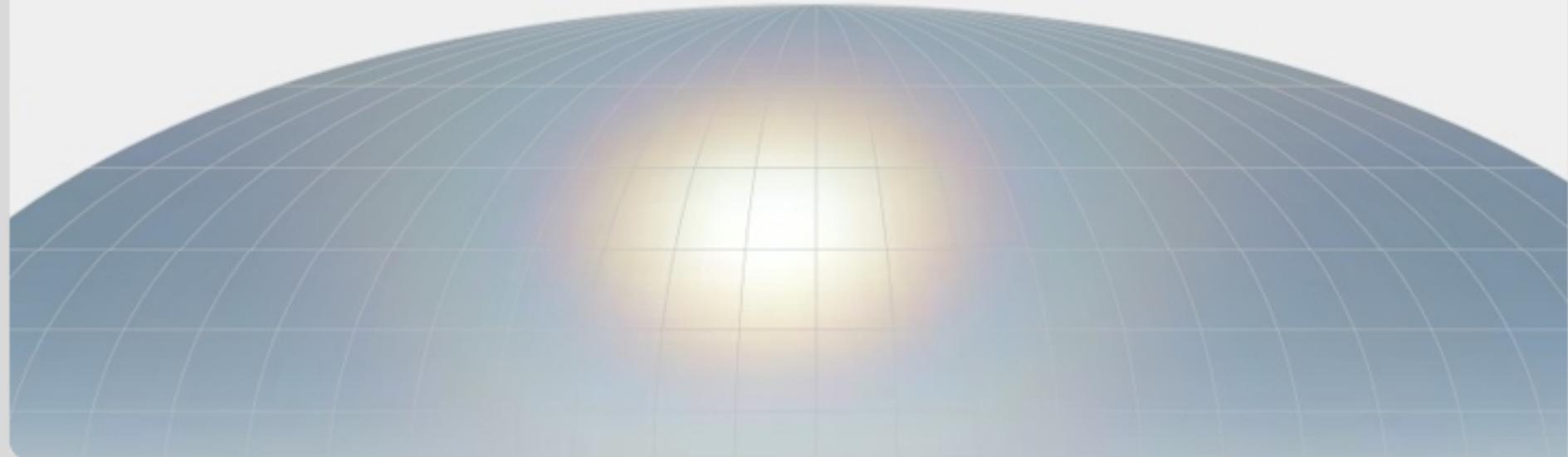




Climate Engineering – is there a plan B for climate?

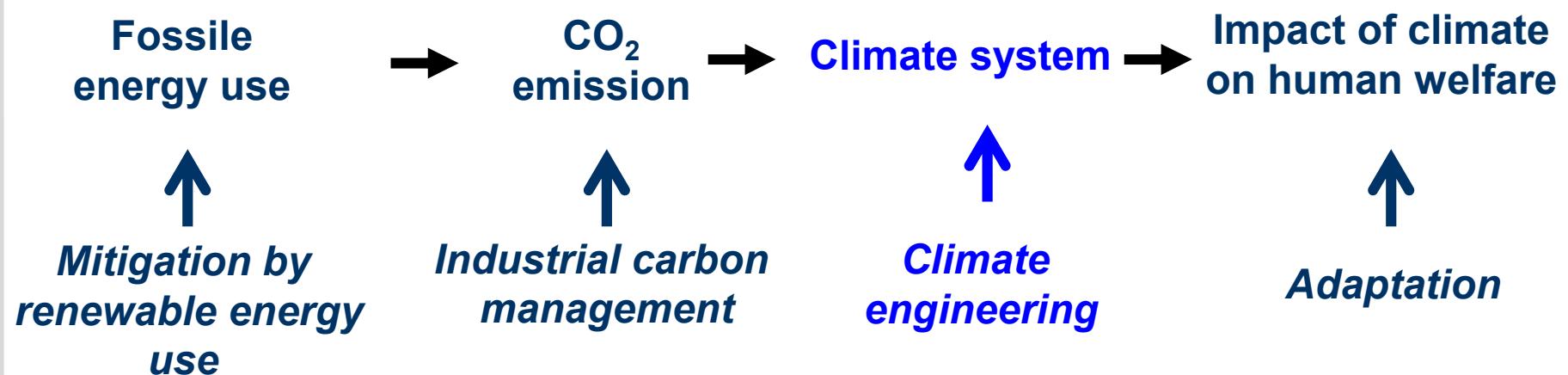
***Thomas Leisner, Karlsruhe Institute of Technology,
and University of Heidelberg, Germany***

Institut für Meteorologie und Klimaforschung, Karlsruhe Institute of Technology und Institut für Physik, Universität Heidelberg

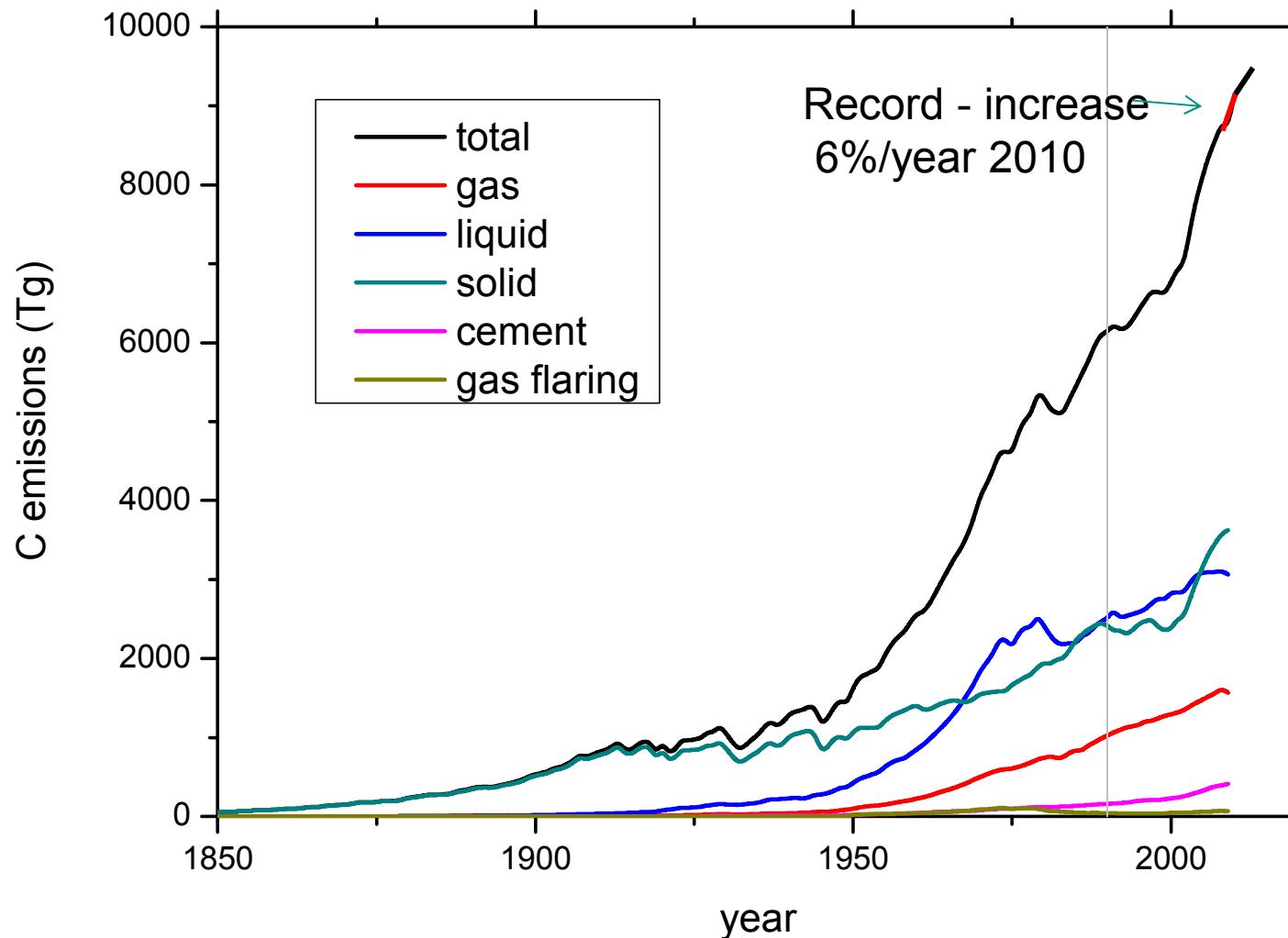


Definition Climate engineering

intentional large-scale manipulation of the environment, with the goal of reducing undesired climate change caused by human influences (Keith, 2000)



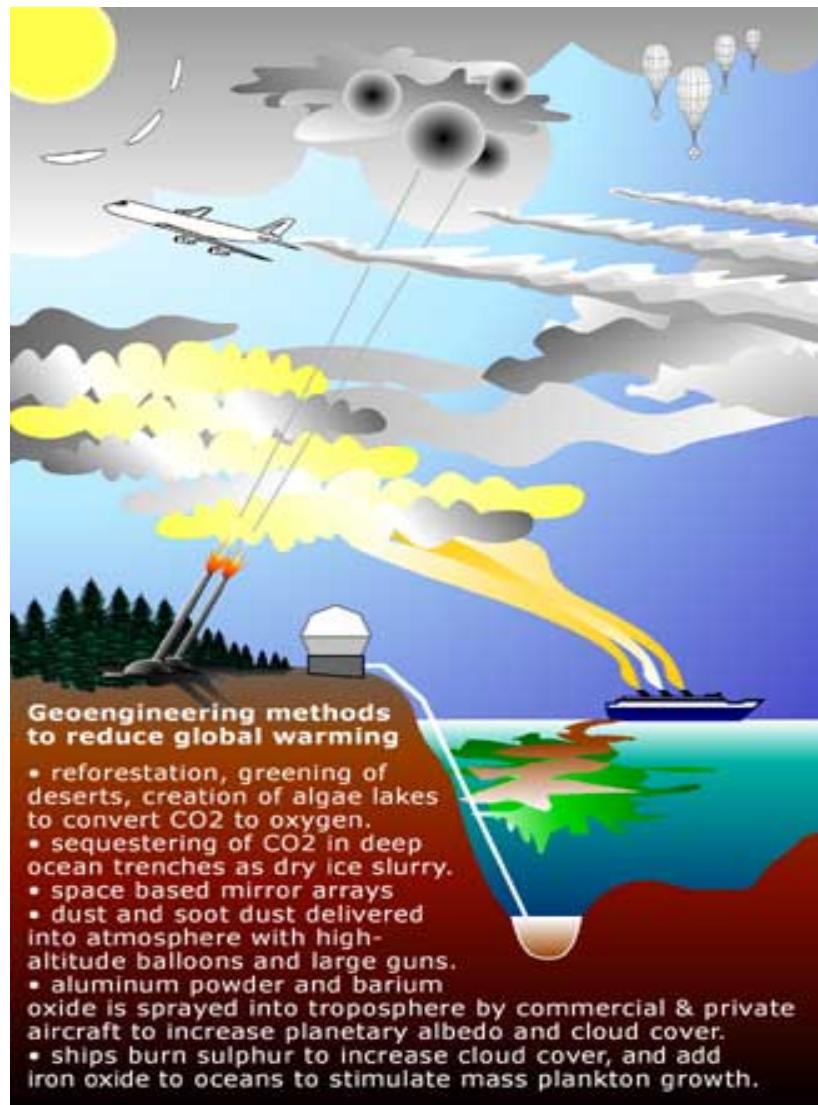
World wide CO₂ emissions



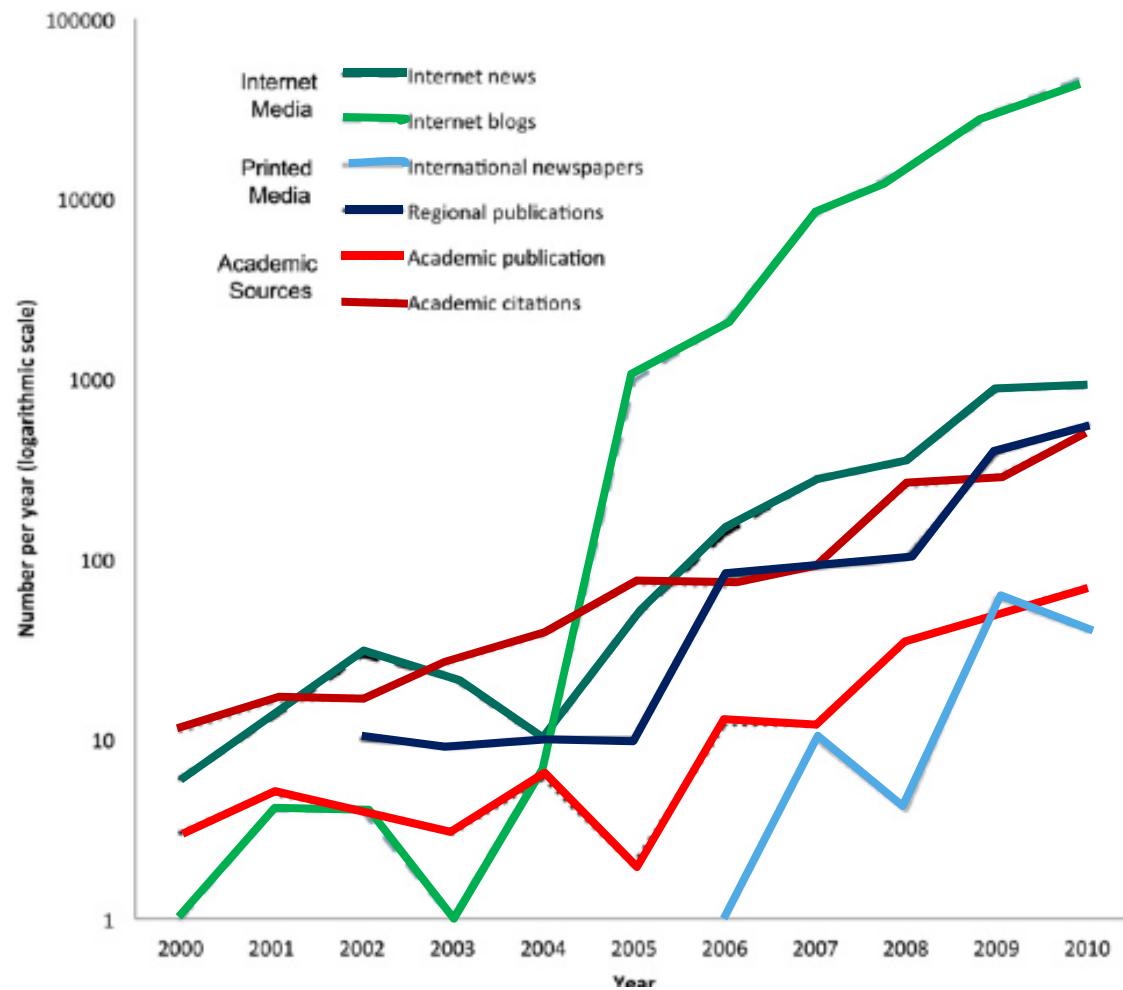
Friedlingstein P., R.A. Houghton, G. Marland, J. Hacke, T.A. Boden, et al. 2010.
Update on CO₂ emissions. Nature Geoscience. 3, 811-812,

Is there a feasible plan B?

