

Constraints on aerosol-cloud-climate forcing

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Outline

- **Need for appropriate retrievals**
 - cloud particle number concentration
 - coincident meaningful aerosol information
- **Usefulness of satellite simulators**
 - Necessary condition for useful comparison
- **Process-oriented vs. climate-oriented evaluation**
 - both are useful
- **Use of models to interpret data**
 - Cause-effect analysis

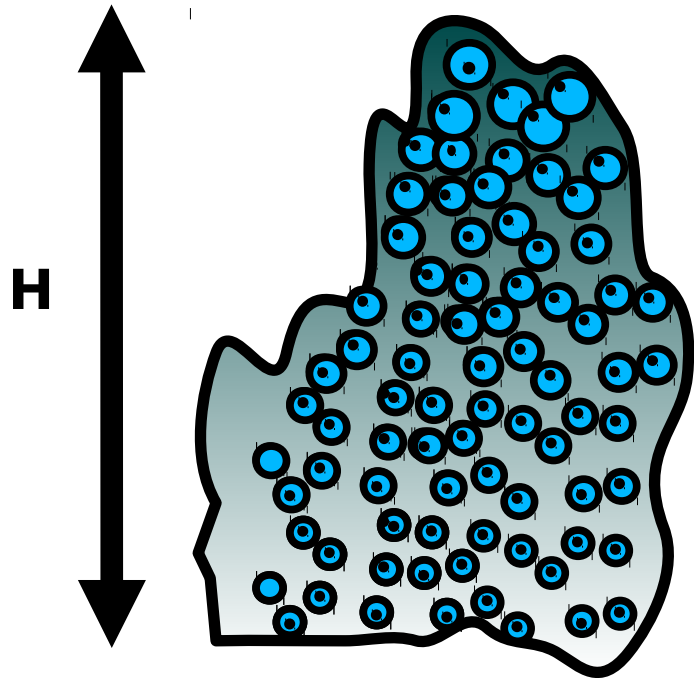
...examples from our group in Leipzig...

Radiative forcing due to aerosol-cloud interactions

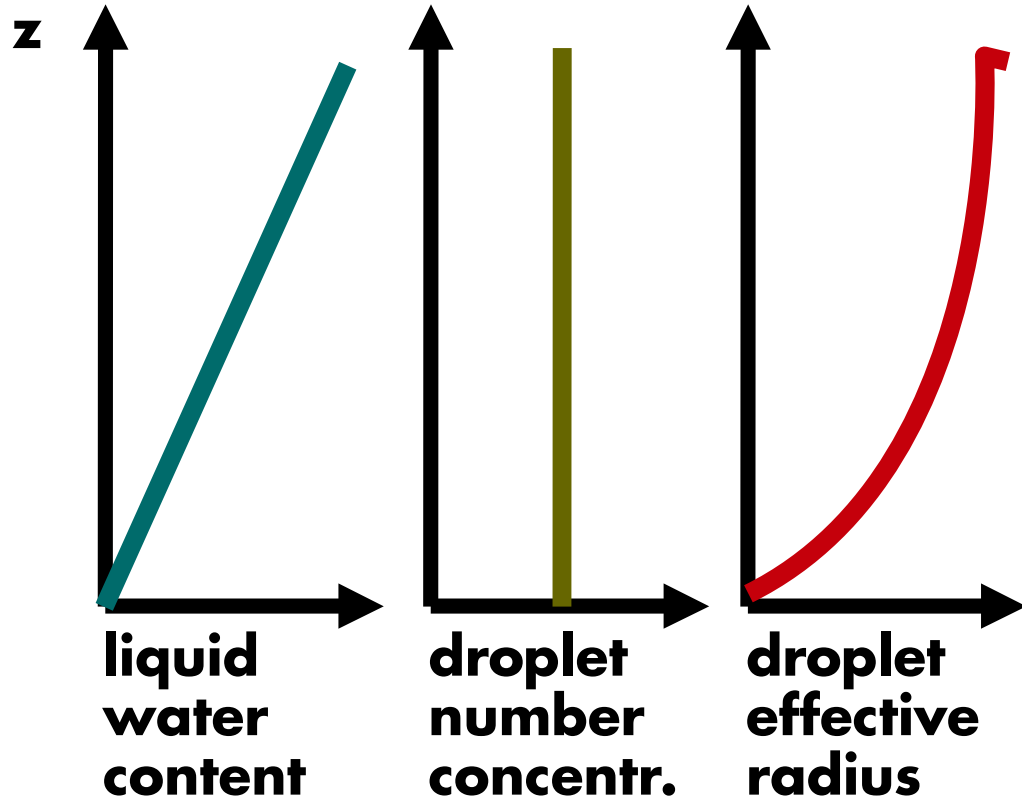
Forcing	Radiation	Cloud particles	Aerosol perturbation
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$$\Delta F_{\text{aci}} = \frac{dR}{d \ln N_c} \cdot \frac{d \ln N_c}{d \ln \alpha} \cdot \Delta \ln \alpha_{\text{ant}}$$

Droplet concentration retrieval



adiabatic cloud

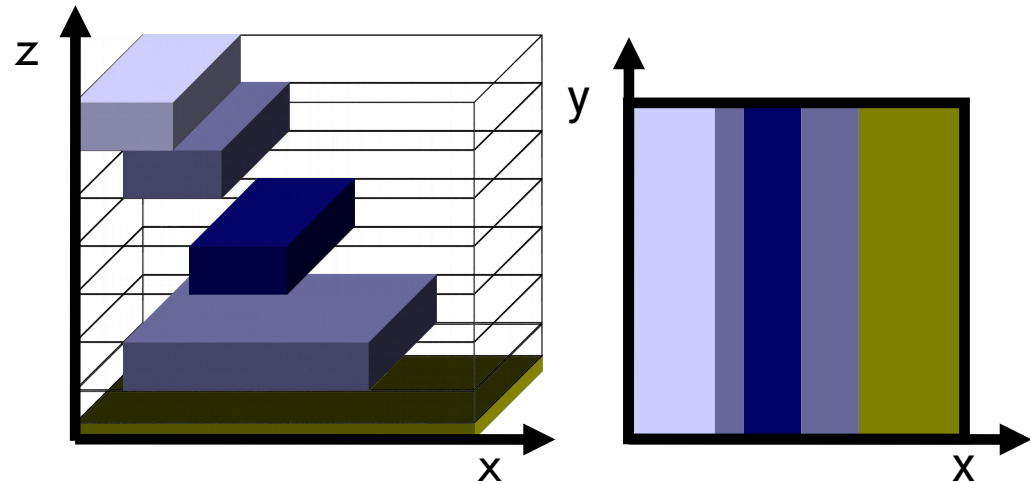


$$N_d \sim \tau_c^{0.5} r_e^{-2.5}$$

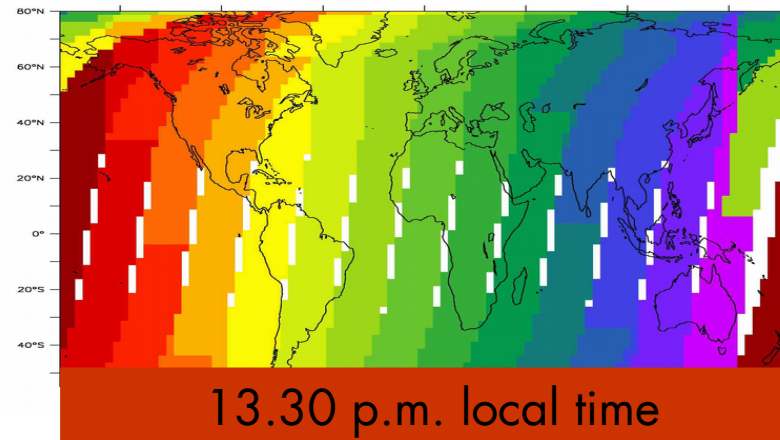
N_d from adiabatic assumption and Nakajima + King J. Atmos. Sci. 1996

Simple “satellite simulator”

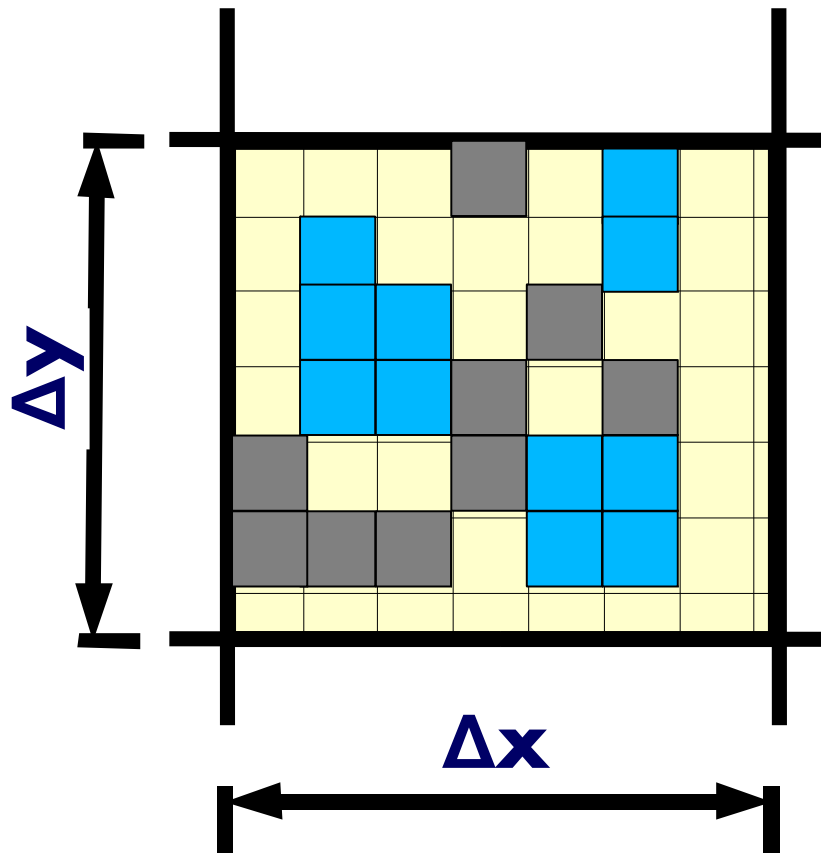
- 2D cloud top quantities from 3D cloud field using overlap assumption



- Sampling of daily fields at satellite overpass time
- Visible clouds only ($\tau_c > 0.3$)



Constructing an aerosol-cloud interaction metric



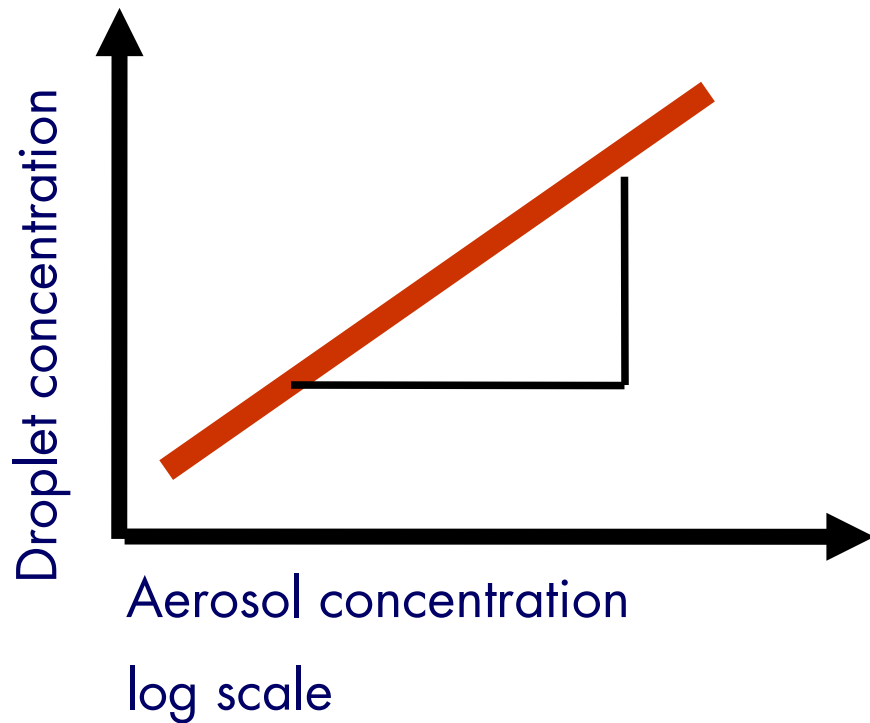
- Aerosol measurements
- Cloud measurements
- No retrieval

Method adopted:

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

$\Delta x / \Delta y$: model resolution
here: $2.5^\circ \times 2.5^\circ$

Constructing an aerosol-cloud interaction metric

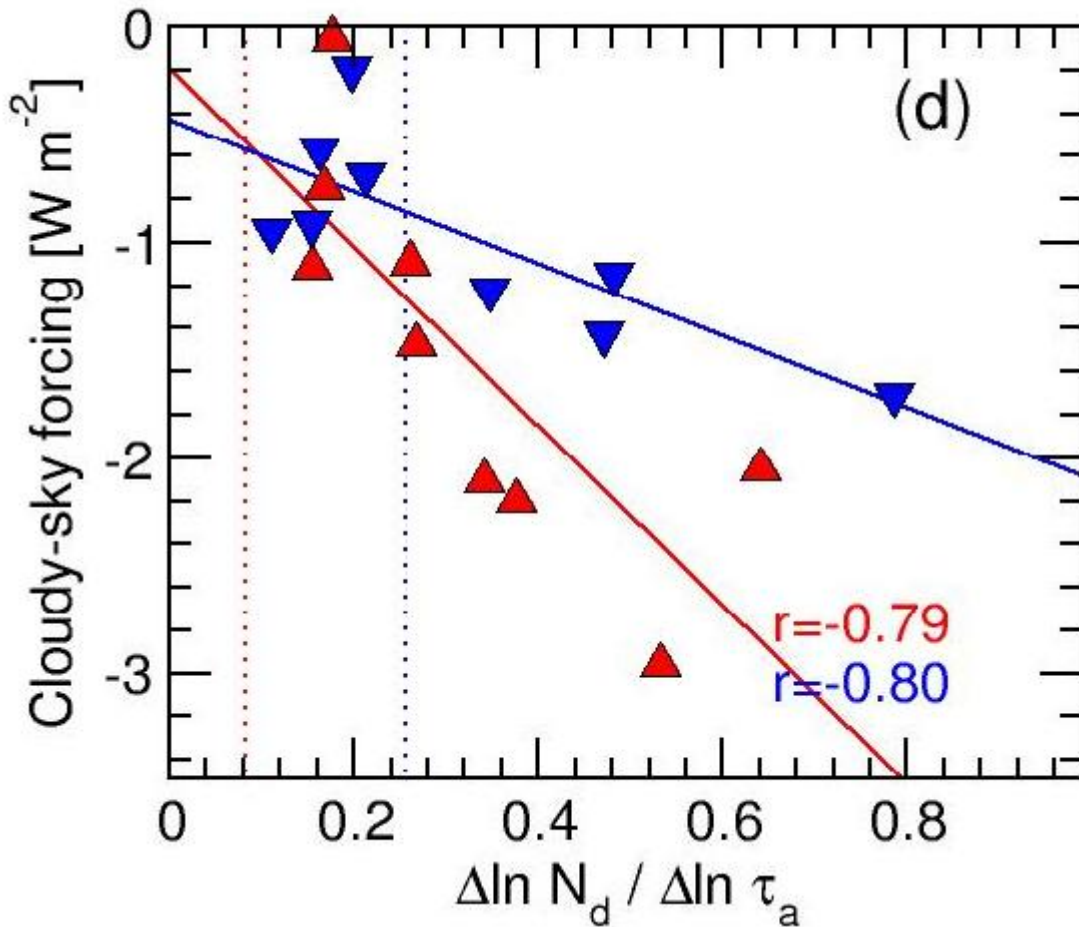


Slope of regression as metric for effect:

$$\frac{d \ln N_d}{d \ln \tau_a} = \frac{\Delta N_d / N_d}{\Delta \tau_a / \tau_a}$$

