Urban Heat Island Amplification Estimates on Global Warming Using an Albedo Model

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Abstract

In this paper we provide nominal and worst case estimates of radiative forcing due to UHI effect (including urban areas) using a Weighted Amplification Albedo Solar Urbanization (WAASU) Model. This is done with the aid of reported findings from UHI footprint studies that simplified estimates for UHI amplification factors. Using this method, we find conservatively between 0.06 and 0.27 Watts/M^2 of radiative long wavelength forcing may be due to the UHI effect (with urban areas). This would increase due to climate feedback and values are suggested. We also provide more aggressive estimates. Results provides insight into the UHI area effects from a new perspective and illustrates that one needs to take into account effective UHI amplification factors when assessing UHI's warming effect on a global scale. Lastly, such effects likely show a more persuasive argument for the need of world-wide UHI albedo goals.

1. Introduction

It is concerning that there are so few UHI publications recently on their possible influences to global warming. Part of the motivation for this paper is to illustrate the continual need for more up-to-date related studies including UHI amplification effects (that include their urban areas) as will be discussed in this paper. The subject of UHI effect having significant contributions to global warming is very important and should remain so. The topic has a controversial history. One such paper, McKitrick and Michaels (2007) found that the net warming bias at the global level may explain as much as half the observed land-based warming. This study was criticized by Schmidt (2009) and defended for a period of about 10 years by Mckitrick (see McKitrick Website). Other authors have also found significance (Zhao, 1991; Feddema et al., 2005; Ren et al., 2007, 2008; Jones et al., 2008; Stone, 2009; Zhao, 2011; Yang et al. 2011, and Haung et al. 2015). These studies used land-based temperature station data to make assessments. Although the studies have all found global warming UHI significance with different assessments, they have yet to influence the IPCC enough to necessitate albedo recommendations in their many reports and meetings like the CO_2 effort. This is important because, we feel it is important that the IPCC's be more proactive in this area in helping the global community recognizing the need for UHI albedo goals. Although they have provided reports on UHIs including health related issues, the response to their reports does not appear to be effective on the global scale compared with the on-going CO_2 effort. Surely promoting UHI albedo recommendations would make a large impact.

The contention that UHI effects are basically only of local significance is most likely related to urban area estimates. For example, IPCC (Satterthwaite et. al. 2014) AR5 report references Schneider et al. (2009) study that resulted in urban coverage of 0.148% of the Earth (Table 1). This seemingly small area tends to dismiss the contention that UHI effect can play a large scale role in global warming. Furthermore, estimates of how much of land has been urbanized vary widely in the literature and this is in part due to the definition of what is urban and the datasets used. Despite the growing importance of urban land in regional to global scale environmental studies, it remains extremely difficult to map urban areas at coarse scales due to the mix of land cover types in urban environments, the small area of urban land relative to the total land surface area, and the significant differences in how different groups and disciplines define the term 'urban'.

Furthermore, global warming UHI amplification effects are not quantified to a large degree related to area estimates. Because of this, the average solar heating area itself has not been quantified as part of such area estimates on land size effect and typically unrelated to important building solar heating areas.

Table 1. Urbanization area extent estimates from various sources

Percent of Land	Percent of Earth	References
2.7	0.783	GRUMP (2005), using NASA satellite light studies based on 2004 data and supplemented with census data
1%	0.29	NASA (2000) Satellite data, Galka (2016)
0.51	0.148	Schneider et al. (2009), based on 2000-2001 data and referenced in the IPCC report (Satterthwaite, 2014)
0.5%	0.145	Zhou (2015), based on a 2000 data set

Surface area land approximations vary widely and most are obtained with satellite measurements sometimes supplemented in some way with census data. Table 1 captures some papers that are of interest.

