The case for using a Sunlight Reflector at Earth's L-1 point to stop global warming[1]

Introduction

The rising dangers from Global Warming indicate reducing Greenhouse Gas emissions will not be sufficient to avoid seriously damaging climate change. Carbon Dioxide Removal (CDR) is therefore widely discussed.

This paper argues that CDR by itself will be too expensive and slow. It therefore recommends the construction of a Sunlight Reflector at Earth's L-1 point[2] to hold down temperatures until the combined action of reducing emissions and CDR has brought Greenhouse Gases (CO_{2e}) in the atmosphere down to a level which provides an acceptable climate.

While this Sunlight Reflector idea is not new – it was, for example, explored in detail in a 2006 paper by the University of Arizona's Roger Angel[3] – recent changes have transformed it from the realm of science fiction into a realistic, effective, and affordable means of stopping climate change.

Specifically, advances in reusable rockets are dramatically reducing the cost of launching to Low Earth Orbit. This, and improvements in computer systems for controlling spacecraft, make using Solar Reflectors in space an affordable, attractive option.

This paper has the following sections

- The Royal Society's 2009 Geoengineering study
- Changes since the Royal Society's 2009 Geoengineering study
- Impact on Earth of a Sunlight Reflector at its L-1 point.
- So, what action to take?
- End Notes
- Attachment on why Geoengineering is now essential.

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[1] **This paper has been prepared** by J Robert Gibson 29th Nov 2023: under Creative Commons License
www.envr.ust.hk/our-division/people/faculty-staff/rgibson.html

[2] **Earth's L-1 point** is directly between the Sun and Earth. It is 1.5 million kilometres on the Sun side of Earth, as this is the point where Earth's gravity partly balances the Sun's gravity resulting in a satellite at this point orbiting the Sun at the same angular velocity as Earth, thus keeping Earth in its shadow.

[3] **Roger Angel's feasibility study** www.pnas.org/doi/abs/10.1073/pnas.0608163103

The UK Royal Society's[4] 2009 Geoengineering Study

An excellent starting point for understanding geoengineering options is the UK Royal Society's 2009 paper: *Geoengineering: climate: science, governance and uncertainty.*[5] It evaluated six options for using Carbon Dioxide Removal (CDR), six for using Solar Radiation Management (SRM), and one for Carbon Capture and Storage at Source (CCSS).

Table 5.1. Summary of ratings accorded to the methods assessed in Chapters 2 and 3.

Method	Effectiveness	Affordability	Timeliness	Safety
Afforestation	2	5	3	4
BECS	2.5	2.5	3	4
Biochar	2	2	2	3
Enhanced weathering	4	2.1	2	4
CO_2 air capture	4	1.9	2	5
Ocean fertilisation	2	3	1.5	1
Surface albedo (urban)	1	1	3	5
Surface albedo (desert)	2.5	1	4	1
Cloud albedo	2.5	3	3	2
Stratospheric aerosols	4	4	4	2
Space reflectors	4	1.5	1	3
CCS at source	[illegible]	[illegible]	4	5

CDR

SRM

CCSS

Scoring: '5' is best and '1' is 'poor.

48 I September 2009 I Geoengineering the Climate The Royal Society

Figure 1 - Table 5.1 extracted from " Geoengineering the Climate" by the UK Royal Society

The Royal Society's conclusion includes (Para 3.5 on Page 36 of its report):

- SRM methods may provide a useful tool for reducing global temperatures rapidly should the need arise.
- Global techniques [of SRM] appear to be the safest methods for reducing global average temperature[6].
- The early stage of development of space-based methods, and their high R&D costs relative to other global SRM methods, mean that they are unlikely to be feasible in the medium term.

And it further noted that (Page 58):

- Space-based SRM methods would provide a more uniform cooling effect than surface or cloud-based methods, and, if long-term geoengineering is required, they may be more cost-effective than the other SRM methods. But development of the necessary technology is likely to take decades.

Hence, as shown in table above, Sunlight Reflectors (highlighted in blue) were rated as **Effective** and **Safe**, but **too Expensive** and **taking too much time to deploy**.

[4] **The Royal Society** is a leading independent academic society in the UK. It is dedicated to promoting excellence in science for the benefit of humanity. https://royalsociety.org/

[5] **Geoengineering** https://royalsociety.org/topics-policy/publications/2009/geoengineering-climate/

[6] **Global techniques** are safer as regional action risks changing weather patterns.

