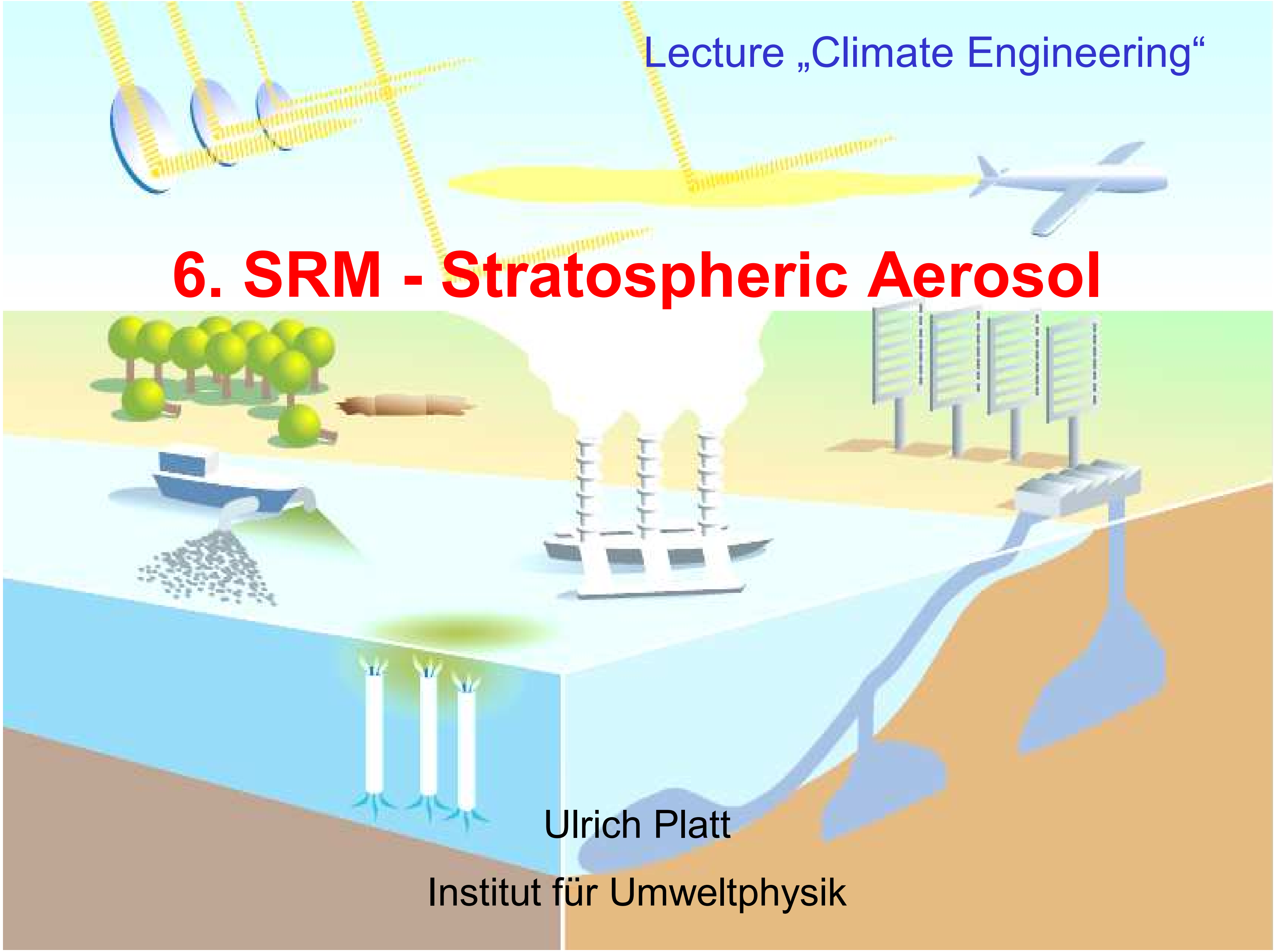
Lecture „Climate Engineering“

6. SRM - Stratospheric Aerosol



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 - 1

Crutzen P. (2006), Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma? An Editorial Essay, Clim. Change, doi:10.1007/s10584-006-9101-y.

English J.M., Toon O.B., and Mills M.J. (2012), Microphysical simulations of sulfur burdens from stratospheric sulfur geoengineering, Atmos. Chem. Phys., 12, 4775–4793.

Heckendorn P., Weisenstein D., Fueglistaler S., Luo B.P., Rozanov E ., Schraner M., Thomason L.W. and Peter T. (2009), The impact of geoengineering aerosols on stratospheric temperature and ozone, Environ. Res. Lett. 4, 045108, doi:10.1088/1748-9326/4/4/045108.

Kleinschmitt C., Boucher O., and Platt U. (2018), Sensitivity of the radiative forcing by stratospheric sulfur geoengineering to the amount and strategy of the SO2 injection studied with the LMDZ-S3A model, Atmos. Chem. Phys. 18, 2769–2786.

Kremser, S., Thomason, L.W., von Hobe, M., Hermann, M., Deshler, T., Timmreck, C., Toohey, M., Stenke, A., Schwarz, J. P.,Weigel, R., Fueglistaler, S., Prata, F. J., Vernier, J.-P., Schlager, H., Barnes, J. E., Antuña-Marrero, J.-C., Fairlie, D., Palm, M., Mahieu, E., Notholt, J., Rex, M., Bingen, C., Vanhellemont, F., Bourassa, A., Plane, J. M. C., Klocke, D., Carn, S. A., Clarisse, L., Trickl, T., Neely, R., James, A. D., Rieger, L., Wilson, J. C., and Meland, B. (2016), Stratospheric aerosol—Observations, processes, and impact on climate, Reviews of Geophysics, 54, 278–335, doi:10.1002/2015RG000511.

Laakso A., Partanen A.-I., Kokkola H., Laaksonen A., Lehtinen K.E.J. and Korhonen H. (2012), Stratospheric passenger flights are likely an inefficient geoengineering strategy, Environ. Res. Lett. 7, 034021 (7pp), doi:10.1088/1748-9326/7/3/034021.

Literature - 2

McClellan J., Sisco J., Suarez B., Keogh G. (2011), Geoengineering Cost Analysis, Final Report AR10-182, Aurora Flight Sciences Corp., Cambridge, Mass. 02142.

Niemeier U., Schmidt H., and Timmreck C. (2011), The dependency of geoengineered sulfate aerosol on the emission strategy, Atmos. Sci. Lett., 12, 189–194, doi:10.1002/asl.304,

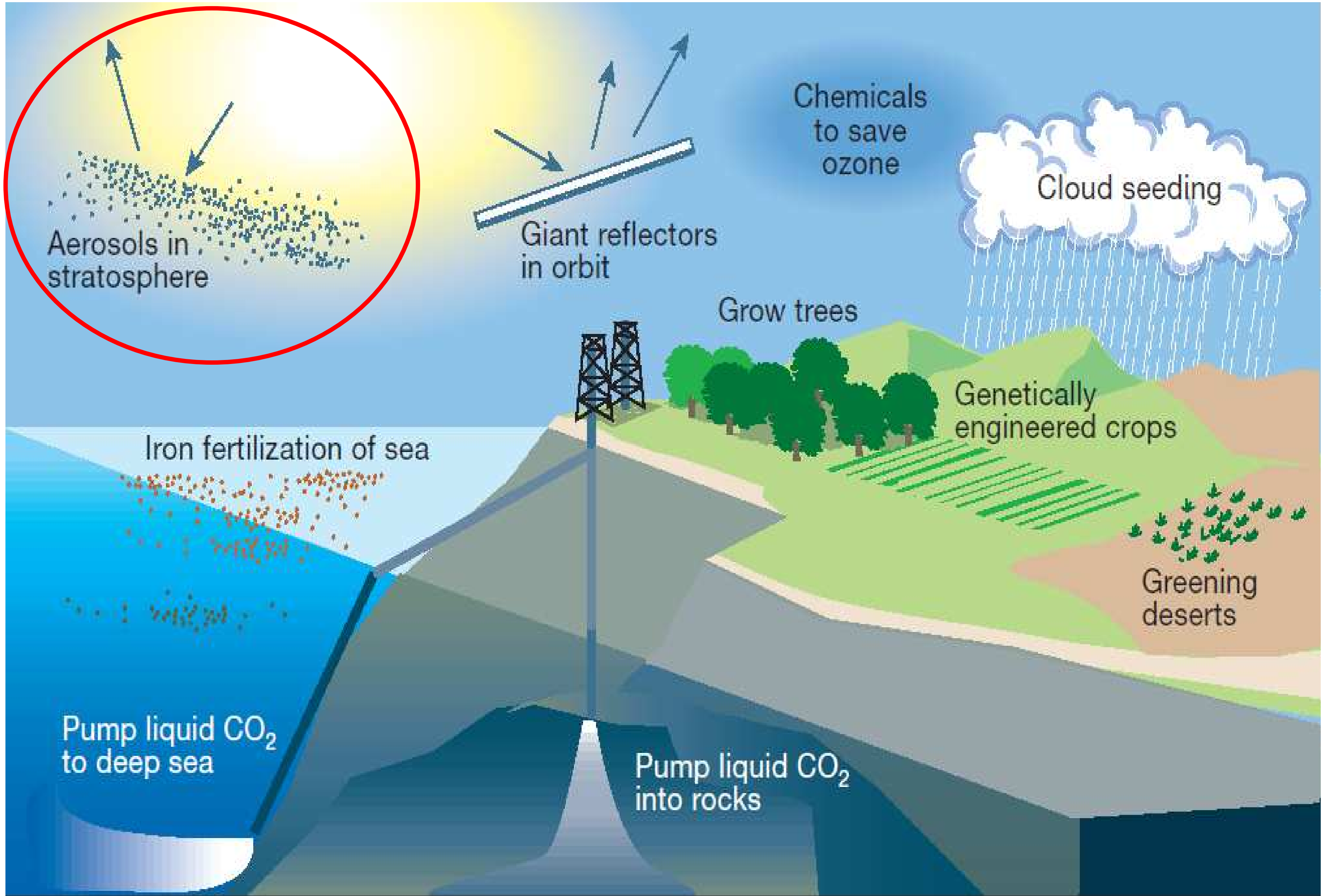
Pierce J.R., Weisenstein D.K., Heckendorn P., Peter T., and Keith D.W. (2010), Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft, Geophys. Res. Lett. 37, L18805, doi: 10.1029/2010GL043975.

Rasch P.J., Tilmes, J., Turco R. P., Robock A., Oman I., Chen C.C., Stenchikov G. I., Garcia, R. (2008), An overview of geoengineering of climate using stratospheric sulphate aerosols, Philosophical transactions of the Royal Society A, 4007 – 4037.

Tuck A.F., Donaldson D.J., Hitchman M.H., Richard E.C., Tervahattu H., Vaida V., Wilson J. C. (2008), On geoengineering with sulphate aerosols in the tropical upper troposphere and lower stratosphere, Climatic Change 90, 315 – 331.

Contents of Today's Lecture

- Stratospheric Particle injection – Inspired by volcanoes
- Stratospheric Sulfur Aerosol – optimum particle size
- Scalability of sulfur injections
- Side effects of stratospheric particles
- „Improved aerosol“
- Delivery techniques
- Effect on climate
- Conclusion



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

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

Stratospheric Particle Injection – Inspired by Volcanic Eruptions

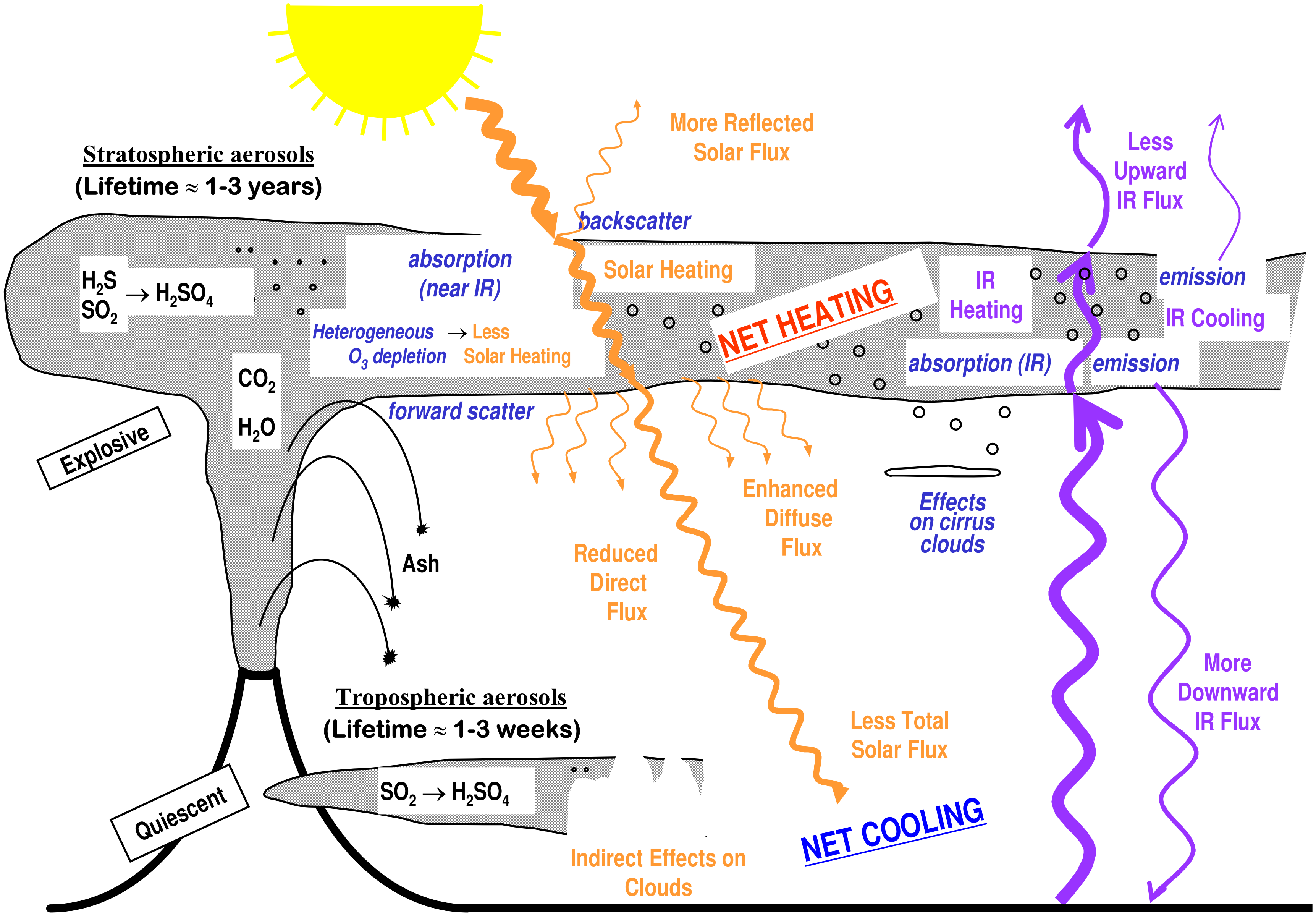
Budyko, Michail: *Climatic Changes*. American Geophysical Society, Washington, DC, 1977 (translated from original 1974 publication in Russian).

Crutzen P. (2006), Albedo Enhancement by Stratospheric Sulfur Injections: A Ccontribution to Resolve a Policy Dilemma? An Editorial Essay, Climatic Change (2006),

Policy Dilemma: CO_2-emission (heating Earth) comes with SO_2-Aerosol (cooling Earth)

"Nevertheless, again I must stress here that the albedo enhancement scheme should only be deployed when there are proven net advantages and in particular when rapid climate warming is developing, paradoxically, in part due to improvements in worldwide air quality."

Stratospheric Sulfate Aerosol



from a presentation by Alan Robock, Heidelberg 2010

Mount Pinatubo (1)
Eruption June 1991

Photo: NASA

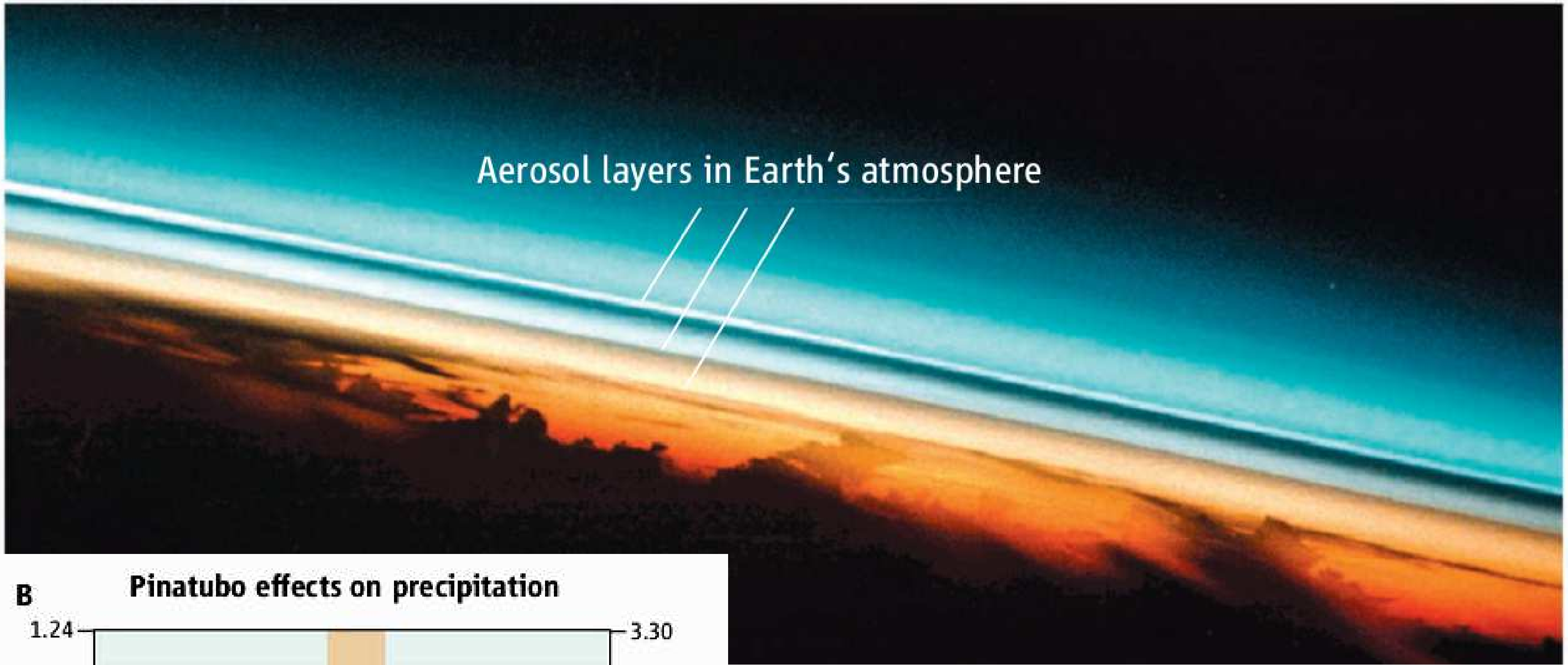
before

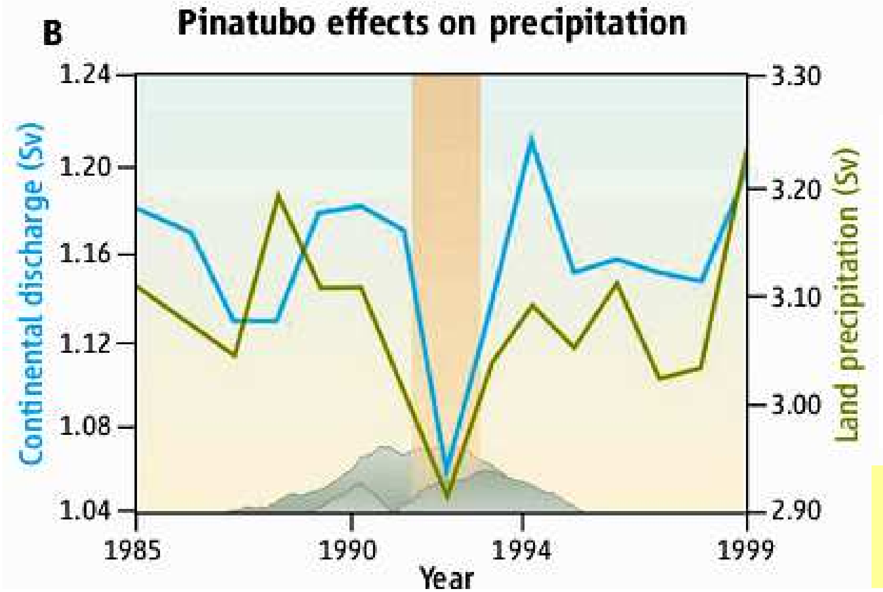
after

Mount Pinatubo (2)

A

Pinatubo aerosols as seen from the space shuttle Atlantis

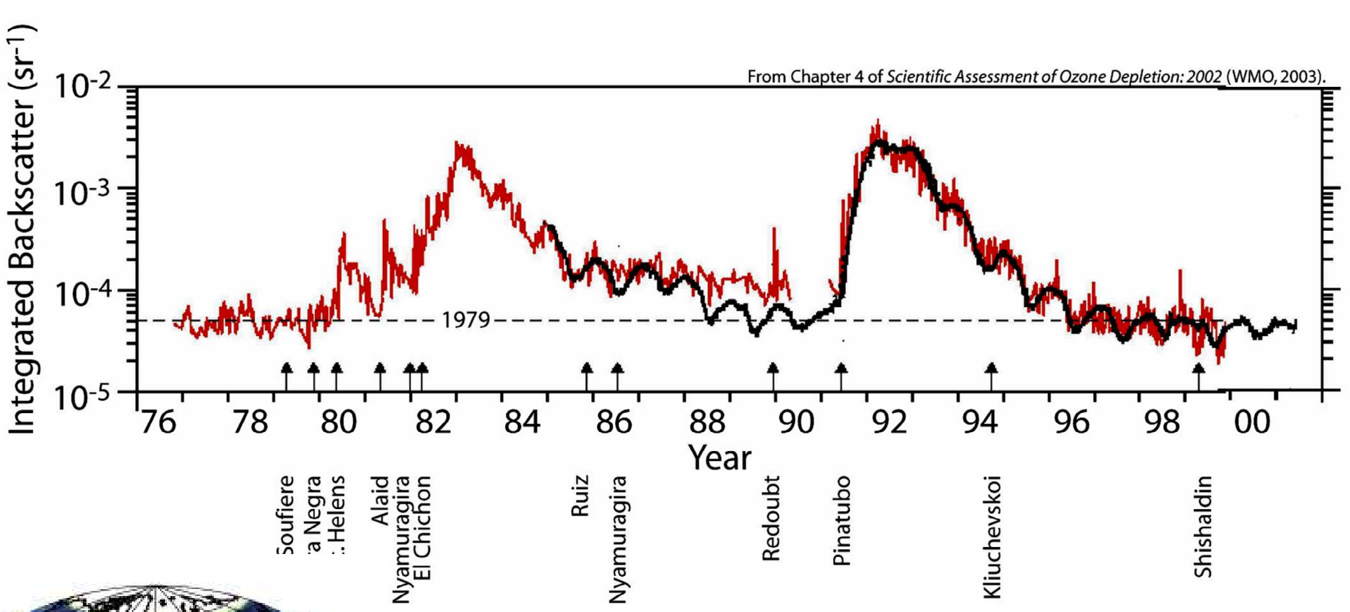


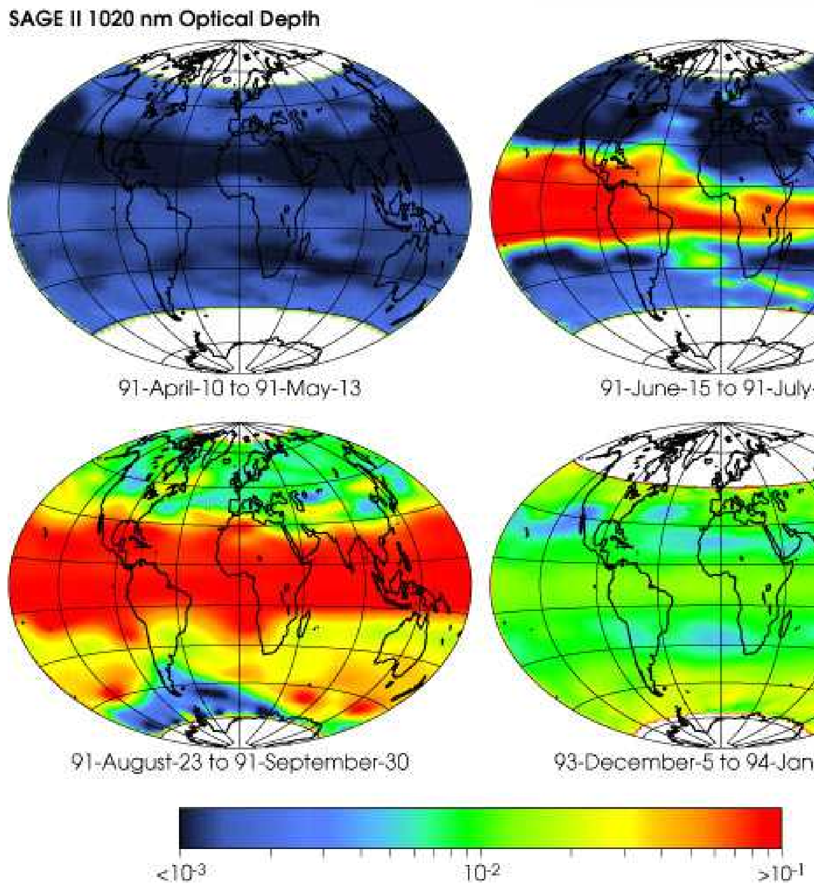


A) Optically thick layers of stratospheric aerosol, taken from space shuttle Atlantis on 11 Aug. 1991. Foto: Earth Sciences & Image Analysis Laboratory, NASA, Johnson Space Center.
B) Continental discharge averaged over the annual water year (October through September values); 1 Sv = 10^6 m^3/s.
From: K.E. Trenberth, A. Dai, Geophys. Res. Lett. 34, L15702, (2007).

Hegerl G.C. and Solomon S. (2009), Risks of Climate Engineering, SCIENCE 325, 955-956.

