Radiative Aerosol Indirect Effects Overview

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With thanks (and slides) to P. Artaxo, G. Feingold, S. Ghan, U. Lohmann, D. Rosenfeld, H. Wang,

Climate Forcing

- A measure of the net change in the energy balance of the Earth system in response to some external perturbation.
  - (Watts per square meter)
  - quantifies the energy imbalance that occurs when the external change takes place
  - *Does not measure the system response*

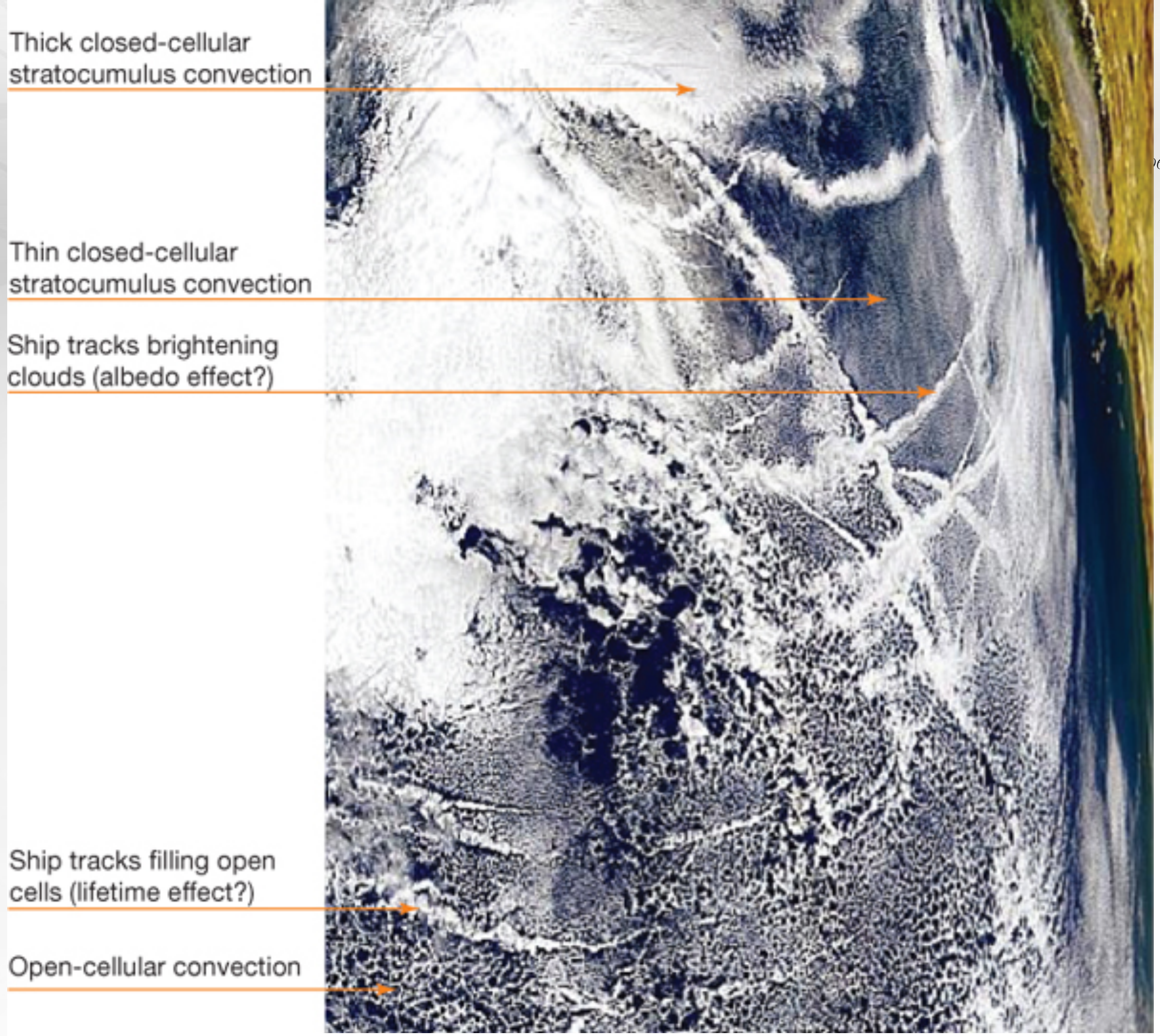
- Indirect Effect (frequently now called **Aerosol-cloud interaction)**
  - A process by which *aerosol changes* affects the optical properties and evolution of clouds through the aerosol role as *cloud condensation nuclei or ice nuclei*, particularly in ways that affect radiation or precipitation;
  - Processes which clouds and precipitation affect aerosol. .

Theory and Observations

Humans do affect clouds

Simple theory suggests

More aerosol
→ more drops
→ smaller drops
→ more reflective clouds



- CO_2 doubling compensated by (Slingo, 1990):
  - **120%** increase in droplet concentrations
  - **40%** decrease in cloud drop size
  - **12%** increase in oceanic cloud cover

