5. SRM: Reflectors in Space

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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 CO₂ 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
Contents of Today's Lecture

• Reflectors in space – how much shading is needed?
• Low Earth Orbit (LEO)
• The Lagrange Points
• L1-Reflectors
• Transport into space
• Question of cost …
• Conclusions
Literature


Abstract:
The accelerated rate of increase in atmospheric CO₂ concentrations in recent years and the inability of human-kind to move away from carbon-based energy system have led to the revival of the idea of counteracting global warming through geoengineering schemes. Two categories of geoengineering proposals have been suggested: solar radiation management (SRM) and carbon dioxide removal (CDR) methods. SRM schemes would attempt to reduce the amount of solar radiation absorbed by our planet. Placing reflectors or mirrors in space, injecting aerosols into the stratosphere, and enhancing the albedo of marine clouds are some of the proposed SRM methods. In this section, the various space-based SRM methods which are likely to reduce the incoming solar radiation uniformly across the globe are discussed. In the past decade, the effects of these space sunshades on the climate system have been simulated using climate models by reducing the amount of incoming solar radiation by appropriate amounts (reduced solar constant). Key modeling results on the extent of global and regional climate change mitigation, unintended side effects, and unmitigated effects are briefly discussed.
Reflectors in Space: How much shading is Needed?

Area of shade, \( A_S \):

\[
A_S = f \cdot \frac{\pi R_E^2}{\varepsilon}
\]

\( R_E = \) Radius of Earth
\( f = \) Shading factor
\( \varepsilon = \) Shading efficiency

\[
f = \frac{4 \cdot S_{gh}}{(1-A) \cdot S_0} = \frac{S_{gh}}{S}
\]

\( A = \) Earth albedo (0.3)
\( S_0 = \) Solar constant (1342 W/m\(^2\))
\( S_{gh} = \) Greenhouse radiative forcing to be compensated
\( S = S_0/4(1-A) = \) Solar input
How much shading is Needed? - Examples

Example: We wish to offset temperature change due to $2\times$CO$_2$:

Primary forcing: $3.7 \text{ W/m}^2$
(Note: There will be little or no feedback if we compensate primary forcing)

Incident Radiation on Earth (surface averaged): $S_0 \approx 342 \text{ W/m}^2$

minus reflection ($A=0.7$):

$S \approx 239.4 \text{ W/m}^2$

We need to shade an area of: $A_S = 3.7 / 239.4 \times$ cross section of Earth ($\pi R^2$)

$A_S \approx 0.0154 \times 1.29 \times 10^8 \text{ km}^2 \approx 2 \times 10^6 \text{ km}^2$ ($\varepsilon=1$)

Assuming a sheet of $d = 0.01 \text{ mm}$ thickness this would correspond to a volume of $V = A_S \cdot d$

$V \approx 2 \times 10^7 \text{ m}^3$

Weight (assuming a density of $5 \text{ t/m}^3$)

$10^8 \text{ t}$

Govindasamy and Caldeira 2000 show that the geoengineering schemes that reduce the incident solar radiation uniformly by about 1.8% (i.e.
Problem: Radiation Pressure

Reflecting surface (R=1):

In Incoming
Photon: \(p_{ph} = \frac{E_{ph}}{c}\)  
Reflected
Photon: \(p_{ph} = -\frac{E_{ph}}{c}\)

\[\Delta p = 2p_{ph} = 2 \frac{E_{ph}}{c}\]

Force:

\[F = \Delta p \cdot \hat{n}_{ph} = 2 \frac{E_{ph}}{c} \cdot \frac{P}{E_{ph}} = 2 \frac{P}{c}\]

for 1 m\(^2\) \(P = 10^3\) W,

with \(c = 3 \cdot 10^8\) m/s:

\(F \approx 6.6 \cdot 10^{-6}\) N

Absorbing surface (R=0):

Absorbing for SW radiation, Reflecting for LW radiation

Absorbing for LW radiation, i.e. Emissivity = 1

\[\Delta p = p_{SWph} - n \cdot p_{LWph} = \frac{E_{SWph}}{c} - n \cdot \frac{E_{LWph}}{c}\]

\[= \frac{E_{SWph}}{c} - n \cdot \frac{n}{c} = 0\]

Problem: LW-radiation follows Lambertian emission pattern!
Sunshades in Space

Questions:

• Low Earth Orbit (LEO)
• Higher Earth Orbits?
• Lagrange Point (L1)
• Origin of the shading material
Shading efficiency:

\[ \varepsilon = \frac{2R_E}{2\pi(R_E + h)} = \frac{R_E}{\pi(R_E + h)} \leq \frac{1}{\pi} \]
Possible LE-Orbits

- **Polar Orbit**: shading of the disk: $\propto \frac{1}{\cos \varphi}$, $\varphi = \text{Latitude}$

- **Equatorial Orbit**: shading of surface area: Independent of latitude

- **Inclined Orbit** (inclination $<90^\circ$): Shading limited to latitude band with $\varphi < 90^\circ$
The Earth Ring Concept

Earth Ring Concept, $R \sim 1.3-1.7 \, R_E$, With Shepherding Satellites

Temperatures by Latitude Bands

Ring Radii in multiples of $R_E$

- 1.2-1.3
- 1.3-1.4
- 1.4-1.5
- 1.5-1.6
- 1.6-1.7
- 1.7-1.8

Pearson et al. 2006
• Relatively easy to reach (velocity $\approx 8$ km/s)
• Radiation pressure relatively unimportant (gravitational forces about $10^5$ times larger than at L1!)
• Shading efficiency $< 0.3$
• May endanger space flight by overpopulating near Earth space
Contour plot of the effective potential due to gravity and the centrifugal force of a two-body system in a rotating frame of reference.

Arrows indicate the gradients of the potential - downhill toward them (red) or away from them (blue). Counterintuitively, the L4 and L5 points are the high points of the potential. At the points themselves these forces are balanced.
Shading at L1

Sun, Earth, Moon, and L1

Earth and Moon rotate around a common centre of gravity, thus Earth „wobbles“ around this point.

From: Angel 2006
Shade at L1: Earth „Wobble“ and Radiation Pressure

Wobble of Earth leads to a „shading efficiency“ $\varepsilon < 1$

Radiation pressure can be compensated by moving the shade further away from Earth (i.e. closer to the sun)
Sunshade properties for 1.8% flux reduction:

(a) Shadowing efficiency and total area.

(b) Total mass for different reflectivities $R$ and areal densities $\rho_s (x1)$ in gm$^{-2}$.

From: Angel 2006
Reflector Design: Dielectric Sheet with Holes

Choosing the thickness $d$ so that:

$$d = \frac{\lambda}{n} + m\lambda$$

$\rightarrow$ Wave front of radiation penetrating shield will be retarded by $\lambda/2$ compared to radiation traversing the hole

$\rightarrow$ Destructive interference
## Suggested Space-Shading Schemes

<table>
<thead>
<tr>
<th>Author</th>
<th>Description</th>
<th>Requirements</th>
<th>Mass, kg</th>
<th>Maintenance</th>
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<tbody>
<tr>
<td><strong>Earth Orbit Systems</strong></td>
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</table>
| Mautner, 1991; Pearson et al., 2002 | Saturn-like particle rings               | $R = 1.2\text{-}1.5\ R_e$  
$R = 1.3\text{-}1.6\ R_e$ | $3.4\times10^{11}$  
$2.1\times10^{14}$  
$2.3\times10^{12}$ | Replenish as necessary |
| NAS, 1992               | Orbiting mirrors in random LEO orbits     | 55,000 mirrors,  
$A = 100\ \text{km}^2$ |                | Uncontrolled; collisions, debris |
| Pearson et al., 2002    | Controlled spacecraft  
50,000 to 5 million spacecraft | 5x10^9 | Active control |
| **Solar Orbit Systems** |                                          |                                                   |                |                              |
| Early, 1989; Mautner, 1991 | L$_1$ lunar glass from mass driver  
D = 2000 km,  
10 $\mu$m thick | 10$^{11}$ | Active control |
| Mautner and Parks, 1990 | L$_1$ thin-films  
31,000 solar sails,  
3x10$^{12}$ m$^2$ each | 5x10$^{14}$ | Active control |
| Hudson, 1991            | L$_1$ parasol                            |                                                   |                | Active control |
| Teller, et al., 1997    | L$_1$ metallic scattering  
D = 638 km  
$T = 600$ angstroms | 3.4x10$^{6}$ | Active control |
| McInnes, 2002           | L$_1$ metallic reflector  
D = 3648 km | 4x10$^{11}$ | Active control |
| **Other Concepts**      |                                          |                                                   |                |                              |
| Korycansky et al., 2001 | Move Earth using Kuiper-belt-objects  
150-km object;  
One encounter every 6000 years | 10$^{19}$ | Actively moved, low delta-V |
| Criswell, 1985          | Lower sun’s mass to slow brightening  
Remove plasma from magnetic poles | 2x10$^{28}$ | Continual spacecraft ops |