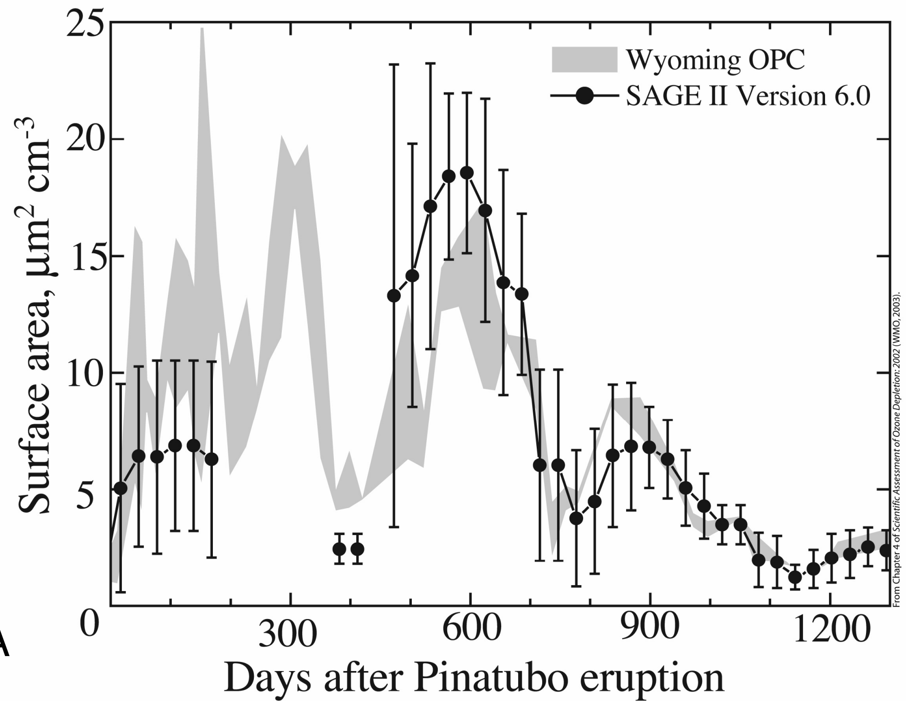
Mount Pinatubo (3)





NASA

WMO (2003)



Mount Pinatubo (4)

Effects of Mount Pinatubo, Philipines volcanic eruption (June 1991) on the radiation balance and on the hydrological cycle as an analog of geoengineering

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

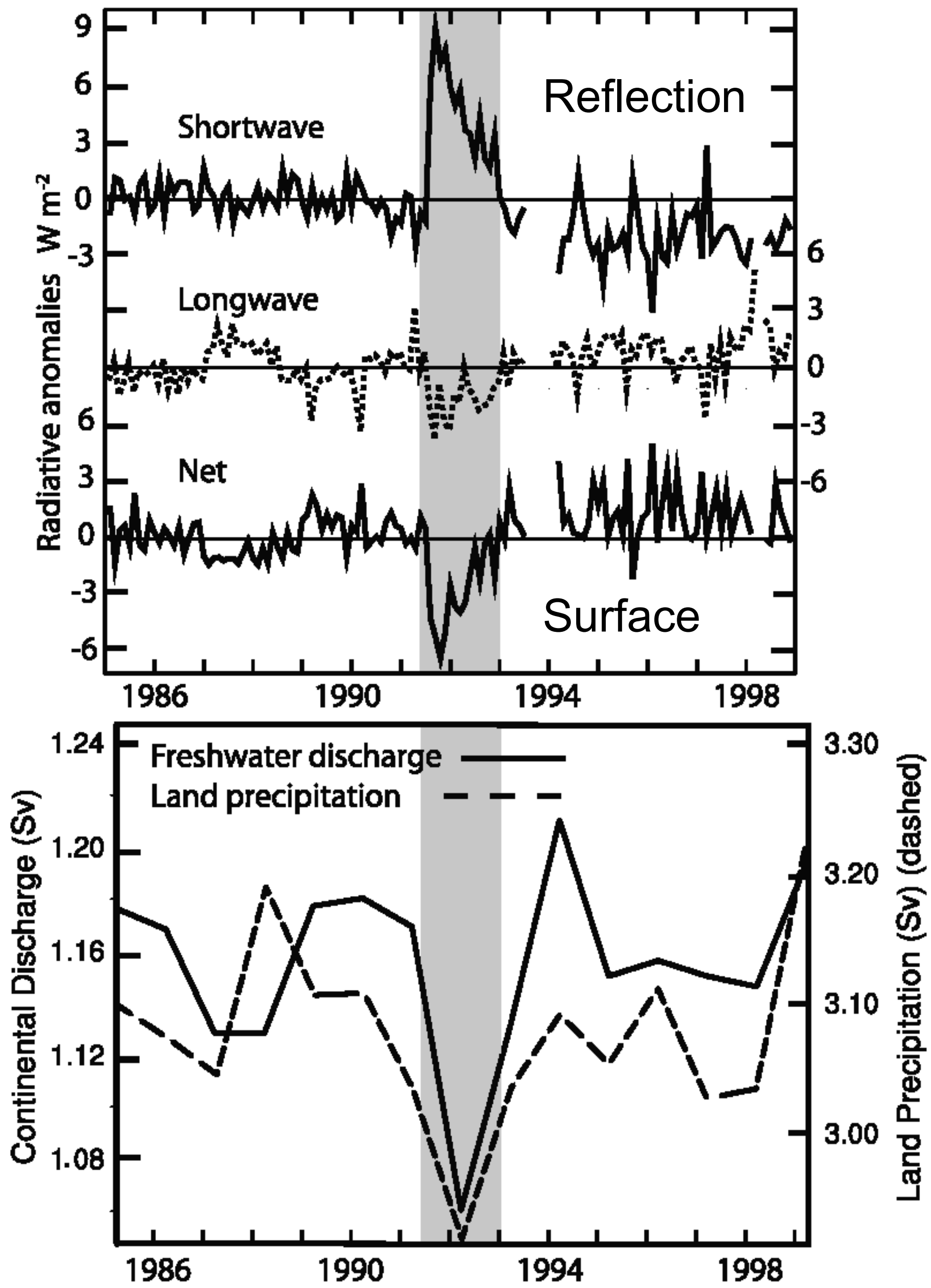
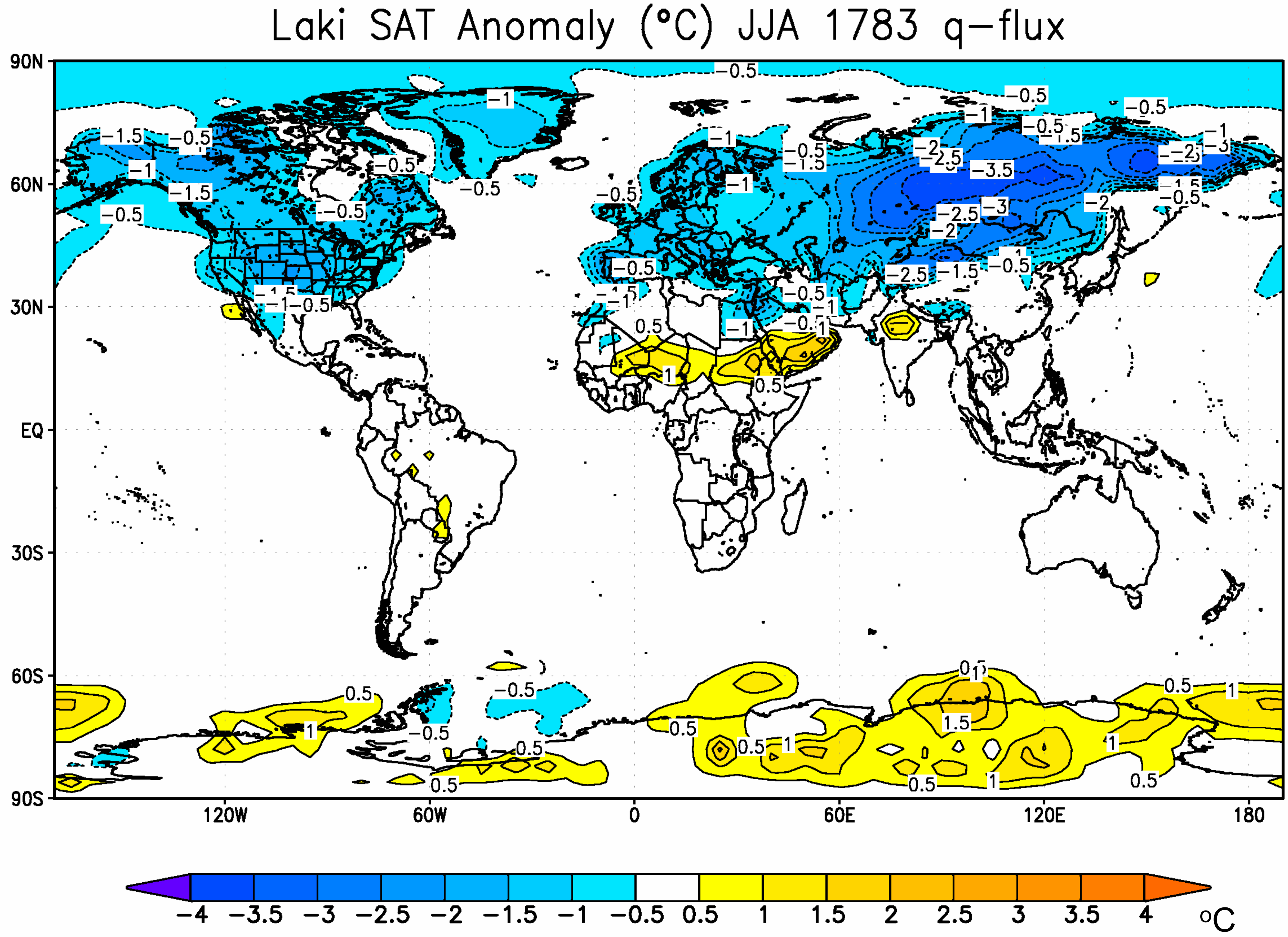


Figure 2. (top) Adapted time series of 20°N to 20°S ERBS non-scanner wide-field-of-view broadband shortwave, longwave, and net radiation anomalies from 1985 to 1999 [*Wielicki et al.*, 2002a, 2002b] where the anomalies are defined with respect to the 1985 to 1989 period with Edition 3_Rev 1 data [*Wong et al.*, 2006]. (bottom) Time series of the annual water year (Oct. to Sep.); note slight offset of points plotted vs. tick marks indicating January continental freshwater discharge and land precipitation (from Figure 1) for the 1985 to 1999 period. The period clearly influenced by the Mount Pinatubo eruption is indicated by grey shading.

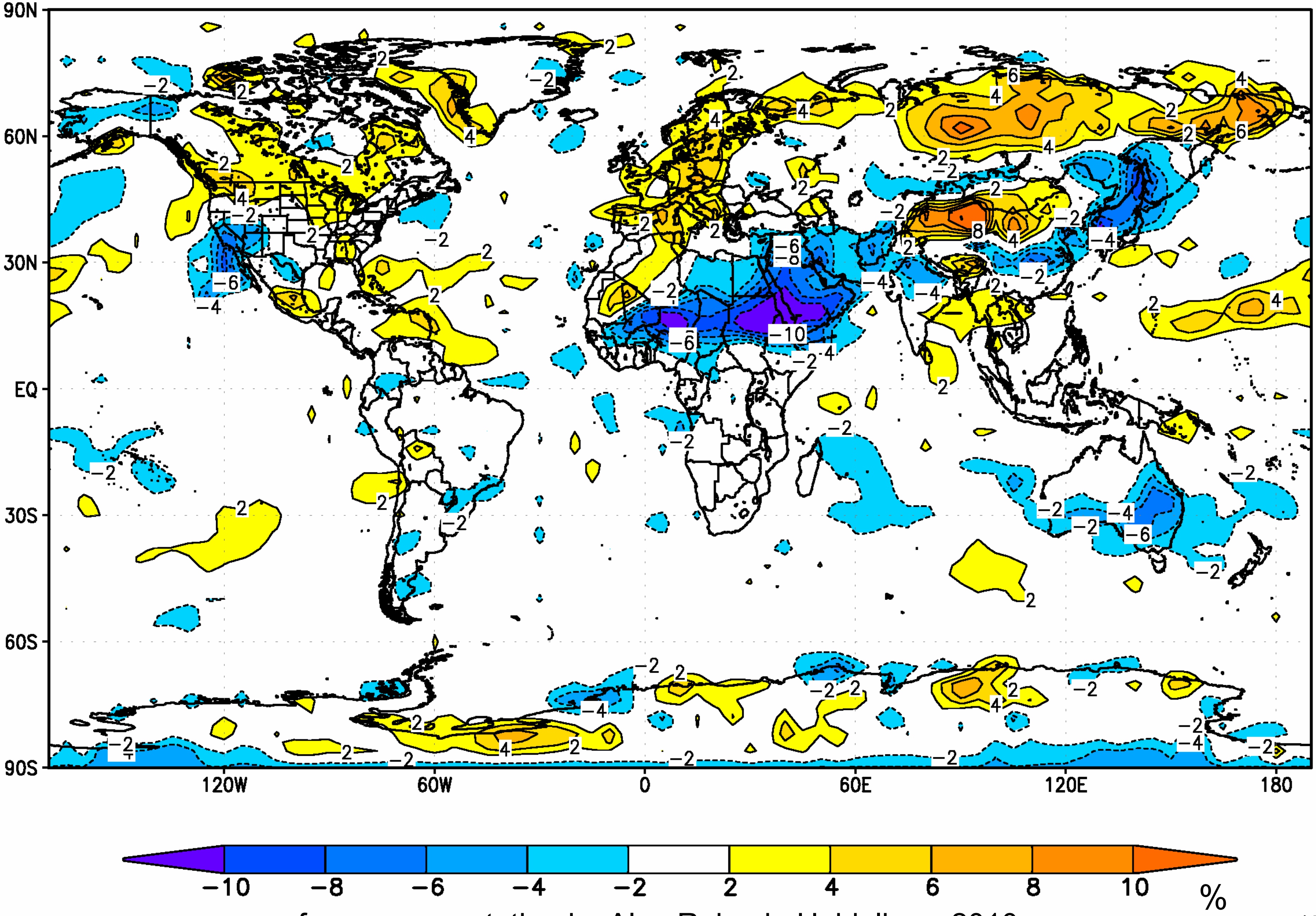
from a presentation by Alan Robock, Heidelberg 2010

1783-84, Lakagígar (Laki), Iceland



from a presentation by Alan Robock, Heidelberg 2010

Laki Cloud Cover Anomaly (%) JJA 1783 q-flux



from a presentation by Alan Robock, Heidelberg 2010

Effectiveness of Particles in the Stratosphere

Parameter	Property	Dependance on radius (r)
Scattering of radiation	Cross-sectional area Albedo (of the particle) (also: „colour“)	r^2 $\frac{r}{\text{wavelength}}$
Mass (instantaneously required in the stratosphere)	Volume, Density	r^3
Lifetime (determines amount of mass to be deposited in the strat. annually)	Settling velocity Coagulation	r^2 (or r) $\sqrt{\text{Mass}} \propto r^{3/2}$
Chemical Effectivity	Surface area	r^2

Aerosol Physics: Settling Velocity

Why don't aerosol particles simply drop to the ground?

Settling velocity v of a spherical particle (mass m) in a viscous fluid (e.g. air):

a) Acceleration by gravitational force minus buoyancy:

$$F_G = mg - b = \frac{4\pi}{3} r^3 g \left(\rho_p - \rho_f\right) \approx \frac{4\pi}{3} r^3 g \rho_p$$

ρ_p: Density of the particle
ρ_f: Density of the fluid

b) Deceleration by frictional (drag) force: Stokes' law

$$F_S = 6\pi\mu r v$$

μ: dynamic viscosity of the fluid
r: radius of the particle

Stokes' law is valid for laminar flow up to Re $\approx$ 0.1

→ Settling (or terminal) velocity from $F_G = F_S$:

$$v = \frac{2}{9} \cdot \frac{g r^2}{\mu} \cdot \rho_p$$

Note: $v \propto r^2$

E.g. for particle with r = 1 μm, $\rho = 10^3$ kg/m^3 in air: $v \approx 10^{-4}$ m/s or 10 m/d

Stratosphere: Do Particles Settle Faster in Thin Air?

Settling velocity:

$$v = \frac{2}{9} \cdot \frac{gr^2}{\mu} \cdot \rho_p$$

Dynamic viscosity:

$$\mu = \rho_{air} \cdot \underbrace{\nu}_{\text{kinematic viscosity}} = \rho_{air} \cdot \frac{1}{3} \lambda_{air} v_{molec}$$

Mean free path:

$$\lambda_{air} = \frac{1}{\sqrt{2} n \sigma} = \frac{M}{\sqrt{2} \cdot \rho_{air} N_{Avogadro} \sigma}$$

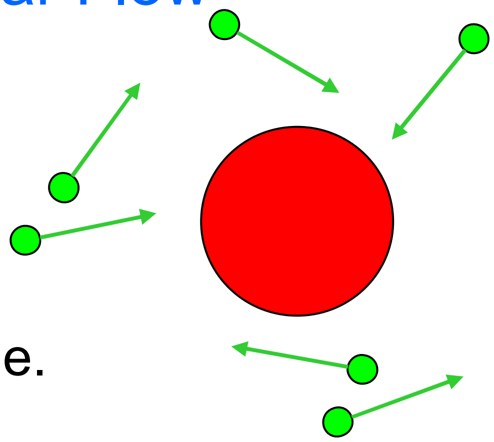
M = Molar Mass (kg/mole) of air

σ = collision cross section of air molecules

$$\Rightarrow \mu = \rho_{air} \cdot \frac{1}{3} \frac{M}{\sqrt{2} \cdot \rho_{air} N_{Avogadro} \sigma} v_{molec} = \underbrace{\frac{1}{3\sqrt{2}} \frac{M}{N_{Avogadro} \sigma}}_{\text{constant}} \cdot \underbrace{v_{molec}}_{\propto \sqrt{T}}$$

Dynamic viscosity is independent of pressure! → settling velocity (of large particles) essentially independent of altitude (only T-effect)

Small Particles: Molecular Flow



Very small particles: Is continuum mechanics O.K.?

Knudsen Number: $$Kn = \frac{\text{mean free path}}{\text{particle radius}} = \frac{\lambda_{air}}{r}$$

For Kn << 1 the fluid can be described as a continuum, i.e. by macroscopic quantities such as viscosity and density.

For air: Remember $\lambda_{air} = \left(\sqrt{2} n \sigma\right)^{-1} \approx 0.06\ \mu m$ at 1 atm, $2.4\ \mu m$ at 25 mbar

Thus for particle with r =1 μm: Kn ≈ 0.06 << 1 (1 atm), Kn ≈ 2.4 at 25 mbar

For Kn > 1 (λ_{air} > r) we are in the regime of molecular flow.
Stokes' law for the frictional force must be modified.

$$F_S = 6\pi\mu r v \frac{1}{1 + A \cdot Kn} \xrightarrow[A \approx 1]{r \to 0} 6\pi\mu v \frac{r^2}{\lambda_{air}}$$ Stokes-Cunningham formula

→ Settling velocity for large Kn (small particles, low pressure):

$$v = \frac{2}{9} \cdot \frac{g \lambda_{air} r}{\mu} \cdot \rho_p \quad \propto \frac{1}{p}, \propto r$$

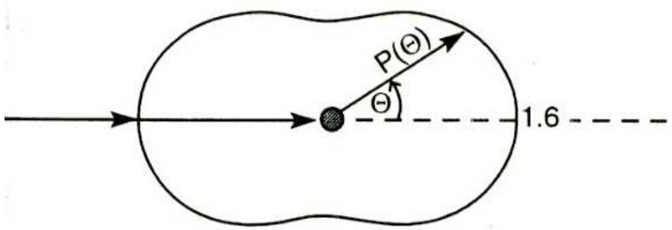
Note: $v \propto r$ (not r^2)

→ Small particles do settle faster in the stratosphere!

Rayleigh scattering: scattering on air molecules

radius of scatterers $r \ll \lambda$

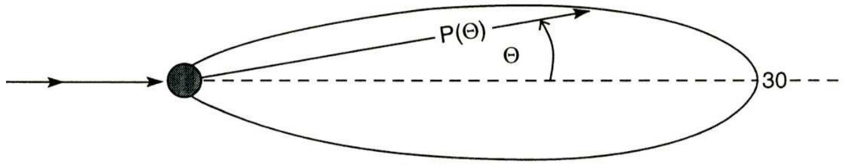
SW radiation ($\lambda \approx$ 100s of nm) and gas molecules ($r \approx 0.1$ nm)



Mie scattering: Scattering on particles, aerosols, droplets

radius of scatterers $r \geq \lambda$

SW radiation and aerosol particles or droplets (100 nm < r < 50 µm)



Size parameter x to compare particle size and wavelength of light:

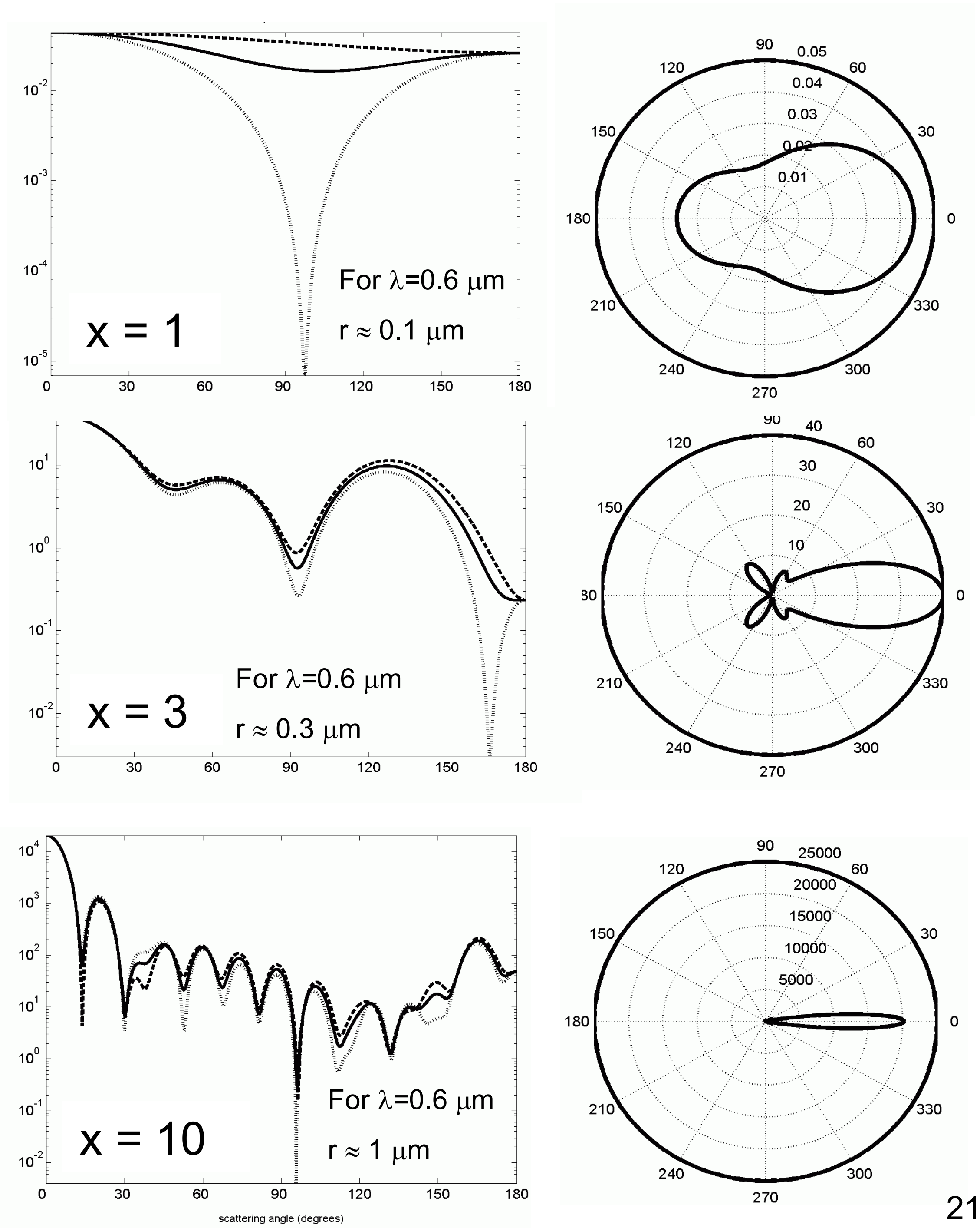
$$x = \frac{2\pi r}{\lambda}$$

$x \ll 1$ for molecules and fine particles: Rayleigh Scattering

$x \geq 1$ for coarse particles and clouds: Mie Scattering

ng Phase Functio

Problem: Scattering mostly forward, in particular for large particles



Size Parameter:

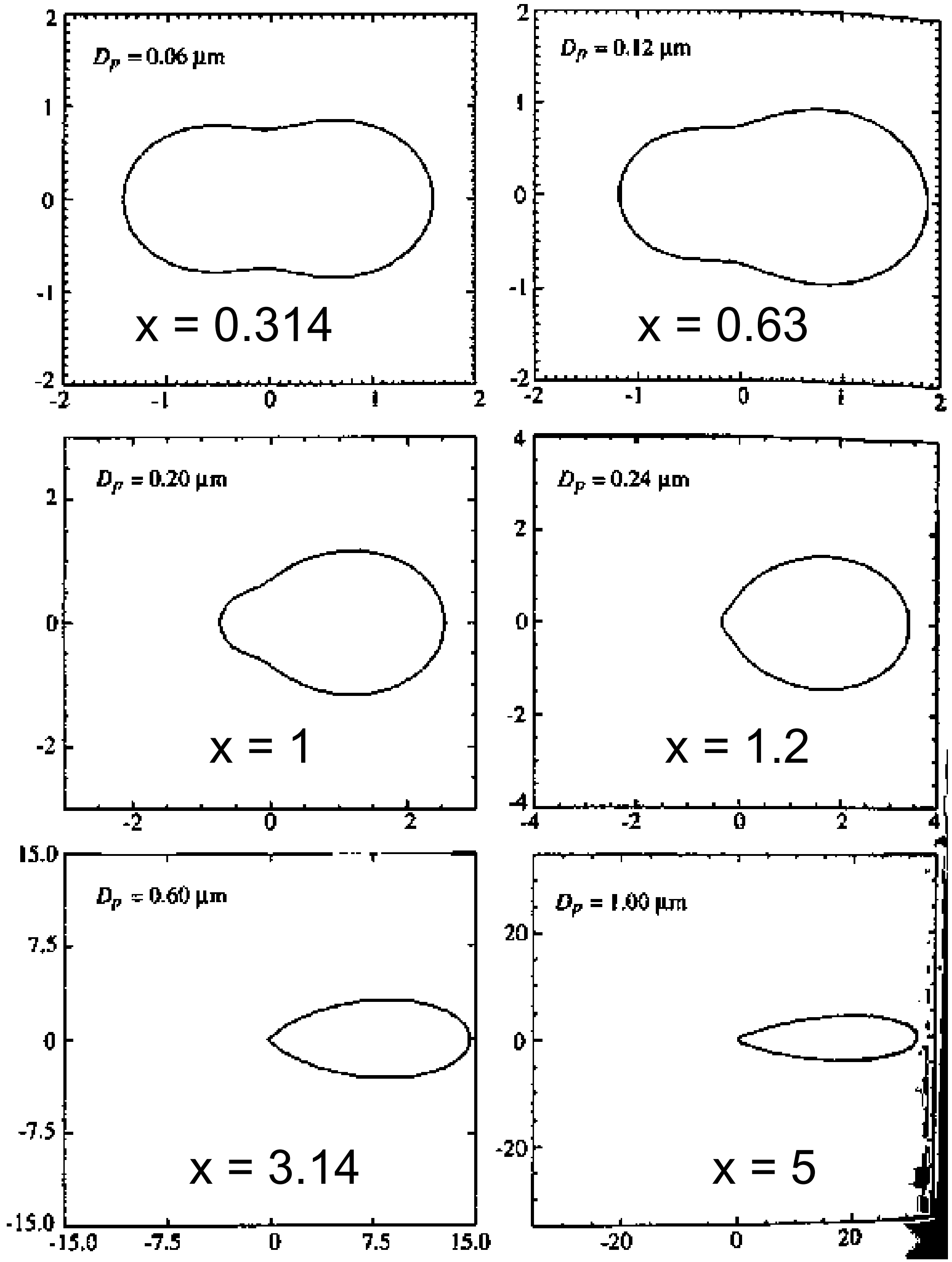
$$x = \frac{2\pi r}{\lambda}$$

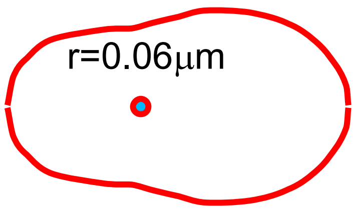
→ Particles must be small!

From: Thesis Sanghavi

More Phase Functions

λ = 0.6μm

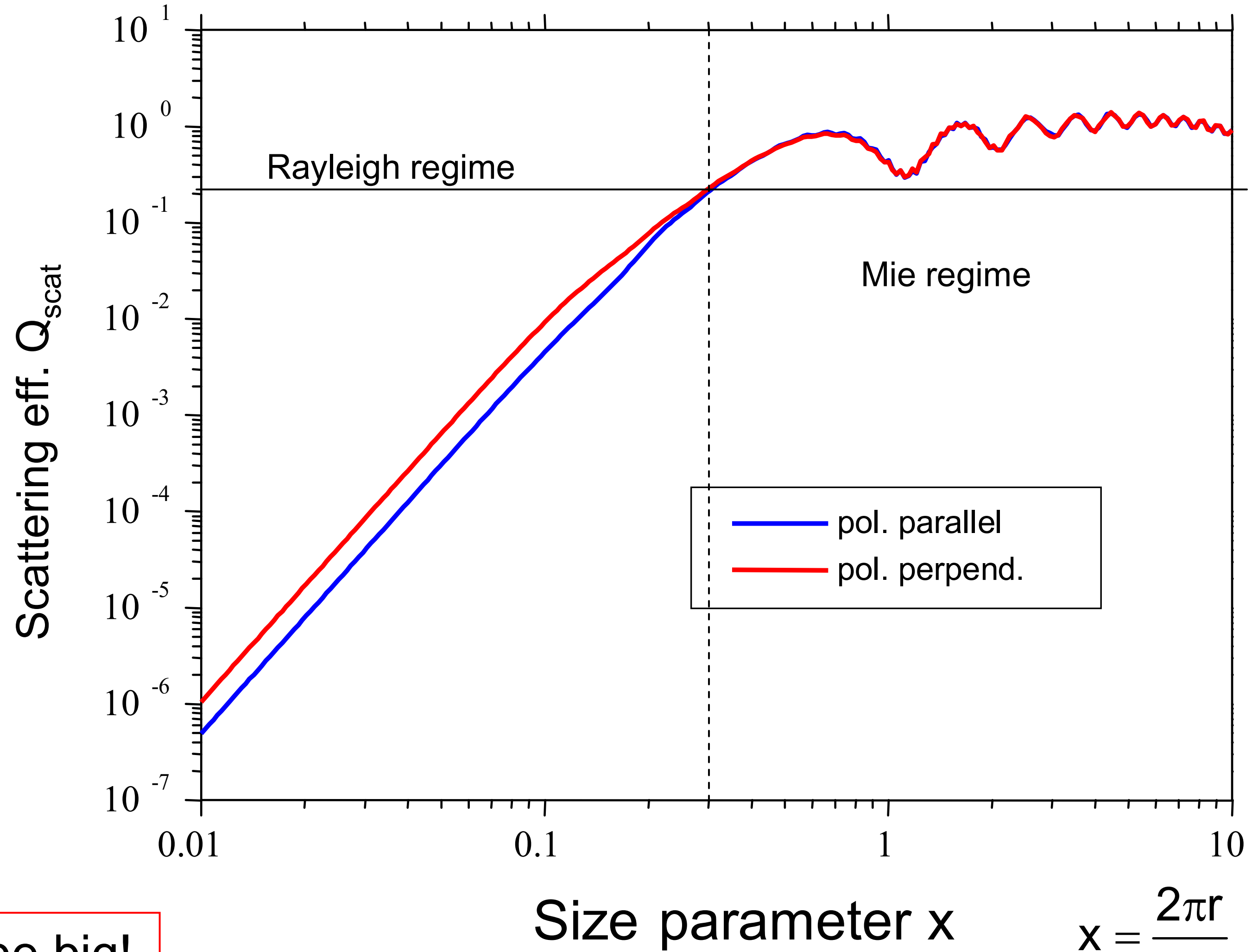




Scattering Efficiency as a Function of Particle Size

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

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



$$x = \frac{2\pi r}{\lambda}$$

→ Particles must be big!

Optimal Particle Size?

