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?

Johannes **Quaas**[1] and Ulrike **Lohmann**[2]

1 Institute for Meteorology · Universität Leipzig
johannes.quaas@uni-leipzig.de · www.uni-leipzig.de/~quaas

2 Institute for Atmospheric and Climate Science· Eidgenössische Technische Hochschule Zürich
ulrike.lohmann@env.ethz.ch · http://www.iac.ethz.ch/people/ulohmann

Clouds and Aerosols

(1) How do aerosols, clouds and precipitation interact?

~~(2) Why is it relevant?~~

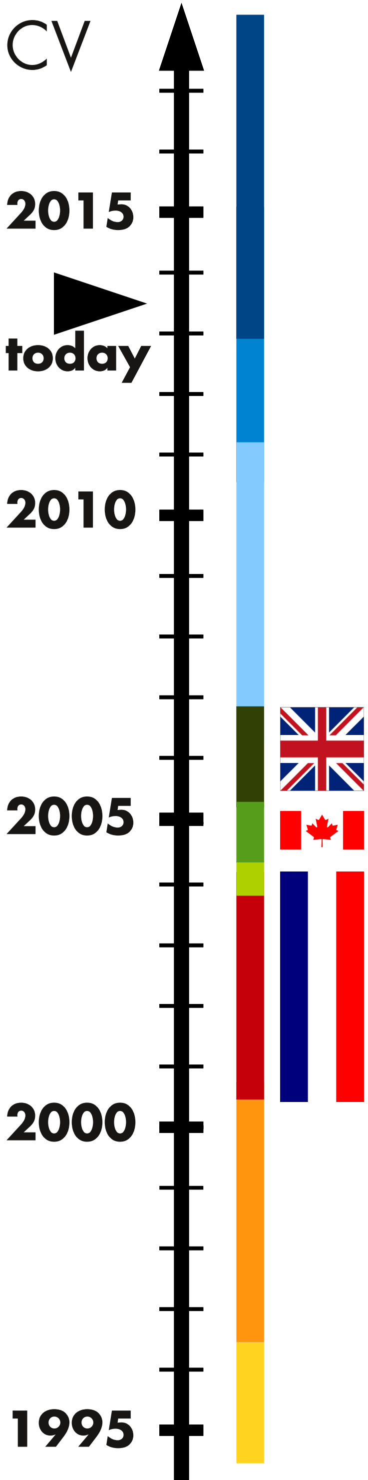
(3) How do we model and observe these interactions?

Johannes **Quaas**[1] and Ulrike **Lohmann**[2]

1 Institute for Meteorology · Universität Leipzig
johannes.quaas@uni-leipzig.de · www.uni-leipzig.de/~quaas

2 Institute for Atmospheric and Climate Science· Eidgenössische Technische Hochschule Zürich
ulrike.lohmann@env.ethz.ch · http://www.iac.ethz.ch/people/ulohmann

CV



Lecturer at EUCLIPSE summer school

Professor, Univ Leipzig

Junior Research Group, MPI for Meteorology, Hamburg

Post-Doc, MetOffice Hadley Centre, Exeter

Post-Doc, MPI-M, Hamburg and Dalhousie Univ, Halifax

Post-Doc, LMD/IPSL Palaiseau

PhD, LMD/IPSL, École Polytechnique, Paris

Studies of Meteorology, Univ Cologne

Studies of Physics, Univ Essen

1. Aerosols

Definition: Solid or liquid particles suspended in a gas
Here: All particles in the atmosphere that are not cloud or precipitation particles

e.g., Stier et al., Atmos. Chem. Phys. 2005

1. Aerosols

Definition: Solid or liquid particles suspended in a gas
Here: All particles in the atmosphere that are not cloud or precipitation particles

1.1 Chemical characterisation

Species		**Source (partly anthropogenic)**
Mineral dust	(DU)	windblown, mostly from deserts (also: roads, agriculture)
Sea salt	(SS)	windblown
Sulfate	(SO_4)	combustion, biogeochemistry, volcanos
Soot, Black carbon	(BC)	combustion (fossil fuel, biomass, wildfires)
Organic matter	(OM)	combustion, biogeochemistry
Nitrate	(NH_4)	air chemistry, fertilisers, combustion

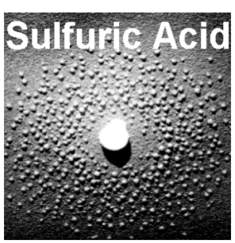
e.g., *Stier et al., Atmos. Chem. Phys. 2005*

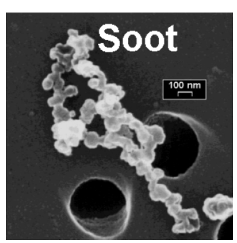
1. Aerosols

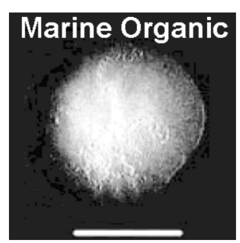
Definition: Solid or liquid particles suspended in a gas
Here: All particles in the atmosphere that are not cloud or precipitation particles

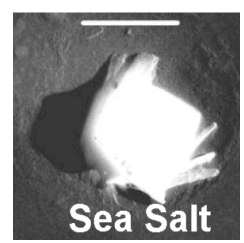
1.1 Chemical characterisation

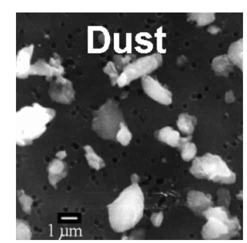
Species		Source (partly **anthropogenic**)
Mineral dust	(DU)	windblown, mostly from deserts (also: roads, agriculture)
Sea salt	(SS)	windblown
Sulfate	(SO_4)	combustion, biogeochemistry, volcanos
Soot, Black carbon	(BC)	combustion (fossil fuel, biomass, wildfires)
Organic matter	(OM)	combustion, biogeochemistry
Nitrate	(NH_4)	air chemistry, fertilisers, combustion









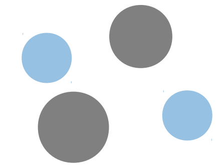


Primary aerosols (emitted in form of particles)

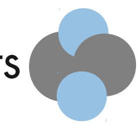
Secondary aerosols (emitted as gas, transformed in the atmosphere to particles)

1.2 Mixing state

External mixture: Pure chemical composition per particle

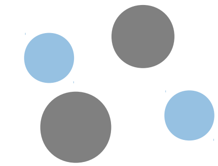


Internal mixture: A particle consists of different chemical components

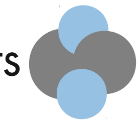


1.2 Mixing state

External mixture: Pure chemical composition per particle



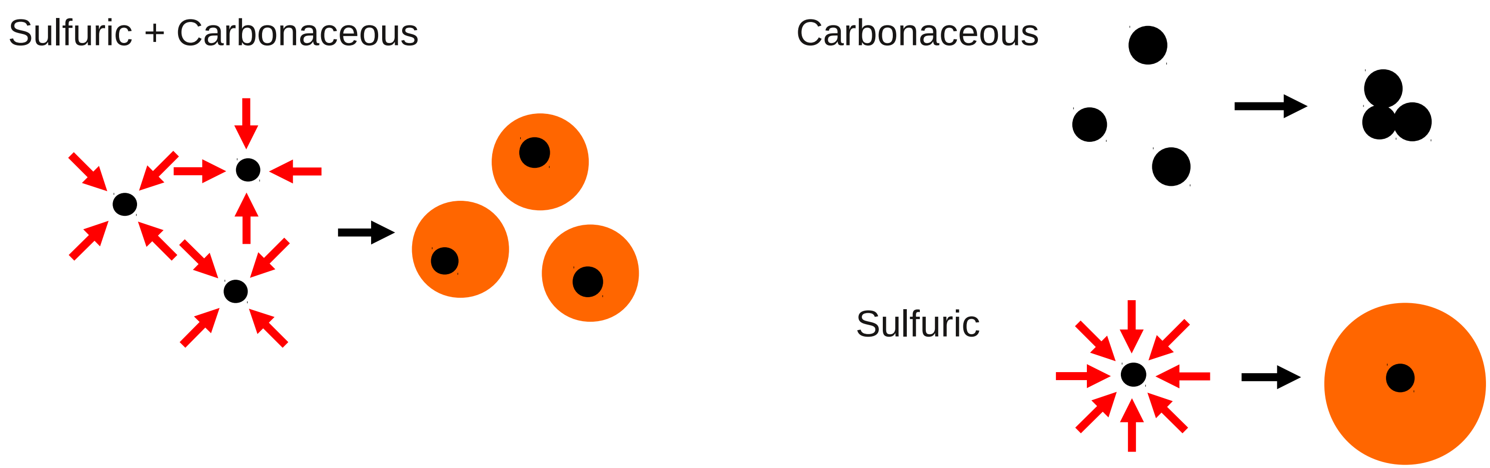
Internal mixture: A particle consists of different chemical components



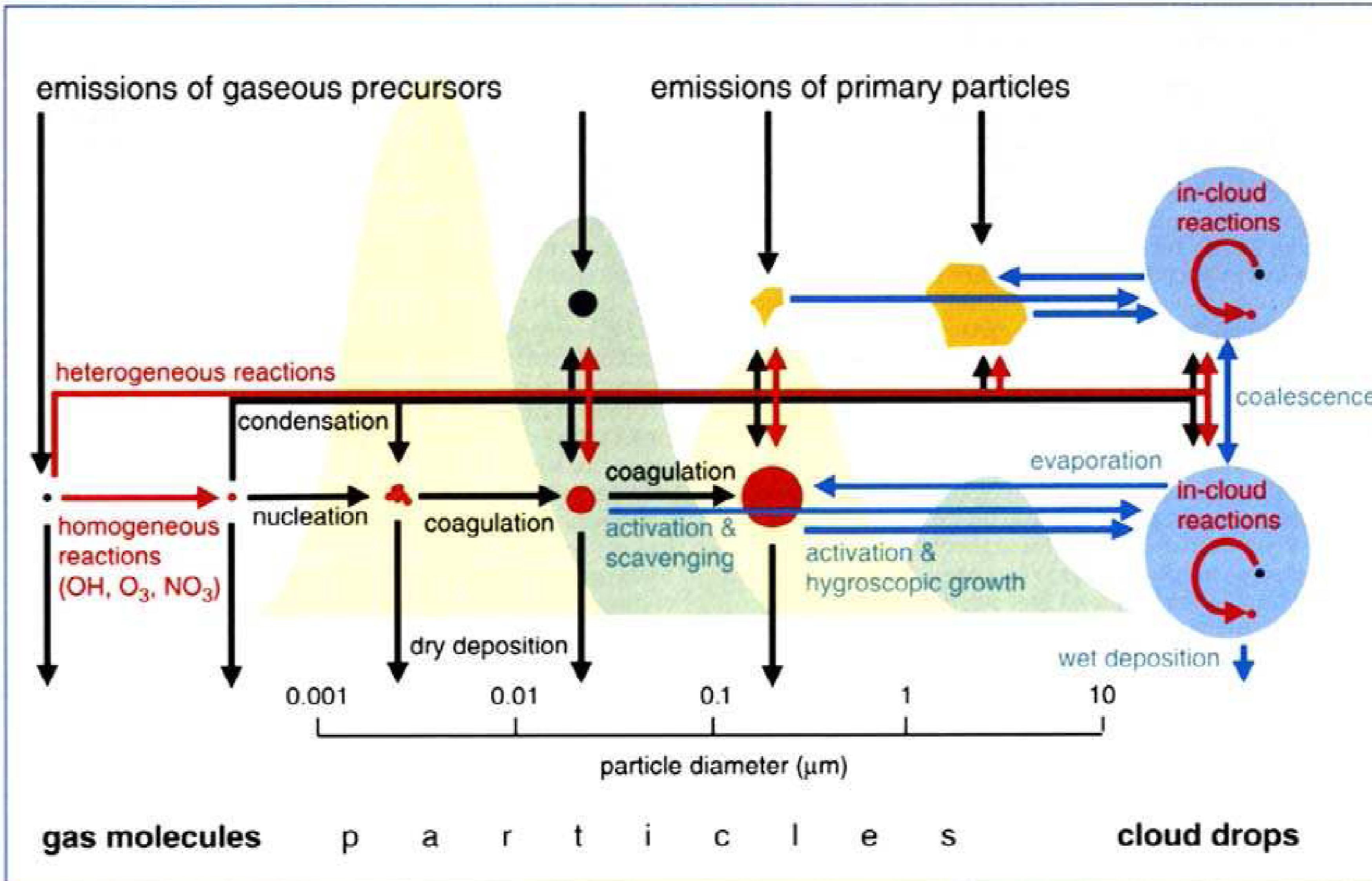
Interactions of particles:

(i) microphysical (by collision and coalescence, as in clouds, see Hanna Pawlowska's talk)
(ii) chemical (e.g., condensation of SO_2 onto dust or black carbon)

processing of aerosols also called "aging"



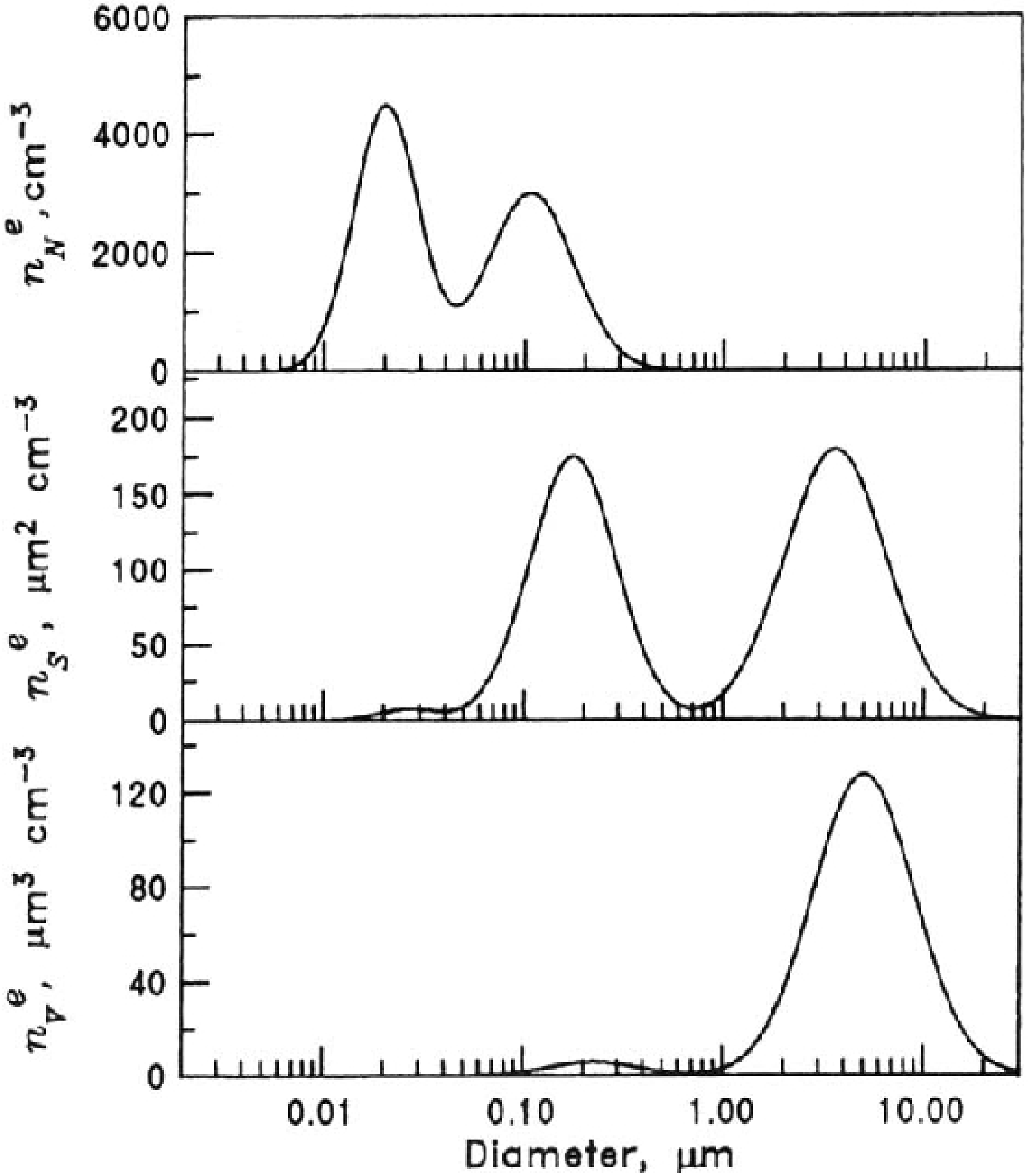
1.2 Size characterisation



1 Å = 0.1 nm. H_2 Molecule ~ 1.4 Å diameter

e.g., Stier et al., Atmos. Chem. Phys. 2005

1.4 Size distributions



Log-normal size distributions
typical: 2-3 different "**modes**"

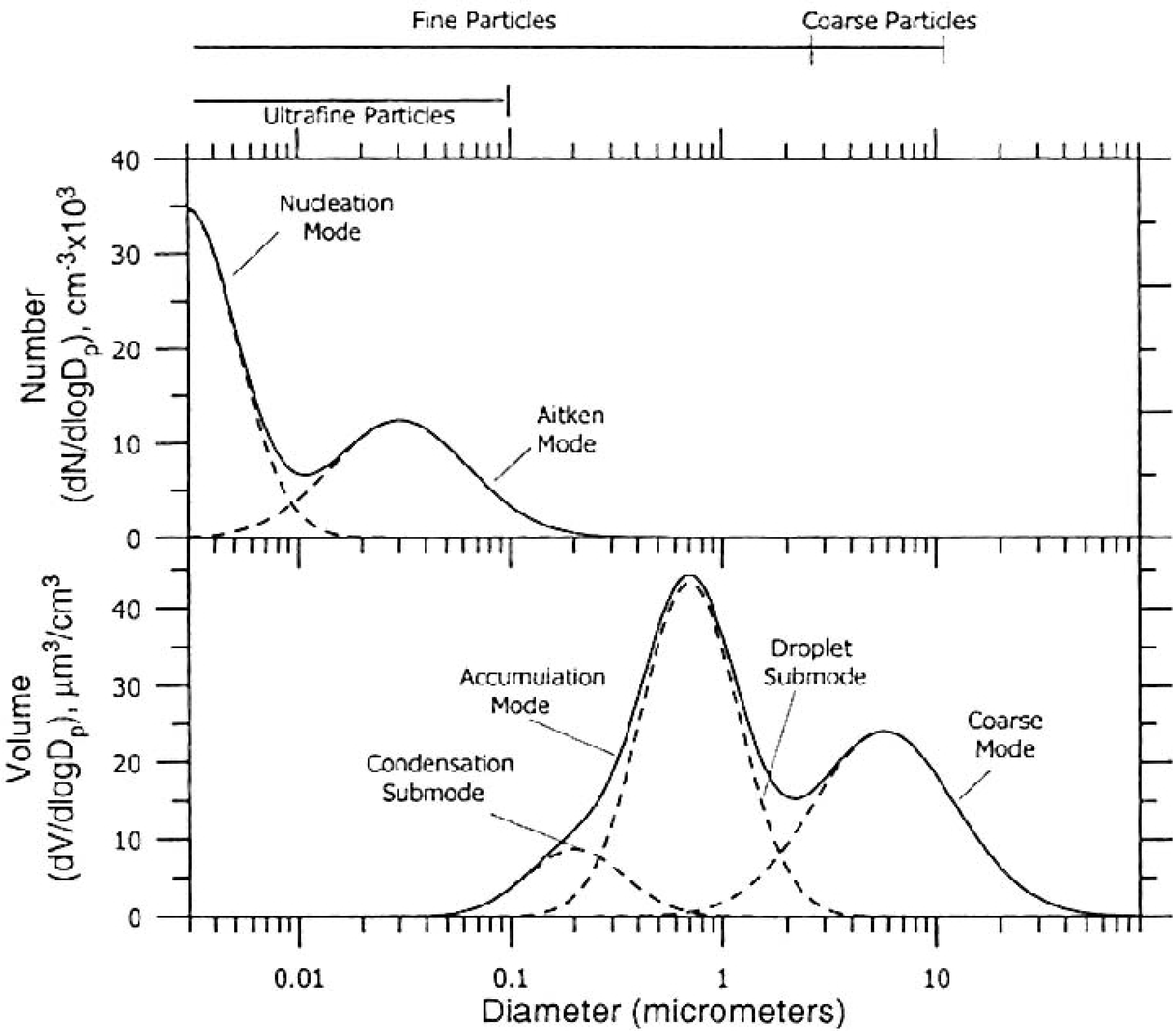
by number → cloud interaction

by surface → scattering

by volume → mass

Seinfeld and Pandis, Atmospheric Chemistry and Physics, Wiley, 2006

1.4 Size distributions



Simplified descriptions

< 1μm fine mode
> 1μm coarse mode

PM10:
Mass of particles with diameters > 10μm

PM2.5
PM1

Seinfeld and Pandis, Atmospheric Chemistry and Physics, Wiley, 2006

1.5 Continuity equation

In general necessary: one continuity equation per aerosol type and size class
May be simplified by considering just a few aerosol types and/or a few aerosol size classes (e.g., modes, or bulk representation)

$$\frac{D}{Dt} q_a = \Sigma S_a$$

q_a – aerosol mass concentration
S_a – aerosol sources/sinks

sources: emission (at surface)
chemical and microphysical transformation

sinks: dry deposition
wet deposition
chemical and microphysical transformation

Seinfeld and Pandis, Atmospheric Chemistry and Physics, Wiley, 2006

1.6 Chemical transformations of sulfur dioxide to sulfate

Sulfur is emitted by combustion of fossil and biofuel in form of SO_2

Oxidation in the air by OH radical:

$$SO_2 + OH + M \rightarrow HOSO_2 + M$$

$$HOSO_2 + O_2 \rightarrow HO_2 + SO_3$$

$$SO_3 + H_2O + M \rightarrow H_2SO_4 + M$$

Seinfeld and Pandis, Atmospheric Chemistry and Physics, Wiley, 2006

1.6 Chemical transformations of sulfur dioxide to sulfate

Sulfur is emitted by combustion of fossil and biofuel in form of SO_2

Oxidation in the air by OH radical:

$$SO_2 + OH + M \rightarrow HOSO_2 + M$$

$$HOSO_2 + O_2 \rightarrow HO_2 + SO_3$$

$$SO_3 + H_2O + M \rightarrow H_2SO_4 + M$$

Oxidation within cloud and precipitation particles (aqueous chemistry):

$$SO_2(g) + H_2O \rightleftharpoons SO_2 \cdot H_2O$$

dissolution of gaseous SO_2 proportional to its partial pressure (Henry's law)

$$SO_2 \cdot H_2O \rightleftharpoons H^+ + HSO_3^-$$

$$HSO_3^- \rightleftharpoons H^+ + SO_3^{2-}$$

$$SO_3 + O_3 \longrightarrow SO_4 + O_2$$

further oxidation consuming ozone

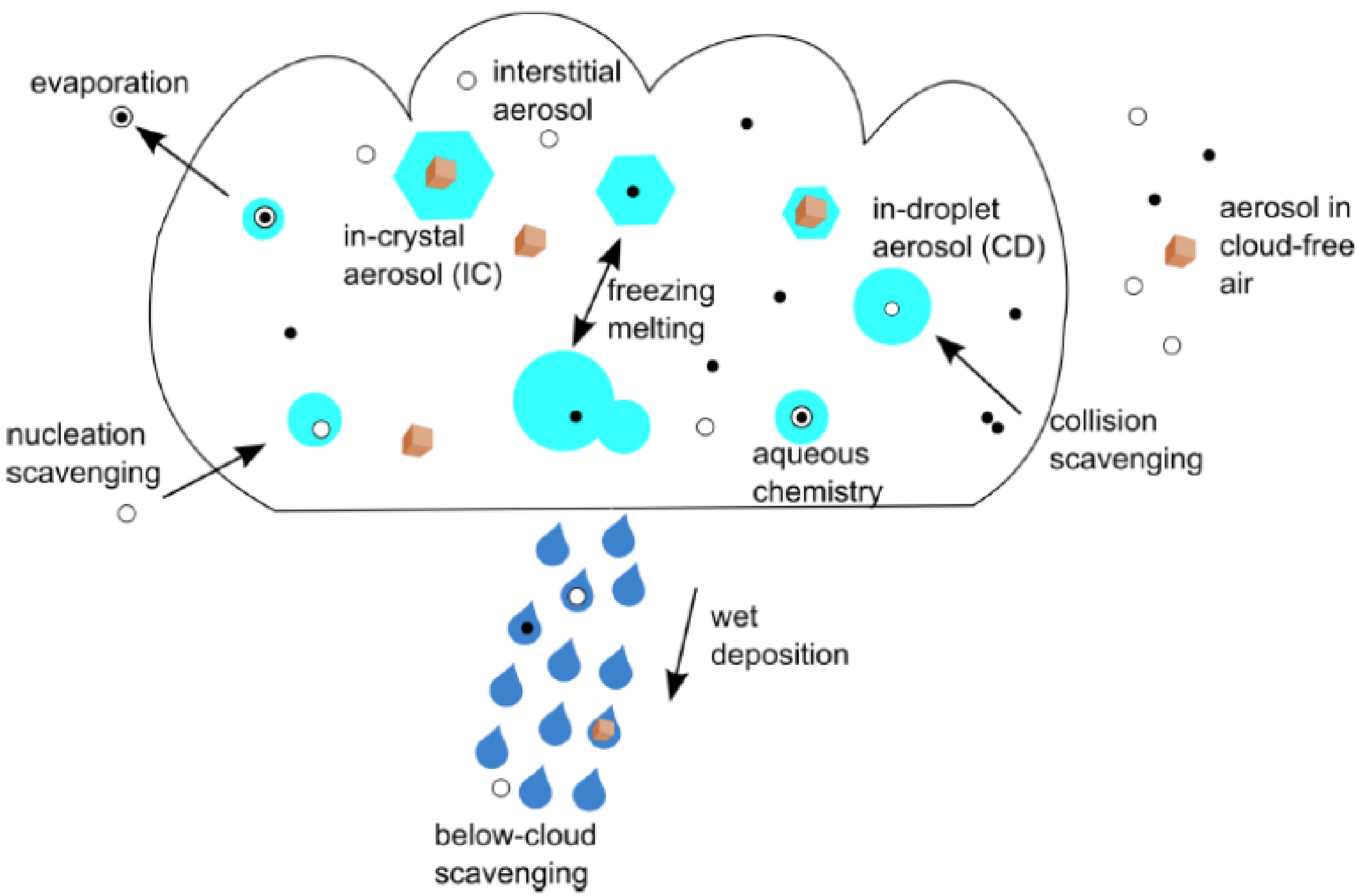
Aqueous production of sulfate usually much more efficient.

Seinfeld and Pandis, Atmospheric Chemistry and Physics, Wiley, 2006

1.7 Cloud processing of aerosols

(i) aqueous chemistry (see example above)

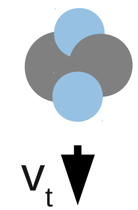
(ii) coagulation inside cloud droplets:
→ particles within cloud droplets / ice crystals from one internally mixed particle
→ usually much better cloud condensation nuclei capabilitites



1.8 Aerosol sinks

1. Dry deposition

Sedimentation velocity (see Hanna Pawlowska's talk)
→ Stokes regime, $v_T \sim r_a^2$

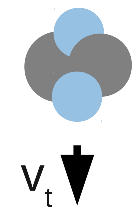


since aerosol particles are small, fall velocity usually relatively slow

1.8 Aerosol sinks

1. Dry deposition

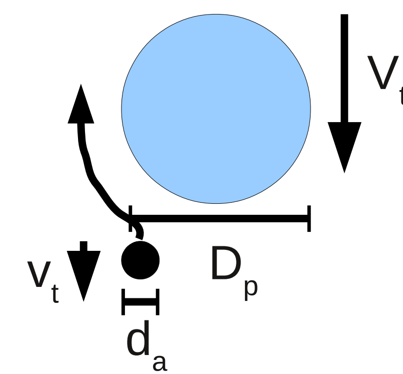
Sedimentation velocity (see Hanna Pawlowska's talk)
→ Stokes regime, $v_T \sim r_a^2$



since aerosol particles are small, fall velocity usually relatively slow

2. Wet deposition

(i) Aerosols inside cloud droplets / ice crystals
- the condensation/ice nuclei and/or aerosols taken up by collision/coalescence
- Deposition as rain forms in clouds



(ii) Aerosols below precipitating clouds
- taken up by collision/coalescence

Where present, wet deposition is much more effective.

1.9 Aerosol lifetime

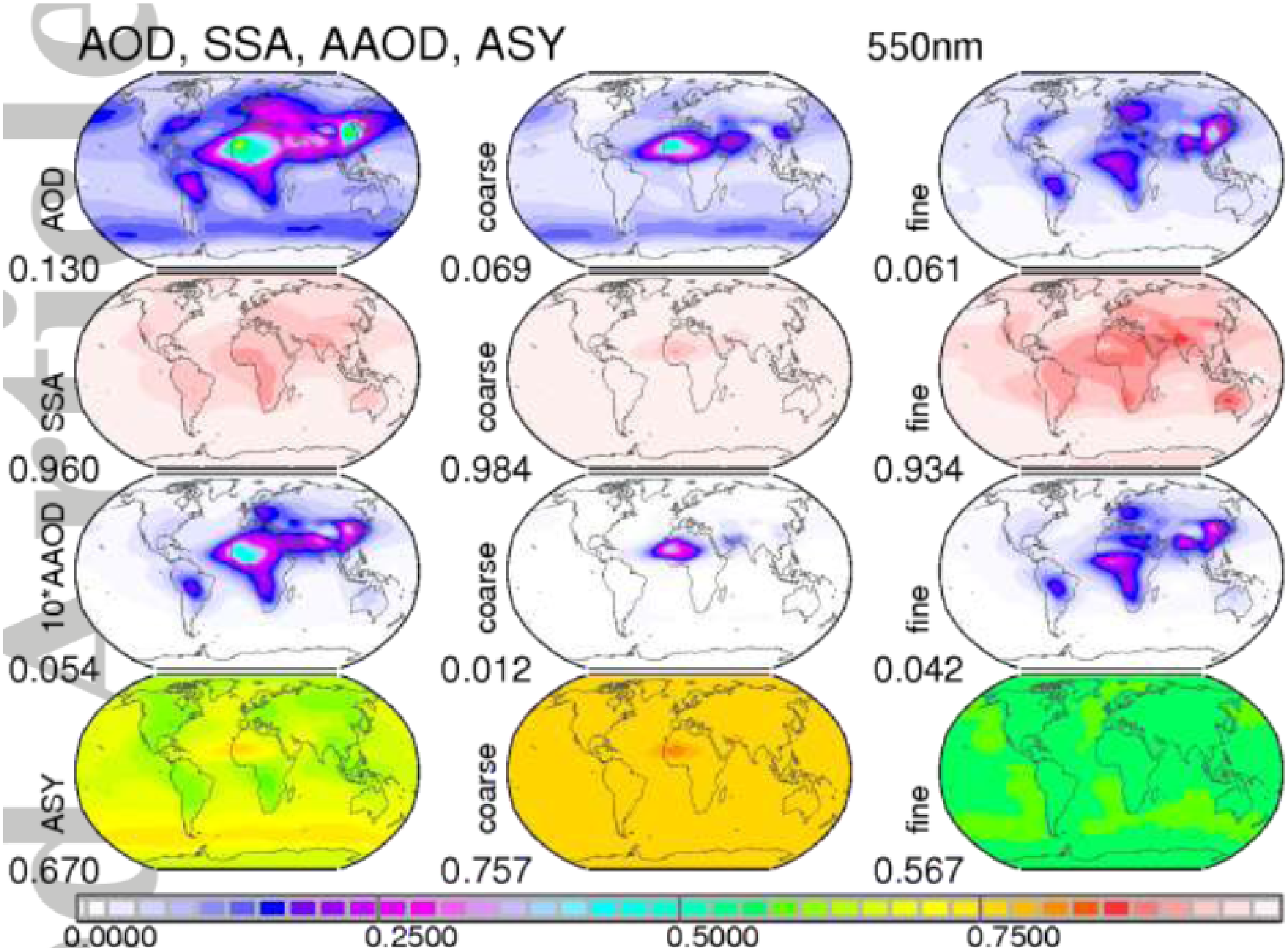
For a stationary situation, $\frac{D}{Dt}q_a = 0$, in the global mean, the average aerosol lifetime is:

$$\tau_a = \frac{M_a}{S_a}$$

the total atmospheric mass divided by the average source strength.