One key paper listed in the table that we study here is due to Schneider et al. (2009) since it is cited by the AR5 2014 IPCC report (Satterthwaite et al. 2014). In Schneider paper, the larger area found in the GRUMP 2005 study in Table 1 is criticized. These area estimates are important in our paper as we are using a *Weighted Amplification Albedo Solar Urbanization (WAASU) Model*. Amplification factors that we will use are related to such urban coverage. Therefore, we decided to use both the Schneider et al. and GRUMP studies as the nominal and worst cases urbanization area estimates respectively. Furthermore they were both done using data set from around 2000 which is a convenient time to extrapolate down to 1950 and up to 2019 (see Sec. 3).

In our study, where we introduce the WAASU model, we will see that it has some advantages over the ground-based temperature studies like McKitricks and Michaels. The model is non probabilistic, in line with the way typical energy budgets are calculated, it uses only two key parameters (urban coverage, and average albedo). Because it is simplistic, it has transparency compared with the complex land-based studies.

UHI Amplification Effects

The table below lists the global warming causes and amplification effects. In this section we will summarize only the UHI amplification effects listed in the table since the root causes and the main global warming amplification effects are fairly well known.

Table 2. Global Warming Cause and Effects

Global Warming Causes →	Population → Expanding Urban Heat Islands (UHI), Roads & Increases in Greenhouse gas
Global Warming Feedback Amplification Effects →	Increase in Specific Humidity, Decrease in Relative Humidity, Decrease in land albedo due to cities & roads, Decrease in water type areas from loss of albedo (reflectivity) due to Ice and snow melting
Urban Heat Island Amplification Effects →	UHI Solar Heating Area (Building Areas), UHI Building Heat Capacities, Humidity Effects and Hydro-Hotspots, Reduced Wind Cooling, Solar Canyons, Loss of Wetlands, Increase in Impermeable Surface, Loss of Evapotranspiration Natural Cooling.

The UHI amplification effects that we consider to dominate listed in the Table are as follows:

- ***The humidity amplification effect:*** This has been observed. For example, Zhao et al. (2014) noted that UHI temperature increases in daytime ΔT by 3.0°C in humid climates but decreasing ΔT by 1.5°C in dry climates. They noted that such relationships imply that UHIs will exacerbate heat wave stress on human health in wet UHI climates. One explanation for this is how heat dissipates through convection which is more difficult in humid climates. Another explanation is that warmer air holds more water vapor. This can increase local specific humidity so that there could be local greenhouse effects.

- ***The heat capacity and solar heating area amplification effect:*** This contributes to the day-night UHI cycle. Here in most cities, it is observed that daytime atmospheric temperatures are actually cooler compared to night. For example, in a study by Basara et al. (2008) in Oklahoma city UHI it was found that at just 9-m height, the UHI was consistently 0.5–1.75°C greater in the urban core than the surrounding rural locations at night. Further, in general UHI impact was strongest during the overnight hours and weakest during the day. This inversion effect can be the results of massive UHI buildings acting like heat sinks, having giant heat capacities and storing heat in their reservoir via convection as solar radiation is absorbed during the day. This often reduces the UHI day effect, but at night buildings cools down, giving off their stored heat that increases local temperatures to the surrounding atmosphere. This effect increases with city growth as buildings have gotten substantially taller (Barr 2019) since 1950.

- ***The Hydro-hotspot amplification effect:*** This effect is not well addressed. Here atmospheric moisture source is a complex issue due to Hydro HotSpots (HHS). Hydro hotspots occur when buildings are hot due to sun exposure. Then during precipitation periods, the hot highly evaporation surfaces increase localized water vapor in the air via the effect that warm air holds more moisture. This increase in local greenhouse gas, could blanket city heat and increase infrared radiation during these periods. This, as discussed above, is another possible UHI humidity amplification.

- ***Reduced Wind Cooling and Solar Canyons:*** In UHIs reduced wind is a known effect due to building wind friction which inhibits cooling by convection. As well, tall buildings create solar canyons and trap sunlight reducing the average albedo although some benefits occurs from shading. In general, both have the effect of amplifying the temperature profile of UHIs.

