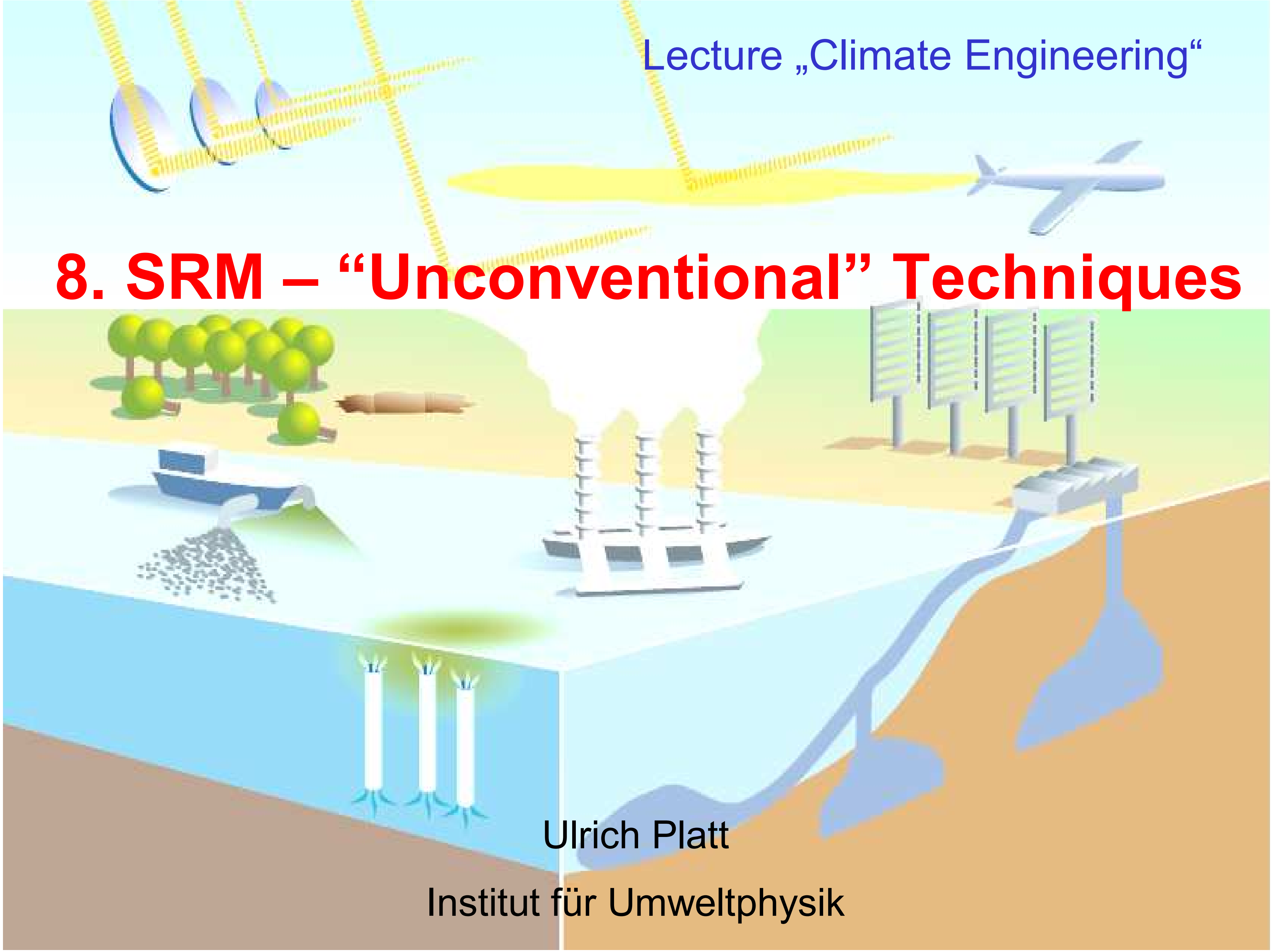
Lecture „Climate Engineering“

8. SRM – “Unconventional” Techniques



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

Akbari, H.; Menon, S.; Rosenfeld, A. (2009), Global cooling: increasing world-wide urban albedos to offset CO_2, Climatic Change, Jg. 95, S. 275–286.

Cool Roofs (2011), Promotion of cool roofs in the EU, online verfügbar unter http://www.coolroofs-eu.eu/, zuletzt geprüft am 17.11.2011.

Irvine P.J., Ridgwell A., and Lunt D.J. (2011), Climatic effects of surface albedo geoengineering, J. Geophys. Res. 116, D24112, doi:10.1029/2011JD016281.

Lenton T.M. and Vaughan N.E. (2009), The radiative forcing potential of different climate geoengineering options, Atmos. Chem. Phys., 9, 5539–5561.

Mitchell D.L. and Finnegan W. (2009), Modification of cirrus clouds to reduce global warming, Environ. Res. Lett. 4, 045102 (8pp).

Ridgwell, A.; Singarayer, J. S.; Hetherington, A. M.; Valdes P. A. (2009), Tackling regional climate change by leaf Albedo bio-geoengineering, Current Biology 19, S. 146–150.

Seitz, R. (2011), Bright water: hydrosols, water conservation and climate change, Climatic Change 105, 365–381.

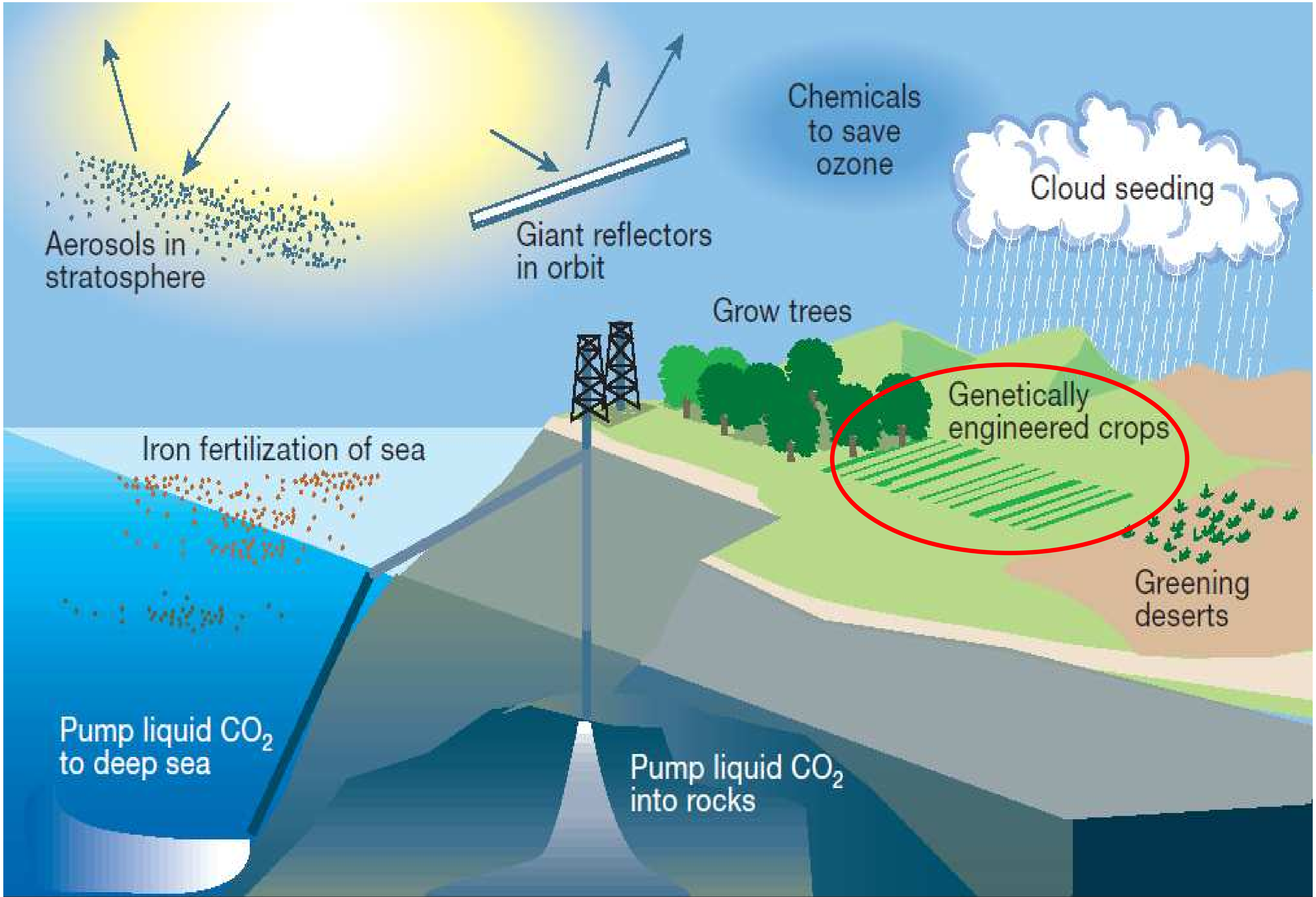
Shindell D., Kuylenstierna J.C.I., Vignati E., Dingenen van R., Amann M, Klimont Z., Anenberg S.C., Muller N., Janssens-Maenhout G., Raes F., Schwartz J., Faluvegi G., Pozzoli L., Kupiainen K., Höglund-Isaksson L., Emberson L., Streets D., Ramanathan V., Hicks K., Oanh N.T.K., Milly G., Williams M., Demkine V., Fowler D. (2012), Simultaneously Mitigating Near-TermClimate Change and Improving Human Health and Food Security, Science 335, 183-, DOI: 10.1126/science.1210026.

Singarayer, J. S.; Ridgwell, A.; Irvine, P. (2009), Assessing the benefits of crop albedo bio-geoengineering, Environmental Res. Lett. 4, 45110-.