March 24, 2008

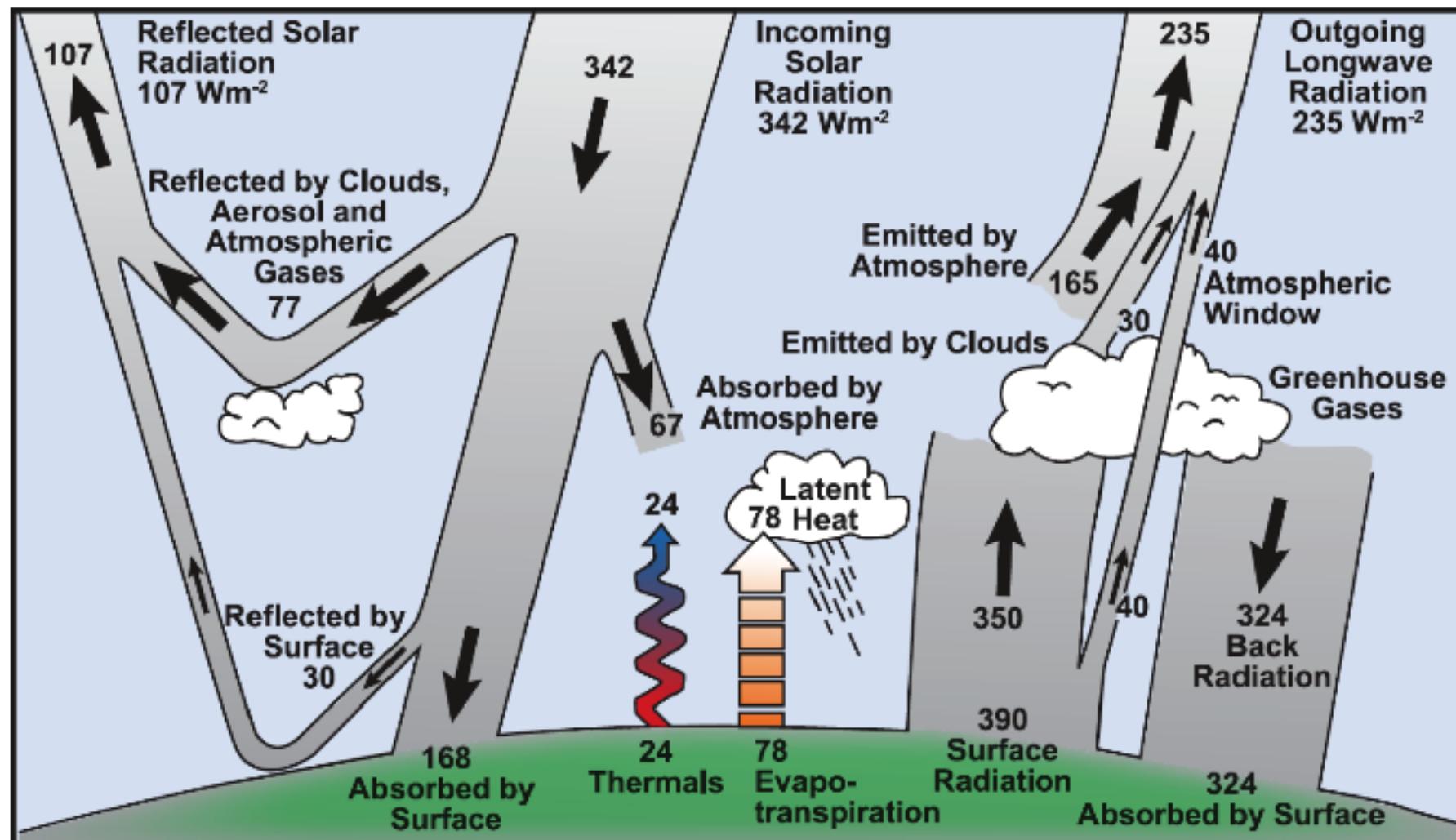


Climate Engineering: Ignoring is not an option



A.M. Mercer, D.W. Keith and J.D. Sharp, Environ. Res. Lett. 6 (2011) 044006

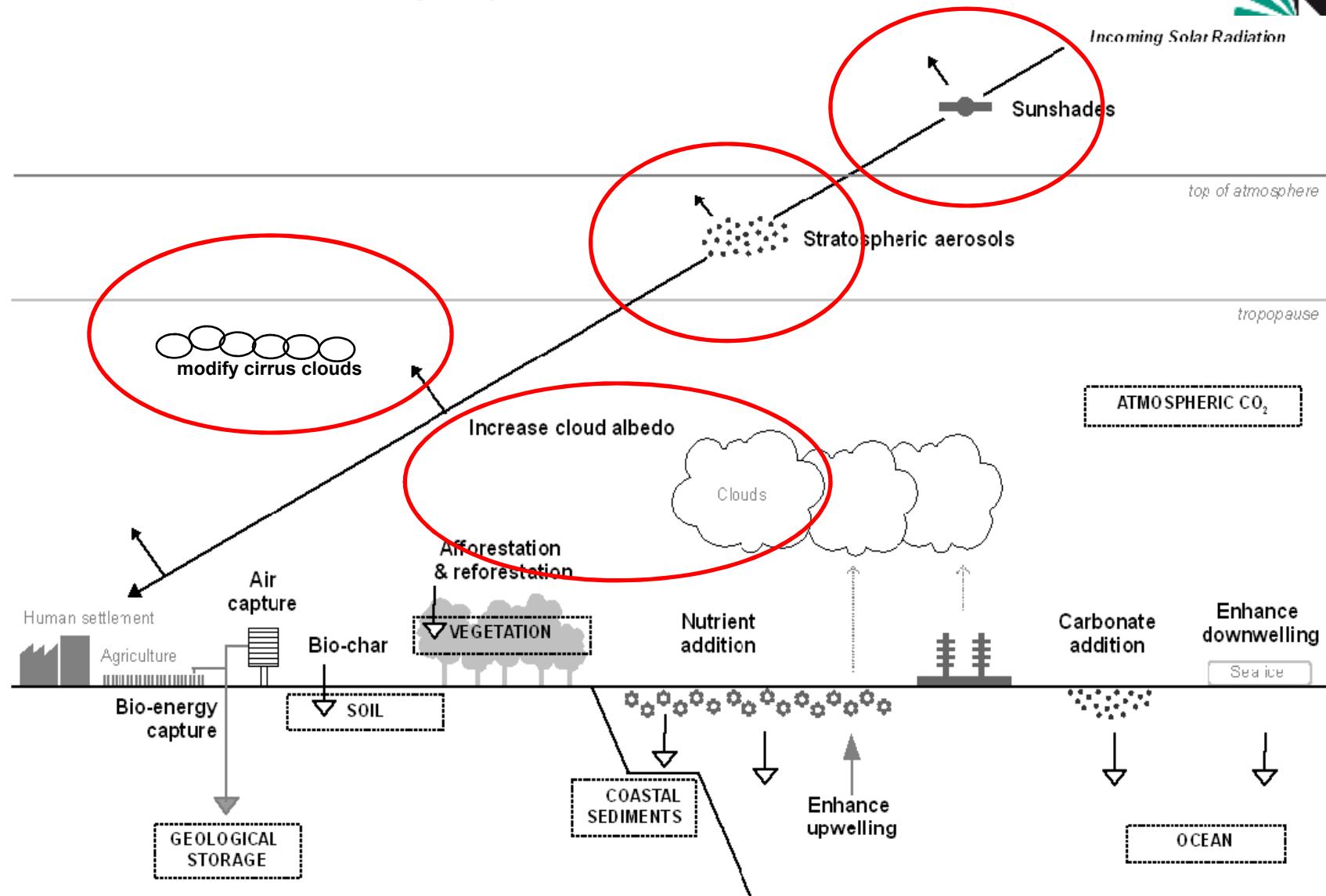
The global energy budget



Current energy imbalance $0.85 \pm 0.15 \text{ W/m}^2$

IPCC 2007

CE Overview of proposals



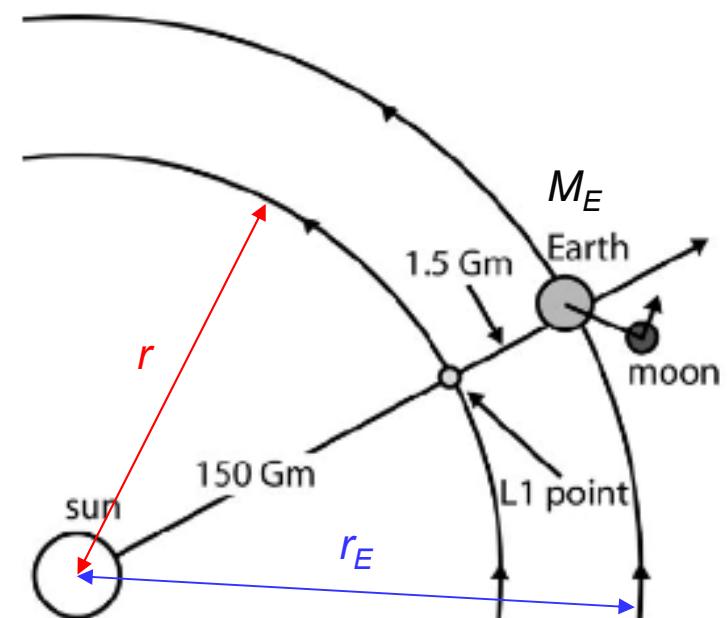
Sunshades: (Angel, PNAS, 2006)

Lagrange point 1- (unstable equilibrium), active stabilization

Implementation: Cloud of disk shaped optical elements, stabilized by active modulation of radiation pressure. Diam.: ~1 m; weight: 1g; Number: 1.6×10^{13} Total weight 12 Mt.

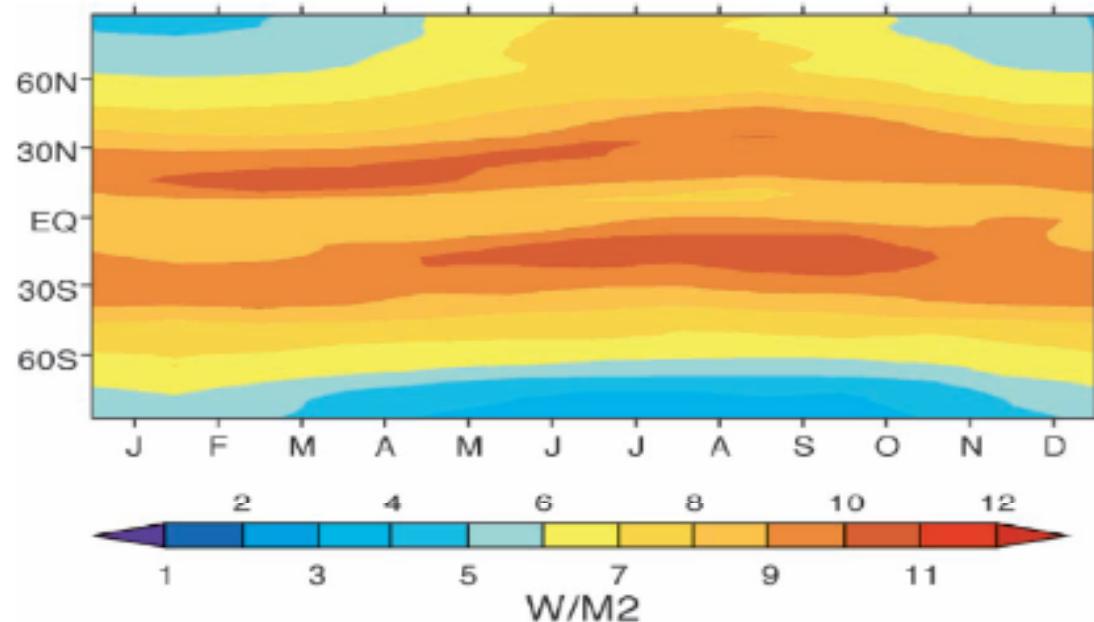
Transport: elektromagn. Railgun, ion propulsion, assumed cost:

50 \$/kg down from currently 20000 \$/kg →
several 1000 Billion US\$

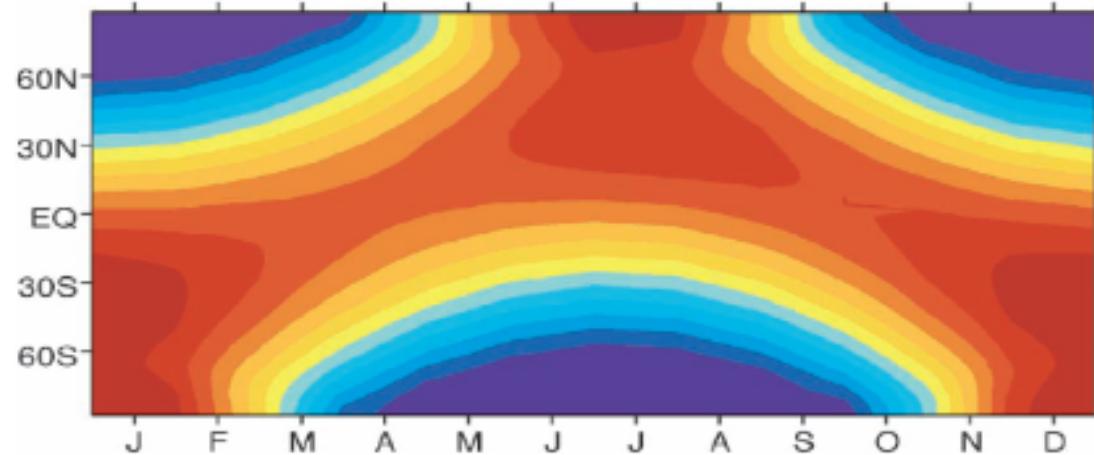


Spatial and temporal distribution of climate forcing

(a) warming
 $\times 4 \text{ CO}_2$

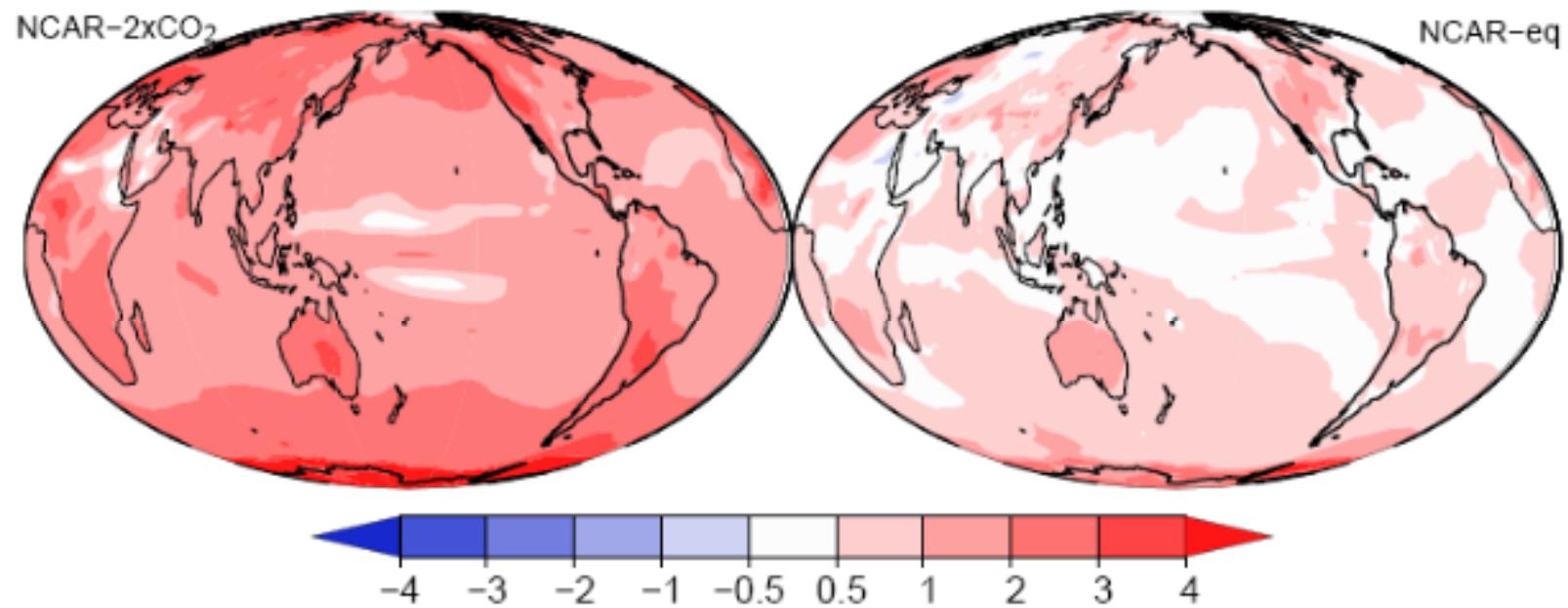


(b) Cooling by SRM



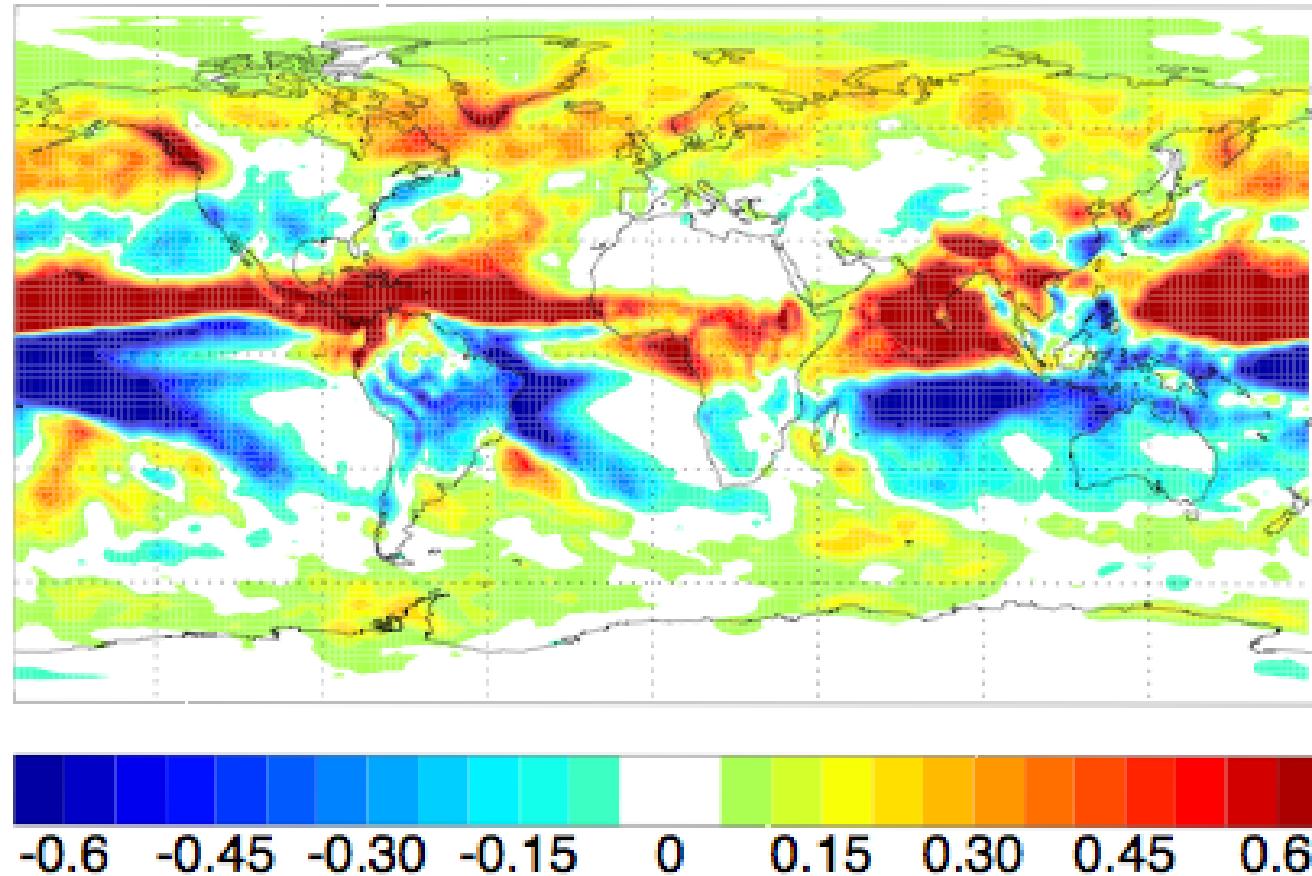
Govindasamy et. al.
Global and Planetary
Change 37 (2003) 157–168

Temperature effect of SRM surprisingly homogeneous



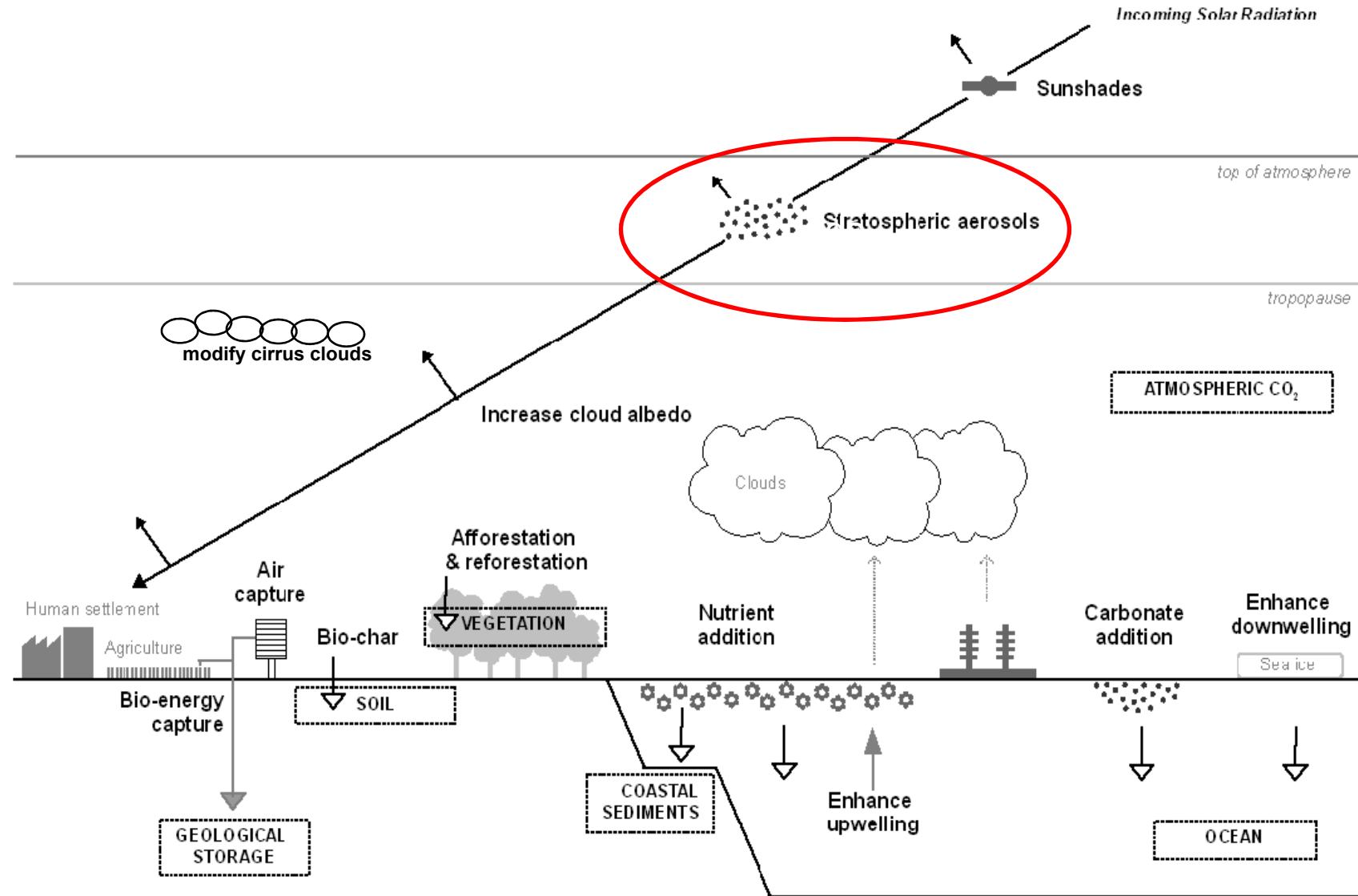
Govindasamy et. al.
Global and Planetary Change 37 (2003) 157–168

