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

(*This paper is a short version of the more complete paper Vixra 2006.0198*)

Alec Feinberg[†]

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Abstract

Solar geoengineering is vital in global warming as results can reverse trends and reduce the probability of a tipping point. As well, the pace and depth of implementing the Greenhouse Gas (GHG) solution is tenuous. This paper focuses on the implementation of a surface solar geoengineering solution to global warming. 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. Often, to the contrary, urbanization and road construction selection of high solar-absorbing materials continues to be the norm. The solar solution is incorrectly overlooked by comparison to GHG mitigation. This paper provides basic modeling and motivation in our UHI assessments by illustrating the potential impact for reverse forcing. We provide insights into "Earthly components" that can be utilized to increase the opportunity for reducing climate change. Modeling shows that by solar geoengineering hotspots such as UHIs, the effective area could be roughly 11 times smaller than nominal non-hotspot regions in influencing global warming. Indications suggest the corrective action area sizes are of the order of UHI coverage. The versatile model presented, also shows significant global warming estimates due to UHIs and their coverage.

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 alternative albedo solutions. Unlike geoengineering solutions, GHG mitigation is highly difficult to result in reversing climate change, especially with reports on large deforestation occurring [1].

Implementation is a key focus on geoengineering an albedo surface solution which can be productive in many areas including cooling off UHIs [2]. This work is based on the results of a companion paper [3] that will help to setup our goals. There have been a number of geoengineering solutions proposed [4-6] that are either atmospheric of surface-based. In this study, we focus on targeting surface regions.

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 these as Solar Amplified Areas (SAA) relative to Nominal Land Albedo (NLA) areas (25% albedo, see Sec. 3.2).

In terms of short wavelength absorption, these target factors are likely most important. Each factor amplifies solar radiation absorption compared to a nominal land area. 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 [3] have found significant warming due to UHIs, the only motivated work in this area is a result of health concerns. Therefore, albedo cool roof solutions have not received adequate attention compared to GHG efforts. This is unfortunate and makes the business of solar solution and it's financing less desirable. Therefore, a key strategy employed in this study is to demonstrate the advantages and feasibility in cooling solar amplified areas, such as UHIs. Our results show that although UHIs contribute to global warming, fortunately

- they also have a cooling potential of about 6 times their estimated warming, if highly reflective albedo changes could be made (see Section 3.2).

[†] A. Feinberg, Ph.D., DfRSoft Research, email: dfrsoft@gmail.com, ORCID: 0000-0003-4364-2460

2.0 Data and Methods

In our initial paper on geoengineering the albedo solution to global warming [3], identified simple models and key parameters for geoengineering an adequate solution. From this work, results (also see Appendix A and B) show a solution for a 1.5% albedo change can be estimated as

$$\Delta P_{\mathrm{Re}v\_S} = -\Lambda_{\%\Delta\alpha\Delta T}\ \%\Delta\alpha\ (1+f)\ A_R = \Delta P_T\ (1+f)\ A_R = -4.8W/m^2 \tag{1}$$

and $\beta^4\Delta P_{\mathrm{Rev\ S}}=\Delta P_{\mathrm{Rev\ OLWR}}=-2.97\mathrm{W/m^2}$ [3] so that

$$\Delta T_{\mathrm{Re}v} = -\frac{2.97\mathrm{W/m^2}}{\lambda_o} = -0.89°K \tag{2}$$

Here we define

ΔP_{Rev} is the reverse power per unit area change
$\Lambda_{\%\Delta\alpha\Delta T}$ = albedo-plank parameter, 1Watt/m^2/%ΔAlbedo [3] (also see Appendix C)
%Δα is the percent change in the global albedo, we are using 1.5%
f= the re-radiation parameter about 0.63 [3] (also see Appendix A)
A_R is an estimate of the anticipated GW feedback reduction, taken as 2 [3]
$\Delta P_T = \Lambda_{\%\Delta\alpha\Delta T}\ \%\Delta\alpha$ is the reverse forcing change from the target area, with values listed it is 1.5W/m^2
λ_o is the Planck parameter taken as 3.3 W/m^2/°K
$\Delta P_{\mathrm{Rev\ OLWR}}=-2.97\mathrm{W/m^2}$ is the change in the outgoing longwave radiation

If we take the increase warming trend at the end of 2019 as 0.95°K, then this is about a 93% correction. As well, in this study anticipating an allowance for the climate system to equilibrate [7] is not considered. Furthermore, we expect that prior to a tipping point; a positive compared to a negative albedo change, may not have a strong hysteresis effect.