Leisner T., Duft D., Möhler O., Saathoff H., Schnaiter M., Henin S., Stelmaszczyk K., Petrarca M., Delagrange R., Haod Z., Lüder J., Petit Y.,Rohwetter P., Kasparian J., Wolf J.-P., and Wöste L. (2013), Laser-induced plasma cloud interaction and ice multiplication under cirrus cloud conditions, PNAS Early Edition

Contents of Today's Lecture

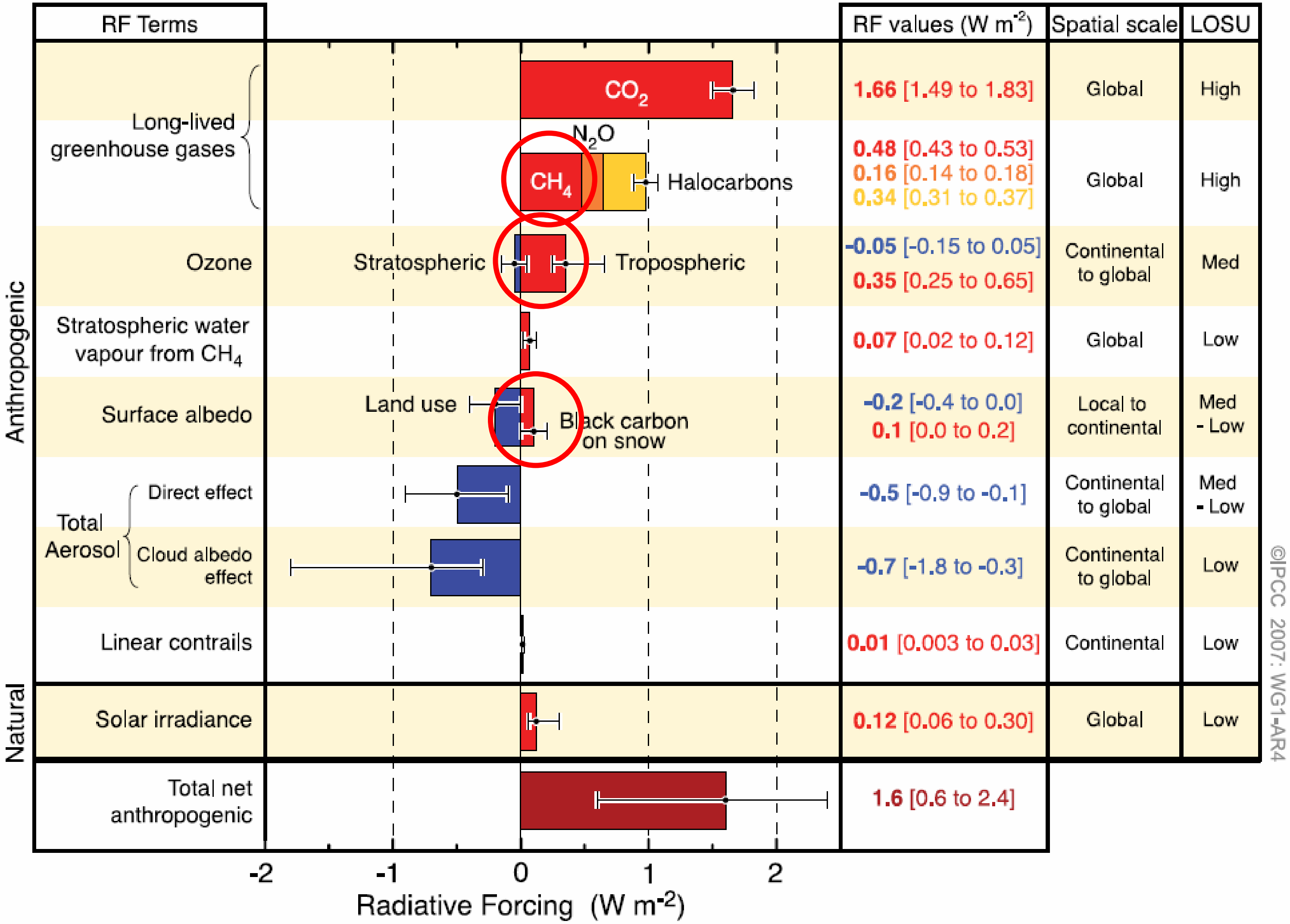
- Don‘t forget the non-CO_2 greenhouse gases
- Albedo enhancement
  - Brighter Plants
  - Brighter Deserts
  - White Roofs
  - Bright Water
- Influence IR-Albedo
- Even stranger ideas
- Conclusion



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

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

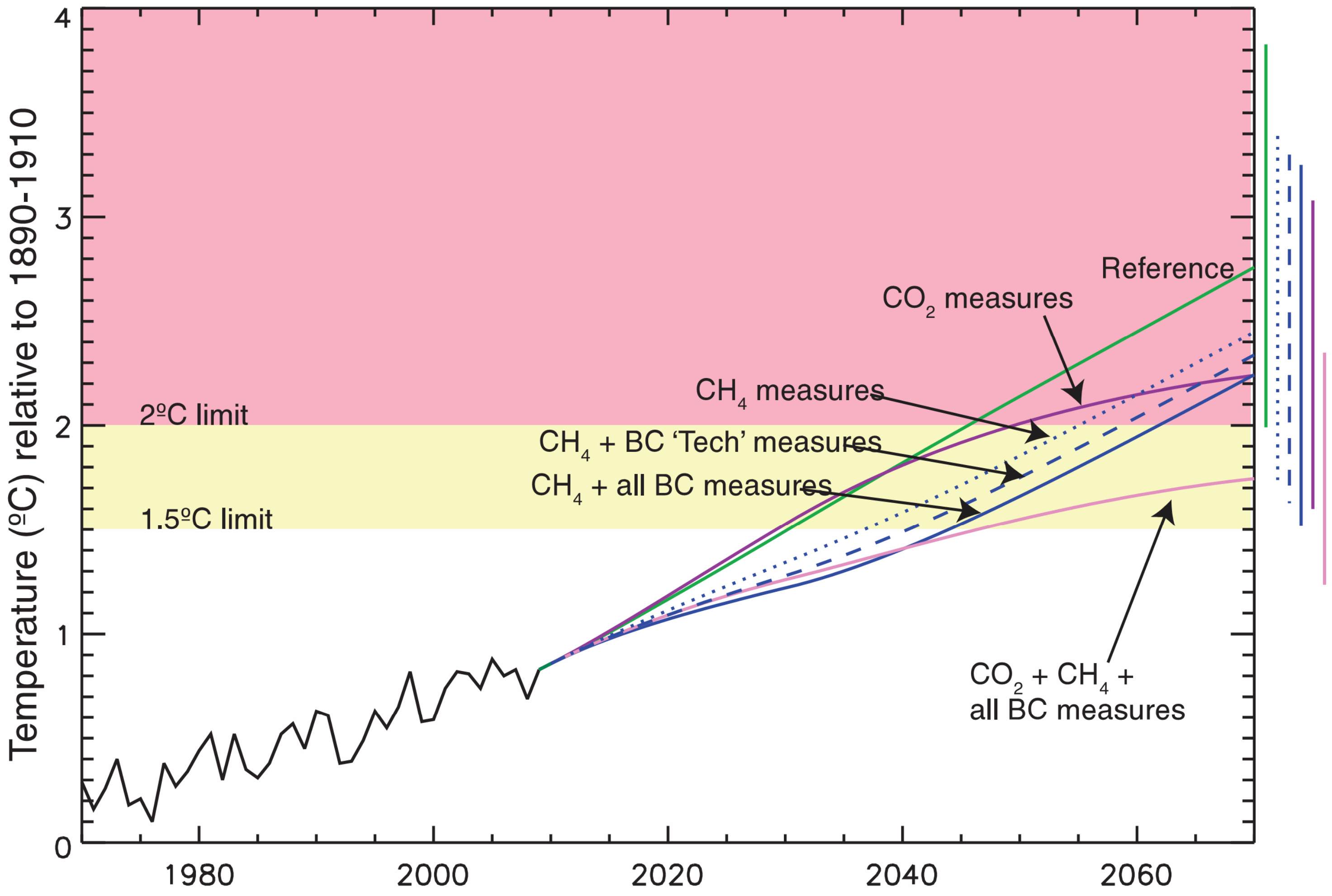
Non-CO_2 Radiative Forcing Components



CH4 – an interesting case ...

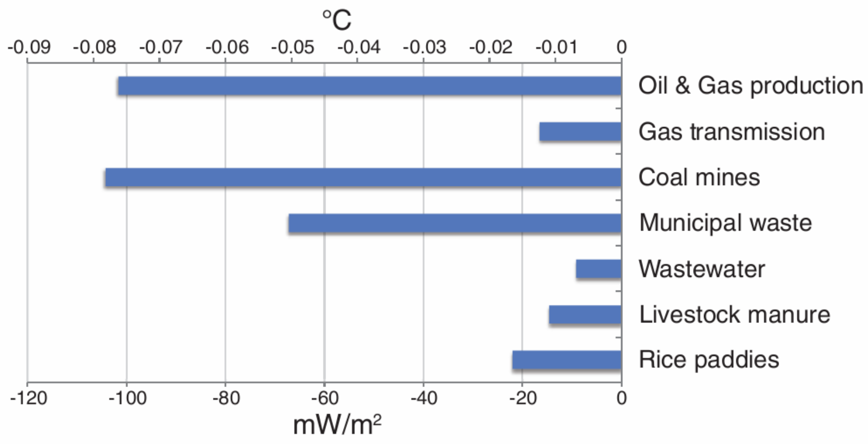
Mitigation, Health, and Food Security?

