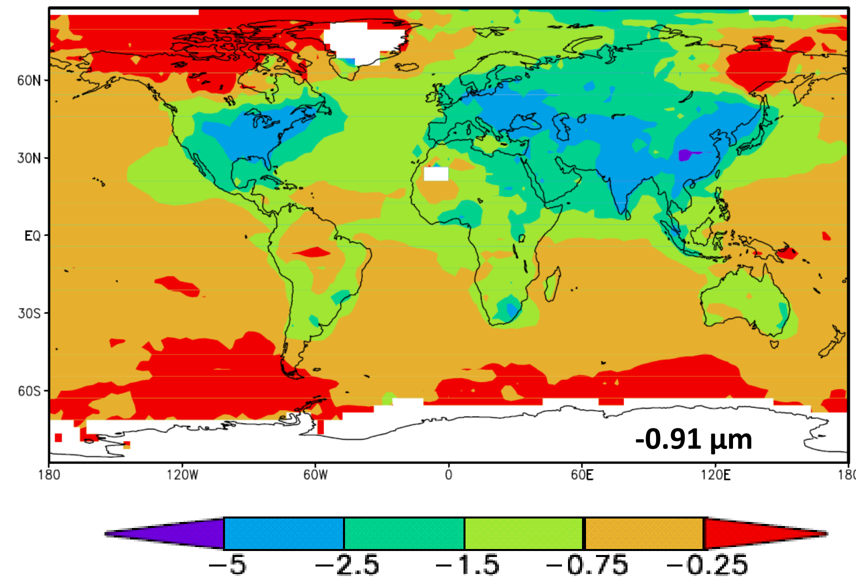
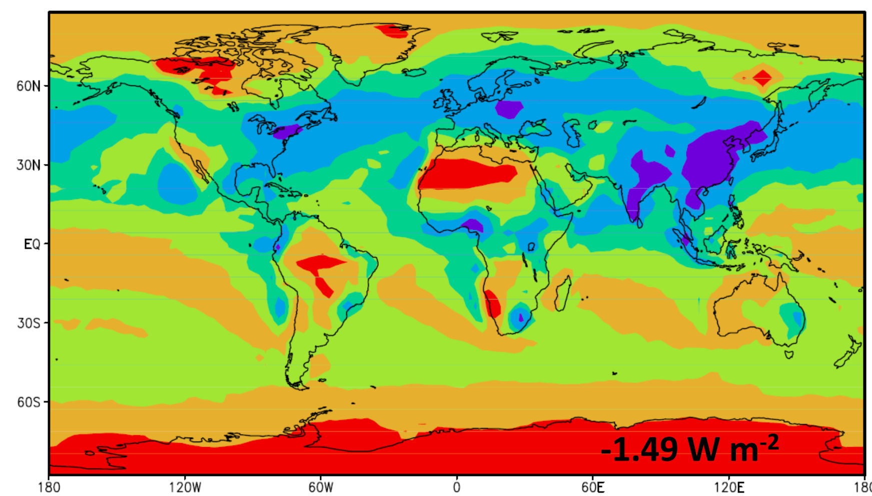




1+2. indirect radiative forcing

Present day:

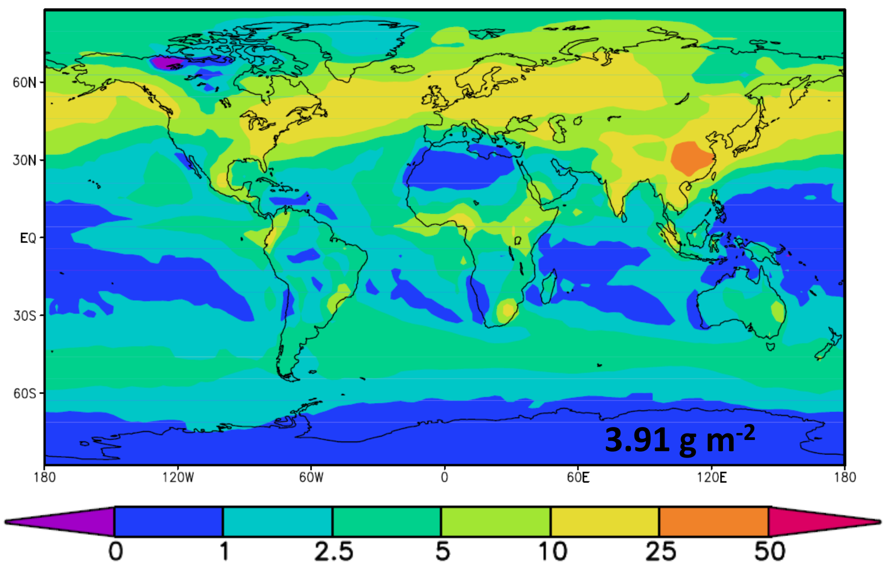
LWP = 133.6 g m^{-2}
Reff = 12.95 µm
CDNCint = 3.95e6 cm^{-2}