Data and Methods

We see from the previous section that estimating climate change impact just based on the UHI and Urban area coverage as in Table 1, cannot take into account solar heating building sidewall areas, massive heat capacities, the humidity effects, wind reduction and the solar canyon effect which amplify UHI effects beyond its own climate area.

In order to estimate the UHI amplification effects, it is logical to first look at UHI footprint studies as they provide some measurement information. Zhang et al. (2004) found the ecological footprint of urban land cover extends beyond the perimeter of urban areas, and the footprint of urban climates on vegetation phenology they found was 2.4 times the size of the actual urban land cover. In a more recent study by Zhou et al. (2015), they looked at day-night cycles using temperature difference measurements. In this study they found UHI effect decayed exponentially toward rural areas for majority of the 32 Chinese cities. Their study was very thorough and extended over the period from 2003 to 2012. They describe China as an ideal area to study since it has experienced the rapidest urbanization in the world in the decade they evaluated. They found that the "footprint" of UHI effect, including urban areas, was 2.3 and 3.9 times of urban size for the day and night, respectively. We note that the average day-night amplification footprint coverage factor is 3.1.

Zhou et al. (2015) found that the FP physical area (km^2), correlated tightly and positively with actual urban size, with the correlation coefficients higher than 79%.

Looking at Table 2, we see that the UHI Amplification Factor (AF_{UHI}) is highly complex and not easy to assess from first principles and would be some function of Table 2 components in 2019 where

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

where

$\overline{Build}_{Area}$ =Average Building Solar Area
$\overline{Build}_{C}$ = 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

For example, a basic formulation we might suggest could involve average power (N) ratios over all urban cities compared to a 1950 reference year

$$AF_{UHI\ for\ 2019} = \left(\frac{\left(\overline{Build}_{Area}\right)_{2019}}{\left(\overline{Build}_{Area}\right)_{1950}}\right)^{N_1} \left(\frac{\left(\overline{Build}_{C}\right)_{2019}}{\left(\overline{Build}_{C}\right)_{1950}}\right)^{N_2} \left(\frac{\left(\overline{R}_{wind}\right)_{2019}}{\left(\overline{R}_{wind}\right)_{1950}}\right)^{N_3} \left(\frac{\left(\overline{LossE}_{vtr}\right)_{2019}}{\left(\overline{LossE}_{vtr}\right)_{1950}}\right)^{N_4} \left(\frac{\left(\overline{Hy}\right)_{2019}}{\left(\overline{Hy}\right)_{1950}}\right)^{N_5} \left(\frac{\left(\overline{S}_{canyon}\right)_{2019}}{\left(\overline{S}_{canyon}\right)_{1950}}\right)^{N_6}$$

In order to provide some estimate of this factor, we noted that in the Zhou et al. (2015) study, they observed a 79% correlation (or higher) between the footprint and the urbanized size. This type of correlation infers a reasonable way to provide an estimate of this complex factor. Area estimates have been obtained in the next Section in Table 4 between 2019 and 1950 time frames, and yield the following results for the Schneider et al. (2009) and the GRUMP 2005 extrapolated area results

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

Between the two studies, the UHI area amplification factor average is 3.1. Coincidently, this is the same factor observed in the Zhou et al. (2015 study) for the average footprint. This factor may seem high. However, it is likely conservative. There are other effects that would be difficult to assess. For example, increases in global draught due to loss of wet lands, deforestation effects due to urbanization and draught related fires. It could also be important to factor in changes of other impermeable surfaces since 1950 such as highways, large parking lots, and so forth.

Extrapolated Area to 1950 and 2019

In order to assess the urbanized area and determine the UHI amplification factor ratio, we need to project the Schneider and GRUMP area estimates down to 1950 and up to 2019. Both use datasets from around 2000 so this is a convenient somewhat middle time frame. Here we decided to use the world population growth rate (World bank 2018) which varies by year as shown in Appendix A in Figure A1. We used the average growth rate per ½ decade for iterative projections (that averaged between 1.3% and 1.6% per year).