The idea: Reduce CH_4, soot (Black Carbon)



Shindell et al. Science 335, 183-189, 2012, DOI: 10.1126/science.1210026

Possible Reduction in Climate Forcing by CH_4-Control Measures



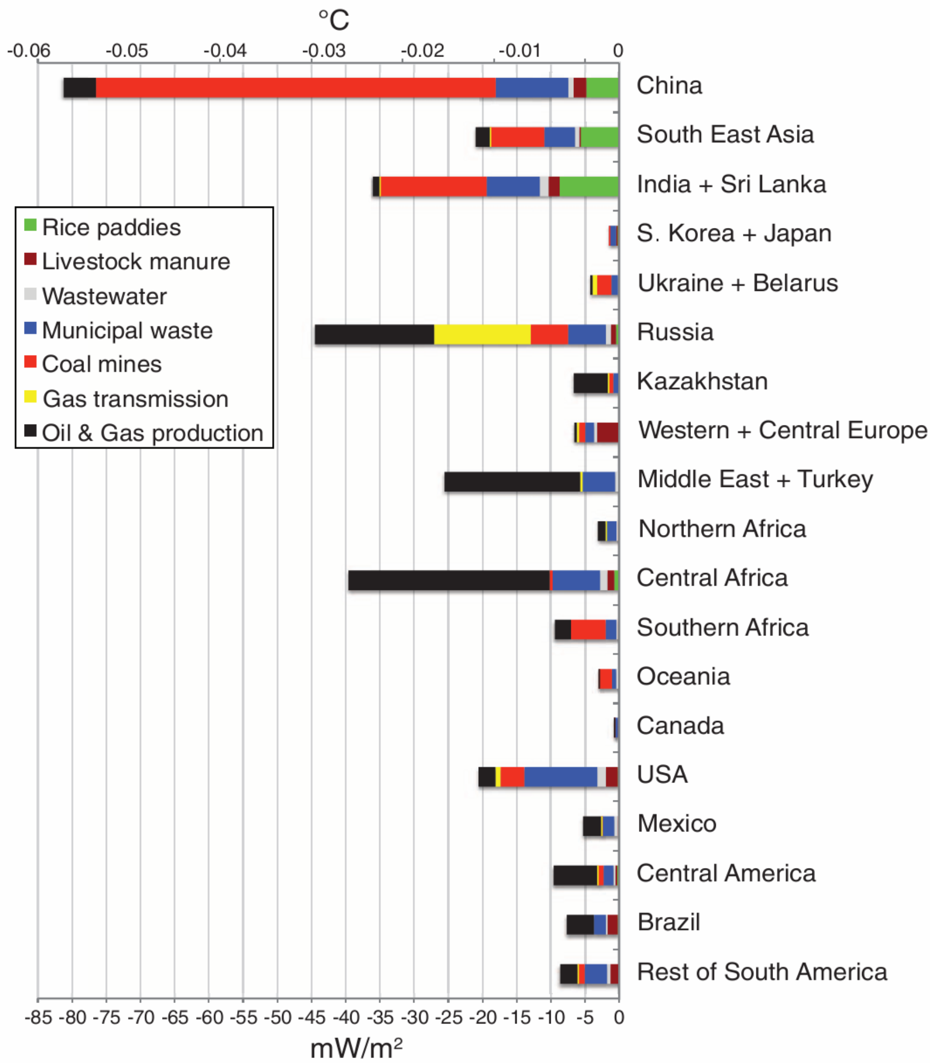


Fig. 3. Global mean radiative forcing (bottom *x* axes) and temperature response (top *x* axes) from CH_4 and ozone in response to CH_4 measures. Global totals by (**left**) emission control measure, and (**right**) values by region and sector are shown. Temperature response is the approximate equilibrium value. Uncertainties are ~10% in forcing and ~50% in response.

Overall around 0.3 W/m^2

For comparison:
CO_2-doubling corresponds to 3.7 W/m^2

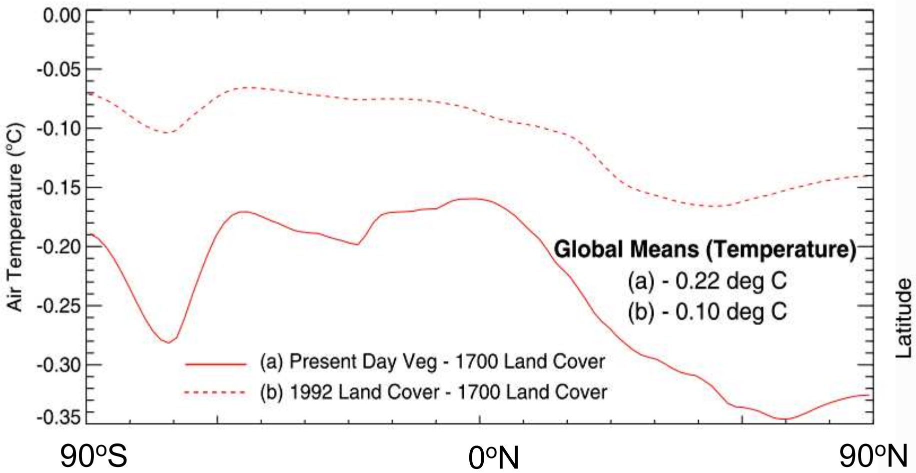
Shindell et al. Science 335, 183-189, 2012, DOI: 10.1126/science.1210026

Change of Earth Surface Albedo due to Agriculture

Table 1. Vegetation Types and Specified Parameter Values (Derived From *DeFries and Townsend* [1994] and *Sellers et al.* [1996])

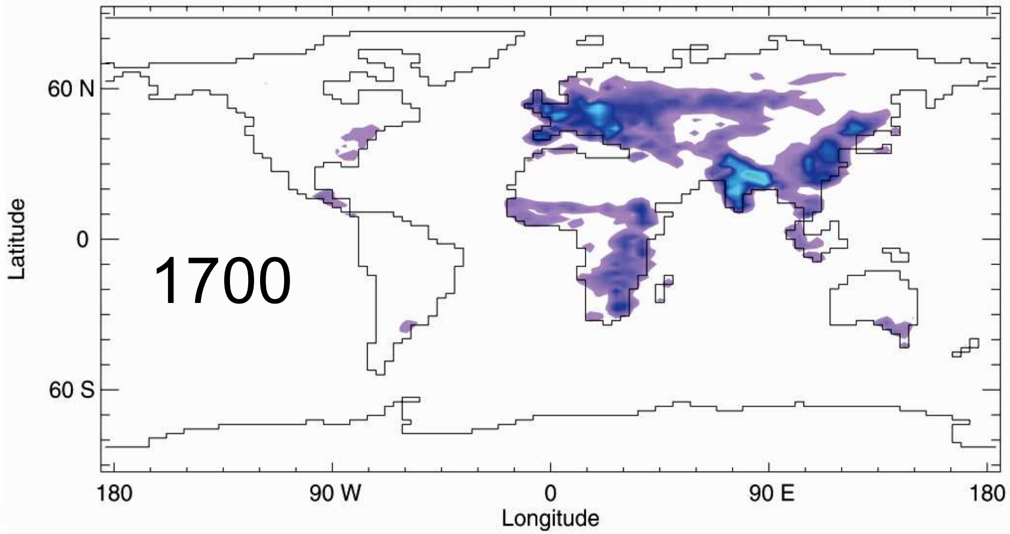
From: Matthews et al. (2003

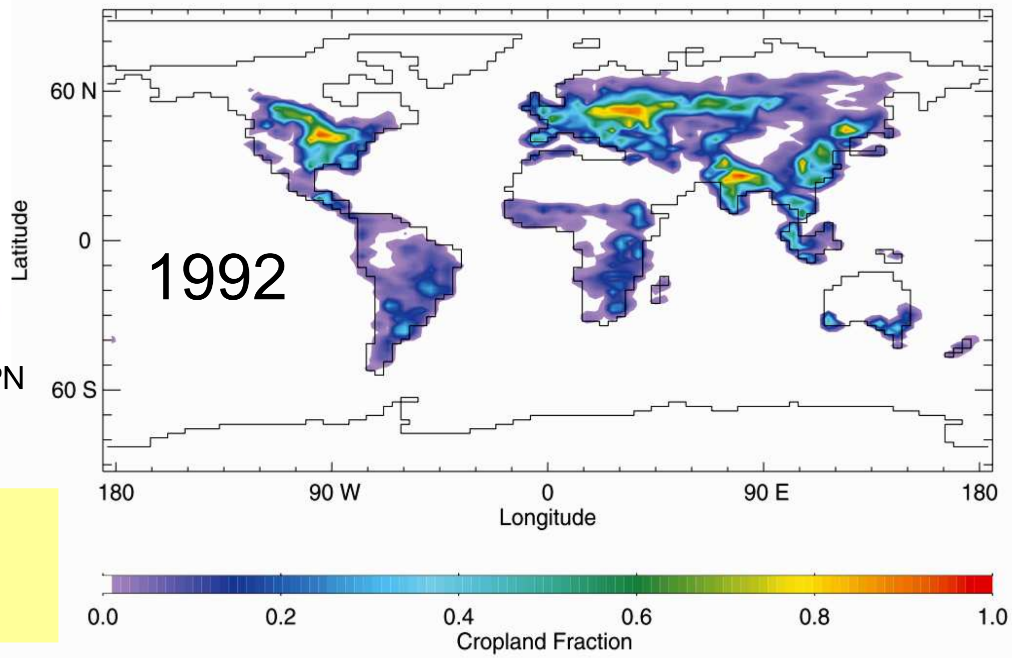
Vegetation Type	Albedo	Roughness length (m)
Tropical Forest	0.13	2.86
Temperate/Boreal Forest	0.11	0.91
Grassland/Savanna/Cropland	0.17	0.11
Shrubland	0.17	0.05
Tundra	0.20	0.04
Desert	0.28	0.04
Rock/Ice	0.14	0.02



H.D. Matthews et al. (2003), Radiative forcing of climate by historical land cover change, Geophys. Res. Lett. 30 (2), 1055, doi:10.1029/2002GL016098.

Fraction of cropland areas, from Ramankutty and Foley [1999].

