Solar Geoengineering to Stop Annual Global Warming

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Abstract: Solar geoengineering (SG) solutions have many advantages compared to the difficulty of carbon removal (CR): SG produces fast results, is shown here to have much higher efficiency than CR, is not related to fossil fuel legislation, and is something we all can participate in brightening the Earth with cool roofs, and roads. SG requirements detailed previously to mitigate global warming (GW) have been concerning primarily because of overwhelming goals and climate circulation issues. In this paper, higher feasibility is provided for solar geoengineering applications by focusing on physics-based estimates to stop annual increases in GW. Annual solar geoengineering (ASG) area modification requirements found here are generally 50 to possibly higher than 150 times less compared to the challenge of full SG GW mitigation. Results indicate that AI paint drone technology is likely needed for Earth brightening to meet annual mitigation goals. As well, results indicate much higher feasibility for L1 space shading compared to prior literature estimates for full GW mitigation. However, stratosphere injections appear challenging in the annual approach. A serious issue with implementing ASG is the problem of worldwide negative SG which currently dominates yearly practices with the application of dark asphalt roads and roofs. This issue is discussed.

Keywords: solar geoengineering; modeling; space mirrors; earth mirrors; desert modification; space clusters; stratosphere injection

1. Introduction

This paper provides fundamental physics-based annual solar geoengineering (ASG) equations to aid in estimated requirements for yearly area solar radiation modification (SRM). Therefore, this paper provides initial assessments without using computer-aided full climate solutions. Solar geoengineering physics should add a deeper understanding of annual requirements. Estimates are simplified by focusing on temperature which is the key thermodynamic driver for the climate system and ASG.

The IPCC worries about an increase of a 1.5°C rise over the pre-industrial period. This is estimated to possibly occur around 2039-2043 at the current rate of yearly temperature increases. This can be estimated from Figure 1 which shows the short-term GW trends occurring around 2052. However, the graph displays changes since 1975. The IPCC warning is referenced to the pre-industrial period. Translating Figure 1 to the pre-industrial period requires adding about 0.17°C. Then this would occur around 2043 from the graph.
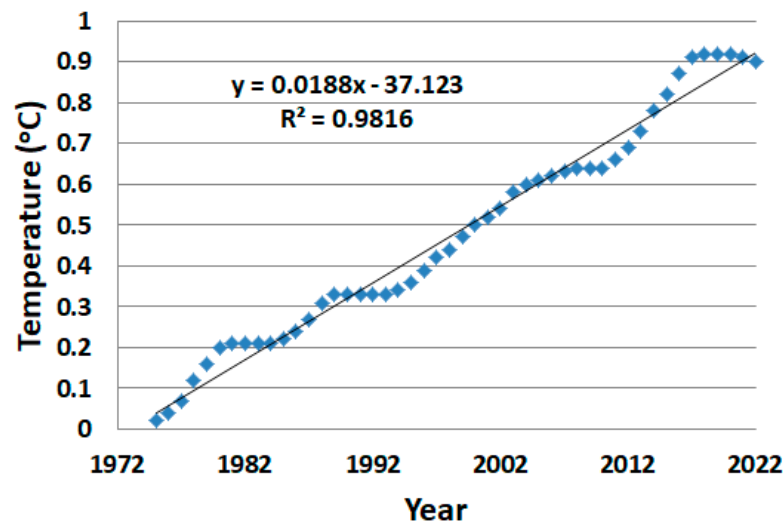
Figure 1. Global warming linear short-term trend (smoothed) assessment [7].

ASG will require timely yearly construction rate reflective modified areas both on Earth and possibly in space to reduce some of the Sun's energy to mitigate yearly global warming increases. Thus, a key purpose of ASG is to maintain the status quo allowing time for future mitigation improvements and because goals are limited to mitigating yearly warming increases, many controversial SG issues are minimized.

From the graph's equation, the current rate of global warming is an increase in temperature of 0.019°C/year. To maintain the status quo for zero global warming growth, we can divide up the ASG construction task into two parts for simplicity. Half relegated to the stratosphere (Sec. 3.4) or space shading methods. Half relegated to land-based solutions such as that proposed by project MEER [1] but on a larger scale (see Sec 3.4). Therefore, a reasonable goal is to mitigate a 0.019°C/year global warming increase which should minimize circulation concerns [2–5] and many other controversial issues. This goal turns out to be about 50 to possibly higher than 150 times less mitigation in Earth brightening area modification requirements compared to prior full mitigation estimates [6].

Most of the current SRM literature is focused on stratosphere aerosol injections (SAI). As this is covered by computer-aided models and there are a lot of concerns in this area, this paper focuses more on Earth-brightening and L1 space Sun dimming solutions. However, we do overview some of the physics that may be helpful for SAI. There are many reasons that SAI may not be appropriate for ASG. The primary one is yearly maintenance needs [2–5]. This is less of a problem in SRM methods like Earth-brightening. For example, negative SRM appears well maintained in the area of asphalt roads and roofs This negative example, illustrates the low maintenance requirements that could occur with Earth-brightening modifications. Negative solar geoengineering is a worldwide problem and impedes opportunities for positive SG advances. This needs to be addressed and is discussed in Sec. 4.4.