τ_a – aerosol optical depth

"ACI metric" $dN_c / \ln a$ as emergent constraint



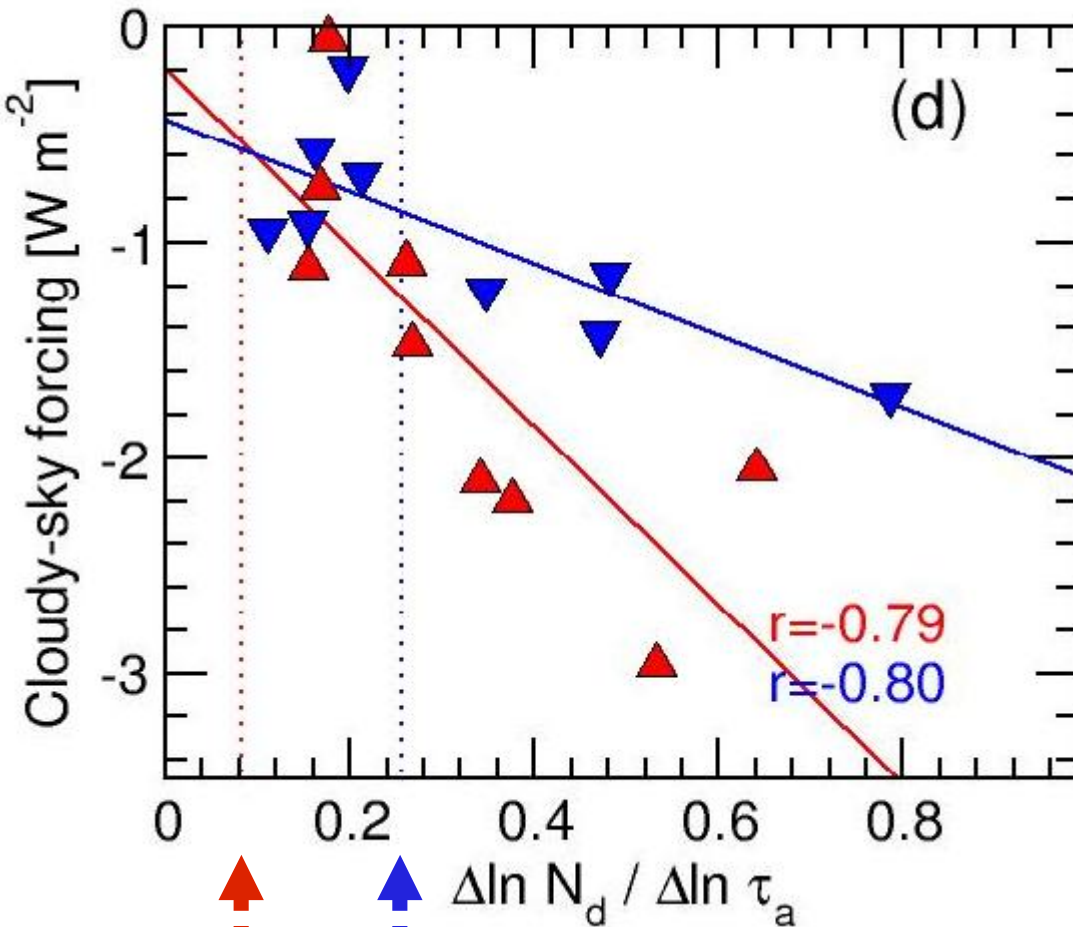
land

ocean

Different climate models
AEROCOM initiative

Cloudy-sky effective
radiative forcing
vs. ACI metric

“ACI metric” $dN_c / \ln a$ as emergent constraint



▼ land
▲ ocean

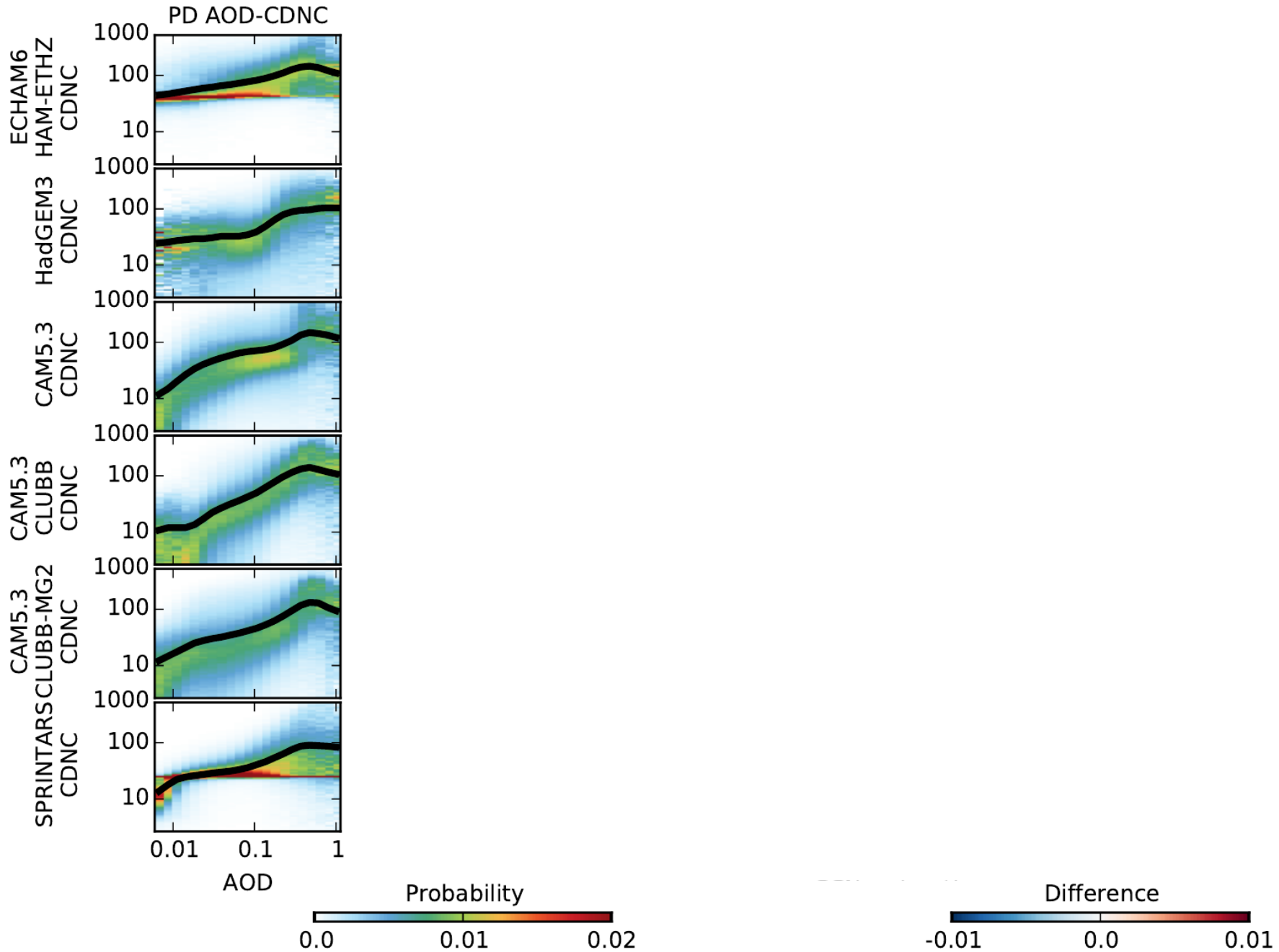
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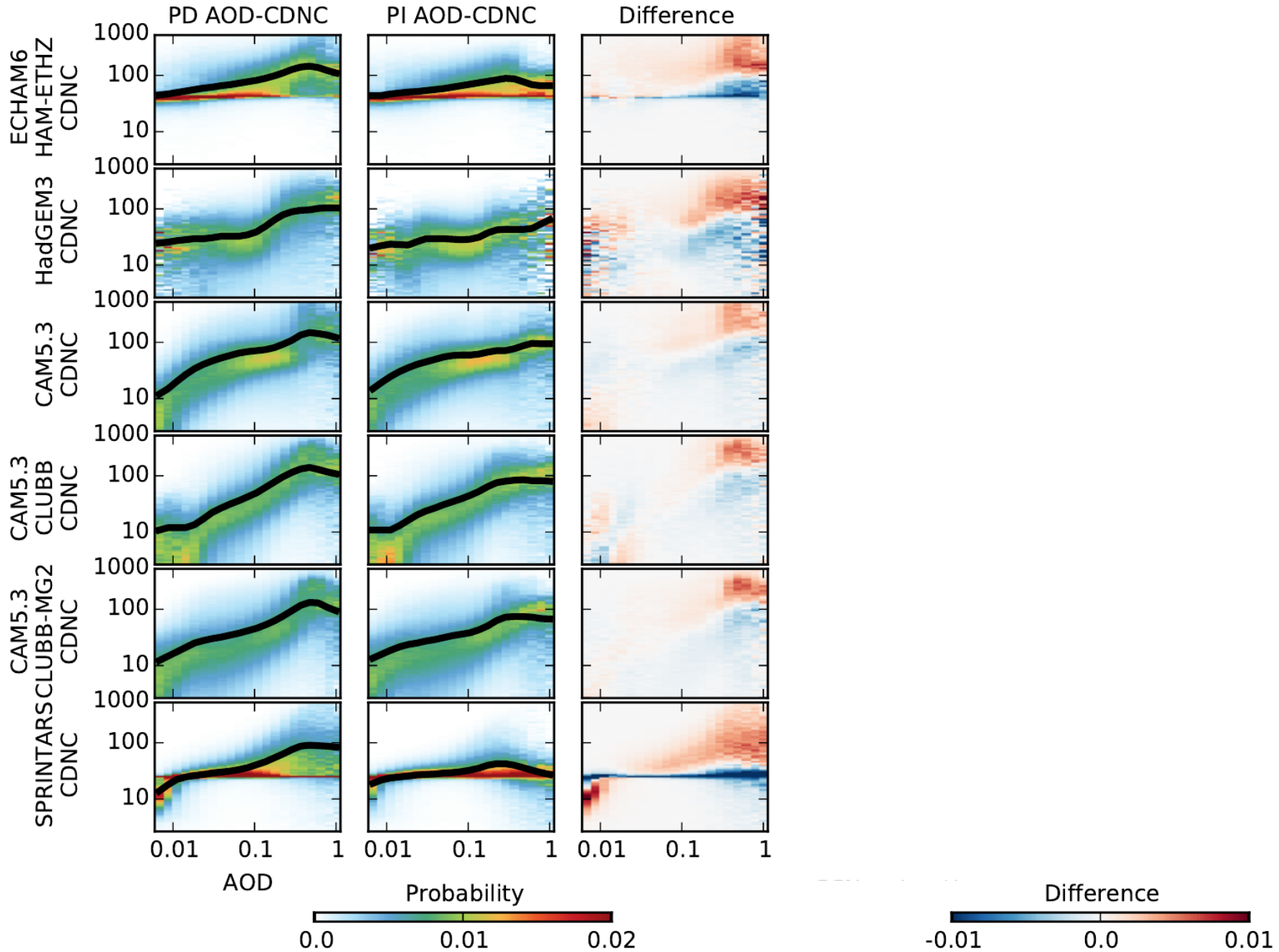
↑
↑
MODIS estimates
land and ocean

estimate	modelled	scaled
clear	-0.3	-0.4 Wm^{-2}
cloudy	-1.1	-0.7 Wm^{-2}
total	-1.5	-1.2 Wm^{-2}

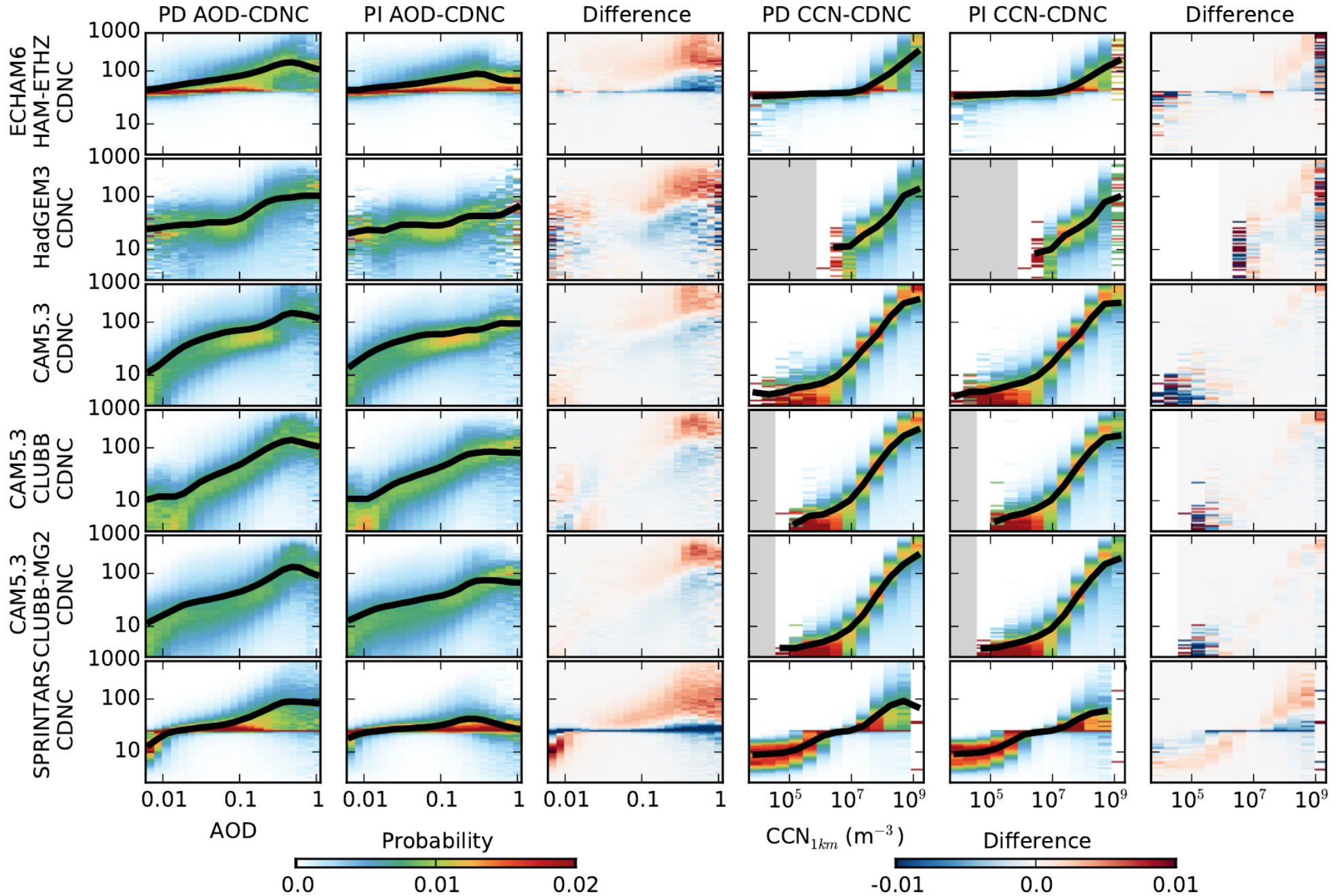
Usefulness of joint histograms and additional aerosol information



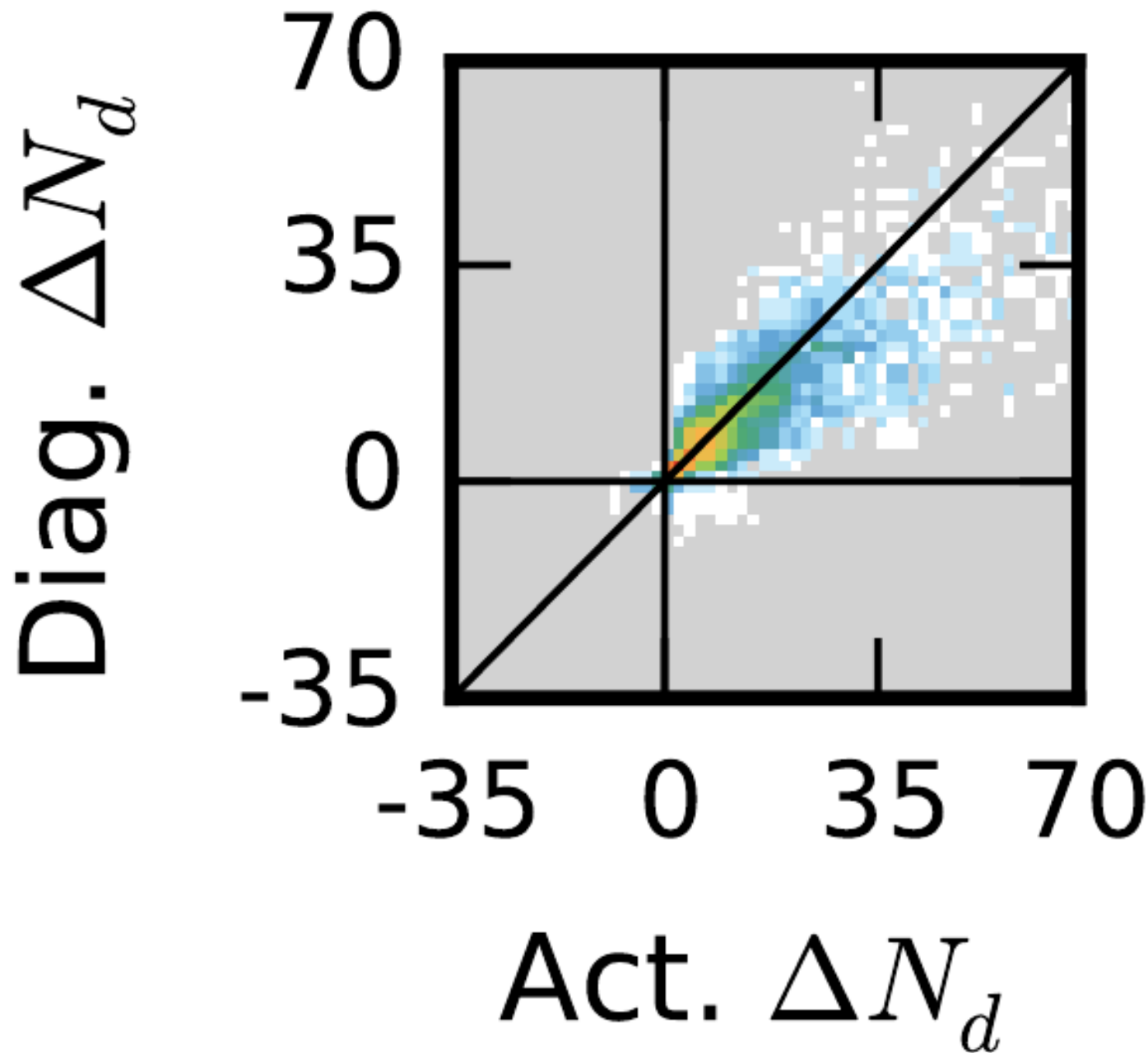
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Usefulness of joint histograms



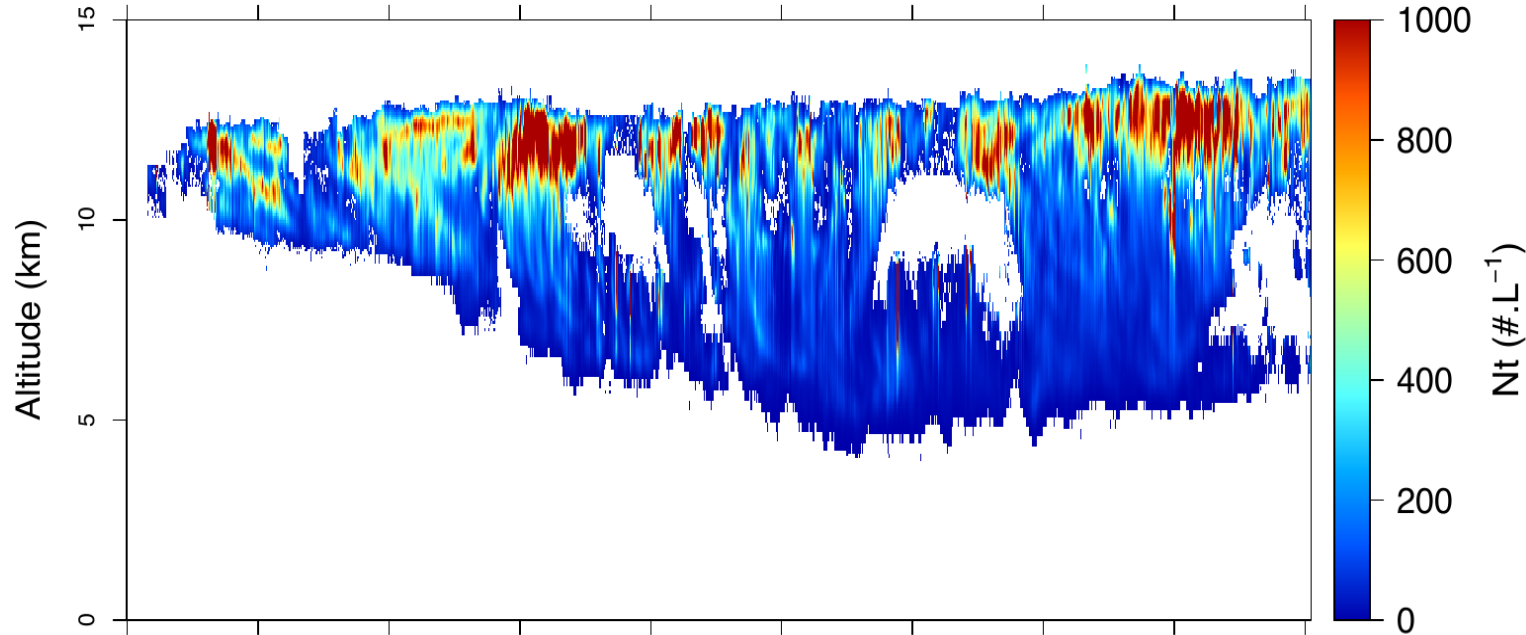
What about ice clouds? - *Ice crystal number concentration*



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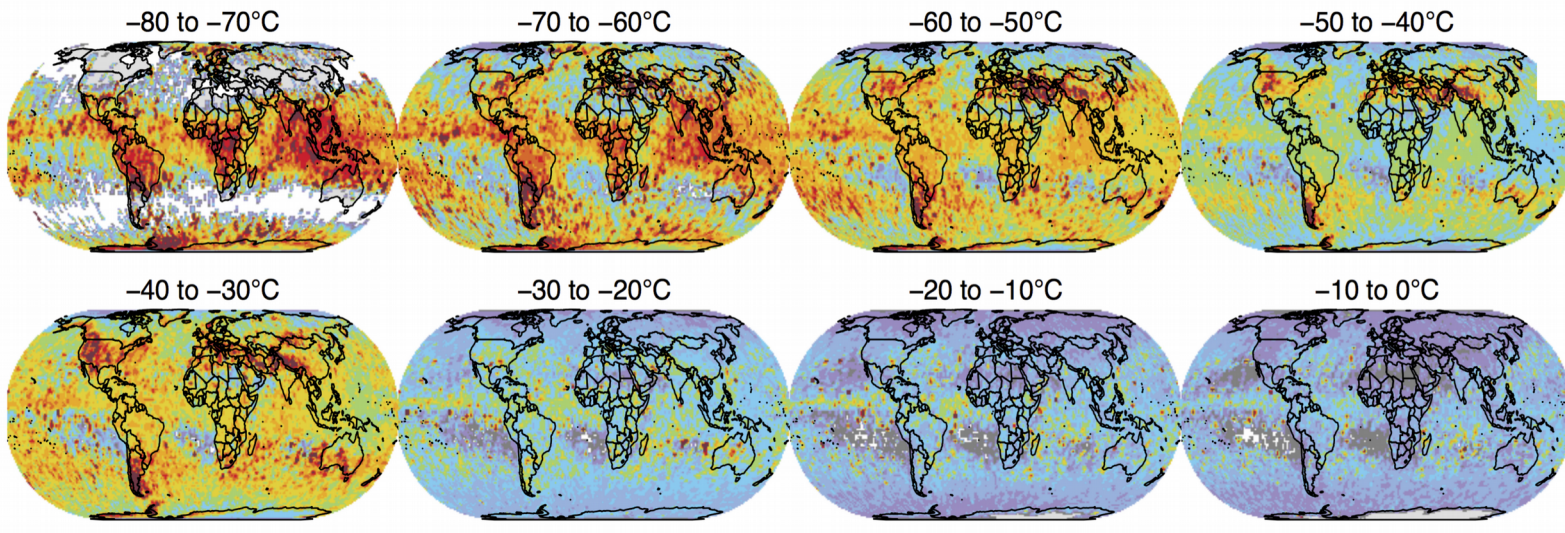
Time (UTC)

03:30:40 03:31:00 03:31:20 03:31:40 03:32:00 03:32:20 03:32:40 03:33:00 03:33:20 03:33:40



Based on Cloudsat
raDAR – CALIPSO
LiDAR (DARDAR)

← vertical profile
example



Isothermal
geographical
distribution

Conclusions

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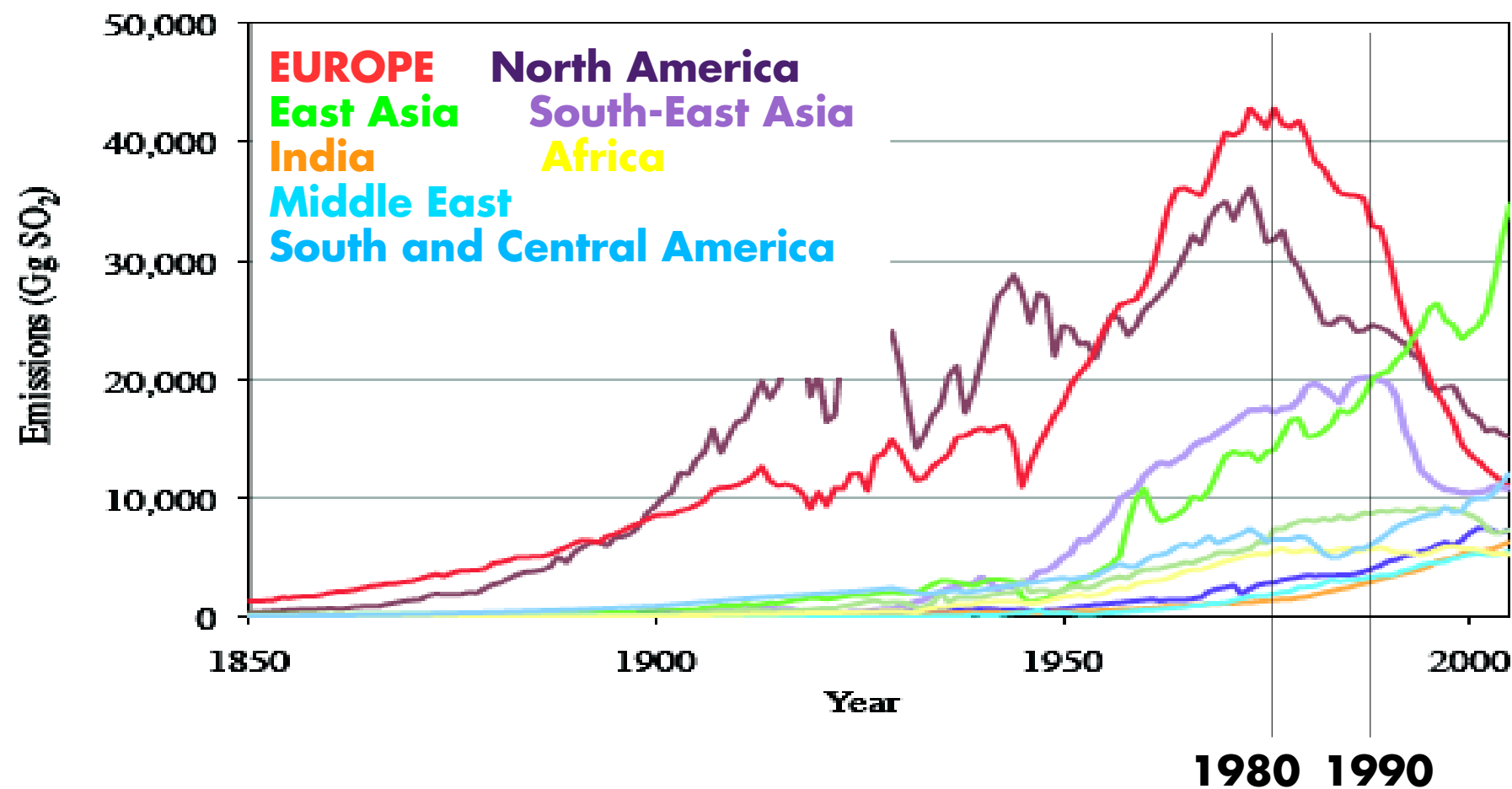
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Strong trends in anthropogenic aerosol emissions