Source: Pearson et al. 2006

Increase radius of Earth orbit from 1
→ 1.5 AU within $5 \times 10^9$ years
→ 1.01 AU within $10^8$ years (?)
Transport to Space

• Rockets
  → Only technology, which is actually available today

• Electromagnetic Accelerator
  → May be developed

• Ion Thruster (space only)

• Space Elevator
  → Fundamental design problems
The "Rocket Equation": Assumption: Fuel is burned, the released energy is used to "exhaust" the combustion products.

\[ v = v_e \cdot \ln \left( \frac{M_0}{M} \right) \]

\( M_0 = \) Initial mass of the rocket (e.g. at launch)

\( M = \) Final mass of the rocket (after all fuel is burned), i.e. the weight of the rocket structure

\( V_e = \) velocity of exhausted gas

Typical exhaust gas velocities \( v_e \) for rocket engines burning various propellants are:

- 2.9 to 4.5 km/s for liquid bipropellants
- 2.1 to 3.2 km/s for solid propellants \( \rightarrow \) 2.5 - 4.0 km/s

\[ \frac{v}{v_e} = \ln \left( \frac{M_0}{M} \right) \Leftrightarrow \frac{M_0}{M} = e^{\frac{v}{v_e}} = "Mass\ Ratio" \]

\( e^{\frac{v}{v_e}} \approx 7.4 \ldots 24.5 \ & \text{Low Earth Orbit: } v_1 \approx 8 \text{ km/s } \)
\( \approx 16.4 \ldots 88.2 \ & \text{Escape Velocity: } v_2 \approx 11.2 \text{ km/s } \)

Mass Ratios \( M_0/M > 10 \) are difficult to reach \( \rightarrow \) multi-stage rockets
Example Ariane 5 ECA

Initial mass: 760-780 t
Height: 56 m
Payload (LEO): 21 t
Initial thrust: 12.5 MN

Main stage (EPC H158 modified):
Initial mass: \( M_0 = 170.5 \) t
Empty mass: \( M = \) 12.5 t
Exhaust velocity: \( v_e = 4320 \) m/s
Thrust (ground) \( F_g = 0.815 \) MN

Average mass ratio:
no payload: \( 716/78.5 \approx 9.1 \)
20t payload: \( 736/98.5 \approx 7.5 \)

Solid fuel booster (EAP P241)
Initial mass: \( M_0 = 273 \) t
Empty mass: \( M = \) 33 t
Exhaust velocity: \( v_e = 2692 \) m/s
Thrust (ground) \( F_g = 5.06 \) MN
Rail Guns


B = \frac{\mu_0 l}{4\pi} \left( \frac{1}{x} + \frac{1}{d - x} \right) \approx \frac{\mu_0 l}{d\pi}

Force:

F = l dB \approx \frac{\mu_0 l^2}{\pi} \approx 4 \cdot 10^{-7} \cdot l^2 \frac{N}{A^2}
The Question of Cost

Cost as a function of total mass of project and payload per launch vehicle

- Lowest cost at about 200-500 launches
- Example: 1.8% shading in LEO at 1μm thickness and ε=0.3
  - $3 \times 10^7$ t (or $3 \times 10^{10}$ kg) total mass
  - total cost: $\approx 10^{14}$ $ (500,000 billion $)

Source: Pearson et al. 2006
## Cheaper Solutions?

