Clouds and Aerosols

(1) How do aerosols, clouds and precipitation interact?
(2) Why is it relevant?
(3) How do we model and observe these interactions?

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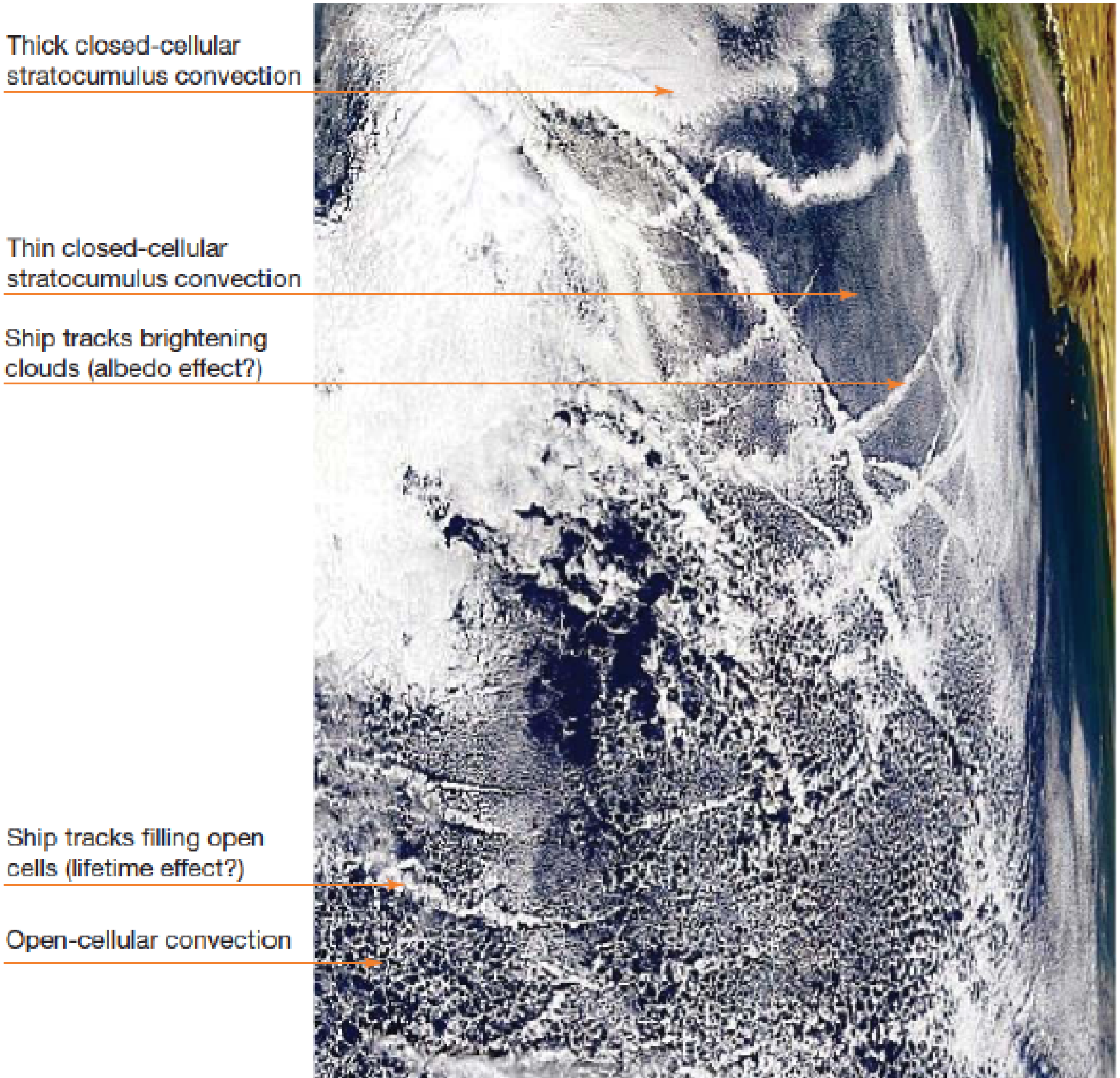
5. Searching for the aerosol indirect effect

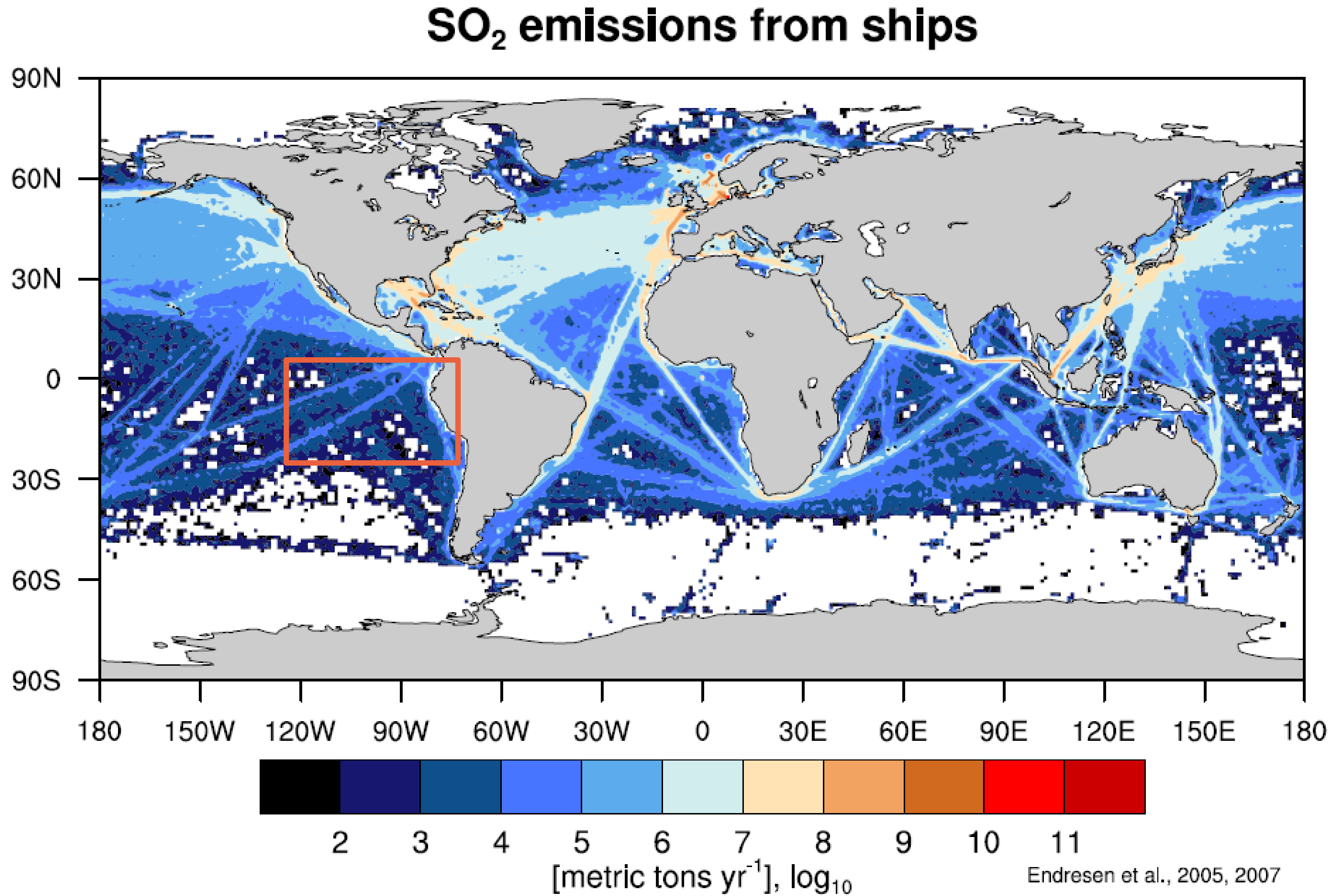
5. Searching for the aerosol indirect effect

5.1 Ship tracks



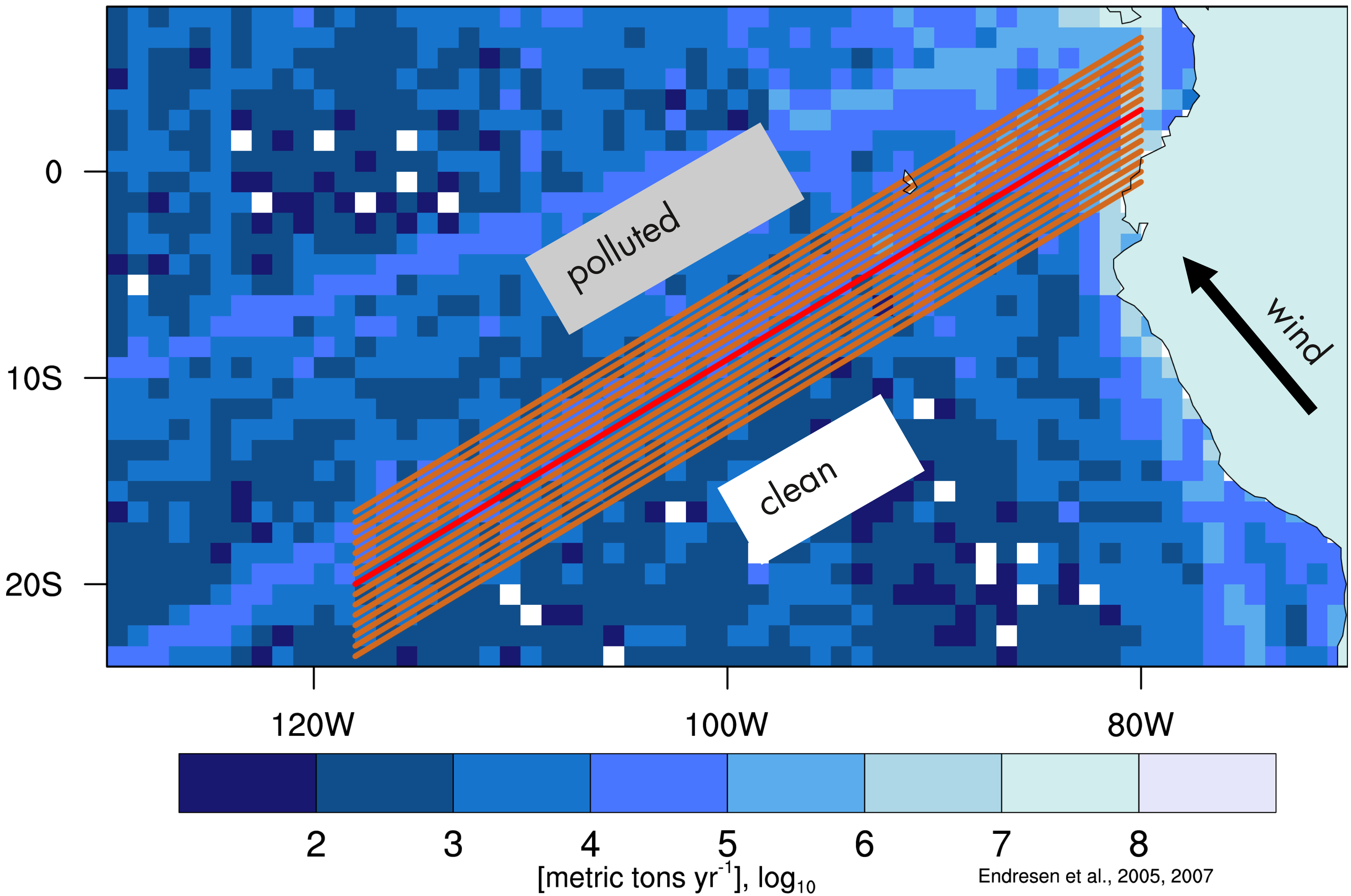
Stevens and Feingold, Nature 2009; Goren and Rosenfeld, J. Geophys. Res., 2012

5.2 Ship tracks at a large scale



Peters, Quaas and Graßl, J. Geophys. Res. 2011

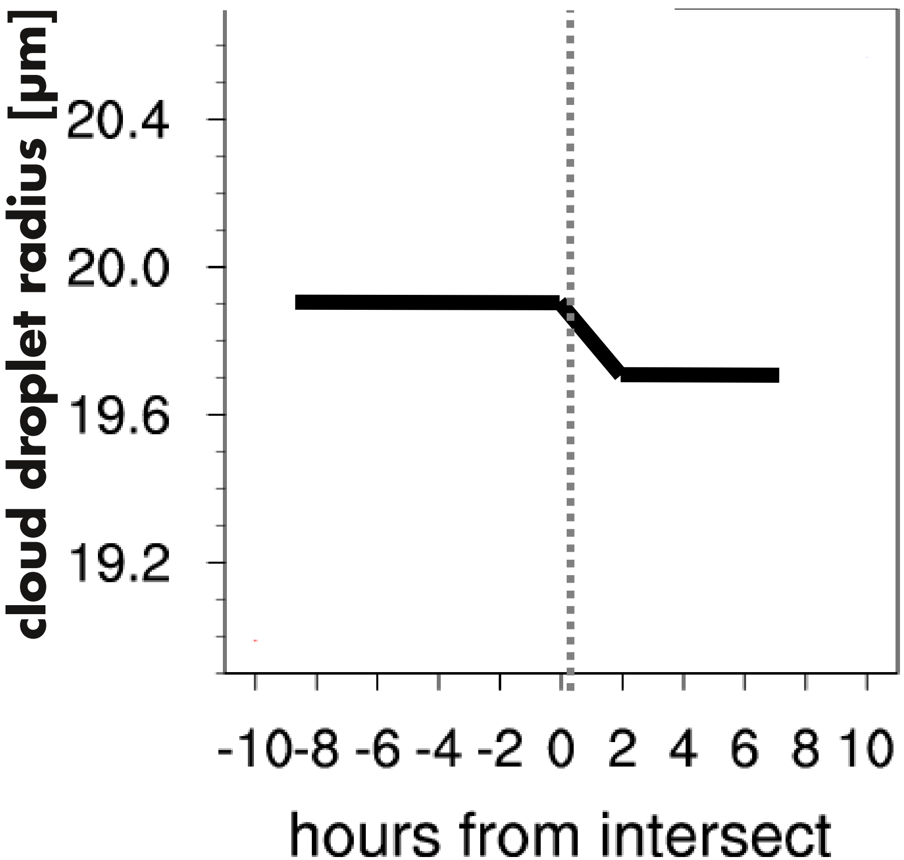
5.2 Ship tracks at a large scale



colour code: SO2 ship emissions (log scale)

.2 Ship tracks at a large scale

Indirect effect: **cloud droplet radius decrease?**

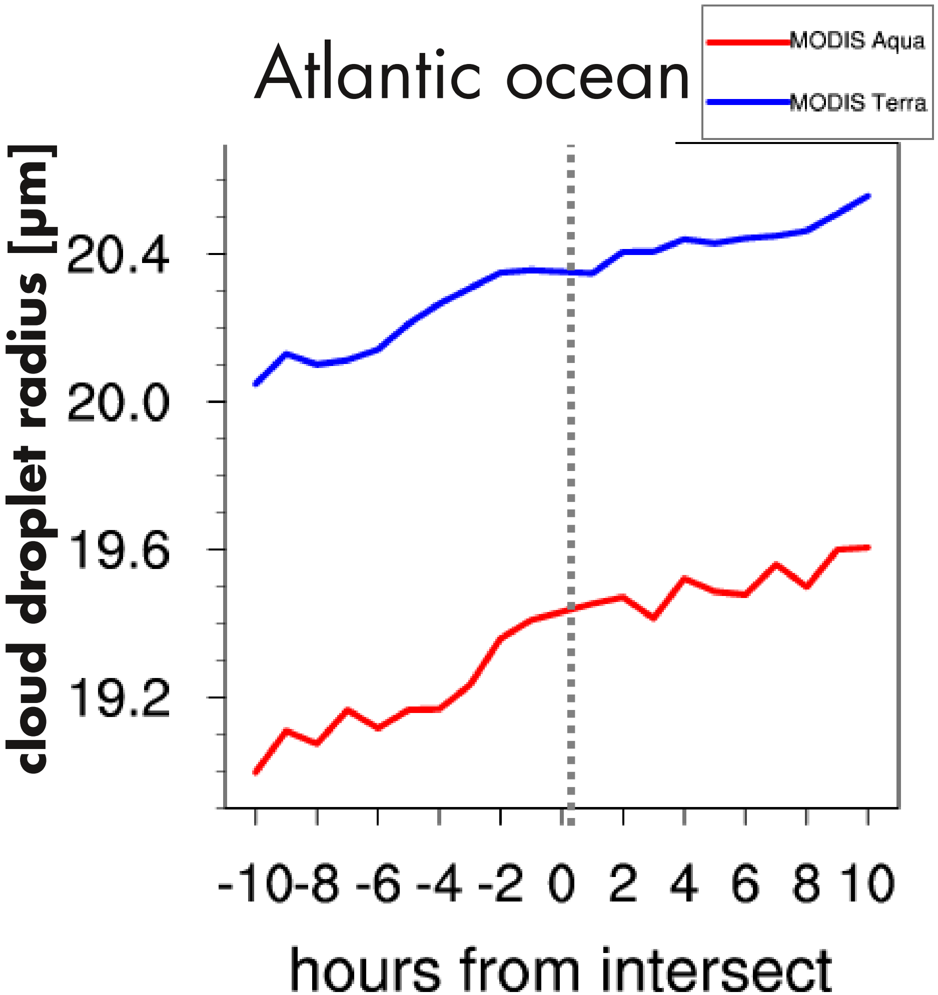


Expected idealised indirect effect result:

→ Cloud droplet radius decreases due to pollution

5.2 Ship tracks at a large scale

Indirect effect: **cloud droplet radius decrease?**



Expected idealised indirect effect result:

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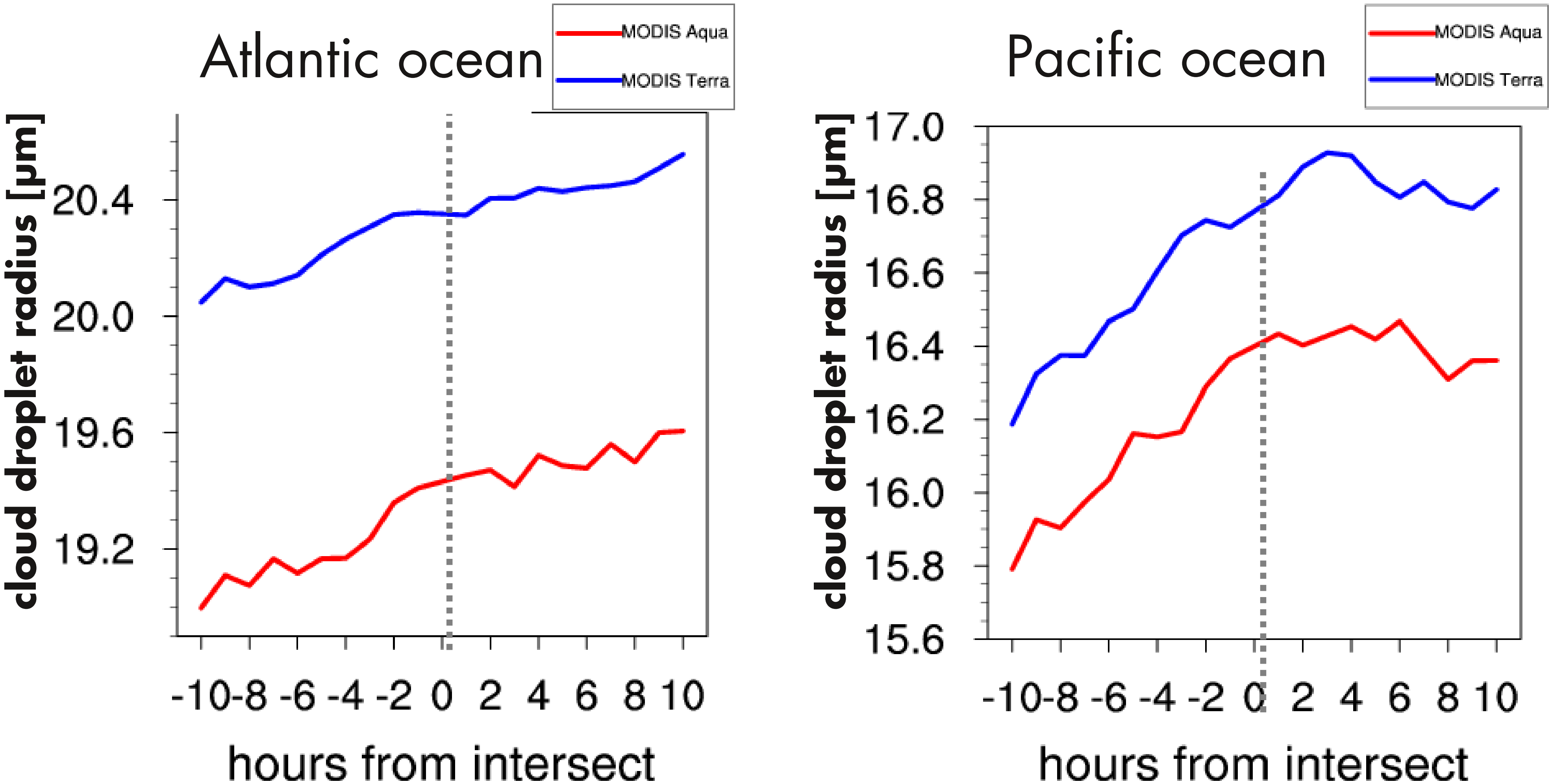
Peters, Quaas and Graßl, J. Geophys. Res. 2011

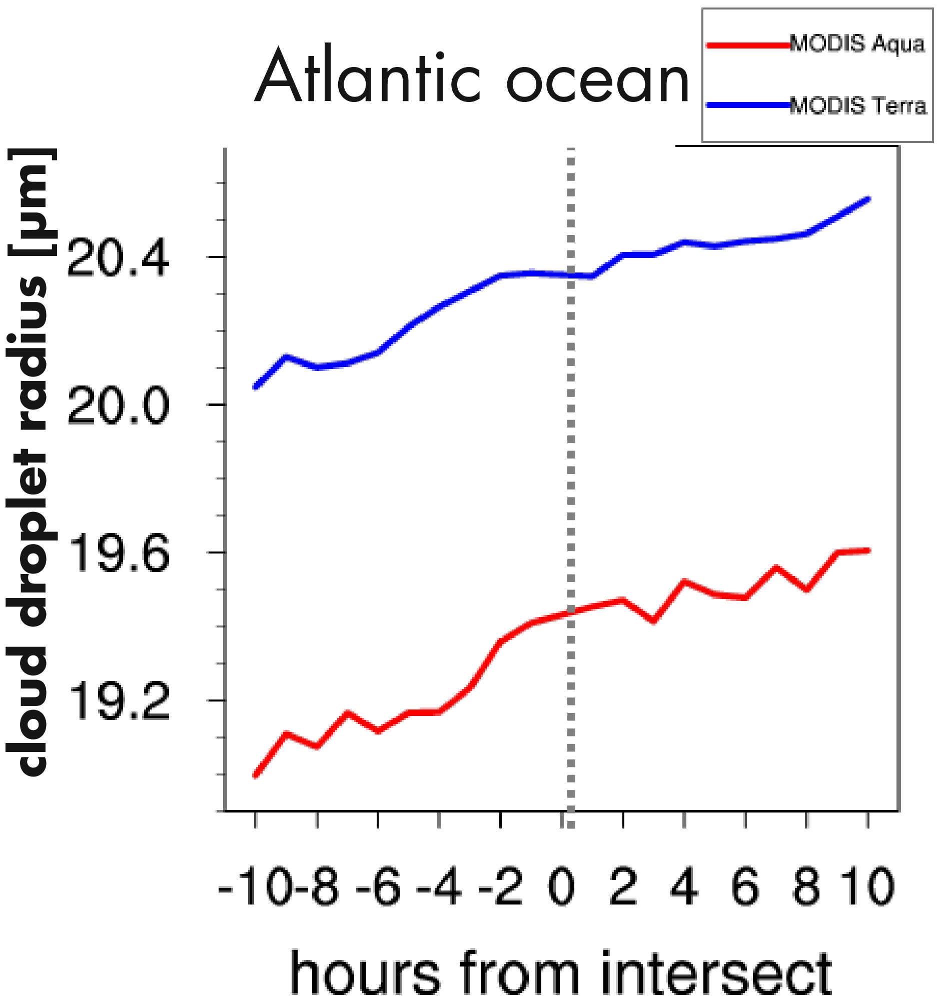
5.2 Ship tracks at a large scale

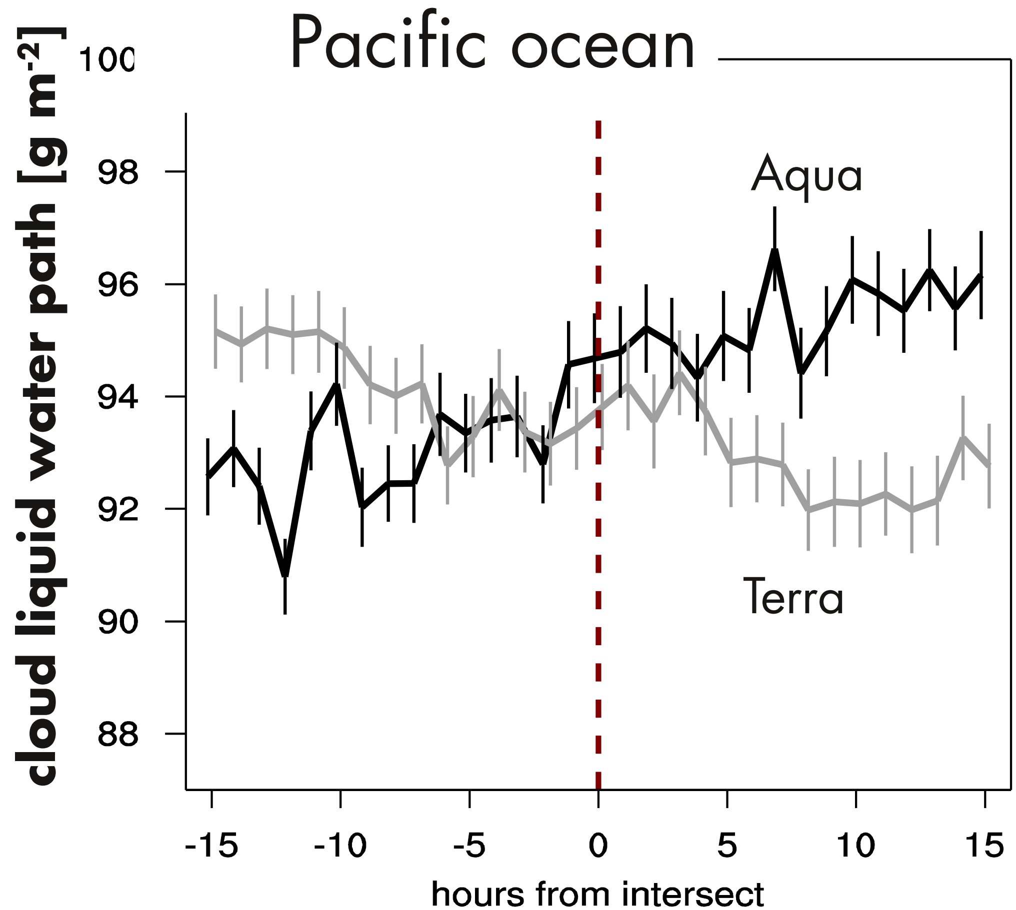
Indirect effect: **cloud droplet radius decrease?**



5.2 Ship tracks at a large scale

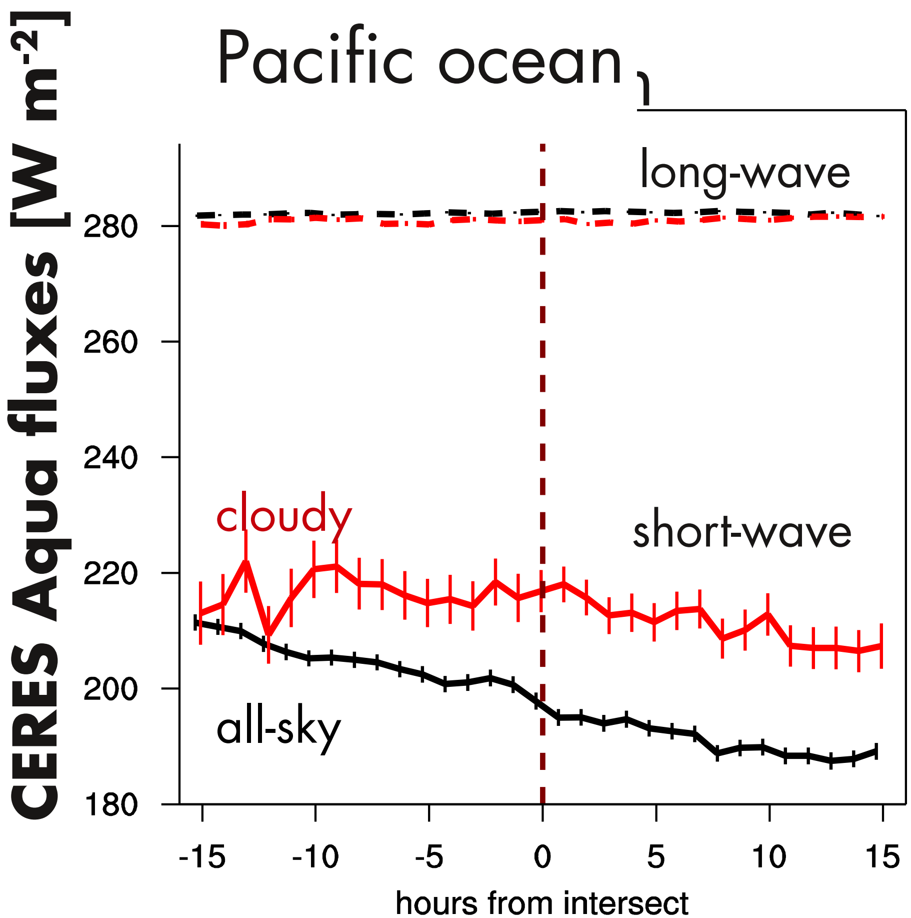
Indirect effect: **cloud droplet radius decrease?** **cloud liquid water path increase?**



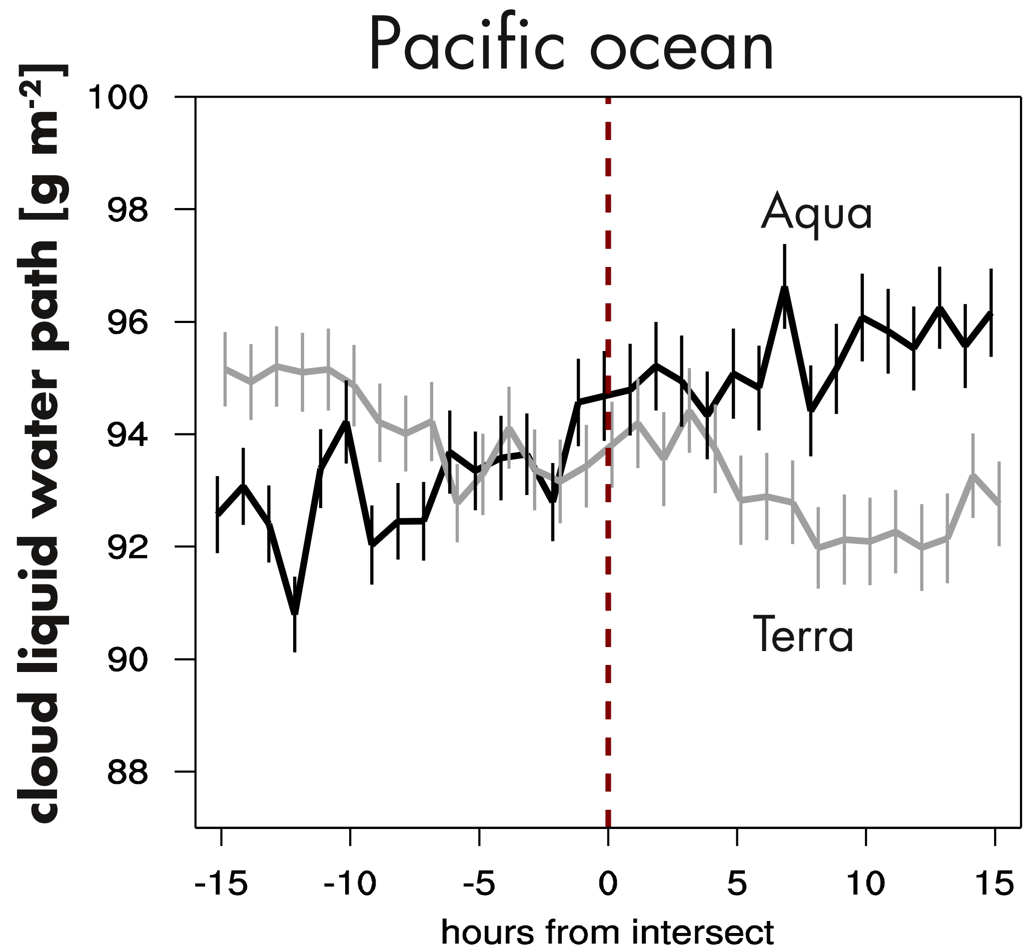


5.2 Ship tracks at a large scale

Radiation flux changes?