Note that the 1+f factor accounts for one process of initial absorption change ΔP_T followed by subsequent partial re-radiation from GHGs. This is described in detail in our companion paper [3]. This value helps to clarify our goal.

2.1 Albedo Modeling

We can write the short wavelength solar absorption as

$$P = \frac{Q}{A} = \frac{S_N}{4}\sum_i \frac{A_i'}{A}(1-\alpha_i) + \frac{S_N}{4}\mathrm{H}_{T-N}\frac{A_T'}{A}(1-\alpha_T) + \frac{S_N}{4}\frac{A_C}{A}(1-\alpha_C) \tag{3}$$

Here A_i is the i^{th} effective area having an albedo α_i, $S_N=1361W/m^2$ and A 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 $H_{T\text{-}N}$, a function of the heat capacity, mass, temperature storage, and solar irradiance. Essentially this has the effect of amplifying the target area. $H_{T\text{-}N}$ is described and enumerated in Appendix C.

We note that the Earth Albedo change will only be a function of the target area variation, so from Eq. 3

$$\left(dP_T\right)_\alpha = \frac{S_N}{4}\mathrm{H}_{T-N}\frac{A_T'}{A}(-d\alpha_T) \tag{4}$$

where the subscript α indicates all other Earth albedo components are held constant.

The overall equation prior to changing the albedo is subject to the constraints

$$P = 240W/m^2\ \ and\ \ A = \sum_i A_i' + A_T' + A_C = A_E' + A_C\ but\ \ A_E' = (1-\%A_C)xA_E = 0.33A_E \tag{5}$$

This indicates that because of the cloud coverage term A_C, about 67% of the actual Earth's area A'_E [8] is covered from direct sunlight. This is likely conservative as clouds do let some sunlight through. However, that leaves 33% of the Earth available for solar radiation absorption.

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

$$P' = \frac{Q'}{A} = \frac{S_N}{4}\sum_i \frac{0.33A_i}{A}(1-\alpha_i) + \frac{S_N}{4}\frac{0.33A_T}{A}\mathrm{H}_{T-N}(1-\alpha_T') + \frac{S_N}{4}\frac{A_C}{A}(1-\alpha_C) \tag{6}$$

Using the example goal P_T=1.5W/m^2 in Eq. 1, the change in heat absorbed is a function of the target area as indicated by Eq. 4, where

$$\Delta P_T = P - P' = \frac{S_N}{4}\frac{0.33A_T\mathrm{H}_{T-N}}{A}\left[(\alpha_T' - \alpha_T)\right] = 1.5W/m^2 \tag{7}$$

However, the same results can be obtained by changing the albedo of a nominal area; so in this case $\mathrm{H}_{T-N}=1$. The equivalent change for the NLA is

$$\Delta P_{T-N} = \frac{S_N}{4}\frac{0.33A_N}{A}\{(\alpha_N' - \alpha_N)\} = 1.5W/m^2 \tag{8}$$

3.0 Results and Discussion

Comparing the target to the nominal areas, we have

$$\frac{\Delta P_T}{\Delta P_{T-N}} \approx \frac{A_T\mathrm{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right]}{A_N\left[(\alpha_N' - \alpha_N)\right]} = 1 \tag{9}$$

As an example, assume $\mathrm{H}_{T-N} \approx 9$ (see Appendix B), α_N=0.25 (see Sec. 3.2), α_T=0.12 [13], and for $\alpha_N'=\alpha_T'$=0.9, we obtain

$$\frac{A_N}{A_T} = \frac{\mathrm{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right]}{\left[(\alpha_N' - \alpha_N)\right]} = \frac{9\left[(0.9-.12)\right]}{\left[(0.9-0.25)\right]} = 10.8 \tag{10}$$