For sulfate, $M_a \sim 4$ Mt, $S_a \sim 200$ Mt yr^{-1} → $\tau_a \sim 1$ week

1.10 Aerosol distributions: Kinne climatology



optical depth (AOD)

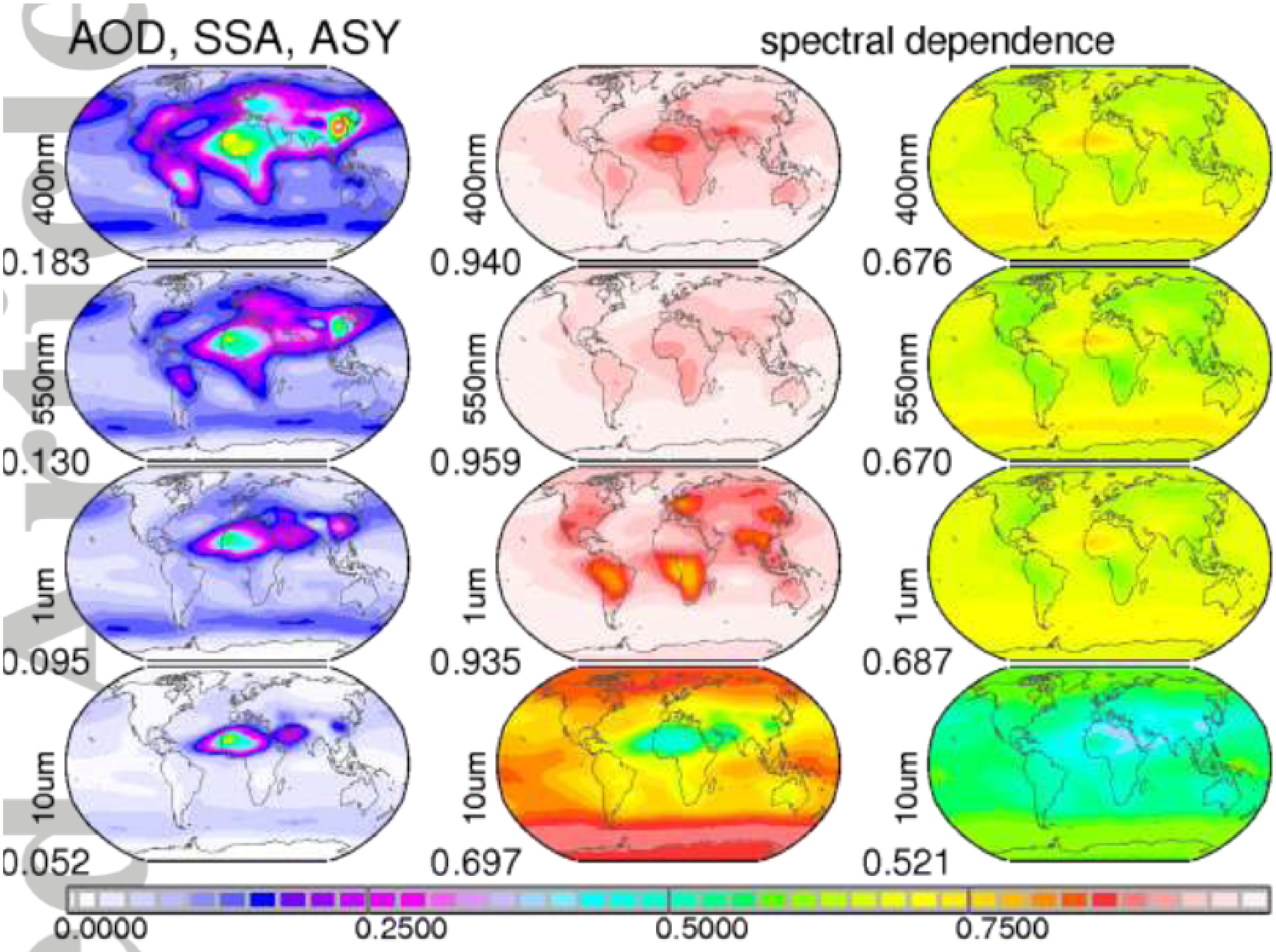
single scattering albedo

absorption AOD

assymetry parameter

Kinne et al., J. Adv. Model. Earth Syst. 2013

1.10 Aerosol distributions: Kinne climatology



400 nm

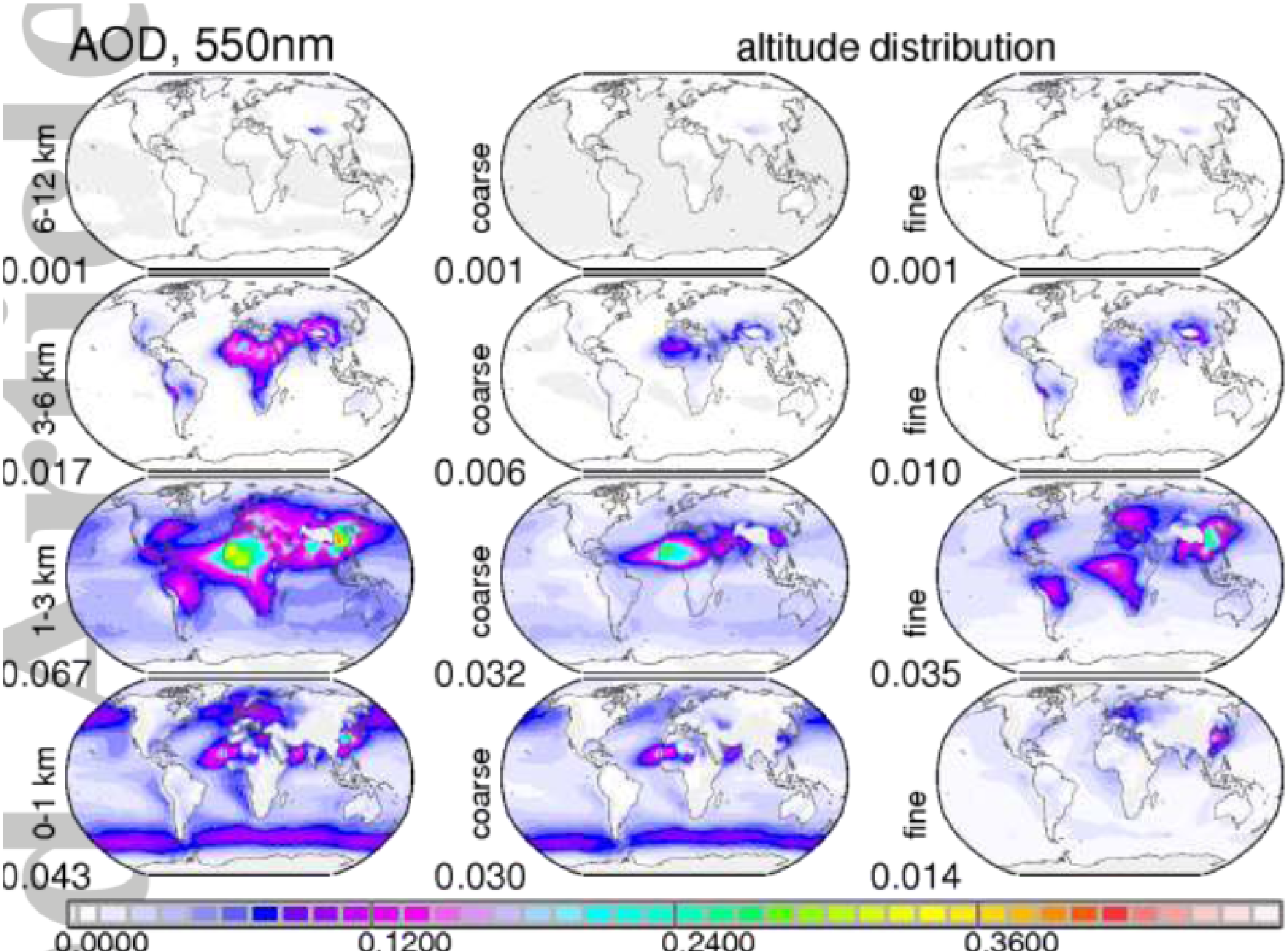
550 nm

1 μm

10 μm

Kinne et al., J. Adv. Model. Earth Syst. 2013

1.10 Aerosol distributions: Kinne climatology



6 – 12 km

3 – 6 km

1 – 3 km

0 – 1 km

Kinne et al., J. Adv. Model. Earth Syst. 2013

1.11 Light scattering and absorption: direct and semi-direct effects

→ aerosol particles scatter sunlight
(appear white from above)

1.11 Light scattering and absorption: direct and semi-direct effects

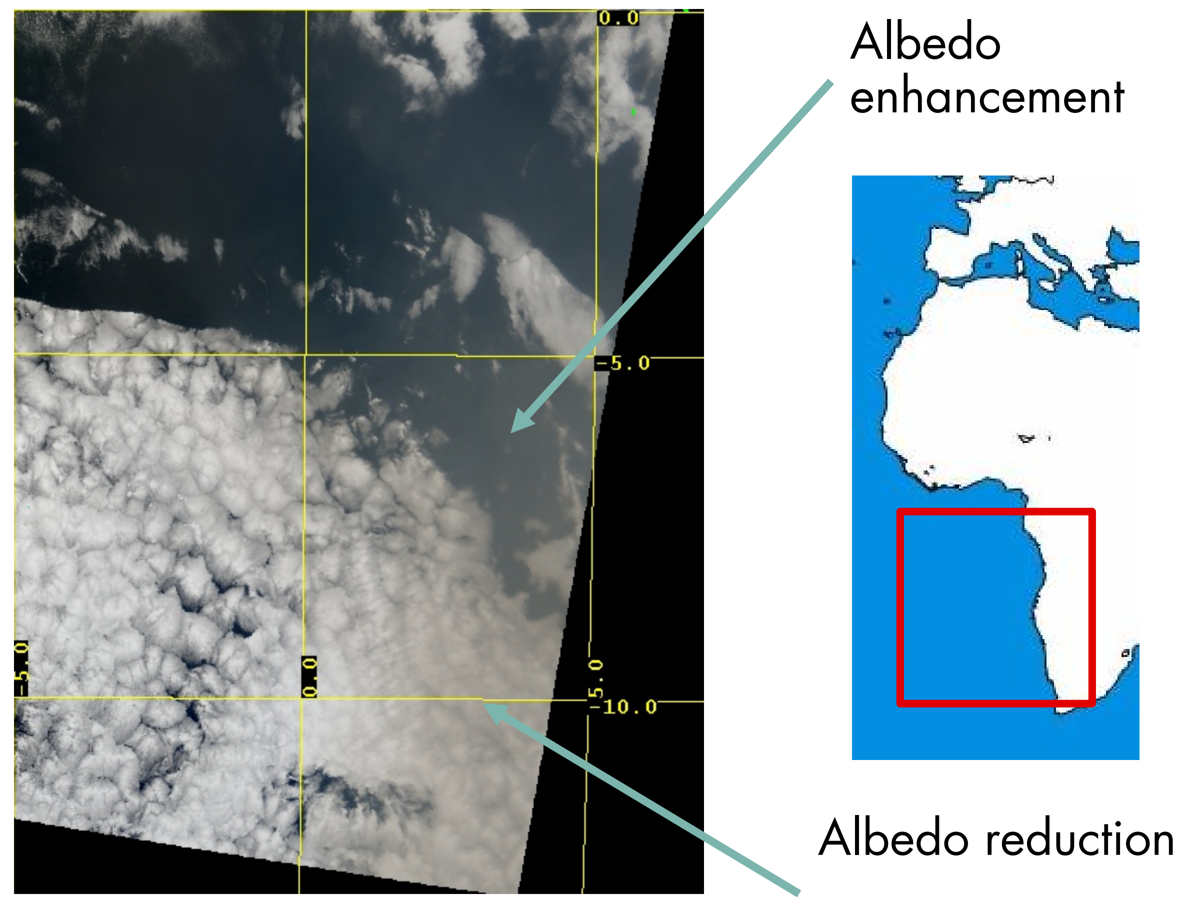
→ aerosol particles scatter sunlight
(appear white from above)

→ some also absorb sunlight
(appear black)

1.11 Light scattering and absorption: direct and semi-direct effects

→ Scattering acts to cool system (top-of-atmosphere) and surface
no effect within the atmosphere

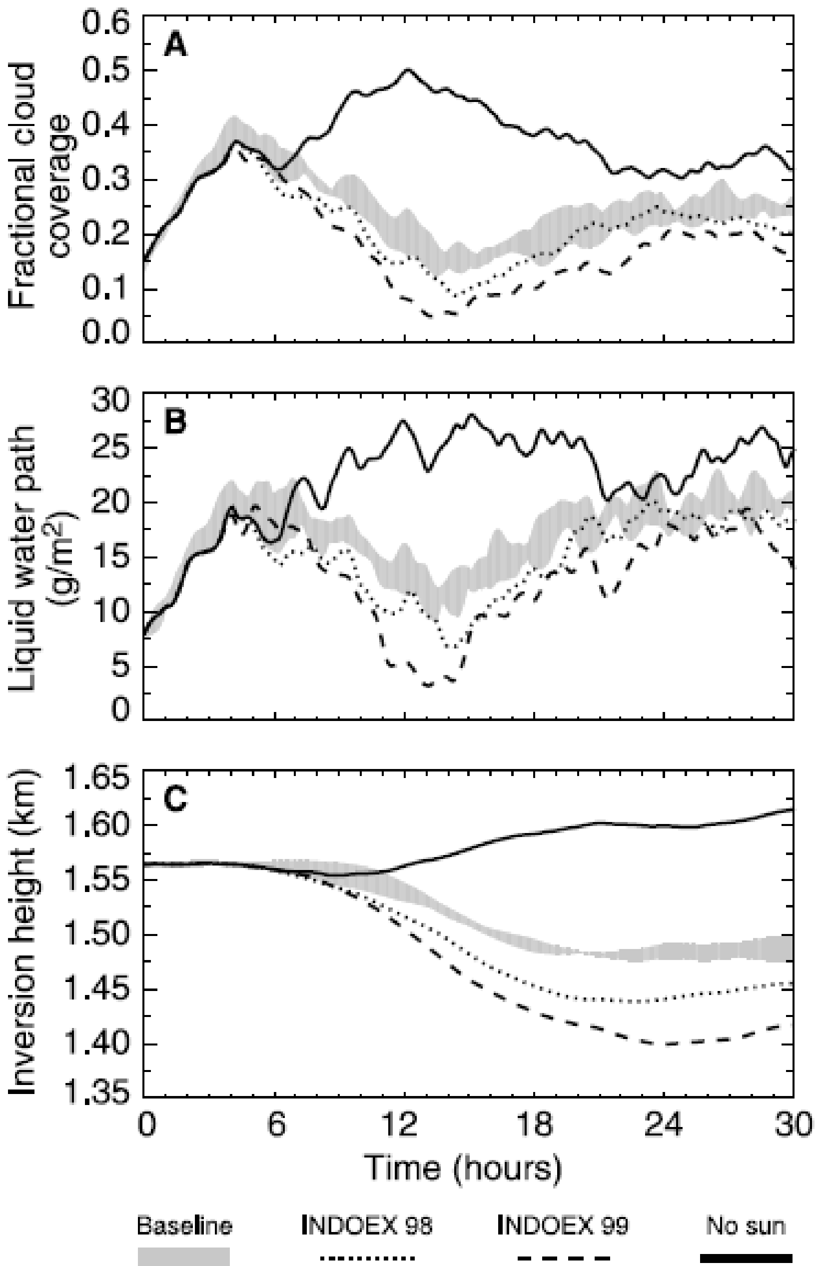
→ Absorption acts to warm the system
cools the surface
warms the atmosphere



MODIS 13 August 2006

e.g. Peters et al., Atmos. Chem. Phys. 2011

1.12 Semi-direct effect?



Large-eddy simulations

→ Aerosol absorption heats the upper boundary layer and reduces inversion and subsequently cloudiness

→ could be opposite if aerosol layer is above clouds

Ackerman et al., Science 2000

2. No particles – no fog

Youtube "No particles no fog"
http://www.youtube.com/watch?v=EneDwu0HrVg

2.1 Köhler equation

(see lecture by Hanna Pawlowska)

$$S(r,T,B) \equiv \frac{p_{v,\mathrm{sat,drop}}}{p_{v,\mathrm{sat}}} = \exp\left(\frac{A(T)}{r} - \frac{B}{r^3}\right)$$

curvature effect (Kelvin term) — solution effect (Raoult term)

in thermodynamic equilibrium

S – saturation ratio

(saturation vapour pressure above solution droplet vs. saturation vapour pressure over flat water surface)

↔ relative humidity

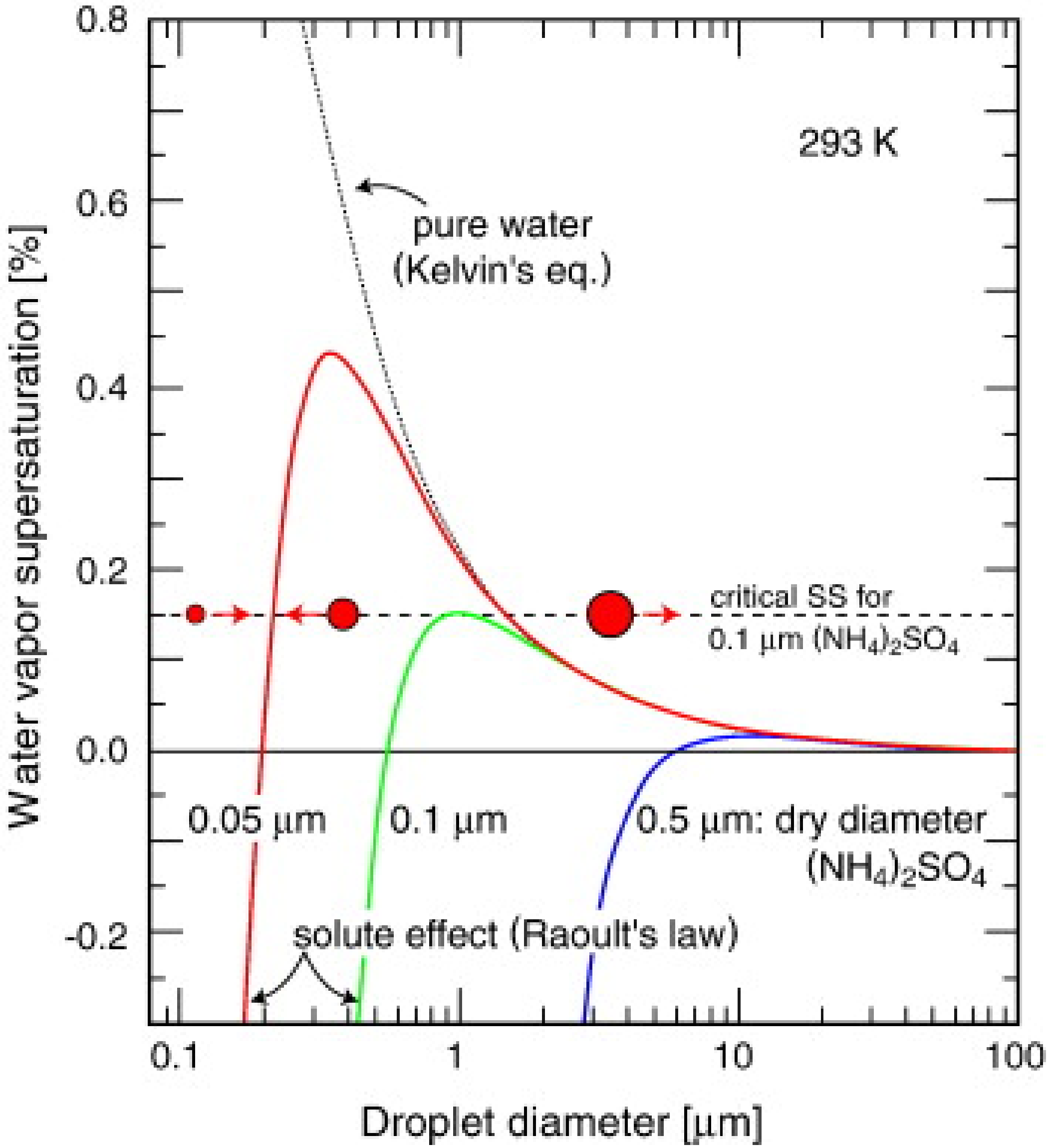
r – haze droplet radius

B – aerosol term

→ dependent on aerosol mass ~ r_a^3

→ dependent on solubility.

2.1 Köhler curve



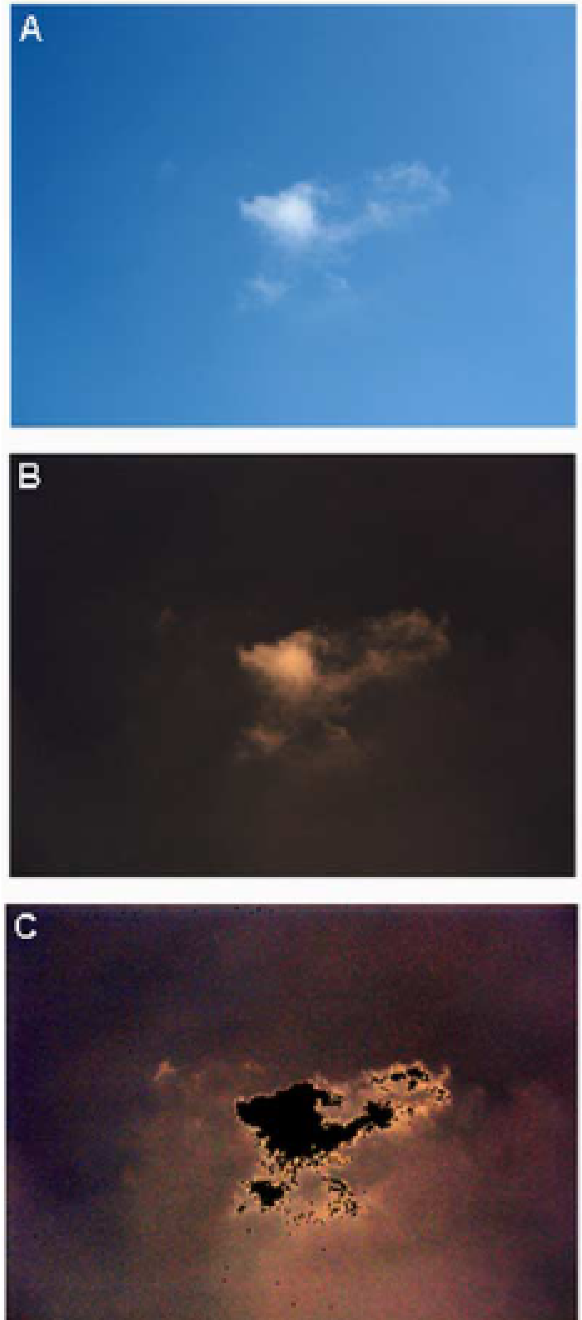
(i) Haze particles stable at low humidities

(ii) Cloud droplets do not nucleate at 100% relative humidity

(iii) Aerosol particle size very important

(iv) Solubility relevant

2.2 Some results on basic aerosol-cloud interactions



true-colour image of dissipating cumulus

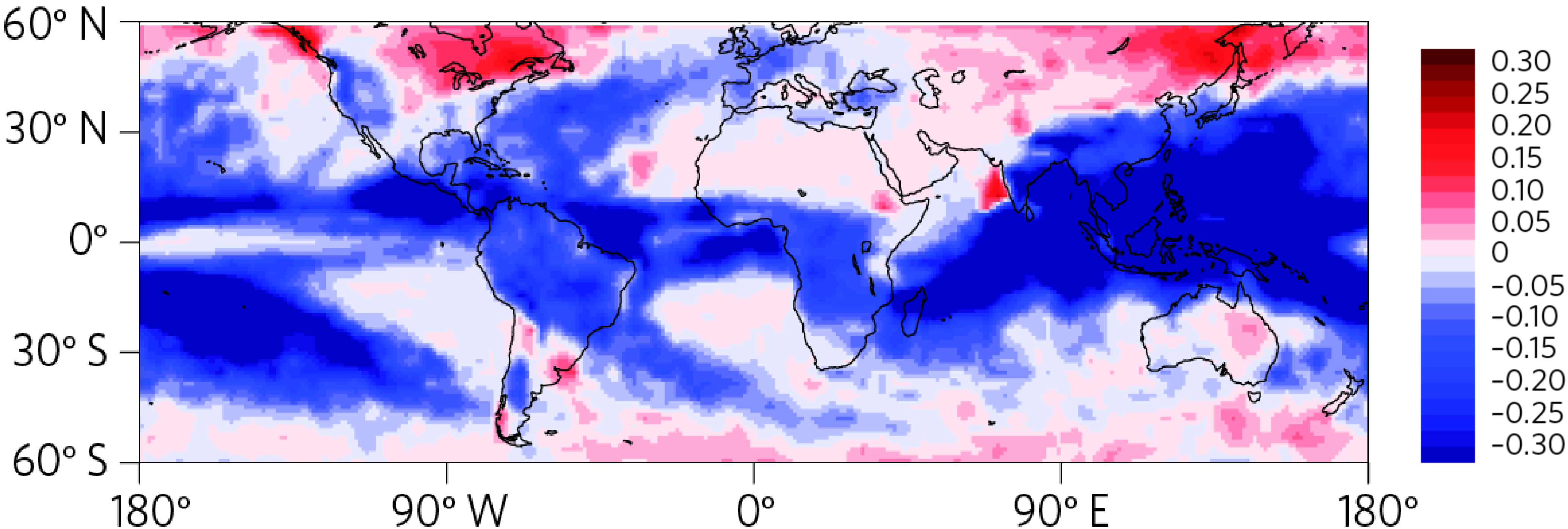
background gradients (molecular scattering) removed

cloud masked and increased sensitivity

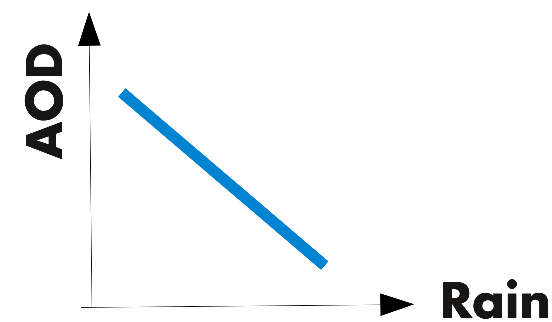
Koren et al., Geophys. Res. Lett. 2007

2.2 Some results on basic aerosol-cloud interactions

Statistical relationship between aerosol optical depth (logarithm of solar radiation dampening) and precipitation intensity



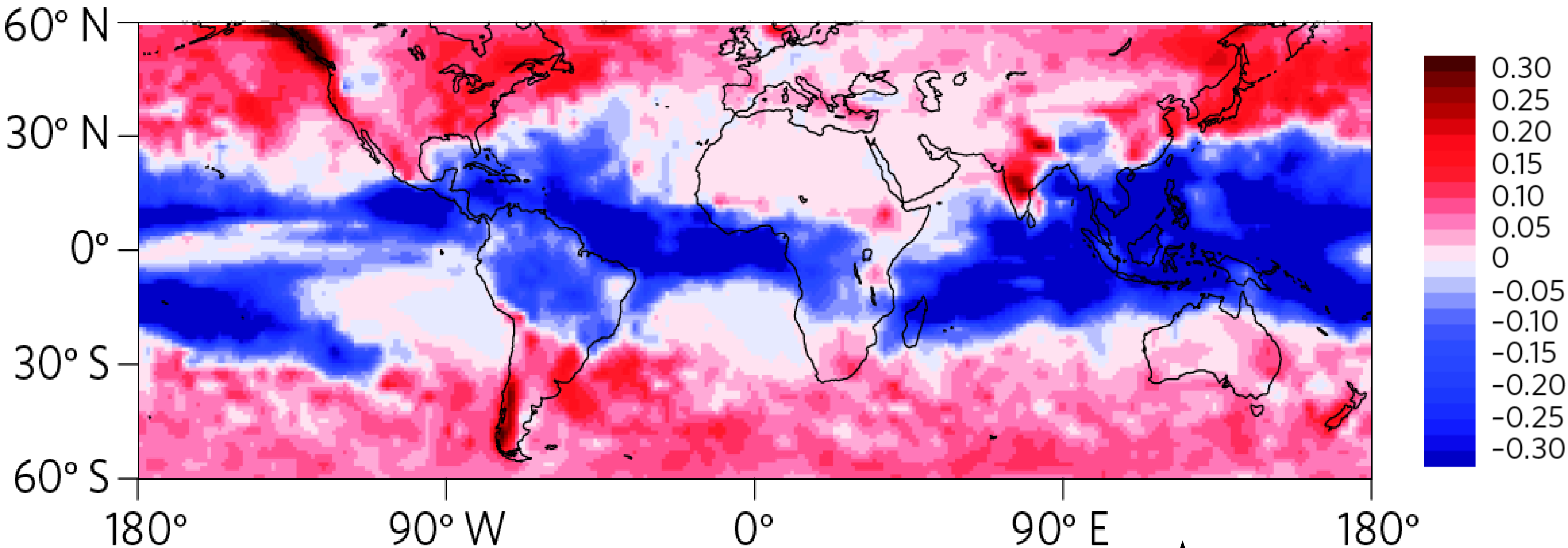
At each grid-point for one season of data difference between upper and lower tercile in aerosol optical depth (**dry** aerosol) in rain intensity [mm hour^{-1}]



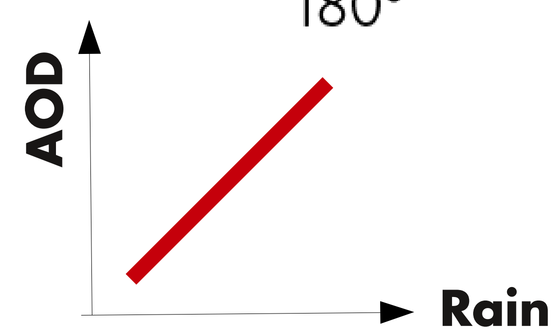
Boucher and Quaas, Nature Geosci. (comment to Koren et al.) 2013

