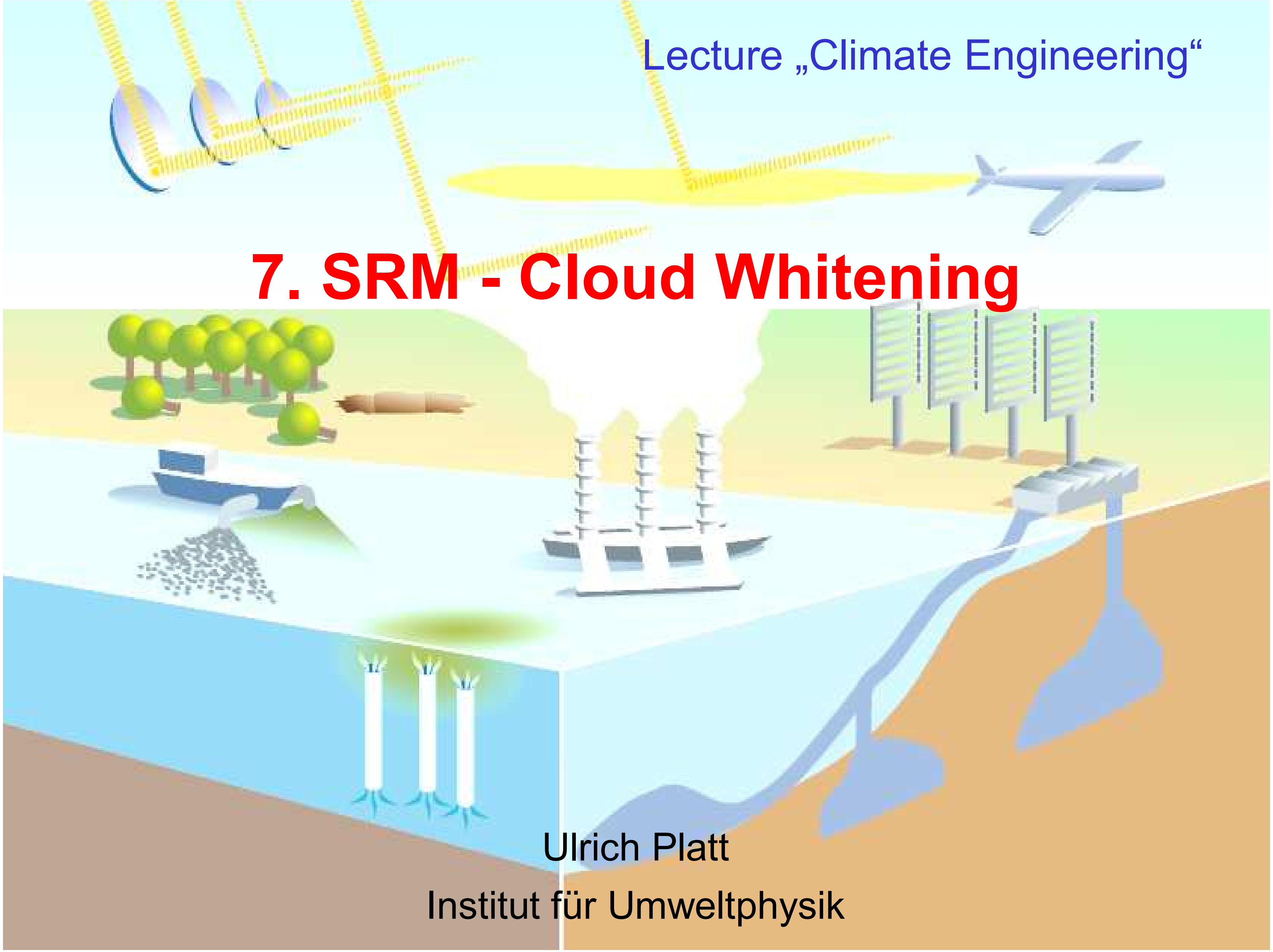


Lecture „Climate Engineering“

7. SRM - Cloud Whitening

Ulrich Platt

Institut für Umweltphysik

Lecture Program of „Climate Engineering

Part 1: Introduction to the Climate System (4 sessions)

1. Introduction and scope of the lecture
2. The Climate System – Radiation Balance
3. Elements of the Climate System - Greenhouse Gases, Clouds, Aerosol
4. Dynamics of the Climate System - Sensitivity, Predictions

Part 2: Climate Engineering Methods - Solar Radiation Management, SRM

1. SRM – Reflectors in space
2. SRM – Aerosol in the Stratosphere
3. SRM – Cloud Whitening
4. SRM – Anything else

Part 3: Climate Engineering Methods – Carbon Dioxide Removal, CDR

1. Direct CO_2 removal from air
2. Alkalinity to the ocean (enhanced weathering)
3. Ocean fertilization
4. Removal of other greenhouse gases

Part 4: CE – Effectiveness, Side Effects (3 sessions)

1. Comparison of Techniques, characterisation of side effects
2. Other parameters than temperature
3. Summary

Literature

Partanen A.-I., Kokkola H., Romakkaniemi S., Kerminen V.-M., Lehtinen K.E.J., Bergman T., Arola A., and Korhonen H. (2012), Direct and indirect effects of sea spray geoengineering and the role of injected particle size, J. Geophys. Res. 117, D02203, doi:10.1029/2011JD016428.

Bower K., Choularton T., Latham J., Sahraei J., Salter S. (2006), Computational assessment of a proposed technique for global warming mitigation via albedo-enhancement of marine stratocumulus clouds, Atmospheric Research 82, 328–336.

Cooper G., Foster J., Galbraith L. , Johnston D., Neukermans A., Ormond B., Wang Q. (2011) Supercritical Saltwater Spray for Marine Cloud Brightening, Poster A11B-0066 at AGU Fall Meeting 2011, San Francisco, USA.

Cooper G., Johnston D., Foster J., Galbraith L., Neukermans A., Ormond R., Rush J., Wang Q. (2013), A Review of Some Experimental Spray Methods for Marine Cloud Brightening, International Journal of Geosciences, 2013, 4, 78-97, doi:10.4236/ijg.2013.41009

Jones A., Haywood J., and Boucher O.(2009), Climate impacts of geoengineering marine stratocumulus clouds, J. Geophys. Res. 114, D10106, doi:10.1029/2008JD011450.

Korhonen H., Carslaw K.S. and Romakkaniemi S. (2010), Enhancement of marine cloud albedo via controlled sea spray injections: a global model study of the influence of emission rates, microphysics and transport, Atmos. Chem. Phys., 10, 4133–4143.

Kravitz, B.; Robock, A.; Oman, L.; Stenchikov, G. L.; Marquardt, A. (2009), Acid Deposition from Stratospheric Geoengineering with Sulfate Aerosols, Journal of Geophysical Research, Jg. 114, doi:10.1029/2009JD011918.

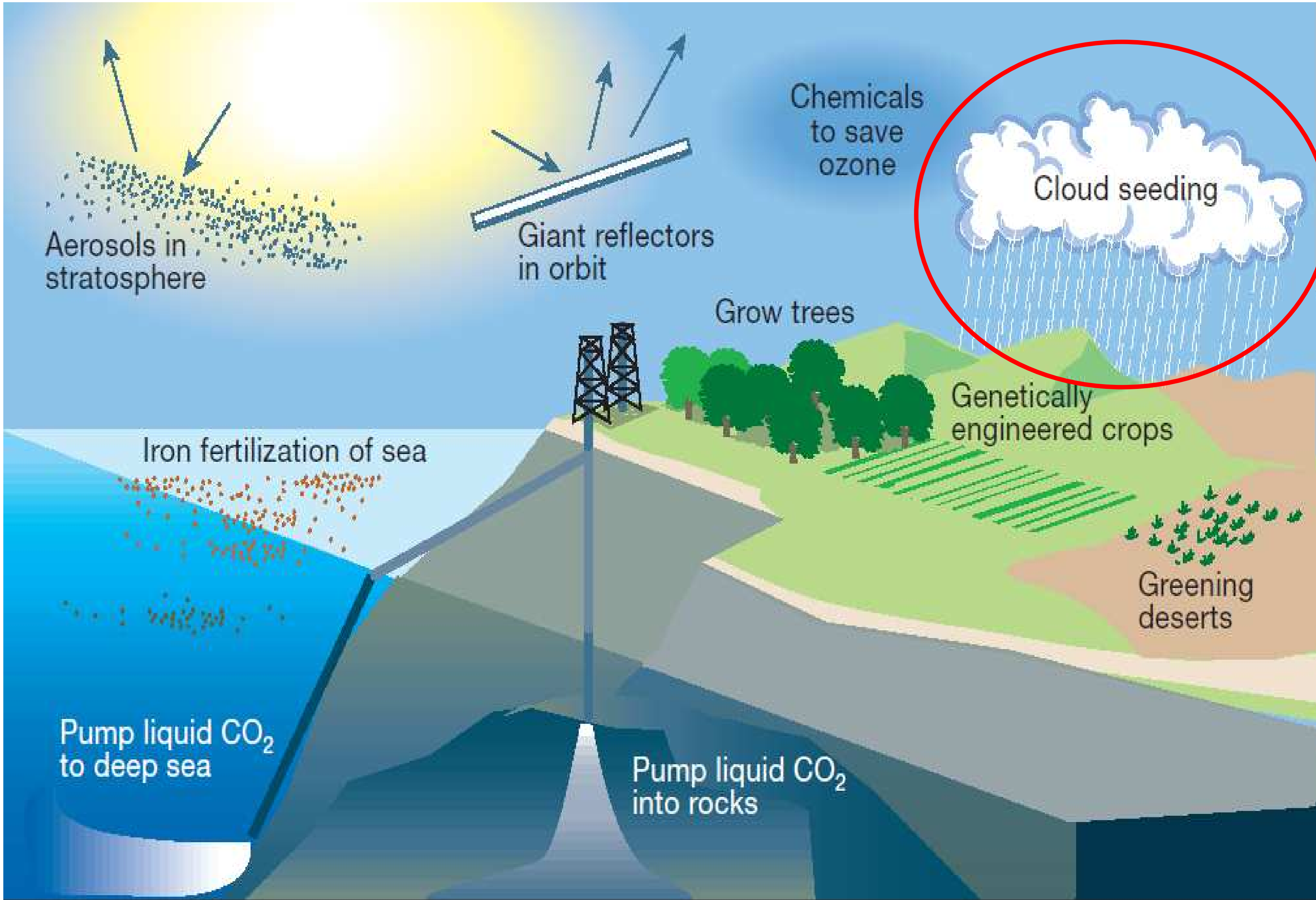
Kravitz, B.; Robock, A.; Oman, L.; Stenchikov, G. L.; Marquardt, A. (2010), Correction to "Acid Deposition from Stratospheric Geoengineering with Sulfate Aerosols", Journal of Geophysical Research, Jg. 115, doi:10.1029/2010JD014579.

Latham J. (1990), Control of global warming?, Nature 347, 339–340, doi:10.1038/347339b0.

Salter S., Sortino G. and Latham J. (2008), Sea-going hardware for the cloud-albedo method of reversing global warming, Phil. Trans. R. Soc. A 366, 3843–3862, doi:10.1098/rsta.2008.0136.

Contents of Today's Lecture

- Cloud Albedo
- How to change the Cloud Albedo
- The „Twomey – Effect“ (1st Aerosol indirect effect)
- Cloud Seeding
- Problems with Cloud Seeding
- Side Effects of Cloud Seeding
- Conclusion



Schematic representation of various climate-engineering proposals (courtesy B. Matthews).

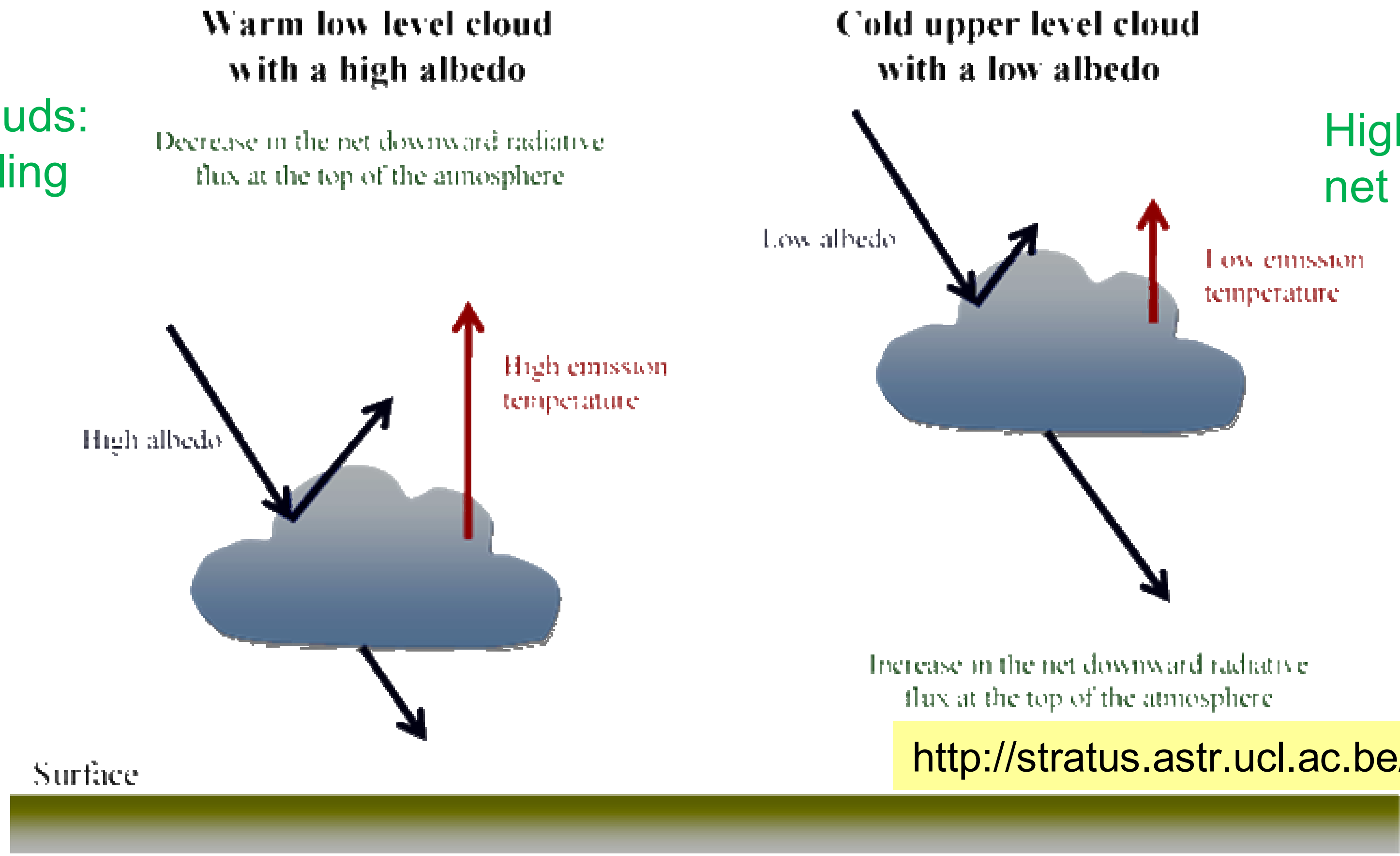
Keith, David, 2001: Geoengineering, *Nature*, **409**, 420.