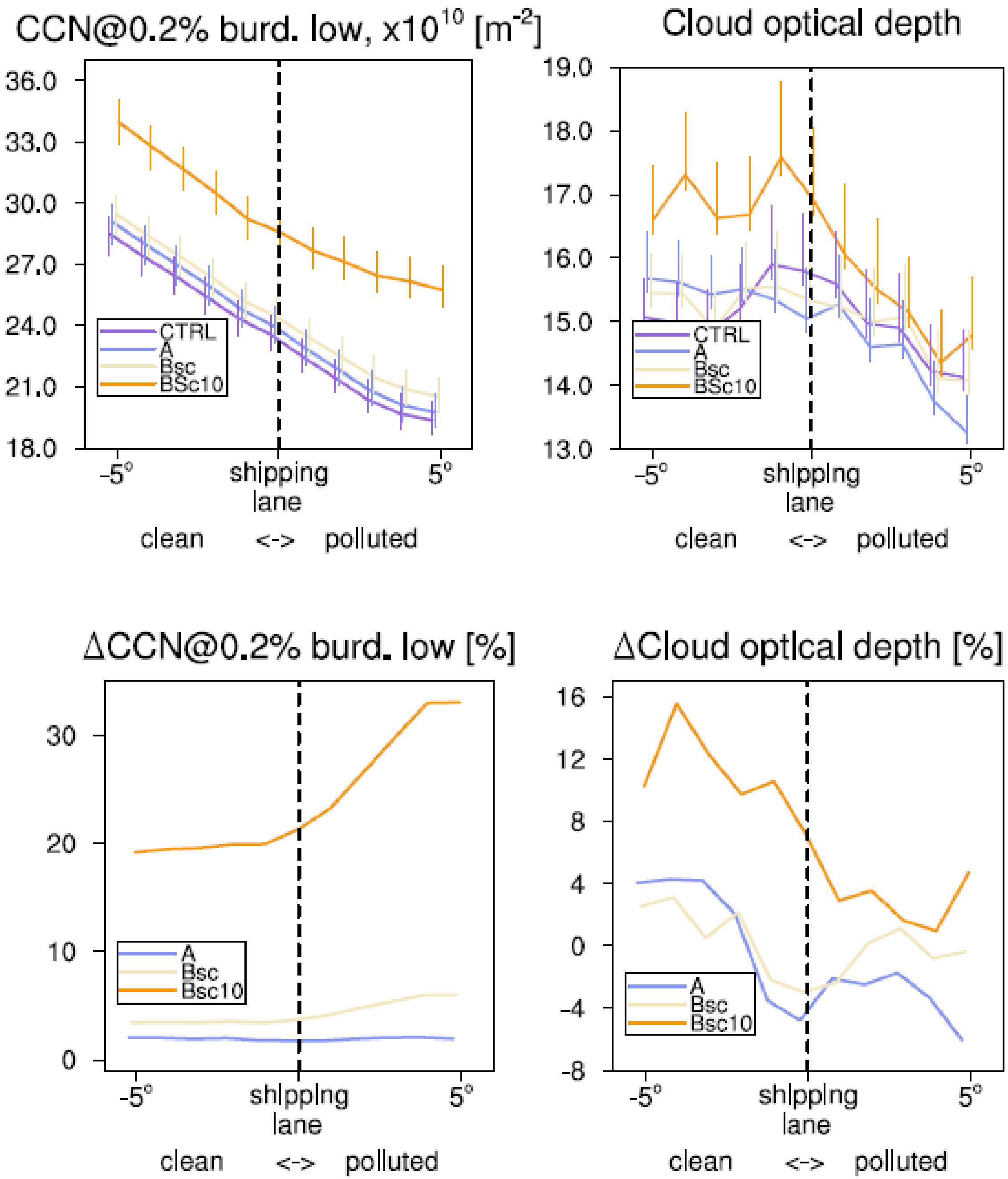


cloud liquid water path increase?



Peters, Quaas and Graßl, J. Geophys. Res. 2011

5.2 Ship tracks at a large scale



→ **Caveat:**

in model simulations no clear signal either (despite global mean forcing up to -1.9 Wm^{-2} due to ship emissions alone)

Peters, Quaas, Stier and Graßl, submited to Tellus

5.3 Hemispherical contrast

Satellite observations over oceans

	Northern hemisphere	Southern hemisphere
Fine-mode aerosol optical depth	**0.094**	**0.061**

→ hemispherical contrast in **aerosol**

Feng and Ramanathan, Tellus 2010

5.3 Hemispherical contrast

Satellite observations over oceans

	Northern hemisphere	Southern hemisphere
Fine-mode aerosol optical depth	0.094	0.061
Droplet effective radius [µm]	12.1	13.0

→ hemispherical contrast in aerosol **and cloud droplet radii**

Feng and Ramanathan, Tellus 2010

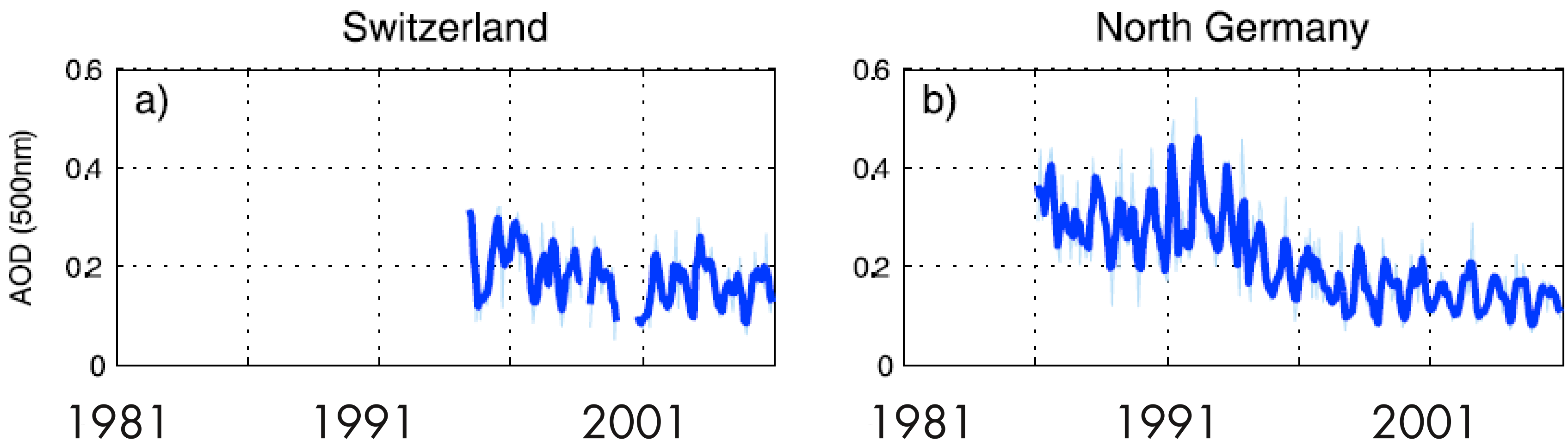
5.3 Hemispherical contrast

Satellite observations over oceans

	Northern hemisphere	Southern hemisphere
Fine-mode aerosol optical depth	0.094	0.061
Droplet effective radius [μm]	12.1	13.0
Cloud optical depth	12.6	12.1

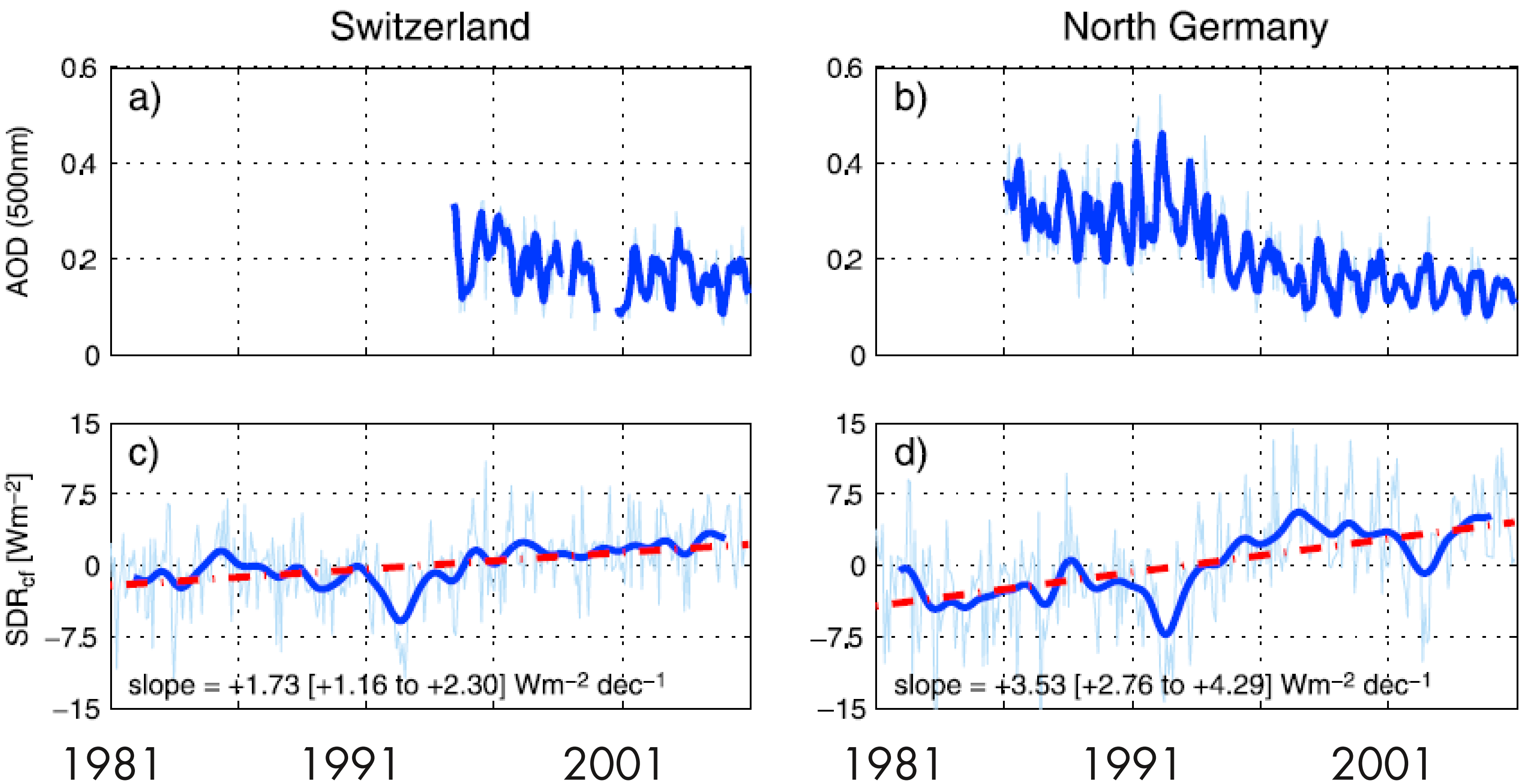
→ hemispherical contrast in aerosol and droplet effective radii
→ **not in cloud optical depth** (slightly larger liquid water path in SH)

5.4 Solar dimming and brightening



Aerosol optical depth

5.4 Solar dimming and brightening

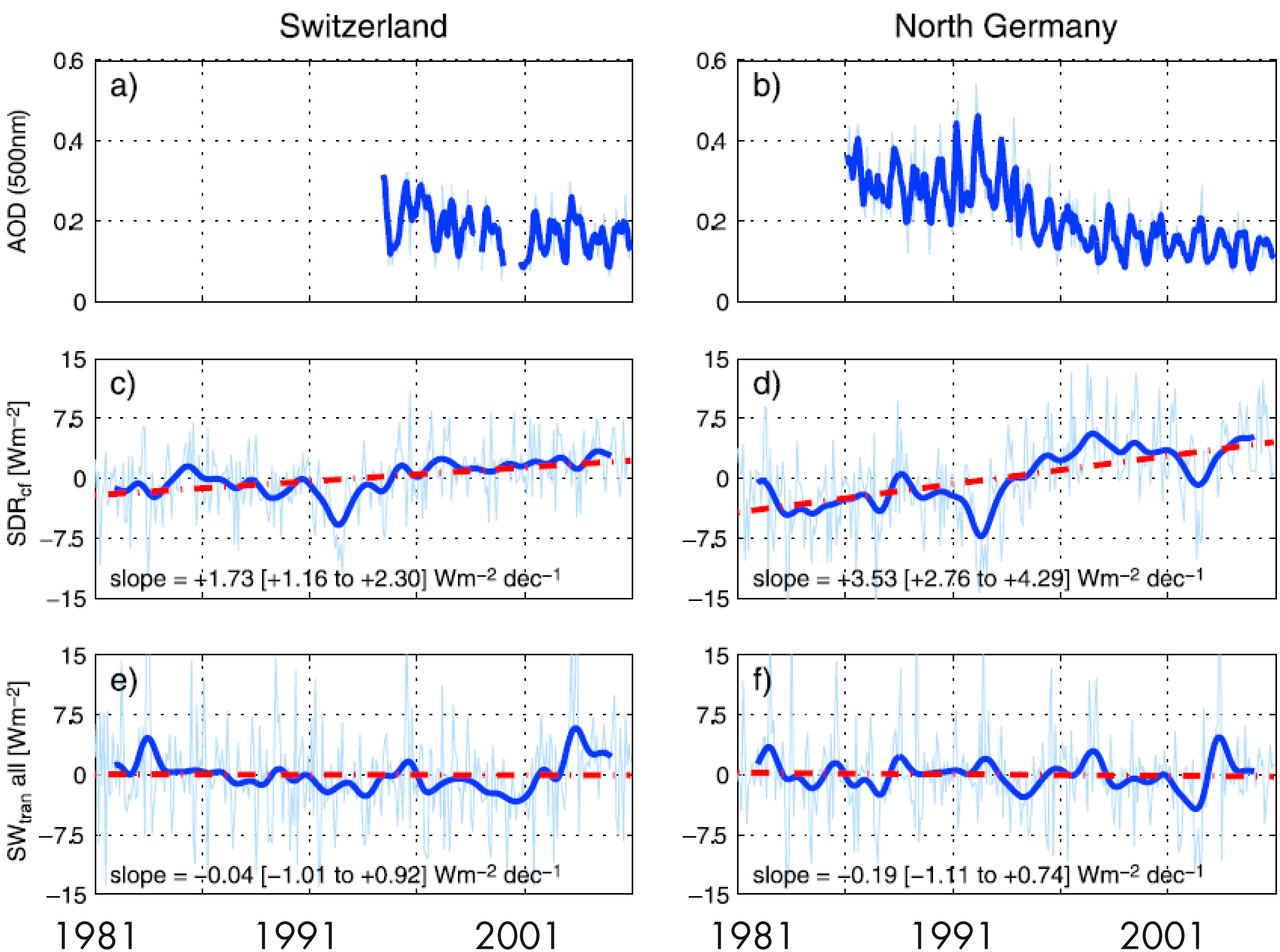


Aerosol optical depth

Clear-sky surface solar radiation

Ruckstuhl, Norris, Philipona, J. Geophys. Res. 2010
see also Norris and Wild, J. Geophys. Res. 2007

5.4 Solar dimming and brightening



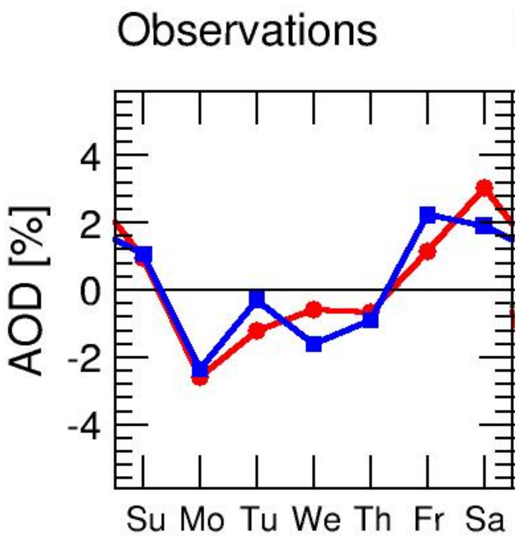
Aerosol optical depth

Clear-sky surface solar radiation

All-sky surface solar radiation

Ruckstuhl, Norris, Philipona, J. Geophys. Res. 2010
see also Norris and Wild, J. Geophys. Res. 2007

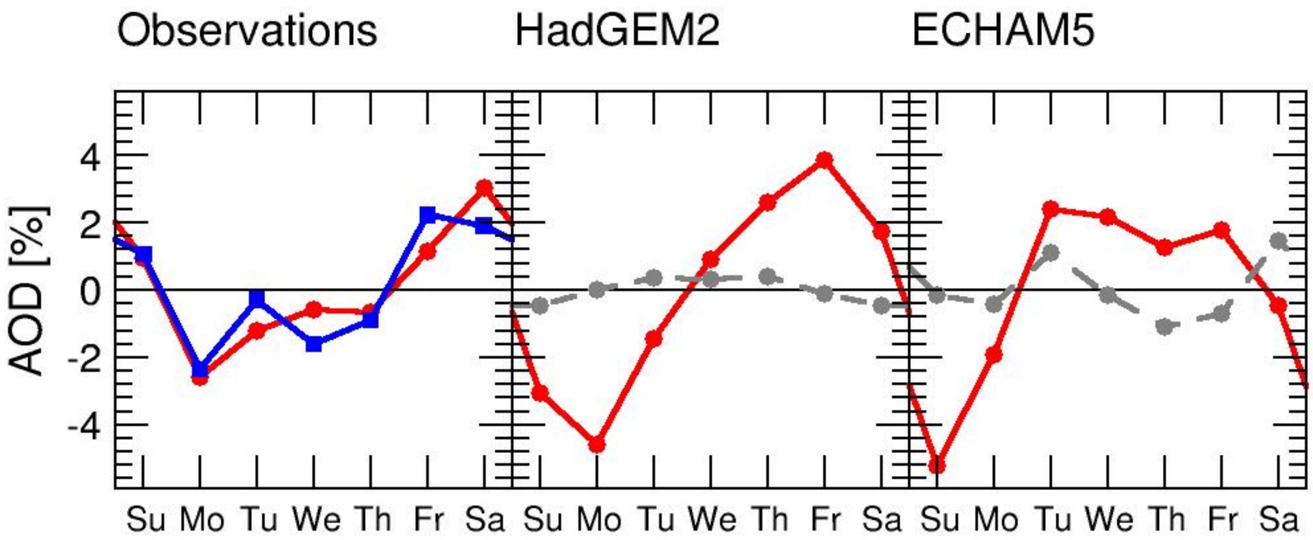
.5 Weekly cycle



MODIS Terra
MODIS Aqua

Quaas et al., Atmos. Chem. Phys. 2009

5.5 Weekly cycle

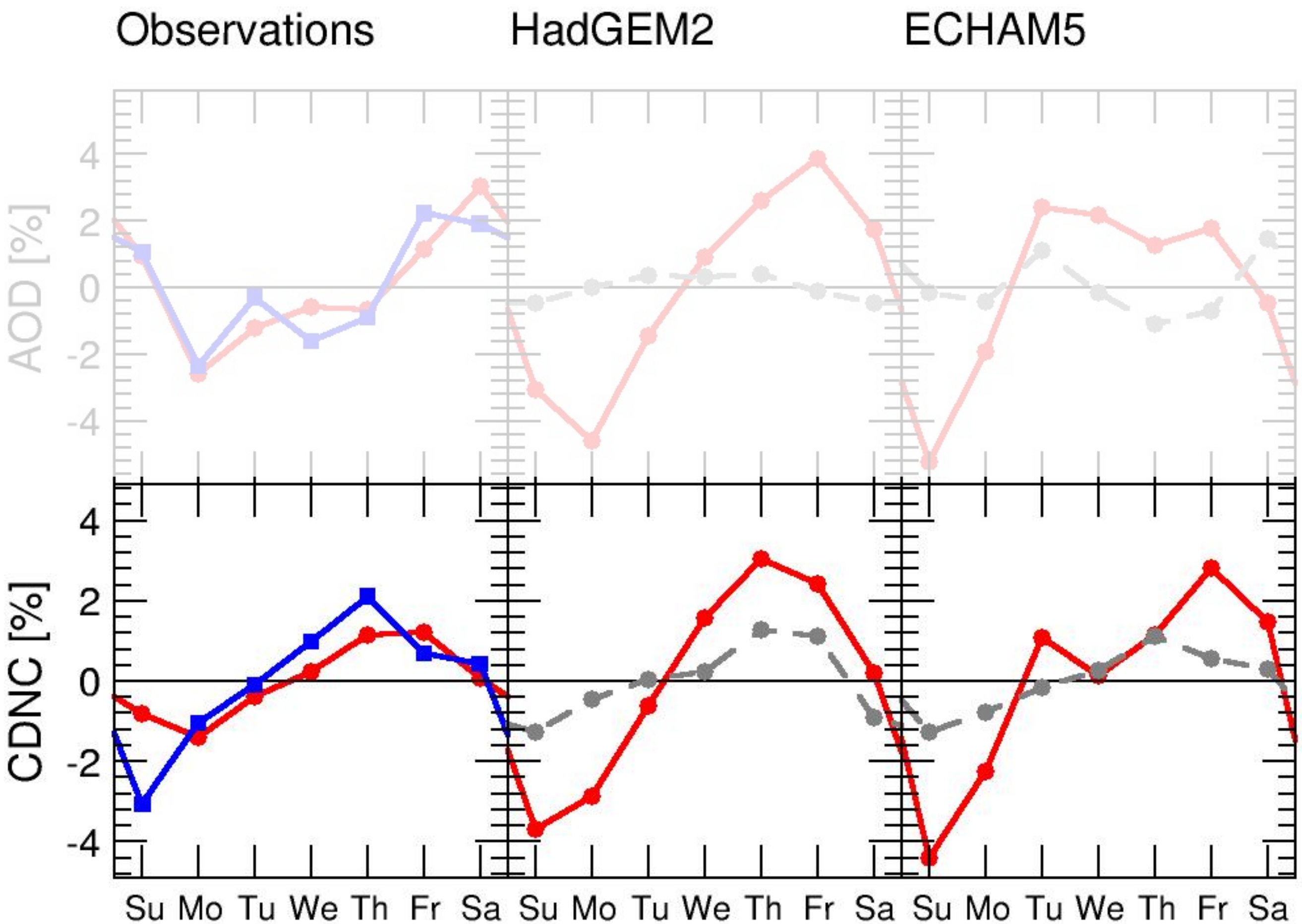


MODIS Terra
MODIS Aqua

Model experiment
Model control

Aerosol optical depth

5.5 Weekly cycle

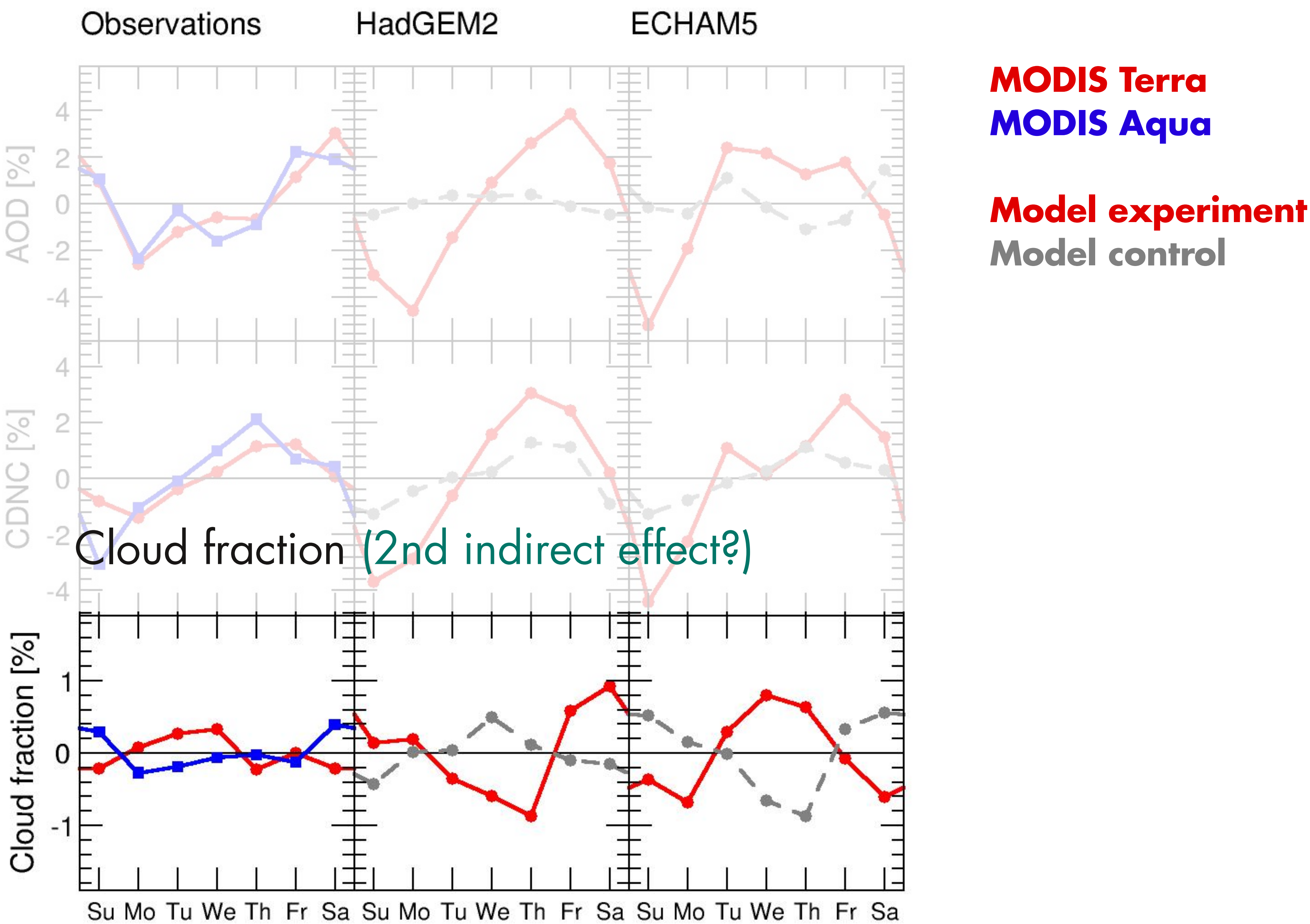


MODIS Terra
MODIS Aqua

Model experiment
Model control

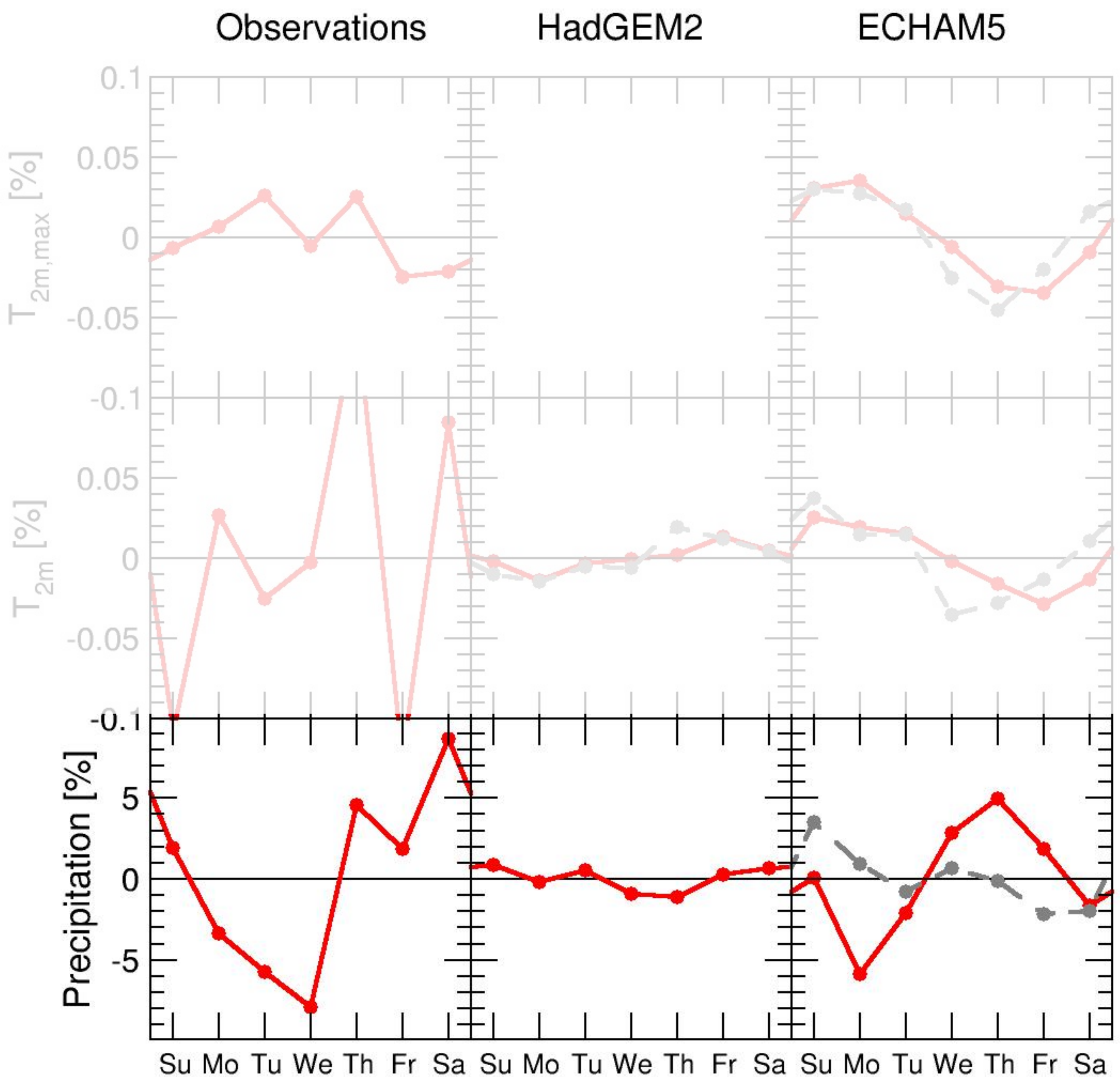
Cloud droplet number concentration
(1st indirect aerosol effect)

5.5 Weekly cycle



Quaas et al., Atmos. Chem. Phys. 2009

5.5 Weekly cycle

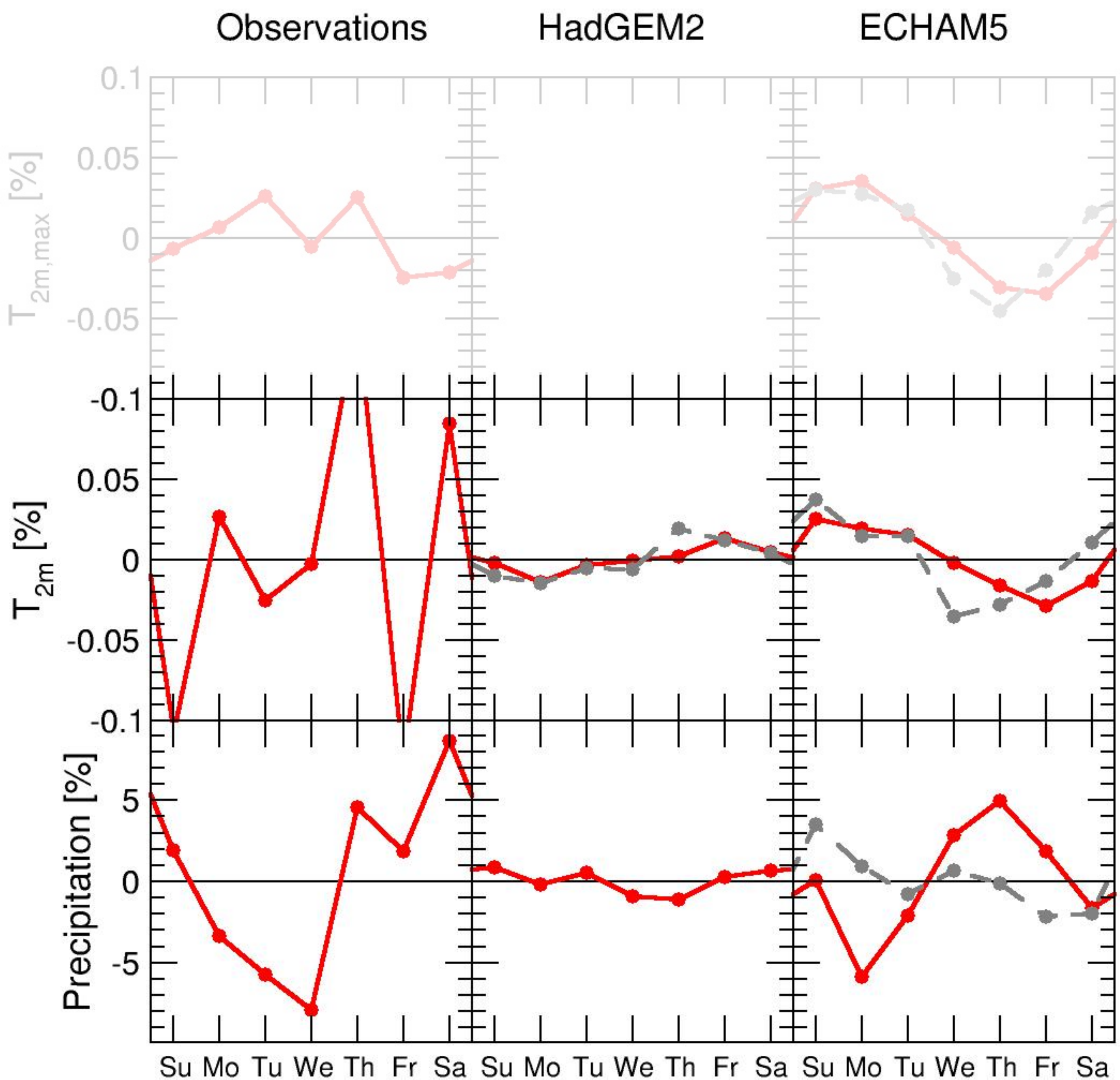


MODIS Terra
MODIS Aqua

Model experiment
Model control

Precipitation

5.5 Weekly cycle



MODIS Terra
MODIS Aqua

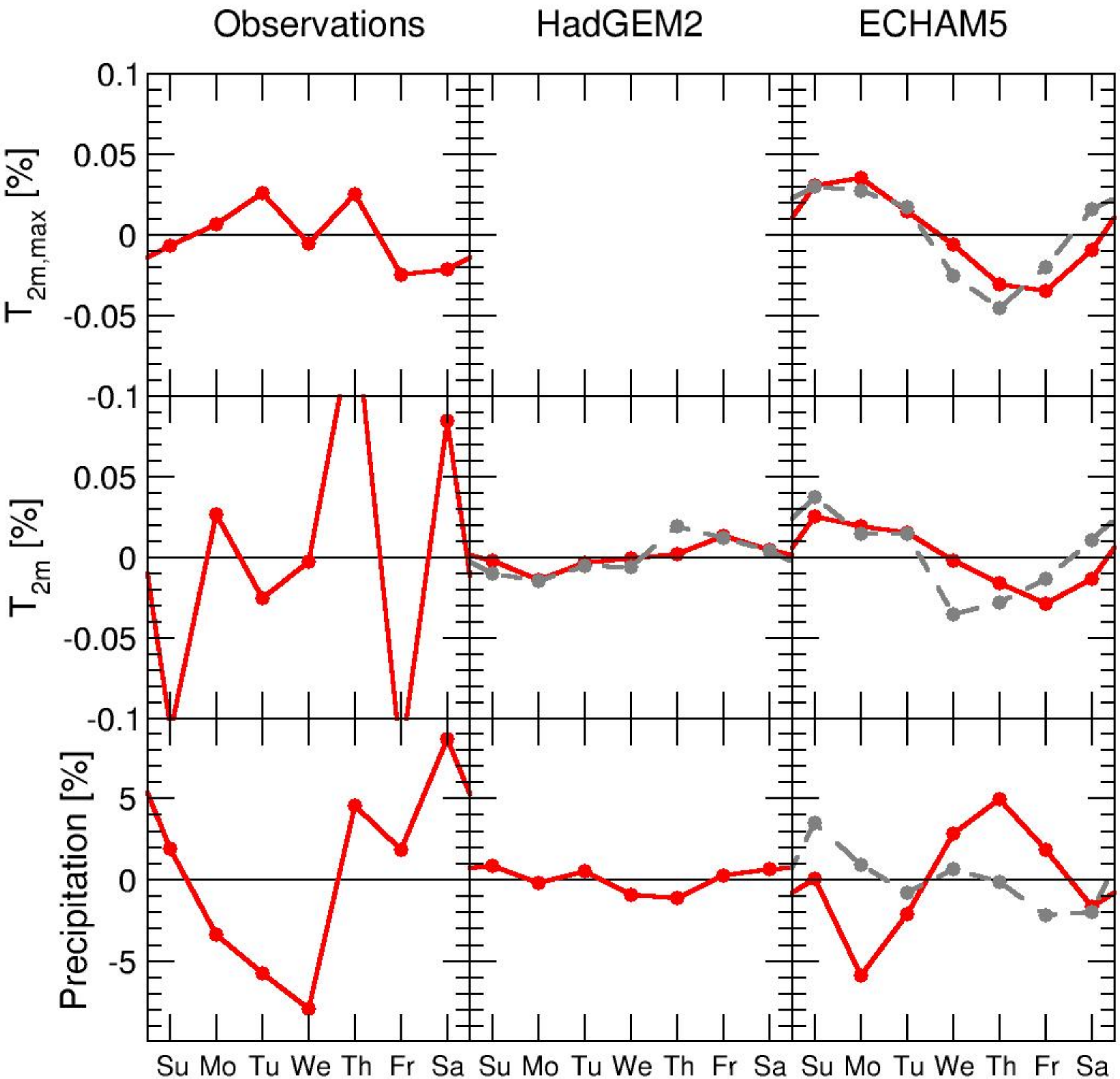
Model experiment
Model control

Temperature

Precipitation

Quaas et al., Atmos. Chem. Phys. 2009

5.5 Weekly cycle



MODIS Terra

MODIS Aqua

Model experiment

Model control

Max. Temperature

Temperature

Precipitation

Quaas et al., Atmos. Chem. Phys. 2009

5.6 Weather modification

5.7 Aerosol forcing – cloud radiative effect

Global-mean cloud radiative effect (solar) ~ 50 Wm^{-2}

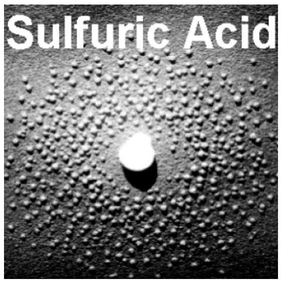
Global-mean aerosol indirect radiative forcing (solar) ~ -2 to 0 Wm^{-2}

