Indirect Effects: Aerosol and Cloud Microphysics

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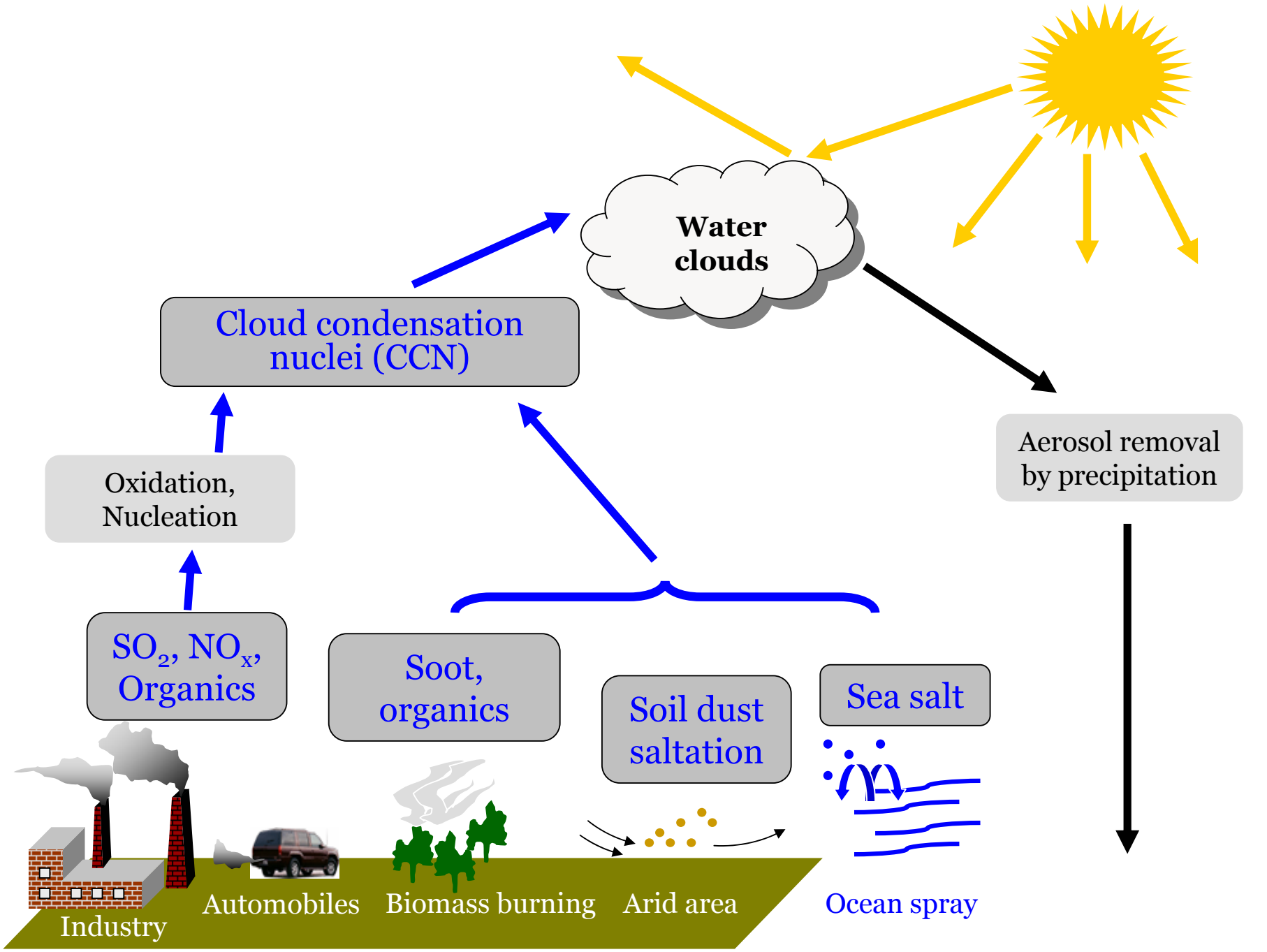
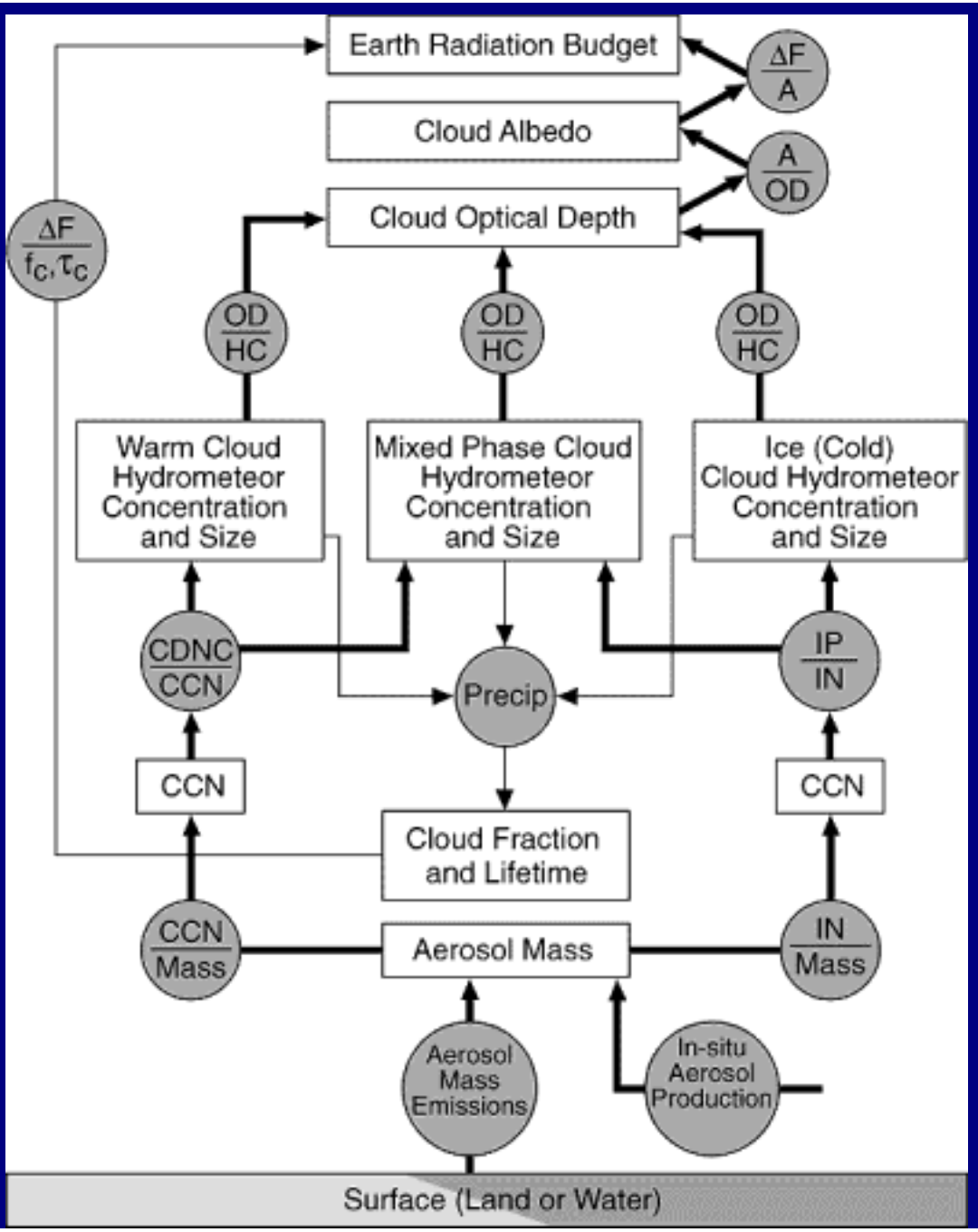
Outline

- What are aerosol indirect effects?
  - Twomey effect
  - Cloud lifetime effect
  - Semi-direct effect
- Evidence of the different indirect aerosol effects from field studies
- Estimates of global mean indirect aerosol effects
- Conclusions


Water clouds
Cloud condensation nuclei (CCN)
Oxidation, Nucleation
SO_2, NO_x, Organics
Soot, organics
Soil dust saltation
Sea salt
Aerosol removal by precipitation
Industry
Automobiles
Biomass burning
Arid area
Ocean spray