2. Method and Data

2.1. Zero global warming growth

In this paper, the approach is to provide basic physics-based estimates to achieve just enough solar geoengineering to reverse the potential yearly increase in global warming. In this paper, this is referred to as annual solar geoengineering. For example, global warming from 1975 to 2022 was 0.9°C [7]. If a status quo annual solar geoengineering approach was applied, the ideal result would be a zero temperature increase. The warming level would stay at 0.9°C. According to Figure 1, the current temperature reversal requirement for ZGWG is

$$T_R = -0.0188°C/year \qquad (1)$$

2.2. Theory

In this section, the basic physics-based ASG goals are presented. The numbers used in this section and Sec. 3 can be updated for more complex computer-aided models depending on the reader's interest and the changing climate. As well, we mostly use averages in approximating estimates. The estimated general requirements to offset a temperature increase in energy units is

$$T_R = -0.0188 °C/year = -0.102 Wm^{-2}/year \qquad (2)$$

This conversion to energy units can be obtained from the Stephan-Boltzmann relation where

$$\Delta P = P_2 - P_1 = \sigma(T_2^4 - T_1^4) = 0.102 Wm^{-2} \qquad (3)$$

Here T_1 is taken as the average surface temperature of the Earth of about 14.5°C and T_2=14.5 °C+0.0188°C=14.519°C.

The SG strategy developed by the author [6] indicates to reverse the global warming that occurred from 1950 to 2019 having a temperature rise of 0.95°C, would require a reversal of $\Delta P_{Rev} = -5.1 Wm^{-2}$. This is just the global warming rise from 1950 to 2019 of 0.95°C in energy units where $\Delta P_{Rev} = -\sigma(T_{2021}^4 - T_{1950}^4) = -5.1 Wm^{-2} = -\sigma\left((288.6K)^4 - (287.65K)^4\right)$. Here 287.65K=14.5°C is roughly the average temperature of the Earth. Then we can write for full global warming mitigation (from 1950 to 2019) from the author's prior work [6], the reversal equates to

$$\Delta P_{Rev} = -5.1 Wm^{-2} = -\Delta P_T (1 + f_1)\, \overline{A}_F \qquad (4)$$

In this equation, the reverse forcing due to an albedo change of the target is denoted by ΔP_T. We note that increasing the reflectivity of a hotspot surface reduces its associated greenhouse gas effect This is estimated in Eq. 4 with the 1+f term where f is approximately 0.62 [8]. This is due to the average re-radiation estimate of 62% [8]. In this equation, we assume that feedback, which is dominated by water vapor, will also reverse. That is, SG reverse forcing causes a cooling effect and cooler air holds less water vapor. In Eq. 4, the average feedback value is estimated in 2019 as $\overline{A}_F = 2.15$ [8,9]. We note that many other authors have anticipated a similar feedback-doubling effect [10,11]. However, this value can be written with temperature dependence, and this is discussed in Sec. 2.3.

Then inserting $\overline{A}_F = 2.15$ into Eq. 4, we can write

$$\Delta P_T = -\frac{2.38 W/m^2}{(1+f)} = -1.47 W/m^2 \qquad (5)$$

This is the estimated goal for a total reversal of global warming from 1950 to 2021. Other updated estimates may be used depending on the reader's interest. Since in this paper, we are interested in zero global warming annual growth, the ASG requirement for a reversal is approximated as (from Eq. 3-5)

$$\Delta P_{ASG} = -\frac{1.47 W/m^2}{5.11 W/m^2} x 0.102 W/m^2/Yr = -0.0293 W/m^2/Yr. \qquad (6)$$

This is the estimated main reverse forcing results used in this paper.

2.2.1. Greenhouse gas equivalent reduction from SRM

It is helpful to note the SG advantage in Eq. 5. To mitigate the 5.1Wm^{-2} in Eq. 4, requires an estimated SG change of -1.47Wm^{-2} compared to trying to do it with GHG removal which would require the full 2.38Wm^{-2}. This yields a work savings of 0.91Wm^{-2} (=2.38Wm^{-2}-1.47Wm^{-2}). This is a 38% (=0.91Wm^{-2} /2.38Wm^{-2}) SG advantage [8] yielding much higher efficiency compared to CR. That is in SG, we need to take into account a 1+f re-radiation extra reduction in Eq. 5, (i.e., increasing the reflectivity of a hotspot surface additionally reduces its associated greenhouse gas effect [8]).

Therefore, by cooling a hotspot, we effectively reduce its GHG effect. Essentially, if we did full GW mitigation of the increases from 1950 to 2019 using SRM, we would reduce effectively 0.91Wm^{-2} of the associated GHG effect. Many authors do not consider this SG 'effective GHG reduction'. Yet, on average, an additional 62% of SRM goes into its associated "GHG equivalent reduction'.