2.2 Some results on basic aerosol-cloud interactions

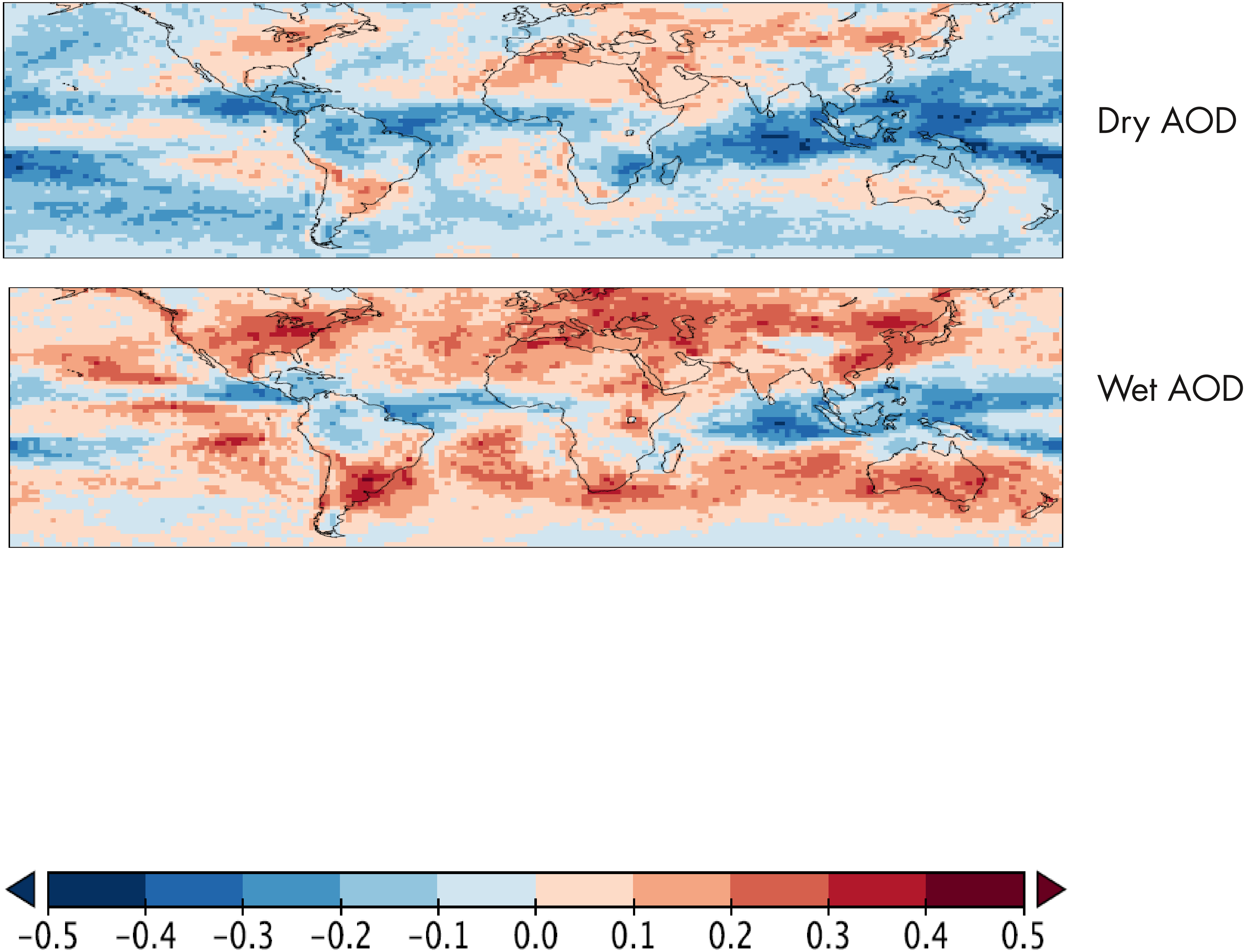
Statistical relationship between aerosol optical depth (logarithm of solar radiation dampening) and precipitation intensity



At each grid-point for one season of data difference between upper and lower tercile in aerosol optical depth (**wet** aerosol) in rain intensity [mm hour^{-1}]

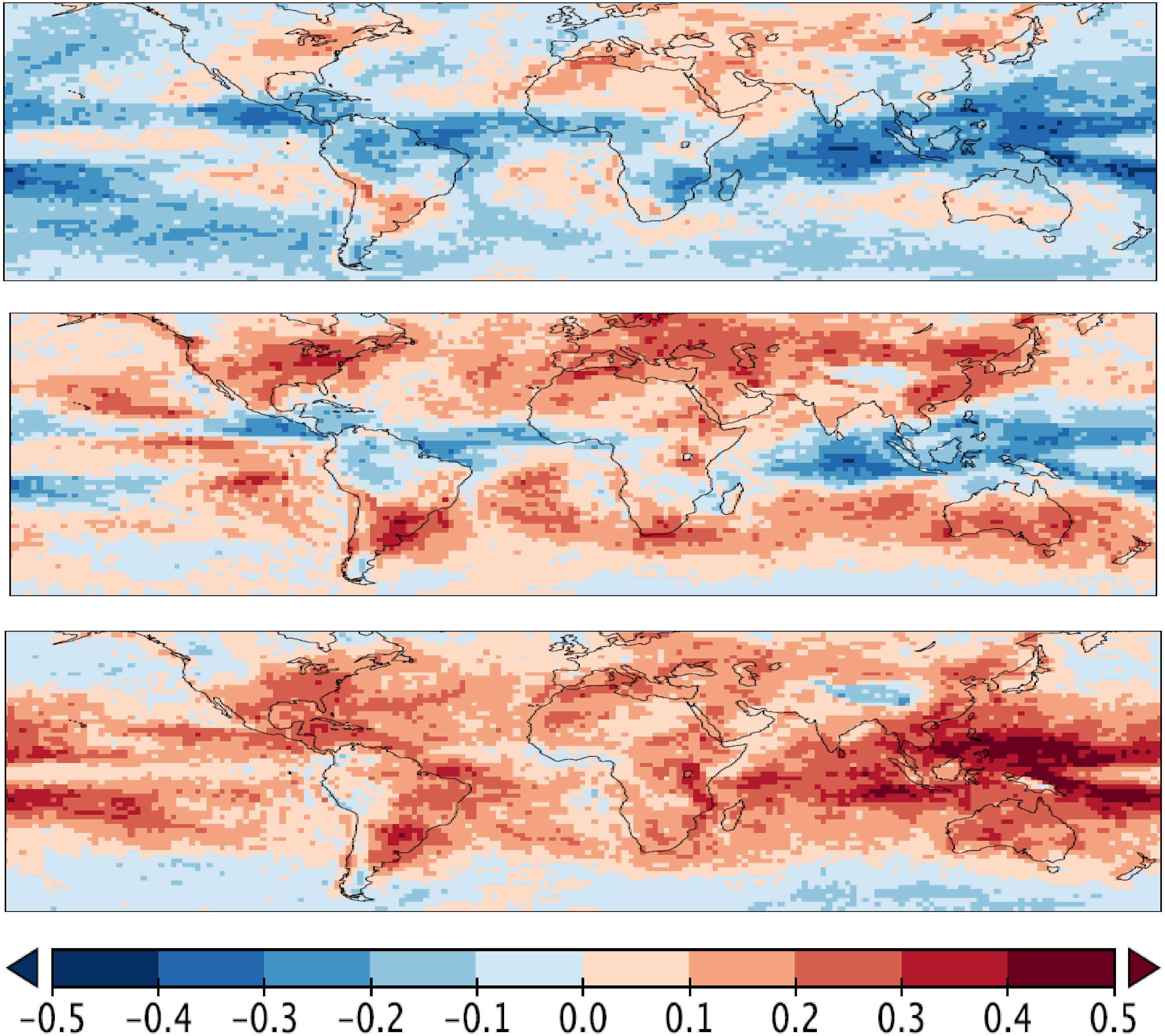


Statistical relationship between AOD and cloud cover



Grandey et al., Atmos. Chem. Phys. 2013

Statistical relationship between AOD and cloud cover



Dry AOD

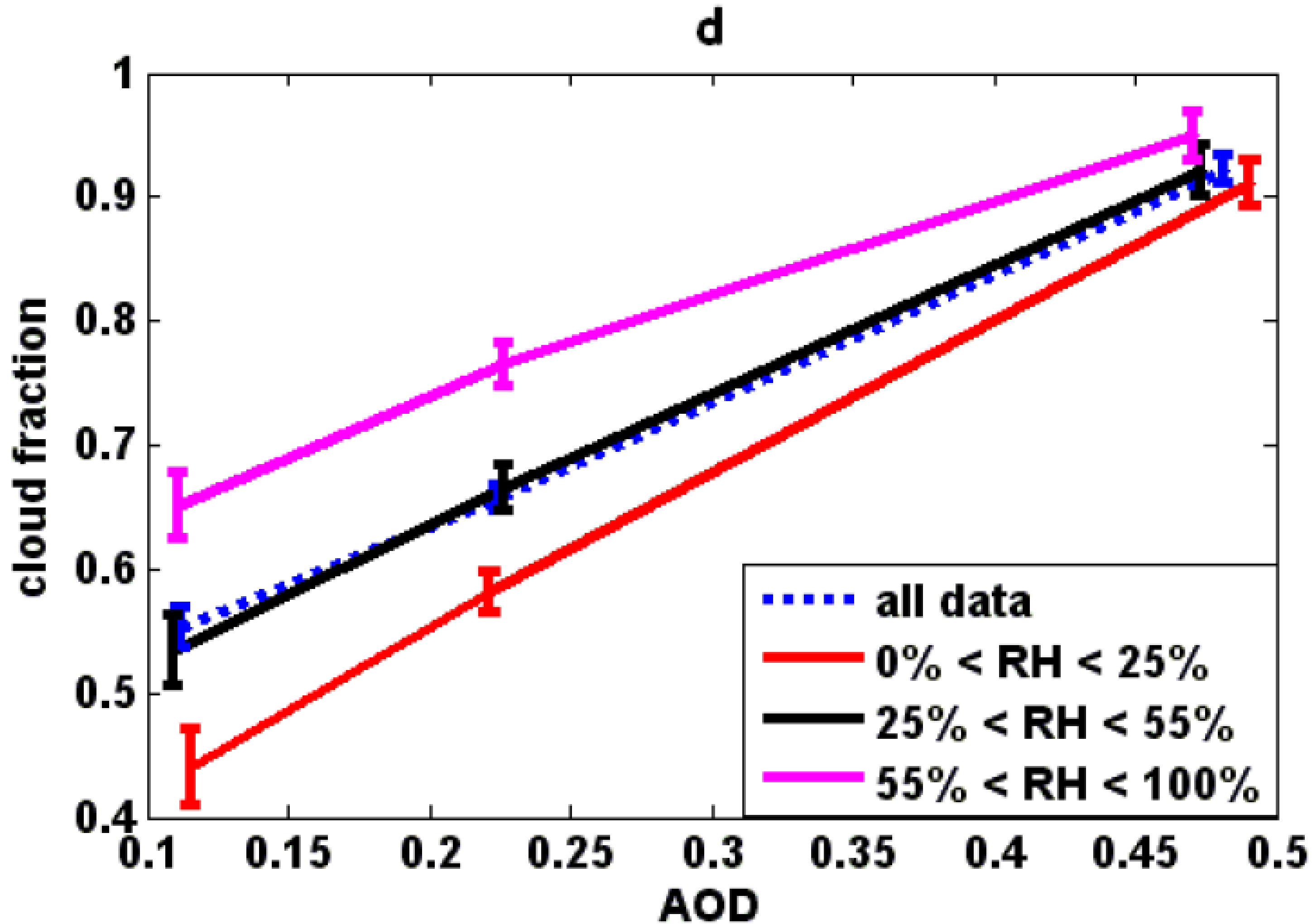
Wet AOD

No scavenging by convective precipitation

Grandey et al., Atmos. Chem. Phys. 2013

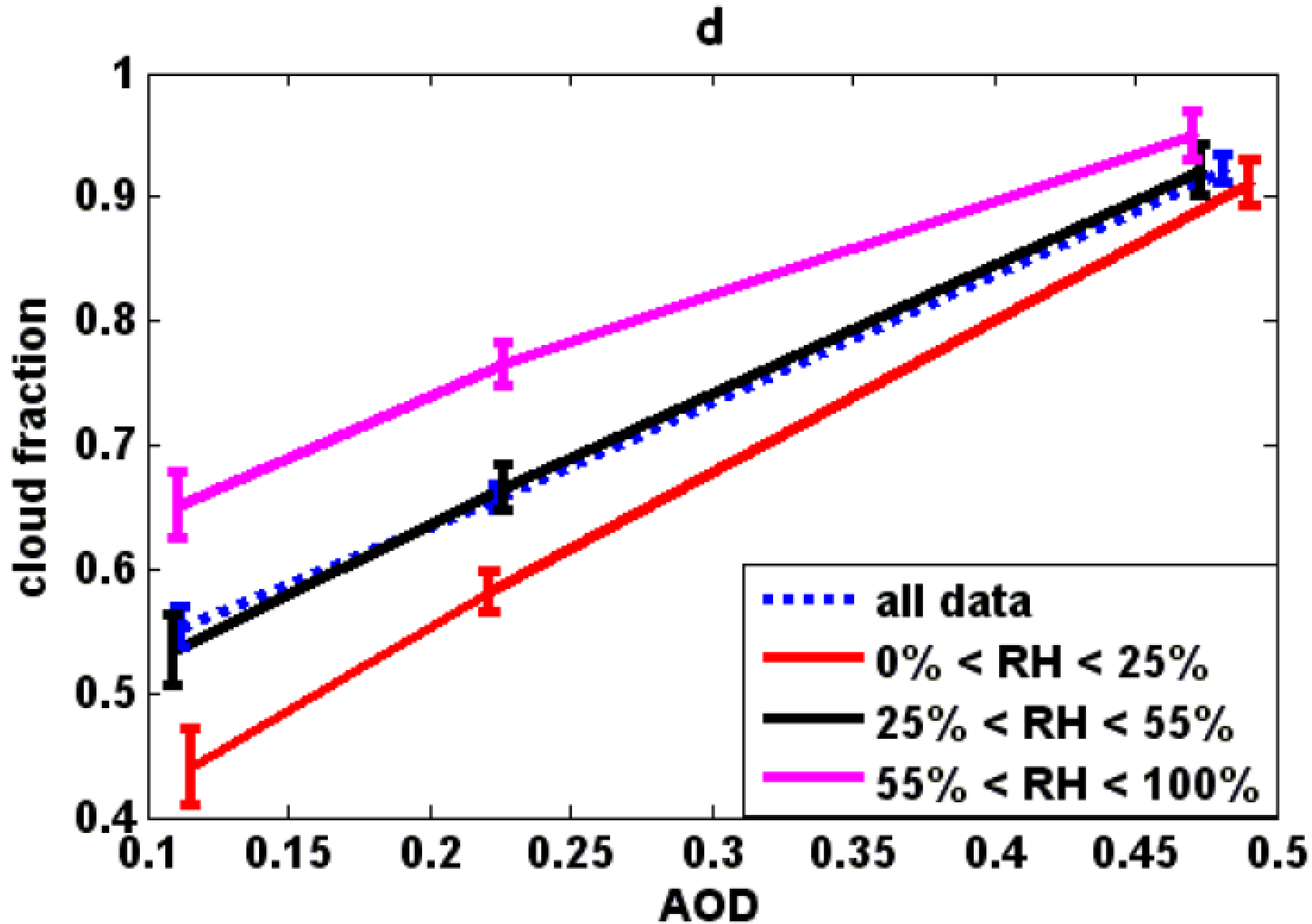
2.2 Some results on basic aerosol-cloud interactions

MODIS cloud fraction as a function of AOD for classes of re-analysis relative humidity at 350 hPa



2.2 Some results on basic aerosol-cloud interactions

MODIS cloud fraction as a function of AOD for classes of re-analysis relative humidity at 350 hPa



→ even for RH < 25% cloud fractions of up to 90%.

→ **subgrid-scale variability of humidity** essential (strong non-linearity of swelling)

→ see Poster by Vera Schemann and Matthias Brück

2.3 Radiation sensitivity: First aerosol indirect effect

See Hélène Chepfer's lecture:

$$\tau = \frac{3}{2}\frac{L}{\rho_w r_e}$$ (vertically homogeneous droplet size distribution)

with $r_e = \beta\, r_v$ and $N_d = \int_0^\infty n(r)dr$ the total cloud droplet number concentration

$$r_e = \beta \sqrt[3]{\frac{3}{4\pi}\frac{q_l}{\rho_w}\frac{1}{N_d}}$$

$$\tau \propto \sqrt[3]{N_d}$$ optical depth a cube-root function of droplet concentration, N_d.

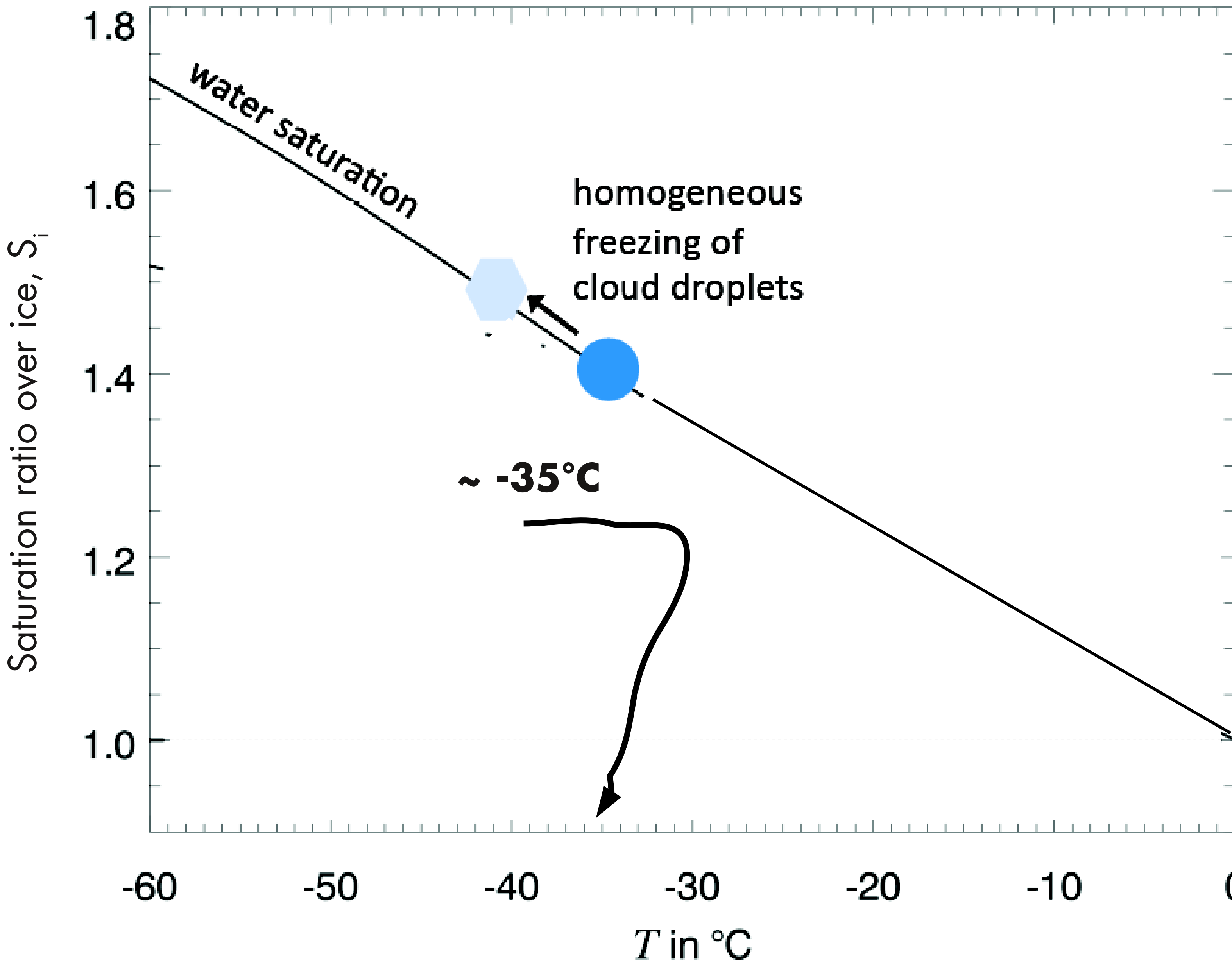
In two-stream approximation for the cloud albedo, α:

$$\Delta \ln \alpha = (1-\alpha)\Delta \ln \tau$$

For constant droplet spectrum shape and liquid water path:

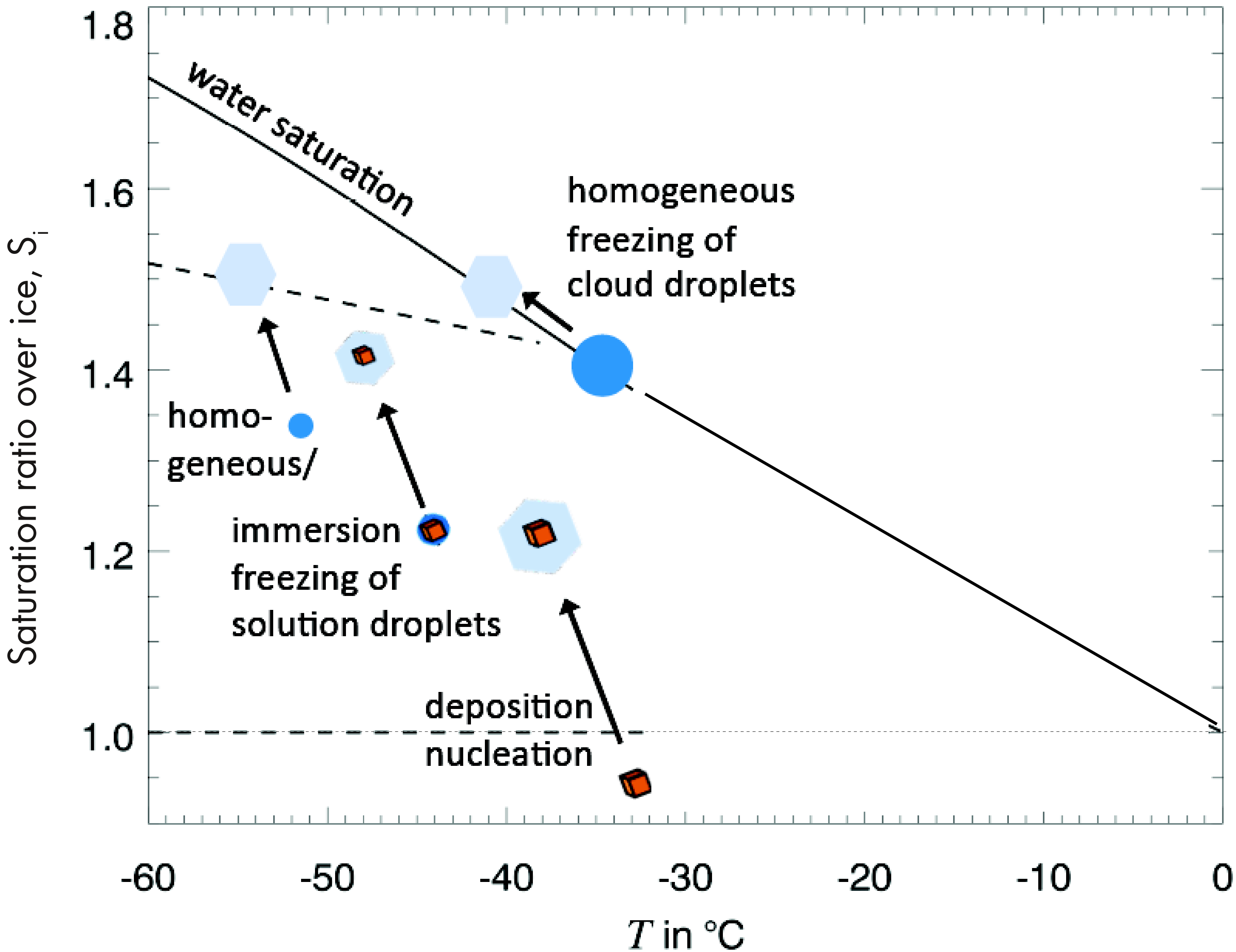
$$\frac{\Delta \ln \alpha}{\Delta \ln N_d} = \frac{1-\alpha}{3}$$ → **first aerosol indirect effect (Twomey effect)**

2.4 Ice crystals



→ **First indirect effect**

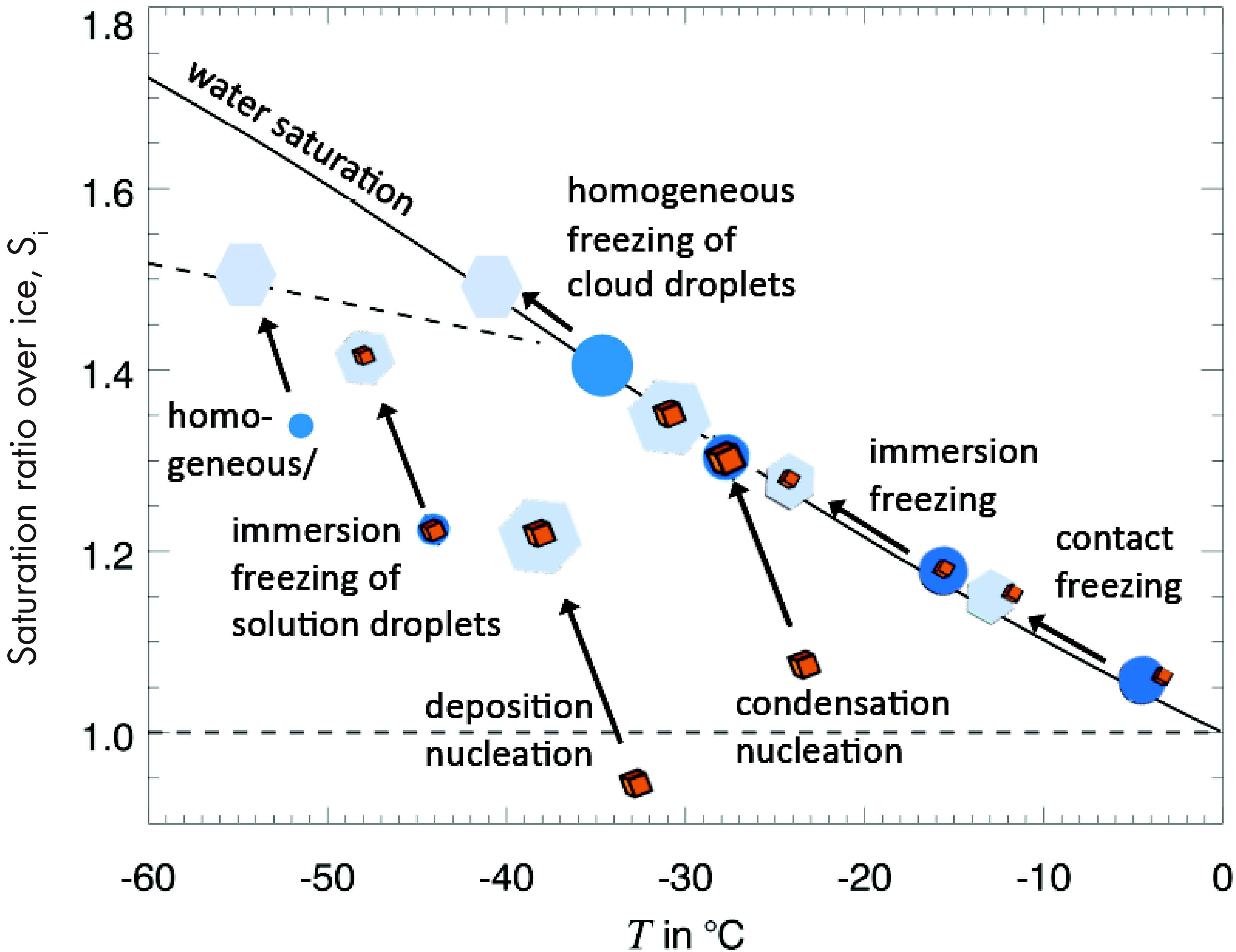
2.4 Ice crystals



→ **First indirect effect**

→ **First indirect effect**

2.4 Ice crystals



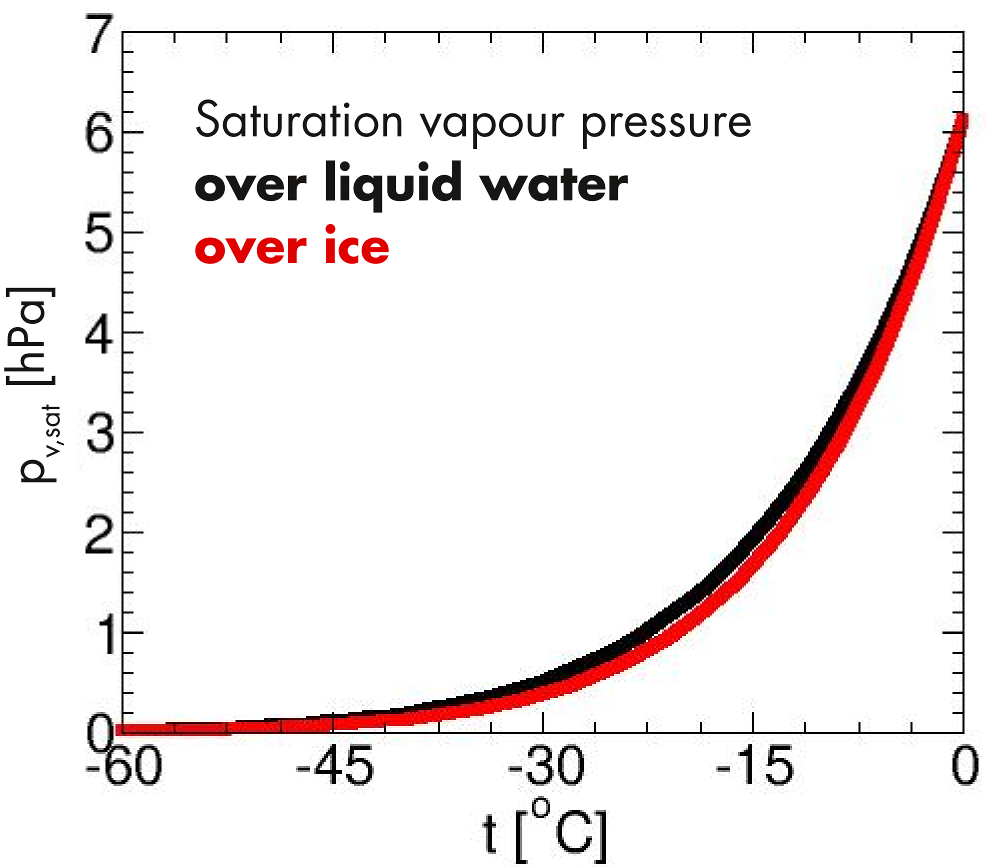
heterogeneous freezing of cloud droplets

→ effect ?

2.5 Mixed-phase clouds

(i) Freezing of drops is a function of droplet size:
→ In larger drops the probability of formation of an ice germ is larger

(ii) Ice crystals grow at the expense of liquid droplets:
→ Bergeron-Findeisen process



2.6 Glaciation and de-activation effects

(i) first indirect effect (homogeneous & deposition freezing)

(ii) Bergeron-Findeisen process:
if IN lead to early onset of freezing, the entire cloud might glaciate
→ precipitation → reduced lifetime

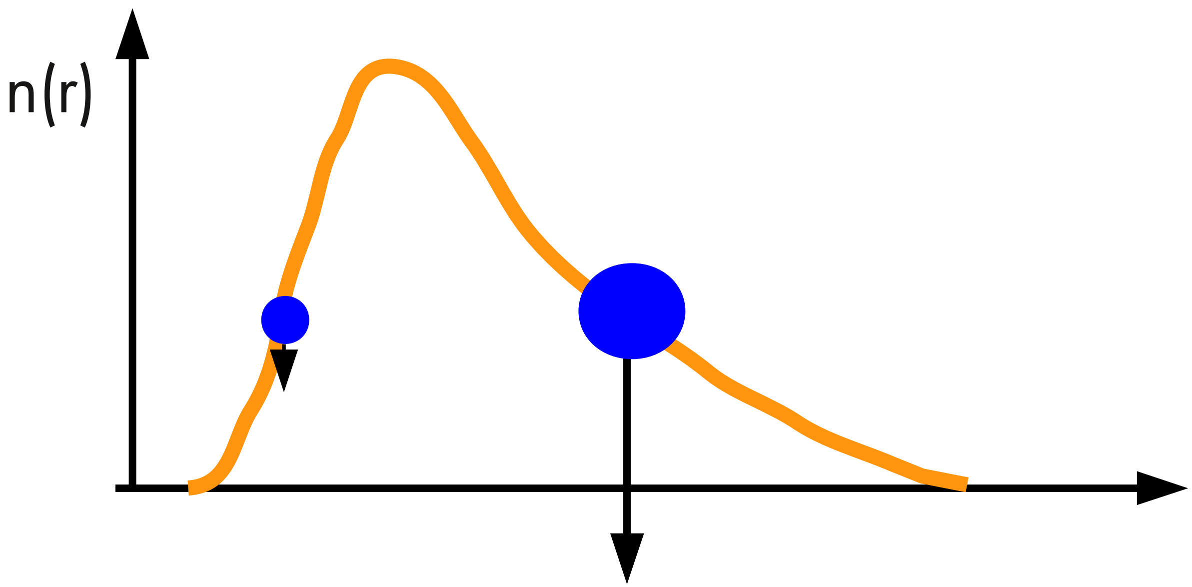
(iii) De-activation of IN:
if sulfate condenses onto dust particles, they may not serve as IN any more
→ longer lifetime ?

