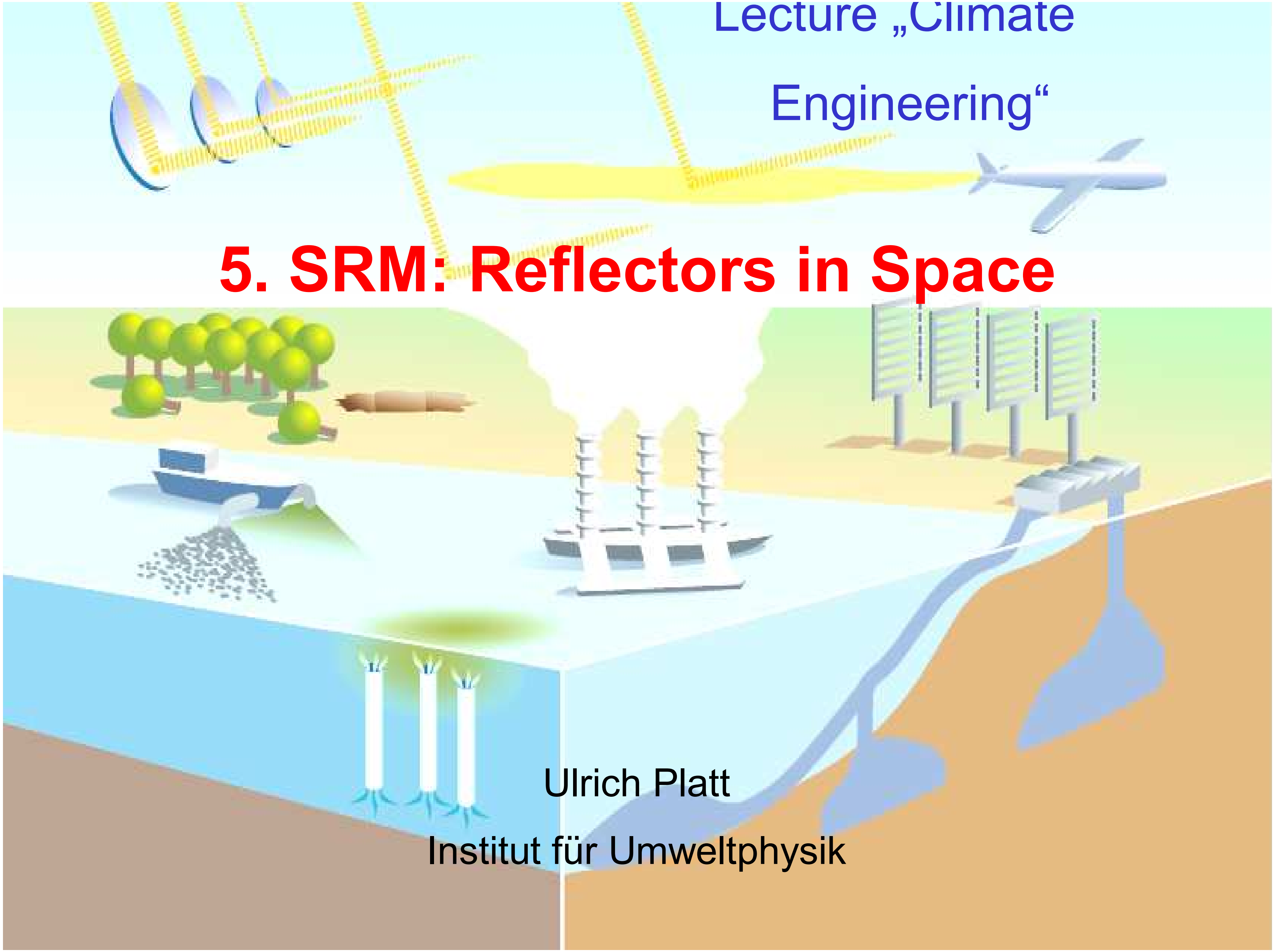


Lecture „Climate Engineering“

5. SRM: Reflectors in Space

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

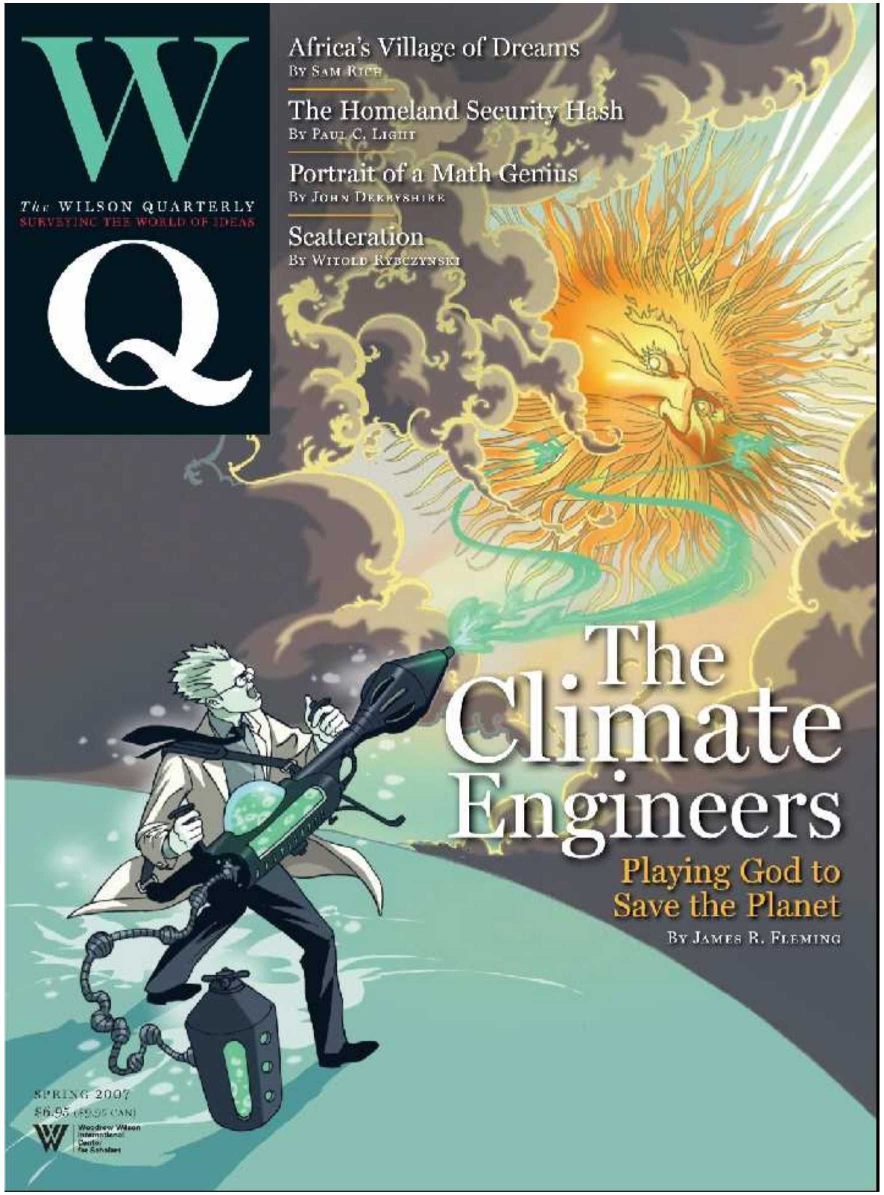
1. Direct CO_2 removal from air
2. Alkalinity to the ocean (enhanced weathering)
3. Ocean fertilization
4. Removal of other greenhouse gases

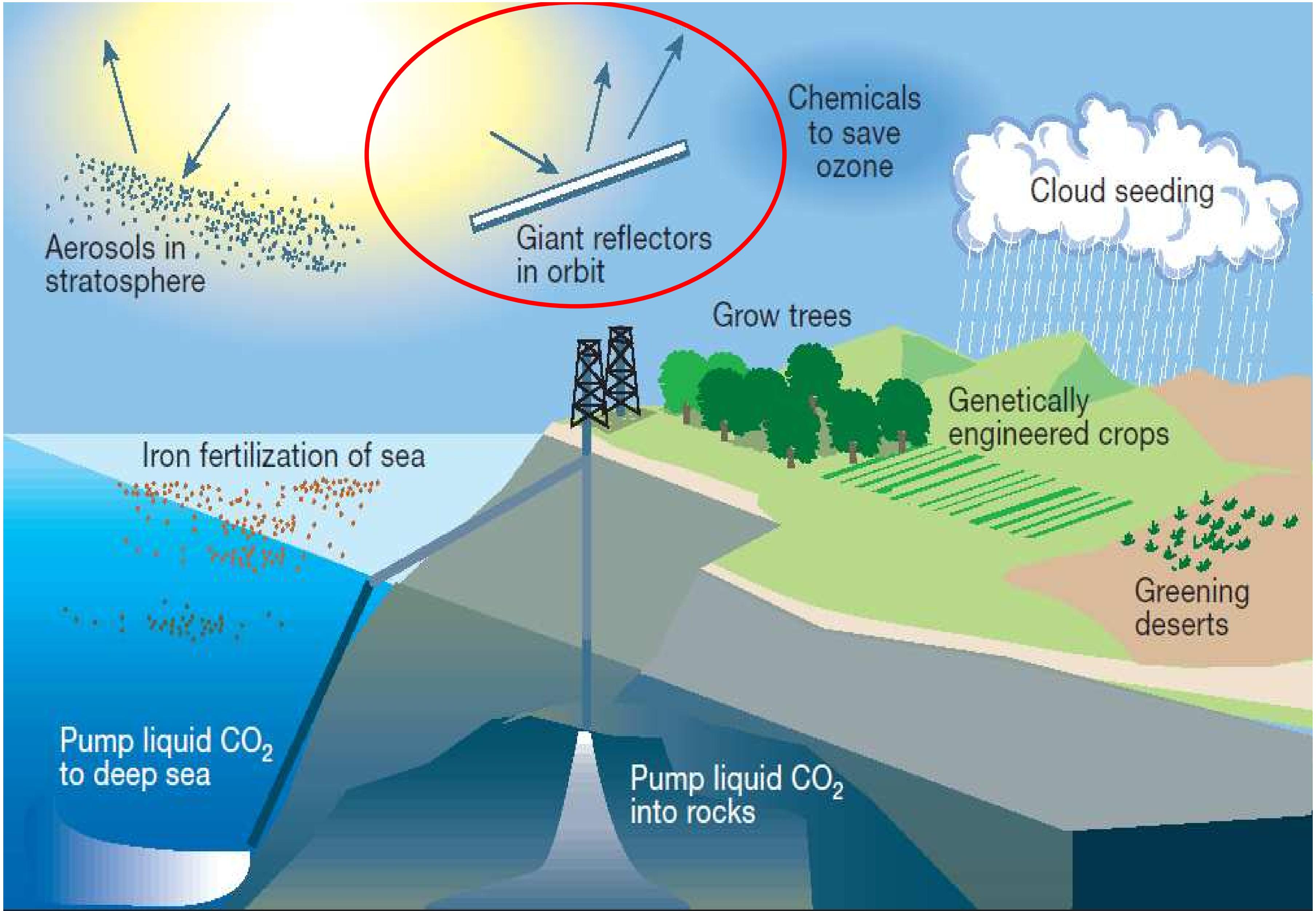
Part 4: CE – Effectiveness, Side Effects (3 sessions)

1. Comparison of Techniques, characterisation of side effects
2. Other parameters than temperature
3. Summary

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





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

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

Literature

Angel R. (2006), Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1), *Proc. National Acad. of Sciences USA* **103**(46), 17184-17189.

Early J.T. (1989), The space based solar shield to offset greenhouse effect. J. Br. Interplanet. Soc. 42, 567–569.

Govindasamy B. and Caldeira K. (2000), Geoengineering Earth’s radiation balance to mitigate CO_2-induced climate change, Geophys. Res. Lett. 27, 2141–2144.

Kosugi T. (2010), Role of sunshades in space as a climate control option, Acta Astronautica 67, 241–253.

McInnes C.R. (2002), Space-based geoengineering: Challenges and requirements, J. Br Interplanet Soc. 55, 307–311.

Pearson J., Oldson J., and Levine E. (2006), Earth Rings for Planetary Environment Control, Star Technology and Research, Inc., Proc. 53rd International Astronautical Congress 10-19 Oct. 2002, Houston, Texas, USA, IAF-02-U.1.01.

Penn J. and Lindley C.A. (2003), Acta Astronomica 52, 49–75.

Seifritz W. (1989), Mirrors to halt global warming?, Nature 340, 603.

Teller E., Wood L., Hyde R. (1997), Global Warming and Ice Ages: I. Prospects for Physics Based Modulation of Global Change. UCRL-231636/UCRL JC 128715. Lawrence Livermore National Laboratory, Livermore, CA, USA.

Watson R.T., Zinyowera M.C., Moses R.H., Dokken D.J. (1995), Climate change impacts, adaptations and mitigation of climate change: scientific–technical analyses. IPCC, UN Environmental Program/WMO, Cambridge Univ. Press, pp. 799–822. Chap. 25.