More Evidence from Satellite

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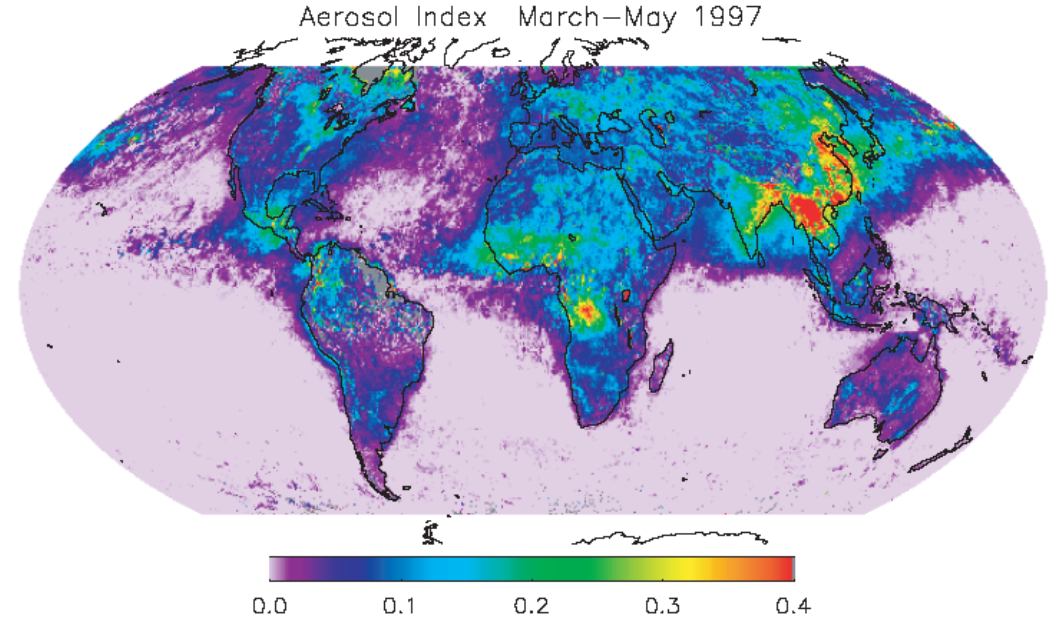
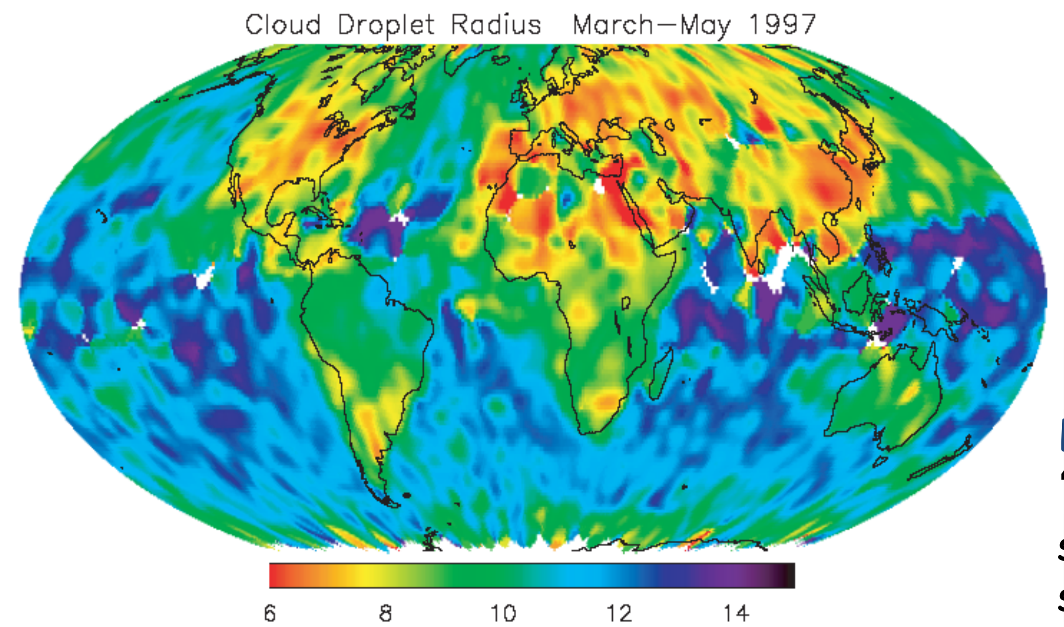
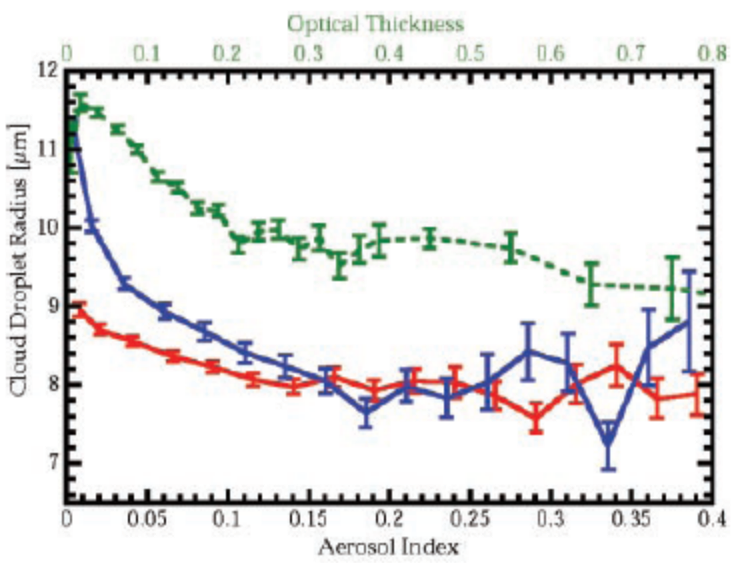
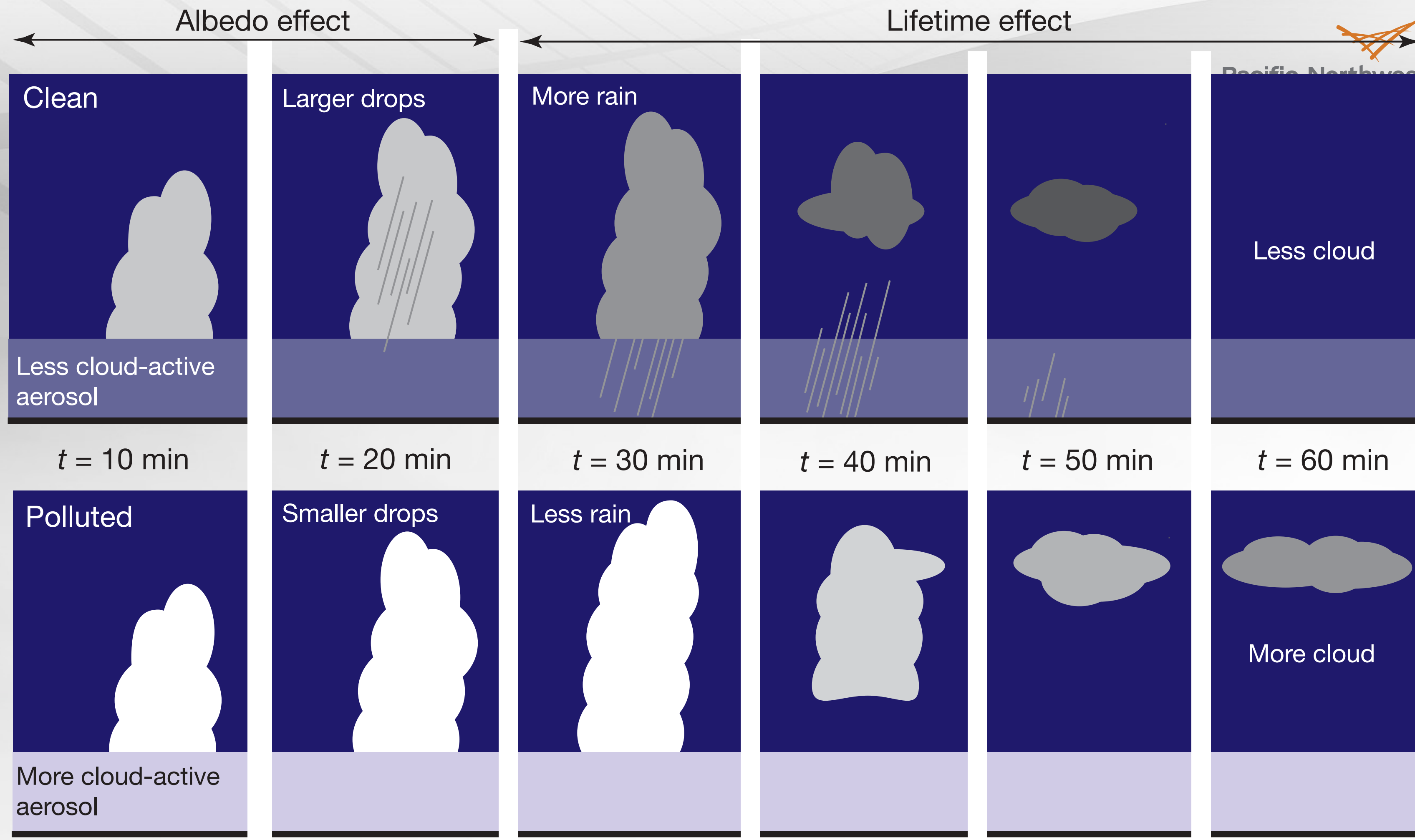






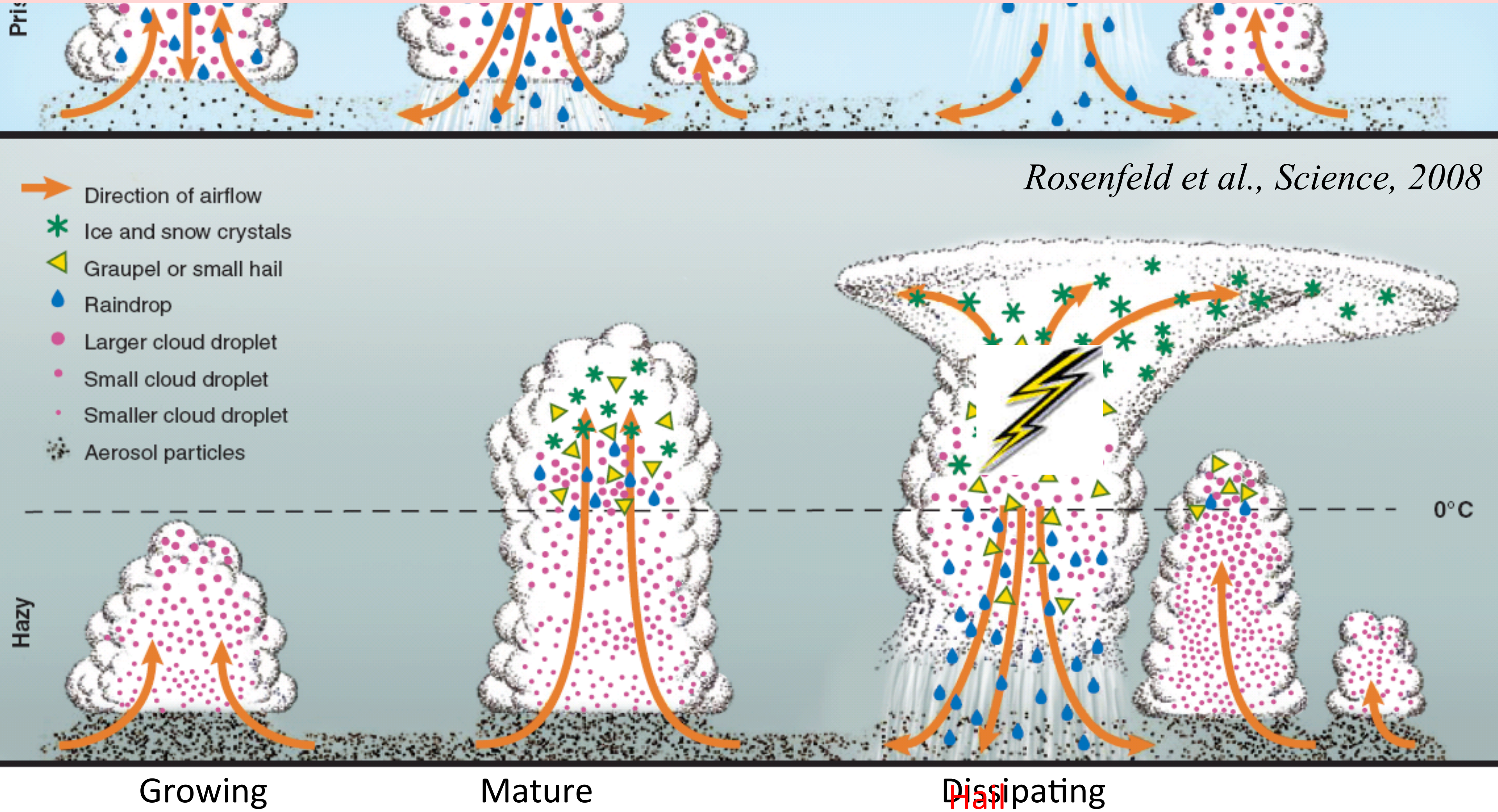
Breon, Tanre, and Generoso, "Aerosol effect on cloud droplet size monitored from satellite", *Science*, 2002



