6. SRM - Stratospheric Aerosol

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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


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.


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
Stratospheric Particle Injection – Inspired by Volcanic Eruptions


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

Explosive NET COOLING
(Stratospheric aerosols
(Lifetime \approx 1-3 years)

\[ \text{\(H_2S \rightarrow H_2SO_4\)} \]
\[ \text{\(SO_2 \rightarrow H_2SO_4\)} \]

Ash

Stratospheric Heating

Heterogeneous \(\rightarrow\) Less \(O_3\) depletion \(\rightarrow\) Less Solar Heating

Solar Heating

\[ \text{\(\text{absorption (near IR)}\)} \]

More Reflected Solar Flux

Net Heating

Tropospheric aerosols
(Lifetime \approx 1-3 weeks)

\[ \text{\(SO_2 \rightarrow H_2SO_4\)} \]

Indirect Effects on Clouds

Net Cooling

H2S \(\rightarrow\) H2SO4

\[ \text{\(CO_2\)} \]

\[ \text{\(H_2O\)} \]

more reflected solar flux

less upward IR flux

net heating

net cooling

Effects on cirrus clouds

Enhanced Diffuse Flux

Reduced Direct Flux

Less Total Solar Flux

More Downward IR Flux

from a presentation by Alan Robock, Heidelberg 2010
Mount Pinatubo (1)
Eruption June 1991

Photo: NASA

before

after
Mount Pinatubo (2)

Pinatubo aerosols as seen from the space shuttle Atlantis


B) Continental discharge averaged over the annual water year (October through September values); 1 Sv = $10^6$ m$^3$/s.


Hegerl G.C. and Solomon S. (2009), Risks of Climate Engineering, SCIENCE 325, 955-956.
Mount Pinatubo (3)

SAGE II 1020 nm Optical Depth

91-April-10 to 91-May-13
91-June-15 to 91-July-25
91-August-23 to 91-September-30
93-December-5 to 94-January-16

NASA

WMO (2003)
Mount Pinatubo (4)

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


**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
Laki SAT Anomaly (°C) JJA 1783 q–flux

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

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

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

$\rho_p$: Density of the particle
$\rho_f$: Density of the fluid

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

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

$\mu$: dynamic viscosity of the fluid
$r$: radius of the particle

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

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

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

Note: $v \propto r^2$

E.g. for particle with $r = 1$ $\mu$m, $\rho = 10^3$ 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:
\[ \mu = \rho_{air} \cdot \frac{v_{kinematic \, viscosity}}{\mu} = \rho_{air} \cdot \frac{1}{3} \lambda_{air} v_{molec} \]

Mean free path:
\[ \lambda_{air} = \frac{1}{\sqrt{2}n\sigma} = \frac{M}{\sqrt{2} \cdot \rho_{air} N_{Avogadro} \sigma} \]

\[ \Rightarrow \mu = \rho_{air} \cdot \frac{1}{3} \sqrt{2} \cdot \frac{M}{\rho_{air} N_{Avogadro} \sigma} v_{molec} = \frac{1}{3\sqrt{2}} \frac{M}{N_{Avogadro} \sigma} \cdot v_{molec} \]

Dynamic viscosity is independent of pressure! \( \rightarrow \) 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: \[ \text{Kn} = \frac{\text{mean free path}}{\text{particle radius}} = \frac{\lambda_{\text{air}}}{r} \]

For \( \text{Kn} << 1 \) the fluid can be described as a continuum, i.e. by macroscopic quantities such as viscosity and density.

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

Thus for particle with \( r = 1 \, \mu\text{m} \): \( \text{Kn} \approx 0.06 << 1 \) (1 atm), \( \text{Kn} \approx 2.4 \) at 25 mbar

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

\[ F_S = 6\pi\mu rv \frac{1}{1+A\cdot\text{Kn}} \xrightarrow{r \to 0, A \approx 1} 6\pi\mu rv^2 \frac{r^2}{\lambda_{\text{air}}} \]

\[ \rightarrow \text{Settling velocity for large Kn (small particles, low pressure):} \]

\[ v = \frac{2}{9} \cdot \frac{g\lambda_{\text{air}}r}{\mu \cdot \rho_p} \propto \frac{1}{\rho_p} \propto r \]

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

\[ \rightarrow \text{Small particles do settle faster in the stratosphere!} \]
Aerosol Physics: Aerosol – Radiation Interaction

