On Geoengineering and Implementing an Albedo Solution with Urban Heat Islands Global Warming and Cooling Estimates

Key Words: Albedo Solution, Global Warming Solution, Global Warming Re-radiation Model, Albedo Modeling, Hotspot Mitigation, UHI Global Warming Estimates

Abstract

Surface albedo geoengineering is vital in Global Warming (GW) as results can reverse trends and reduce the probability of a tipping point. Although an albedo solution is reasonably practical, work in this area appears stagnant and even implementing Urban Heat Island (UHI) cool roofs on a global level has not yet been widely adopted. This paper provides basic modeling and motivation by illustrating the potential impact of reverse forcing. We provide insights into "Earthly areas" that might be utilized to increase the opportunity for reducing warming. Modeling shows that by solar geoengineering select hotspots with aspects like large heat capacities, such as UHIs, and possibly mountain regions, the effective area could be roughly 11 times smaller than nominal non-hotspot regions in influencing global warming. We find that between 0.2% and 1% of the Earth would require modification to resolve most of global warming. This represents about a 1.5% global albedo change. Results are highly dependent on modeling aspects like heat capacity, irradiance, and albedo changes of the area selected. The versatile model was also used to provide UHIs global warming and cooling estimates illustrating their importance.

1.0 Introduction

When we consider climate change solutions, in the race against time, it is advantageous to look at the practical aspects of implementing an albedo solution. Given the slow progress reported with greenhouse gas reduction, and the continual increase in the Earth's average yearly temperature, it is important to revisit the alternate albedo solution. Unlike geoengineering solutions, Greenhouse Gas (GHG) reduction is highly difficult to result in reversing climate change, especially with reports on large desertification and deforestation occurring [1].

Implementation is a key focus on geoengineering an albedo surface solution. There have been a number of geoengineering solutions proposed [2-4] that are either atmospheric of surface-based. In this study, we focus on targeting surface regions and present practical engineering formulas and values.

The target areas that have the highest impacts are likely ones with:

- high solar irradiance
- large heat capacities
- low albedo
- ability to amplify nature's albedo

To clarify the last target area, we infer that cooling down certain areas may cause natural compounding albedo changes to occur, such as increases in snowfall and ice formations. We can term hotspot regions as Solar Amplified Areas (SAA) relative to Nominal Land Albedo (NLA) areas (approximately 25% albedo, see Sec. 5.2).

Although the task is highly challenging, it is easier to do geoengineering of surface reflectivity compared with building cities. Often, UHIs and impermeable surfaces are haphazardly constructed in terms of solar absorption considerations. While numerous authors [5-17] have found probable significance that UHIs with their coverate contribute to GW (see supportive results in Section 5.2), the only motivated work in this area is a result of health concerns. Therefore, albedo cool roof solutions and other UHI mitigations have not received adequate attention compared to GHG efforts. This oversight is unfortunate and makes the business of an albedo solar solution and it's financing less desirable. It is important that not just scientists understand the importance of the albedo solution. There is a lack of knowledge when it comes to the word albedo and its potential contribution. We cannot expect architects, road engineers, car designers, city planners, politicians and so forth, to incorporate environmental considerations and solutions, if these concepts are not widely understood. Therefore, a key strategy employed in this study is to demonstrate the advantages, feasibility and importance of cooling solar amplified areas made by man (and possibly nature). We provide simple geoengineering equations that can aid designers. We need to recognize that the whole is equal to the sum of the parts in global warming; humankind's resolve to greenhouse gas and albedo improvements, both need to be addressed for a realistic solution.

2. Outline for Geoengineering and Implementing an Albedo Solution

We present a brief outline to overview and clarify our modeling objectives and motivate interests.

Section 3: In this section we first identify a key Planck-albedo parameter

$$\gamma_{\%\Delta\alpha\Delta T} \approx 1W/m^2/\Delta\%\alpha \tag{1}$$

The parameter multiplied by %Δα (albedo percent albedo change) converts to ΔP_T, the reverse forcing from the target area, where the total reverse forcing $\Delta P_{\text{Rev}\_S}(\gamma_{\%\Delta\alpha\Delta T}, \%\Delta\alpha, \Delta P_T)$ is described

Section 4: In this section an Albedo model is developed to use the ΔP_T goal where

$$\Delta P_T = \frac{A_T}{A_E}\frac{S_o}{4}0.33\text{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right] \tag{2}$$

Here S_o=1360W/m^2, the factor, $H_{T\text{-}N}$ is the hotspot irradiance sensible heat storage potential. This is a function of the heat capacity, mass, temperature storage, and solar irradiance by comparison to a nominal area (see Appendix B and C). Here α_T is the initial target albedo, α_T' is the modified target albedo, and 0.33 is the estimate fraction of time the target area is not covered by clouds. Then the final goal relative to fraction of Earth's area, A_E, needing modification is

- A_T/A_E, where A_T is the target area

Section 5: In this section, we provide examples on implementation of these models for different target areas including UHIs yielding their warming and cooling estimates.

Therefore, our task is to essentially find reasonable values for ΔP_{Rev_S}, f_2, $H_{T\text{-}N}$, $\gamma_{\%\Delta\alpha\Delta T}$, A_F ΔP_T, %Δα, in order to estimate a geoengineering GW solution by modifying the select fractional target area A_T/A_E of the Earth.