Lohmann, J. Atmos. Phys. 2002; Storelvmo et al., Env. Res. Lett. 2008

2.7 Microphysics

Terminal fall velocity depends on particle radii

→ particles with different sizes fall at different speeds

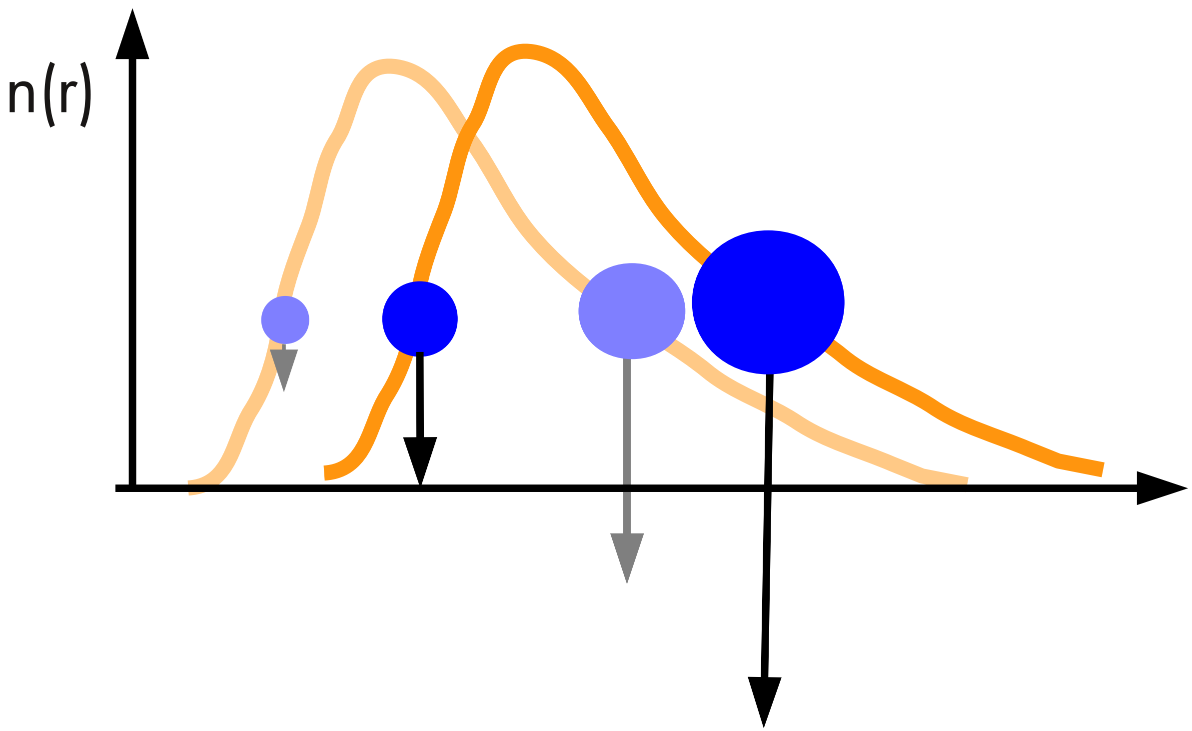


2.7 Microphysics

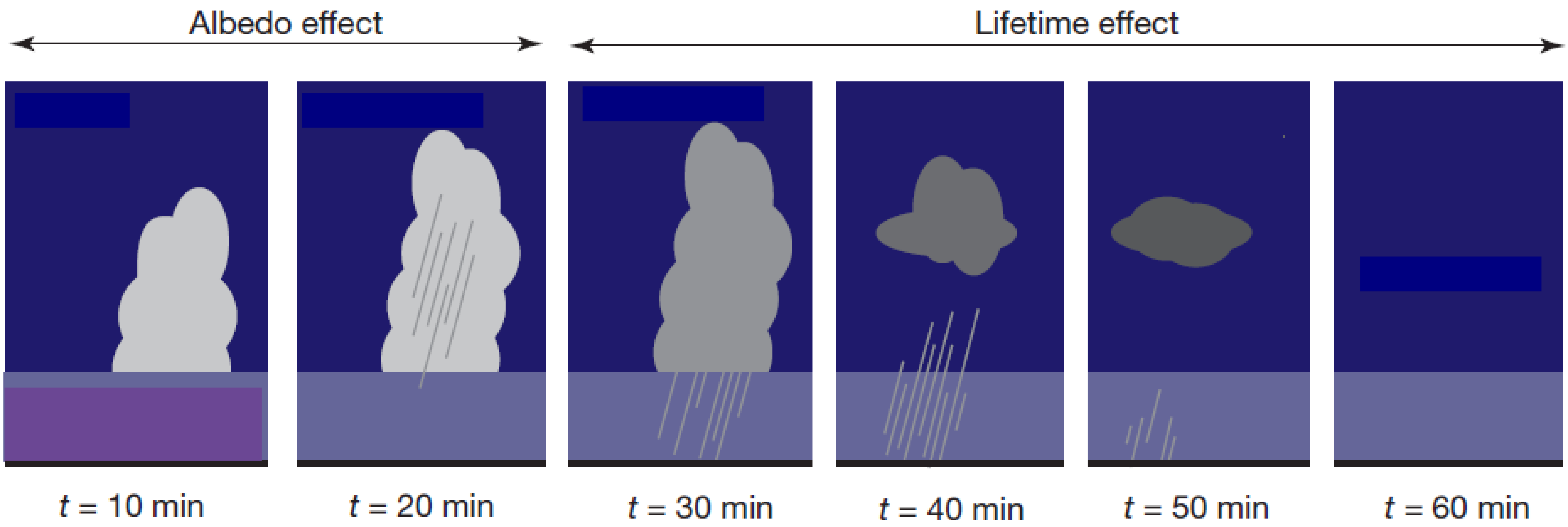
Terminal fall velocity depends on particle radii

→ particles with different sizes fall at different speeds

→ shift in droplet size spectrum affects collision/coalescence process

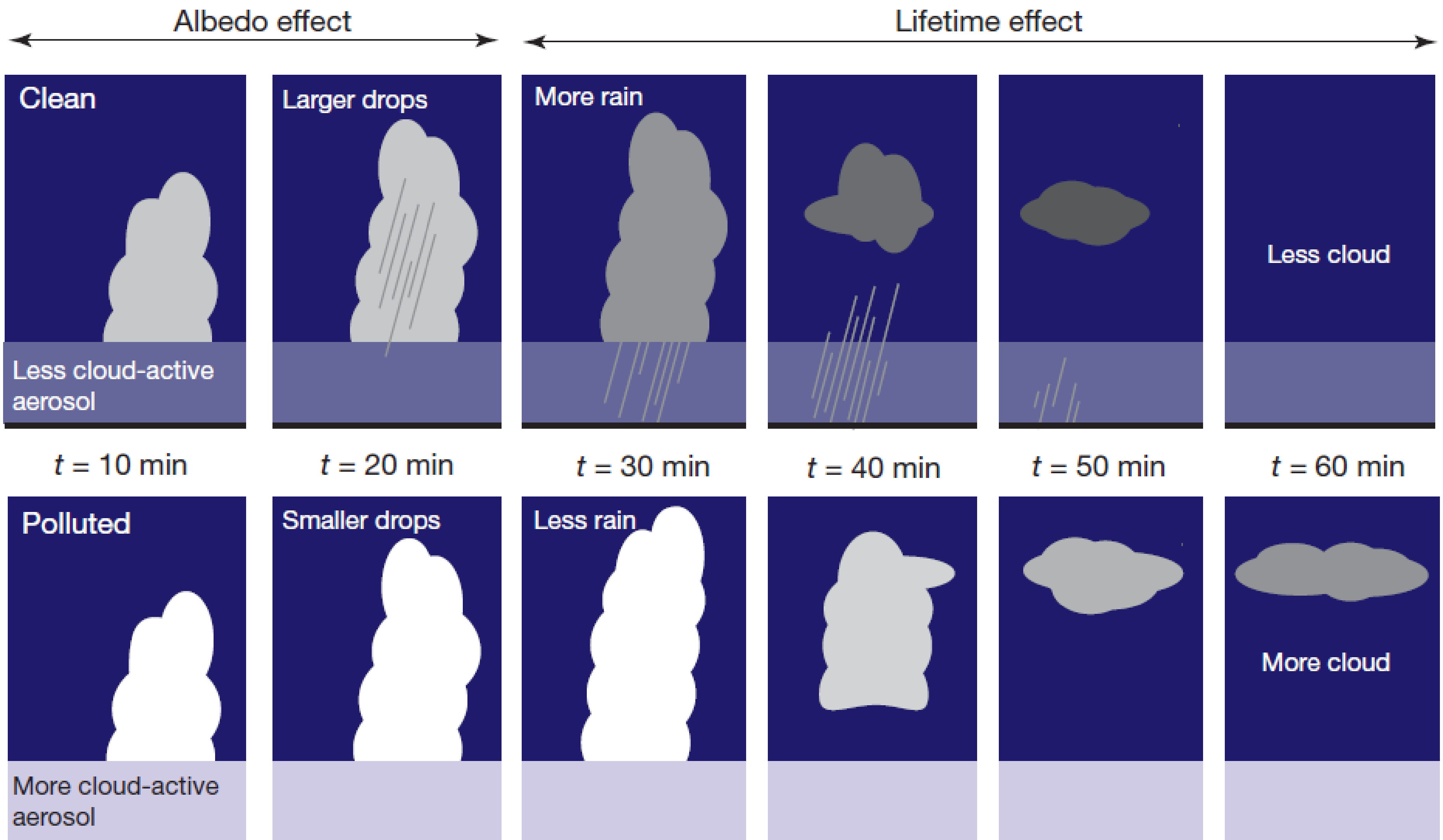


2.8 Cloud lifetime effect



Albrecht, Science 1989; Stevens and Feingold, Nature 2009

2.8 Cloud lifetime effect



→ larger cloud liquid water path
→ larger cloud fraction

Albrecht, Science 1989; Stevens and Feingold, Nature 2009

2.9 Water budget consideration

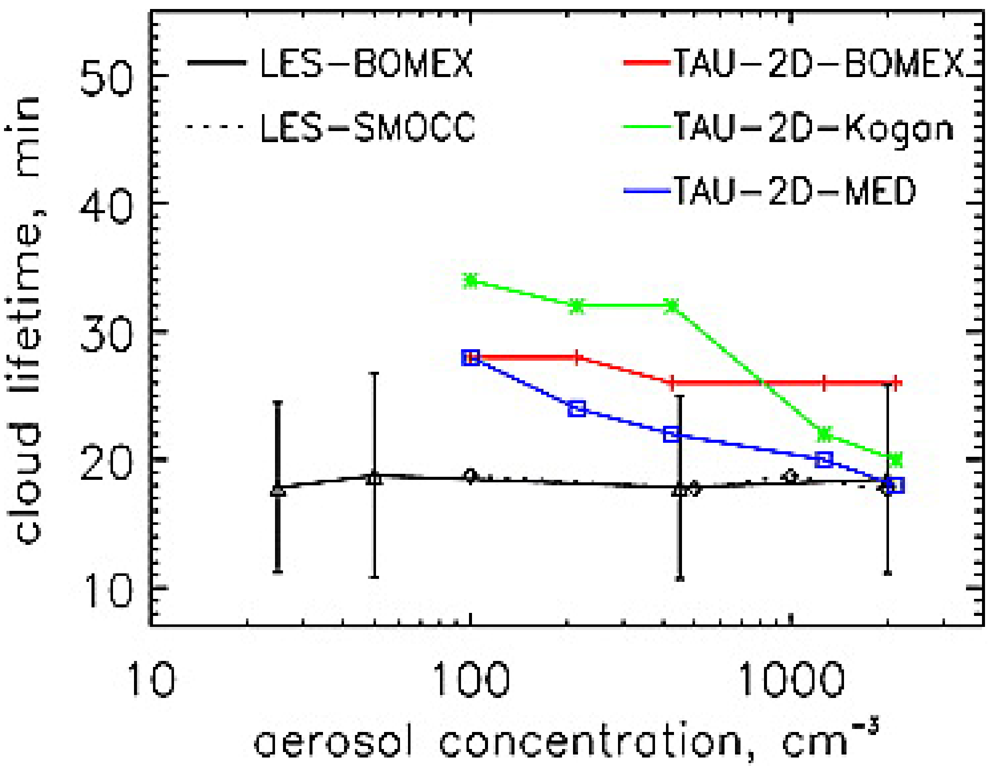
→ Total water (water vapour, cloud water, precipitation water) is conserved.
→ Changes in accumulated precipitation (at a large scale over long times) possible only if evaporation fluxes change

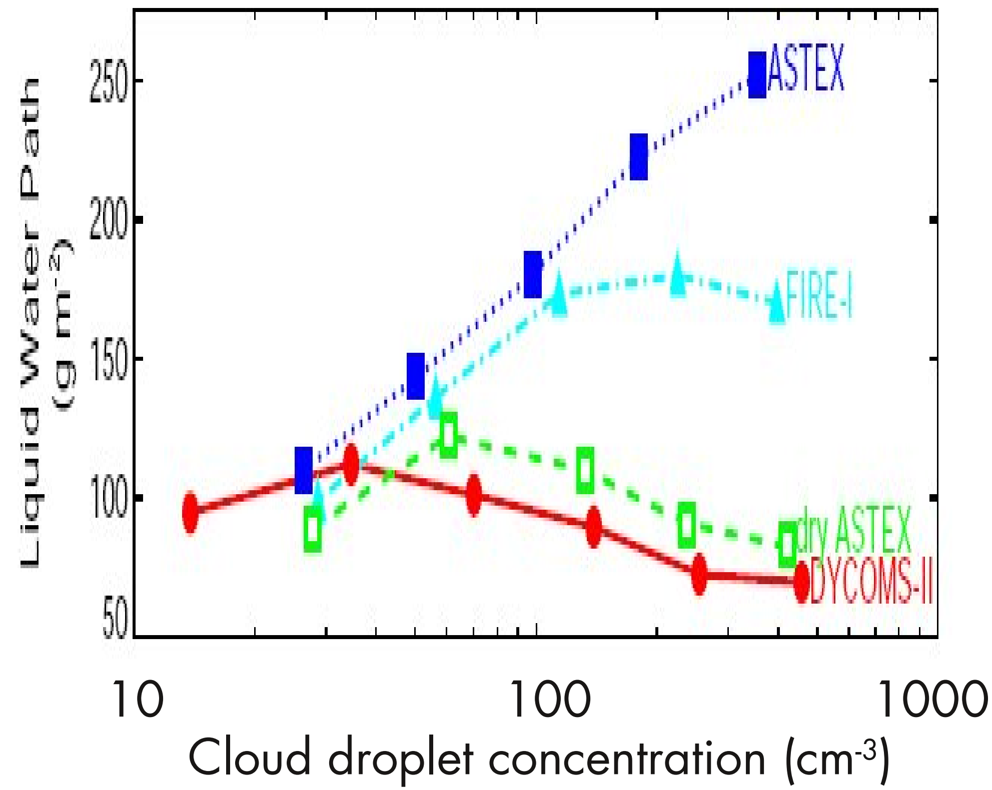
$$< P >= \int_{\text{area}} \int_{t=0}^{\tau} p(P) I(P) \, dt dA$$

A – Area
t – time
p(P) – probability of occurrence of precipitation
I(P) – intensity of precipitation

→ Precipitation characteristics [p(P) and I(P)] not constrained by this.

2.10 Feedbacks, "dampening"

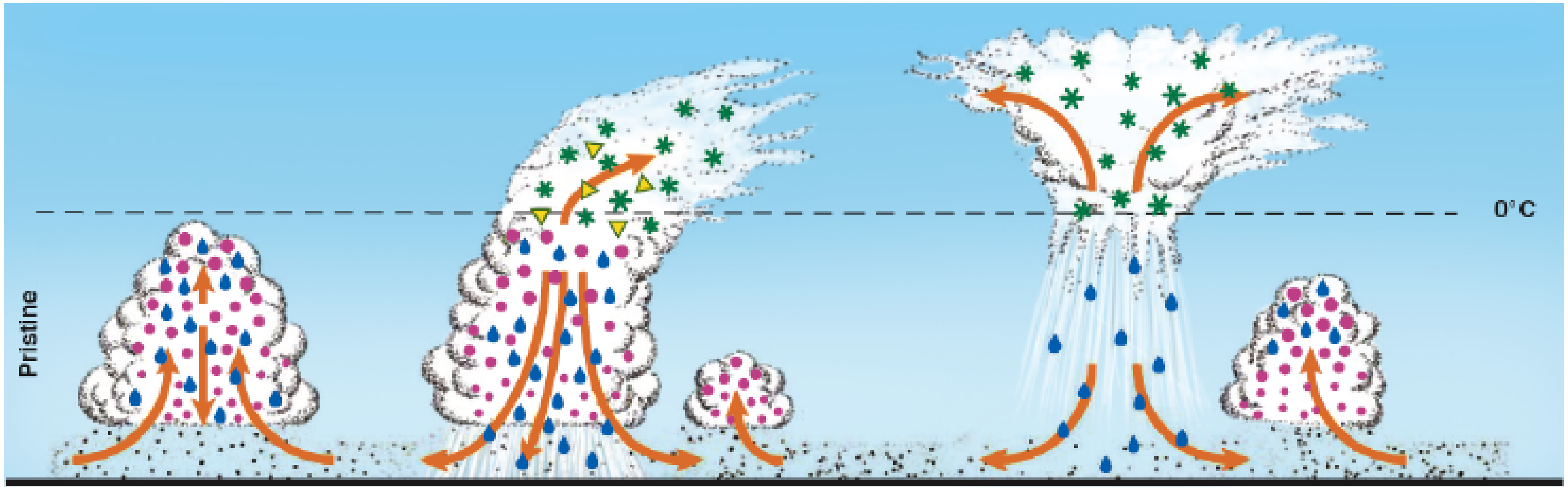




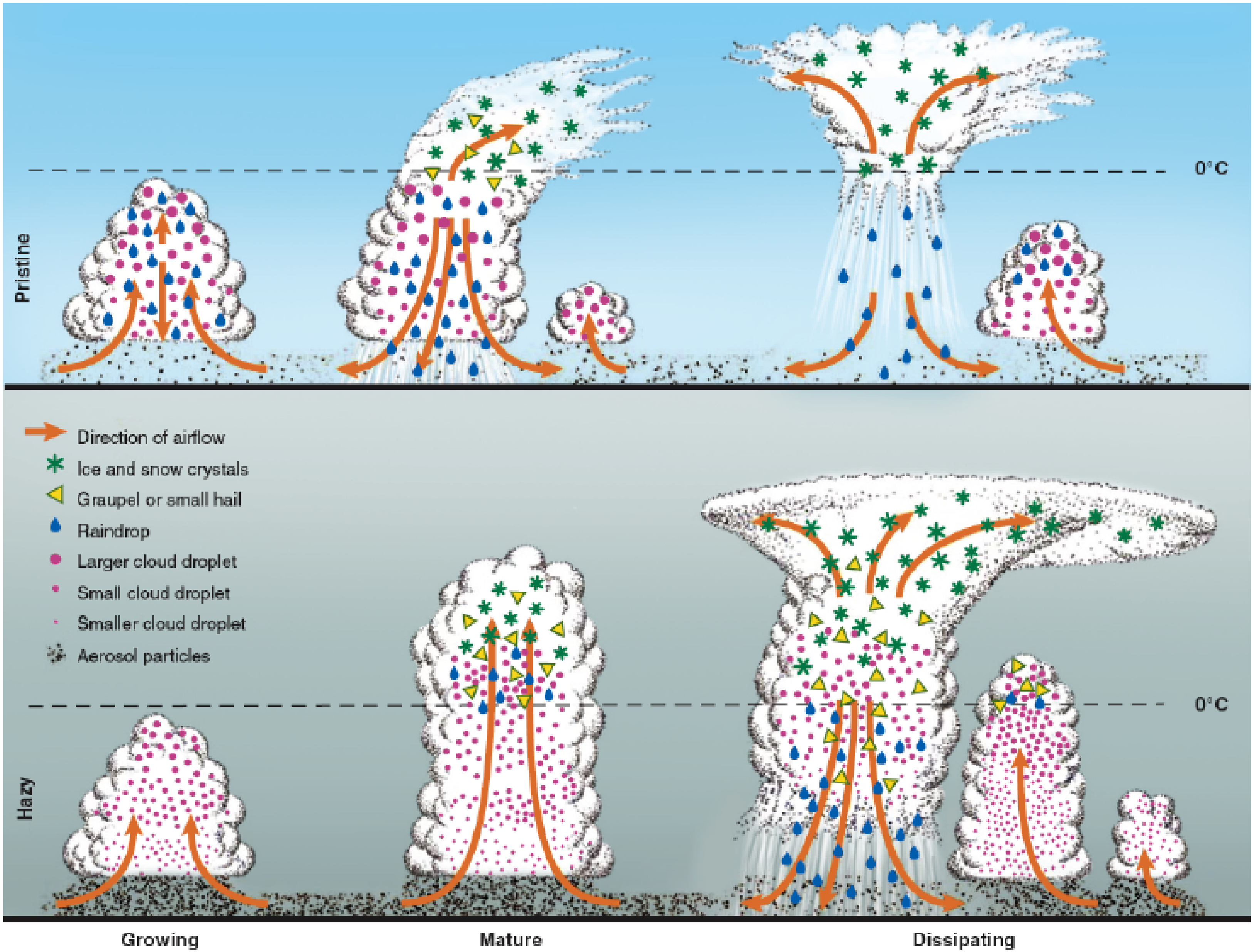
Large-eddy simulations for different cases
→ often shorter rather than longer cloud lifetimes due to faster evaporation of smaller droplets
→ liquid water path response also different for different cloud regimes

Jiang et al., Geophys. Res. Lett. 2006; Ackerman et al., Nature 2004

2.11 Freezing effect: Invigoration



2.11 Freezing effect: Invigoration



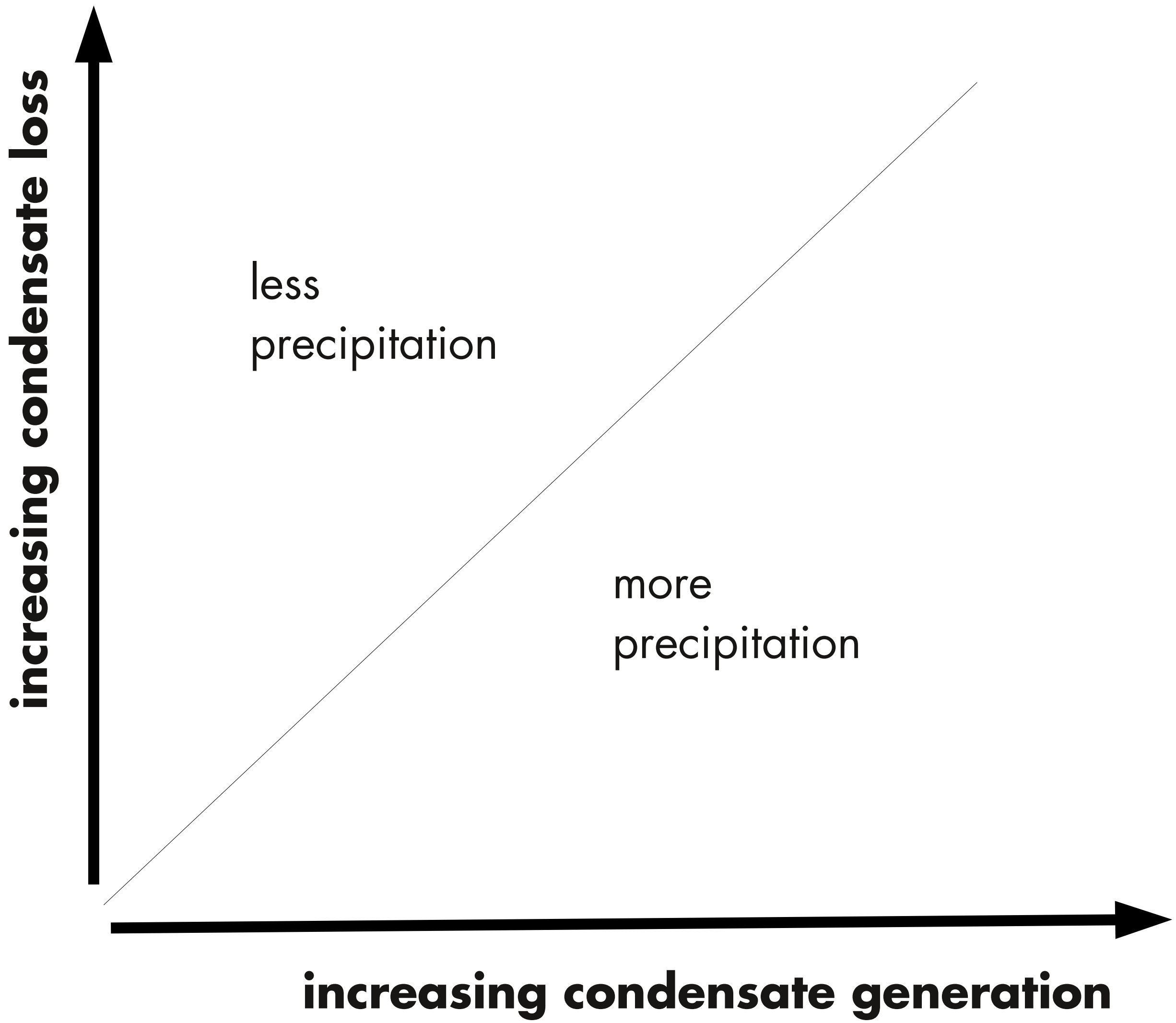
(i) delayed precipitation
→ more liquid water brought to freezing level

(ii) smaller droplets freeze later (higher)
→ grow more
→ more liquid water freezes

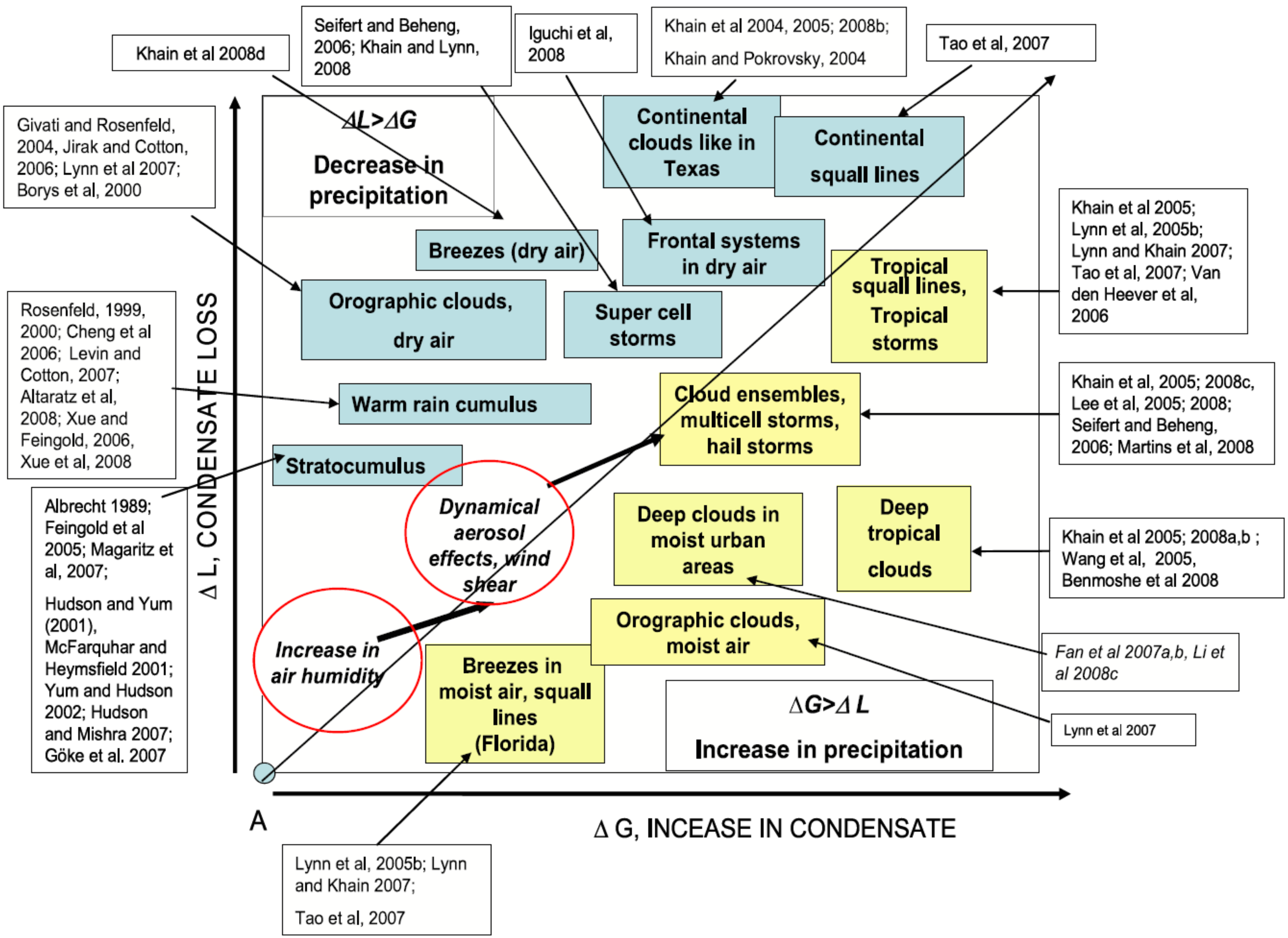
→. more latent heat release

Rosenfeld et al., Science 2008

2.12 Results from small scales on condensate



2.12 Results from small scales on condensate

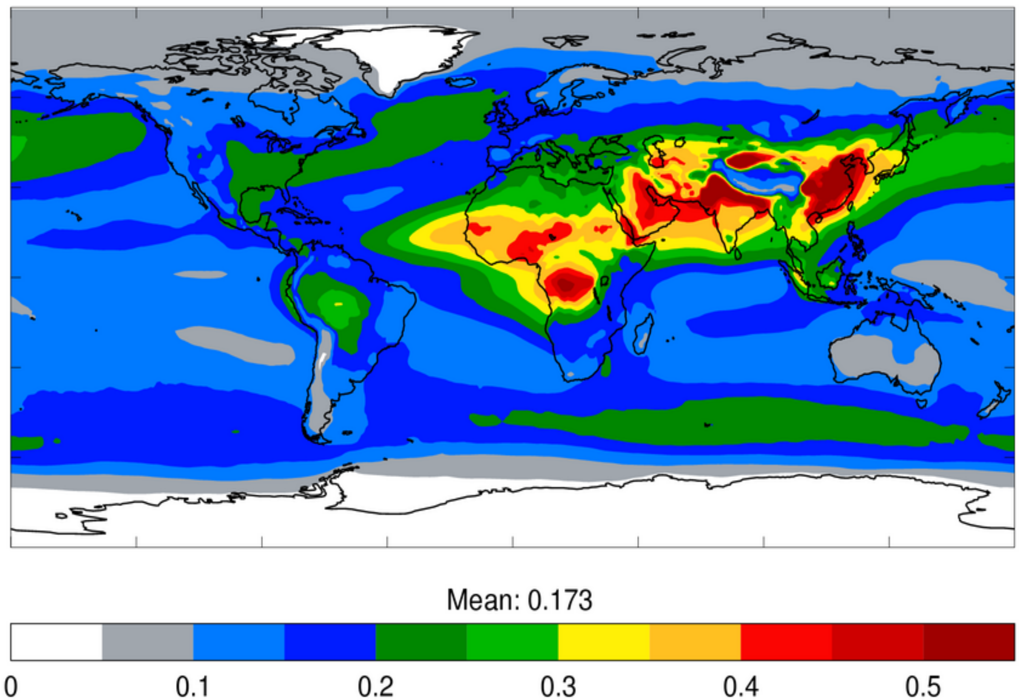


Khain, Env. Res. Lett. 2008

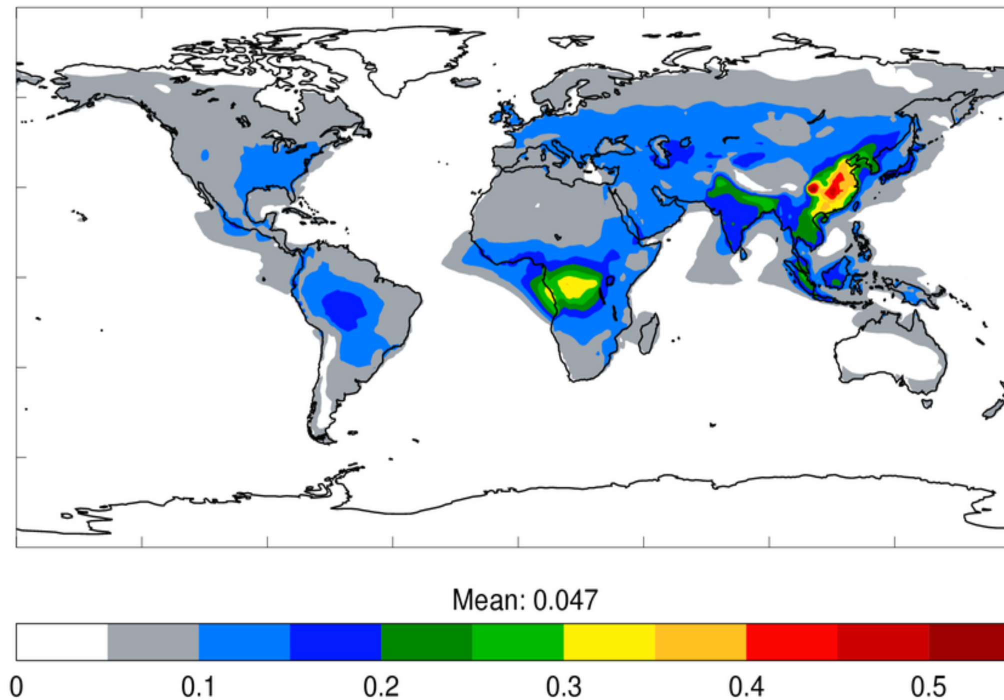
3. Anthropogenic aerosols

3.1 Monitoring Atmospheric Composition and Climate: MACC reanalysis

(see Poster Karoline Block)