Global circulation and precipitation patterns change



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

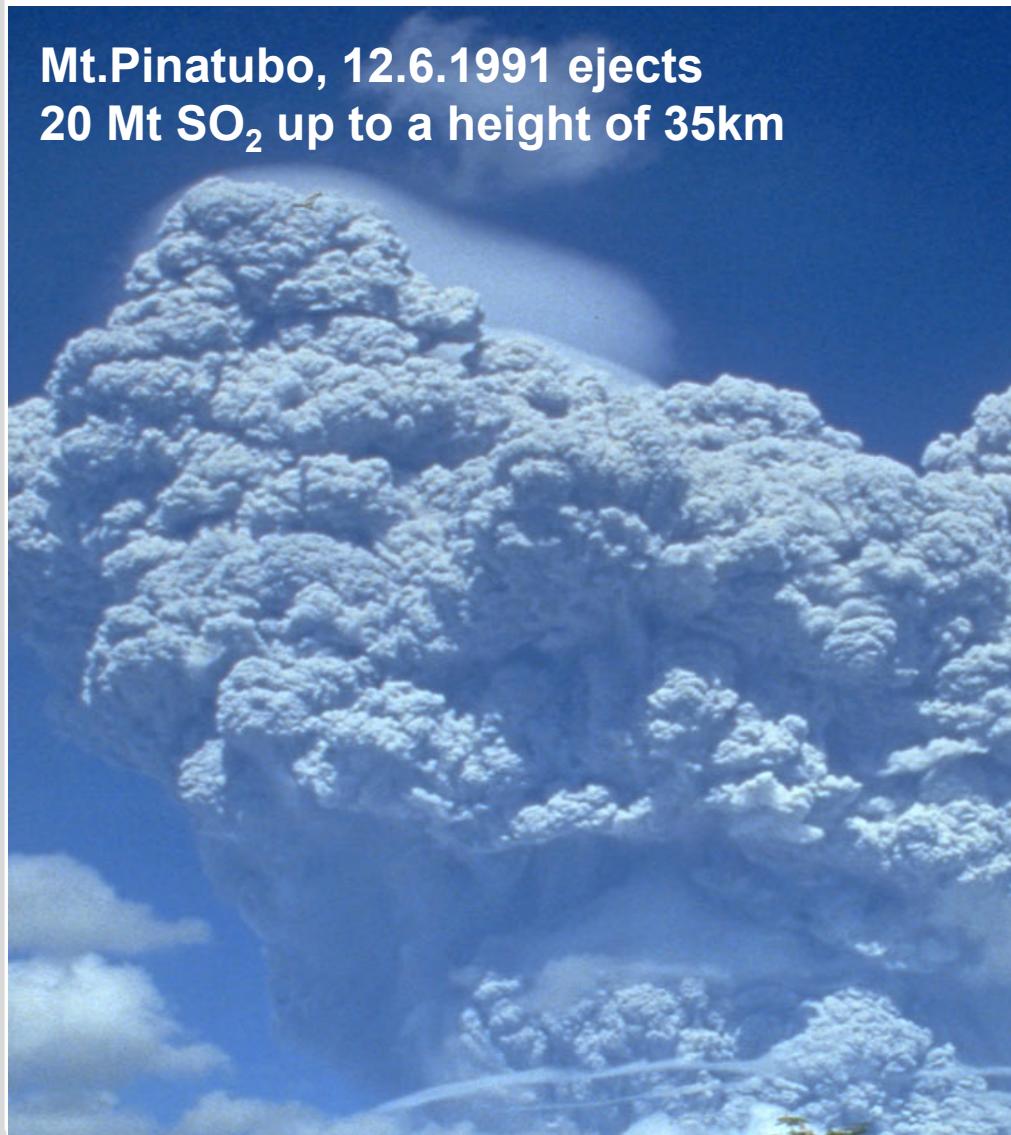
CE Overview of proposals



Augmenting the stratospheric aerosol layer



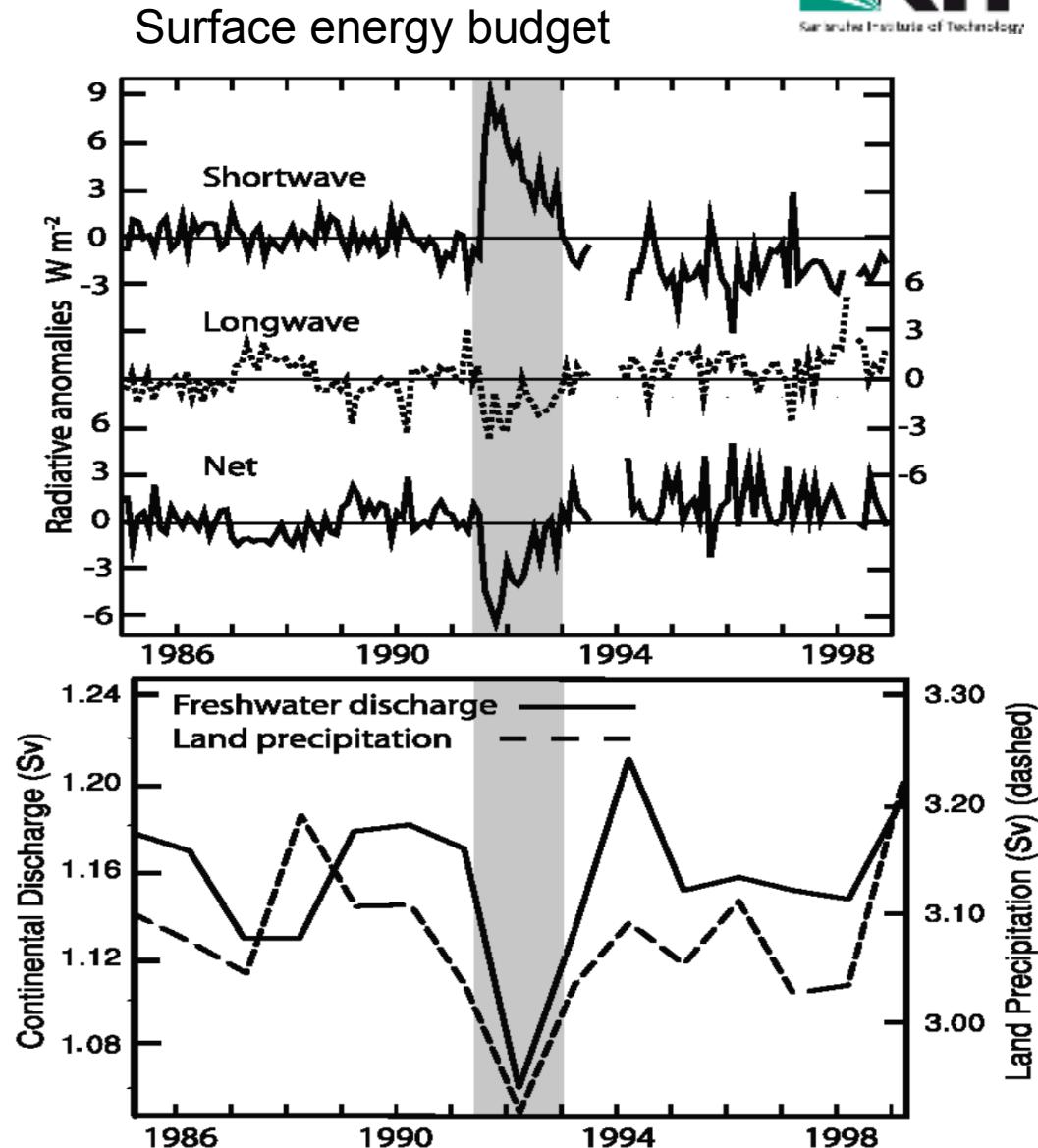
**Mt.Pinatubo, 12.6.1991 ejects
20 Mt SO₂ up to a height of 35km**



Effect of Mt. Pinatubo Eruption

Effects of Mount Pinatubo,
Philippines volcanic eruption
(June 1991) on the radiation
balance and on the
hydrological cycle.

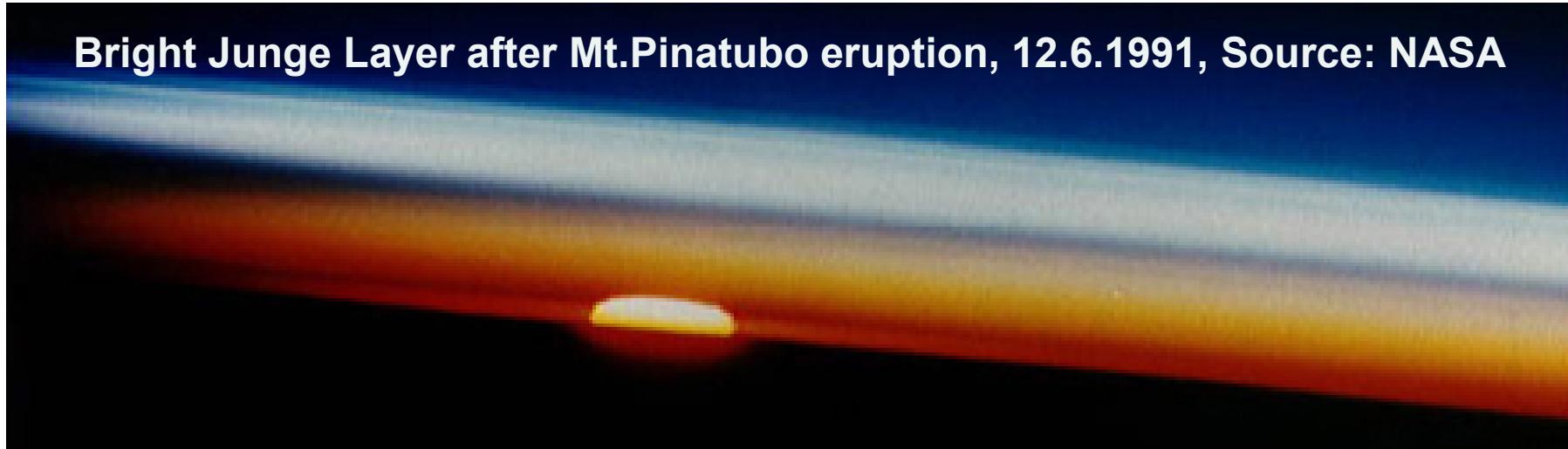
Trenberth and Dai (2007)
Geophys. Res. Lett.



Sulfuric acid climate engineering

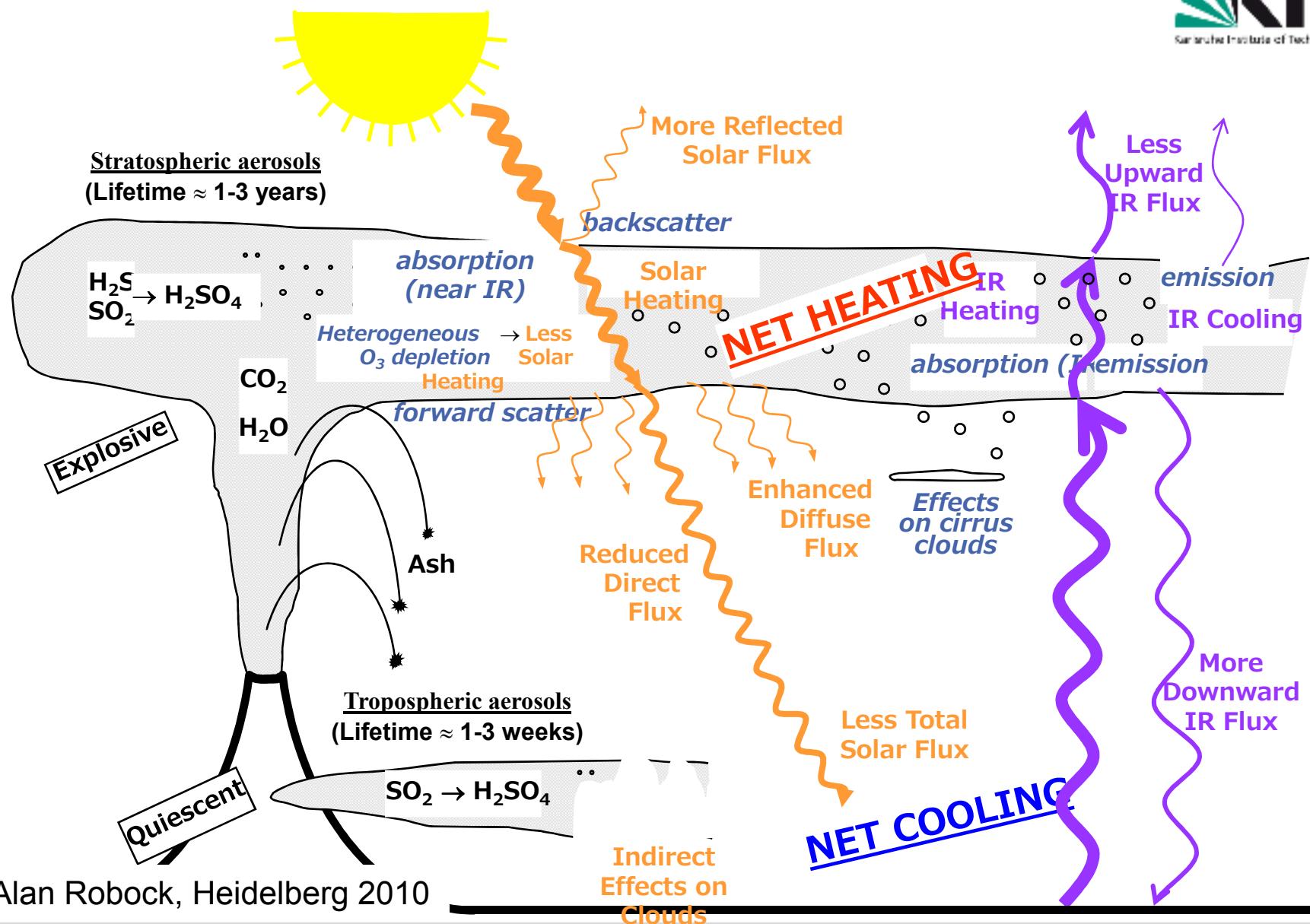
The promise: Budyko, Keith, Crutzen...

Bright Junge Layer after Mt.Pinatubo eruption, 12.6.1991, Source: NASA



- 5Mt stratospheric S/a can compensate the equivalent of CO₂ doubling
- This is equivalent to about 10% of anthropogenic sulfur emissions.
- Costs: A few billions US\$ per year, if existing military aircraft are used (KC-135 Strato max. height 15km).
- potential: more than 10 W/m²

Sulfuric acid aerosol in the stratosphere

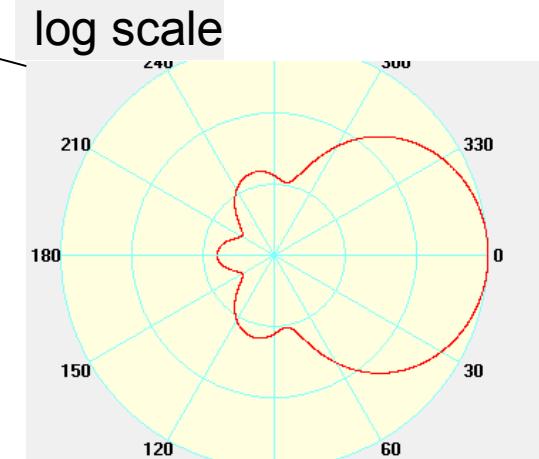
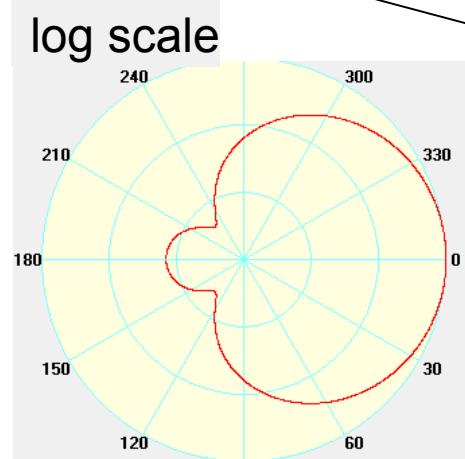
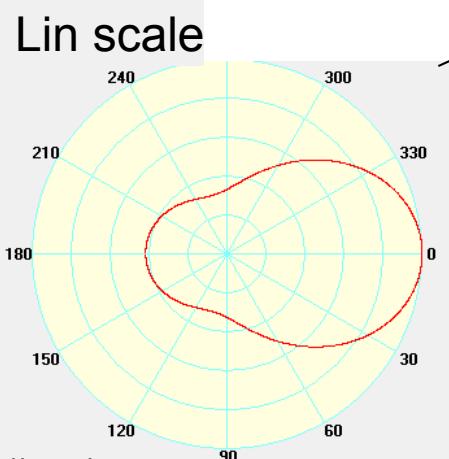
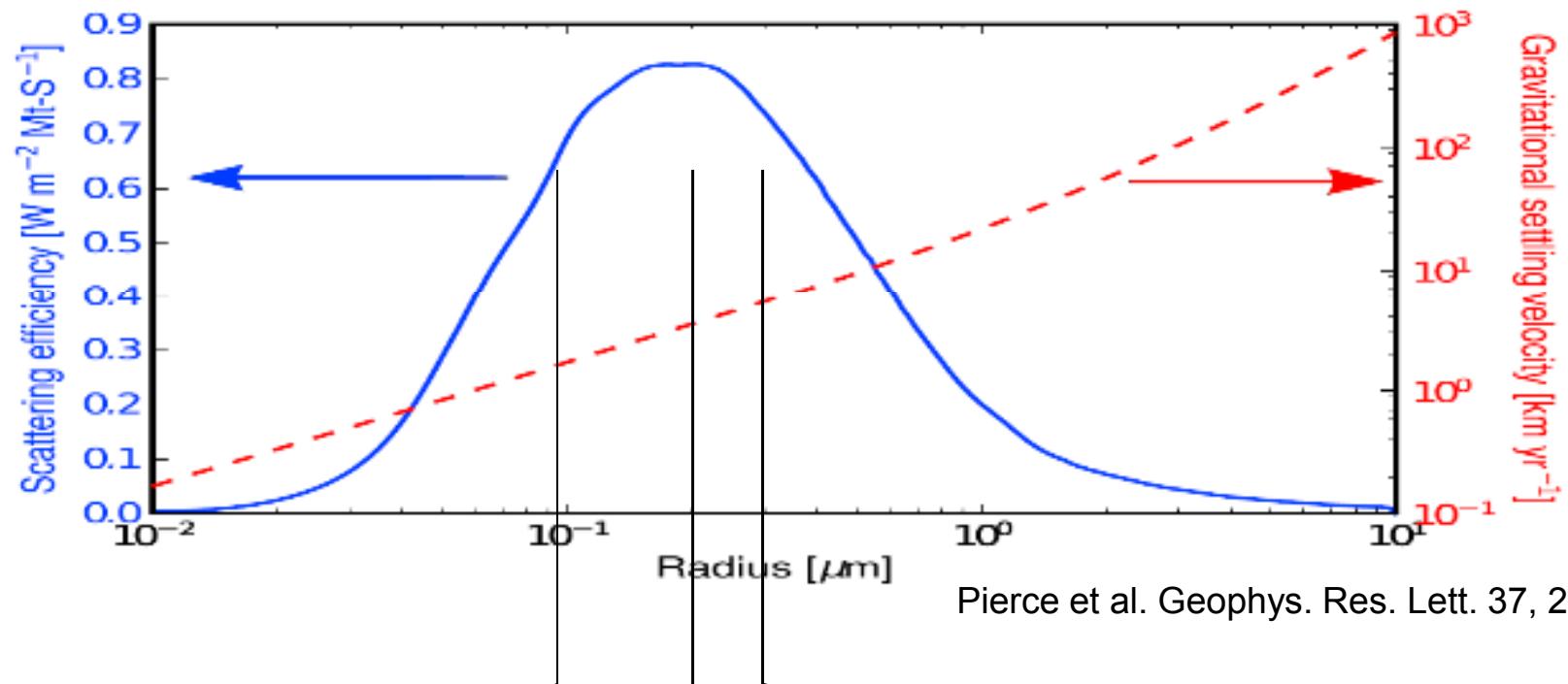