This GHG-albedo effect may also help to decrease the high levels of possible CO_2 and often water vapor feedback re-radiation that can occur in UHIs in the presence of high heat flux [12,13].

Unfortunately, alternately worldwide negative solar geoengineering equivalently increases the GHG effect by this 1+f factor (Sec. 4.4), and its additional associated water vapor feedback increases. When these average effects are considered in addition to the background climate, urbanization heat fluxes from impermeable surfaces are problematic on both the local and global levels [13,14] as discussed in Sec. 4.4.

2.2.2. Area estimates for annual solar geoengineering

To estimate the Eq. 6 area modification requirements for a -0.0293Wm^{-2} reversal, the approach is to use the author's derived solar geoengineering estimate [6] that is given by

$$\Delta P_T = \Delta P_{ASG} = -\frac{X_S S_o}{4} \frac{A_T}{A_E} X_C \mathrm{H}_T \left[(\Delta \alpha_T) \right] \qquad (7)$$

This physics-based SG equation indicates that in Earth brightening, as anticipated, the reversal is proportional to the target area A_T, the amount of irradiance X_C falling on the target with global averages of 47% [15], and the average solar energy over 24 hours, $S_o/4$. In addition, the albedo change is $\Delta \alpha_T = \alpha'_T - \alpha_T$, where the target's albedo changes from α_T to its SG increase α'_T.

Note that a space irradiance factor X_S has been introduced, and is generally taken as unity. However, for space mirror application, the optimal L1 point rotates around the Sun with the same angular speed as the Earth, thus allowing constant shading. Then the irradiance shading occurs 24 hours a day and the Earth's curvature is not a factor. This increases $S_o/4$ to S_o. To account for the increase in space irradiance, we can let $X_S=4$ in Eq. 7.

This equation also provides provisions for targets in urban heat island (UHI) areas which can have microclimate de-amplification effects denoted by H_T [13,16]. For example, in UHIs, the solar canyon effect amplifies warming when buildings reflect light onto pavements amplifying heat at the surface. Other amplification issues can include re-radiation due to the increase in local CO_2 GHGs, local water vapor feedback, temperature inversions, loss of wind and evapotranspiration cooling, increases in solar heating of impermeable surfaces from building sides, pavements heat fluxes, and so forth [13]. Some of these effects will reverse and de-amplify, increasing cooling, and can be accounted for in Eq. 7 with the H_T variable. City heat flux amplification is often observed by the UHI's dome and footprint. The footprint and dome growth are indications of amplified heat flux that is observed to spread beyond the boundaries of the city itself both horizontally and vertically [13,16].

2.3. The Potential Advantage in Earth Brightening of Hotspots

In terms of an albedo change, it is clear from Eq. 4, the larger the albedo change, the smaller the required target area that is needed to meet a specific SG goal. However, the impact of different albedo changes, according to Equations 4 and 5, creates the same average water vapor feedback effect. Therefore, we would like to assess the effect of cooling a high-temperature hotpot surface by considering its feedback temperature dependence rather than using an average $\overline{A}_F$ factor. We later define a hotspot area below.

To look at hotspot issues, consider the Clausius-Clapeyron relation. To assess this potential effect, Eq. 4 can be written with temperature dependence

$$\Delta P_{\mathrm{Rev}}(T) = -5.1 Wm^{-2} = -\Delta P_T (1 + f_1) A_F(T) \qquad (8)$$

The rule of thumb is a decrease in water vapor goes as the temperature ratio. However, the most accurate method is to use the Clausius-Clapeyron humidity relationship between two temperature changes as

$$A_F(T) = Exp\left[-2.465E6/461.5\{1/T_2 - 1/T_1\}\right] = CC(T_2, T_1) \qquad (9)$$

Here T_1 and T_2 are in degrees K, 2.465E6 J-kg^{-1} is the latent heat of vaporization and 462 J-kg^{-1} K^{-1} is the specific gas constant for water vapor, and we can denote the Clausius-Clapeyron humidity relationship by CC.

For example, if we take the average temperature of the Earth as 14.5°C, the estimated A_F factor at 27°C is

$$A_F(T) = CC(14.5°C, T) = CC(14.5°C, 27°C) = 2.17 \qquad (10)$$

This is close to the average $\overline{A}_F = 2.15$. It is estimated that water vapor feedback is dominated by tropical areas [10,11] where an average temperature of 27°C would be reasonable. This provides a helpful point estimate for the average value $\overline{A}_F = 2.15$.