Indirect aerosol effects on climate

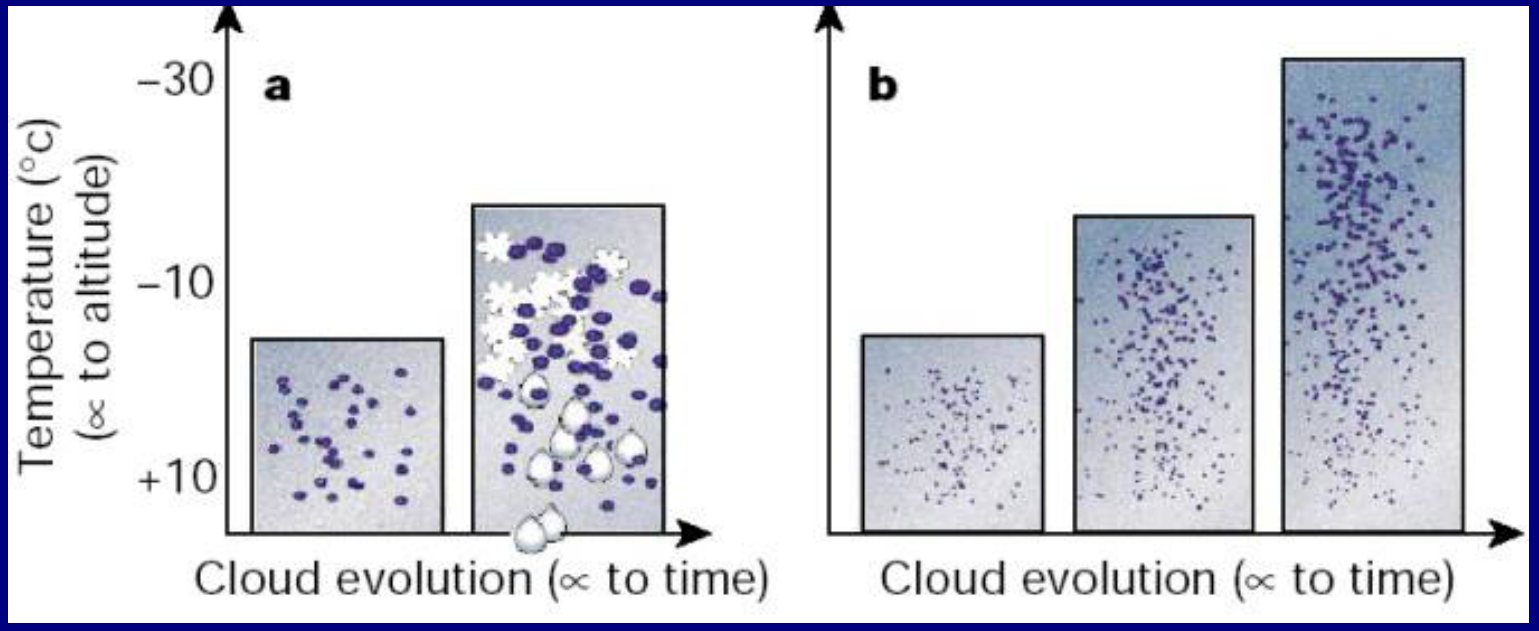


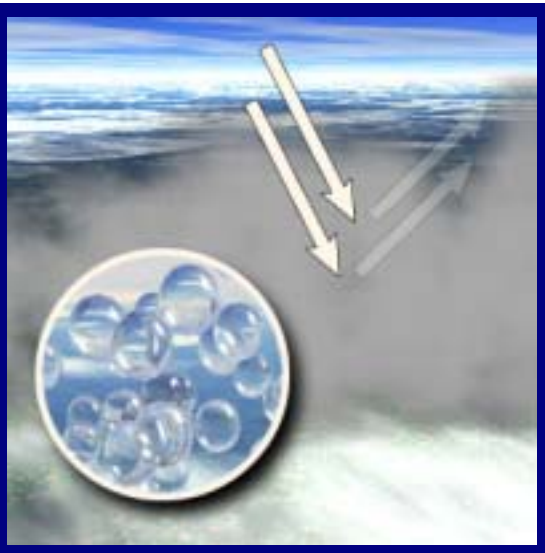
Penner et al., IPCC, 2001

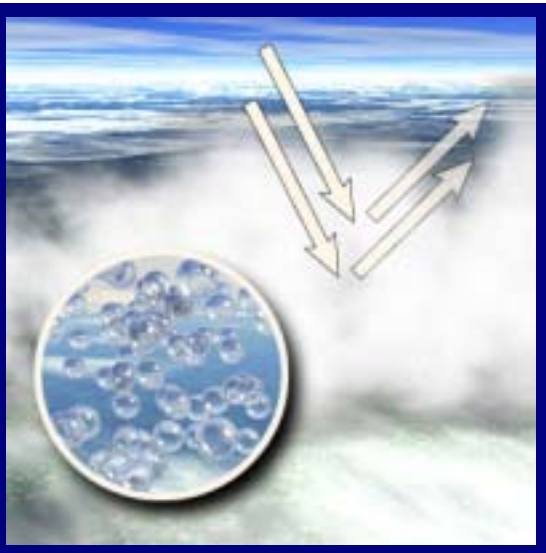
Different aerosol effects on water clouds

- Cloud albedo effect (pure forcing)
  - for a constant cloud water content, more aerosols lead to more and smaller cloud droplets → larger cross sectional area → more reflection of solar radiation
- Cloud lifetime effect (involves feedbacks)
  - the more and smaller cloud droplets will not collide as efficiently → decrease drizzle formation → increase cloud lifetime → more reflection of solar radiation
- Semi-direct effect (involves feedbacks)
  - absorption of solar radiation by black carbon within a cloud increases the temperature → decreases relative humidity → evaporation of cloud droplets → more absorption of solar radiation (opposite sign)