3.0 Geoengineering a Reverse Forcing Solution

In this section, we present and describe a simple solar geoengineering formula needed for a reverse forcing estimates due to a percent global albedo change from a target area given by

$$\Delta P_{\text{Rev}\_S} = -\gamma_{\%\Delta\alpha\Delta T}\ \%\Delta\alpha\ (1+f_Y)\ A_F = \Delta P_T\,(1+f_Y)\ A_F \tag{3}$$

Here we define

$\Delta P_{\text{Rev S}}$ is the reverse power per unit area change
%Δα is the percent global albedo change due to modification of a target area
$\gamma_{\%\Delta\alpha\Delta T}$ = Planck-albedo parameter, 1Watt/m^2/%ΔAlbedo
$1+f_Y$= the albedo-GHG re-radiation parameter with f_y about 0.63 for year Y=2019 (see Appendix A)
A_F is an estimate of the anticipated GW feedback amplification reduction factor (Appendix A.4)
$\Delta P_T = \gamma_{\%\Delta\alpha\Delta T}\ \%\Delta\alpha$ is the reverse forcing change from the target area T

The Planck-albedo parameter is so named as it relates to blackbody (P_α) absorption. Its value can be estimated when considering an albedo change from two different time periods, having a global albedo change from α_1 to α_2 or we can simplify it as follows [5]

$$\gamma_{\%\Delta\alpha} = \frac{(\Delta E_o)_\alpha}{\frac{\alpha_1-\alpha_2}{\alpha_1}100} = \frac{E_o(\alpha_1-\alpha_2)}{\frac{\alpha_1-\alpha_2}{\alpha_1}100} = E_o\alpha_1/100 \approx 1W/m^2/\%\Delta albedo \tag{4}$$

Here the incoming solar radiation at the top of the atmosphere is E_o=1360W/m^2/4=340W/m^2 and when α_1 is 0.294118, the value is 1.000W/m^2/Δ%albedo. We note the value 29.4118% (100W/m^2/340W/m^2) and E_o are given in AR5 [18] in their energy budget diagram.

As an example, in Appendix A, an analysis of the warming was estimated from 1950 to 2019, and results are presented in Table A-1. The change in the long wavelength radiation ΔP_α is estimated as 0.15352W/m^2 due to an albedo percent change of 0.15% (from 1950 to 2019) so that

$$\gamma_{\%\Delta\alpha} = \Delta P_\alpha / \%\Delta albedo = 1.023 W/m^2 / \Delta\% albedo \tag{5}$$

This parameter can provide a relatively simple and reasonable estimate of the reverse forcing that occurs due to a global percent albedo change from a target area change of the Earth. Then the corresponding estimated power reduction ΔP_T in long wavelength radiation due to an albedo target area reverse forcing is

$$\Delta P_T = -\gamma_{\%\Delta\alpha\Delta T} \quad \%\Delta\alpha \tag{6}$$

However, there is also a reduction in the re-radiation from GHG. This factor is $1+f_Y$. Here f_Y is the fraction of re-radiation that occurs from GHG where Y represents the estimated value for that year. This value can reasonably be assessed and its value found in Appendix A is $f_Y=f_{2019}\approx0.6276$ for 2019.

Lastly we have included an allowance for anticipated feedback amplification reduction denoted as A_F (see example in the next Section),

The effect of the target change results can be quantified as

$$Effect = \frac{\Delta P_{\mathrm{Rev\_}S}}{\Delta P_{Total\_Feedback\_amp}} \tag{7}$$

Here $\Delta P_{\mathrm{Total+Feedback\_amp}}$ is the total forcing with feedback amplification that has occurred.

3.1 Example of a Reverse Forcing Goal

In this section, we consider a goal of 1.5% geoengineering albedo change, with f_y=0.6276 and a decrease in water-vapor feedback anticipated, we might use a value of $A_F\approx2.0$ [20]. According to Appendix A, Eq. A-12 this is estimated as 2.022. Then from Eq. 3

$$\Delta P_{\mathrm{Rev\_}S} = -1\mathrm{W/m^2/\%}\text{ x } 1.5\%\text{ x }(1+f_2)\text{ x }2.022 = -1.5\mathrm{W/m^2}x(1+0.6276)\text{ x }2.022 = -4.94\text{ Watt/m}^2 \tag{8}$$

This estimate can be compared with the re-radiation model results in Table A-1 showing a forcing with feedback amplification yield 5.12 W/m^2 since 1950. This would indicate a significant resolution to the current warming trend since 1950, where ΔT_s=0.95°K that occurred by the end of 2019 (see Eq. A-13). Then the relative effect from Eq. 7 is

$$Effect = \frac{4.94W/m^2}{5.12W/m^2} = 96.4\% \tag{9}$$

for this particular geoengineering solution (Table A-1). The temperature reduction can be estimated from Eq. 9 as

$$\Delta T_{\mathrm{Rev\_}S} = -0.964\, x\, \Delta T_S = -0.926°K \tag{10}$$

As one might suspect, a 1.5% albedo change requires a lot of modified area. Feasibility is discussed in the rest of this paper. We note a number of solar geoengineering solutions have been proposed [2-4].

4.0 Converting the Reverse Forcing Goal to a Target Area

We can write the short wavelength solar absorption as

$$P = \frac{Q}{A} = \frac{S_o}{4}\sum_i \frac{A_i'}{A_E}(1-\alpha_i) + \frac{S_o}{4}\mathrm{H}_{T-N}\frac{A_T'}{A_E}(1-\alpha_T) + \frac{S_o}{4}\frac{A_C}{A_E}(1-\alpha_C) \tag{11}$$

Here A_i' is the i^{th} effective area having an albedo α_i, S_o=1360 W/m^2 and A_E is the surface area of the Earth and A_C is effective cloud coverage. We consider a change to a hotspot target effective area A_T with albedo α_T. In addition, because we select a particularly problematic solar absorbing target compared to a nominal area (N), it has hotspot irradiance sensible heat storage potential H_{T-N}, a function of the heat capacity, mass, temperature storage, and solar irradiance. Essentially this has the effect of amplifying the target area. H_{T-N} is described and enumerated in Appendix B and C. As an example, many UHIs, due to their large heat capacity act like large heat sink. This is just one of the many reasons that UHI are often hotter at night than during the day resulting from solar energy stored up during the daytime (see Appendix C).

The overall equation prior to changing the albedo is subject to the area constraint

$$A_E = A_{EU} + A_{EC} = \left(\sum_i A_i' + A_T'\right) + A_C = 0.33\left(\sum_i A_i + A_T\right) + A_C \qquad (12)$$

and

$$A_{EU} = 0.33\left(\sum_i A_i + A_T\right),\ A_{EC} = A_C \qquad (13)$$

Here we have denoted the portion of the Earth covered from direct sunlight by clouds as A_{EC}=A_C= 67%A_E [21]. Then the uncovered portion of the Earth is A_{EU}=33%A_E. This is likely conservative as clouds do let some sunlight through. However, that means that roughly on average only 33% of the time areas on the Earth receive direct sun during daylight hours.