Cost of different launch techniques (LEO):

<table>
<thead>
<tr>
<th>Launch Technique</th>
<th>Unit Cost of Material Launching, $/kg</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Earth</td>
</tr>
<tr>
<td>Conventional Rockets</td>
<td>1,000-3,000</td>
</tr>
<tr>
<td>EM or Gun Launch Plus Orbiting Tether</td>
<td>100-500</td>
</tr>
<tr>
<td>Ion Rockets</td>
<td>-</td>
</tr>
<tr>
<td>Rotating Space Tethers</td>
<td>-</td>
</tr>
<tr>
<td>Electromagnetic (EM) Mass Drivers</td>
<td>-</td>
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</tbody>
</table>

Source: Pearson et al. 2006
## Evaluation of Space-Borne Shades

<table>
<thead>
<tr>
<th>Technology</th>
<th>Maturity&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Potential effectiveness&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Cost factors&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Potential consequences&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scatterers or reflectors in space</td>
<td>Low (TRL 2):</td>
<td>Potentially fully effective:&lt;br&gt;• Spacecraft’s limited lifetime</td>
<td>• Design, fabrication, testing, acquisition, and deployment of a fleet of millions to trillions of&lt;br&gt;reflecting or scattering spacecraft&lt;br&gt;• Launch vehicle&lt;br&gt;• Infrastructure and operation&lt;br&gt;• Estimates in the scientific literature vary significantly: an estimate of $1.3 trillion and an estimate of less than $5 trillion</td>
<td>Earth-orbit technologies:&lt;br&gt;• A cool band in the tropics with unknown effects on ocean currents, temperature, precipitation, and wind&lt;br&gt;• A multitude of bright “stars” in the morning and evening that would interfere with terrestrial astronomy</td>
</tr>
</tbody>
</table>
Change in net long-wave radiative flux at the tropopause when CO$_2$ is quadrupled with respect to the Control case (in Wm$^{-2}$), zonally averaged as a function of time of year.


Reduction in incoming solar radiation (due to shading) needed to compensate forcing due to 4xCO$_2$.

→ Change in solar radiation has a latitudinal and seasonal pattern markedly different from the radiative forcing of CO$_2$. 
This idealized climate engineering simulation indicates that relatively simple climate engineering may be able to diminish temperature changes in most of the world.

Model Calculations of the Precipitation Change for 2xCO2

Annual mean precipitation changes in the (a,b) 2xCO2 and (c,d) Global 1.84 simulations. Shown are precipitation changes from the 1xCO2 cases (a,c) and areas where the temperature change is statistically significant at the 0.05 level (b,d). This idealized climate engineering simulation indicates that relatively simple climate engineering is likely to be able to diminish precipitation changes in most of the world.
Temperature Change vs. Insolation Reduction

Change in global annual mean temperature as a function of percentage of reduction in the top-of-atmosphere insolation. Despite large differences in the spatial extent of the insolation reduction, the global mean temperature response is similar.

Surface temperature changes for the “Geoengineered” 4xCO$_2$ simulation.

Although solar radiation has a spatial pattern greatly different to that of radiative forcing due to 4xCO$_2$, a reduction in solar forcing largely compensates the temperature response to CO$_2$ quadrupling.

Effect on Sea Ice

Annual mean sea ice thickness in the Control (top panel), “4xCO₂” (middle panel) and “Geoengineered 4xCO₂” (bottom panel) simulations. The reduction in solar forcing in “Geoengineered 4xCO₂” simulation largely compensates the decrease in sea ice thickness and area coverage in the “4xCO₂” simulation.

Consequences of CE Offsetting 2xCO$_2$ on the Global Temperature Distribution
Leverage Factor for Space Reflectors

We assume $10^8$ t of reflector weight for counteracting $3.7 \text{ W/m}^2$ ($\text{CO}_2$ – doubling, from 280 ppm pre-industrial to 560 ppm) 

$\text{CO}_2$-Mass (additional 280 ppm): 2237 Gt 

Rocket mass from Earth: 100 – times larger 

$\rightarrow 10^{10}$ t 

Assumed Lifetime: 100 years 

$\rightarrow 10^8$ t/year or 100 Mt/year 

$$R_{\text{Lev}} = \frac{2237 \text{ Gt}}{100 \text{ Mt}} \approx 2.24 \cdot 10^4 \text{ per year}$$
Summary

• Space-borne reflectors are possible in principle
• LEO and L1 are particular options with specific advantages and disadvantages
• Design of lightweight reflectors is a challenge
• With present technology costs are prohibitive
• Future – yet totally unproven – technology may make this CE-option more economic
• Lifetime (decades) is in an unfortunate range: Too long in case side effect of this CE-measure should prove to be severe, too short to make it economic