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. 7

$$\Delta P_T = \frac{S_N}{4}\frac{0.33A_T\mathrm{H}_{T-N}}{A_E}\left[(\alpha_T' - \alpha_T)\right] = 1.5W/m^2 \tag{11}$$

For H_{T-N}=1, α_T'=0.9, and α_T=0.12 then

$$\Delta P_T = 340\frac{A_T}{A}\left[0.78\right]x0.33 = 1.5W/m^2 \tag{12}$$

and

$$\frac{A_T}{A} = 0.01714 = 1.714\%\,of\ Earth \tag{13}$$

For H_{T-N}=10, α_T'=0.9, and α_T=0.12 then

$$\frac{A_T}{A} = 0.1714\%\,of\ Earth \tag{14}$$

Recall that the goal for a 1.5W/m^2 corresponded to a 1.5% albedo change (see Sec. 2.0). We can check results of $A_T/A=1.714\%$ when $H_{T\text{-}N}=1$, yields a 1.5% albedo change using a related expression to Eq. 7. This is give by

$$\Delta\alpha\% = 0.33\frac{A_T}{A}\frac{[(\alpha_T' - \alpha_T)]}{\alpha} = 0.33(1.714\%)\frac{[(0.9-0.12)]}{0.294118} = 1.5\% \tag{15}$$

where the global albedo is taken as α=0.294118 which is indicated in AR5's energy budget figure [9].

3.1 Cooling Estimates Compared to Urban Heat Island Area

Since UHI are likely good target areas, we can compare these results to the total global urbanized area. One key issue is that we do not expect that an albedo change to 0.9 is realistic. Yet we use it as a potential theoretical goal. In order to make comparisons we note that 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 [10] 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% [2] in 2019. Similarly, a study from GRUMP [11] showing global urbanization value in 2000 of 0.783% extrapolates to 0.953% [2] of the Earth's area in 2019. These extrapolations are based on an average yearly urbanization growth rate between 1.3% to 1.6% [3]. Lastly, note that UHIs have their own hotspot amplification factors [3] that vary between 3.1 and 8.4 (see Appendix D) which are listed in Table 1 and can be applied 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 D) are summarized in Table 1.

Table 1 Cooling estimates for relative to UHI areas

$H_{T\text{-}N}$	A_T/A (% of Earth)	Schneider Factor (A_T/A) /0.188% (Conservative)	GRUMP Factor (A_T/A)/ 0.953
1	1.714	9.1	1.8
3.1	0.55	2.93	0.58
8.4	0.2	1.06	0.21
9	0.19	1	0.2

*A_T/A represent 94% of the solution (see Sec. 2)

Note that an IPCC (Satterthwaite et. al. [12]) AR5 report references the Schneider et al. [10] results in urban coverage of 0.148% of the Earth.

Table 1 results are highly dependent on $H_{T\text{-}N}$ which is overviewed in Appendix D. It is important to develop better estimates for both $H_{T\text{-}N}$ and urbanization sizes than estimated here. We note that the 0.12 albedo value applies to UHI [13], which is acceptable upper value when looking for hotspot targets. The albedo and two $H_{T\text{-}N}$ values cited here have been studied in Feinberg [2]. The assessments for H_{T_N} applicable to UHIs are also provided to aid the reader in Appendix D. Results in Table 1 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, indicate that the potential area needed may be 3 times their current size. Therefore, if this was proven to be the most accurate estimate, supplementary target areas would be required to reach the 93% objective. Furthermore it is unrealistic to realize an overall UHI albedo goal of 0.9 due to their complex nature, but it provides a theoretical goal.

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 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.

3.2 Warming Estimates Due to Urban Heat Island Area

We can use this same model to estimate the global warming contributions due to UHIs. In this case, instead of α_T'=0.9, we evaluate by restoring the UHIs to their original estimated albedo value of α_T'=0.25. This albedo value is based on a study by He et. al. [21] which found the land albedo varied from 0.1 to .4 having an average of 0.25. Then using the $H_{T\text{-}N}$ values in Section 3.1, we estimate the percent of the Earth needed to obtain a 93% solution and compare results to the known UHI coverage areas.