We now alter the target albedo α_T to $\alpha_T'$of a SAA so that

$$P' = \frac{Q'}{A} = \frac{S_o}{4}\sum_i \frac{0.33A_i}{A_E}(1-\alpha_i) + \frac{S_o}{4}\frac{0.33A_T}{A_E}\mathrm{H}_{T-N}(1-\alpha_T') + \frac{S_o}{4}\frac{A_C}{A_E}(1-\alpha_C) \qquad (14)$$

Note the 0.33 cloud factor is now added. The change in heat absorbed is just a function of the target change where from Eq. 14

$$\left(dP_T'\right)_\alpha = \frac{S_o}{4}\frac{0.33A_T\mathrm{H}_{T-N}}{A_E}(-d\alpha_T) \qquad (15)$$

where the subscript α indicates all other Earth albedo components are held constant. Using the example goal of the target area ΔP_T=1.5W/m^2 in Eq. 3 and 8, Equation 15 is just

$$\Delta P_T = P - P' = -\frac{S_o}{4}\frac{0.33A_T\mathrm{H}_{T-N}}{A_E}\left[(\alpha_T' - \alpha_T)\right] = -1.5W/m^2 \qquad (16)$$

However, the same results can be obtained by changing the albedo of a nominal area; so in this case H_{T-N} =1 (see Appendix B). The equivalent change for the NLA is

$$\Delta P_{T-N} = -\frac{S_o}{4}\frac{0.33A_N}{A_E}\left\{(\alpha_N' - \alpha_N)\right\} = -1.5W/m^2 \qquad (17)$$

5.0 Area Estimates

Comparing the target SAA to the NLA, we have

$$\frac{\Delta P_T}{\Delta P_{T-N}} \approx \frac{A_T\mathrm{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right]}{A_N\left[(\alpha_N' - \alpha_N)\right]} = 1 \qquad (18)$$

As an example, assume $\mathrm{H}_{T-N} \approx 9$ (see Appendix B), α_N=0.25 (see Sec. 5.2), α_T=0.12 [22], and for α_N'=α_T'=0.9, we obtain

$$\frac{A_N}{A_T} = \frac{\mathrm{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right]}{\left[(\alpha_N' - \alpha_N)\right]} = \frac{9\left[(0.9-.12)\right]}{\left[(0.9-0.25)\right]} = 10.8 \qquad (19)$$

This indicates that the nominal area would have to be about 11 times larger than the target area for equivalent results.

In assessing our goal, we have from Eq. 16

$$\Delta P_T == \frac{S_o}{4}\frac{0.33 A_T \mathrm{H}_{T-N}}{A_E}\left[(\alpha_T' - \alpha_T)\right] = -1.5W/m^2 \tag{20}$$

For $H_{T\text{-}N}=1$, $\alpha_T'=0.9$, and $\alpha_T=0.12$ then

$$\Delta P_T = -340\frac{A_T}{A_E}\left[0.78\right]x0.33 = -1.5W/m^2 \tag{21}$$

and

$$\frac{A_T}{A_E} = 1.71\% \, of \;Earth \tag{22}$$

For $H_{T\text{-}N}=10$, $\alpha_T'=0.9$, and $\alpha_T=0.12$ then

$$\frac{A_T}{A_E} = 0.171\% \, of \;Earth \tag{23}$$

Recall that the goal for a 1.5W/m^2 corresponded to a 1.5% albedo change (see Sec. 3.1). We can check this results for $A_T/A=1.71\%$ when $H_{T\text{-}N}=1$, using a related expression to Eq. 20. This is given by

$$\Delta\alpha\% = 0.33\frac{A_T}{A_E}\frac{\left[(\alpha_T' - \alpha_T)\right]}{\alpha} = 0.33(1.71\%)\frac{\left[(0.9-0.12)\right]}{0.294118} = 1.5\% \tag{24}$$

as expected where the global albedo is taken as α=0.294118 which is indicated in AR5's energy budget figure [18].

5.1 Cooling Estimates Compared to Urban Heat Island Areas

Since UHI are likely good target areas, we can compare these results to the total global urbanized area. Such estimates of urbanization unfortunately vary widely partly due to the confusing definition of what is urban. However, two studies are of interest. A Schneider study [23] on 2000 data estimated that 0.148% of the Earth was covered by UHI and the associated surrounding urban areas. Due to city growth, this extrapolates to 0.188% [5] in 2019. Similarly, another study from GRUMP [24] found global urbanization with a larger value in 2000 of 0.783% extrapolates to 0.953% [5] of the Earth's area in 2019. These extrapolations are based on an average yearly urbanization growth rates between 1.3% and 1.6% [5]. It is interesting that the IPCC (Satterthwaite et. al. [25]) AR5 report references this Schneider et al. [23] results in urban coverage. Lastly, note that UHIs have their own hotspot amplification factors assessed in Appendix C [5] with two estimates provided of 3.1 and 8.4. These are listed in Table 2 for $H_{T\text{-}N}$. Therefore, compared to these 2019 estimates for urban heat island and surrounding areas, the required area changes for different $H_{T\text{-}N}$ values (discussed in Appendix C) are summarized in Table 2.

Table 2 Cooling required areas relative to UHI areas

$H_{T\text{-}N}$	A_T/A (% of Earth) $\alpha_T' = 0.9\ (\alpha_T' = 0.5)$	Schneider Factor (A_T/A) /0.188% $\alpha_T' = 0.9\ (\alpha_T' = 0.5)$	GRUMP Factor (A_T/A)/ 0.953 $\alpha_T' = 0.9\ (\alpha_T' = 0.5)$
1	1.714 (3.52)	9.12 (18.7)	1.80 (3.69)
3.1	0.553 (1.13)	2.94 (6.03)	0.58 (1.19)
8.4	0.204 (0.419)	1.08 (2.23)	0.21 (0.44)
9	0.190 (0.39)	1.01 (2.08)	0.20 (0.41)

*A_T/A represent 96% of the solution (see Sec. 5.1)

Table 2 results are highly dependent on target albedo change and $H_{T\text{-}N}$ which is overviewed in Appendix B and C. Results in Column 2 suggest that 0.2% to 1.1% of the Earth would require modification to resolve 96% of global warming depending on the target values for alpha and $H_{T\text{-}N}$. This is roughly a factor of 6 to 1 times the Schneider's

UHI size estimate. It is important to develop better estimates for both H_{T-N} and urbanization sizes than estimated here. Other important factors may exist such as hydro-hotspots.