To justify this we see that Figure A2a illustrates that building material aggregates (USGS 1900-2006) used to build cities and roads correlates well to population growth (US Population Growth 1900-2006).

It is also interesting to note that building materials for cities and roads also correlates well to global warming trends (NASA 1900-2006) shown in Figure A2b.

Column 2 in Table 4 show the projections with the actual year (~2000) data point tabulated value also listed in the table (also see Table 1). Next we apply the UHI amplification factor of 3.1 and 6.2 with the additional factor of 2 taking into account a possible doubling feedback effect to the percent of the Earth values (see Table 1) shown in the Schneider and GRUMP studies. Therefore, under these assumptions, the urban effective amplification coverage used in the WAASU model is shown in Column 4.

Table 3. Extrapolated and amplified urbanized coverage estimates

Year	Urban coverage Percent of Earth	Amplification Factor Effect	Effective Amplification Coverage Area Effect
IPCC Schneider Study			
1950	0.059*	1	0.059%
2000-2001	0.0051x29%=0.148		
2019	0.188*	3.1 AF_{UHI}**	**0.583%**
Worst Case GRUMP Study			
1950	0.316%*	1	**0.316%**
2000	0.027x29%=0.783%		
2019	0.952%*	3.1 AF_{UHI}**	**2.95%**

*Growth rate of cities using world population yearly growth rate in Fig A1, **AF_{UHI} is the area amplification factor for 2019 referenced to 1950.

Weighted Amplification Albedo Solar Urbanization (WAASU) Model Overview for 1950 & 2019

The WAASU model is very straightforward; it is based on a global weighted albedo model. The Earth Albedo is given by

$$Earth\ Albedo = \sum_i \{\%\, Earth\ SurfaceArea_i\ x\ \ Surface\ Item\ Albedo_i\} + Cloud\ Area\ \ x\ \ Cloud\ Albedo \tag{1}$$

Model Constraints

This model is subject to the constraint

$$Total\ Area = \sum_i \{\%\, Earth\ SurfaceAreas_i\} + \%Cloud\ Area = 100\%$$

and the normalization constraint for the Earth surface areas is then

$$\sum_i \{\%\, Earth\ SurfaceAreas_i\} = 100\% - \%Cloud\ Area$$

To simplify things as much as possible, only five Earth constituents are used: Water, Sea Ice, Land, UHI coverage, and Clouds (where land is its area minus the UHI coverage). These components are fairly easy to estimate and references for their values are provided in Appendix C.

In order to provide as realistic an analysis as possible, the IPCC report (Hartmann et al., 2013) assessment of the Earths energy budget is used. The table below summarizes the albedo constraints to IPCC values found in their report

Table 4. IPCC Earth energy budget values (Hartmann et al., 2013)

IPCC Item	Value Provided W/M2	Albedo %
Solar Incident Power	340	-
Earth Albedo	100/340	29.4118
Cloud Albedo	76/340	22.3529
Earth Surface Albedo	24/340	7.0588

The fixed components of our model maintain relative consistency from 1950 to 2019. The non-fixed value is the urban coverage. The only unknown value is the land albedo (minus the UHI coverage) and this value is adjusted to obtain the IPCC global albedo of 29.4118%. This is used as a starting value for 1950. Then we insert the 2019 increase in UHI coverage area. This will increase the Earth's area to greater than 100%. We then renormalize this by the constraint in Equation XYZ.

Results and Discussion

In 2019, using the extrapolated area coverage in Table 3 with its amplification factor of 3.1, the resulting global albedo change is from 29.4118% (Table 5a) to 29.3956% for the Schneider nominal case (shown in Table 5b). For the GRUMP worst case, the albedo changes from 29.4118% (Table 6a) to 29.3322% (Table 6b**).**

Although factors are held constant, since urban coverage increases in 2019, this increases the solar surface area of the Earth, which will occur with city growth of tall buildings and their solar areas. This new area, however small, requires renormalization in the model of the Earth components of the WAASU model (see Appendix B). While the model is sensitive to urban coverage changes, it works well with renormalization showing a high level of consistency with urban coverage proportionality changes. This is indicated in Table 8 where we will see that the GRUMP 2019 area sensitivity is 10.6 (=2.87/0.271) compared with the Schneider area sensitivity of 10.55 (=0.58/.055).