Space Sunshades and Climate Change

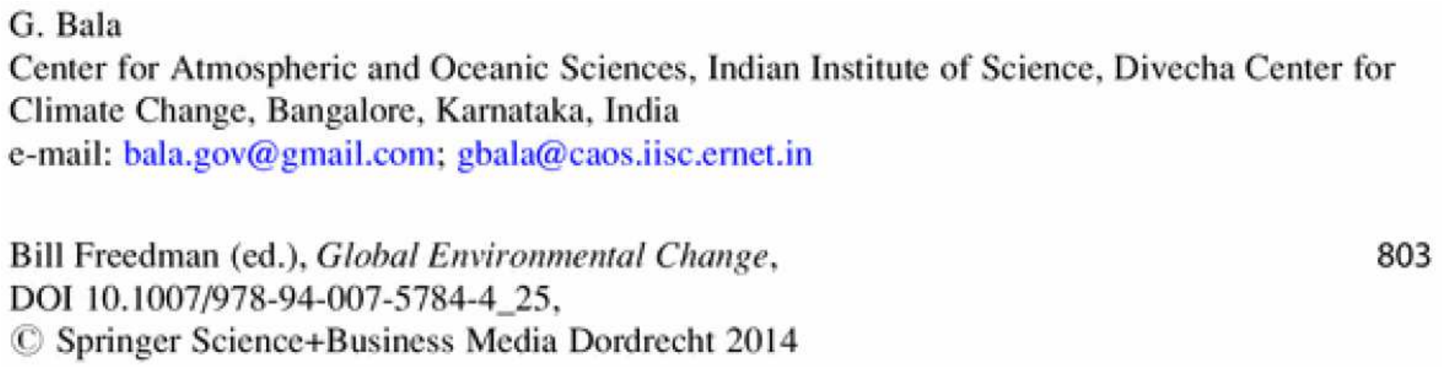
Govindasamy Bala

Springer: Global Environmental Change
Handbook of Global Environmental Pollution Vol. 1, 2014, pp 803-815 (11 Jul 2014)

„Space Sunshades and Climate Change“ Govindasamy Bala

Abstract:

The accelerated rate of increase in atmospheric CO_2 concentrations in recent years and the inability of humankind 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.



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Bill Freedman (ed.), *Global Environmental Change*,
DOI 10.1007/978-94-007-5784-4_25,

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

ε = 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 whish to offset temperature change due to 2xCO_2:

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

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

minus reflection (A=0.7): S
≈ 239.4 W/m^2

We need to shade an area of: A_S=3.7/239.4 * cross section of Earth (πR^2)

f $\approx$ 0.0154

* $1.29 \cdot 10^8$ km$^2 \approx 2 \cdot 10^6$ Km^2 (ε=1)

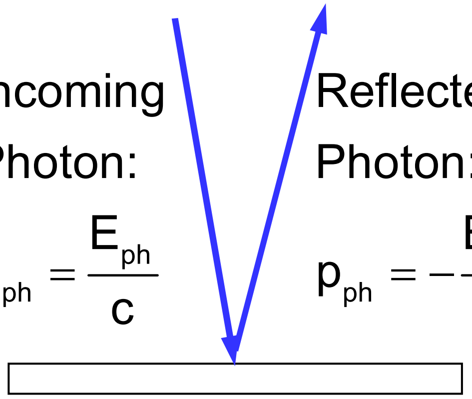
Assuming a sheet of d = 0.01 mm thickness this would correspond to a volume of $V = A_S \cdot d$
$\approx 2 \cdot 10^7$ m^3

Weight (assuming a density of 5 t/m^3) $\approx$
10^8 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):



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:

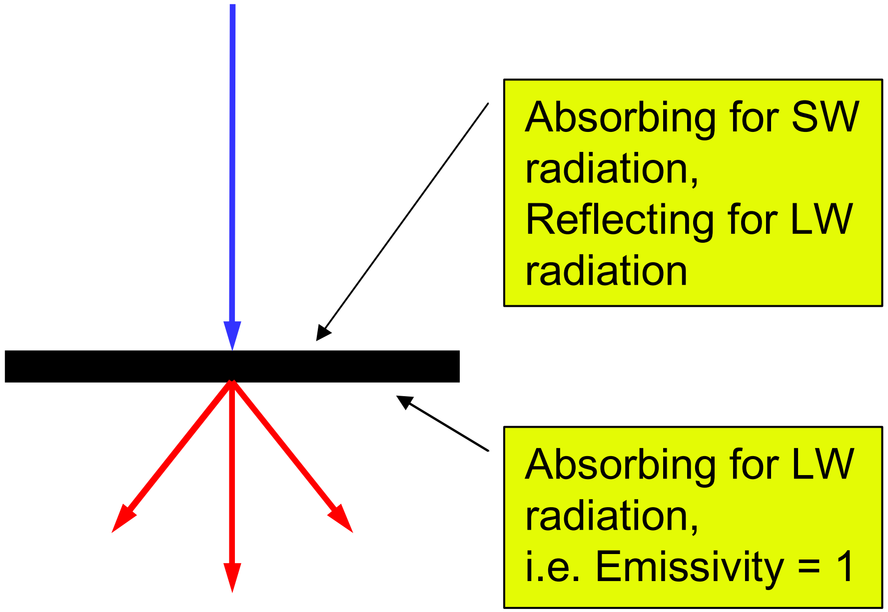
$$F = \Delta p \cdot \dot{n}_{ph} = 2\frac{E_{ph}}{c} \cdot \frac{P}{E_{ph}} = 2\frac{P}{c}$$

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

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

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

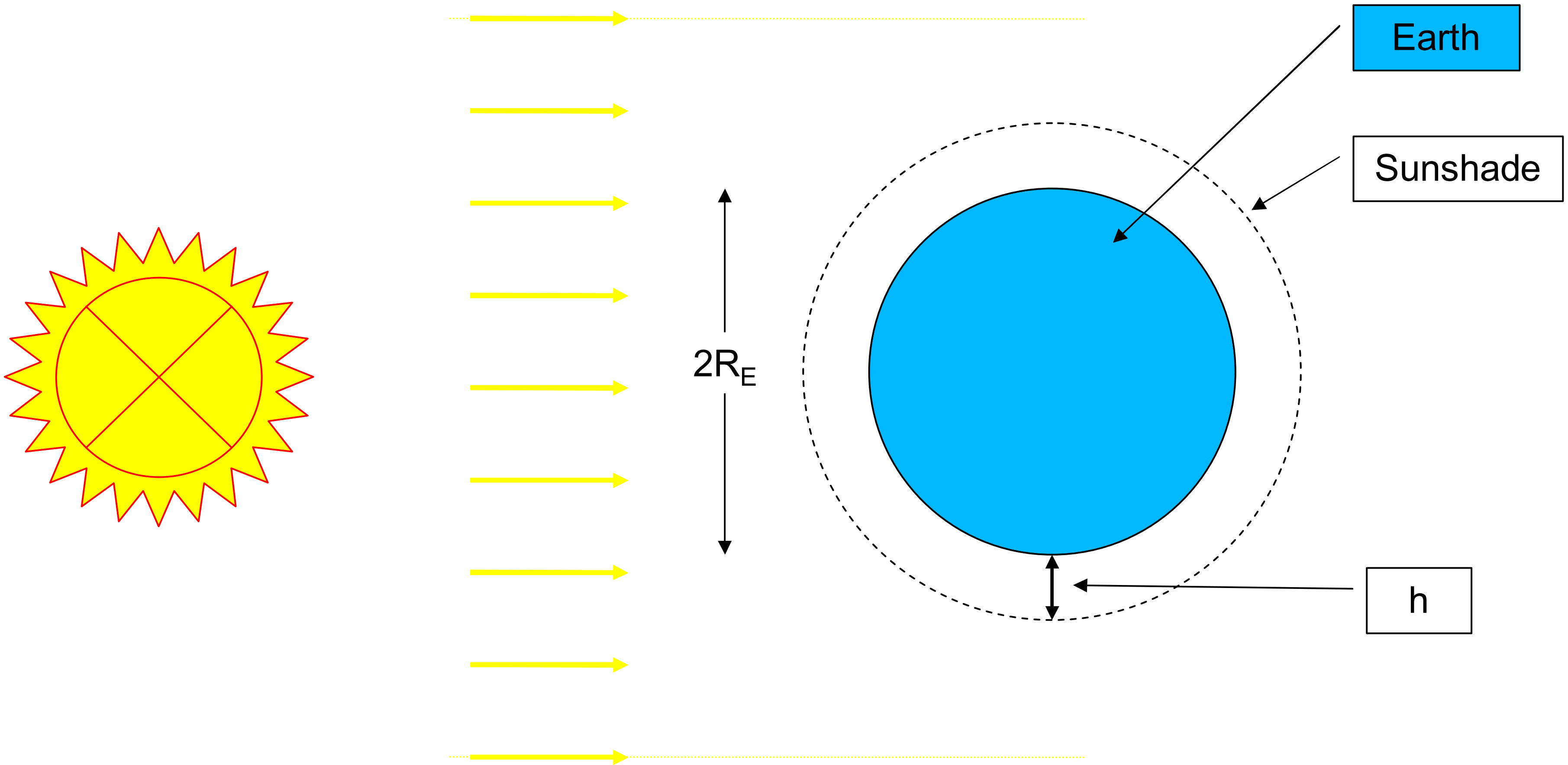
Problem: LW-radiation follows Lambertian emission pattern!

Sunshades in Space

Questions:

- Low Earth Orbit (LEO)
- Higher Earth Orbits?
- Lagrange Point (L1)
- Origin of the shading material

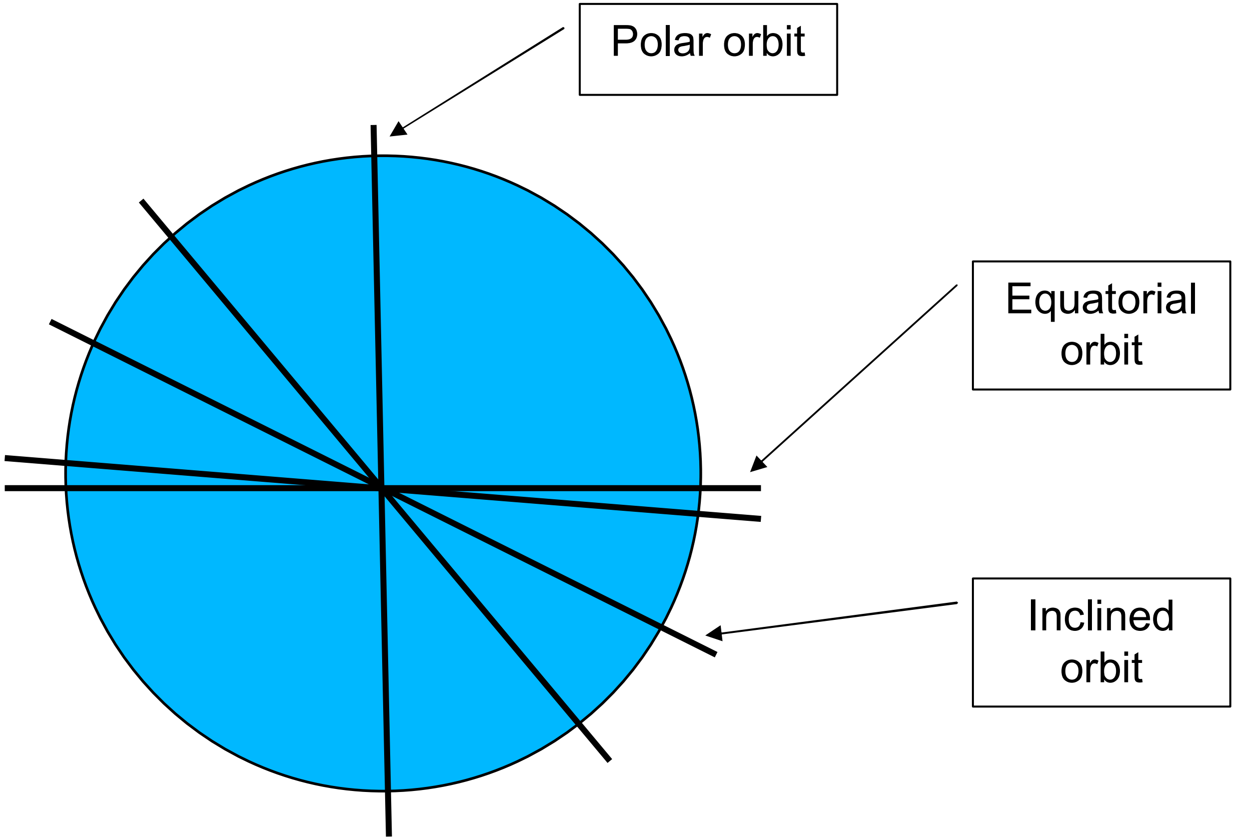
Sunshades in LEO



Shading efficiency:

$$\varepsilon = \frac{2R_E}{2\pi\left(R_E + h\right)} = \frac{R_E}{\pi\left(R_E + h\right)} \leq \frac{1}{\pi}$$