The Role of Clouds in Radiation Balance

SW-Effect of clouds: Reflection of solar radiation (albedo) → cooling
LW-effect of clouds: Reduced emission from cold cloud top → warming

Low clouds: High albedo → strong SW-effect; warm → little LW-effect
High clouds: Low albedo → little SW-effect; cold → strong LW-effect

Low clouds:
net cooling

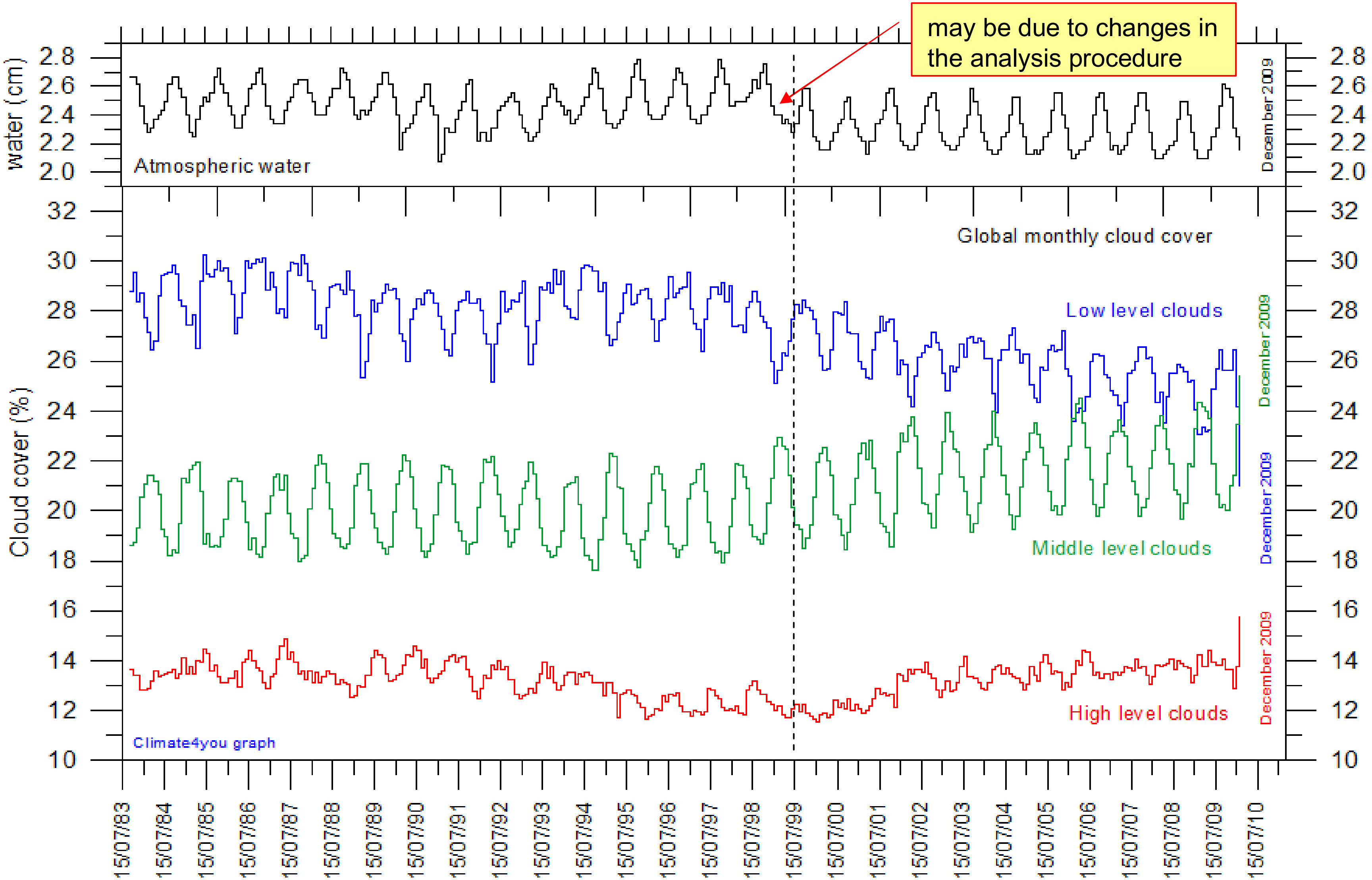


High clouds:
net warming

http://stratus.astr.ucl.ac.be/textbook

Overall: net cooling effect, globally averaged -13 W/m^2 (Ramanathan et al. 1989).

The Global Cloud Cover



Monthly variations in global cloud cover for high, middle and low clouds and total amount of water vapour in the atmosphere (July 1983 - Dec. 2009).

→ Amount of low clouds (net cooling effect on global temp.) decreased from ≈29% (1986) to ≈25% (2007).

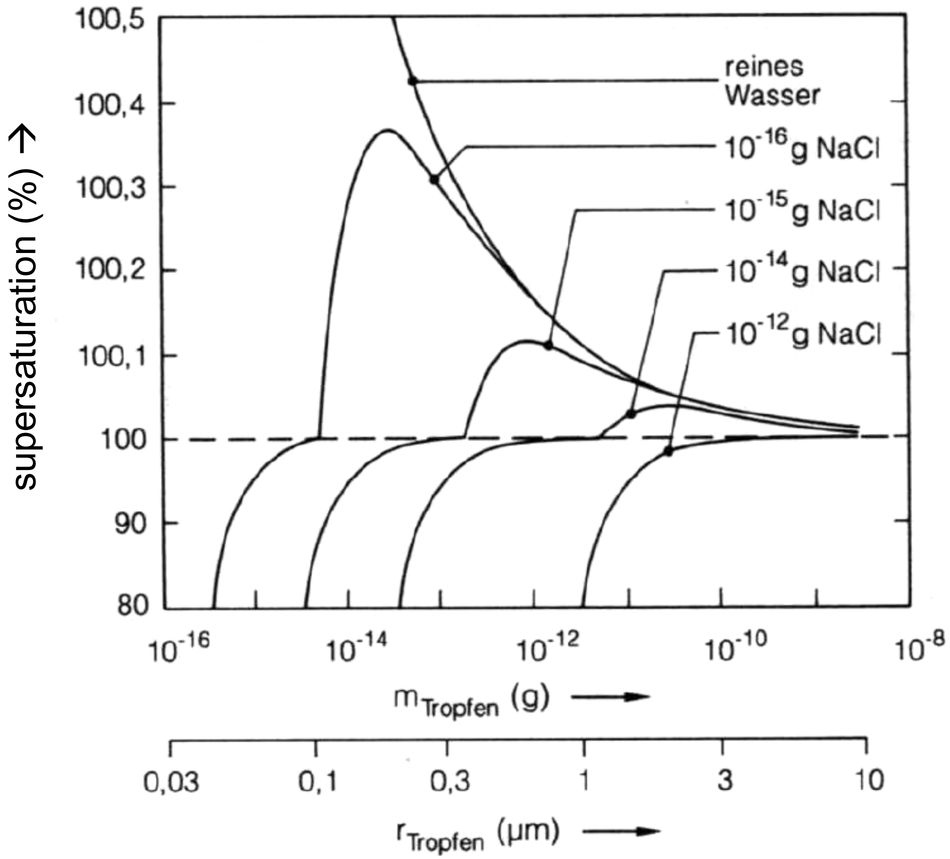
→ Amount of middle clouds (no clear net effect on global temp.) increased slowly from ≈20% (1984) to ≈22% (2007).

→ Amount of high clouds (net warming effect) decreased slightly until around 1999, and has since then again increased somewhat.

Data source: The International Satellite Cloud Climatology Project (ISCCP). The ISCCP datasets are obtained from passive measurements of IR radiation reflected and emitted by the clouds. Last data: December 2009.

How do Clouds Form?

- "A cloud forms when $p_{H2O}=p_{sat,H2O}$",
  i.e. when air is saturated with respect to water vapour
- Reached by:
  - cooling
    - lifting: forced lifting, convection
    - radiation cooling (→ radiation fog)
  - mixing of air masses with different T, p_{H2O}
  - addition of water vapor, e.g. cold air moving over warm lake/ocean

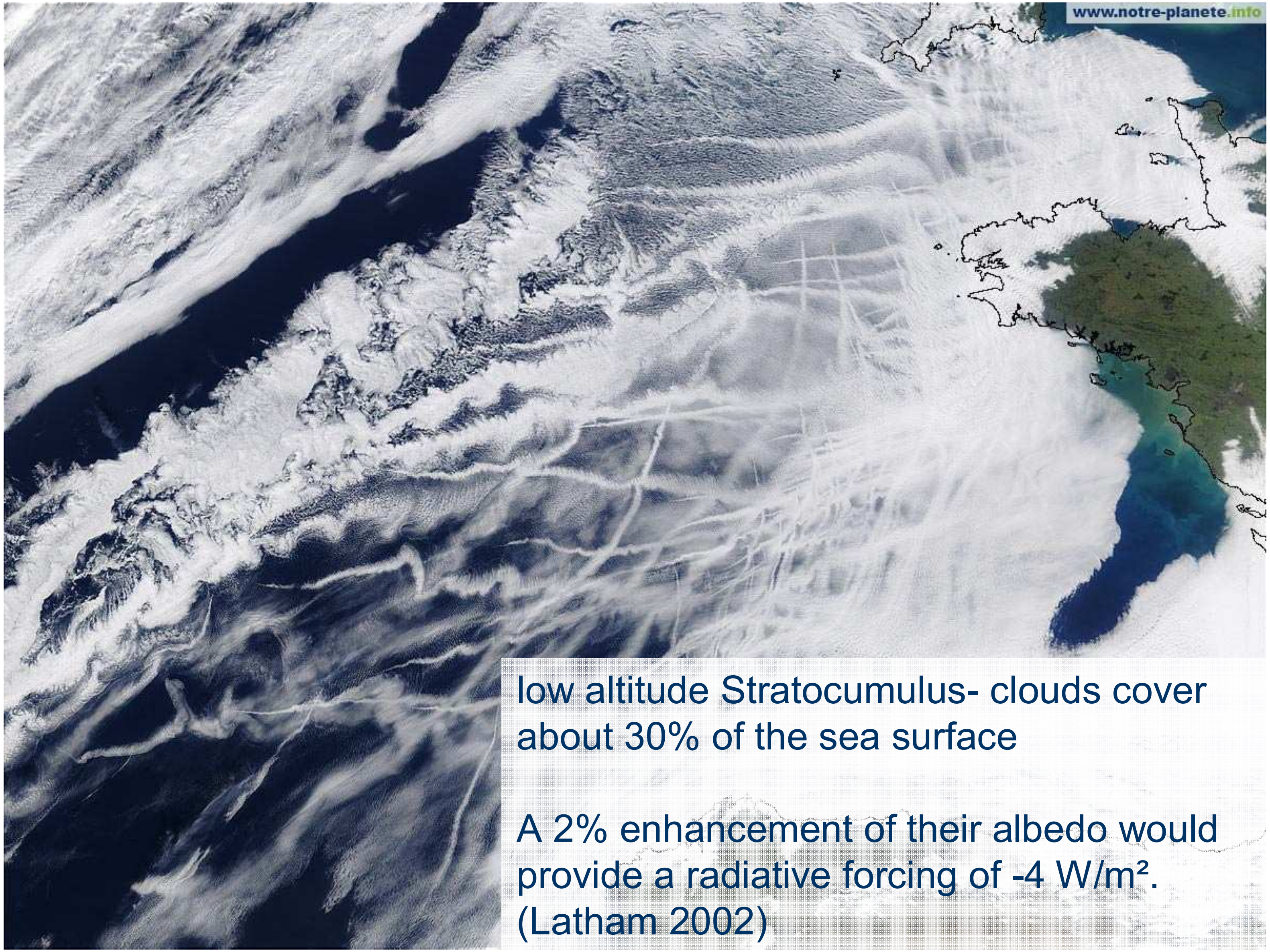


Roedel (1992)

→ Liquid water droplets form, always by „heterogeneous condensation" i.e. water condenses on pre-existing, small particles (aerosol).