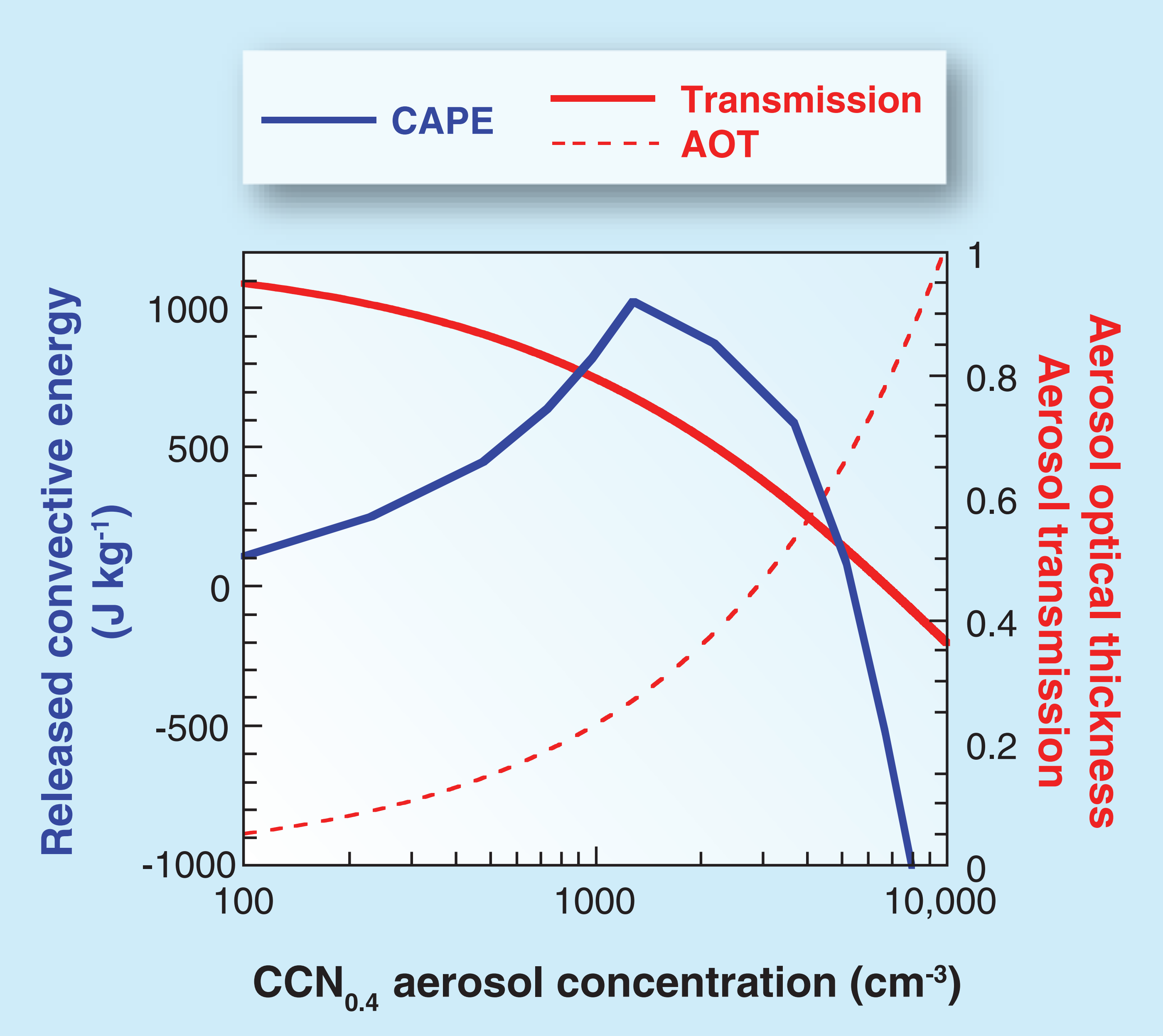
Cloud Albedo and Lifetime Effect as outlined in Stevens and Feingold, 2006: In polluted air masses clouds consist of more droplets the coalesce into raindrops less effectively leaving longer lived clouds. A cartoon of a timeline for two cloud system scenarios.

Positive radiative forcing (warming) due to invigoration:

1. Colder cloud tops radiating less thermal energy to space.
2. Higher anvils expand on larger areas and become thinner and therefore reflecting less solar radiation for the same amount of emitted thermal radiation.



Rosenfeld, 2008



Convective Cloud Depth and Cloud Fraction changes due to Aerosols

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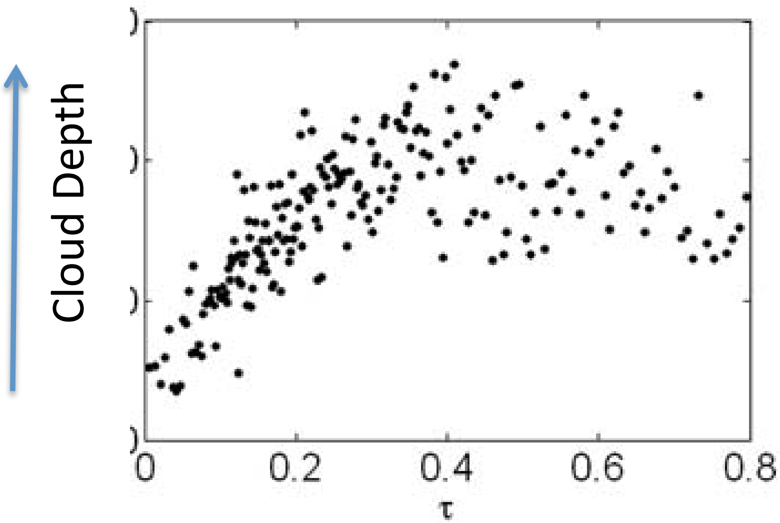
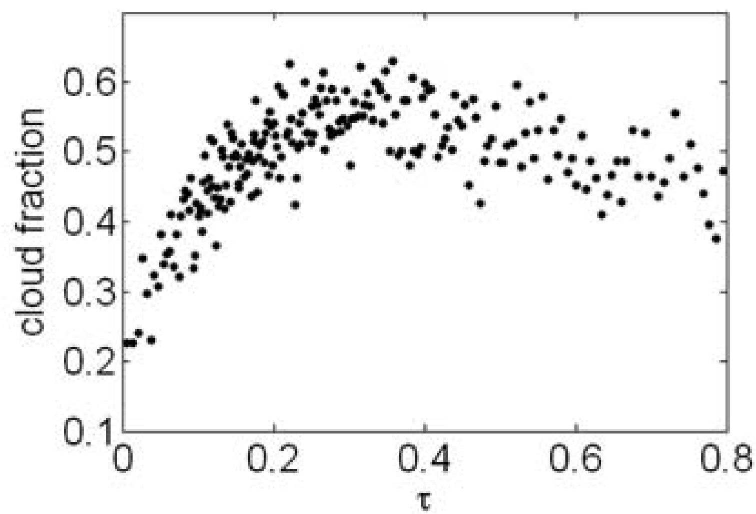
Koren, 2008