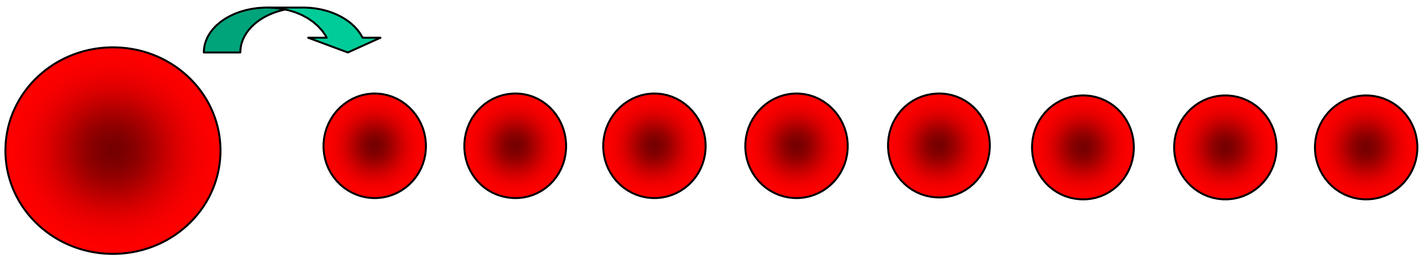
Small Particles → More Surface/Mass (less mass needed)

→ But at size parameter $x < 1$ rapidly decreasing scattering efficiency

→ But more scattering in backward direction

→ also: particles settle less rapidly

→ However, the useful lifetime of particles is also limited by the stratospheric circulation



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

Aerosol Backscatter Fraction as a Function of Size Parameter

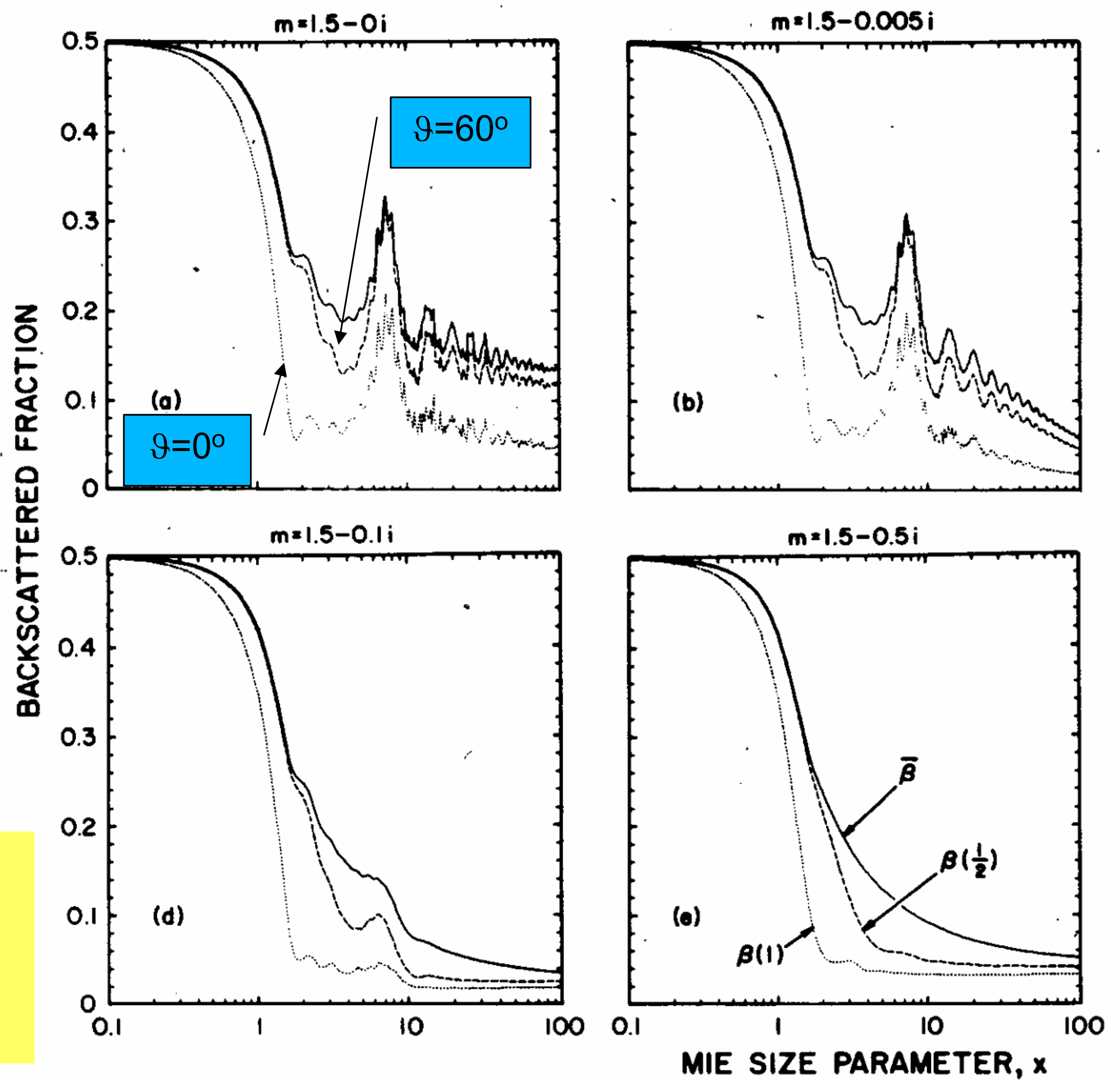
Backscatter Fraction(BF)

$$\beta = \beta\left(\underbrace{\mu}_{\cos\vartheta}\right)$$

ϑ = scattering angle

$$\bar{\beta} = \int_0^1 \beta(\mu)\,d\mu$$

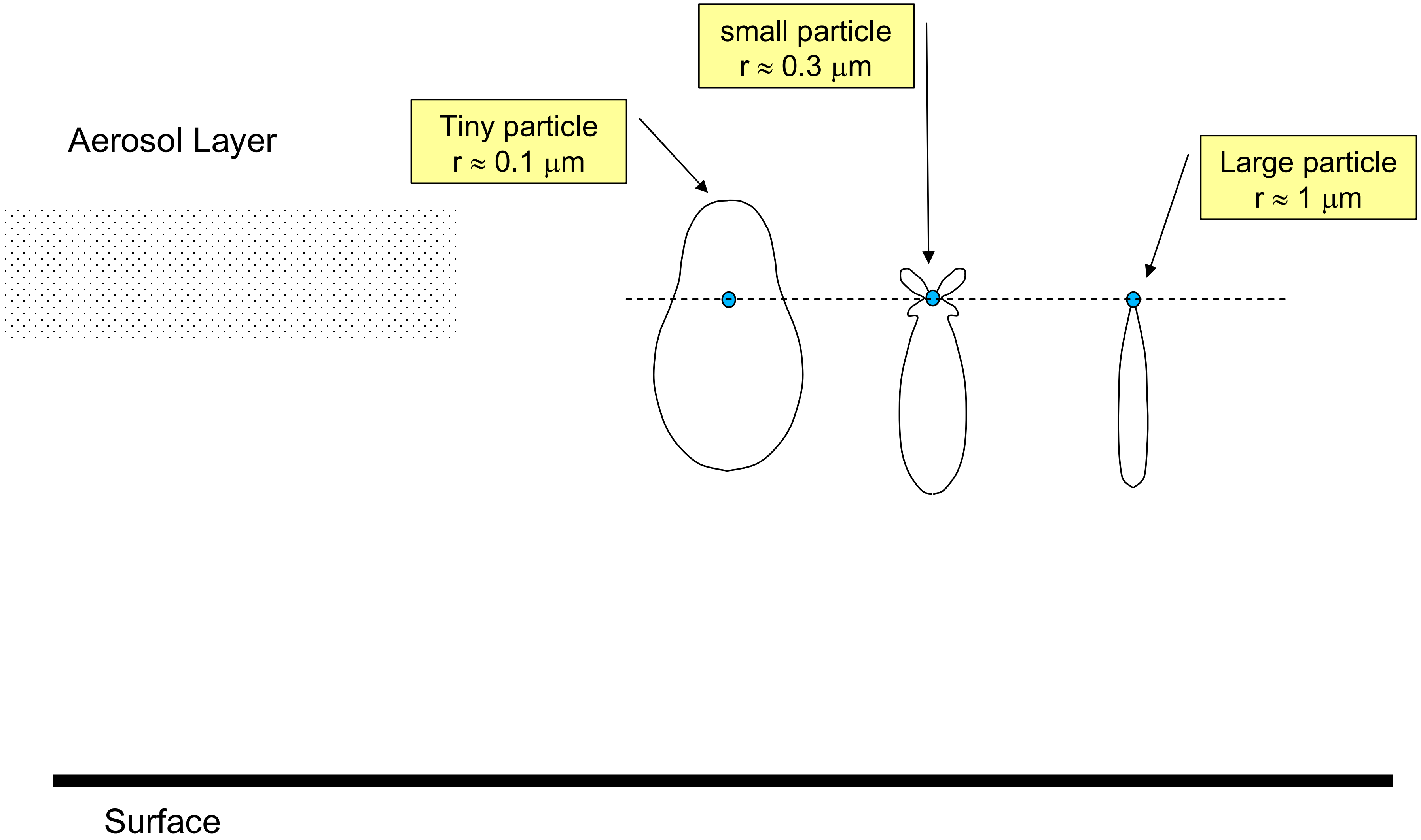
= BF for omnidirectional illumination



Wiscombe W. and Grams G. (1976), The back-scattered fraction in two-stream approximations, J. Atmos. Sci. 33, 2440–2451.

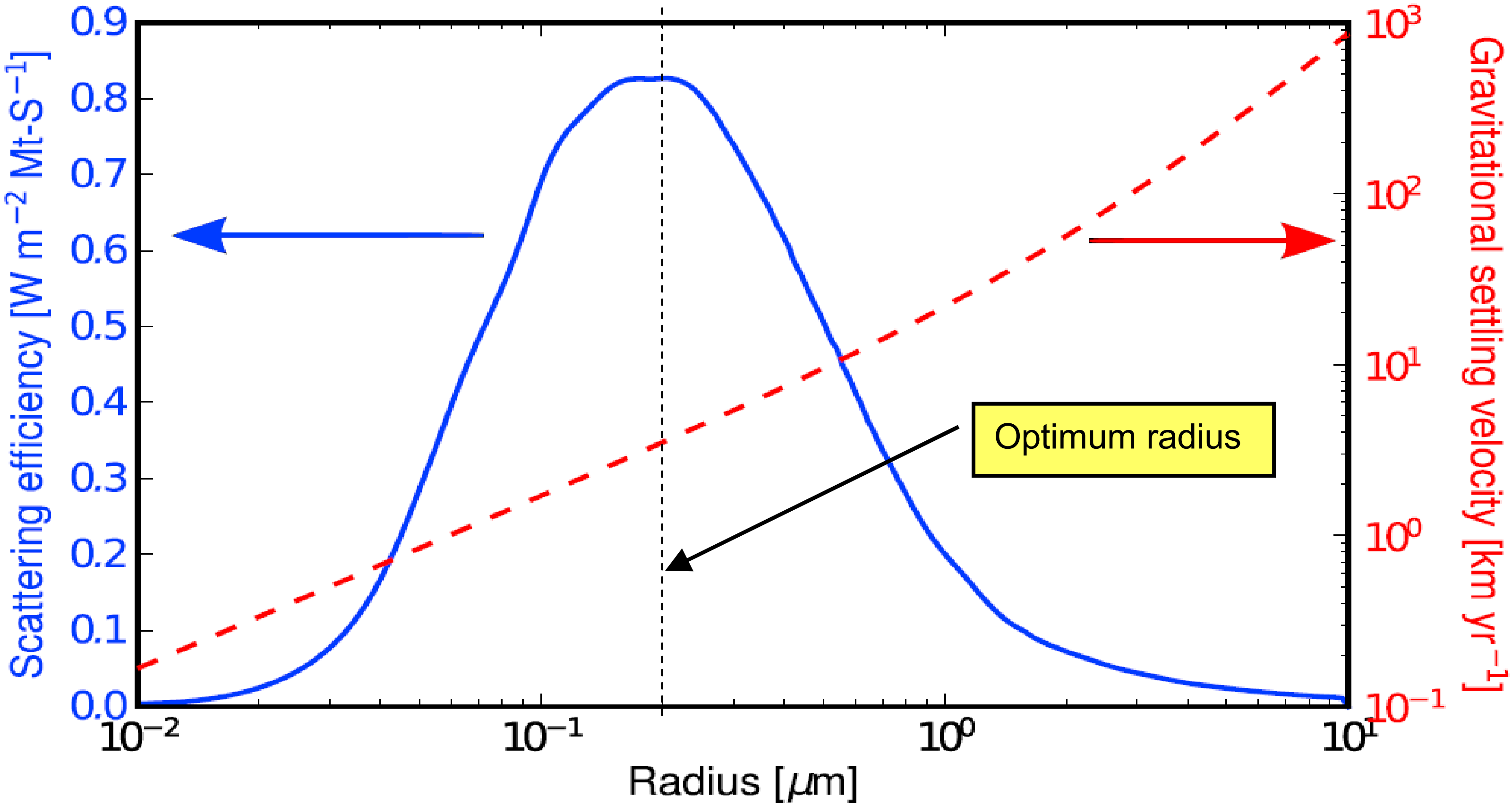
Scattering of Short-Wave Radiation λ=0.6 μm

Mie Scattering Diagrams



Optimal Particle Size

Pierce et al. Geophys. Res. Lett. 37, L18805, doi:10.1029/2010GL043975, 2010

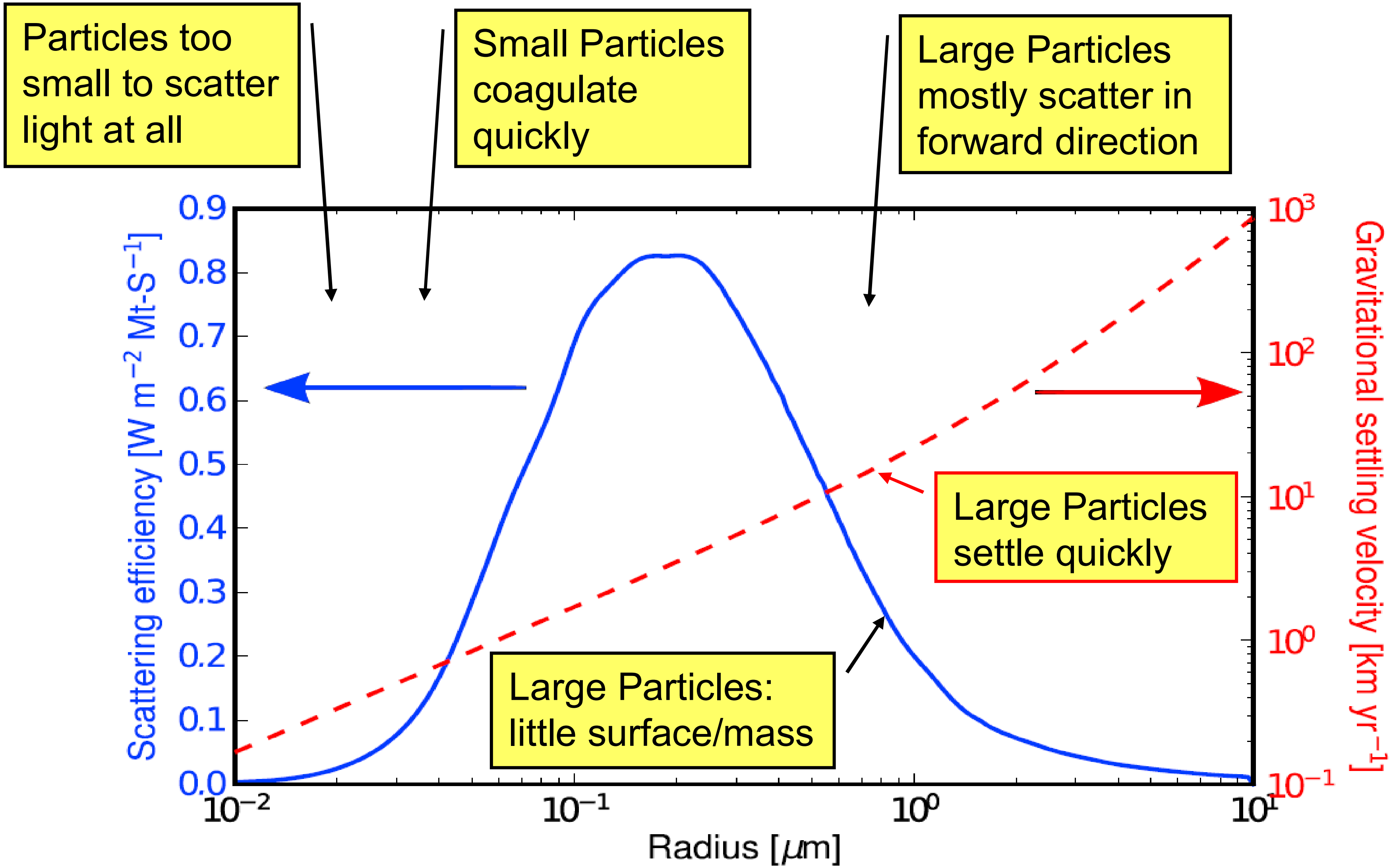


Dependence of parameters of the radiative forcing of stratospheric aerosol on radius

Blue: SW-cooling effect relative to the particle mass in the stratosphere

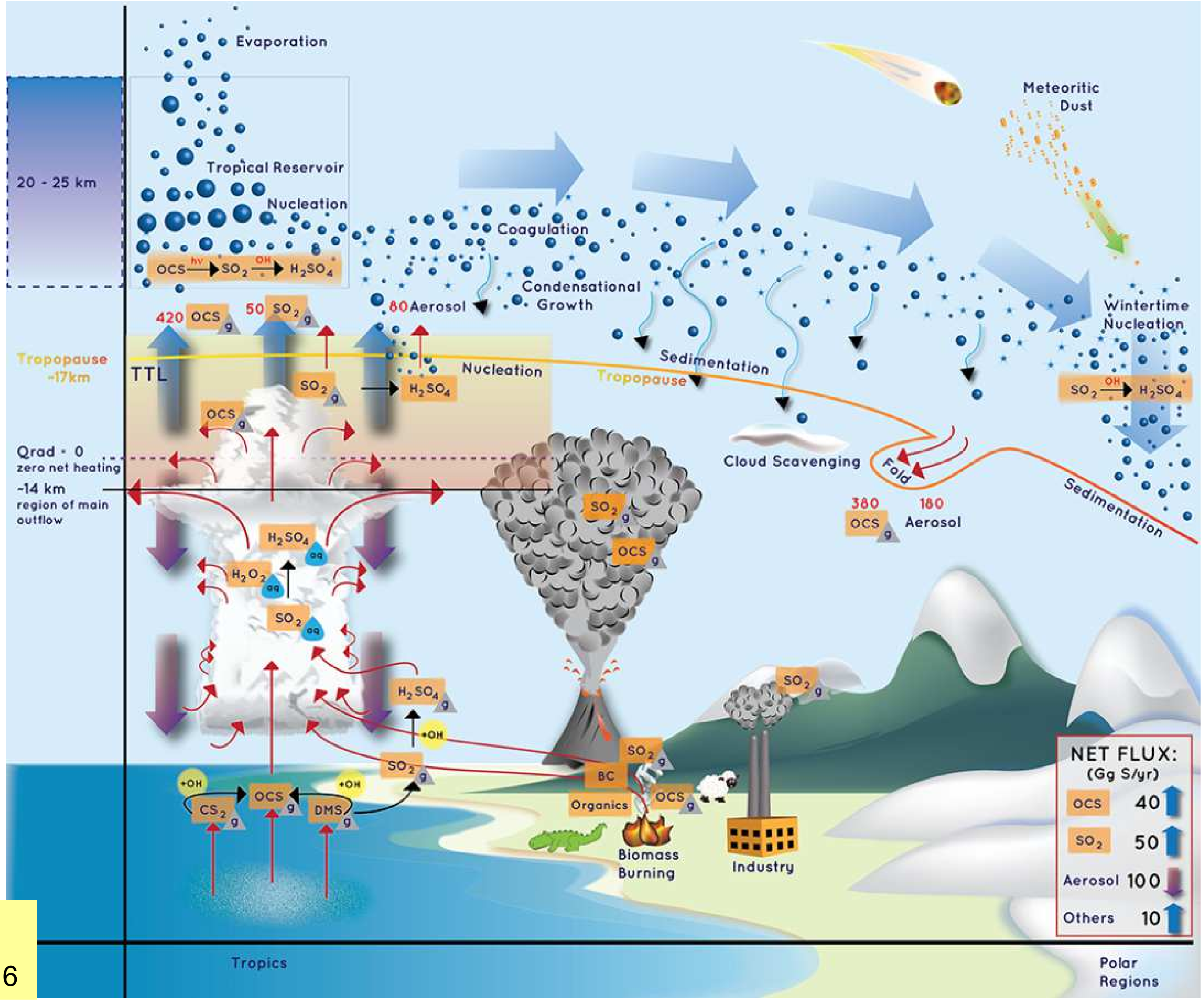
Red: Settling velocity of the particles (calculated for 25 km altitude).

Problems of Stratospheric Aerosol SRM



Pierce et al. Geophys. Res. Lett. 37, L18805, doi:10.1029/2010GL043975, 2010

Stratospheric Aerosol Life Cycle



From:

Kremser et al., 2016

Which Particle Size-Distribution will Result?

Processes:

1) $SO_2 \rightarrow H_2SO_4$ conversion
2) Nucleation (new particle formation)
3) Condensation (growth of existing particles)
4) Coagulation
5) Sedimentation

SW Scattering vs. LW scattering

Optimum particle radius $r=0.2\mu m$

→

Size parameter for visible (SW) radiation:

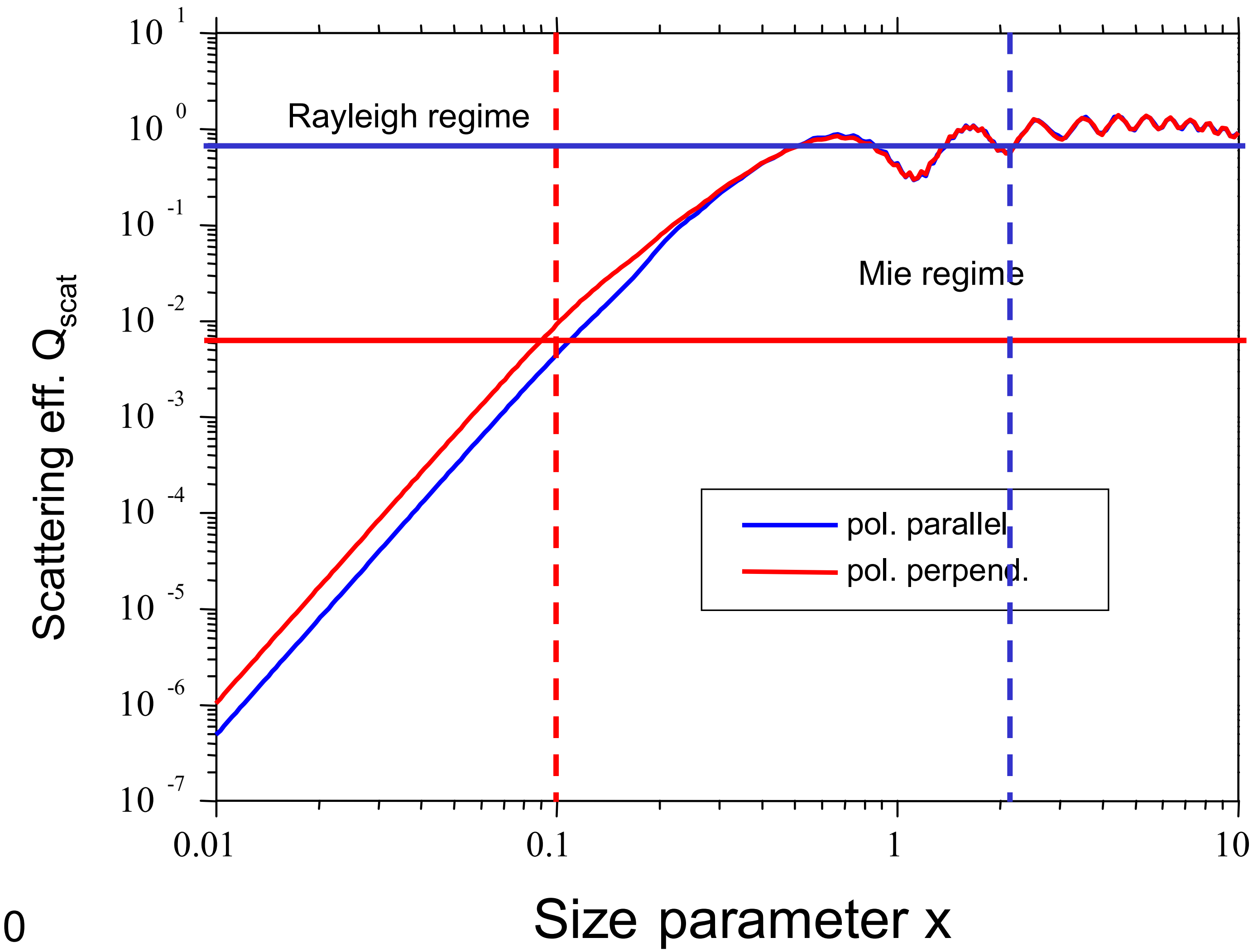
$$x_{SW} = \frac{2\pi r}{\lambda} \approx \frac{2\pi \cdot 0.2\mu m}{0.6\mu m} \approx 2.1$$

$$\Rightarrow Q_{scatt} \approx 0.8$$

Size parameter for thermal IR (LW) radiation:

$$x_{LW} \approx \frac{2\pi \cdot 0.2\mu m}{12\mu m} \approx 0.10$$

$$\Rightarrow Q_{scatt} \approx 0.007$$



Coagulation of Sulfuric Acid-Aerosol

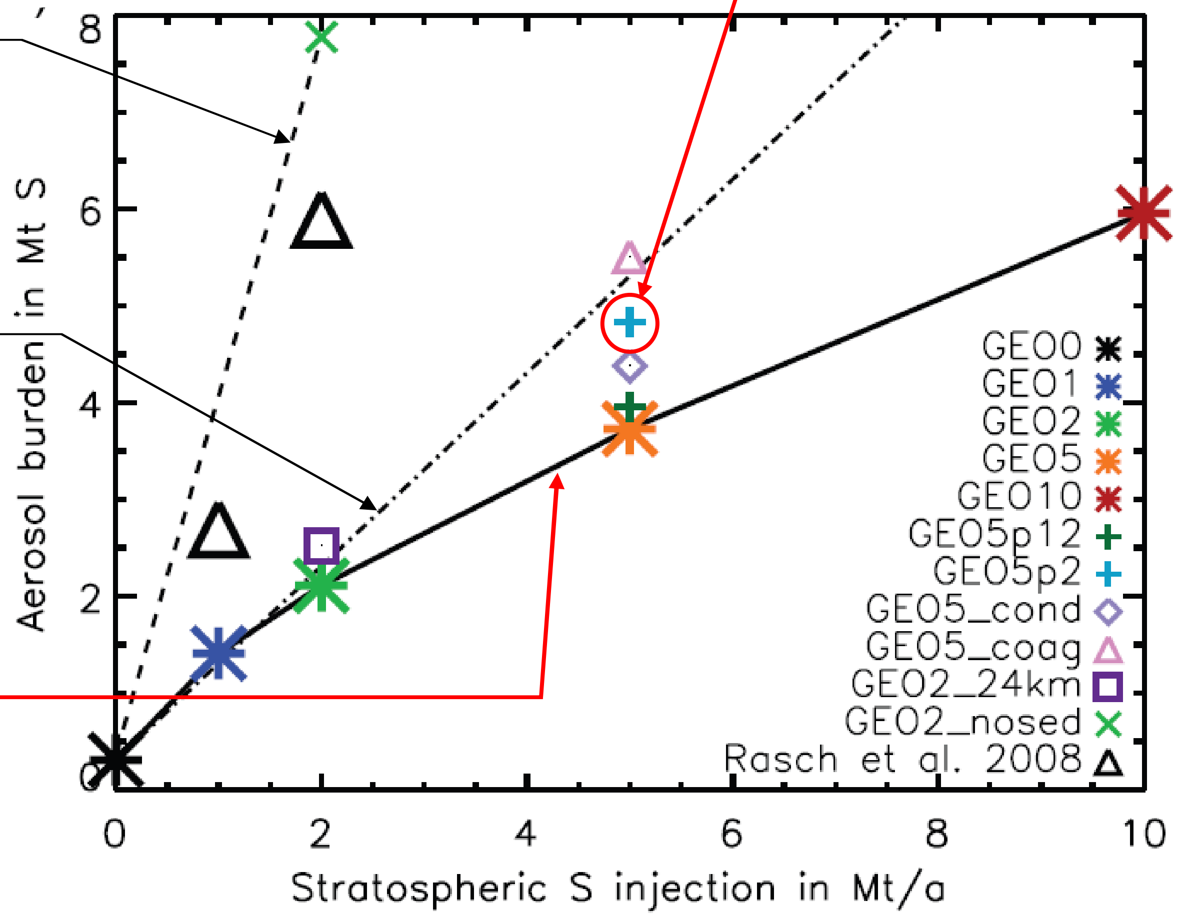
All calculations assume injection in the latitude range 5°S-5°N at 20±0.6km altitude.

Total aerosol mass in the stratosphere (in Mt) as function of the annually injected mass (Mt/Jahr), **No Sedimentation**

Total aerosol mass in the stratosphere (in Mt) as function of the annually injected mass (Mt/Jahr), **assuming 1 year lifetime.**

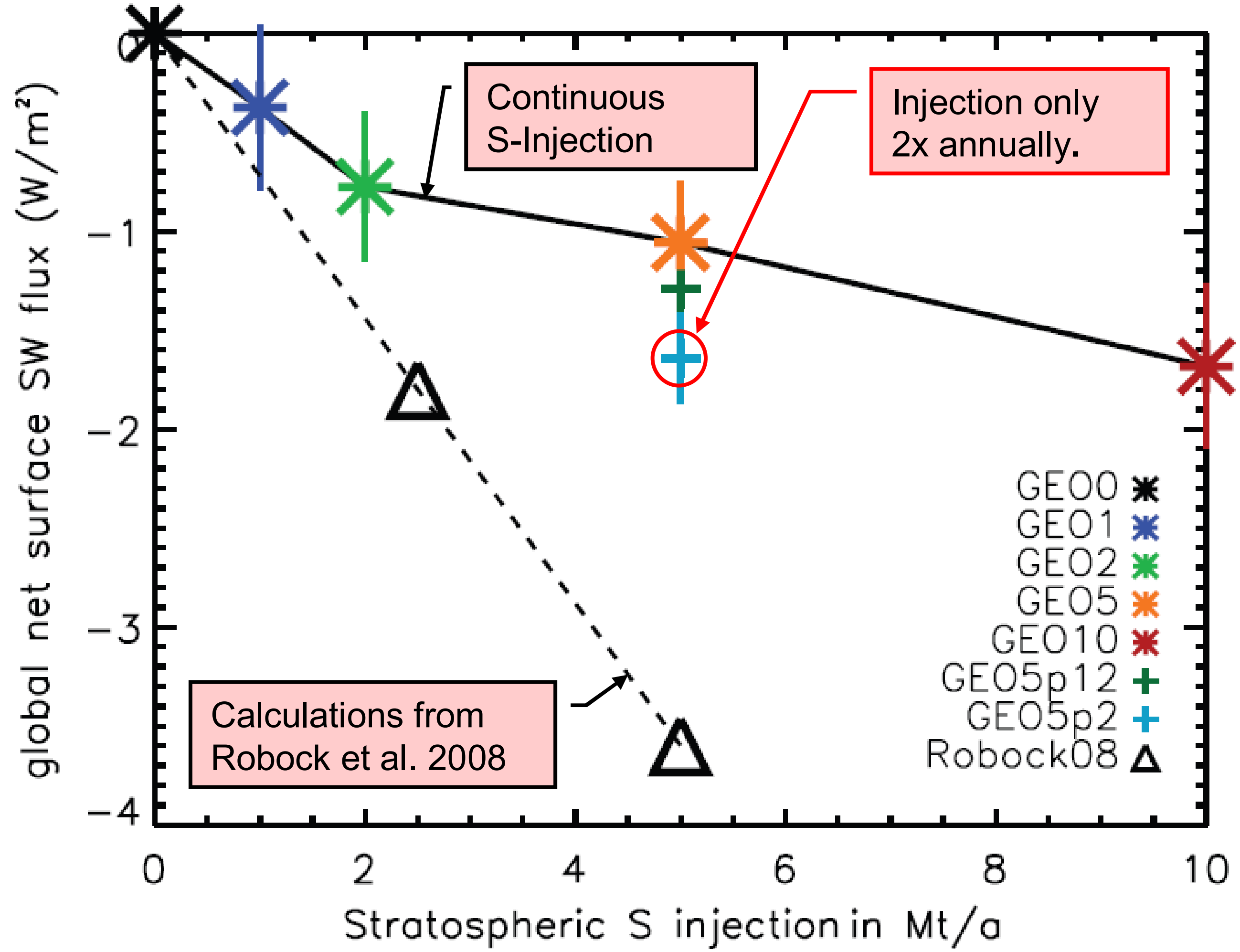
Total aerosol mass in the stratosphere (in Mt) as function of the annually continuously injected mass (Mt/Jahr), **Calculation includes coagulation and deposition.**

Injection only 2x annually**.**



Heckendorn P, Weisenstein D., Fueglistaler S., Luo B.P., Rozanov E., Schraner M., Thomason L.W. and Peter T. (2009), The impact of geoengineering aerosols on stratospheric temperature and ozone, Environ. Res. Lett. 4, 045108 (12pp) doi:10.1088/1748-9326/4/4/045108.