→ search for maximum 4% effect

6. Modelling in general circulation models

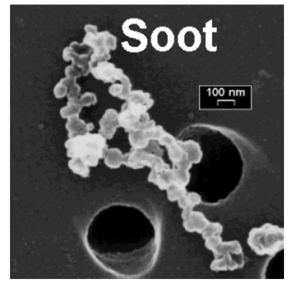
6.1 Aerosol modelling

Sulfate

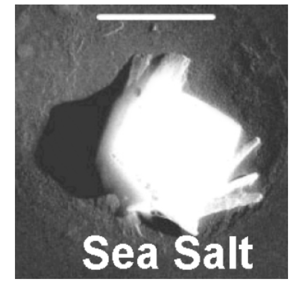


Organic Matter

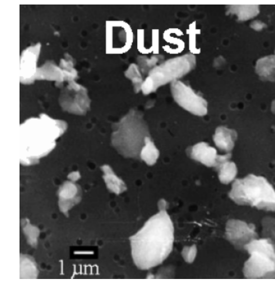
Black Carbon

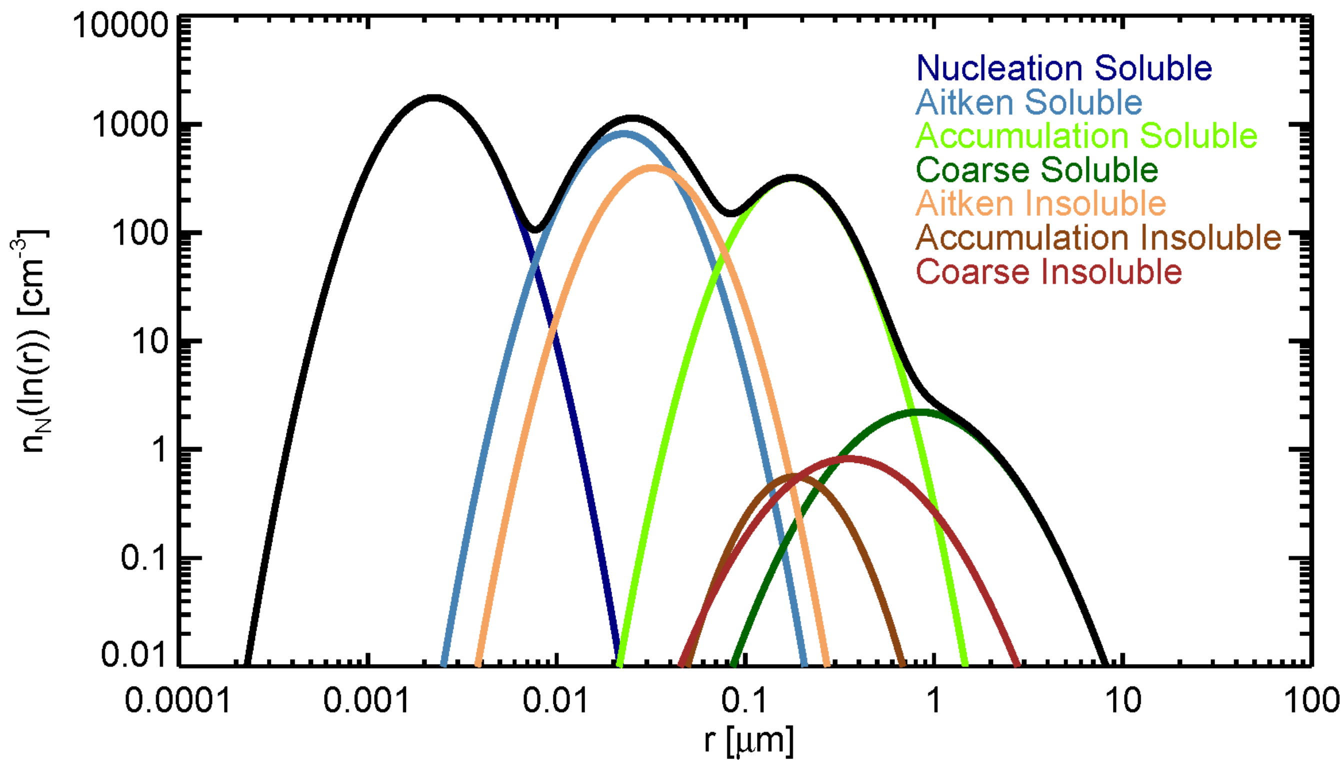


Sea Salt



Mineral Dust





Log-normal modes of internally mixed soluble and insoluble particles

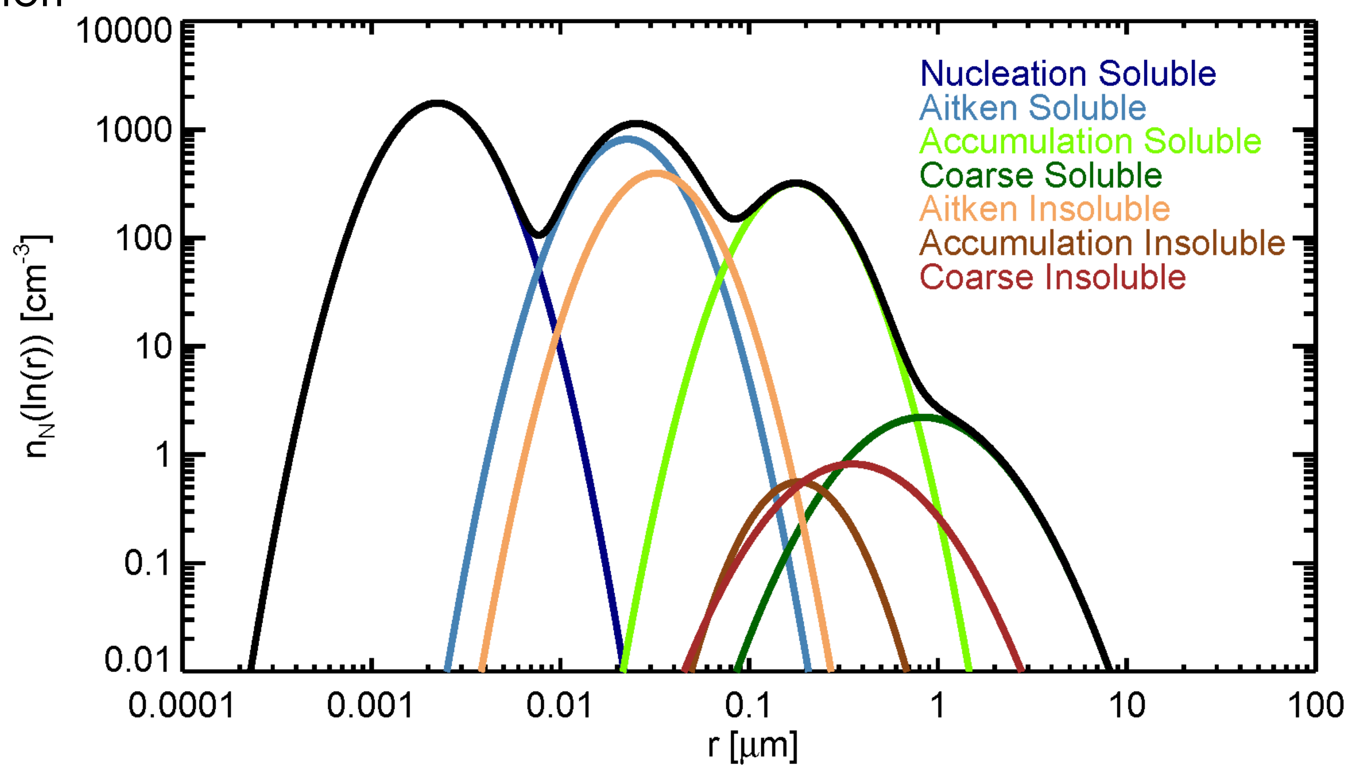
Standard deviation fixed

Zhang et al., Atmos. Chem. Phys. 2012

6.1 Aerosol modelling

Interactions:

- Simple sulfur and secondary organic chemistry
- Neutral and charged nucleation of sulfate particles
- Condensation of sulfate on existing particles
- Coagulation
- Nucleation of sulfate particles
- Inter-modal transfer
- Kappa approach for humidification
- Cloud processing
- Dry deposition
- Wet scavenging



Zhang et al., Atmos. Chem. Phys. 2012

6.1 Aerosol modelling

Feedbacks within a model

(i) Transport

(ii) Wet deposition

(iii) Cloud condensation nuclei / ice nuclei

(iv) Air chemistry (oxidants, nitrogen cycle)

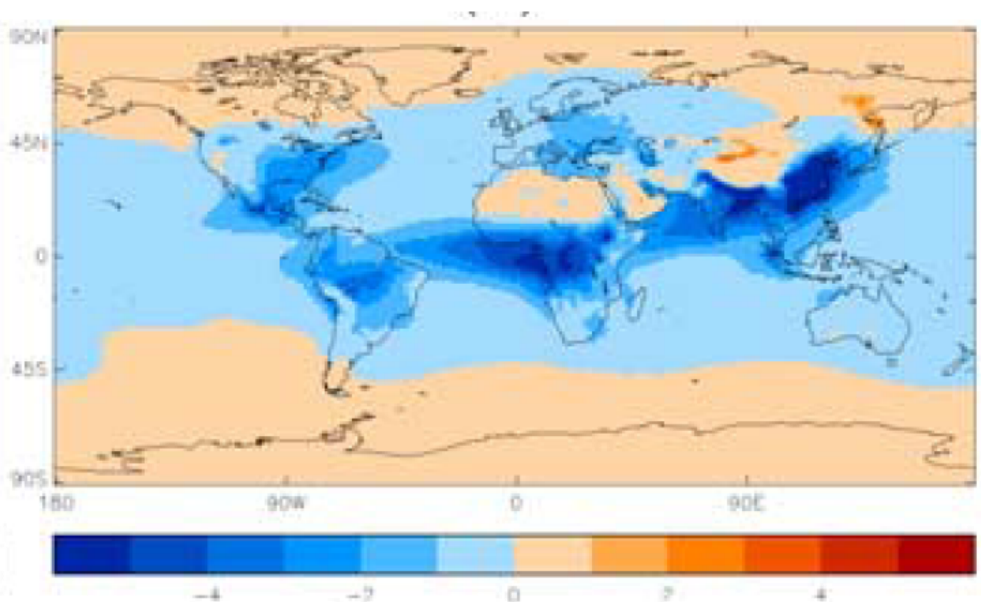
(v) Ocean biogeochemistry (DMS)

(vi) Vegetation (secondary organic aerosols, SOA)

6.2 Reference atmosphere for radiative forcing

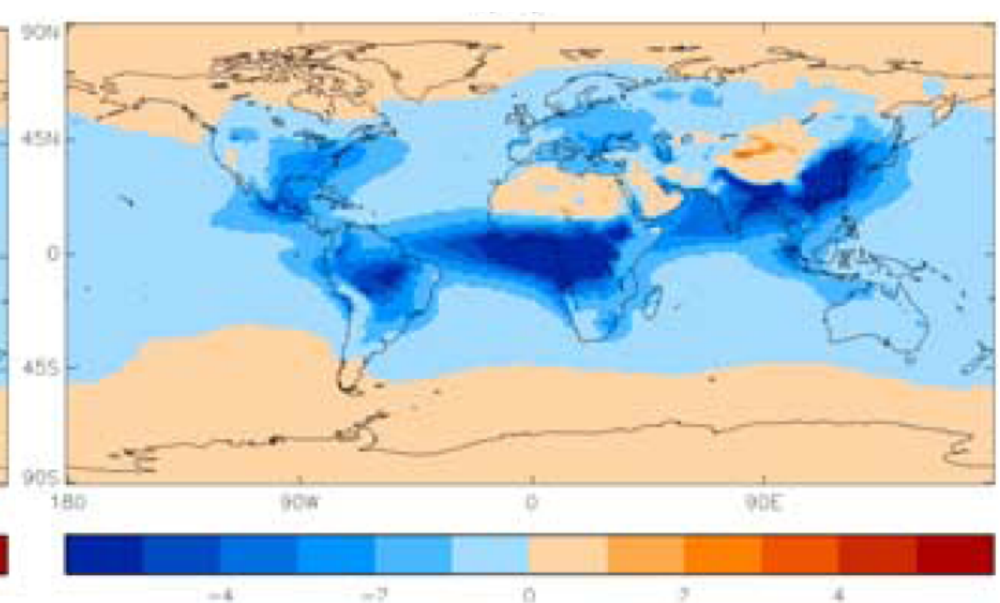
- year 1850 (even 1750) anthropogenic aerosols not zero
- if not all natural aerosols are considered, the forcing is overestimated (logarithmic)
- if not full variability of aerosols considered forcing overestiated (logarithmic)

present-day vs. 1860



G −0.63 O: −0.51 L: −0.91

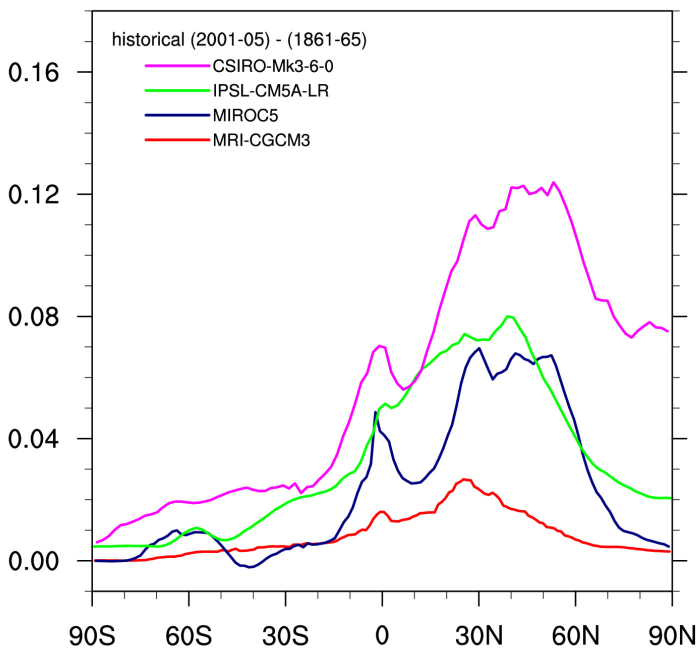
present-day vs. natural



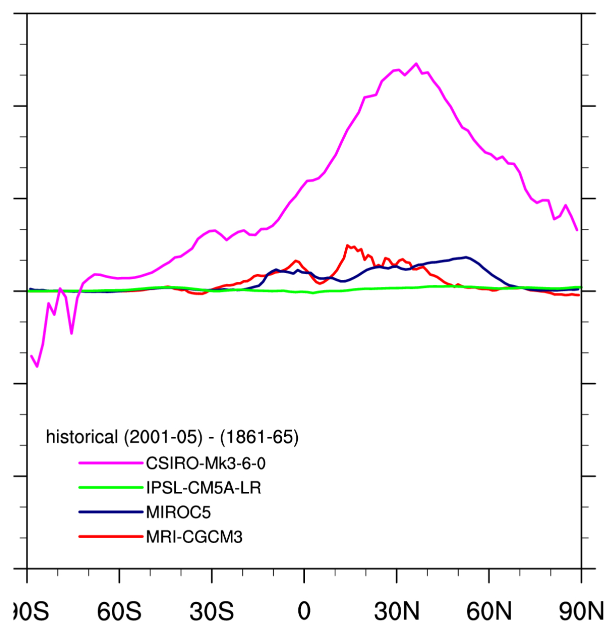
G −0.81 O: −0.64 L: −1.23

6.2 Reference atmosphere for radiative forcing

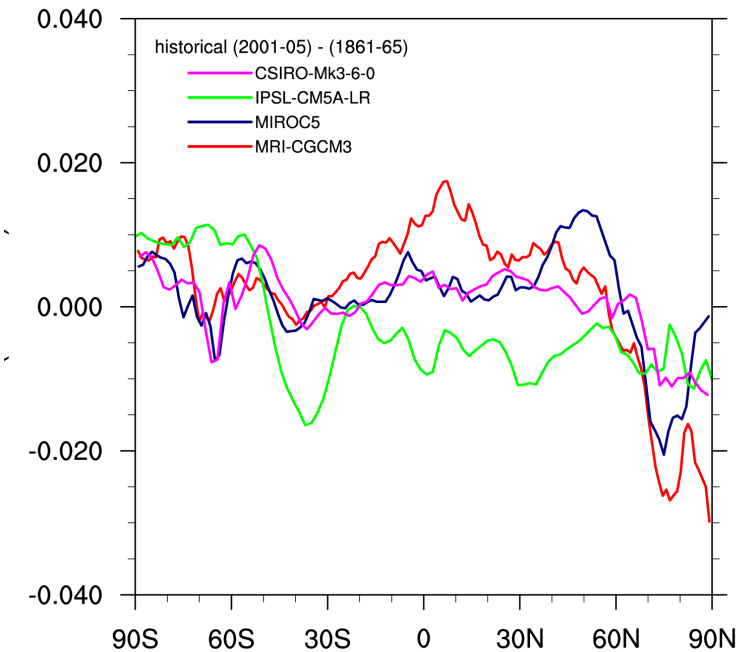
Aerosol concentration



Droplet concentration



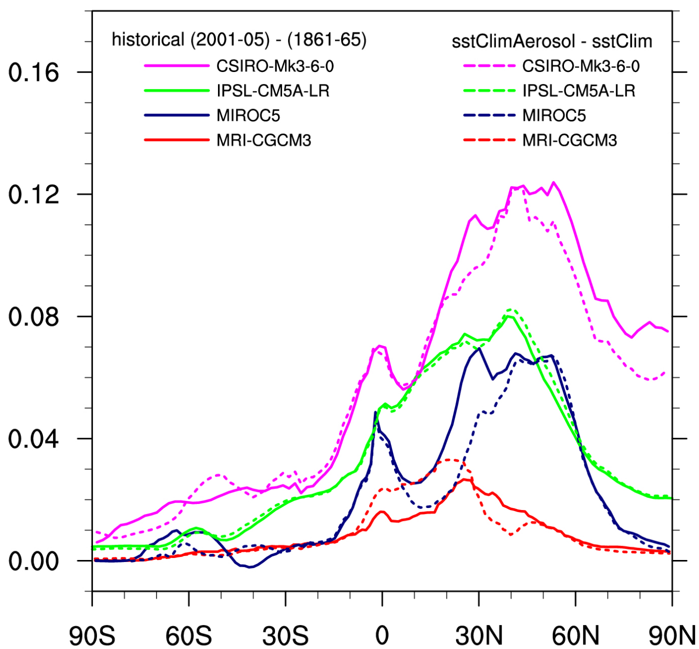
Planetary albedo



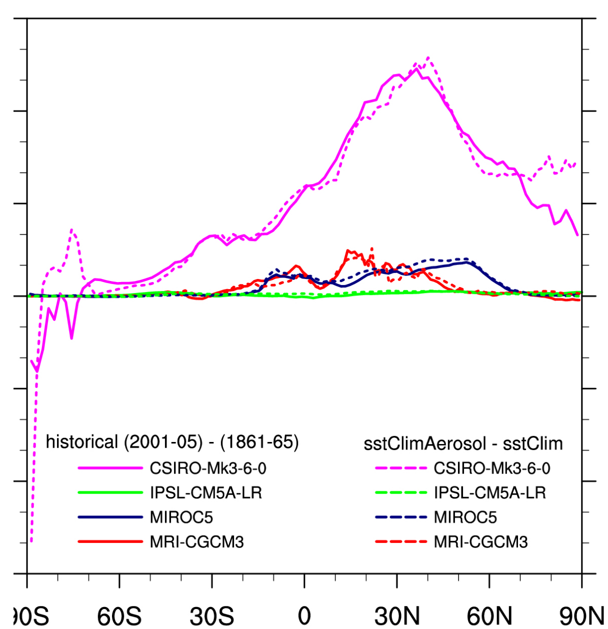
Results from the historical simulations 2001-05 vs. 1881-85 from CMIP5

6.2 Reference atmosphere for radiative forcing

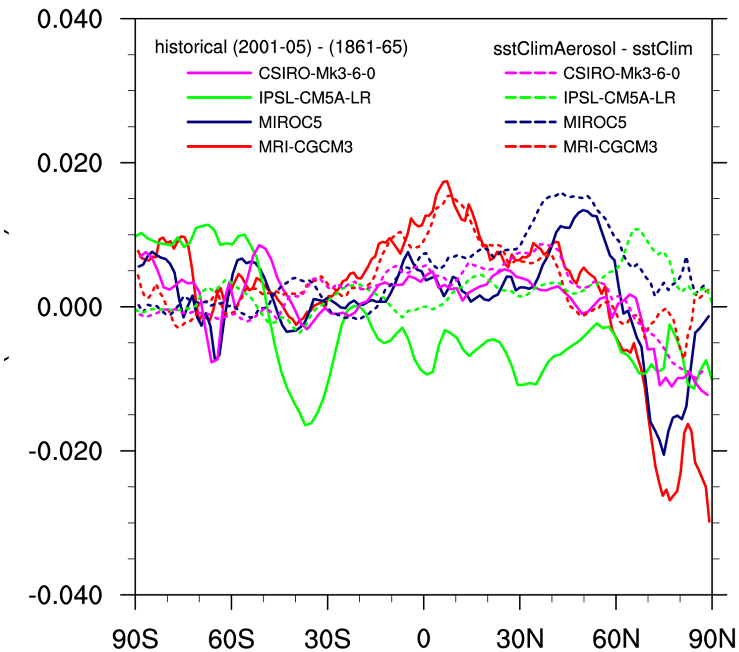
Aerosol concentration



Droplet concentration

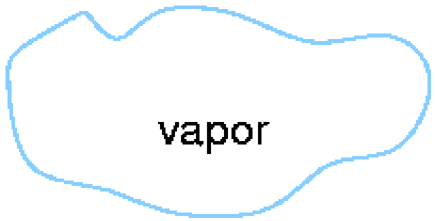


Planetary albedo

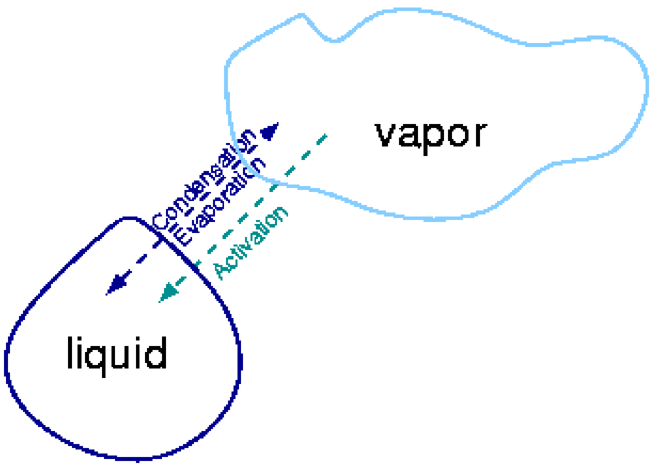


Results from the historical simulations 2001-05 vs. 1881-85 from CMIP5

vs. Results from idealised SSTClimAerosol simulations (dotted)

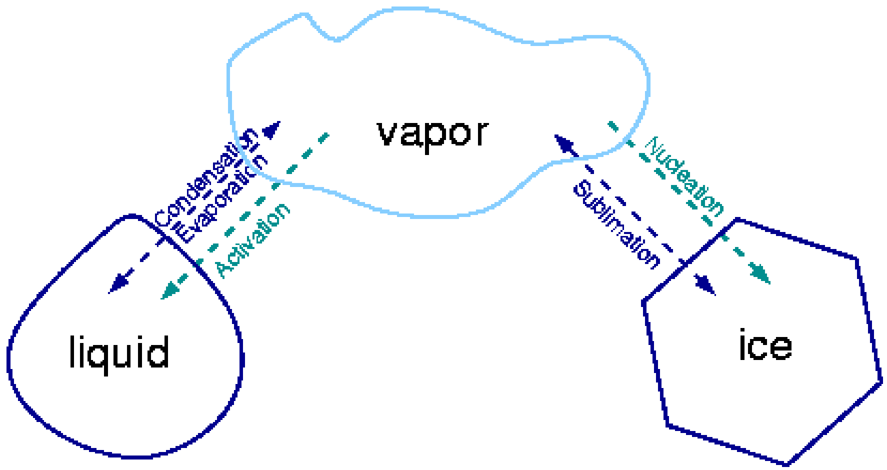

vapor

6.3 Cloud microphysical modelling



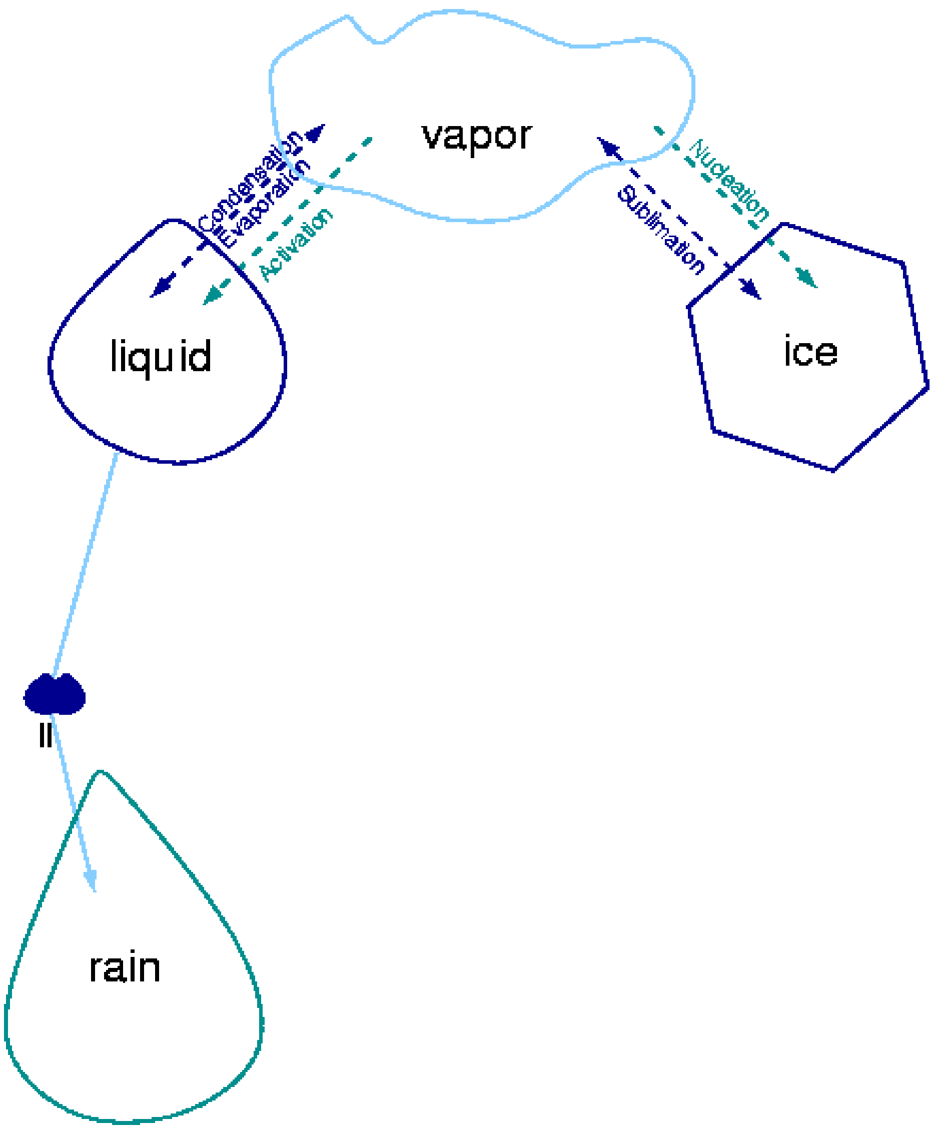
- droplet activation
- diffusion growth
  (condensation / evaporation)

6.3 Cloud microphysical modelling



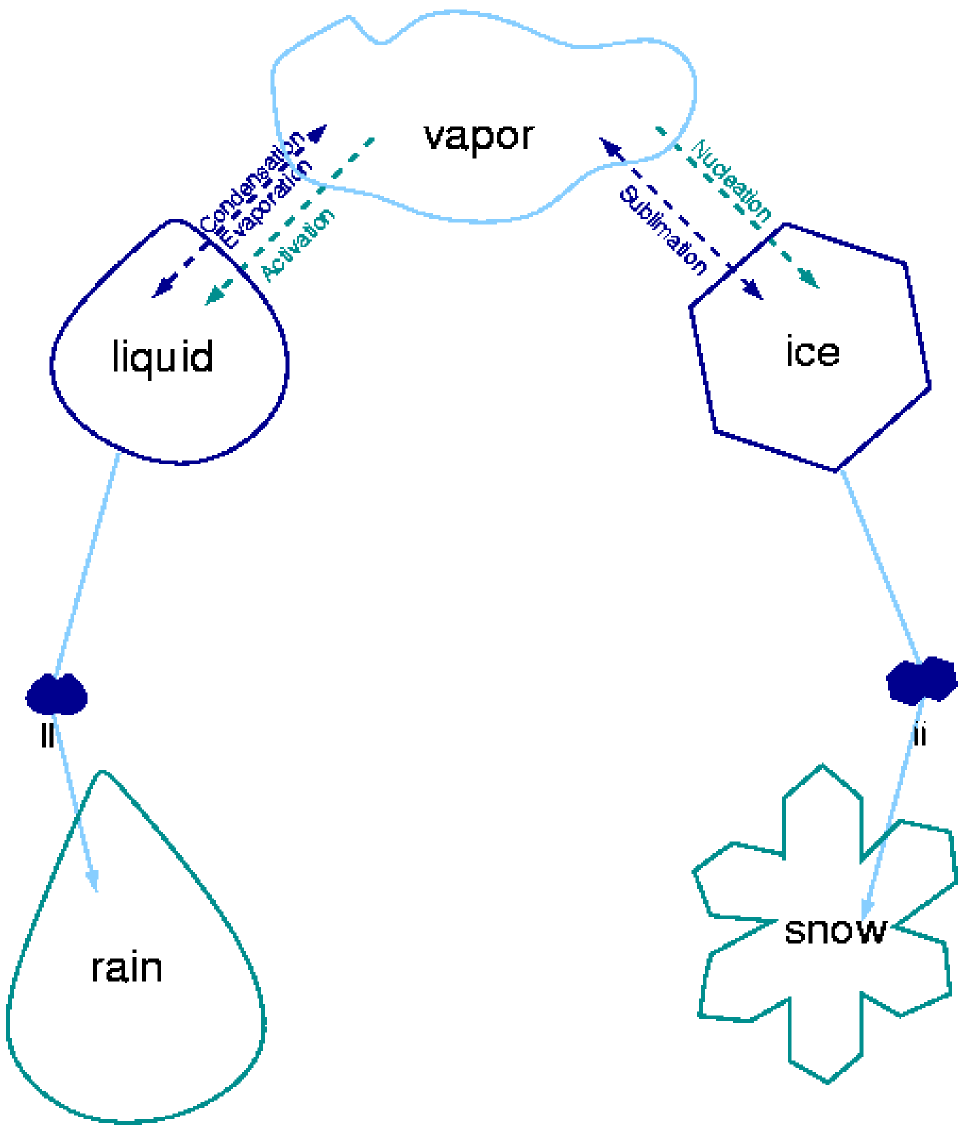
- nucleation
- diffusion growth (sublimation)