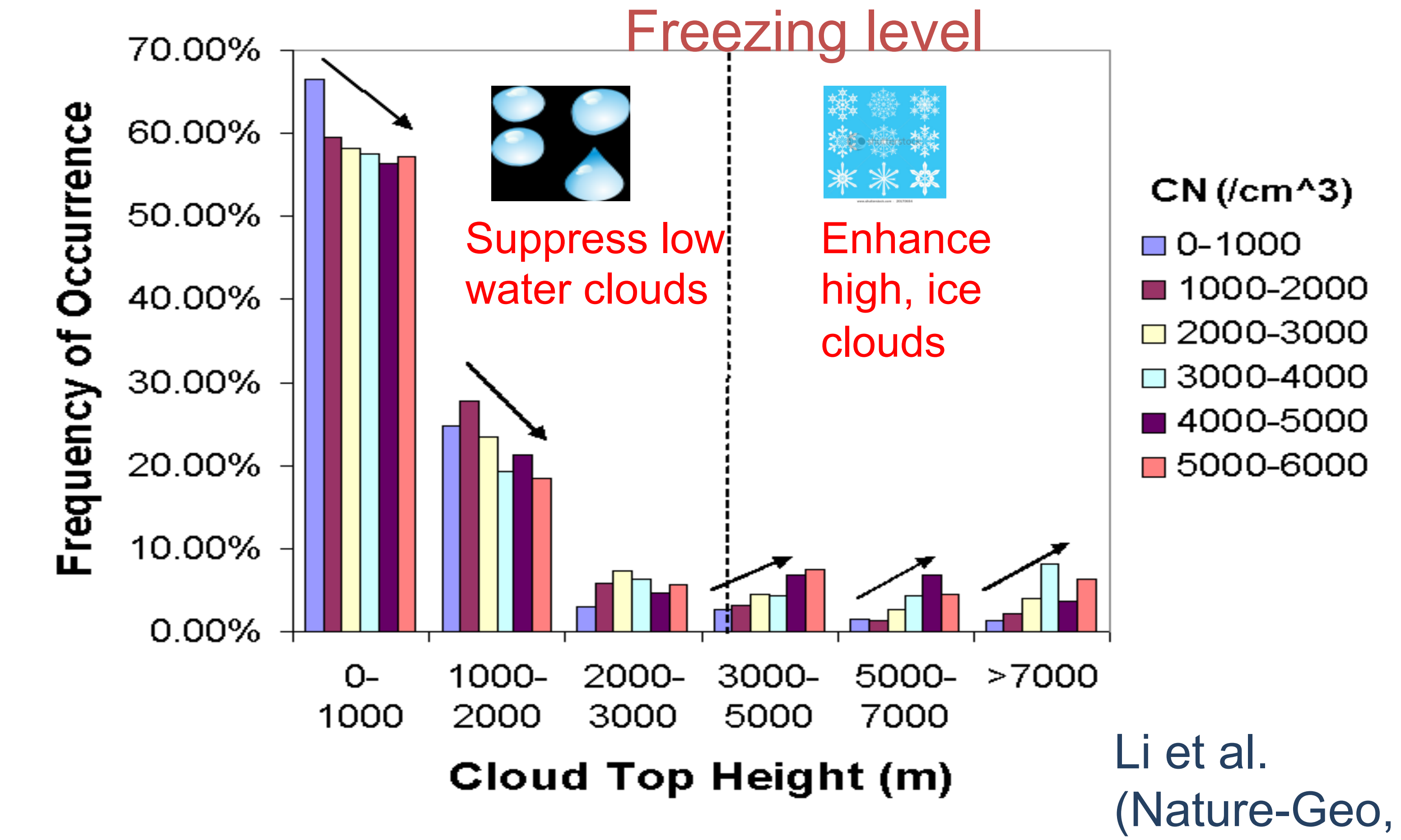


Aerosol Amount



Aerosol Amount

Effects of Aerosols on the Frequency of Cloud Occurrence in monsoon regions



Li et al. (Nature-Geo, 2011)

As CN increases, deep (ice-phase) clouds occurred more frequently but low (liquid-phase) clouds occurred less frequently

- Longwave Indirect Effect (Lubin and Vogelman, 2006)
  - Emissivity ~ $1/r_e$, changes in the arctic surface fluxes ~

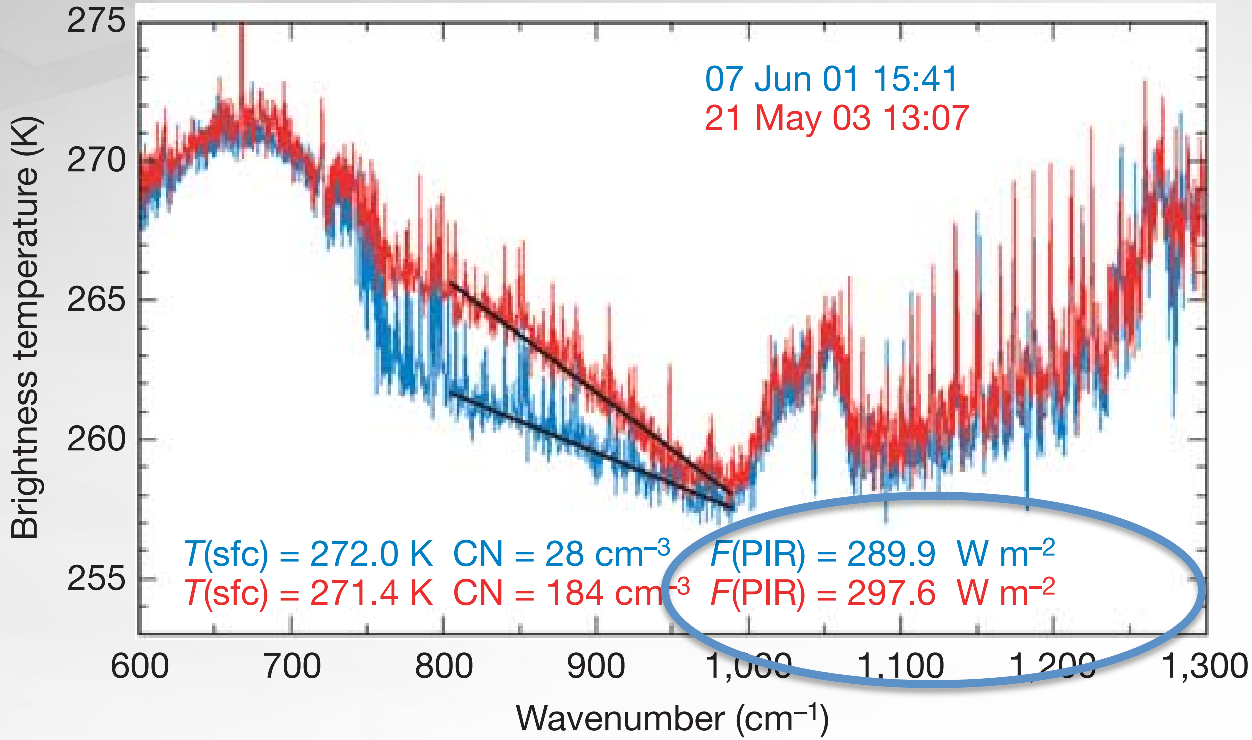


Figure 2 | Examples of AERI measurements. Downwelling emission spectra measured by the NSA AERI beneath two clouds with very different condensation nuclei (CN) concentrations. Near-surface (2 m) air temperature *T*(sfc) and pyrgeometer-measured downwelling longwave flux *F*(PIR) are also indicated.