Cooling Effekt of Sulfur Injetions into the Stratosphere



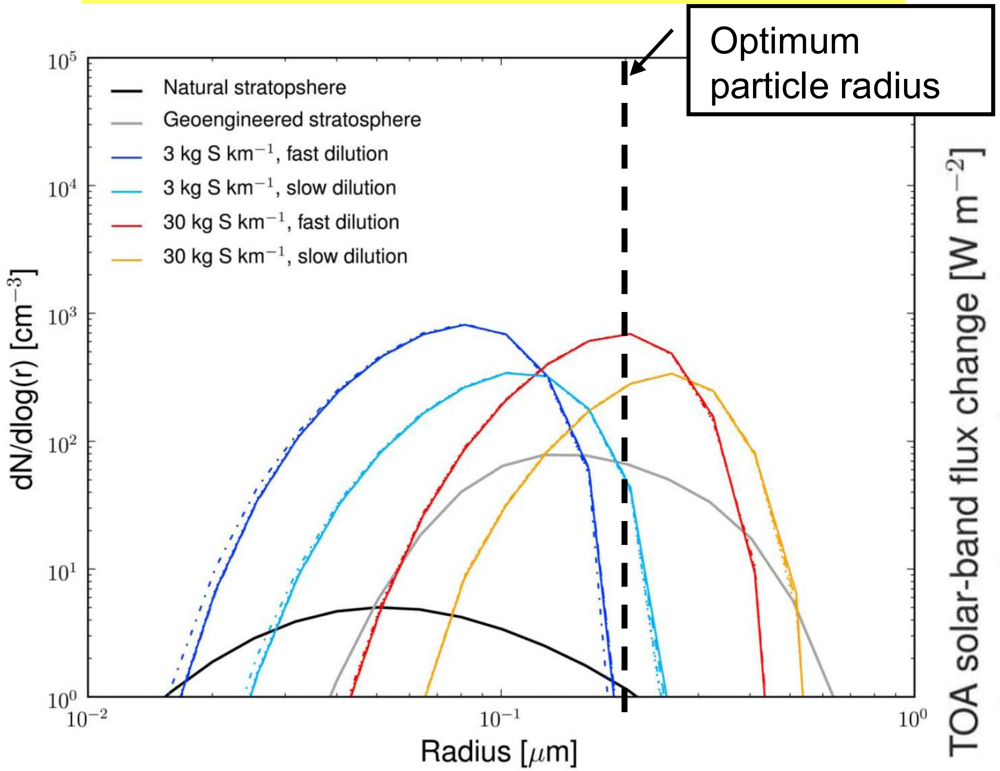
Calculations of Heckendorn et al. 2009:
Reduction of the global net Insolation (net SW-Flx) as function of the mass of sulfur (in Mt/year) annually injected into the stratosphere.

→ At large amounts of S the cooling effect increases only marginally!

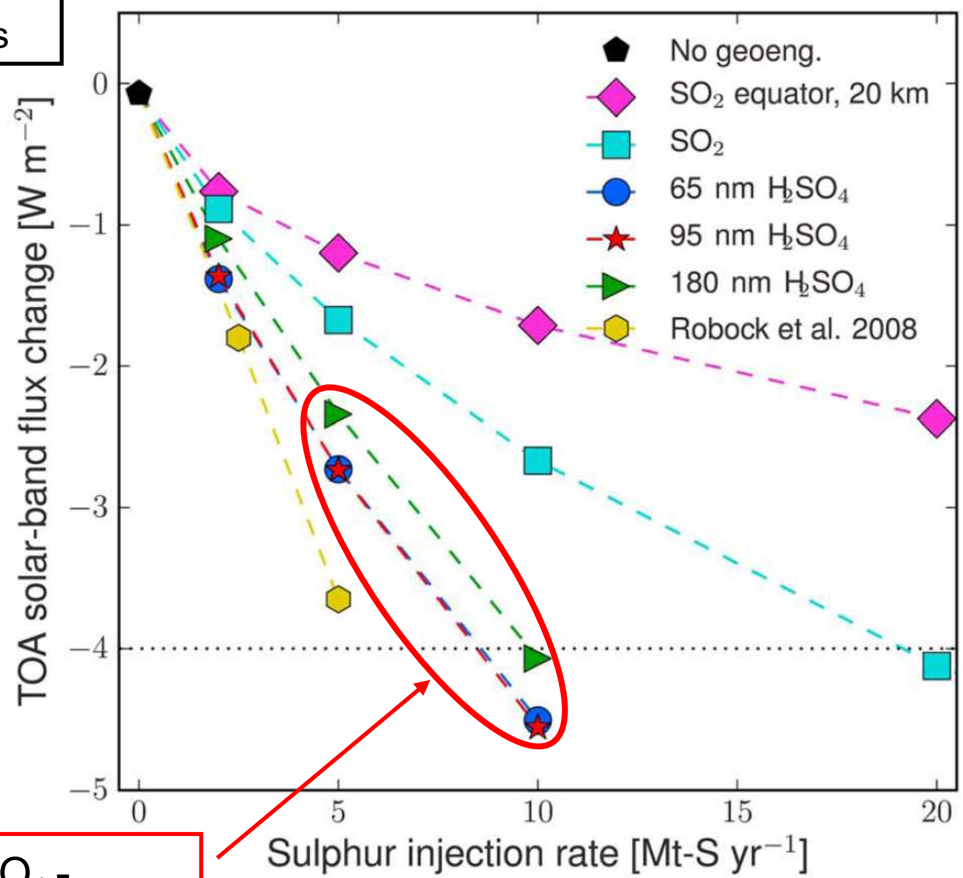
→ Extrapolation from Volcanic events too optimistic!

Solution of the Coagulation Problem – by direct Injection of Sulfuric Acid into the Stratosphere?

Aerosol size distribution for direct H_2SO_4 – injection into the stratosphere



Reduction of the radiative forcing as function of annual mass of sulfur injected



Injection of H_2SO_4 - aerosol instead of SO_2

However, see:

Niemeier et al. 2011

English et al. 2012

Pierce et al. Geophys. Res. Lett. 37, L18805, doi:10.1029/2010GL043975, 2010

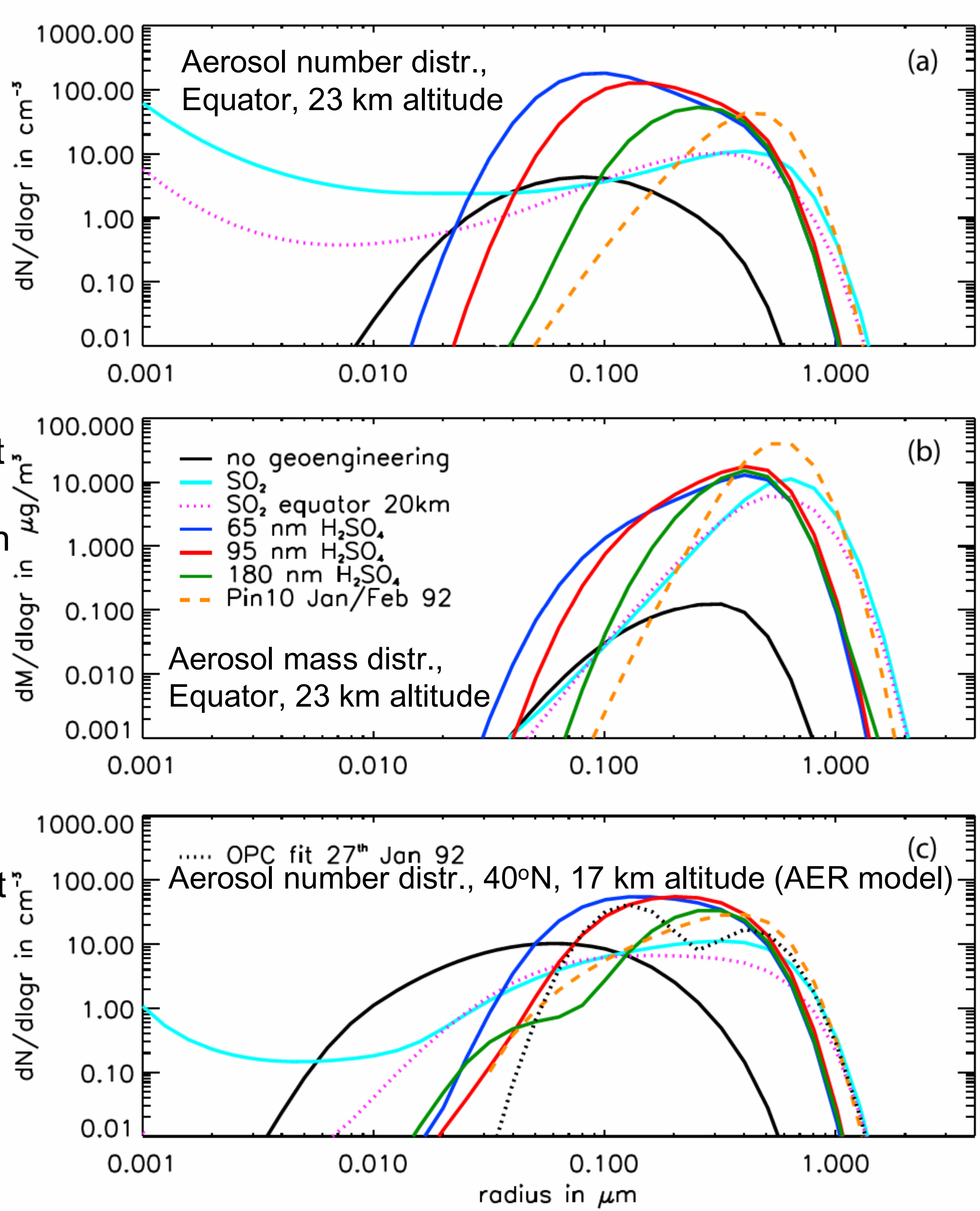
Stratospheric Aerosol
(annual average)

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

Dashed magenta lines:
Geoengineering (5 MTS/a) as SO_2 at a single grid point centered at the equator and 20 km [from Heckendorn et al., 2009].

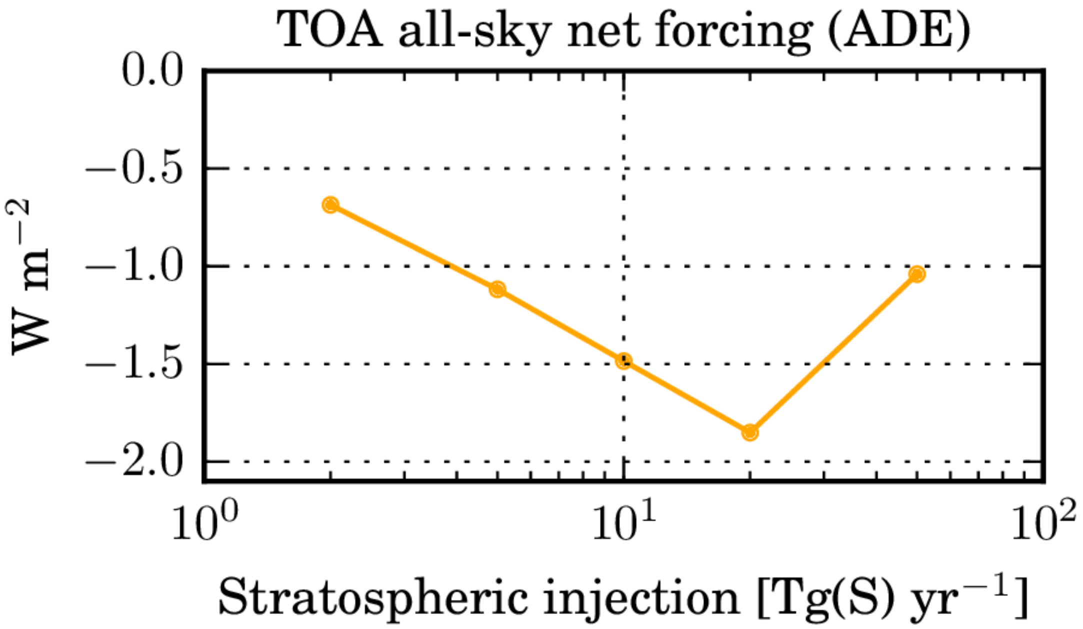
Dashed orange lines:
AER model simulation for January–February 1992 following the Mt. Pinatubo eruption.

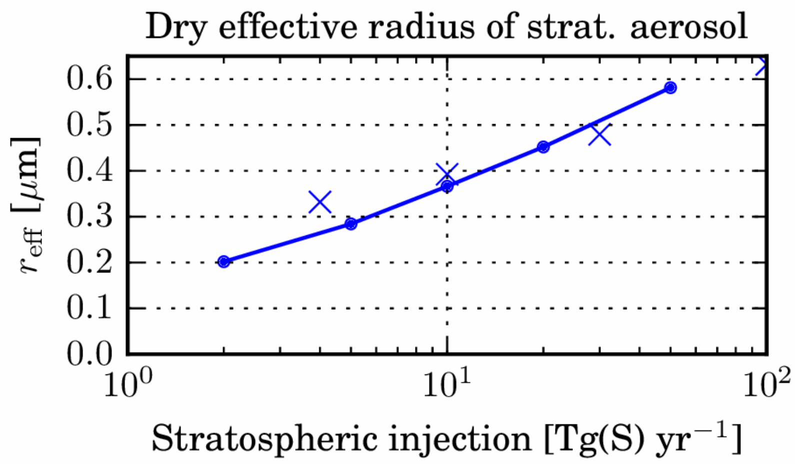
Dashed black line: size distribution fit to measurements by optical particle counter at 41°N in Jan. 1992

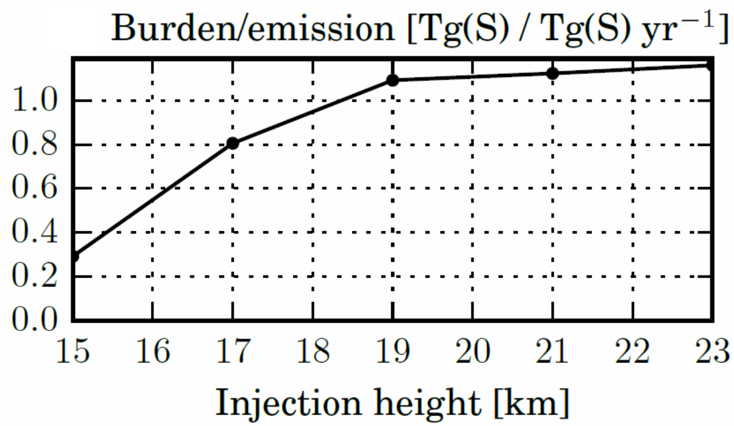


Pierce et al. Geophys. Res. Lett. 37, L18805, 2010, doi:10.1029/2010GL043975

SRM-2: Our Model Calculations: For equatorial SO_2 injections -2.0 W/m^2 could not be exceeded.







- IR-Absorption of particles counter-acts SW-Reflection
- Higher sulfate concentration leads to larger, less effective, particles
- Many Side-Effects

Kleinschmitt C., Boucher O., Bekki S., Lott F., and Platt U. (2017), The Sectional Stratospheric Sulfate Aerosol module S3A-v1 within the LMDZ general circulation model: Description and evaluation against stratospheric aerosol observations, Geosci. Model Dev. 10, 3359–3378.

Kleinschmitt C., Boucher O., and Platt U. (2018), Sensitivity of the radiative forcing by stratospheric sulfur geoengineering to the amount and strategy of the SO_2 injection studied with the LMDZ-S3A model, Atmos. Chem. Phys. 18, 2769–2786.

Side effects of Strat. Sulfur CE

Possible destruction of stratospheric Ozone

Casualties due to S-aerosol settling back into the troposphere

Change in Crop yield

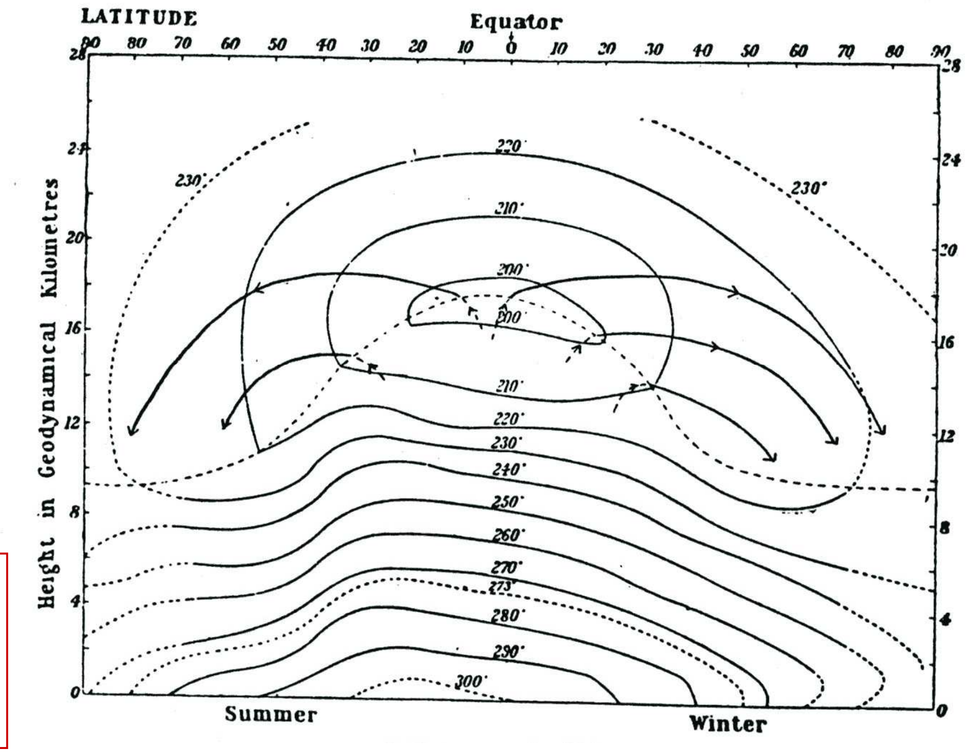
Change the colour of sky (less blue)

Perturb stratospehric circulation

Pongratz, J., Lobell, D.B., Cao, L. and Caldeira, K., 2012. Crop yields in a geoengineered climate. Nature Clim. Change, 2(2): 101-105, doi:10.1038/nclimate1373

Stratospheric Flow:
Brewer-Dobson Circulation

In principle air rises at the equator, penetrates the tropopause and decends again at the poles.
Fig. (top) original sketch by Brewer (1949)

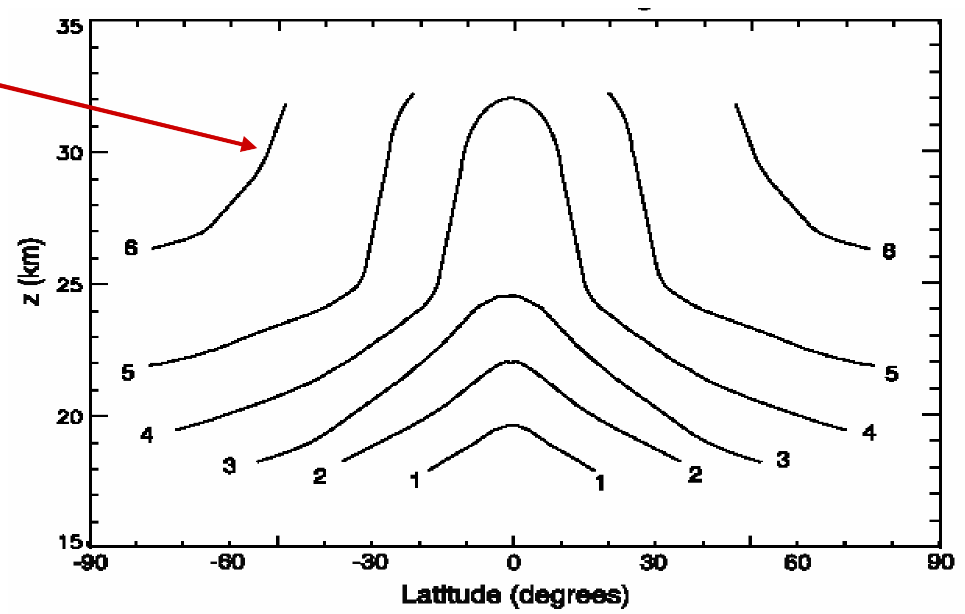


Aerosol (or precursor species) released at the equator will be transported to the pols within a few years.

Lines of constant “age” (in years) of stratospheric air.

The CO_2-mixing ratio in the (well mixed) troposphere increases monotonously, therefore the CO_2-mixing ratio indicates when the air entered the stratosphere.

Data from Waugh and Hall 2002



The Global sulfur cycle

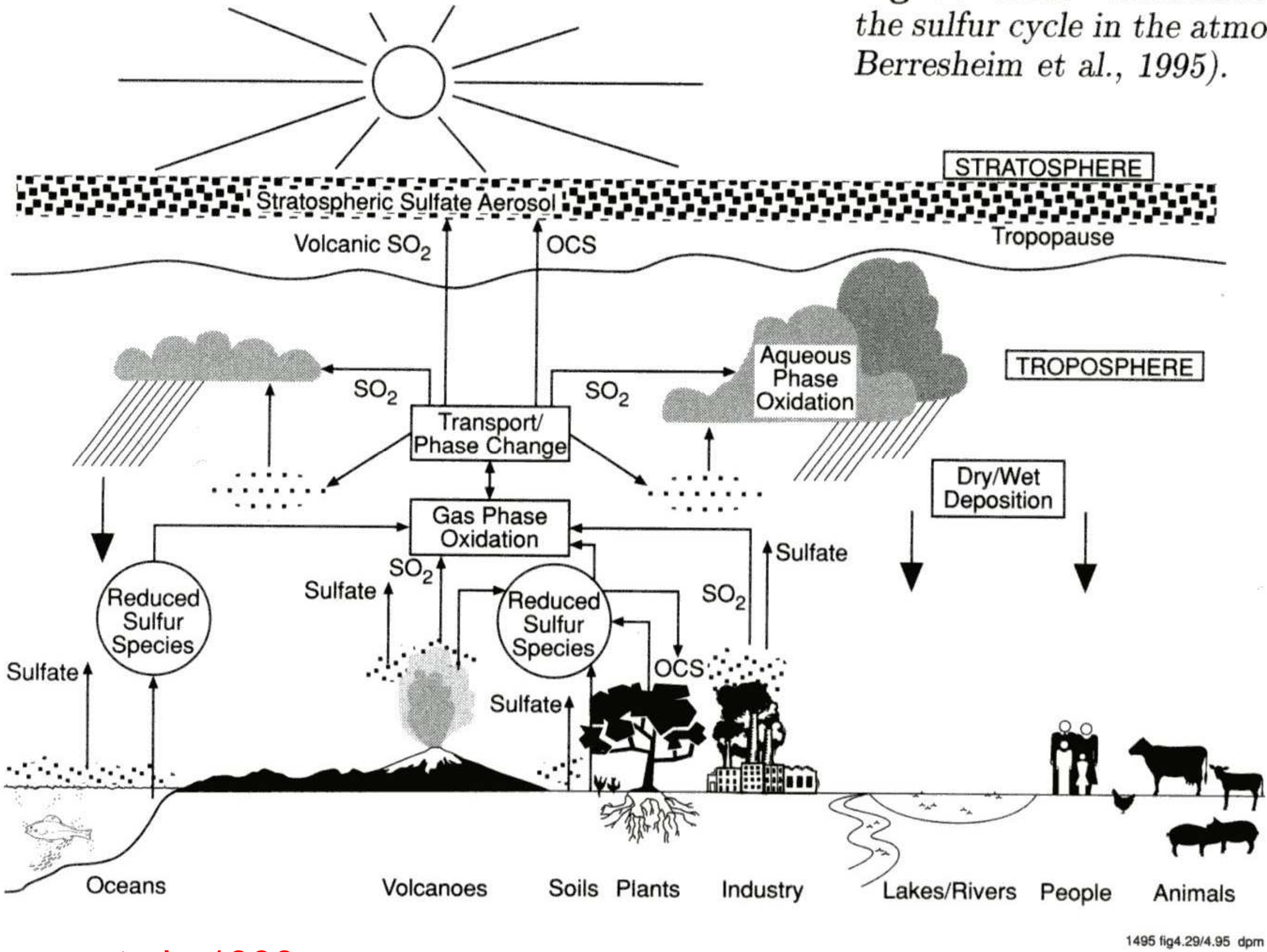


Figure 5.32. *Schematic diagram of the sulfur cycle in the atmosphere (from Berresheim et al., 1995).*

Brasseur et al., 1999

Leverage Ratio of Stratospheric Aerosol

Remember:

$$R_{Lev} = \frac{Mass\ of\ Greenhouse\ Gas\ the\ effect\ of\ which\ is\ neutralized}{Mass\ of\ material\ needed\ for\ the\ measure}$$

Assuming that 10 MtS/year can reduce the forcing by ≈ 4 W/m² (optimistic)

we can say that this would approximately cancle the effect of CO_2-doubling (from 280 ppm pre-industrial to 560 ppm, actually 3.7 W/m²).

Mass of 280 ppm of atmospheric CO_2:

$$\mathrm{M_{CO2}}(1\,\mathrm{ppm}) = \frac{\mathrm{M_{CO2}}}{\overline{\mathrm{M}}_{\mathrm{Air}}} \cdot 10^{-6} \cdot \mathrm{M_{Atm}}$$

$$\mathrm{M_{Atm}} = \frac{\overline{\mathrm{P}}_{\mathrm{Atm}} \cdot \mathrm{A_{Earth}}}{\mathrm{g}} \approx \frac{1.01325\,\mathrm{Pa} \cdot 5.1 \cdot 10^{14}\mathrm{m}^2}{9.81\,\mathrm{N/kg}} \approx 5.266 \cdot 10^{18}\,\mathrm{kg}$$

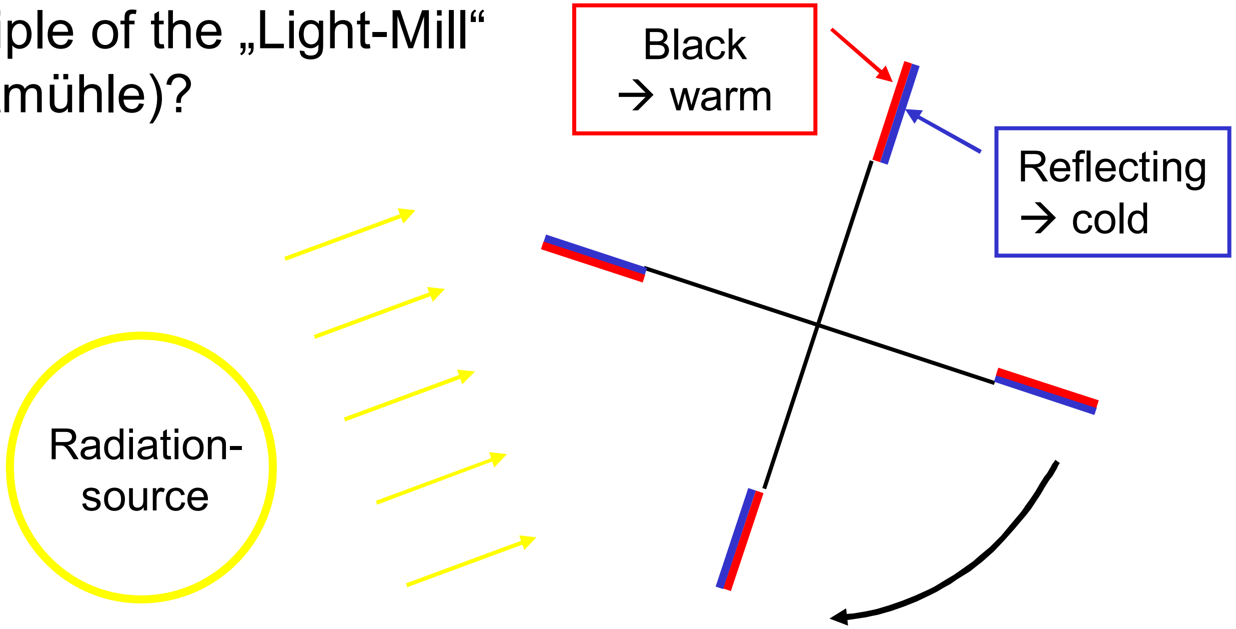
$$\mathrm{M_{CO2}}(1\,\mathrm{ppm}) \approx \frac{44}{29} \cdot 10^{-6} \cdot 5.266 \cdot 10^{18}\,\mathrm{kg} \approx 7.99 \cdot 10^{12}\,\mathrm{kg} \approx 8\,\mathrm{Gt}$$

$$\mathrm{M_{CO2}}(280\,\mathrm{ppm}) \approx 2237\,\mathrm{Gt\ CO_2}\ (610\,\mathrm{GtC})$$

$$R_{Lev} = \frac{2237\,Gt}{10\,Mt} \approx 2.24 \cdot 10^5\ per\ year$$

How could Particle Sedimentation be prevented?

Prinziple of the „Light-Mill“ (Lichtmühle)?