Possible LE-Orbits



Polar orbit

Equatorial orbit

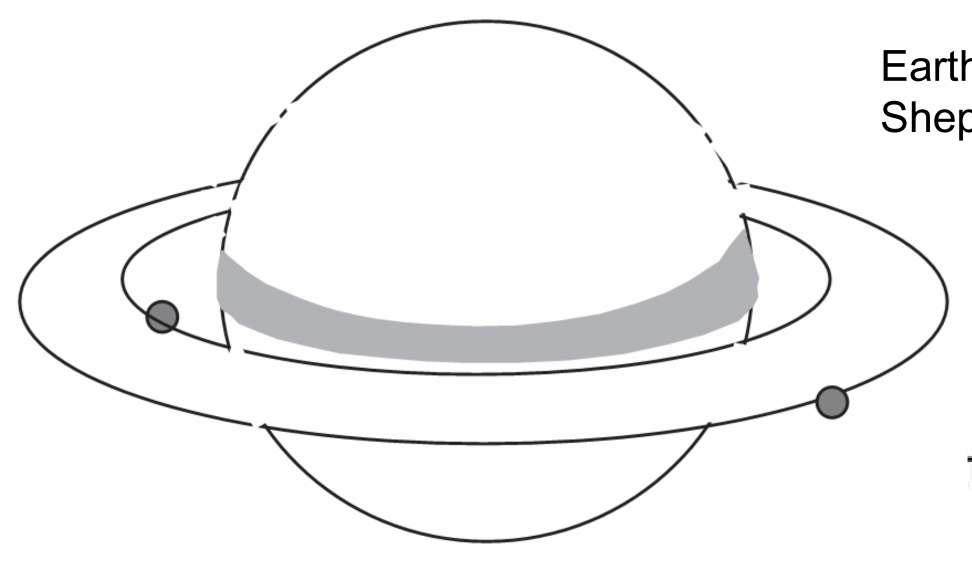
Inclined orbit

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

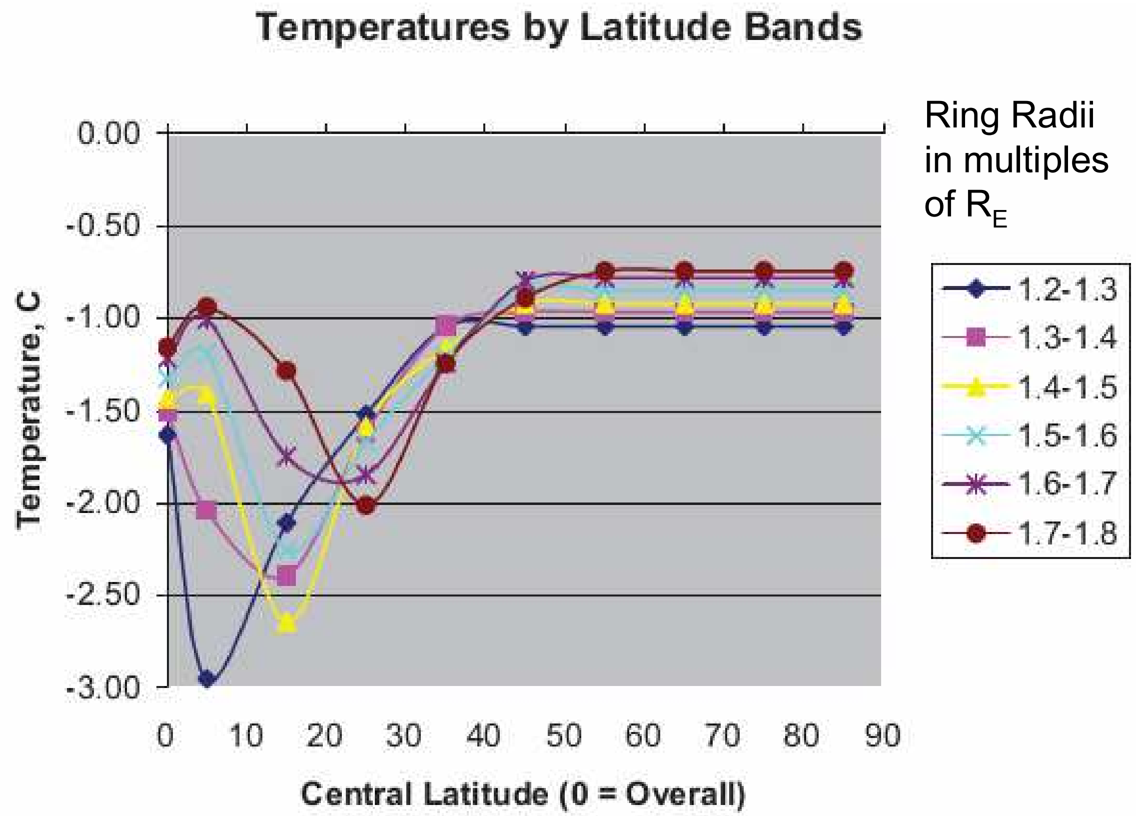
- shading of surface area: Independent of latitude

Inclined orbits (inclination <90°): Shading limited to latitude band with $\varphi < 90^o$

The Earth Ring Concept



Earth Ring Concept, R ~ 1.3-1.7 R_E, With Shepherding Satellites



Pearson et al. 2006

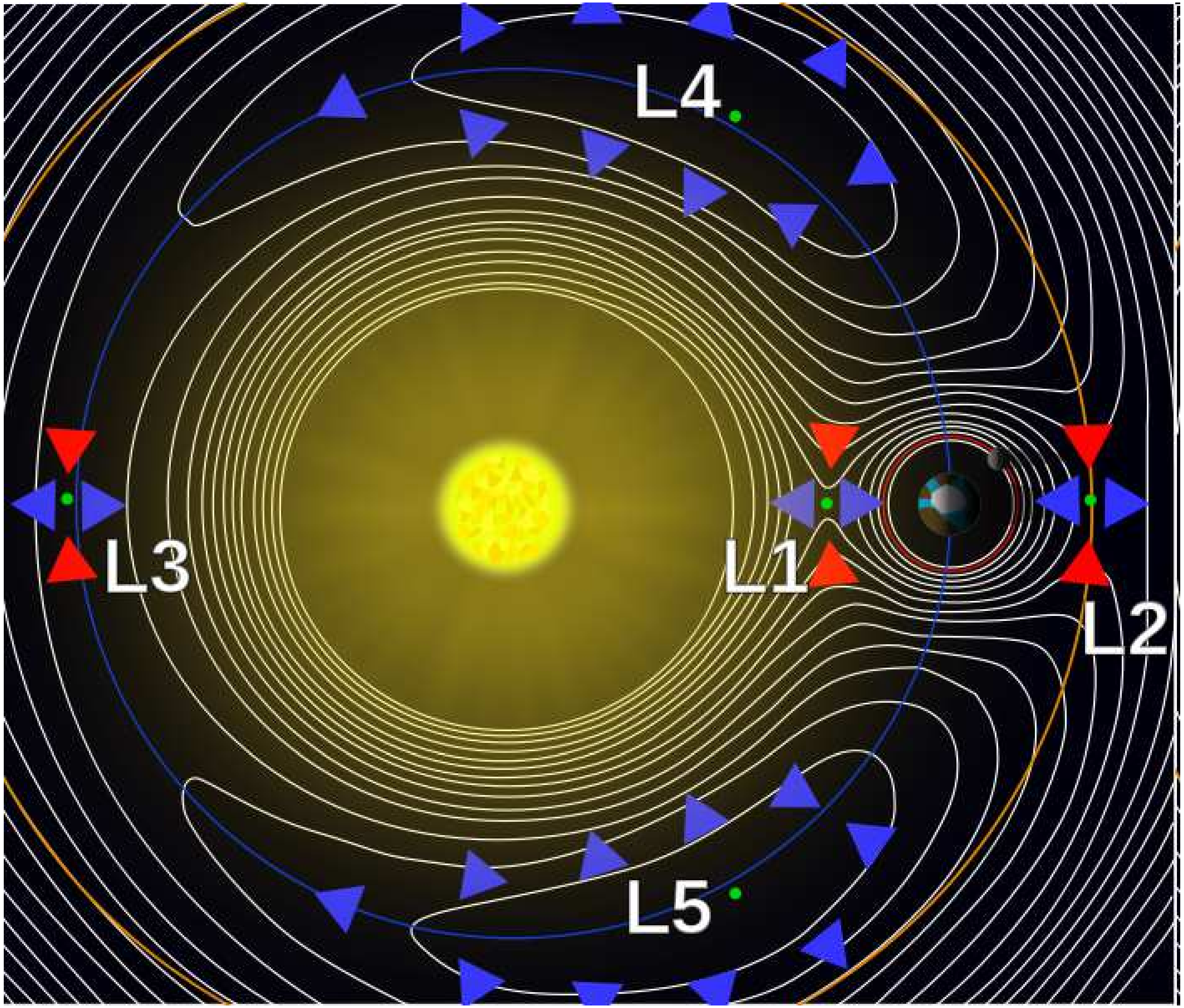
LEO Orbits

- 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

Lagrange Points

Contour plot of the effective potential due to gravity and the centrifugal force of a two-body system in a rotating frame of reference.

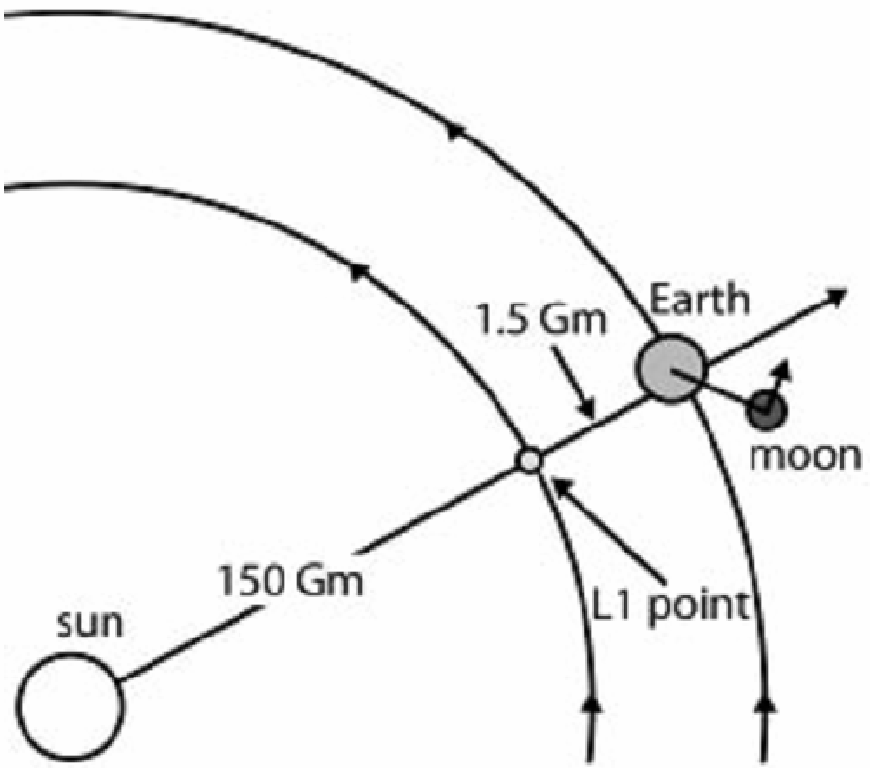
Arrows indicate the gradients of the potential - downhill toward them (red) or away from them (blue). Counterintuitively, the L4 and L5 points are the high points of the potential. At the points themselves these forces are balanced.



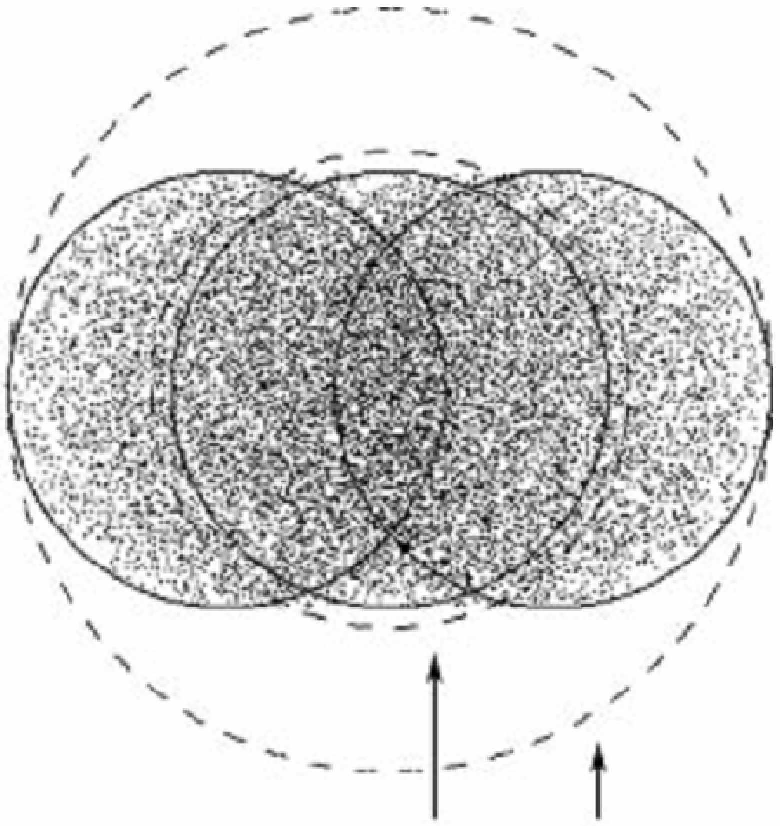
From Wikipedia, the free encyclopedia

Shading at L1

Sun, Earth, Moon, and L1



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



Penumbras from 1.5 and 2.4 Gm

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

Sunshade properties for 1.8% flux reduction:

(a) Shadowing efficiency and total area.