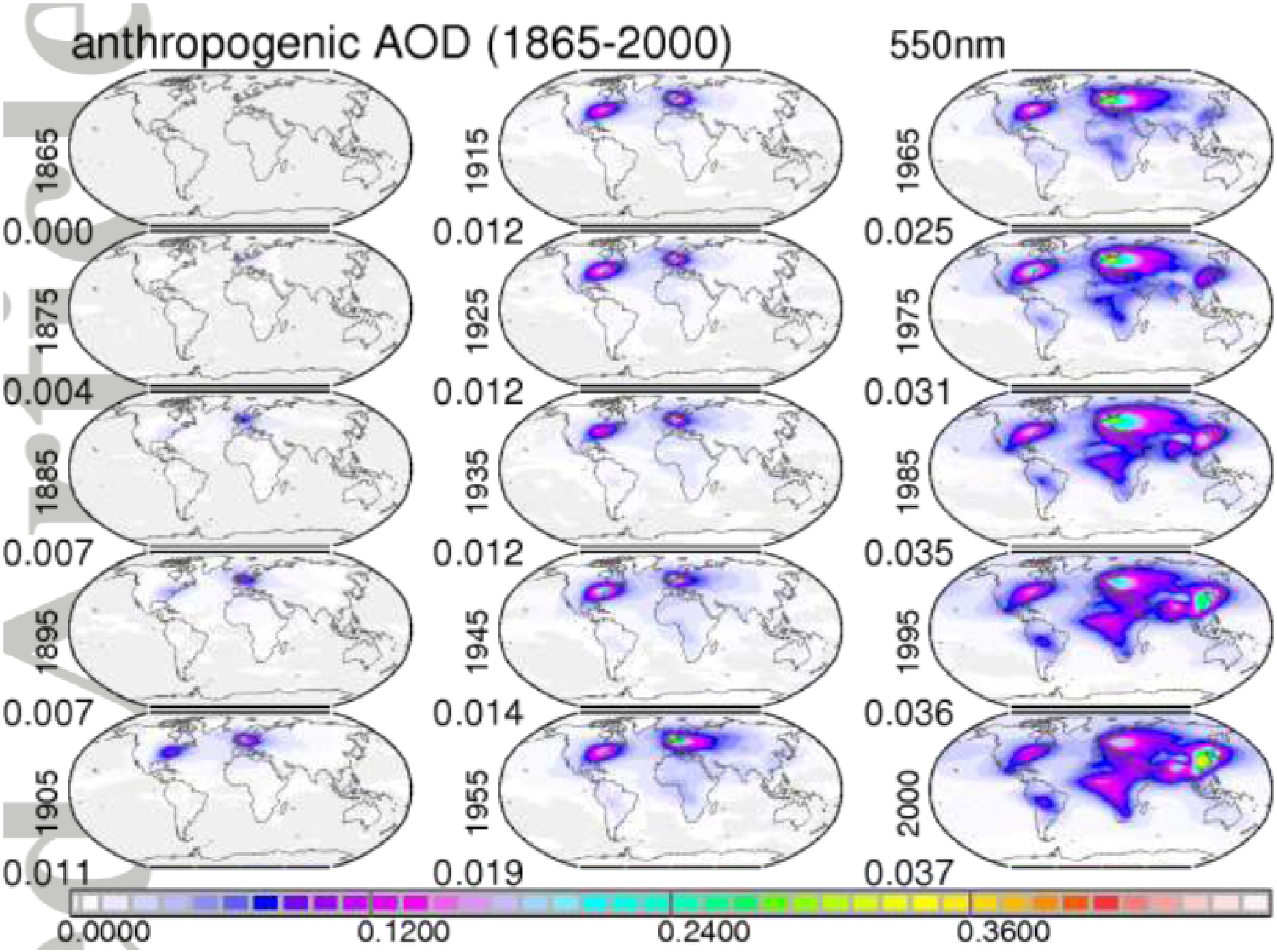
Total Aerosol optical depth (2003-05)
Global annual mean: 0.173



Anthropogenic AOD:
Global annual mean: 0.047
(~ 30%, large regional variability)

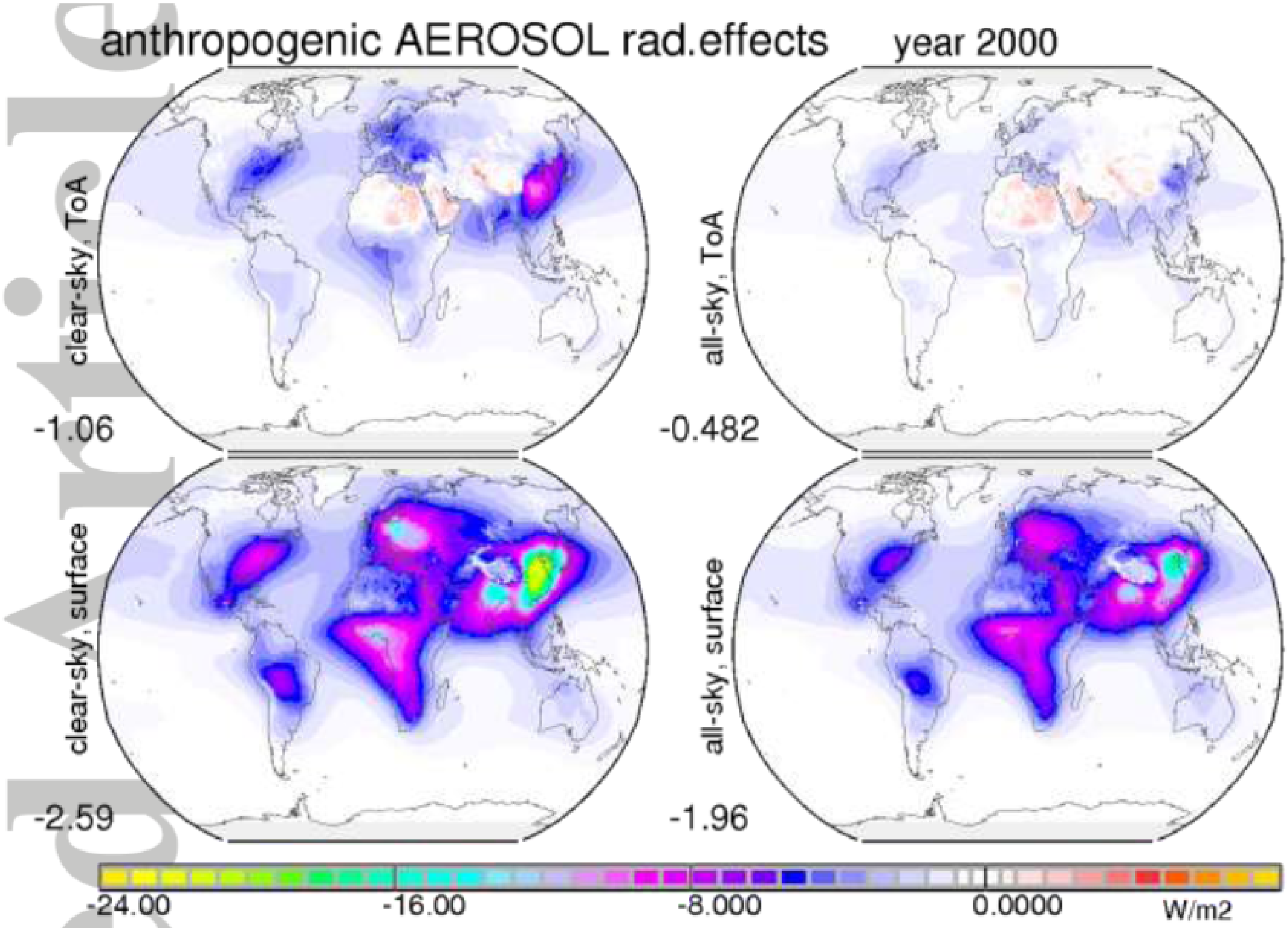
Bellouin, Quaas, Boucher, Morcrette, Atmos. Chem. Phys. 2013

3.2 Anthropogenic aerosols: Kinne climatology



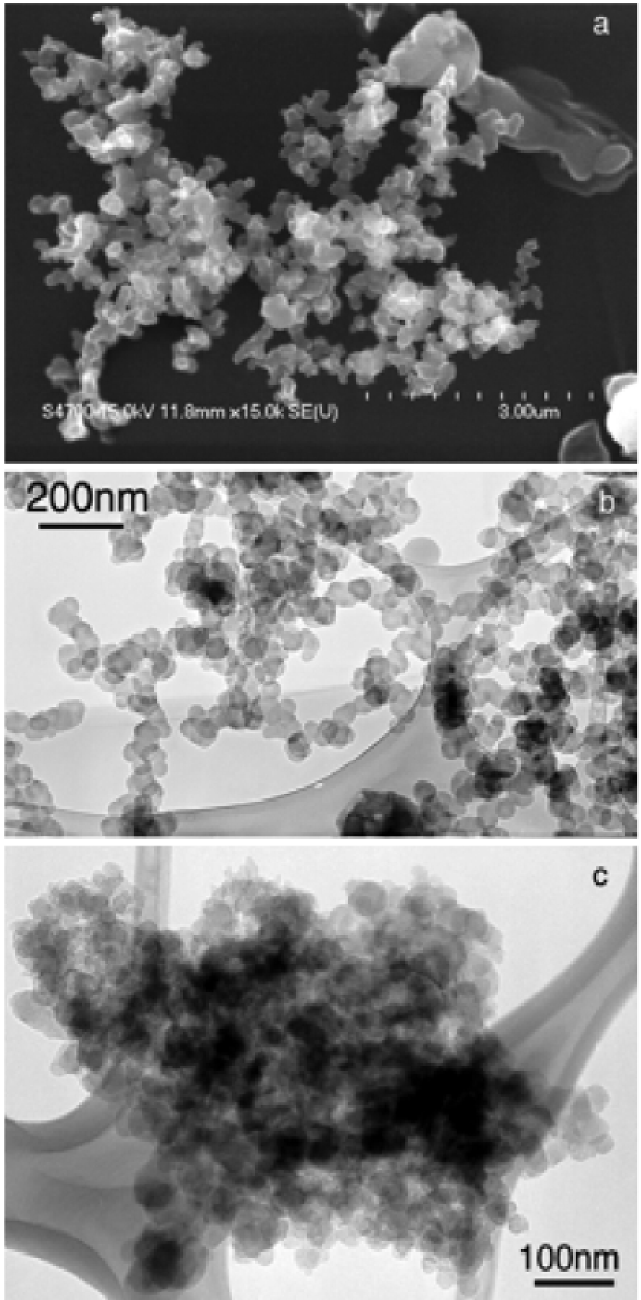
Kinne et al., J. Adv. Model. Earth Syst. 2013

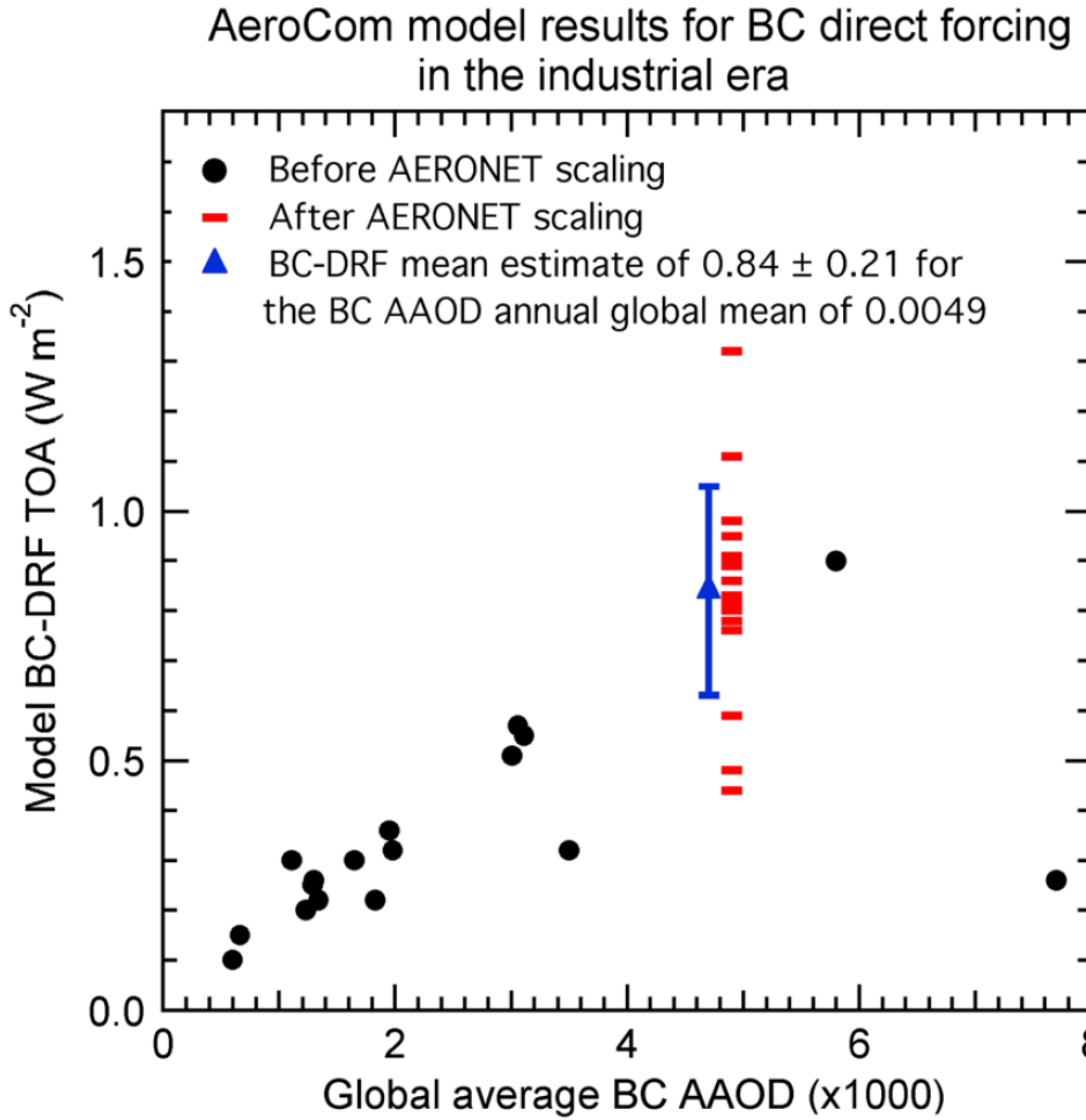
3.2 Anthropogenic aerosols: Kinne climatology



Kinne et al., J. Adv. Model. Earth Syst. 2013

3.3 Anthropogenic direct effect: Soot





Bond et al., J. Geophys. Res. 2013

3.4 Anthropogenic aerosol indirect radiative forcing

Forcing | Radiation | Cloud particles | Aerosol perturbation

$$\Delta F_{\mathrm{aie}} = \frac{\mathrm{d}R}{\mathrm{d}\ln N_{\mathrm{c}}} \cdot \frac{\mathrm{d}\ln N_{\mathrm{c}}}{\mathrm{d}\ln \alpha} \cdot \Delta \ln \alpha_{\mathrm{ant}}$$

3.4 Anthropogenic aerosol indirect radiative forcing

Forcing Radiation Cloud particles Aerosol perturbation

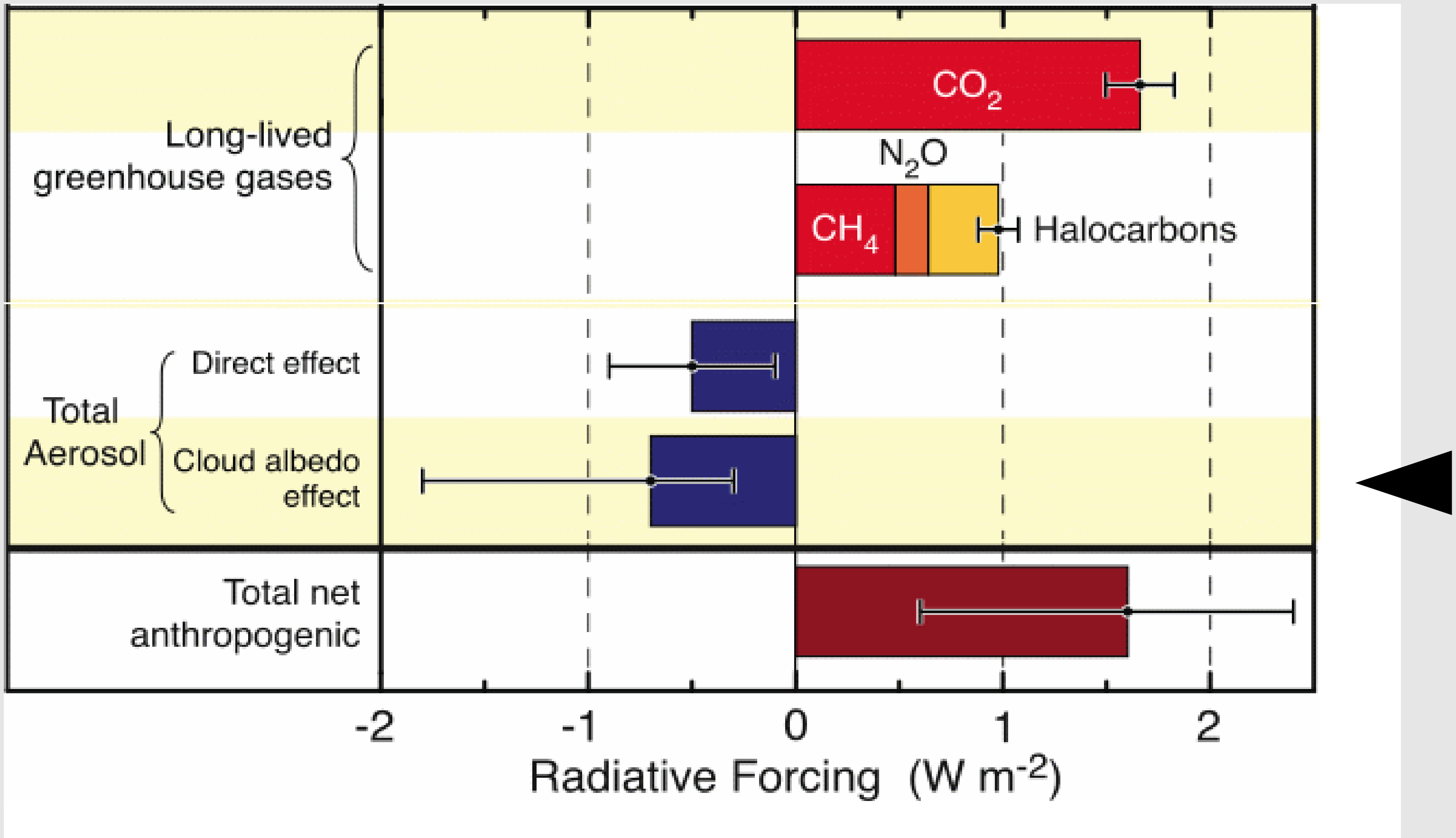
$$\Delta F_{\mathrm{aie}} = \frac{\mathrm{d}R}{\mathrm{d}\ln N_{\mathrm{c}}} \cdot \frac{\mathrm{d}\ln N_{\mathrm{c}}}{\mathrm{d}\ln \alpha} \cdot \Delta \ln \alpha_{\mathrm{ant}}$$

$$= \underbrace{\frac{\partial R}{\partial \ln N_{\mathrm{c}}}}_{\text{First indirect effect}} + \underbrace{\frac{\partial R}{\partial f}\frac{\partial f}{\partial \ln N_{\mathrm{c}}} + \frac{\partial R}{\partial L}\frac{\partial L}{\partial \ln N_{\mathrm{c}}} + \frac{\partial R}{\partial T_{\mathrm{top}}}\frac{\partial T_{\mathrm{top}}}{\partial \ln N_{\mathrm{c}}}}_{\text{Second indirect effect}}$$

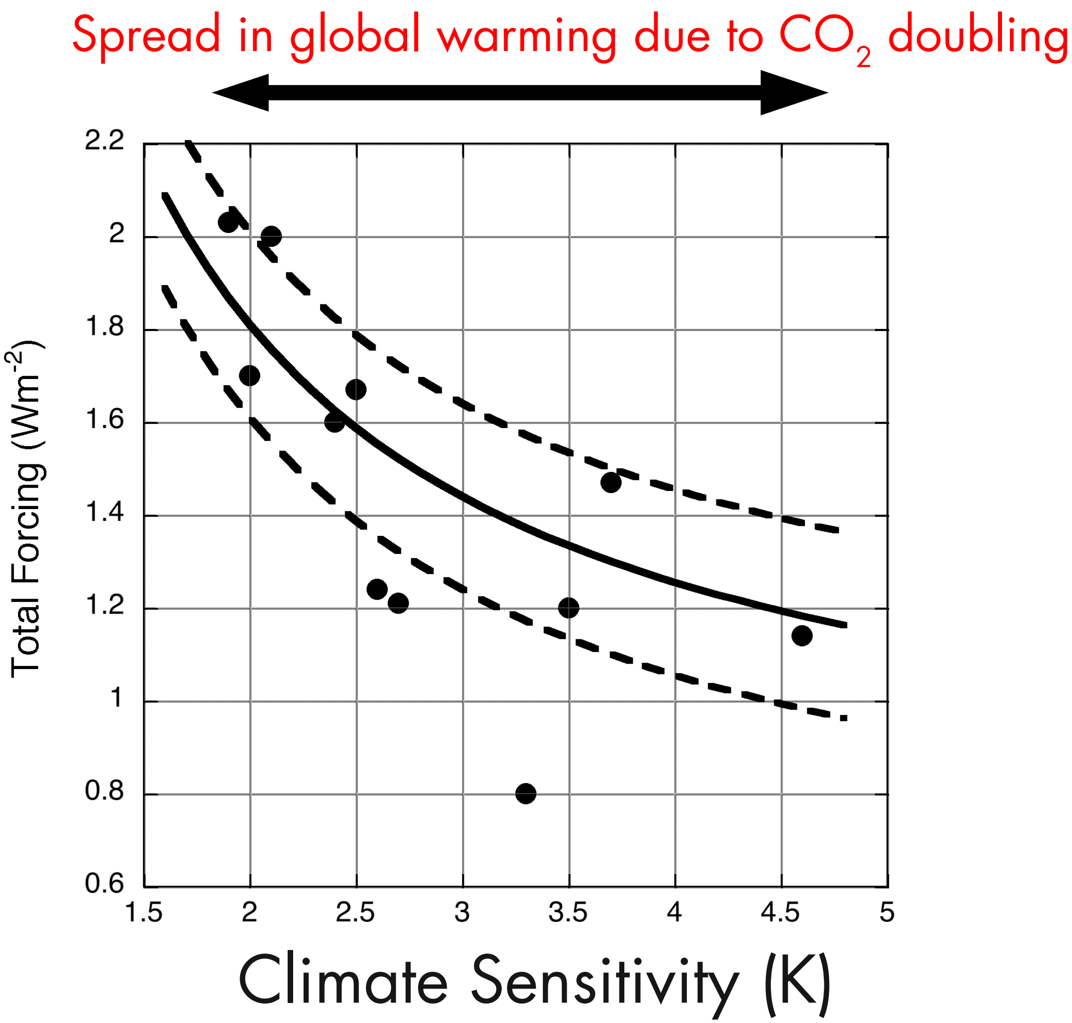
First indirect effect

Second indirect effect
Cloud fraction f, Water path L, Top temperature T_{top}

3.4 Anthropogenic aerosol forcing: Quantitative estimates



4. Importance for climate
4.1 Link to climate sensitivity

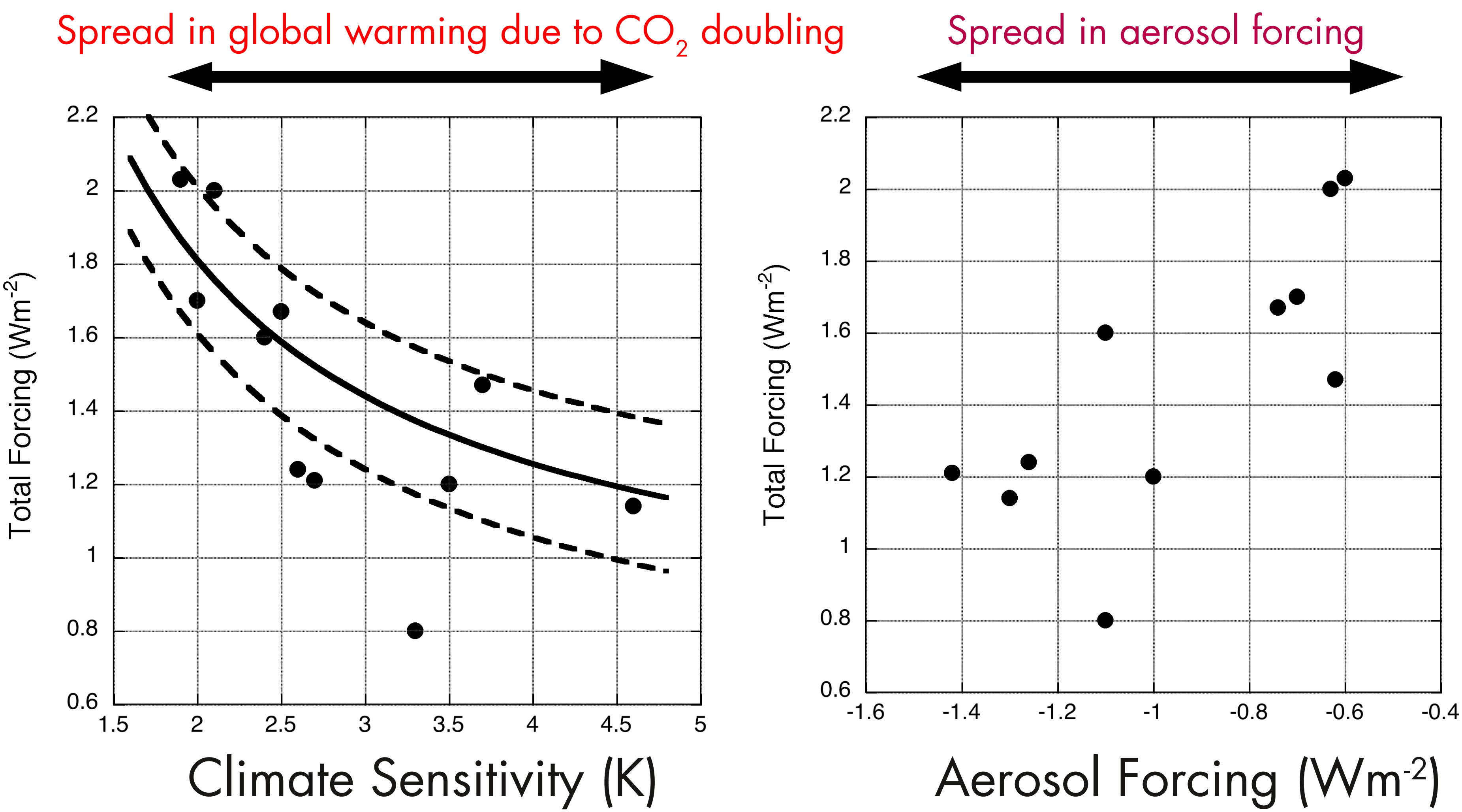


In CMIP3 climate models:

Climate sensitivity uncertainty

Kiehl, Geophys. Res. Lett., 2007

4.1 Link to climate sensitivity

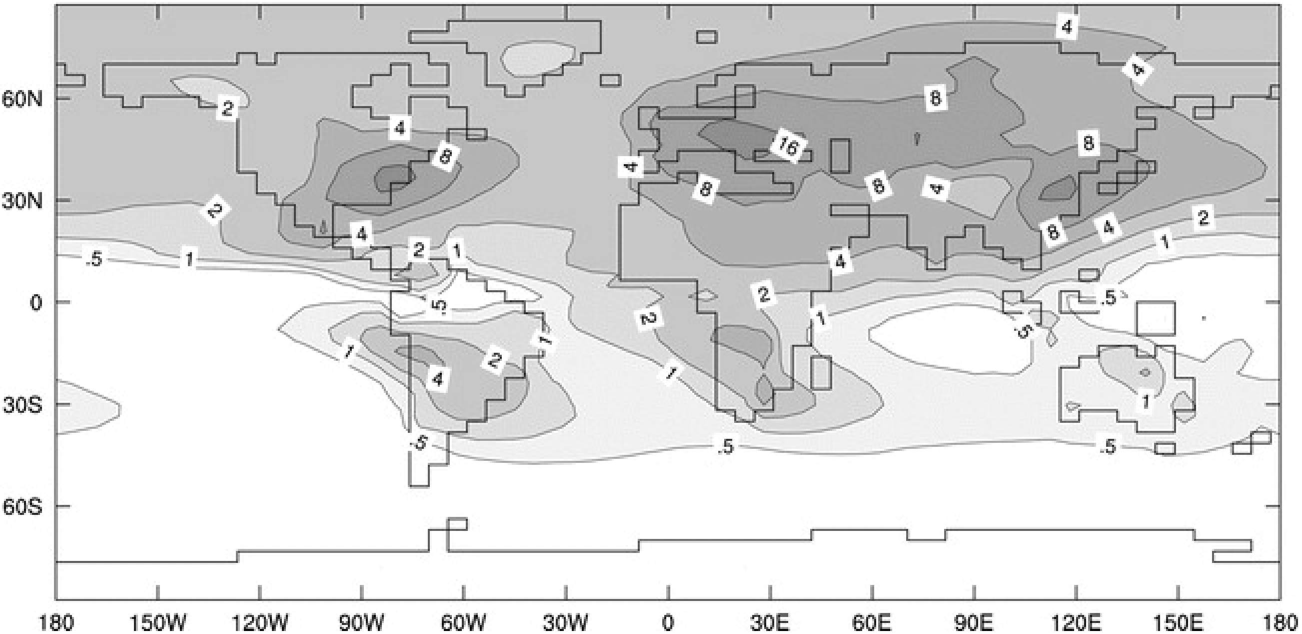


In CMIP3 climate models:

Climate sensitivity uncertainty ↔ Aerosol forcing uncertainty

Kiehl, Geophys. Res. Lett., 2007

4.2 Effects on dynamics: Sahel drying

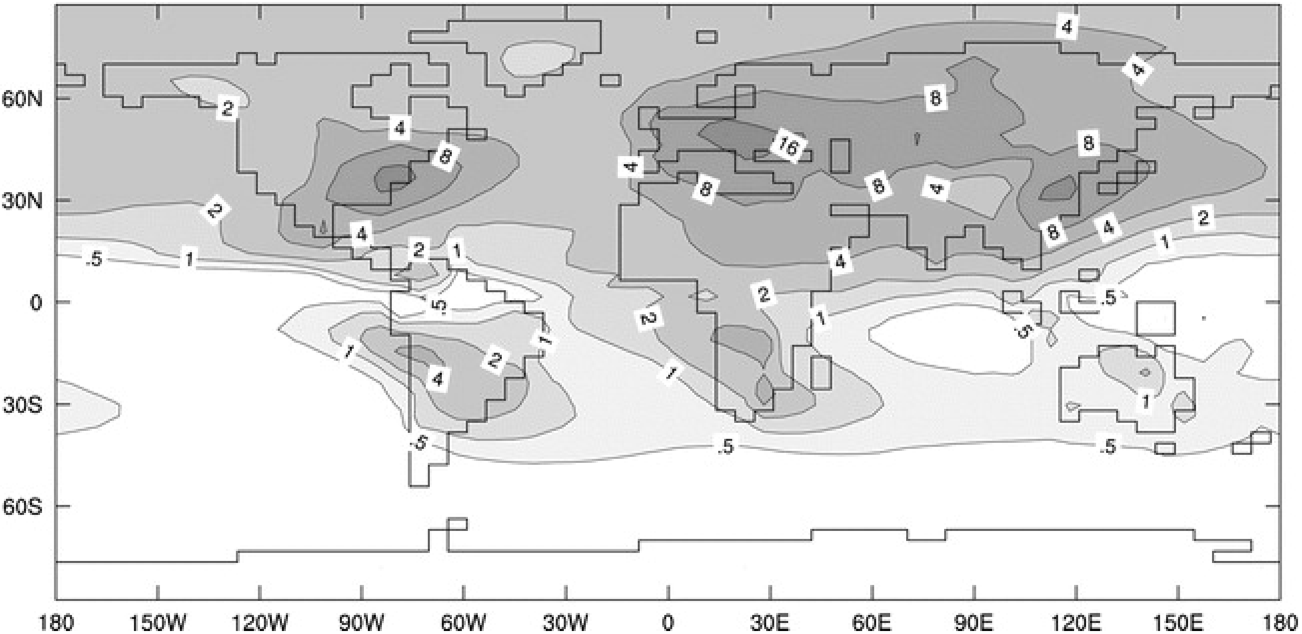


Simulated change in sulfate aerosol burden [mg m^{-2}], annual mean peak at 16 mg m^{-2}

Strong forcing: -1.8 W m^{-2} in global mean

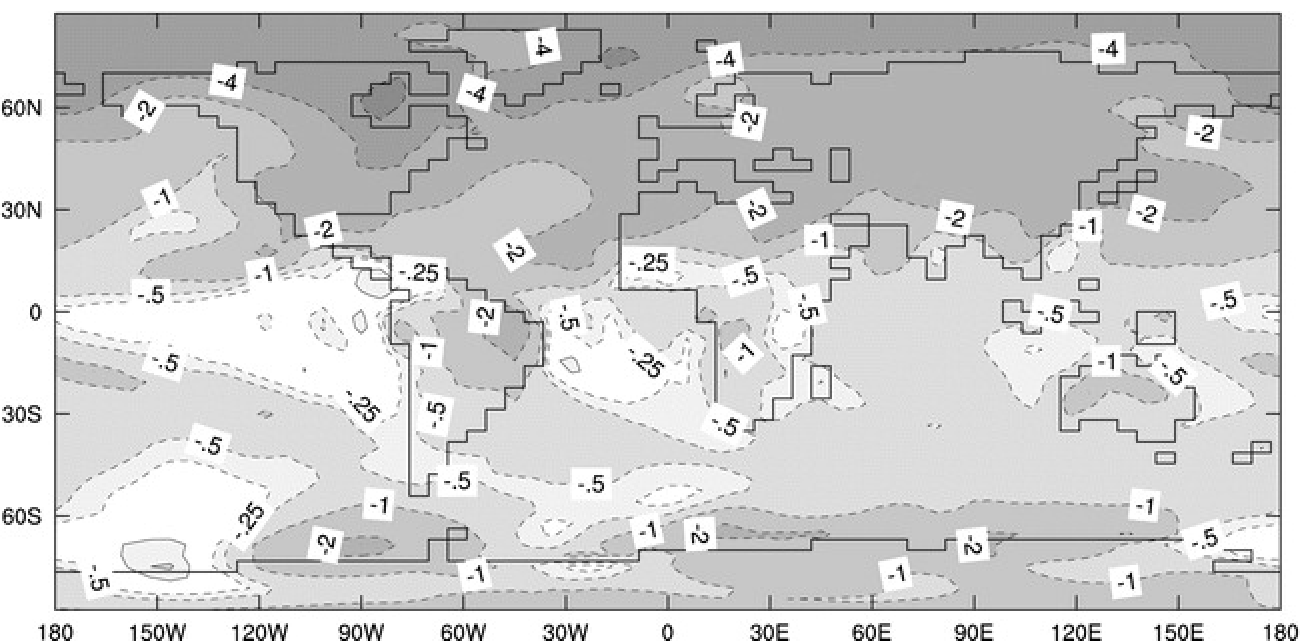
Rotstayn and Lohmann, J Climate 2002

4.2 Effects on dynamics: Sahel drying



Simulated change in sulfate aerosol burden [mg m^{-2}], annual mean peak at 16 mg m^{-2}

Strong forcing: -1.8 W m^{-2} in global mean



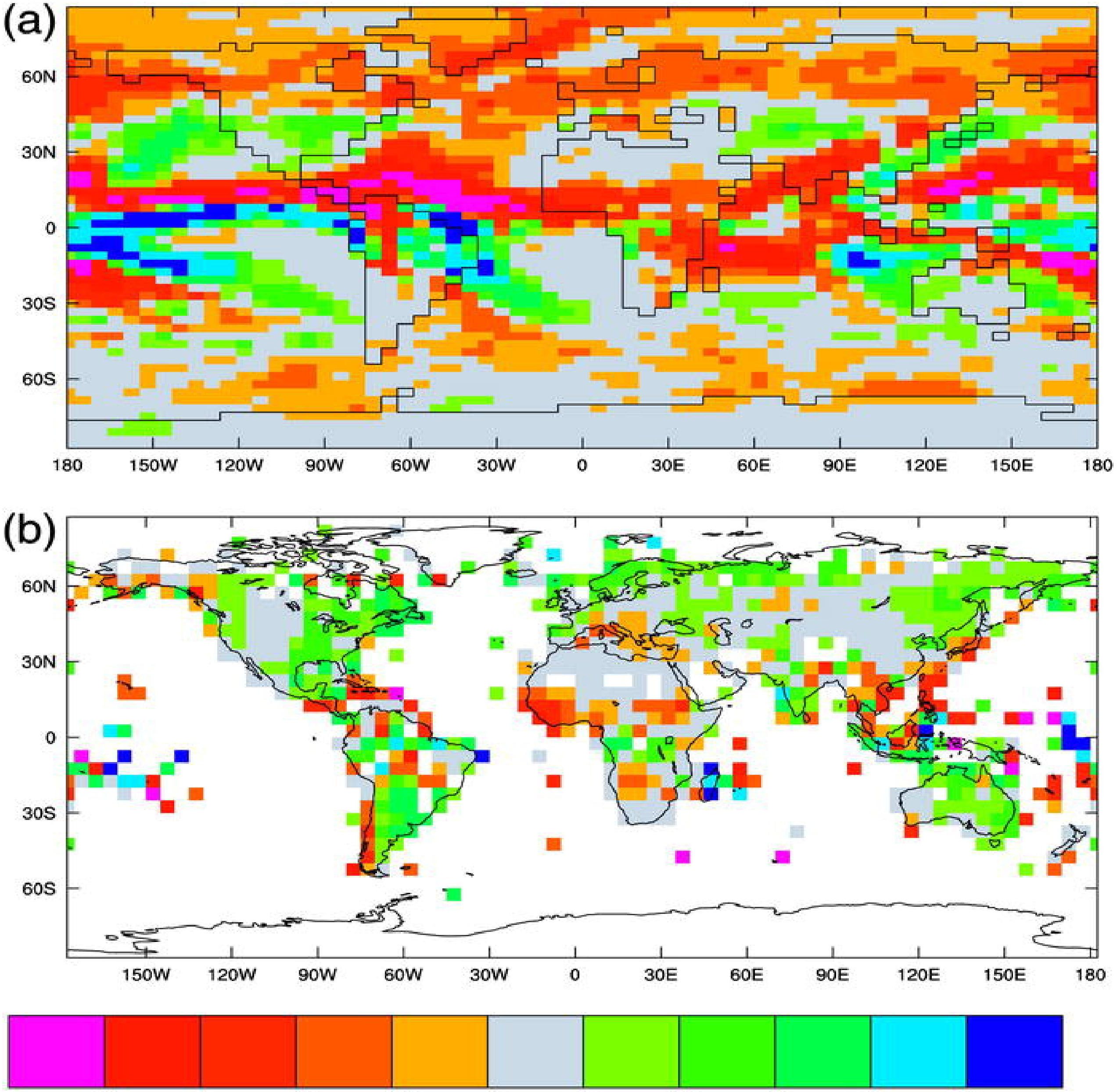
Simulated corresponding surface temperature change [K]
Peak at -8 K, -2 K widespread over Northern hemisphere mid- to high latitudes

Rotstayn and Lohmann, J Climate 2002

4.2 Effects on dynamics: Sahel drying

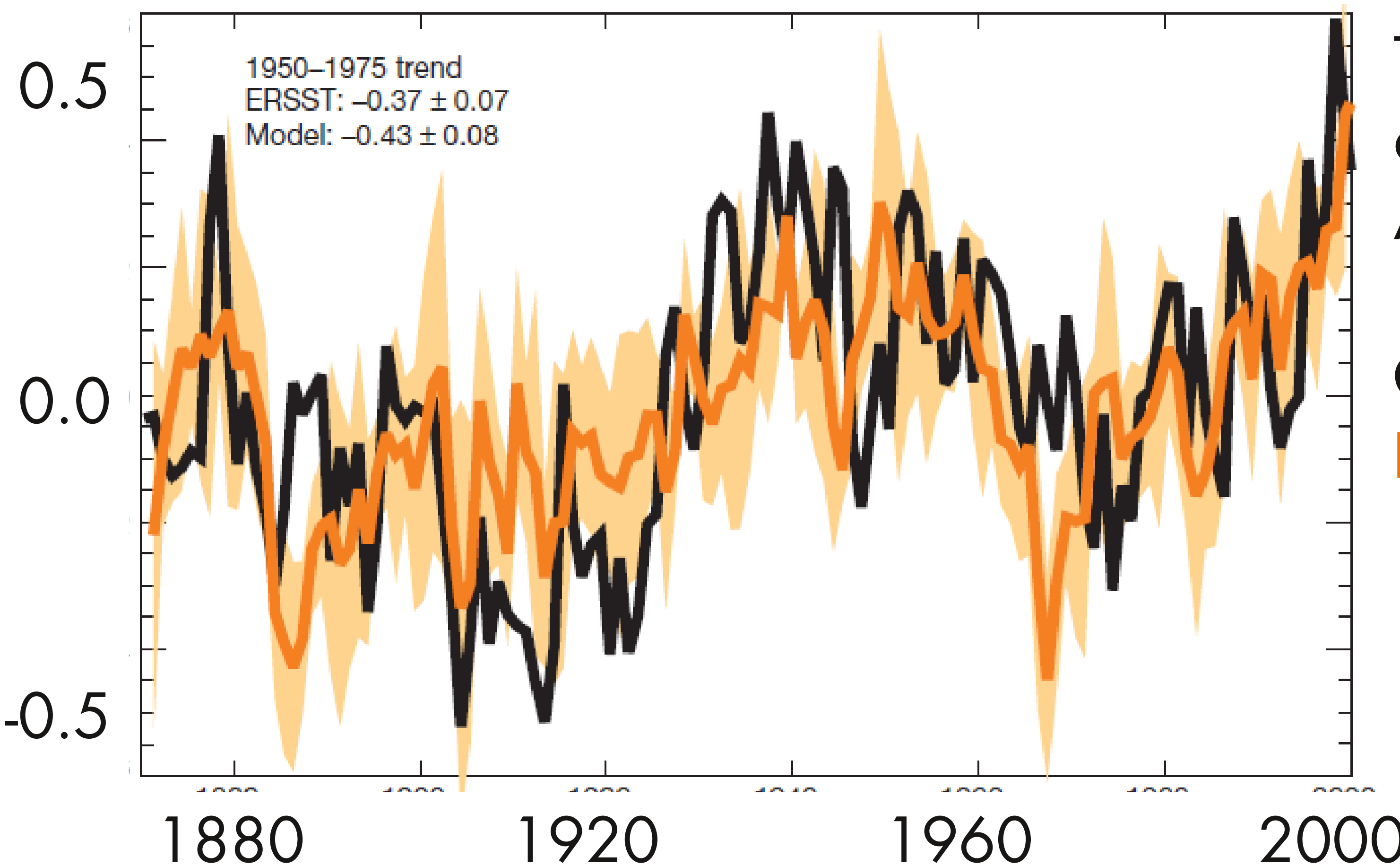
Trends in annual-mean precipitation

Top: Simulated
Bottom: Observed



Rotstayn and Lohmann, J Climate 2002

4.3 Effects on dynamics: North Atlantic Oscillation

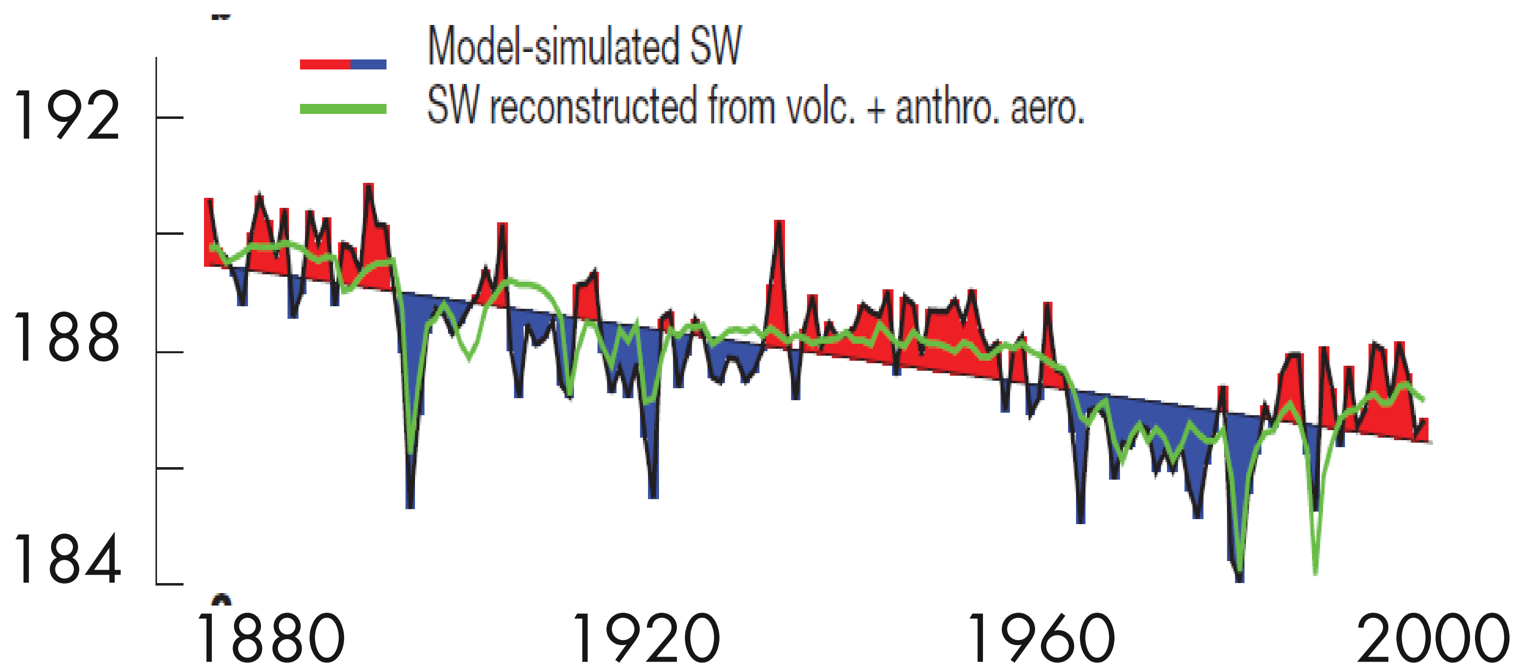


Temperature anomalies North Atlantic Ocean [K]

Observations

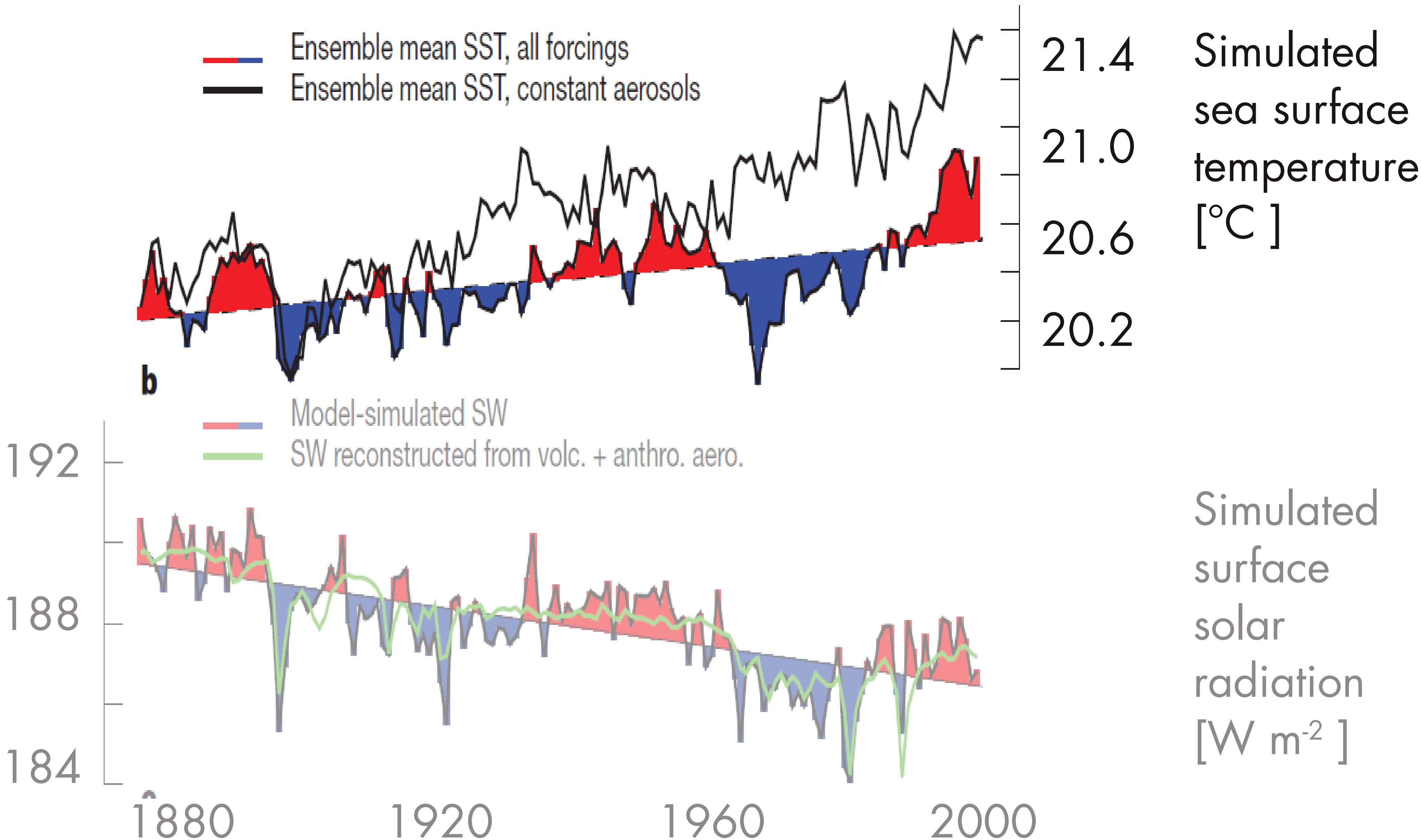
HadGEM2-ES

4.3 Effects on dynamics: North Atlantic Oscillation



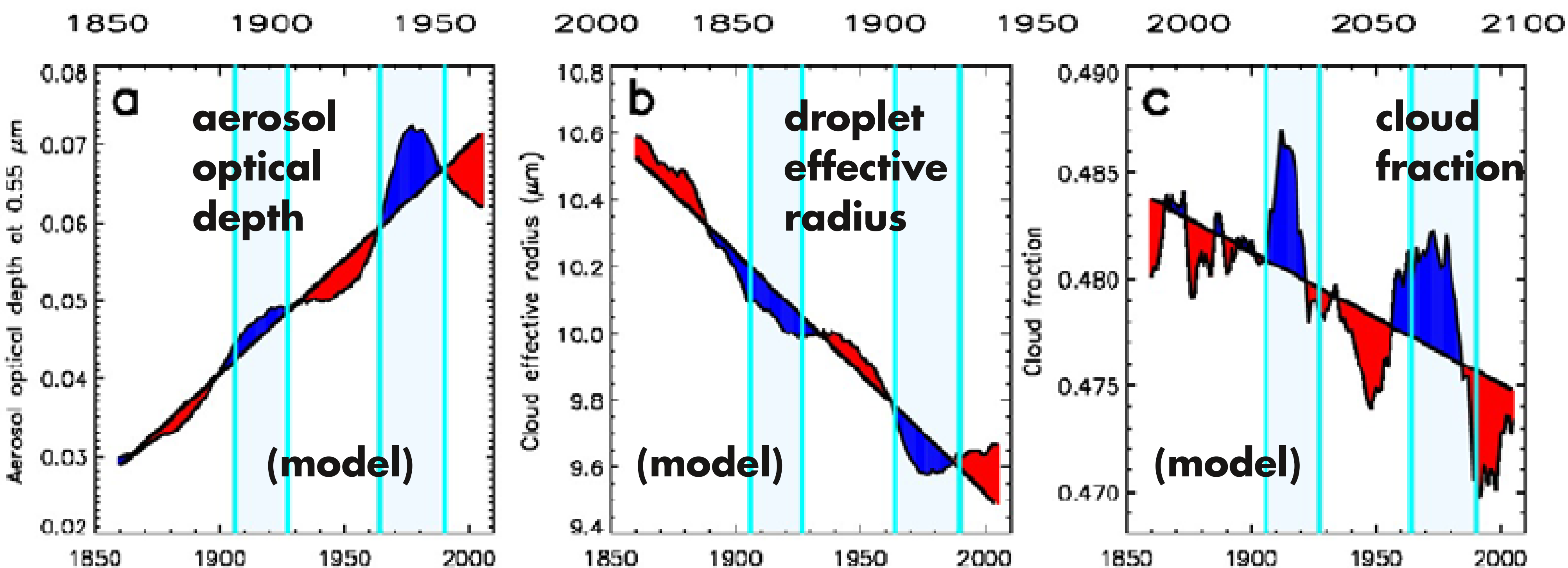
Simulated surface solar radiation [W m^{-2}]