Global Anthropogenic SO₂ Emissions



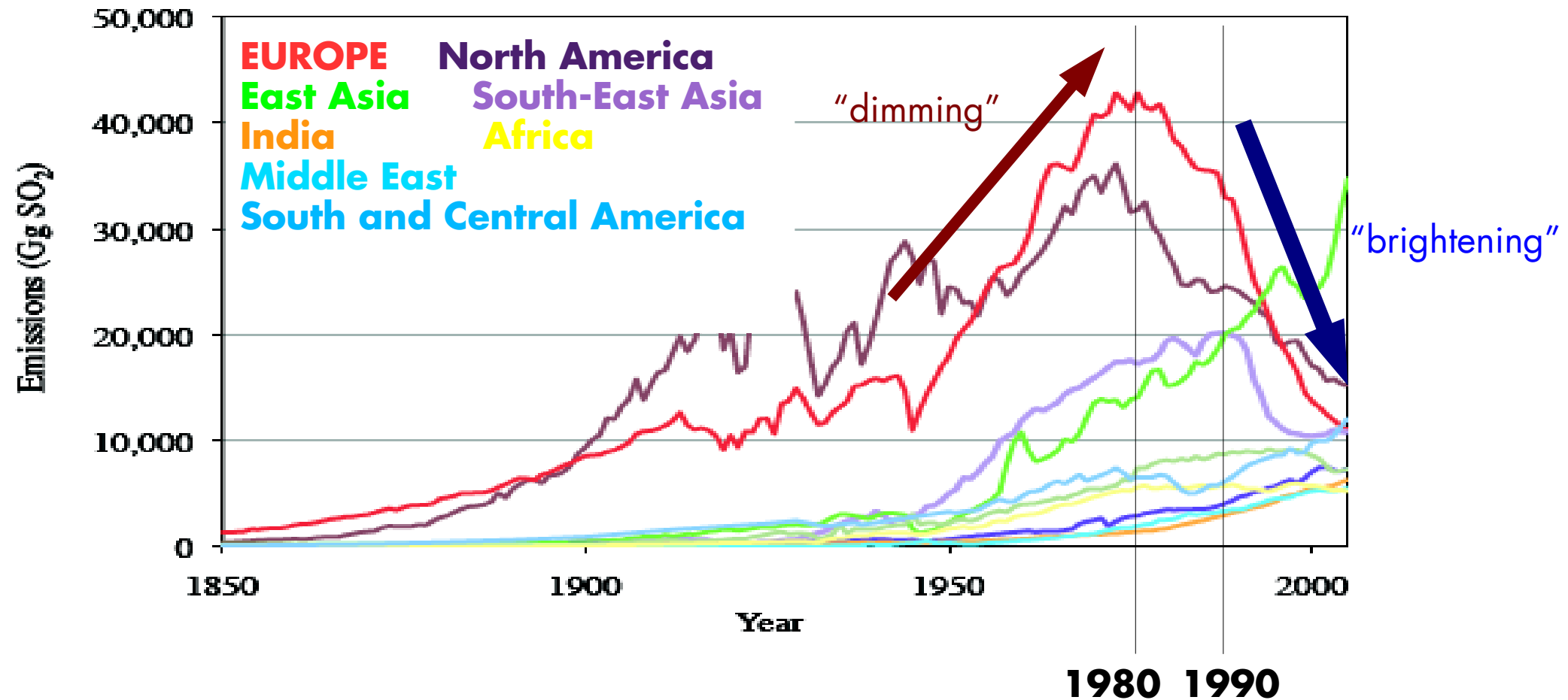
Smith et al., Atmos. Chem. Phys. 2011

Strong trends in anthropogenic aerosol emissions

Focus on Europe

- "Fall of the wall" 1989 with economic restructuring in Eastern Europe
- Implementation of air quality legislation in Western Europe

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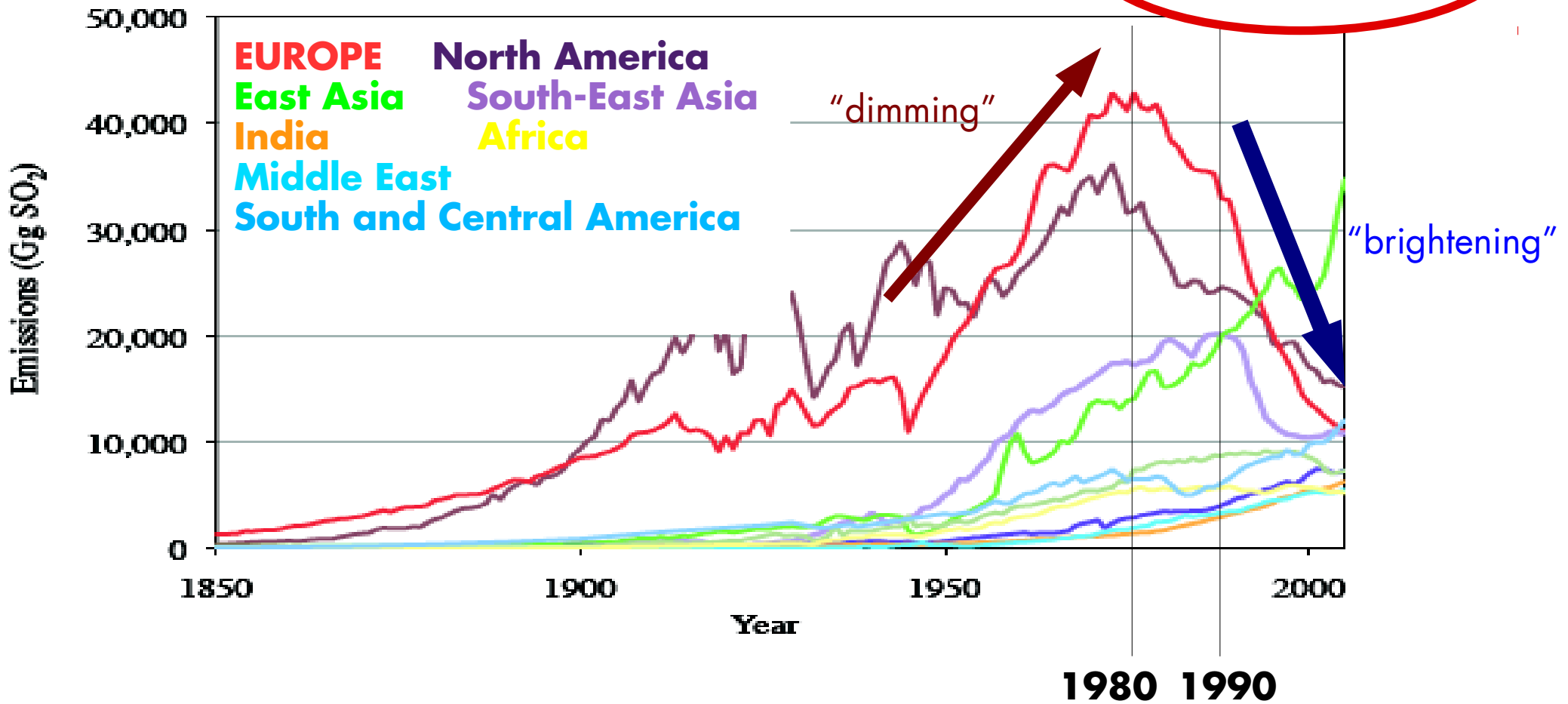
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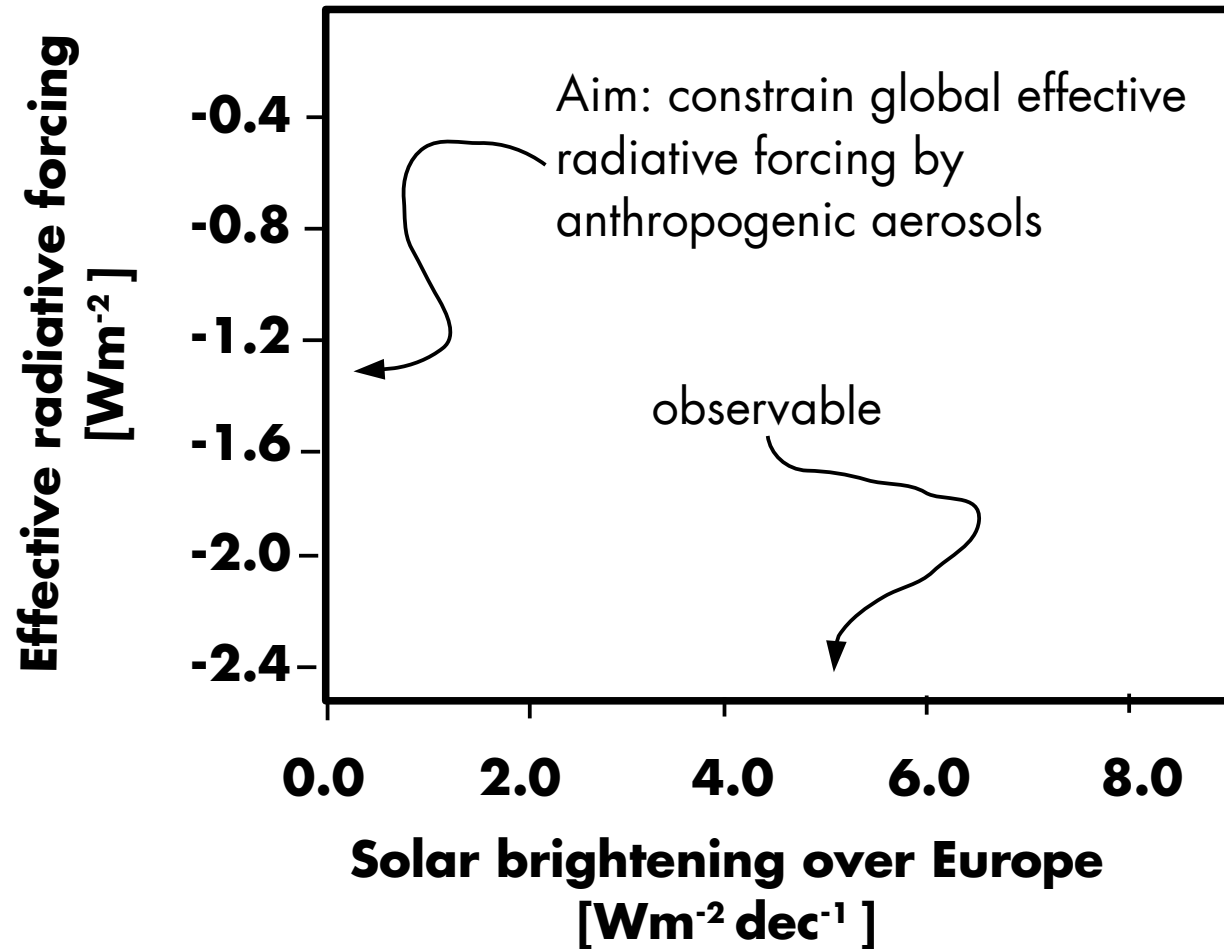
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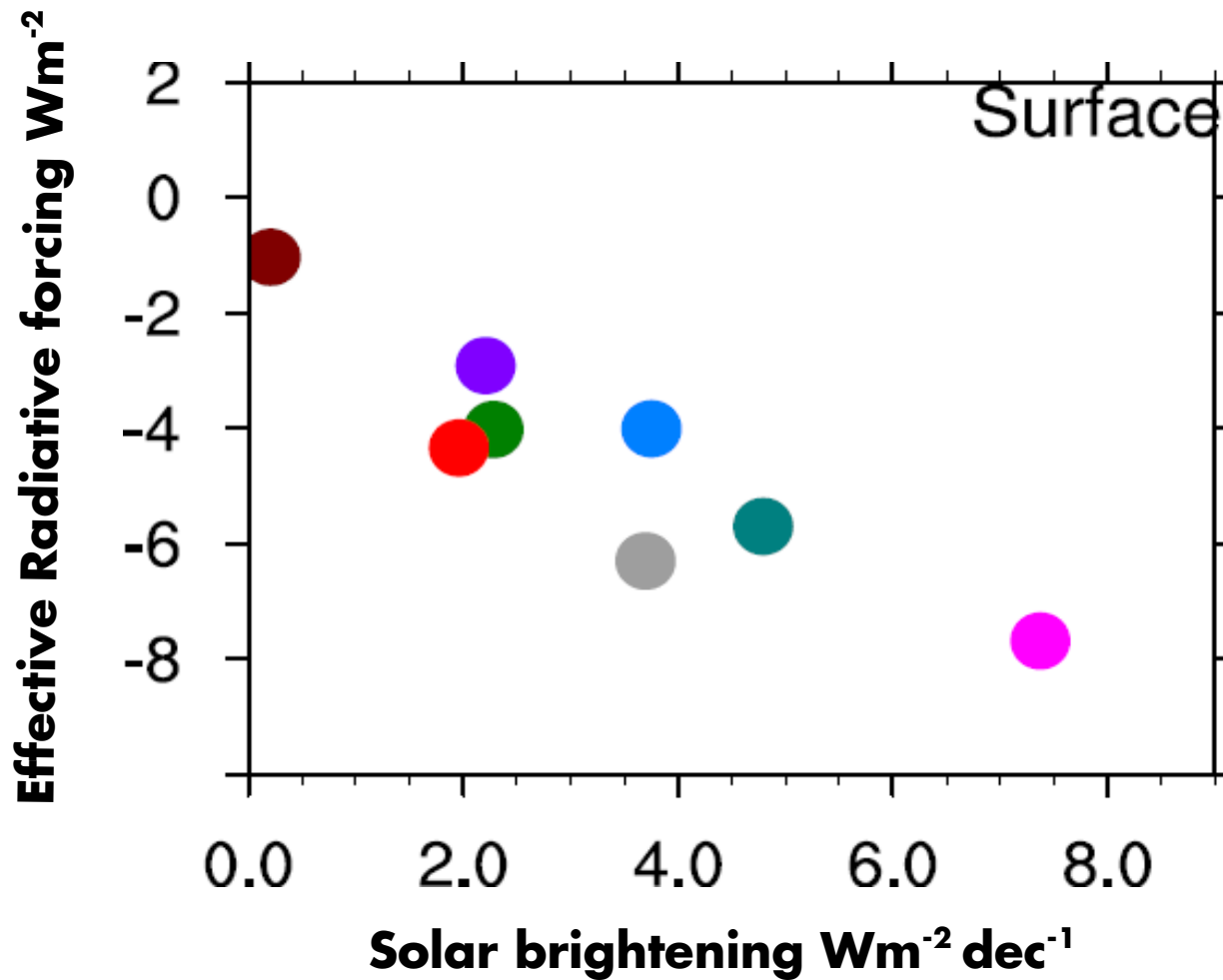
1990 - 2005



Link to effective aerosol radiative forcing



Effective forcing at the surface over continental Europe

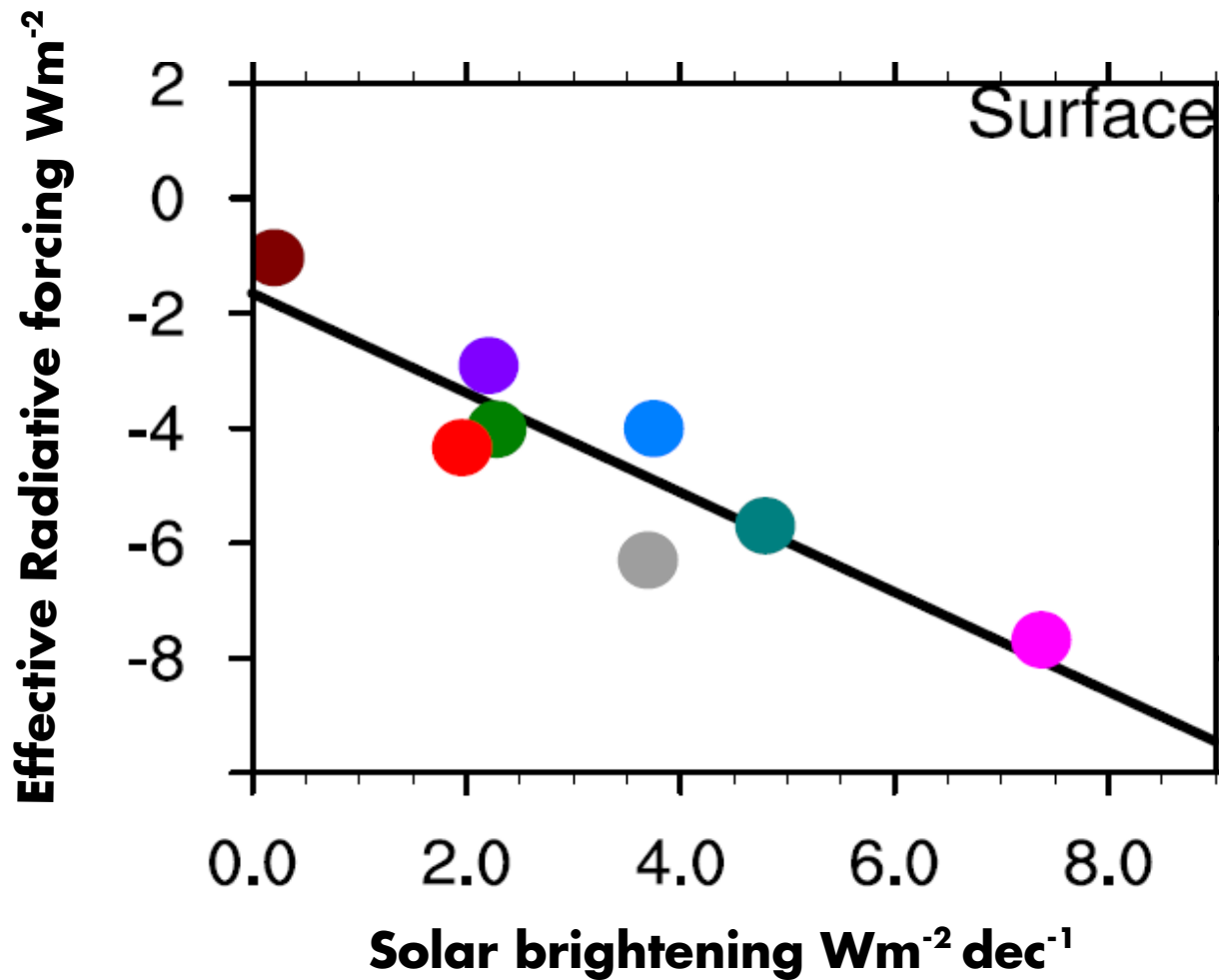


CMIP5 models

- Brightening trend 1990 – 2005
- sampled at GEBA stations
- from “historical” simulation

- Effective forcing from “SSTClimAerosol” - “SSTClim” simulations

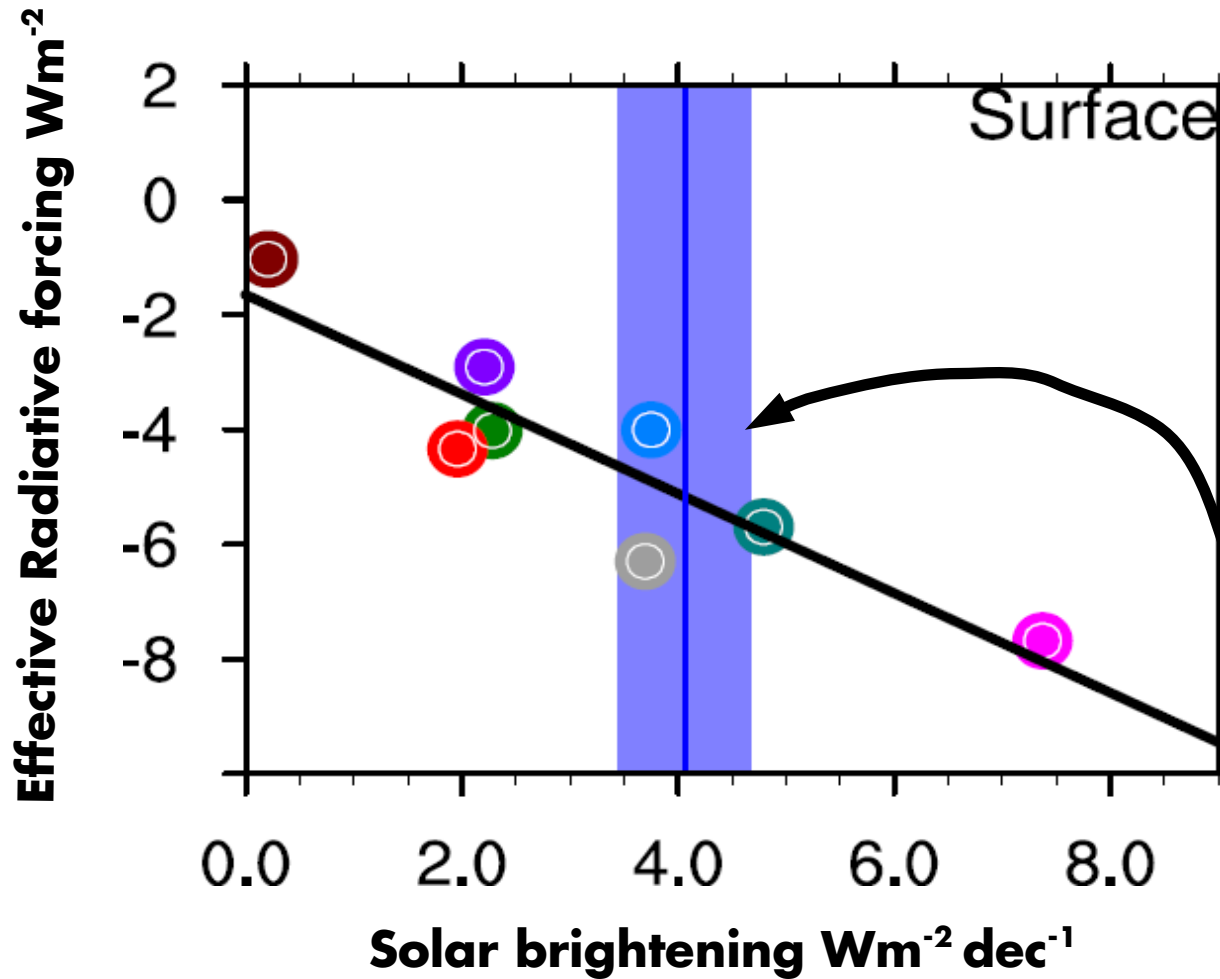
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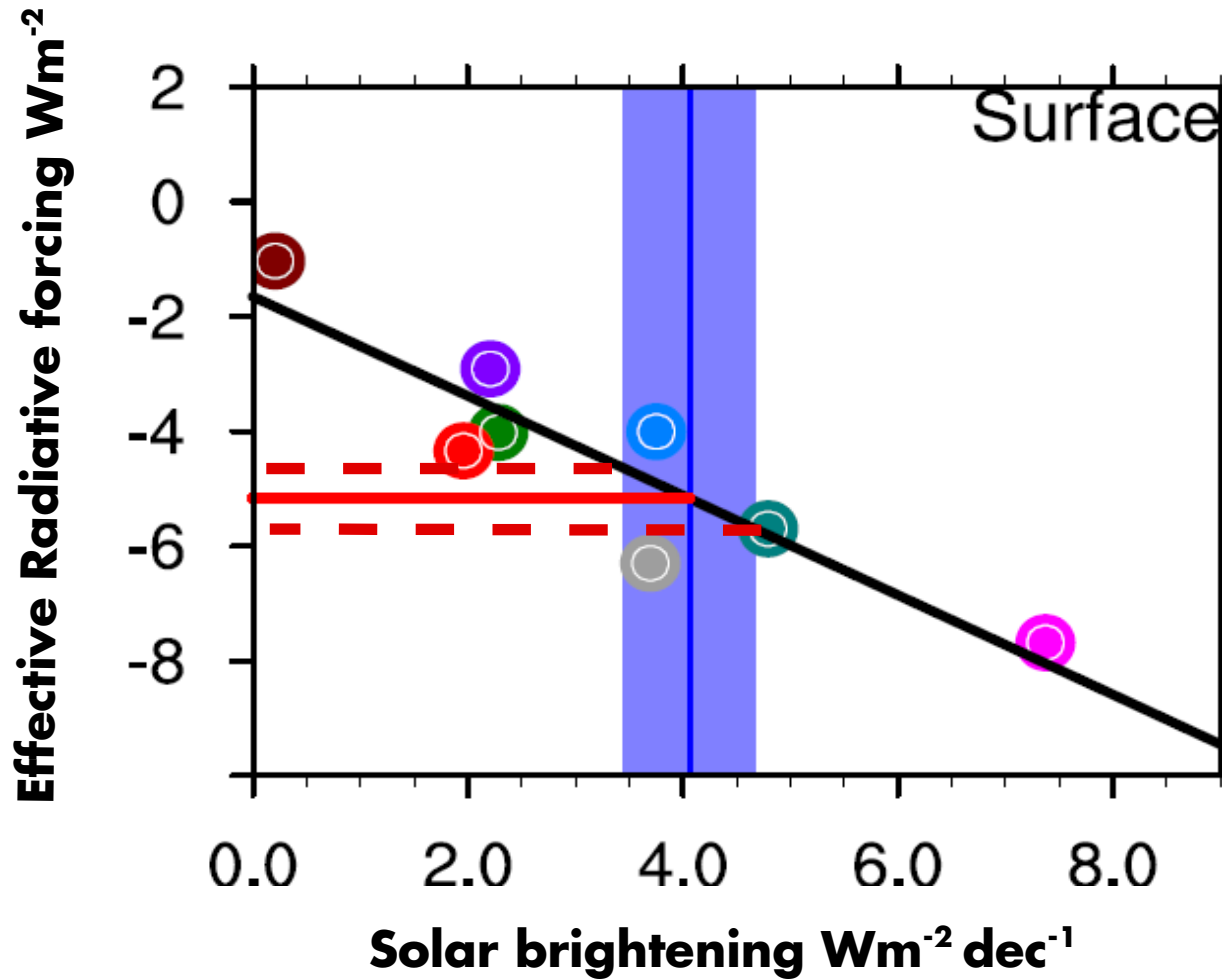
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- all-sky surface solar radiation
- statistical uncertainty (standard deviation of regression slope plus variation of start/end year of regression)