Consider an effort to do Earth brightening focusing solely on hotspot areas. As an example, consider a hotspot asphalt surface area averaging 61°C that is changed to a cool road close to the region's ambient which in this example we take as 33°C. Then the Clausius-Clapeyron relation indicates the potential for a local region cooling to reduce its water vapor effect and how it could change its feedback factor. Then the potential feedback factor could effectively increase to

$$A_F(T) = CC(33°C, 61°C) = 4.3 \qquad (11)$$

Compared to $\overline{A}_F = 2.15$, the local value is doubled to $A_F(T) = 4.3$. Then according to Equations 4 and 5, Eq. 6 local goal would be cut in half where

$$\Delta P_{ASG} = -\frac{0.735W/m^2}{5.11W/m^2} \times 0.102W/m^2/Yr = -0.0147W/m^2/Yr. \qquad (12)$$

This feedback is related to thermal equilibrium and how it can factor into reducing water vapor content in the atmosphere and its potential local re-radiation effect. Therefore, these are potential estimates and likely maximum assessments. A full computer climate model may provide more insight. This is simply an example to help illustrate the importance of hotspot cooling and its potential water vapor feedback effect. Note in comparison to Eq. 5, ASG in this case is a factor of 100 times reduced. Section 3.4 summarizes this maximum hotspot cooling potential results. Sec. 3.1 illustrates the potential full advantage of selecting hotspot targets for cooling and the importance of being able to cool T2 where T2 >> T1. We might then define a hotspot as having the potential in which $A_F(T)$ is reasonably greater than the estimated average $\overline{A}_F = 2.15$.

Note that a factor of two higher (Eq. 11) is not unreasonable for an urban heat island water vapor feedback compared to the standard atmosphere. Zhao et al. [17] compared similarly constructed cities with twenty-four located in the humid southeastern United States to 15 cities in dry climates. They found an average ΔT increase of 3.3 K observed in daytime hours in humid climates with little differences in nighttime hours. Feinberg [12] modeled UHI water vapor feedback based on Zhao et al.'s [17] data set. The mathematical treatment found a UHI local feedback value of 3.4 Wm^{-2} K^{-1} [12] for cities in humid environments at 15 °C. This is about a factor of 2.1 higher compared to some authors' estimates for average feedback in the standard atmosphere [11].

Again on the flip side, we note the potential water vapor feedback increases are likely associated with worldwide negative solar geoengineering (Sec. 4.4).

3. Results

3.1. Cool pavement model estimate

As an example, consider the required area for worldwide cool pavements. We can consider an average asphalt pavement albedo of about $\alpha_T = 0.1$, and using cool road methods, estimate an

increase for the pavement albedo of $\alpha'_T = 0.4$. Then considering an average irradiance of $X_C = 0.47$, with $X_S = 1$, $\mathrm{H}_T = 1$, and $\overline{A}_F = 2.15$, and using a 50% ASG reversal goal, the requirement is

$$\Delta P_{ASG\_50\%} = -\frac{S_o X_S}{4} \frac{A_T}{A_E} X_C \mathrm{H}_T \left[(\alpha'_T - \alpha_T) \right] = -340 W \, m^{-2} \frac{A_T}{A_E} 0.47 [0.3] = -0.01465 W \, m^{-2} Yr^{-1} \quad (13)$$

Solving we obtain the SG target area percentage for half of ZGWG yielding an area modification of

$$\frac{A_T}{A_E} = 0.0305\% \, per \, year \quad\quad\quad (14)$$

The pavement modification area that needs to be cooled for a $\Delta\alpha_T = 0.3$ change equates to

$$A_T = 0.000305 x 196.6 E 6 mi^2 = 60,000 mi^2 \quad\quad\quad (15)$$

This yields an equivalent radius of 138 miles. This result is summarized in Section 3.4. This is simply an example to provide estimated area modification requirements. Other values may be used depending on the reader's interest.

For pavements that are cooled with $A_F = 4.3$ (see Sec. 2.3), the requirement for the area modification is much less according to Sec. 2.3. In this case it is likely that $\Delta\alpha_T > 0.3$. Letting $\Delta\alpha_T = 0.5$ for this example, the area modification is reduced to

$$A_T = 18,011 mi^2 \quad\quad\quad (16)$$

This yields a reduced equivalent radius of 76 miles. This result is also summarized in Sec. 3.4. Note that to achieve these results; the goal for 50% mitigation is reduced by more than half.

If we could do full global warming SG mitigation for per the equivalent cool pavements in Eq. 15 but with $\Delta P = 1.47 Wm^{-2}$, $\Delta\alpha_T = 0.3$, $A_F = 2.15$, the area required would be about 6 million square miles. In comparison, this ASG requirement where $\Delta P_{ASG} = -0.0293 W/m^2/Yr.$, $\Delta\alpha_T = 0.5$, and hotspot mitigation with $A_F = 4.3$, the resulting area reduction is 36,000mi². The ASG area factor is reduced by about 160 compared to full SG mitigation.

3.2. L1 Space shading estimates

We can translate an A_T area modification requirement to a solar reflective space disc mirror-type shading application. In this case, we note that most authors consider the Sun-Earth L1 position as optimum. For the irradiance in space mirror shading estimation, we can take X_C=100% and X_S=4 (as discussed above). Sun-shading can effectively translate to changing a target on Earth's reflectivity to ~100% from the average Earth's albedo of 30%, so that $\Delta\alpha_T$=0.7. Using these parameters and our 50% ASG goal, Eq. 7 is

$$\Delta P_{ASG-SpaceMirror} = -\frac{X_S S_o}{4} \frac{A_T}{A_E} X_C \left[(\alpha'_T - \alpha_T) \right] = -1361 Wm^{-2} \frac{A_T}{A_E} (1)[(0.7)] = 0.01465 Wm^{-2} \quad (17)$$

Solving we obtain the SG percentage for half of ZGWG of

$$\frac{A_T}{A_E} = 0.0015\% \, per \, year \; (50\% \, mitigation) \quad\quad\quad (18)$$

This yields a disc of about 7843 km² (radius 50 km). Results are summarized in Sec. 3.4.