Alan Robock, Heidelberg 2010

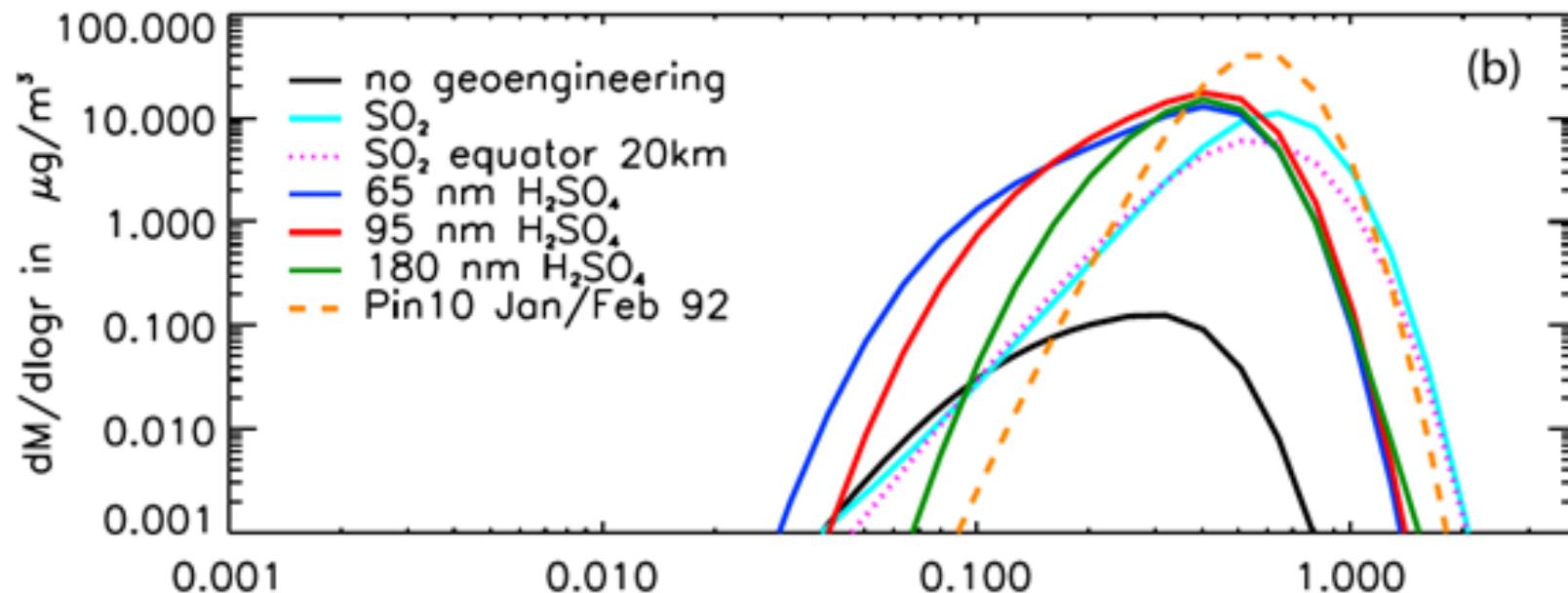
Gaseous S - Injection

- In the stratosphere,, H_2S or SO_2 is photochemically oxidized to SO_3 and with water, sulfuric acid (H_2SO_4) droplets condense
- The droplet size is determined by the precursor concentration, the rate of oxidation and the time since injection. Generally, a size distribution is formed.
- Droplets grow by condensation or collision- coalescence processes
- The growth of droplets is more rapid, if the initial size distribution is wide
- Pulse- wise injection creates more narrow size distribution than continuous injection

The key: Particle Size



Stratospheric Aerosol



Black line: Background stratospheric aerosol

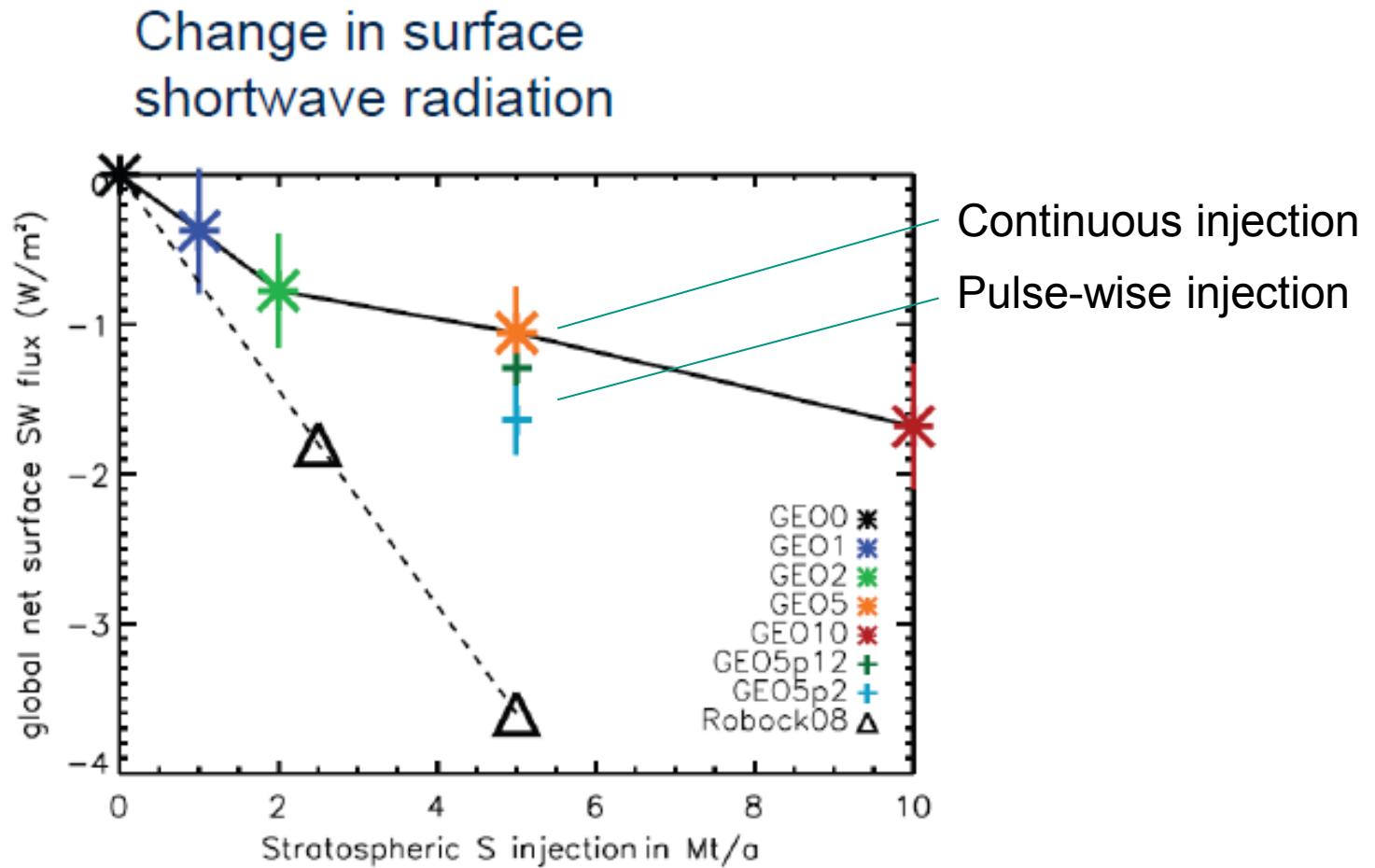
Coloured lines: Geoengineering (5 MT S/a), emissions spread between 30°S and 30°N and 20 and 25 km, various scenarios.

Dashed orange lines:

AER model simulation for January–February 1992 following the Mt. Pinatubo eruption.

Heckendorn et al., 2009

How does aerosol dynamics affect SRM efficiency?



Heckendorf et al. (2009) Environ. Res. Lett. 4,

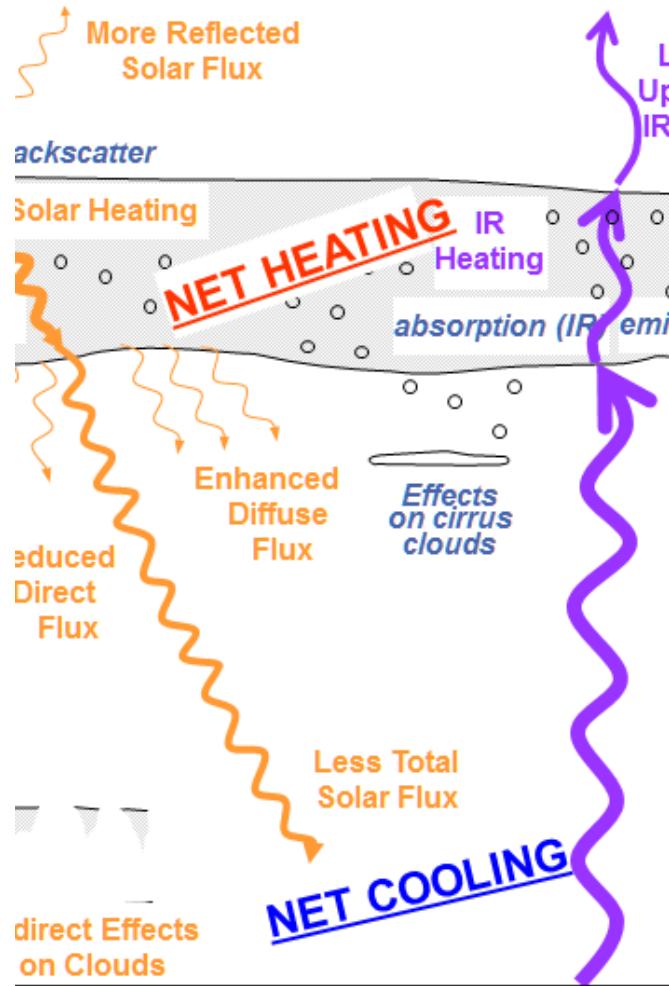
Direct emission of H₂SO₄:

J. R. Pierce et al, GRL 37^A, 18805, (2010)



- Currently no sprayers for desired droplet size range available
- Corrosion and clogging issues
- Weight considerations: H₂S: SO₂ : H₂SO₄*H₂O 1: 2: 4
- Near aircraft dynamics of spray not investigated
- Has to be emitted in target height

Dynamical feedback of stratospheric sulfur injection on cirrus clouds



Stratospheric CE reduces vertical temperature gradient →

Diminished updraft velocities →

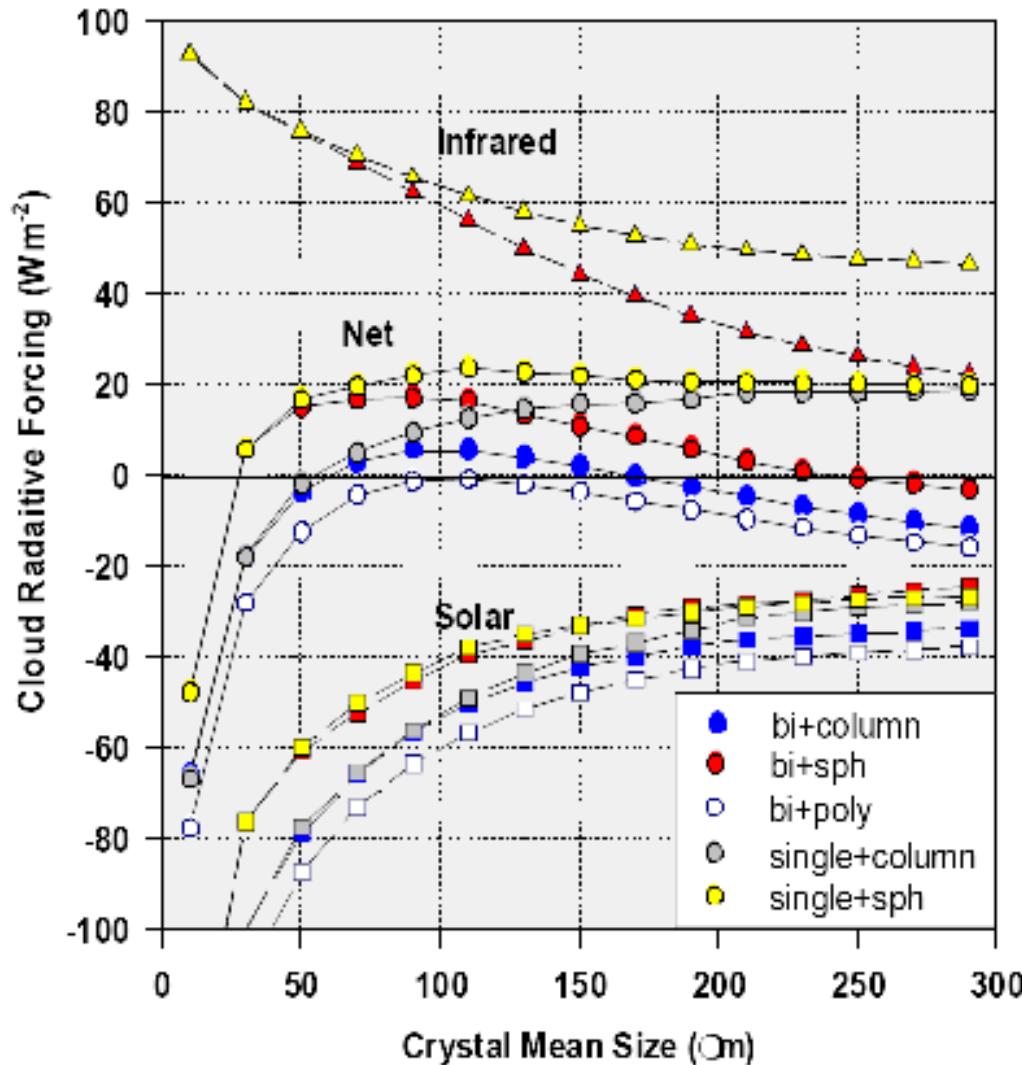
Less homogeneous ice nucleation →

Less but larger cirrus ice crystals that settle more rapidly

Effects of stratospheric sulfate aerosol geo-engineering on cirrus clouds
M. Kübbeler et al., Geophys. Res. Lett., 39, 2012

Ice growth and cirrus clouds radiative budget

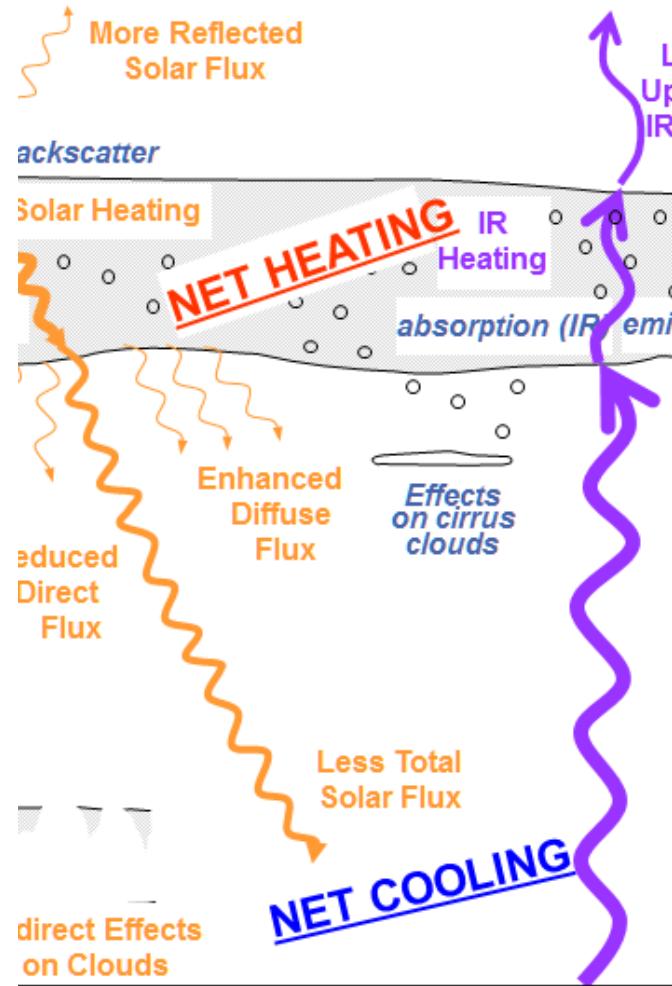
Zhang, Macke, Albers (1999)



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- size matters
→ natural: mostly warming
→ contrail-induced: cooling