4.3 Effects on dynamics: North Atlantic Oscillation



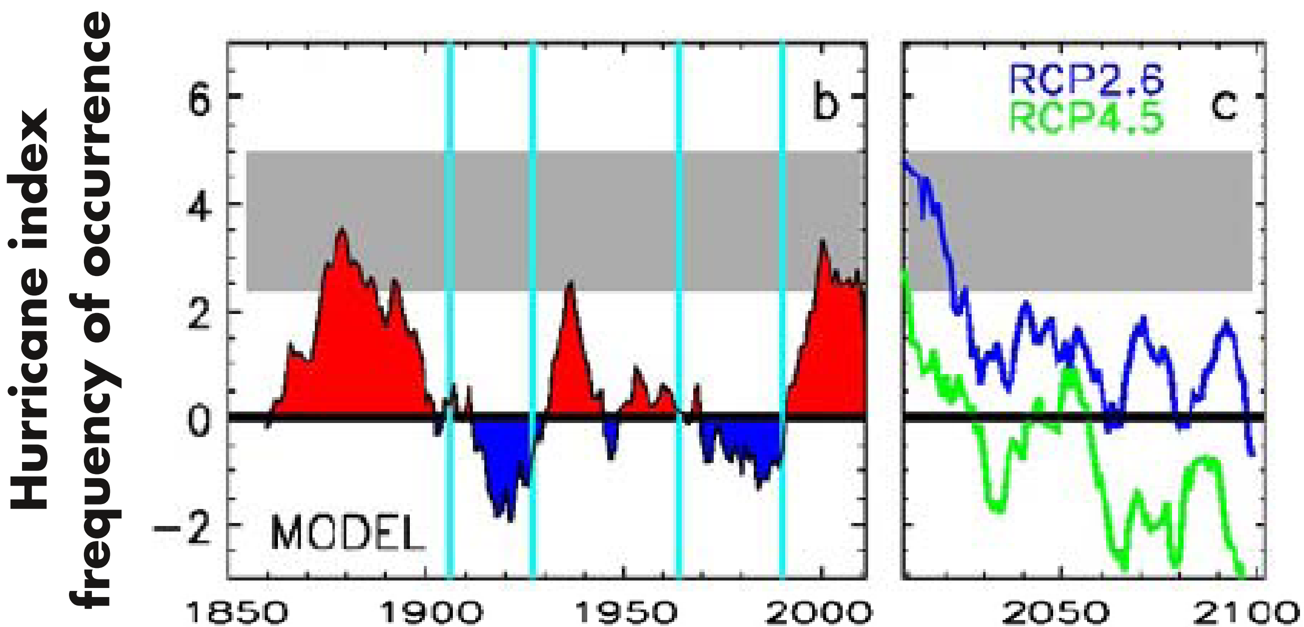
Booth et al., Nature 2012

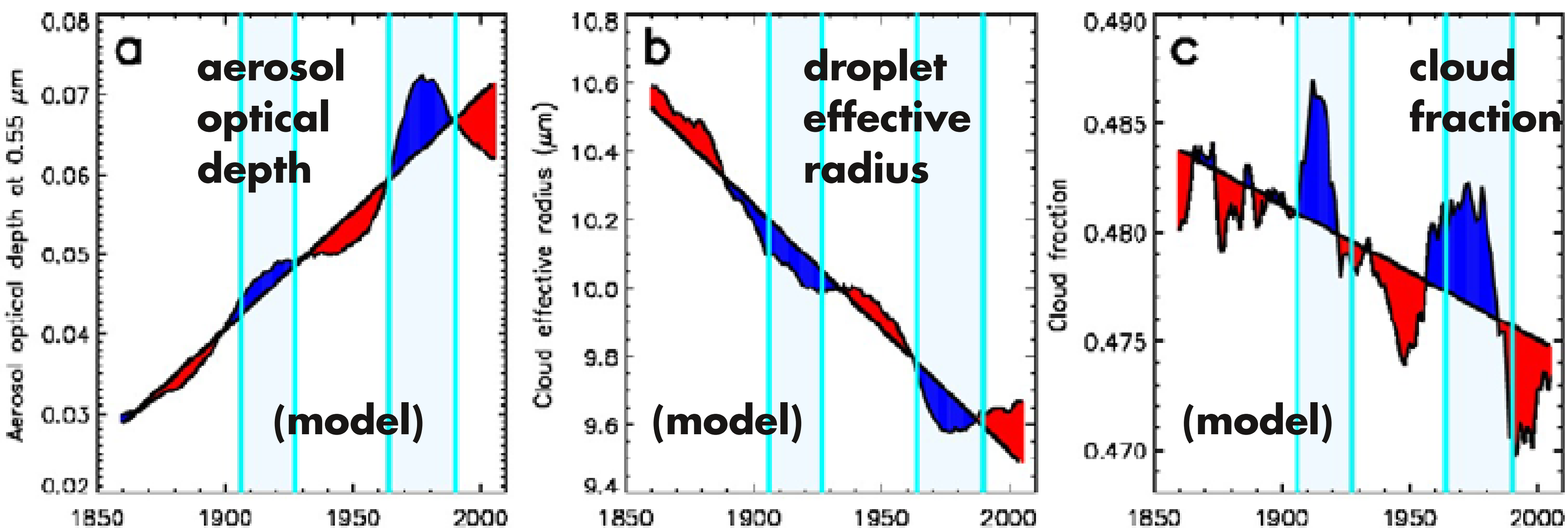
4.4 Effects on dynamics: Hurricanes



Dunstone et al., Nature Geosci. 2013

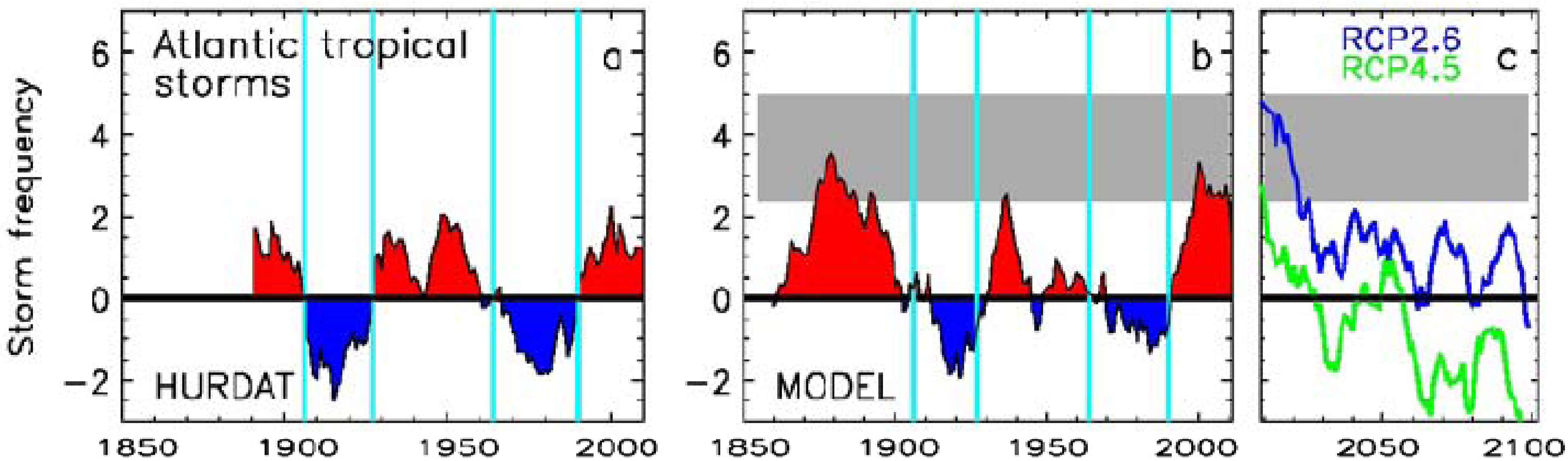
4.4 Effects on dynamics: Hurricanes

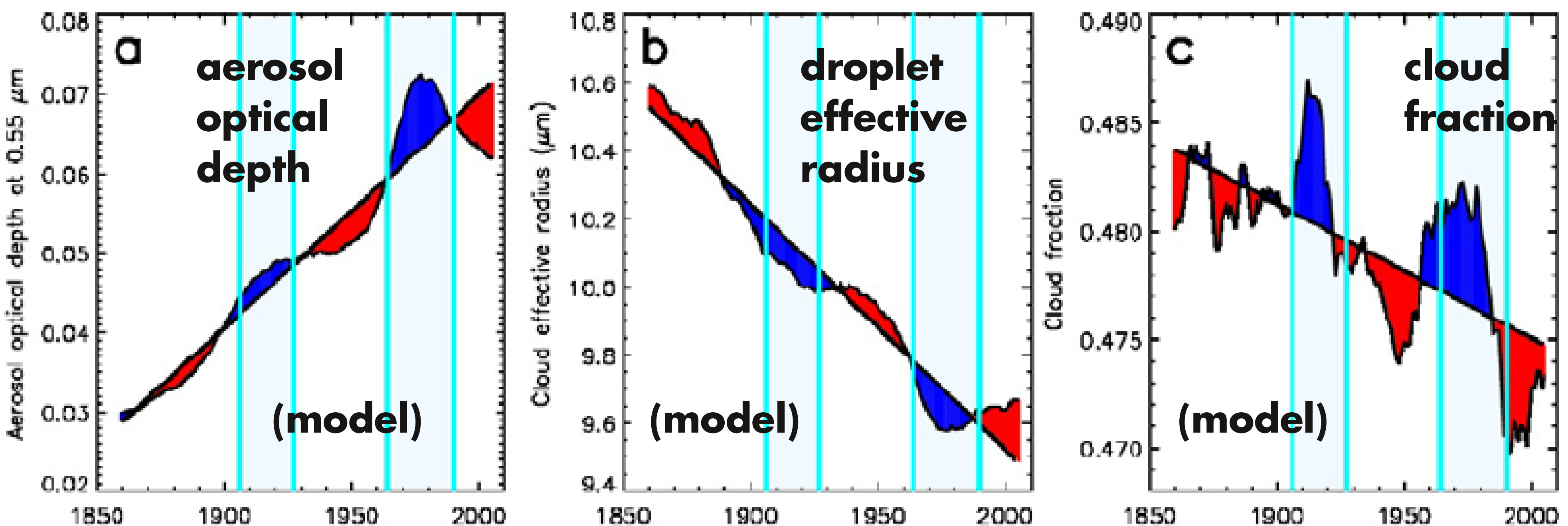




Dunstone et al., Nature Geosci. 2013

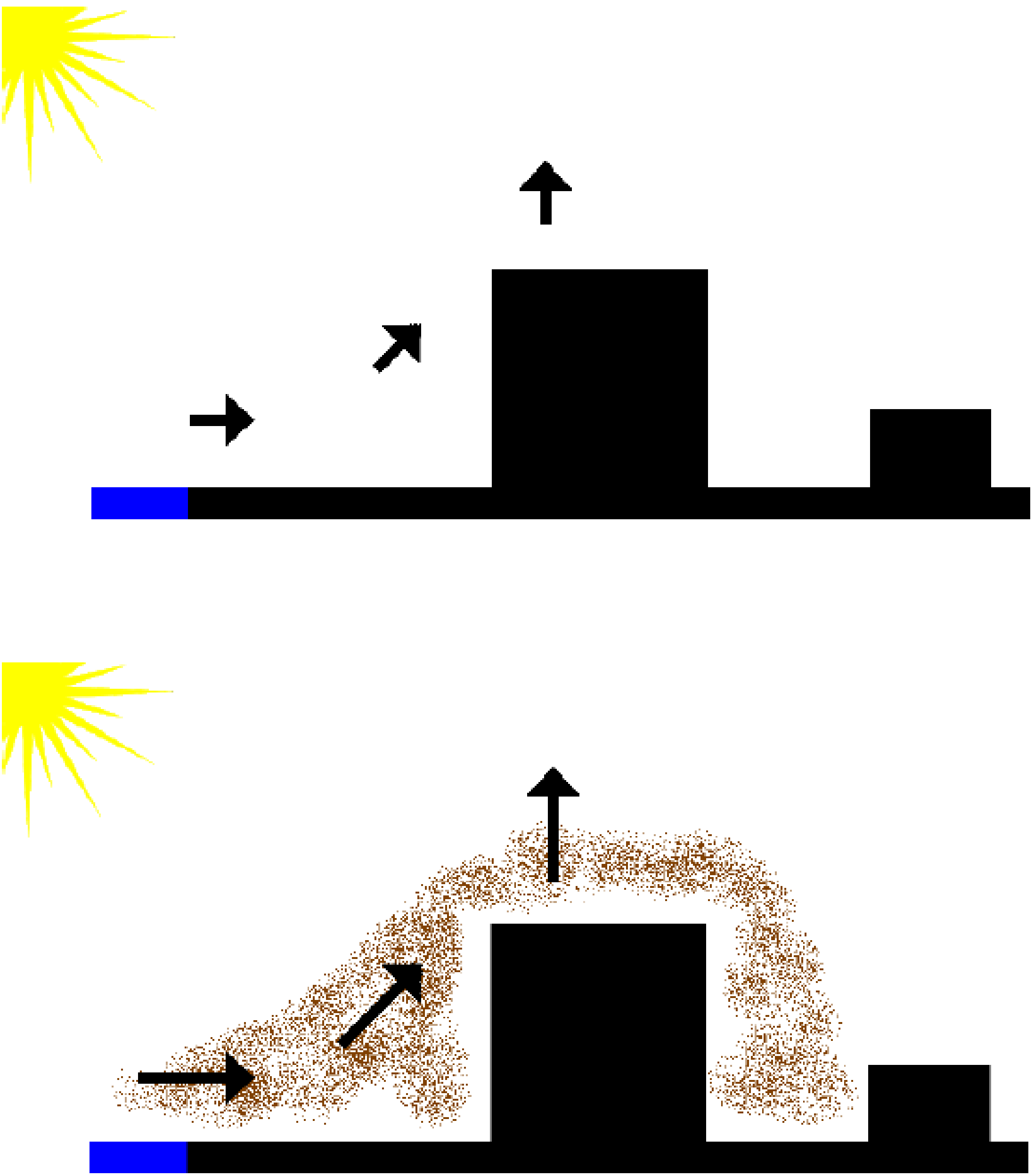
4.4 Effects on dynamics: Hurricanes





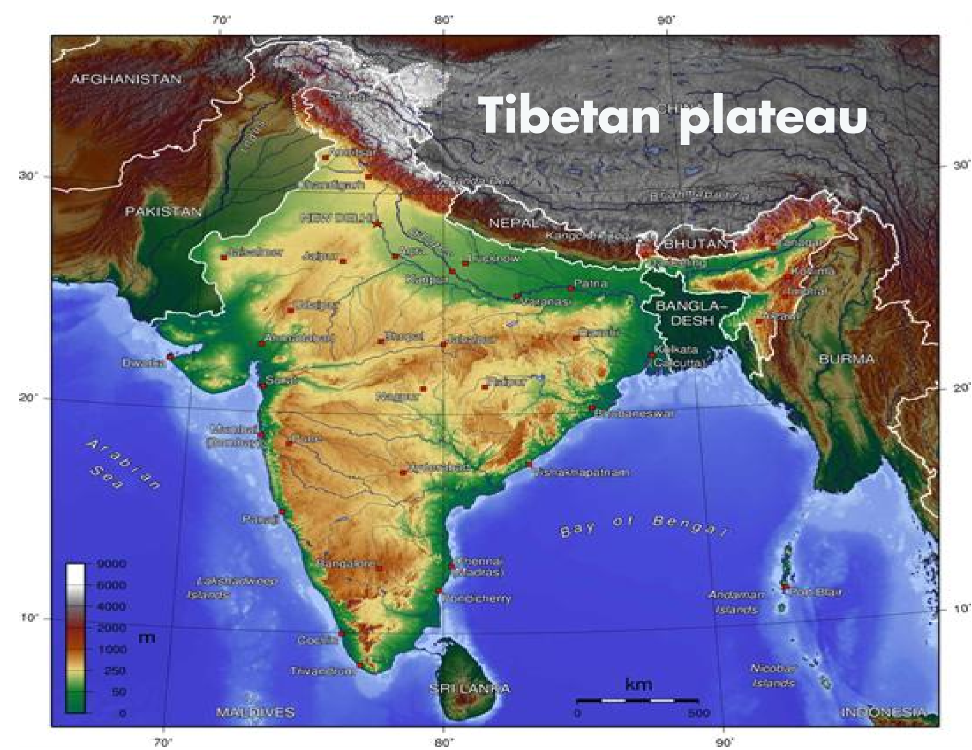
Dunstone et al., Nature Geosci. 2013

4.5 Effects on dynamics: Monsoon



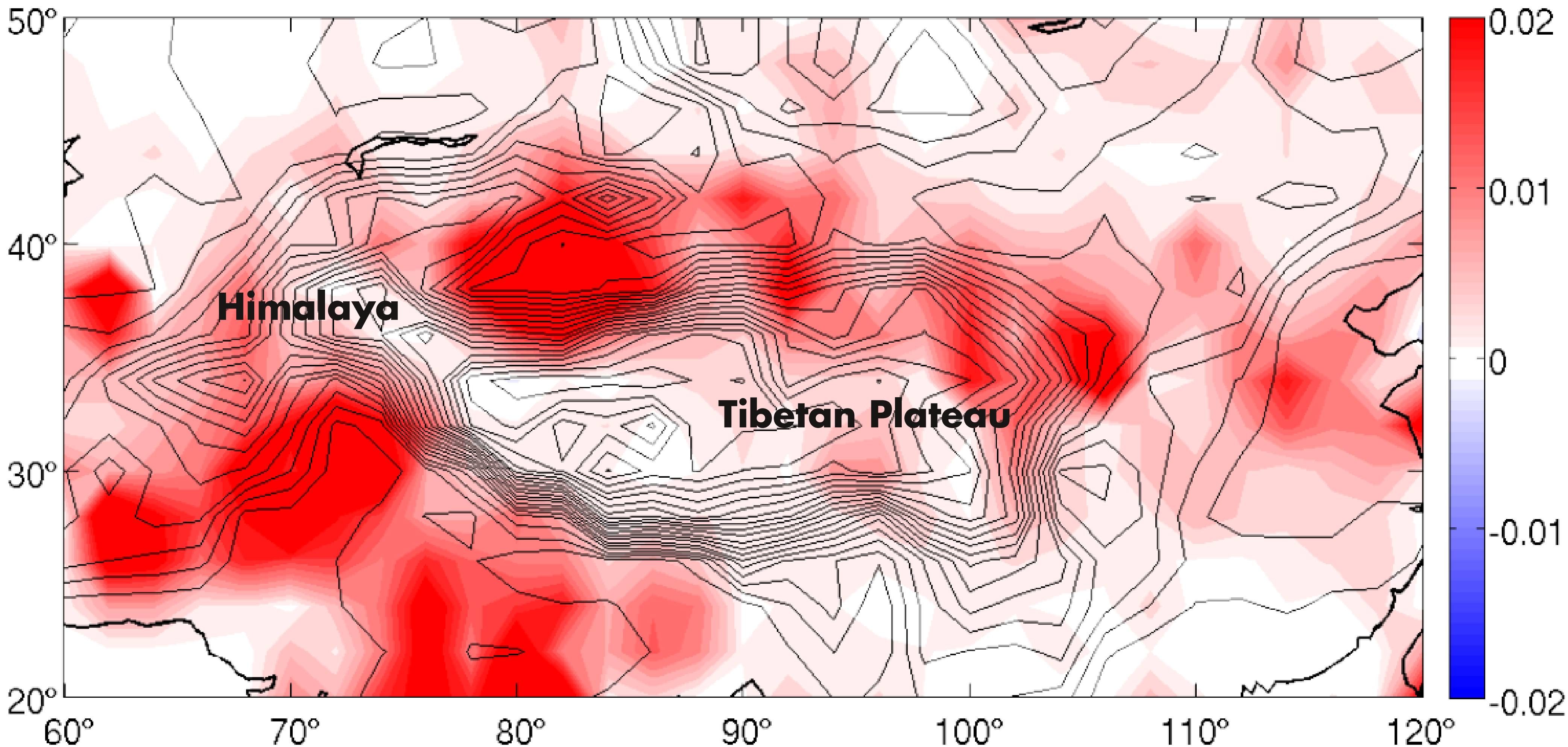
"Elevated heat pump"-hypothesis

Absorption of sunlight over Tibetan Plateau enforces monsoon circulation?



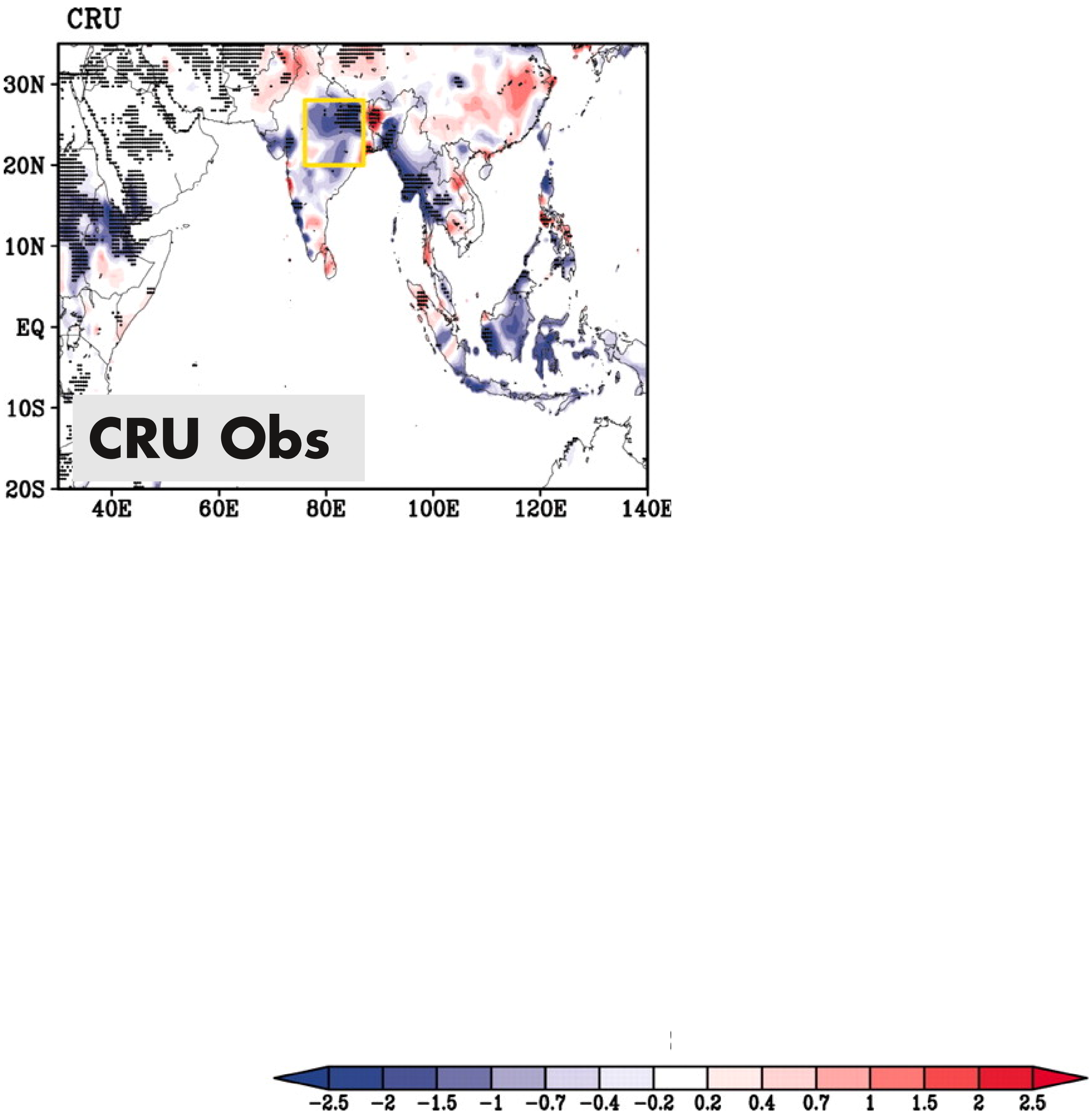
Kuhlmann and Quaas, Atmos. Chem. Phys. 2010

Heating rates [K day^{-1}] by aerosol
(CALIPSO lidar satellite data and radiative transfer modelling)



Kuhlmann and Quaas, Atmos. Chem. Phys. 2010

4.5 Effects on dynamics: Monsoon

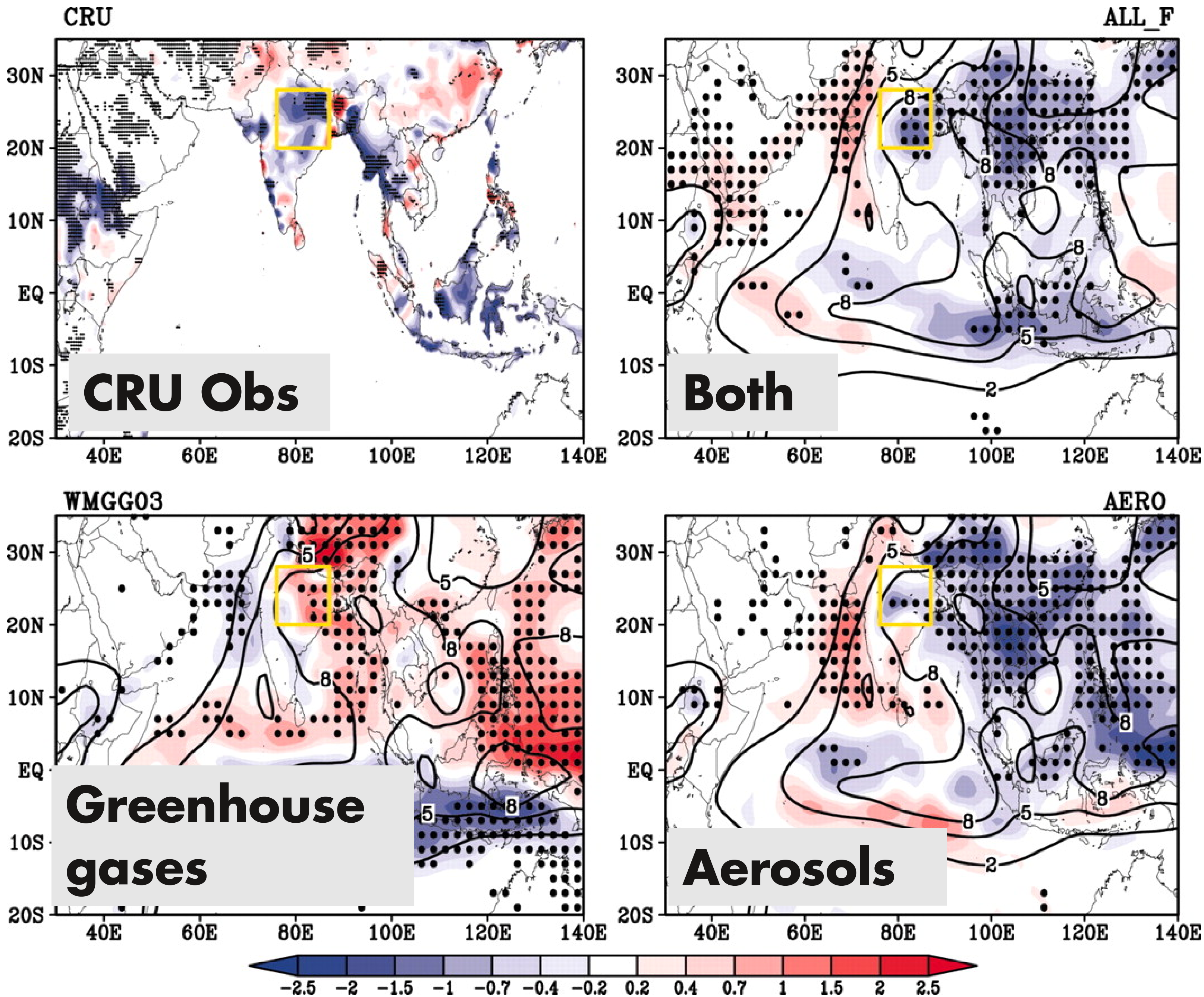


Linear trends 1950-1999 in June-September precipitation

[mm day^{-1} (50 yr)$^{-1}$]

Bollasina et al., Science 2011

4.5 Effects on dynamics: Monsoon



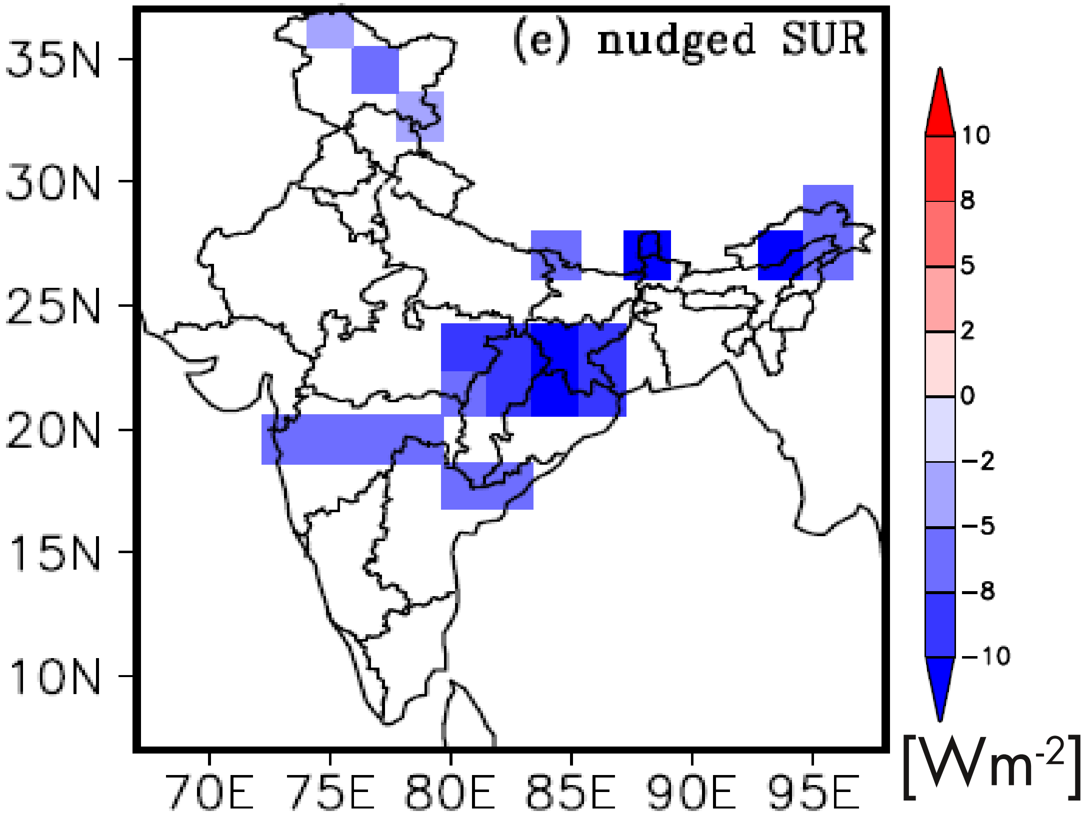
Linear trends 1950-1999 in June-September precipitation

[mm day^{-1} (50 yr)$^{-1}$]

Slowdown of meridional overturning compensates hemispherical energy imbalance

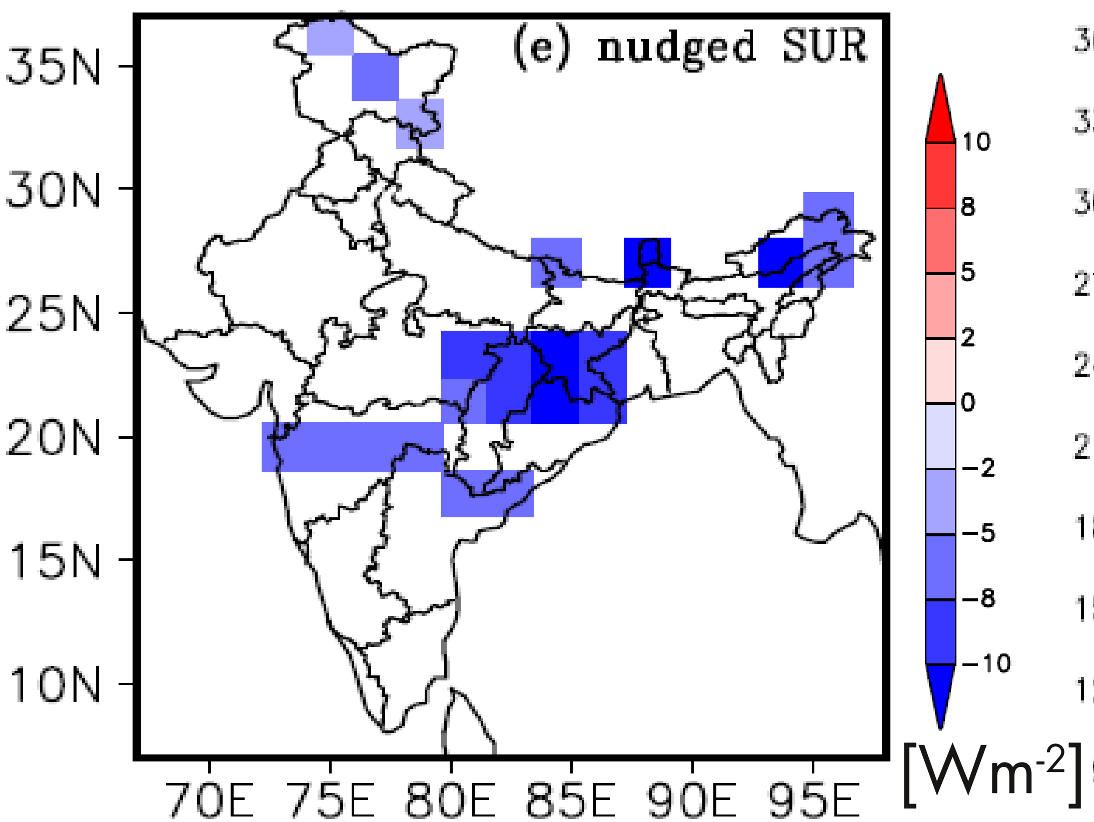
Bollasina et al., Science 2011

Surface radiative forcing
due to anthropogenic aerosol

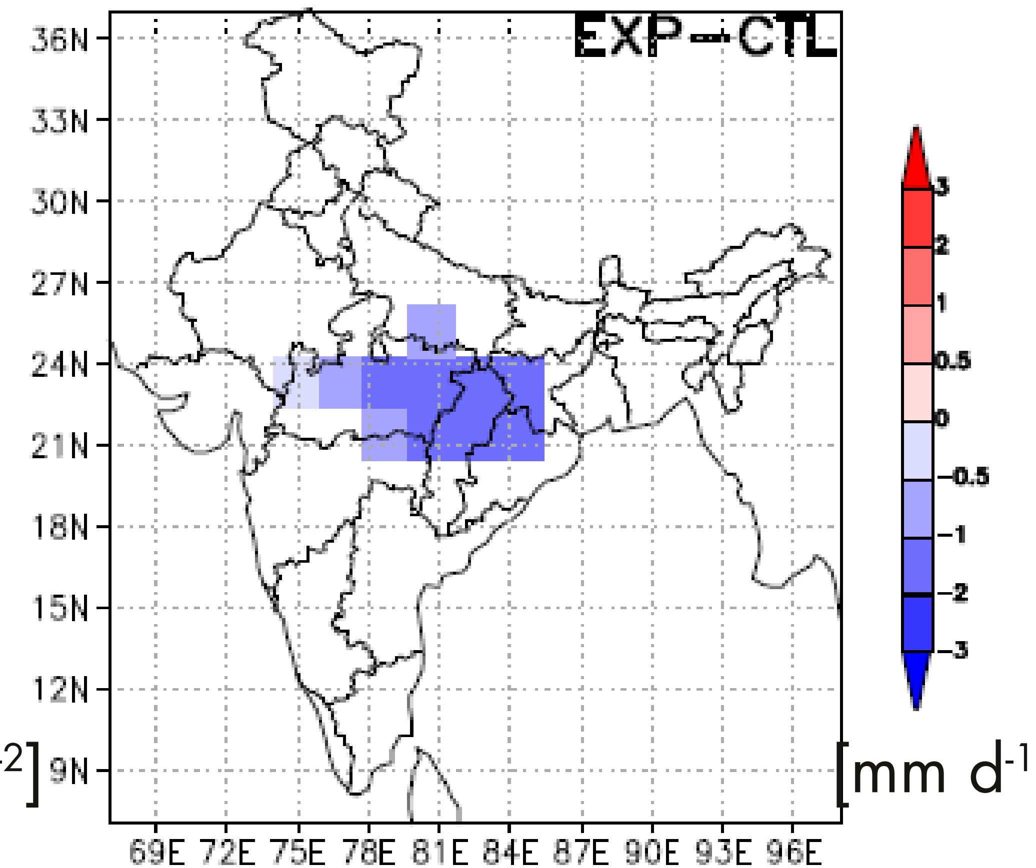


Cherian, Venkataraman, Quaas, Ramachandran, J. Geophys. Res., 2013

Surface radiative forcing
due to anthropogenic aerosol



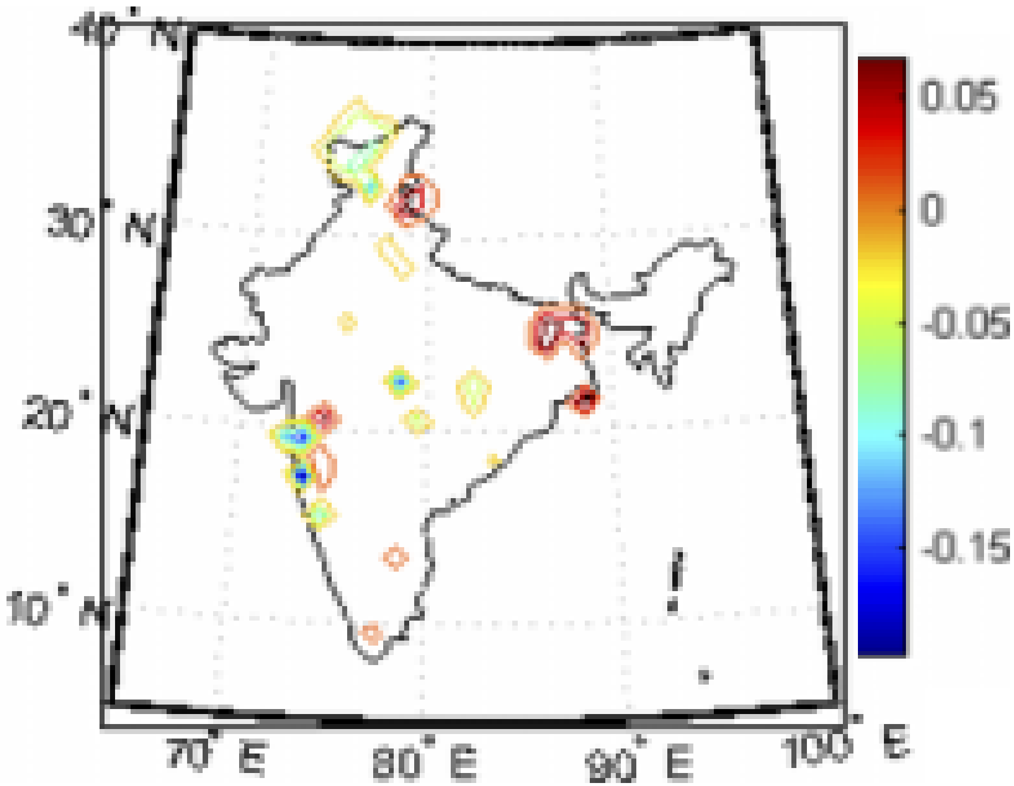
Monsoon precipitation change
due to anthropogenic aerosol