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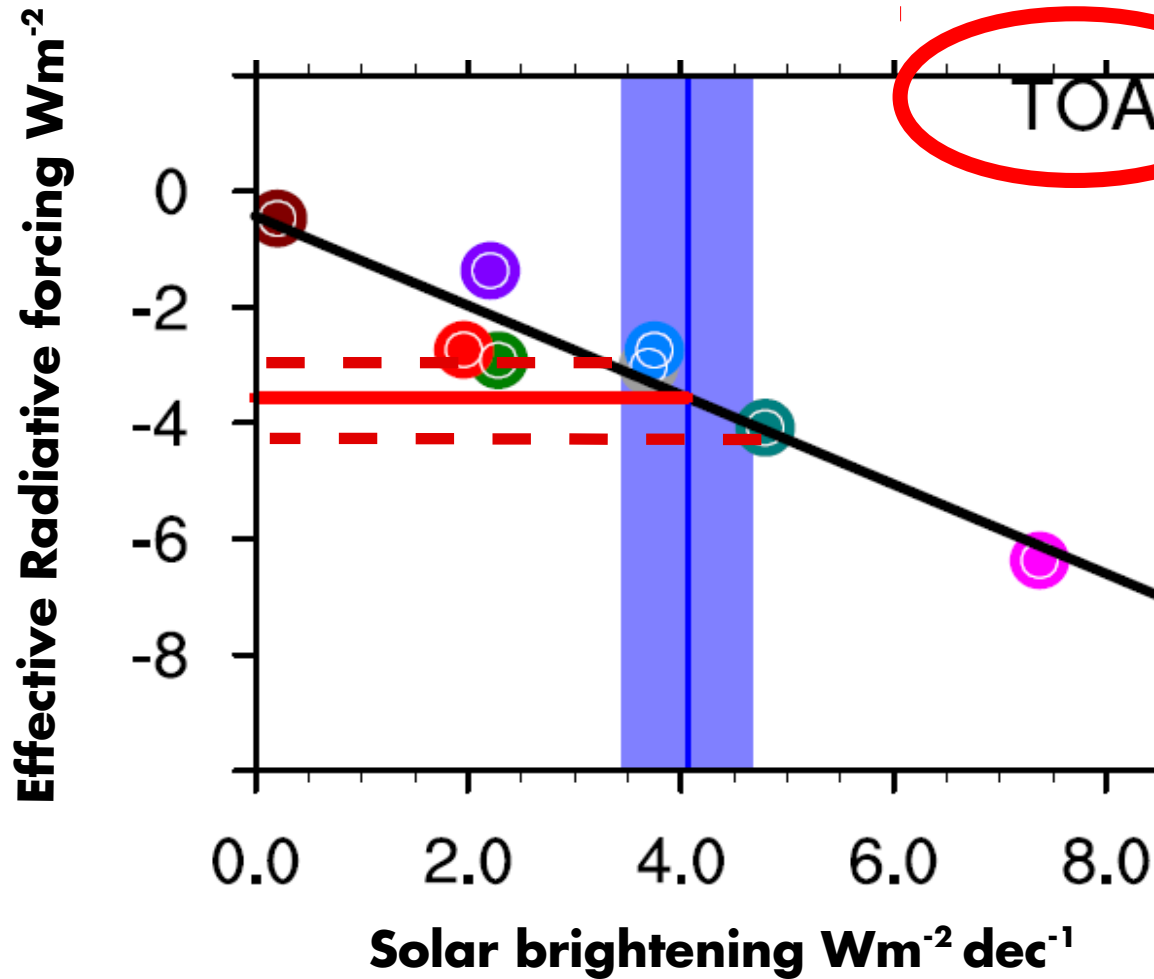
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Constrain effective forcing

- over Europe
- at surface
- **$-5.2 \pm 1.6 \text{ Wm}^{-2}$**

Effective forcing at the surface over continental Europe



→ **top-of-atmosphere Europe: $-3.6 \pm 1.4 \text{ Wm}^{-2}$**

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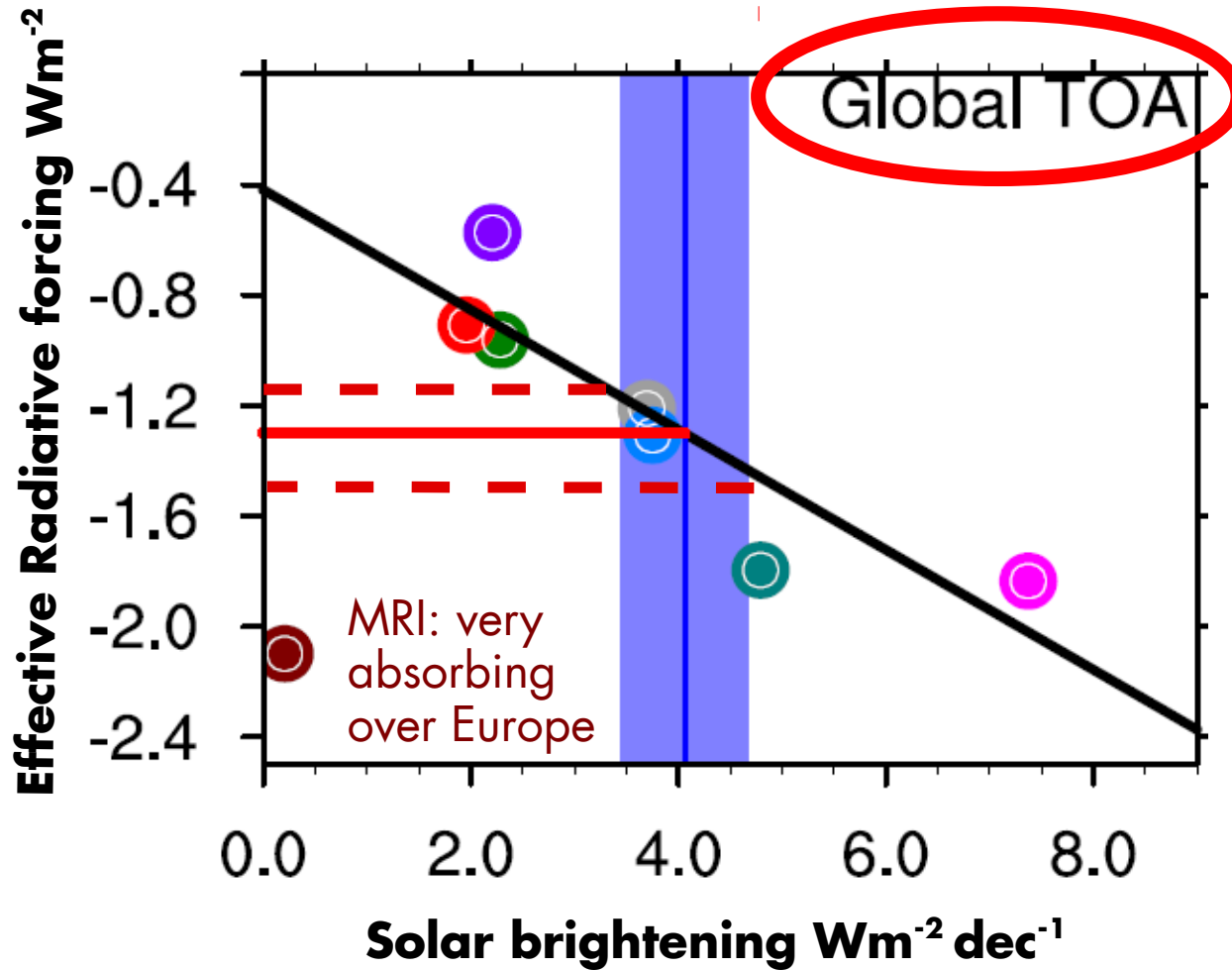
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Effective forcing at the surface over continental Europe



- **top-of-atmosphere Europe: $-3.6 \pm 1.4 \text{ Wm}^{-2}$**
- **global effective forcing: $-1.3 \pm 0.4 \text{ Wm}^{-2}$**

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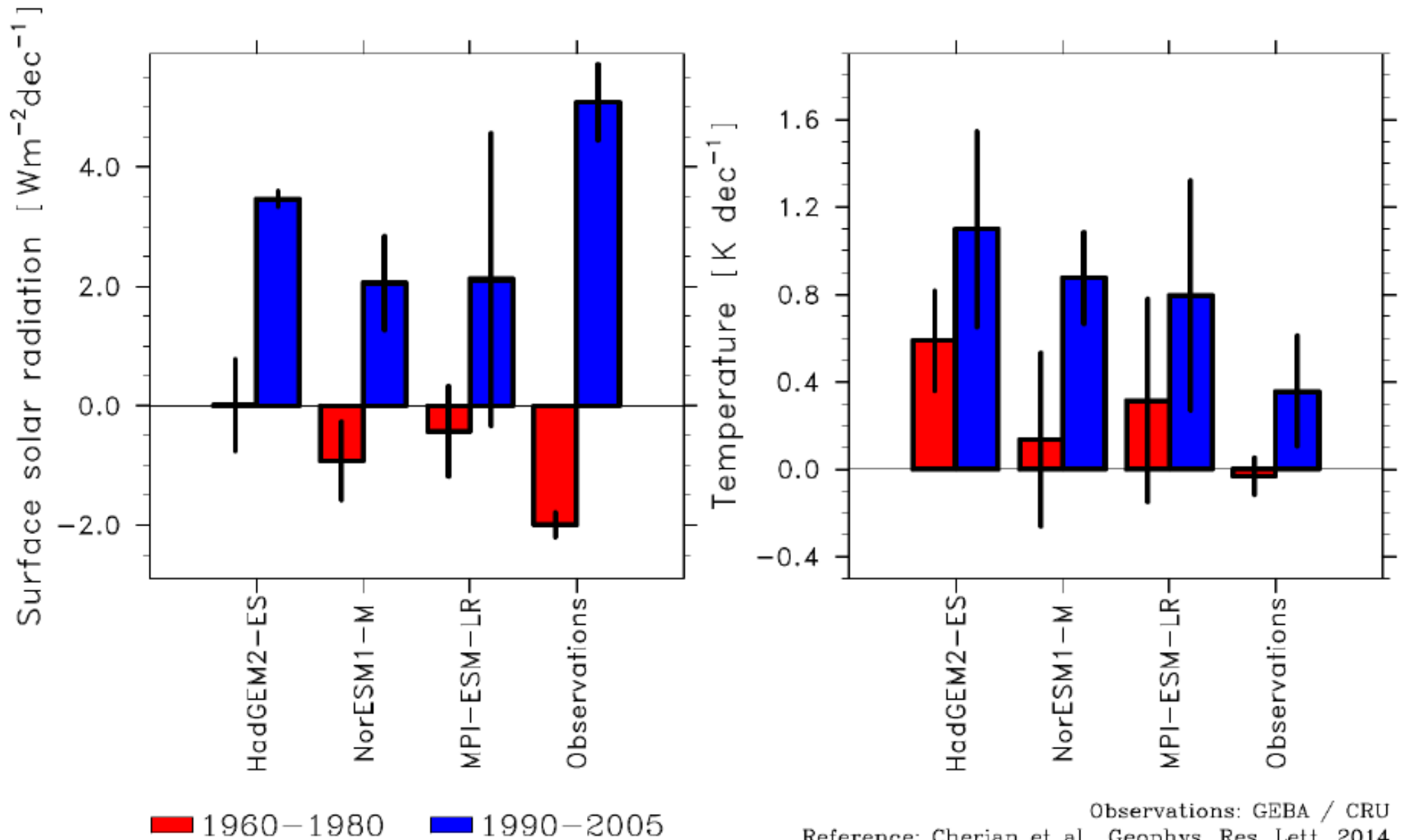
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Building confidence in climate models to simulate policy scenarios



Conclusions

■ Need for appropriate retrievals

- cloud particle number concentration (liquid and ice)
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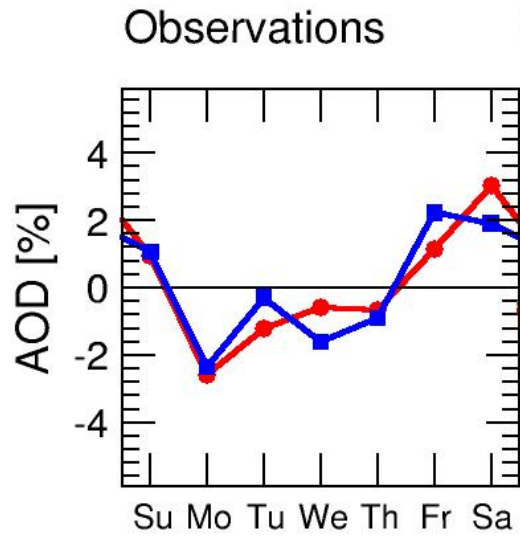
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- both are useful
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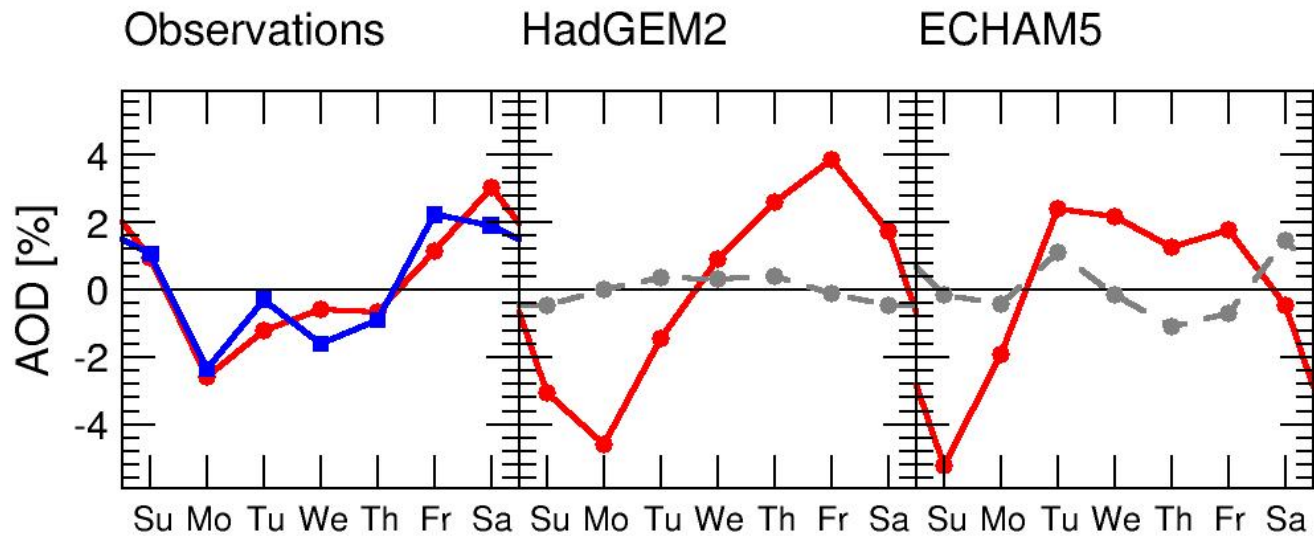
Weekly cycle



MODIS Terra
MODIS Aqua

Continental Europe
03/2000 – 03/2008 data

Weekly cycle

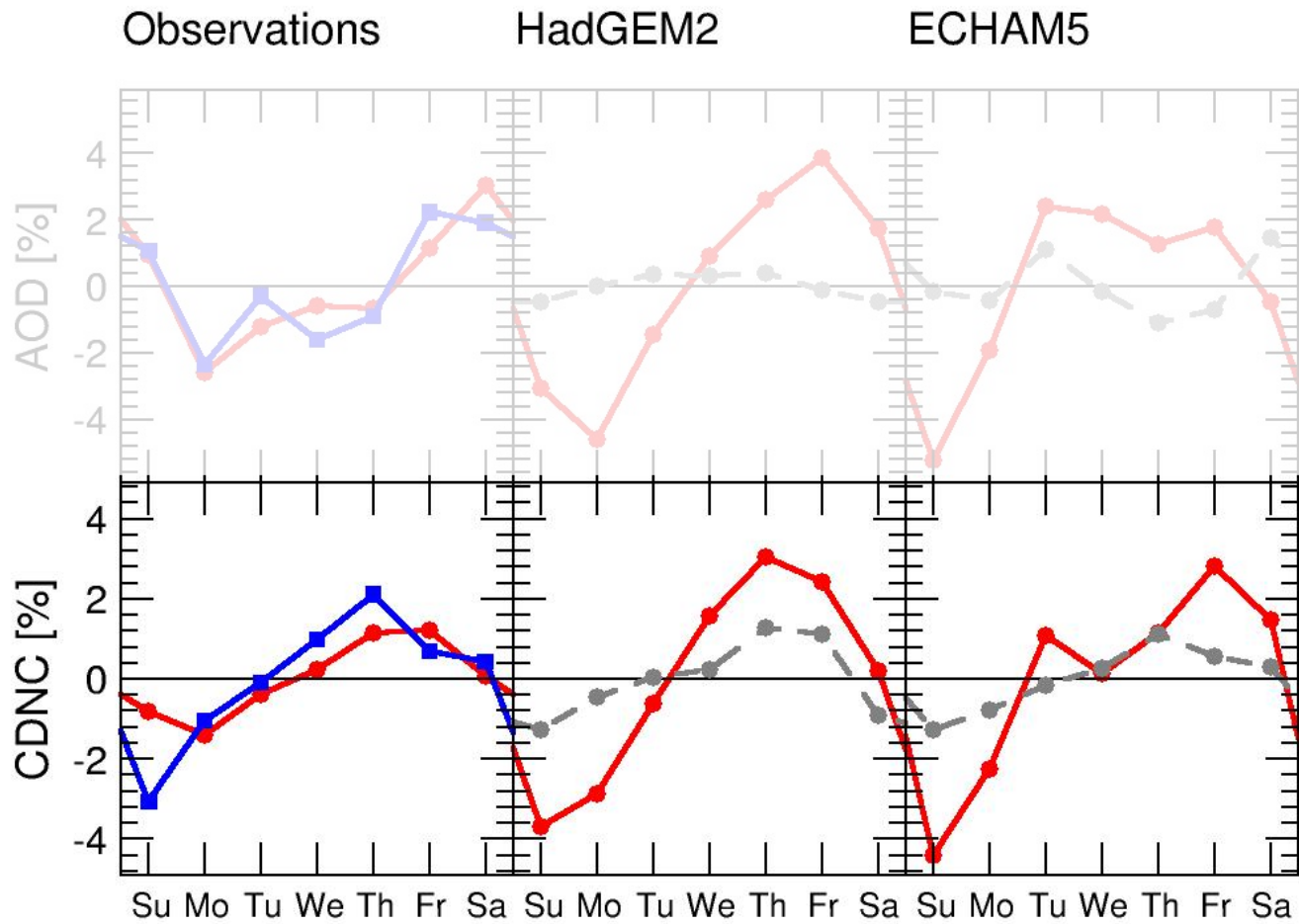


MODIS Terra
MODIS Aqua

Model experiment
Model control

Aerosol optical depth

Weekly cycle

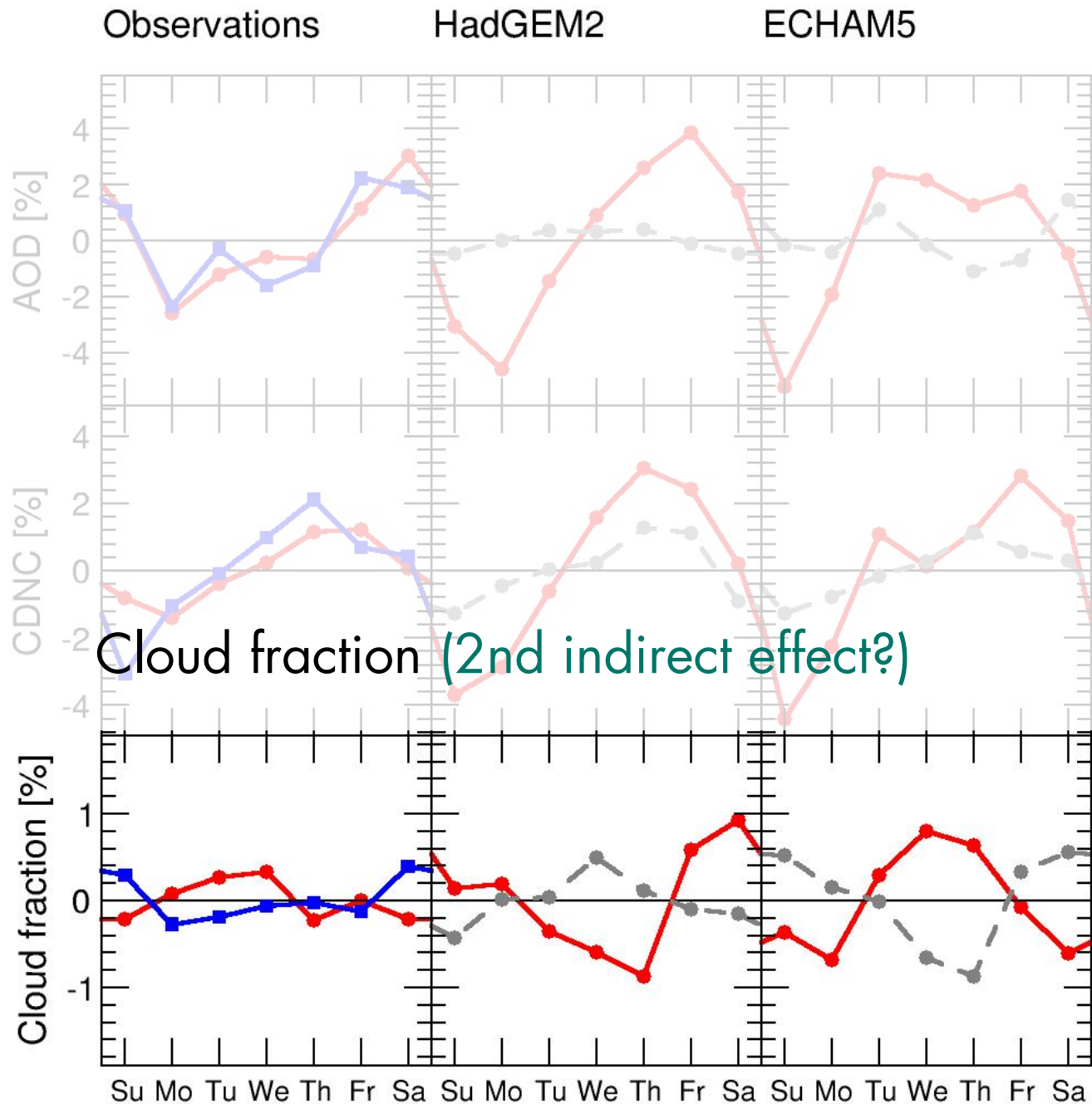


MODIS Terra
MODIS Aqua

Model experiment
Model control

Cloud droplet number concentration
(1st indirect aerosol effect)

Weekly cycle



MODIS Terra
MODIS Aqua

Model experiment
Model control

Cloud fraction (2nd indirect effect?)