→ these particles (typ. radius ≈0.2 μm) are called Cloud Condensation Nuclei (CCN)

Enhanced Cloud Reflectivity due to Ship Traffic



low altitude Stratocumulus- clouds cover about 30% of the sea surface

A 2% enhancement of their albedo would provide a radiative forcing of -4 W/m². (Latham 2002)

Aerosol Indirect Effects

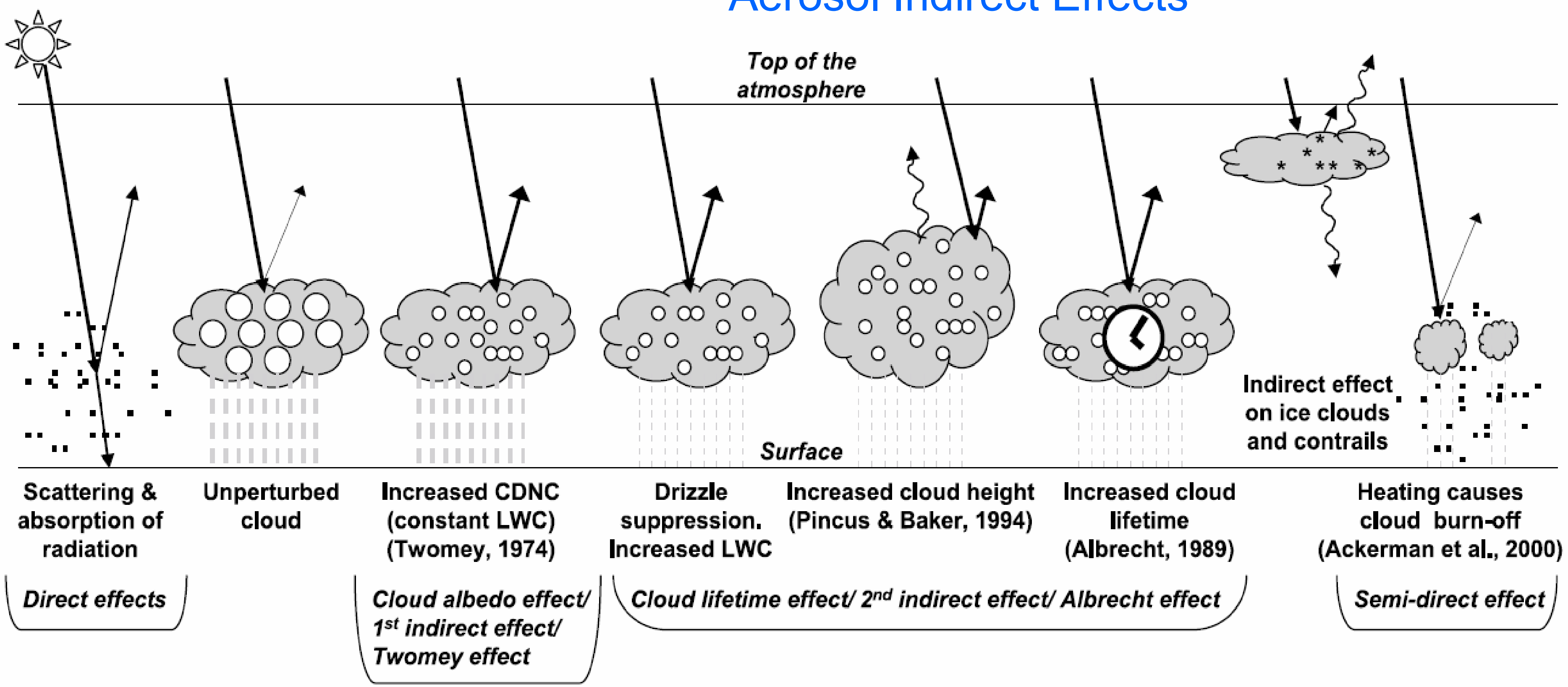


Figure 2.10. *Schematic diagram showing the various radiative mechanisms associated with cloud effects that have been identified as significant in relation to aerosols (modified from Haywood and Boucher, 2000). The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content.*

IPCC AR4 2007

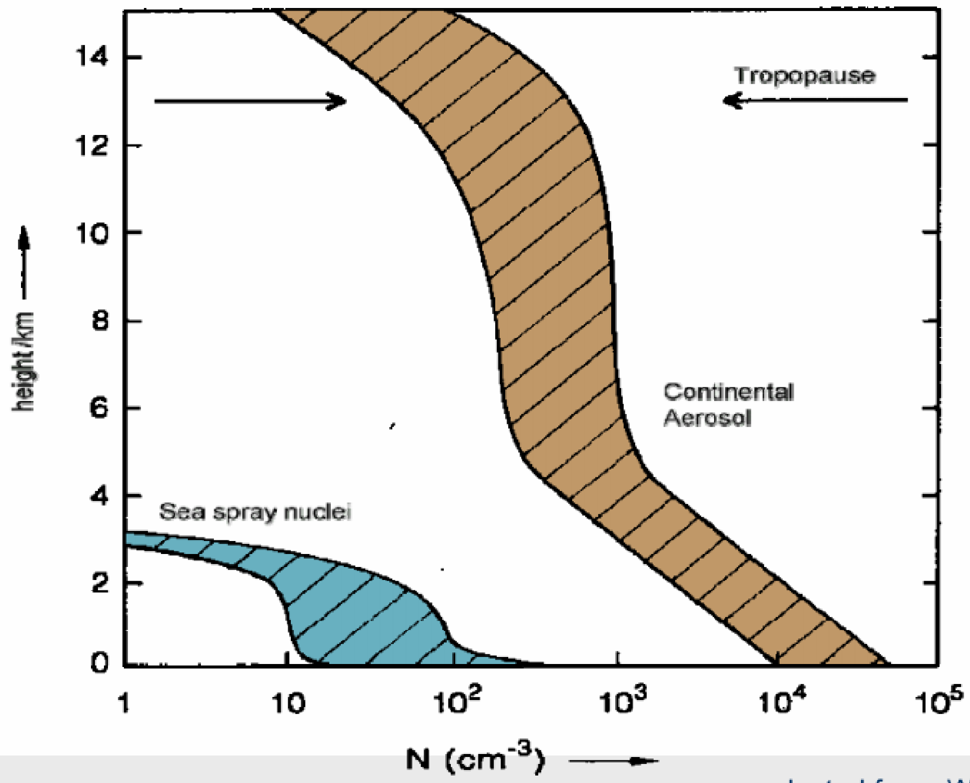
CCN: Cloud Condensation Nuclei
CDNC: Cloud Droplet Number Concentration
LWC: Liquid Water Content

Twomey, S. (December 1974). "Pollution and the planetary albedo". *Atmos. Environ.* 8 (12): 1251–6. doi:10.1016/0004-6981(74)90004-3.

Particles in the Atmosphere

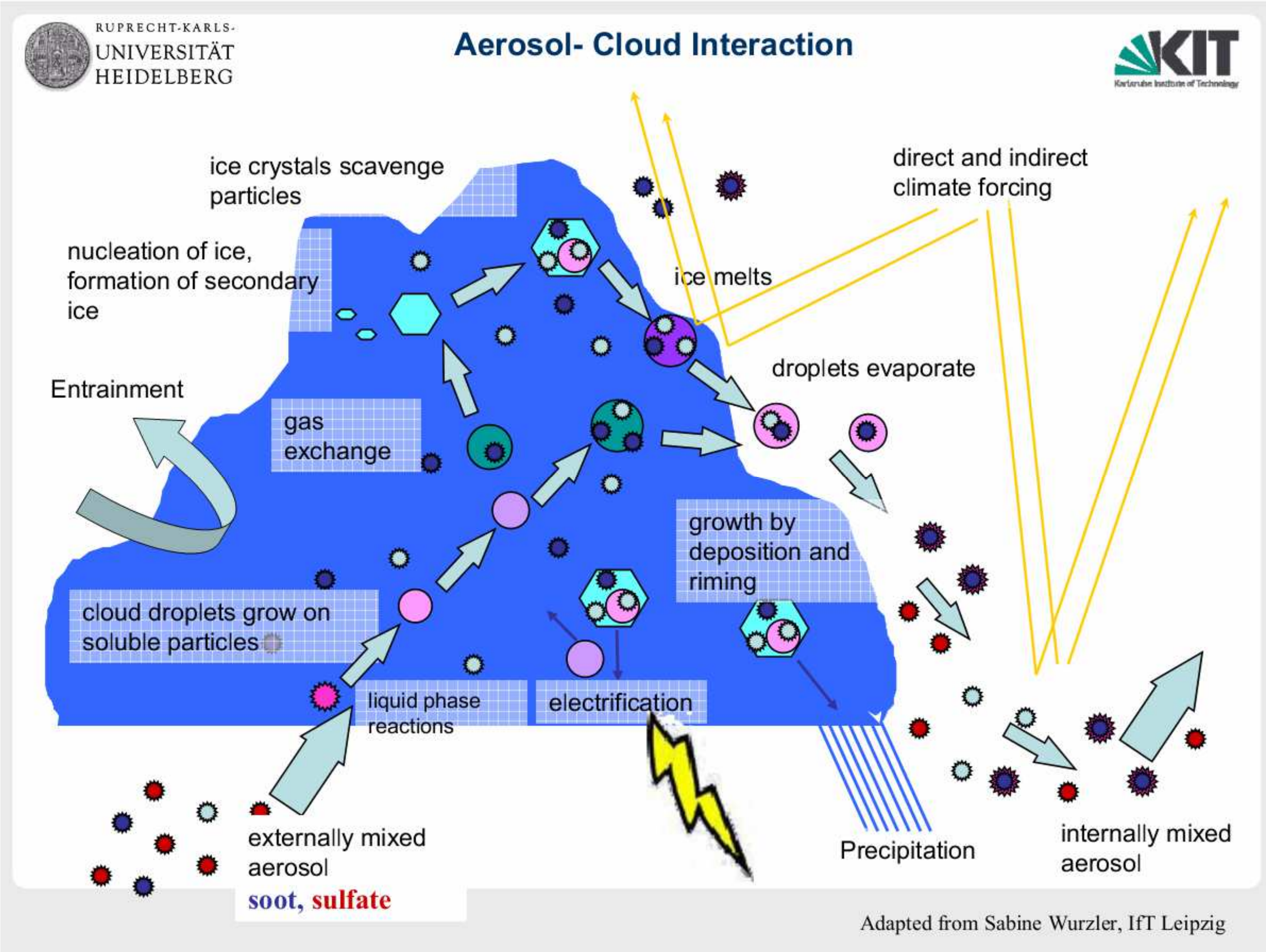
Airborne particles mainly from ammonium sulfate, sea salt, minerals, black carbon or high molecular weight organic matter

Concentration: 1000 - 100000 particles per cm³ in the low atmosphere



adapted from: W. Rödel, Physik unserer Umwelt – die Atmosphäre, Springer

Aerosol – Cloud Interations



„Cloud Whitening“ – The Idea

In large, remote areas of the ocean the number density of cloud condensation nuclei (CCN) is very low (several 10 CCN/cm^3).

→ Clouds consist of relatively few, relatively large droplets

By artificially adding more CCN the clouds change to contain more, however smaller droplets. (note that the liquid water contents (LWC) of the clouds is not altered by adding CCN)

→ More droplets have larger surface, even if LWC and thus total volume remains constant.

→ Cloud albedo increases

→ More incoming shortwave radiation is reflected

→ Planet is coolded

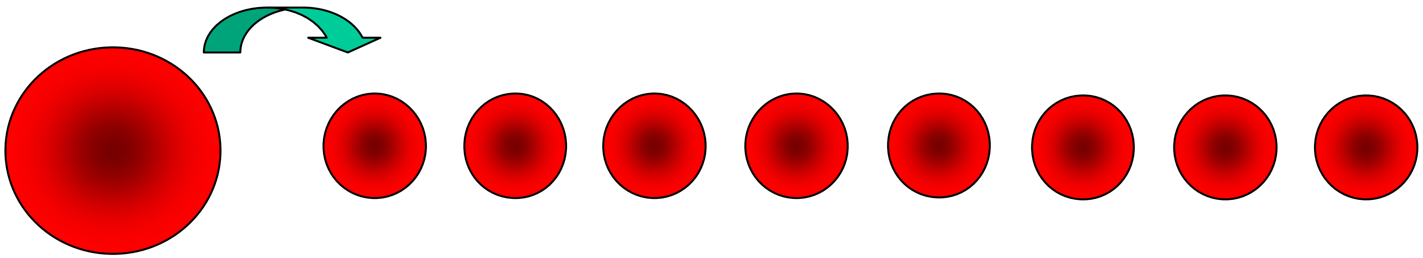
Optimal Cloud Droplet Size?

Small Particles → More Surface/Volume (Volume can not be changed)

→ Somewhat more scattering in backward direction

→ also: Droplets settle less rapidly

→ Precipitation is less likely
→ Cloud lifetime is enhanced

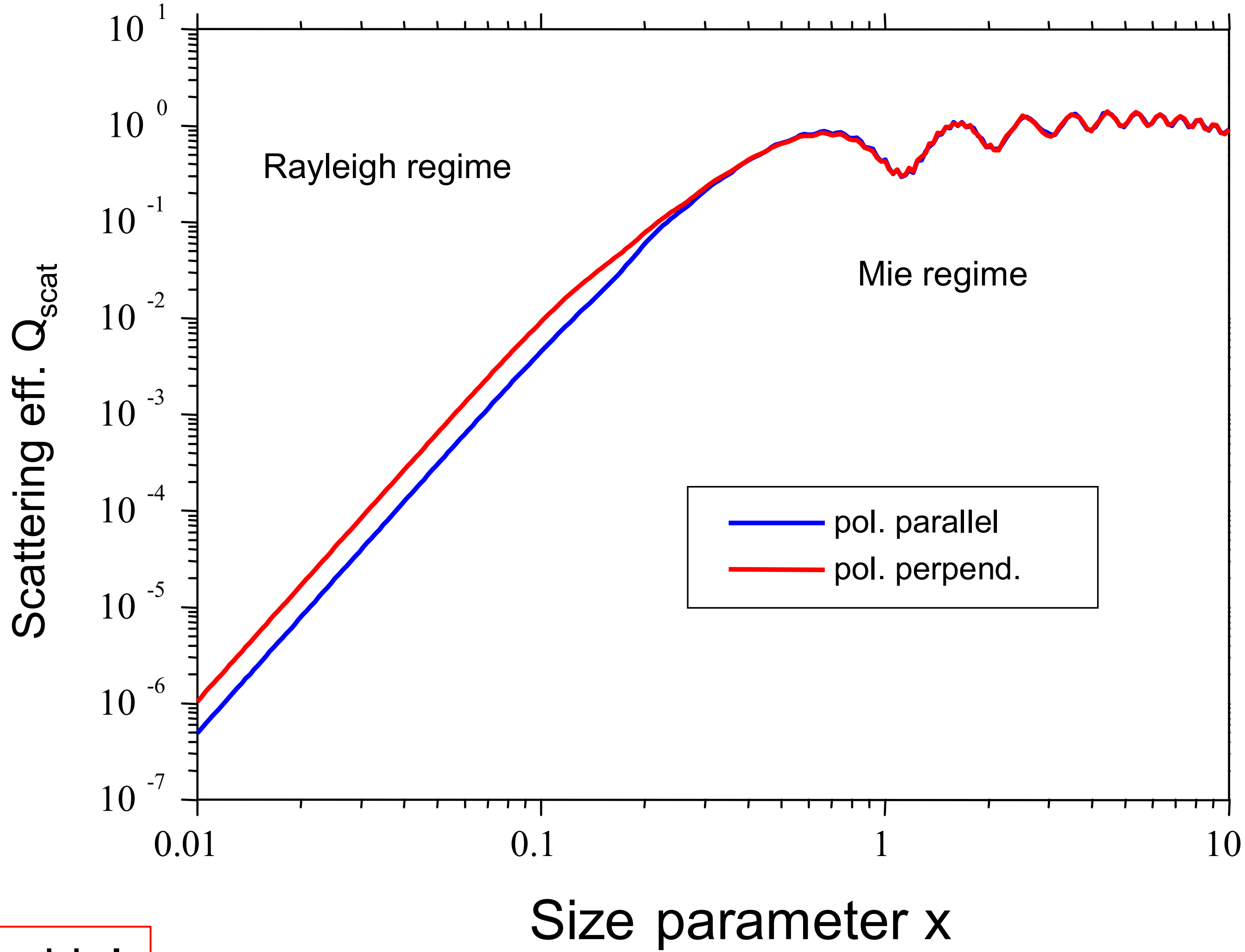


1 large droplet, radius r → 8 small droplets, radius r/2, same total volume but twice the total surface area