- UHI surfaces create hydro-hotspots [26] which may contribute to higher values of H_{T-N}. A hydro-hotspot is a hot surface that creates moisture in the presence of precipitation. Such surfaces create excess moisture in the atmosphere promoting a local greenhouse effect. Zhao et al. [28] observed that UHI temperatures increase in daytime ΔT by 3.0°C in humid climates but decreasing ΔT by 1.5°C in dry climates. Therefore, UHI in humid climates could be prioritized.

We see that H_{T-N} is a highly complex factor for UHIs. We note that the 0.12 albedo value applies to UHI [22], may be a good upper value when looking for hotspot targets. The albedo and two H_{T-N} values cited here have been studied by the author [5]. These assessments for H_{T_N} applicable to UHIs are also provided to aid the reader in Appendix C. Results in Table 2 illustrate feasibility and the probable geoengineering challenges.

A worldwide effort would provide motivation from a number of key benefits; resolving much of global warming, providing assurance against a tipping point, and local health benefits by cooling off cities. UHIs pose a number of challenges in trying to cool off their areas. The Schneider results in Row 2 and 3 indicate that the potential area needed may be 2.2-6 times their current size while the GRUMP results are a factor of about 5 smaller. Therefore, if the Schneider estimate was proven to be the most accurate, supplementary target areas would be required to reach the 96% objective. Note in these estimates we used the target albedo goal of $\alpha_T'=0.5$, as it is unrealistic to realize an UHI albedo goal of 0.9 due to their complex nature.

Generally, UHIs meet a lot of the requirements for good targets having high heat capacity with large hotspot areas and massive sensible heat storage. One helpful aspect to note is that cool roof and building implementation also allows for more stable albedo maintenance over time compared to other areas like mountain regions. However, the complex nature of cities also makes it highly challenging.

5.2 Warming Estimates Due to Urban Heat Islands

We can use this same model to estimate the global warming contributions due to UHIs. In this case, instead of $\alpha_T'=0.9$ or 0.5, we evaluate by restoring the UHIs to their original estimated albedo value of $\alpha_T'=0.25$ (pre-UHI era). This albedo value is based on a study by He et al. [29] which found that land albedo varies from 0.1 to 0.4 with an average of 0.25. Then using the H_{T-N} values in Section 5.1 (also see Appendix C), we estimate the percent of the Earth needed to obtain a 96% solution and compare results to the known UHI coverage areas.

For $H_{T-N}=3.1$, $\alpha_T'=0.25$, and $\alpha_T=0.12$ then from Eq. 20

$$\Delta P_T = -340W/m^2 \frac{A_T}{A_E} x3.1x\left[(0.25-0.12)\right]x0.33 = -1.5W/m^2 \tag{25}$$

and

$$\frac{A_T}{A_E} = 3.31\% \tag{26}$$

of the Earth. Similarly for $H_{T-N}=8.4$, $\alpha_T'=0.25$, and $\alpha_T=0.12$ then

$$\frac{A_T}{A_E} = 1.22\ \%\, of\ Earth \tag{27}$$

Table 3 summarized the warming trend results. Results in Column 5 and 6 are reasonably comparable to Feinberg 2020 [5] (finding between 5% and 44% of GW could be due to UHIs and their coverage). This model shows that between 6% and 81% of global warming could be due to UHIs and their coverage. Note that this is fairly independent of the GHG parameter f_2 compared with results if f_1 were used we would see very little difference. This indicates the relative possible importance of UHIs. We note these large variations are mainly due to the difficulty in estimating H_{T-N} and a knowledge of UHI area coverages (i.e., Schneider vs. GRUMP study). However, the model provides a reasonable way to make estimates which can be further refined once better values are known.

Table 3 UHI Warming estimates

H_{T-N}	A_T/A (% of Earth)	Schneider Factor (A_T/A) /0.188% (Conservative)	GRUMP Factor (A_T/A)/ 0.953	GW% 1/Schneider Factor / 0.964*	GW% 1/GRUMP Factor / 0.964*
3.1	3.31	17.61	3.47	6	30
8.4	1.22	6.49	1.28	16	81

*A_T/A GW represent 96.4% of the solution (see Sec. 3.1), and are adjusted to 100% in Column 5 & 6

Furthermore, we note the cooling potential in Table 2 is about a factor of 3 to 6 times compared to the warming shown in Table 3. For example in Table 2 and 3, the area warming to cooling ratio 17.6/2.94 yields an effective potential factor of 6 for α'_T=0.9, and a factor of 2.9 (17.6/6.03) for α'_T=0.5 . As stated above, obtaining the full cooling potential (α'_T=0.9) for UHIs and their impermeable surfaces is likely unobtainable due to the complex nature of cities therefore the value α'_T=0.5 is a better guide.

5.3 Some Hotspot Target Areas

There are many hotspots that provide likely target areas. Deserts would be highly difficult to maintain any albedo change. However, mountains, UHI cool roofs in cities, and impermeable surface such as roads might be logical target areas. Some interesting known hotspots include

- Flaming Mountains, China
- Bangkok, Thailand (planet's hottest city)
- Death Valley California
- Titat Zvi, Israel
- Badlands of Australia
- Urban Heat Islands & all Impermeable surfaces, humid cities
- Oceans [2]

We note that mountain areas (while certainly environmentally unfriendly) in cool regions should not be excluded; natural compounding albedo effects may occur from increases in snow-fall and ice formations. Albedo changes could be performed in summer months and then in winter months compounding effects assessed.