Table 5a. Schneider Results (Albedo=29.4118, 1950)

Surface	Albedo	% Area of Surface	Normalized Earth Area	Weighted Albedo %
		71		
Sum of Water Type	A	B	C=A x B x (1-0.67)	A x C
Sea Ice	0.6	15	4.95	2.970
Water	0.06	56	18.48	1.109
Sum of Land Type		29		
Land - (UHI + Coverage)	0.3118	28.941	9.55053	2.978
UHI + Coverage	0.12	0.059	0.01947	0.002
		∑=100.000	33.000	7.05882
			Cloud Area	
Clouds	0.3336	67	67	22.35294
∑ Sum Earth %			100.000	
∑ Global Albedo				29.4118

Table 5b. Schneider Results (Albedo=29.3956%, 2019)

Surface	Albedo	Normalized % Surface Area	Normalized Earth Area	Weighted Albedo %
		70.6298		
Sum of Water Type	A	B	C=A x B x (1-0.67)	A x C
Sea Ice	0.6	14.9218	4.924194	2.955
Water	0.06	55.7081	18.383673	1.103
Sum of Land Type		29.37		
Land - (UHI + Coverage)	0.3118	28.79	9.5007	2.962
UHI + Coverage	0.12	0.58	0.1914	0.023
		∑=100.000	33.000	7.0197
			Cloud Area	
Clouds	0.3336	67	67	22.3529
∑ Sum Earth %			100.000	
∑ Global Albedo				29.3956

Table 6a. GRUMP Results (Albedo=29.4118, 1950)

Surface	Albedo	% Surface Area	Normalized Earth Area	Weighted Albedo %
		71		
Sum of Water Type	A	B	C=A x B x (1-0.67)	A x C
Sea Ice	0.6	15	4.95	2.970
Water	0.06	56	18.48	1.109
Sum of Land Type		29		
Land - (UHI + Coverage)	0.3135	28.684	9.46572	2.968
UHI + Coverage	0.12	0.316	0.10428	0.013
Sum Surface %		∑=100.000	33.000	7.0588
			Cloud Area	
Clouds	0.3336	67	67	22.3529
∑Sum Earth %			100.000	
∑ Global Albedo				29.4118

Table 6b. GRUMP Results (Albedo=29.3956%, 2019)

Surface	Albedo	Normalized % Surface Area	Normalized Earth Area	Weighted Albedo %
		69.1778		
Sum of Water Type	A	B	C=A x B x (1-0.67)	A x C
Sea Ice	0.6	14.615	4.82295	2.894
Water	0.06	54.5628	18.005724	1.080
Sum of Land Type		30.8221		
Land - (UHI + Coverage)	0.3135	27.9478	9.222774	2.891
UHI + Coverage	0.12	2.8743	0.948519	0.114
Sum Earth %		∑=100.000	33.000	6.8655
			Cloud Area	
Clouds	0.3336	67	67	22.3529
∑ Sum Earth %			100.000	
∑ Global Albedo				29.3322

Table 8 provides a summary of albedo changes found in the WASSU model along with the expected solar long wave radiation increase. From the above global WAASU model the estimates of the Earth's radiated long wavelength absorption and emission are estimated using the equation

$$P_{Total}=340\ W/m^2\ (1\text{-Albedo}) \qquad (3)$$

Then the change from 1950 to 2019 represents the increase in long wave radiation given by

$$\Delta P_{Total}=340\ W/m^2\ \{(1\text{-Albedo})_{2019}-(1\text{-Albedo})_{1950}\} \qquad (4)$$

(where models typically treat the Earth as a perfect black body with emissivity of ~1). Results are compiled in Table 5. The table also includes "what if" estimates, if we could change urbanization to be more reflective with cool roofs. The values here are relative to the conservative UHI amplification values.