6.3 Cloud microphysical modelling



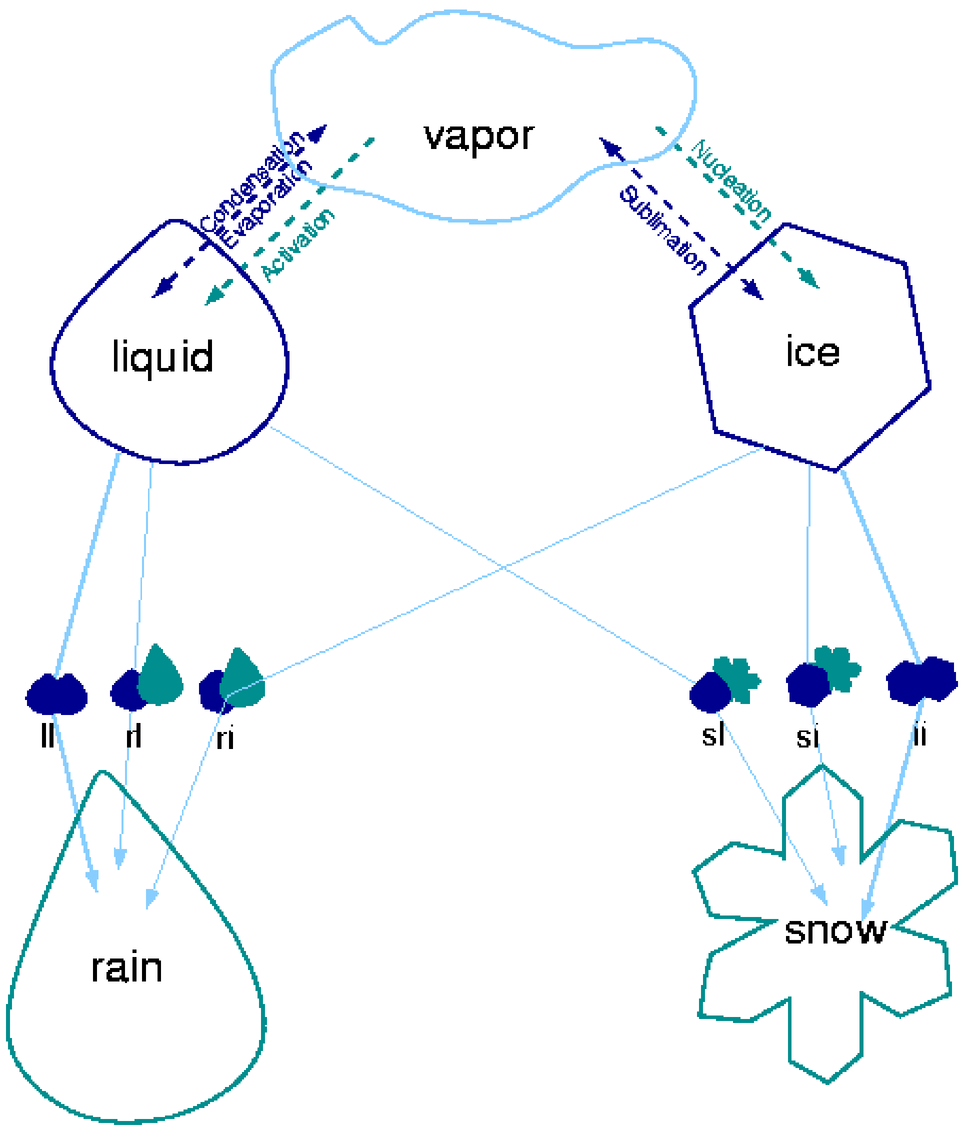
„autoconversion“ -
initial collision/coalescence

6.3 Cloud microphysical modelling



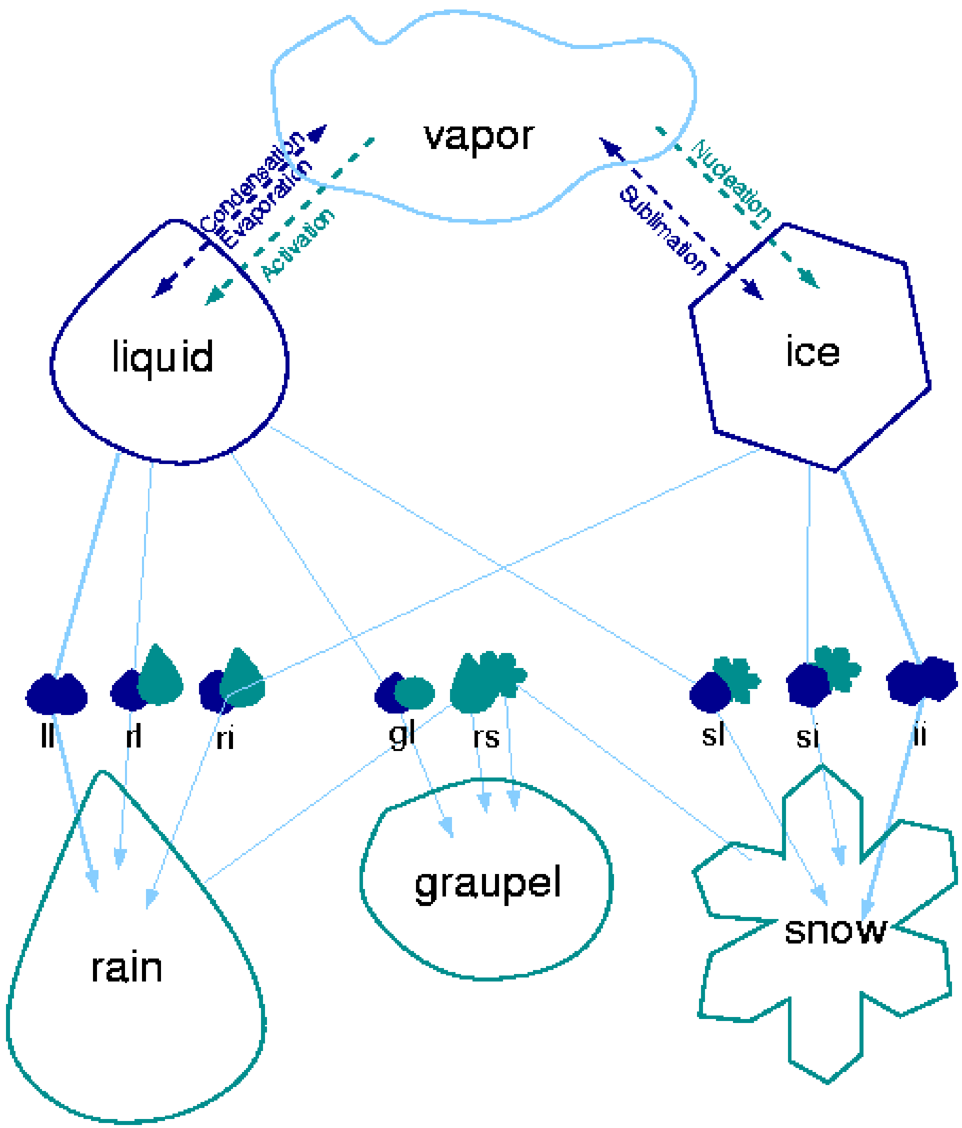
aggregation
- initial formation of snowflakes

6.3 Cloud microphysical modelling



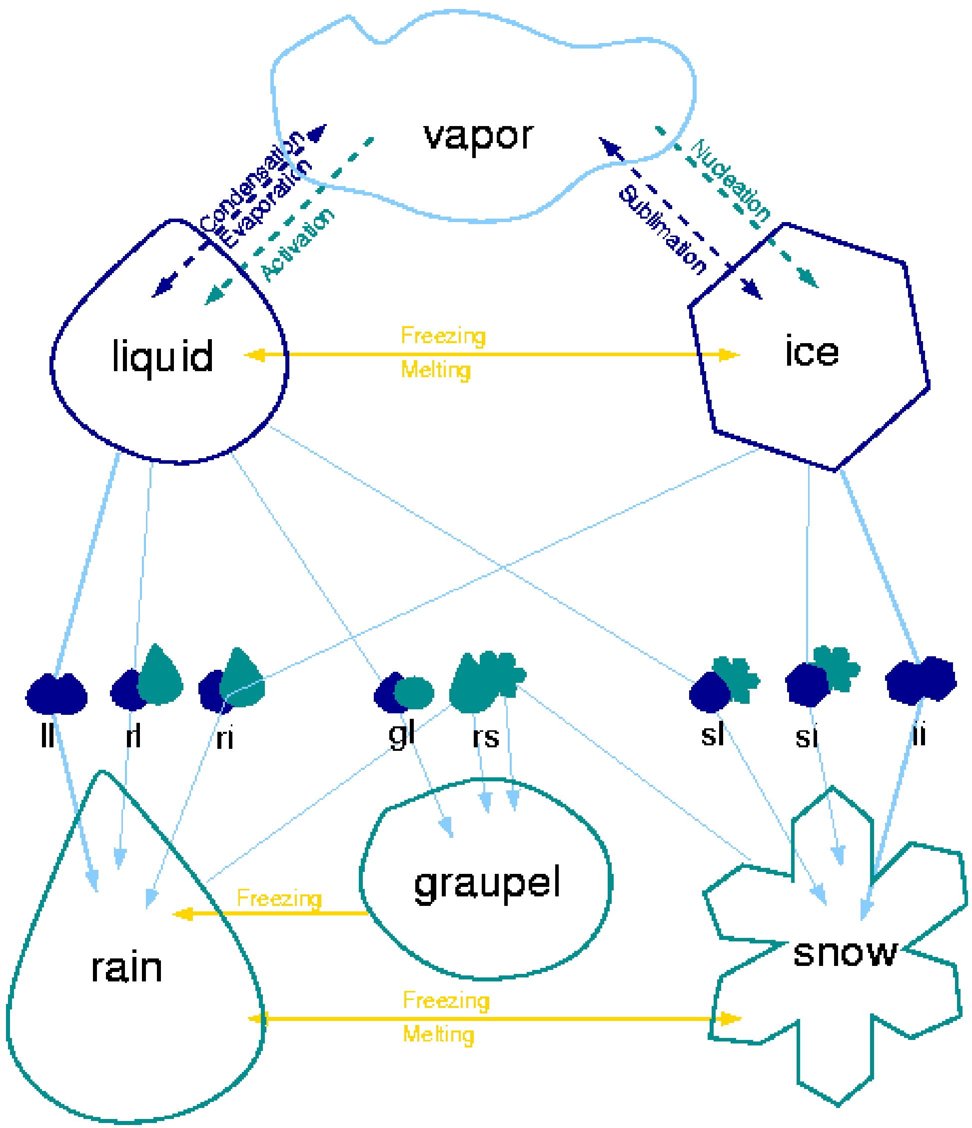
accretion
- collision/coalescence processes

6.3 Cloud microphysical modelling



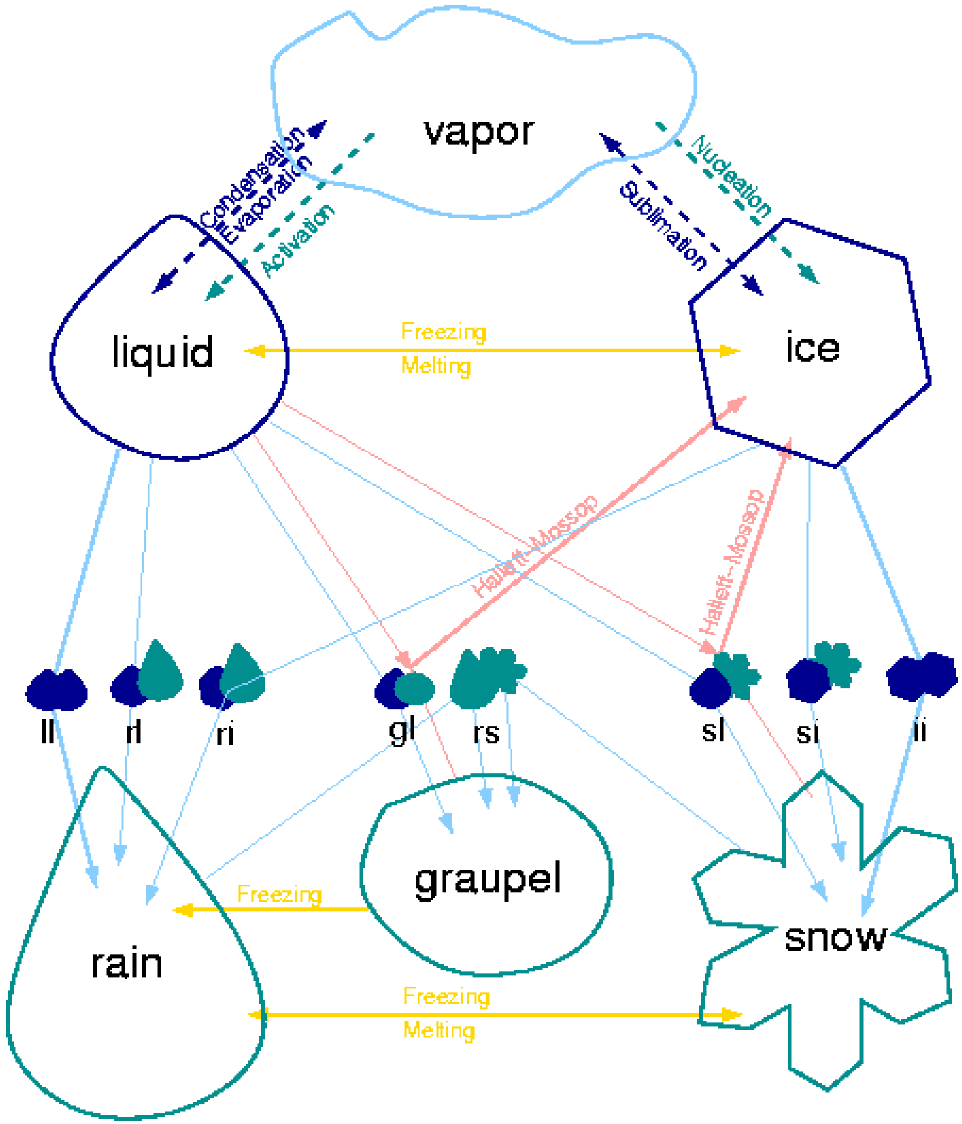
riming
collision/coalescence

6.3 Cloud microphysical modelling



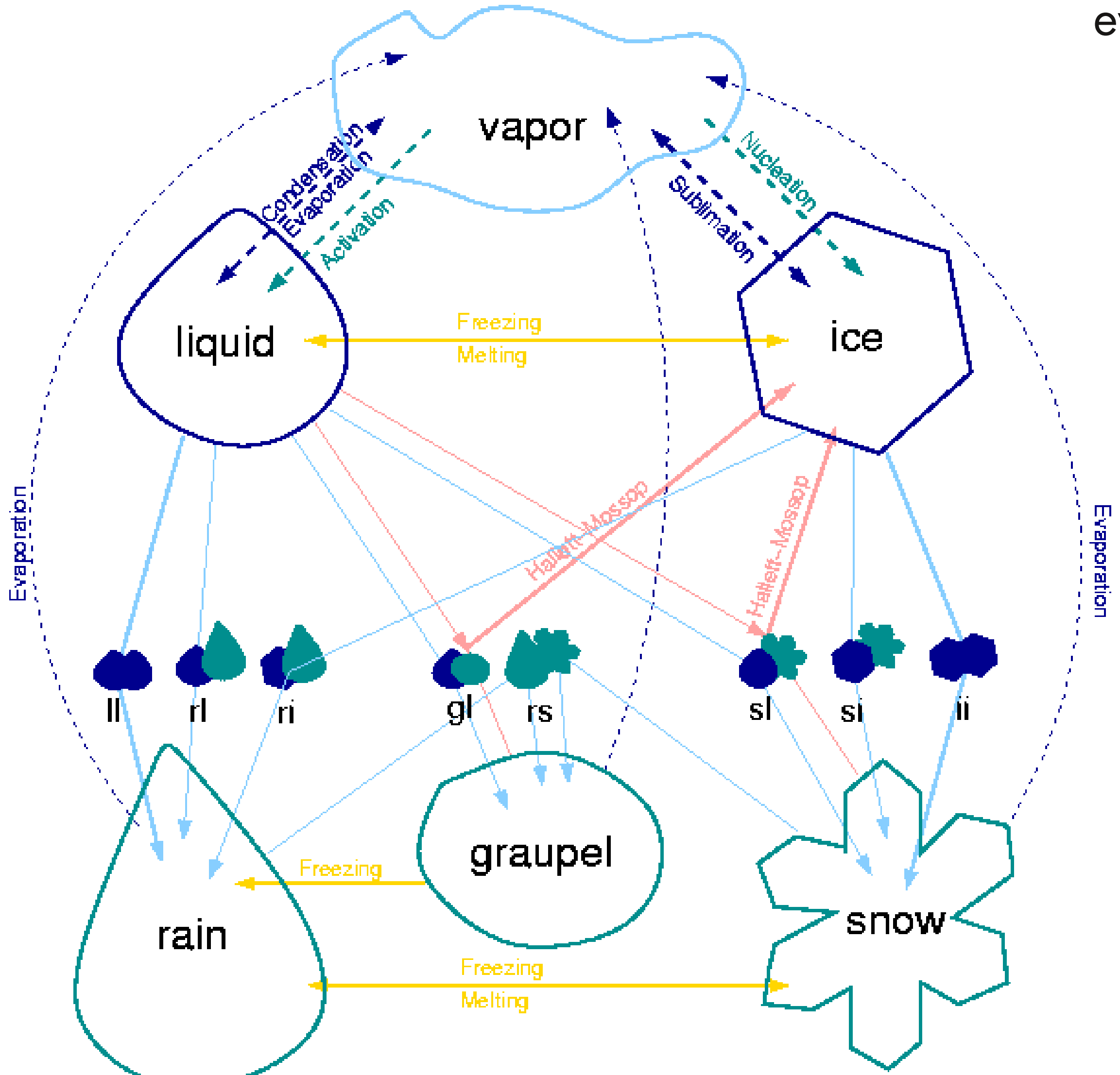
melting
freezing

6.3 Cloud microphysical modelling



secondary ice production

6.3 Cloud microphysical modelling



evaporation of precipitation

6.3 Cloud microphysical modelling

Representation in large-scale models

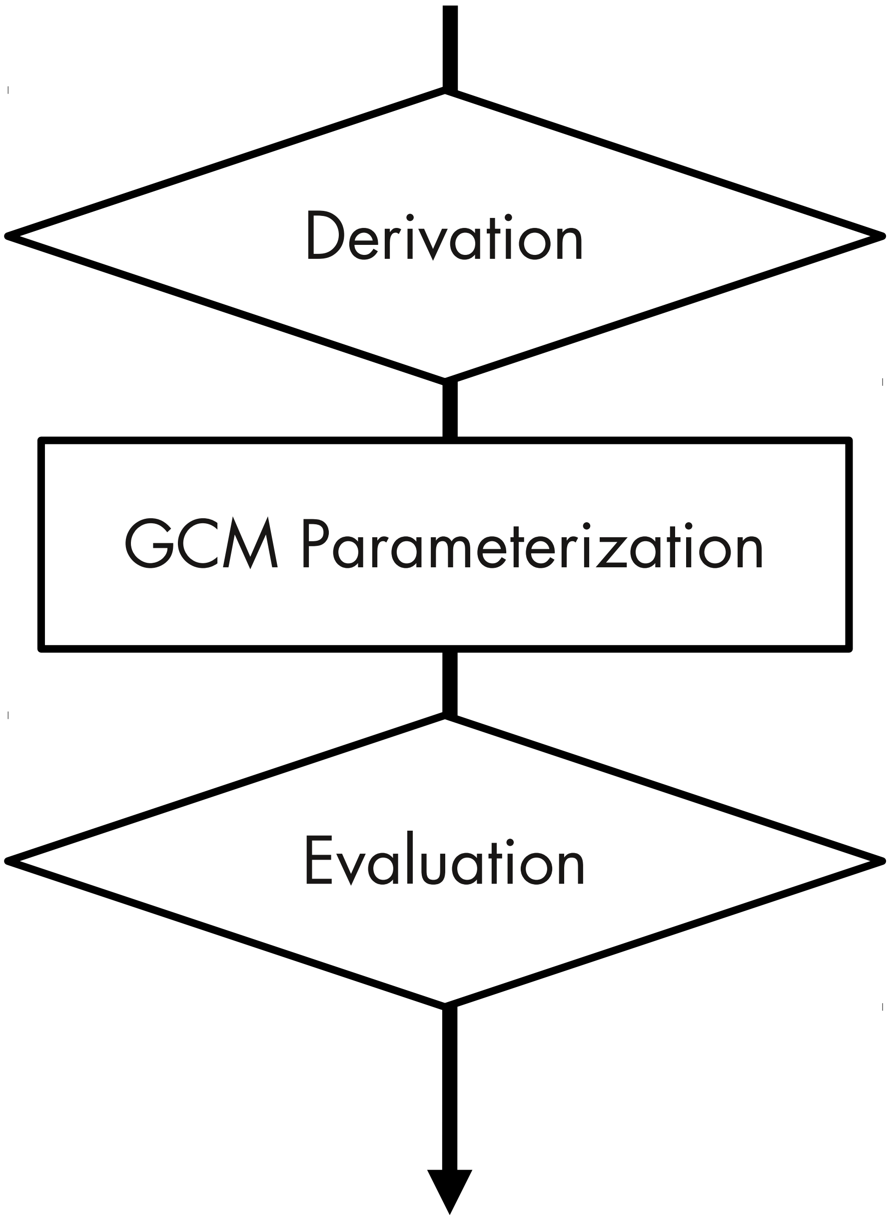
(i) **bulk** vs. bin scheme (resolve or not size distributions)

(ii) one vs. **two** moments (just masses or also numbers)

(iii) **vapour, liquid, ice**, rain, snow, graupel, hail, ...

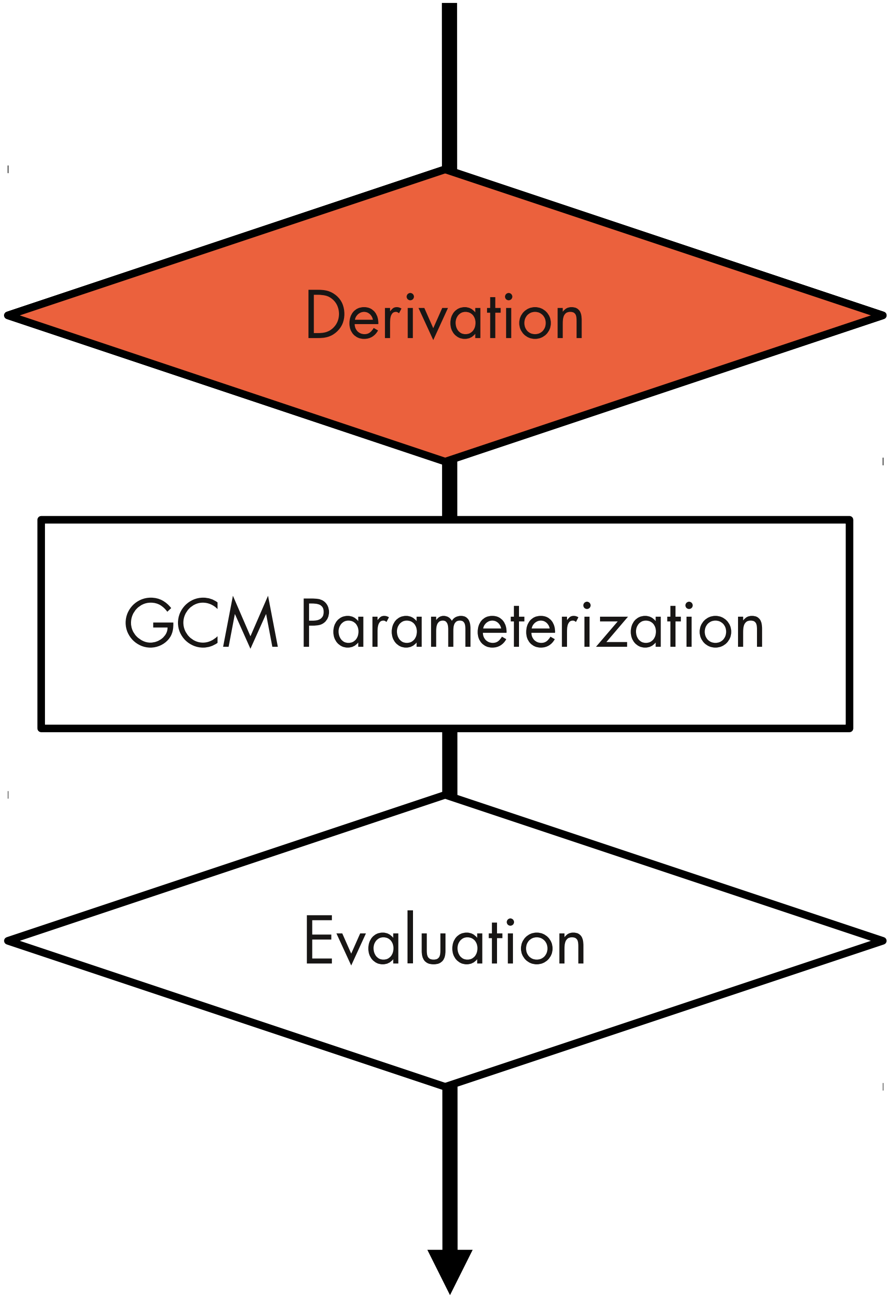
7. Evaluation of parameterisations

7.1 Implementation of a new process



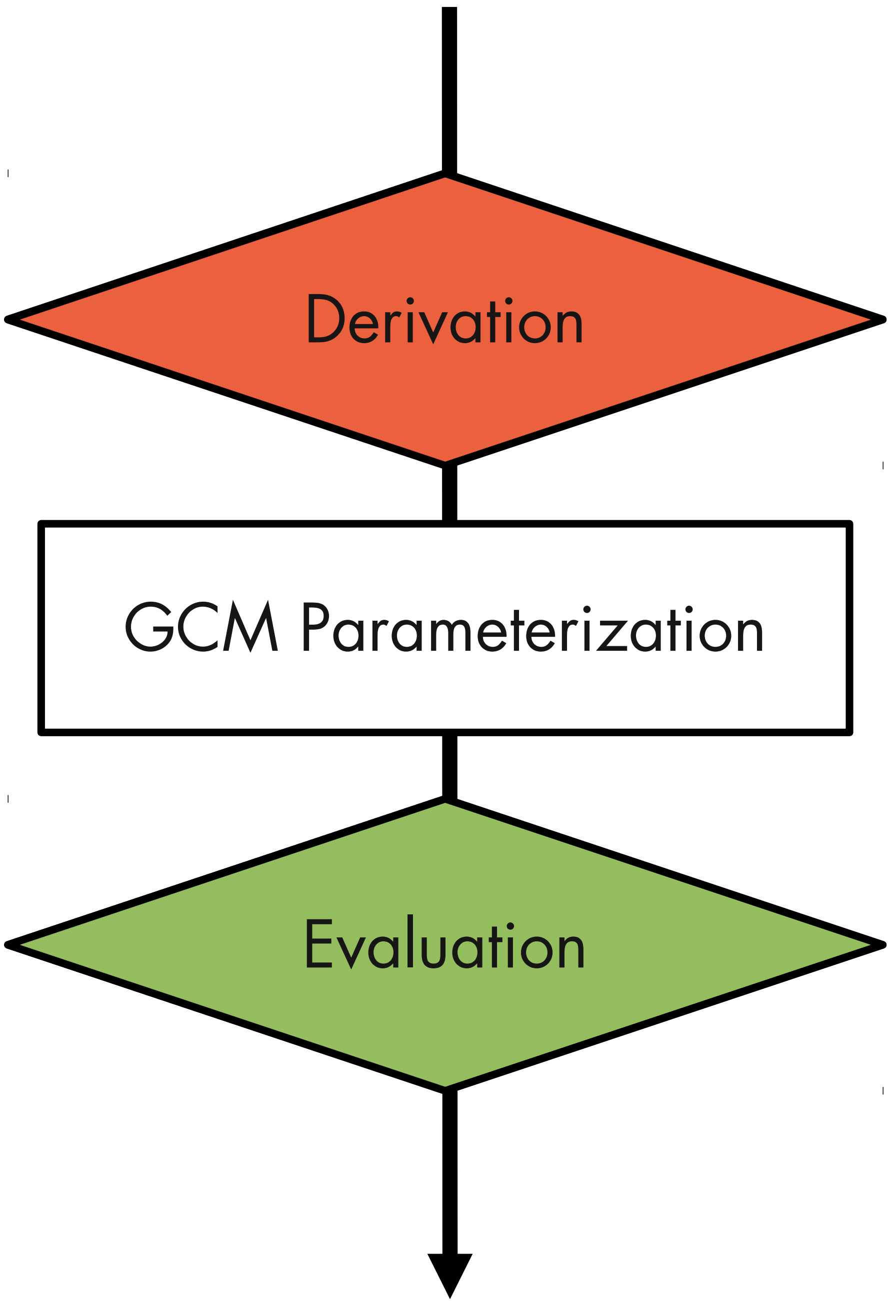
Lohmann, Quaas, Feichter, Kinne, Bull. Am. Meteorol. Soc., 2007

7.1 Implementation of a new process



1. First principles
2. Laboratory studies
3. Dedicated field campaigns
4. High-resolved models

7.1 Implementation of a new process



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1. Constraints from satellite-derived statistics
2. Constraints from data assimilation

Lohmann, Quaas, Feichter, Kinne, Bull. Am. Meteorol. Soc., 2007

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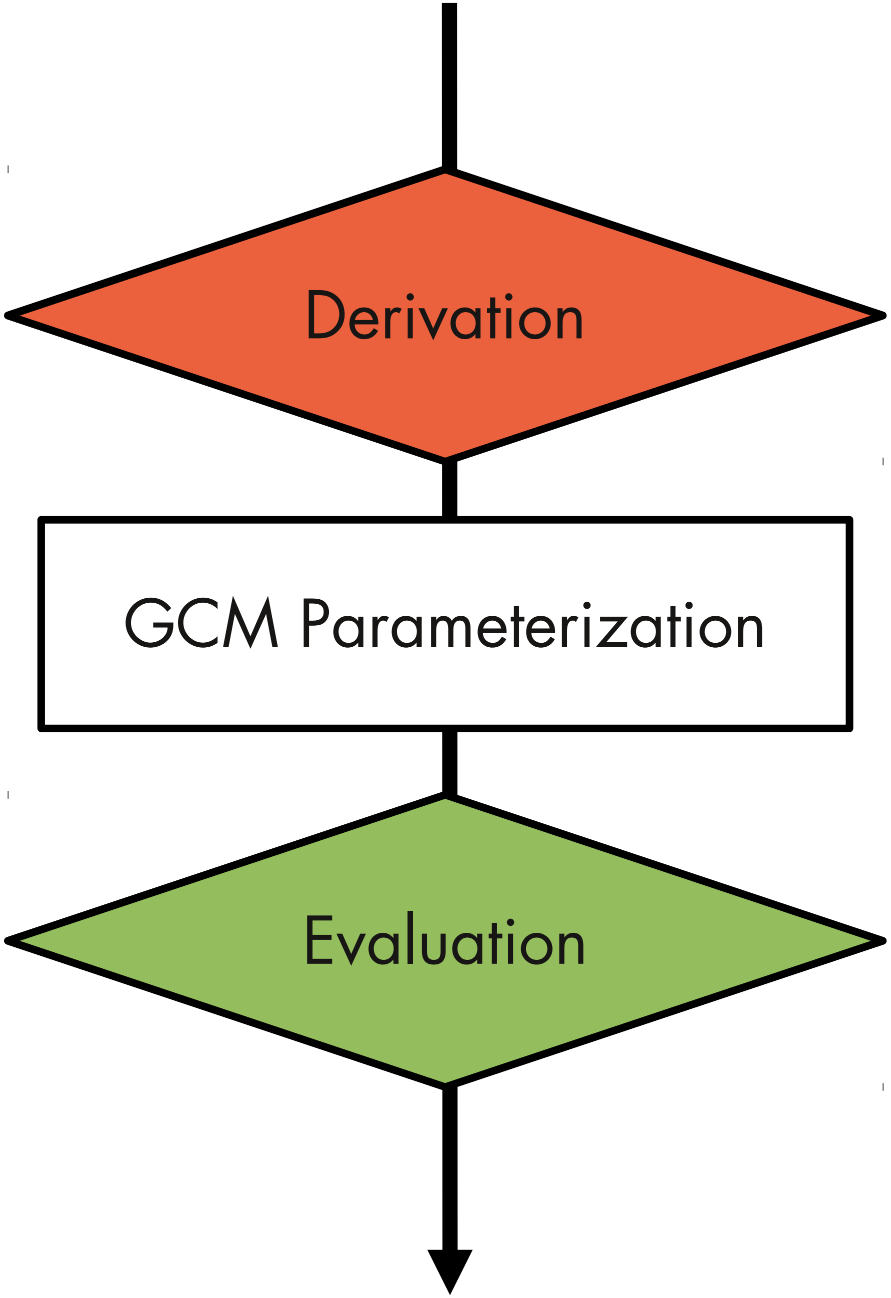