As a summary, Equations 3 and 20 can be combined to provide a resulting solar geoengineering equation for reverse forcing obtained in this study where

$$\Delta P_{\mathrm{Rev\_}S} = -\gamma_{\%\Delta\alpha\Delta T} \ \%\Delta\alpha \ (1+f) \ A_R = -\left\{ \frac{S_o}{4} 0.33\mathrm{H}_{T-N} \frac{A_T}{A_E} \left[(\alpha'_T - \alpha_T) \right] \right\} (1+f) \ A_R \tag{28}$$

with suggested values H_{T-N}=6, α_T'=0.5-0.9, α_T=0.12, ΔP_{Rev_S}=4.9W/m^2, and f=0.63.

6. Conclusions

The albedo solution is vital in mitigating global warming. Today, technology has numerous advances that include improvements in materials, drone capability, and artificial intelligence, which could be helpful in geoengineering surfaces. Humankind has addressed many technological challenges successfully. It is not illogical to consider a global albedo solution while time permits before a potential tipping point.

In this paper we have provided a number of important estimates that include:

- A reverse forcing albedo reduction goal of -1.5W/m^2 that can result in -4.9W/m^2 of reverse forcing with feedback representing a 96% global warming solution.
- The target area required is about 0.2% to 1% (Table 2) of the Earth, if proper hotspots are cooled with highly reflective surfaces
- Changing the albedo has a 1.63 benefit factor due to less GHG re-radiation

- Selecting proper hotspots can reduce the required target area by an estimated factor of 11 compared to non-hotspot areas. Likely target areas may include problematic hotspots such as UHIs and impermeable surfaces. While certainly environmentally unfriendly, we may have to consider mountains regions and ocean areas [2]
- The global cooling potential of UHIs is about a factor of three to six times higher than their warming contribution if highly reflective surfaces can be realized
- UHIs and their coverage likely contribute significantly to global warming. This is in agreement with other studies [5-17]. This suggests a reasonable risk exists that major greenhouse gas reduction goals [30], may fall short of global warming mitigation expectations
- UHI estimates are highly dependent on $H_{T\text{-}N}$ and urbanization estimates
- UHI in humid climates should be prioritized.

Finally, we suggest:

- Tasking agencies worldwide, such as NASA, to work full time on solar geoengineering, which at this late time should be one of our highest priorities
- Worldwide albedo guidelines for both UHIs and impermeable surfaces similar to on-going CO_2 efforts
- Worldwide guidelines for future albedo design considerations of cities
- Changing impermeable surfaces of buildings, roads, sidewalks, driveways, parking lots, industrial areas such as airports, distribution centers, and roof tops to reflective surfaces. We note that their cooling potential can be much larger compared to their warming contribution, and a full review should be performed
- Manufacturing cars to be more reflective including reducing their internal solar heating. Although, worldwide cool vehicles (e.g., silver or white) may not contribute significantly to global warming mitigation, recommending them could. It would help raise badly needed albedo awareness similar to electric automobiles that help improve CO_2 emissions. It could increase interest in similar projects thereby promoting other related changes by city planners and architects for cool roofs, reflective building designs, and road engineers for pavement color changes and so forth.

Appendix A: Re-radiation Global Warming Model Introduction

When initial solar absorption occurs, part of the long wavelength radiation given off is re-radiated back to Earth. In the absence of feedback we denote this fraction as f_1. This presents a simplistic but effective model

$$P_{\mathrm{Pre}-Industrial} = P_\alpha(1+f_1) = \sigma T_S, \text{ where } P_\alpha = \frac{S_o}{4}(1-\alpha) \quad \text{(A-1)}$$

where T_s is the surface temperature. As one might suspect, f_1 turns out to be exactly β^4 in the absence of feedback, so that f_1 is a redefined variable taken from the effective emissivity constant of the planetary system. We identify this as 0.618034 here. One of the main goals in this appendix is to find the re-radiation f_2 for 2019. That is, in 2019, due to increases in GHGs, we anticipate an increase in the re-radiation fraction so that

$$f_2 = f_{2019} = f_1 + \Delta f = \beta_1^4 + \Delta f \approx \beta_2^4 + \Delta f \quad \text{(A-2)}$$

In this way $f_{2019} = f_2$ is a function of f_1. The RHS of Eq. A-2 indicates that $\beta_1 \approx \beta_2$ (see varication results in Eq. A-16 and A-17). Estimating Δf will not cause much error since it is relatively small compared to $(1+f_1)$ which is fairly accurate in geoengineering.

A.1 Basic Re-radiation Model and Estimating f_1

In geoengineering, we are working with absorption and re-radiation, we define

$$P_{Total} = \sigma T_S^4 = \sigma\left(\frac{T_e}{\beta}\right)^4 \text{ and } P_\alpha = \sigma T_\alpha^4 = \sigma\left(\beta T_S\right)^4 \quad \text{(A-3)}$$

The definitions of $T_\alpha = T_e$, T_S and β are the emission temperature, surface temperature and typically $\beta \approx 0.887$, respectively. Consider a time when there is ***no feedback issues*** causing warming trends. Then by conservation of energy, the equivalent power re-radiated from GHGs in this model is dependent on P_α with

$$P_{GHG} = P_{Total} - P_\alpha = \sigma T_S^4 - \sigma T_\alpha^4 \quad \text{(A-4)}$$

To be consistent with $T_\alpha=T_e$, since typically $T_\alpha\approx255^oK$ and $T_s\approx288^oK$, then in keeping with a common definition of the global beta (the proportionality between surface temperature and emission temperature) for the moment $\beta=T_\alpha/T_s=T_e/T_S$.

This allows us to write the dependence

$$P_{GHG} = \sigma T_S^4 - \sigma T_\alpha^4 = \frac{\sigma T_\alpha^4}{\beta^4} - \sigma T_\alpha^4 = \sigma T_\alpha^4\left(\frac{1}{\beta^4}-1\right) = \sigma T_\alpha^4\left(\frac{1}{f}-1\right) \quad \text{(A-5)}$$

Note that when $\beta^4=1$, there are no GHG contributions. We note that f, the re-radiation parameter equals β^4 in the absence of forcing.