Cloud evolution in a clean and polluted atmosphere

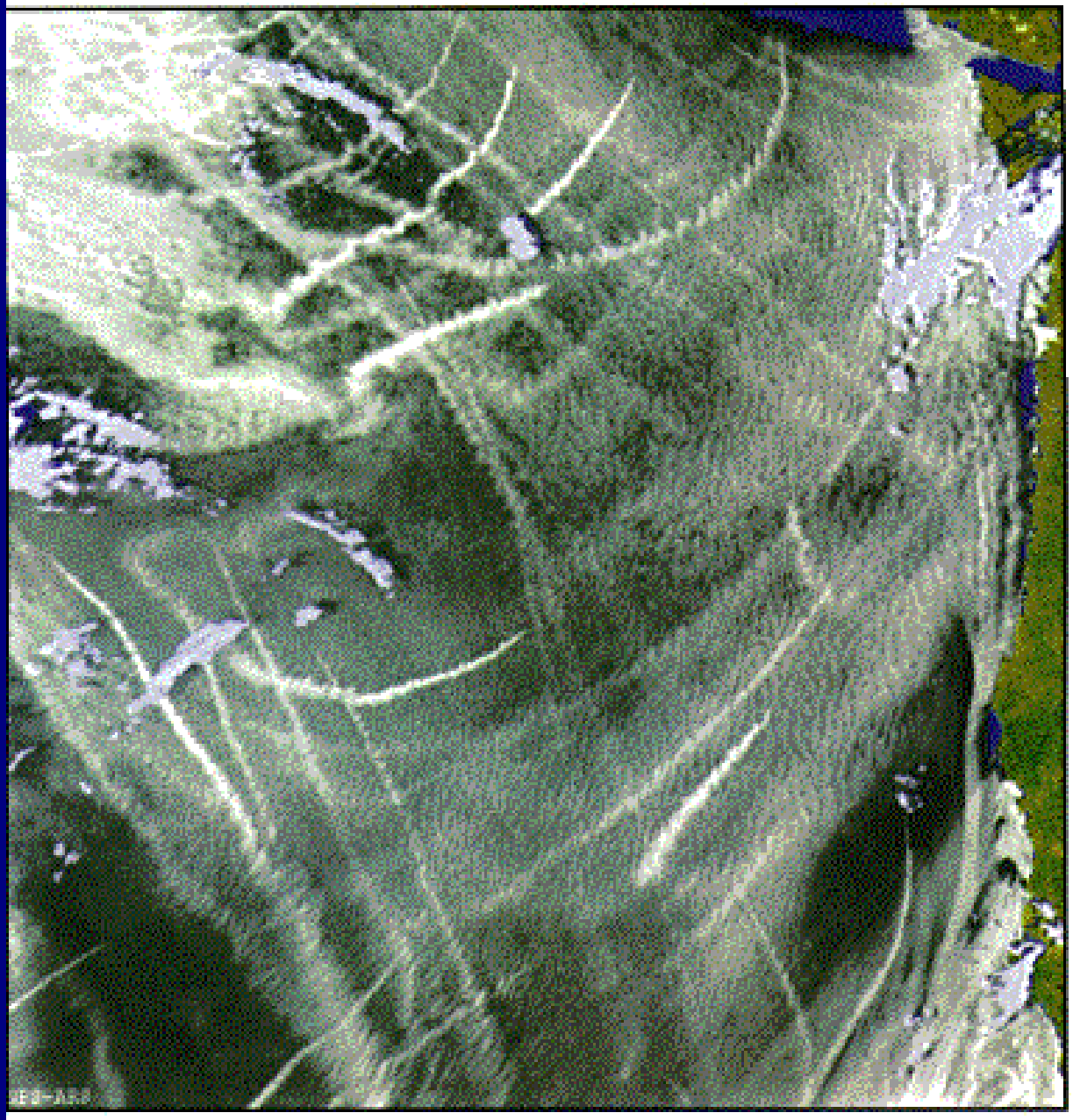






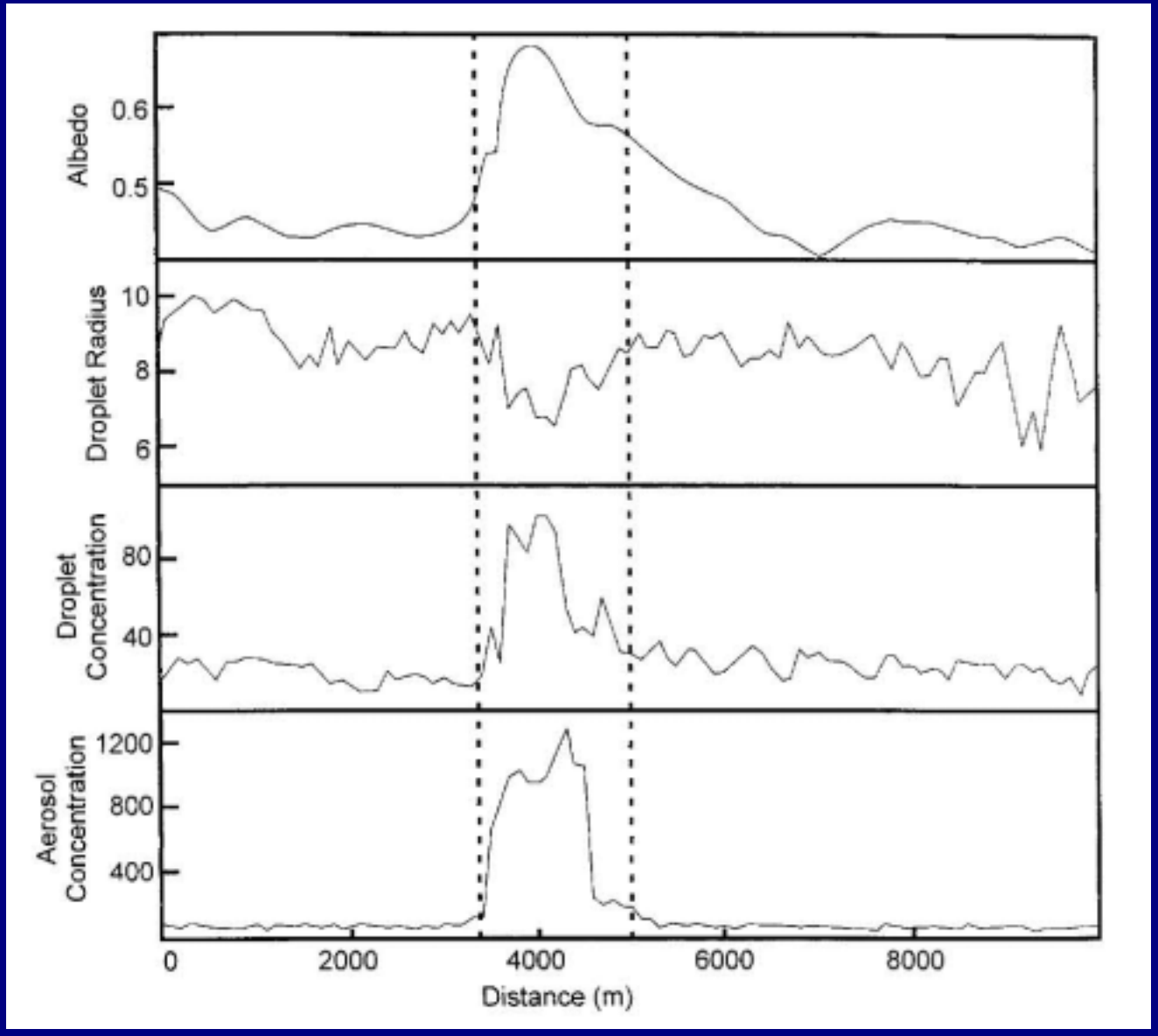
Kaufman et al. 2002

Shiptracks off the coast of Washington



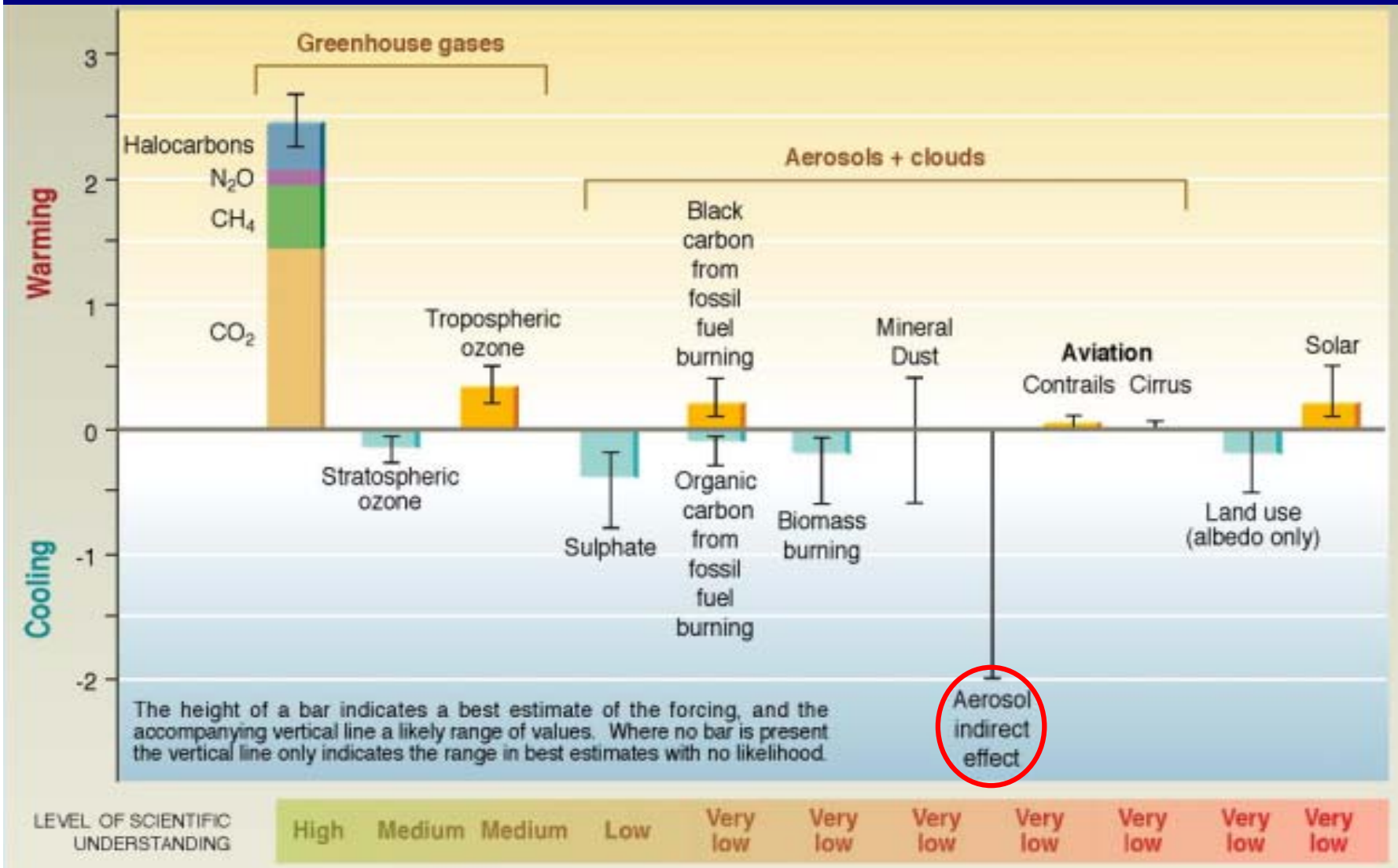
Durkee et al., 2000

Evidence for the cloud albedo effect

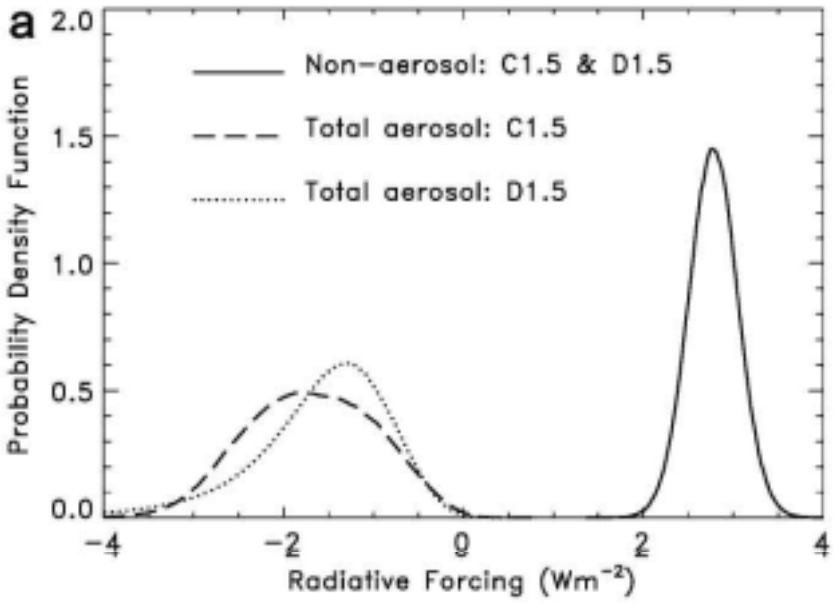


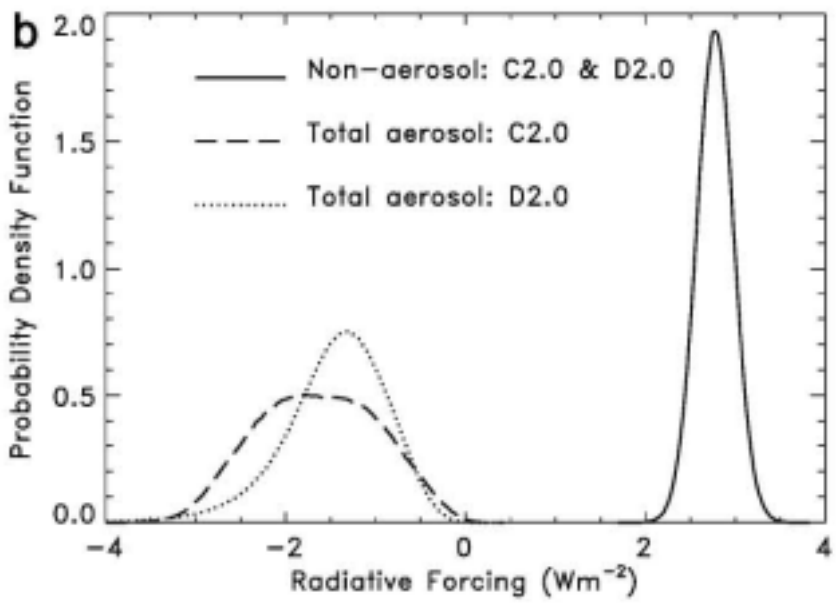
Durkee et al., JAS, 2000

Top-of-the-atmosphere global-mean radiative forcing (W m^{-2}) for 2000 relative to 1750 *[IPCC, 2001]*



Estimate of the total radiative (aerosol and non-aerosol) forcing since pre-industrial times