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7.2 Evaluation metric

Definition: **Metric**

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...quantifying the ability of models to simulate particular phenomena

...scalar that can be used to gauge how well a model simulates the aspect of climate analysed

...agreement or disagreement between model and observations

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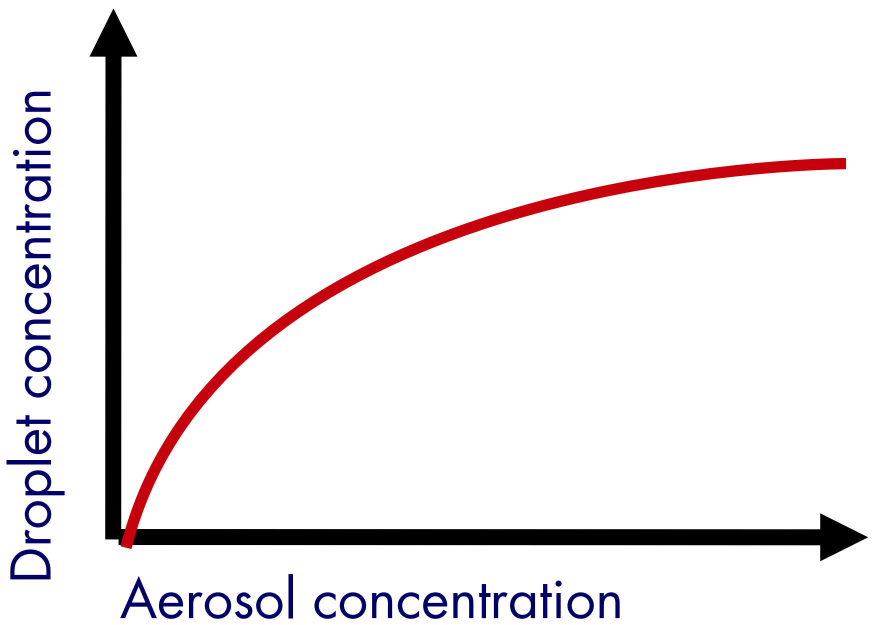
WMO Working group on Coupled Modelling (WCGM)

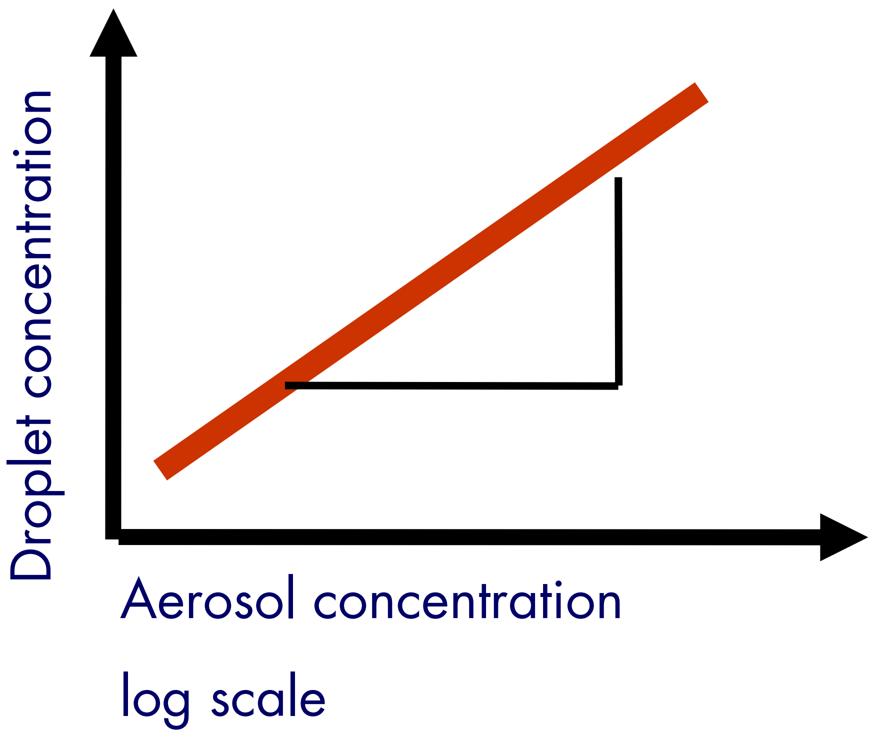
Effect of anthropogenic aerosols on droplet concentration



Feingold et al., Geophys. Res. Lett. 2003

7.2 Evaluation metric

Effect of anthropogenic aerosols on droplet concentration



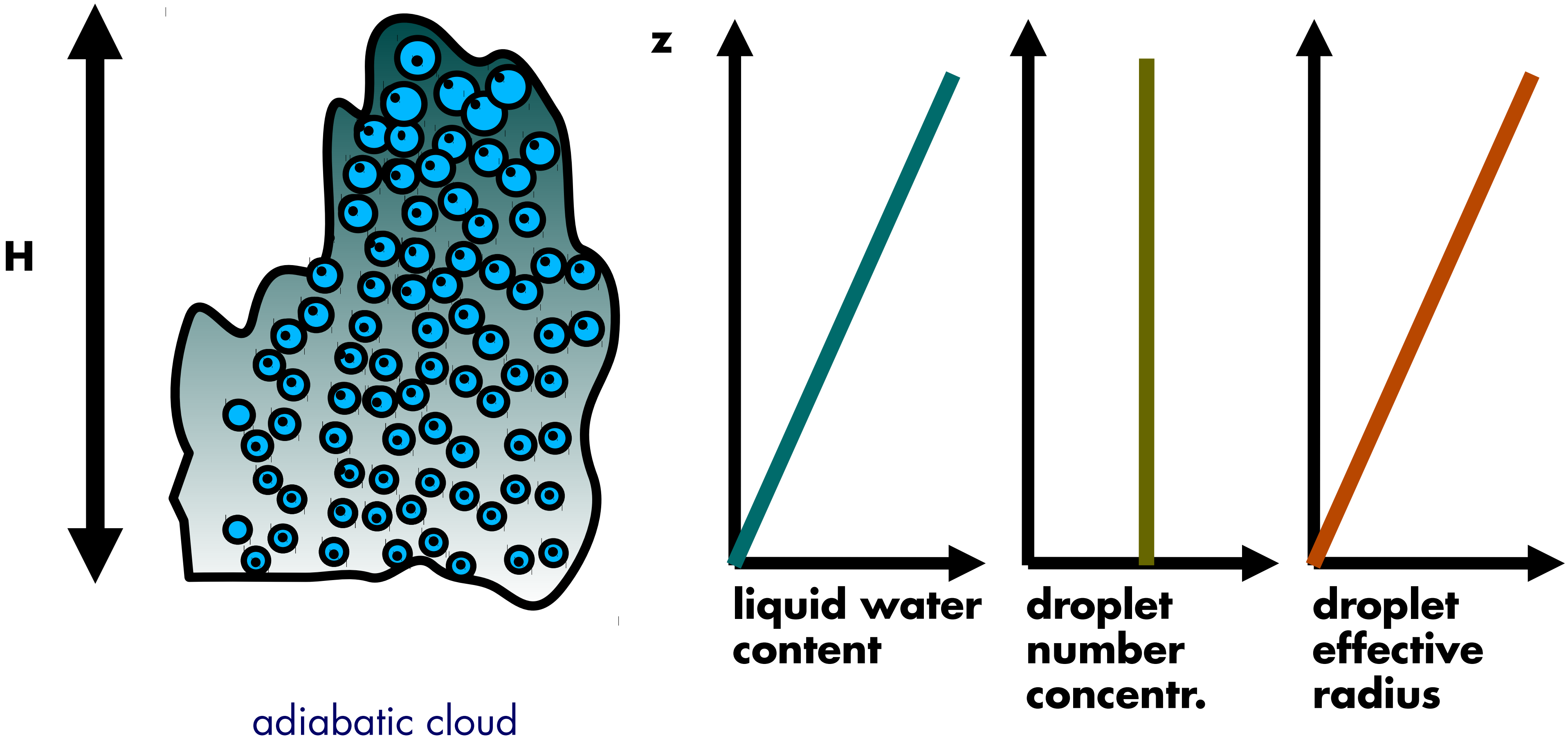
Slope of regression as metric for effect:

$$\frac{d \ln N_d}{d \ln \alpha} = \frac{\Delta N/N}{\Delta \alpha/\alpha}$$

α – aerosol concentration

Feingold et al., Geophys. Res. Lett. 2003

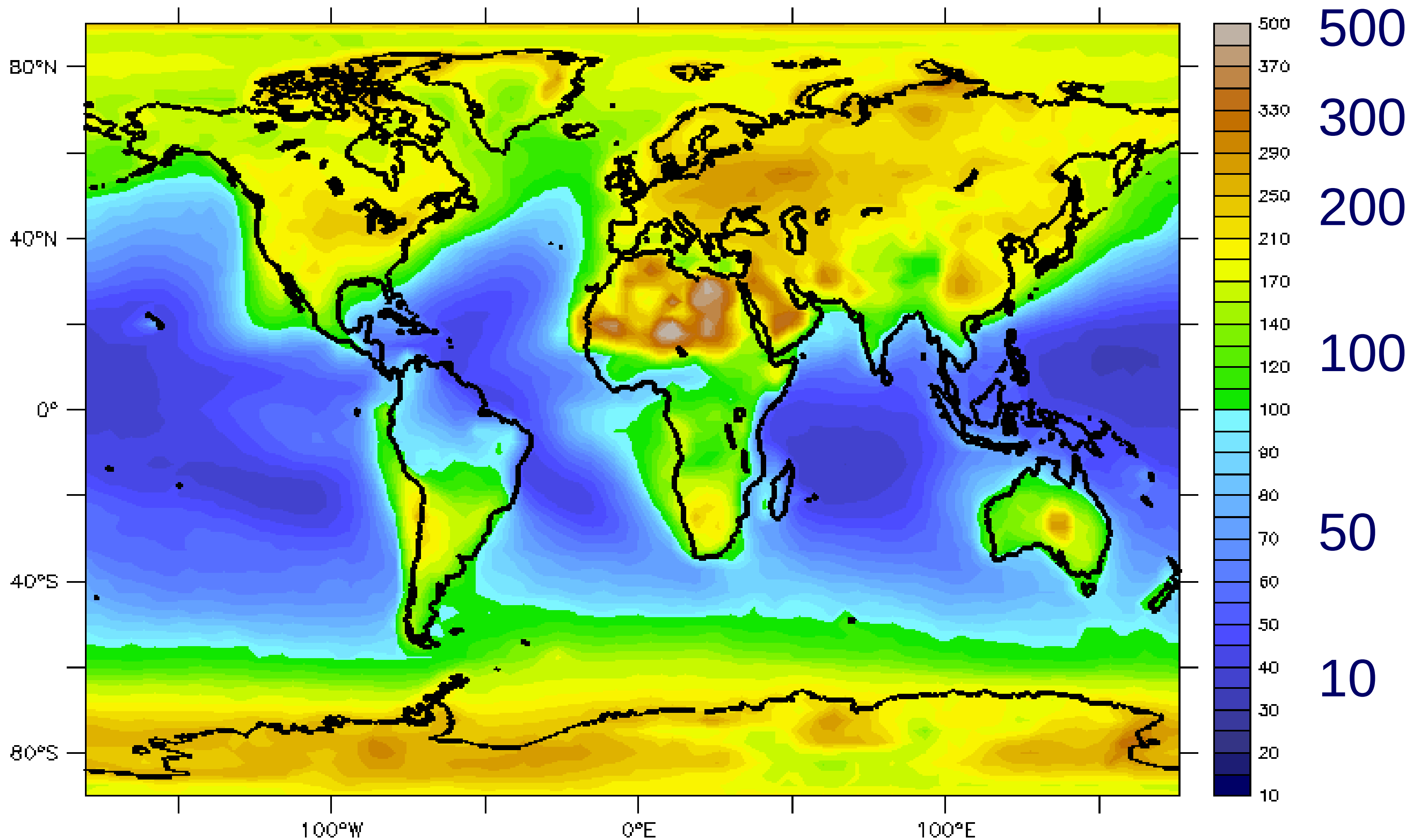
7.2 Evaluation metric



$$N_d = \gamma \tau_c^{1/2} r_e^{-5/2}$$

7.2 Evaluation metric

Adiabatic cloud droplet number concentration (CDNC) [cm^{-3}]

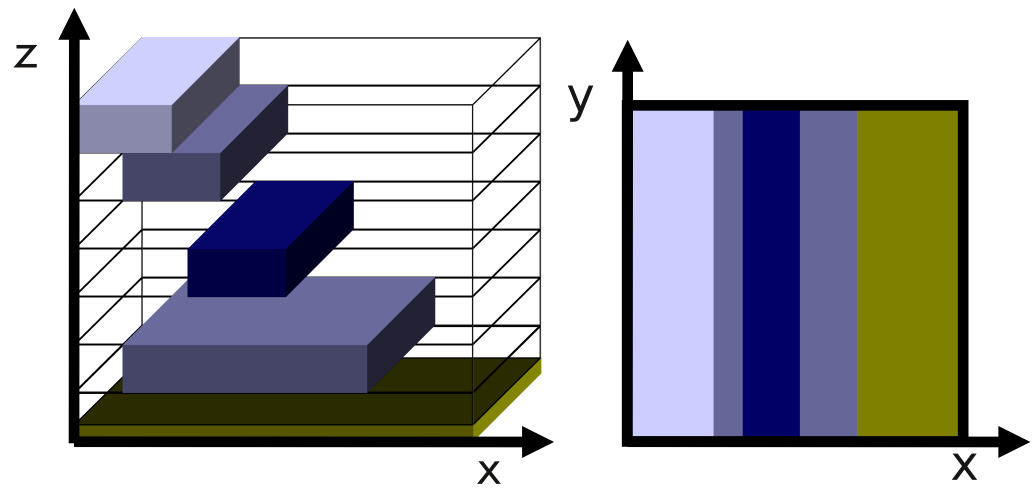


MODIS for 03/2000 – 02/2005

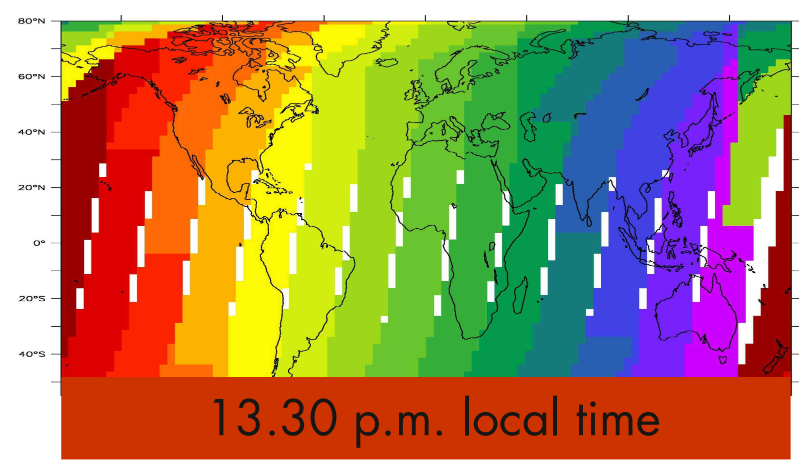
Quaas et al., Atmos. Chem. Phys. 2006

7.2 Evaluation metric

- 2D cloud top quantities from 3D cloud field using overlap assumption

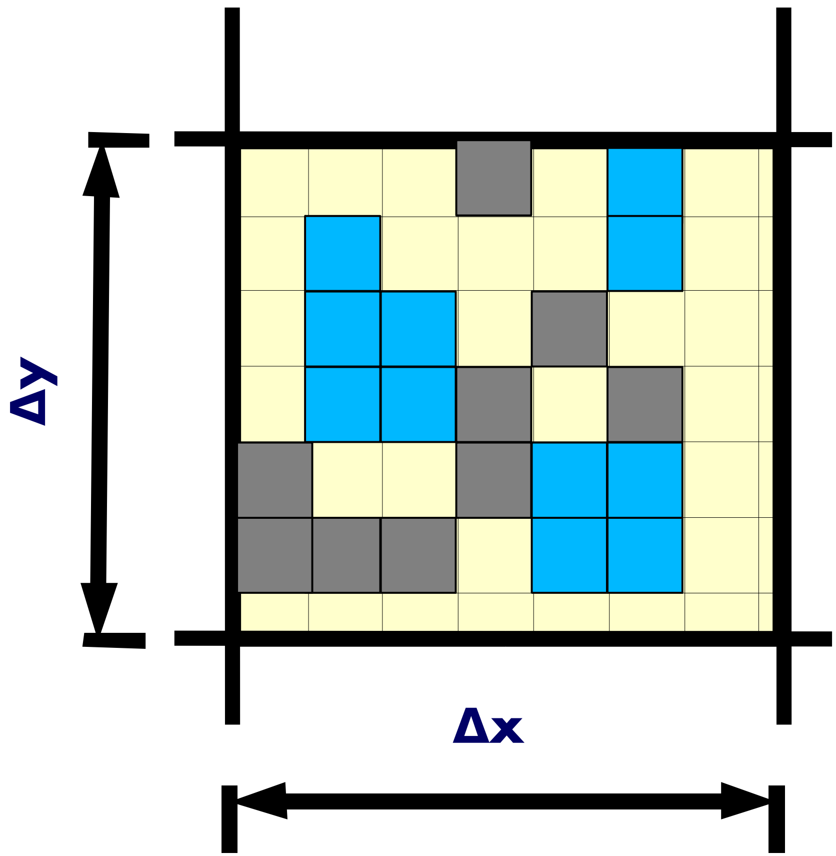


- Sampling of daily fields at satellite overpass time



- Visible clouds only ($\tau_c > 0.3$)

7.2 Evaluation metric



Aerosol measurements

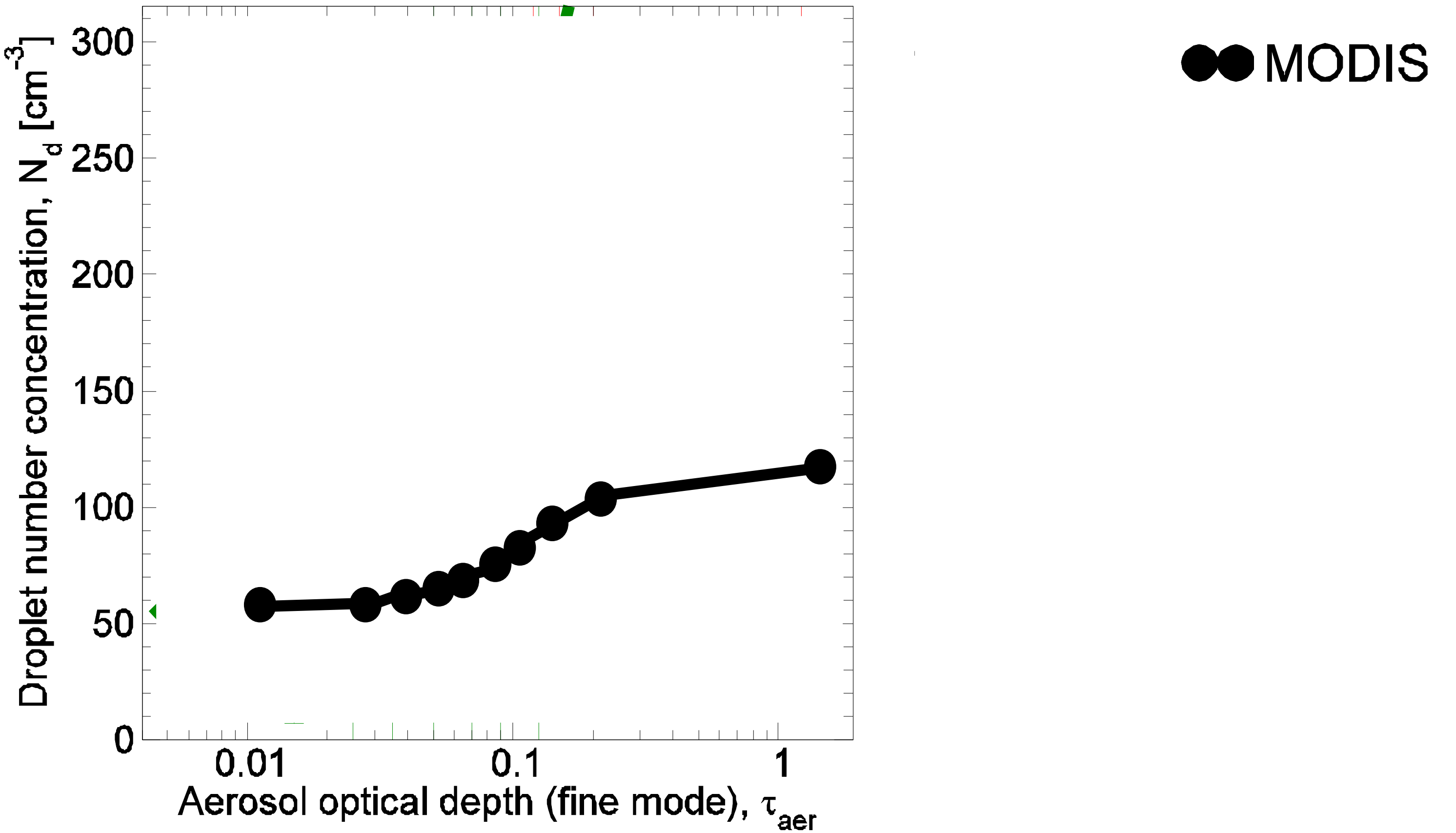
Cloud measurements

No retrieval

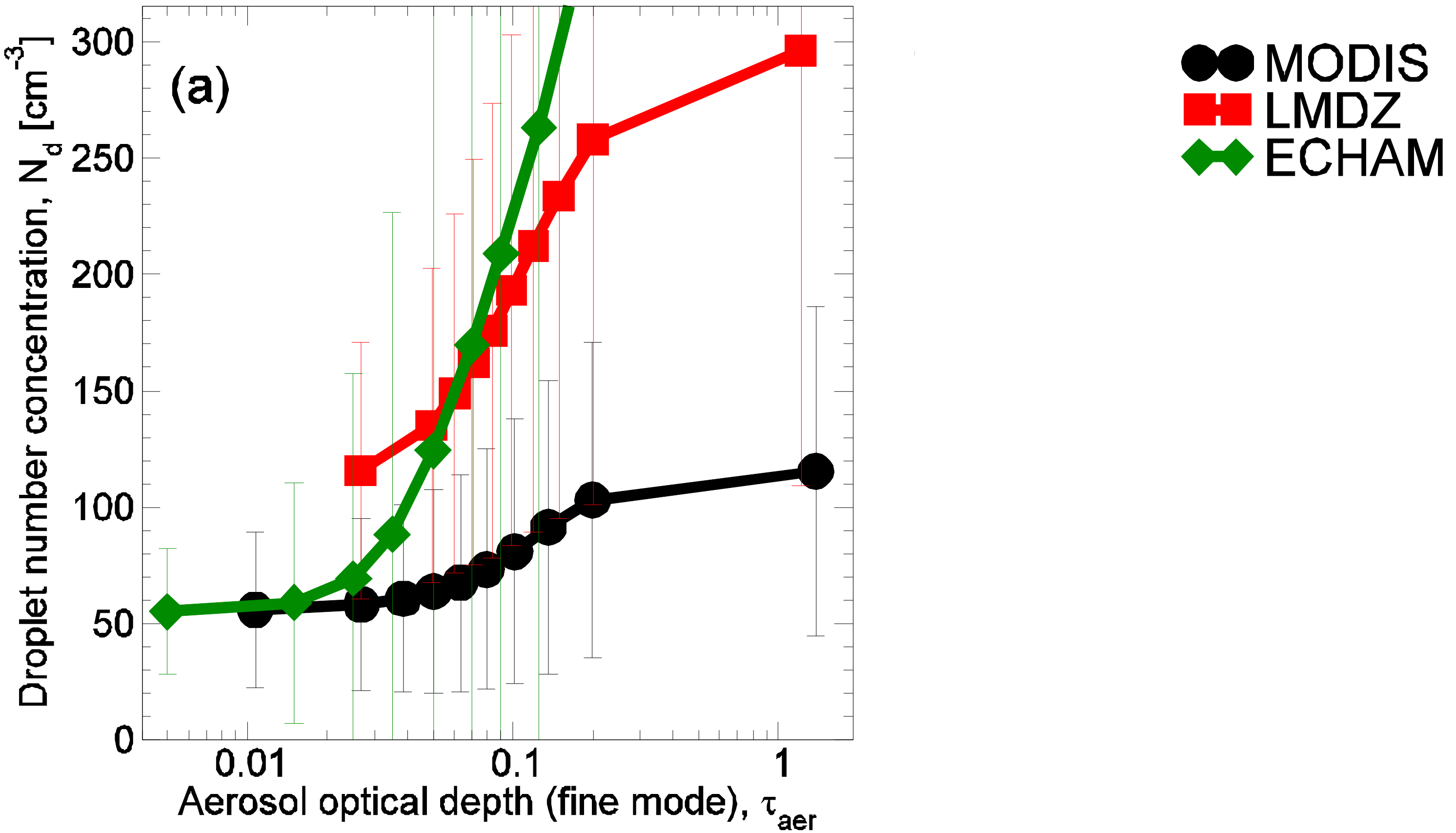
Method adopted:
relate aerosol and cloud quantities within a model gridbox (daily values)

Δx / Δy : model resolution
here: 2.5° x 2.5°

7.3 Evaluation of diagnostic cloud droplet number concentration



7.3 Evaluation of diagnostic cloud droplet number concentration



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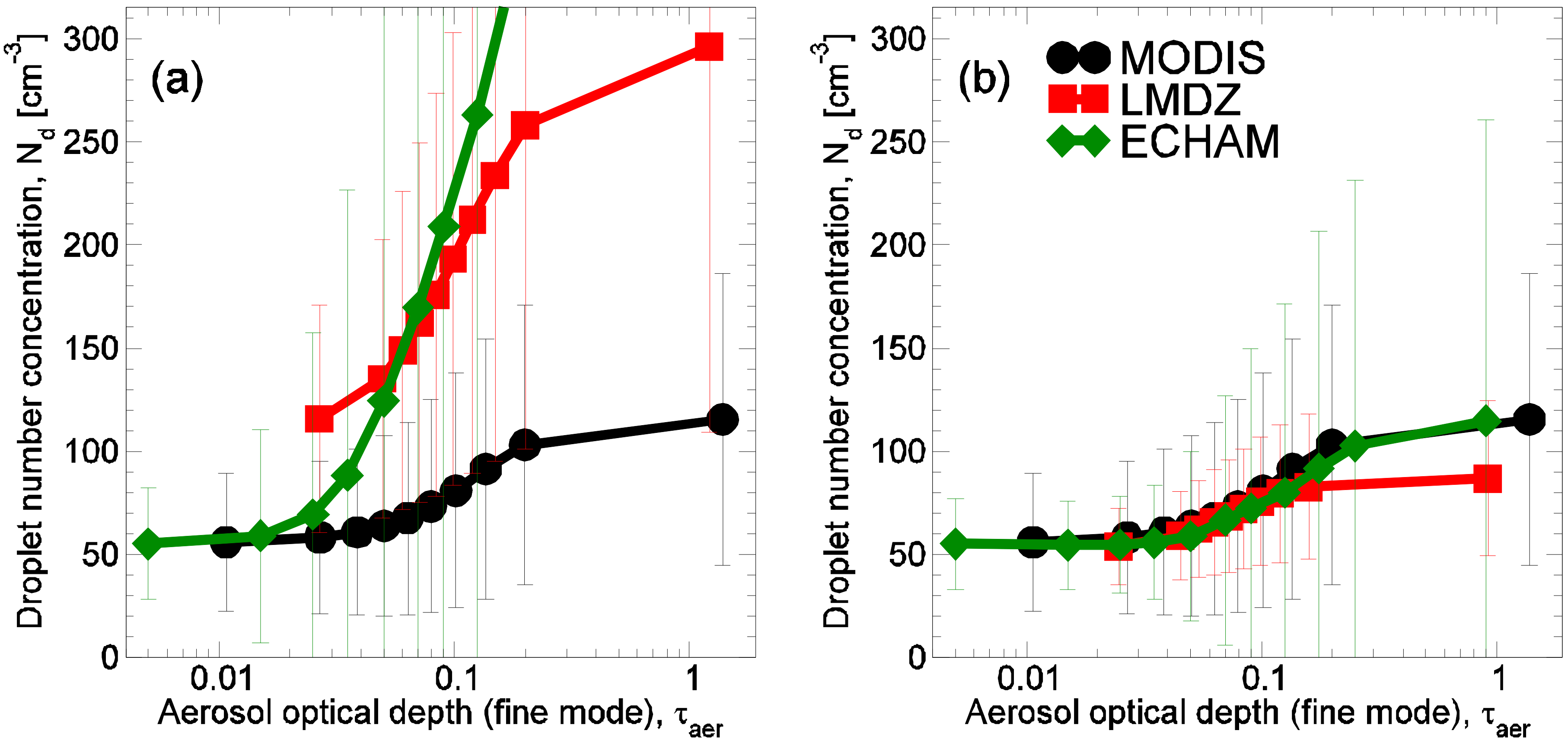
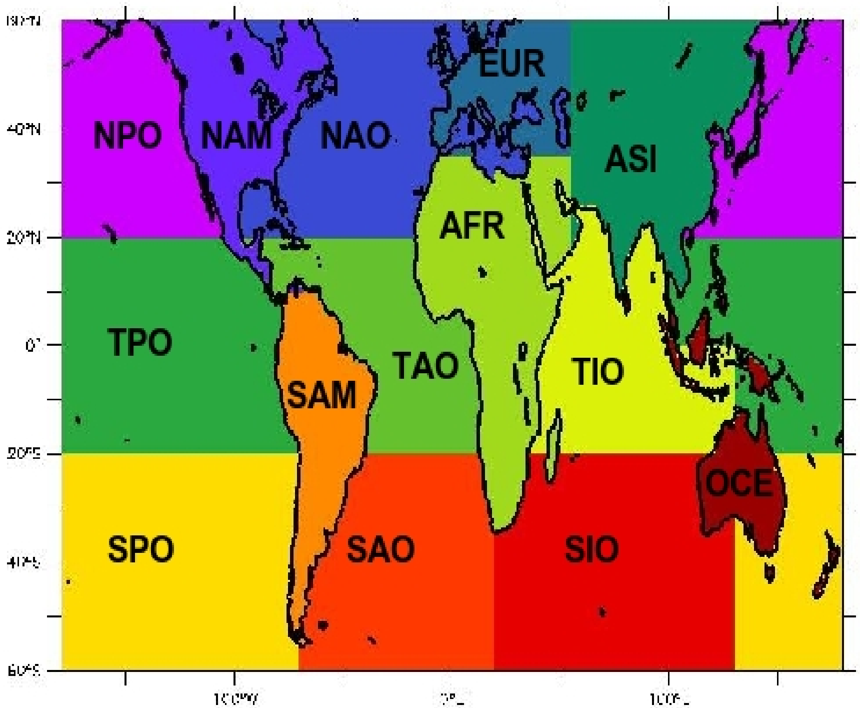
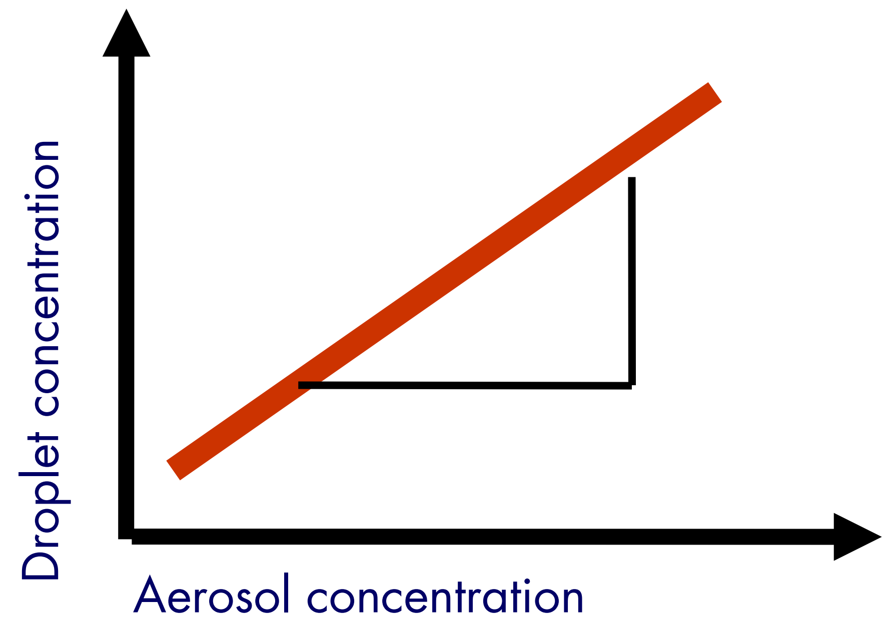


Quaas, Boucher, Lohmann, Atmos. Chem. Phys. 2006

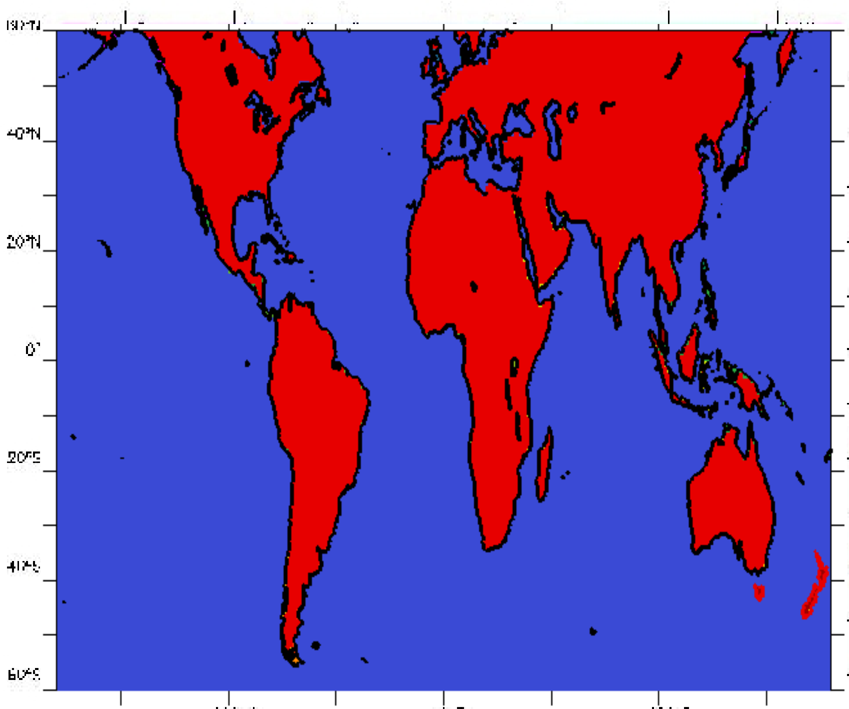
7.4 Model intercomparison and evaluation