Scattering Efficiency as a Function of Particle Size

Scattering coefficient or efficiency compares scattering cross-section to geometrical cross-section:

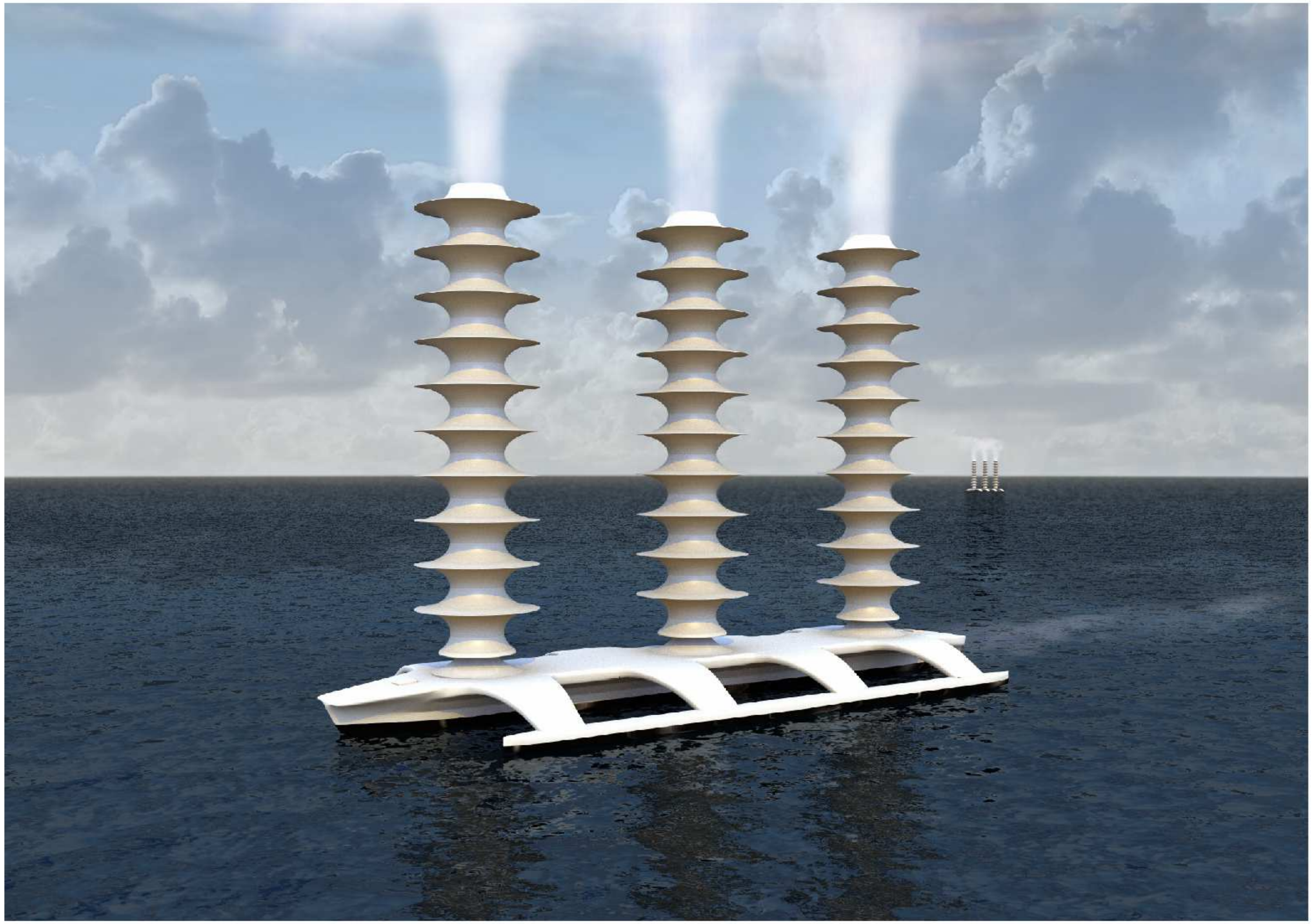
$$Q_{scat} = \frac{\sigma_{scat}}{\pi r^2}$$



→ Particles must be big!

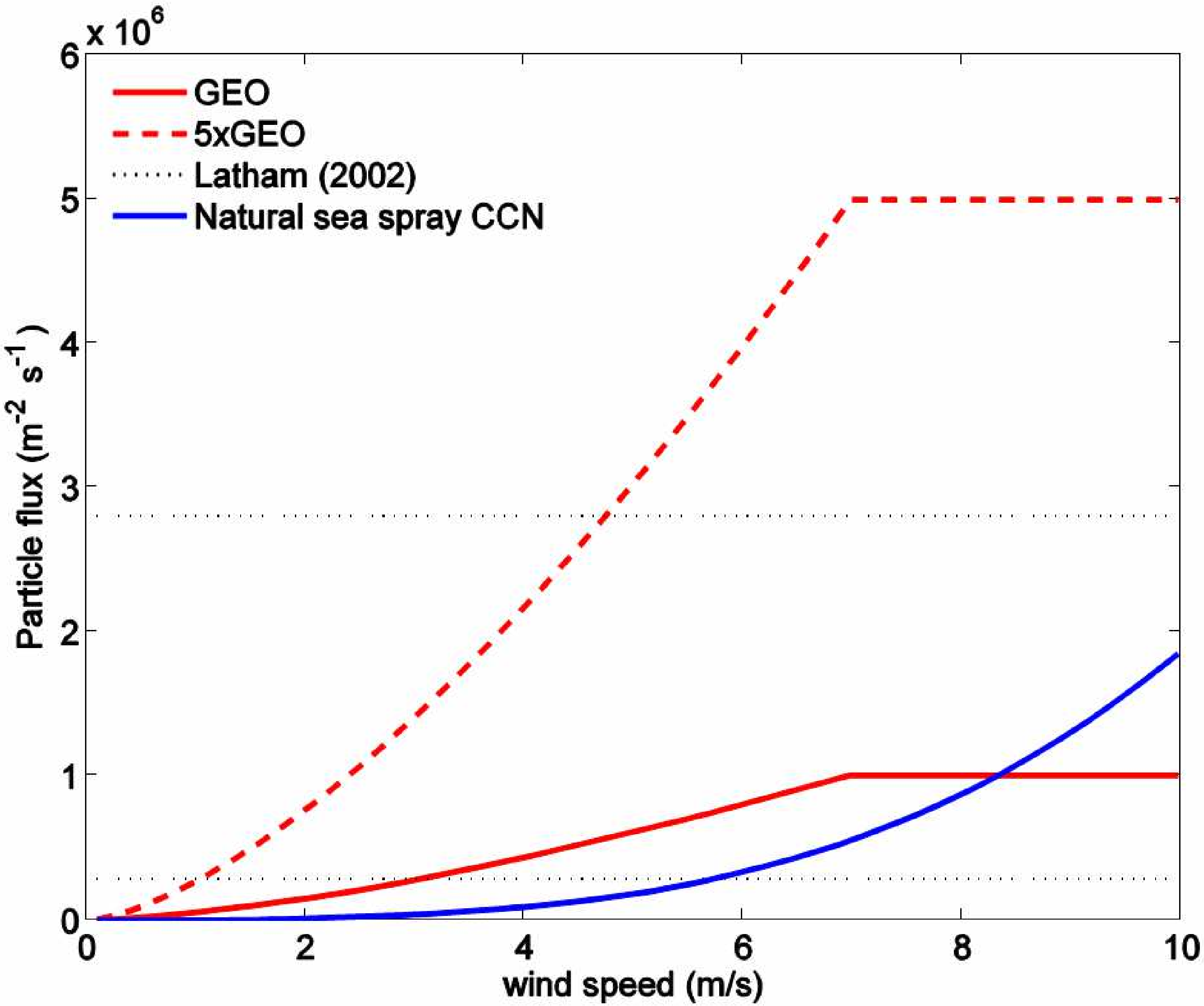
Cloud Whitening

Scheme by John Latham (University of Manchester, NCAR) and Steve Salter (University of Edinburgh) to increasing cloud albedo by injecting more sea salt cloud condensation nuclei into marine stratus clouds.



from a presentation by Alan Robock, Heidelberg 2010

How ManyParticles are Needed?



Wind speed dependence of simulated geoengineering fluxes (red lines) and natural flux of sea spray particles larger than 70 nm (blue line). Black dotted line shows the Latham (2002) estimate range for a flux needed to produce 400 additional cloud droplets per cm-3.

John Latham‘s Scheme

Low-level, non-overlapped marine stratiform clouds cover about a quarter of the oceanic surface (Charlson et al. 1987) typ. albedo, A, ≈0.3–0.7 (Schwartz & Slingo 1996).

Latham (1990, 2002): Ameliorate global warming by enhancement of the natural droplet number concentrations (N_0) in such clouds.
→ Increase ΔA in their albedo (the first indirect or Twomey effect (1977)), and also possibly increase lifetime (the second indirect, or Albrecht effect (1989)),
→cooling.
N_0 values in these clouds range typically from approximately 20 to 200 cm^{-3}.

Dissemination - at or close to the ocean surface - of monodisperse seawater (NaCl) droplets ≈1μm in size,
→ sufficiently large salt masses always to be activated - as cloud condensation nuclei (CCN)
→form ΔN additional droplets when (shrinking by evaporation in the subsaturated air en route)
→they rise into the cloud bases.
The total droplet concentration N after seeding thus lies between ΔN and ($N_0+\Delta N$), because some of the natural CCN which would be activated in the absence of seeding may not be in its presence, owing to the lower supersaturations that prevail.

Cloud Whitening Quantitative (1)

Average solar flux at the surface:

$$S = \frac{1}{4} S_0 (1 - A) = \frac{S_0}{4} - \frac{S_0}{4} A$$

$$\frac{dS}{dA} = -\frac{S_0}{4}$$

$$dS = -\frac{S_0}{4} \cdot dA \approx -342 \cdot dA \frac{W}{m^2}$$

$$dA = -\frac{4}{S_0} \cdot dS$$

S = Solar Flux received by Earth

S_0 = solar constant ≈ 1368 W/m^2

Required change in cloud albedo (A_c):

$$\Delta A_C = \frac{\Delta A}{f_1 \cdot f_2 \cdot f_3} = -\frac{4}{S_0} \cdot \frac{\Delta S}{f_1 \cdot f_2 \cdot f_3}$$

$$\Delta A_C \approx -5.7 \cdot \frac{4}{S_0} \cdot \frac{\Delta A}{f_3} \approx -0.0167 \frac{\Delta S}{f_3}$$

$$= 0.0167 \frac{S_{gh}}{f_3} \approx \frac{S_{gh}}{60 \cdot f_3}$$

A_C = Cloud Albedo

f_1 = Fraction of Earth covered by ocean ($f_1 \approx 0.7$)

f_2 = Fraction of ocean covered by suitable clouds ($f_2 \approx 0.25$)

f_3 = Fraction of clouds actually seeded

S_{gh} = greenhouse forcing to be compensated,

For f_3 = 1 and S_{gh} = 3.7 W/m^2 → $\Delta A_C \approx 0.06$

Cloud Whitening Quantitative (2)

Cloud albedo increase resulting from seeding clouds with seawater CCN and thus increasing the droplet number concentration from N_0 (unseeded) to N (seeded) (Schwartz & Slingo 1996):

$$\Delta A_C \approx 0.075 \cdot \ln\left(\frac{N}{N_0}\right) \Leftrightarrow \frac{N}{N_0} = \exp\left(\frac{\Delta A_C}{0.075}\right) \approx 2.2 \ (\Delta A_C \approx 0.06\ ) \Rightarrow N - N_0 \approx N_0$$

Optimum particle size: r = 0.15 µm

$$m_{particle} = \rho \frac{4}{3}\pi r^3,\ \rho_{NaCl} \approx 2170 \frac{kg}{m^3}$$
$$\approx 3 \cdot 10^{-17} kg$$

Assuming N_0 = 100 cm^{-3} (10^8 m^{-3}) in a layer of h=1000 m thickness → $10^{11} m^{-2}$

Surface of Earth·$(f_1 f_2) \approx 10^{14}$ m^2

Total mass of aerosol: $m_{aerosol} \approx A_{Earth} \cdot (f_1 f_2) \cdot N_0 h \cdot m \approx 10^{14} \cdot 10^{11} \cdot 3 \cdot 10^{-17} \approx 3 \cdot 10^8$ kg salt

→ 10^{10} kg sea water

assuming a CCN lifetime of 3 days one obtains a „spray rate“ of ≈ $4 \cdot 10^4$ kg/s or 40 m^3/s

Maximum realistic ΔA_C:

Maximum achievable $\frac{N}{N_0} \approx 10 \Rightarrow$

$$\Delta A_C \approx 0.075 \cdot \ln(10) \approx 0.17$$

Leverage Factor for Cloud Whitening

We assume 10^{10} kg (10^7 t) of sea water per 3 days for counteracting 3.7 W/m^2 (CO_2 – doubling, from 280 ppm pre-industrial to 560 ppm)

CO_2-Mass (the additional 280 ppm): 2237 Gt

Sea water mass: $\approx 10^9$ t / year 1 Gt/year

→ Leverage Factor:

$$R_{Lev} = \frac{2237\,Gt}{1\,Gt} \approx 2.24 \cdot 10^3 \; per\ year$$

Leverage Factor for Cloud Whitening – Energy Perspective

Spray 10^9 t of sea water/year

Surface energy: 1.5 kJ/liter or 1.5 MJ/t

→Total energy consumption: $1.5 \cdot 10^9$ MJ/year

→1 ton of coal (or oil) is roughly equivalent to 40000 MJ

→Assuming an efficiency of 40% we have $\approx 1.5 \cdot 10^4$ MJ

→Thus the energy consumption is equivalent to $\approx 10^5$ t of oil or coal annually