Table 8. Albedo and Radiative Increase Model Results with UHI Effective Area

Year	Urban Extent Global Area %	UHI Effective Global Surface % Area	Normalized UHI Effective Global Surface %Area	Albedo Cities	Global Weighted Albedo	ΔP_{Total} UHI Radiative Increase W/m² (%GW)*	Model Area Sensitivity $\frac{Norm\,\%\,Area}{W/m^2}$
Nominal Case IPCC Schneider 2009 Study							
1950	0.059	0.059	0.059	0.12	29.4118	0	—
2019	.188	0.583	0.58	0.12	29.3978	0.055 (1.55%)*	10.55
What if	0.188	0.583	0.58	0.204	29.4118	-0.055 (-1.54%)*	—
Worst Case GRUMP 2005 Study							
1950	0.316%	0.316	0.316	0.12	29.4118	0	—
2019	0.952%	2.95	2.8743	0.12	29.3322	0.271 (7.5%)*	10.61
What if	0.952%	2.95	2.8743	0.2039	29.4118	-0.271 (-(-7.5%)*	—

*Percent of Warming estimate, P=340x(1-Albedo), $\%GW=\{(P/\sigma)^{0.25}{}_{2019}-(P/\sigma)^{0.25}{}_{1950}\}/0.95^{\circ}C$

The general results are summarized:

- Nominal Schneider case from 1950 to 2019 is 0.055 W/m² due to urban amplification coverage. This would equate to about 1.55% of global warming assuming the total increase from 1950 is about 0.95°C in 2019.
- Worst GRUMP case from 1950 to 2019 is 0.271 W/m² due to urban amplification coverage. This would roughly equate to about 7.5% of global warming assuming the total increase from 1950 is about 0.95°C in 2019.
- "What if" corrective action results of cool roofs indicates that changing city albedos in both the Schneider and the GRUMP case from 0.12 to 0.204 would reverse the increase in emission back to 1950 levels.

We note that radiation increase goes as the area change. That is, an increase in normalized area from 0.58 (Schneider) to 2.8743 (GRUMP) yielding a factor of 3.96% (=(2.874-.58)/.58) increase. This is also the increase observed in the long radiation of 0.055W/M2 (Schneider) to 0.271W/M2 (GRUMP) is a similar increase of 3.93 (=(0.271-.055)/.055). This is also illustrated in the Table showing little change in the area sensitivity value. We also note that in both the Schneider and GRUMP case, implementing cool roof show the same changes UHI effective albedo value requirment increase to 0.204 from 0.12 in order to reverse the warming trend.

5. Conclusions

In this paper we were able to estimate using UHI effect (with urban area) amplification coverage estimates with the aid of estimated UHI amplification factors. These estimates inserted into our WAASU model found that between 4.0 and 22% of global warming is related to UHI effect. The model found that the effect on global warming was proportional to the UHI amplification area coverage. This was noted since the amplification factors doubled using a half spherical coverage in the aggressive assessment; the model then found global warming results roughly also doubled from 8.52% to 43%. As area estimates and UHI amplification factors are very sensitive to the final results, it is clear refined estimates are needed.

Only UHI amplification effects were considered, global amplification effects in Table 2 were not speculated on to factor in. It is known that such feedback factors are positive (van Nes, 2015). For example, water-vapor feedback alone, which is one of the most important in our climate system, has the capacity to about double the direct warming (Manabe and Wetherald, 1967; Randall et al., 2007, Dessler et. al, 2008). Other global amplification factors have not been quantified such as albedo decrease due to loss of ice and snow. However, using just water-vapor feedback, it suggests values could then range 8% to 86% of global warming due to the UHI effect. This result, obtained now from a totally different perspective using a WASSU model, provides some credence to the McKitrick and Michaels 2007 contention that UHI effect's net warming bias at the global level may explain as much as half the observed land-based warming.