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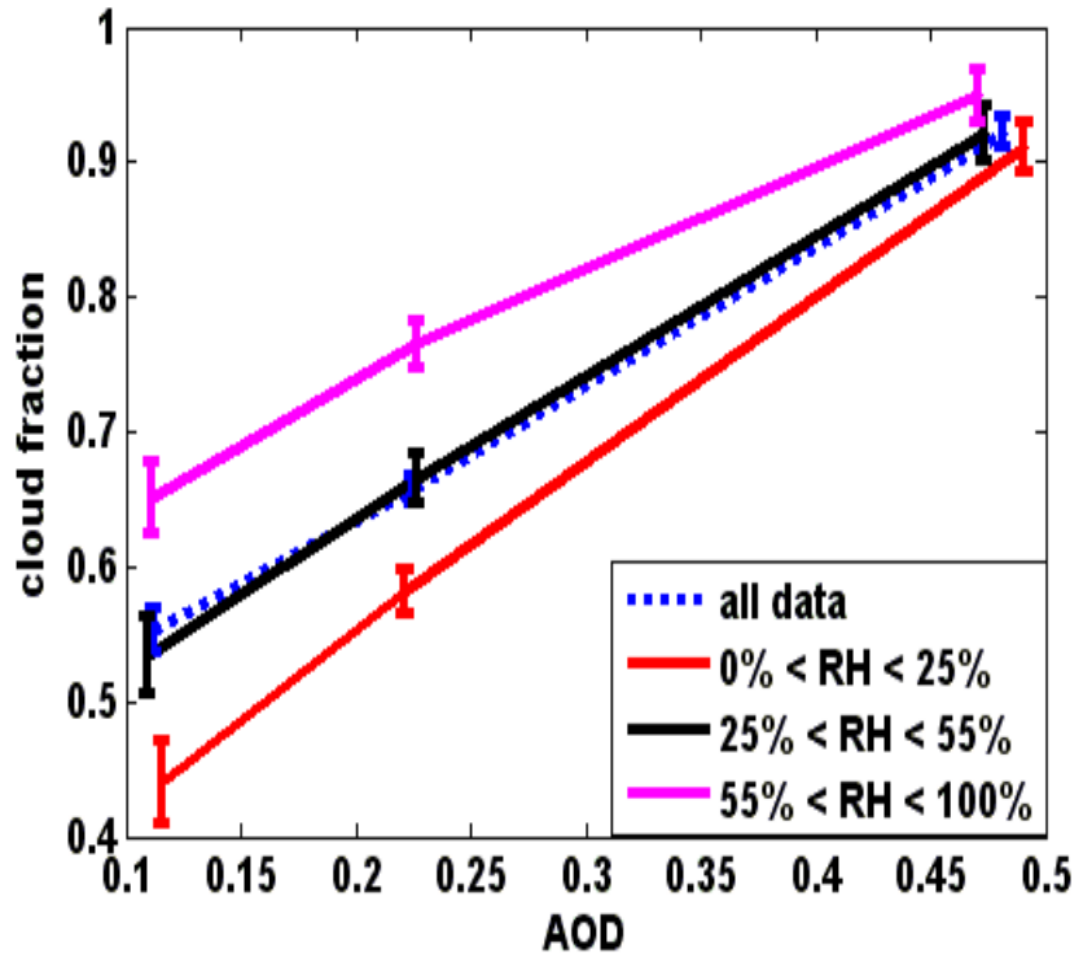
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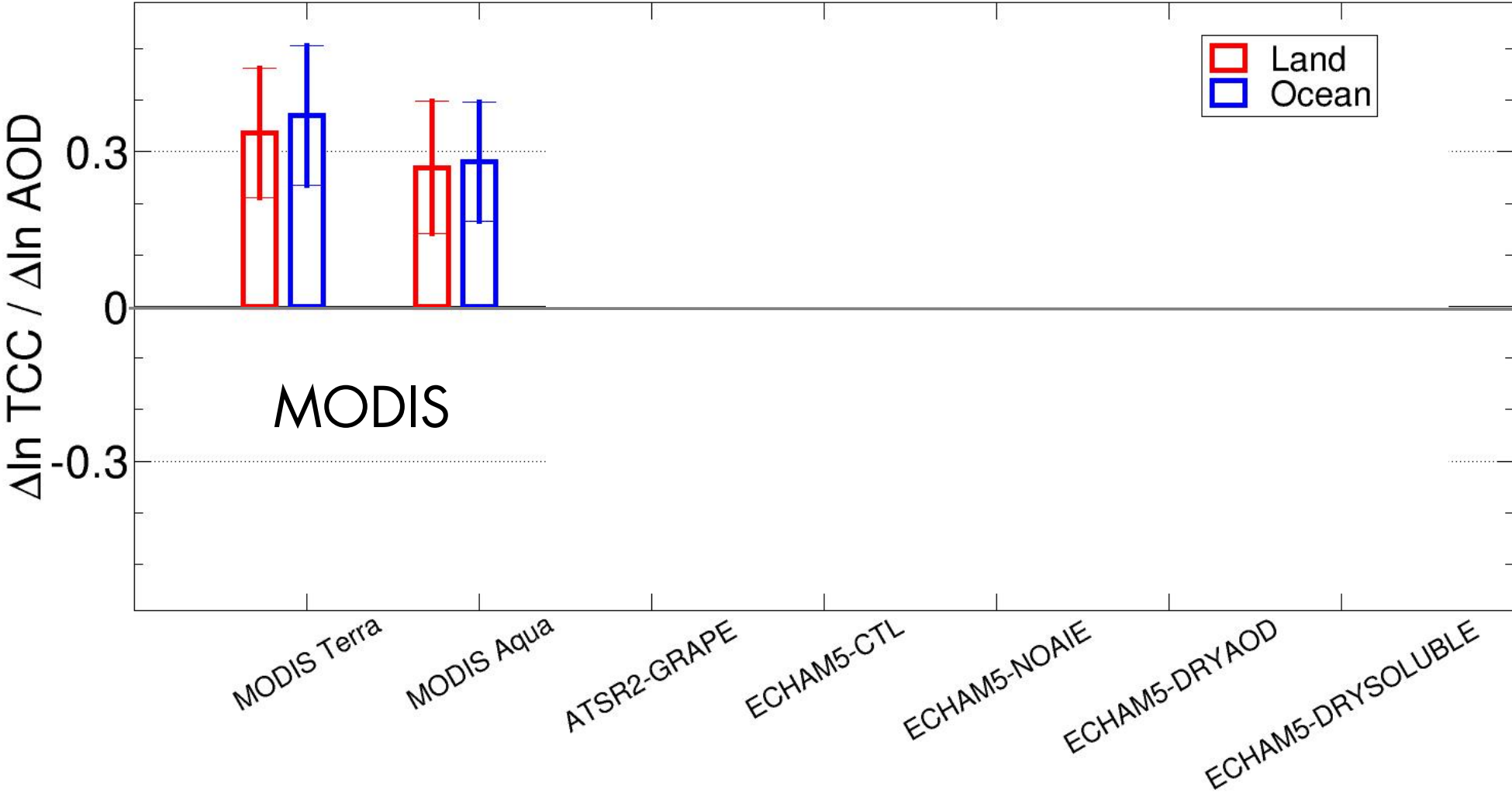


AOD – cloud + precipitation relationships

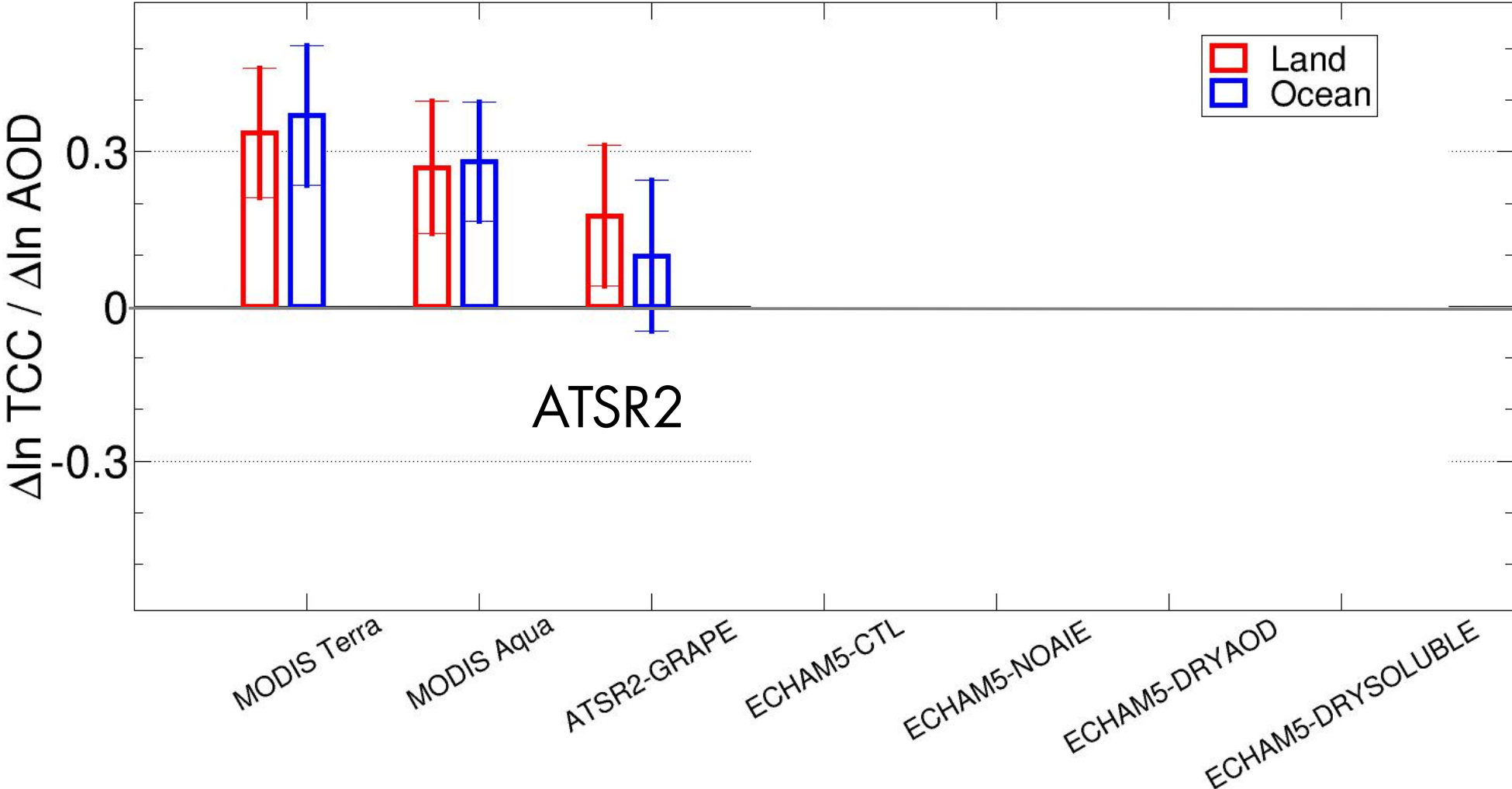


Strong cloud lifetime effect?

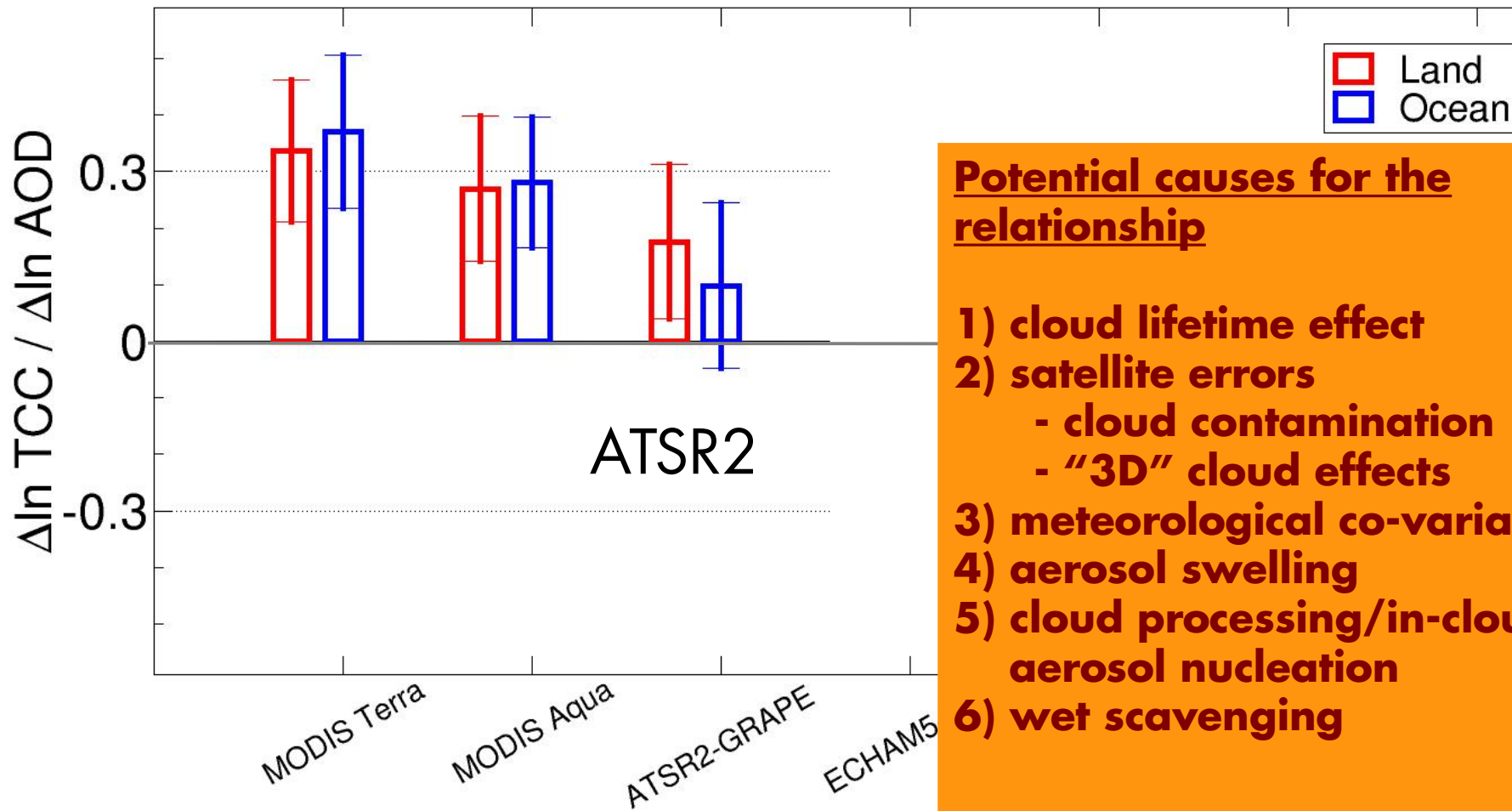
AOD - cloud cover relationship



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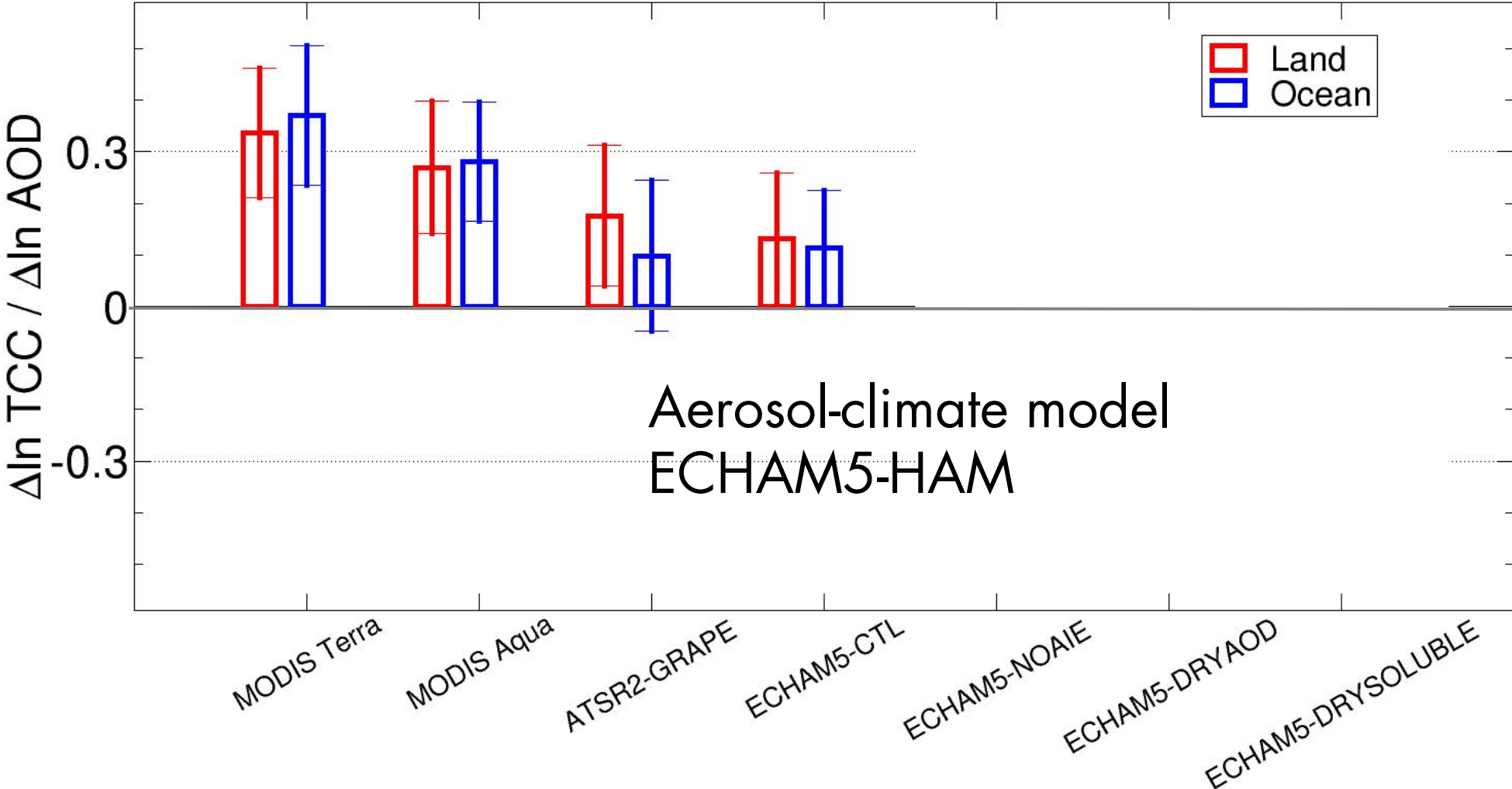
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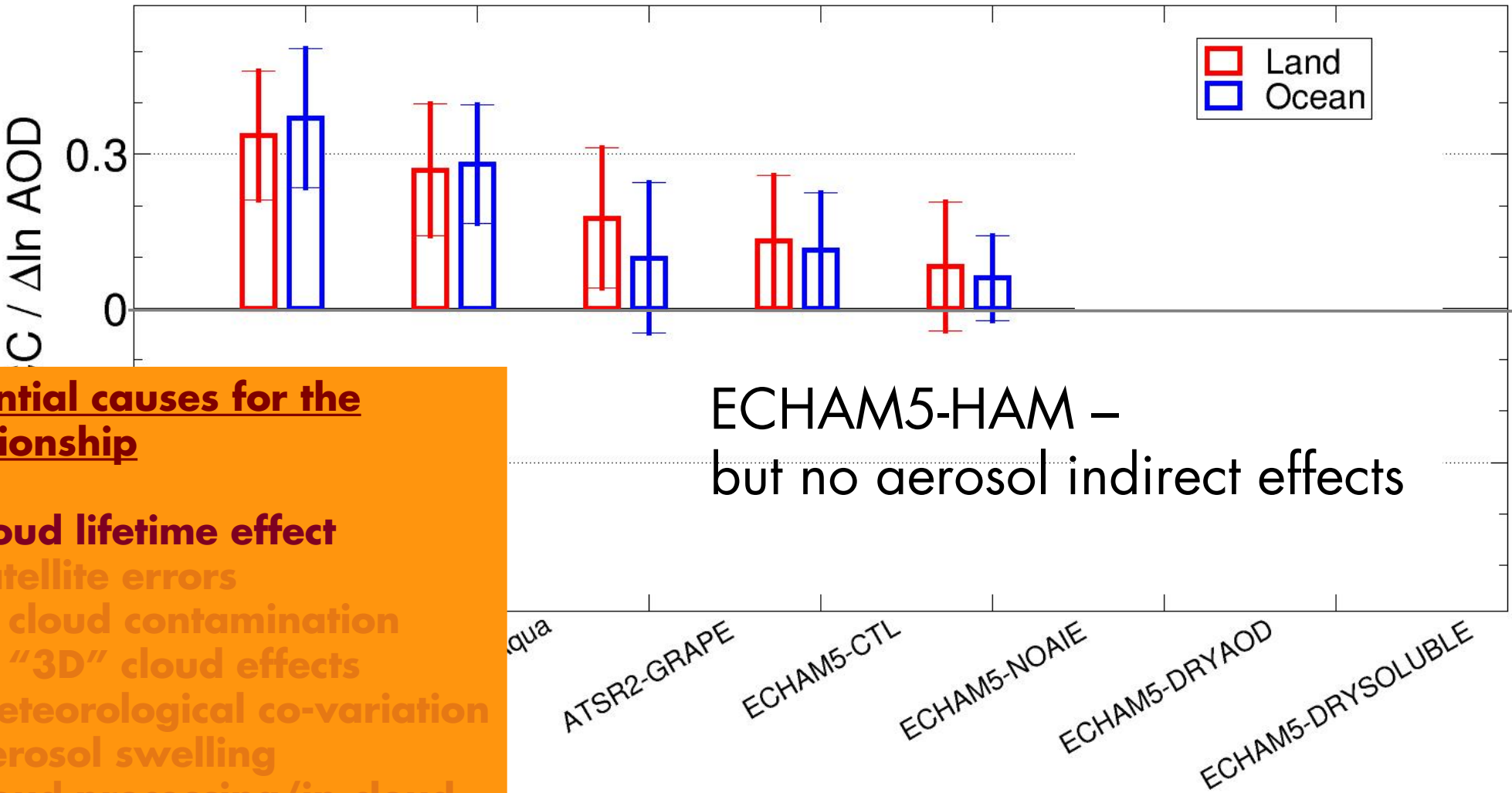
Potential causes for the relationship