**Rayleigh** scattering: scattering on air molecules
- radius of scatterers $r \ll \lambda$
- SW radiation ($\lambda \approx 100$s 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 < $r < 50$ $\mu$m)

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

\[ x = \frac{2\pi r}{\lambda} \]

- $x << 1$ for molecules and fine particles: Rayleigh Scattering
- $x \geq 1$ for coarse particles and clouds: Mie Scattering
Problem: Scattering mostly forward, in particular for large particles

Size Parameter:

\[ x = \frac{2\pi r}{\lambda} \]

\[ x = 1 \quad \text{For } \lambda = 0.6 \, \mu m \quad r \approx 0.1 \, \mu m \]

\[ x = 3 \quad \text{For } \lambda = 0.6 \, \mu m \quad r \approx 0.3 \, \mu m \]

\[ x = 10 \quad \text{For } \lambda = 0.6 \, \mu m \quad r \approx 1 \, \mu m \]

\( \rightarrow \) Particles must be small!

From: Thesis Sanghavi
More Phase Functions

$\lambda = 0.6 \mu m$

$r = 0.06 \mu m$
Scattering Efficiency as a Function of Particle Size

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

\[ Q_{\text{scat}} = \frac{\sigma_{\text{scat}}}{\pi r^2} \]

Particles must be big!

\[ x = \frac{2\pi r}{\lambda} \]

\[ \longrightarrow \text{Rayleigh regime} \]

\[ \longrightarrow \text{Mie regime} \]
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)

\[ \beta = \beta \left( \frac{\mu}{\cos \vartheta} \right) \]

\( \vartheta = \text{scattering angle} \)

\[ \bar{\beta} = \int_{0}^{\vartheta} \beta(\mu) d\mu \]

= BF for omnidirectional illumination

Scattering of Short-Wave Radiation $\lambda=0.6 \, \mu m$

Mie Scattering Diagrams

Aerosol Layer

Tiny particle $r \approx 0.1 \, \mu m$

small particle $r \approx 0.3 \, \mu m$

Large particle $r \approx 1 \, \mu m$

Surface
Optimal Particle Size

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

- Particles too small to scatter light at all
- Small Particles coagulate quickly
- Large Particles mostly scatter in forward direction
- Large Particles settle quickly
- Large Particles: little surface/mass

Stratospheric Aerosol Life Cycle

From: Kremser et al., 2016
Which Particle Size-Distribution will Result?

Processes:

1) $\text{SO}_2 \rightarrow \text{H}_2\text{SO}_4$ conversion
2) Nucleation (new particle formation)
3) Condensation (growth of existing particles)
4) Coagulation
5) Sedimentation
Optimum particle radius $r=0.2\mu m$

$\rightarrow$

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**.

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?

Injection of $\text{H}_2\text{SO}_4$ - aerosol instead of $\text{SO}_2$

Aerosol size distribution for direct $\text{H}_2\text{SO}_4$ – injection into the stratosphere

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

Optimum particle radius

However, see:
Niemeier et al. 2011
English et al. 2012

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

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., 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 stratospheric circulation

Stratospheric Flow: Brewer-Dobson Circulation

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

Aerosol (or precursor species) released at the equator will be transported to the poles 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:

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

Assuming that 10 MtS/year can reduce the forcing by \( \approx 4 \ W/m^2 \) (optimistic)

we can say that this would approximately cancel the effect of CO\(_2\)-doubling (from 280 ppm pre-industrial to 560 ppm, actually 3.7 \( W/m^2 \)).

Mass of 280 ppm of atmospheric CO\(_2\):

\[
M_{CO_2}(280 \text{ ppm}) \approx 2237 \text{ Gt CO}_2 \left(610 \text{ GtC}\right)
\]

\[
R_{Lev} = \frac{2237 \text{ Gt}}{10 \text{ Mt}} \approx 2.24 \cdot 10^5 \text{ per year}
\]
How could Particle Sedimentation be prevented?