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

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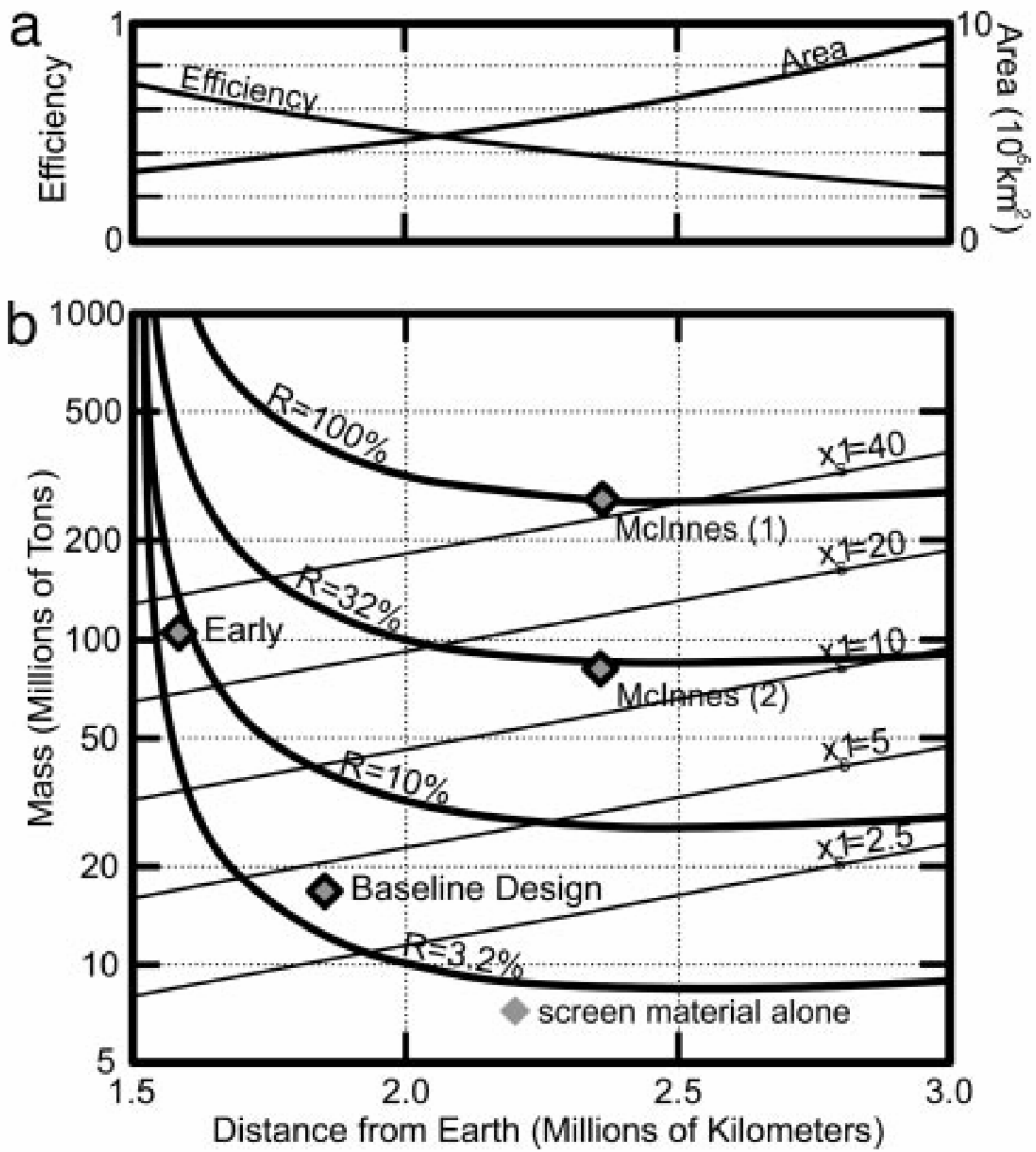
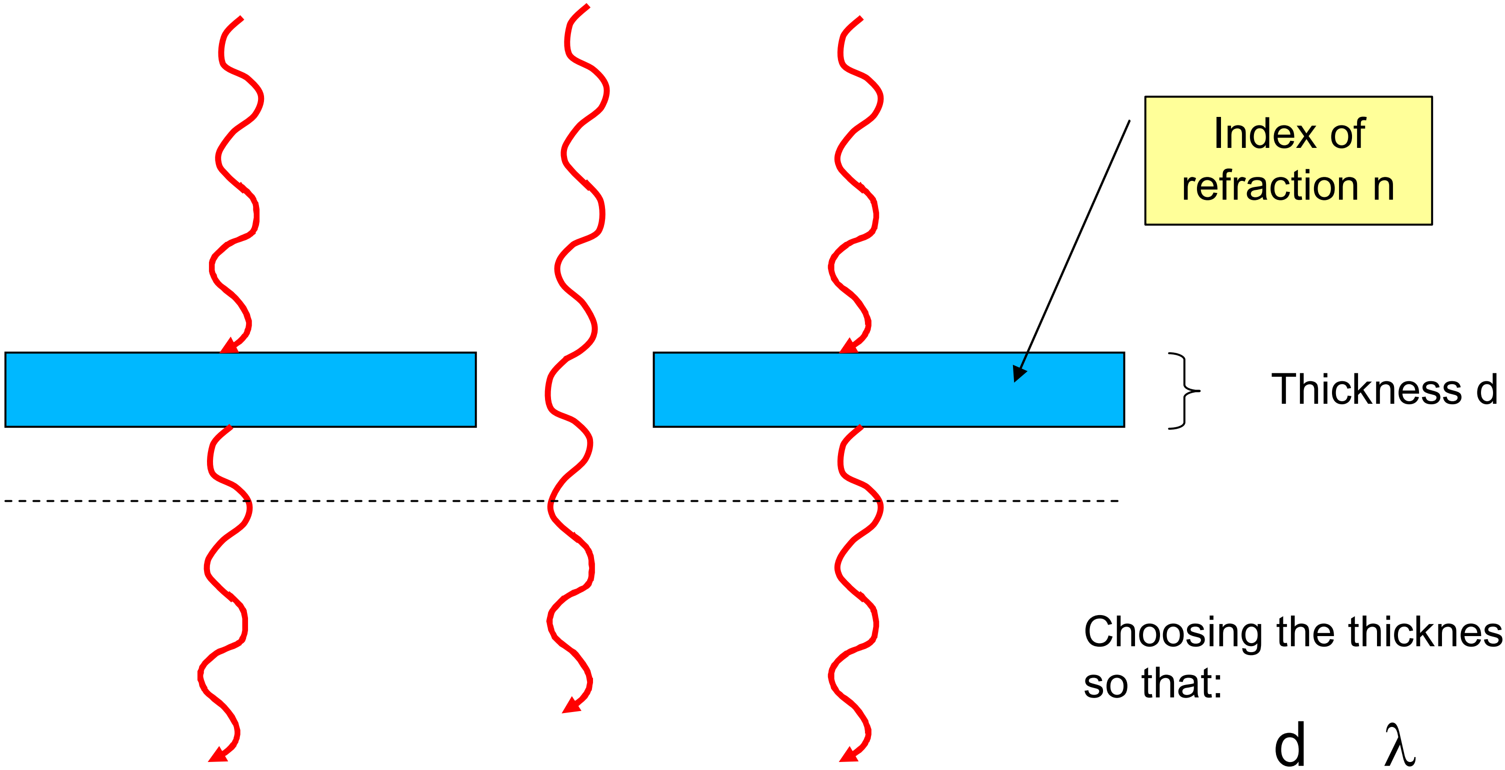


From: Angel 2006

Reflector Design: Dielectric Sheet with Holes



Index of refraction n

Thickness d

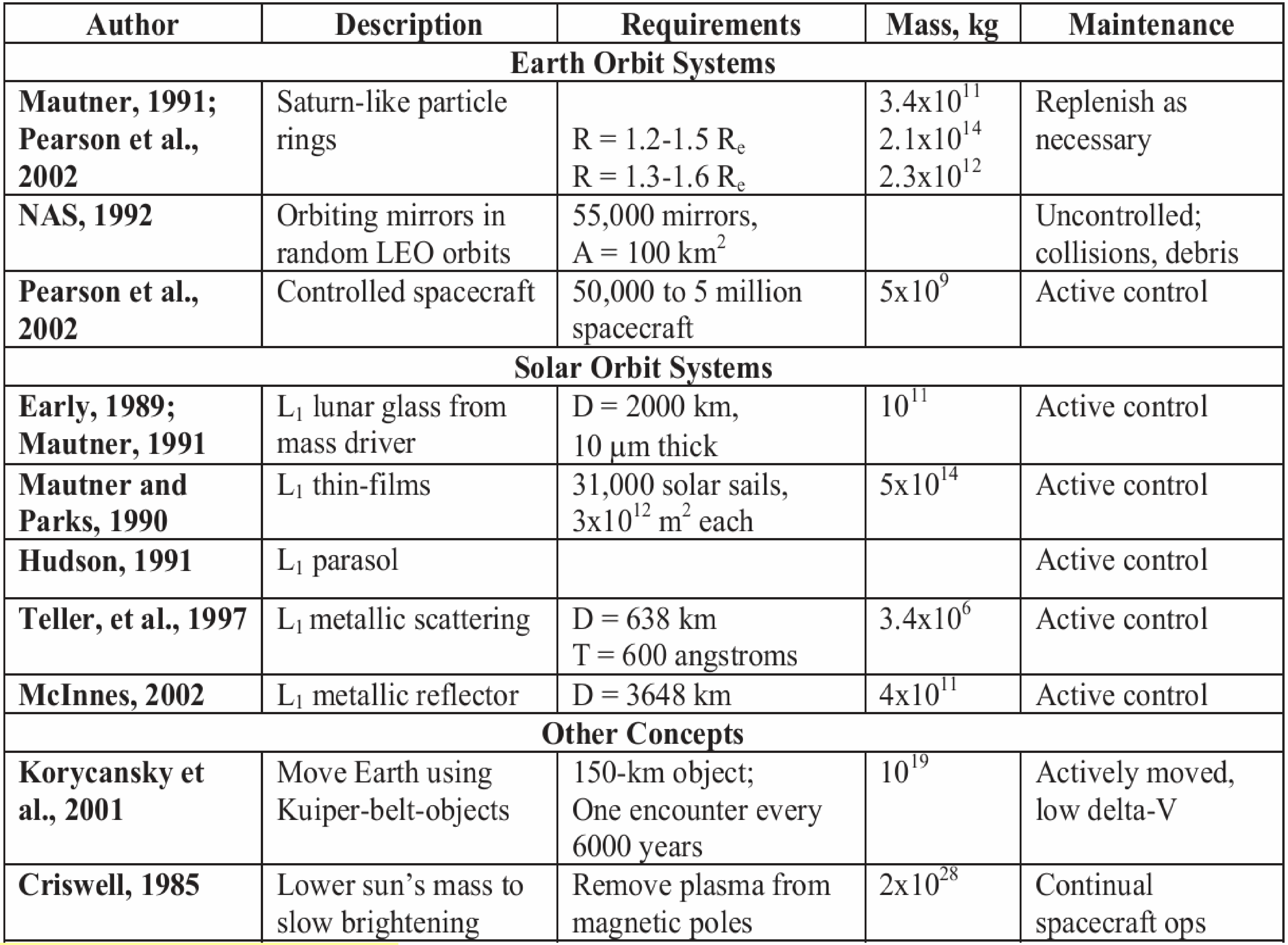
Choosing the thickness d so that:

$$\frac{d}{n} = \frac{\lambda}{2} + m\lambda$$

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

→ Destructive interference

Suggested Space-Shading Schemes

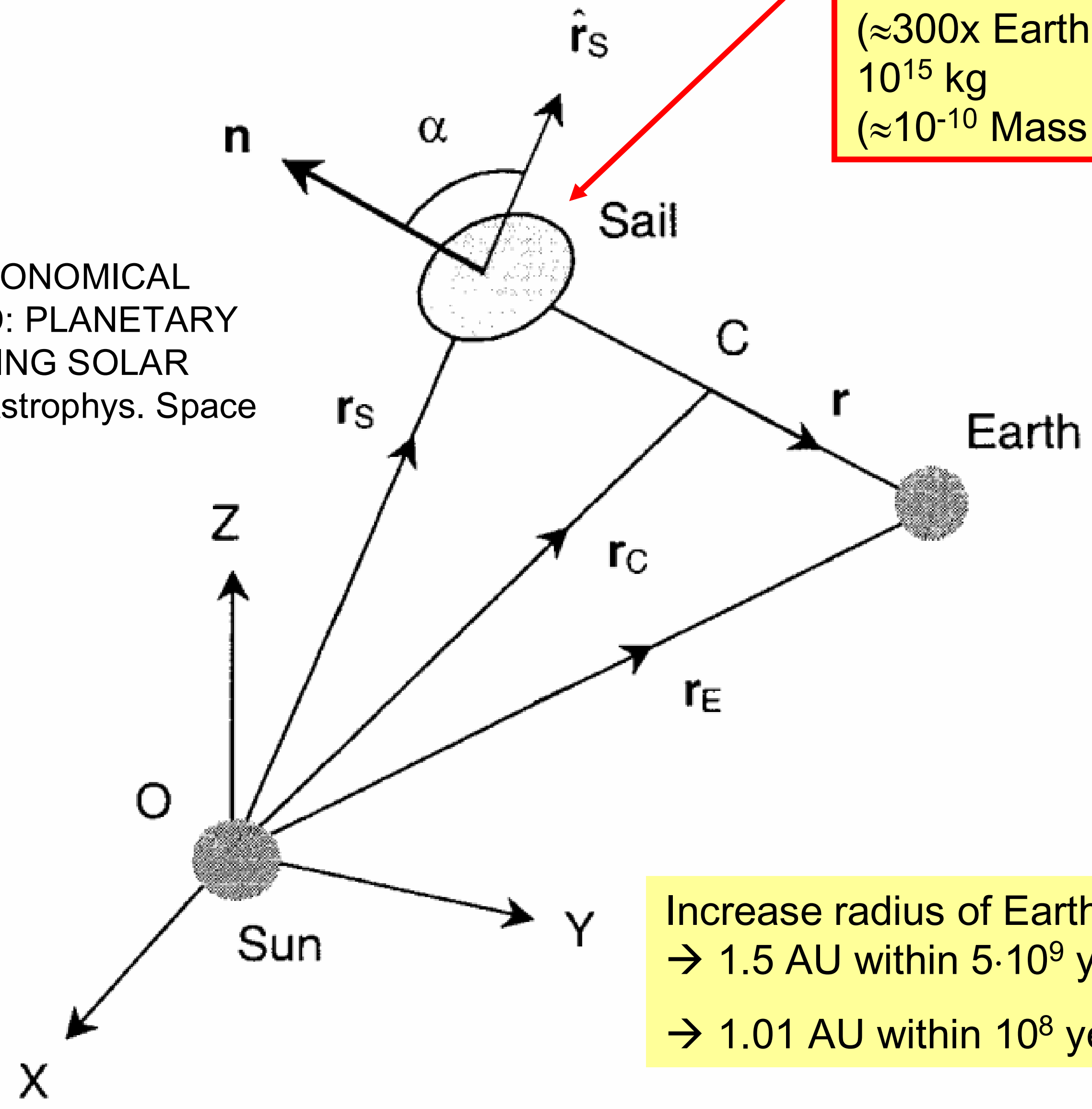


Author	Description	Requirements	Mass, kg	Maintenance
Earth Orbit Systems				
Mautner, 1991; Pearson et al., 2002	Saturn-like particle rings	$R = 1.2\text{-}1.5\ R_e$ $R = 1.3\text{-}1.6\ R_e$	3.4×10^{11} 2.1×10^{14} 2.3×10^{12}	Replenish as necessary
NAS, 1992	Orbiting mirrors in random LEO orbits	55,000 mirrors, $A = 100\ km^2$		Uncontrolled; collisions, debris
Pearson et al., 2002	Controlled spacecraft	50,000 to 5 million spacecraft	5×10^9	Active control
Solar Orbit Systems				
Early, 1989; Mautner, 1991	L_1 lunar glass from mass driver	$D = 2000$ km, 10 µm thick	10^{11}	Active control
Mautner and Parks, 1990	L_1 thin-films	31,000 solar sails, $3 \times 10^{12}\ m^2$ each	5×10^{14}	Active control
Hudson, 1991	L_1 parasol			Active control
Teller, et al., 1997	L_1 metallic scattering	$D = 638$ km $T = 600$ angstroms	3.4×10^6	Active control
McInnes, 2002	L_1 metallic reflector	$D = 3648$ km	4×10^{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	2×10^{28}	Continual spacecraft ops

Source: Pearson et al. 2006

Change Earth-Orbit ??

C.R. McInnes (2002), ASTRONOMICAL ENGINEERING REVISITED: PLANETARY ORBIT MODIFICATION USING SOLAR RADIATION PRESSURE, Astrophys. Space Sci. 282, 765–772.



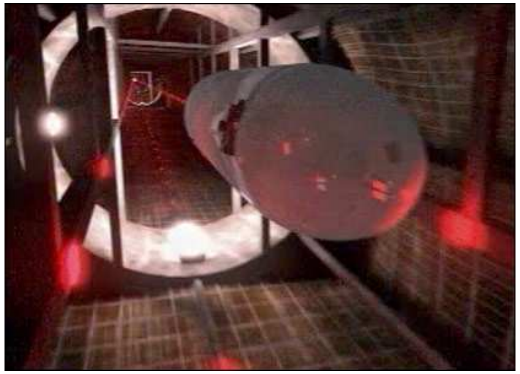
$5 \cdot 10^{16}$ m^2
(≈300x Earth cross sect.)
10^{15} kg
(≈10^{-10} Mass of Earth)

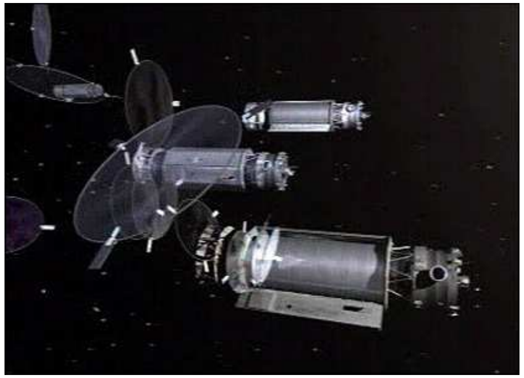
Increase radius of Earth orbit from 1 → 1.5 AU within $5 \cdot 10^9$ years

→ 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





Rockets

The „Rocket Equation“:

$$v = v_e \cdot \ln\left(\underbrace{\frac{M_0}{M}}_{\text{Mass Ratio}}\right)$$

Assumption: Fuel is burned, the released energy is used to „exhaust“ the cobustion products.

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 → 2.5 - 4.0 km/s

$$\frac{v}{v_e} = \ln\left(\underbrace{\frac{M_0}{M}}_{\text{Mass Ratio}}\right) \Leftrightarrow \frac{M_0}{M} = e^{\frac{v}{v_e}} = \text{"Mass Ratio"}$$

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

Mass Ratios M_0/M >10 are difficult to reach
→ 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) Fg = 0.815 MN

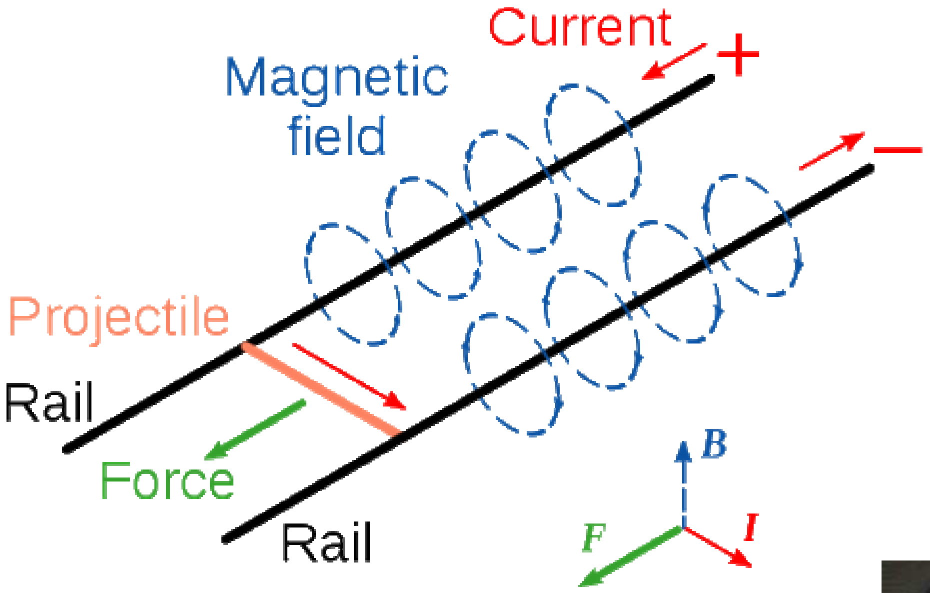
Solid fuel booster (EAP P241)
Initial mass: M_0 = 273 t
Empty mass: M = 33 t
Exhaust velocity: ve = 2692 m/s
Thrust (ground) F_g = 5.06 MN

Average mass ratio:

no payload:
$716/78.5 \approx 9.1$

20t payload:
$736/98.5 \approx 7.5$

Rail Guns

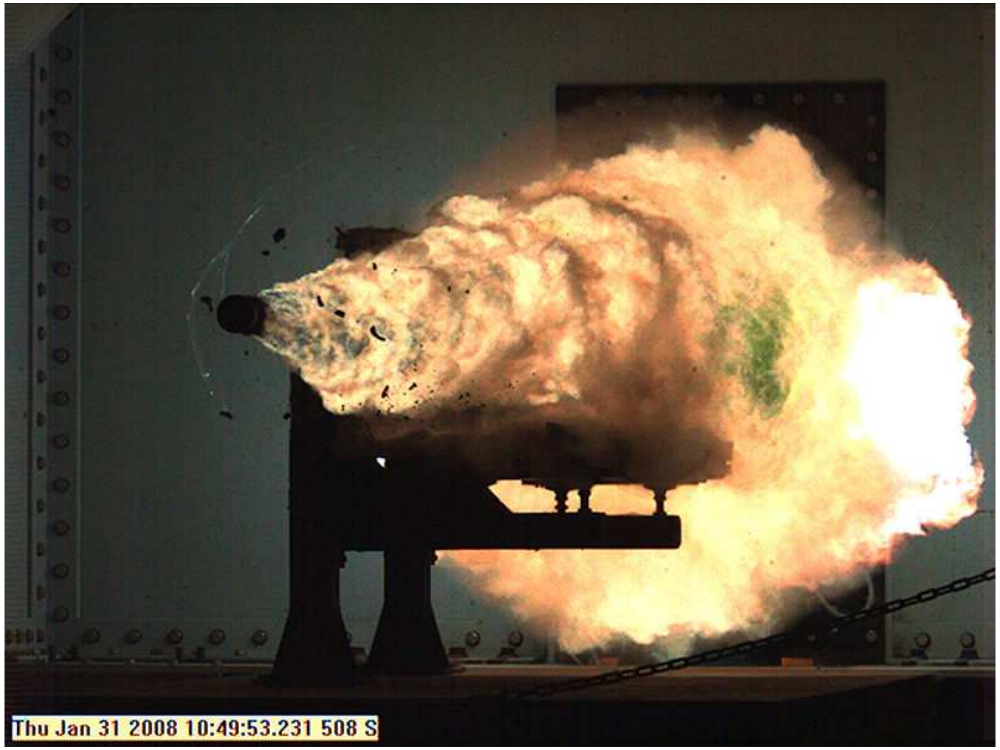


Source: Wikipedia

$$B = \frac{\mu_0 I}{4\pi}\left(\frac{1}{x} + \frac{1}{d-x}\right) \underbrace{\approx}_{x=d/2} \frac{\mu_0 I}{d\pi}$$

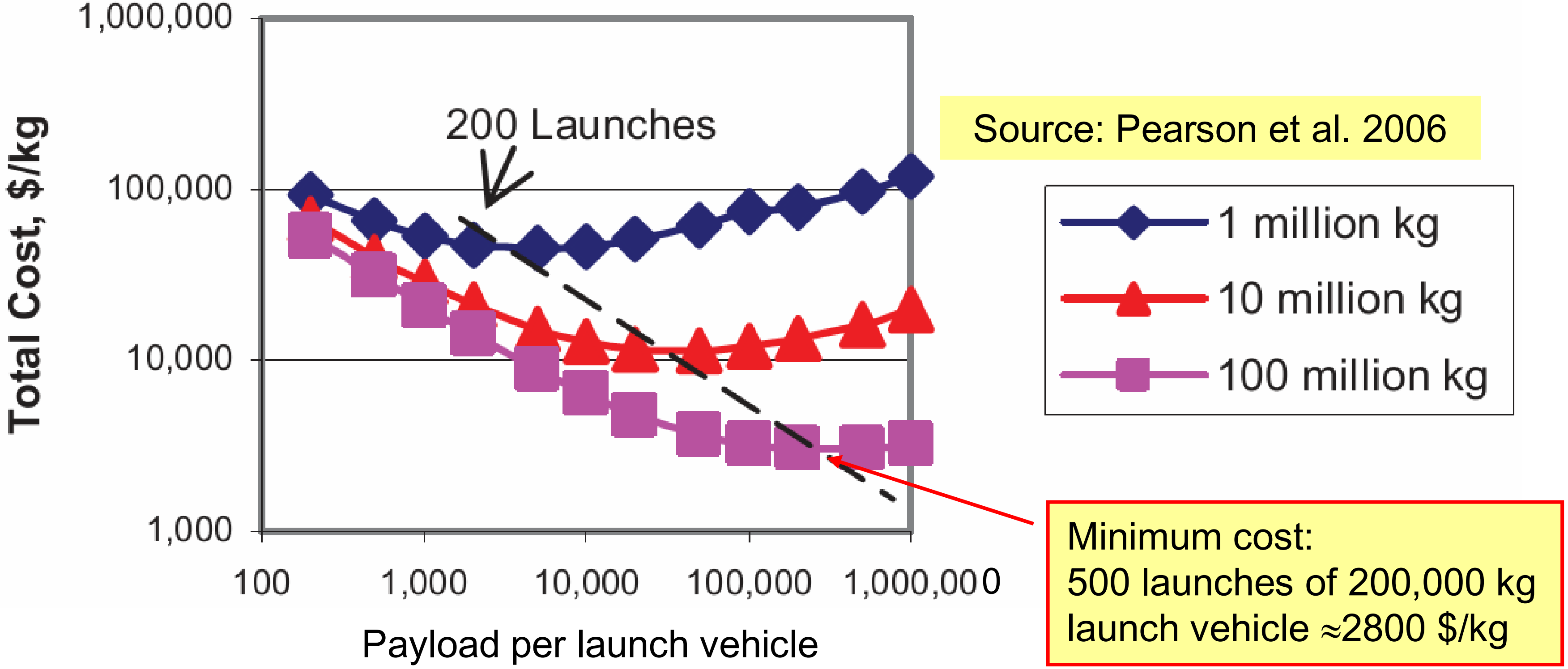
Force :

$$F = IdB \approx \frac{\mu_0 I^2}{\pi} \approx 4 \cdot 10^{-7} \cdot I^2 \frac{N}{A^2}$$