Model Results

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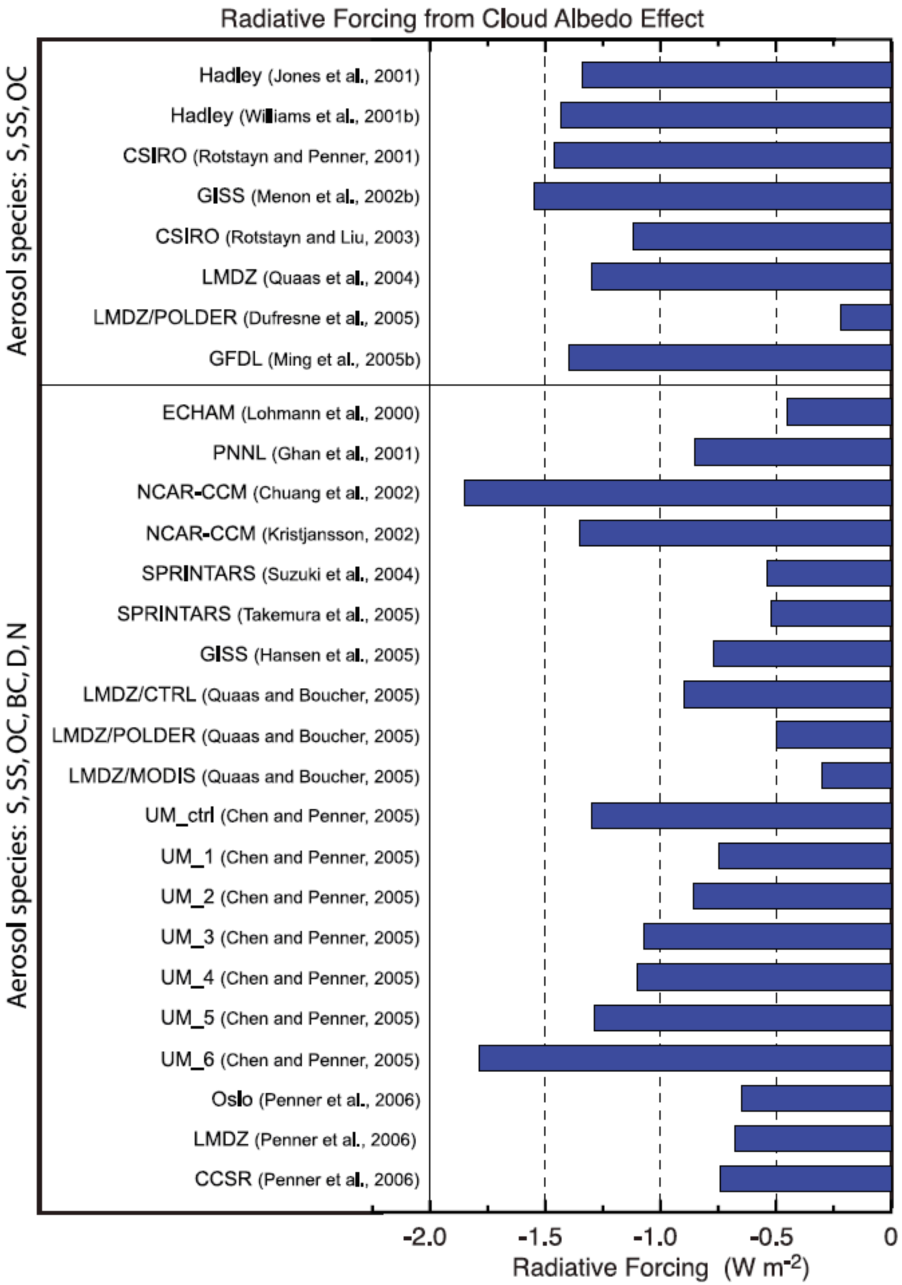
Consensus (IPCC, AR4, Chapt 7) Aerosol Cloud effects

Table 7.10a. *Overview of the different aerosol indirect effects and their sign of the net radiative flux change at the top of the atmosphere (TOA).*

Effect	Cloud Types Affected	Process	Sign of Change in TOA Radiation	Potential Magnitude	Scientific Understanding
Cloud albedo effect	All clouds	For the same cloud water or ice content more but smaller cloud particles reflect more solar radiation	Negative	Medium	Low
Cloud lifetime effect	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby presumably prolonging cloud lifetime	Negative	Medium	Very low
Semi-direct effect	All clouds	Absorption of solar radiation by absorbing aerosols affects static stability and the surface energy budget, and may lead to an evaporation of cloud particles	Positive or negative	Small	Very low
Glaciation indirect effect	Mixed-phase clouds	An increase in IN increases the precipitation efficiency	Positive	Medium	Very low
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay freezing causing super-cooled clouds to extend to colder temperatures	Positive or negative	Medium	Very low

Table 7.10b. *Overview of the different aerosol indirect effects and their implications for the global mean net shortwave radiation at the surface, F_{sfc} (Columns 2-4) and for precipitation (Columns 5-7).*

Effect	Sign of Change in F_{sfc}	Potential Magnitude	Scientific Understanding	Sign of Change in Precipitation	Potential Magnitude	Scientific Understanding
Cloud albedo effect	Negative	Medium	Low	n.a.	n.a.	n.a.
Cloud lifetime effect	Negative	Medium	Very low	Negative	Small	Very low
Semi-direct effect	Negative	Large	Very low	Negative	Large	Very low
Glaciation indirect effect	Positive	Medium	Very low	Positive	Medium	Very low
Thermodynamic effect	Positive or negative	Medium	Very low	Positive or negative	Medium	Very low



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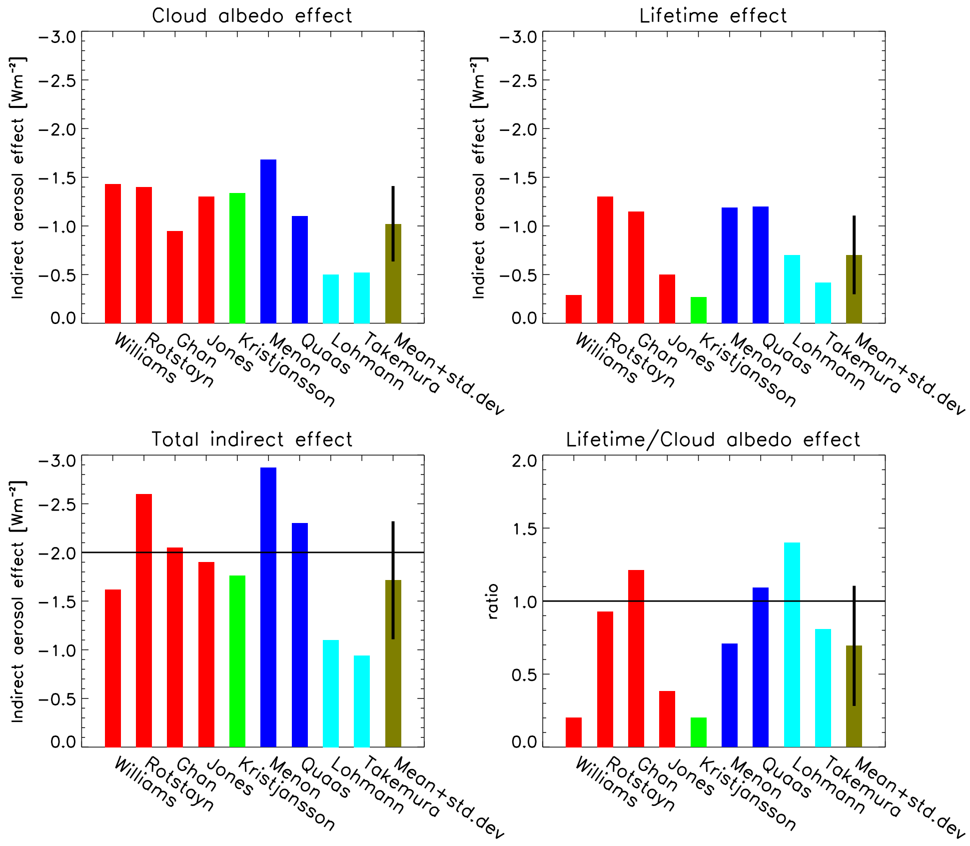
Models show a factor of 3 variability
In the Cloud-Albedo Effect
IPCC AR4, Figure 2.14

Ensemble mean: -0.7 W/m2

[-1.8 to 0.3 W/m2]

Cloud albedo versus cloud lifetime effect



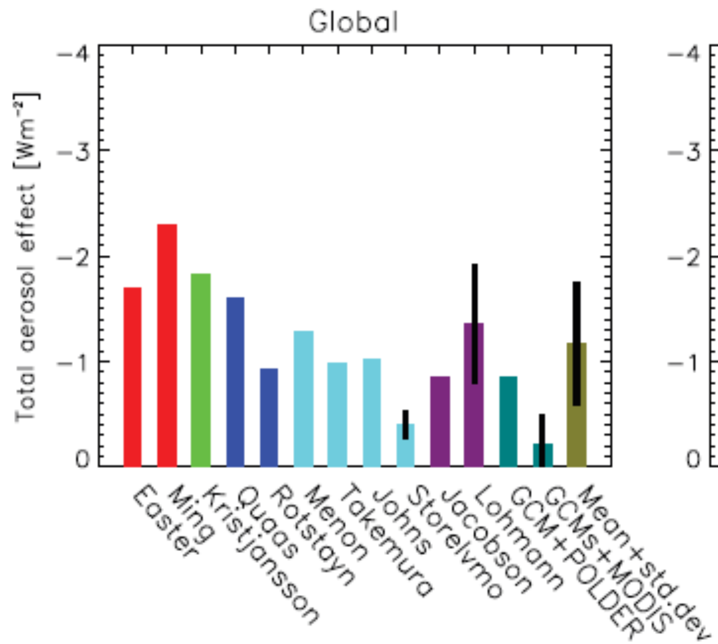
- Sulfate
- Black carbon (BC) and sulfate
- Organic aerosols (OC) and sulfate
- BC, OC and sulfate