Note when we talk about space mirrors with a value for A_T/A_E, this value becomes the required percent of incident solar radiation that is estimated to be reflected away from the Earth to achieve a mitigation goal in Eq. 17.

3.3. Annual Stratospheric Injection Estimates

Results appear quite challenging to meet ASG area modification requirements (summarized in Sec. 3.4) for both Earth brightening or space mirror size estimates. Unfortunately, there is no easy solution. Although this paper does not focus on SAI as it is often assessed with computer climate models, it is helpful to overview the ASG estimated differences compared to full GW mitigation. Much has been written about an alternate less expensive Sun-dimming temporarily reflecting particle method such as SO₂ injected into the stratosphere [18–23]. Here SO₂ injected into the stratosphere at the top of the atmosphere (TOA) reduces the Sun's energy reaching the Earth through solar reflection. As an estimate for annual SAI, we can use the equation given by Niemeier and Timmreck [24] where the reduction in radiation at the top of the atmosphere ΔR_{TOA} is

$$\Delta R_{TOA} = -65 Wm^{-2} \exp - (2246 Mt(S) yr^{-1} / I_{SO_2})^{0.23} \qquad (19)$$

The actual injection rate I_{SO_2} (in units of MT(S)/year - megatonnes of SO₂ per year) for full GW reduction according to Eq. 6 requires a goal of 1.47Wm⁻². To provide the first-year annual requirements rather than full mitigation, the injection rate using Eq. 19 is 32x less as shown in Table 1. Here full climate mitigation requires an injection of 6.9MT(S)Yr⁻¹ for a goal of 1.47Wm⁻², whereas, for the first year, the ASG goal is reduced to an injection of 0.216Mt(S)Yr⁻¹ for a 0.01465 Wm⁻² 50% reduction goal. Unfortunately, depending on the SO₂ dissipation per year, this would need to be possibly doubled in the second year, tripled in the third year, and so forth for ZGWG.

Table 1. SO₂ Injection requirements for SRM.

Stratosphere Injection	Full Reversal	Annual 50% Reversal
DR$_{TOA}$ (Wm⁻²)	1.47	0.01465
I_{SO_2} (Mt(S)Yr⁻¹)	6.9	0.216
Savings	0.4	32x

The stratosphere area modification required has not been fully established. Initial assessments appear problematic as outlined in the next section due mainly to the reflection efficiency. Estimates are often equated to one Pinatubo eruption which may be unreliable.

3.3.1. CaCO₃ Stratospheric Injections – Alternate approach

In this section, a CaCO₃ injection rate example is provided for ASG. Here, we can use the approach of Eq. 7 rather than Eq. 19 to illustrate stratosphere area requirements that may provide some alternate insights. Consider the Earth's average albedo of about $\alpha_T = 0.3$, then for this CaCO₃ example, assume an increased reflectivity by a factor of 2 with a CaCO₃ injection bringing an area's atmospheric albedo to $\alpha'_T = 0.6$. Then, considering full irradiance, $X_C = 1$, with $H_T = 1$, and using a 50% reversal annual climate mitigation goal for half of zero global warming growth, in Eq. 7 yields

$$\Delta P_{SQSG\_50\%} = -\frac{S_o X_S}{4} \frac{A_T}{A_E} X_C H_T [(\alpha'_T - \alpha_T)] = -340 W\, m^{-2}(1) \frac{A_T}{A_E}(1)(1)[0.3] = -0.01465 W\, m^{-2} \quad (20)$$

Solving we obtain the SG stratospheric target area modification initial estimated

$$\frac{A_T}{A_E} = 0.0144\% / eff \qquad (21)$$

We will likely have a fractional overlap of particles decreasing the efficiency issues which is denoted by eff. For example, for an 80% efficiency in Eq. 21, the results is $\frac{A_T}{A_E} = 0.0144\%/0.8 = 0.018\%$. This stratosphere area modification equates to

$$A_T = 28,237\,mi^2/eff = 7.31E10\,m^2/eff \qquad (22)$$

Estimates for the specific surface area (m²/g) of $CaCO_3$ vary widely depending on the type of $CaCO_3$ from 5-24 m²/g [25] to 30-60 m²/g [26]. If we conservatively use 10 m²/g, we can calculate the injection rate using Eq. 22 as

$$7.31E10 m^2/10 m^2/g/yr./eff = 7310 \text{ metric tons/yr.}/O = 0.0073Mt(CaCO3)/yr./eff \qquad (23)$$

For a 70% efficiency

$$0.0073Mt(CaCO3)/yr./eff = 0.010Mt(CaCO3) \qquad (24)$$

This is one partial solution as the dissipation rate in this approach needs to be estimated to maintain coverage over time. The area saturated is given by Eq. 21 with *eff*=0.7 and is $A_T/A_E = 0.02\%$. Because of this large area and its replenishing needs, in the annual approach, particle injection is difficult due to the cumulative yearly requirements. Such estimates are likely better assessed with a computer model.