The Question of Cost

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



Source: Pearson et al. 2006

Minimum cost:
500 launches of 200,000 kg
launch vehicle ≈2800 $/kg

→ Lowest cost at about 200-500 launches

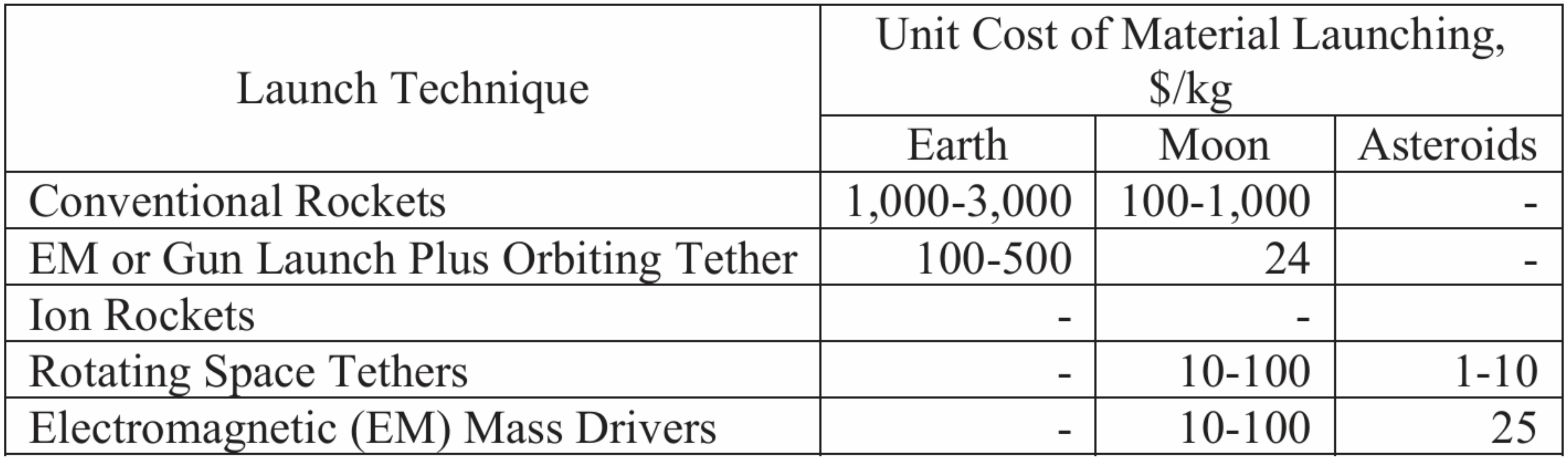
Example: 1.8% shading in LEO at 1μm thickness and ε=0.3

→ $3 \cdot 10^7$ t (or $3 \cdot 10^{10}$ kg) total mass

→ total cost: ≈10^{14} $ (500,000 billion $)

Cheaper Solutions?

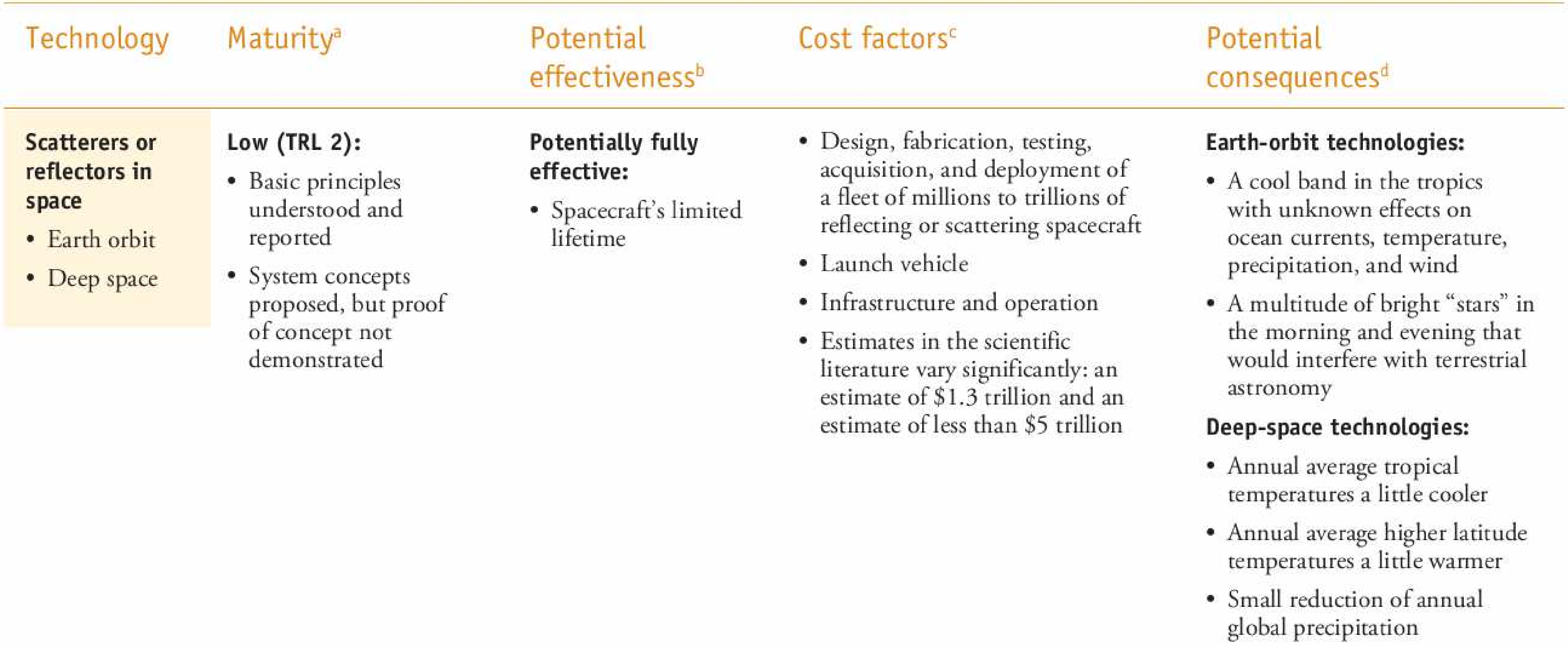
Cost of different launch techniques (LEO):



Launch Technique	Unit Cost of Material Launching, $/kg		
	Earth	Moon	Asteroids
Conventional Rockets	1,000-3,000	100-1,000	-
EM or Gun Launch Plus Orbiting Tether	100-500	24	-
Ion Rockets	-	-	
Rotating Space Tethers	-	10-100	1-10
Electromagnetic (EM) Mass Drivers	-	10-100	25

Source: Pearson et al. 2006

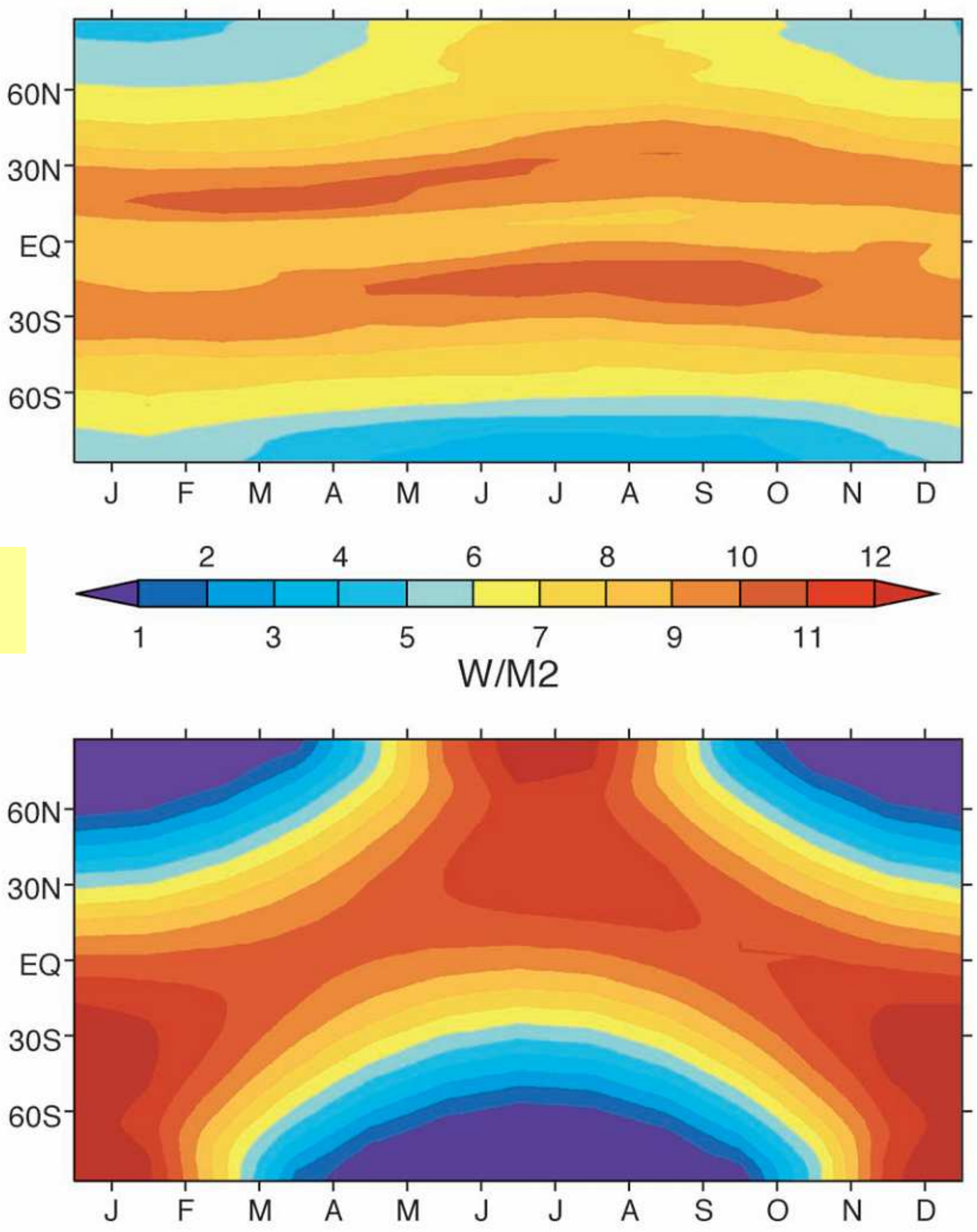
Evaluation of Space-Borne Shades



Technology	Maturity[a]	Potential effectiveness[b]	Cost factors[c]	Potential consequences[d]
Scatterers or reflectors in space • Earth orbit • Deep space	**Low (TRL 2):** • Basic principles understood and reported • System concepts proposed, but proof of concept not demonstrated	**Potentially fully effective:** • Spacecraft's limited lifetime	• Design, fabrication, testing, acquisition, and deployment of a fleet of millions to trillions of reflecting or scattering spacecraft • Launch vehicle • Infrastructure and operation • Estimates in the scientific literature vary significantly: an estimate of $1.3 trillion and an estimate of less than $5 trillion	**Earth-orbit technologies:** • A cool band in the tropics with unknown effects on ocean currents, temperature, precipitation, and wind • A multitude of bright "stars" in the morning and evening that would interfere with terrestrial astronomy **Deep-space technologies:** • Annual average tropical temperatures a little cooler • Annual average higher latitude temperatures a little warmer • Small reduction of annual global precipitation

Source: Climate engineering, Technical status, future directions, and potential responses
Center for Science, Technology, and Engineering
United States Government Accountability Office, GAO, July 2011, GAO-11-71

SW versus LW



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.