However, given even our conservative results, the study still points to the need for albedo enhancements like cool roofs in cities and urban areas to help stop related global warming anomalies.

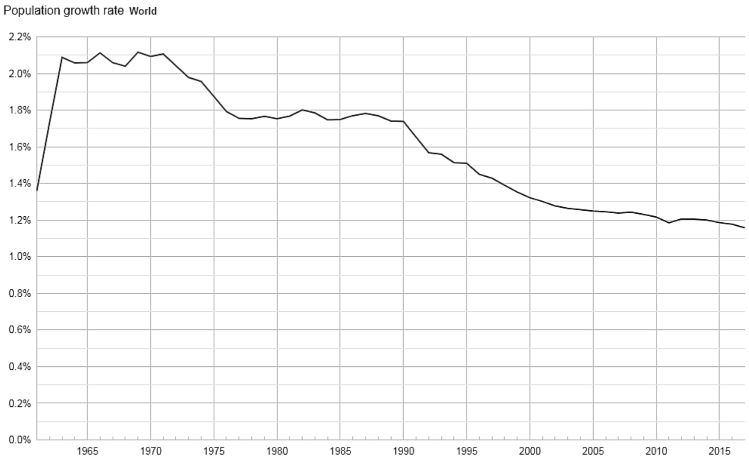
Below we provide suggestions and corrective actions which include:

- Creating IPCC goals to include the need for albedo enhancements in existing UHIs and roads
- A directive for future albedo design requirements of city and roads
- Recommend an agency like NASA be tasked with finding applicable solutions to cool down UHIs.
- Recommendation for cars to be more reflective. Here although world-wide cars likely do not embody much of the Earth's area, recommending that all new manufactured cars be higher in reflectivity (e.g., silver or white) would help raise awareness of this issue similar to electric cars that help improve CO2 emissions

We stress again that the IPCC is the main governing force and the only agency capable of promoting such albedo changes for cities and roads. Therefore, whether it is just for UHI known health reasons or due to studies similar to ours, we strongly urge the IPCC to set albedo goals and include such goals in their global meetings.

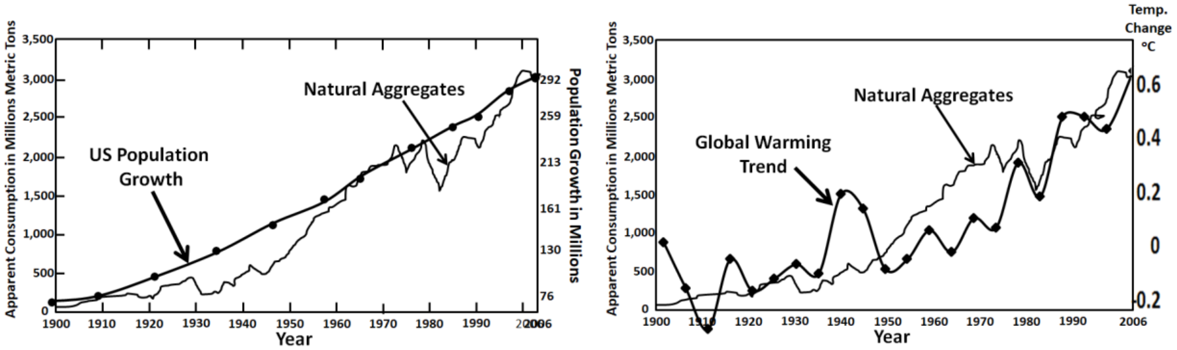
Appendix A Growth Rates and Natural Aggregates Information

Below is a plot of the world population growth rate that varies from about 2.1 to 1.1. This is used to make growth rate estimate of urban coverage. We note that natural aggregate used to build cities and roads are reasonably correlated to population growth in Figure A2a. Also of interest (Fig. A2b) is the fact that one can see some correlation to global warming with the use of natural aggregates.