3.4. Overview of estimates

Table 2 provides an overview of the needed estimates based on the suggested inputs to mitigate the annual global warming growth trend of 0.019°C/year for ASG. The results in Table 2 are divided, with Earth brightening area modification of surface land and half to space-type application. The objective for each is to reduce the incoming solar energy by -0.01465Wm⁻² per year for 50% annual GW mitigation. Therefore, any two combinations would ideally meet the ASG requirements. Note that in Table 2, the H_T value, as an example, is taken as 3 for UHI areas and conservatively 2 for Earth mirrors used on urban rooftops as often implemented by project MEER [1]. This H_T average estimate can vary depending on the UHI microclimate [13]. In the case of something like sea-type floating mirrors, H_T=1, also shown in Table 2.

Table 2. ASG requirements for land and space.

Earth Brightening					Space		
Parameters	Pavements	Desert Treatment	UHIs	Earth (Sea) Mirrors	L1 Space Shading Parameters		Stratosphere Injections
DP_{ASG}(Wm⁻²)	-0.01465	-0.01465	-0.0147	-0.01465	DP_{ASG}(Wm⁻²)	-0.01465	-0.01465
X_C, X_S	0.47, 1	0.92, 1	0.47, 1	0.7, 1	X_C, X_S	1, 4	1, 1
$\Delta\alpha_T$	0.3	0.44	0.1	0.75	$\Delta\alpha_T$	0.7	0.3
H_T	1	1	3	2 (1)	H_T	1	1
$\overline{A}_F$	2.15	2.15	2.15	2.15	$\overline{A}_F$	2.15	2.15
Earth Brightening Results					L1 Space Disc Results		CaCO₃ Injec.
A_T/A_E	0.0305%	0.0106%	0.031%	0.0041% (0.0082%)	A_T/A_E Earth Shade	0.00154%	0.0144%/*eff*
A_T (Mi²)	60,035	20,940	60,035	8061 (16,124)	Shade A_T (Mi², km²)	3023, 7843	~27,924,~74,322
Radius (Mi)	138	81.6	138	51 (71.6)	Shade Radius (Mi, km)	31, 50	~94.3, ~153.8
A_T (km²)	1.56E+05	5.42E+04	1.6E+05	2.1E+04 (4.2E+04)	Disc Area (Mi², km²)*	3023, 7843	-
Radius (km)	223	131	223	81.6 (115)	Disc Radius (Mi, km)*	31, 50	-

*Depends on Sun blocking efficiency of the disc and actual distance relative to L1.

Note the ASG requirement (Eq. 6) compared to full mitigation (Eq. 5) is ~50 times (=1.47Wm^{-2}/0.029Wm^{-2}) reduced in energy flux requirements and area modification (per Eq. 7). For example, desert treatment is reduced from the author's initial estimate of 1.0% [6] to 0.010% for 50% annual mitigation in Table 2. Therefore the areas in annual mitigation are in general a factor of 50 times smaller which also minimizes any potential circulation concerns [2–5]. Table 2 suggests several options including multiple combinations that can be considered in annual mitigation. For hotspot cooling shown in Table 3, this has the potential to reduce area requirements by a factor of over 150 (per Eq. 16).

Table 3. ASG potential hotspot possible requirements.

T2, T1	61°C, 33°C
$\Delta\alpha_T$ X$_C$	0.5, 0.47
A$_F$	4.3
DP$_{ASG}$(Wm^{-2})	-0.01465
A$_T$/A$_E$	0.0092%
A$_T$ (Mi^2)	18,011
Radius (Mi)	76
A$_T$ (km^2)	0.47E+05
Radius (km)	122

4. Discussion

4.1. Solar Radiation Management

4.1.1. Solar geoengineering allocation by country area

If we take Eq. 14 for cool roads and double it for the task of a full year of ASG it yields $\frac{A_T}{A_E} = 0.061\%$ per year. To aid solar radiation management, we can allocate our goal amongst countries by their area. For example, consider the requirements for the United States (with an area of 3.8E6 mi^2) and England (with an area of 5E4 mi^2). Then the area requirements with surface albedo change $\Delta\alpha_T = 0.3$ in Sec. 3.1 are:

- U.S. mitigation =0.00061 x 3.8E6mi^2=2,318mi^2/Yr or 6.4mi^2/day with a radius of 27.2mi/Yr or 0.074mi/day
- England mitigation =0.00061 x 5E4mi^2=30.5mi^2/Yr or 0.084mi^2/day with a radius of 3.1mi/Yr or 0.0085mi/day
   Such goals are obtainable with drone paint spray technology (see Sec. 4.2).
   Costs associated with solar geoengineering in space can similarly be divided possibly by a country's population for a mitigation tax. This can aid in the cost of solar radiation space management.