Changes since the Royal Society's 2009 Geoengineering study:

1) Geoengineering is now essential as (See the <u>Attachment</u> on pages 8 & 9):

- **Humanity has failed to reduce its GHG emissions**. As a result, the trend line for Earth's average temperature is already about 1.2 C above the 1859-1900 average, with the 2023 being an exceptionally hot year at between 1.3 and 1.5 C above. Further, Jim Hansen et al 2nd Nov 2023 paper on '**Global warming in the pipeline'**[7] shows2.0 C as a mid-range projection for 2040.
- **The impact of current global warming.** Earth's climate system, given the number of extreme weather events, appears to be more sensitive to Global Warming than scientific projections made in 2009.

2) The need for Geoengineering is now widely recognised. The IPCC climate science reports have noted the need for it for some years. Publications calling for it in the lead up to this year's COP include:

- The United Nations Environment Agency's 2023 Emissions Gap Report[8].
- The Economist on 25th Nov 2023: *Special Report: The new economy net zero needs Carbon Dioxide removal*[9].

So which type of geoengineering to use? The answer is both Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM) are needed.

- CDR is needed to first reduce, and then reverse, the growth of CO_2 in the atmosphere. This will both decrease global warming and curb ocean acidification. It will, however, take decades to do this even with the expenditure of several percent of global GDP.
- SRM is needed to stop global warming, and to lower temperatures to a safer level until a time, years in the future, when CDR has removed sufficient CO_2 from the atmosphere.

Regarding CDR: The first six types of geoengineering listed by The Royal Society in **Figure 1** (Page 2) are CDR. Many pilot projects and research initiatives for these types of CDR are underway or being discussed. Moving to the large scale needed is likely to be very expensive as:

- Low-cost types of CDR, such as Afforestation, have limited long-term capacity.
- CDR types with theoretically unlimited capacity such as Direct Air Capture have a high cost.

Regarding Carbon Capture and Storage at Source (CCSS). This is similar to CDR and is the last item on the Royal Society's list. It captures CO_2 from the exhaust gases of industrial plants. This costs less than Direct Air Capture as these exhaust gases have a much higher concentration of CO_2 than the atmosphere. That said, the cost is still substantial so regulations or carbon-pricing will be needed to get companies do it. The European Union

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[7] **Global warming in the pipeline** https://academic.oup.com/oocc/article/3/1/kgad008/7335889

[8] **UNEP Emissions Gap report 2023** 20Nov 2023 www.unep.org/resources/emissions-gap-report-2023?gclid=CjwKCAiAsIGrBhAAEiwAEzMlCy6NJU9rH33tVer5MGIAaqVqO_DWYp75IFMh3aKbAKN9a7ciVIaVRxoCVioQAvD_BwE

[9] **The Economist Special Report:** The new economy net zero needs Carbon Dioxide removal. **www.economist.com/special-report/2023-11-25**

(EU) will be a leader on this once its Carbon Border Adjustment Mechanism comes. into force. It will cover cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. For these it will:

- Require plants making these items within the EU to buy credits from the EU-Emissions Trading Scheme to cover their CO_2. emissions; and,
- Charge imports of these items into the EU the difference between the EU ETS price and source country carbon price.

Regarding Solar Radiation Management (SRM) This covers the remaining six types of Geoengineering listed by the Royal Society.

The most actively discussed SRM technique is creating 'Stratospheric Aerosols' at low cost by flying aircraft using high-sulphur fuels in the stratosphere. This, however, has three disadvantages:

- Regional variations in the use of stratospheric aerosols may change weather patterns, leading to increased rainfall in some areas and reductions in others. The resulting floods and droughts may have dire consequences for agriculture and for water management. This could cause conflict between countries who disagree on the merits and effectiveness of aerosol injection programmes.
- The aerosols increase acid rain, which is harmful[10].
- As aerosols are removed by rain they must be replaced by further injections into the atmosphere.
- Stopping the aerosol injection program would lead to rapid increases in global warming. Thus, once started, the consequences of stopping before CO2 levels are reduced may be very damaging.

The other non-space SRM options all have their deficiencies as is listed in the Royal Society report.

3) Technological advances are making building a Sunlight Reflector at the L1 point much faster and cheaper.