Chemical feedback of stratospheric sulfur injection on cirrus clouds

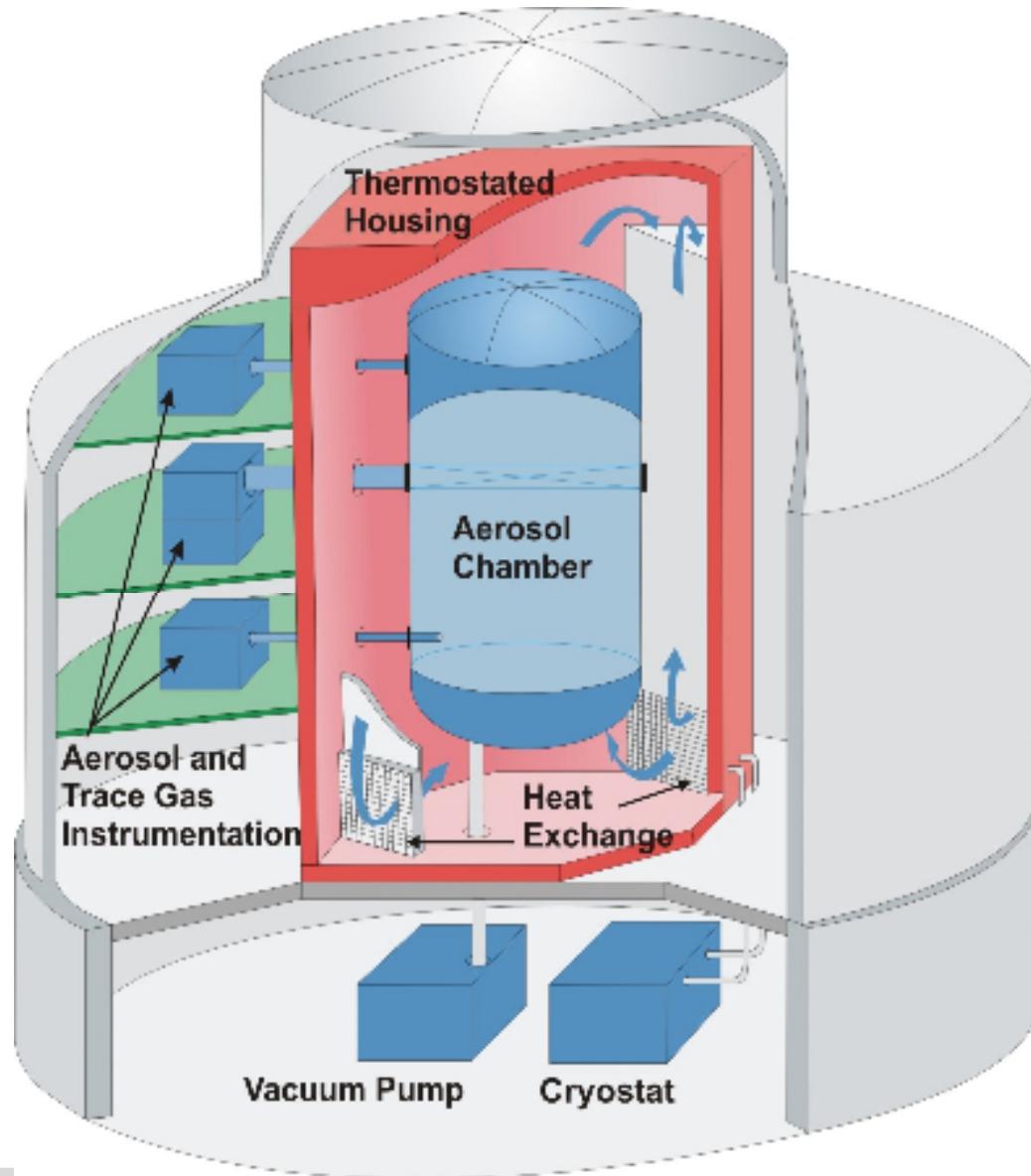


Sulfuric acid finally penetrates into the troposphere,

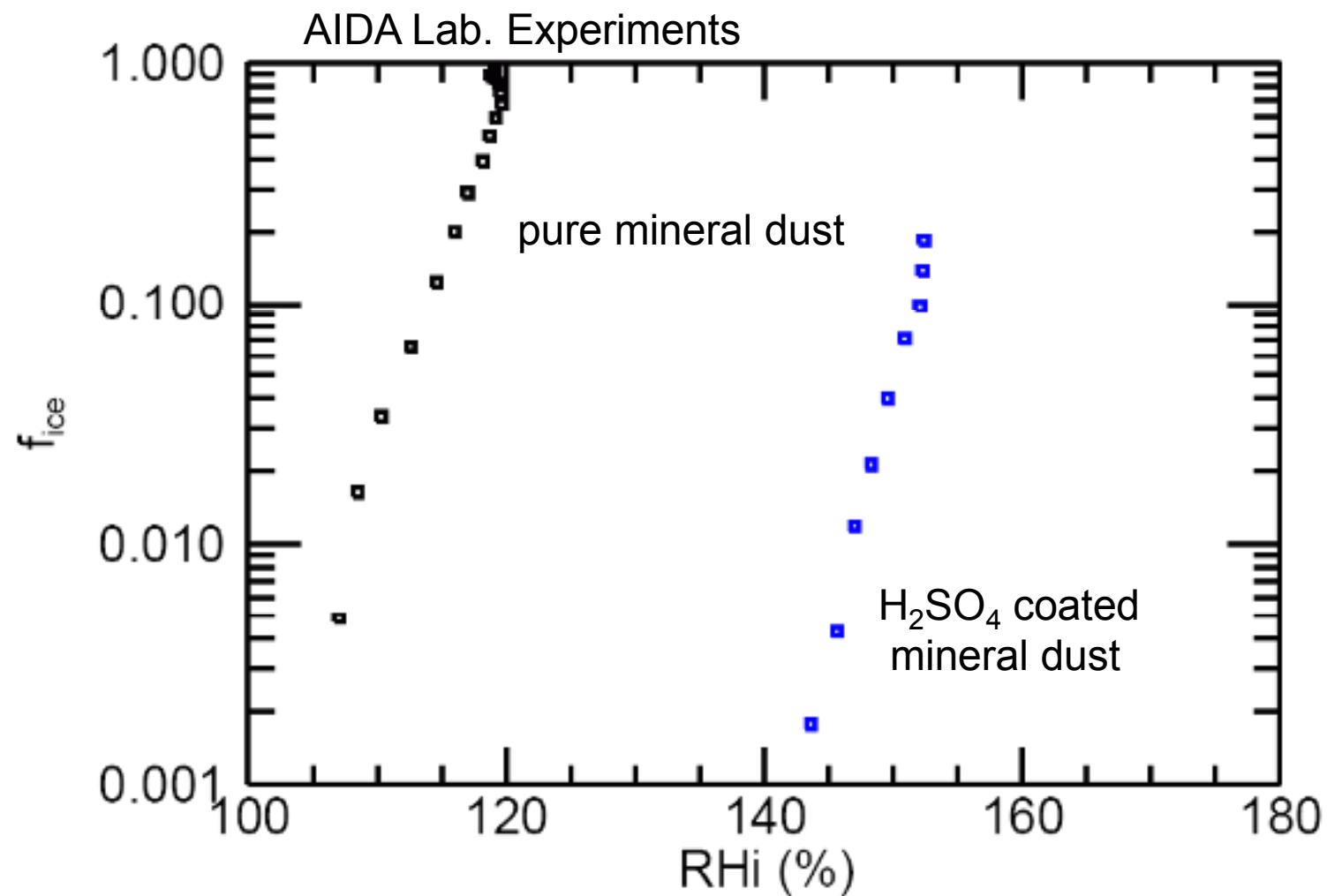
evaporates and condenses
on tropospheric aerosol particles

Modifies their ice nucleation ability

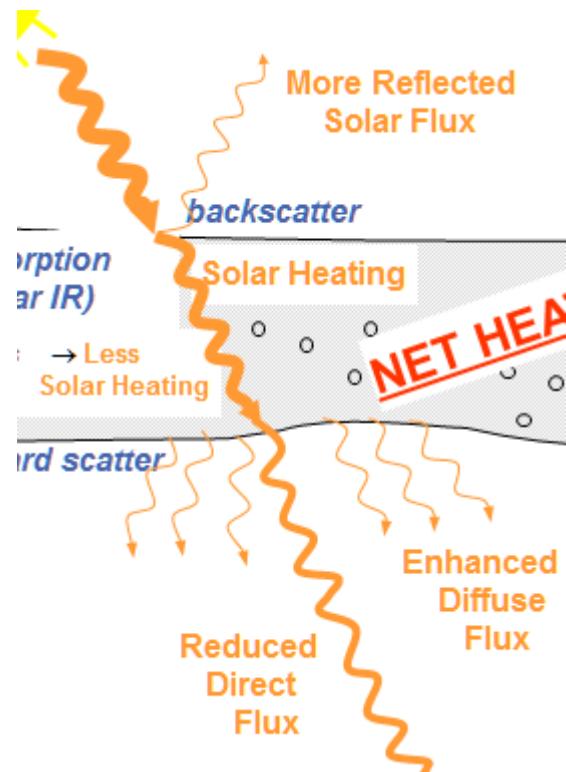
The AIDA aerosol and cloud chamber at KIT



Chemical feedback of stratospheric sulfur injection on cirrus clouds



Stratospheric sulfur feedback on biodiversity



Particle larger $\sim 0.3 \mu\text{m}$ dia. scatter light predominantly in forward direction

Reduced solar flux

Strongly reduced direct flux

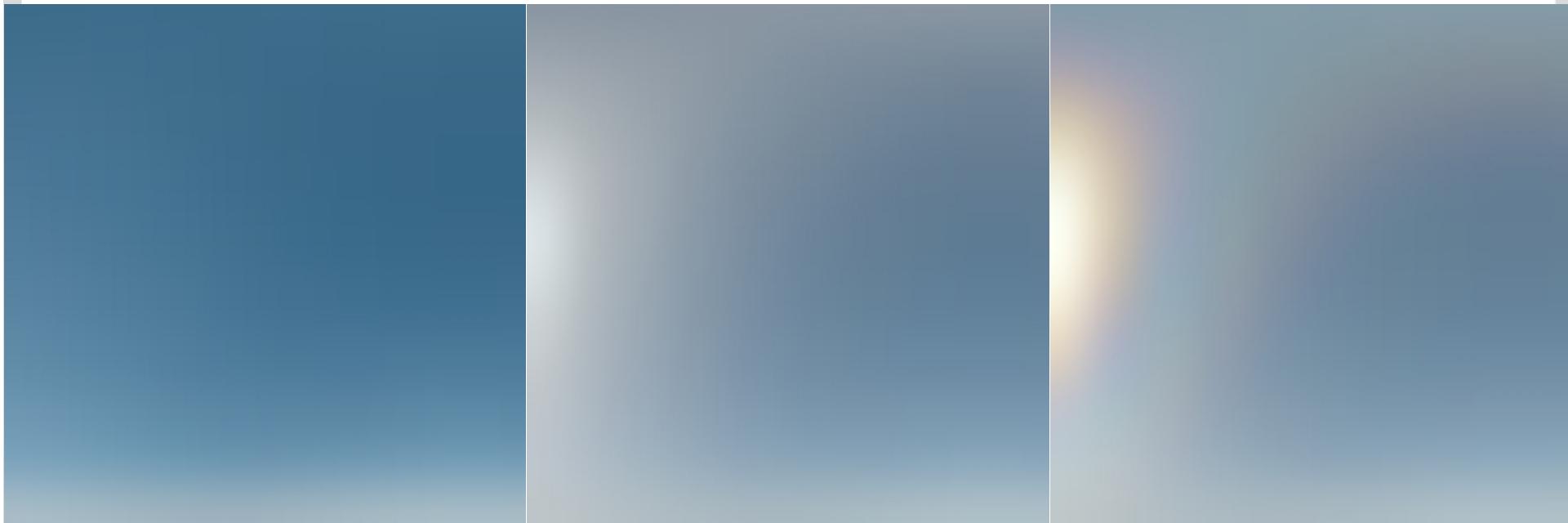
Enhanced diffuse flux

Evolutionary pressure on vegetation,
plants relying on direct radiation suffer,
plants adapted to diffuse radiation profit.

Geoengineering Skies



Eva Ahbe, Ulrich Platt, Thomas Leisner und Tim Deutschmann

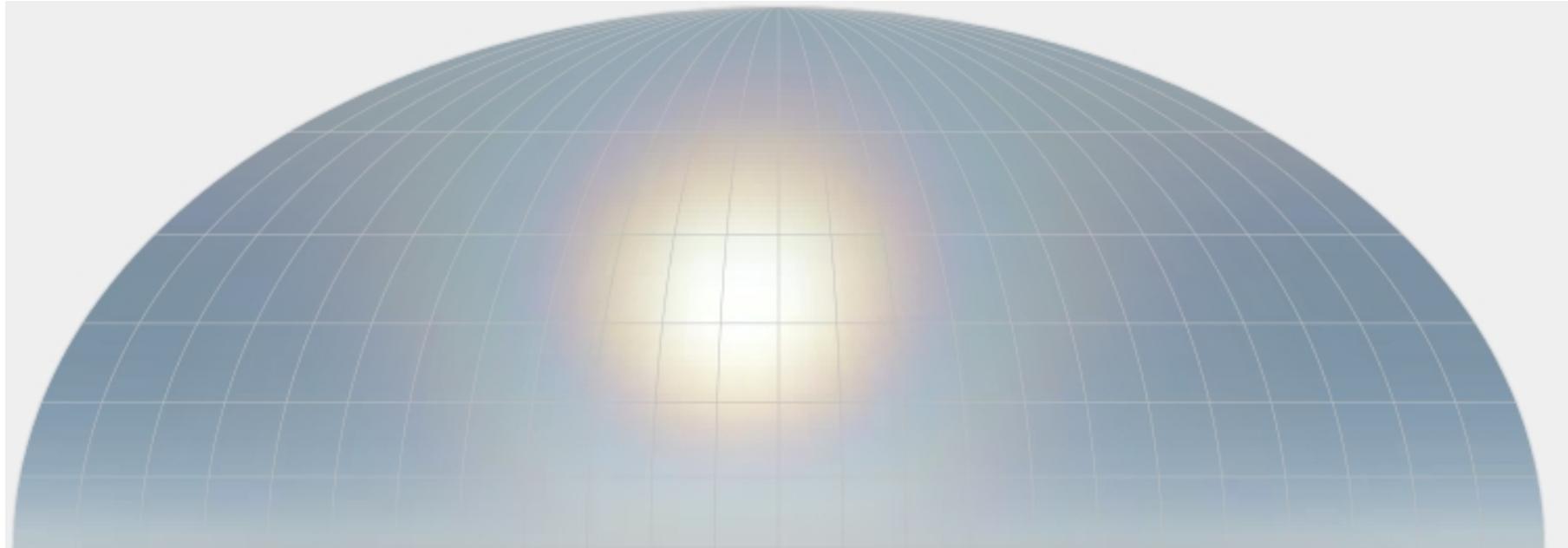


None 0

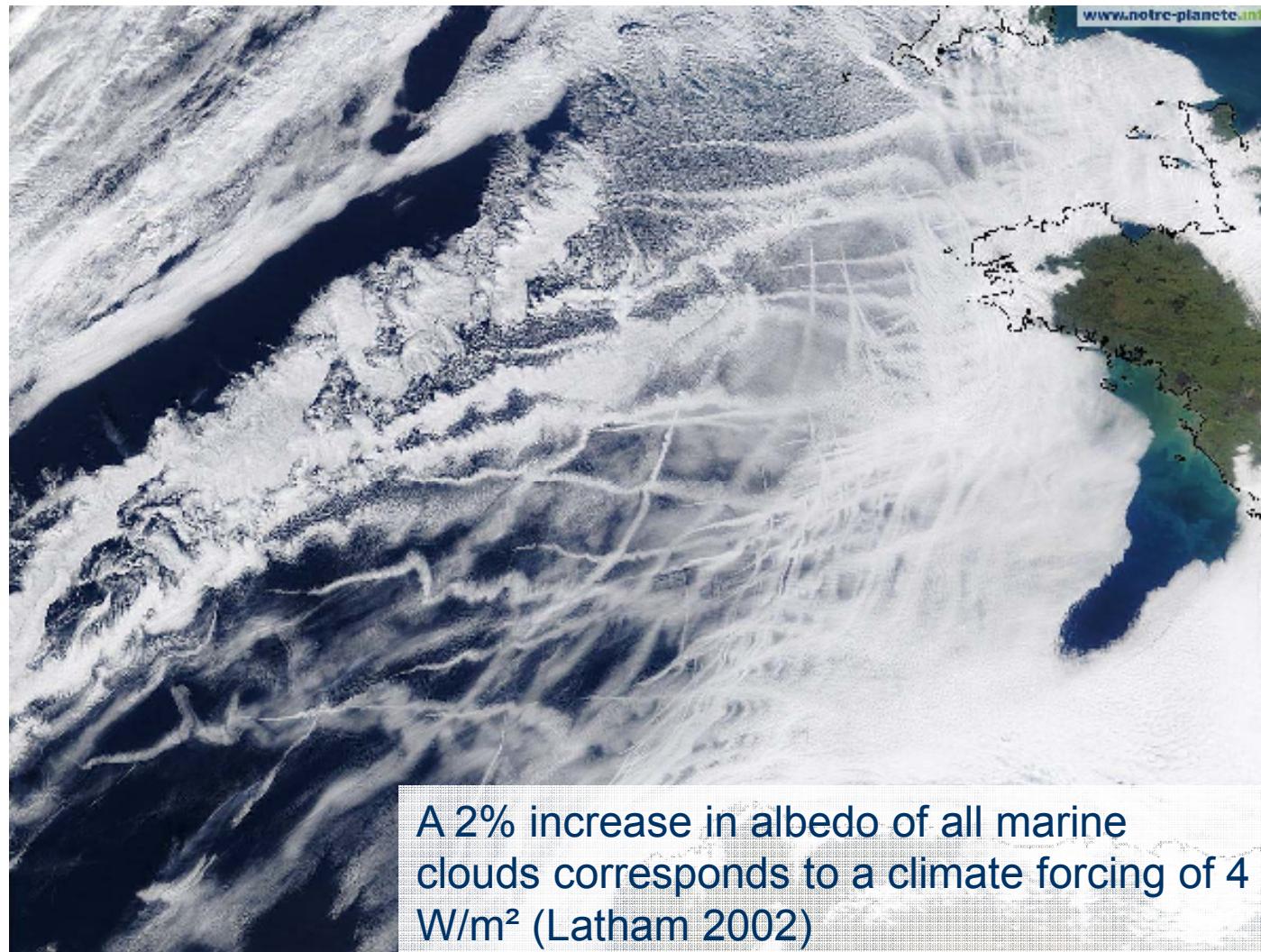
Wide size distr.
Pinatubo sulfate
2x CO₂

Narrow size distr.
Kravitz 8.5
2x CO₂

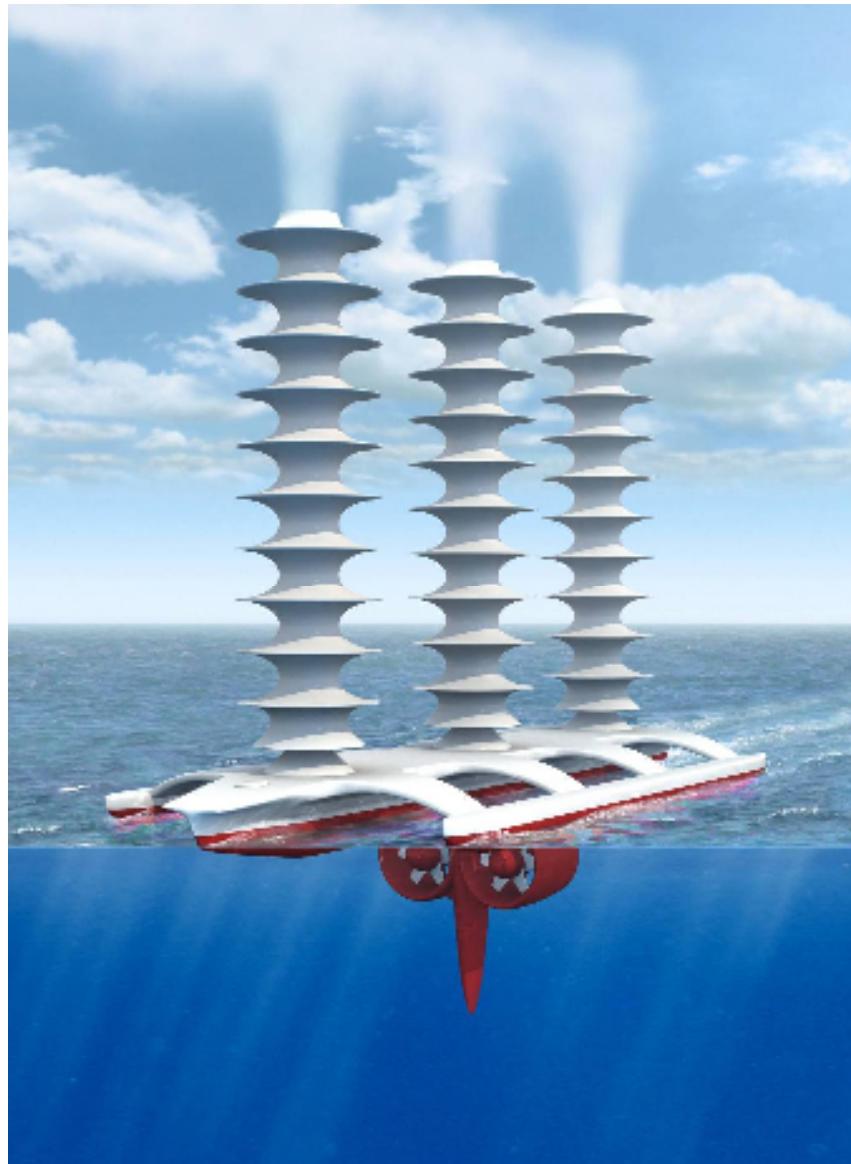
The „Climate Engineering“ Halo



Marine cloud brightening (MCB) analogous to shiptracks



MCB according to J. Latham und S. Salter



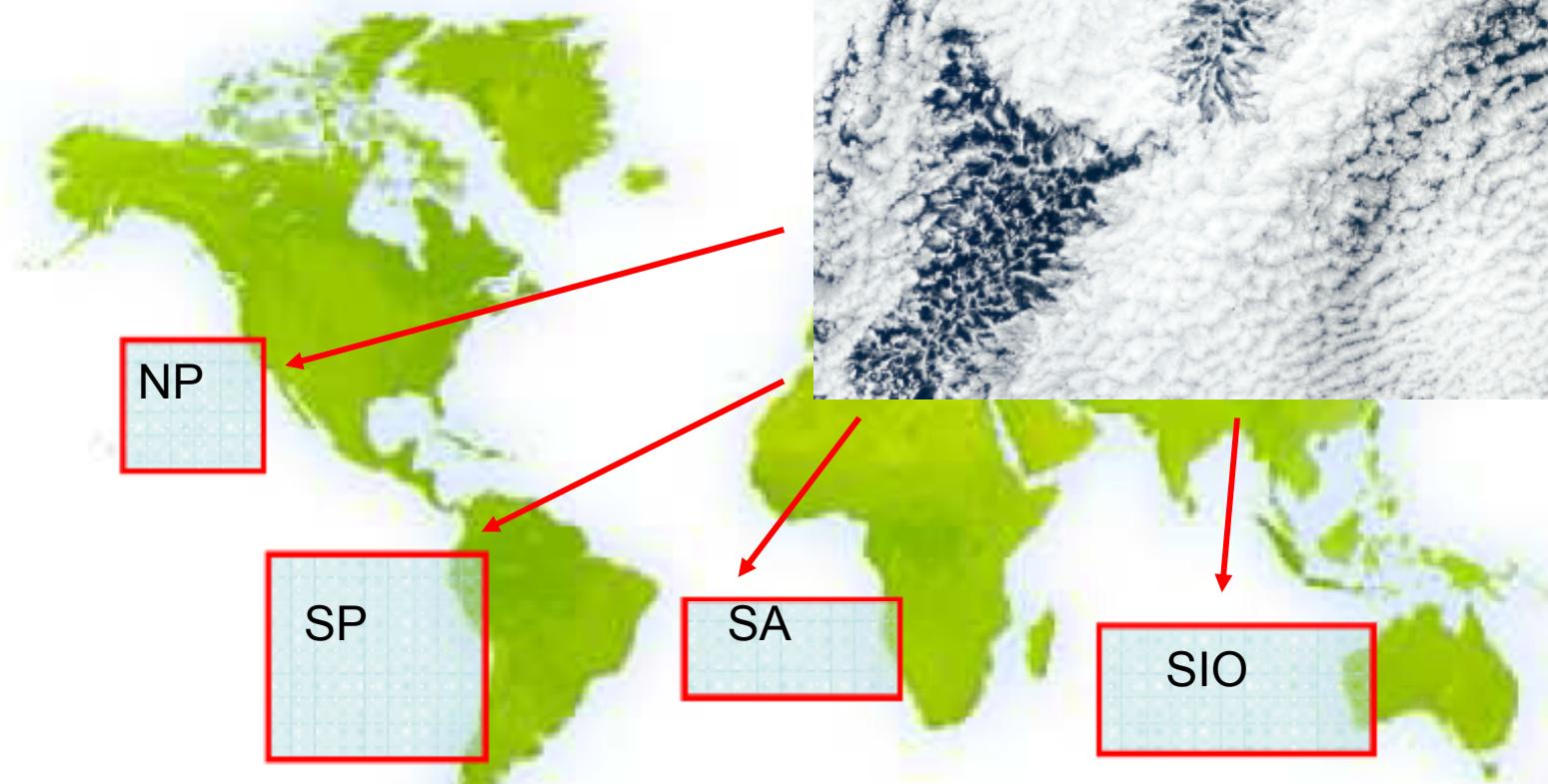
J. Latham:

Spray $d=300\text{nm}$ ($m=10^{-16}\text{kg}$) NaCl particles from evaporating sea water. Results in up to 20% increase in cloud albedo.