Wrong explanation 1:

Radiation pressure, Photons have momentum (p=E/c) but it is too small:

solar radiation: $\approx 10^{-4}$ W/cm^2 → $3\cdot 10^{14}$ Photons/s,
Momentum of a photon $\approx 10^{-27}$ kgm/s
→ Force $\approx 3\cdot 10^{-13}$ Newtons (for 1 cm^2)

Moreover: Momentum transfer to black surface: p, reflecting surface: 2p
→ wrong rotational direction

Wrong explanation 2 (Wikipedia):

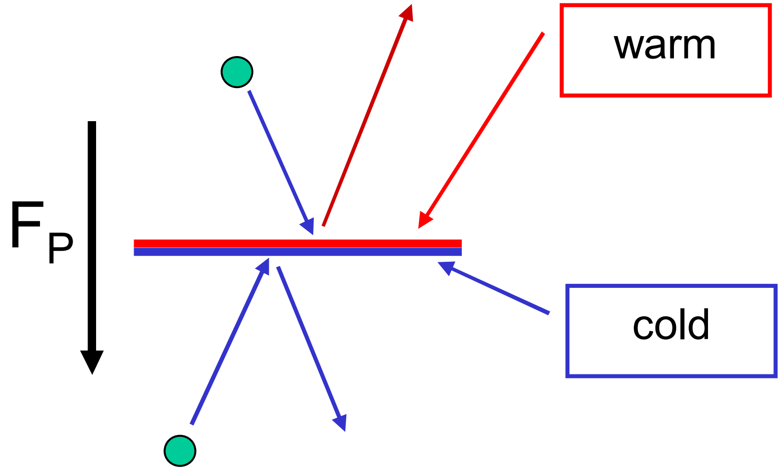
Warm layer of air at black surface provides larger pressure ...

Photophoretic Effects

Proposition: „Photophoretic Levitation“

Two mechanisms:

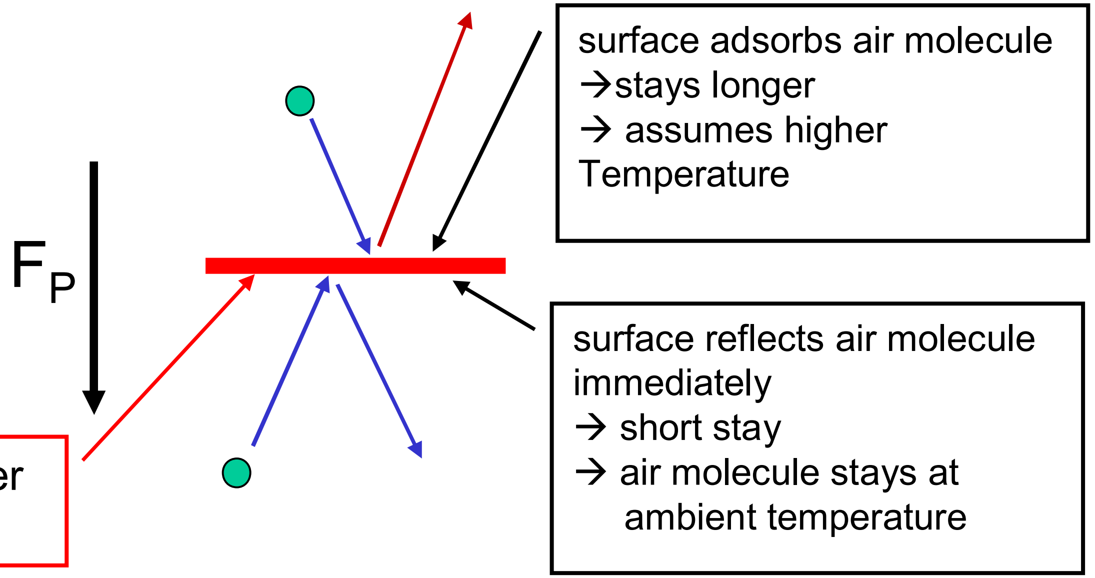
1) **Temperature effect:** Warm/cold surface
Problem: Heat conduction within the (tiny) particle



2) **Akkommodation coefficient effekt:**
„sticky“/less „sticky“ surface

Akkommodation coefficient

α **=** probability that a colliding air molecule assumes the temperature of the particle



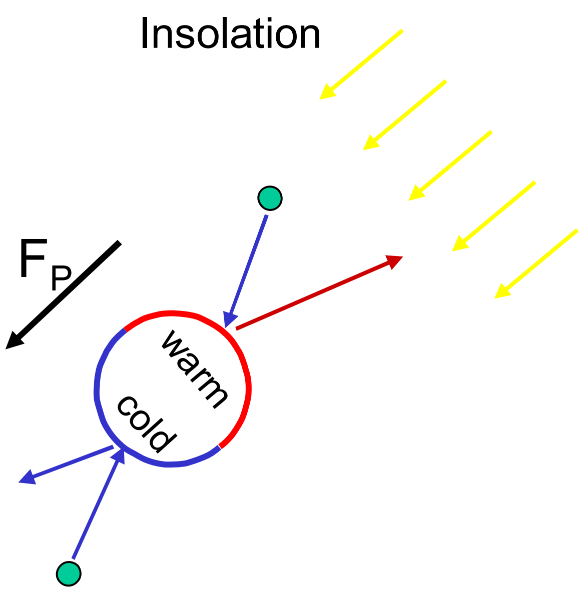
Beide Flächen wärmer als umgebende Luft

Possible Solution of the Settling Problem: Photolevitation of the Particles

Thermal gradient force

Direction given by the orientation of the radiation field

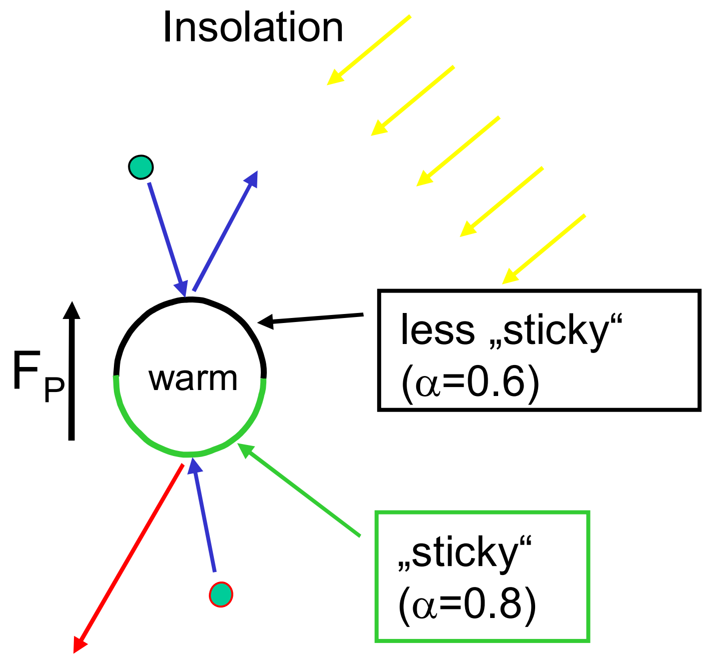
→ Independent from the orientation of the particle



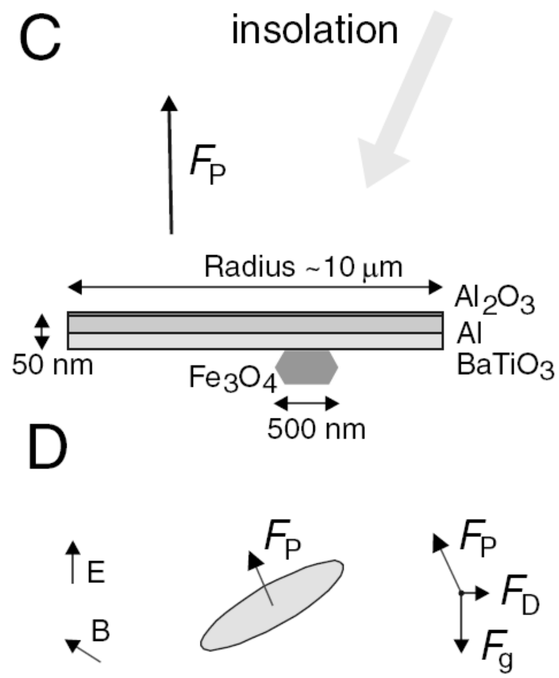
Akkommodation coefficienten-force

Direction given by the orientation of the particle

Problem: Orientation?



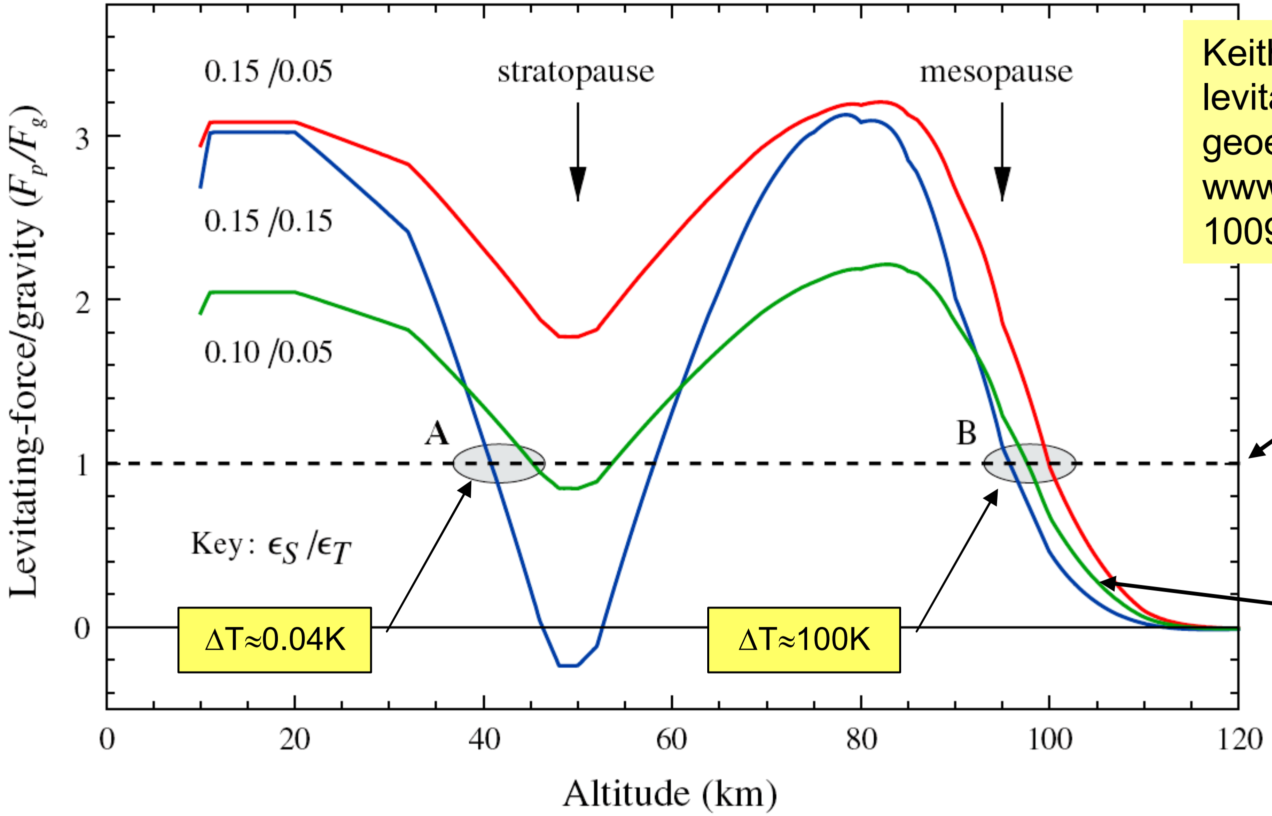
Special Levitation-disklets



Orientation in the atmospheric electric field + perhaps Earth magnetic field

Keith, D.W. (2010) Photophoretic levitation of engineered aerosols for geoengineering, PNAS, www.pnas.org/cgi/doi/10.1073/pnas.1009519107

Levitated Particles



Keith, D.W. (2010) Photophoretic levitation of engineered aerosols for geoengineering, PNAS, www.pnas.org/cgi/doi/10.1073/pnas.1009519107

Levitation force = gravity force → particle floats

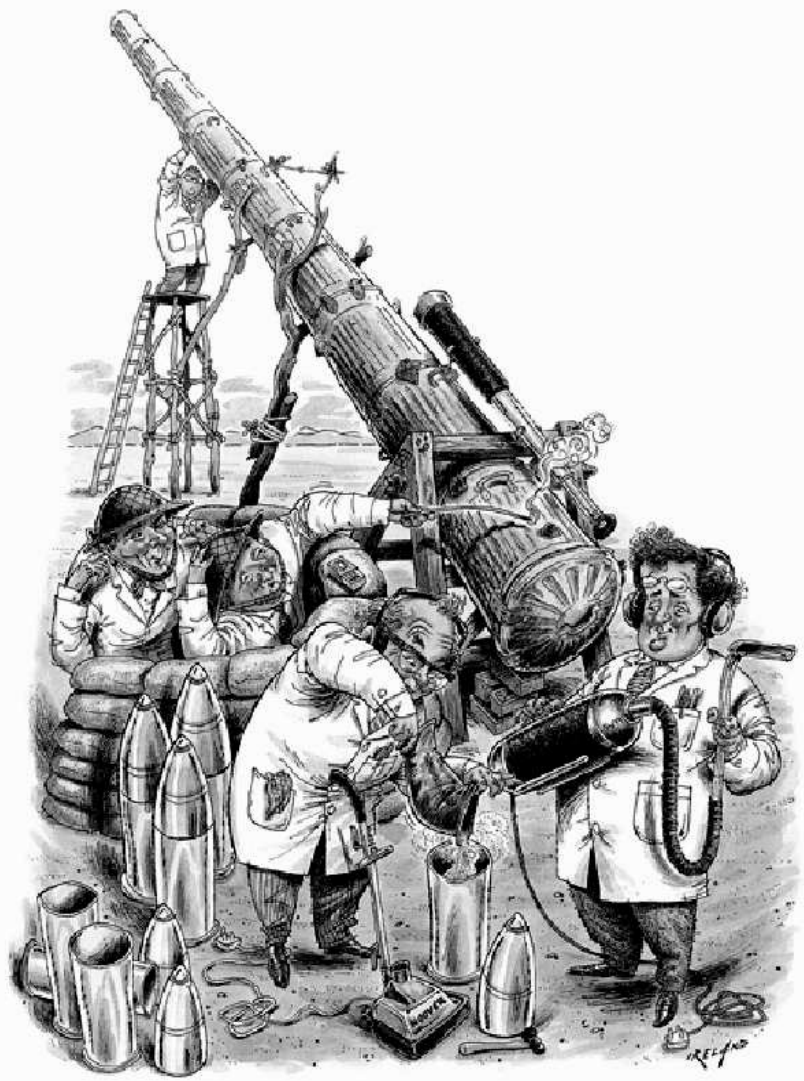
3 curves for different ratios of the emissivity in the visible and thermal IR spectral ranges, respectively

Advantages and Disadvantages of levitated Particles:

- Much less mass required compared to sulfuric acid (ca. 1/10, mostly due to improved back-scattering)
- Less mass/year required due to longer lifetime → e.g. 10 y. lifetime (instead of 1 y. for S-Aerosol): 1/100 of annual transport requirements
- Manufacturing and deployment of particles unclear.
- Long lifetime: How to get rid of the particles if desired?

Delivery of Particles to the Stratosphere

- Aircraft: Large Commercial Airliner (Boeing 747 Class)
- Modified Gulfstream Class
- New Design Airplane
- Hybrid Airship
- Gun (Mark 7 16")
- Gun (Modernized Mark 7)
- Rocket
- Chimney (high towers)
- Slurry Pipe
- Gas Pipe
- Other Techniques



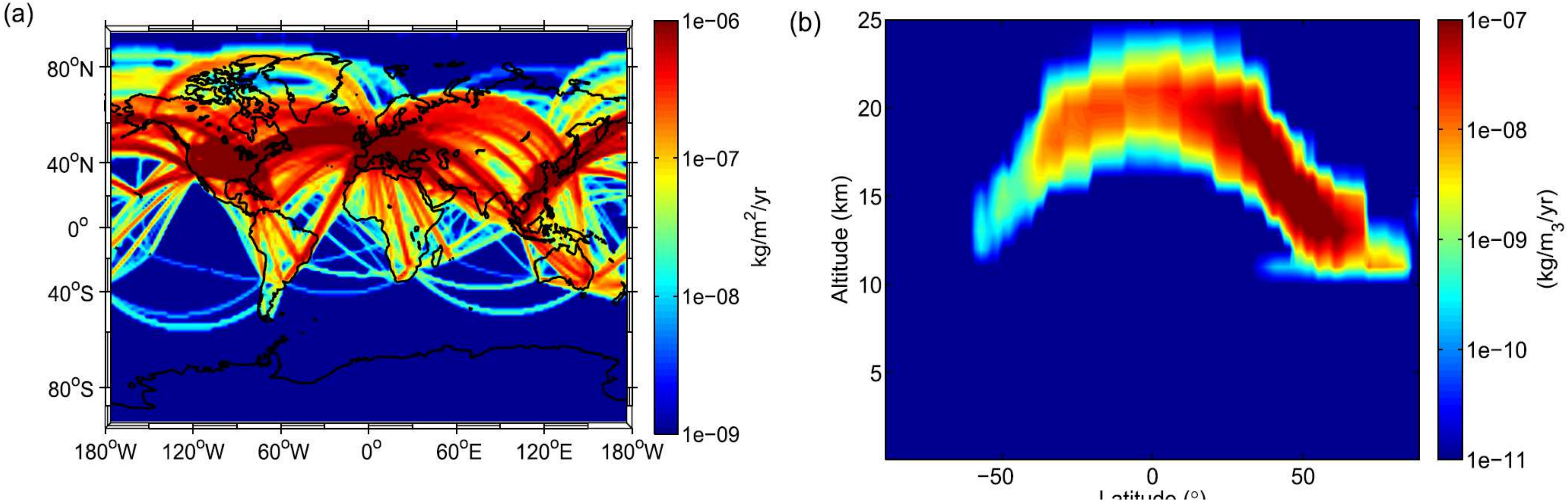
Ridicule greeted a 1992 proposal to combat global warming by shooting reflective particles into the atmosphere. The response could be different today.

Spring 2007 ■ Wilson Quarterly 47

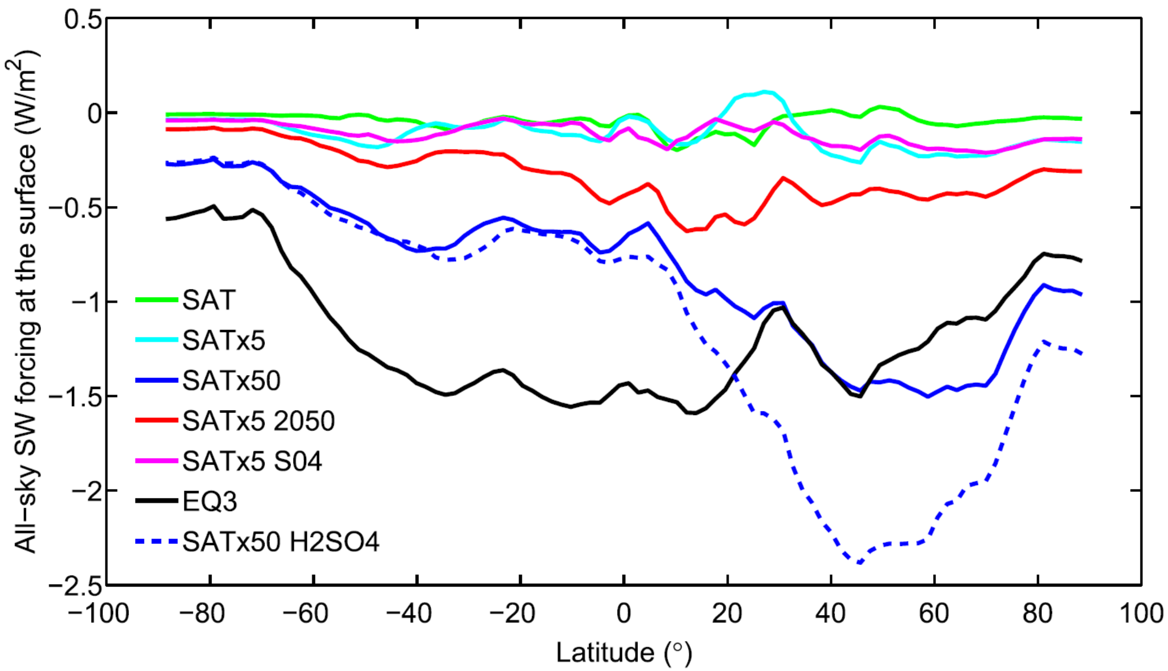
McClellan et al. 2011

Type	Representative Airplane	Properties	Availability	
Large Cargo Aircraft	Boeing 747 (-200)	• Large cargo capacity • Long range • Efficient	Dozens available used, approx. 600 built	
High Perfor-mance Airlifter	Boeing C-17	• Large cargo capacity • Short range • High lift wing	Available new while production line remains open	
Supersonic Bomber	Rockwell B-1B	• Large cargo capacity • Long range • High altitude • Sensitive technology	Probably not available, 100 built (Russian Tu-160 Blackjacks may be available, 35 built)	
Business Jet	Gulfstream G550/650 (C-37A)	• Large cargo capacity OR fuel capacity • Well suited to high altitude	Available used and new, approx. 190 built	
High Perfor-mance Zoom Climber	MacDonnell Douglas F-15	• Large Payload • Fast time-to-climb • High Altitude • High maintenance and fuel costs	Questionable availability, ap-prox. 1200 built. Numerous similar in storage	

Sulfur Injection from Commercial Aircraft?



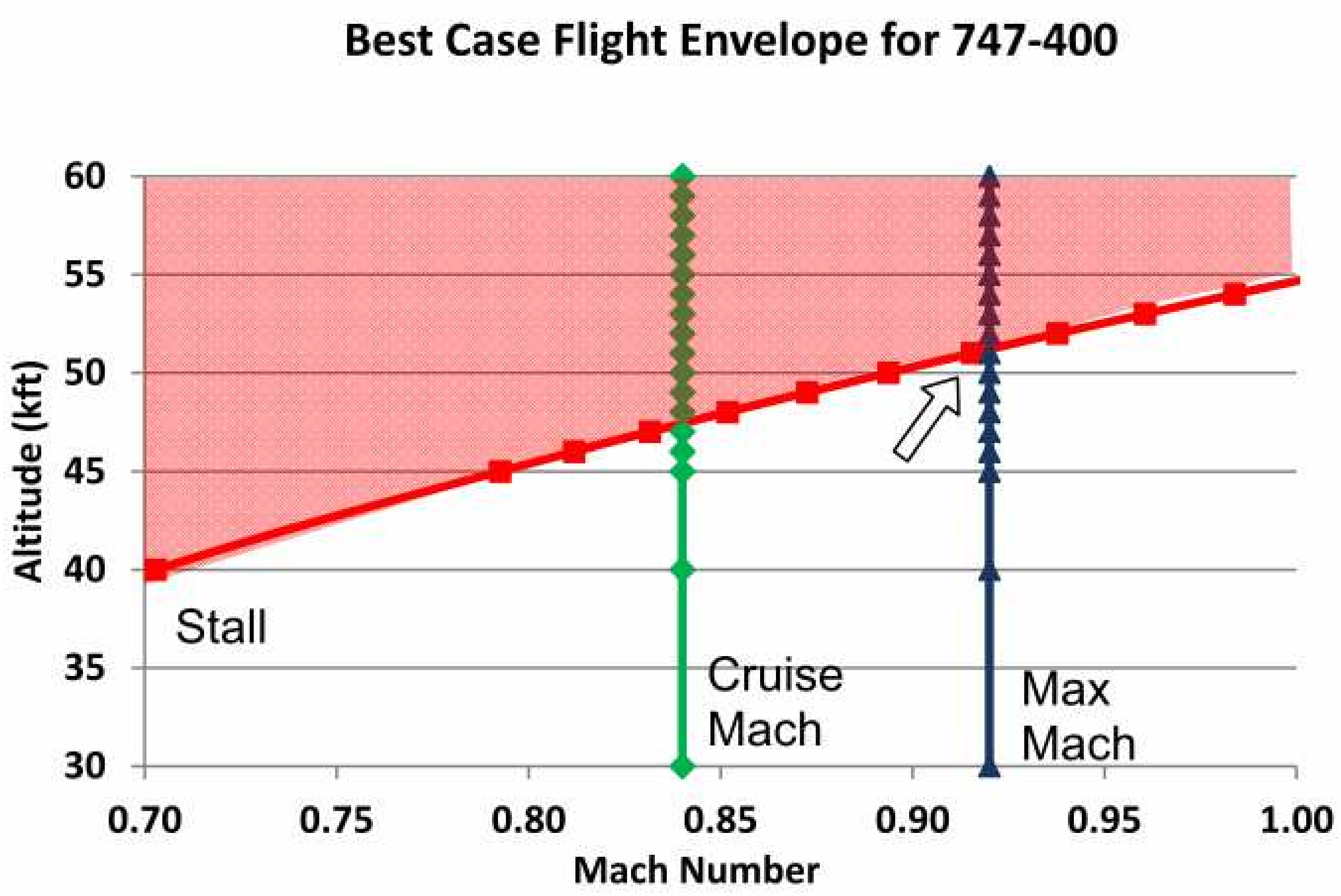
Maximum negative forcing below ≈1.5 W/m^2, even if fuel sulfur contents is icreased 50-fold (from 0.6 g/kg to 30 g/kg)



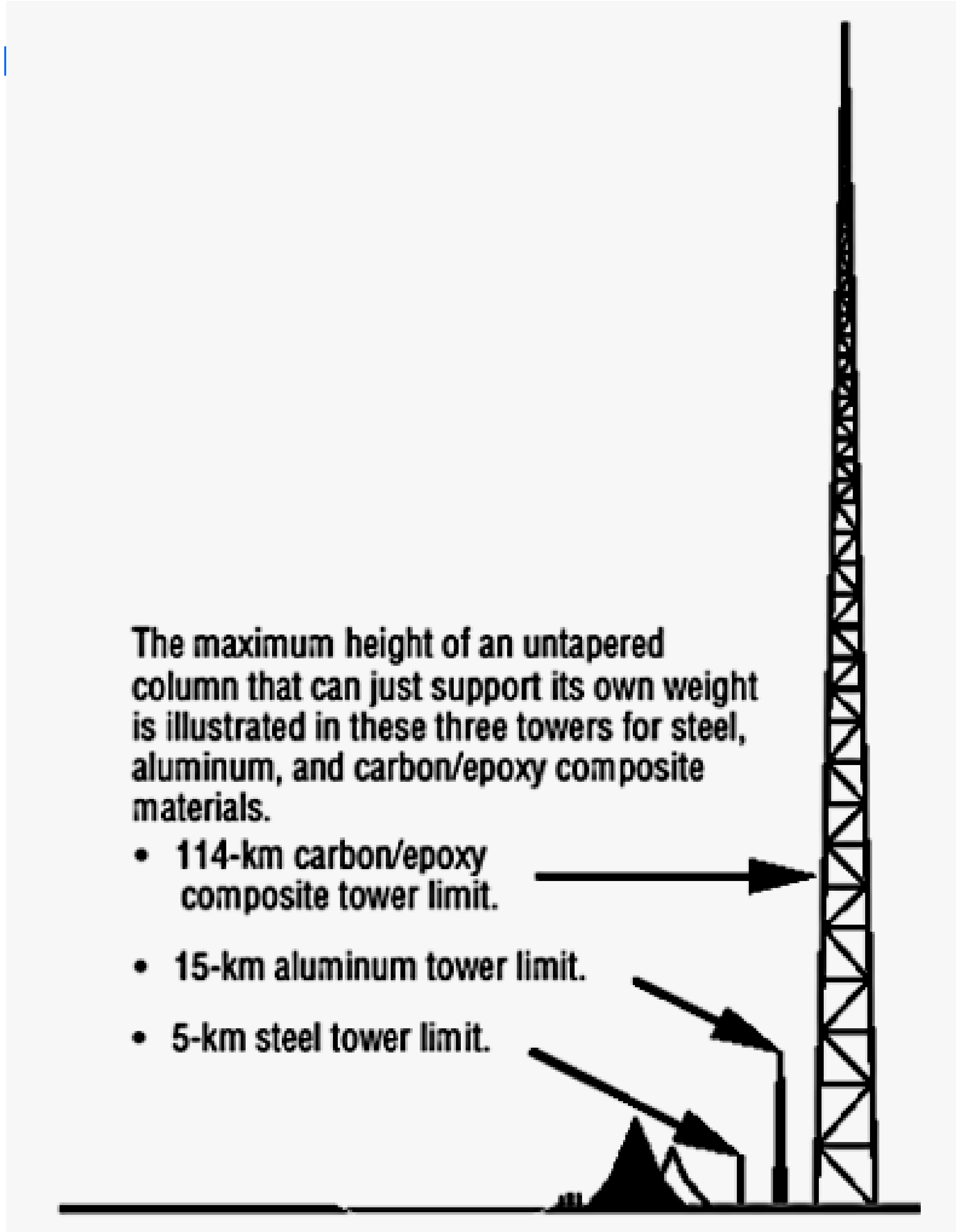
Laakso A., Partanen A.-I., Kokkola H., Laaksonen A., Lehtinen K.E.J. and Korhonen H. (2012), Stratospheric passenger flights are likely an inefficient geoengineering strategy, Environ. Res. Lett. 7, 034021 (7pp), doi:10.1088/1748-9326/7/3/034021.

The „Coffin Corner“

McClellan et al. 2011



High Towe


The maximum height of an untapered column that can just support its own weight is illustrated in these three towers for steel, aluminum, and carbon/epoxy composite materials.
• 114-km carbon/epoxy composite tower limit.
• 15-km aluminum tower limit.
• 5-km steel tower limit.

The SPICE - Project

CLIMATE CHANGE

Cancelled project spurs debate over geoengineering patents

SPICE research consortium decides not to field-test its technology to reflect the Sun's rays.