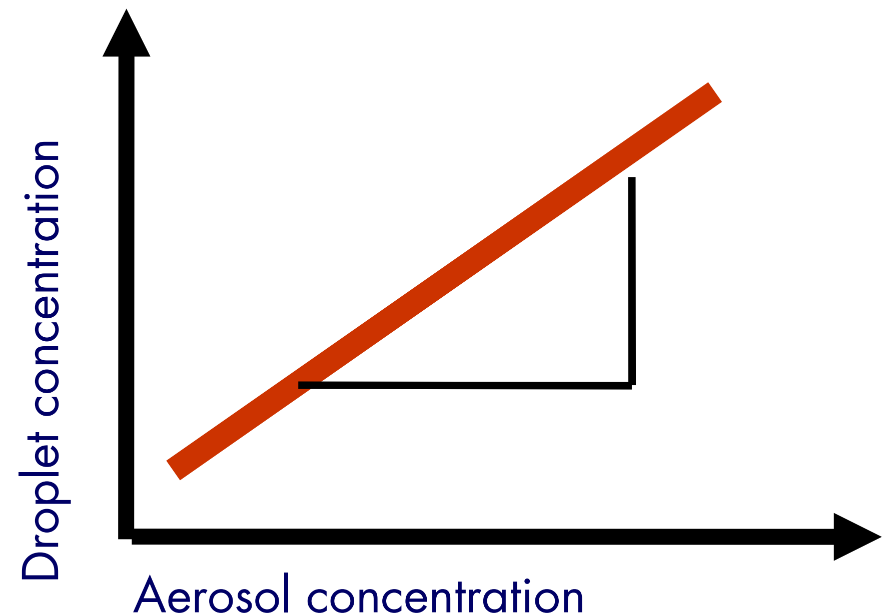




Analyse separately
- 14 different regions
- 4 seasons (MAM,JJA,SON,DJF)

7.4 Model intercomparison and evaluation



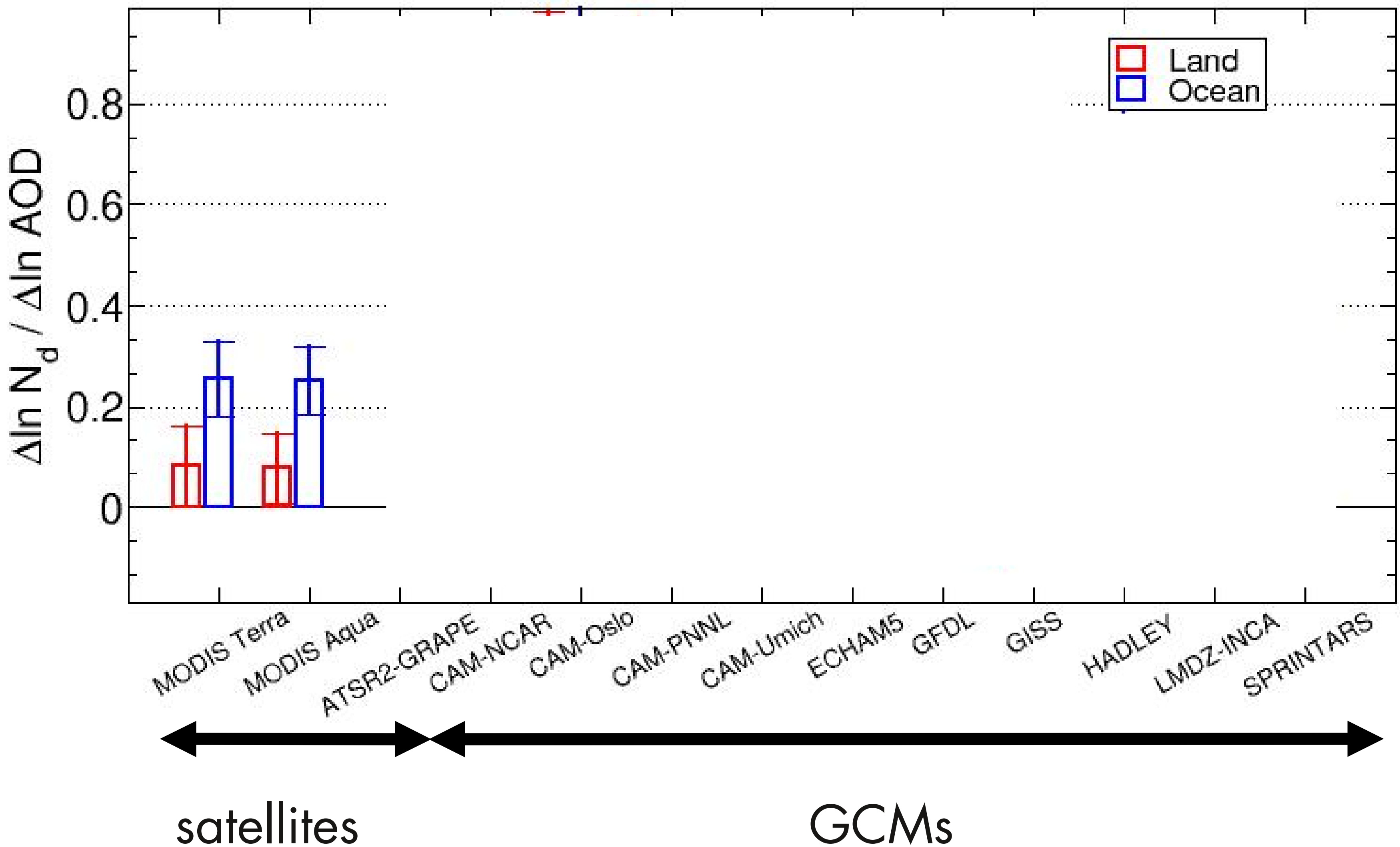


Analyse separately

- 14 different regions
- 4 seasons (MAM,JJA,SON,DJF)

… but show here the summary for **land** and **ocean.**

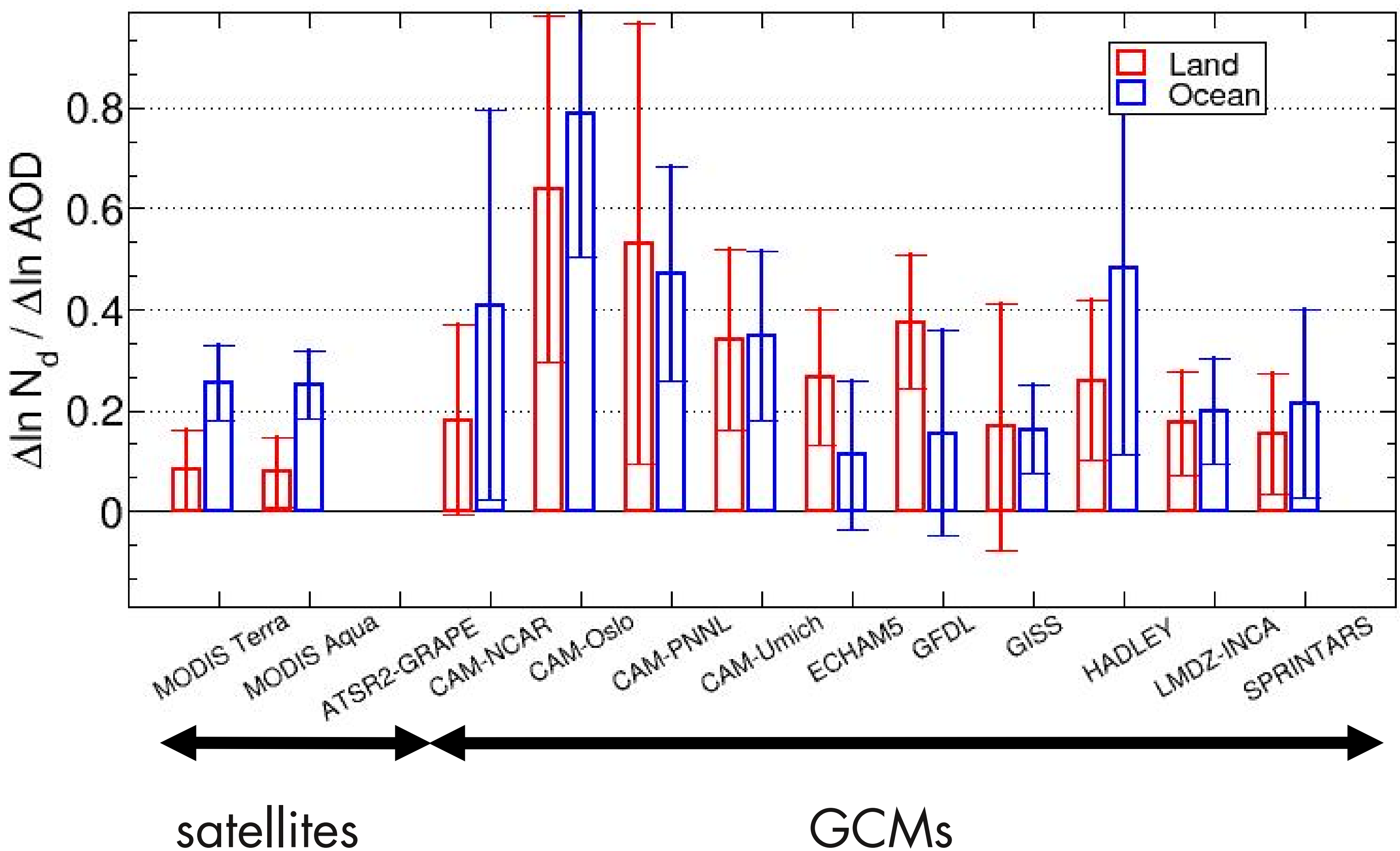
→ relationship of droplet number concentration and aerosol optical depth



Quaas et al., Atmos. Chem. Phys. 2009

7.4 Model intercomparison and evaluation

→ relationship of droplet number concentration and aerosol optical depth



Quaas et al., Atmos. Chem. Phys. 2009

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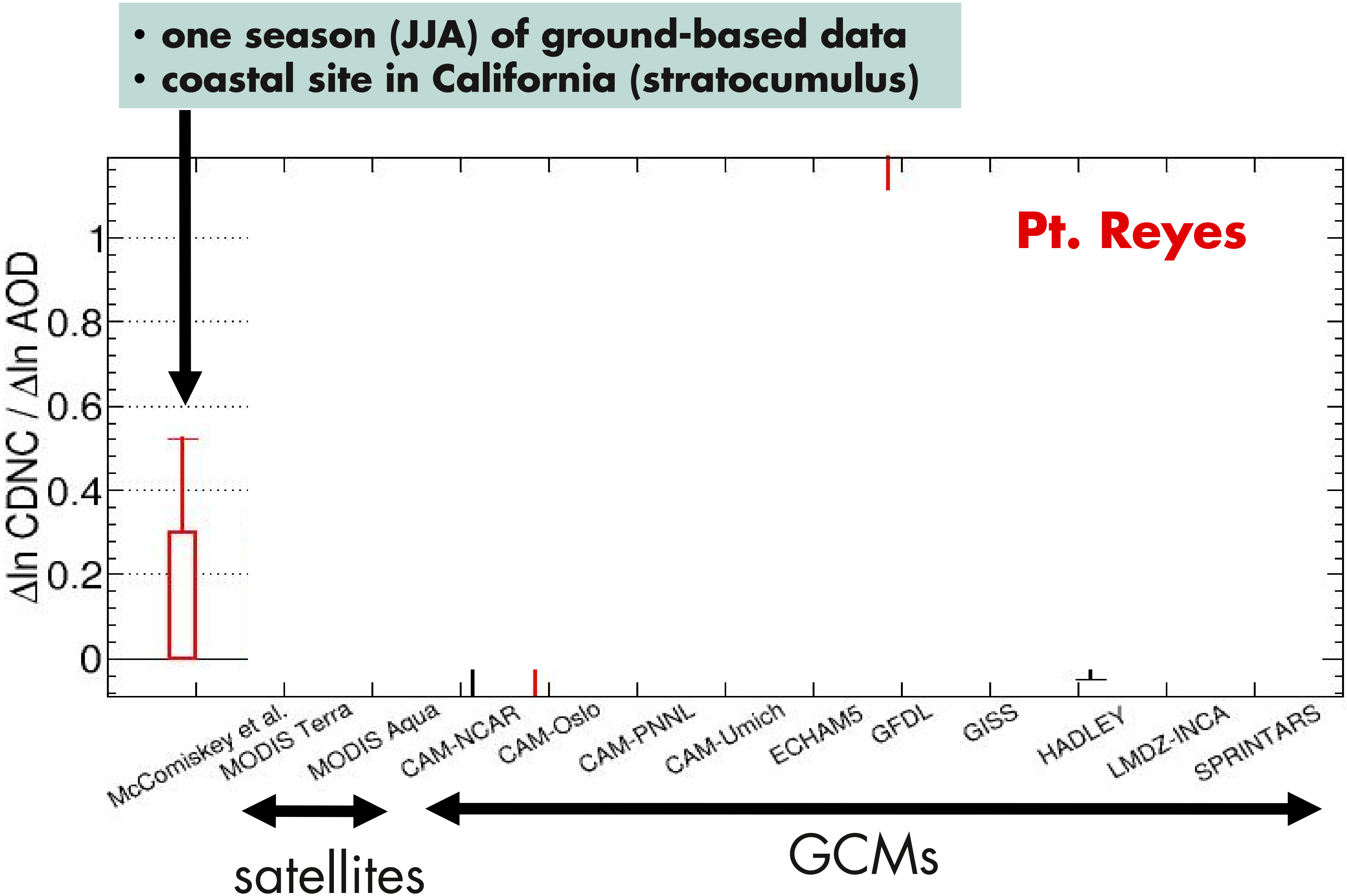
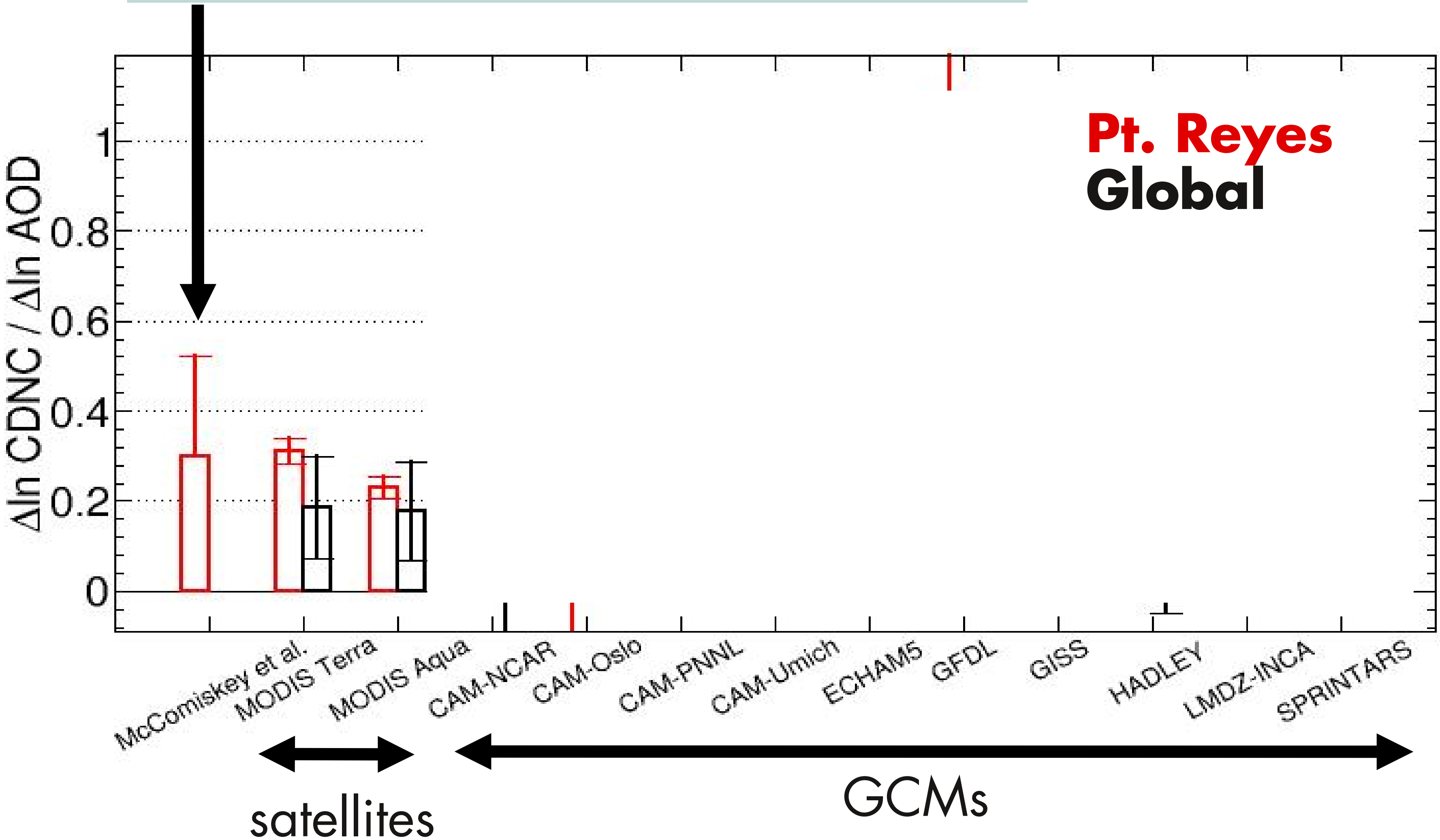


McComiskey et al., J. Geophys. Res., 2009

7.4 Model intercomparison and evaluation

- one season (JJA) of ground-based data
- coastal site in California (stratocumulus)



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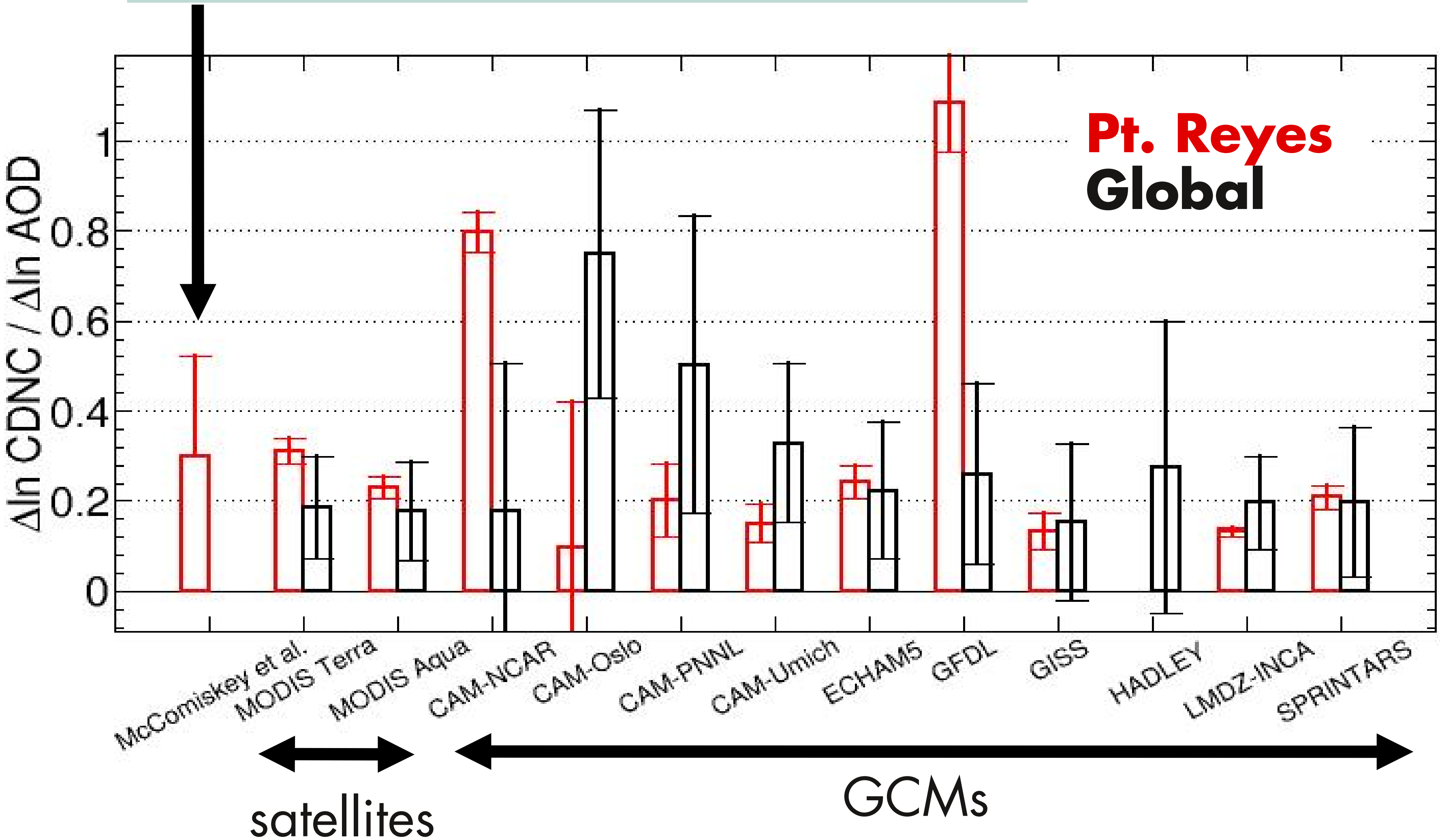
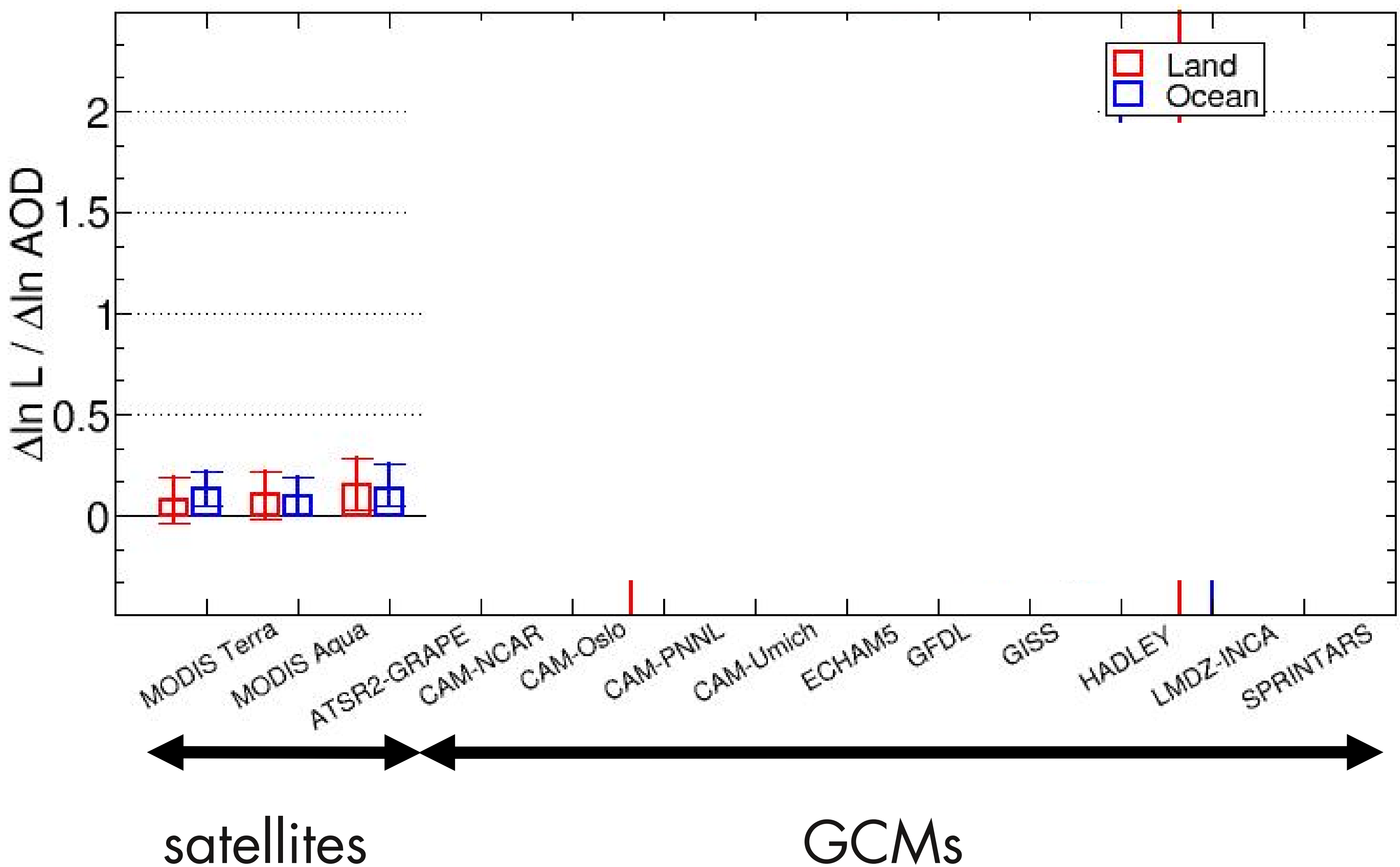


McComiskey et al., J. Geophys. Res., 2009; Quaas et al., Atmos. Chem. Phys. 2009

7.4 Model intercomparison and evaluation

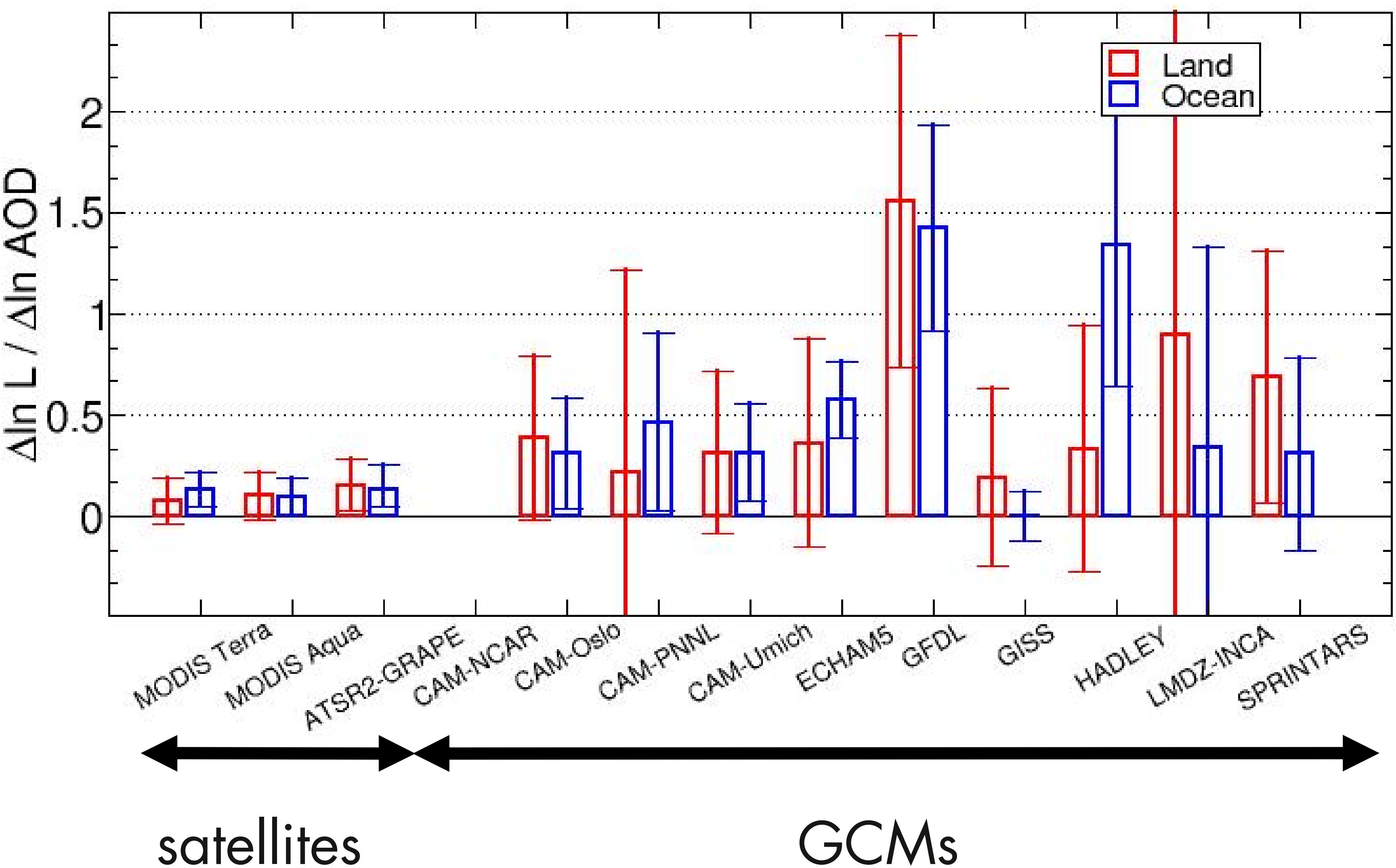
→ relationship of **cloud liquid water path** and aerosol optical depth



Quaas et al., Atmos. Chem. Phys. 2009

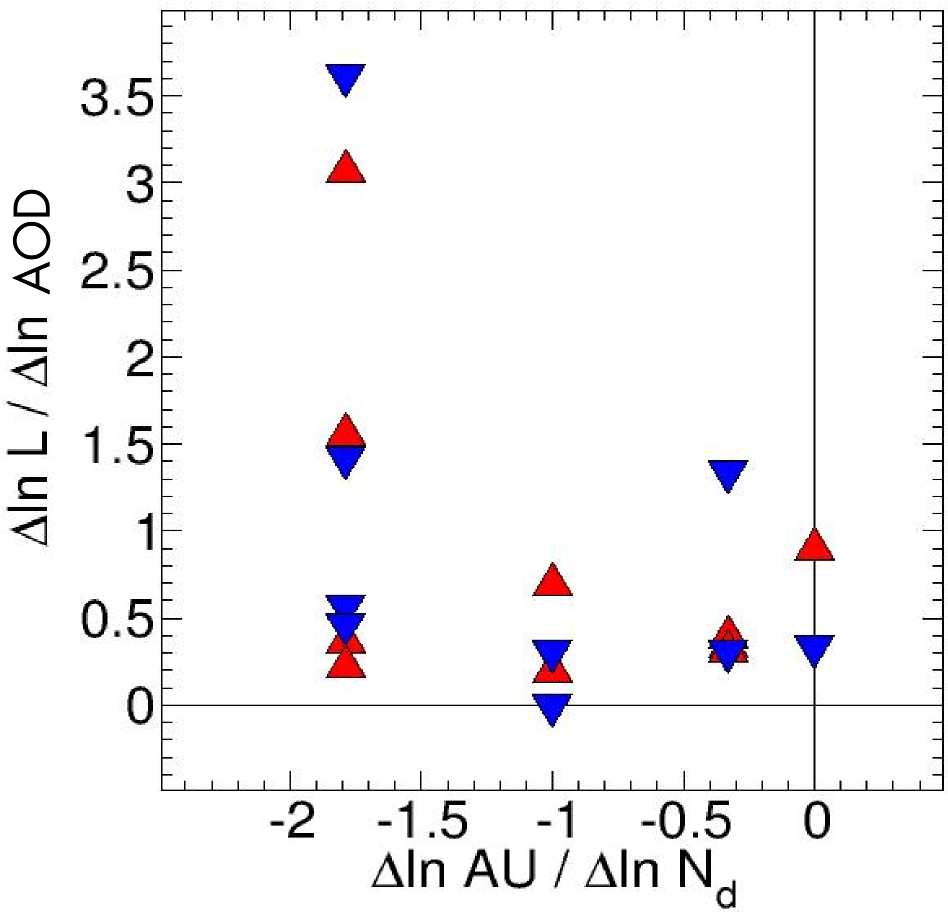
7.4 Model intercomparison and evaluation