Works best in clean marine air

S. Salter: Unmanned, wind powered vessels spray 50 kg seawater/s. Are directed to most susceptible regions. A fleet of about 10000 such vessels would be needed.

Regions most susceptible to cloud brightening



Persistente tiefliegende Stratocumulus-Wolken,
Sehr geringe natürliche CCN- Konzentration

Aerosol size (CCN activity) matters

natural marine



Ideal seeding



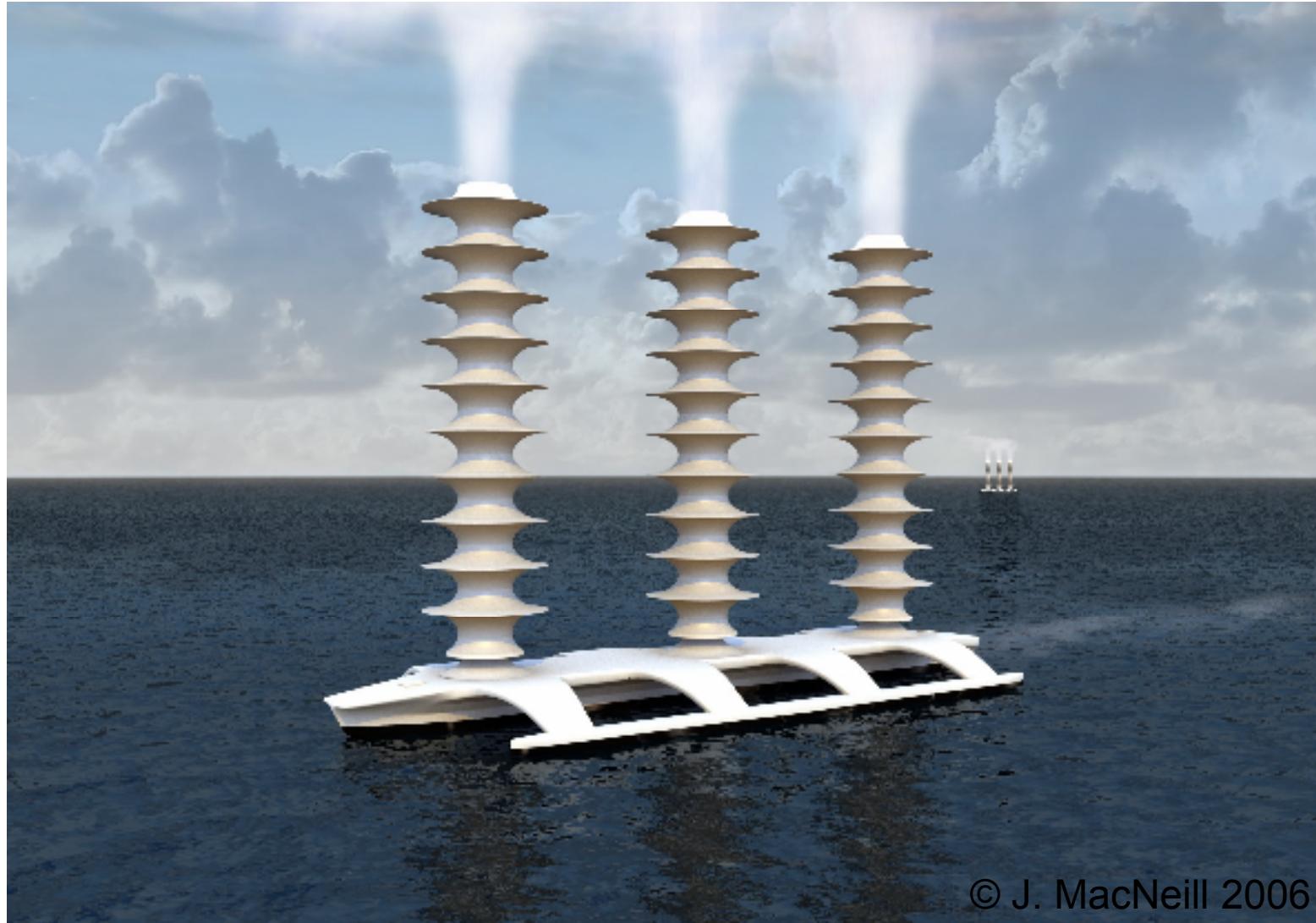
large CCN



small CCN

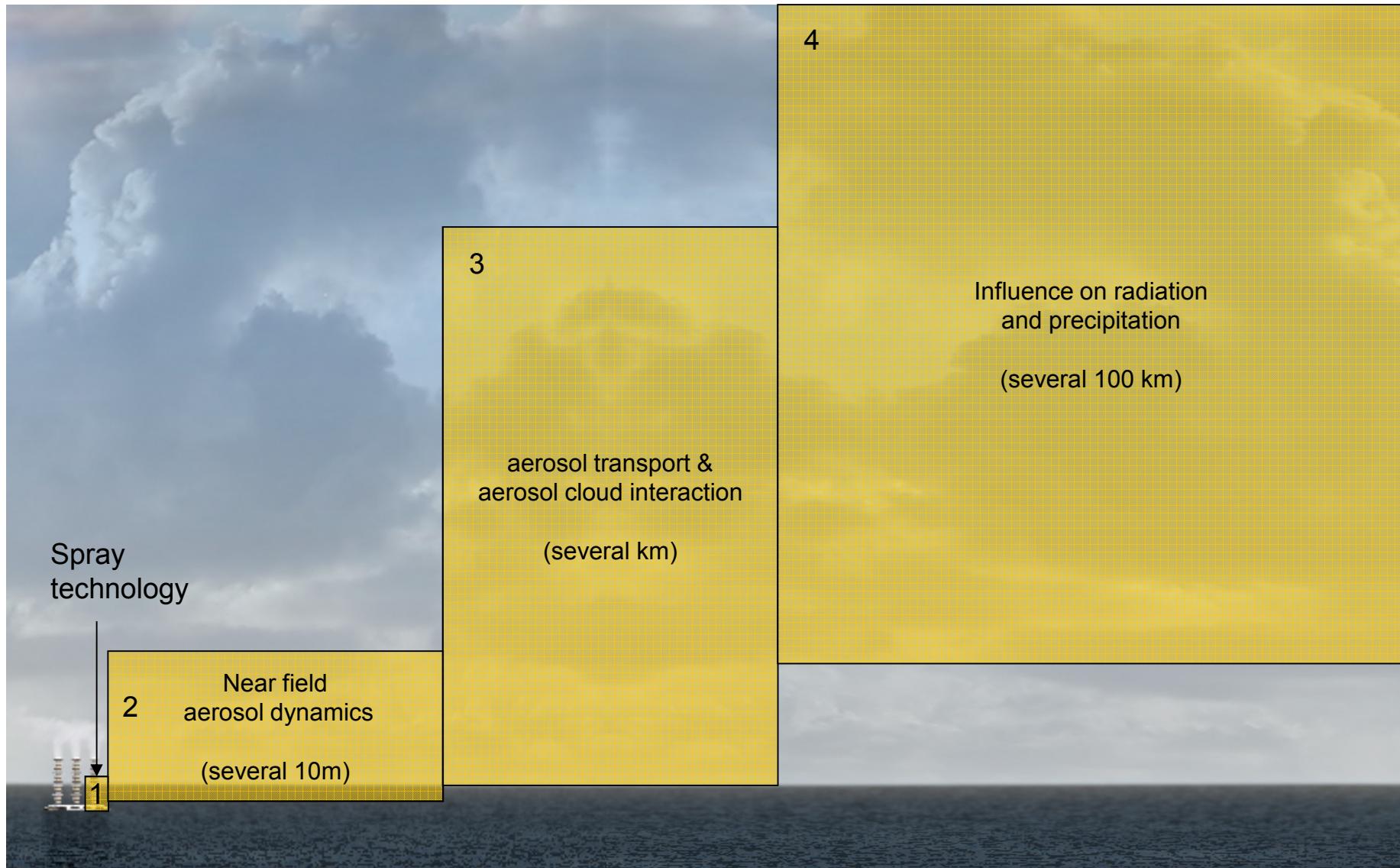


How realistic is the proposed technology

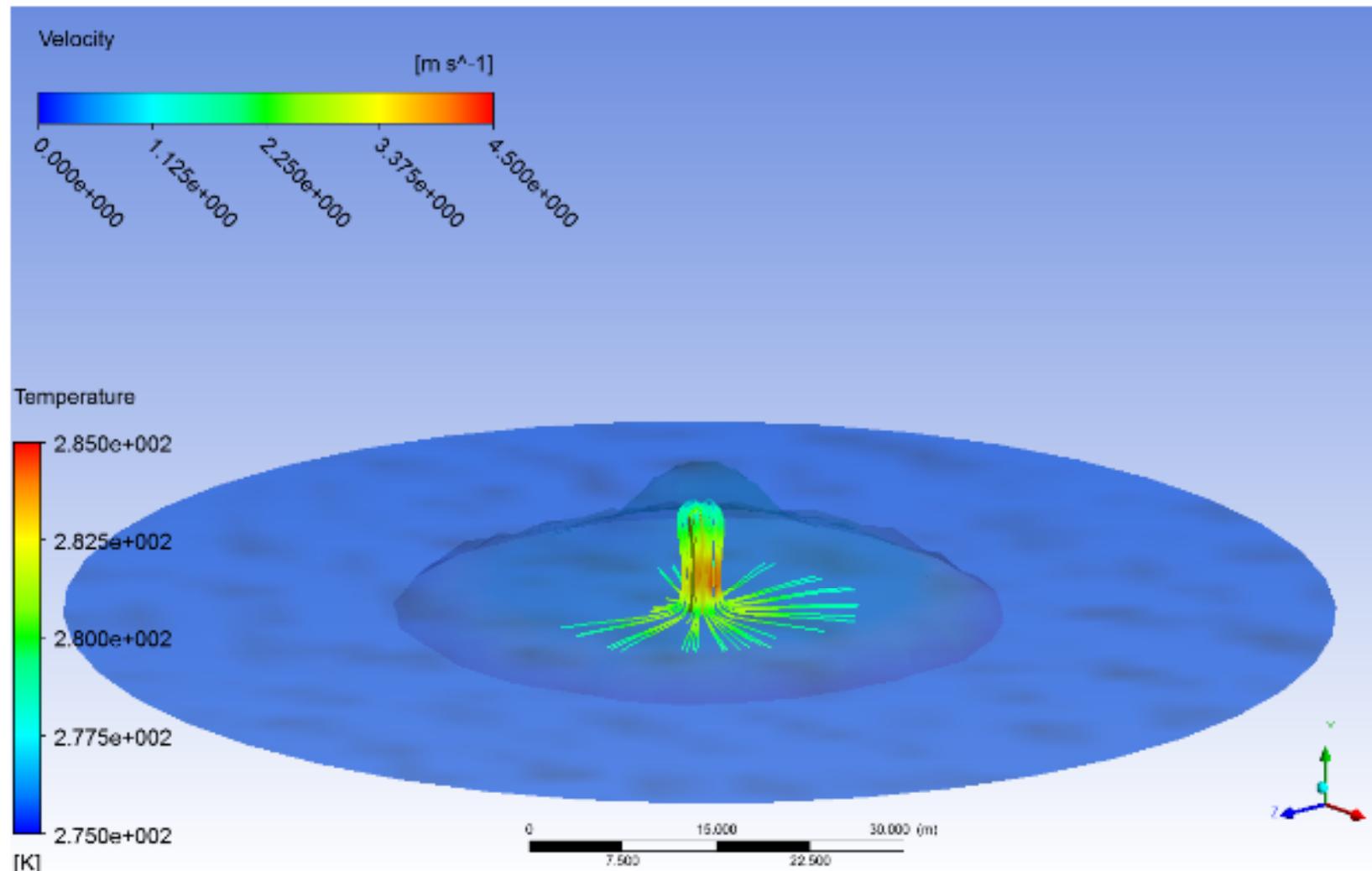


© J. MacNeill 2006

Scales involved in cloud seeding

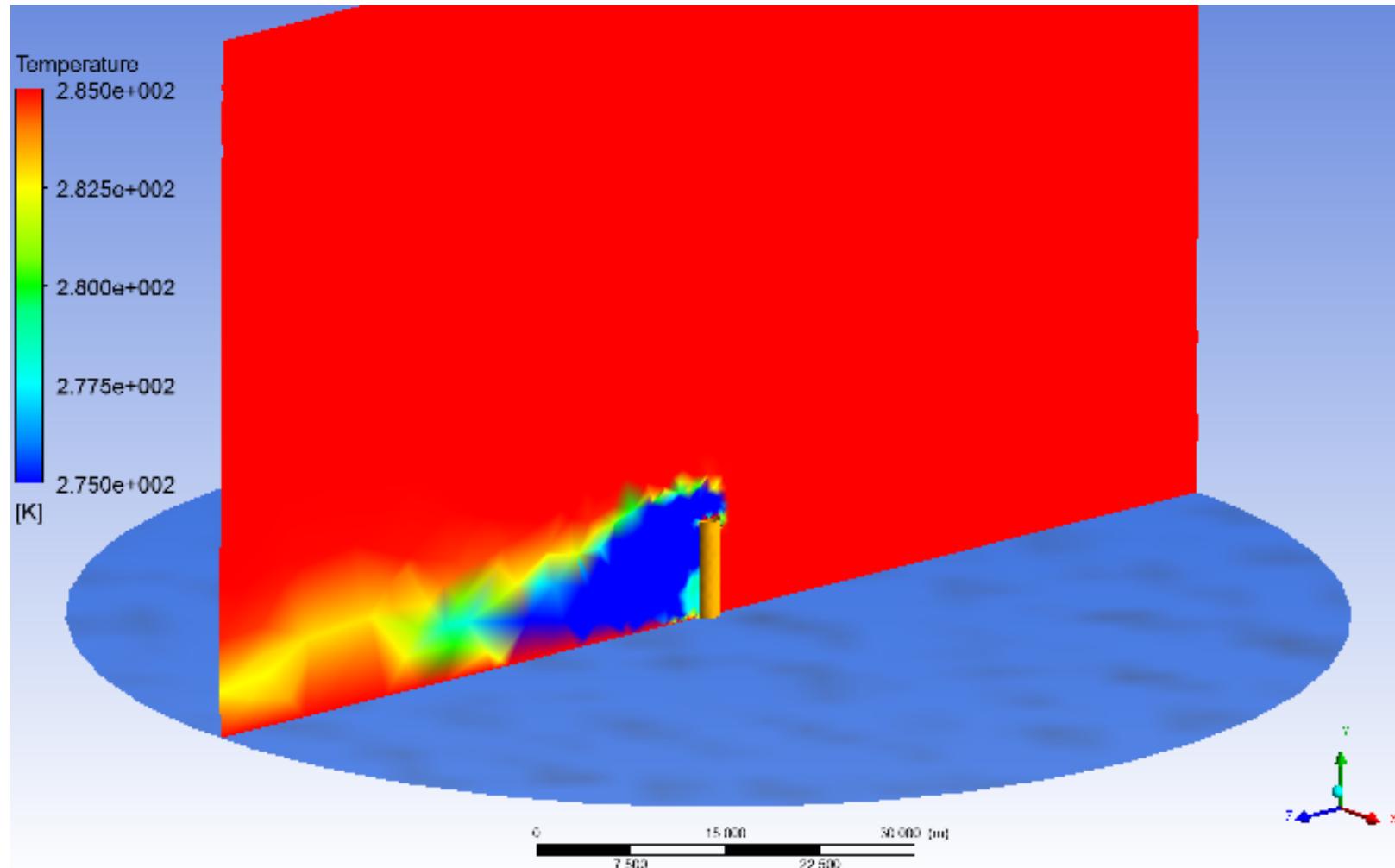


Example: No wind conditions



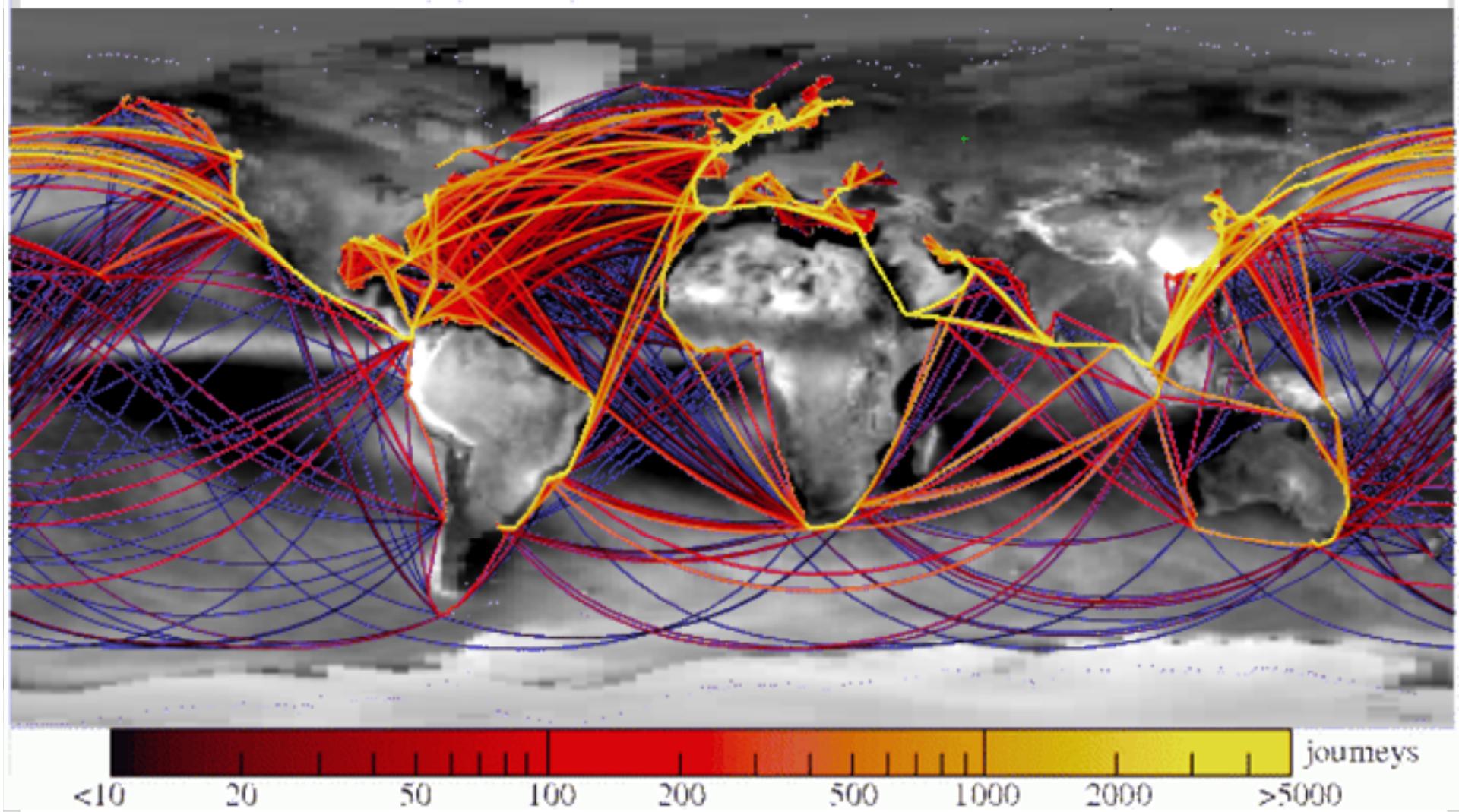
Particles are completely uptaken by sea due to gravitational, inertial and phoretic forces

The devil hides in the details



Cold pool (- 10°C) generated, most (>70%) of the particles uptaken by sea

Does it work? Is international shipping changing the cloud albedo?