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



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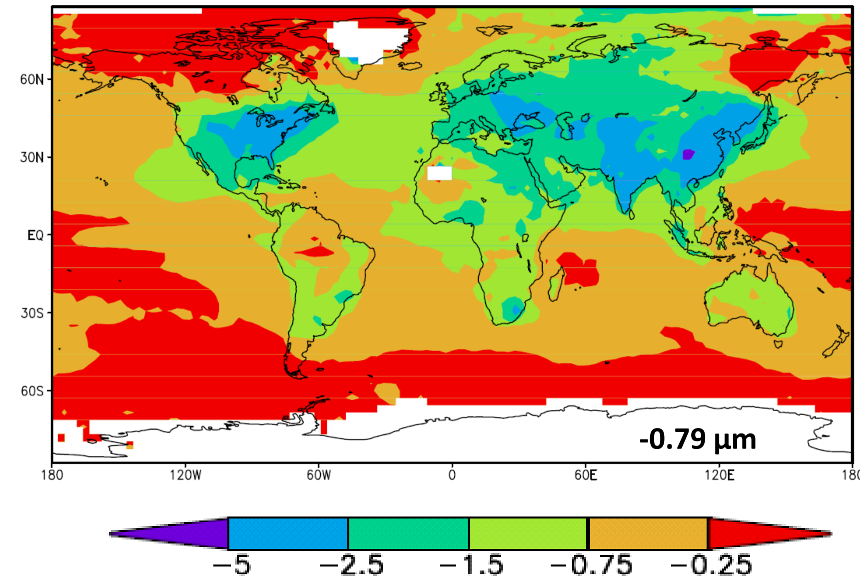
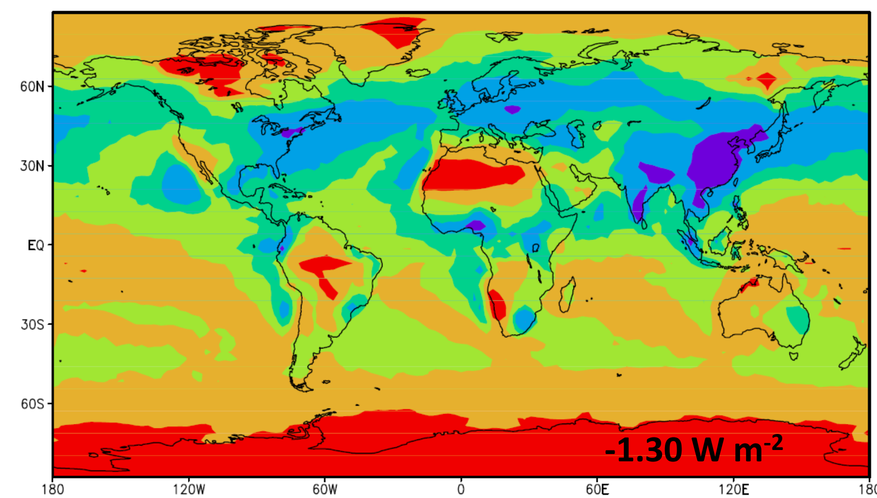




1+2. indirect radiative forcing

Present day:

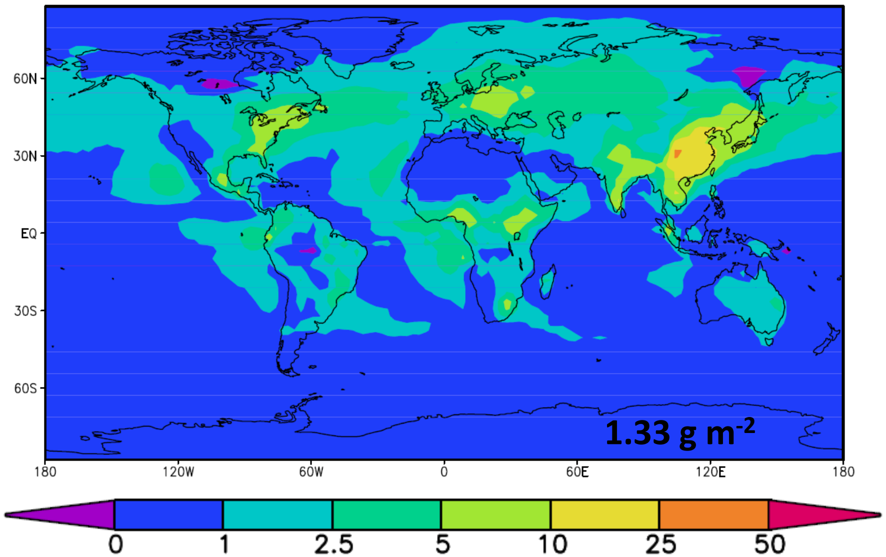
LWP = 136.3 g m^{-2}
Reff = 12.64 µm
CDNCint = 3.95e6 cm^{-2}

Pre-industrial:

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

$CDNC_{min}$ = 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}

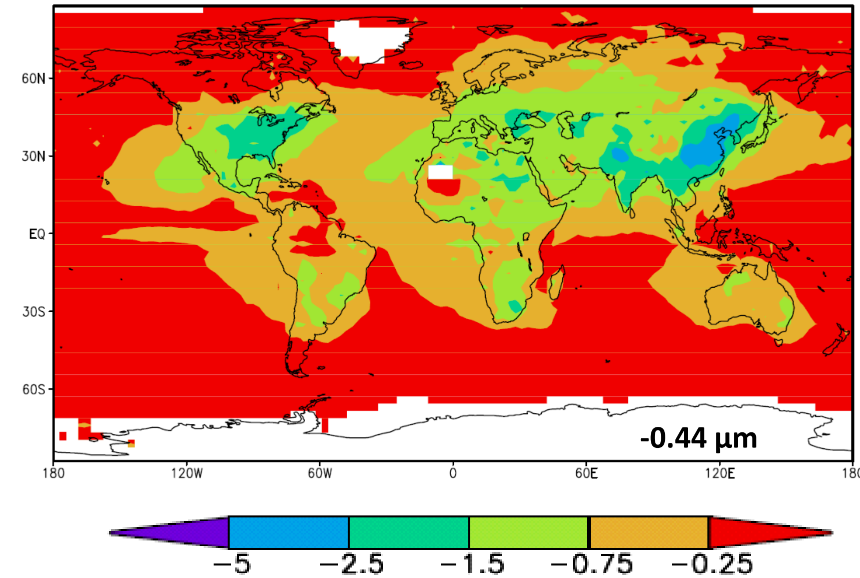
Pre-industrial:

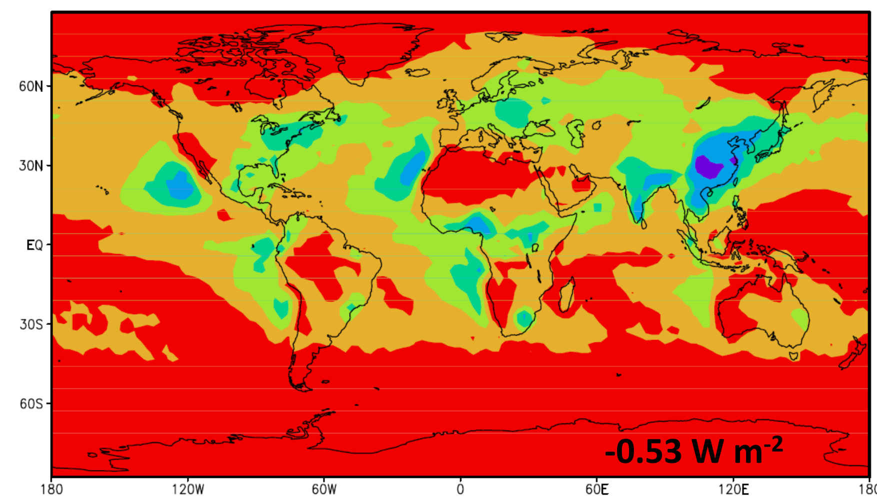
LWP = 148.1 g m^{-2}

Reff = 11.43 µm

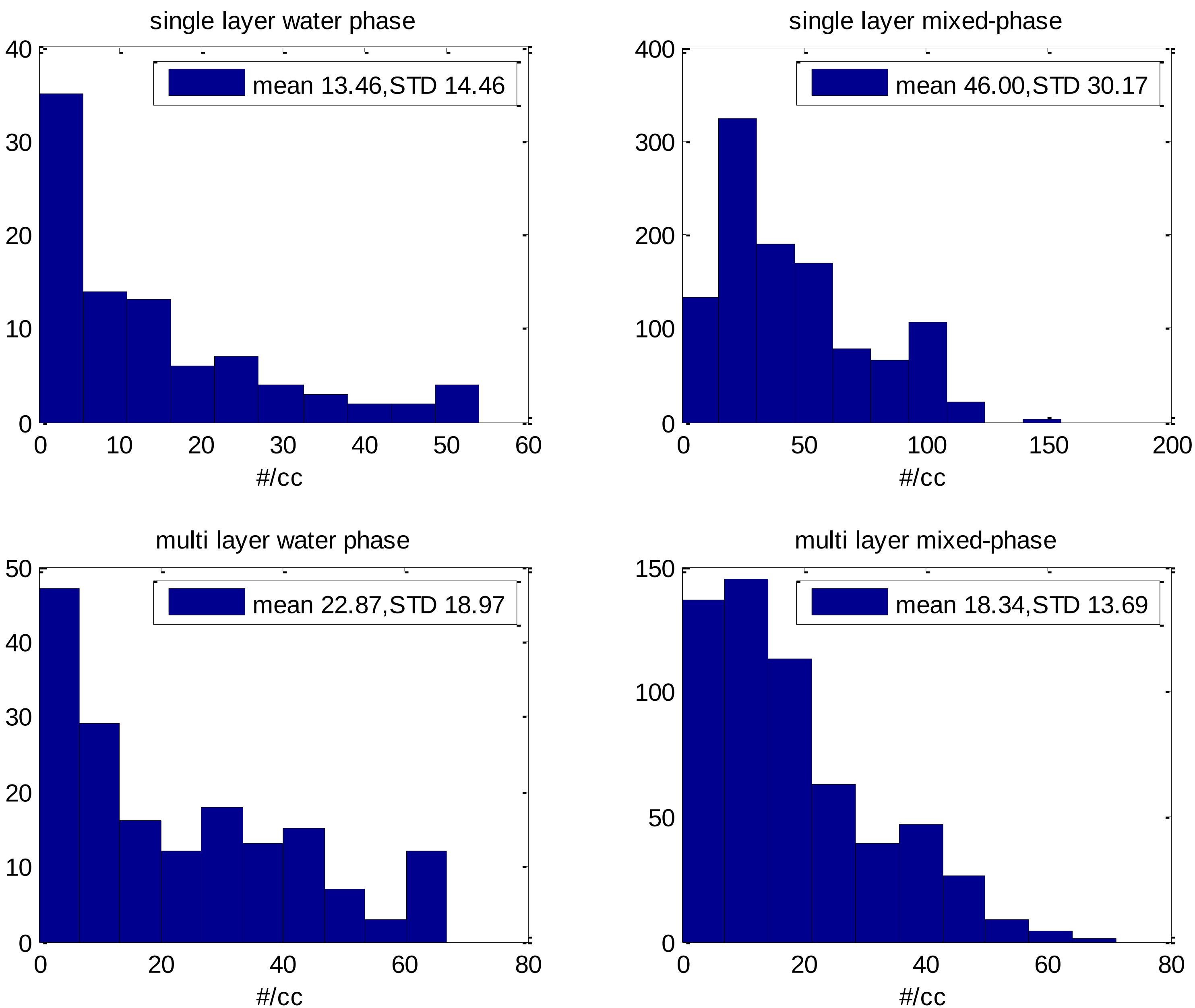
CDNCint = 2.57e6 cm^{-2}

Change in effective radius as seen from satellite