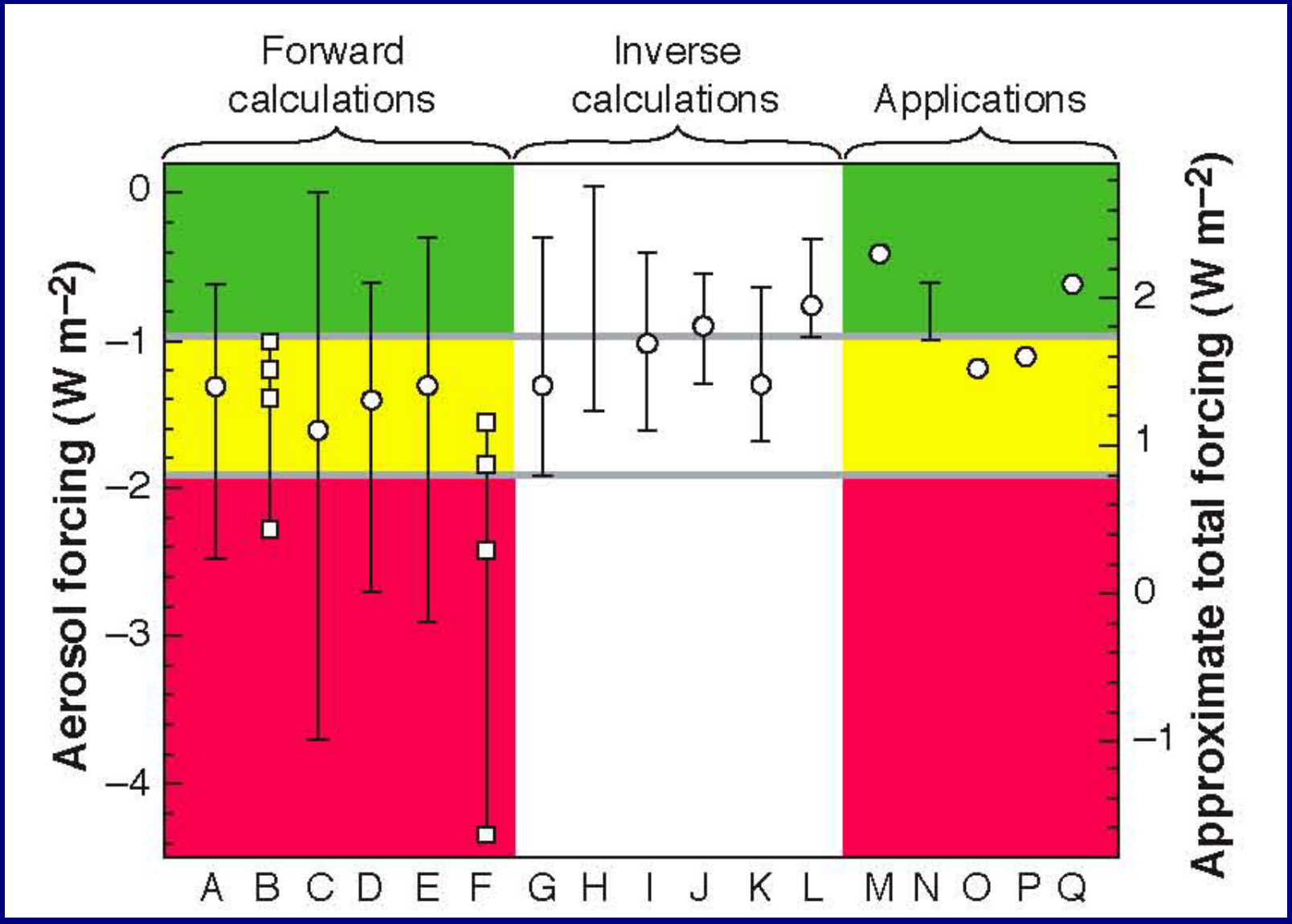




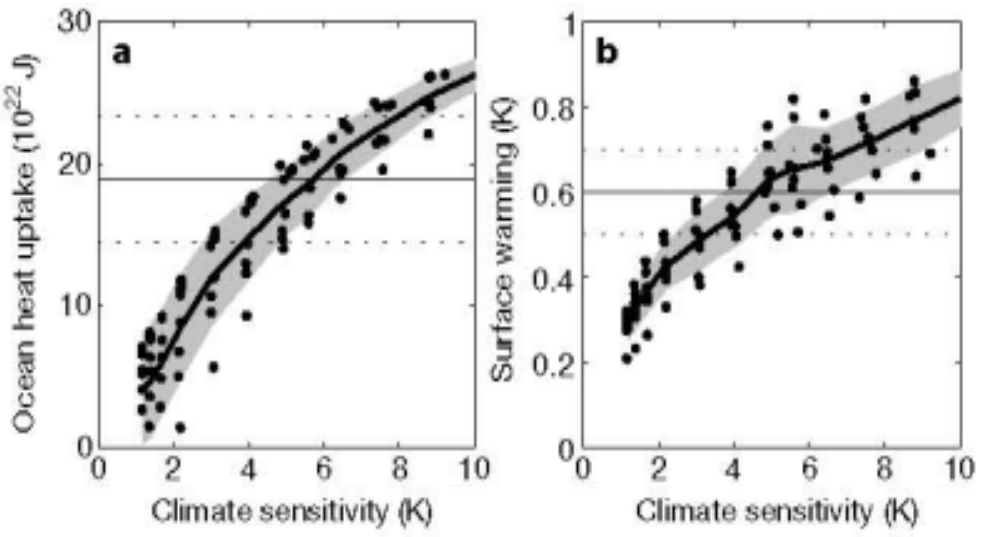
Boucher and Haywood, Clim. Dyn., 2001

Summary of aerosol forcing estimates

[Anderson et al., Science, 2003]



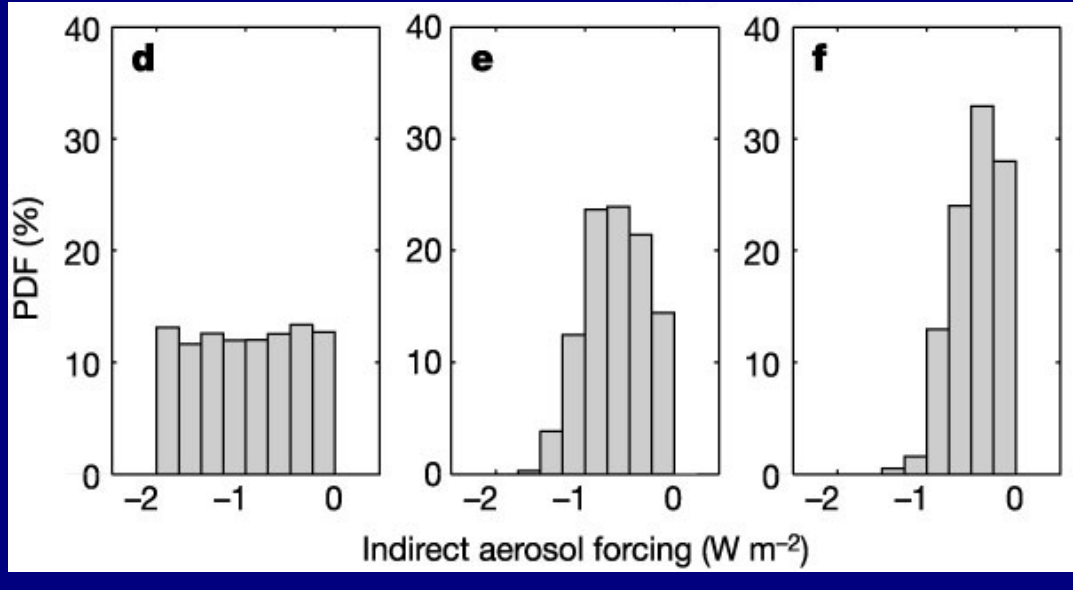
Example of an inverse simulation *[Knutti et al., 2002]*



Simulated relation between climate sensitivity ($\Delta T/2xCO_2$) and atmospheric and oceanic warming:
a) global ocean heat uptake from 1955-1995 in the upper 3 km
b) atmospheric temperature from 1900-2000

Probability density functions of the global mean indirect effect:

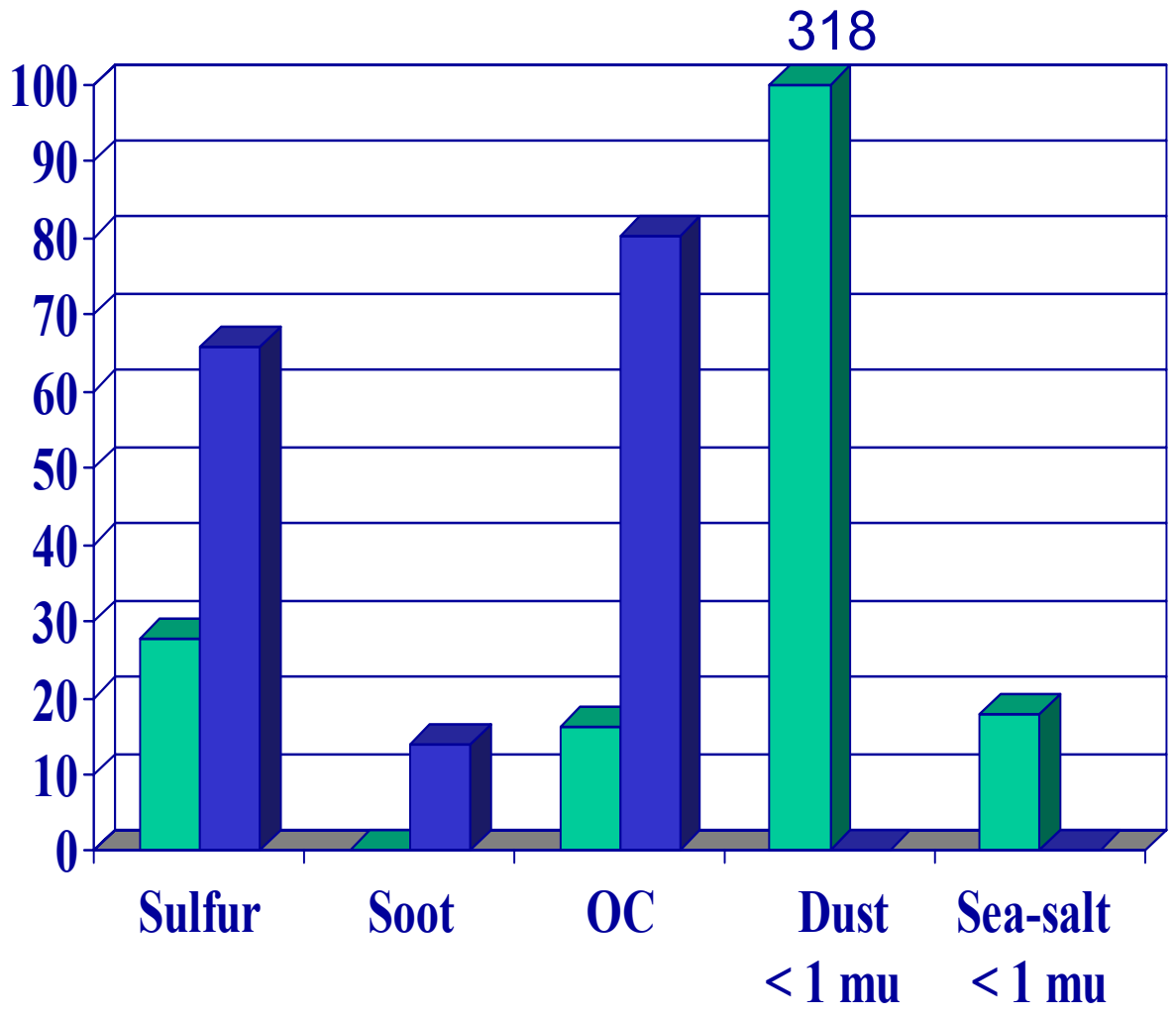
d) not constrained
e) contrained by observed T record
f) also constrained by the IPCC climate sensitivity



How are aerosol effects on clouds simulated in climate models?

- Predict aerosol mass concentrations:
  - *sources* (aerosol emissions of the major aerosol species: sulfate, black carbon, organic carbon, sea salt, dust)
  - *transformation* (dry and wet deposition, chemical transformation and transport)
- Need a good description of cloud properties:
  - *precipitation formation* (collision/coalescence of cloud droplets and ice crystals, riming of snow flakes)
- Need to parameterize aerosol-cloud interactions:
  - *cloud droplet nucleation* (activation of hygroscopic aerosol particles)
  - *ice crystal formation* (contact and immersion freezing, homogeneous freezing in cirrus clouds)

Global annual mean aerosol emissions (representative for 1985)