The cost and speed of deploying a Sunlight Reflector at the L1 point has been reduced dramatically. Detail:

- Capability to launch consignments/equipment into Low Earth Orbit **(LOE)** is now far greater than in in 2009. Launch costs have been reduced by one order of magnitude with a further order of magnitude in prospect. (End Note 1)
- The optimum design of a Sunlight Reflector at the L1 is likely to be for a very large number of modest-sized robotic spacecraft using solar sails. The combination of SpaceX's Starlink satellite technology and NASA's Advanced Composite Solar Sail System (**ACS3)** project's technology has the potential to mass-produce these and deploy them economically at the LI point. Detail:
    - The core structure and computer control systems for the satellites can be based on the ones Starlink is producing at low cost in their thousands (End Note 2).
    - Solar sails which double as Sunlight Reflectors can be developed from the **ACS3-**project to provide large shading surfaces at low mass. These provide thrust to keep the satellites in the desired formation near the L-1 point obviating the need to carry fuel for this purpose. (End Note 3)

[10] Britannica on Acid Rain: www.britannica.com/science/acid-rain

Impact on Earth of a Sunlight Reflector at its the L1 point.

How big will the Sunlight Reflector need to be?

At the outset, a small Sunlight Reflector could be built at the L1 point as a technology demonstrator. This can then be gradually expanded to a size that cancels-out Earth's Energy Imbalance and stops further global warming. (But not, of course, ocean acidification.) It can then be further expanded to reduce temperatures.

- Calculations suggest the Sunlight Reflector would need an area of 404,000 km^2 to cancel the estimated average Energy Imbalance of 0.87W/m^2 for the 2010 – 2018 period. (See End Note 4)
- A larger Sunlight Reflector will be required by 2030 given the increases in CO_{2e} since the 2010 – 2018 average.

How, besides reducing global warming, will a Sunlight Reflector at the L-1 point affect Earth?

- The Sun's large size coupled with the 1.5 million km distance from the Reflector at the L1 point to Earth means the Reflector will not create a 'sharp focus' shadow on Earth. Rather it will provide a partial reduction in sunlight on the whole of the planet. This has the great advantage that it is highly unlikely to affect weather patterns.
- The shadow will dim the sunlight received on Earth by an estimated 0.25% (See End Note 4). This will reduce photosynthesis but probably by less than the boost to plant growth provided by higher CO_2 levels in the atmosphere.

The advantages of such reflectors at the L1 point include:

- They do not conflict with other uses of near-Earth space.
- They shade the Earth all the time, whereas reflectors in Earth's orbit shade it less than 50% of the time.
- They shade the Earth uniformly and so there is no reason to believe they will change weather patterns.
- They are scalable. When the cooling they provide is not needed, they can be moved slightly to one side of the L1 point so they no longer shade Earth. They could then be repositioned to provide shade if necessary. Or, if preferred, they could be disposed of in a heliocentric orbit away from Earth.

So, what action to take?

One way to explore the feasibility and cost of building the Sunlight Reflector at the L1 point is to Invite bids from aerospace companies including SpaceX and Blue Origin.

Note that:

- Both Elon Musk (for SpaceX) and Jeff Bezos (for Blue Origin) are investing heavily to develop space-faring capability with the philanthropic injection of their personal fortunes. Building a Sunlight Reflector at the L1 point probably aligns with their objectives.
- As noted in this memo, SpaceX and Starlink have developed, or are developing, most of the technology needed. SpaceX has a track record of innovating at speed.

- Similarly Blue Origin is developing the New Glenn as a heavy-lift, re-usable rocket and a satellite system similar to Starlink.

END NOTES

1. Cost of launch to Low Earth Orbit (LEO):

The key to reducing cost to LEO is for rockets to be reliable and reusable. **SpaceX's Falcon 9** is leading the way on this[11]

- The first successful landing of the first stage of its rocket was in 2015.
- It has proved extremely reliable with its current version flying 226 times without a failure.
- This year it has already lifted over 1,000 tonnes into LOE.
- SpaceX charges about US$2,900 per kilogram for a Falcon 9 launch to LOE and currently doesn't face competition which can offer near this price. It is believed that its cost of operating the rocket is significantly less that the amount it charges.

SpaceX is developing its **'Starship'** rocket to be fully and rapidly reusable delivering 150 tonnes to LOE. This both brings the cost per launch down and enables many flights per year. The plan[12] for NASA's Artemis III Moon landing, for example, requires between 15 to 20 launches launching about 3,000 tonnes to LOE within a few weeks.

Blue Origin's New Glenn[13] is another very large rocket being developed to be fully reusable with the objective of low-cost launch to LOE. There is less information on it than SpaceX, as it is at an earlier stage of development.