BY DANIEL CRESSEY

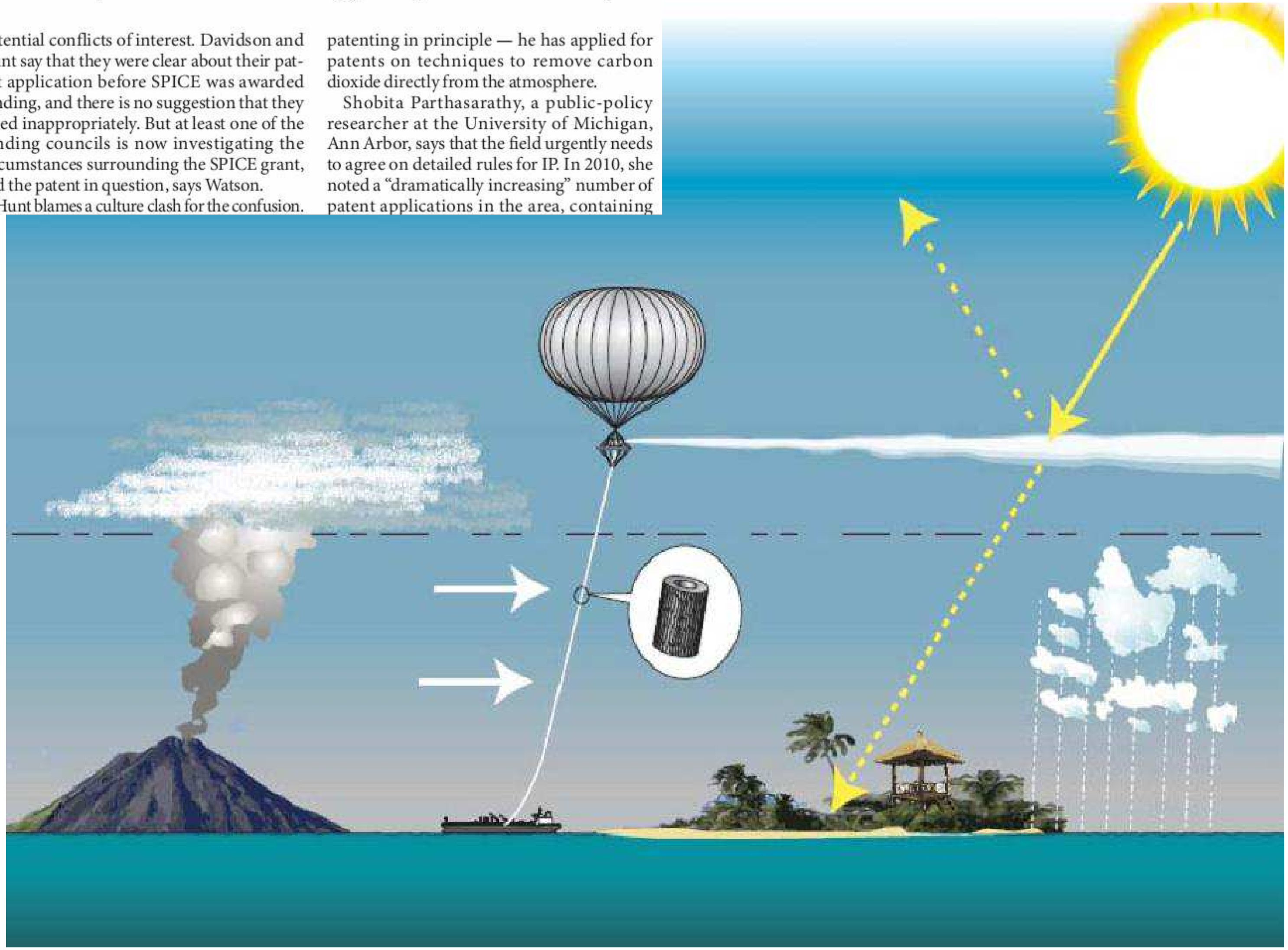
Technologies to keep Earth cool could one day provide a radical fix for climate change — and, in a world struggling to control its greenhouse-gas emissions, could also prove highly lucrative for inventors.

But should individual researchers, or companies, be allowed to own the intellectual potential conflicts of interest. Davidson and Hunt say that they were clear about their patent application before SPICE was awarded funding, and there is no suggestion that they acted inappropriately. But at least one of the funding councils is now investigating the circumstances surrounding the SPICE grant, and the patent in question, says Watson.

Hunt blames a culture clash for the confusion. patenting in principle — he has applied for patents on techniques to remove carbon dioxide directly from the atmosphere.

Shobita Parthasarathy, a public-policy researcher at the University of Michigan, Ann Arbor, says that the field urgently needs to agree on detailed rules for IP. In 2010, she noted a "dramatically increasing" number of patent applications in the area, containing

Nature 485, May 24, 2012, p. 429.



Source: Wikipedia,

Hughhunt

Simplified Delivery of Sulfur to the Stratosphere

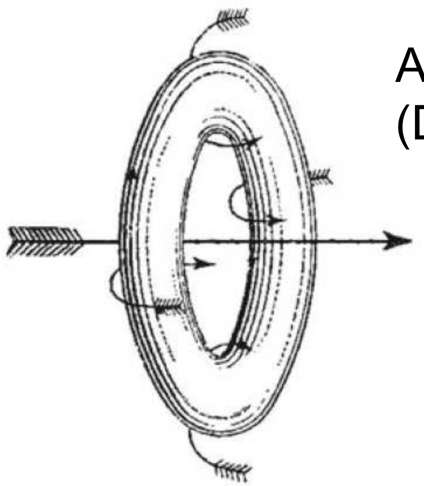
Small Device

Source: Wikipedia

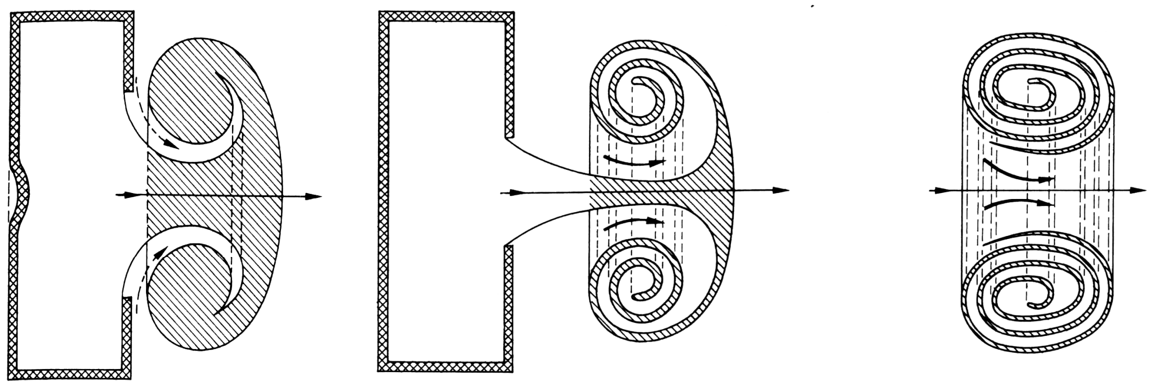
Vortex Rings (Smoke rings)

Exist also without smoke
Helmholtz, H.: Über Integrale der hydro-dynamischen Gleichungen, welche den Wirbelbewegungen entsprechen. Journal für die reine und angewandte Mathematik, Berlin; 1826, 25 - 55

What are Smoke Rings (Vortex Rings)?



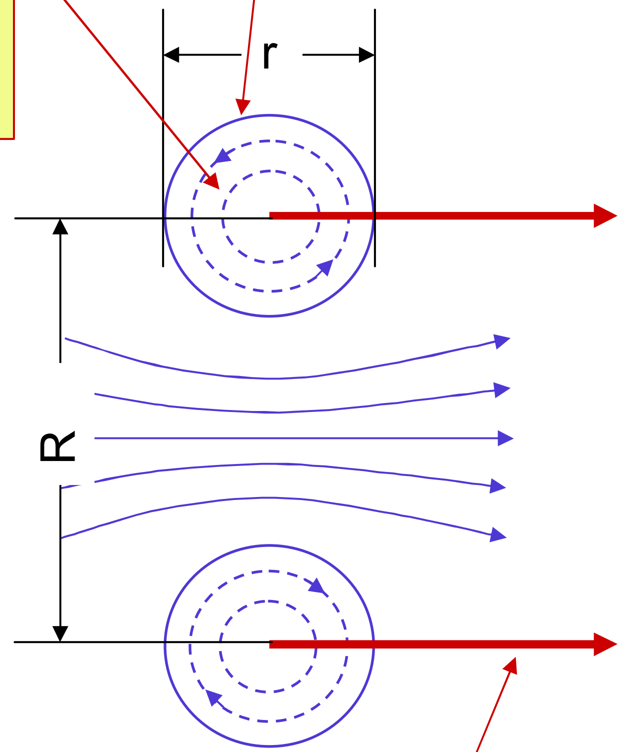
A vortex ring
(Drawing by Helmholtz)



Vortex ring generator

Energy contents proportional to volume $(=2\pi^2 r^2 R) \approx R^3$

Energy loss: proportional to surface area $(=4\pi^2 rR) \approx R^2$



Direction of motion of the entire ring

Simplified Delivery of Sulfur to the Stratosphere – Smoke Rings (Vortex Rings)

A 10cm dia. smoke ring can travel 10-20m and still bring a card-house to collaps

The range of a smoke ring scales with the volume/surface ratio, i.e. with R

(Assuming R/r = constant)

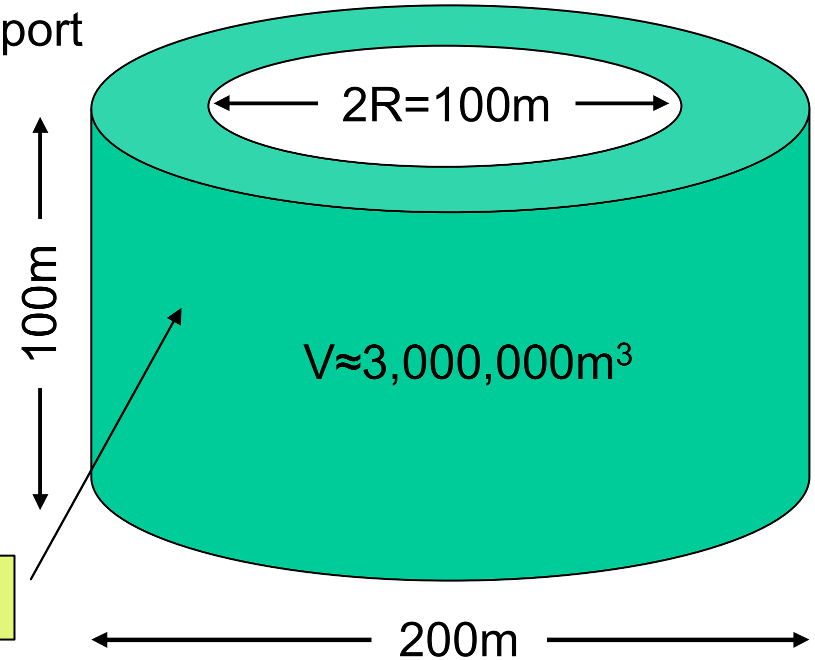
→ changing R from 0.05m to 50m would change the range to Z=10 – 20 m to Z ≈ 10 - 20 km

Volume of a vortex ring (r=5m, R=50m): V≈24000 m^3

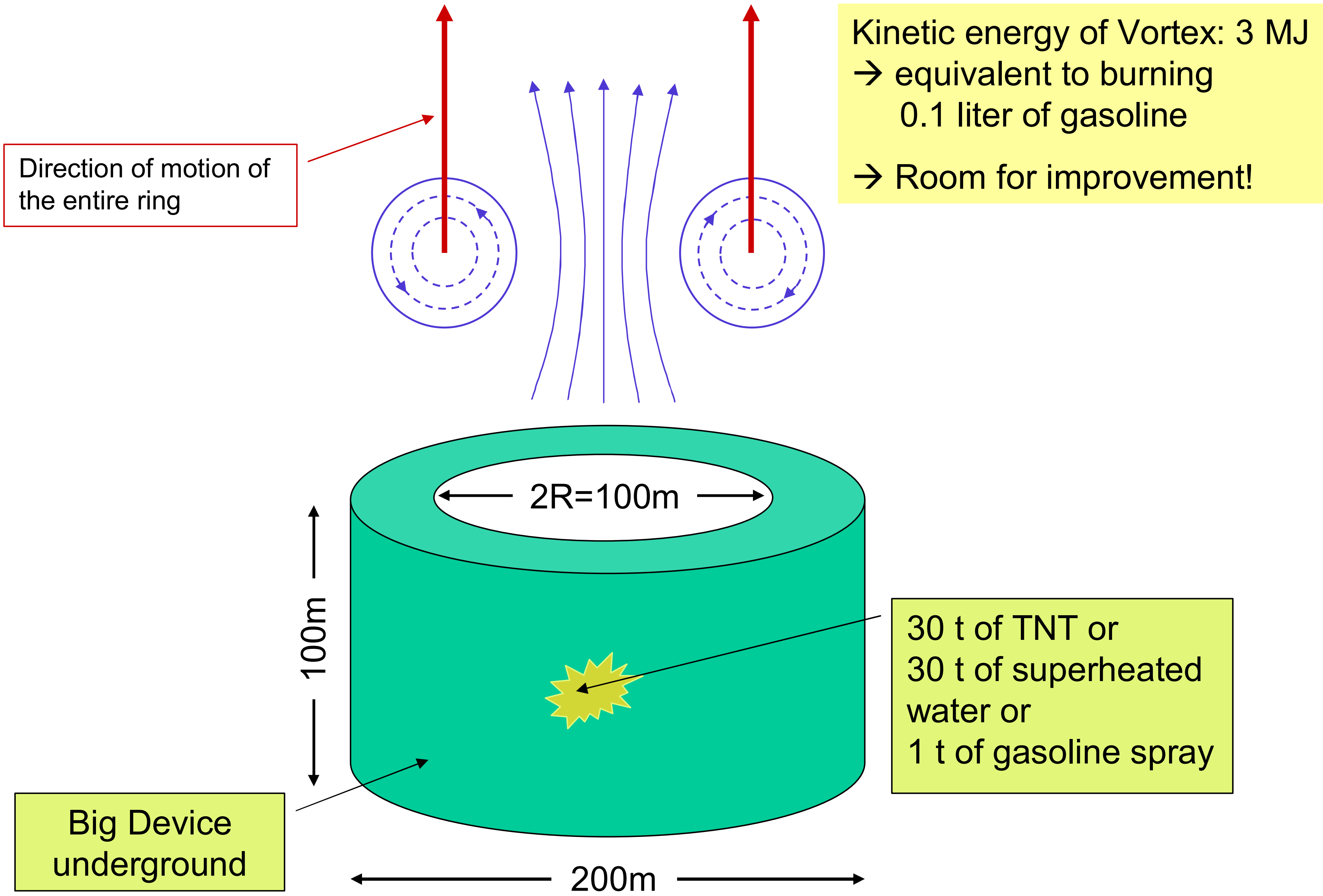
SO_2 - Weight ≈60 t
→ Firing the device every 3 minutes would transport 1 million t of SO_2 per year to stratosphere

Pressure increase needed to fire vortes ring:
p ≈ 5mBar or V ≈ 15,000m^3
30t of TNT (not bad for 60t of SO_2, compare atillery)

Alternatives to TNT:
30t of superheated water
1t of gasoline spray

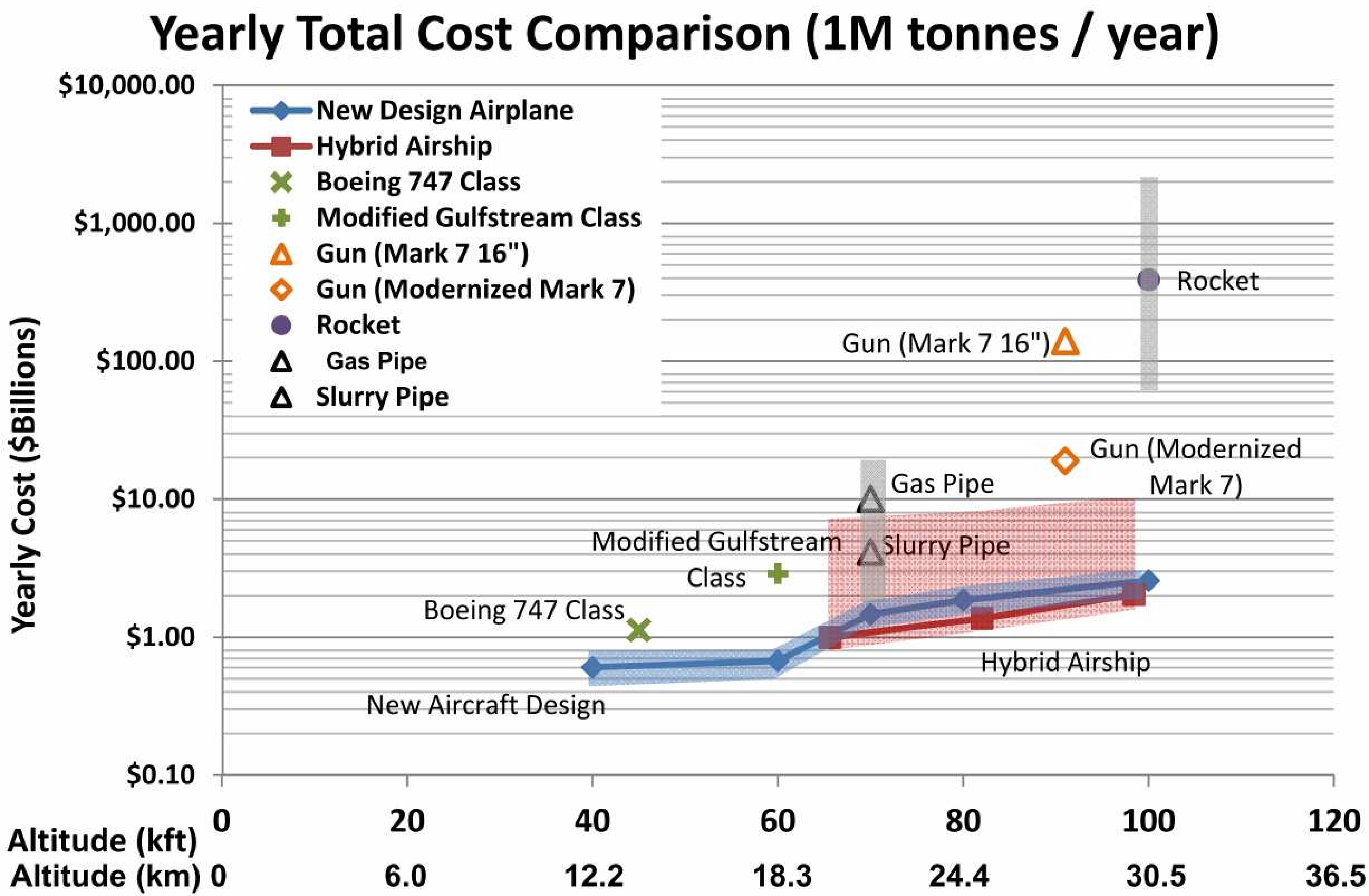


Smoke Ring Delivery of SO_2 (or Aerosol) to the Stratosphere



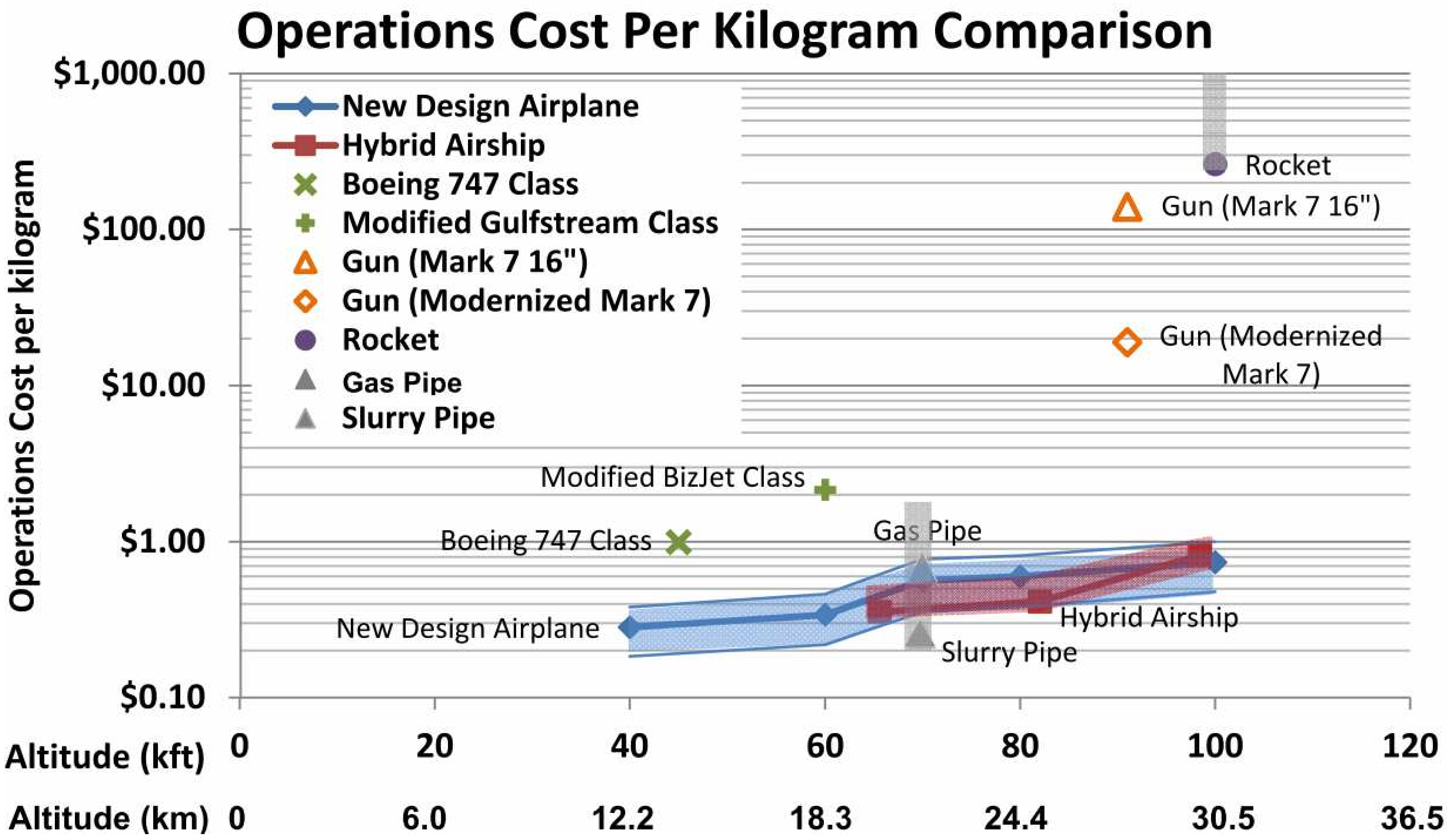
The Question of Cost - 1

McClellan et al. 2011



The Question of Cost - 2

McClellan et al. 2011



Gun Systems

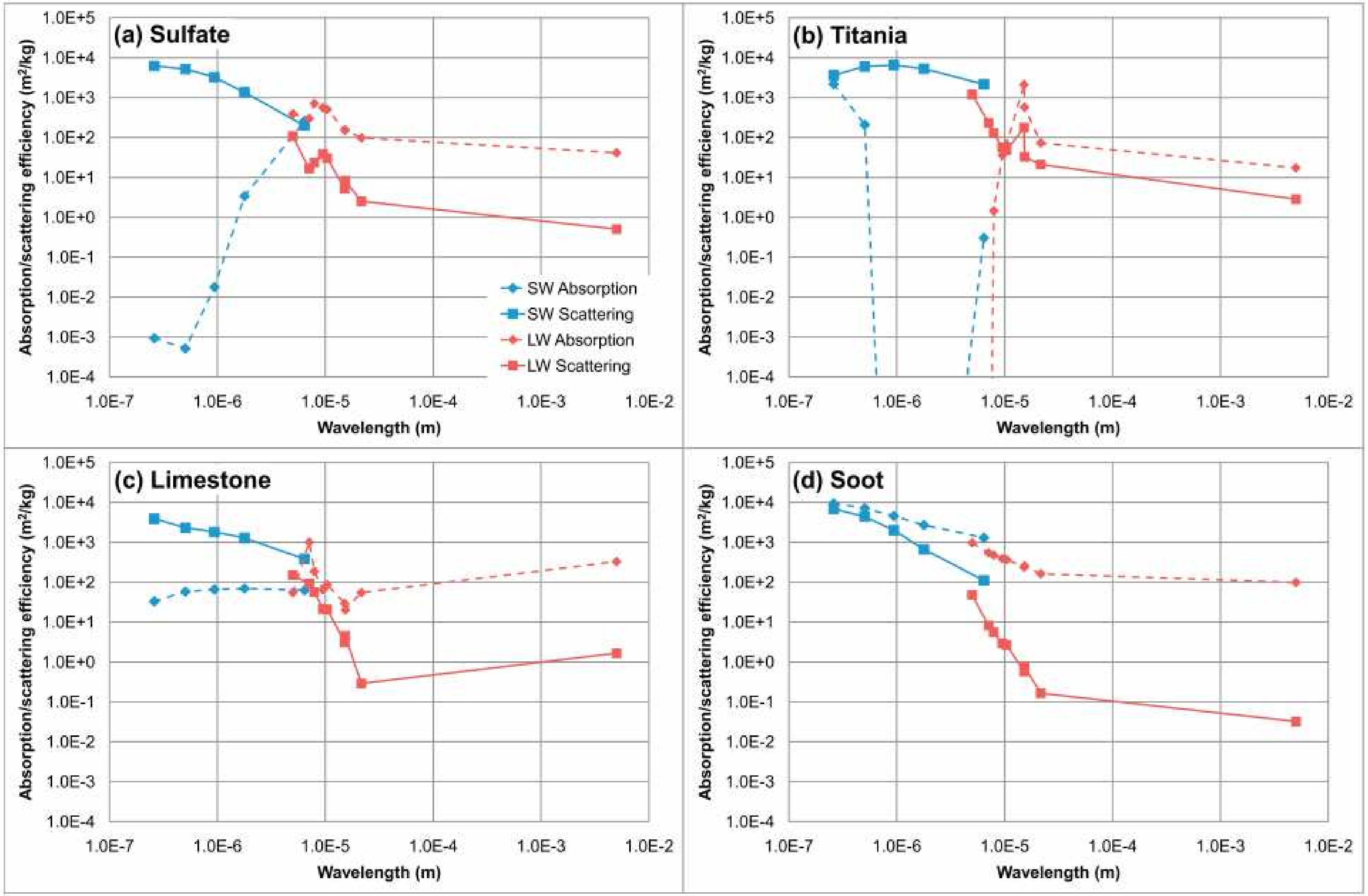
Table 15: Gun System Analysis Inputs

Item	Value[44,45,46]
Shell Mass (kg)	862
Payload Per Shell (kg)	70
Gun powder Mass per shot (kg)	297
Powder Cost per kg	$22
Muzzle Velocity (m/s)	760
Cost per New Barrel ($)	$7,500,000
Cost of Shell	$3,000
Full Time Personnel Per Barrel	2
Fire Rate	2 / min
Shots Per Barrel Lining	1500
Cost Of Barrel Relining	$335,000
Barrel availability due to relining, maintenance	50%

McClellan et al. 2011

The „Side Effects“ of Stratospheric Geoengineering

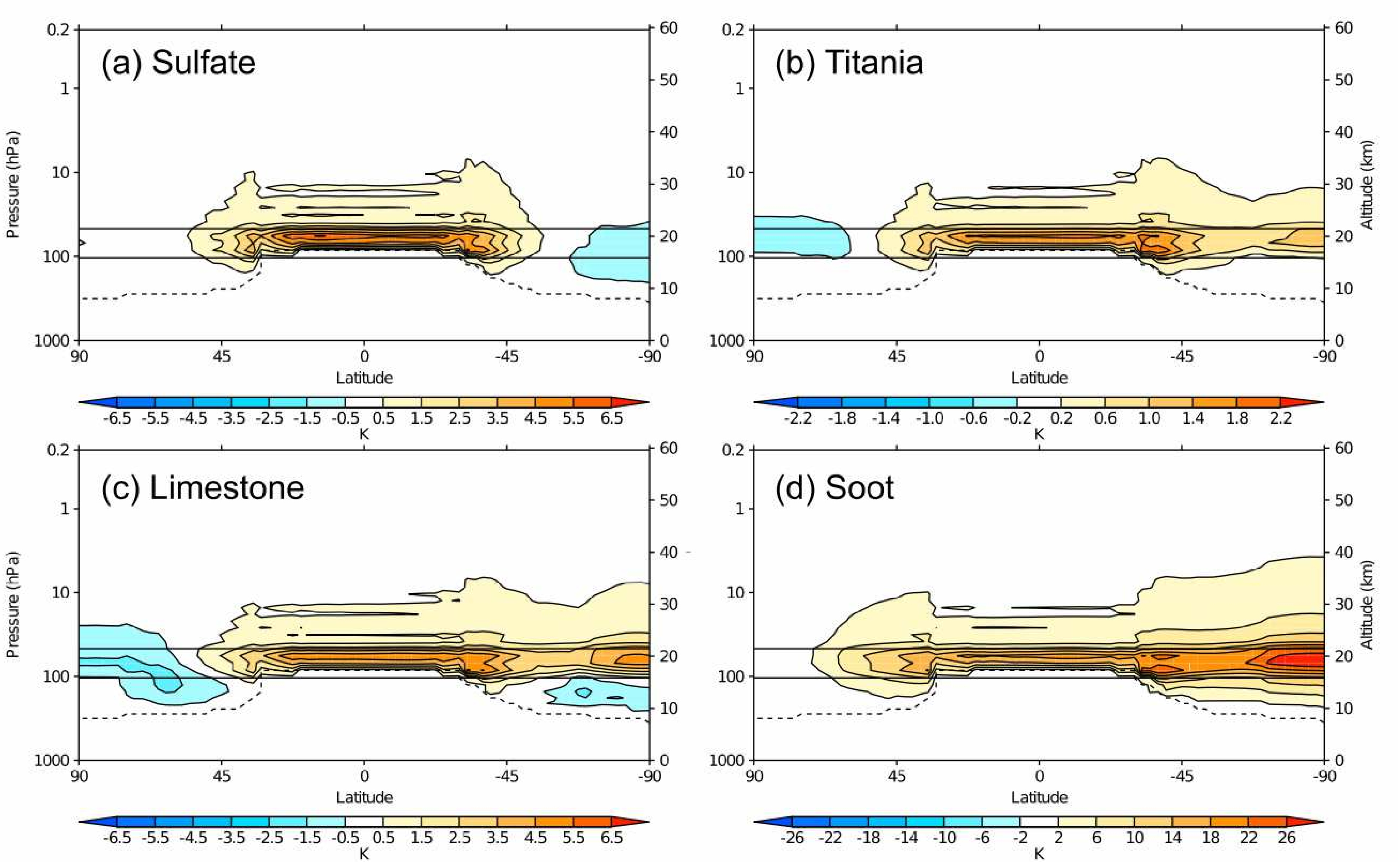
Stratospheric Heating



Absorption/scattering efficiencies for the SMALL/WIDE aerosol size distributions. Points are plotted at the mid-point of each wavelength interval.