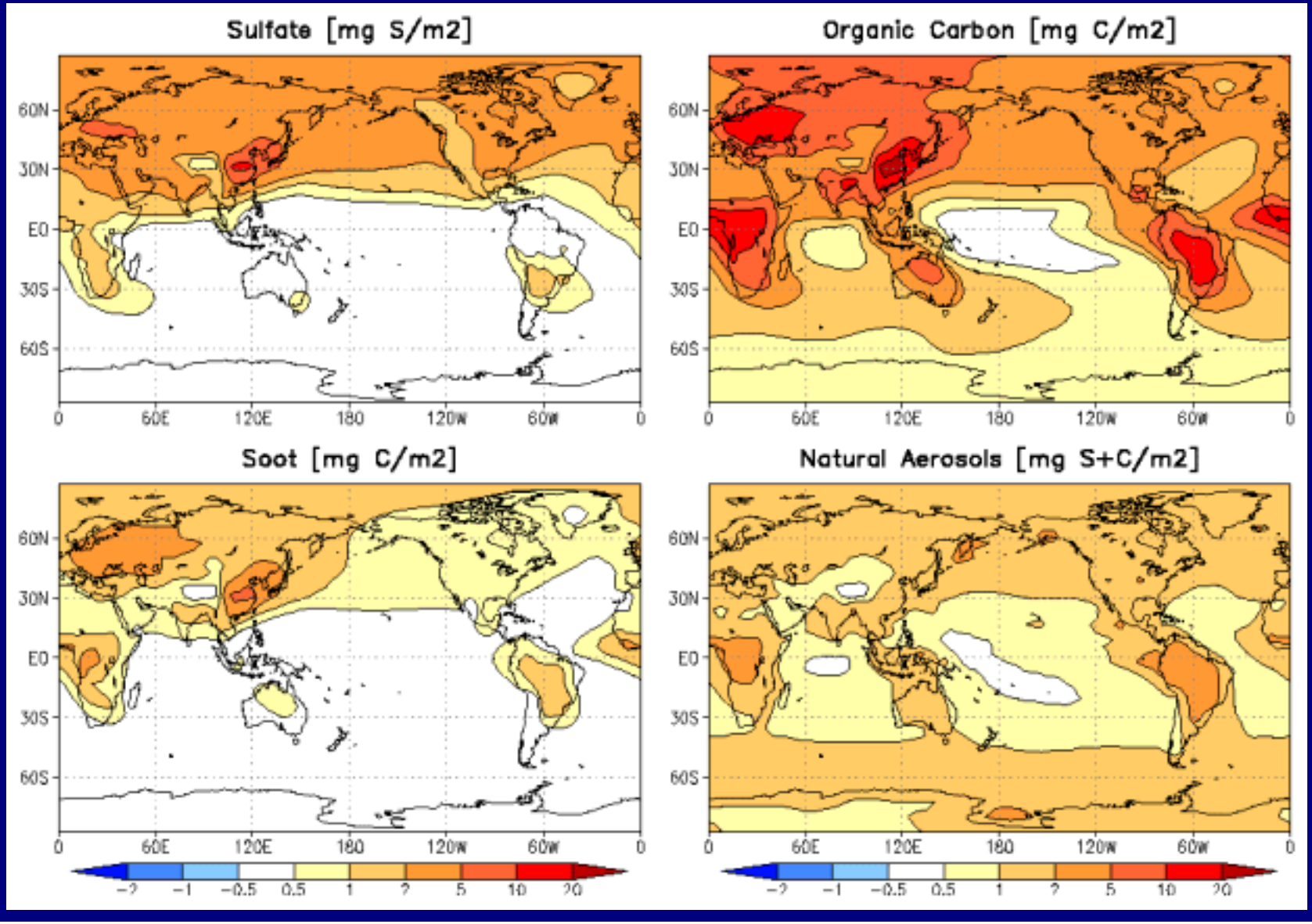
Tg S/C per year

Natural

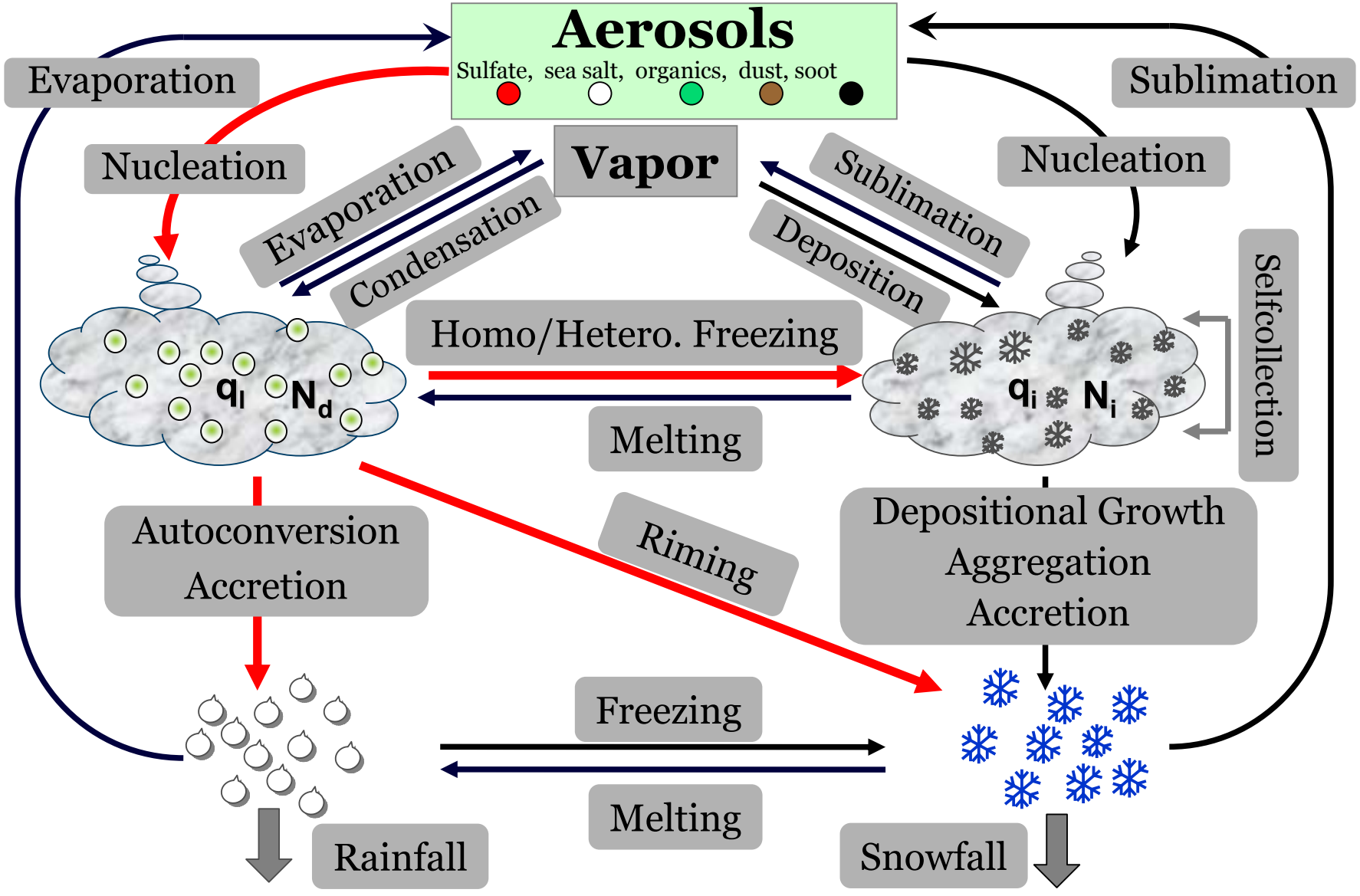
Anthropogenic

Anthropogenic Emissions from *Biomass burning* and *Fossil fuel use*

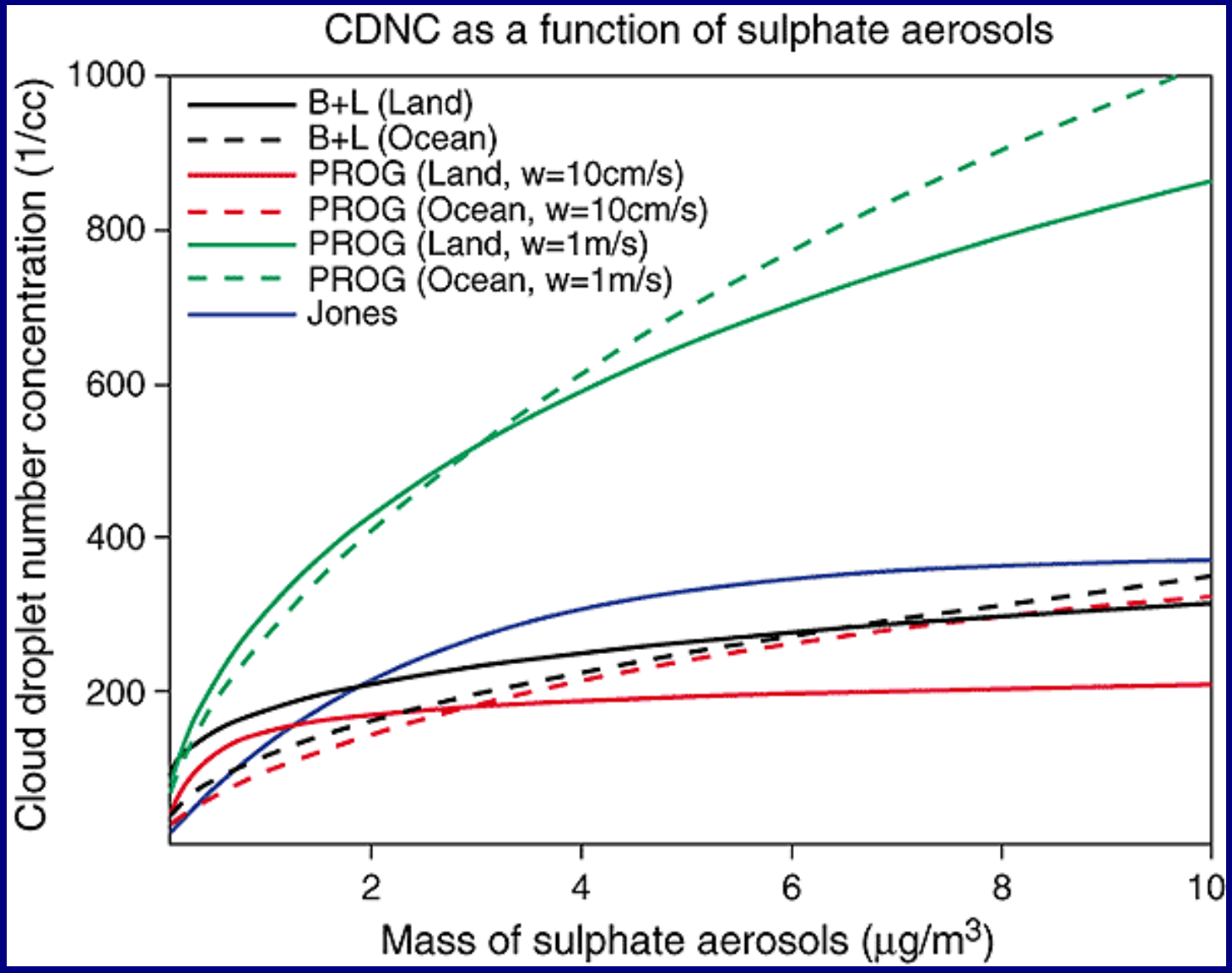
Aerosol mass resulting from human activity