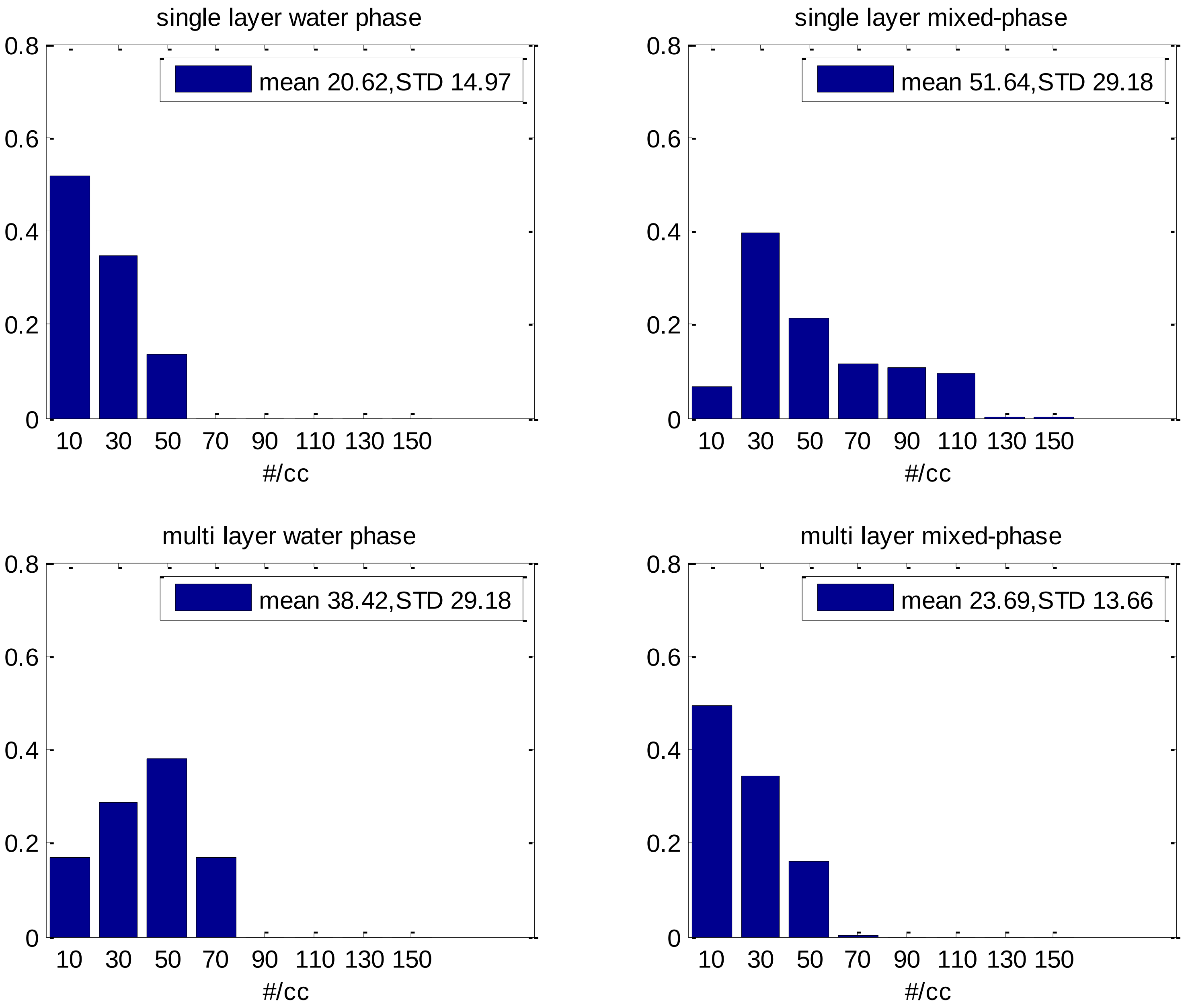


1+2. indirect radiative forcing



McFarquhar and Zhang, U. Illinois

LWC>0.05g/m³



McFarquhar and Zhang, U. Illinois