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

Wrong explanation 1:
Radiation pressure, Photons have momentum \((p=E/c)\) but it is too small:

solar radiation: \(\approx10^{-4}\) W/cm\(^2\) \(\rightarrow\) \(3\cdot10^{14}\) Photons/s,
Momentum of a photon \(\approx10^{-27}\) kgm/s
\(\rightarrow\) Force \(\approx3\cdot10^{-13}\) Newtons (for \(1\) cm\(^2\))

Moreover: Momentum transfer to black surface: \(p\), reflecting surface: \(2p\)
\(\rightarrow\) wrong rotational direction

Wrong explanation 2 (Wikipedia):
Warm layer of air at black surface provides larger pressure ...
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**
\[ \alpha = \text{probability that a colliding air molecule assumes the temperature of the particle} \]
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

Insolation

Orientation in the atmospheric electric field + perhaps Earth magnetic field

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
<table>
<thead>
<tr>
<th>Type</th>
<th>Representative Airplane</th>
<th>Properties</th>
<th>Availability</th>
</tr>
</thead>
</table>
| Large Cargo Aircraft                | Boeing 747 (-200)       | • Large cargo capacity  
• Long range  
• Efficient                                                                 | Dozens available used, approx. 600 built                                    |
| High Performance 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 Performance Zoom Climber       | MacDonnell Douglas F-15 | • Large Payload  
• Fast time-to-climb  
• High Altitude  
• High maintenance and fuel costs                                               | Questionable availability, approx. 1200 built, Numerous similar in storage |
Maximum negative forcing below $\approx 1.5 \text{ W/m}^2$, even if fuel sulfur contents is increased 50-fold (from 0.6 g/kg to 30 g/kg).

McClellan et al. 2011

The „Coffin Corner“

Best Case Flight Envelope for 747-400

Altitude (ft)

Stall

Cruise Mach

Max Mach

Mach Number

0.70 0.75 0.80 0.85 0.90 0.95 1.00

60
55
50
45
40
35
30
High Towers

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

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 Cresseey

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...
Simplified Delivery of Sulfur to the Stratosphere

Vortex Rings (Smoke rings)

Exist also without smoke
Journal für die reine und angewandte Mathematik, Berlin; 1826, 25 - 55

What are Smoke Rings (Vortex Rings)?

A vortex ring
(Drawing by Helmholtz)

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

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

Direction of motion of the entire ring

Vortex ring generator
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 collapse.

The range of a smoke ring scales with the volume/surface ratio, i.e. with \( R \) (Assuming \( R/r = \text{constant} \))

\[ \text{changing } R \text{ from } 0.05m \text{ to } 50m \text{ would change the range to } Z=10 \text{ – } 20 \text{ m to } Z \approx 10 \text{ - } 20 \text{ km} \]

Volume of a vortex ring \( (r=5m, R=50m) \): \( V \approx 24000 \text{ m}^3 \)

\( \text{SO}_2 \text{ - Weight } \approx 60 \text{ t} \)

\[ \text{Firing the device every 3 minutes would transport 1 million t of } \text{SO}_2 \text{ per year to stratosphere} \]

Pressure increase needed to fire vortex ring:
\[ p \approx 5\text{mBar or } V \approx 15,000\text{m}^3 \]

30t of TNT (not bad for 60t of \( \text{SO}_2 \), compare artillery)

Alternatives to TNT:
30t of superheated water
1t of gasoline spray
Smoke Ring Delivery of SO$_2$ (or Aerosol) to the Stratosphere

Direction of motion of the entire ring

Kinetic energy of Vortex: 3 MJ
→ equivalent to burning 0.1 liter of gasoline
→ Room for improvement!

Big Device underground

30 t of TNT or 30 t of superheated water or 1 t of gasoline spray

2R=100m

100m

200m
Yearly Total Cost Comparison (1M tonnes / year)

- New Design Airplane
- Hybrid Airship
- Boeing 747 Class
- Modified Gulfstream Class
- Gun (Mark 7 16"")
- Gun (Modernized Mark 7)
- Rocket
- Gas Pipe
- Slurry Pipe

Altitude (kft) 0 20 40 60 80 100 120
Altitude (km) 0 6.0 12.2 18.3 24.4 30.5 36.5

McClellan et al. 2011
The Question of Cost - 2

McClellan et al. 2011

Operations Cost Per Kilogram Comparison

- New Design Airplane
- Hybrid Airship
- Boeing 747 Class
- Modified Gulfstream Class
- Gun (Mark 7 16")
- Gun (Modernized Mark 7)
- Rocket
- Gas Pipe
- Slurry Pipe

Altitude (kft) 0 20 40 60 80 100 120
Altitude (km) 0 6.0 12.2 18.3 24.4 30.5 36.5
**Gun Systems**

*Table 15: Gun System Analysis Inputs*

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

McClellan et al. 2011
The „Side Effects“ of Stratospheric Geoengineering
Absorption/scattering efficiencies for the SMALL/WIDE aerosol size distributions. Points are plotted at the mid-point of each wavelength interval.