- 1) cloud lifetime effect
- 2) satellite errors
 - cloud contamination
 - "3D" cloud effects
- 3) meteorological co-variation
- 4) aerosol swelling
- 5) cloud processing/in-cloud aerosol nucleation
- 6) wet scavenging

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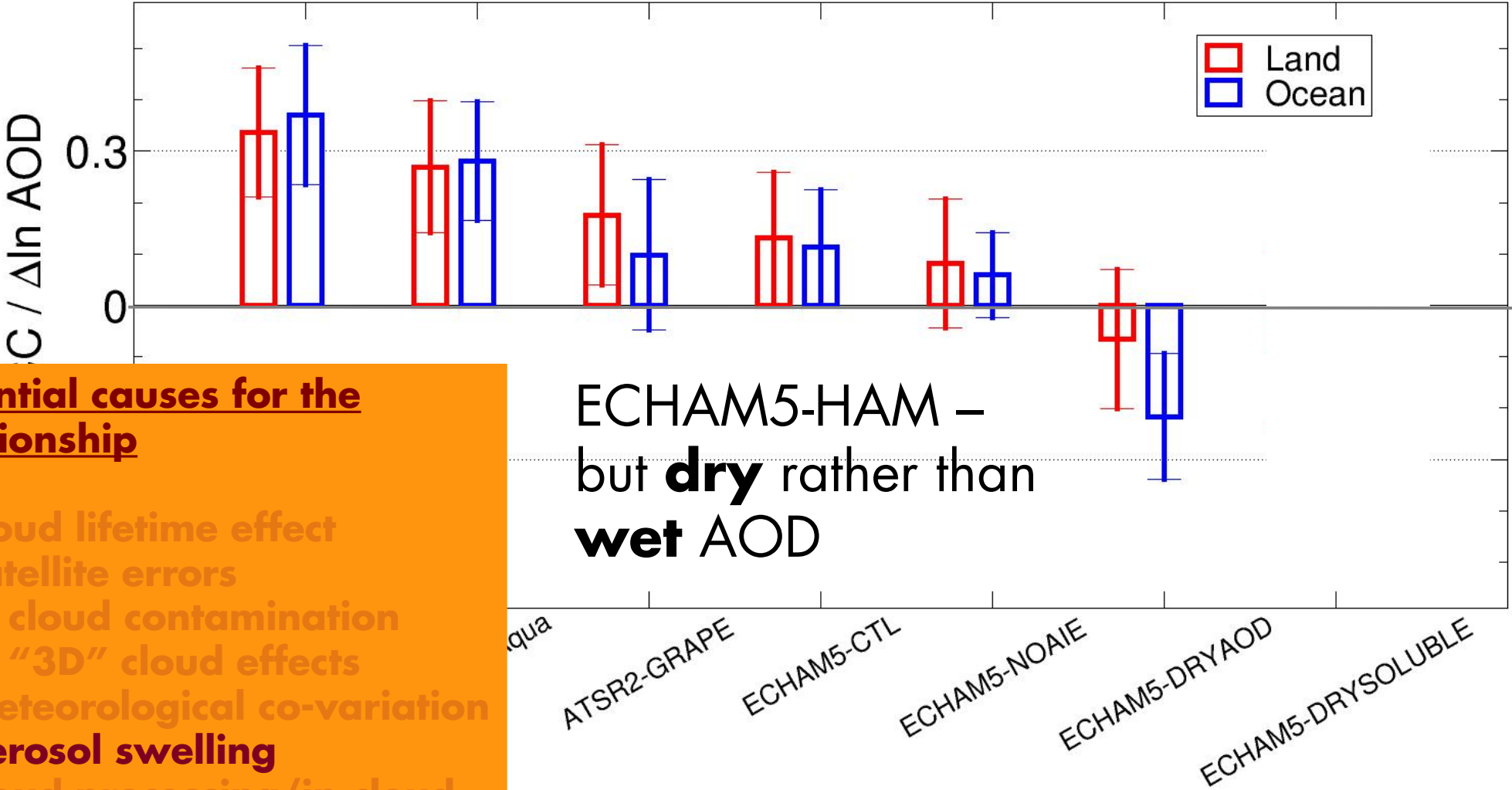


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ECHAM5-HAM –
but no aerosol indirect effects

AOD - cloud cover relationship



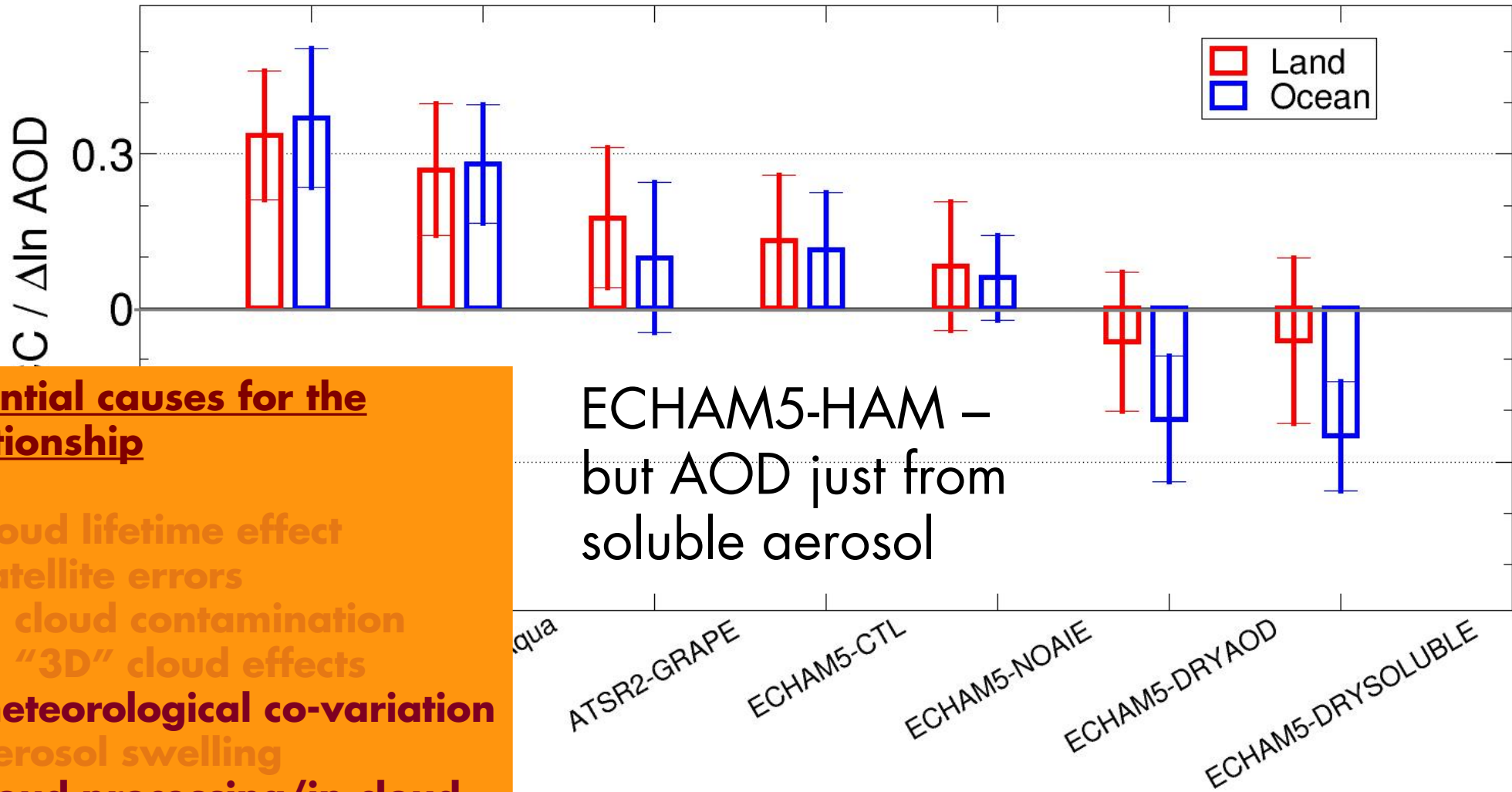
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ECHAM5-HAM – but **dry** rather than **wet** AOD

See also Myhre et al., Atmos. Chem. Phys. 2007

AOD – cloud cover relationship

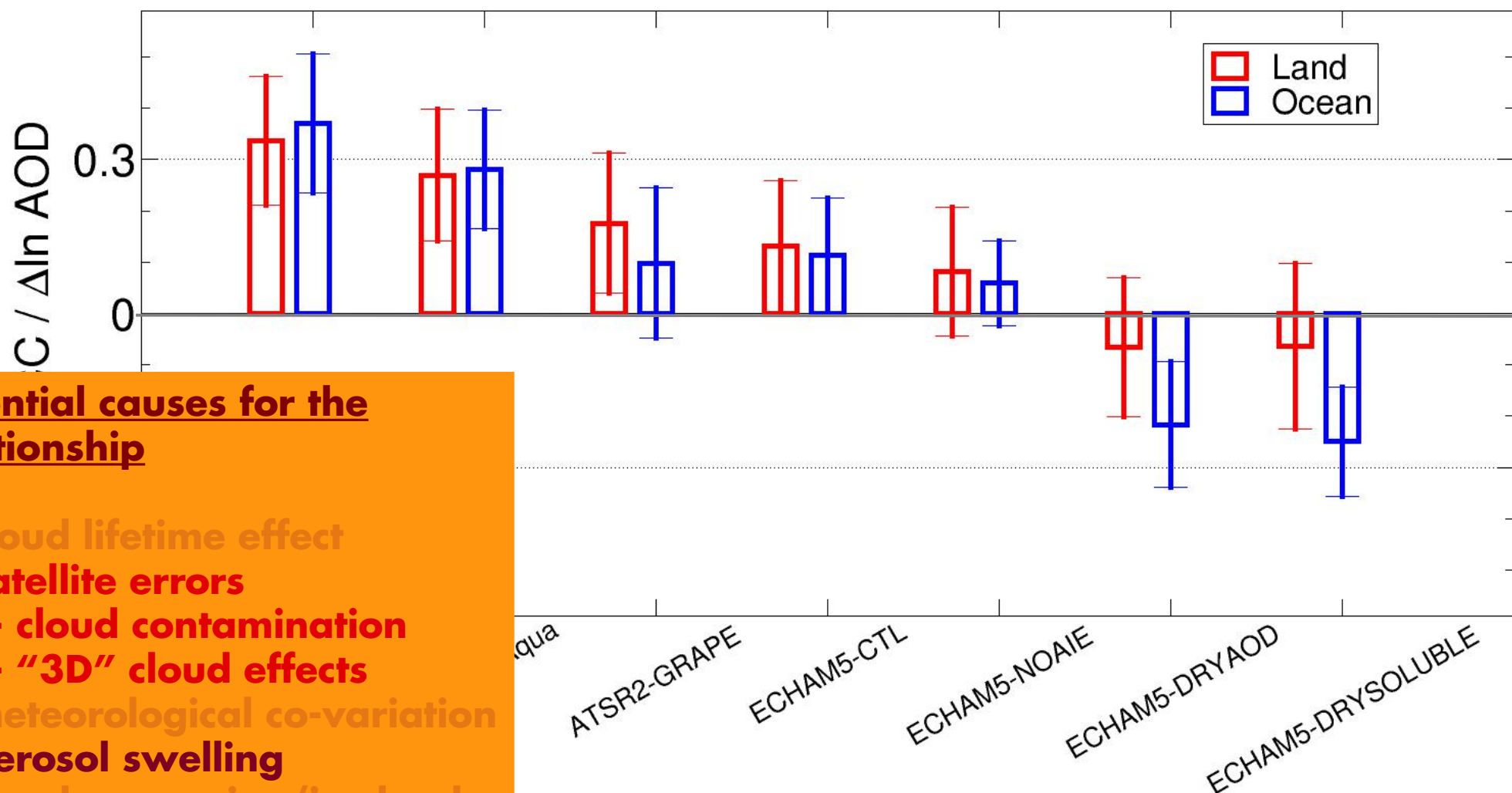


ECHAM5-HAM –
but AOD just from
soluble aerosol

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AOD – cloud cover relationship



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- **Need for good CCN observations**
 - clear-sky aerosol optical depth often poor
 - use CAMS re-analysis adding model information
 - same for anthropogenic perturbation



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- Quality of current N_d retrievals?
- Models suggest: $\Delta N_d / \Delta AOD$ useful “emergent constraint”
- Additional information from joint histograms and aerosol index allow for forcing estimate with $\pm 40\%$ accuracy
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- Relationship cloud fraction – AOD flawed due to humid swelling
- N_d as “mediating factor” → (smaller) negative forcing
- Constraints on simulated cloud lifetime effects from active remote sensing

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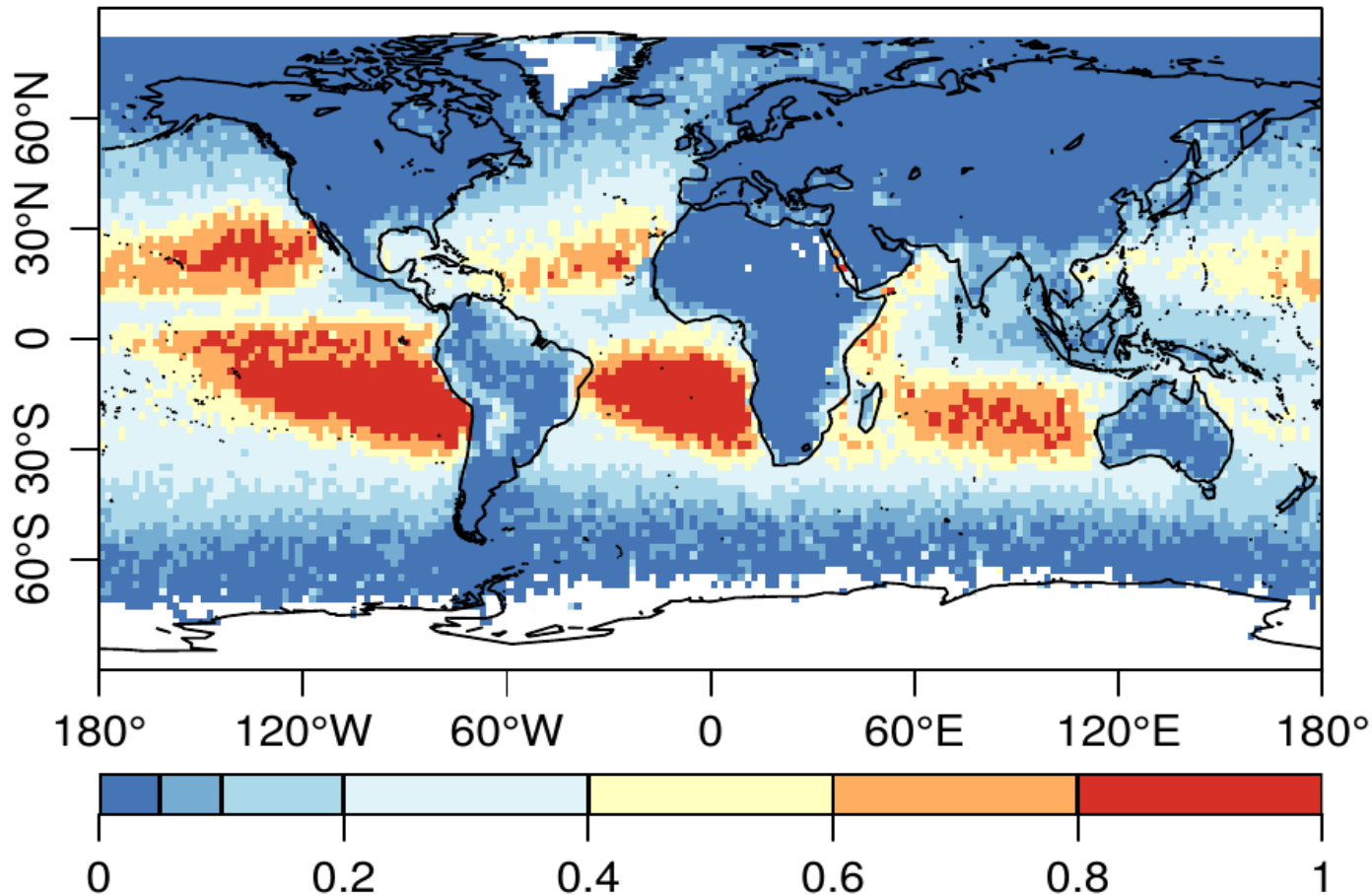
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■ Take home messages

- Modellers are like water – they find their way
- Satellite experts should probably do the retrievals (droplet concentration? ice crystals?)
- Radar/lidar add crucial information

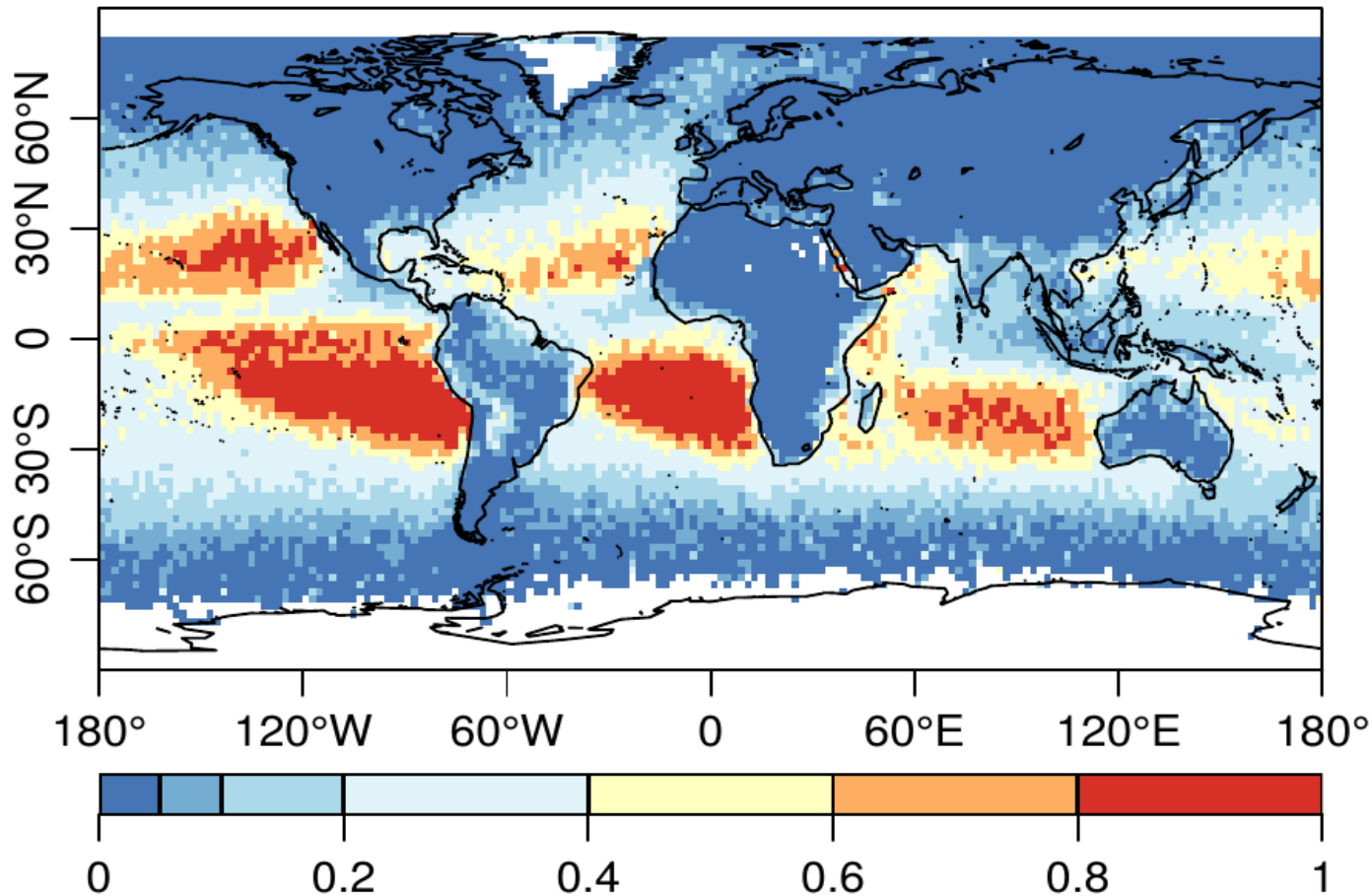
Constraint on precipitation processes



Fraction of surface rain events originating from a liquid-water cloud
("warm rain fraction")