Ferraro A.J., Highwood E.J., and Charlton-Perez A. J. (2011), Stratospheric heating by potential geoengineering aerosols, Geophys. Res. Lett. 38, L24706, doi:10.1029/2011GL049761

Stratospheric Heating



Ferraro A.J., Highwood E.J., and Charlton-Perez A. J. (2011), Stratospheric heating by potential geoengineering aerosols, Geophys. Res. Lett. 38, L24706, doi:10.1029/2011GL049761

Why Endanger Particles the Ozone Layer? (1)

Katalytic Ozone destruction:

$$X + O_3 \rightarrow XO + O_2$$

$$XO + O \rightarrow X + O_2$$

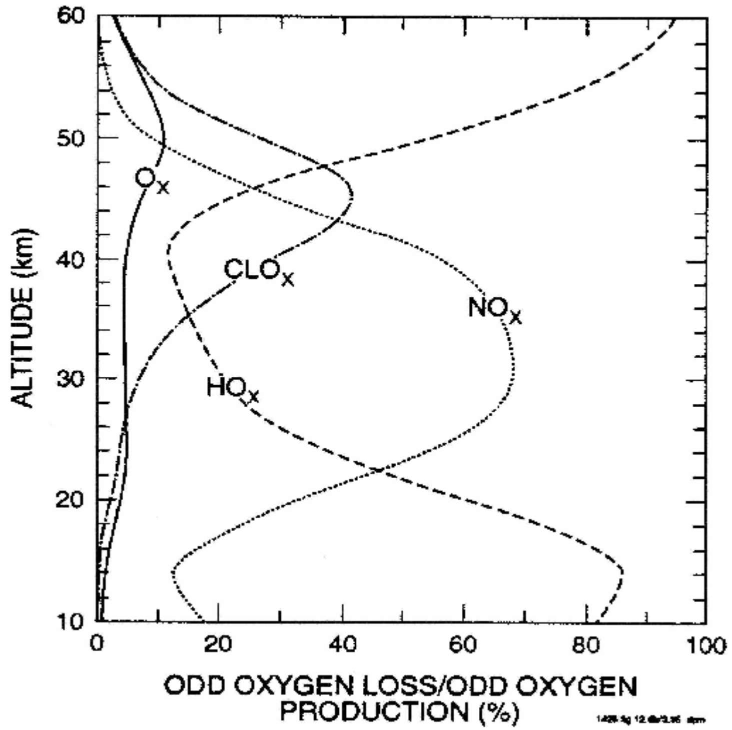
net: $O + O_3 \rightarrow 2O_2$

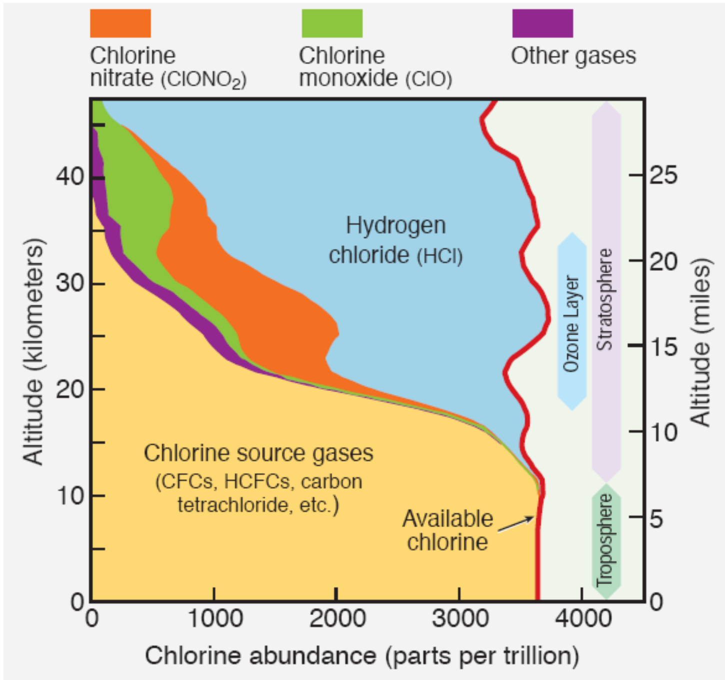
X/XO: „Katalyst“
(e.g. OH/HO_2, NO/NO_2, Cl/ClO, Br/BrO)

HO_X (Bates and Nicolet, 1950)
NO_X (Crutzen, 1970)
ClO_X (Stolarski and Cicerone, 1974;
Molina and Rowland, 1974)

Katalytic ozone destruction explains difference between measured (lower) and calcualted (ca. 3x higher) O_3 – concentrations and their dependence on.

Particles?





Why Endanger Particles the Ozone Layer? (2)

1) Oxides of Nitrogen (one of the katalysts destroying ozone) is converted into (benign) nitiric acid.

$NO_2 + O_3 \rightarrow NO_3$

$NO_2 + NO_3 \rightarrow N_2O_5$

N_2O_5 is converted to HNO_3 at particle surfaces; “denoxification”.

$N_2O_5\,(g) + H_2O\,(p) \rightarrow 2\,HNO_3\,(p)$

→ Reduced formation of $ClONO_2$

2) Reactions at particle surfaces convert “benign” species (HCl, $ClONO_2$), to ozone destruction-katalyst-spezies:

$ClONO_2\,(g) + HCl\,(p) \rightarrow HNO_3\,(p) + Cl_2\,(g)$; $Cl_2 + h\nu \rightarrow 2\,Cl$

$ClONO_2\,(g) + H_2O\,(p) \rightarrow HNO_3\,(p) + HOCl\,(g)$

$HOCl\,(g) + HCl\,(p) \rightarrow Cl_2\,(g) + H_2O\,(p)$

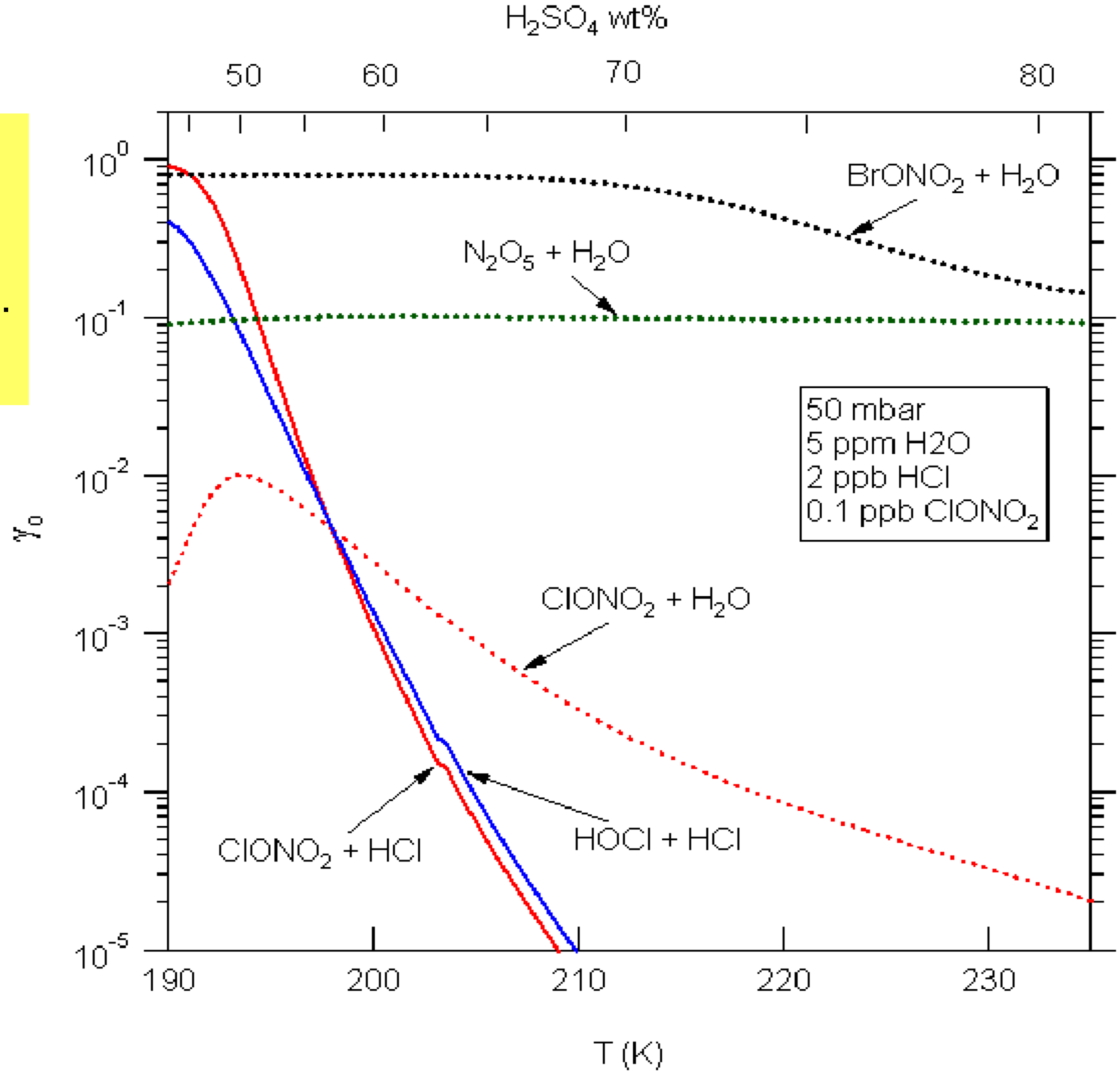
$N_2O_5\,(g) + HCl\,(p) \rightarrow HNO_3\,(p) + ClNO_2\,(g)$

(p) bzw. (g) Reactands at particle or in the gas phase, respectively.

Reaction probability (γ) of NO_X and ClO_X – Reservoir Species at Sulfuric Acid Particles as Function of the Temperature

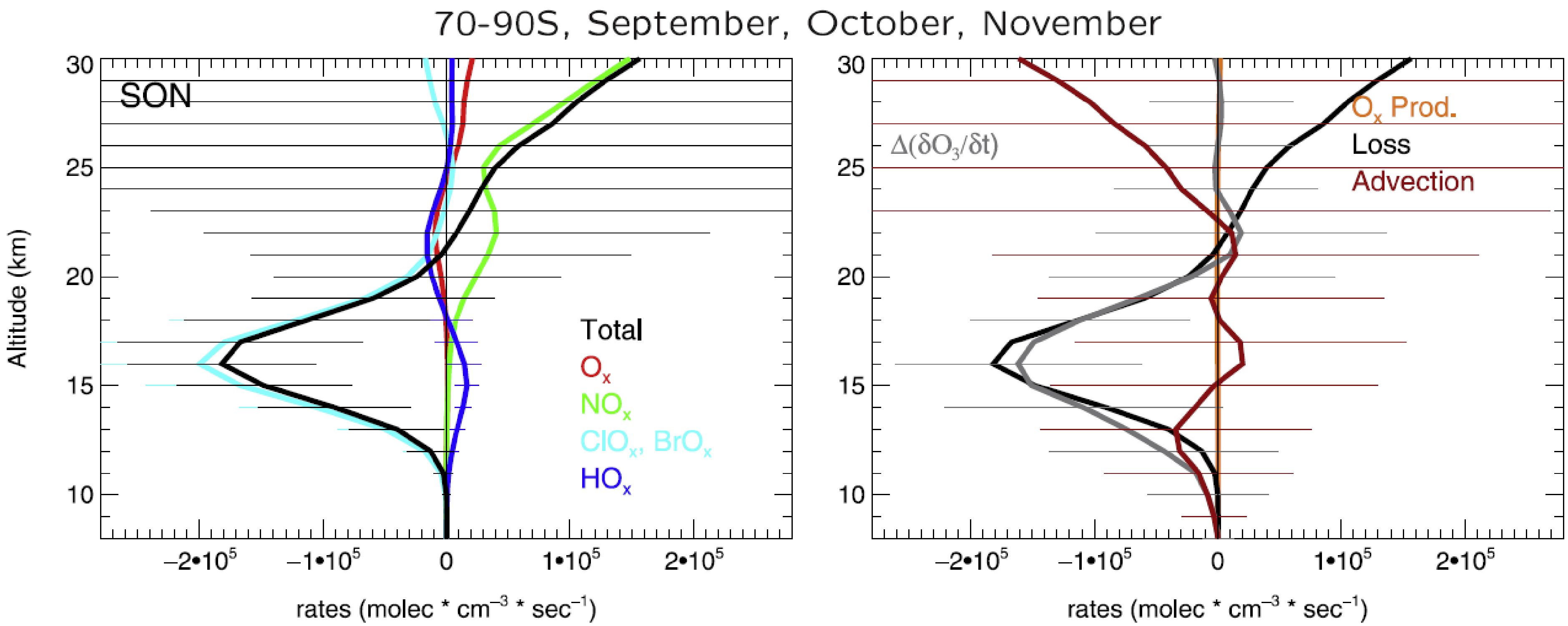
Fortunately most of the reactions at H_2SO_4-particles only take place at very low temperatures.

(polar winter)



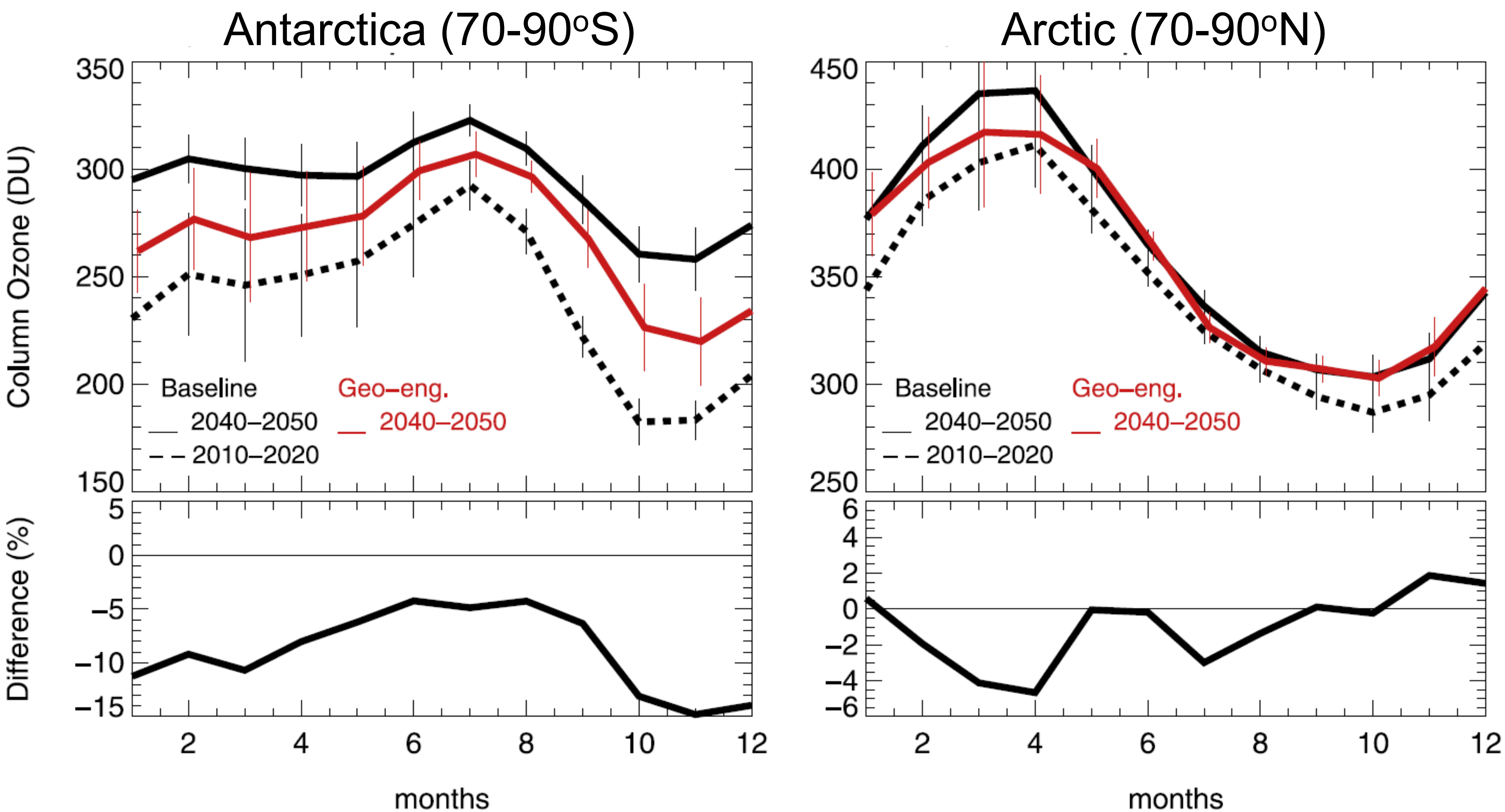
Calculated Effect of stratospheric „Climate-Engineering Aerosol“ on the Ozone Layer

Additional ozone destruction rates due to different katalyst-species in Antarctic Spring, calculated for 2040-2050 and 2 Mt/year sulfur injection.



Tilmes, S., Garcia R.R., Kinnison D.E., Gettelman A., and Rasch P.J. (2009), Impact of geoengineered aerosols on the troposphere and stratosphere, J. Geophys. Res., 114, D12305, doi:10.1029/2008JD011420.

Calculated Annual Variation of the Ozone column Density (in Dobson Units, DU) 2010-2020 vs. 2040-2050 over Antarctca and Arctic (2 Mt-S/year)



The chemical effect is proportional to the injected surface, thus (in good approximation) to the cooling effect!

Tilmes, S., Garcia R.R., Kinnison D.E., Gettelman A., and Rasch P.J.(2009), Impact of geoengineered aerosols on the troposphere and stratosphere, J. Geophys. Res., 114, D12305, doi:10.1029/2008JD011420.

Other Side Effects …

»Der Himmel wäre nie mehr blau«

Im Gespräch mit »Spektrum der Wissenschaft« bewertet der Umweltethiker **Konrad Ott** die Maßnahmen des Climate Engineering aus moralphilosophischer Sicht.

Spektrum der Wissenschaft: *Warum ist Climate Engineering für einen Philosophen und Ethiker ein Thema?*

KONRAD OTT: Schon allein deshalb, weil es zum Problem des Klimawandels gehört. Und der steckt voller ethischer Fragestellungen. Man könnte sogar sagen, dass er im Kern ein umweltethisches Problem ist und kein rein wissenschaftliches oder technisches. Bei seiner Lösung aber bewegt man sich in dem Spannungsfeld zwischen Reduktion von Treibhausgasen, Anpassungsmaßnahmen und den verschiedenen Möglichkeiten des Climate Engineering. maßnahmen eine starke Erwärmung zur Folge hätte. Solange wir noch andere Handlungsoptionen haben, sollten wir auf jeden Fall einen Weg vermeiden, der zukünftige Generationen in eine derart fatale Situation bringen könnte.

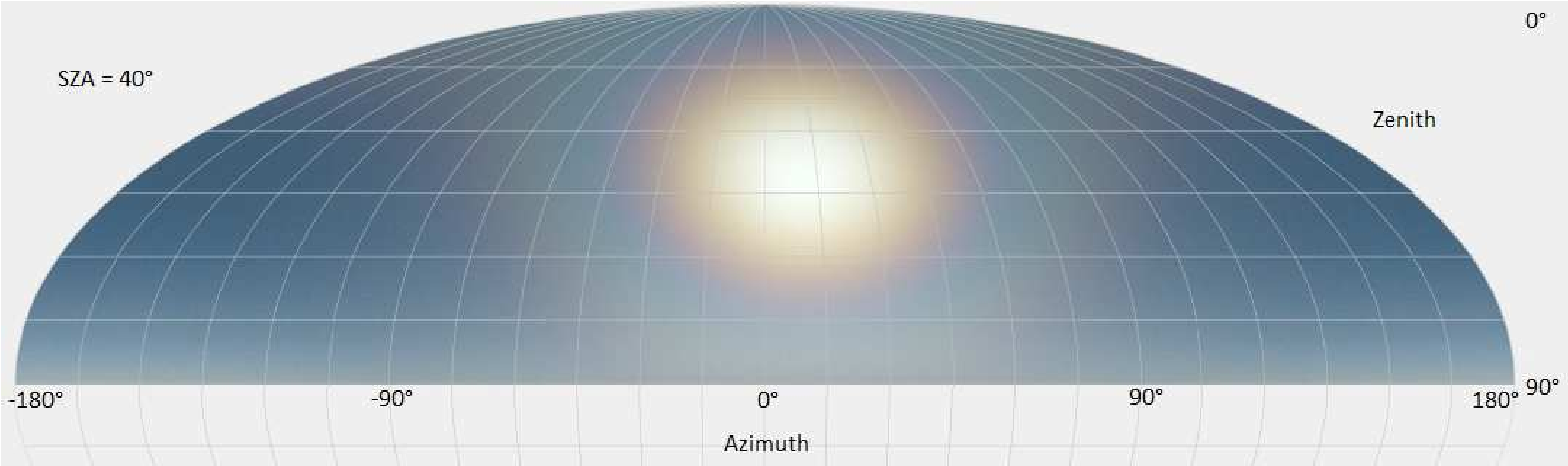
Sehen Sie noch andere ethische Probleme mit der Sulfatinjektion in die Stratosphäre?

OTT: Die gibt es ohne Zweifel. Wenn man das tatsächlich macht, wird sich zum Beispiel die Farbe des Himmels verändern. Er wird nie mehr blau sein, sondern milchig oder gräulich, ähnlich wie Hochnebel. Und wir werden auch die

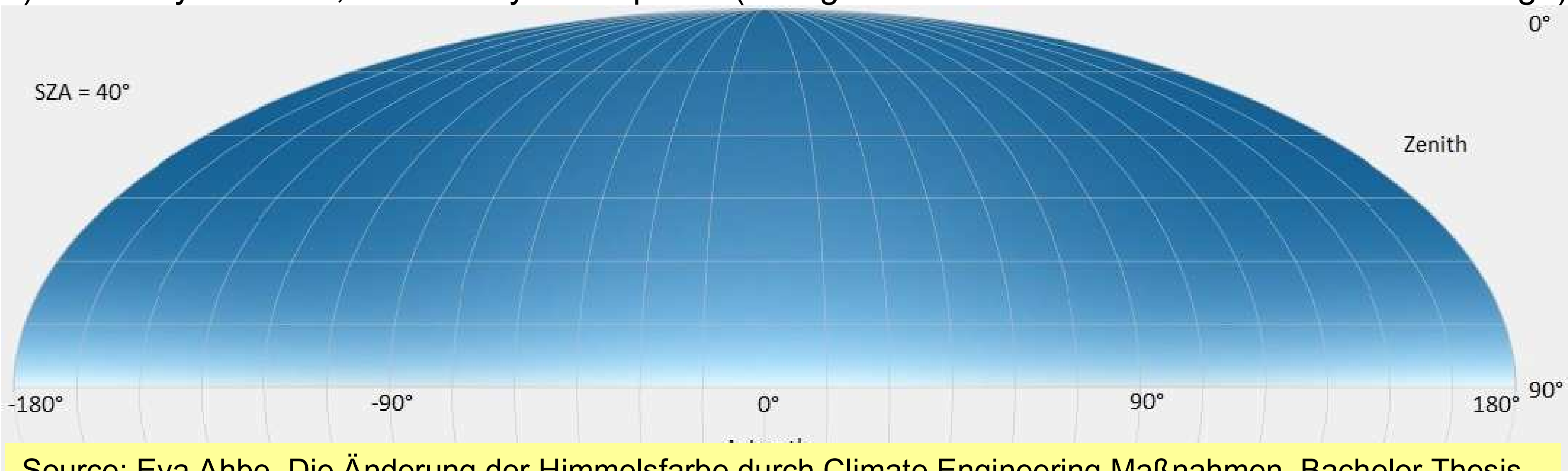
Spektrum der Wissenschaft 4, 2012, S. 12-13

The Colour of Geoengineered Skies

1) CE – Scenario: Compensation of global warming due to $2xCO_2$ by stratospheric sulfate aerosol



2) Clear sky scenario, ozone only atmosphere (background aerosol will make no noticeable change)

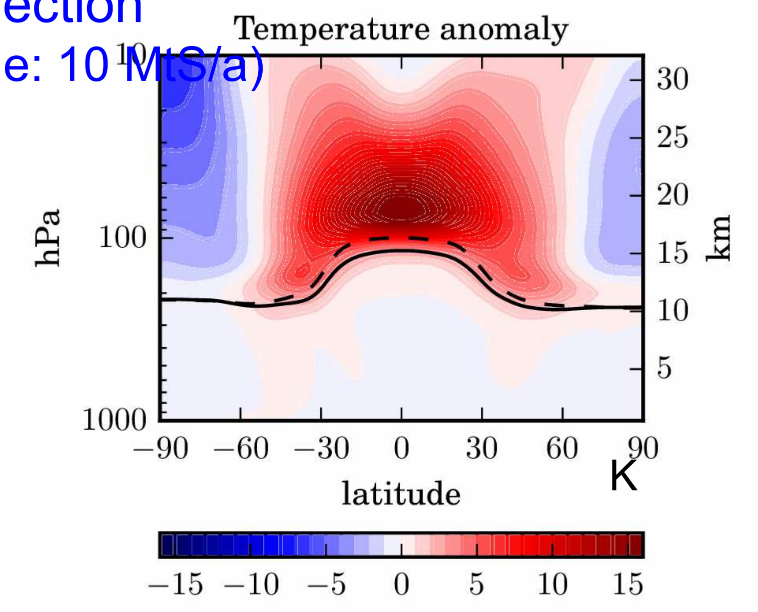


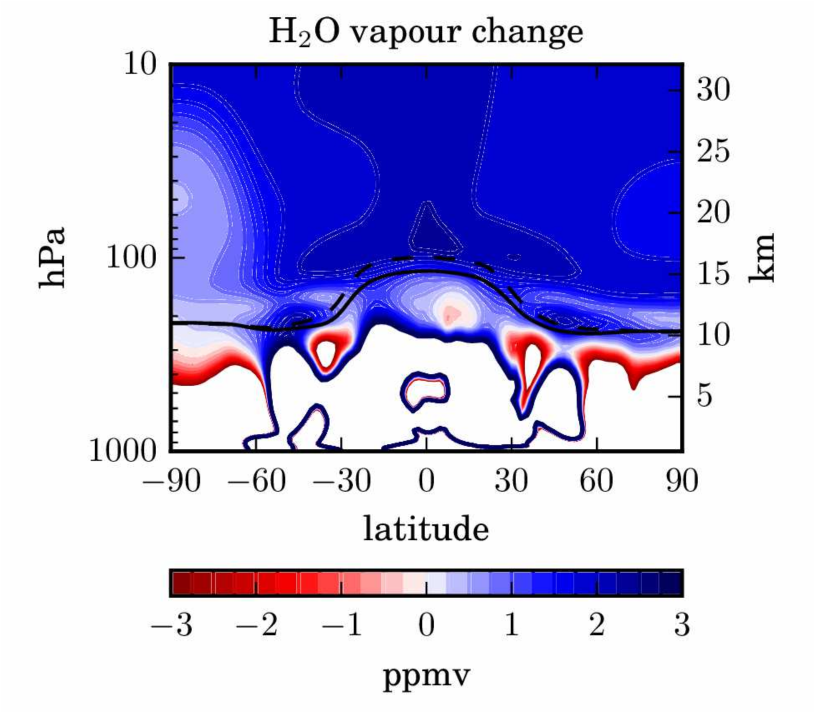
Source: Eva Ahbe, Die Änderung der Himmelsfarbe durch Climate Engineering Maßnahmen, Bachelor Thesis, Univ. Heidelberg, 2013

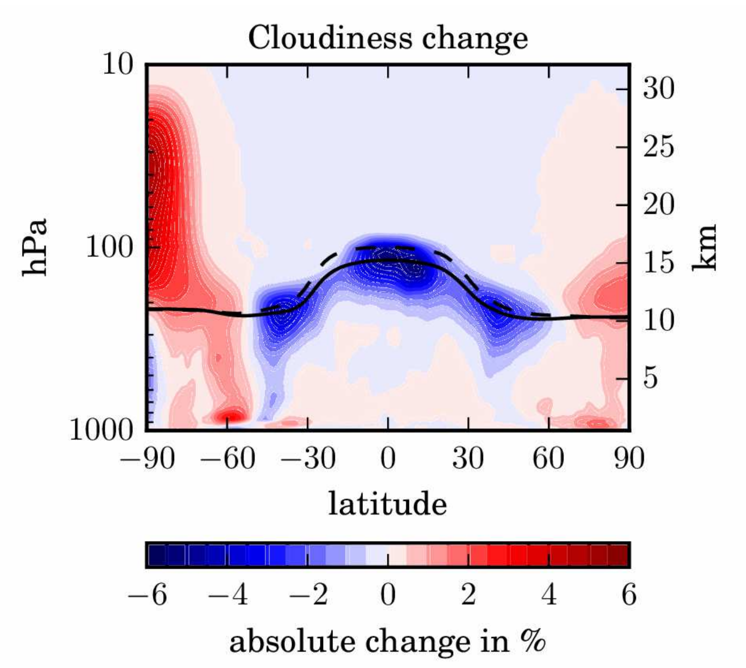
Our Simulations: Side Effects of Stratospheric Sulfur Injection
(Example: 10 MtS/a)

Strong heating of lower stratosphere by the aerosol:

- more stratospheric water vapour
- changes in high clouds
- effective forcing larger than instantaneous forcing