Stratospheric Heating

Why Endanger Particles the Ozone Layer? (1)

Katalytic Ozone destruction:
\[
\begin{align*}
X + O_3 & \rightarrow XO + O_2 \\
XO + O & \rightarrow X + O_2 \\
\text{net:} & \quad O + O_3 \\
& \rightarrow 2O_2
\end{align*}
\]

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 calculated (ca. 3x higher) \(O_3\) concentrations and their dependence on.

Particles?
1) Oxides of Nitrogen (one of the catalysts destroying ozone) is converted into (benign) nitric acid.

\[ \text{NO}_2 + \text{O}_3 \rightarrow \text{NO}_3 \]
\[ \text{NO}_2 + \text{NO}_3 \rightarrow \text{N}_2\text{O}_5 \]

\( \text{N}_2\text{O}_5 \) is converted to \( \text{HNO}_3 \) at particle surfaces; “denitification”.

\[ \text{N}_2\text{O}_5 (g) + \text{H}_2\text{O} (p) \rightarrow 2 \text{HNO}_3 (p) \]

\( \rightarrow \) Reduced formation of \( \text{ClONO}_2 \)

2) Reactions at particle surfaces convert “benign” species (\( \text{HCl}, \text{ClONO}_2 \)), to ozone destruction-katalyst-species:

\[ \text{ClONO}_2 (g) + \text{HCl} (p) \rightarrow \text{HNO}_3 (p) + \text{Cl}_2 (g); \quad \text{Cl}_2 + \text{hv} \rightarrow 2 \text{Cl} \]
\[ \text{ClONO}_2 (g) + \text{H}_2\text{O} (p) \rightarrow \text{HNO}_3 (p) + \text{HOCl} (g) \]
\[ \text{HOCl} (g) + \text{HCl} (p) \rightarrow \text{Cl}_2 (g) + \text{H}_2\text{O} (p) \]
\[ \text{N}_2\text{O}_5 (g) + \text{HCl} (p) \rightarrow \text{HNO}_3 (p) + \text{ClNO}_2 (g) \]

(p) bzw. (g) Reactands at particle or in the gas phase, respectively.
Fortunately most of the reactions at H$_2$SO$_4$-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.

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

Antarctica (70-90°S)

Arctic (70-90°N)

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

»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?

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
The Colour of Geoengineered Skies

1) CE – Scenario: Compensation of global warming due to $2\times CO_2$ by stratospheric sulfate aerosol


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

Consequences of CE on Global Precipitation Patterns

CE-measures offsetting the mean global temperature rise caused by $2\times$CO$_2$

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

Blackstock et al. 2009
Burden of Sulfate from CE
Model Calculations for 2\textsuperscript{nd} decade
(years 11-20 after initiation of CE)

HadGEM2 - Model

![Map of Burden of Sulfate from HadGEM2 Model Calculations]

Mean = 11.8 +/- 0.1 mg[SO\textsubscript{4}] m\textsuperscript{-2}

ModelE - Model

![Map of Burden of Sulfate from ModelE Model Calculations]

Mean = 17.4 +/- 0.02 mg[SO\textsubscript{4}] m\textsuperscript{-2}

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Change in Radiative Forcing due to CE Model Calculations for 2nd decade (years 11-20 after initiation of CE)

HadGEM2 - Model

Mean = -1.1 +/- 0.1 Wm^{-2}

ModelE - Model

Mean = -2.2 +/- 0.1 Wm^{-2}

Changes in Temperature and Precipitation

A1B Scenario (IPCC) – A1B+CE (HadGEM2 – Model)

Annual mean Temp. 2nd decade

Mean = -0.74 K

Precipitation June – July - August

Mean = -0.041 mm day\(^{-1}\)

A1B Scenario (IPCC) – A1B+CE (ModelE – Model)

Mean = -0.69 K

Mean = -0.061 mm day\(^{-1}\)

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 $2\cdot10^5$ per year)

Problems:
Very difficult to achieve optimum particle size
Likely destruction of stratospheric aerosol
Casualties due to sulfate-aerosol ($\approx20,000$ 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 \((1-3) \cdot 10^6\) could theoretically be reached.