From CloudSat / CALIPSO retrievals

Constraint on precipitation processes

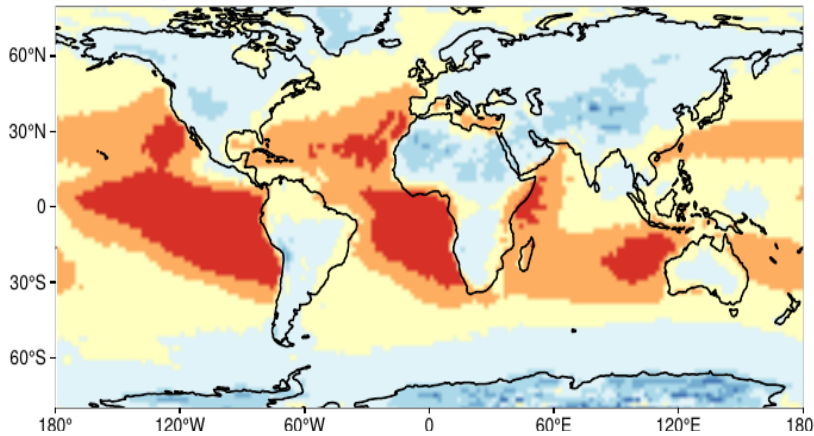


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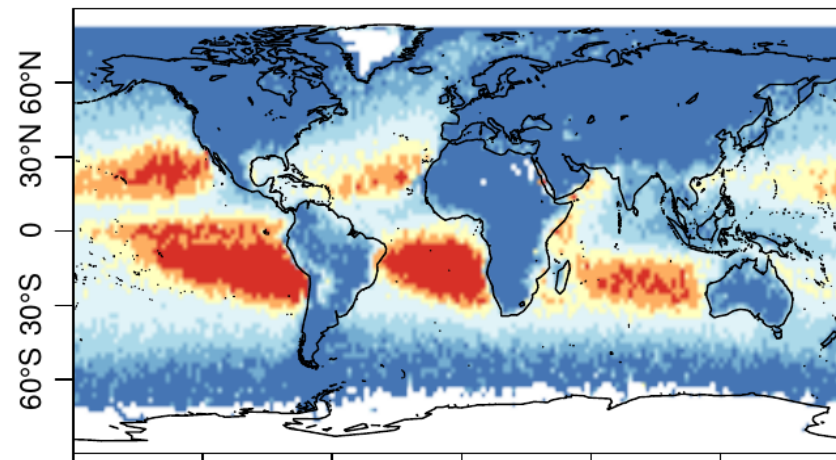
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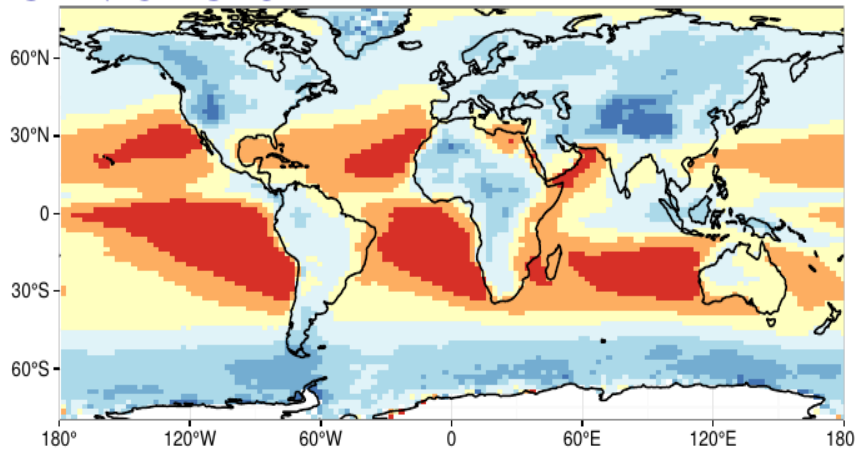
ECHAM-HAM



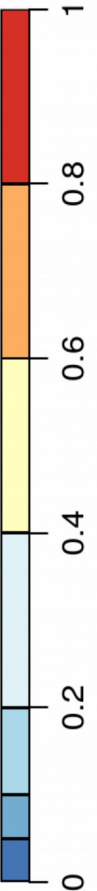
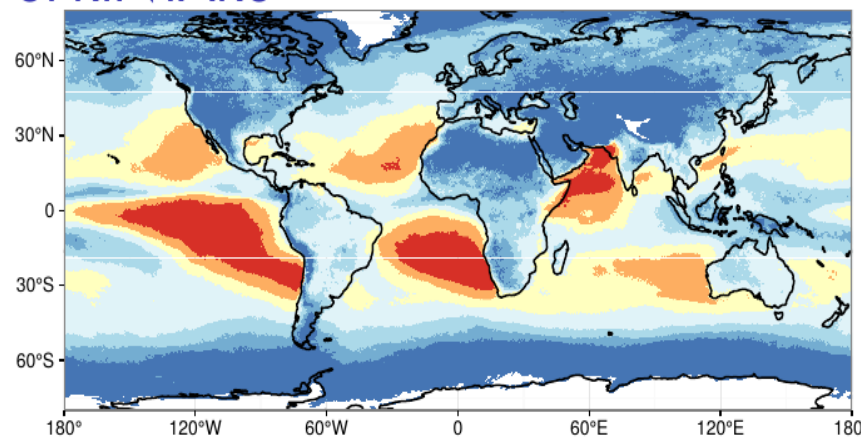
Satellite



CAM5-CLUBB



SPRINTARS



“Warm rain fraction” in climate models and data
→ too much potential for a cloud lifetime effect in many models?

Radiative forcing

Radiative perturbation

Cloud particles

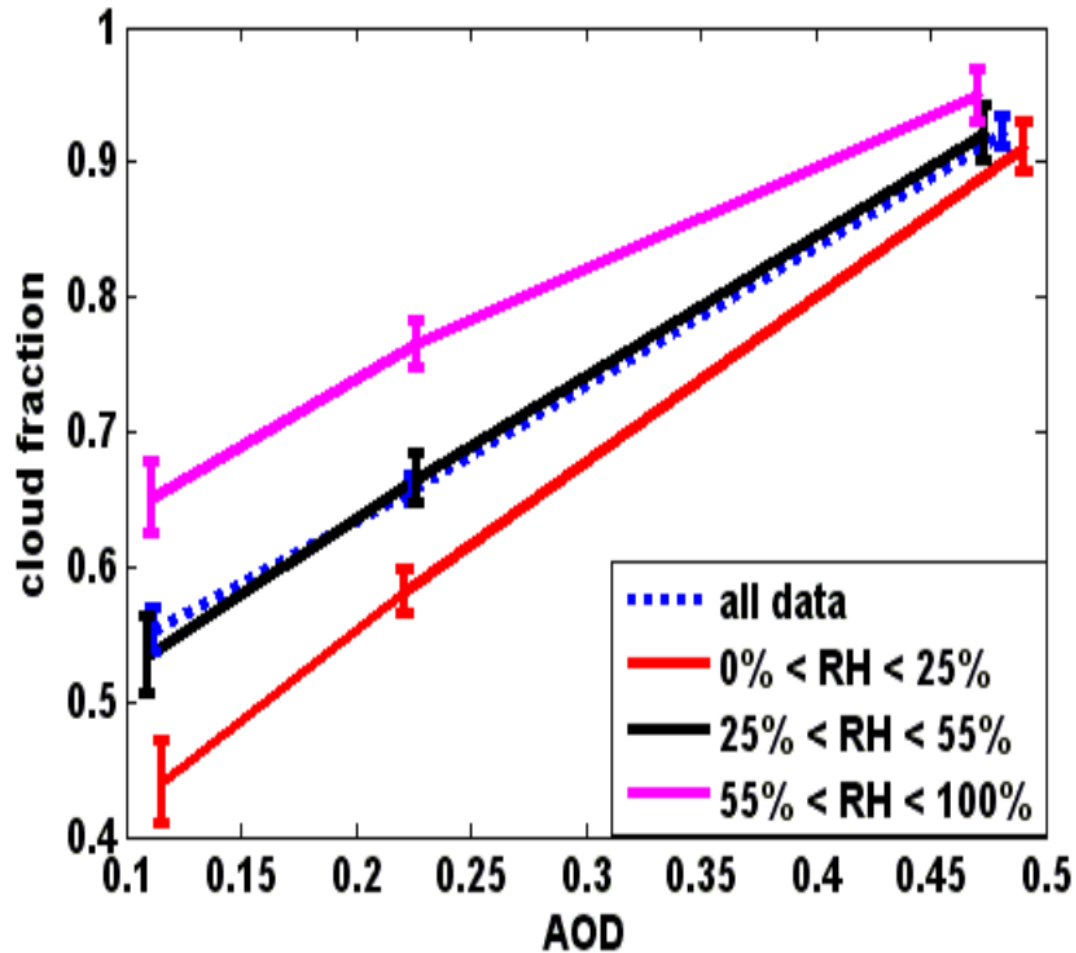
Aerosol perturbation

$$\Delta F_{\text{aci}} = \underbrace{\frac{dR}{d \ln N_c}}_{\text{Radiative forcing } \mathbf{RF}_{\text{aci}} \text{ (1}^{\text{st}} \text{ effect)}} \cdot \frac{d \ln N_c}{d \ln \alpha} \cdot \Delta \ln \alpha_{\text{ant}}$$

$$= \underbrace{\frac{\partial R}{\partial \ln N_c}}_{\text{Radiative forcing } \mathbf{RF}_{\text{aci}} \text{ (1}^{\text{st}} \text{ effect)}} + \underbrace{\frac{\partial R}{\partial f} \frac{df}{d \ln N_c} + \frac{\partial R}{\partial L} \frac{dL}{d \ln N_c} + \frac{\partial R}{\partial T_{\text{top}}} \frac{dT_{\text{top}}}{d \ln N_c}}_{\text{Effective radiative forcing } \mathbf{ERF}_{\text{aci}} \text{ (Adjustments / 2}^{\text{nd}} \text{ effect)}}$$

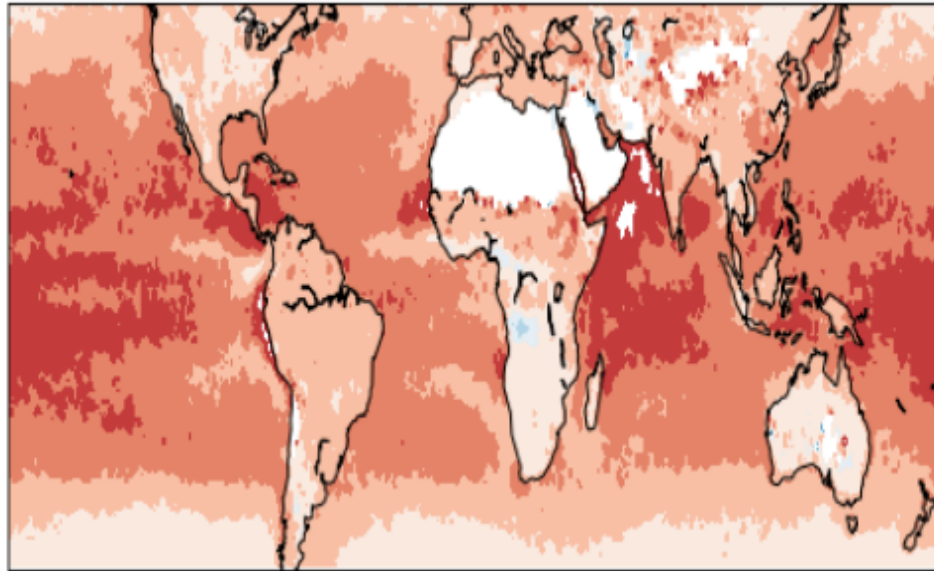
Cloud fraction f , Cloud water path L ,
Cloud top temperature T_{top}

AOD – cloud + precipitation relationships

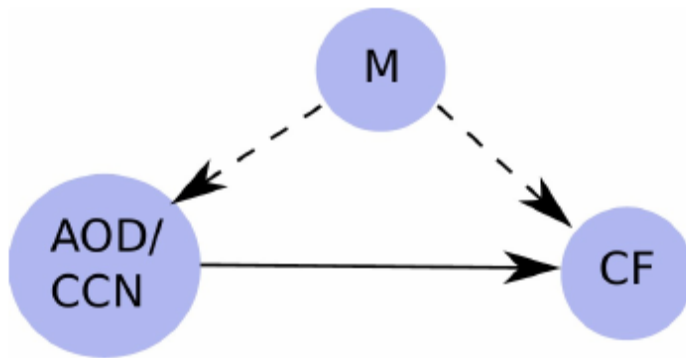
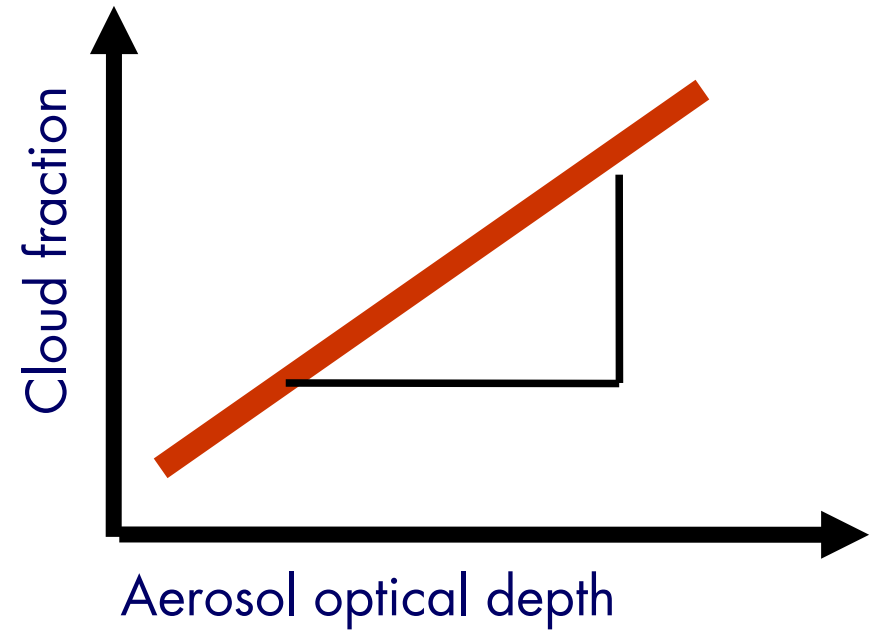
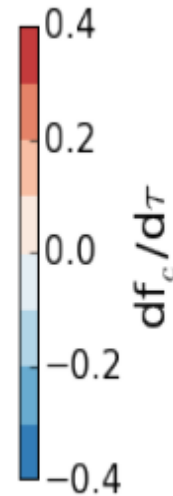


Strong cloud lifetime effect?

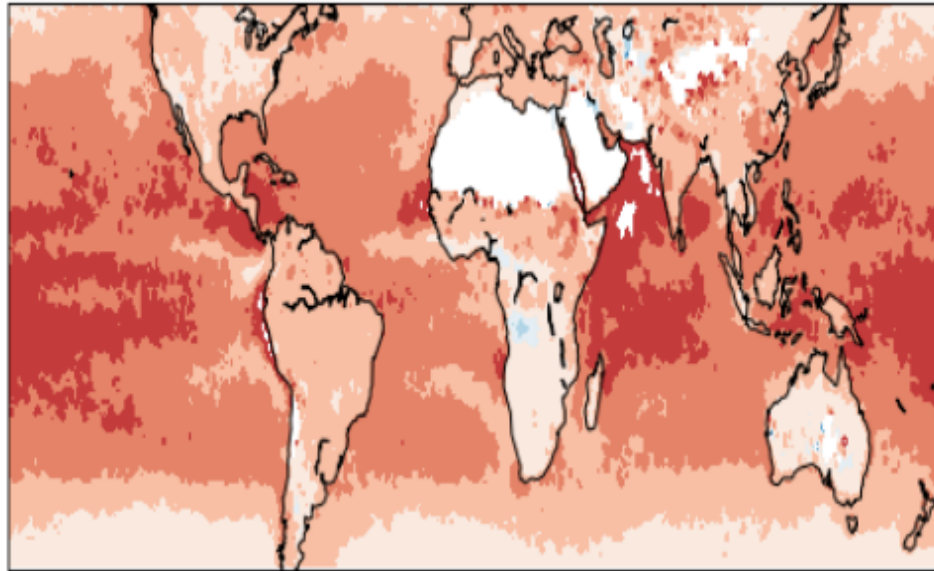
Cloud cover - aerosol relationship



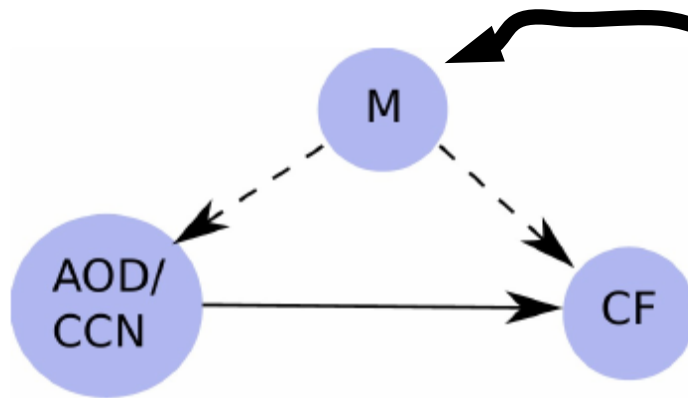
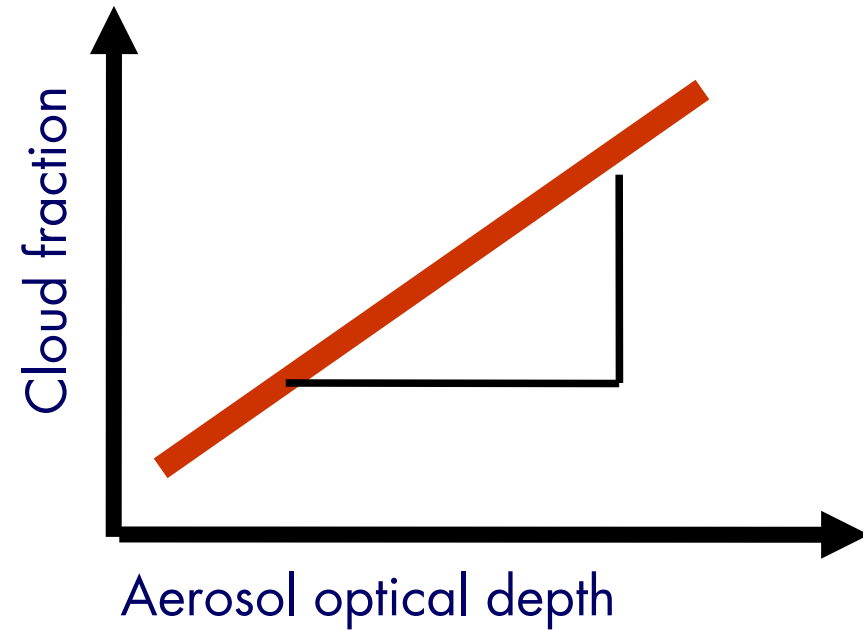
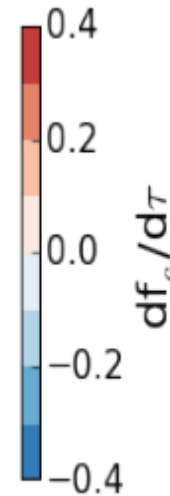
Data from MODIS Aqua (used throughout this work)



Cloud cover - aerosol relationship



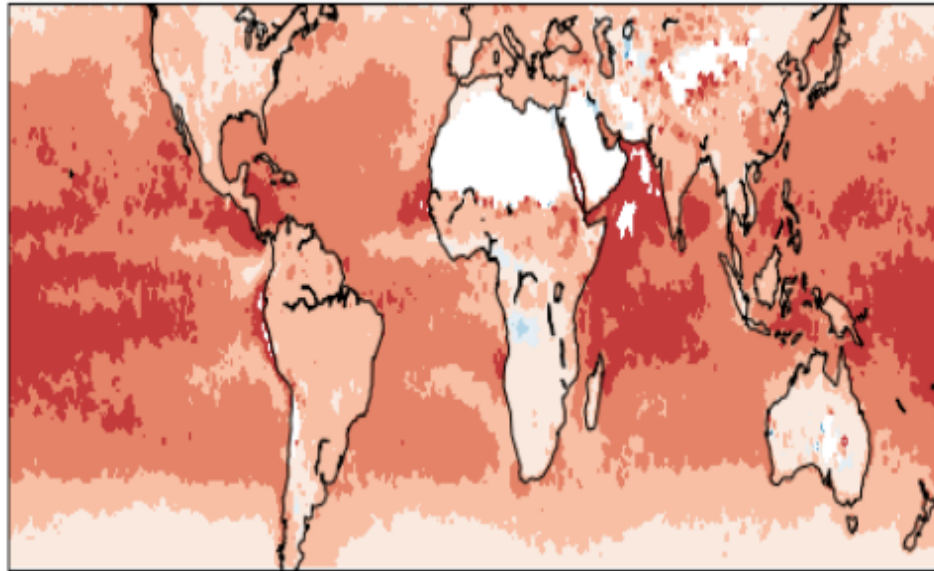
Data from MODIS Aqua (used throughout this work)



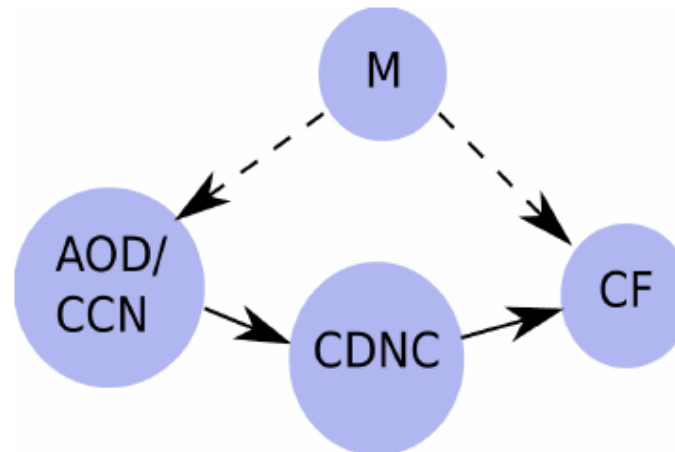
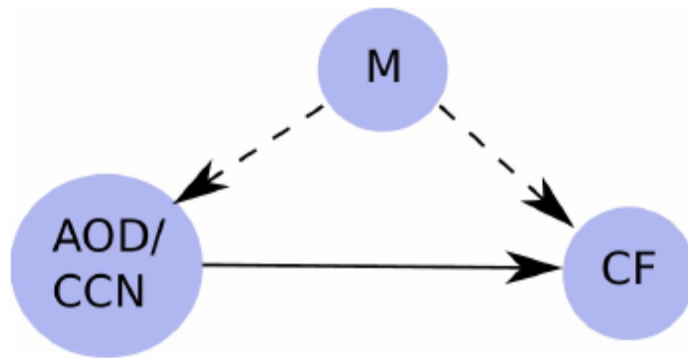
Relative humidity ↗
⇒ AOD ↗ and cloud fraction ↗

(note: RH fluctuations!)