We can also define the blackbody re-radiated by GHGs given by some fraction f_1 such that

$$P_{GHG} = f_1 P_\alpha = f_1 \sigma T_\alpha^4 \quad \text{(A-6)}$$

Consider $f=f_1$, in this case according to Equations A-5 and A-6, it requires

$$P_{GHG} = \sigma T_\alpha^4\left(\frac{1}{f_1}-1\right) = f_1 \sigma T_\alpha^4 \quad \text{(A-7)}$$

This dependence leads us to the solution of the quadratic expression

$$f_1^2 + f_1 - 1 = 0 \text{ yielding } f_1 = 0.618034 = \beta^4,\ \beta = (0.618034)^{1/4} = 0.886652 \quad \text{(A-8)}$$

This is very close to the common value estimated for β and this has been obtained through energy balance in the planetary system providing a self-determining assessment. In geoengineering we can view the re-radiation as part of the albedo effect. In Section A.4, we apply the model to demonstrate its capability. Consistency with the Planck parameter is shown in A.5. We note that the assumption $f=f_1$ only works if planetary energy is in balance without feedbacks. In Appendix A.6, we double check this model in another way by balancing energy in and out of our global system.

A.2 Re-radiation Model Applied to 1950 and 2019

Global warming can be exemplified by looking at two different time periods. The model applied for 1950 needs to be consistent with Eq. A-3 and A-5. Here we will

- assume no forcing issues causing a warming trend in 1950 so that from our model

$$P_{Total\_1950} = P_\alpha + P_{GHG} = P_\alpha + f_1 P_\alpha = P_\alpha(1+f_1) = 1.618 P_\alpha \quad \text{(A-9)}$$

where $P_\alpha = S_o\{0.25x(1-Albedo)\}$ and S_o=1360W/m^2. Although 1950 is not truly pre-industrial, we proceed under the assumption of no changes in GHG and feedback issues at this time to establish our baseline, since geoengineering a solution to earlier dates would pose even higher challenges. Under this assumption, 1+f=1.618 becomes the 1950 albedo-GHG reference value.

A.3 Re-radiation Model Applied to 2019

In 2019 due to global warming trends, to apply the model we assume that feedback can be applied as a separate term and we make use of some IPCC estimates for GHG forcing as a way to calibrate our model. In the traditional sense of forcing, we assume some small change to the albedo and most of the forcing due to IPCC estimates for GHGs where

$$P_{Total\,2019} = P_{\alpha'} + P_{GHG'} = P_{\alpha'}(1+f_2) \quad \text{(A-10)}$$

Then we introduce feedback through an amplification factor A_F as follows

$$P_{Total\,2019\,\&\,Feedback} = P_{1950} + (\Delta P)A_F = P_{1950} + (P_{2019} - P_{1950})A_F = \sigma T_S^4 \quad \text{(A-11)}$$

Here, we assume a small change in the albedo denoted as P_α' and f_2 is adjusted to the IPCC GHG forcing value estimated between 1950 and 2019 of 2.38W/m^2 [39]. Then the feedback amplification factor, is calibrated so that $T_S=T_{2019}$ (see Table A-1) yielding A_F =2.022 [also see ref. 20]. The main difference in our model is that the forcing is about 6% higher than the IPCC for this period. Here, we take into account a small albedo decline of 0.15% that the author has estimated in another study due to likely issues from UHIs [5] and their coverage. We note that unlike f_1, f_2 is not a strict measure of the emissivity due the increase in GHGs.

A.4 Results Applied to 1950 and 2019 and an Estimate for f_2

Since the re-radiation parameter is fixed for f_l=0.618034, to obtain the average surface temperature T_{1950}=13.89^{o}C (287.038^{o}K), the only adjustable parameter left in our basic model is the global albedo. This requires an albedo value of 0.3008 (see Table 1) to obtain T_{1950}.=287.0385^{o}K. This albedo number is reasonable and similar to values cited in the literature [31].

In 2019, the average temperature of the Earth is T_{2019}=14.84^{o}C (287.99^{o}K) given in Eq. A-13. We have assumed a small change in the Earth's albedo due to UHIs [5]. The f_2 parameter is adjusted to 0.6276 to obtain the GHG forcing shown in Column 7 of 2.38W/m^2 [39]. Therefore the next to last row in Table A-1 is a summary without feedback, and the last row incorporated the A_F=2.022 feedback amplification factor.

Table A-1 Model results

Year	T_S(^{o}K)	T_α(^{o}K)	f_1, f_2	α, α'	P_α, $P_{\alpha'}$ (W/m^2)	$P_{GHG'+feedback}$ P_{GHG} (W/m^2)	P_{Total} (W/m^2)
2019	287.5107	254.55	0.6276	30.03488	238.056	149.404	387.460
1950	287.0410	254.51	0.6180	30.08	237.9028	147.024	384.9348
Δ2019-1950	**0.471**	**0.41**	**0.96%**	**(0.15%)**	**0.15352**	**2.38**	**2.5337**
Feedback A_F=2.022	**0.95**	**0.41**	**0.96%**	**0.15**	**0.3104**	**4.812**	**5.12**

From Table A-1 we now have identified the reverse forcing at the surface needed since

$$P_{Total\,2019\_Feedback\ Amp} = P_{1950} + \left(P_{2019} - P_{1950}\right) A_F = 384.927W/m^2 + (2.5337W/m^2)2.022 = 390.05W/m^2 \quad \text{(A=12)}$$

and

$$\Delta T_S = T_{2019} - T_{1950} = \left(390.05/\sigma\right)^{1/4} - 287.0385°K = 287.9899°K - 287.0385°K = 0.95°K \quad \text{(A-13)}$$

as modeled. We also note an estimate has now been obtained in Table A-1 for f_2=0.6276 and A_F=2.022.

A.5 Model Consistency with the Planck Parameter

As a measure of model consistency, the forcing change with feedback, and resulting temperatures T_{1950} and T_{2019}, should be in agreement with expected results using the Planck feedback parameter. From the definition of the Planck parameter λ_o and results in Table A-1, we estimate [19]

$$\lambda_o = -4\frac{\Delta R_{OLW}}{T_S} = -4\left(\frac{237.9028W/m^2}{287.041°K}\right)_{1950} = -3.31524W/m^2/°K \quad \text{(A-14)}$$

and

$$\lambda_o = -4\frac{\Delta R_{OLW}}{T_S} = -4\left(\frac{238.056W/m^2}{287.99°K}\right)_{2019} = -3.306W/m^2/°K \quad \text{(A-15)}$$

Here ΔR_{OLW} is the outgoing long wave radiation change. We note these are very close in value showing miner error and consistency with Planck parameter value, often taken as 3.3W/m^2/^{o}K.