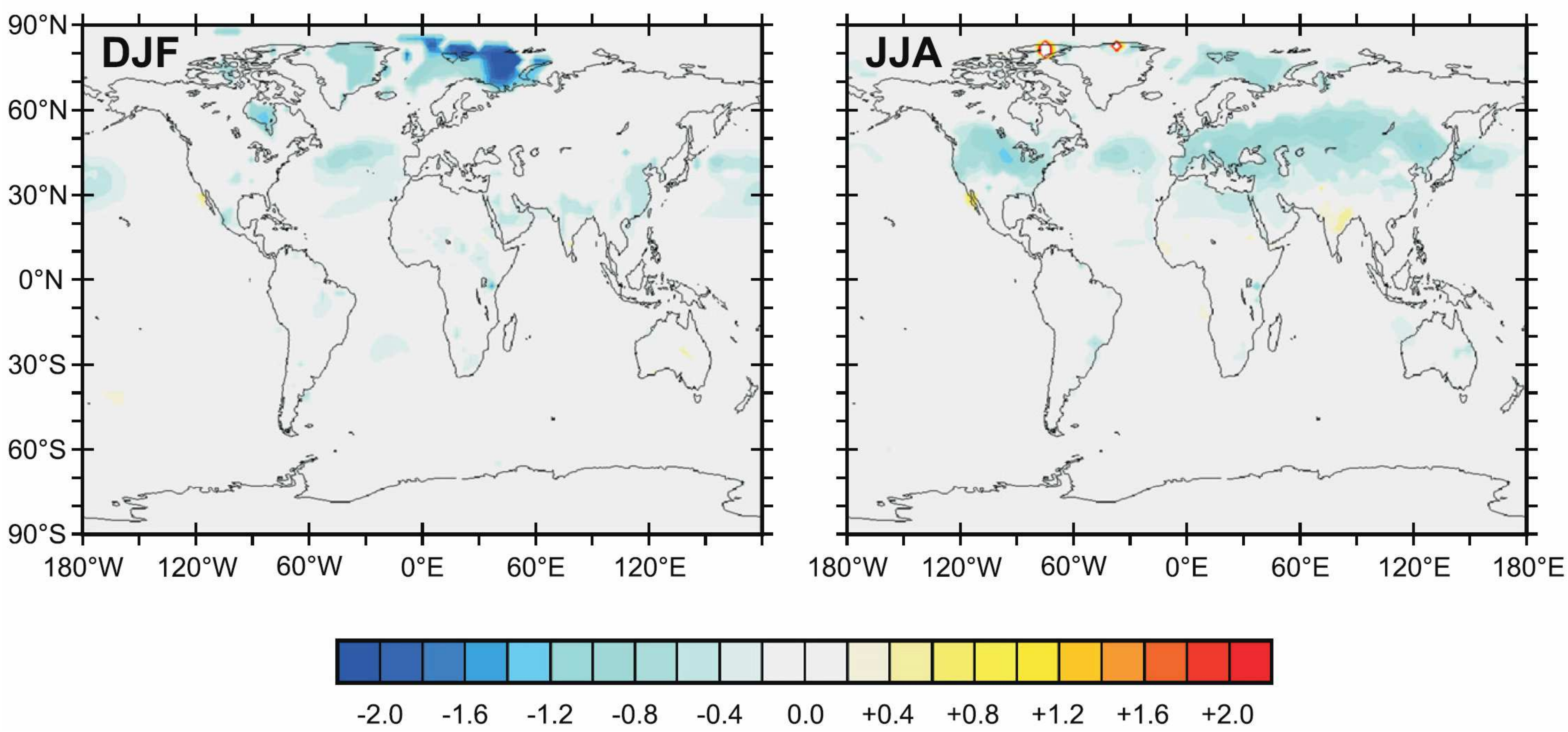




Earth Surface Albedo has Already Changed Due to Agriculture
→ Why not changing it further („Bioengineering“)

Suggestion by Ridgwell et al. (2009): Gene-engineering agricultural plants may enhance their albedo by 0.04
→ Global mean surface air temperature may be reduced by 0.11 K
(in 700 ppm CO_2-case)

Maps of global distribution of surface air temperature changes (Ridgwell et al. 2009):



Bioengineering

- Plants adapted to arid, hot zones have distinctive features to reflect excess solar energy, especially in the near infrared (NIR), which is not used for photosynthesis (Gates et al. 1965).
- A desert shrub, *Encelia farinosa*, has exceptionally bright leaves due to a thick layer of hairs that scatter preferentially in the NIR (700–3,000 nm) (Ehleringer and Bjorkman 1978).
- Other plants have developed reflective leaf hairs on the underside of leaves that can increase leaf level NIR albedo by ~0.1 (Eller and Willi 1977).
- Agricultural scientists have modified crop morphology with concomitant increases in albedo.
- Leaf pubescence in soybeans was increased fourfold over normal varieties to increase crop water use efficiency (Baldocchi et al. 1983), thereby increasing surface albedo by ~0.01 (Nielsen et al. 1984).
- Switching from a potential biofuel crop e.g. corn (albedo: 0.20–0.23) or soybean (albedo: 0.21) sunflower (albedo: 0.24–0.30) could increase surface albedo by ~0.06 (Breuer et al. 2003).

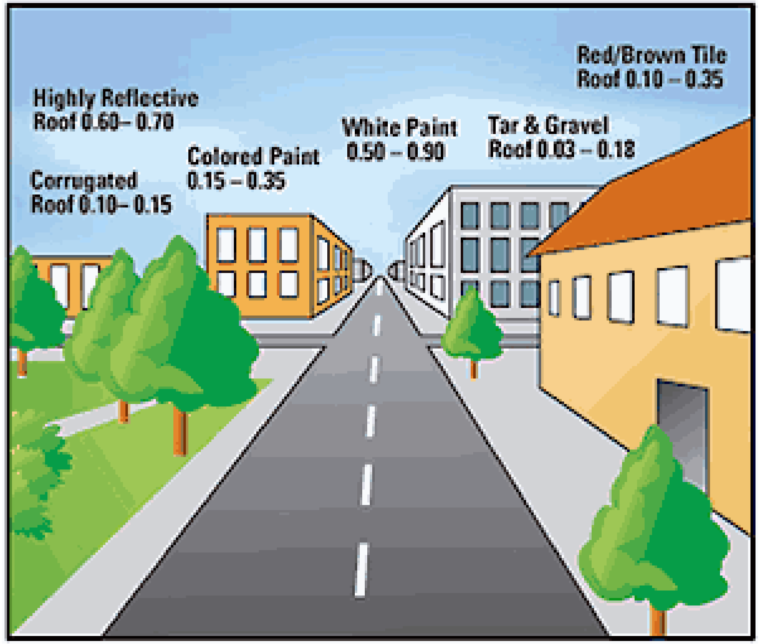
Doughty C.E., Field C.B., McMillan A.M.S. (2011), Can crop albedo be increased through the modification of leaf trichomes, and could this cool regional climate?, Climatic Change 104:379–387, DOI 10.1007/s10584-010-9936-0

Enhance Urban Albedo („White Roofs“)

Total urban area is estimated at 1.2 % of the global land area or 0.4% of total surface of Earth

Urban Surfaces:

Metropolitan Areas	Vegetation	Roofs	Pavements	Other
Salt Lake City	33.3	21.9	36.4	8.5
Sacramento	20.3	19.7	44.5	15.4
Chicago	26.7	24.8	37.1	11.4
Houston	37.1	21.3	29.2	12.4



Albedo change (Akbari et al. 2009):

Surface-type	Albedo change		
	High	Low	This study
Residential roofs	0.3	0.1	0.25
Commercial roofs	0.4	0.2	0.25
Pavements	0.25	0.15	0.15

We may assume an increase of roof albedo from 0.1 → 0.25

Roof fraction ≈0.2 → overall urban albedo change $\Delta A_{urban} \approx 0.03$
More optimistic estimate (Akbari et al. 2009): $\Delta A_{urban} \approx 0.1$

Urban area fraction 0.004 → Global albedo change $1.2 \cdot 10^{-4}$ ($4 \cdot 10^{-4}$)

Effect of Surface Albedo Changes

Radiation incident on the surface:

$$S_{surf} = \frac{S_0}{4}\left(1 - R_{AR} - R_{AA}\right) \approx 342\left(1 - 0.225 - 0.196\right) \approx 198\frac{\mathrm{W}}{\mathrm{m}^2}$$

S_0 = Solar constant

R_{AR} = Fraction reflected by the atmosphere

R_{AA}= Fraction absorbed by the atmosphere

A global albedo change of $1.2 \cdot 10^{-4}$ ($4 \cdot 10^{-4}$)

(neglecting absorption and reflection of radiation on the way back to space)

Would lead to a global average reflection of 0.024 W/m^2 (0.08 W/m^2)

Urban areas are just too small !

Change Desert Albedo

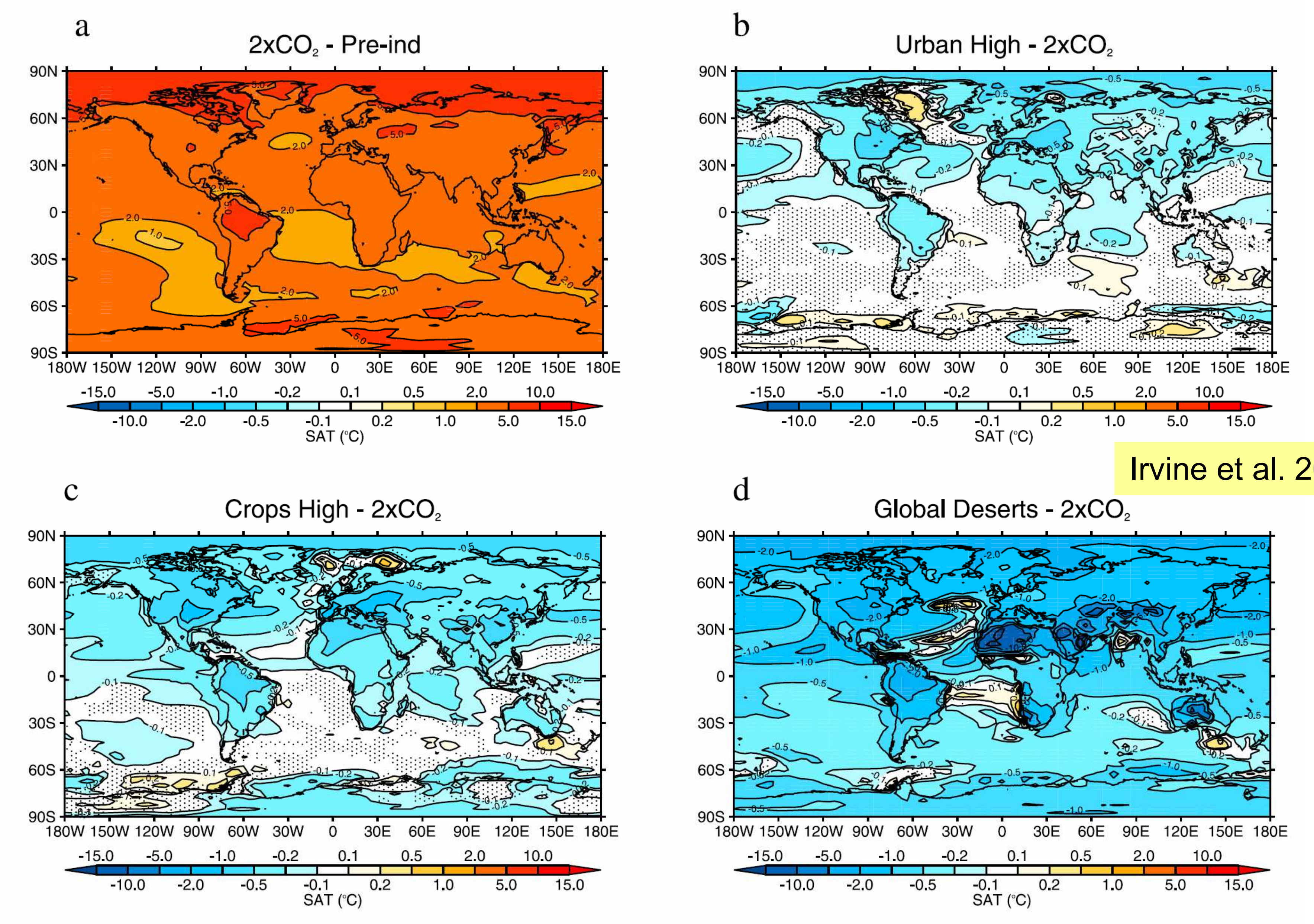
Global Albedo Enhancement Project
by Alvia Gaskill