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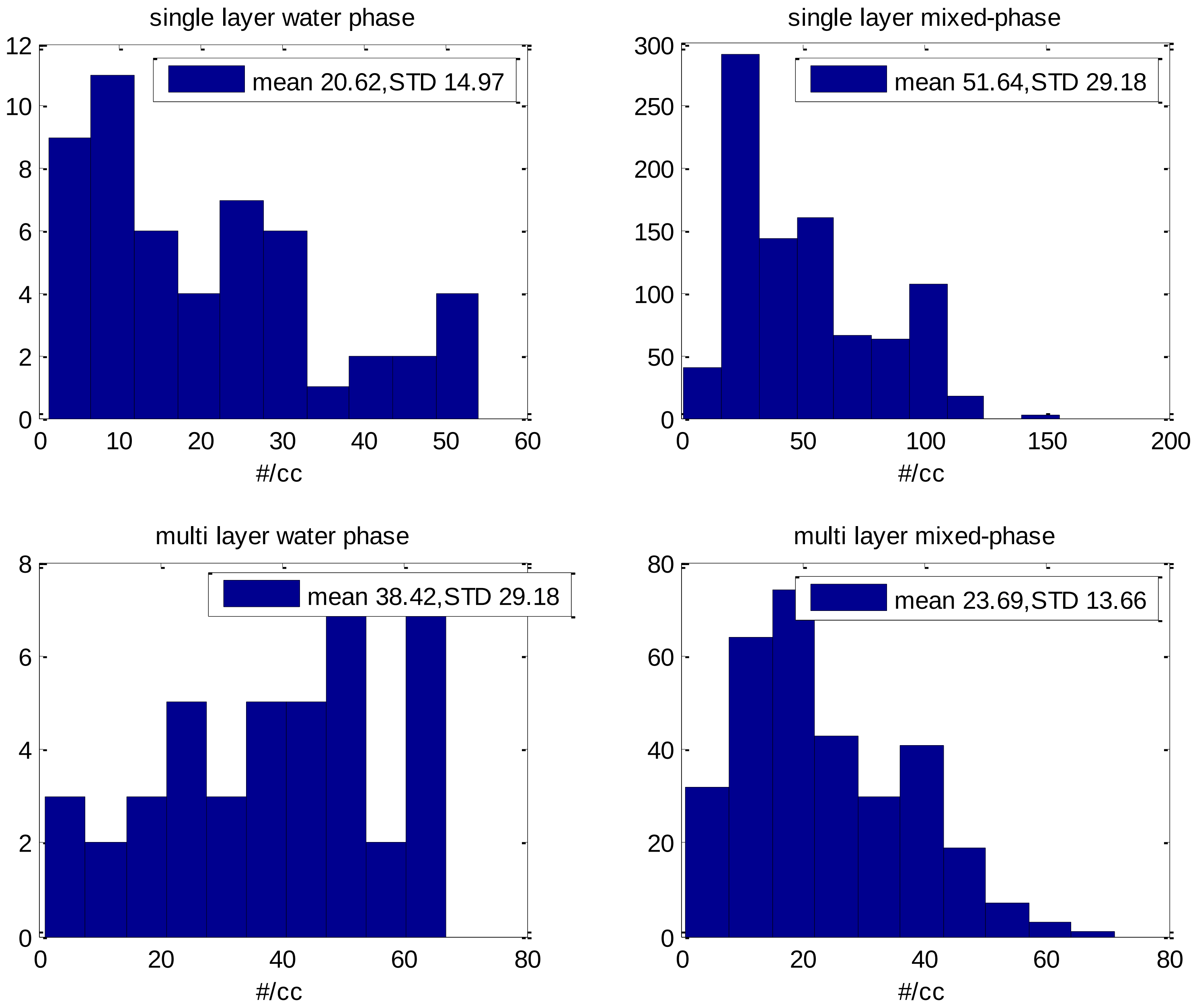


McFarquhar and Zhang, U. Illinois

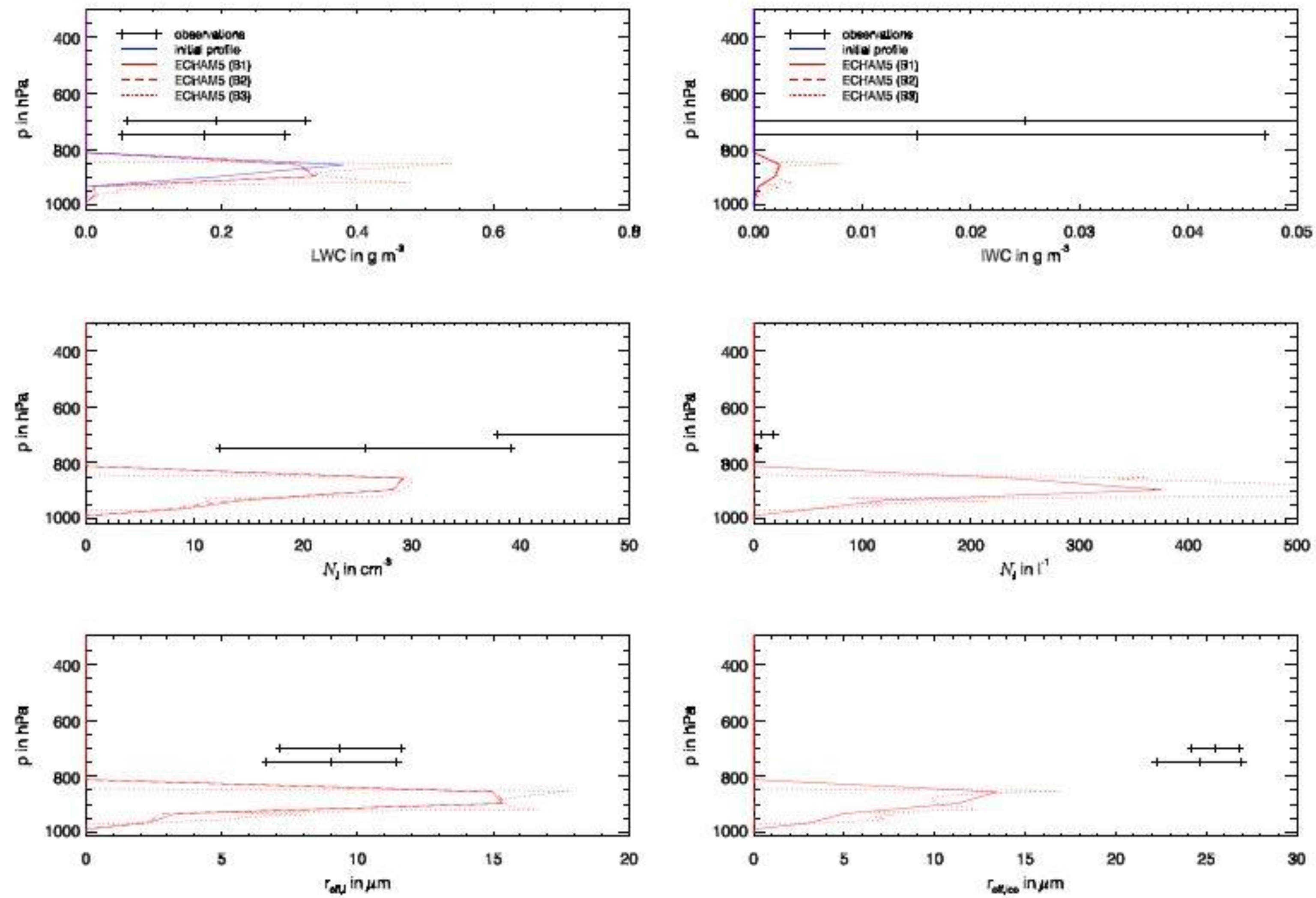
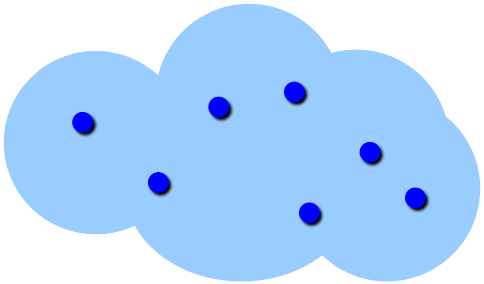