Also note the Betas are very consistent with Eq. A-8 for the two different time periods since from Table A-1

$$\beta_{1950} = \frac{T_\alpha}{T_S} = \frac{T_e}{T_S} = \frac{254.51}{287.041} = 0.88667 \ \textit{and} \ \beta_{1950}^4 = 0.6180785 \quad \text{(A-16)}$$

and

$$\beta_{2019} = \frac{T_\alpha}{T_S} = \frac{T_e}{T_S} = \frac{254.55}{287.5107} = 0.88526 \ and \ \beta_{2019}^4 = 0.6144 \quad \text{(A-17)}$$

A.6 Balancing P_{out} and P_{in} in 1950

In equilibrium the radiation that leaves must balance P_α, from the energy absorbed, so that

$$\begin{aligned} Energy_{Out} &= (1-f_1)P_\alpha + (1-f_1)P_{Total} = (1-f_1)P_\alpha + (1-f_1)\{P_\alpha + f_1 P_\alpha\} \\ &= 2P_\alpha - f_1 P_\alpha - f_1^2 P_\alpha = Energy_{In} = P_\alpha \end{aligned} \quad \text{(A-18)}$$

This is consistent, so that in 1950, Eq. A-18 requires the same quadratic solution as Eq. A-8. It is also apparent that

$$P_\alpha = f_1 P_{Total\_1950} = \beta_1^4 P_{Total\_1950} \quad \text{(A-19)}$$

since

$$P_\alpha = f_1(P_\alpha + f_1 P_\alpha) \ or \ 1 = f_1(1+f_1) \quad \text{(A-20)}$$

The RHS of Eq. A-20 is Eq. A-8. This illustrates f_1 from another perspective as the fractional amount of total radiation in equilibrium. As a final check, the application in Section A.4, Table A-1, illustrate that f_1 provides reasonable results.

Appendix B: Estimating the Potential for Hotspot Irradiance Sensible Heat Storage H_{T-N}

A candidate hotspot irradiance sensible heat storage H_{T-N} was described in Section 6. Here we provide a preliminary suggested model to clarify and enumerate this factor. We note other models may be more appropriate. For example, an alternate method for H_{T-N} applied to UHIs is described in Appendix C. Other more rigorous models can be developed. Such solutions are outside the scope of this paper.

In this example model, we consider a ratio for a target (T) area relative to a nominal (N) area defined in Sec. 5. Consider a target area with sensible heat storage q, due to a mass m, having specific heat capacity Cp experiencing a day-night ΔT change in time τ, and then the suggested potential for sensible hotspot heat storage H_{T-N} has the form

$$H_{T-N} = \frac{q_T}{q_N} x \frac{I_T}{I_N} = \frac{m_T C_{PT} \Delta T_T}{m_N C_{PN} \Delta T_N} x \frac{I_T}{I_N} \approx \frac{\tau_T C_{PT} \Delta T_T}{\tau_N C_{PN} \Delta T_N} x \frac{I_T}{I_N} \quad \text{(B-1)}$$

Here we provide the option of using temperature change in time τ in place of mass. For example, the time to 63% change in ΔT might be useful (similar to a time constant). We also consider that the irradiance (I) term is needed since not all solar absorption energy is stored.

As a numeric example, first consider a 90% irradiance target area (compared to the equator) with nominal mid-latitudes (45°) roughly 70%, compared to say the Arctic and Antarctic Circles at approximately 40% [31]. Then the irradiance ratio is

$$\frac{I\%_T}{I\%_N} = \frac{90\%_T}{70\%_N} = 1.3 \quad \text{(B-2)}$$

For the sensible heat numeric portion, consider a rocky area as the target (such as Flaming Mountains). This can be compared with a nominal vegetative land area. As a rule of thumb, most rocks have a density of 2.65 g/cm^3, about 50% difference compared to a nominal soil area of 1.33 g/cm^3 [33]. The heat capacity of rocks compared with vegetated land is 2000 to 830J/Kg/^{o}K [34]. Then ΔT is estimated from tables for a day-night cycle [34, 35]. The estimate is

$$\frac{q_T}{q_N} = \frac{m_T C_{PT} \Delta T_T}{m_N C_{PN} \Delta T_N} = \frac{\rho_T C_{PT} \Delta T_T}{\rho_N C_{PN} \Delta T_N} = \left(\frac{2.65}{1.33}\right)_\rho \left(\frac{2000}{830}\right)_{C_P} \left(\frac{(10°C)}{(6.9°C)}\right) = 2x2.4x1.45 = 6.96 \quad \text{(B-3)}$$

Then including irradiance

$$H_{T-N} \approx 9 \quad \text{(B-4)}$$

Appendix C: UHI Amplification Factors

An analysis of UHI amplification effects that can be applied to H_{T-N} was originally provided by the author [5] and this work is added here to aid the reader.

C.1 UHI Area Amplification Factor

To estimate H_{T-N} for UHI amplification effects, it is logical to first look at UHI footprint (FP) studies as they provide some measurement information. Zhang et al. [36] found the ecological FP of urban land cover extends beyond the perimeter of urban areas, and the FP of urban climates on vegetation phenology was 2.4 times the size of the actual urban land cover. A more recent study by Zhou et al. [37], looked at day-night cycles using temperature difference measurements in China. This study found UHI effect decayed exponentially toward rural areas for the majority of the 32 Chinese cities. Their comprehensive study spanned from 2003 to 2012. Zhou et al. describes China as an ideal area to study as it has experienced the most rapid urbanization in the world during the decade evaluated. Findings state that the FP of UHI effect, including urban areas, was 2.3 and 3.9 times that of urban size for the day and nights, respectively. We note that the average day-night amplification footprint coverage factor is 3.1.