For $H_{T\text{-}N}$=3.1, α_T'=0.25, and α_T=0.12 then

$$\Delta P_T = \frac{1361W/m^2}{4}\frac{0.33A_T 3.1}{A_E}\left[(.25-.12)\right] = 1.5W/m^2 \tag{16}$$

and

$$\frac{A_T}{A} = 3.3\% \tag{17}$$

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

$$\frac{A_T}{A} = 1.2\ \%\, of\ Earth \tag{18}$$

Table 2 summarized the warming trend results

Table 2 UHI Warming estimates

$H_{T\text{-}N}$	A_T/A (% of Earth)	Schneider Factor (A_T/A) /0.188% (Conservative)	GRUMP Factor (A_T/A)/ 0.953	GW% 1/Schneider Factor / 0.93*	GW% 1/GRUMP Factor / 0.93*
3.1	3.3	17.6	3.5	6.1	31
8.4	1.2	6.4	1.26	16.9	85.4

*A_T/A GW represent 93% of the solution (see Sec. 2), and are adjusted to 100% in Column 5 & 6

Results in Column 5 and 6 are reasonably comparable to Feinberg 2020 [2]. The model shows that between 6.1% and 85% of global warming could be due to UHIs and their coverage. We note these large variations are due to the difficulty in estimating $H_{T\text{-}N}$ and knowledge of UHI area coverages, as shown in the differences found between Schneider and the GRUMP results. However, the model provides a reasonable way to make estimates which can be further refined once better values are known.

Furthermore, we note the cooling potential in Table 1 is about a factor of 6 times compared to the warming shown in Table 2. For example in Table 1, the area cooling ratio 2.93 compared to the warming ratio 17.6 in Table 2, yields an effective potential factor of 6. As stated above, obtaining the full cooling potential for UHIs and their impermeable surfaces is likely unobtainable due to the complex nature of cities. Therefore the cooling potential serves only as a theoretical goal.

3.3 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
- Oceans [4]

We note that mountain areas 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 1 and 11 can be combined to provide a resulting solar geoengineering equation for reverse forcing obtained in this study where

$$\Delta P_{\mathrm{Rev}\_S} = -\Lambda_{\%\Delta\alpha\Delta T}\ \%\Delta\alpha\ (1+f)\ A_R = \left\{ \frac{S_N}{4} 0.33\mathrm{H}_{T-N} \frac{A_T}{A} \left[(\alpha_T' - \alpha_T) \right] \right\} (1+f)\ A_R \tag{19}$$

with suggested values $H_{T\text{-}N}=6$, $\alpha_T'=0.9$, $\alpha_T=.12$, $\Delta P_{\mathrm{Rev}\_S}=4.8\mathrm{W/m}^2$, and $f=0.63$.

4 Conclusions

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

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

- A target albedo goal of -4.8W/m^2 ($\Delta P_{\mathrm{Rev}\_LWR}=-2.97\mathrm{W/m}^2$)
- The target area required to resolve 93% of global warming is about 0.2% to 0.5% (Table 1) of the Earth, if proper hotspots are cooled with highly reflective surfaces. This is likely on the order of UHIs coverage today
- The cooling potential of UHIs is a factor of 6 time higher than their warming contribution if highly reflective surfaces can be realized
- Likely target areas may include problematic hotspots such as UHIs, mountains regions and possibly ocean areas [4]
- Selecting proper hotspots can reduce the required target area by an estimated factor of 11
- Changing the albedo has 1.6 benefit factor due to GHG re-radiation
- UHIs likely contribute significantly to global warming
- Solutions are highly dependent on $H_{T\text{-}N}$.

Finally we suggest:

- Tasking agencies worldwide, such as NASA, to work full time on solar geoengineering, which at this late time should be our highest priority,
- 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 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. Furthermore, such surfaces create hydro-hotspots [22] which may contribute to higher values of $H_{T\text{-}N}$. A hydro-hotspot is a hot surface that creates moisture in the presence of precipitations. Such surfaces create excess moisture in the atmosphere promoting a local greenhouse effect.
- Manufacturing cars to be more reflective including reducing their internal solar heating. Although, worldwide solar cool vehicles (e.g., silver or white) will likely not contribute significantly to global warming mitigation, recommending them would. It will help raise awareness, similar to electric automobiles that help improve CO_2 emissions and could increase interest in similar projects thereby promoting other related changes like cool roofs.