Figure 4.7: Model results for M-PACE period B, averaged over the 12h simulation period. Simulations B1 and B2 lie close together. Observations are aircraft data from McFarquhar et al. (2007), averaged over several vertical spirals for two flights during period B. The standard deviations correspond to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

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

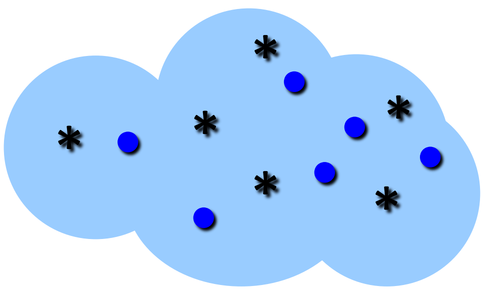
Warm and cold clouds

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

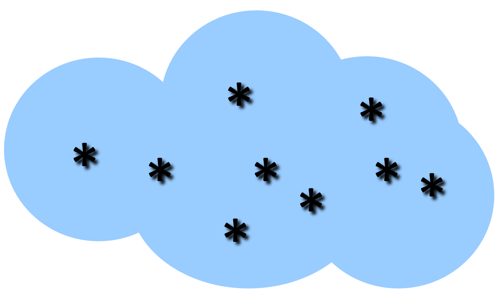


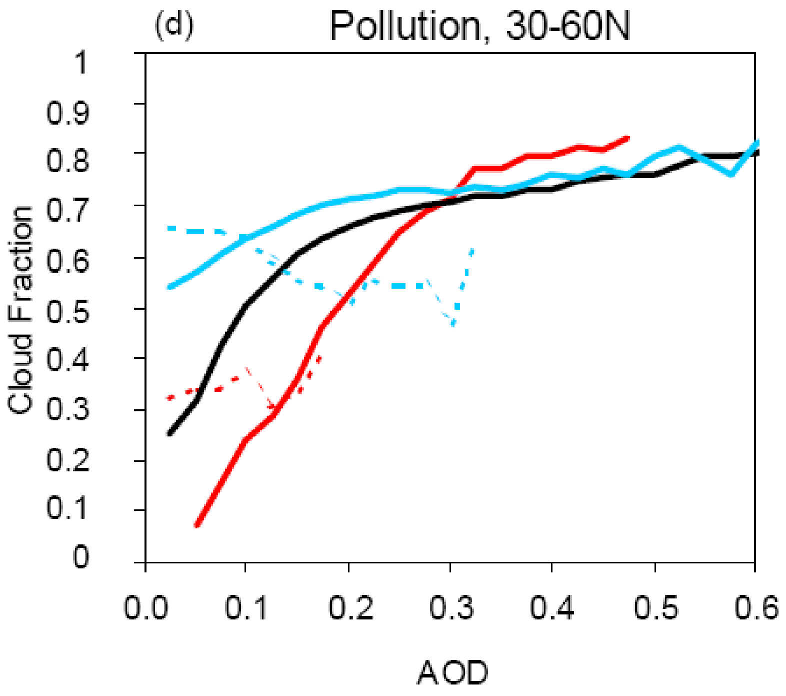
Cold clouds

→ mixed-phase clouds ($\sim -35^{o}C < T < 0^{o}C$)