→Probably insignificant

→Using the schemes of Cooper et al. 2011 (supercritical water spraying) or lectrospraying (Cooper et al. 2013) we need 1000-2000 times more energy

→10^8 t (0.1 GtC or 0.36 Gt CO_2) of fossil fuel annually:
About 1% of present annual fossil fuel consumption
Equivalent 1/7000 of the amount of CO_2 emission, which causes CO_2-doubling

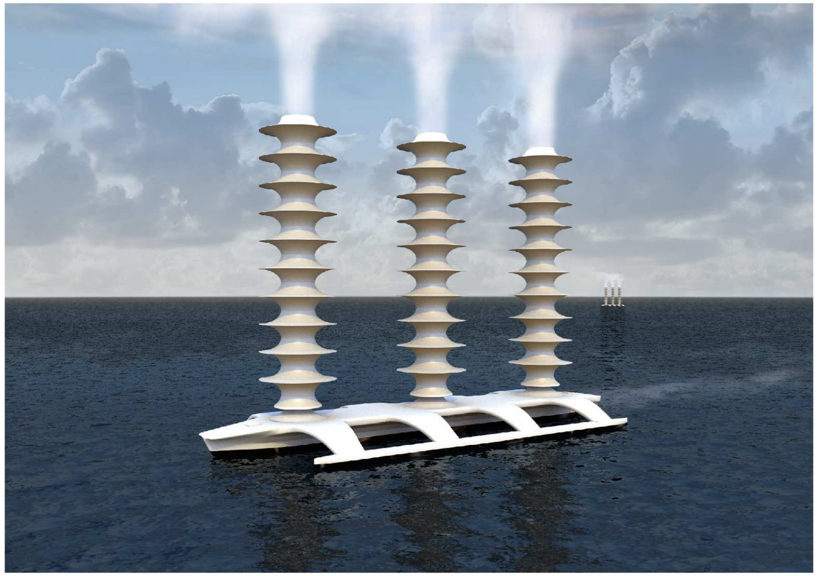
Cloud Whitening Hardware

Deploy several thousand small vessels, each spraying of the order of 10 l sea water per second into small droplets

Droplet size r_d:

$$\frac{r_d}{r} = \sqrt[3]{\frac{V_{water}}{V_{salt}}} = \sqrt[3]{\frac{M_{water}}{M_{salt}/\rho_{salt}}} \approx \sqrt[3]{\frac{1000}{35/2.17}} \approx 3.96$$

$$r_d \approx 4 \cdot r \approx 0.6\,\mu m$$



Energy required for spraying?

Minimum energy = surface energy

$E_S(H_2O) = 0.072\ Jm^{-2}$

$$E_S = 0.072\,\frac{J}{m^2} = \frac{Nm}{m^2} = \underbrace{\frac{N}{m}}_{\text{surface tension}}$$

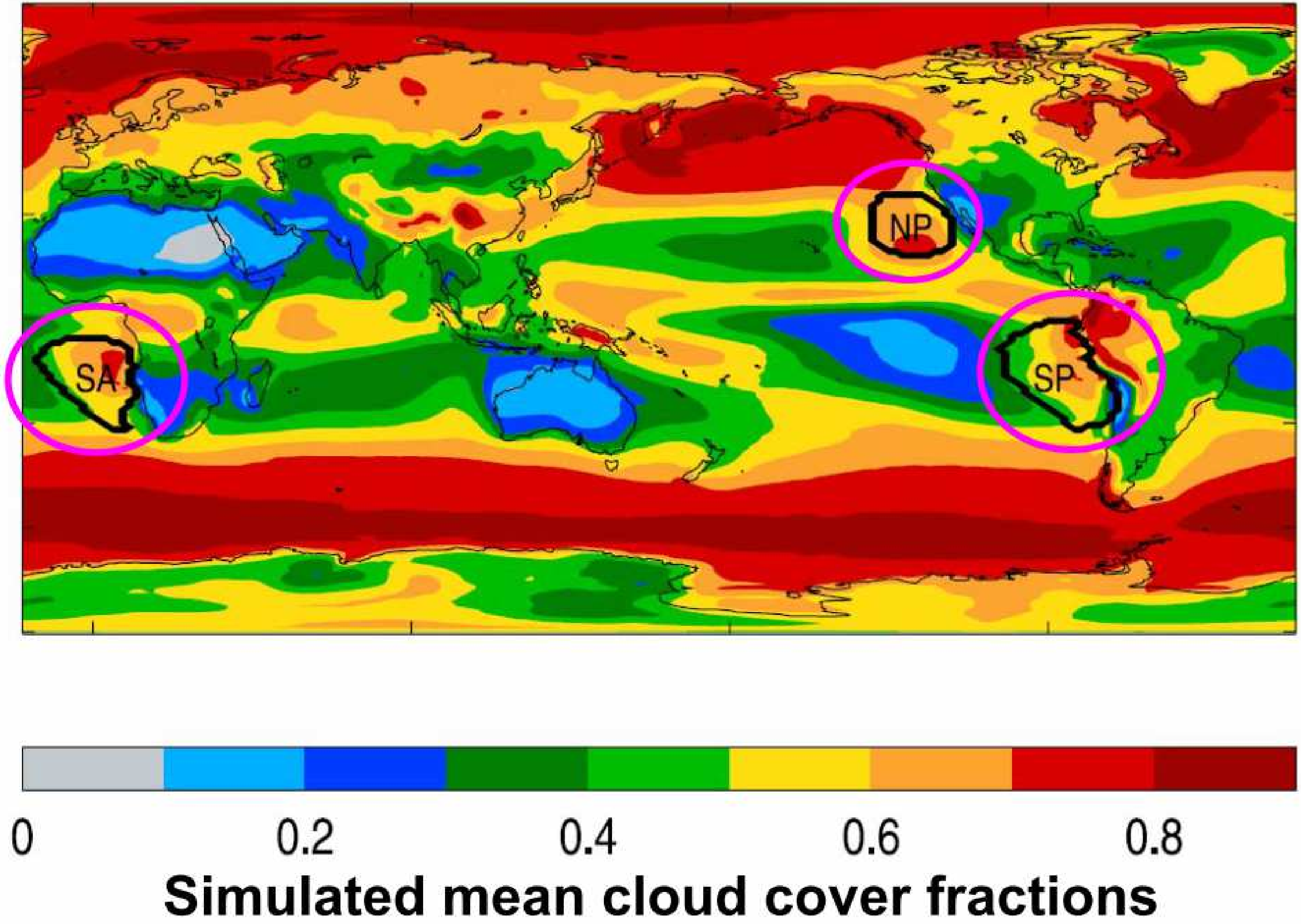
$$E = E_S \cdot A = E_S \cdot 4\pi r^2 \cdot N = E_S \cdot 4\pi r^2 \cdot \frac{V}{\frac{4}{3}\pi r^3} = E_S \cdot \frac{3V}{r}$$

$$\approx 0.072 \cdot \frac{3}{1.5 \cdot 10^{-7}} \approx 1.44 \cdot 10^6\,\frac{J}{m^3} = 1.44\,\frac{kJ}{liter}$$

At 10 l/s this would be 14 KW

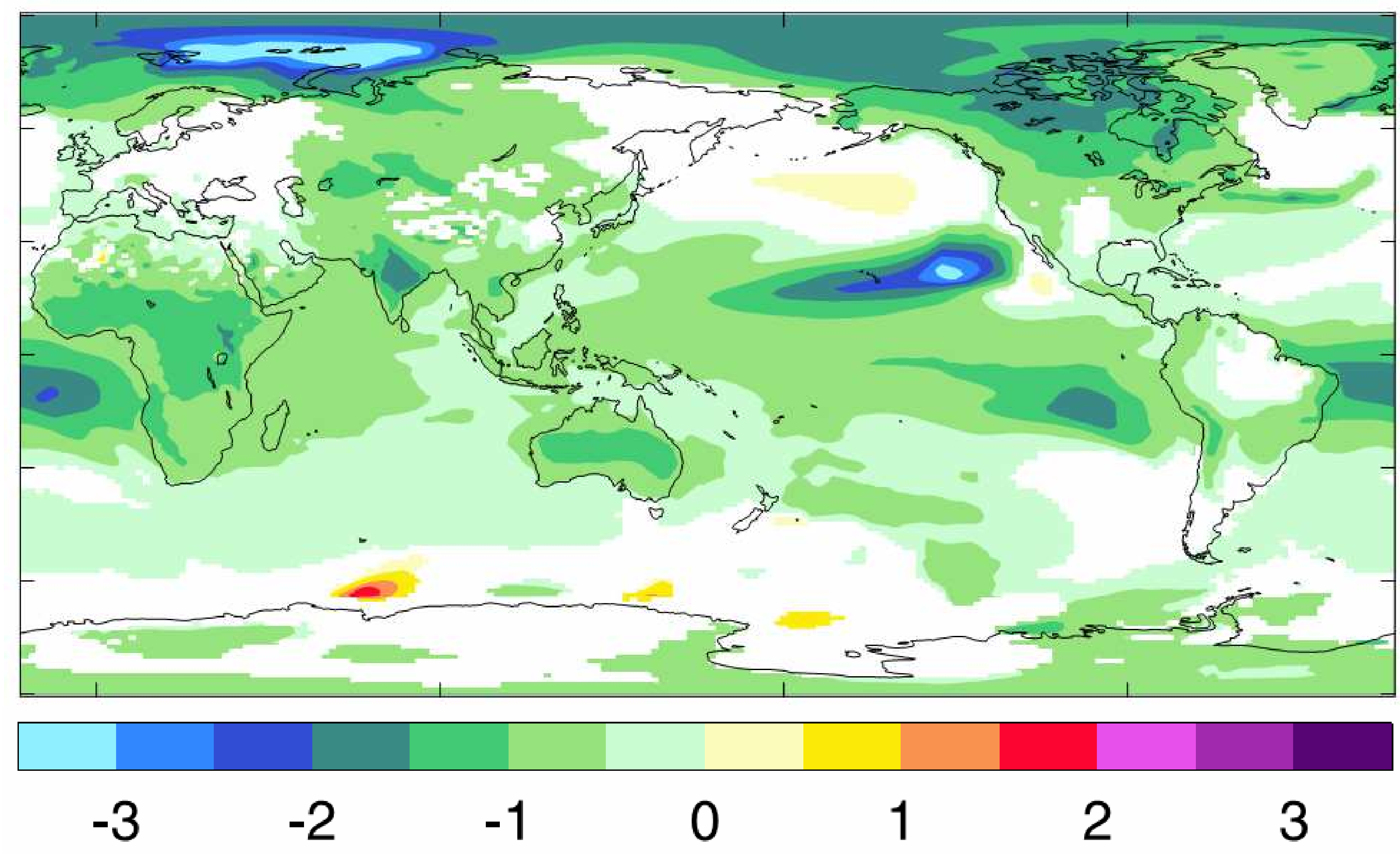
Too good to be true?

Primary Susceptible Regions for Cloud Brightening



Jones et al. 2009

Mean Temperature Change due to Cloud-Whitening CE

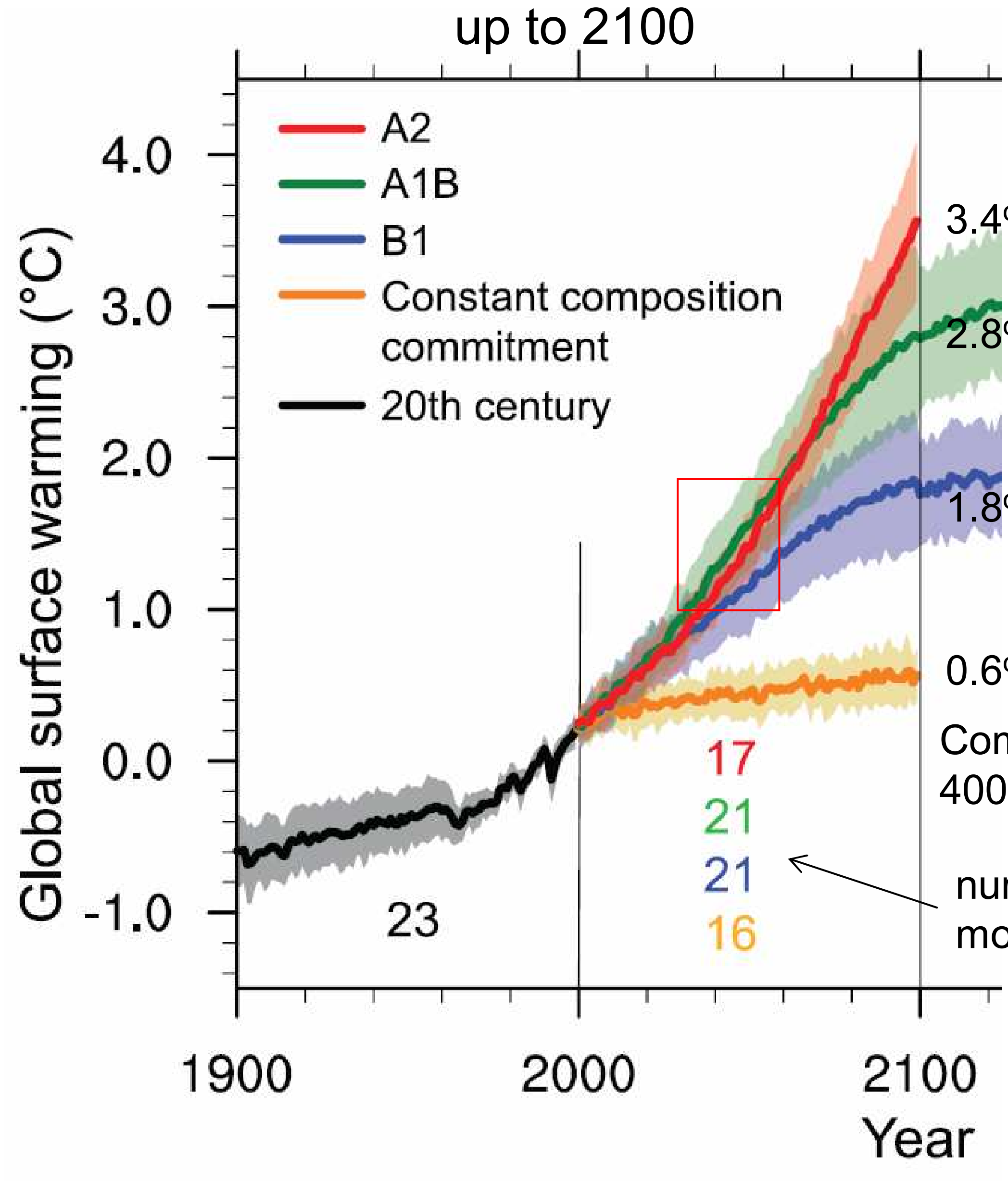


Mean 2030–2059 1.5m temperature change (K) due to CE of the three main marine stratocumulus cloud areas (ALL A1B).
White: Areas where difference is not statistically significant at 5% level.