Lenton and Vaughan 2009

Option	Area (m^2)	Fraction of Earth f_{Earth}	Albedo change within area $\Delta\alpha$	Scaled albedo change of layer	Transmittance factor f_a	Planetary albedo change $\Delta\alpha_p$	Solar radiation at TOA S_0 ($W\,m^{-2}$)	Radiative forcing RF ($W\,m^{-2}$)
Increase marine cloud albedo				$\Delta\alpha_a$				
Mechanical	8.9×10^{13}	0.175	0.074	0.013	0.84	0.011	345	−3.71
Biological	5.1×10^{13}	0.1	0.008	0.000067*	0.84	0.000056	345	−0.019
Increase land surface albedo				$\Delta\alpha_s$				
Desert	1.0×10^{13}	0.02	0.44	0.0088	0.73	0.0064	330	−2.12
Grassland	3.85×10^{13}	0.075	0.0425	0.0032	0.48	0.0015	330	−0.51
Cropland	1.4×10^{13}	0.028	0.08	0.0022	0.48	0.0011	330	−0.35
Settlements	3.25×10^{12}	0.0064	0.15	0.00096	0.48	0.00046	330	−0.15
Urban areas	1.5×10^{12}	0.0029	0.1	0.00029	0.48	0.00014	330	−0.047

Cover deserts with a reflective polyethylene-aluminium surface to increase the mean albedo from 0.36 to 0.8 (Gaskill)

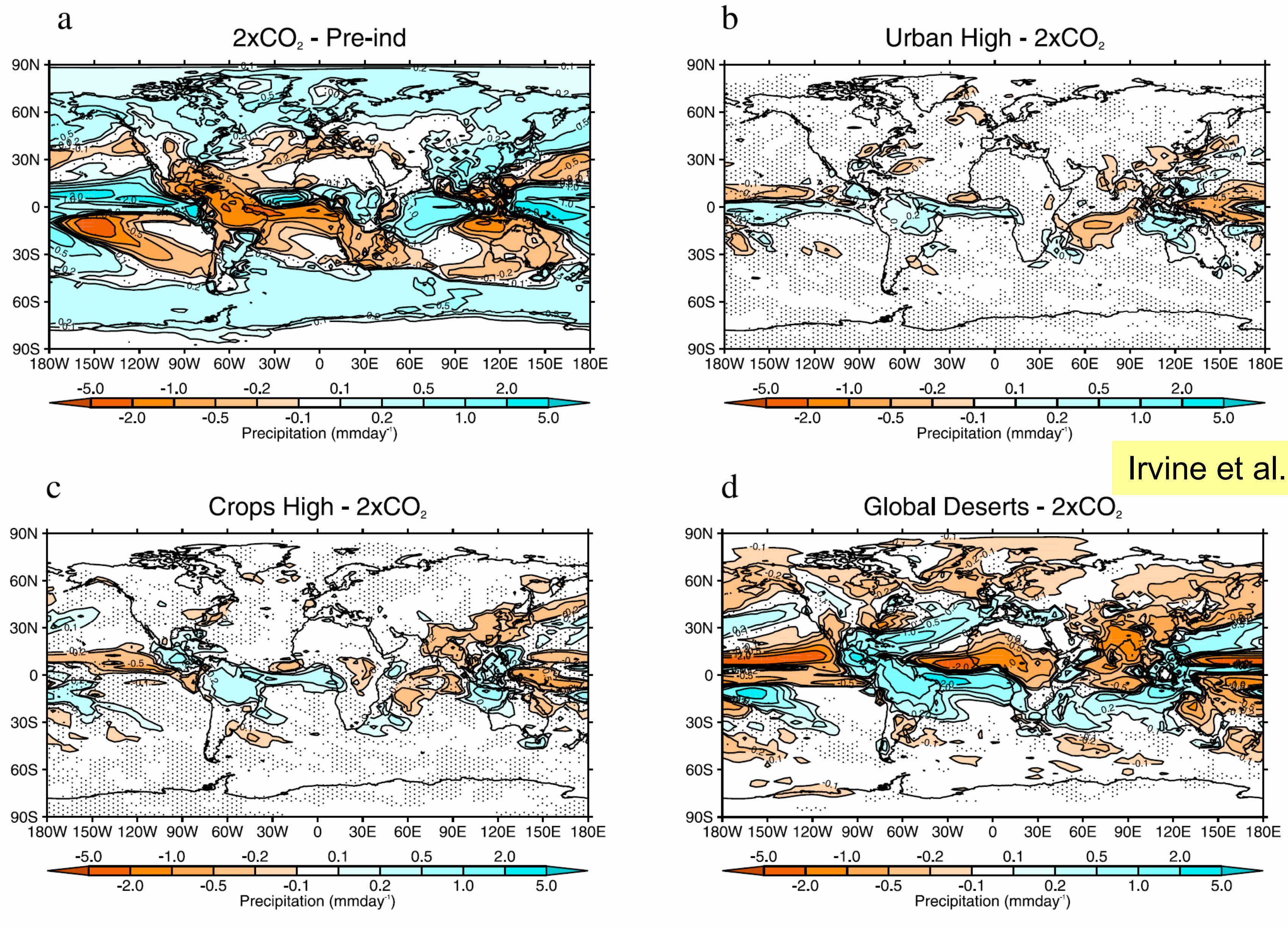
Effect of Different CE-Schemes on Temperature



Irvine et al. 2011

Surface air temperature (SAT) anomaly between 2 x CO_2 and preindustrial and between the various geoengineering schemes and 2 x CO_2. Areas that failed a 5% student t test are stippled.

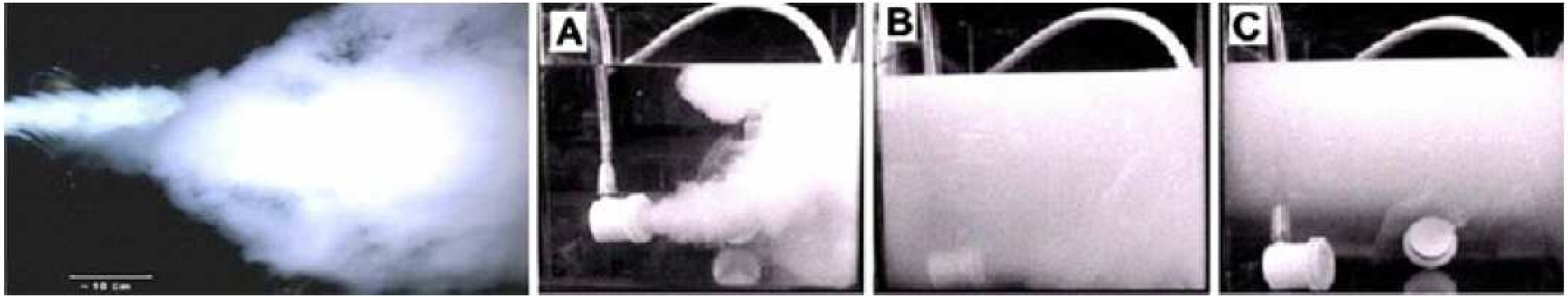
Effect of Different CE-Schemes on Precipitation



Irvine et al. 2011

“Don’t dim the Sun, Brighten the Water”

Russell Seitz, Climatic Change, 2011



Bubbles in the ocean:

Bright water: hydrosols, water conservation and climate change
Russell Seitz, Climatic Change (2011) 105, 365–381

See also:

Bubble, bubble, toil and trouble,
Editorial comment
By Alan Robock, Climatic Change
(2011) 105, 383–385

„Bright Water“ – The Principle

Aerosol Particle, Radius = r

Friction force

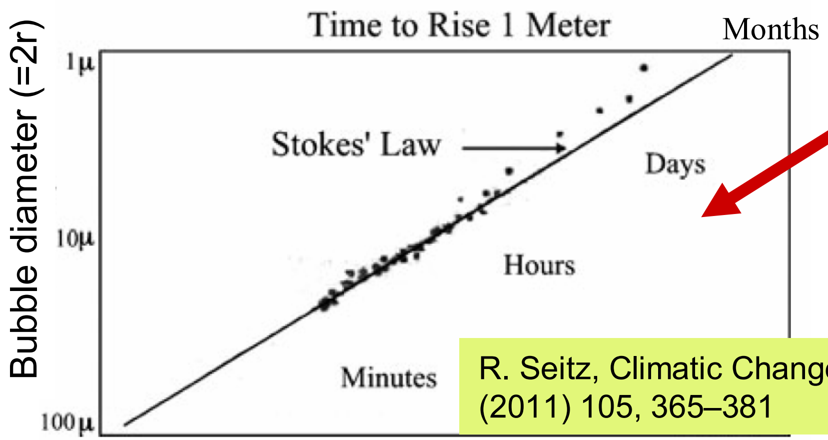
$$F_F = 6\pi r \underbrace{v}_{\text{settling velocity}} \underbrace{\eta}_{\text{viscosity of air}} \propto r$$

..balances...

r=1µm → 10m/day

Gravity force

$$F_G = \frac{4}{3}\pi r^3 \underbrace{\rho}_{\text{Density of particle}} g \propto r^3$$