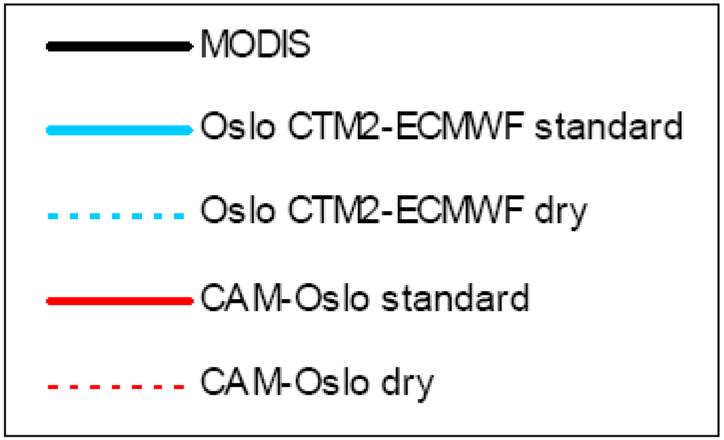


→ ice clouds (cirrus) ($T < \sim -35^{o}C$)





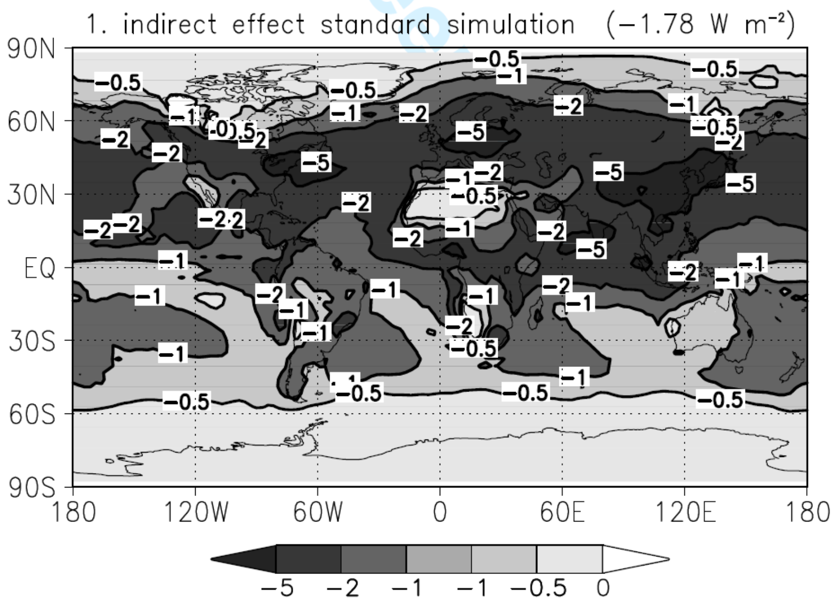
(d)
Pollution, 30-60N
Cloud Fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
AOD



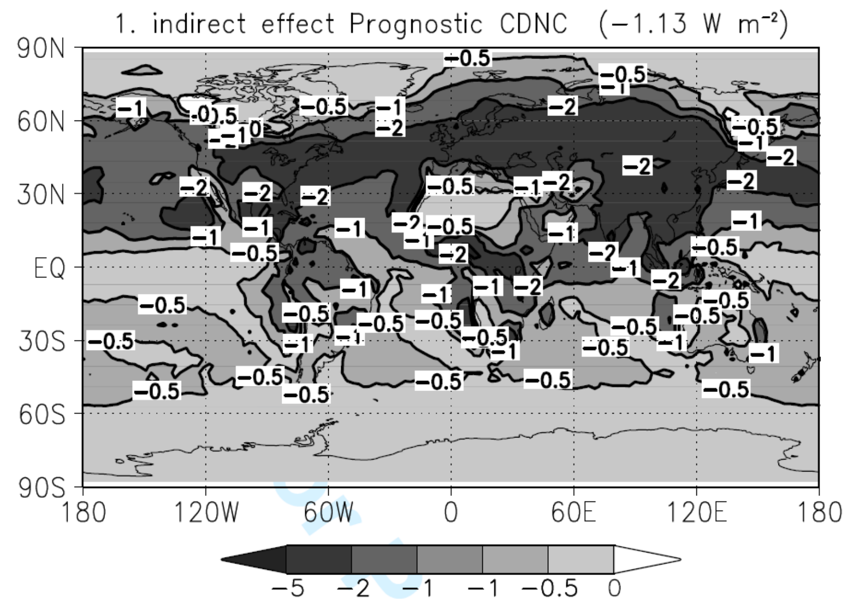
MODIS
Oslo CTM2-ECMWF standard
Oslo CTM2-ECMWF dry
CAM-Oslo standard
CAM-Oslo dry