→ relationship of **cloud liquid water path** and aerosol optical depth



Quaas et al., Atmos. Chem. Phys. 2009

Second aerosol indirect effect implemented overly simplistic in GCMs



Precipitation by autoconversion (AU) depends on cloud droplet number concentration N_d

$$AU \sim N_d^x$$

$x \in \{-1.79, -1.0, -0.33, 0\}$

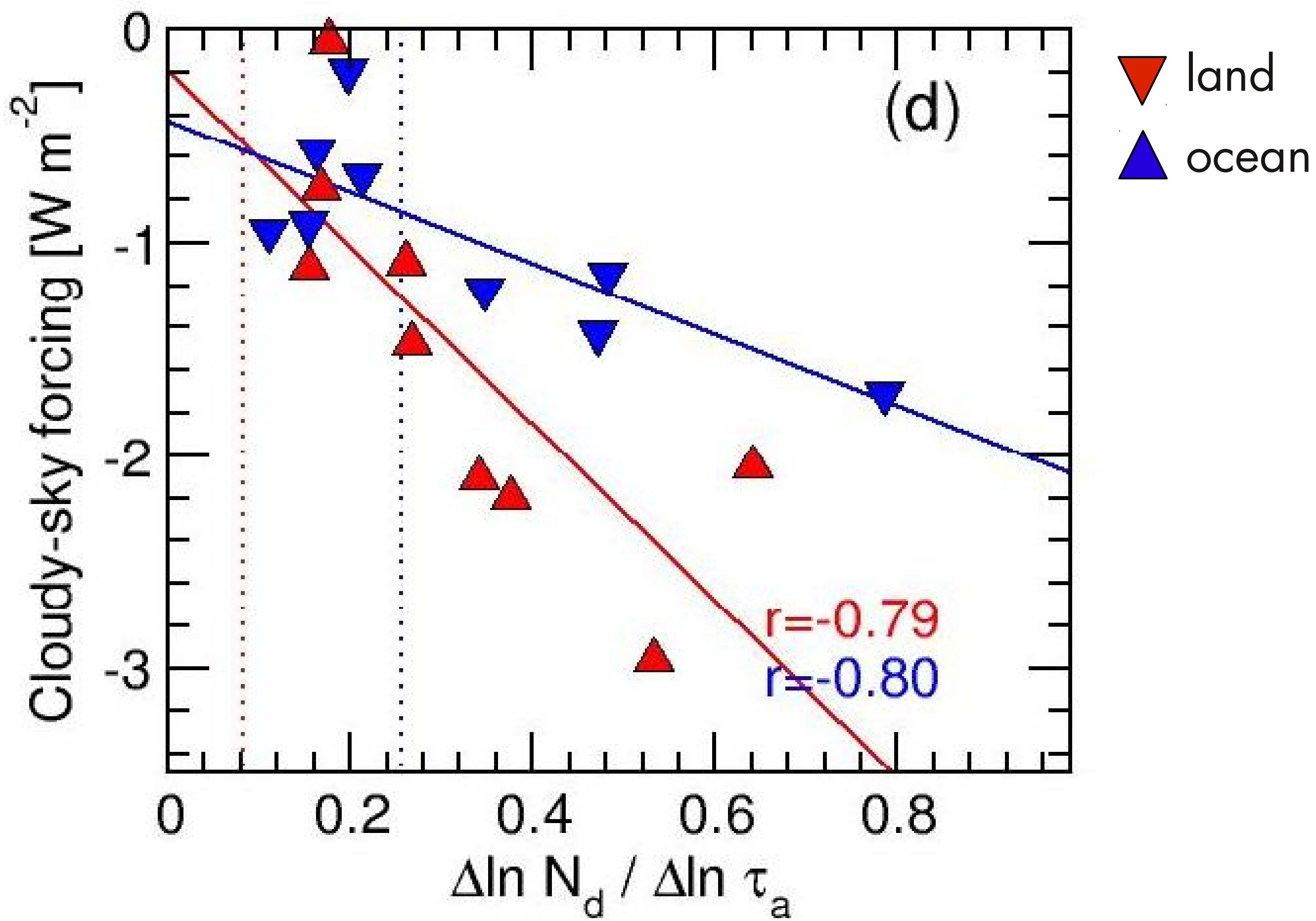
Khairoutdinov and Kogan 2000

Rotstayn & Liu 05
Takemura et al. 05

Rasch and Kristjánsson 98
Jones et al. 01

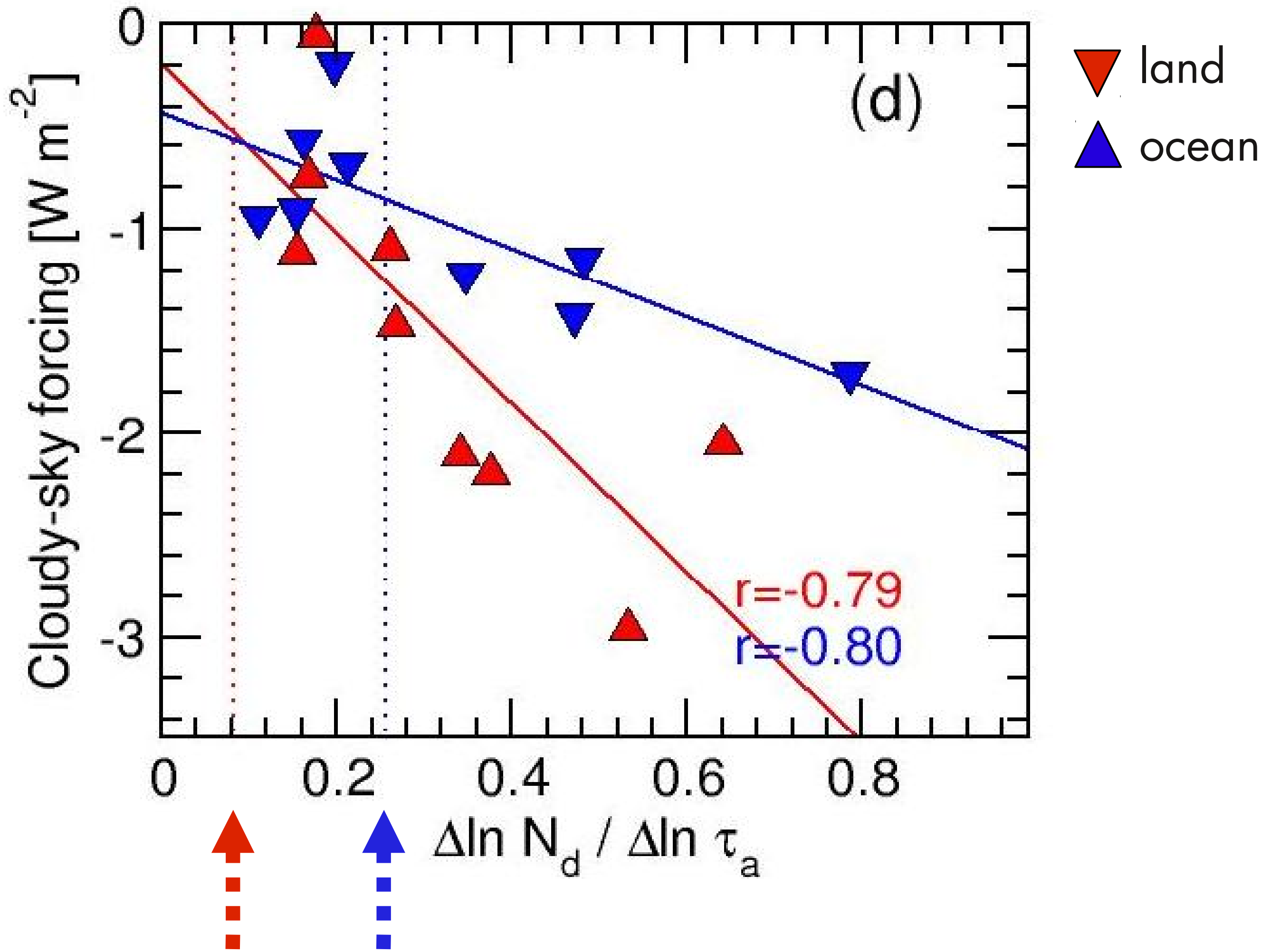
7.5 Constraint on forcing?

Constraint on aerosol indirect forcing



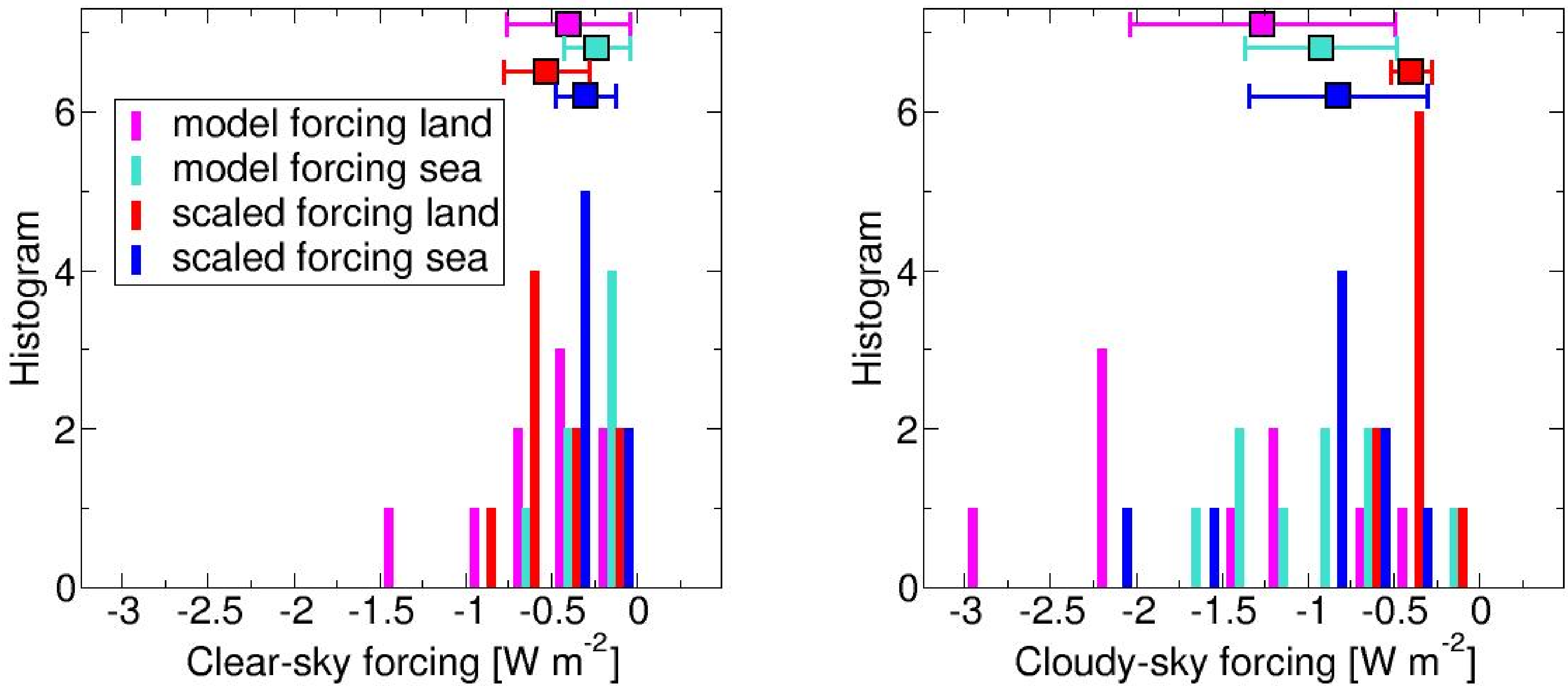
7.5 Constraint on forcing?

Constraint on aerosol indirect forcing



Satellite estimates over land and ocean

7.5 Constraint on forcing?

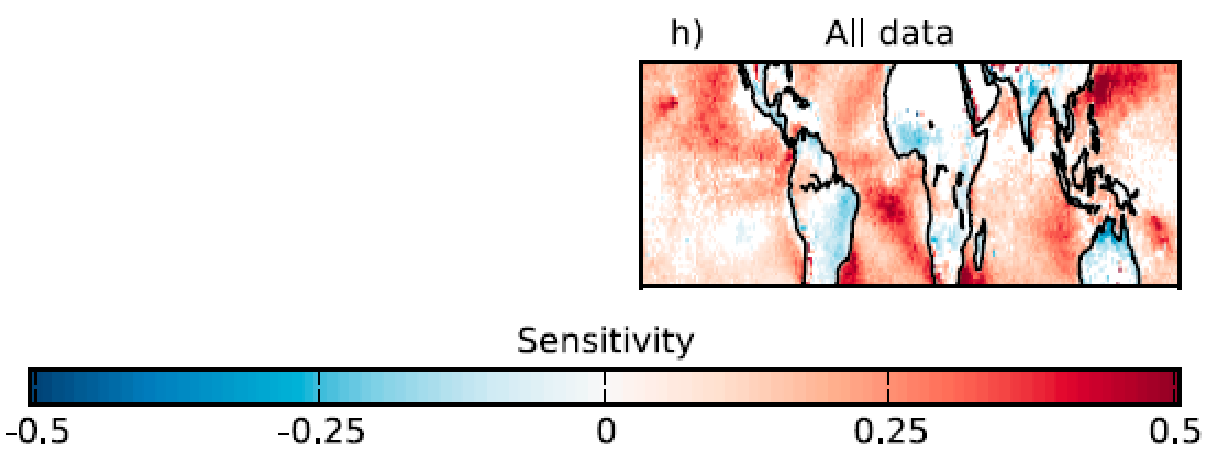


estimate	modelled	scaled
clear	**-0.27±0.23**	**-0.38±0.19 Wm^{-2}**
cloudy	**-1.13±0.51**	**-0.70±0.37 Wm^{-2}**
total	**-1.53±0.60**	**-1.15±0.43 Wm^{-2}**

Quaas et al., Atmos. Chem. Phys. 2009

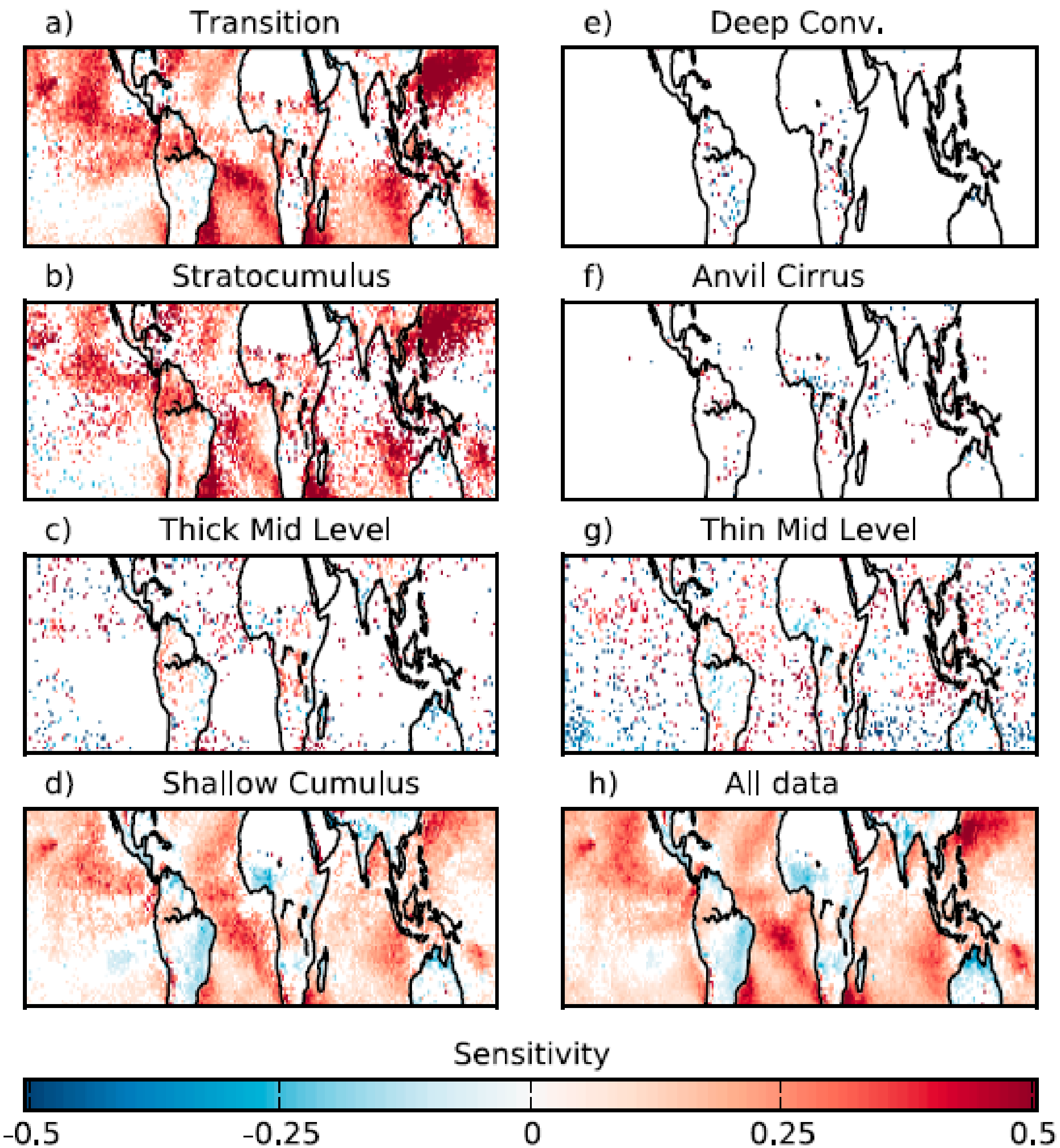
7.6 Relationships by cloud regime

Regression $\Delta\ln N_d$ / $\Delta\ln \tau_a$ by ISCCP clusters (from MODIS data)



(See also Poster by Karoline Block)

7.6 Relationships by cloud regime

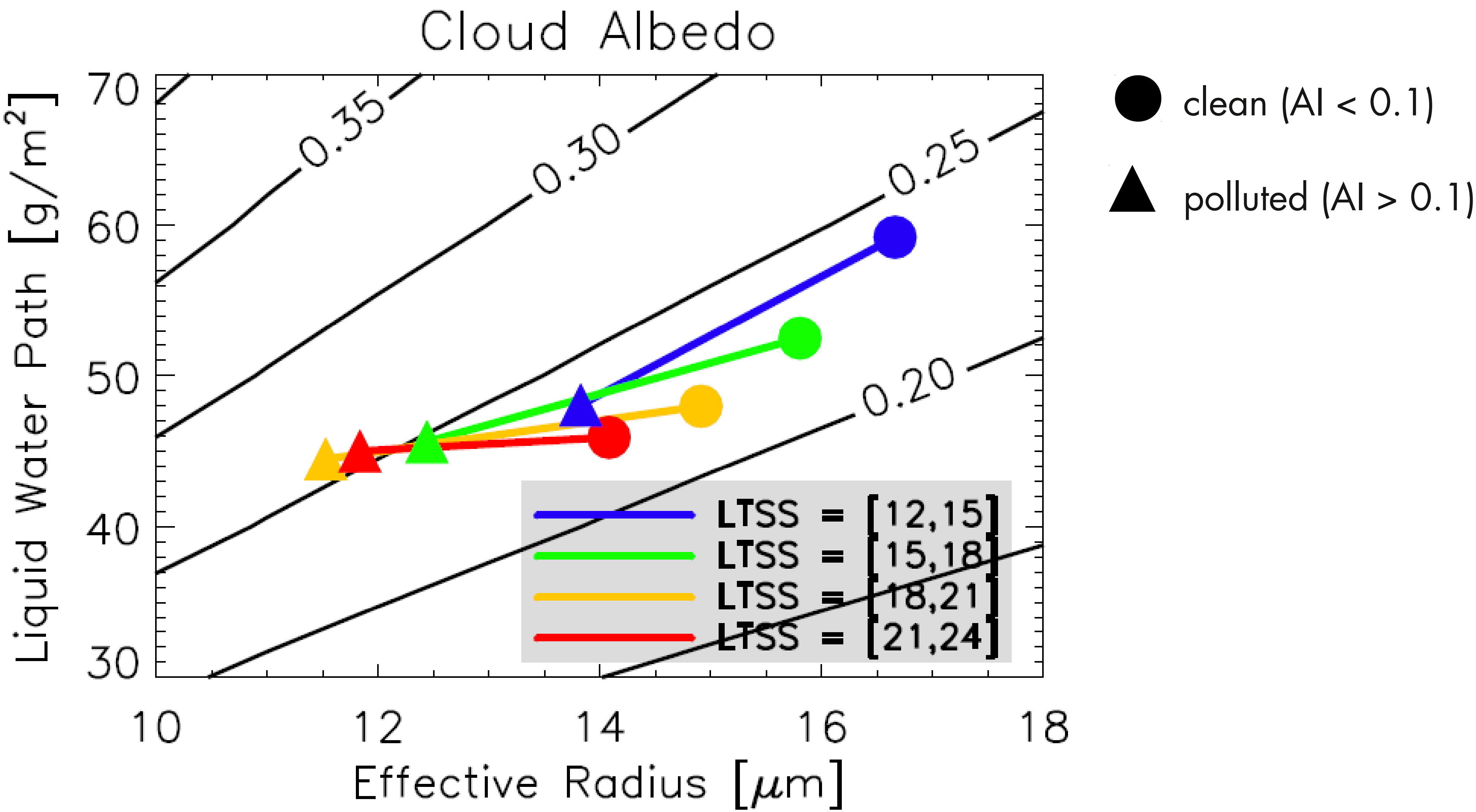


Regression $\Delta \ln N_d$ / $\Delta \ln \tau_a$ by ISCCP clusters (from MODIS data)

(See also Poster by Karoline Block)

Gryspeerdt and Stier, Geophys. Res. Lett. 2013

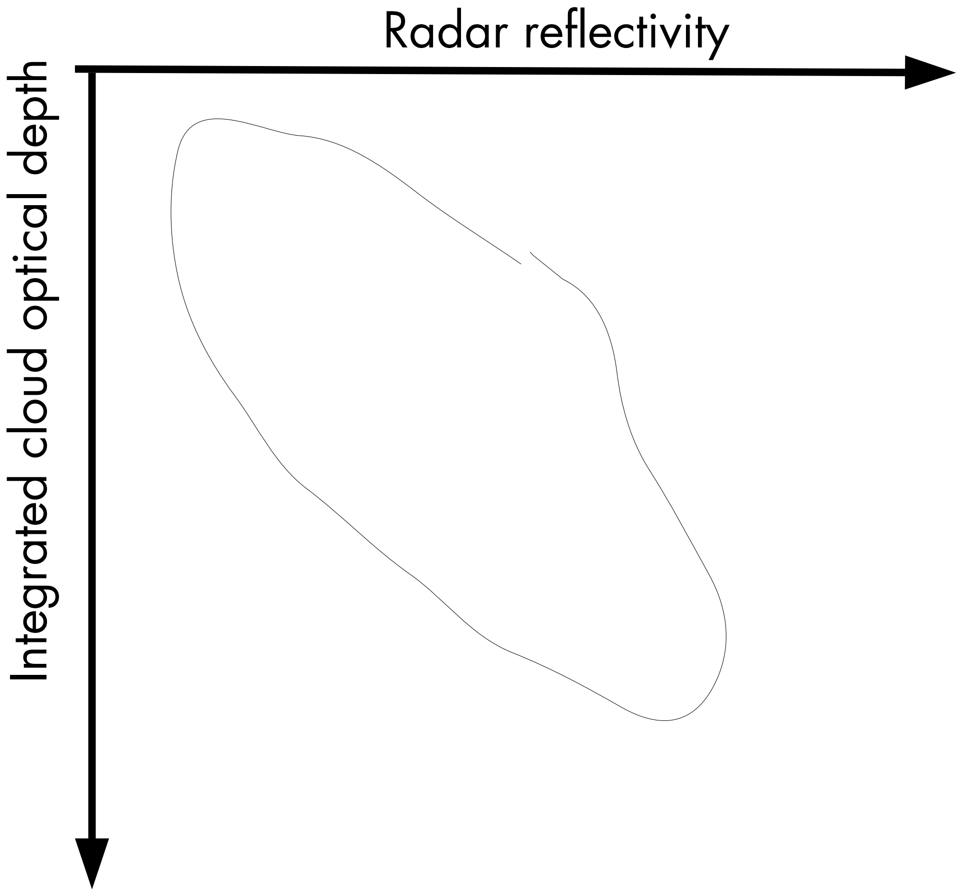
7.6 Regime-dependency



MODIS – AMSR-E – ECMWF data

Lebsock et al., J. Geophys. Res., 2008

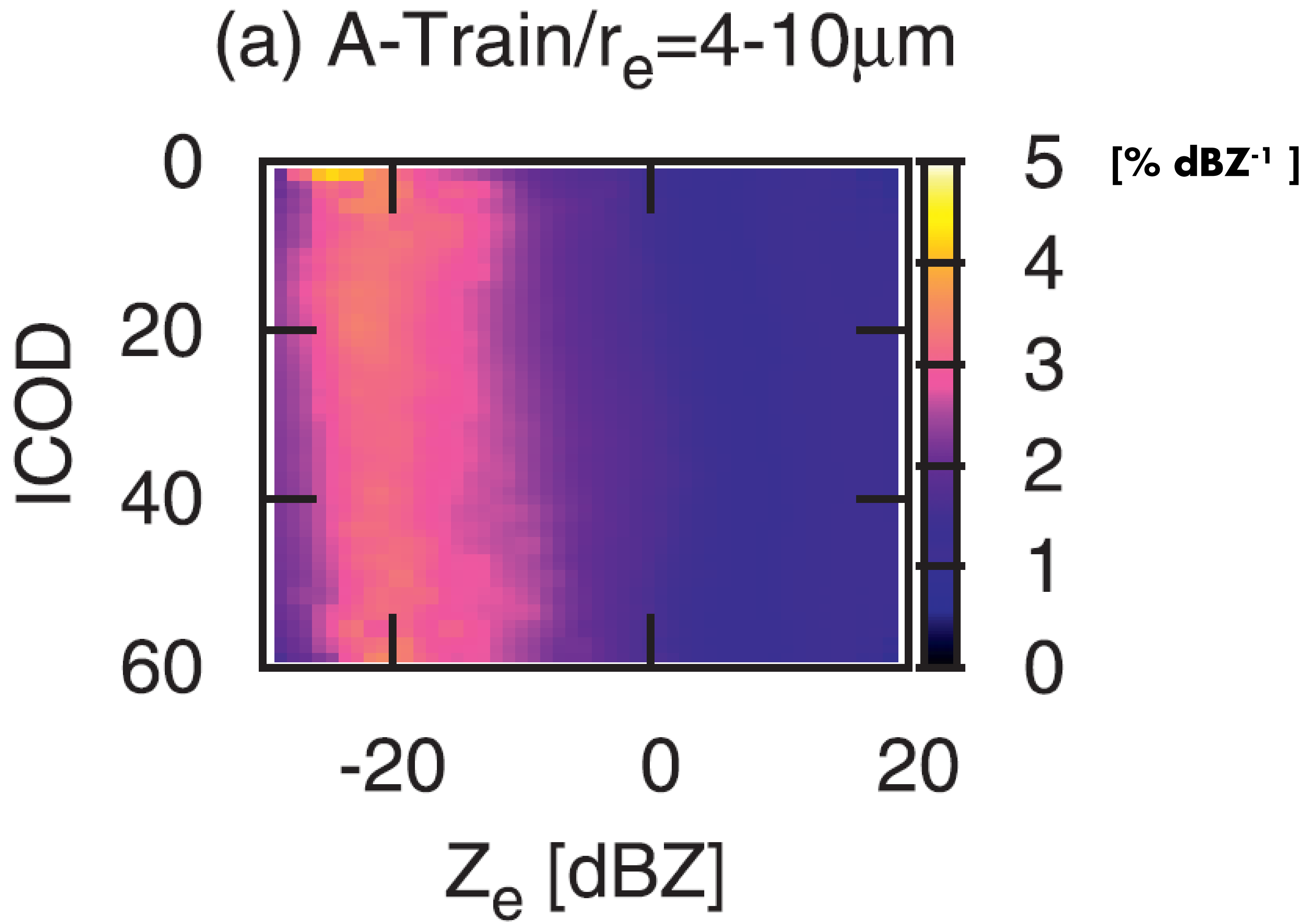
7.7 Precipitation process evaluation



Contour: Frequency of occurrence
(Joint histogram or: CFOOD)

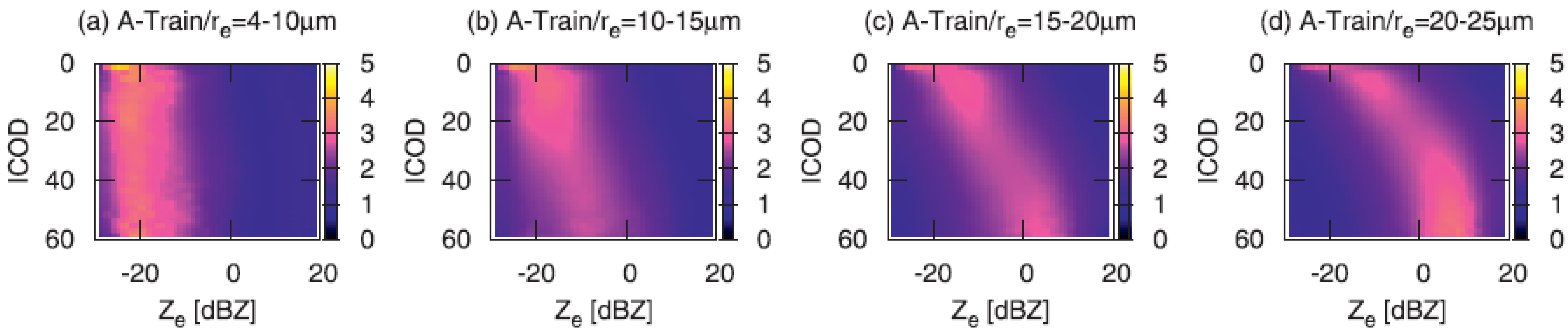
For given cloud droplet effective radius

Data: MODIS (cloud-top droplet radii / cloud optical depth)
CloudSat (reflectivity)



Suzuki et al., J. Atmos. Res. 2011

7.7 Precipitation process evaluation



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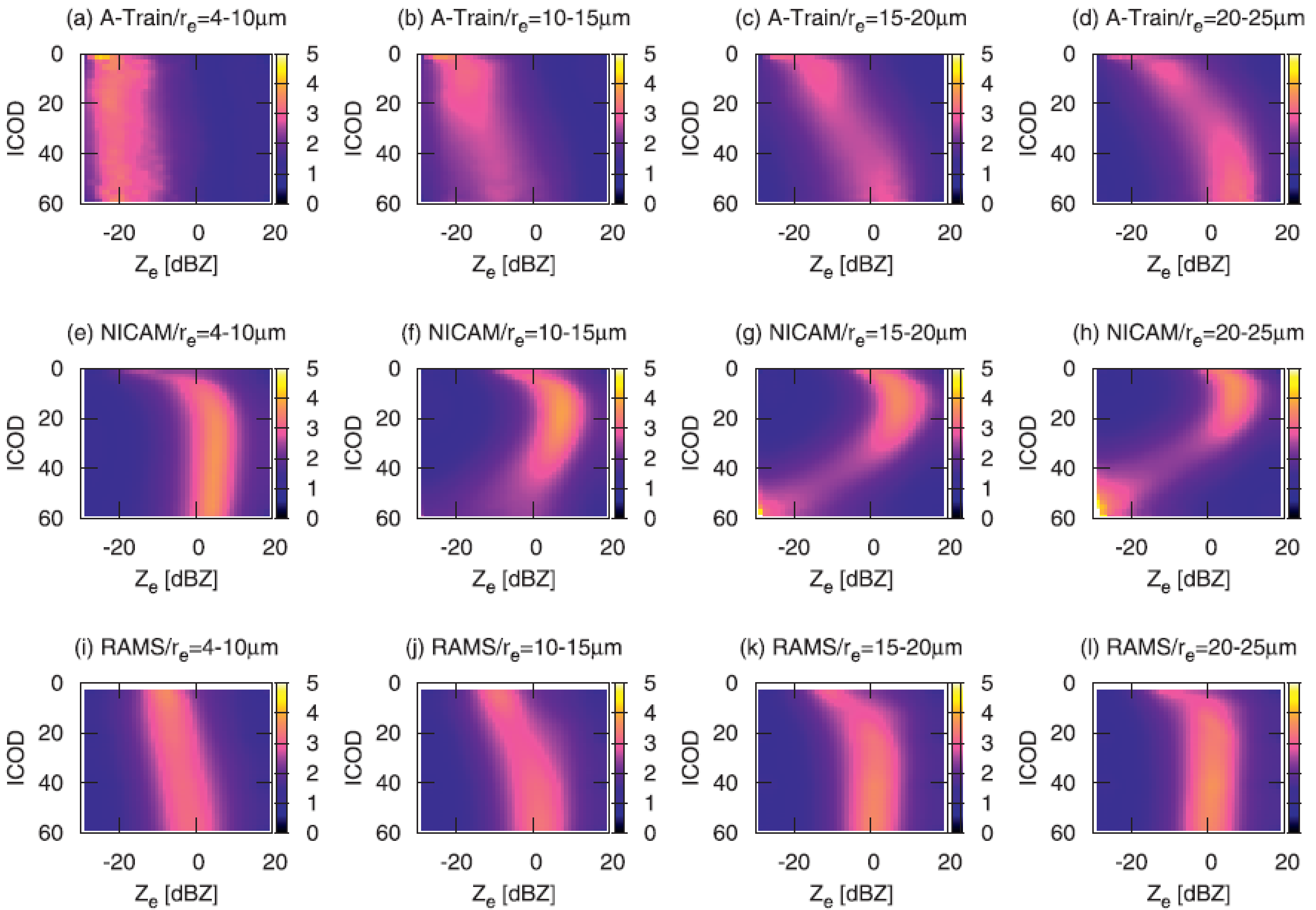
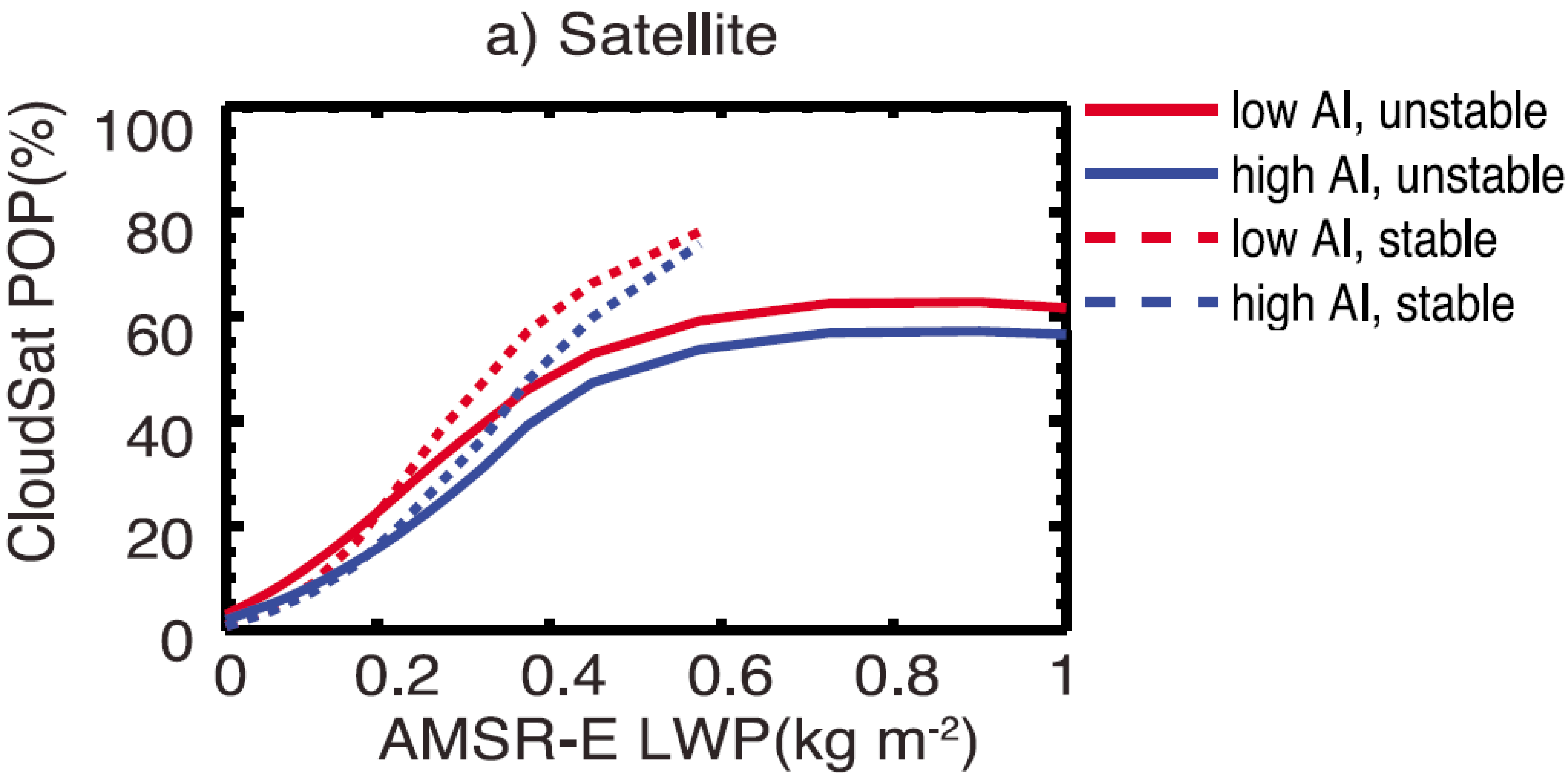