Jones et al. 2009

CE-simulation: Cloud droplet concentration increased from around 100 cm^{-3} to 375 cm^{-3} → Global mean forcing about -1 W/m^2

Reminder from Lecture #4: IPCC Climate Predictions



3.4°C A2

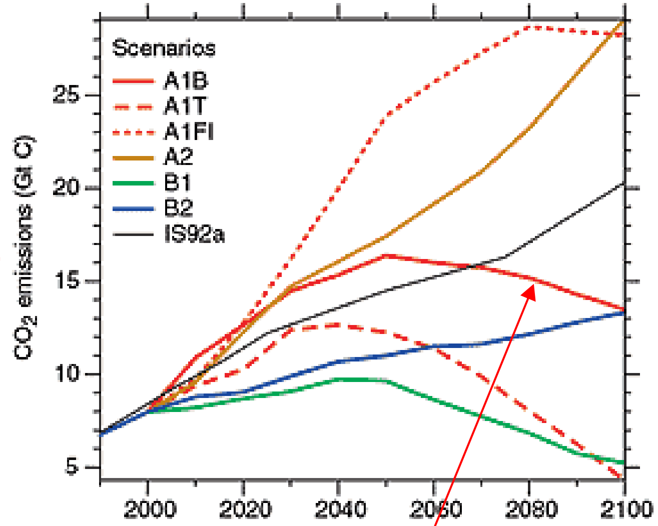
2.8°C A1B

1.8°C B1

0.6°C constant CO_2

Commitment at 400 ppm CO_2

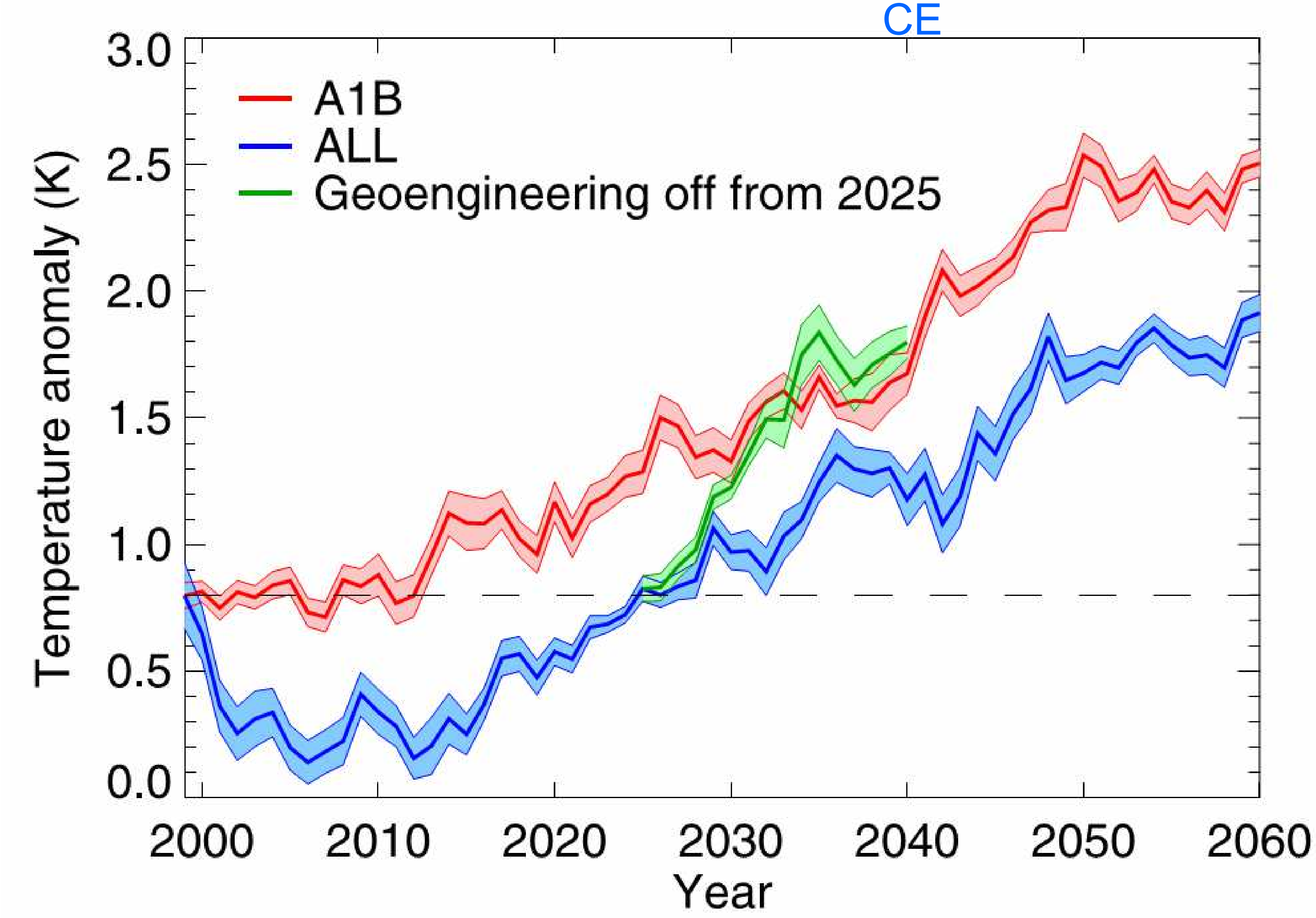
number of models



A1B

IPCC, AR4, 2007

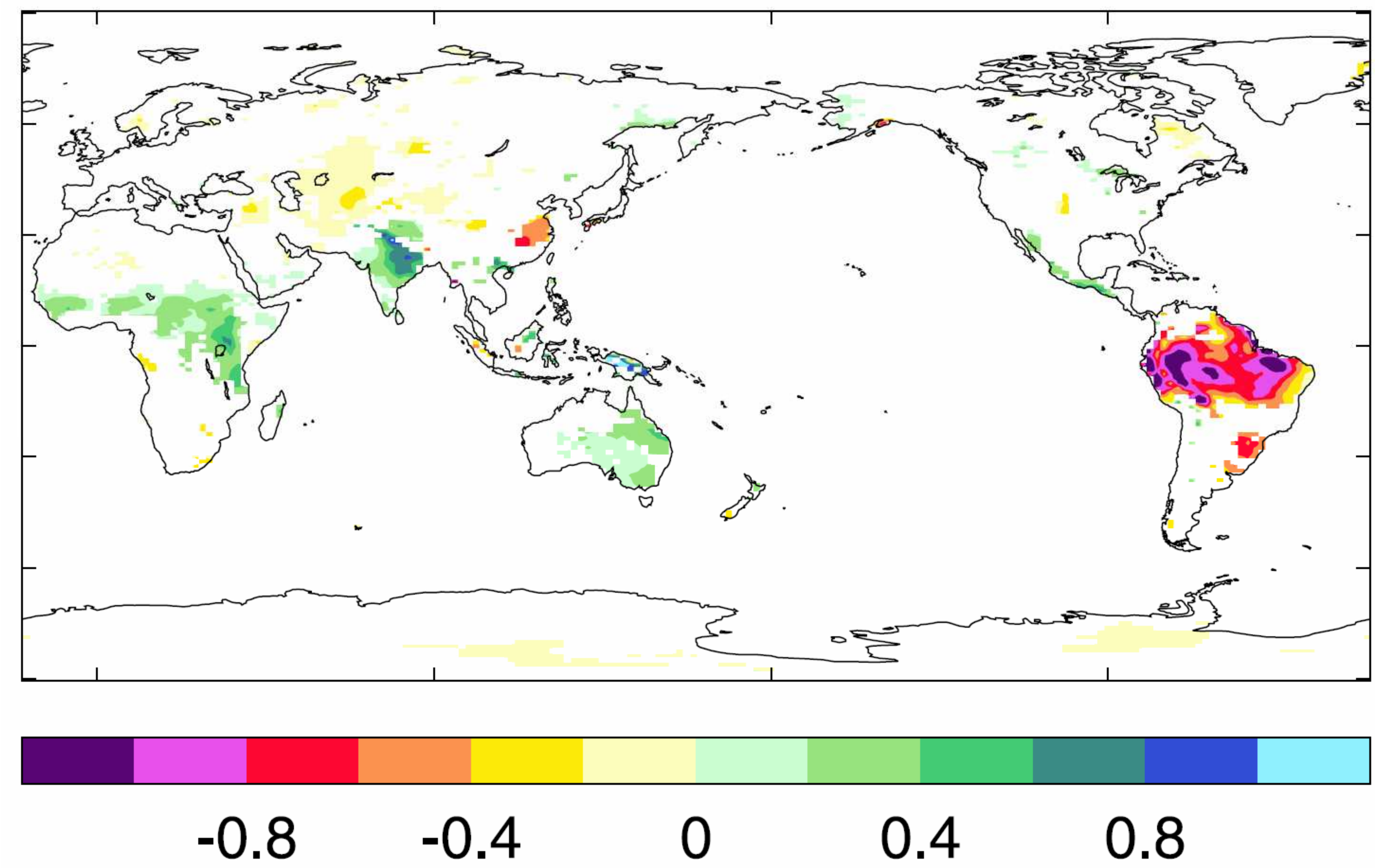
Mean Global T-Change without (A1B) and with (ALL) CE



Evolution of near-surface air temperature anomaly (K) with respect to 1860 in HadGEM2-AO. Red line (A1B): Simulation forced by the SRES A1B scenario. Blue line (ALL): Simulation that also includes the CE of all three stratocumulus areas. Green line: A short simulation initialized from ALL at 2025 but with all CE suspended. Envelopes around the lines: interannual variability in the simulations.

Jones et al. 2009

Mean Precipitation Change due to Cloud-Whitening CE



Mean 2030–2059 change in land precipitation (mm/day) with CE (ALL) versus scenario A1B. White: Land areas where the change is not statistically significant at 5% level are in.

Jones et al. 2009

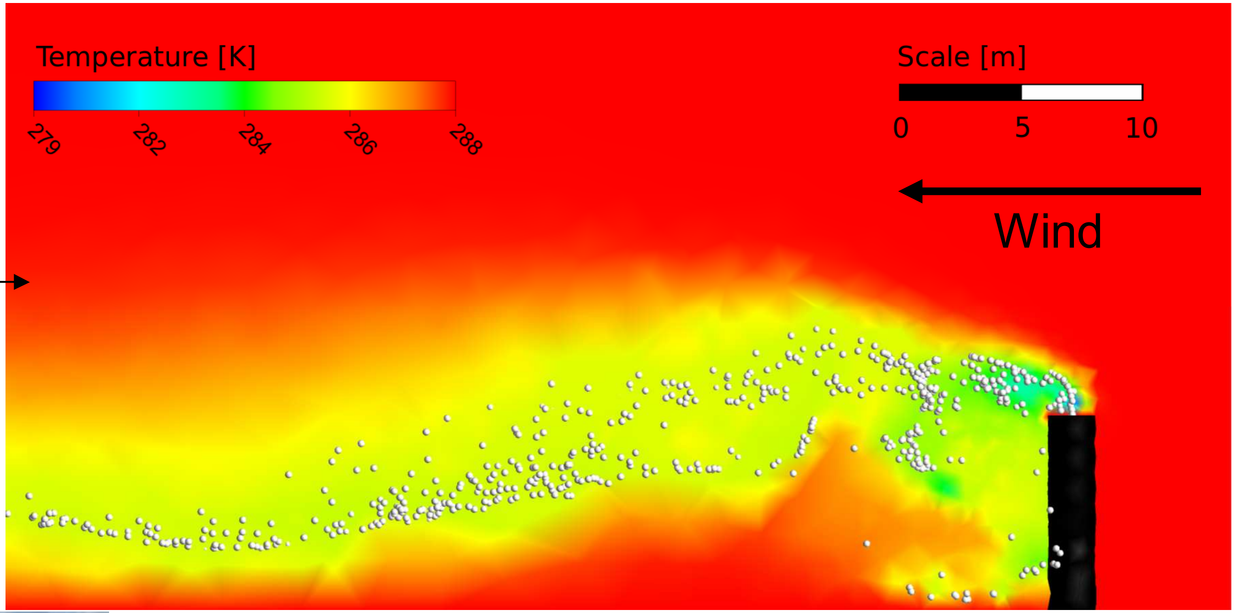
Technical Problems with „Cloud Whitening“ Schemes

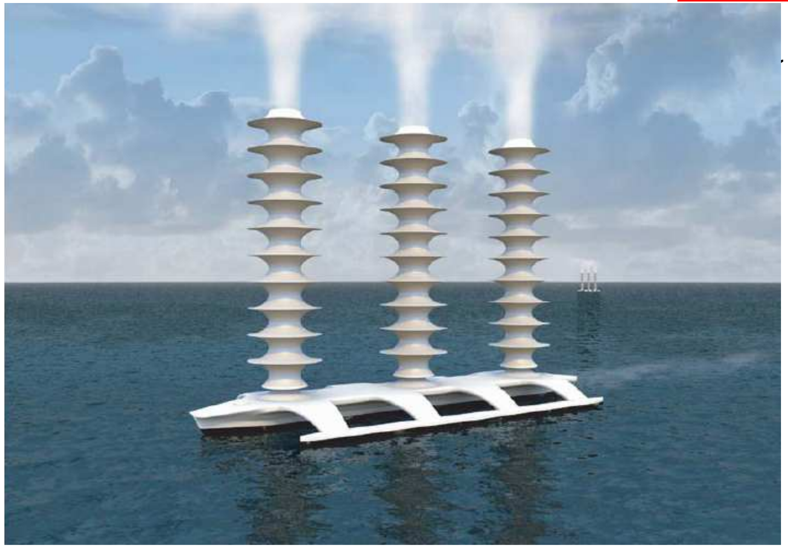
- It is extremely difficult to produce very small particles (r in the range of several 100nm) ?
- Will the particles raise to cloud condensation level?
- Large changes in the climate system due to spatial distribution of cooling by „seeded“ (and thus whitened) clouds
- Standard spraying techniques have efficiencies in the few percent range
  → 14 kW → MW (for 10 l/s)

Will Cloud-Brightening actually Work?