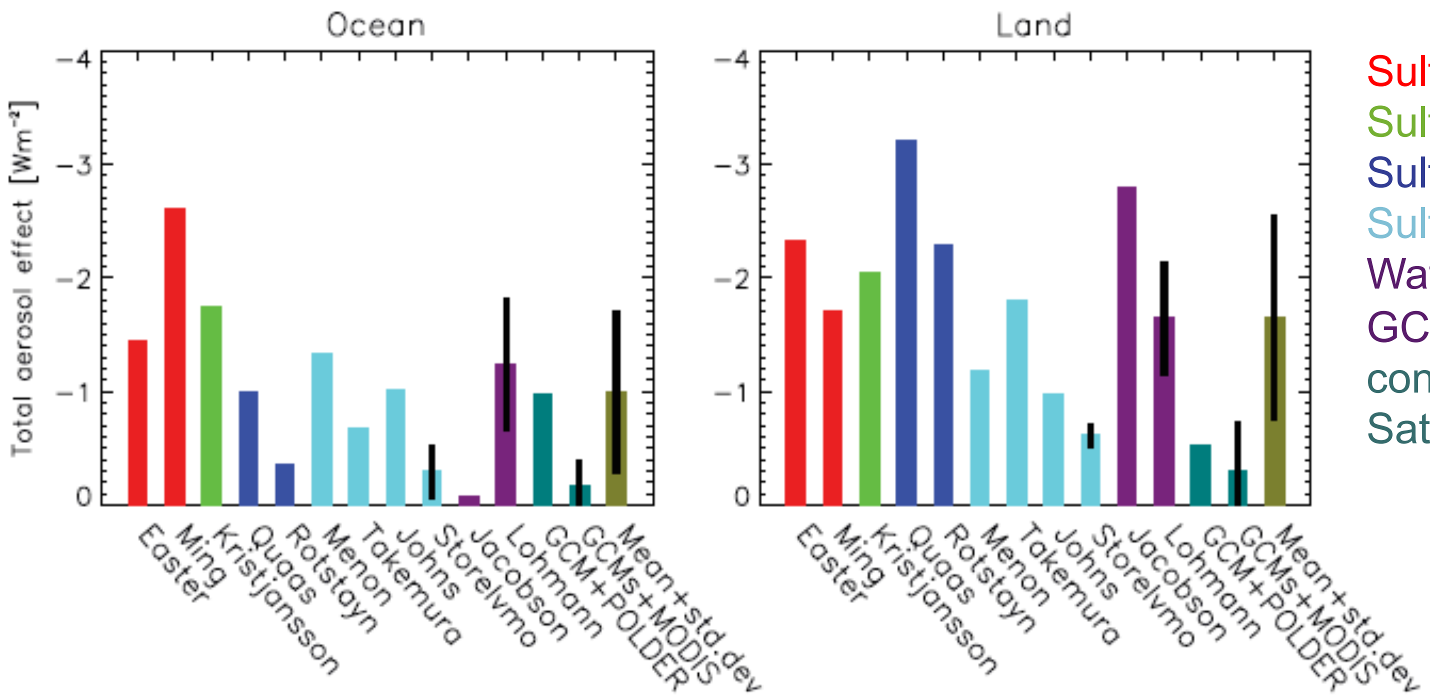
Lohmann and Feichter, ACP, 2005

Info C/O U. Lohmann

Total Aerosol Forcing IPCC AR4 figure 7.21

- 23 models contributed to IPCC AR4 aerosol effects
- 3 models had predicted sulfur
- Most used empirical relationship to calculate Cloud Drop Number
- Most used it only for radiative transfer, not for microphysics





Sulfate
Sulfate+BC
Sulfate+OC
Sulfate+BC+OC
Water and Ice
GCMs constrained by Satellite

Ghan et al, 2012, in press
(forcing contribution at top right)

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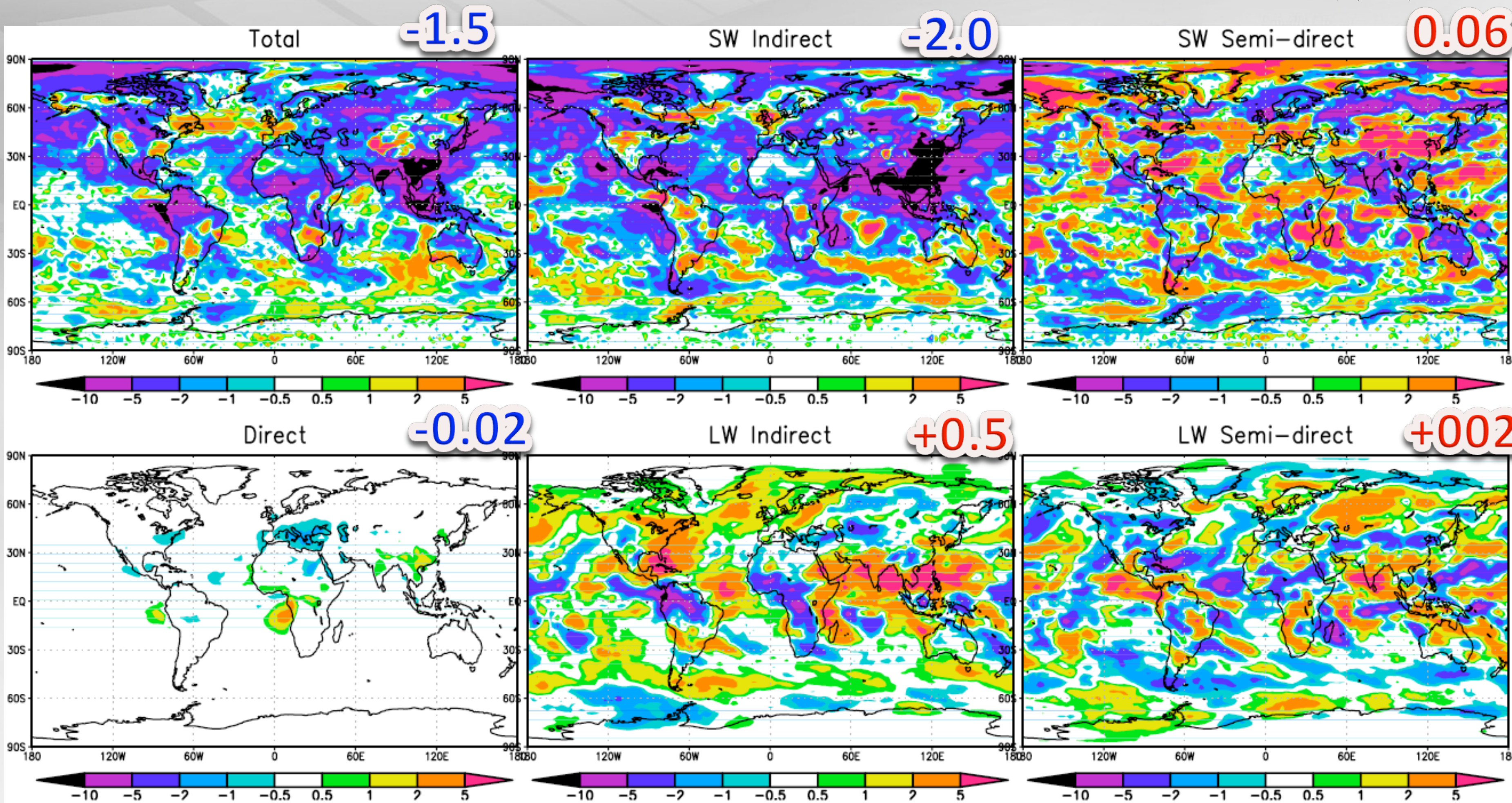


Figure 5. Decomposition of annual mean year 1850 to 2000 total aerosol forcing (W m^{-2}) at top of atmosphere into contributions from shortwave indirect and semi-direct effects, direct effects, and longwave indirect and semi-direct effects, from MAM3.