Problems with „Cloud Whitening“ Schemes



- It is extremely difficult to produce very small particles (r in the range of several 100nm) ?
- The natural occurring aerosol has to be matched in CCN activity
- 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 likely
- Standard spraying techniques have energetic efficiencies in the 10^{-3} range
-

Why “radiation management” is unlikely to save our climate:



- Most suggestions are not feasible with todays technology and are bound to be much more expensive than estimated by the proponents.
- Large meteorological side effects cannot be excluded and reliability for extremes can not be denied.
- There is no legitimated political or legislative institution being able to make global decisions.
- Nobody can guarantee a working radiation management program for centuries. If the program breaks down, the delayed climate change is materialized within a few years..

UNIVERSITÄT HEIDELBERG



MARSILIUS
KOLLEG

The global governance
of climate engineering

Why there is need for research

- After foreseeable climate related extreme events, public pressure for immediate action may grow, and easy fixes will be offered by interested parties. It is wise to be prepared with a sound assessment of the risks and prospects of climate engineering
- Many of the proposed schemes are mere science fiction, that do not pass an in depth examination but provoke a false sense of security
- It might turn out, after all, that some form of climate engineering is a useful ingredient for climate stabilization, in concert with mitigation and adaptation.

Cirrus Climate Engineering

Very thin (subvisible) ice (cirrus) clouds cover wide parts of the upper troposphere.

Opposite to thick lower clouds, they are rather warming than cooling the climate due to their low light scattering and their cold temperature.,.

Taylor- Made ice nuclei might reduce cirrus ice cover.

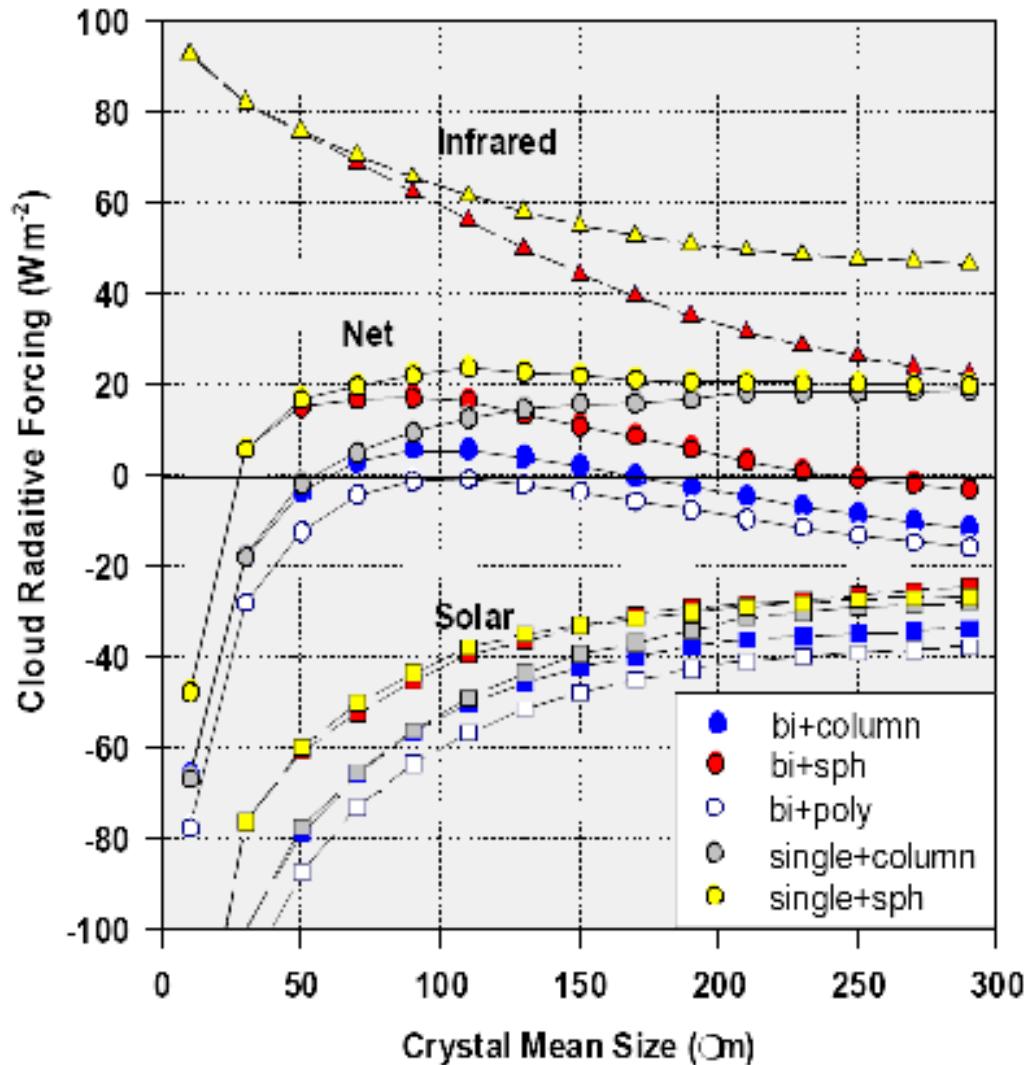
Mitchell and Finnegan suggest to use Bismuth – tri – Iodide additives to aircraft fuel to enhance the concentration of suitable ice nuclei.



D. Mitchell and W. Finnegan, Environ. Res. Lett. 4, 2009

Ice growth and cirrus clouds radiative budget

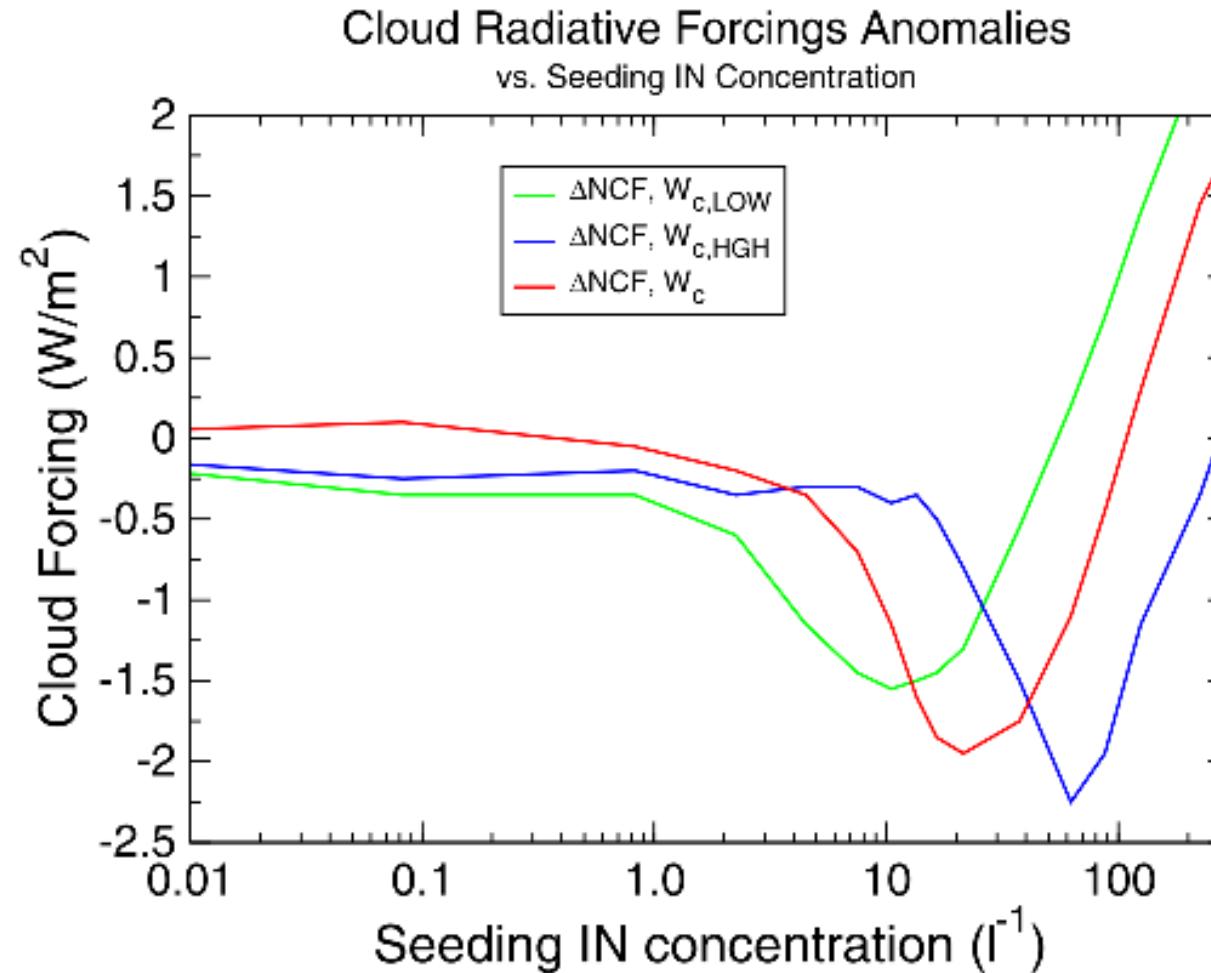
Zhang, Macke, Albers (1999)



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- size matters
→ natural: mostly warming
→ contrail-induced: cooling

CE efficiency as a function of IN concentration and vertical velocity



Storelvmo et al., Geophys. Res. Lett. 2013 Potential max 2W/m²

Acknowledgement

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Monika Niemand
Ottmar Möhler,
IMK-AAF, KIT

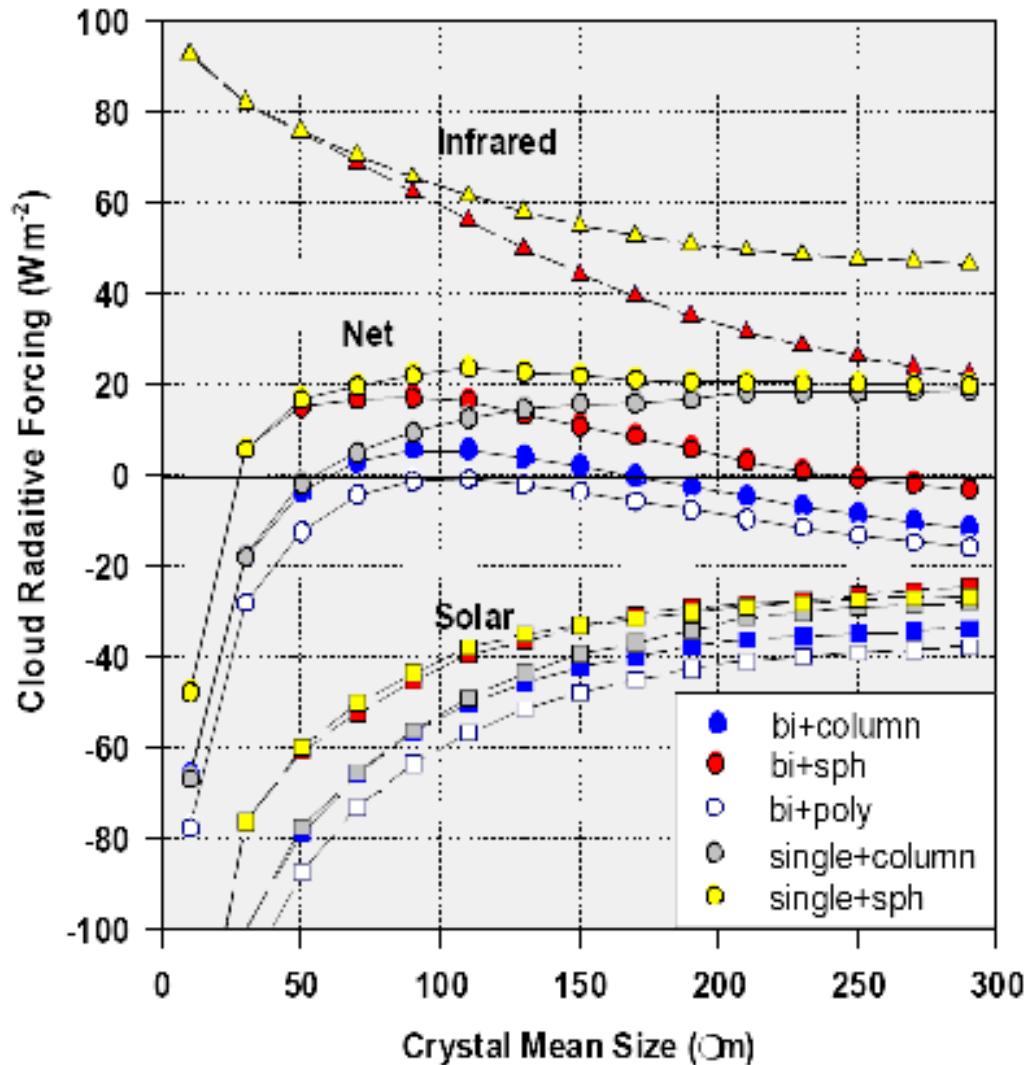
Michael Höpfner IMK-ASF, KIT
Bernhard Vogel IMK-TRO, KIT

Gregor Betz,
Institut für Philosophie, KIT

Ulrich Platt, Eva Ahbe, Tim Deutschmann, Uni Heidelberg

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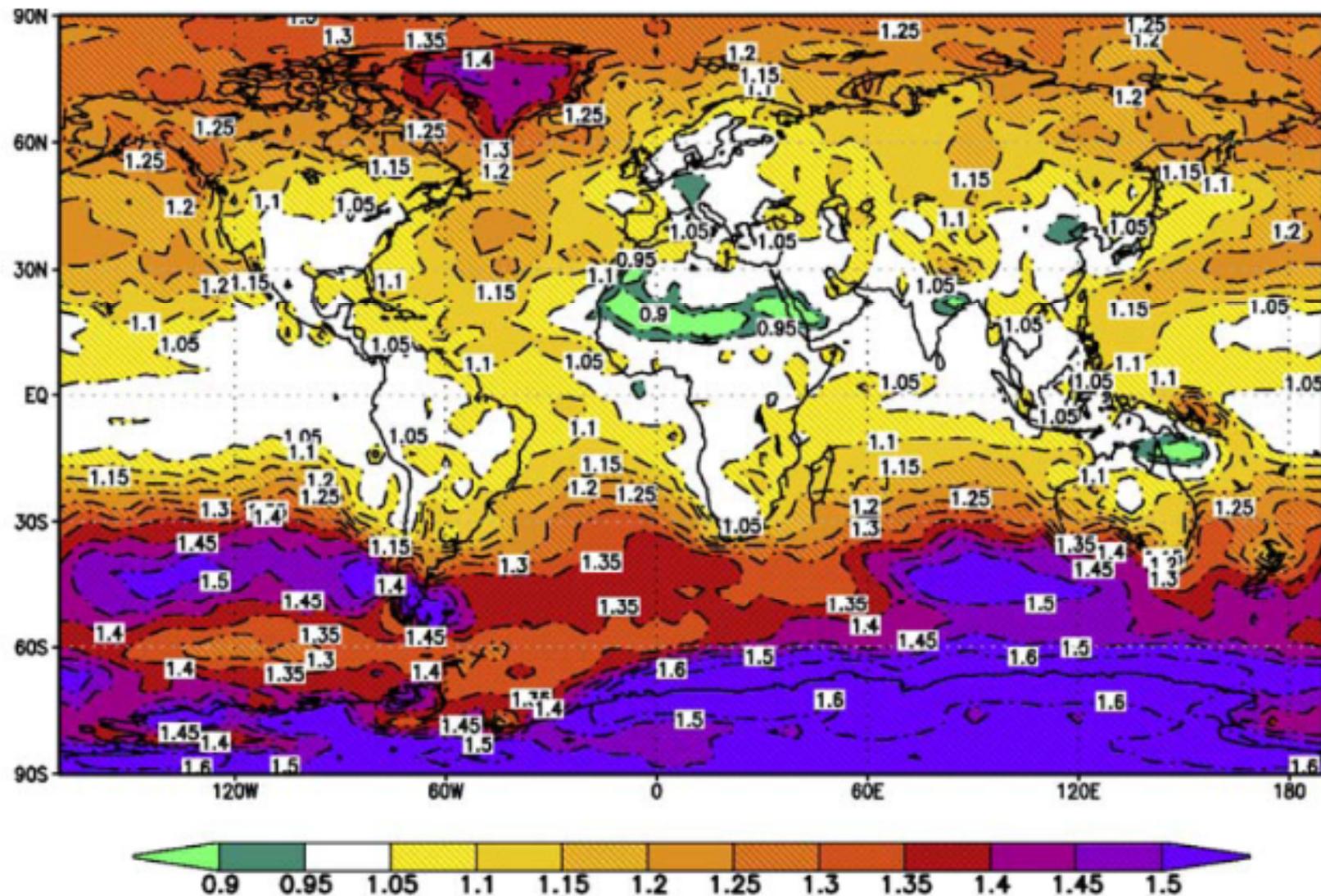
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Where does the sulfur come down?



Is Europe taking Climate Protection serious?



Süddeutsche Zeitung



**25. Februar 2013: Climate Change:
Germanys CO₂ output increasing**

**16. April 2013 Harsh setback for
European climate policy:**

The European parliament set out to save emission trading – but the majority of delegates declines to reduce contingents.