4.1.2. L1 Space particle clusters

Another similar idea that may merit investigation is to use space particle clusters instead of space mirrors, at or near the L1 Sun-Earth region. This idea has been suggested in the past [27]. A cluster of particles such as calcium carbonate or SO$_2$ in space at L1 may have a long suspension time reducing the injection rate. Diffusion would likely be slow due to low outer space temperatures (~2.7K) and studies could be done to estimate issues.

We can estimate the requirement for the solar reduction for an annual SG value using a method in the author's initial study [6]. For example, considering the Earth's solar absorbed radiation estimate as $\frac{S_o}{4}(1-.3) = 238.175W\ m^{-2}$ a required absorption reduction estimate can be found for Eq. 6 from

$$\frac{S_o}{4}(1-.3) = 238.175W\ m^{-2} - 0.0293W\ m^{-2} = 238.1457 \qquad (25)$$

Solving yields S_o=1360.833Wm^{-2}. Then one finds 0.167Wm^{-2} (=1361 Wm^{-2} -1360.833Wm^{-2}) is the reduction required for the incoming solar radiation.

If we measure the transmission of the incoming solar radiation above and below the particle treatment, the transmissibility (TR) from sun-dimming should be [6]

$$TR = 1360.833W\ m^{-2}/1361W\ m^{-2} = 99.9877\% \qquad (26)$$

Measuring the transmissibility is likely a helpful method to assess the injection amount. Note, we can also use similar measurement methods for SAI.

4.2. Earth brightening advances

Earth brightening SG's state-of-the-art potential is a lot higher today. Drone technology has had major advances in painting buildings [28] and agriculture spray methods [29]. For example, consider the US and England's goals for Earth brightening in Sec. 3.4 in terms of area per day

- U.S. Mitigation Goal Earth Brightening is 6.4 mi²/day
- England Mitigation Goal Earth Brightening is 0.084 mi²/day

A typical two gallons per acre agriculture drone can spray about 1 mi²/day [30] which includes refills. Then if we assume paint drones can be designed with similar capabilities, this requires the

- U.S. Mitigation Goal of about 6 drones per day for a full year
- England Mitigation Goal of about 1 drone per day for 31 days per year

Although paint drones are not equivalent and rated similar to agriculture drones, technology improvements likely should be able to provide this type of capability for paint drones. Given AI technological advances, improvement in Earth-brightening drones, while difficult, is likely more feasible than one might think.

New ultra-thin bright white paint surface treatments (98.1% reflective and half as thick) have been developed to help cool the Earth [31,32]. Possibly other technologies could be developed specifically for the Earth-brightening of buildings, streets, desert areas, mountain tops, and UHI areas. Possibly an agency like SpaceX or NASA could vastly improve AI drone use for SG implementation. AI technology could allow for 24hrs a day drone SG work with automatic target brightening, refilling, and target recognition. Furthermore, studies could help assess the best strategies to try and improve coverage areas including mountain ranges since mountains cover about 24% of the Earth. Brightening mountain areas could also increase condensation and snowfall as was done on the Peruvian Andes mountain tops [33] which can increase snowfall and spring runoff to reservoirs in drought-prone areas.

Annual mitigation using Earth mirrors, as suggested by project MEER [1], has several advantages. Mirrors can be placed in areas of high irradiance, yielding a likely large albedo change, and when used in city areas on roofs, H_T>1. These reduce the Earth's annual SG area requirements per Eq. 7. Alternately, it may be of interest to use something like floating sea mirrors which would yield a high albedo change as exemplified in Table 2.

One might question the practice of painting the Earth a light color. Yet, we continue to accept negative solar geoengineering (Sec. 4.4). Unfortunately, we may already be at the point where we are faced with these types of difficult decisions.

4.3. Natural Hotspots

Natural hotspots like deserts and mountain areas are likely good SG targets to consider cooling to help reduce global warming. They may cover a significant area and are relatively free from

urbanized regions. Similar to pavements and UHIs, natural hotspot cooling would likely help reduce atmospheric water vapor feedback. Certainly, natural hotspots would be highly controversial geoengineering targets. Nevertheless, their amplification of heat and its effect on the Earth's temperature will likely be related to their area and temperature differences compared to the global ambient. Some examples of such hotspots include:

- Flaming Mountains, China
- Bangkok Areas in Thailand (with planet's hottest city)
- Death Valley California
- Deserts
- Badlands of Australia

4.4. Worldwide negative solar geoengineering

ZGWG is challenging enough. However, the problem of yearly increases in black asphalt roads, rooftops, and even dark-colored cars worldwide makes the task harder. Although many issues like black electric vehicles and gas cars do not contribute significantly to global warming, it encourages bad behavior in solar color choices. This illustrates the lack of SG awareness which is highly problematic for an increasing population [9]. As a suggestion, restricting cars to light colors would go a long way in greatly increasing such awareness.