Decomposing Liquid Water path changes from Indirect and Semi-Direct effects

Ghan et al, 2012

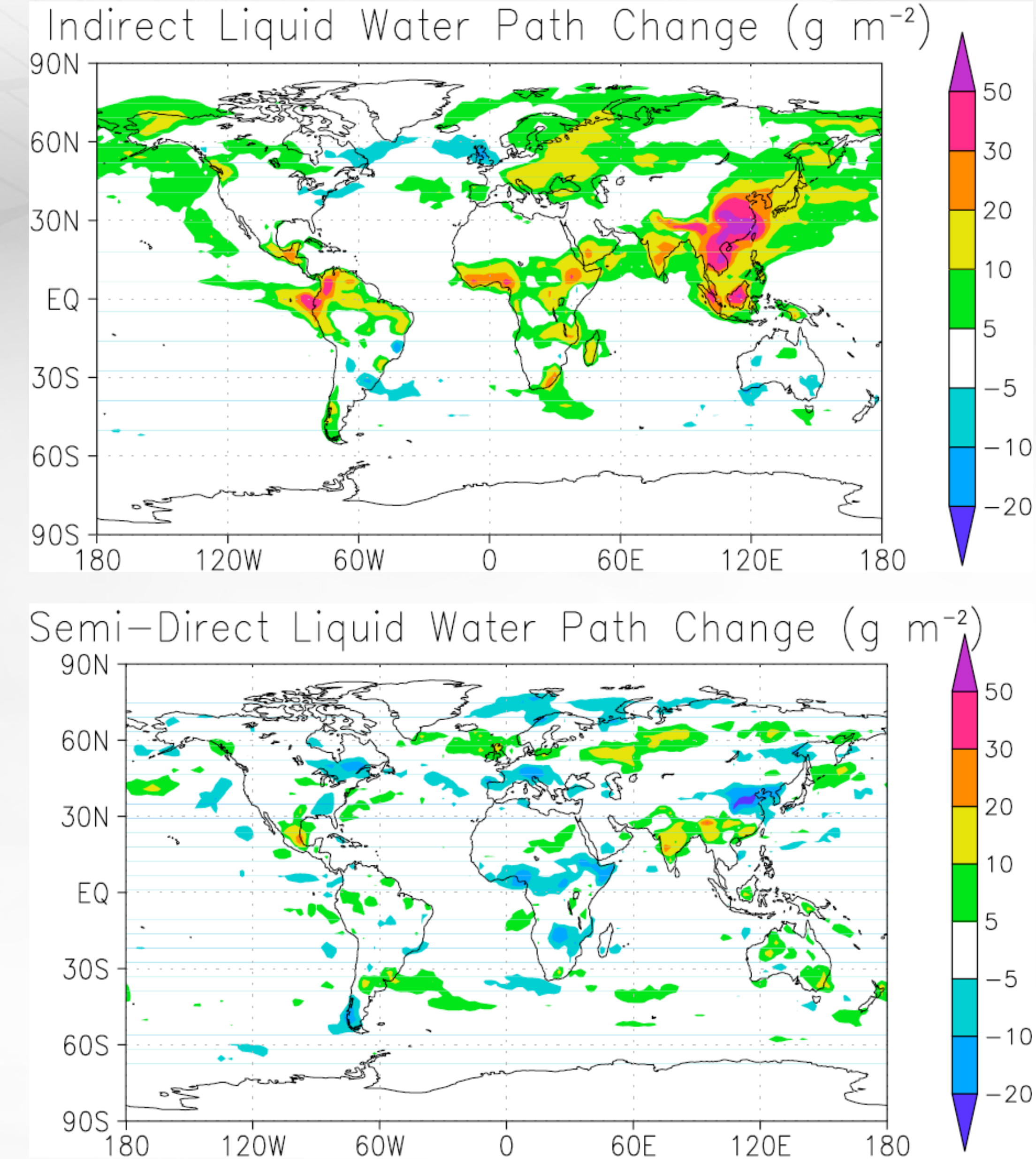
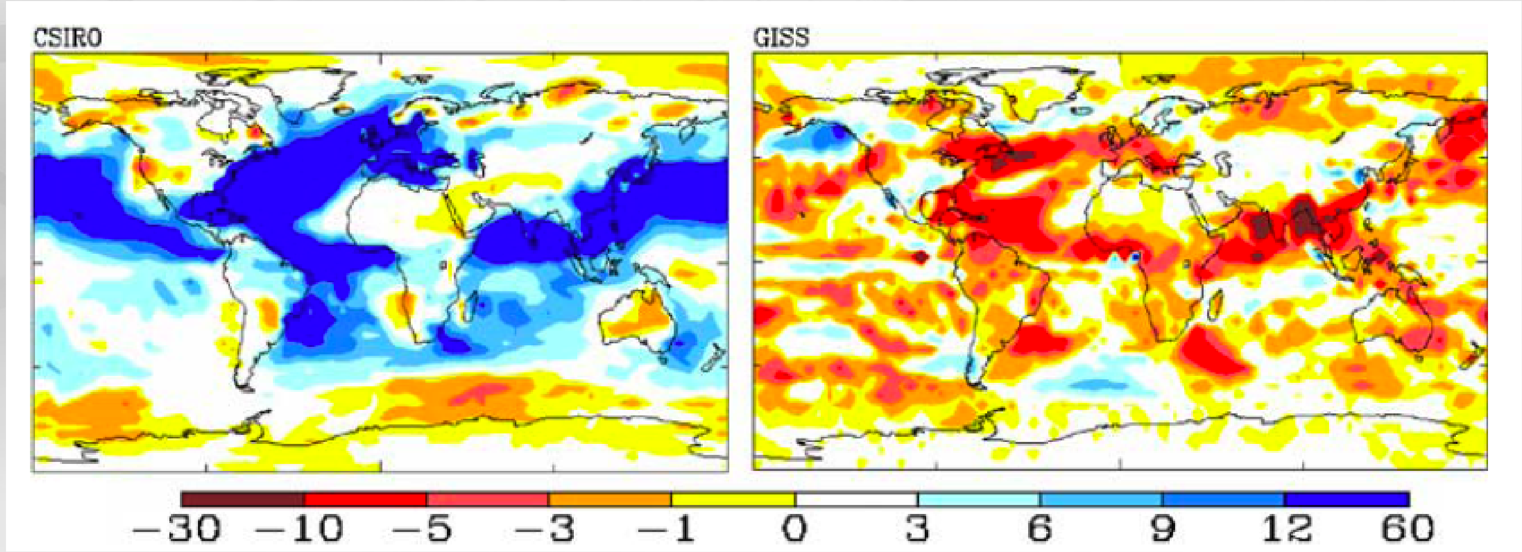


Figure 6. Year 1850 to 2000 change in annual mean liquid water path due to indirect effects (above) and semi-direct effects (below) from MAM3.

Menon and Rotstayn, 2006



Convective Liquid Water Path Changes due to aerosol increases

Indirect Forcing associated with Convection
-1.3 W/m2 (CSIRO), 0.02 W/m2 (GISS)

Role of Primary Aerosols in Cloud Albedo Effect.