Near vessel dynamics of sea salt sprays: How efficient can maritime clouds be seeded? (S. Müller-Klieser, U. Platt, and T. Leisner)

Model output for a sea-going spraying device at 3 m/s wind speed (neutral atmospheric stability).
Air temperature is color coded
Dots: ensembles of particles





Cloud seeding with sea-salt particles (S. Salter et al. 2008)

→ See spray will not rise to cloud-level as shown in Latham's sketch, rather a layer of fog will evolve round the vessel.

Possible Solution to the Fine Particle Problem (1)

Spray supercritical seawater:

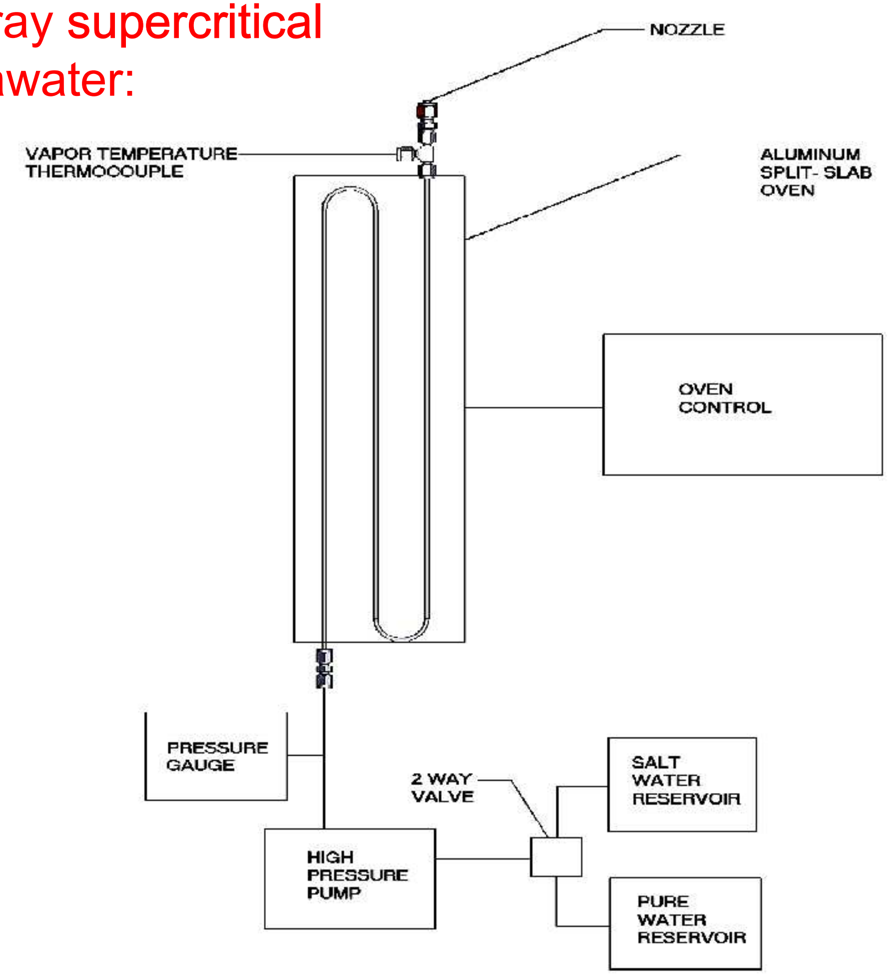


Fig. 3 Experimental apparatus

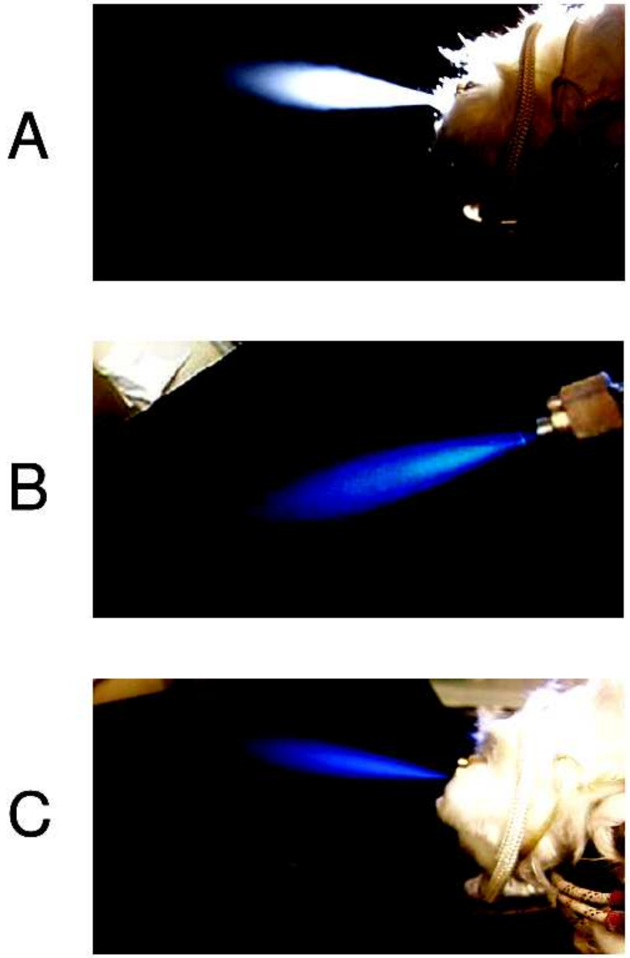


Fig. 4 Supercritical saltwater spray plumes illuminated with white light. A: micron-sized droplets; B, C: submicron-sized salt crystals. Blue color due to Rayleigh scattering of blue light by nanometer-sized salt particles.

From: Cooper et al. 2011

Possible Solution to the Fine Particle Problem (2)

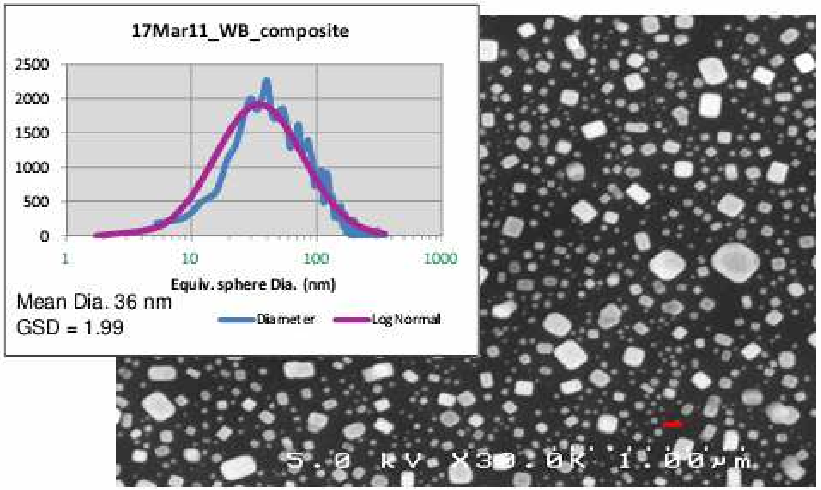


Fig. 8 SEM image of salt particles from supercritical spray of 0.1% sodium chloride (red bar = 100 nm).

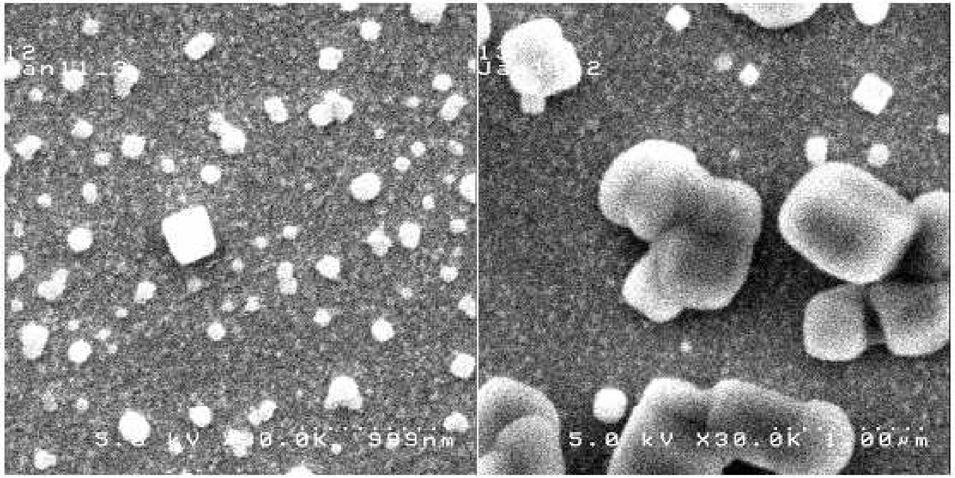


Fig. 9 SEM images of salt particles from supercritical spray in absence (left) and in presence (right) of dense liquid brine.

From: Cooper et al. 2011

Minimum Energy requirement:

Heat water to critical temperature $T_C(H_2O)$ = 373.946 °C

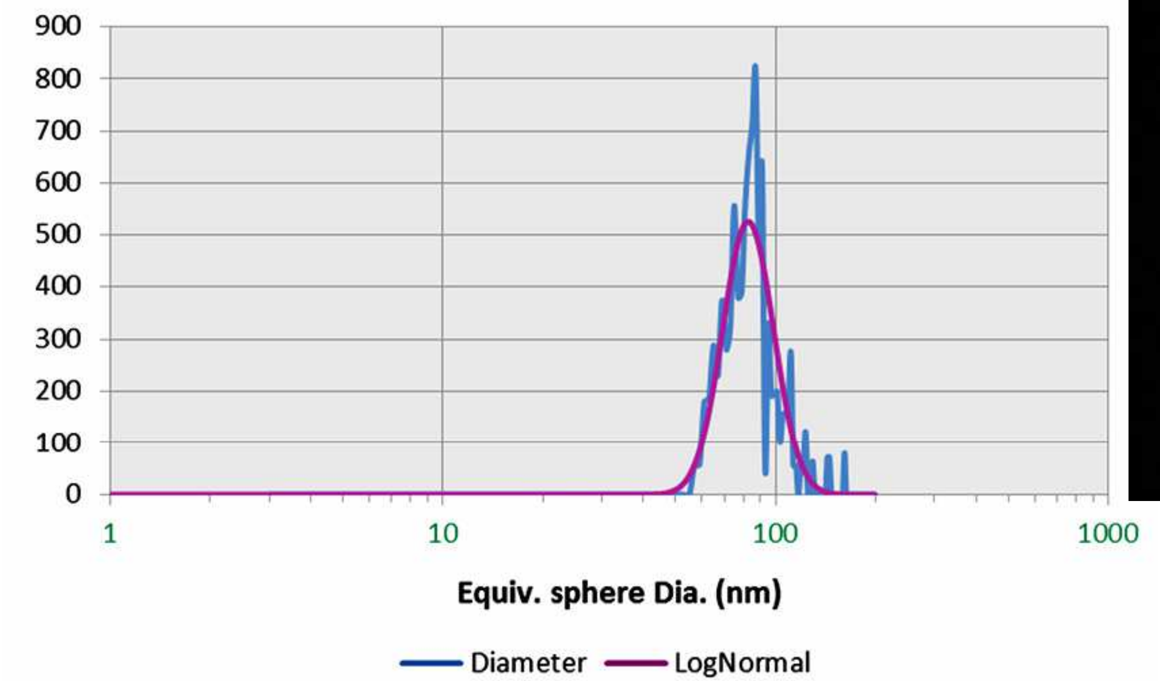
1.570 MJ/kg

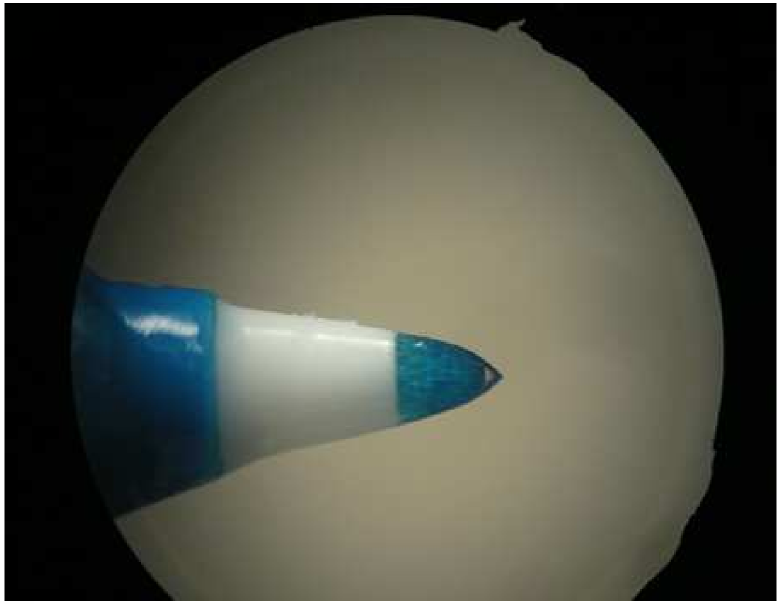
→10 l/s → 16 MW (about 1000 x surface energy)

Cooper et al. 2011: 2.676 MJ/Kg (enthalpy of free steam)

Possible Solution to the Fine Particle Problem (3)

Electrospray from cones





Minimum Energy requirement:

Several KV times 1 charge/particle

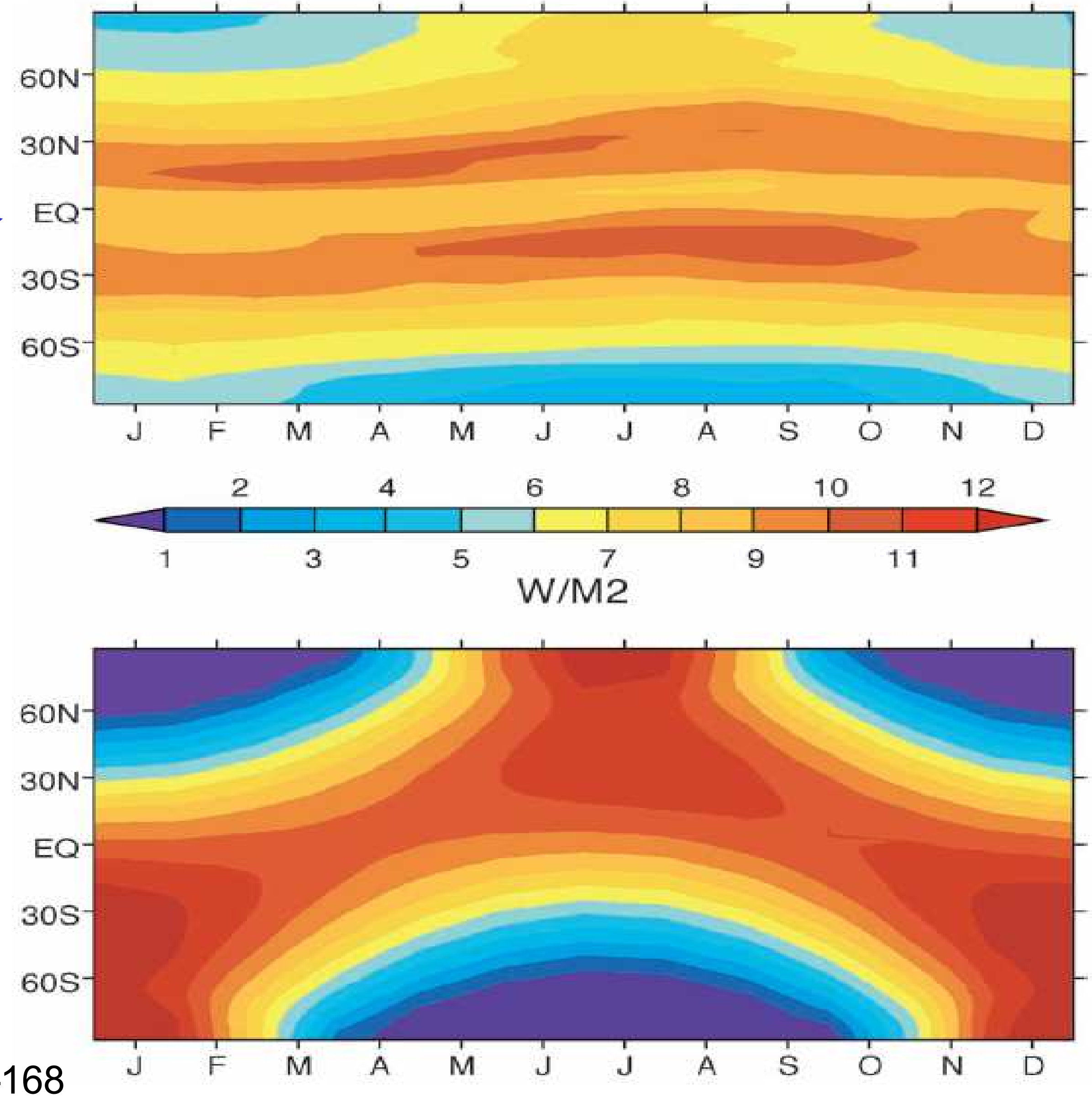
→ ≈50 MW

From: Cooper et al. 2013

Problem: Side-Effects regarding the Spatial and Temporal Distribution of Climate Forcing

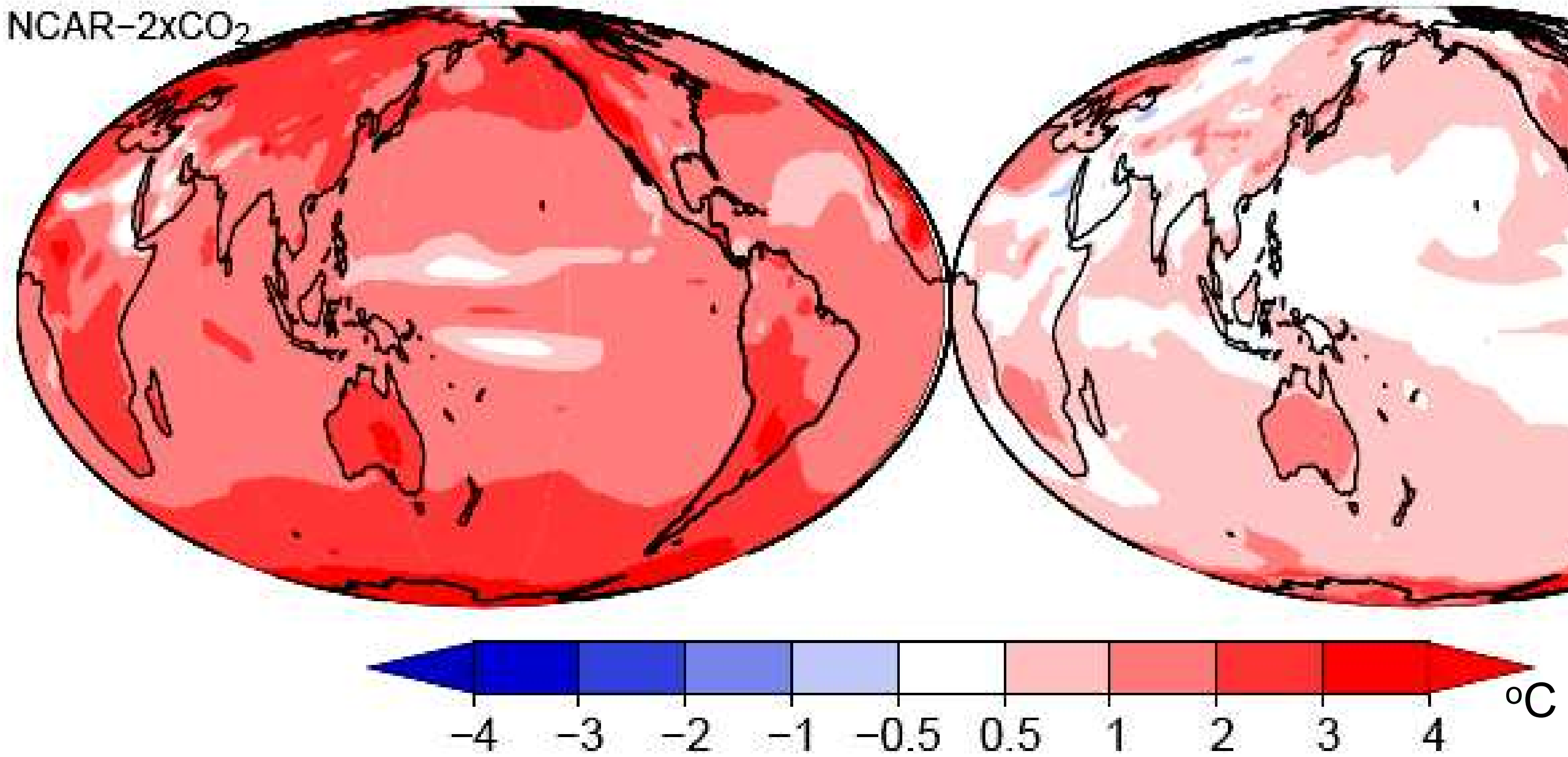
Spatial and temporal distribution of forcing caused by x4 CO_2

(negative) Radiation forcing due to stratospheric aerosol



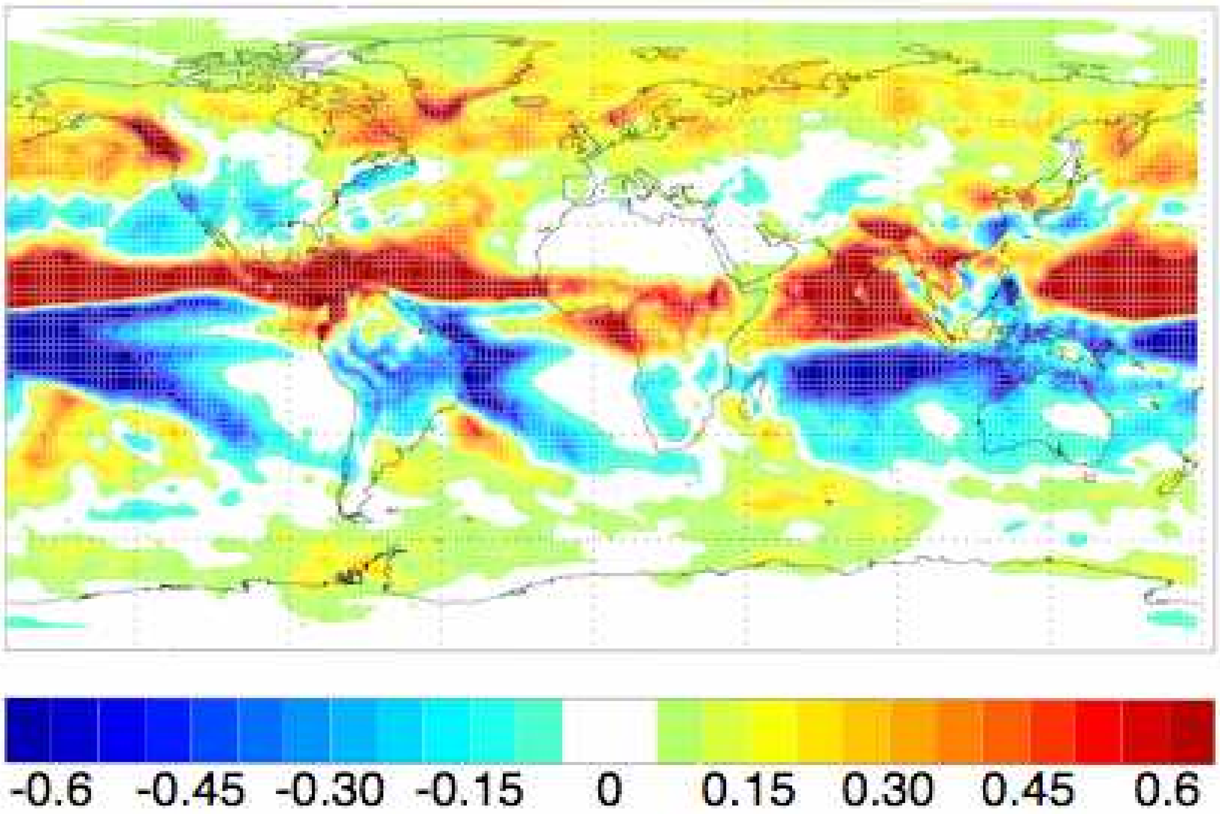
Govindasamy et. al. Global and Planetary Change 37 (2003) 157–168

Consequences of CE Offseting 2xCO_2 on the Global Temperature Distribution



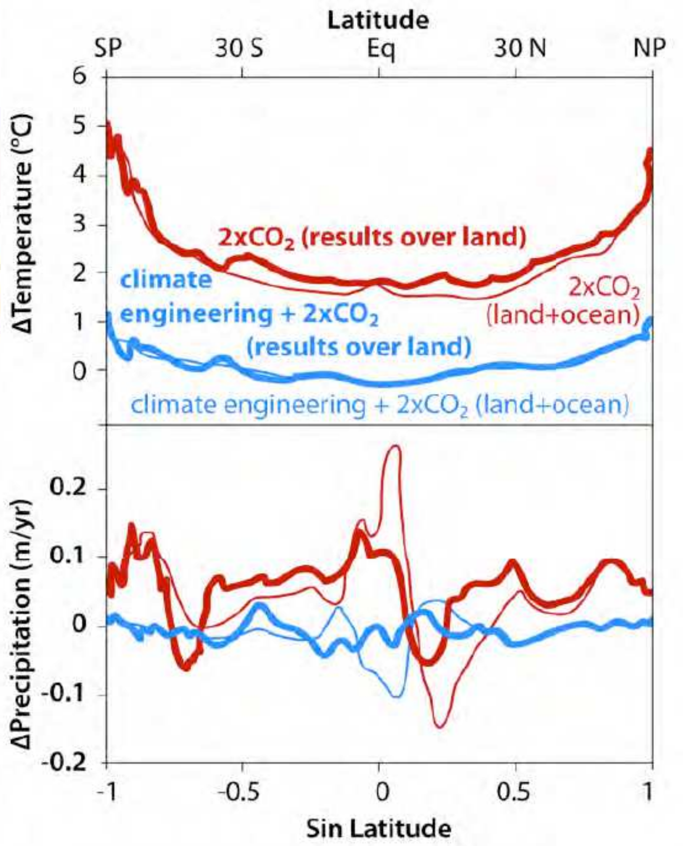
Govindasamy et. al. Global and Planetary Change 37 (2003) 157–168

Consequences of CE on Global Precipitation Patterns



CE-measures offsetting the mean global temperature rise caused by $2xCO_2$

Change in daily precipitation column, (mm),
J. Feichter et al. submitted



Blackstock et al. 2009

Enhancing the Natural Sulfur Cycle to Slow Global Warming?

Wingenter O.W., Elliot S.M., Blake D.R. (2007),
New Directions, Atmospheric Environment, 41 (34), 7373-7375, ISSN: 13522310,
+Atmos. Env. 2008, 42, (19), 4806-4809, ISSN: 13522310.

The Idea:

Iron-fertilize about 5% of the southern ocean area (1nM, 3 x per week)
(don‘t care about C-fixation)

→ Enhance dimethyl-sulfide (DMS) concentration by 20%

→ Enhanced DMS leads to +10% CCN
(since ½ of CCN are due to DMS-oxidation)

→ ≈0.8% albedo increase due to „cloud whitening“ (from 46.0% to 46.4%)

→ Negative forcing of 3 W/m^2 (summer)

See also:
„**The Iron CLAW**“ (M. Harvey, Environmental Chemistry 4 (6), 396-399, 2007)

Conclusions

- CE by Cloud seeding (cloud whitening, sea spray geoengineering) should work in principle.
- Transport of material to the ocean surface is much easier than to stratosphere or into space
  → possibly quite economic solution
- Technological problems, in particular with CCN-production, are not solved
- Cooled areas are largely in the remote, southern Pacific
  → Danger of disturbing global circulation
- CCN-lifetime in the atmosphere is < 1 week, so the CE-measure can be stopped in short time