2. Starlink satellite capability

Starlink's [14].satellite frame and computer systems satellite control are similar to those needed for the Sunlight Reflector satellites It currently has over 5,000 active satellites and plans to increase to 40,000. Each Falcon 9 launch carries twenty-three of these 800kg satellites and Starship planned to carry many more.

3. Development of solar sails which can be used as reflectors

NASA's Advanced Composite Solar Sail System (ACS3) satellites which are due to launch in 2024 fit into a 23x23x34 cm CubeSat and unfold to 80m^2. A 600m^2 version is under development and the technology is believed suitable for a 2,000m^2 sail[15].

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[11] **Falcon 9** https://en.wikipedia.org/wiki/List_of_Falcon_9_and_Falcon_Heavy_launches
[12] www.spacex.com/vehicles/starship/#:~:text=Starship%20Overview&text=Starship%20is%20the%20world's%20most,and%20250%20metric%20tonnes%20expendable.
[13] **New Glenn** www.blueorigin.com/new-glenn
[14] **Starlink** www.starlink.com/technology
[15] **Information on ACS3**:www.nasa.gov/smallspacecraft/what-is-acs3/ and www.youtube.com/watch?v=wsxNgRI_RMs

4. How big must the L1 Sunlight Reflector be to stop global warming?

When calculating this, note that the Sun's large size and the 1.5 million km distance from the Reflector to Earth result in the reflector causing a partial shading of all the planet rather than a 'sharp focus' shadow on part of it. Further, only some of the shadow may cover Earth. In the calculation below I assume 80% shades Earth. A study is needed to determine the correct number.

Secondly, the answer will depend on the level of Greenhouse Gases in the atmosphere and hence Earth's energy imbalance.

Taking the World Meteorological Organisation GCOS study's[16] midpoint for 2010-2018 of 0.87 W/m^2 an area of 404,000 km^2 is needed if 80% of the Sunlight Reflector's shade covers Earth. If 100% of the shade covered Earth, then only 323,000km^2 is needed.

Data		**Source or formula**	**Code**	**Unit**	**Value**
1	Earth's distance from the Sun (an average for its orbit)		De	Million km	147.8
2	L1 point's distance from Earth		Dl1	Million km	1.5
3	Increases in size of the shadow of something at the L1 point when it reaches Earth. (NB: It will not be a specific shadow but rather diffuse partial shadow that has the same radiation reduction impact as a specific shadow.)	De/(De-Dl1)	Sg	%	101.0%
4	Earth's diameter	Wikipedia	Ed	km	12,750
5	Solar Constant = total solar radiation Earth receives from the Sun.		G_{sc}	W/m^2	1,361
6	Average Solar Radiation at top of Earth's Atmosphere	$G_{sc}/4$	SR	W/m^2	340
7	Absorbed Solar Radiation (ASR) after reflection from clouds and the Earth's surface		ASR	W/m^2	240
8	Earth's average Energy Imbalance for 2010 to 2018 per WMO's GCOS		EEI	W/m^2	0.87
Unknowns					
9	% Of the Sunlight Reflector which is covering Earth rather than missing it.	A hopefully prudent guess	P		80.0%
What size Sun Reflector would cancel the average Earth Energy Imbalance for the period 2010 - 2018?					
10	Earth's cross section facing the sun	$\pi*(Ed/2)^2$	Ea	'000 km^2	127,676
11	% of reduction required in SR (solar radiation)	EEI/SR			0.26%
12	Earth's Cross section * % reduction required in SR * growth in shadow due to Earth being further from Sun than the L1 point * % of Sun Reflector which is covering Earth	Ea*P*EEI/(ASR)*Sg)	Sra	km^2	**403,934**
13	**Extent to which the Sunligh reaching Earth is dimmed by this size Sun Reflector**	Sra*p/Ea			**0.25%**
14	Size If 100% of the Sun Reflector covered Earth.			km^2	**323,148**
15	The energy imbalance is updated from the 2010 - 2018 average to a projected 2030 level				Insufficient information

The size of Sunlight reflector needed to stop global warming at a projected CO_{2e} level in 2030 requires estimating how much outbound radiation from Earth has increased due to its warming since the 2010-2018 average.