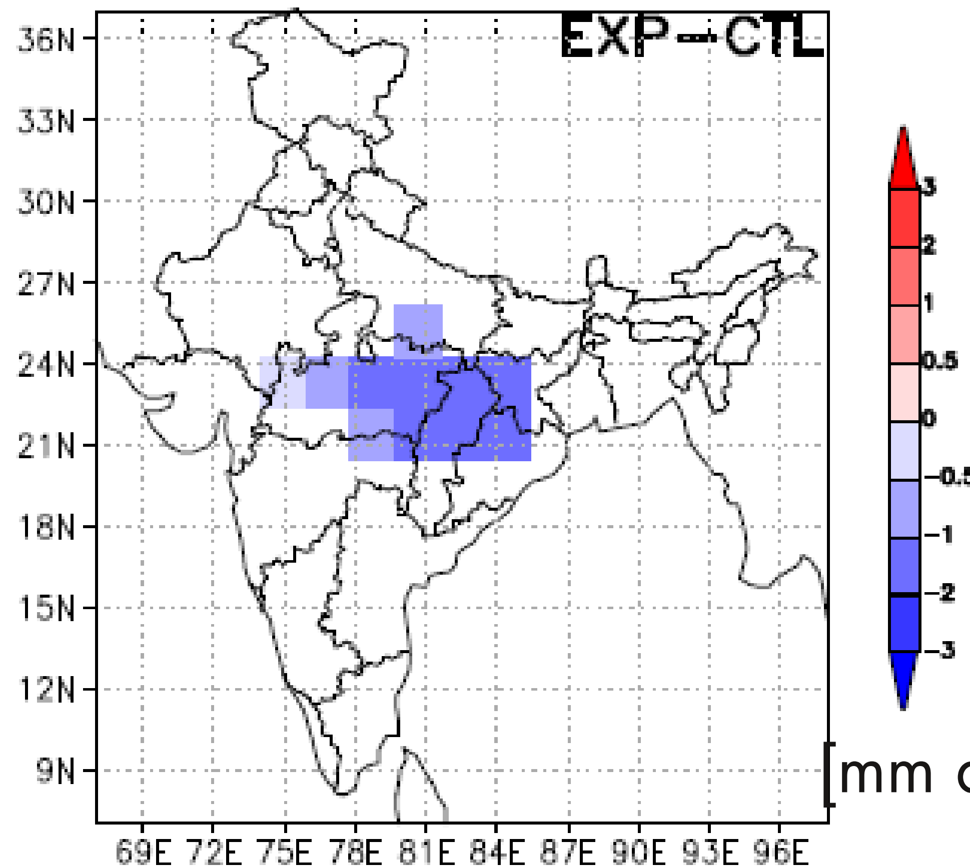
Cherian, Venkataraman, Quaas, Ramachandran, J. Geophys. Res., 2013

4.5 Effects on dynamics: Monsoon

Observed precipitation trend
since 1950 [mm yr^{-1}]



Monsoon precipitation change
due to anthropogenic aerosol



[mm d^{-1}]

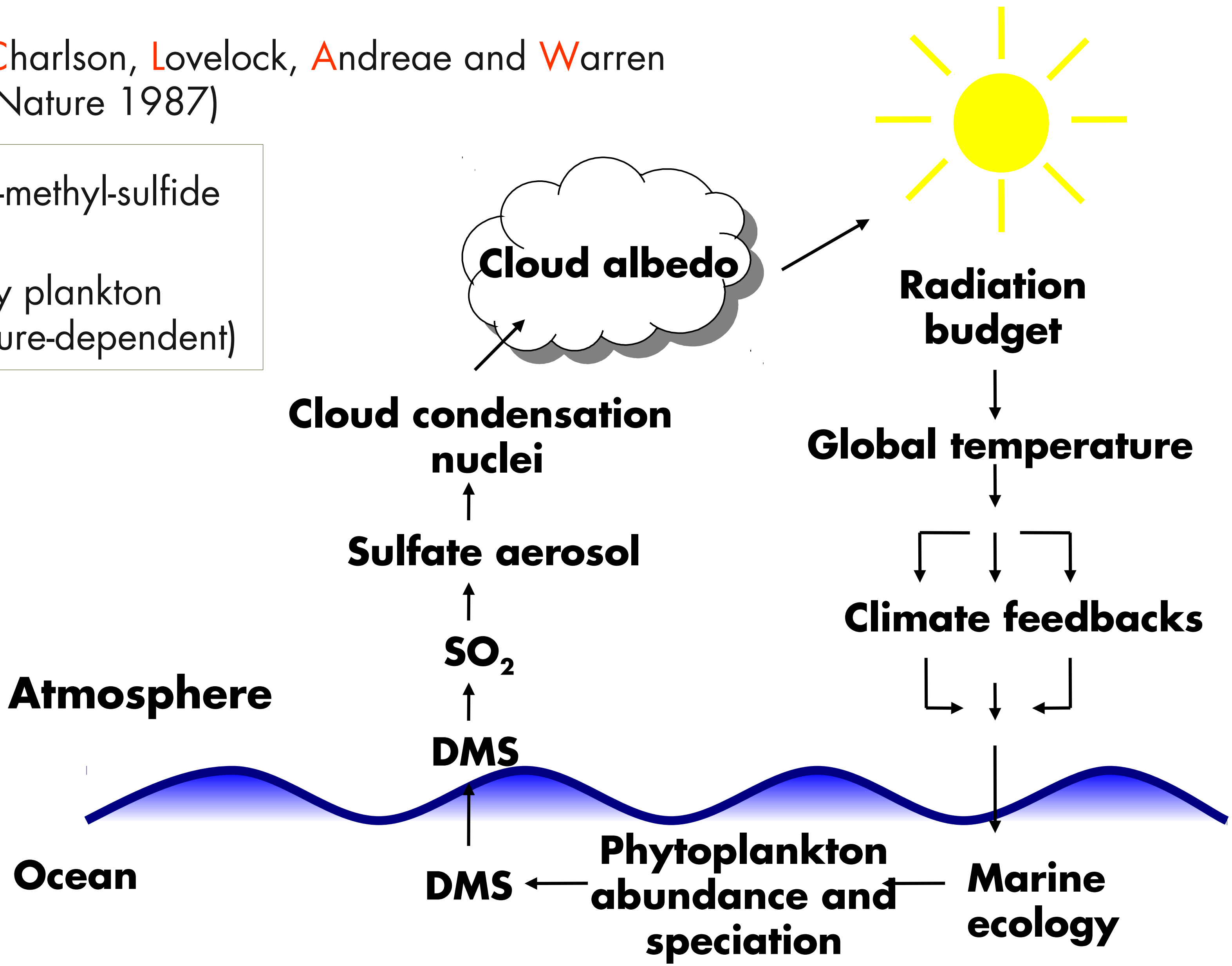
Cherian, Venkataraman, Quaas, Ramachandran, J. Geophys. Res., 2013
Ghosh et al., Atmos. Sci. Lett. 2009

4.6 Stabilising climate feedbacks

4.6 Stabilising climate feedbacks

CLAW : Charlson, Lovelock, Andreae and Warren (Nature 1987)

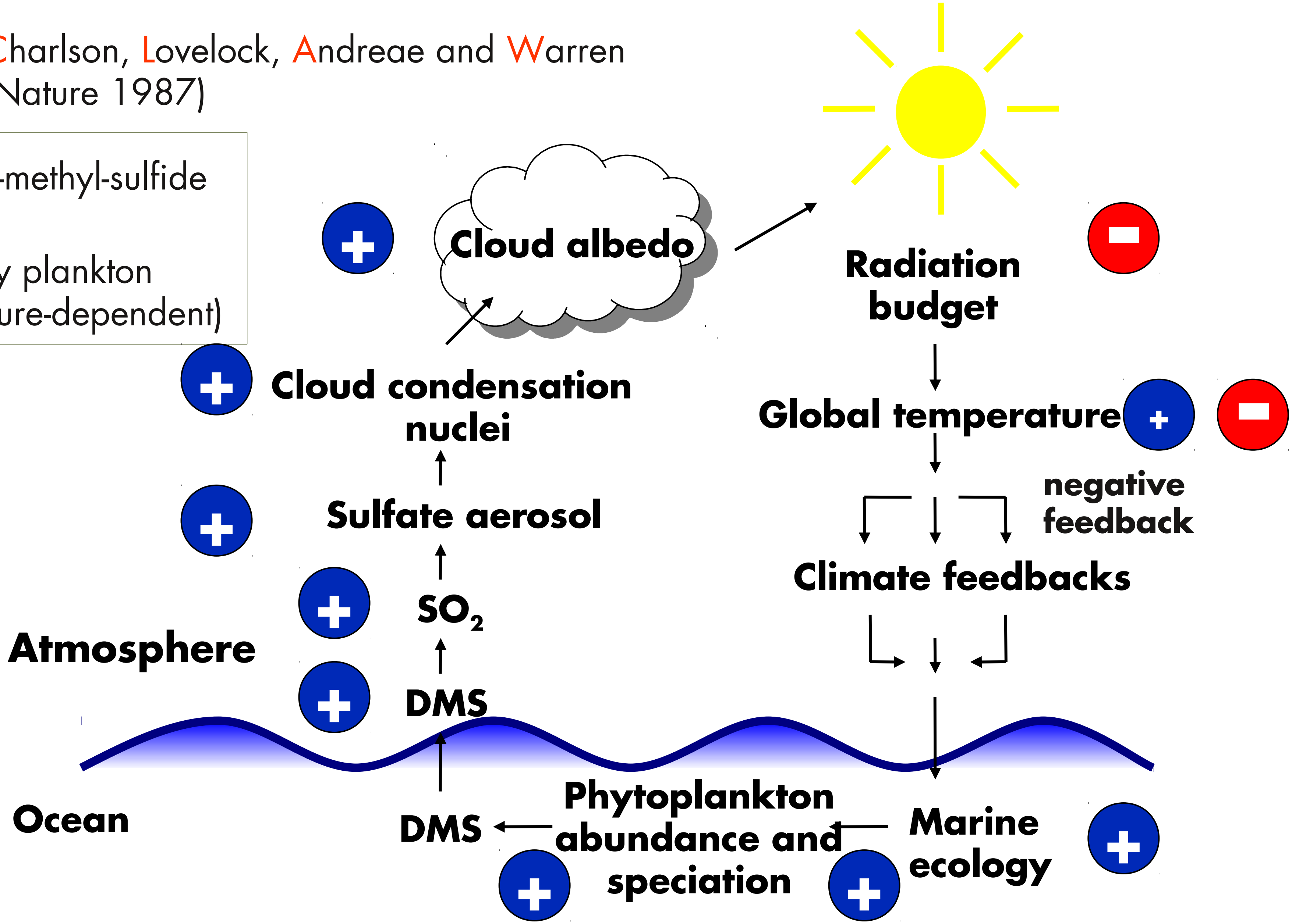
DMS – di-methyl-sulfide
$S(CH_3)_2$
emitted by plankton
(temperature-dependent)



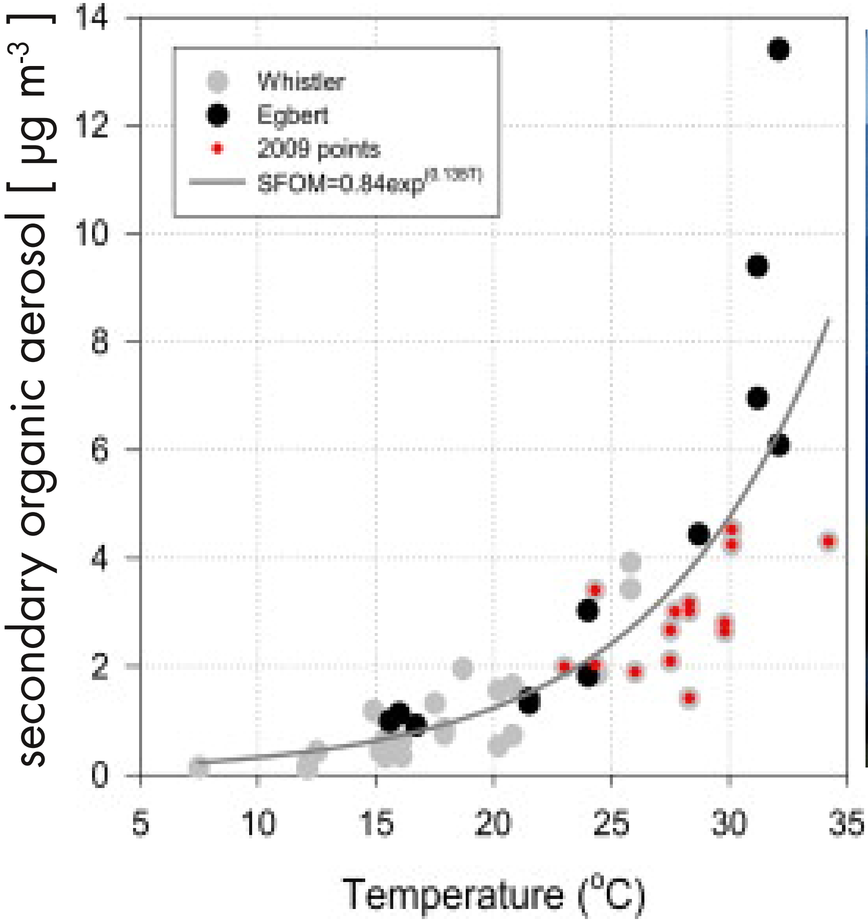
4.6 Stabilising climate feedbacks

CLAW : Charlson, Lovelock, Andreae and Warren (Nature 1987)

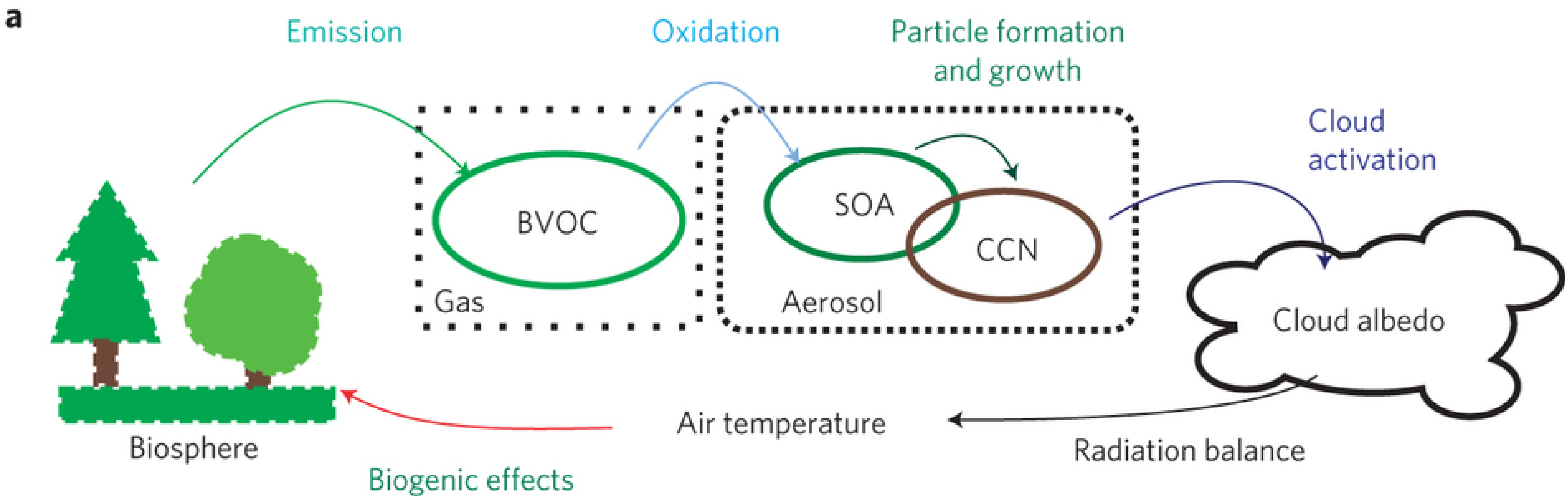
DMS – di-methyl-sulfide
$S(CH_3)_2$
emitted by plankton
(temperature-dependent)



4.6 Stabilising climate feedbacks



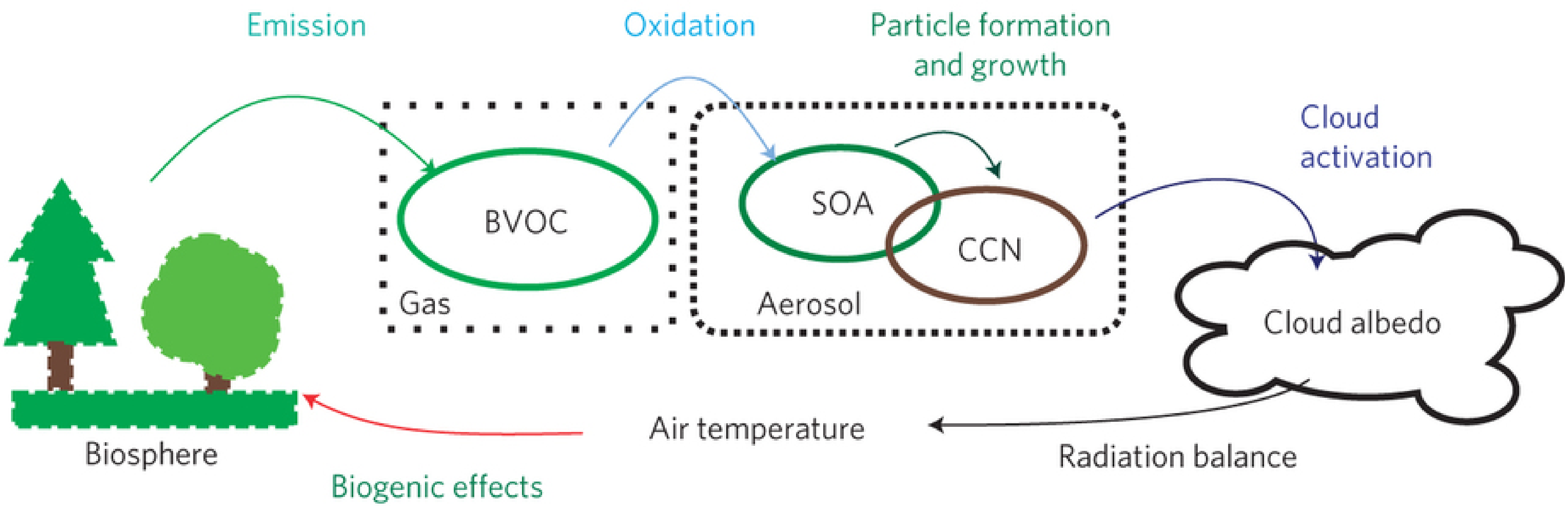
4.6 Stabilising climate feedbacks

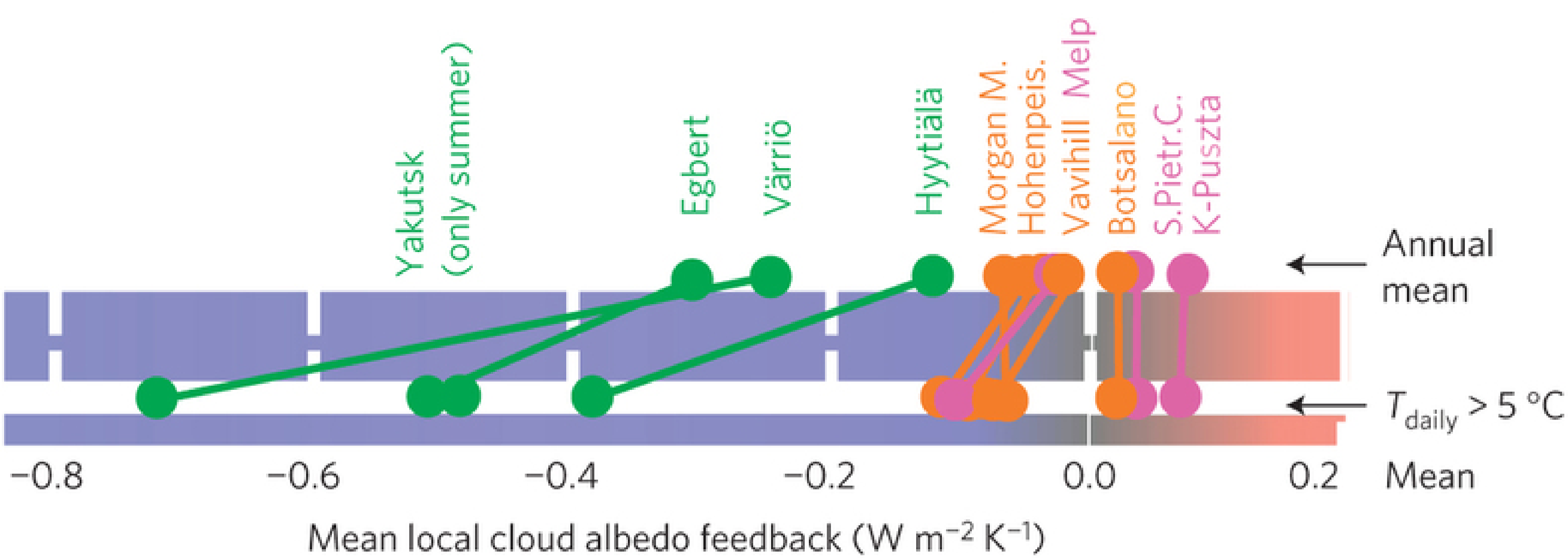


Paasonen et al., Nature Geoscience 2013

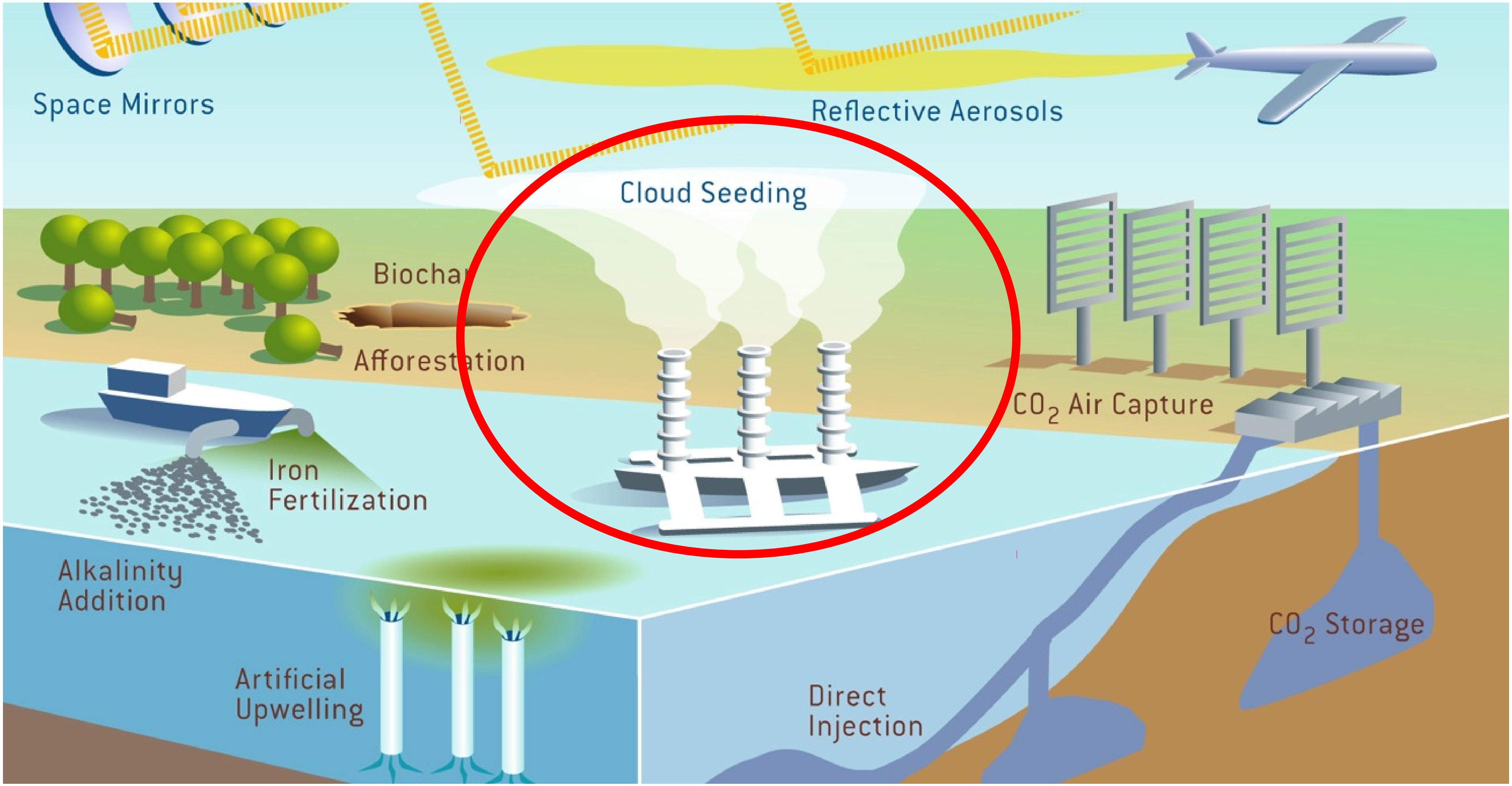
4.6 Stabilising climate feedbacks

a





4.7 Geoengineering



4.8 Co-benefits of improving air quality and mitigating climate change

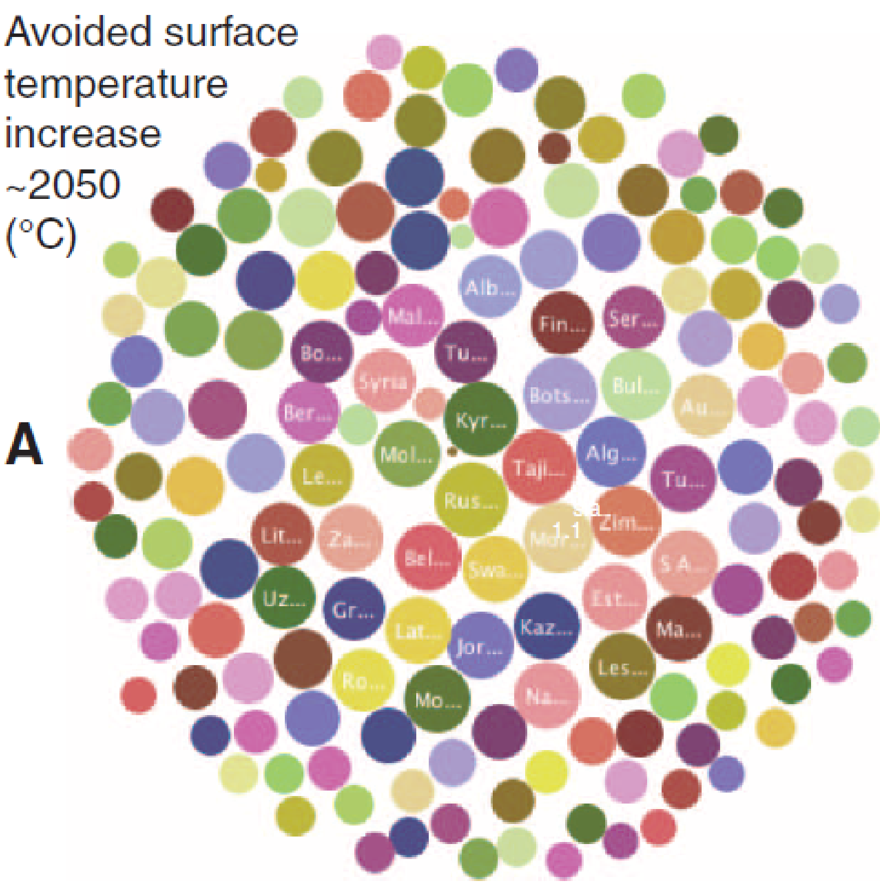
→ Soot bad for health
→ BC warms climate by absorption of sunlight
→ But: co-emitted SO_2 cools, BC might have (cooling) indirect effect on clouds

Shindell et al., Science 2012

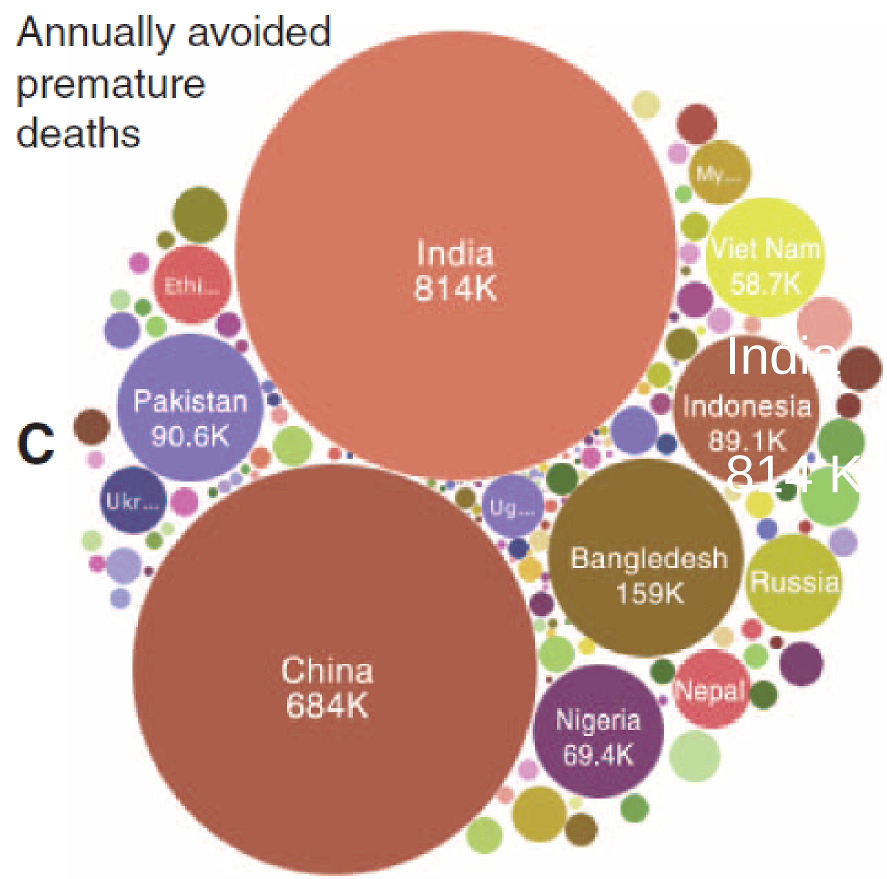
4.8 Co-benefits of improving air quality and mitigating climate change

→ Soot bad for health
→ BC warms climate by absorption of sunlight
→ But: co-emitted SO_2 cools, BC might have (cooling) indirect effect on clouds

If maximum-feasible policies are implemented to cut methan and black carbon:



0.4 K less warming by 2050



1.7M less premature deaths globally

Shindell et al., Science 2012

Conclusions 1/2

- **Effects of clouds and precipitation on aerosols**
  → aqueous chemistry and cloud processing enhances aerosol
  → in-cloud / below-cloud scavenging efficiently removes aerosol
  → aerosol grows to haze in the vicinity of clouds

- **Effects of aerosols on clouds and precipitation**
  → additional aerosol enhances cloud particle concentrations enhancing cloud albedo (first indirect effect)
  → alter cloud microphysical processes (precipitation formation, mixed-phase processes, latent heating; second indirect effect)
  → subsequently change environment and dynamics (buffering?)
  → absorption may alter cloud characteristics (semi-direct effect)

Conclusions 1/2

- **Effects of clouds and precipitation on aerosols**
  → aqueous chemistry and cloud processing enhances aerosol
  → in-cloud / below-cloud scavenging efficiently removes aerosol
  → aerosol grows to haze in the vicinity of clouds

- **Effects of aerosols on clouds and precipitation**
  → additional aerosol enhances cloud particle concentrations enhancing cloud albedo (first indirect effect)
  → alter cloud microphysical processes (precipitation formation, mixed-phase processes, latent heating; second indirect effect)
  → subsequently change environment and dynamics (buffering?)
  → absorption may alter cloud characteristics (semi-direct effect)

Conclusions 2/2

- **Anthropogenic radiative forcings**
  → models show substantial direct and indirect effects
  (-0.4 Wm^{-2} plus -0.9 Wm^{-2})

- **Quantiative understanding essential**
  → for climate sensitivity
  → for weather in Africa, Europe, America, India
  drought NAO Hurricanes Monsoon
  → stabilising feedbacks
  → geoengineering
  → climate mitigation and air quality improvement policies

Conclusions 2/2

- **Anthropogenic radiative forcings**
  → models show substantial direct and indirect effects
  (-0.4 Wm^{-2} plus -0.9 Wm^{-2})

- **Quantiative understanding essential**
  → for climate sensitivity
  → for weather in Africa, Europe, America, India
  drought NAO Hurricanes Monsoon
  → stabilising feedbacks
  → geoengineering
  → climate mitigation and air quality improvement policies

Conclusions 2/2

- **Anthropogenic radiative forcings**
  → models show substantial direct and indirect effects
  ($-0.4\ Wm^{-2}$ plus $-0.9\ Wm^{-2}$)

- **Quantiative understanding essential**
  → for climate sensitivity
  → for weather in Africa, Europe, America, India
  drought NAO Hurricanes Monsoon
  → stabilising feedbacks
  → geoengineering
  → climate mitigation and air quality improvement policies

- Do you have an AA battery for me?