Cloud cover – aerosol relationship

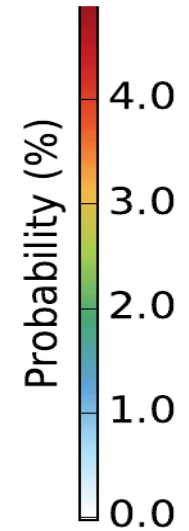
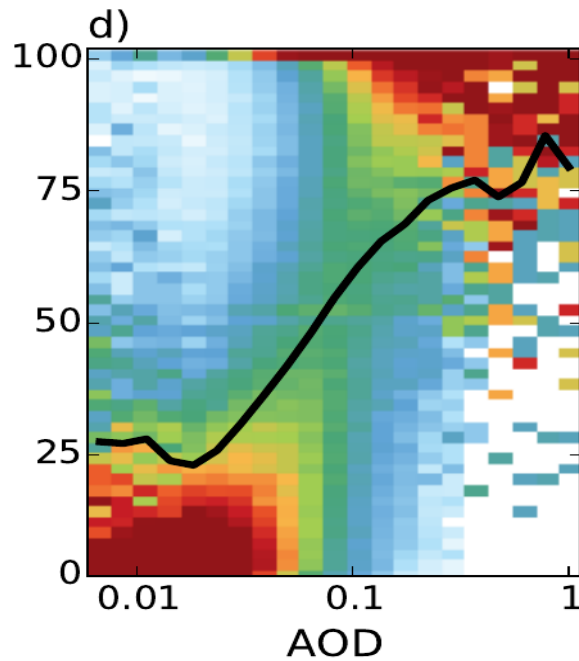
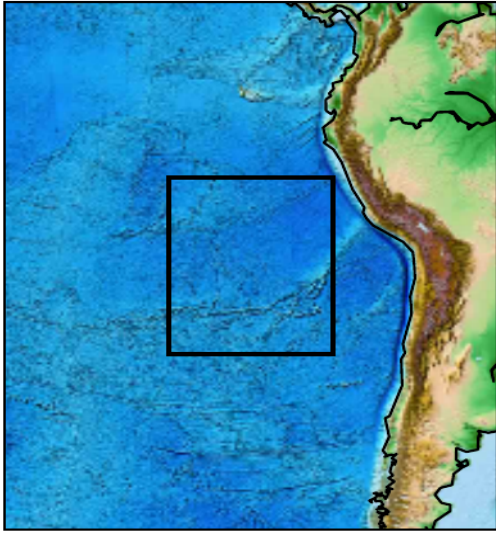


Data from MODIS Aqua (used throughout this work)

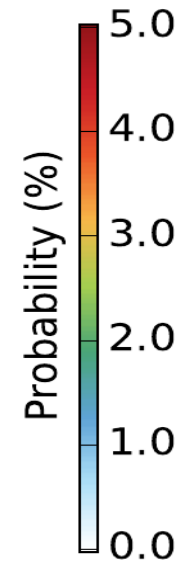
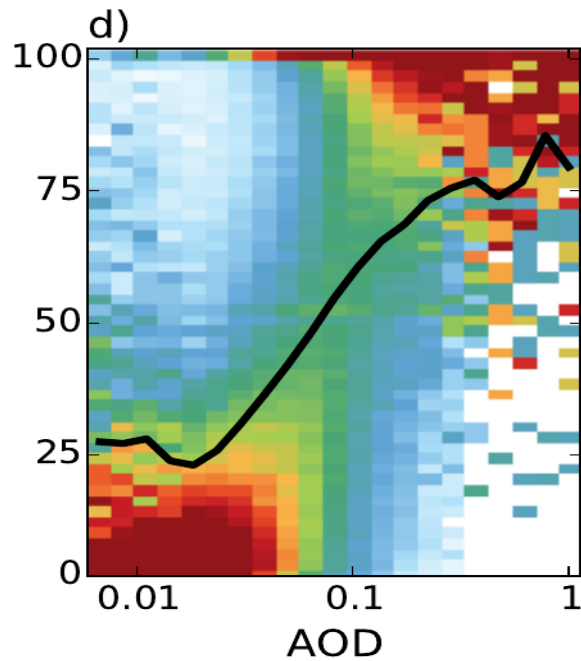
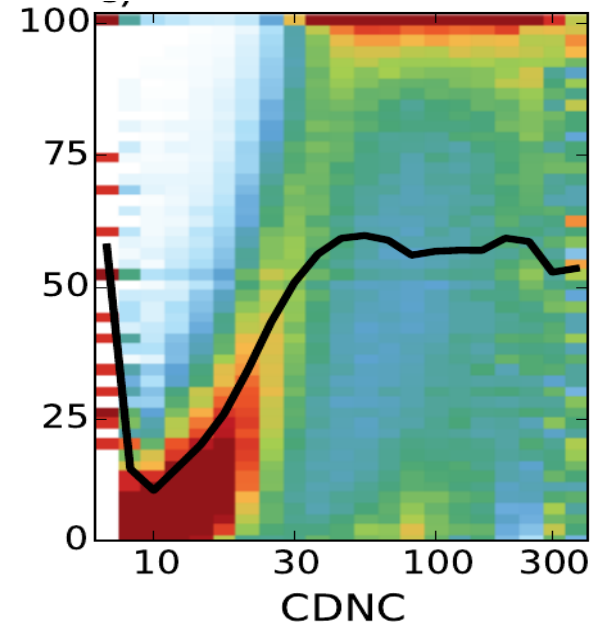
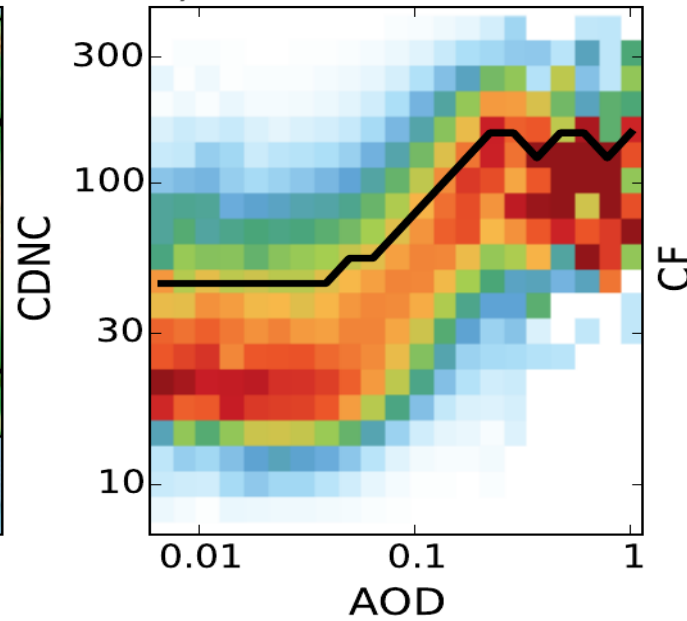
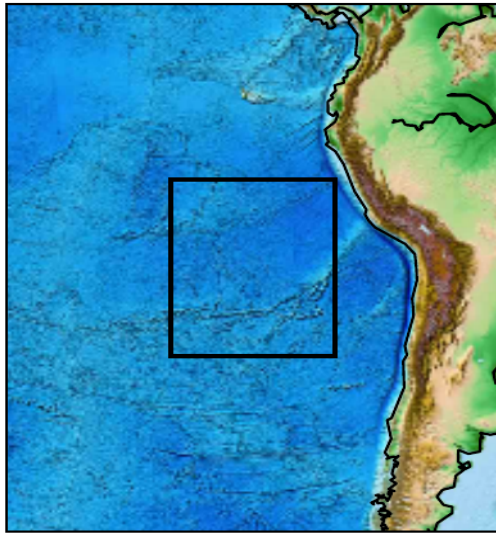


Microphysical pathway: via cloud droplet concentration changes (\sim independent of RH)

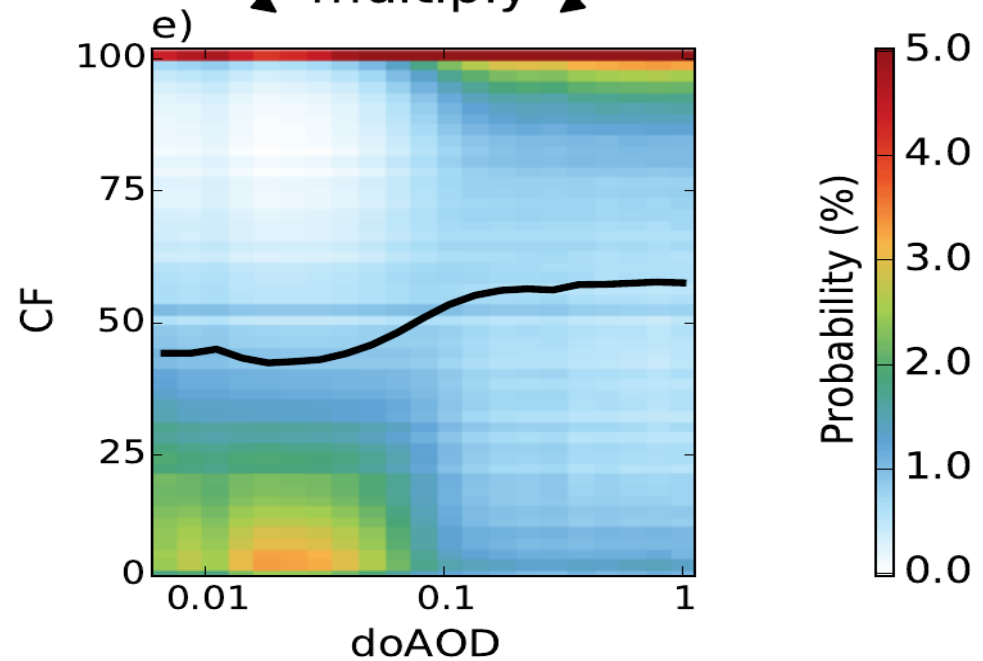
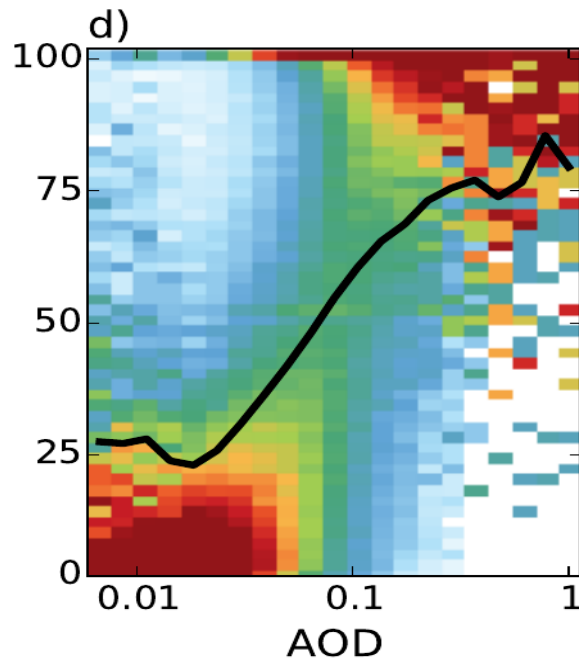
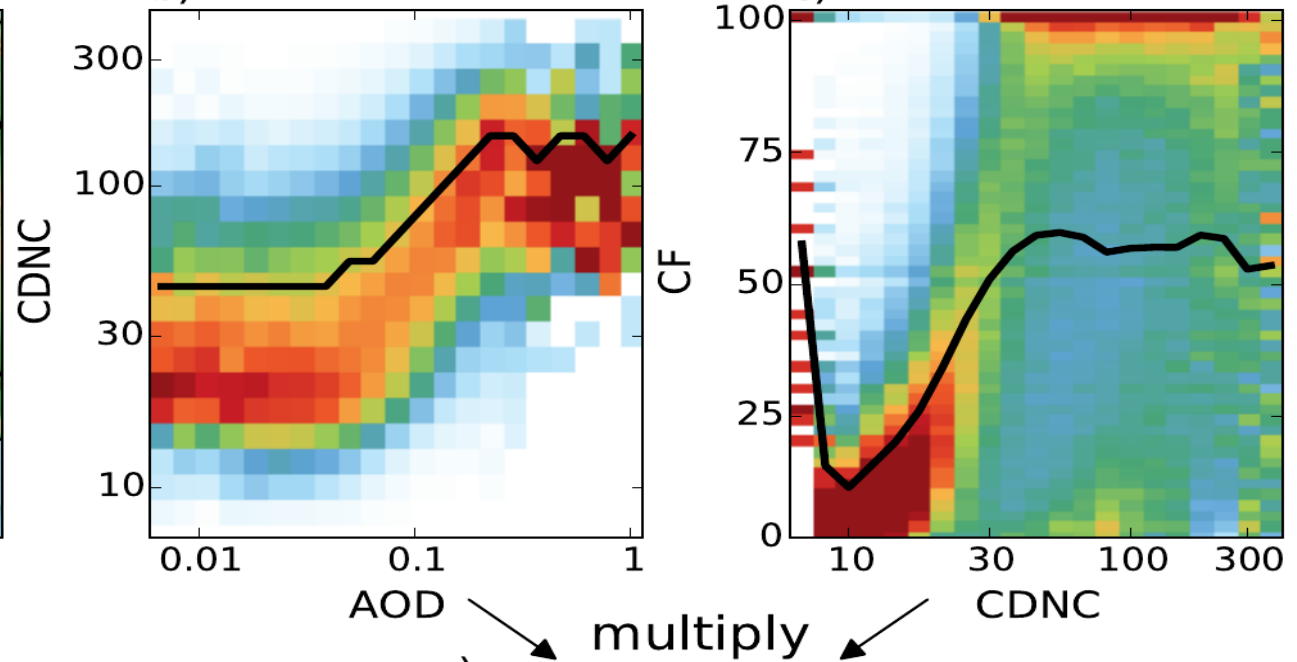
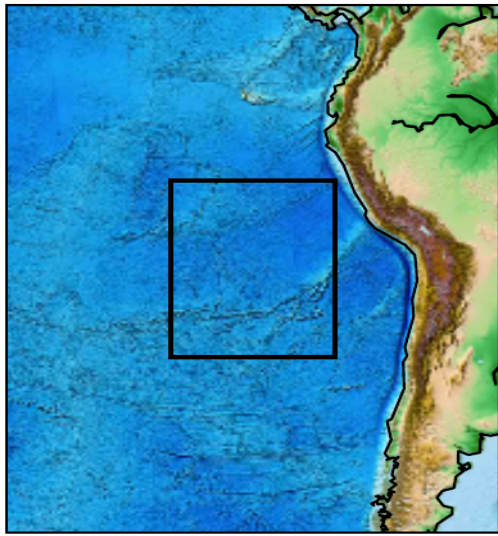
Cloud cover - aerosol relationship: decompose joint PDF



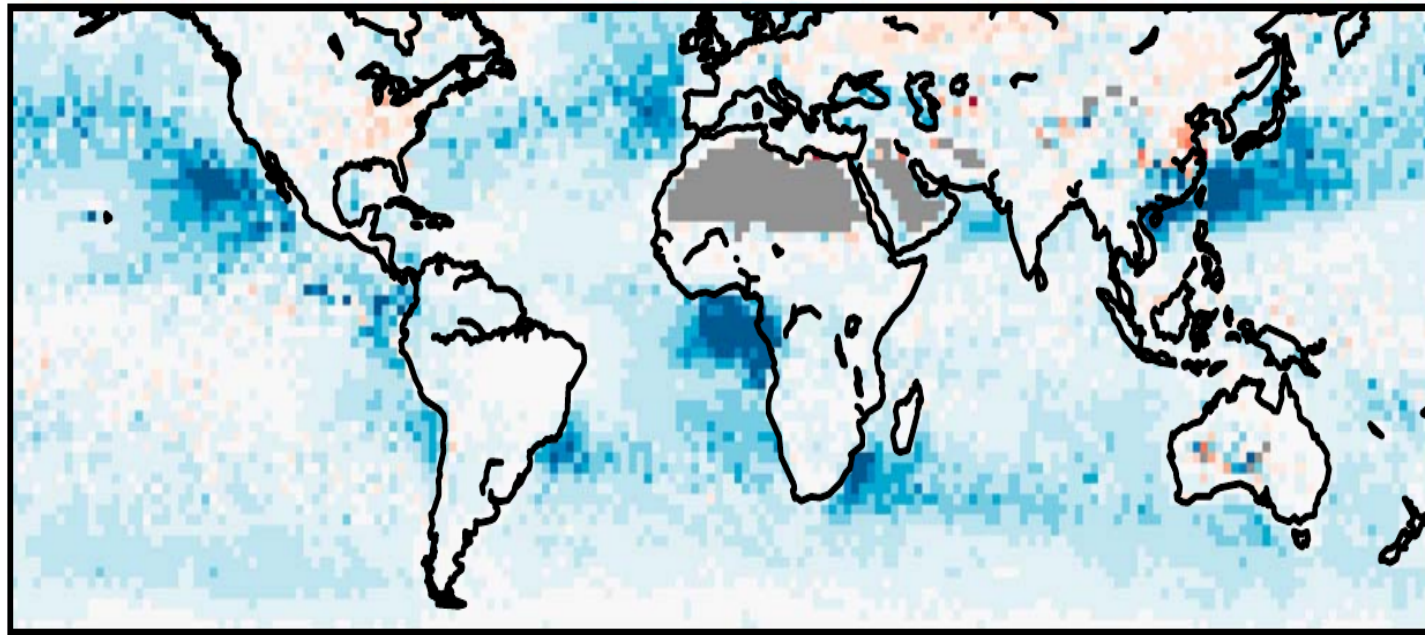
Cloud cover - aerosol relationship: decompose joint PDF



Cloud cover - aerosol relationship: decompose joint PDF



Cloud cover – aerosol relationship



Anthropogenic AOD from
*Bellouin, Quaas, Morcrette
and Boucher (ACP 2013)*

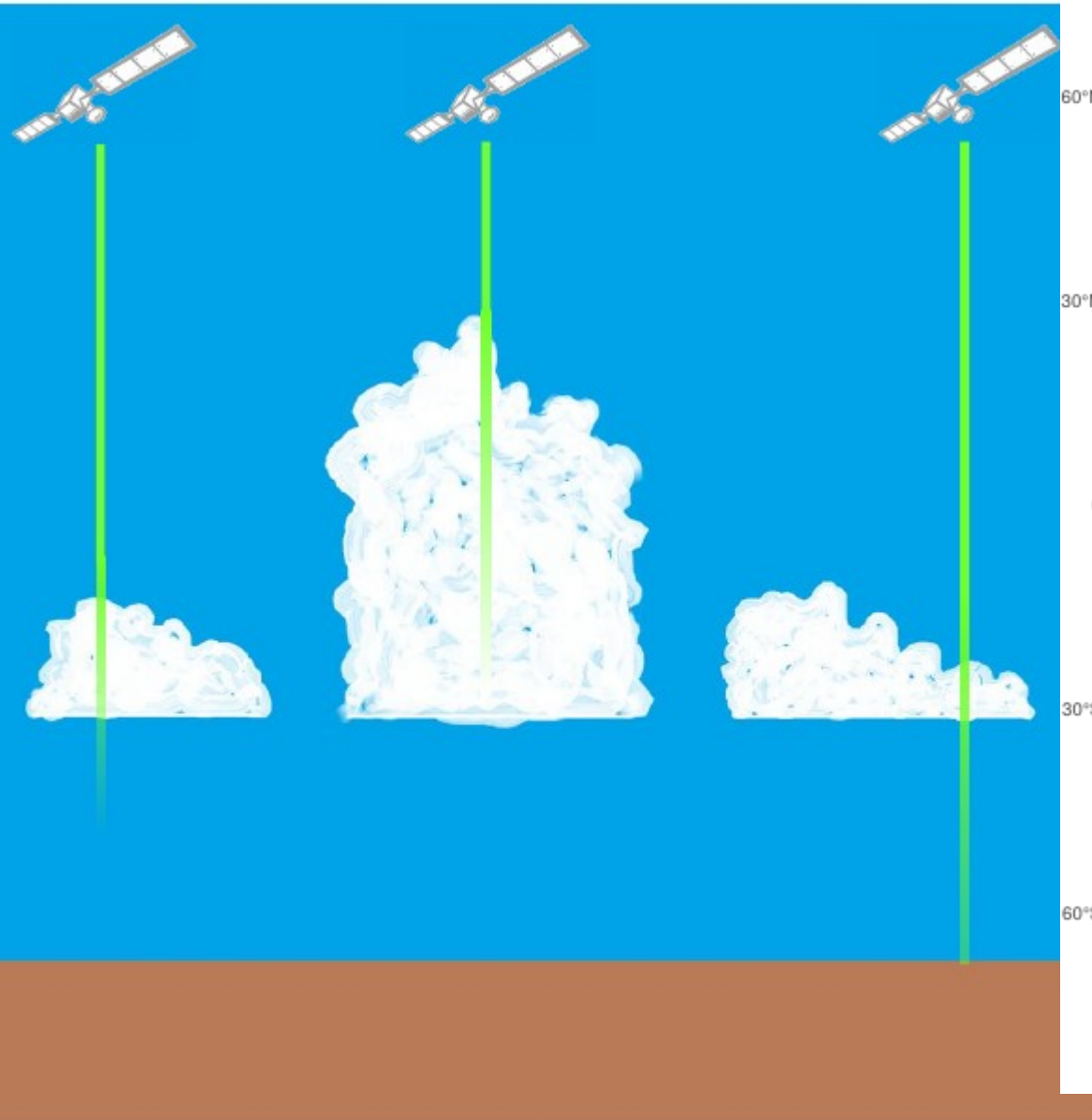
Δ TOA SW (Wm^{-2})



Global annual mean forcing implied

- by AOD – Cloud fraction relationship: **-3 Wm^{-2}**
- by AOD – CDNC – cloud fraction relationship: **-0.48 Wm^{-2}**

Definition of cloud regimes



CBH CALIOP(all): median 2007