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

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

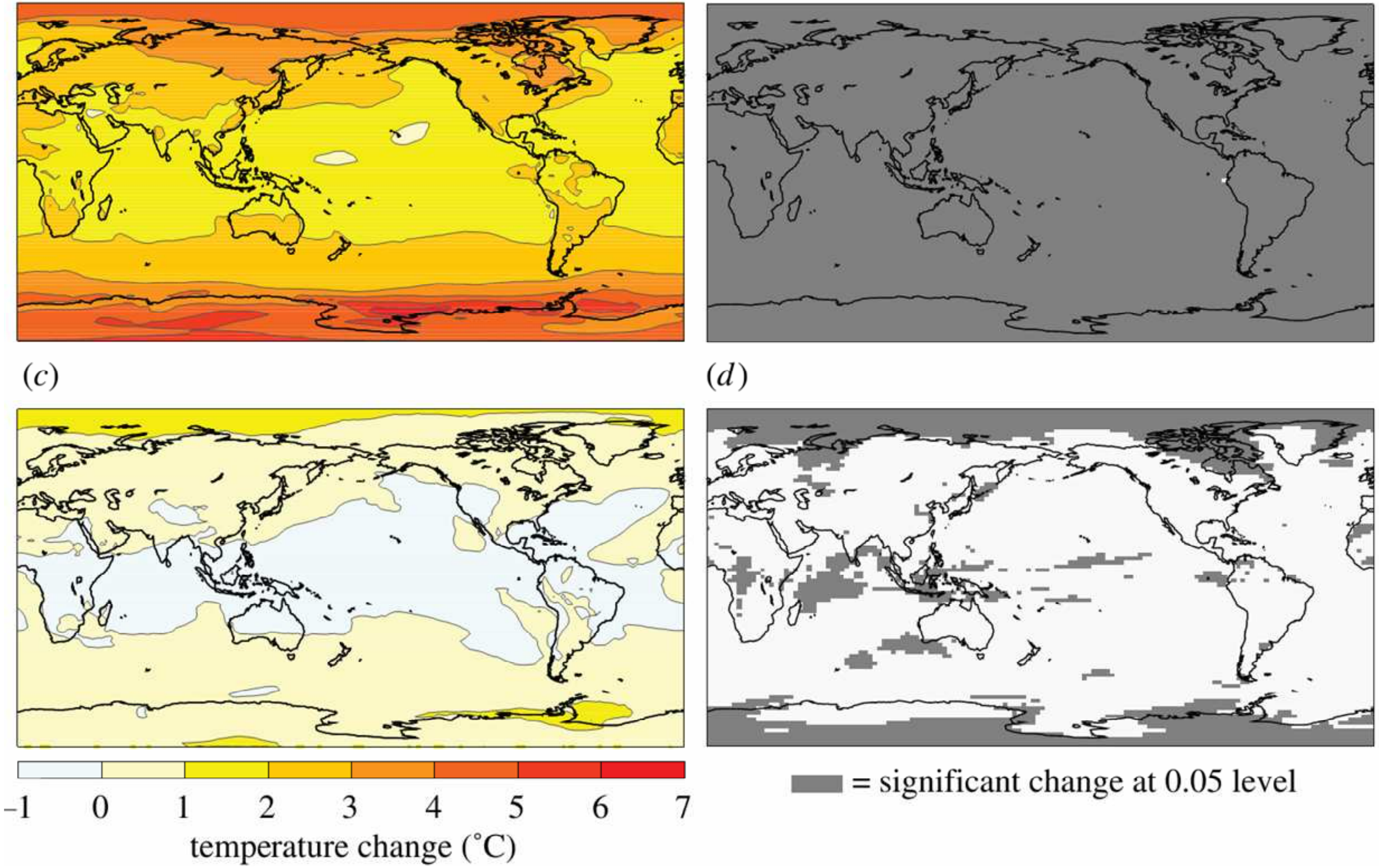
Model Calculations of the Temperature change for $2xCO_2$

Annual mean temperature changes

Areas where temperature change is statistically significant at the 0.05 level

$2xCO_2$ simulation

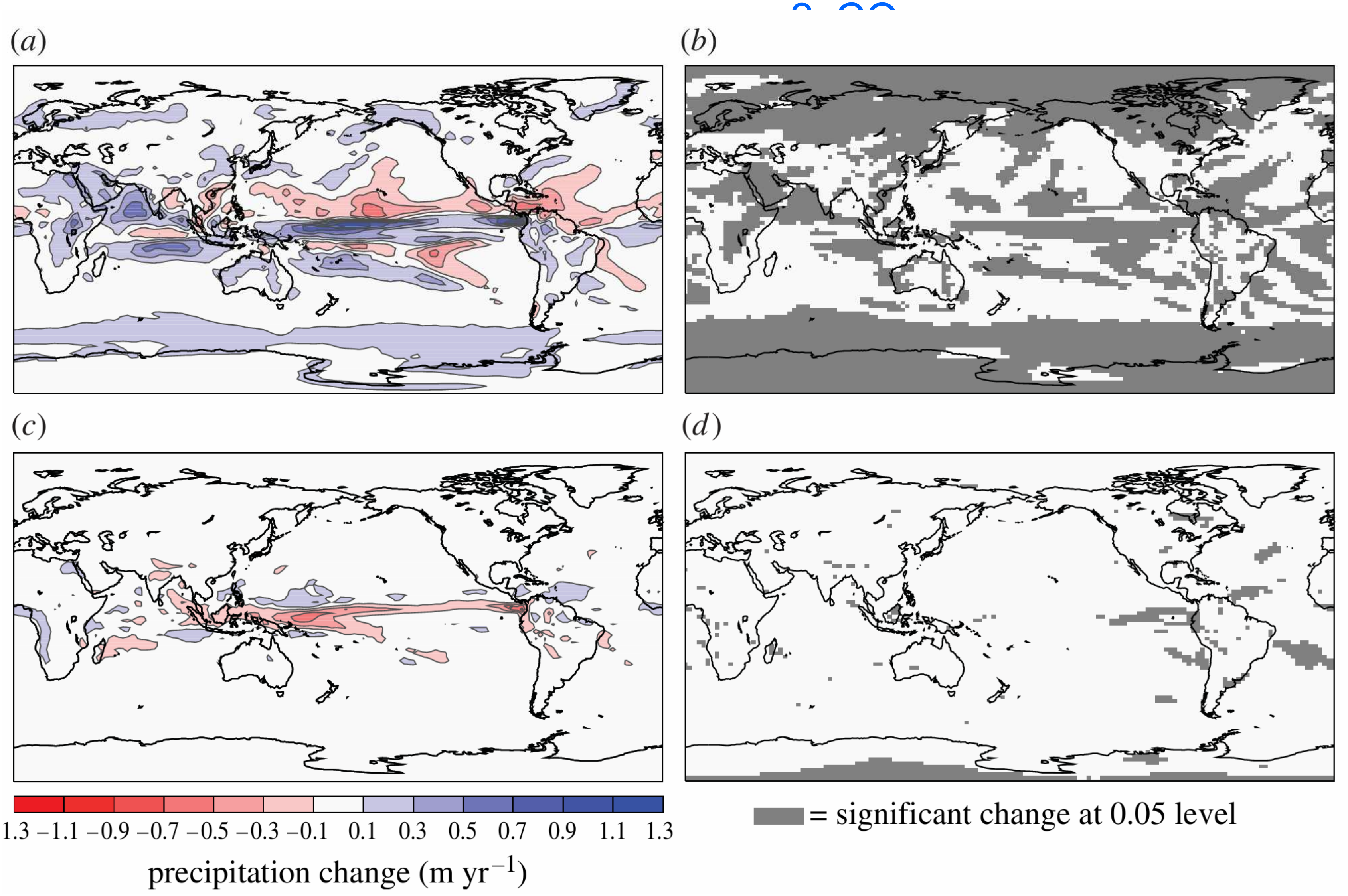
$2xCO_2$ simulation + 1.84 W/m^2 global reduction due to CE



→ This idealized climate engineering simulation indicates that relatively simple climate engineering may be able to diminish temperature changes in most of the world.

CALDEIRA K. and WOOD L. (2008), Global and Arctic climate engineering: numerical model studies, Phil. Trans. R. Soc. A, doi:10.1098/rsta.2008.0132.

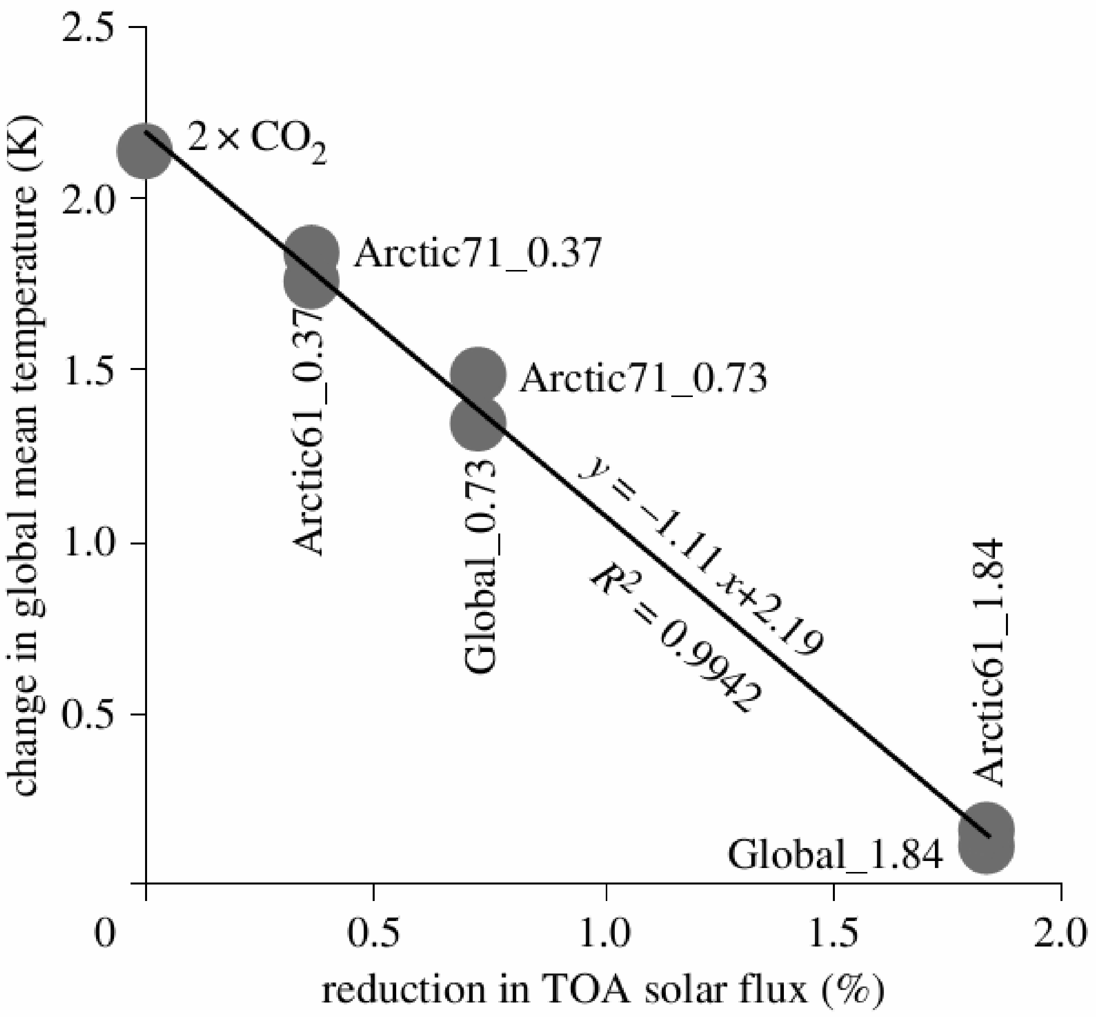
Model Calculations of the Precipitation Change for



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

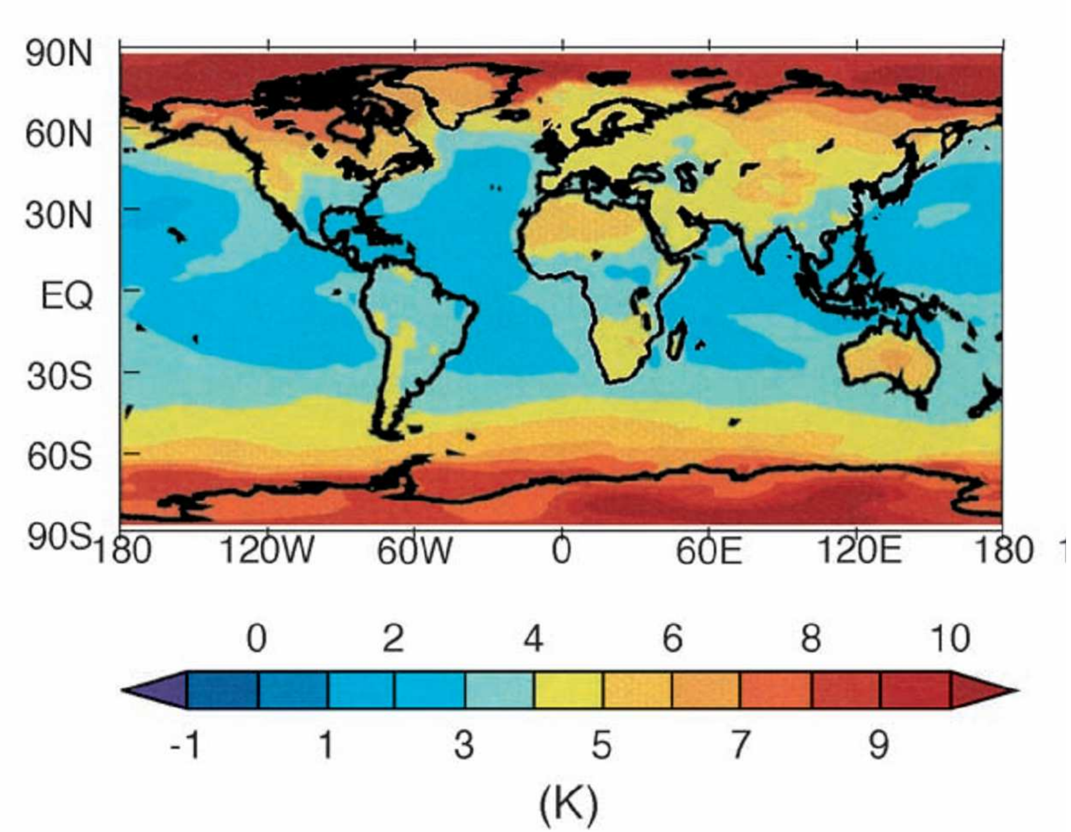
Change in global annual mean temperature as a function of percentage of reduction in the top-of-atmosphere insolation. Despite large differences in the spatial extent of the insolation reduction, the global mean temperature response is similar.