R. Seitz, Climatic Change (2011) 105, 365–381

Bubble (Hydrosol Particle), Radius = r

Boyancy force

$$F_B = \frac{4}{3}\pi r^3 \underbrace{\rho}_{\text{Density of water}} g \propto r^3$$

balances

r=1µm → 10cm/day

Friction force

$$F_F = 6\pi r \underbrace{v}_{\text{rising velocity}} \underbrace{\eta}_{\text{viscosity of water}} \propto r$$

→ Rising velocity proportional to $1/r^2$

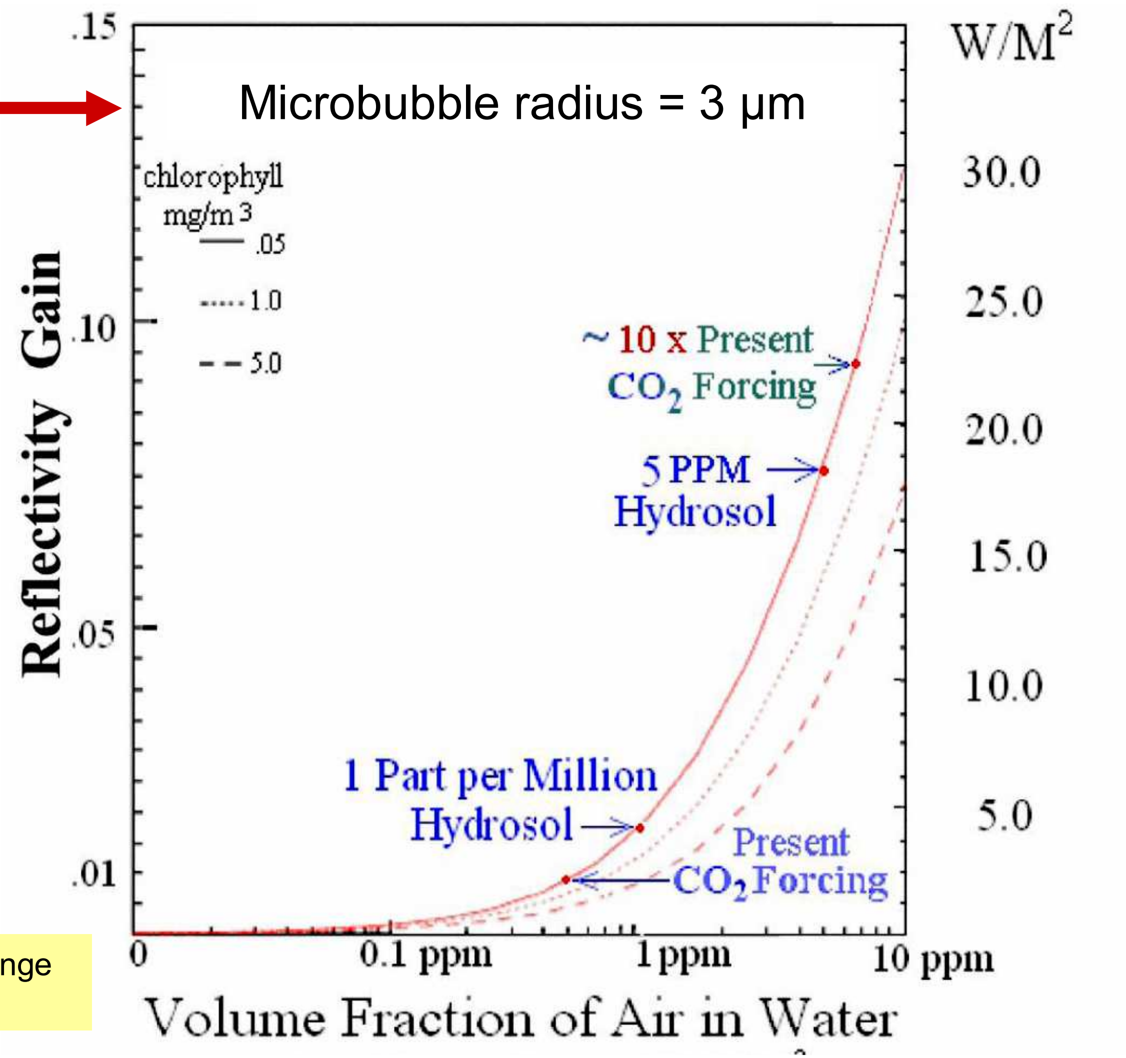
Natural or artificial surfactants may increase bubble lifetime by one order of magnitude or more!

Bright Water – Globally

Natural seawater contains 10^4 – 10^7 microbubbles (radius 10...100µm) per m^3
Volume fraction: ca. 10^{-11} ... 10^{-5} (0.00001 ... 10 ppmv)

They increase Earth's albedo by 10^{-4} to 10^{-3} and cause slight supersaturation of ocean with air.

Albedo increase (absolute and in W/m^2) from Mie model results (r=3µm, Jin et al. 2006).
Average solar flux at surface of 239 W/m^2 is assumed



→ 3-times smaller micro-bubbles (r=1µm) would still increase albedo by 0.1 (≈24W/m^2) at 1.5ppmv air in water (1.5ml/m^3)

R. Seitz, Climatic Change (2011) 105, 365–381

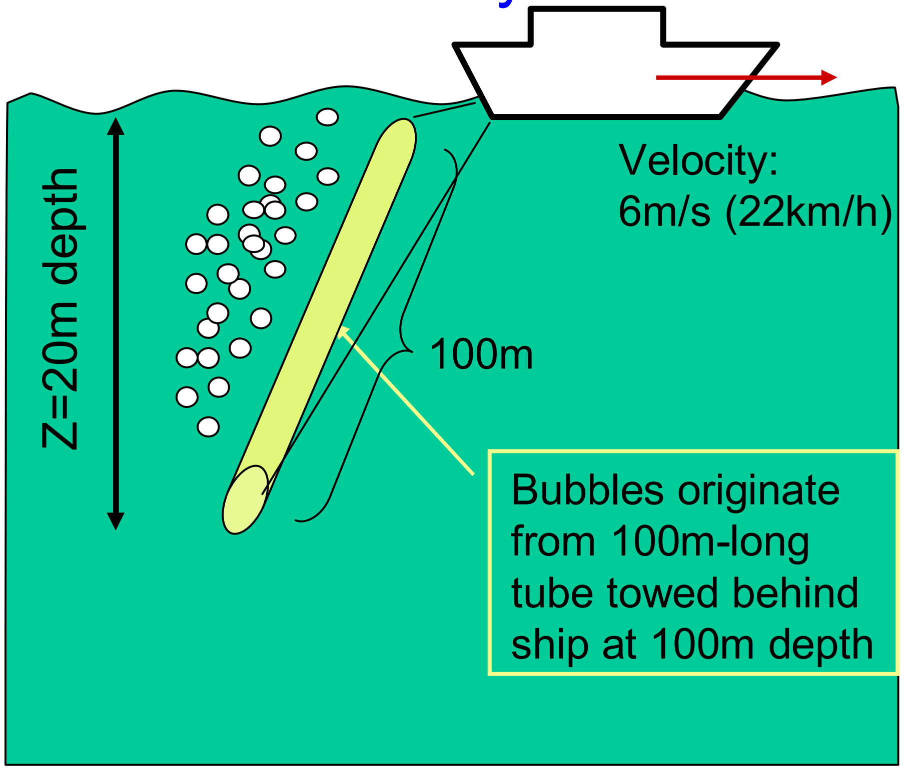
Bright Water – Practically

One ship could seed an area of 0.1 by 20km per hour or about 48 km^2 per day
→ 17500 km^2 per year

Bubbles (1µm) release at 100m depth would result in ≈1 year lifetime

→ A fleet of 3000 ships could keep 50 Mio. km^2 or 10% of the Earth surface (15% of oceans) seeded with microbubbles
→ provide 2-3 W/m^3 negative forcing

→ A larger fleet would provide proportionally more negative forcing.



Ship will seed a volume of 100m (cross track) by 6m (along track) by 10m (layer thickness) = 6000 m^3 per second
5 ppm air-fraction: 60 l/s of air (or Ar)
→ Power requirement: 12 KW

Requires extremely little air and energy!

Problems: 1) How to make such small bubbles (see cloud-withening!)
2) Dissolution of bubbles due to N_2-undersaturation of water

Bright Water – Plastic

Polymers have densities around 1 – 1.5 kg/l

→ If we can make e.g. $\rho_{particle}$ = 1.01 ρ_{water}

→ Particle settlich velocity will be 1% of bubble rise velocity, e.g. 0.1mm/day at r = 1μm

→ Lifetime to settle by 10m will be

$$F_G = \frac{4}{3}\pi r^3 \left(\rho_{particle} - \rho_{water}\right) g \propto r^3$$

≈ 10^5 days or 300 years
(Note: particles will disappear in the deep ocean)

Required amout of polymer:

$50 \cdot 10^6$ km² x 10 m layer x 5ppm volume fraction of particles:

$5 \cdot 10^{13}$ m² x 10m x $5 \cdot 10^{-6} \approx 25 \cdot 10^8$ m³ or 2.5 billion tons

Influence LW-Budget (this is not SRM!)