Suzuki et al., J. Atmos. Res. 2011

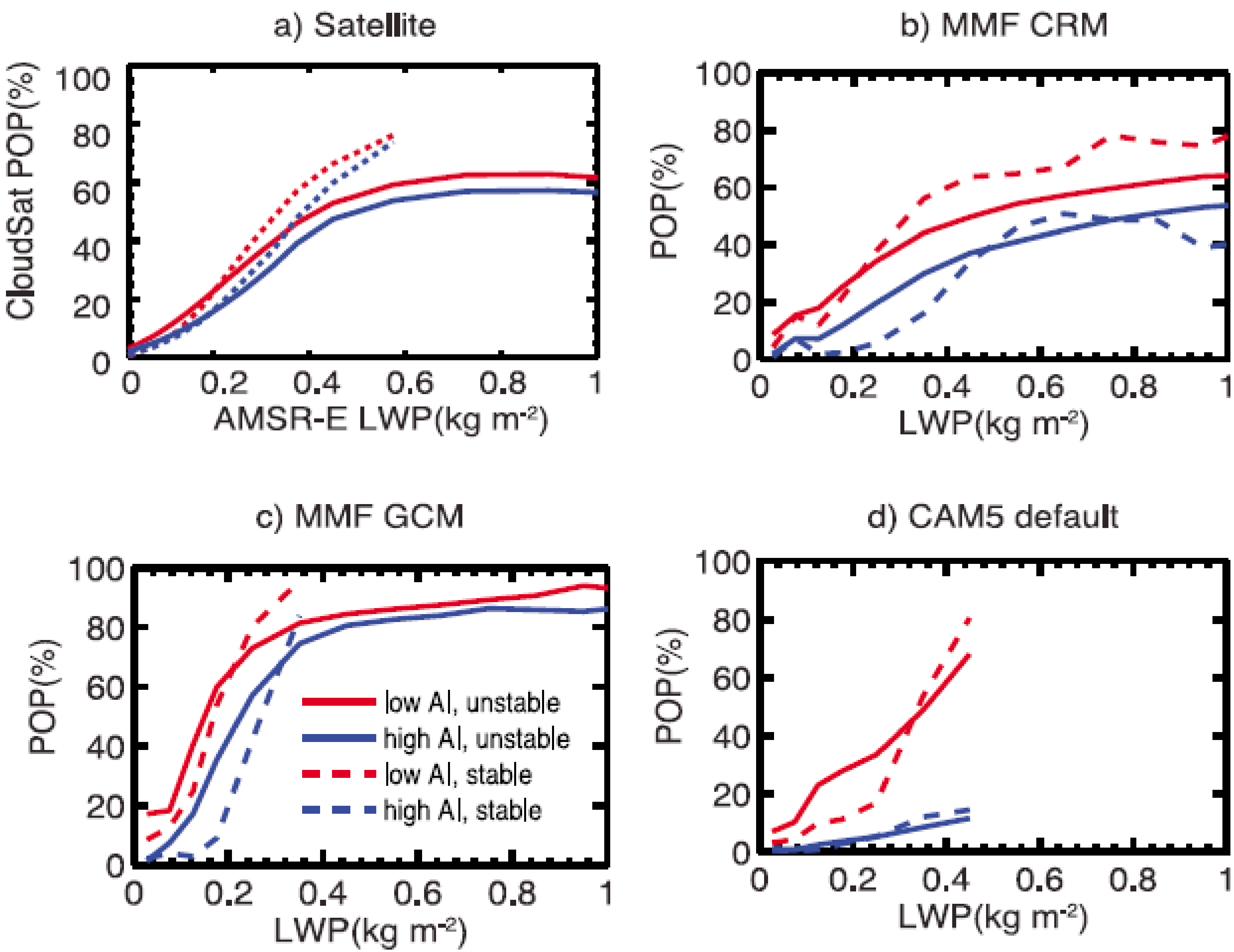
7.8 Precipitation susceptibility



stable: LTS > 18 K (ECMWF data)
unstable: LTS < 13.5 K

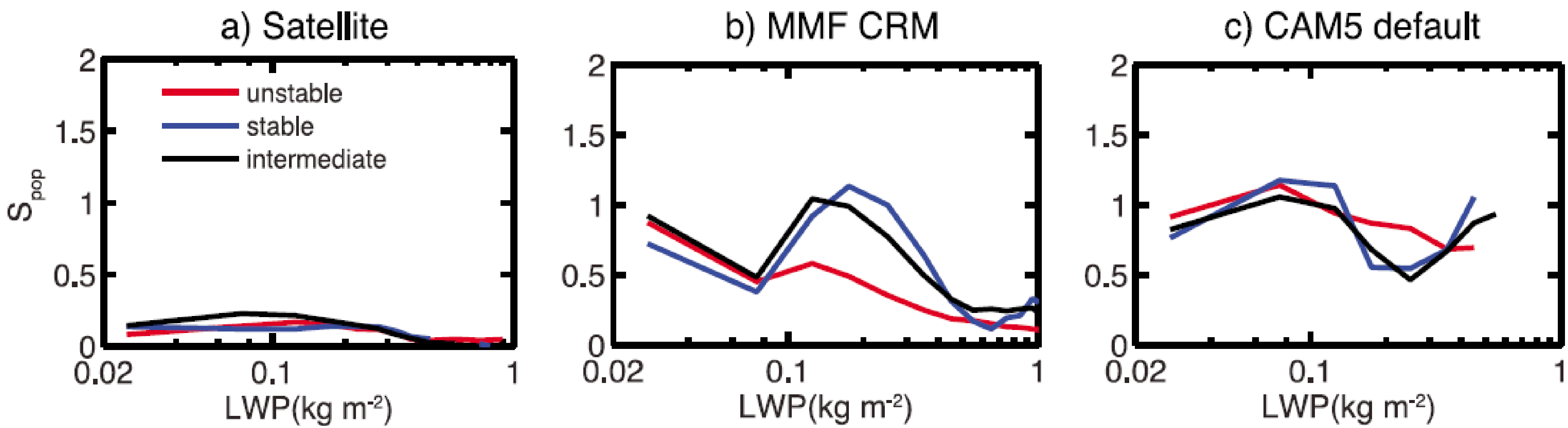
high aerosol index: upper quintile (MODIS $\alpha\tau_a$)
low: lower quintile

7.8 Precipitation susceptibility



Wang et al., J. Geophys. Res. Lett. 2012

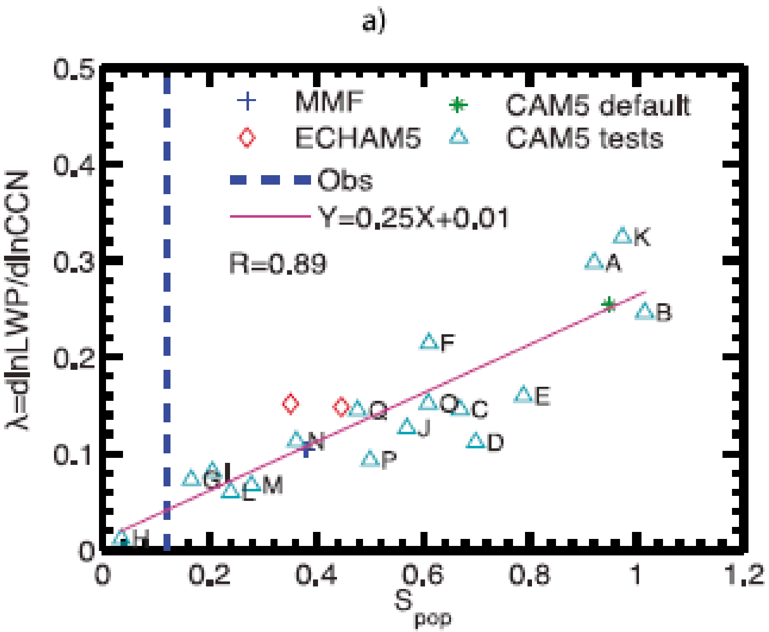
7.8 Precipitation susceptibility



Precipitation susceptibility from linear regression

$S_{pop} = \Delta \ln POP / \Delta \ln (\alpha\tau_a)$

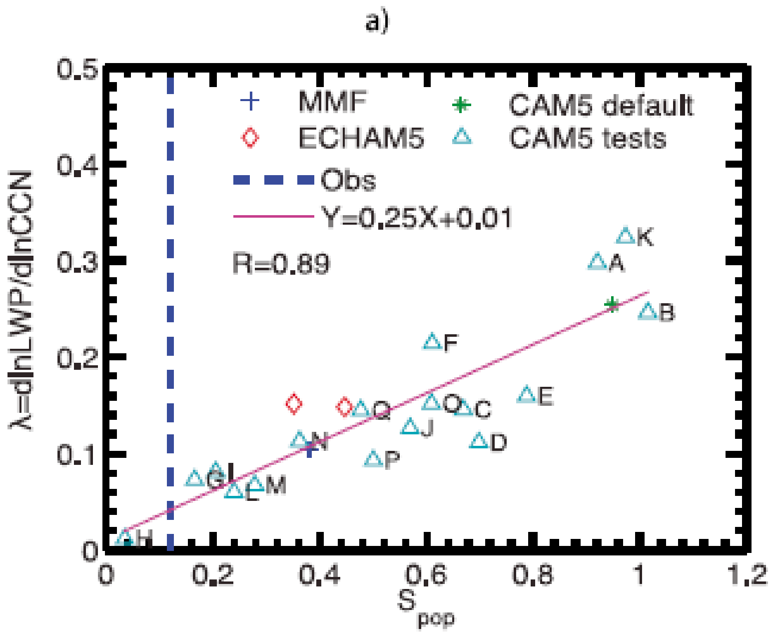
7.8 Precipitation process evaluation: Probability of precipitation



Δ ln L / Δ ln CCN vs. precip susceptibility, S_{pop}

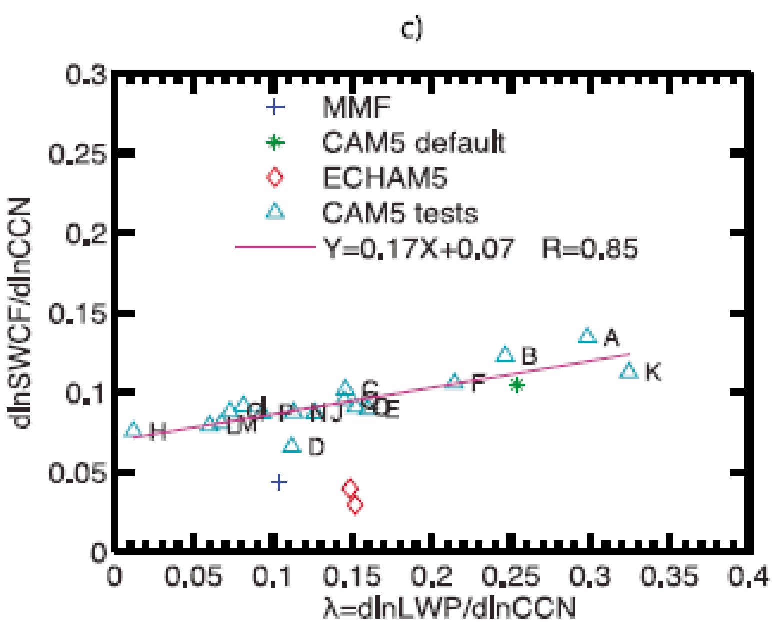
→ good metric to constrain liquid water path susceptibility

7.8 Precipitation susceptibility



$\Delta \ln L / \Delta \ln CCN$ vs. precip susceptibility, S_{pop}

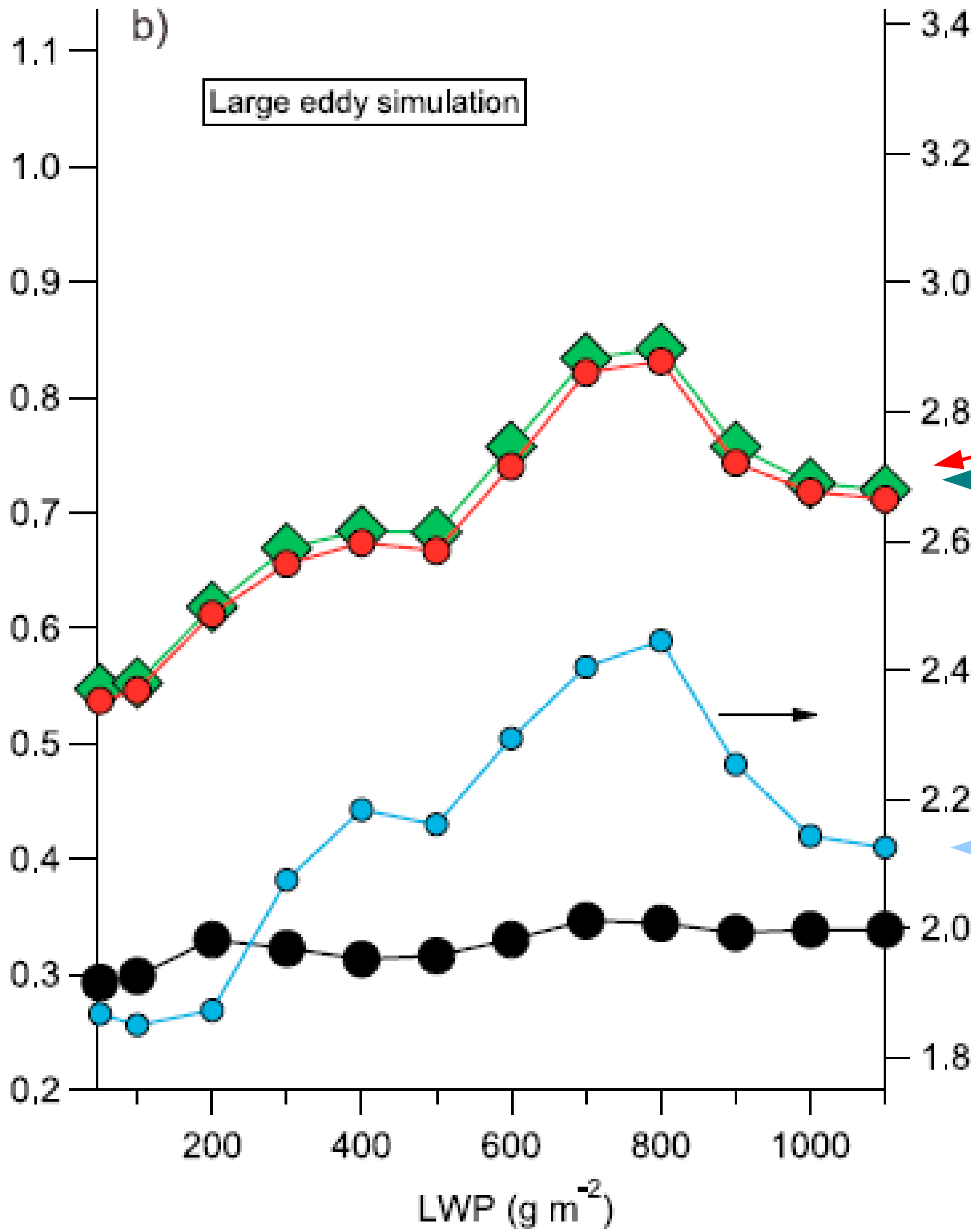
→ good metric to constrain liquid water path susceptibility



$\Delta \ln SWCF / \Delta \ln CCN$ vs. $\Delta \ln L / \Delta \ln CCN$

→ good metric to constrain short wave cloud forcing response

7.9 Precipitation metric decomposed



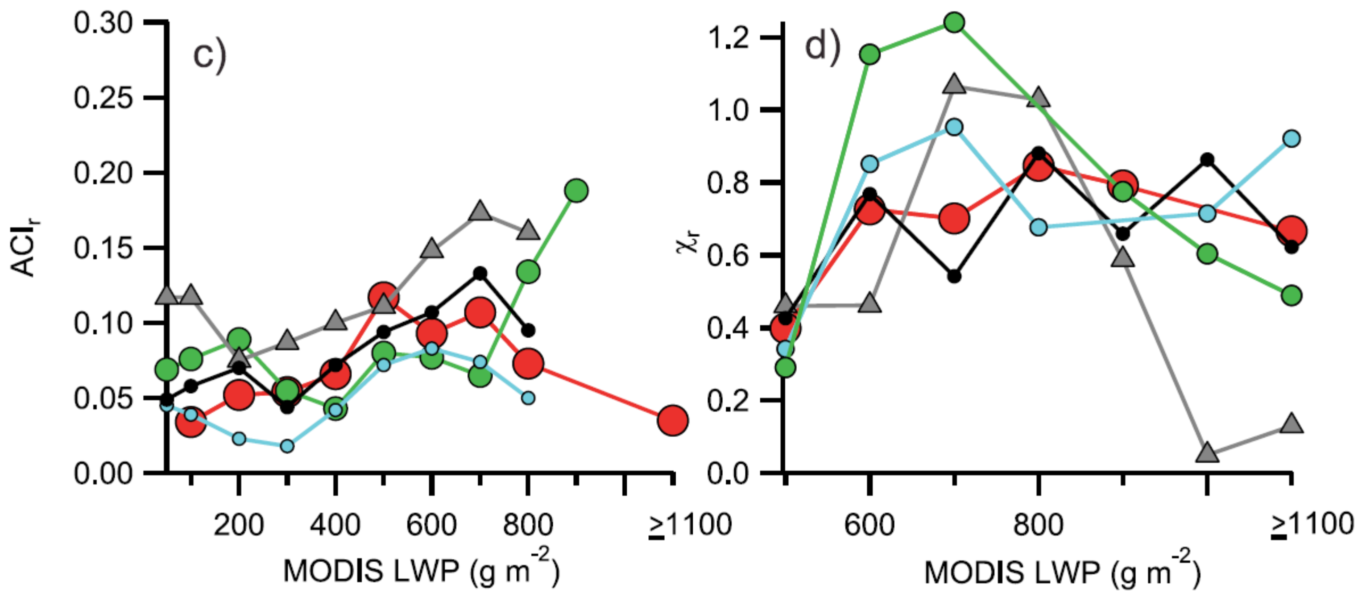
$$\frac{\partial \ln R}{\partial \ln N_d}$$ change in rain rate with droplet concentration

$$\frac{\partial \ln R}{\partial \ln r_e}\frac{\partial \ln r_e}{\partial N_d}$$ decomposed via effect on droplet radii

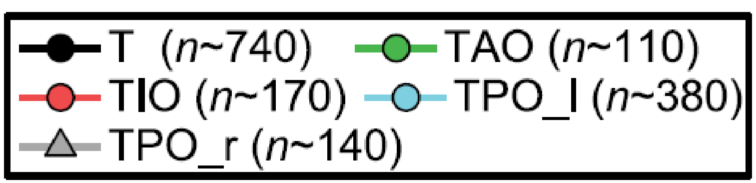
$$\frac{\partial \ln R}{\partial \ln r_e}$$ change in rain rate for changing droplet radii (right axis)

$$-\frac{\partial \ln r_e}{\partial \ln N_d}$$ change in droplet radii with number concentration

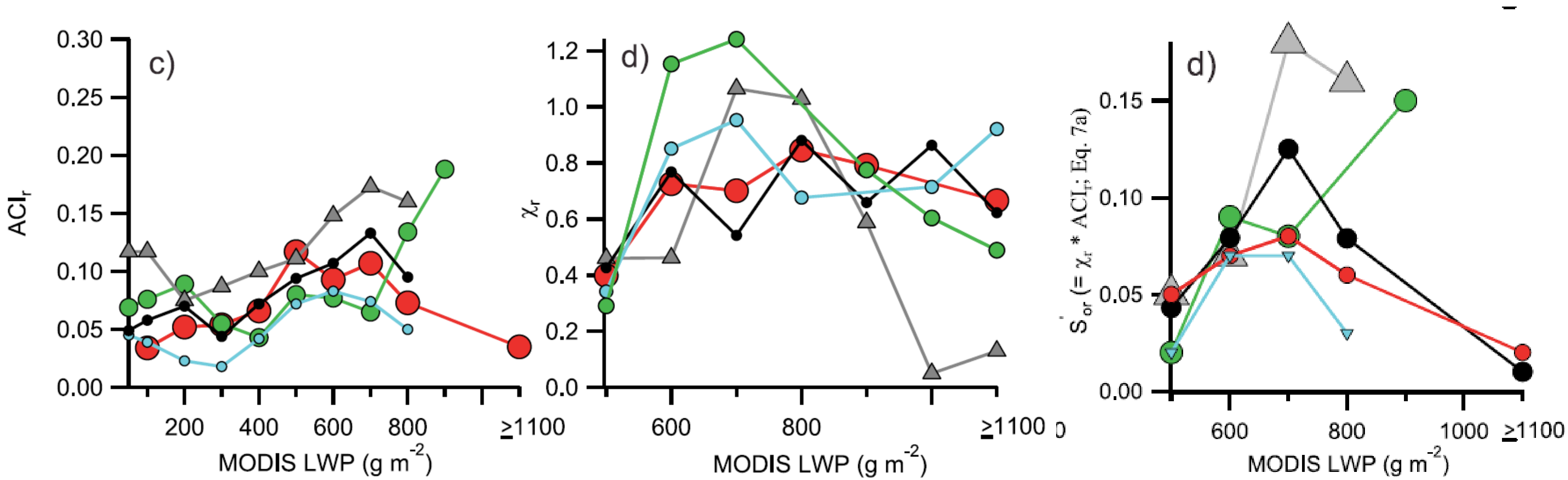
7.9 Precipitation metric decomposed



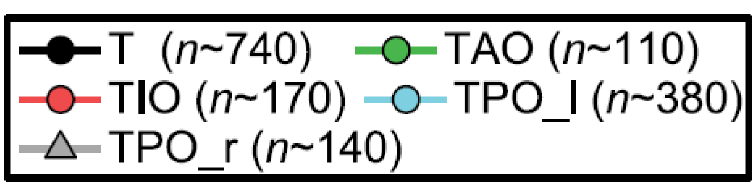
$$-\frac{\partial \ln r_e}{\partial \ln(\alpha \tau_a)} \qquad \frac{\partial \ln R}{\partial \ln r_e}$$



MODIS and CloudSat data for different tropical regions

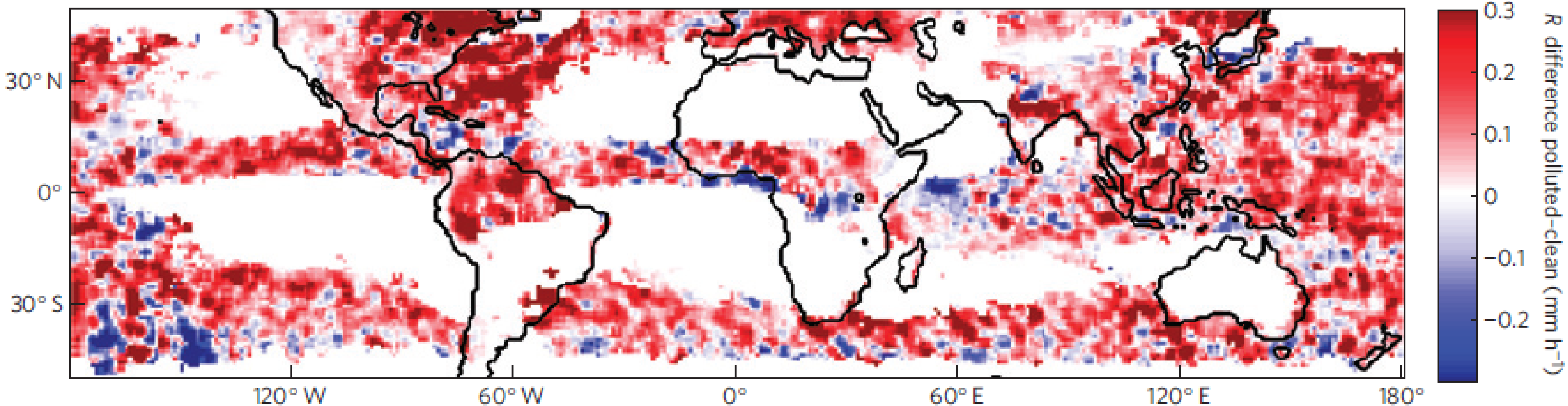


$$-\frac{\partial \ln r_e}{\partial \ln(\alpha \tau_a)} \qquad \frac{\partial \ln R}{\partial \ln r_e} \qquad \frac{\partial \ln R}{\partial \ln r_e}\frac{\partial \ln r_e}{\partial \ln(\alpha \tau_a)}$$

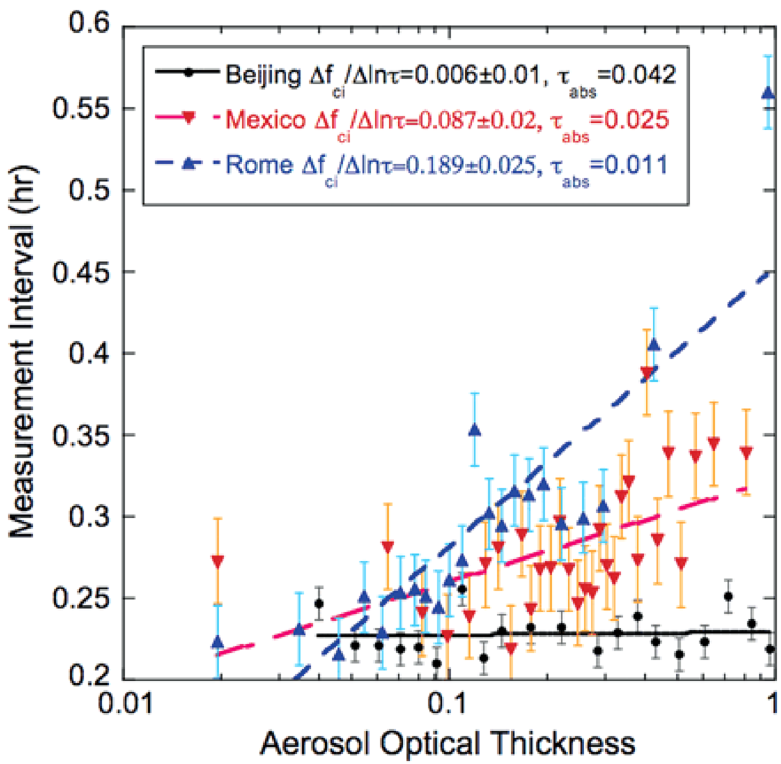


MODIS and CloudSat data for different tropical regions

7.10 Invigoration metric?

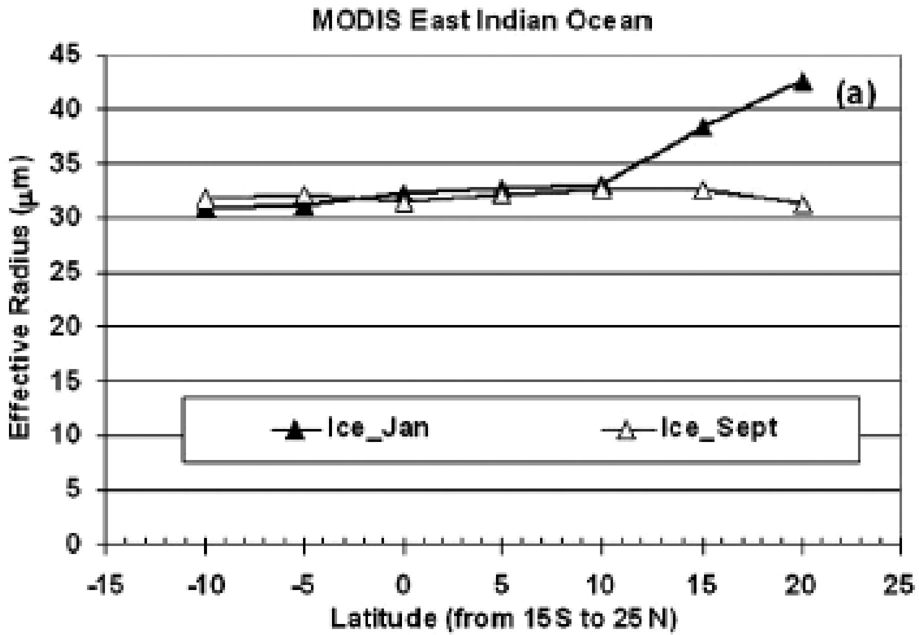


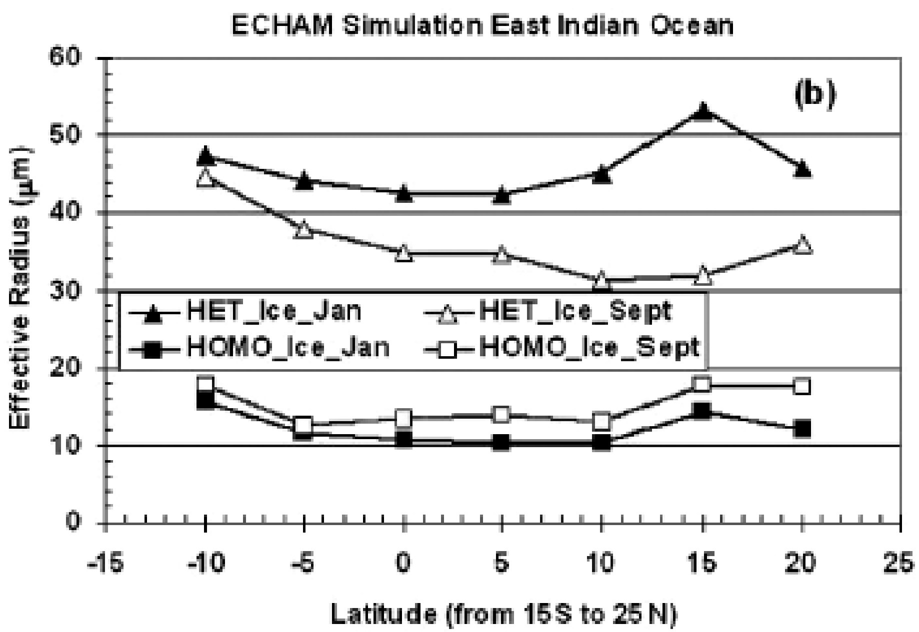
TRMM rain rate upper – lower AOD tercile



Aeronet AOD vs. cloud fraction

7.11 Ice cloud metric?





Chylek et al., Geophys. Res. Lett. 2006

Conclusions 1/2

- **Small signal-to-noise ratio hampers detection of aerosol effects on clouds**
  → no large-scale ship emission effect
  → no hemispherical contrast
  → no solar dimming/brightening
  → no weekly cycle

- **Modeling of aerosol-cloud-precipitation interactions**
  → complexity and feedbacks vs. simplicity and reliability
  → forcing unreliable without good reference and interactions

Conclusions 1/2

- **Small signal-to-noise ratio hampers detection of aerosol effects on clouds**
  → no large-scale ship emission effect…
  → no hemispherical contrast…
  → no solar dimming/brightening…
  → no weekly cycle…

  …**yet**

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Conclusions 1/2

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  → no large-scale ship emission effect...
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  → no weekly cycle...

...**yet**

- **Modeling of aerosol-cloud-precipitation interactions**
  → complexity and feedbacks vs. simplicity and reliability
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Conclusions 2/2

- **Evaluation of processes: Observational metrics**
  → d ln N_d / d ln AOD for first indirect effect
  → results regime-dependent
  → d ln LWP / d ln AOD to highlight problems in second effect
  → combined A-Train data allow for process evaluation
  → probability of precipitation useful metric for second effect
  → precipitation metric needs decomposition

- **Open issues**
  → Reliable forcing quantification for liquid-water clouds?
  → Ice- and mixed-phase effects?
  → Invigoration?
  → Earth system feedbacks?

Conclusions 2/2

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  → d ln N_d / d ln AOD for first indirect effect
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