Aerosol Indirect Forcing in CAM3-Oslo

Diagnostic CDNC



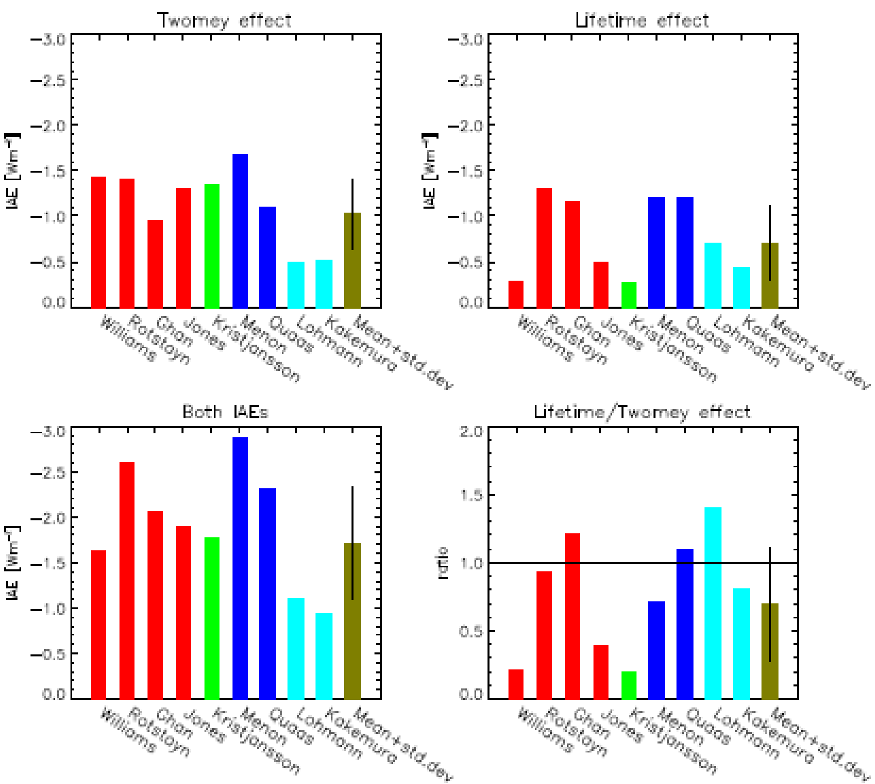
Prognostic CDNC

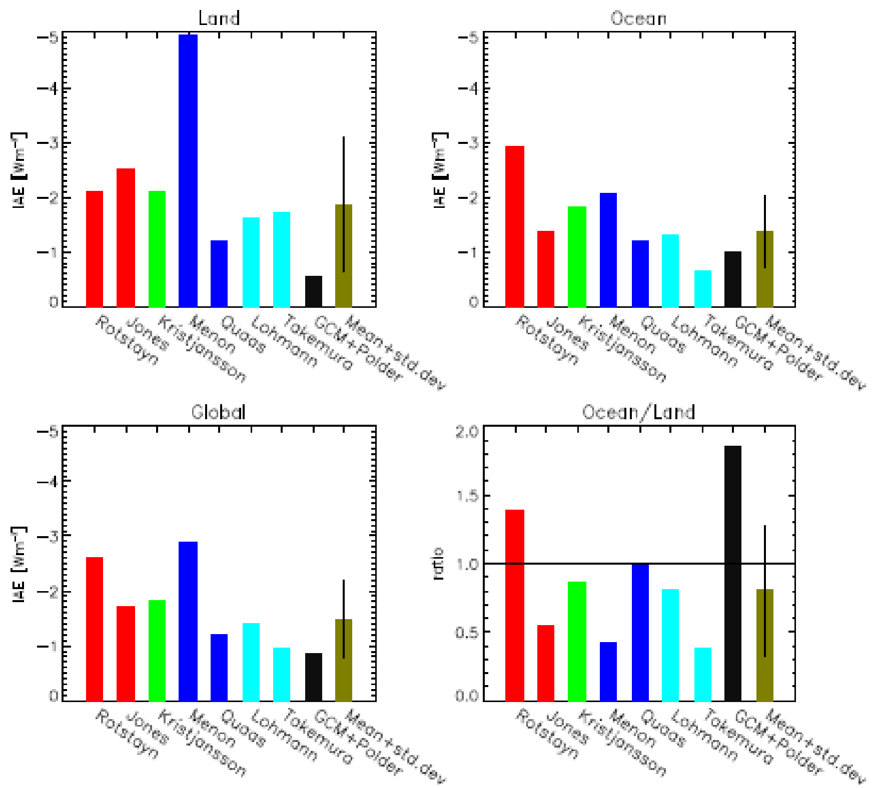


Indirect forcing reduced by 35%, largely due to competition effect!

Seland et al. (2008: Tellus A)

Model Estimates of the Aerosol Indirect Effect





Lohmann & Feichter (2005: ACP)

Cloud Feedback

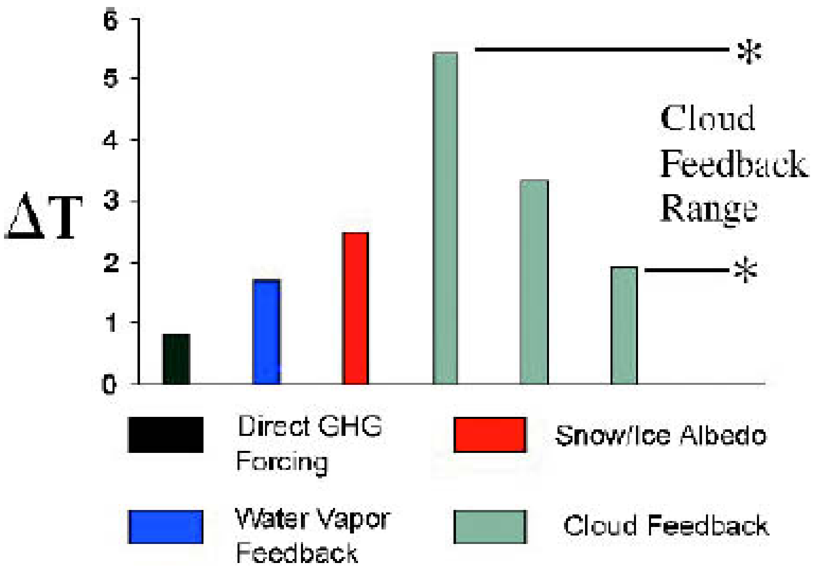


FIG. 13. The response of a single climate model to an imposed doubling of CO_2 as different feedbacks are systematically added in the model (adapted from Senior and Mitchell 1993). Different treatments of cloud processes in the model produce a large spread in predicted surface temperature due to CO_2 doubling.

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

Stephens (2005: J. Climate)