Idea by Mitchell et al. (2008) and Mitchell and Finnegan (2009):

- High cirrus clouds (ice clouds) have a net warming effect between 1.3 and 2.4 W/m^2
- Typically the ice particles form due to homogeneous freezing (at t < -37oC and ice supersaturations of 45-60%
- Addition of small aerosol particles which act as ice nuclei would lead to freezing at higher temperatures and at lower supersaturation

→ Ice crystals get larger

→ Drop faster and reflect less IR radiation („negative Twomey effect“, Kärcher and Lohmann 2003)

→ Shorter lifetime of cirrus clouds

→ Less radiative forcing

Suitable ice nucleating materials:

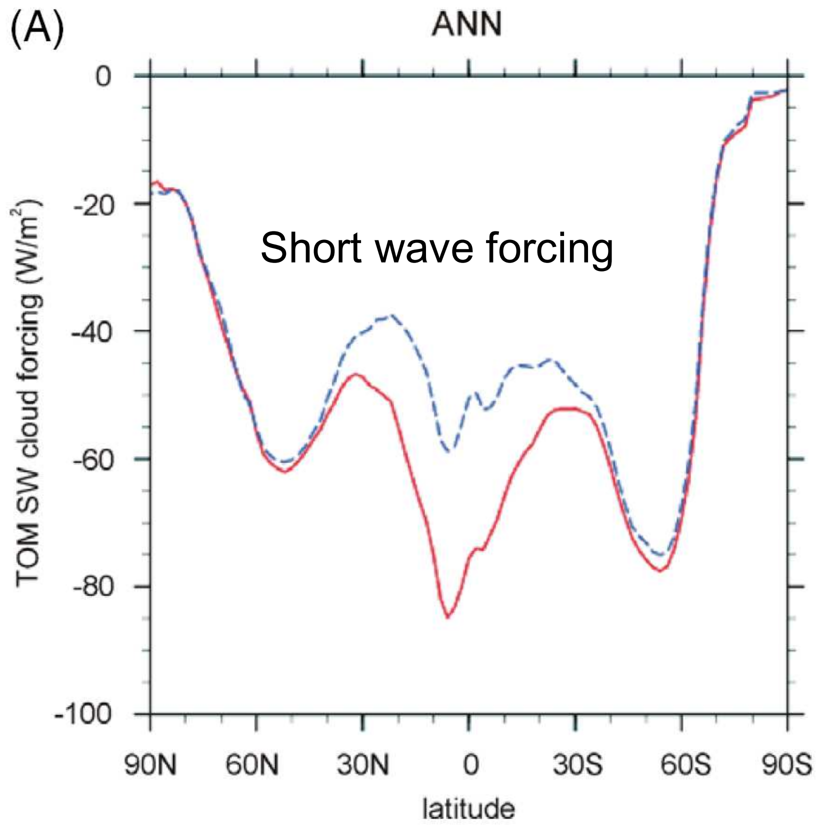
silver iodide (AgI), best known nucleating material

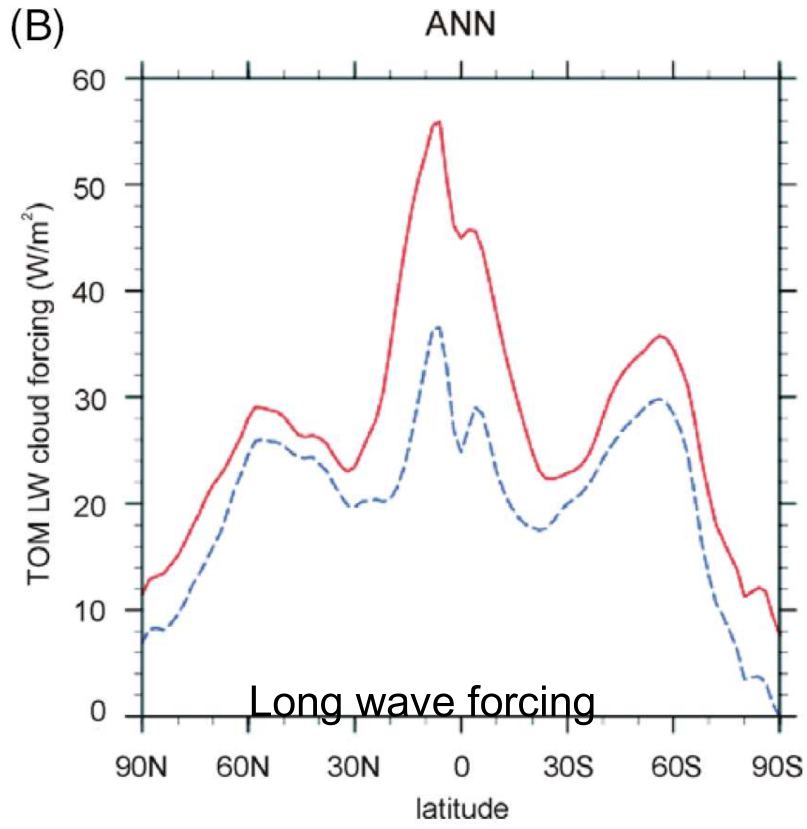
Soot, could be delivered without cost by aircraft

Bismuth tri-iodide (BiI_3) much cheaper than AgI and almost as good

Lee, J.; Yang, P.; Dessler, A. E.; Gao, B. C.; Platnik, S. (2009), Distribution and radiative forcing of tropical thin cirrus clouds, Journal of Atmospheric Science, Jg. 66, doi: 10.1175/2009JAS3183.1.

Effect of Sirrus-Coud Seeding (Model)





Short wave forcing is negative only in the tropics

Long wave forcing is negative at all latitudes

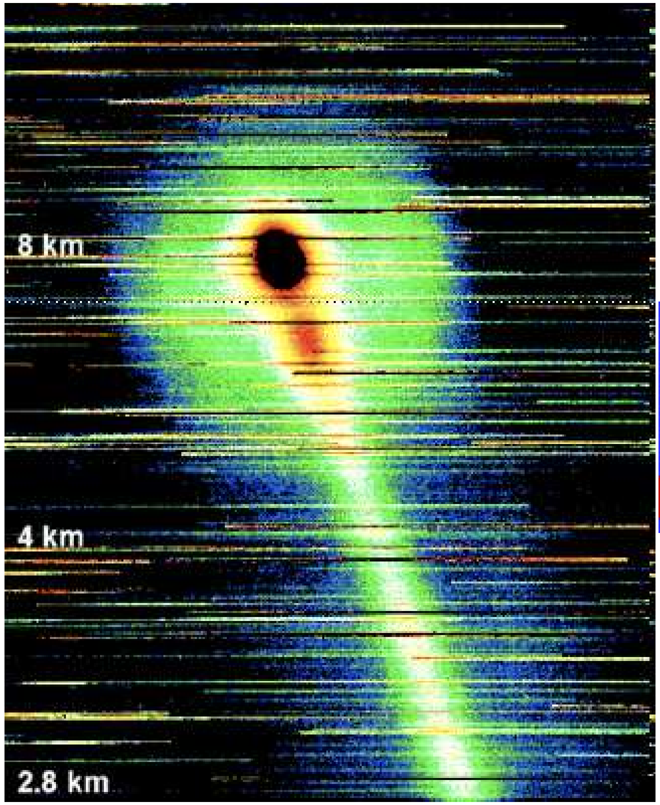
→ Seed high latitudes

Up to -2.8 W/m² may be reached

Mitchell et al. (2008)

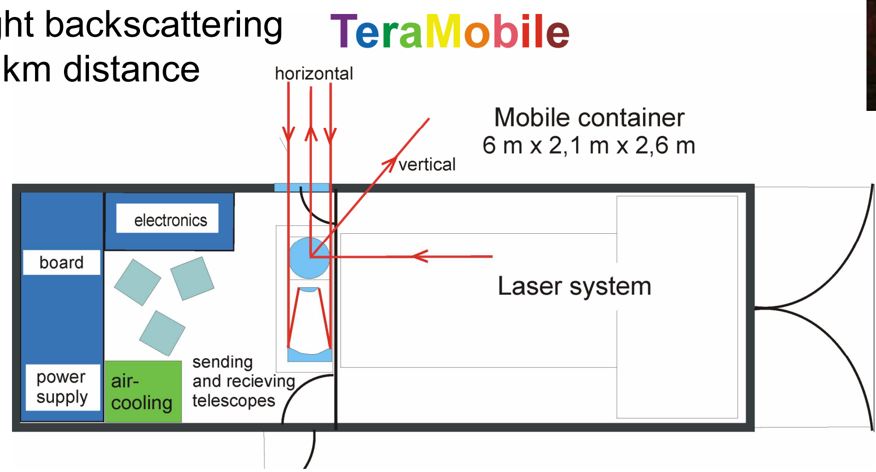
Make Aerosol from Air – The „Teramobile“

Ludger Wöste, Freie Universität Berlin
Jérôme Kasparian, Jean-Pierre Wolf, Université de Genève
Roland Sauerbrey, Forschungszentrum Rossendorf
André Mysyrowicz, Ecole Polytechnique Paliseau
Université Lyon



White-light backscattering up to 18 km distance

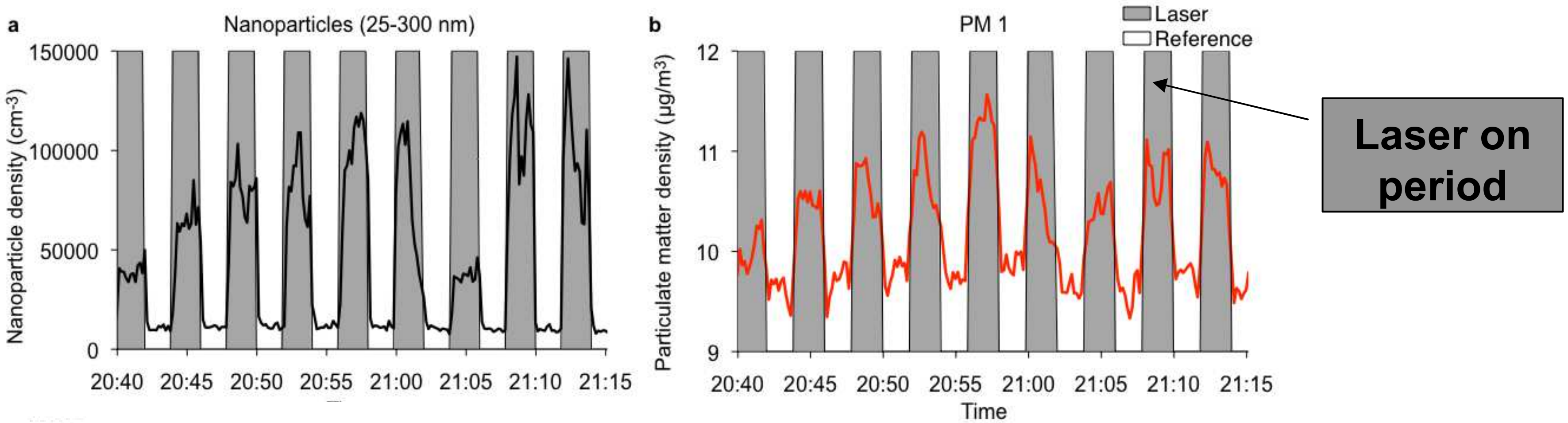
Femtosecond-Terawatt Laser-Pulses

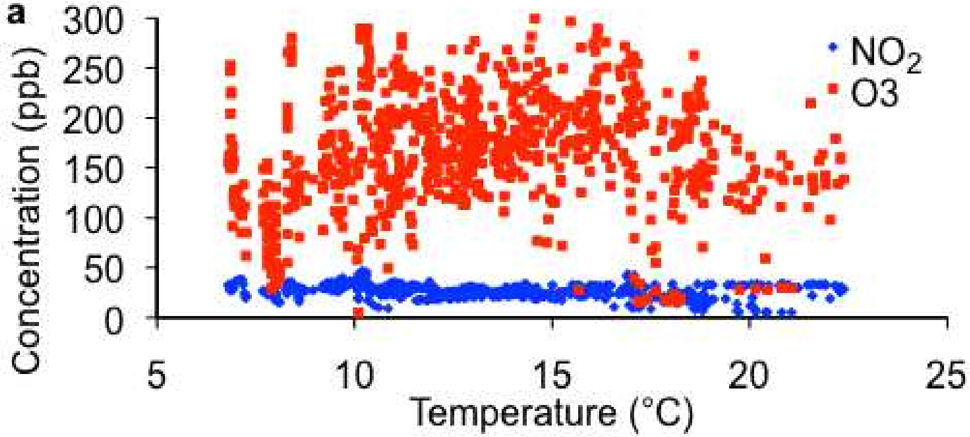


Remote detection of biological aerosols. Tube in the center of the picture: Open cloud chamber generating the bioaerosol simulant. Laser beam is arriving from the left.