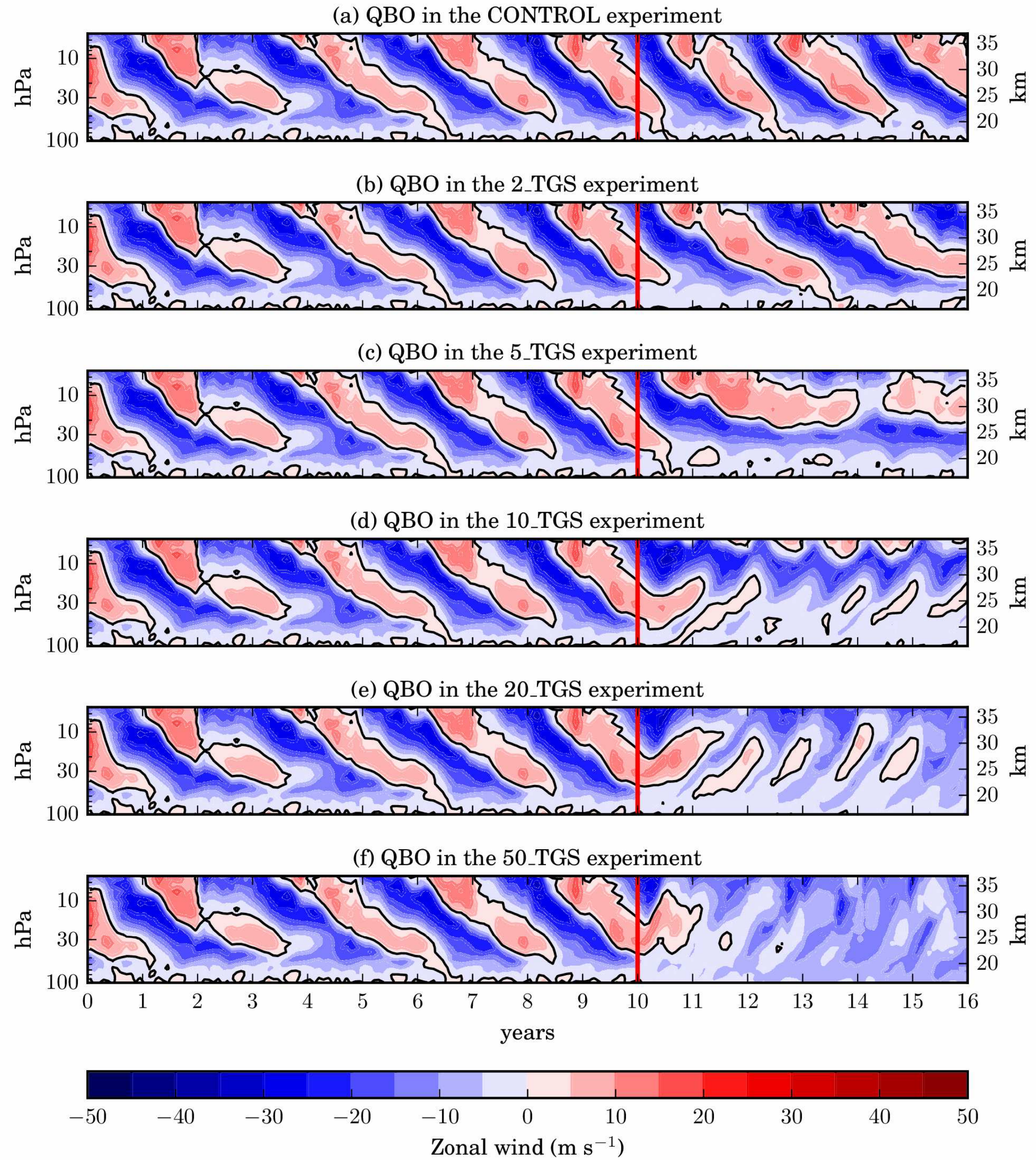
Kleinschmitt C., Boucher O., and Platt U. (2018), Sensitivity of the radiative forcing by stratospheric sulfur geoengineering to the amount and strategy of the SO_2 injection studied with the LMDZ-S3A model, Atmos. Chem. Phys. 18, 2769–2786,

Our Simulations: Side Effects of Stratospheric Sulfur Injection

Strong heating by the aerosol:

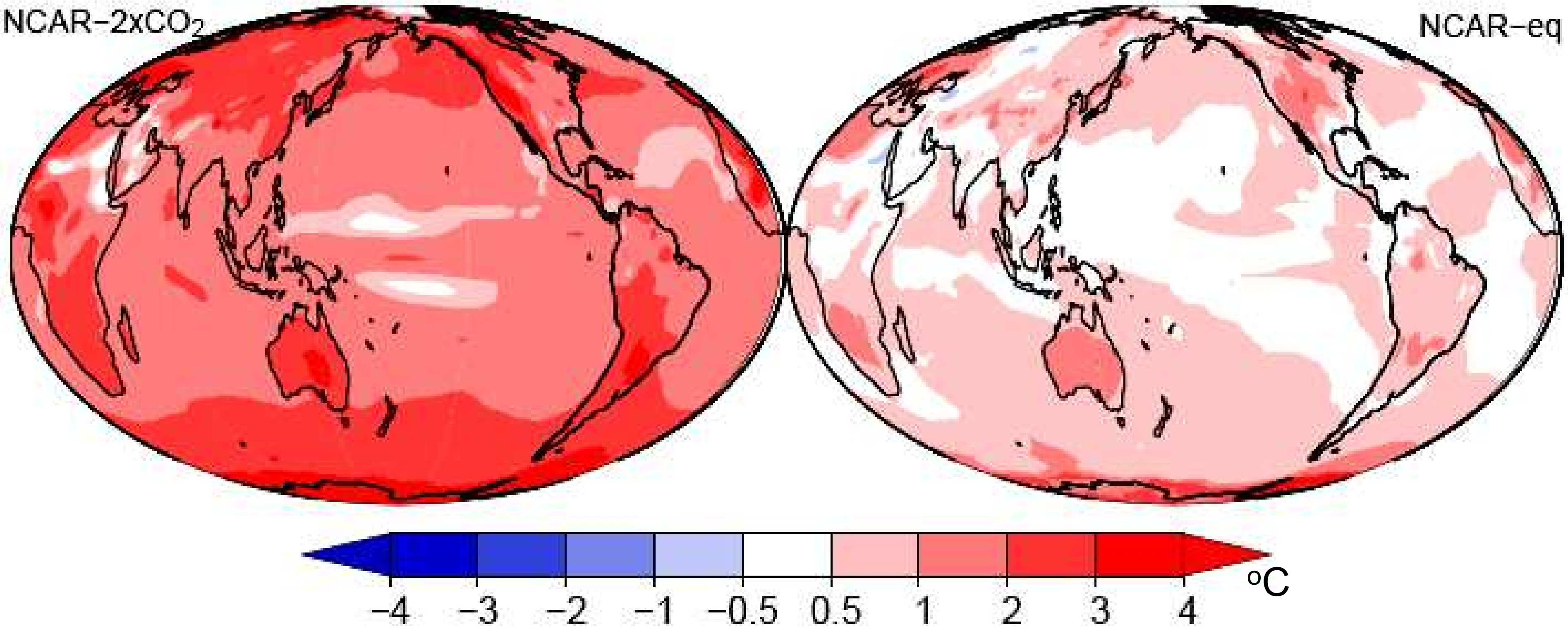
- stratospheric dynamics (QBO) disturbed
- poleward transport is impeded (even larger particles)

→ Quasi-Biennial Oscillation (QBO) breaks down at ≥ 5 TgS/a injection



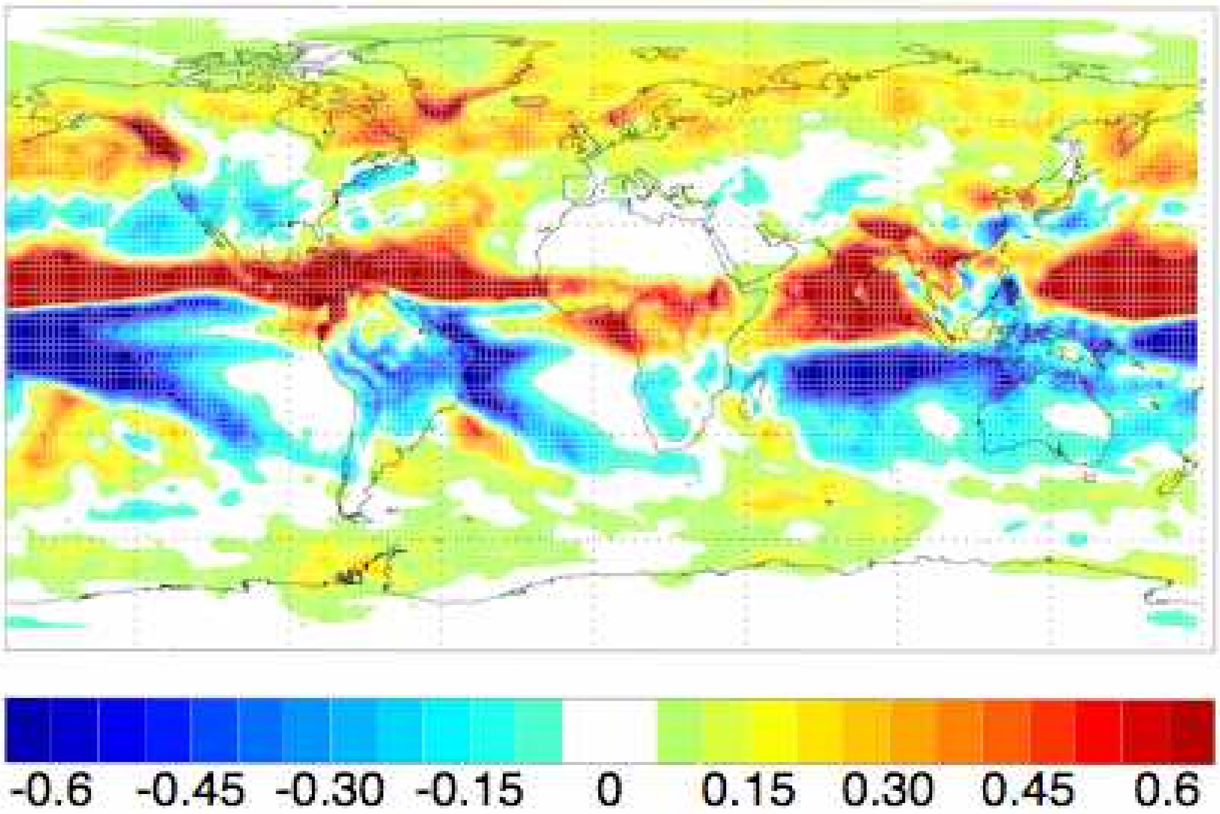
Kleinschmitt C., Boucher O., and Platt U. (2018), Sensitivity of the radiative forcing by stratospheric sulfur geoengineering to the amount and strategy of the SO_2 injection studied with the LMDZ-S3A model, Atmos. Chem. Phys. 18, 2769–2786,

Consequences of CE Offseting $2xCO_2$ on the Global Temperature Distribution

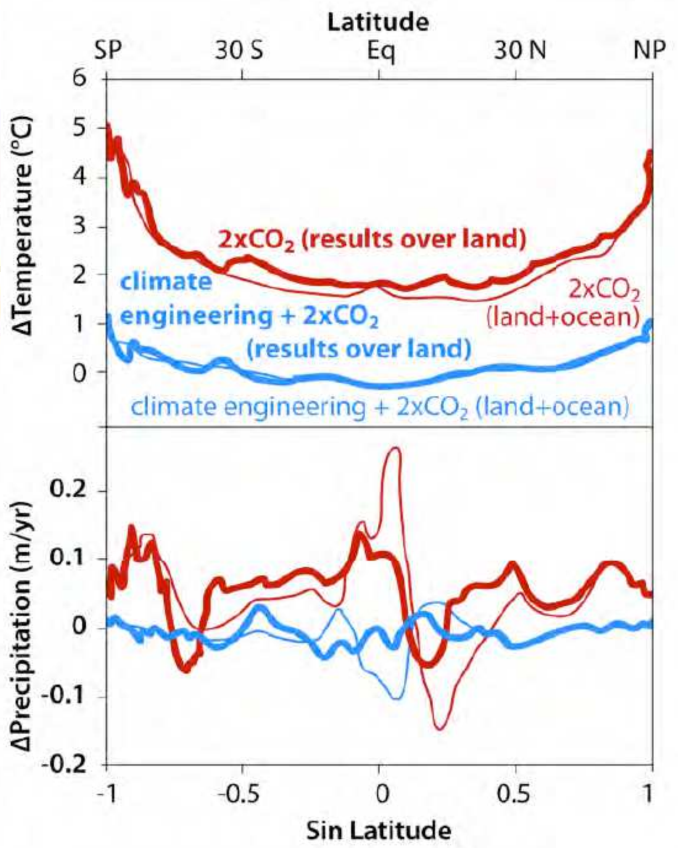


Govindasamy et. al. Global and
Planetary Change 37 (2003) 157–168

Consequences of CE on Global Precipitation Patterns



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



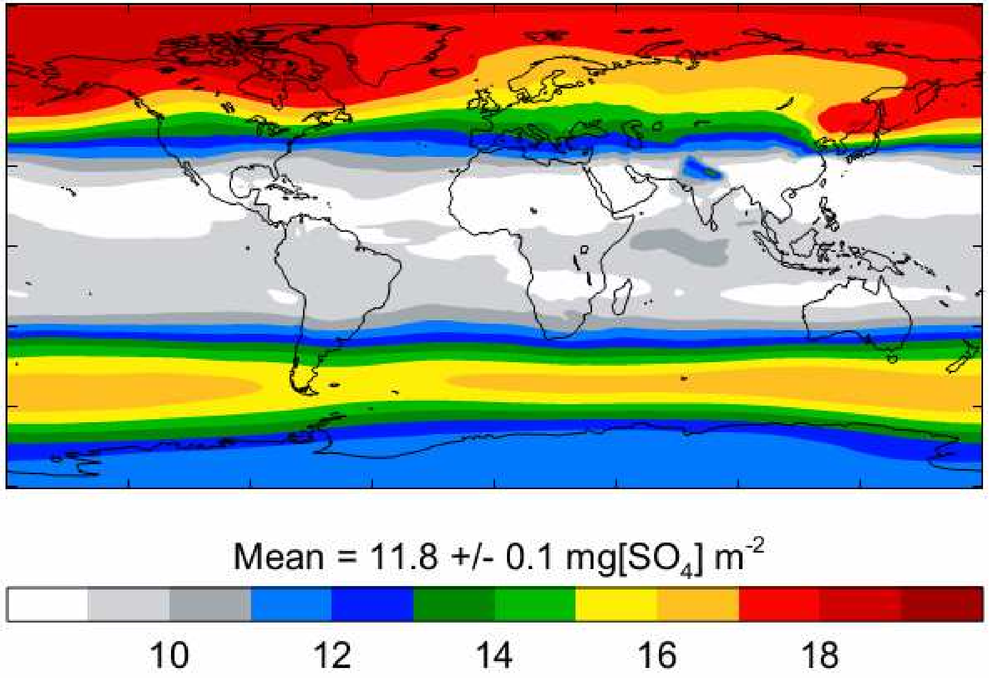
Change in daily precipitation column, (mm), J. Feichter et al. submitted

Blackstock et al. 2009

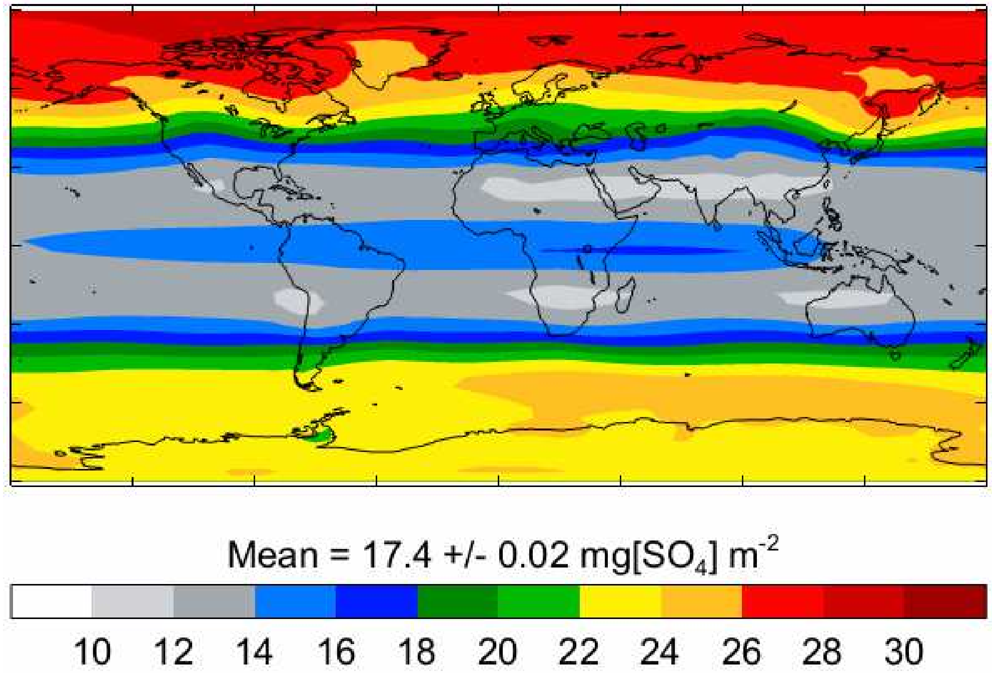
Burden of Sulfate from CE

Model Calculations for 2nd decade (years 11-20 after initiation of CE)

HadGEM2 - Model



ModelE - Model

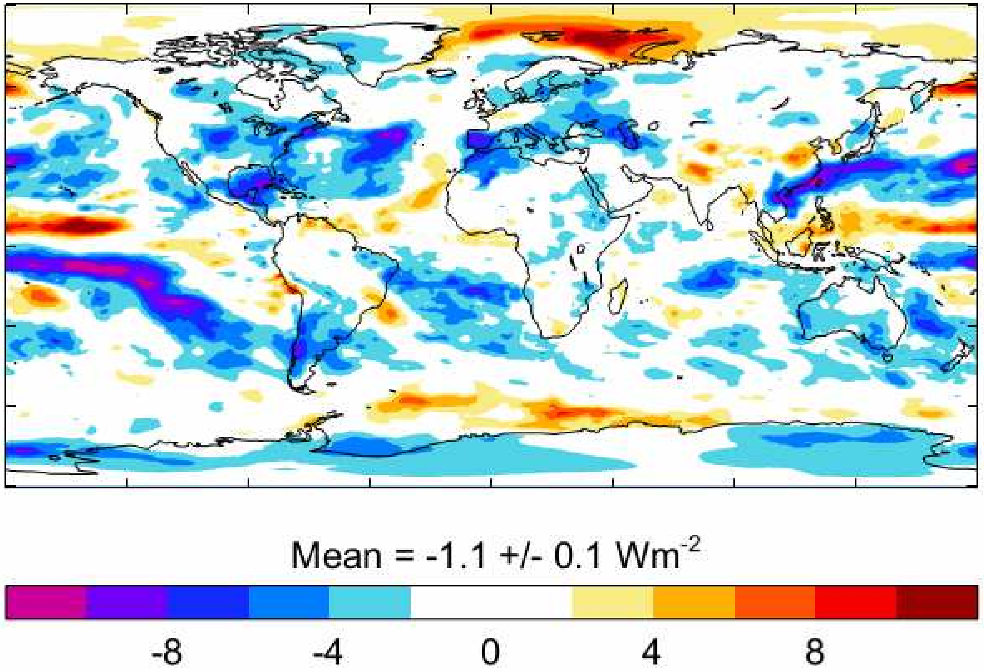


Jones A., Haywood J., Boucher O., Kravitz B., and Robock A. (2010), Geoengineering by stratospheric SO_2 injection: results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE, Atmos. Chem. Phys., 10, 5999–6006.

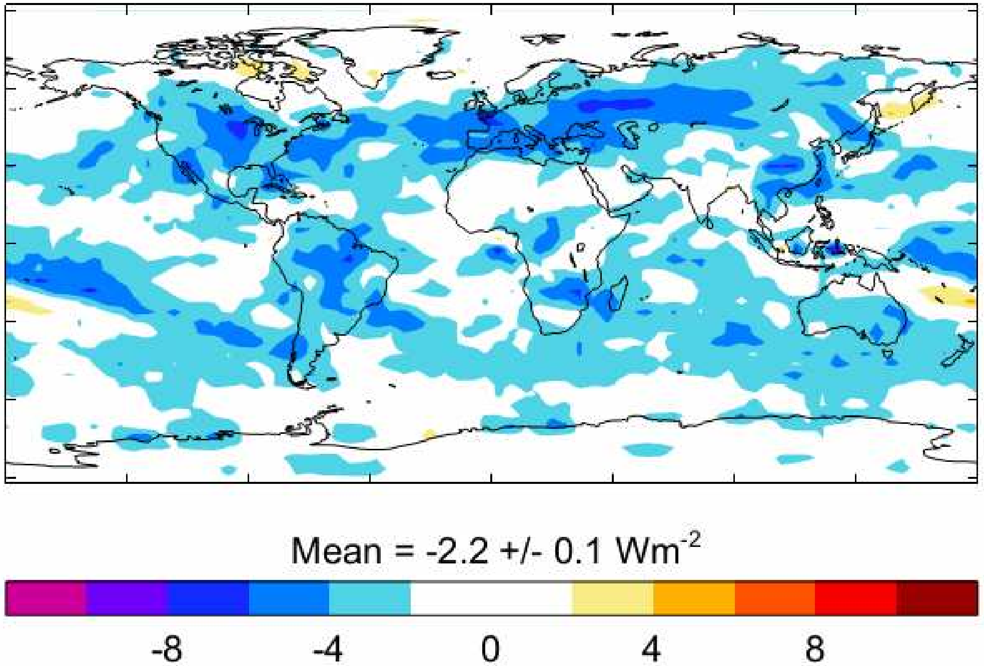
Change in Radiative
Forcing due to CE

Model Calculations for 2n
decade (years 11-20 afte
initiation of CE)

HadGEM2 - Model



ModelE - Model



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Changes in Temperature and Precipitation

A1B Scenario (IPCC)

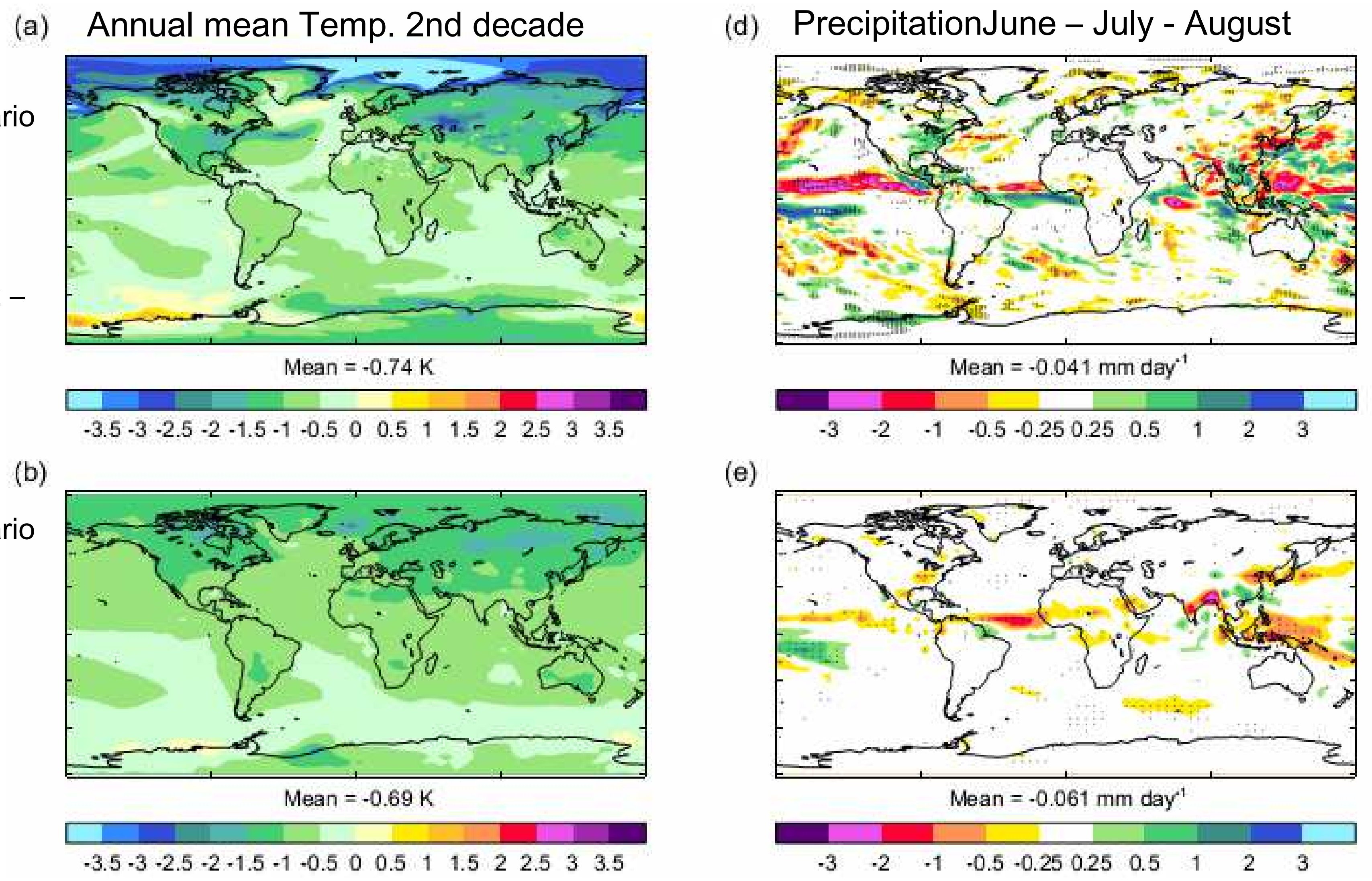
–

A1B+CE (HadGEM2 – Model)

A1B Scenario (IPCC)

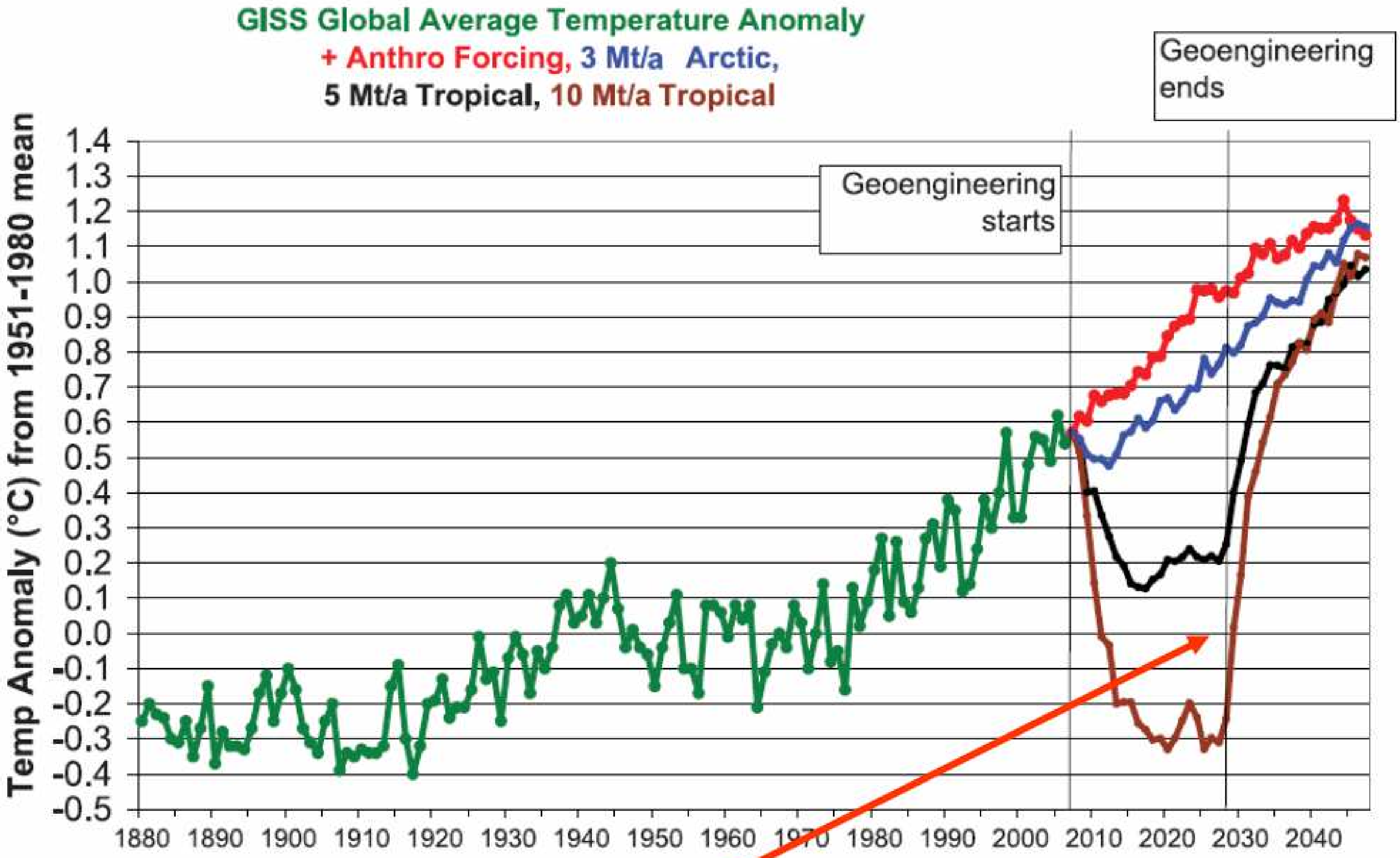
–

A1B+CE (ModelE – Model)



Jones A., Haywood J., Boucher O., Kravitz B., and Robock A. (2010), Geoengineering by stratospheric SO_2 injection: results from the Met Office HadGEM2 climate model and comparison with the Goddard Institute for Space Studies ModelE, Atmos. Chem. Phys., 10, 5999–6006.

What Happens if we stop Climate Engineering Measures?



Very rapid temperature increase if sulfate injections were stopped.

Robock et al. JGR 2008

Advantages and Problems of Stratospheric Particle CE

Advantages:

Relatively cheap to implement (estimated 1-10 billion $ annually)

Very large leverage factor (about $2 \cdot 10^5$ per year)

Problems:

Very difficult to achive optimum particle size

Likely destruction of stratospheric aerosol

Casualties due to sulfate-aerosol (≈20,000 annually per million ton of S-aerosol)

No more blue sky anywhere on the globe

Astronomical observations will be affected

Summary

- A closer look to even the most promising CE-technique i.e. stratospheric aerosol reveals, substantial, fundamental problems
  (how to inject, influence on the ozone layer, required mass).
- Further research on the problem – in particular on nucleation processes - is required.
- Sulfuric acid particles are not optimal because of their chemical effects
- completely different approaches – specially engineered particles – could be promising.
- Leverage factors of $(1\text{-}3)\cdot 10^6$ could theoretically be reached.

Ridicule greeted a 1992 proposal to combat global warming by shooting reflective particles into the atmosphere. The response could be different today.

Spring 2007 ■ Wilson Quarterly 47