Appendix A: Reemission Percent

The re-radiation parameter has a unique value of 0.618 (or $\beta=0.887$). The fundamental re-radiation factor is a redefined variable taken from the effective emissivity constant of the planetary system. The re-radiation parameter changes as greenhouse gases increase in the climate system. However, this causes a deviation from this fundamental value of β where f deviates. The reemission percent in different time periods is detailed in Feinberg [3] and is found to be about 0.63 in 2019.

Appendix B: Estimating the Potential for Hotspot irradiance Sensible Heat Storage $H_{T\text{-}N}$

A candidate hotspot irradiance sensible heat storage potential $H_{T\text{-}N}$ was described in Section 2. Here we provide a preliminary suggested model to clarify and enumerate this factor. It is likely that more rigorous models can be developed. Such solutions are outside the scope of this paper.

We consider a ratio for a target (T) area relative to a nominal (N) area defined in Sec. 2. 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, then the suggested potential for sensible hotspot heat storage $H_{T\text{-}N}$ has the form

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

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 40% [14]. Then the irradiance ratio is

$$\frac{I\%_T}{I\%_N} = \frac{90\%_T}{70\%_N} = 1.3 \tag{B-2}$$

For the sensible heat numeric portion, consider a rocky area as the target (such as Flaming mountain). 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 [15]. The heat capacity of rocks compared with vegetated land is 2000 to 830J/Kg/^{o}K [16]. Then ΔT is estimated from tables for a day-night cycle [17]. The estimate is

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

Then including irradiance

$$H_{T-N} \approx 9 \tag{B-4}$$

Appendix C: Planck-Albedo Feedback Parameter

This parameter comes about from the following assessment [2,3]

$$\Lambda_{\%\Delta\alpha} = \frac{\Delta E_o}{\frac{\alpha_1 - \alpha_2}{\alpha_1} 100} = \frac{E_o\left(\alpha_1 - \alpha_2\right)}{\frac{\alpha_1 - \alpha_2}{\alpha_1} 100} = E_o \alpha_1 / 100 = 1W/m^2/\%\Delta albedo \tag{C-1}$$

where Eo=340 W/m^2 and we see the closer that α_1 is to 29.4118%, the nearer a value of 1.000W/m^2/Δ%albedo is obtained. We note the value 29.4118% (100/340) is listed in AR5 [9]. This value relates for a 1^{o}K change [2,3] so that

$$\Lambda_{\%\Delta\alpha\Delta T} = 1W/m^2/\%\Delta albedo/°K \tag{C-2}$$

Appendix D: UHI Amplification Factors

An analysis of UHI amplification effects which can be applied to $H_{T\text{-}N}$ was originally provided in Feinberg [2] and this work is added here to aid the reader.

Appendix D.1: UHI Area Amplification Factor

To estimate the UHI amplification effects, it is logical to first look at UHI footprint (FP) studies as they provide some measurement information. Zhang et al. [18] 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. [19], 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

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

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. [19] 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.

$$AF_{UHI\,for\,2019} = \frac{\sum\left(UHI\,Area\right)_{2019}}{\sum\left(UHI\,Area\right)_{1950}} \tag{D-2}$$

Area estimates have been obtained in the Feinberg [3] yielding the following results for the Schneider et al. [10] and the GRUMP [11] extrapolated area results:

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

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. [19] 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.

Appendix D.2: Alternate Method Using the UHI's Dome Extent

An alternate approach to check the estimate of Equation D-3, is to look at the UHI's dome extent. Fan et al. [20] 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. D-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 D-3. Fan et al. [20] 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 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. [20] applied to the area of diameter D, the amplification factor should be correlated to the ratios of the dome surface areas:

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

Thus, this equation is a second value for H_{T-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 [2]. We will have two values, 3.1 and 8.4 to work with that provides an upper and lower bounds for effective amplification area.

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