http://www.teramobile.org/

Make Aerosol from Air - Terramobile





160 mJ pulses
240 fs duration (800 nm),
repetition rate 10 Hz
→ Avg. power: 1.6 W

Field experiments show that laser filaments can induce water condensation and fast droplet growth up to several µm in diameter (RH > 70%). This effect probably relies on photochemical formation of ppm-range concentrations of hygroscopic HNO_3, allowing efficient binary HNO_3–H_2O condensation in the laser filaments.

Wille, H. *et al.* Teramobile: a mobile femtosecond-terawatt laser and detection system. *Eur. Phys. J. – Appl. Phys.* **20**, 183-190 (2002).

Make Aerosol from Air – The Chemistry

Known as „Air combustion“

Known from Ozone-Hole chemistry

$$H_2O + \frac{5}{2}O_2 + N_2 + \underbrace{h\nu}_{\text{Photon}} \rightarrow 2\,HNO_3$$

$$HNO_3 + 3\,H_2O \rightarrow \underbrace{HNO_3 \bullet (H_2O)_3}_{\text{Nitric acid trihydrate (NAT)}}$$

NAT will condense and form particles at temperatures of the lower stratosphere.

Note: HNO_3 – concentration must be somewhat higher than in the nautral stratosphere to allow NAT particle formation at mid-latitudes.

Problems: 1) Energy requirements

Assume $G(HNO_3) \approx 1$ (= No. of HNO_3 –molecules per 100eV of radiation energy.
→ 1 Mole of HNO_3 (63g) require 10^7 J
→ $1.5 \cdot 10^{17}$ J for 1 Mio. t of HNO_3
Assume 1 year lifetime of NAT-aerosol:

→ $5 \cdot 10^9$ W or **5000 MW**

2) NAT is much more effective than H_2SO_4 in chlorine activation and thus ozone destruction

Laser-Induced Plasma Ice-Multiplication in Cirrus Clouds

Leisner et al. 2013

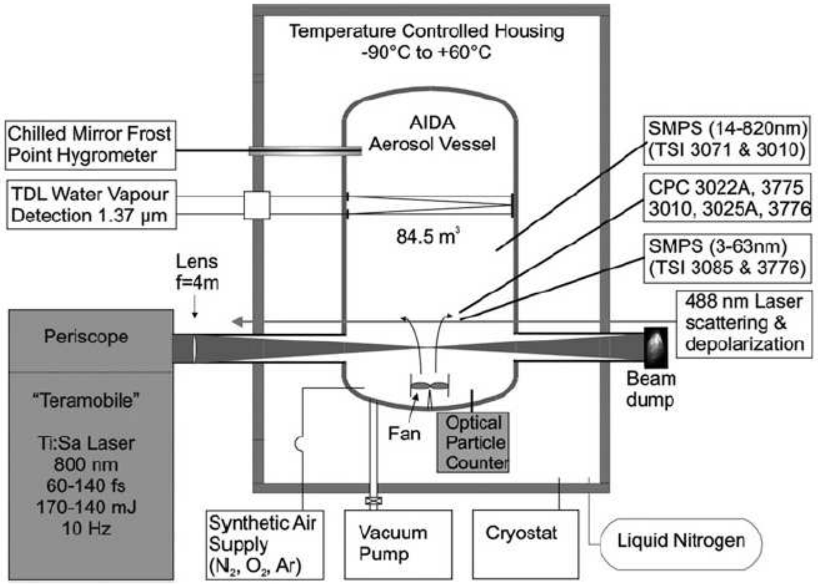
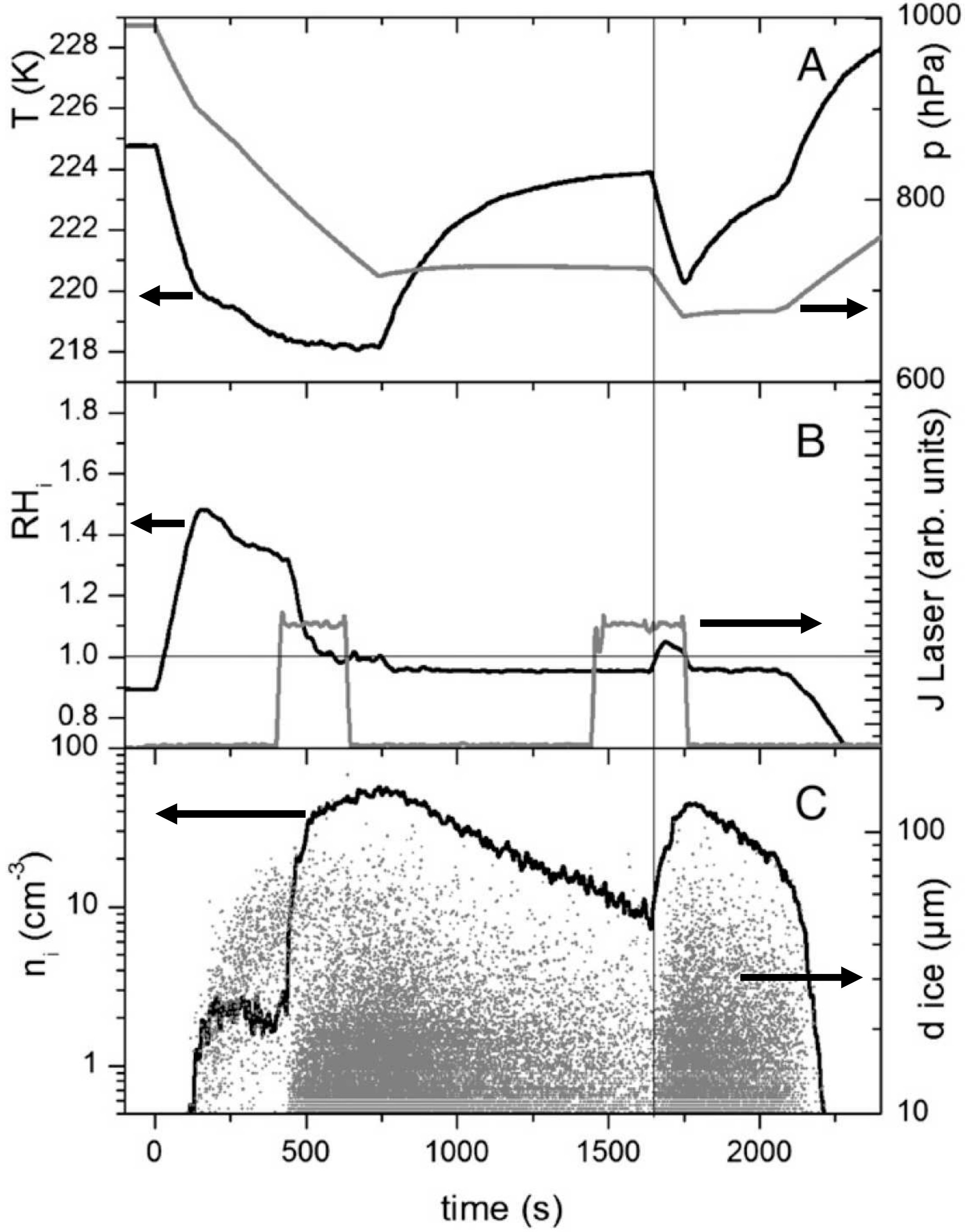


Fig. 4. Schematic of the experimental setup of the Teramobile laser system at the AIDA aerosol and cloud chamber. The terawatt laser beam is generated in a container outside the AIDA hall and directed via transfer optics, a focusing lens (*f* = 4 m), and an entrance window (139-mm diameter, 9.8-mm thickness) across the AIDA vessel and across the air flux from its mixing fan. The beam exits at the opposite side through an exit window into a beam dump.

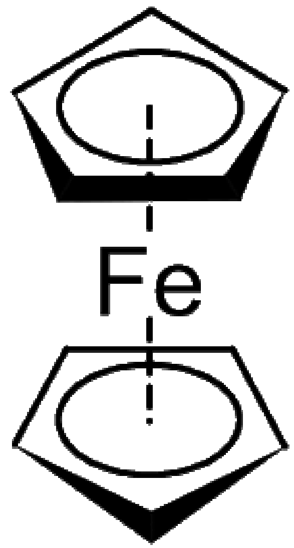


Ferrocene*

Ideas of **Franz D. Öste**:

1) Add ferrocene to jet fuel to introduce iron aerosol to the lower stratosphere

2) Add ferrocene to any fuel to produce **iron oxide aerosol** in the troposphere
   → iron can enhance chlorine atom concentration
   → Cl-atoms reduce CH_4 concentration
   (Note: atmospheric CH_4 has a greenhouse effect equivalent to about 40 ppm of CO_2)



*Ferrocene: Organic iron compound.

Conclusions (Unconventional Techniques)

- There are many new ideas to facilitate CE
- Some of them may actually work
- It is likely that more ideas will emerge ...
  → We should not prematurely settle with the presently discussed techniques
- In fact it could be that – should CE measures ever be implemented – none of the presently discussed techniques are actually used