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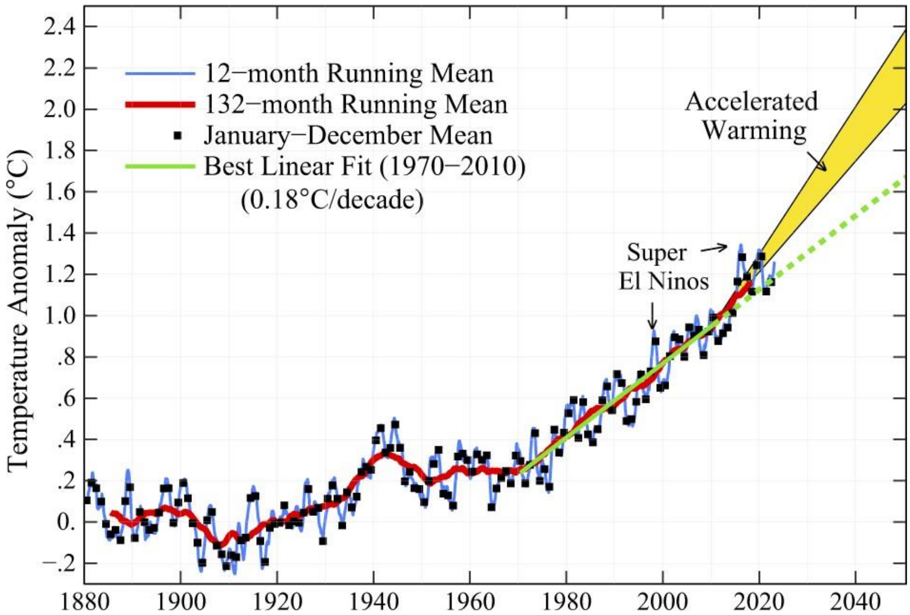
[16] World Meteorological Organisation's Global Climate Observing System (GCOS) see: https://wmo.int/media/news/new-study-shows-earth-energy-imbalance and https://essd.copernicus.org/articles/12/2013/2020/

Attachment

Why Geoengineering is now essential.

Humanity has failed to reduce its GHG emissions. As a result, Earth's temperature is close to 1.5C above the 1859-1900 average. Further, Jim Hansen et al's 2 Nov 2023 paper on '**Global warming in the pipeline'**[17] gives 2.0C as a mid-range projection for 2040.



The Earth's Climate system is proving more sensitive to Global Warming than scientific projections available in 2009. Viz the increasing incidents of extreme weather.

TIME 2nd Nov 2023: We Need Geoengineering to Stop Out of Control Warming, warns Climate Scientist James Hansen[18] (By: ALEJANDRO DE LA GARZA)

James Hansen first warned Congress of the threat from climate change in 1988. Today, in a controversial new peer-reviewed paper published in *Oxford Open Climate Change*[19], he brings a new warning: Scientists are underestimating how fast the planet is warming. And the crisis will have to be met, in part, with geoengineering.

According to the report, Earth will pass 1.5°C of cumulative warming this decade and exceed 2°C of warming before 2050. Scientists think that warming in excess of 2°C could unleash more dangerous effects, like the collapse of Antarctic ice sheets, leading to rapid sea level rise. Limiting warming to 1.5°C, and at least keeping it well under 2°C, is the goal of the Paris Climate Accord, with international policymakers gathering at yearly COP meetings to negotiate actions to meet that goal.

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[17] **Hanson 2nd Nov 2023 paper: Global warming in the pipeline.'**
https://academic.oup.com/oocc/article/3/1/kgad008/7335889
This paper makes the case for geo-engineering It covers the 'Stratospheric Aerosols' and 'Cloud brightening' methods of solar. It makes no mention of Space Based reflection of sunlight.
[18] **TIME article** https://time.com/6330957/james-hansen-climate-warning-geoengineering-study/

[19] This link doesn't work. They may have meant to link to the 'Global warming in the pipeline' paper referenced above.

Climate scientists have been underestimating how sensitive the global climate system will be to increased carbon dioxide emissions, according to the new paper. That's in part because they have been improperly accounting for the effect of sulphur dioxide emissions from coal power plants and ships burning bunker fuel, which mask warming. Sulphur dioxide emissions, in the form of aerosols in the atmosphere, have the effect of reflecting sunlight, but they are also hazardous to human health. In recent years, regulations around the world have caused sulphur dioxide emissions to fall. That's likely helped reduce air pollution responsible for millions of deaths every year, but, according to Hansen, the trade-off has been accelerated warming. This, he says, is part of the reason for the record warming much of the Northern Hemisphere experienced this summer.

"Humanity made a Faustian bargain by offsetting a substantial but uncertain fraction of greenhouse gas warming with aerosol cooling," Hansen said alongside other scientists in a webinar introducing his new paper on Nov. 2. "Now, as we want to reduce all the chronic health effects of aerosols, our first Faustian payment is due."

End