Cloud microphysical processes in a climate model

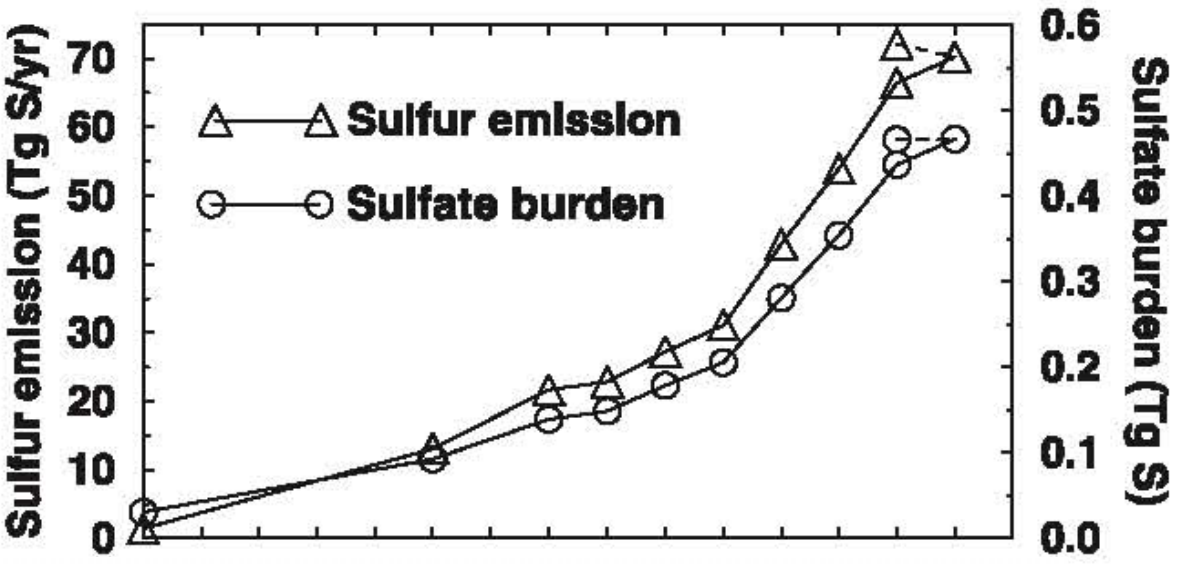


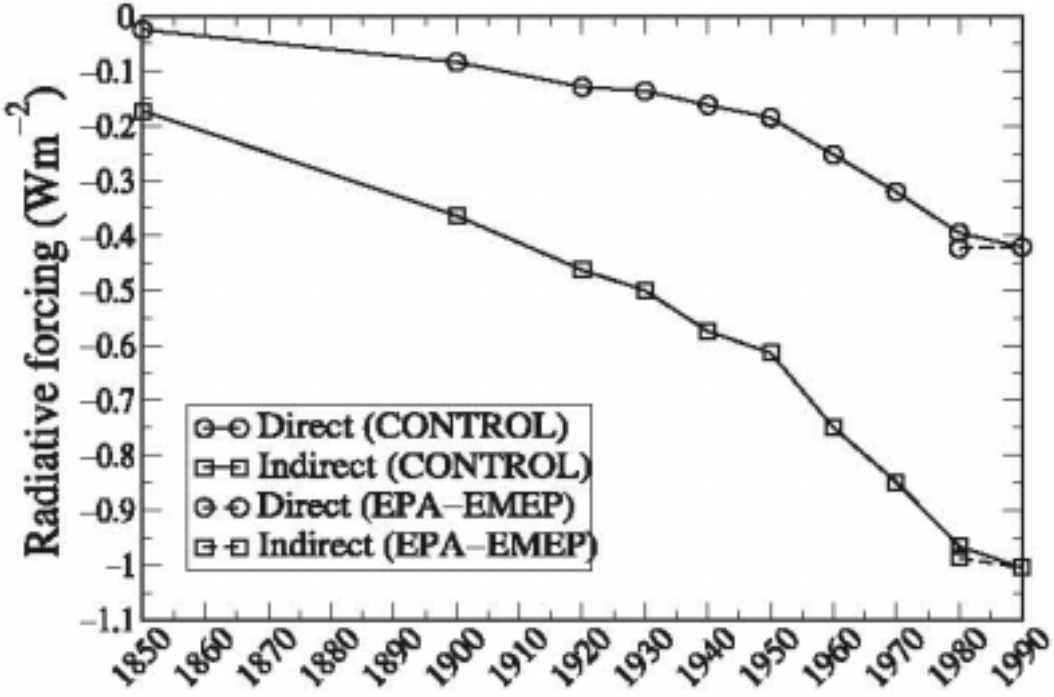
Aerosol - cloud droplet relationships



Penner et al., IPCC, 2001

Temporal evolution of sulphur emission and direct and indirect radiative forcing of sulfate aerosols



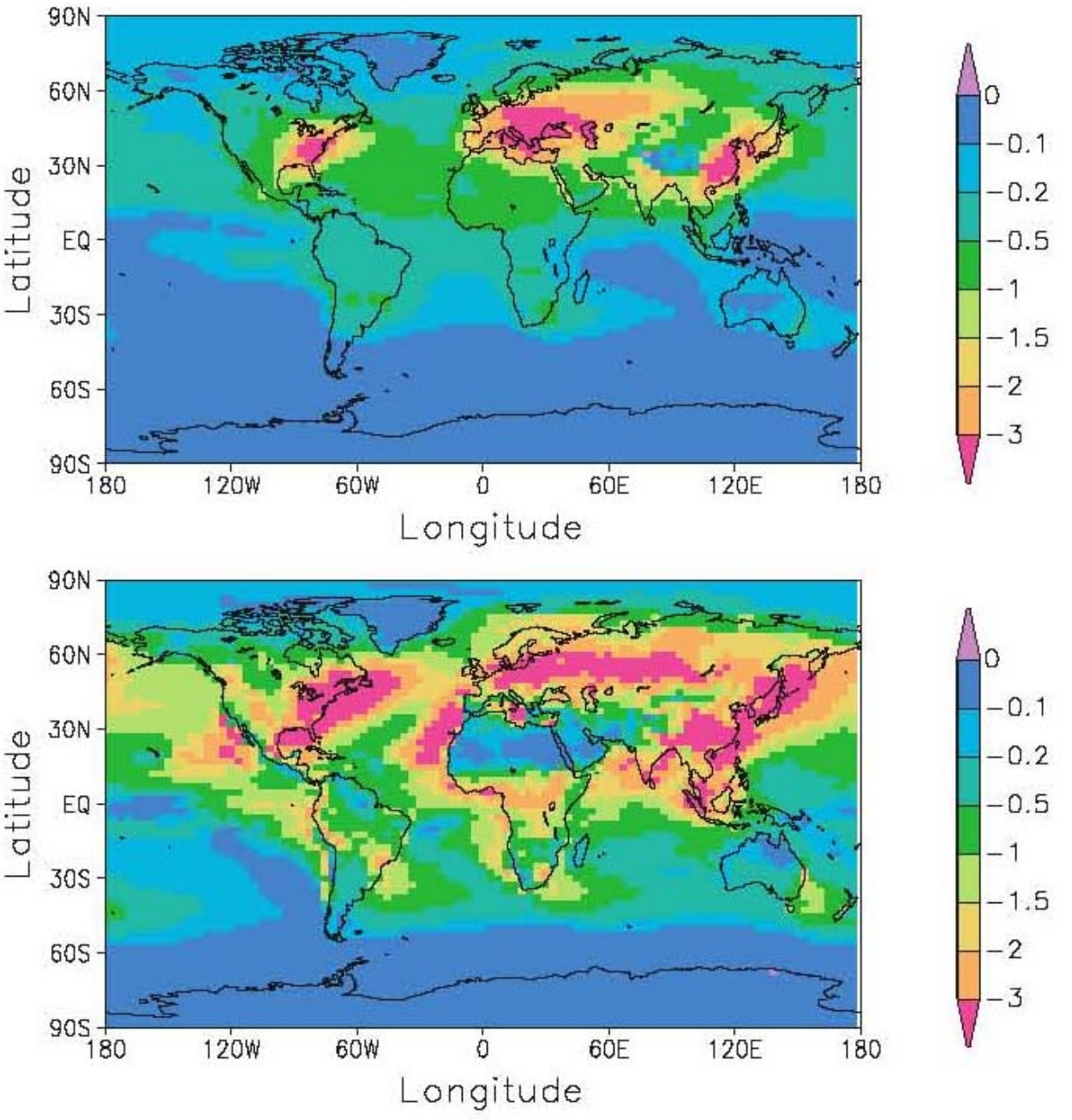


Boucher and Pham, GRL, 2002

Top panel: Direct effect of sulphate aerosols (−0.4 W/m²)

Lower panel: Indirect cloud albedo effect (−1.0 W/m²)

Boucher and Pham, GRL, 2002



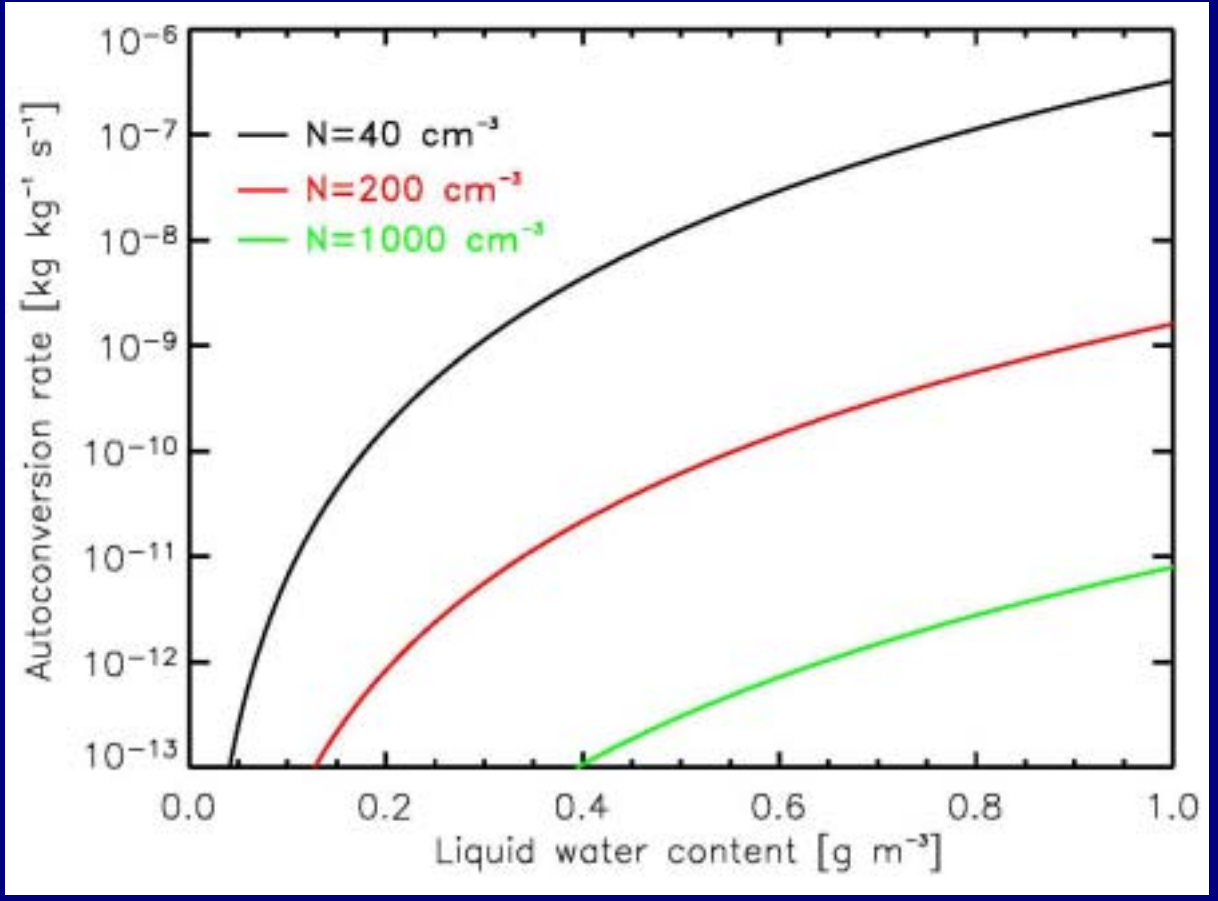
Cloud lifetime effect calculations

The autoconversion rate *(precipitation formation rate in clouds with no ice)* in climate models depends on the cloud water content q_l and the number concentration of cloud droplets N:

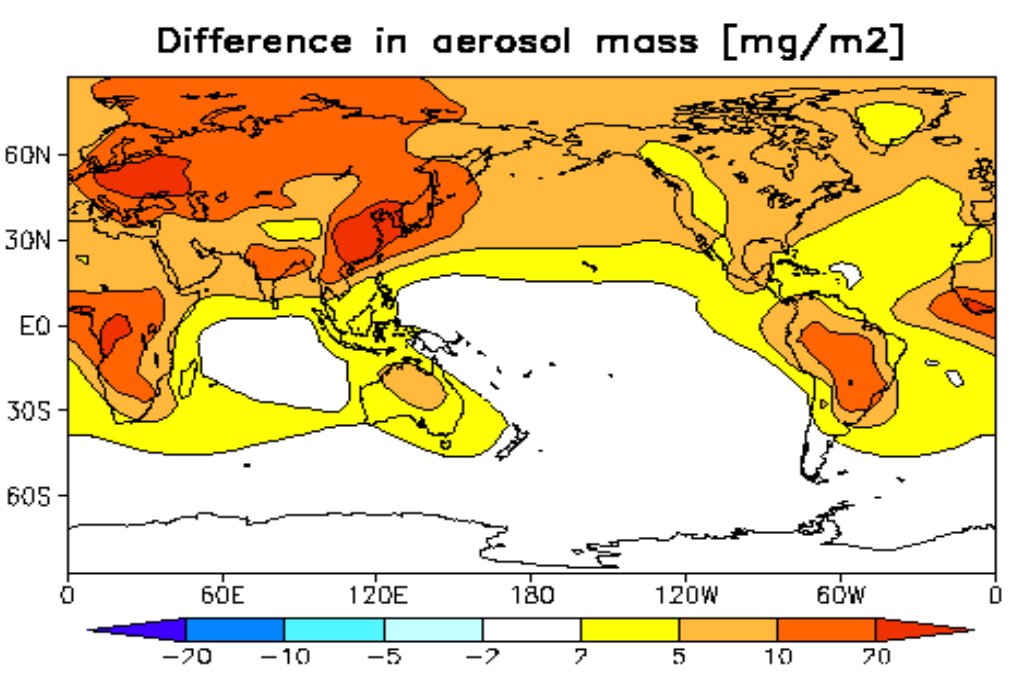
$Q_{aut} \sim q_l^a N^b$

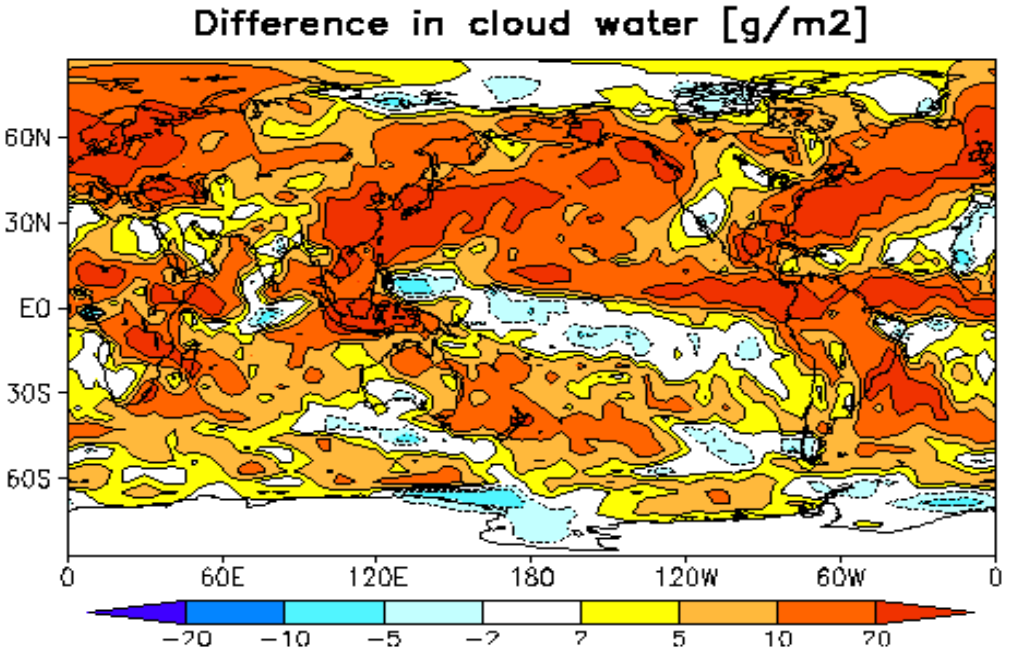
with a=2-5
b=-1 to -3.3

→ more cloud droplets decrease drizzle formation



Aerosol effects on cloud water content between pre-industrial and present-day times