CALDEIRA K. and WOOD L. (2008), Global and Arctic climate engineering: numerical model studies, Phil. Trans. R. Soc. A, doi:10.1098/rsta.2008.0132.

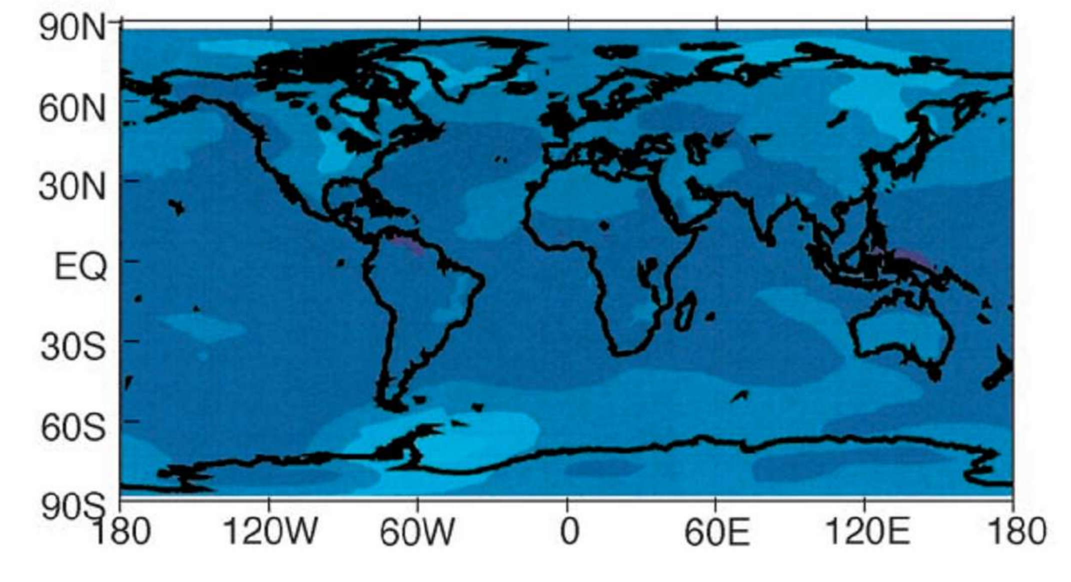
Changes with Geoengineering

Surface temperature changes for the 4xCO_2 simulation



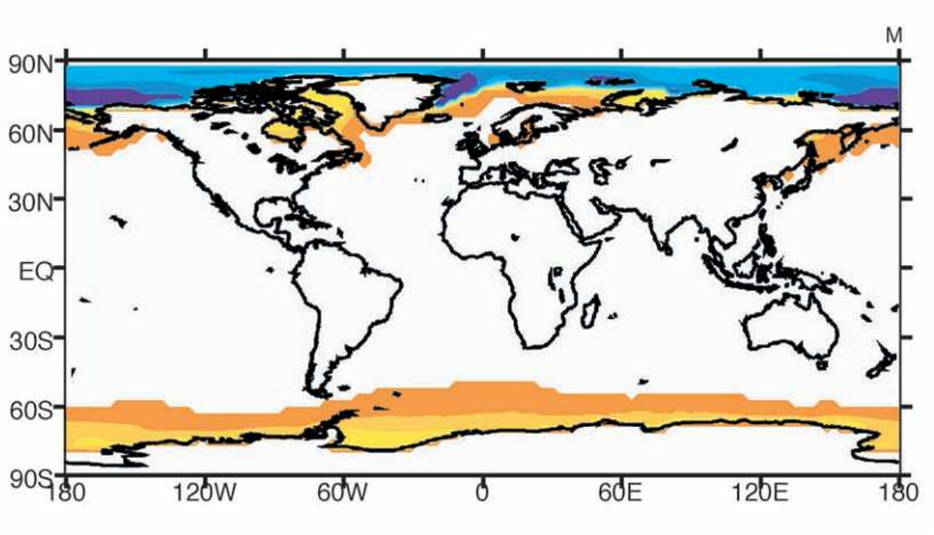
Govindasamy et. al. Global and Planetary Change 37 (2003) 157–168

Surface temperature changes for the “Geoengineered” 4xCO_2 simulation.

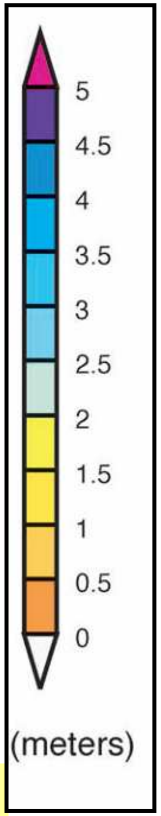


Although solar radiation has a spatial pattern greatly different to that of radiative forcing due 4xCO_2, a reduction in solar forcing largely compensates the temperature response to CO_2 quadrupling.

Effect on Sea Ice

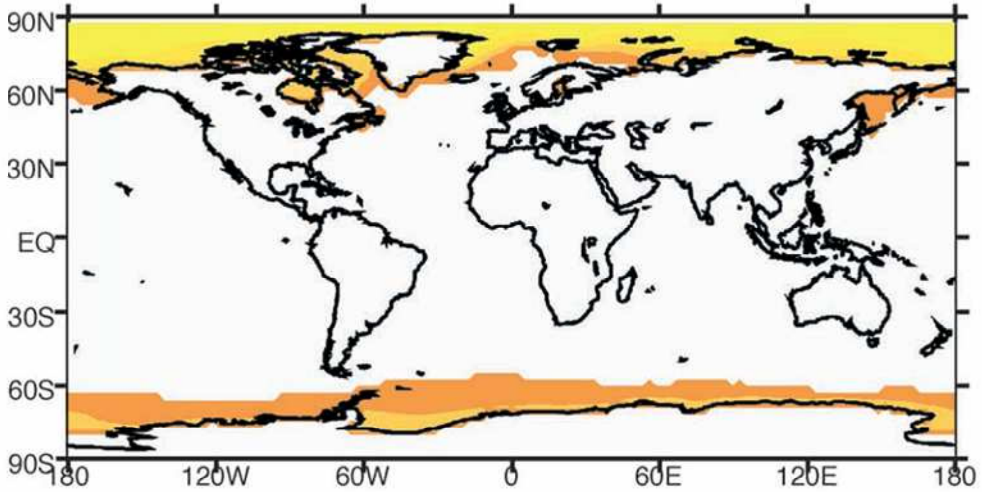


Annual mean sea ice thickness in the Control (top panel), ‘‘$4xCO_2$’’ (middle panel) and ‘‘Geoengineered $4xCO_2$’’ (bottom panel) simulations. The reduction in solar forcing in ‘‘Geoengineered $4xCO_2$’’ simulation largely compensates the decrease in sea ice thickness and area coverage in the ‘‘$4xCO_2$’’ simulation.

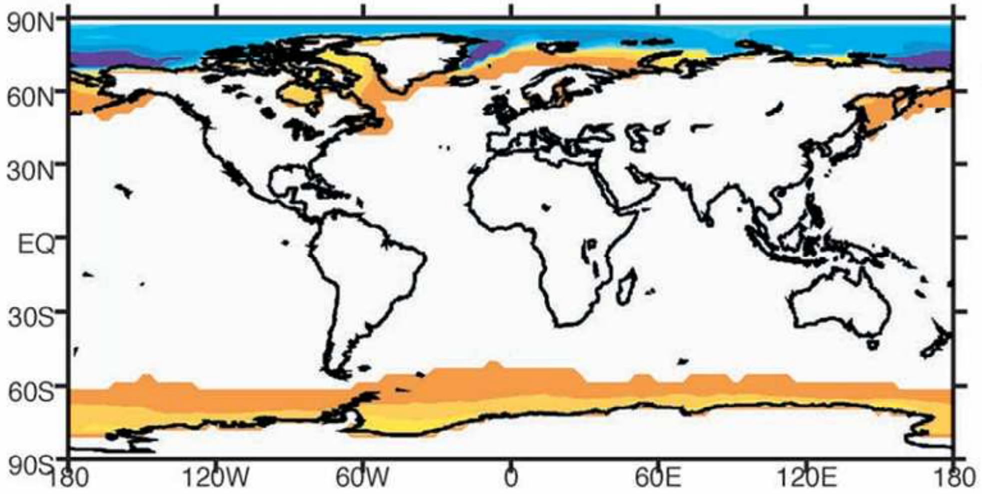


Govindasamy et. al. Global and Planetary Change 37 (2003) 157–168

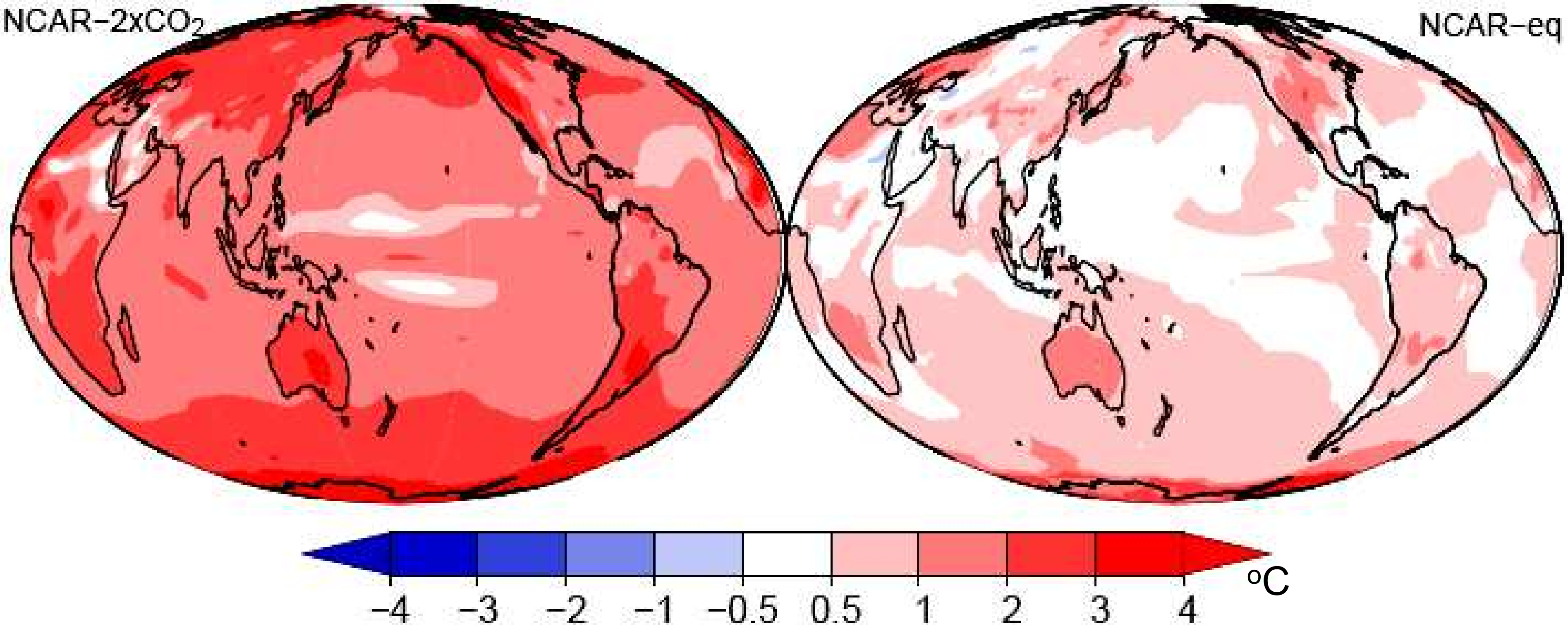
$4xCO_2$



Geoengineered $4xCO_2$



Consequences of CE Offseting 2xCO_2 on the Global Temperature Distribution



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

Leverage Factor for Space Reflectors

We assume 10^8 t of reflector weight for counteracting 3.7 W/m^2 (CO_2 – doubling, from 280 ppm pre-industrial to 560 ppm)
CO_2-Mass (additional 280 ppm): 2237 Gt

Rocket mass from Earth: 100 – times larger

→ 10^{10} t

Assumed Lifetime: 100 years

→ 10^8 t/year or 100 Mt/year

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

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