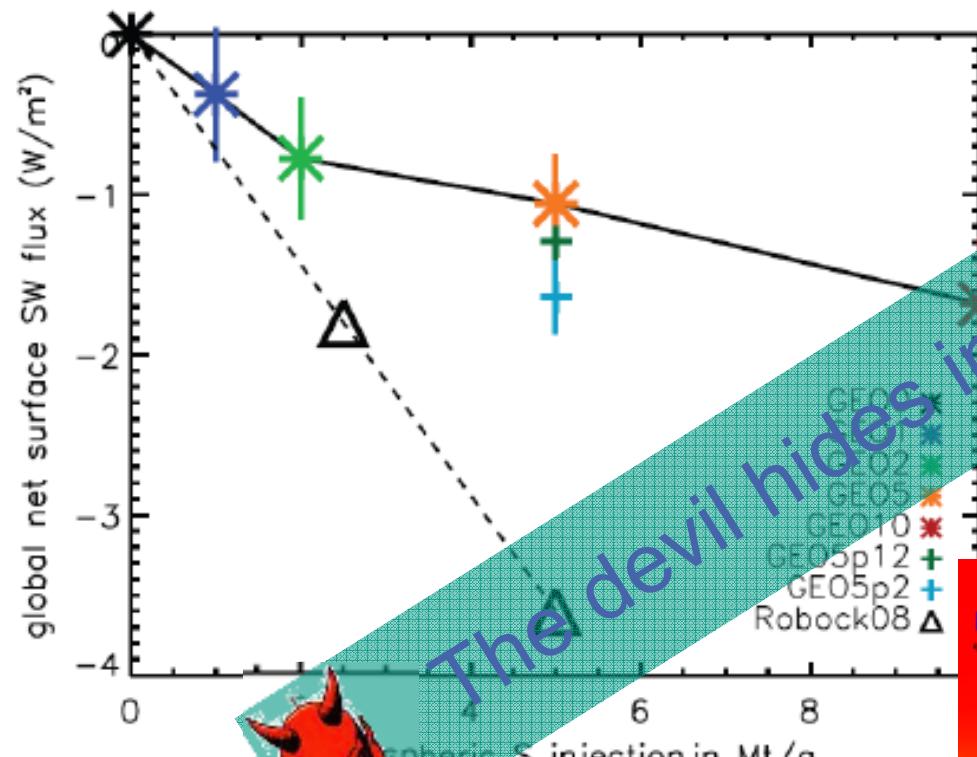
Companies now can continue to pollute the environment at no charge.

**18. April 2013 As if there never was the
Energiewende:**

Germany continues to burn more lignite and coal.

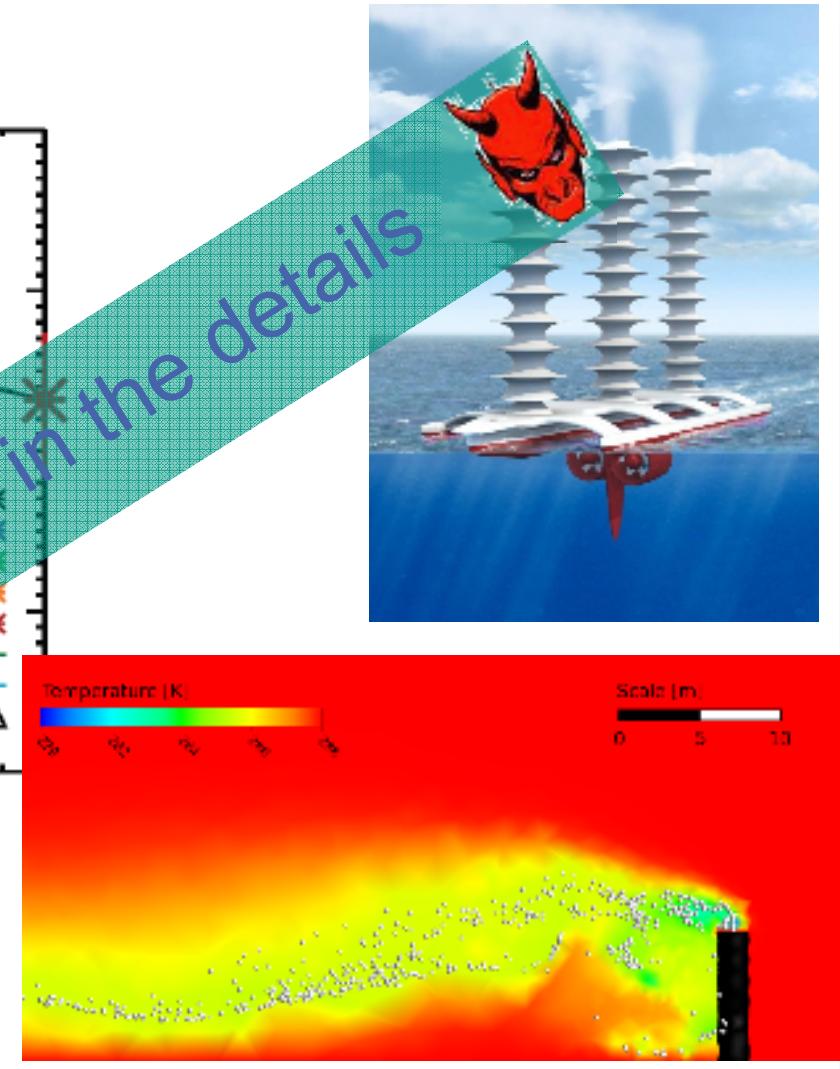
We have to look into the details

Change in surface shortwave radiation



Heckendorf et al. (2009) Environ. Res. Lett. 4,

The devil hides in the details

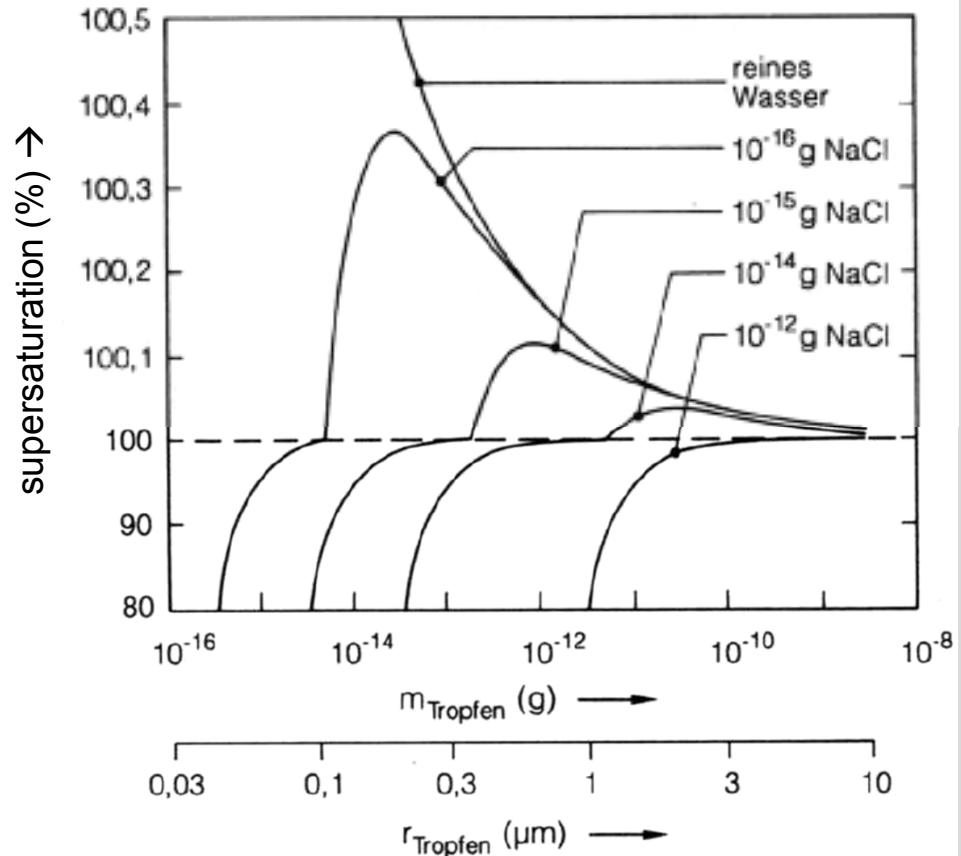


Light scattering from large and small glass spheres



How do Clouds Form?

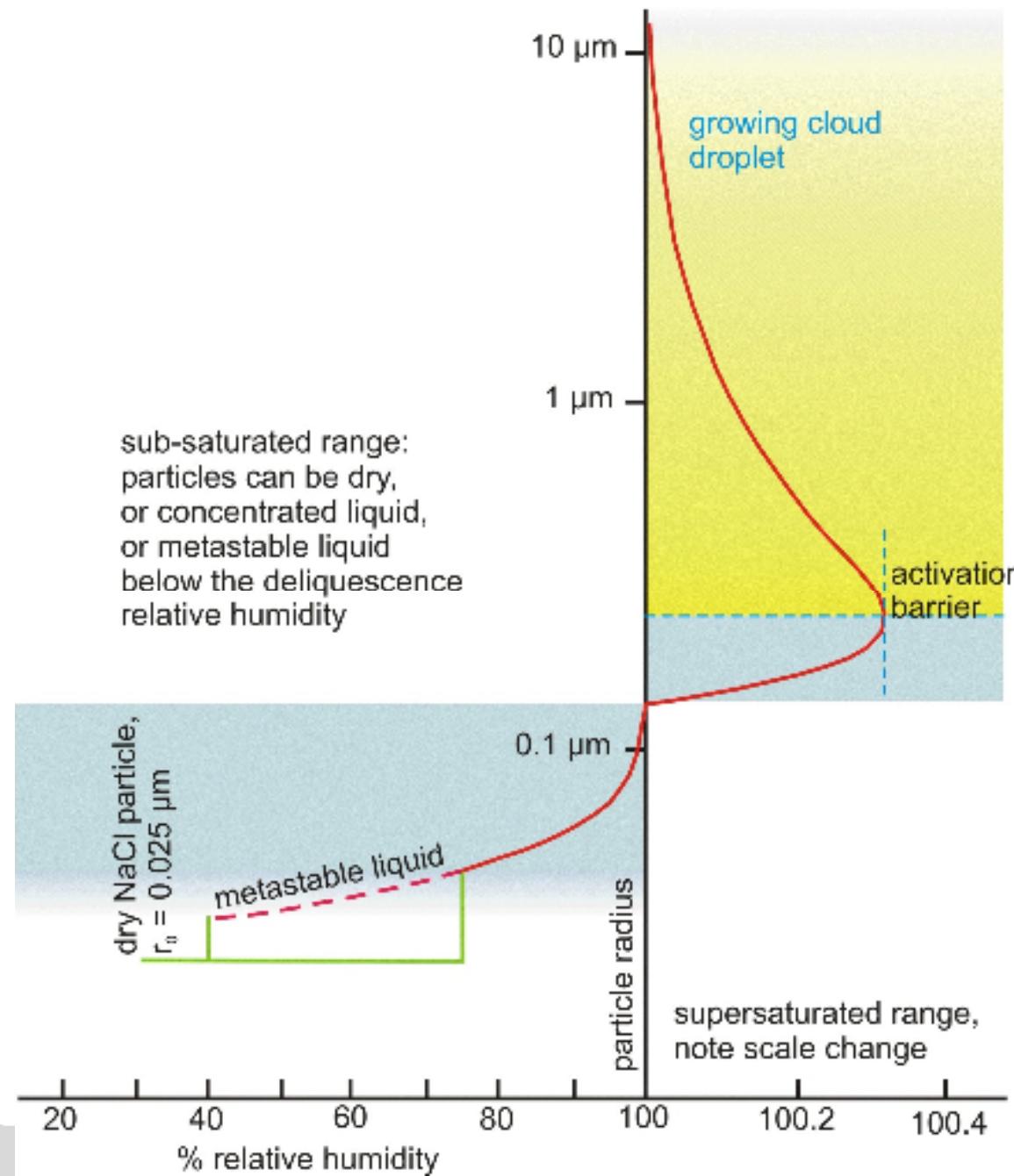
- “A cloud forms when $p_{H_2O} = p_{sat,H_2O}$ ”,
i.e. when air is saturated with respect
to water vapour
- Reached by:
 - cooling
 - lifting: forced lifting,
convection
 - radiation cooling
(→ radiation fog)
 - mixing of air masses with
different T, p_{H_2O}
 - addition of water vapor, e.g. cold
air 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 $\approx 0.2 \mu\text{m}$) are called
Cloud Condensation Nuclei (CCN)



Activated cloud droplets grow indefinitely as long as $\text{RH} > 100.00\%$

haze formation:
aerosol particles grow by absorption of water vapour, but do not activate below threshold relative humidity, here $\text{RH}_{\text{crit}} \sim 100.3\%$

Making sub micron NaCl particles

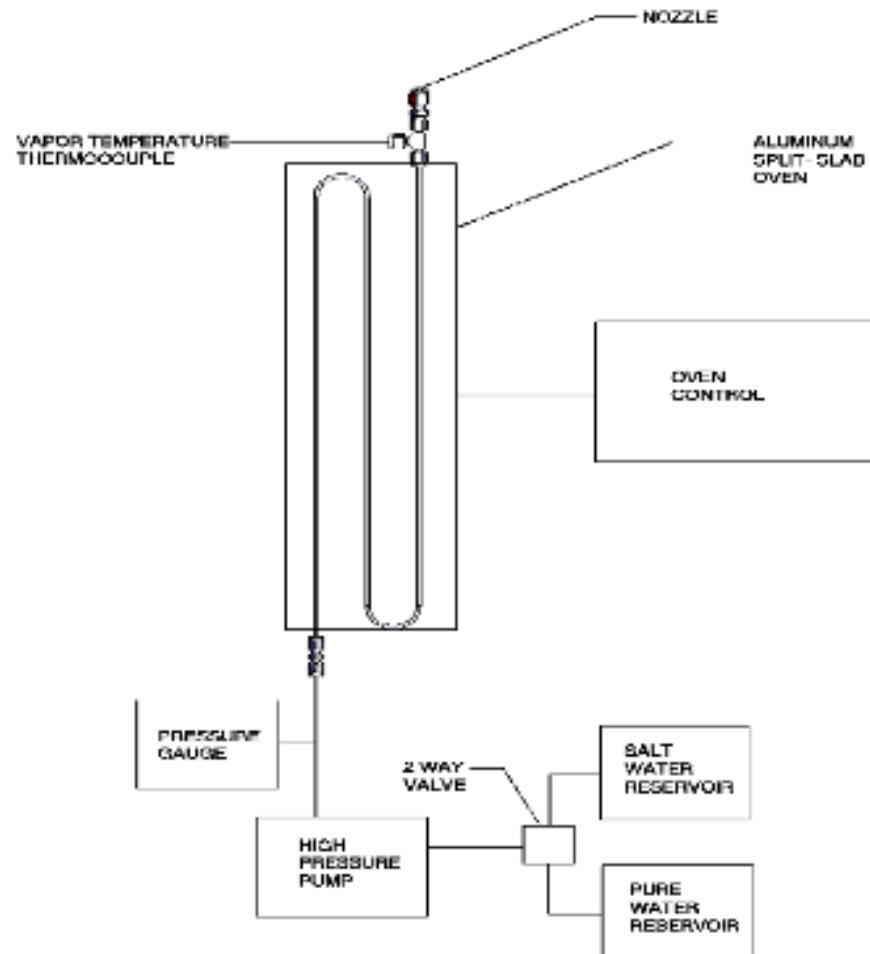


Fig. 3 Experimental apparatus

From: Cooper et al.
53 2011

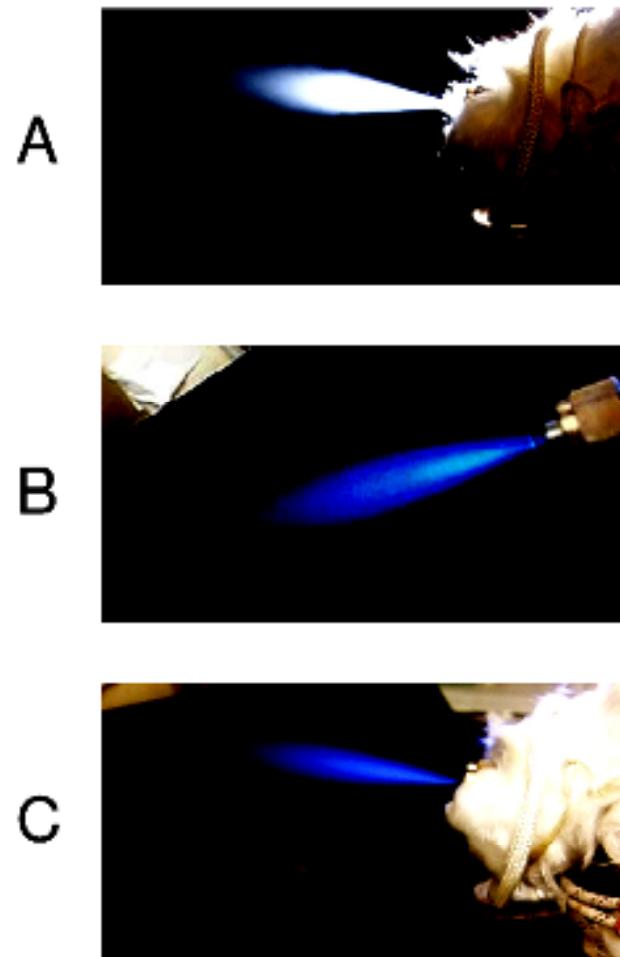


Fig. 4 Supercritical saltwater spray plumes illuminated with white light. A: micron-sized droplets; B, C: submicron-sized salt crystals. Blue color due to Rayleigh scattering of blue light by nanometer-sized salt particles.

Energetic considerations

Per vessel (spraying diam. 1 μm droplets, 10^7 cm^{-3}):
(currently, no such spraying technology exists)

Energy required for spray generation: ~ 1 MW
(extrapolating from current technology)

Kinetic energy for spray flow 0.1 MW

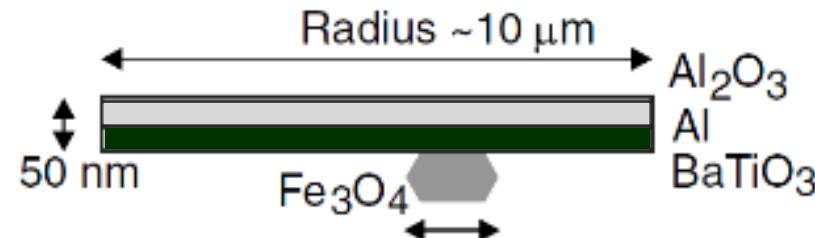
Heat required for droplet evaporation 3 MW
(rises by a factor of 100, if dia. 5 μm droplets are used)

Heat required for supercritical spraying ~ 30 MW

Artificial Aerosols for Climate Engineering?

David Keith, PNAS, Aug. 2010

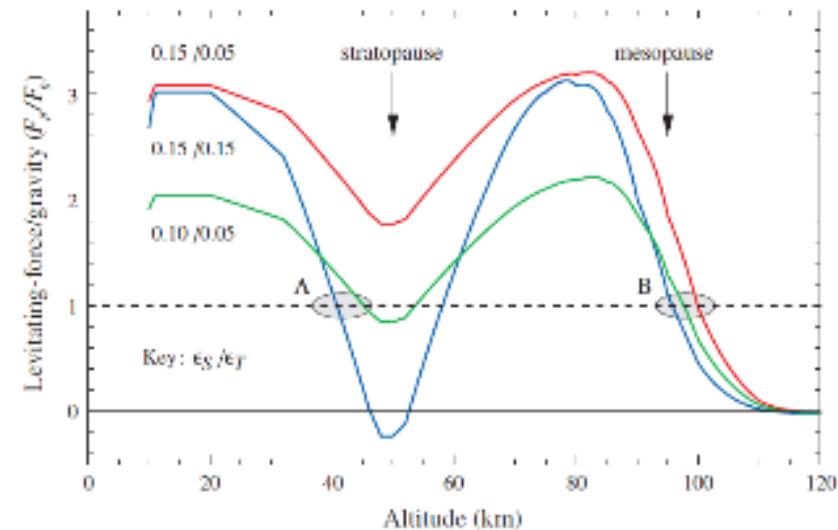
- Microstructured reflectors



Advantages:

- Tailor-made optical properties
 - factor of 10 less mass needed
 - forward scattering suppressed
 - IR-transparent
- Self – lofting
 - Long lifetime
 - factor of 10 less mass needed

- Levitated by sunlight



Disadvantages/Problems:

- Potentially hazardous materials
- High costs of manufacturing
- Untested and untried principle

Why science should consider Climate Engineering now:



- After foreseeable climate related extreme events, calls for rapid action might mount and simple solutions might be offered. It might be too late by then start researching into risks and side effects of CE.
- We should not leave the issue to politics and commercial enterprises only

Regional variations in temperature and precipitation are still expected