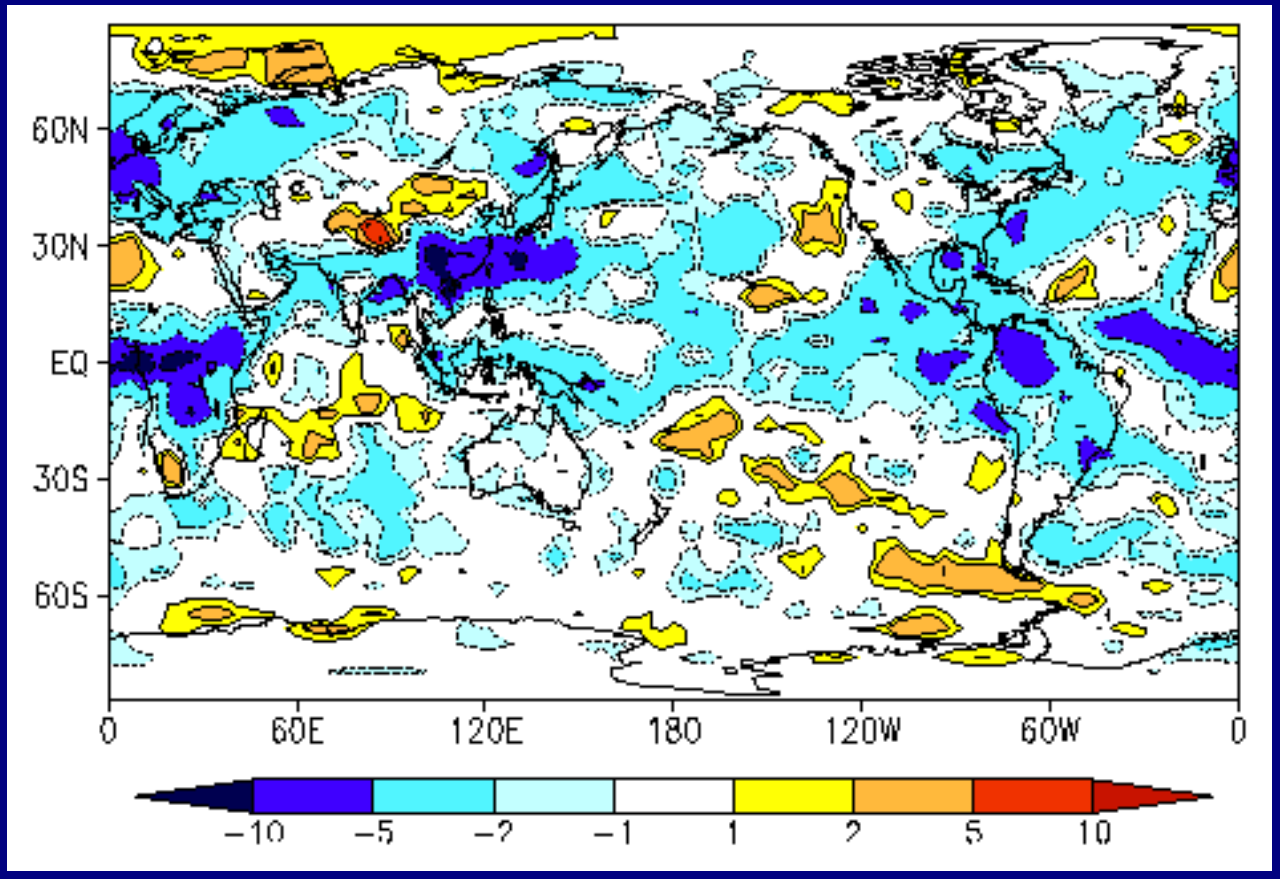




Indirect aerosol effect

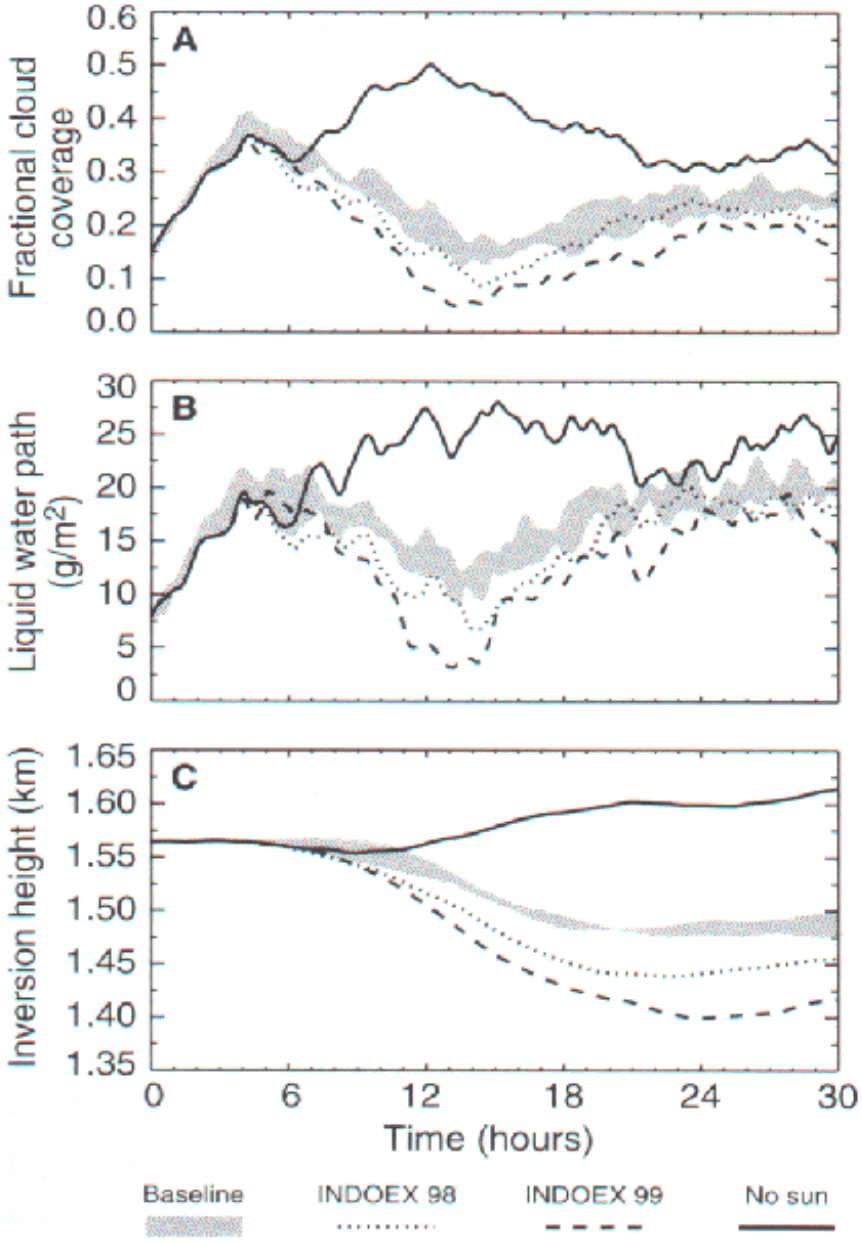
Difference between two 5-year simulations one with pre-industrial and one with present-day aerosol emissions

[Global mean change in top-of-the-atmosphere net radiation: -1.4 W/m²]



Peng and Lohmann, GRL, 2003

Semi-direct effect

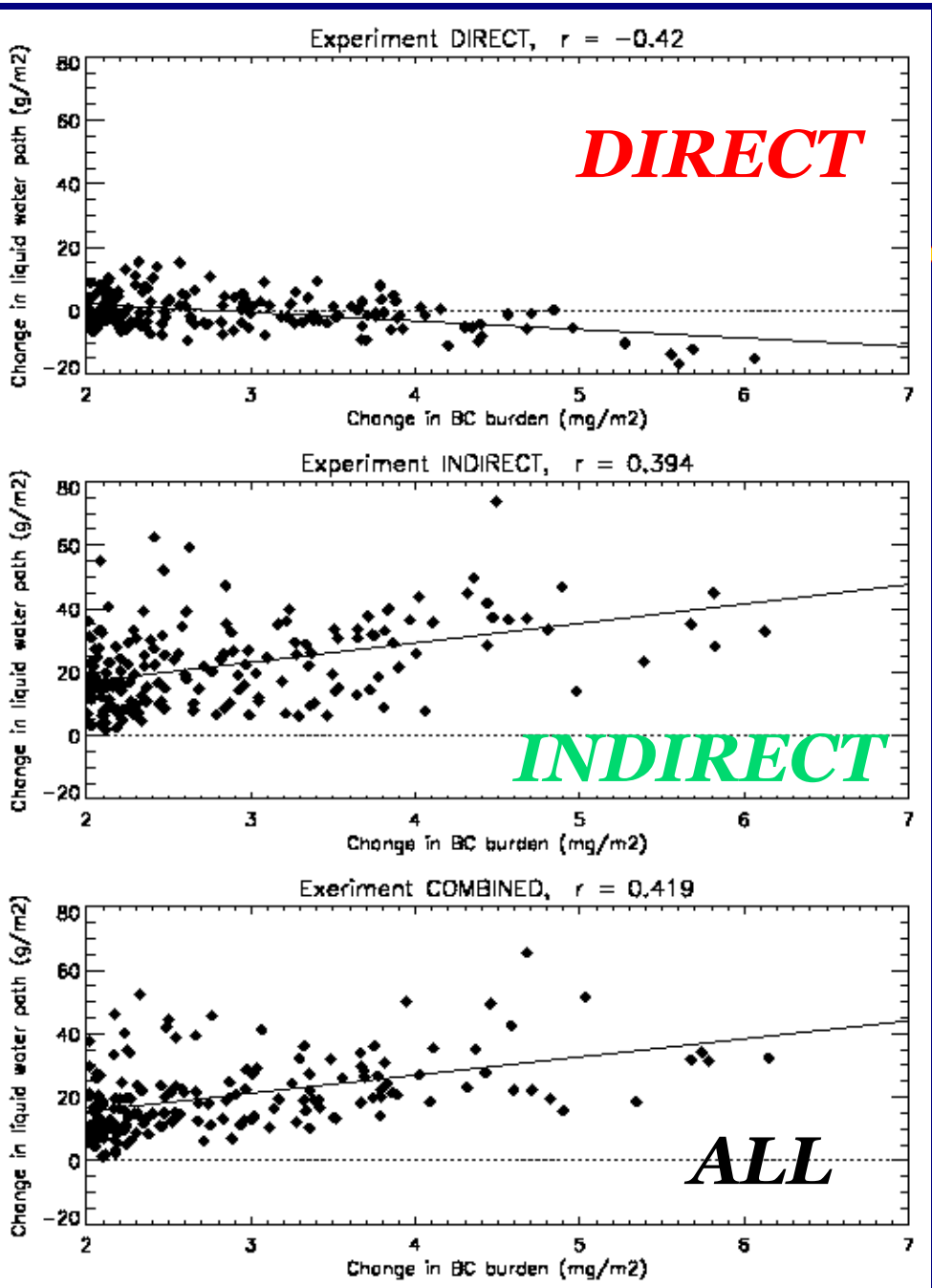


Ackerman et al., Science, 2000

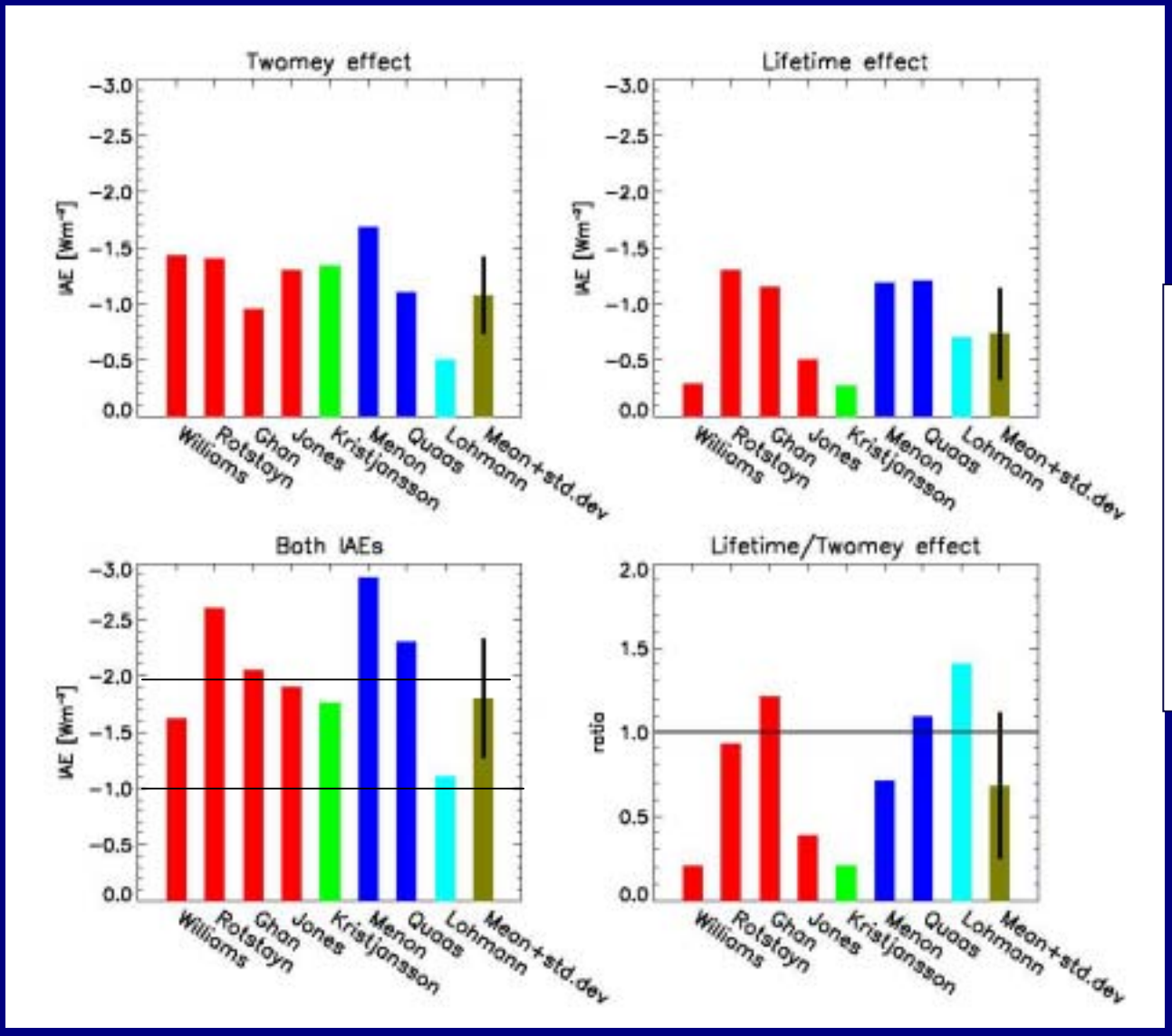
Semi-direct effect

Change in liquid water path with black carbon for the experiments DIRECT, INDIRECT and ALL

Lohmann and Feichter, GRL, 2001



Global mean indirect aerosol effect (Twomey vs. lifetime) from different climate models



Sulfate

Soot (BC) and sulfate

Organic aerosols (OC) and sulfate

BC, OC and sulfate

Lohmann and Feichter, ACP, 2005

Summary

- Aerosol effects on the radiative balance are significant. At the top-of-the atmosphere, the cooling effect from sulfate and organic aerosols is partly offset by the warming by black carbon.
- All aerosols cause a reduction of solar radiation at the Earth surface.
- In addition aerosols significantly influence air quality and the hydrological cycle.
- We will know more about each individual aerosol species, including their effects on ice clouds, by the time the Forth IPCC Assessment report is published.