In terms of global warming, these issues are a form of 'negative solar geoengineering'. Currently, it is estimated that roads occupy about 14% of all manmade impermeable surface areas [34] of which impermeable surfaces occupy an estimated 0.26% of the Earth [35]. Then the estimated area of the Earth occupied by roads is small, about 0.0364%. This is a bit higher compared to Eq. 14 estimated requirement for area modification. By comparison to the estimated total impermeable surfaces, it is a factor of 8.5 times higher than the Eq. 14 requirement (0.26%/0.0305%). This illustrates the difficult task of annual surface area modification requirements and the issues involved in negative solar geoengineering. Feinberg (2023) estimated that 1.1% of global warming is likely due to asphalt roads using only the average feedback factor which if brightened similar to concrete with an albedo increase of 5, could have reduced global warming by 5.5%. An MIT pavement study [36] concluded that in all U.S. urban areas, an increased temperature of 1.3°C occurs in summer months and heatwaves are 41% more intense with 50% more heatwave days due to asphalt pavements. Expansion of cities is increasing rapidly where 55% of the world's population lives and this is expected to grow to about 70% by 2050 [37].

Feinberg [6] estimated that heat from asphalt roads and roofs can produce 7.5 times more energy in heat pollution per acre than a solar power plant where studies have found they average about 0.33GWh per acre per year [38]. Furthermore, a gallon of gas equates to 33.6 kWh [39]. Then this heat pollution equates to 74,200 gallons of gasoline energy per year per acre.

This illustrates the enormous energy in an acre of asphalt heat pollution and how black roads and roofs make significant incremental warming contributions.

Negative solar geoengineering also has the potential to increase local and global water vapor feedback as it creates increases in warm air which can hold more water vapor. Hotspots can increase water vapor feedback dramatically as illustrated in the assessment in Sec. 2.3 and 3.1. As discussed previously, Zhao et al. [17] observed that UHI temperatures increase in the daytime (ΔT) by 3.3 K more in humid compared to dry climates. A primary issue in humid UHI areas is the use of black asphalt which, given the worldwide urban heatwave problems, this author feels should be banned in most cases. The warming consequences of black asphalt are not fully understood, but it is bad for the local environment and is well-documented for many problems, especially in concentrated urban areas where heatwaves cause related health issues [36,40].

5. Conclusion

In this paper, estimates are provided for annual solar geoengineering requirements. The results illustrate many challenges. However, results show higher feasibility for annual solar geoengineering modification to help mitigate global warming. This is due to reductions in goals that lead to a factor

of 50 to possibly over 150 times less area modification requirements compared to full SG mitigation. This minimizes circulation concerns and many other controversial issues.

Many recommendations are made in this paper. These include the use of and calculations for ASG, the use of drone technology for SG modification, the suggested method of using space clusters that may be highly useful, and UHI use of the H_T value in Table 2. Results in general point to challenging but feasible solutions. Suggestions are provided for solar radiation management using area allocations by country for Earth brightening to improve feasibility (Sec 4.1).

It is pointed out that for SG to be effective; it is helpful to address many global warming issues including the ongoing negative solar geoengineering especially the practice of black asphalt use. We should not condone the bad behavior of dark color choices whether it be in automotive or the construction practices of roads, houses, and buildings. It also impedes the efforts of positive solar geoengineering. Such issues should be addressed in worldwide climate meetings. There is little time left to meet the IPCC suggested 1.5^{o}C goal as shown in Figure 1. The longer we delay in implementing a SG program, the more unacceptable our status quo will be due to increases in global warming reducing our options. This paper provides improved solar geoengineering feasibility with annual mitigation goals that can greatly supplement carbon removal and reduction efforts.

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List of abbreviations and nomenclature

Solar geoengineering	**SG**	**Reverse forcing change in Watts/m²**	**DP$_{Rev}$**
Zero global warming growth	ZGWG	Reverse forcing albedo change from a target area T in Watts/m²	ΔP_T
top of the atmosphere	TOA	Reverse forcing albedo change from a target area T in Watts/m²	ΔP_T
Solar radiation management	SRM	Re-radiation factor (62%)	f
Greenhouse gas	GHG	Secondary feedback amplification, taken as 2.15	A$_F$
Long Wavelength	LW	Solar irradiance averaging 47%	Xc
		Space irradiance: Space=4, else=1	X$_S$
Transmissibility	TR	Annual reversal in Watts/m²	DP$_{ASG}$
Target area	A_T	Target albedo, SG target's albedo modification	α_T, α'_T
Earth area	A_E	$\alpha'_T - \alpha_T$	$\Delta \alpha_T$
Temperature reversal	T$_R$	microclimate amplification factor	H$_T$
Average solar radiation 340Wm^{-2}	$S_o/4$	Radiation change, at the TOA	ΔR_{TOA}
Annual solar geoengineering	ASG	SO₂ Injection rate, Particle *Overlap*	I_{SO_2}, O
Clausius-Clapeyron relation	CC	Stratosphere Aerosol Injections	SAI

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