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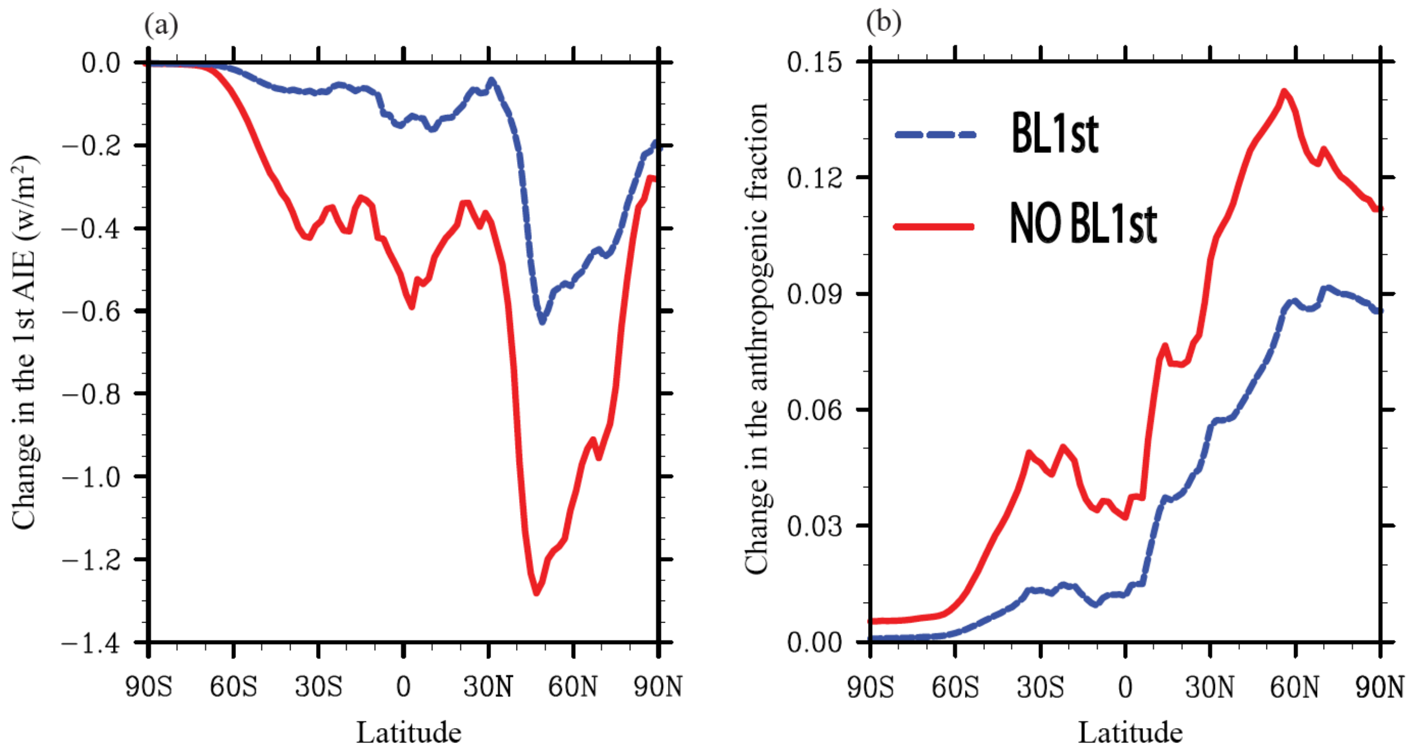
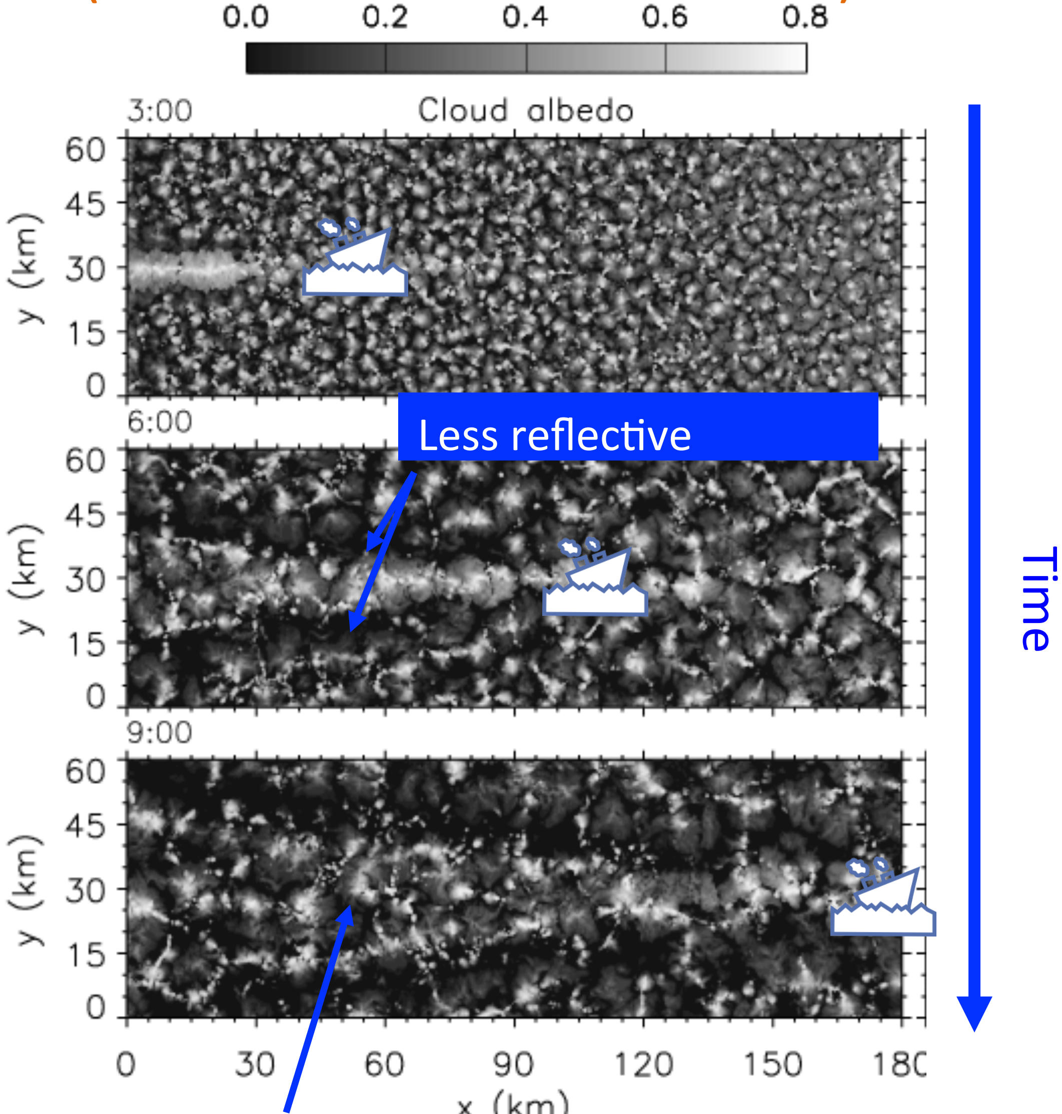
Wang and Penner



Cloud Albedo Effect	Without Primary SO4	With Primary SO4
Without BL Nucleation	-1.6	-2
With BL Nucleation	-1.5	-1.7

Change in cloud dynamics from aerosol injection (a satellite view of the model)

Wang and Feingold (2009b)



Clouds in ship track break up and open

Scientists are still searching for the right ways to characterize cloud aerosol interactions but progress is being made

550 M. O. Andreae: Global CCN and AOT correlations

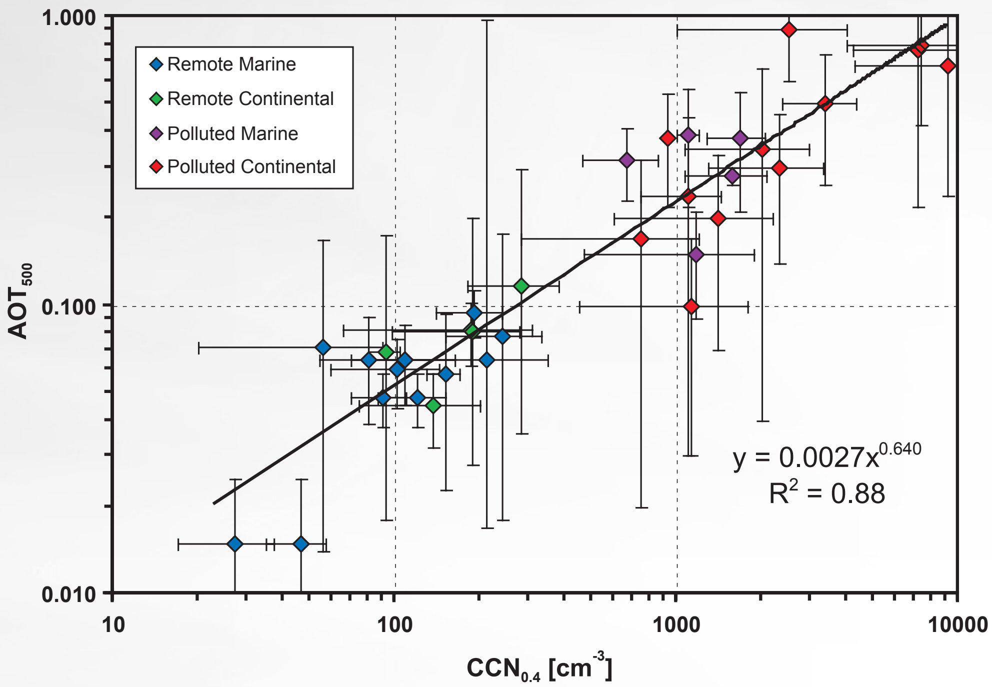


Fig. 1. Relationship between AOT_{500} and $CCN_{0.4}$ from investigations where these variables have been measured simultaneously, or where data from nearby sites at comparable times were available. The error bars reflect the variability of measurements within each study (standard deviations or quartiles).

Take home messages

- Aerosol impacts on clouds are readily seen in observations
- The range of impacts are so large that it is difficult to isolate which are the most important to climate
- Scientists are still searching for the right ways to characterize cloud aerosol interactions but progress is being made
- I think there are natural sources of aerosol, potentially important to the Indirect Effect that are poorly accounted for
  - Many VOC sources
  - Biogenic particles (marine and continental)
  - Accurate characterization of natural submicron aerosol sources
- GCM Characterization for aerosol cloud interactions is very challenging
  - To do it “right” requires explicit characterization of features that are sub-grid-scale
- Modelers will still assign a low level of confidence to their ability to quantify aerosol indirect effects in climate models