The UHI Amplification Factor (AF) is highly complex, making it difficult to assess from first principles as it would be some function of

$$AF_{UHI\ for\ 2019} = f\left(\overline{Build}_{Area}\ x\ \overline{Build}_{C_p}\ x\ \overline{R}_{wind}\ x\ \overline{LossE}_{vtr}\ x\ \overline{Hy}\ x\ \overline{S}_{canyon}\right) \quad \text{(C-1)}$$

were

$\overline{Build}_{Area}$ =Average building solar area

$\overline{Build}_{C_p}$ = Average building heat capacity

$\overline{R}_{wind}$ = Average city wind resistance

$\overline{LossE}_{vtr}$ = Average loss of evapotranspiration to natural cooling & loss of wetland

$\overline{Hy}$ = Average humidity effect due to hydro-hotspot

$\overline{S}_{canyon}$ = Average solar canyon effect

To provide some estimate of this factor, we note that Zhou et al. [36] found the FP physical area (km^2), correlated tightly and positively with actual urban size having a correlation coefficients higher than 79%. This correlation can be used to provide an initial estimate of this complex factor. Therefore, as a model assumption, it seems reasonable to use area ratios for this estimate.

$$AF_{UHI\ for\ 2019} = \frac{\sum(UHI\,Area)_{2019}}{\sum(UHI\,Area)_{1950}} \quad \text{(C-2)}$$

Area estimates have been obtained in the Feinberg [5] yielding the following results for the Schneider et al. [23] and the GRUMP [24] extrapolated area results:

$$AF_{UHI\ for\ 2019} = \frac{(Urban\,Size)_{2019}}{(Urban\,Size)_{1950}} \approx \begin{cases} \left(\dfrac{[0.188]_{2019}}{[0.059]_{1950}}\right)_{\text{Schneider}} = 3.19 \\ \left(\dfrac{[0.952]_{2019}}{[0.316]_{1950}}\right)_{GRUMP} = 3.0 \end{cases} \quad \text{(C-3)}$$

Between the two studies, the UHI area amplification factor average is 3.1. Coincidently, this factor is the same observed in the Zhou et al. [37] study for the average footprint. This factor may seem high. However, it is likely conservative as other effects would be difficult to assess: increases in global drought due to loss of wet-lands, deforestation effects due to urbanization, and drought related fires. It could also be important to factor in changes of other impermeable surfaces since 1950, such as highways, parking lots, event centers, and so forth.

The area amplification value of 3.1 is then considered as one of our model assumptions for H_{T-N}.

C.2 Alternate Method Using the UHI's Dome Extent

An alternate approach to check the estimate of Equation C-3, is to look at the UHI's dome extent. Fan et al. [38] using an energy balance model to obtain the maximum horizontal extent of a UHI heat dome in numerous urban areas found the nighttime extent of 1.5 to 3.5 times the diameter of the city's urban area (2.5 average) and the daytime value of 2.0 to 3.3 (2.65 average).

Applying this energy method (instead of the area ratio factor in Eq. C-3), yields a diameter in 2019 compared to that of 1950 with an increase of 1.8. This method implies a factor of 2.5 x 1.8=4.5 higher in the night and 2.65 x 1.8=4.8 in the day in 1950 with an average 4.65. This increase occurs 62.5% of the time according to Fan et al., where their steady state occurred about 4 hours after sunrise and 5 hours after sunset yielding an effective UHI amplification factor of 2.9. We note this amplification factor is in good agreement with Equation C-3. Fan et al. [38] assessed the heat flux over the urban area extent to its neighboring rural area where the air is transported from the urban heat dome flow. Therefore the heat dome extends in a similar manner as observed in the footprint studies. If we use the dome concept, we obtain some vertical extent which is a logical when considering GW. We can make an assumption that the actual surface area for the heat flux is increased by the surface area of the dome. We actually do not know the true diameter of the dome, but it is larger than the assessment by Fan et al. Using the dome extend due to Fan et al. [38] applied to the area of diameter D, the amplification factor should be correlated to the ratios of the dome surface areas:

$$AF_{UHI\ for\ 2019} = \left(\frac{D_{2019}}{D_{1950}}\right)^2 = 2.9^2 = 8.4 \tag{C-4}$$

Thus, this equation is a second value for $H_{T\text{-}N}$, where it is reasonable to use the ratios of the dome's surface area for an alternate approach in estimating the effective UHI amplification factor [5]. We will have two values, 3.1 and 8.4 to work with that provides an upper and lower bounds for effective amplification area.

Appendix D: Albedo Compared to GHG Change

A change in albedo forcing compared with a change in GHGs can be described. The variation in the energy due to an average albedo change and its re-radiation is

$$\Delta P_{\bar{\alpha}} = \Delta P_{\alpha'} + f_2 \Delta P_{\alpha'} = 1.6276\ \Delta P_{\alpha'} = 1.63x0.153 = 0.25 \tag{D-1}$$

The average change in GHGs can be written in terms of Δf

$$\Delta P_{\overline{GHG'}} = \Delta f\ P_{\alpha} = 0.96\%\left(238\right) = 2.29 \tag{D-2}$$

This resulting ratio from Table 1 is

$$\frac{\Delta P_{\bar{\alpha}}}{\Delta P_{\overline{GHG'}}} = \frac{\Delta P_{\alpha'}}{\Delta f}\frac{(1+f_2)}{P_{\alpha'}} = \frac{0.154W/m^2}{0.0096}\frac{1.6276}{238W/m^2} = 0.109 \tag{D-3}$$

Note this ratio is of course dependent on the 2019 albedo 0.15% change. However, it also provides a valuable estimate. We note this is an alternate way to estimate the amount of albedo change to equate to the change in the GHG.

$$\Delta P_{\overline{GHG'}} = \frac{\Delta P_{\bar{\alpha}}}{0.109} = \frac{1.6276\ \Delta P_{\alpha'}}{0.109} = 2.29W/m^2 \tag{D-4}$$

We note in Eq. 8 we required 1.5% albedo change to resolve 96% of global warming. In this alternate method, the estimate is 1.43%, which is in reasonable agreement.

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