Data from World Bank Last updated: Jul 6, 2018

Figure A1 Population growth rate by year from 1960 to 2018, World Bank, 2018



(a) **(b)**

Figure A2 **a)** Natural aggregates correlated to U.S. Population Growth (USGS 1900-2006) **b)** Natural aggregates correlated to global warming (NASA 2020)

Appendix B Related Warming Estimates and Other Amplification Factors

Although the global warming from UHI does not appear to contribute much, when other amplification factors are estimated, more significance can be obtained. In this section, additional and alternative amplification factors are suggested. Global warming estimates are also provided. Such factors can be contentious; therefore we have chosen to provide these in the appendix mainly as an aid for the reader and also illustrate possible increase in significance.

Global Feedback Amplification Factor

There is a wide range of estimates of climate feedback sensitivity driven by uncertainties in how water vapor, clouds, and other factors change as the Earth warms. Climate feedbacks are mixed and some will amplify (positive feedback) or diminish the effect of warming from the root cause effects (see for example Hausfather 2018). The actual feedback is known to be positive (van Nes, 2015). Climatologist will often approximate such factors frequently in reference with CO_2 doubling theory as positive. For example, water-vapor feedback alone, which is one of the most important in our climate system, is thought to have the capacity to about double the direct warming (Manabe and Wetherald, 1967; Randall et al., 2007, Dessler et. Al, 2008). It seems conservative then, given the numerous positive feedback mechanisms that a factor of 2 is not unreasonable. This factor would apply equally to UHI warming contribution similar to CO2. This factor is summarized in Table

UHI Dome Effect

Fan et. Al (2017) using an energy balance model to obtain the maximum horizontal extent of a heat dome in an urban area, found the nighttime extent of 1.5 to 3.5 times the diameter of the city's urban area and the daytime value of 2.0 to 3.3. The day-night extents average about 2.6 times to that of the city's diameter.

Applying this energy method instead of the area ratio where we found a factor of 3.1, we note that the diameter in 2019 compared to that of 1950 increased by about a factor of 1.8. Using this method implies that the average extent then is about 2.6 x 1.8=4.6 higher than in 1950.

This is an indication that the energy released by the UHI has increased by this amount since 1950. Furthermore, according to Fan et al., they noted this to occur about 4 hours after sunrise and about 5 hours after sunset. This day-night energy is effectively doubles the solar input as it is the equivalent of energy absorption compared to a normal earth surface 62.5% of the time (15 hours of radiation). This energy build up and release around the clock is the equivalent of twice the solar energy input 62.5% of the time (i.e., 2 x 0.625) adding a factor of about 1.25 energy increase to the reference year of 1950. This is tabulated in the table below.

Table 9. UHI & global amplification factors and missing factors

Urban Climate Amplification	Suggested Range	Amplification Factor	Where Applied
UHI Area Amplification Factor	3-3.19	3.1	Applied to 2019 UHI Area
UHI Dome Effect		4.6	
Day-Night Time Factor		1.25	
Suggested GWF Factor	1-3	x 2	Applied to Radiative Forcing

Appendix C: Albedo Model Renormalization Information

Table 5a and b are reproduced to illustrate renormalization methods.

Table 5a. Schneider Results (Albedo=29.4118, 1950)

Surface	Albedo	% Area of Surface	Normalized Earth Area	Weighted Albedo %
		71		
Sum of Water Type	A	B	C=A x B x (1-0.67)	A x C
Sea Ice	0.6	15	4.95	2.970
Water	0.06	56	18.48	1.109
Sum of Land Type		29		
Land - (UHI + Coverage)	0.3118	28.941	9.55053	2.978
UHI + Coverage	0.12	0.059	0.01947	0.002
		∑=100.000	33.000	7.05882
			Cloud Area	
Clouds	0.3336	67	67	22.35294
∑ Sum Earth %			100.000	
∑ Global Albedo				29.4118

Table 5b. Schneider Results (Albedo=29.3956%, 2019)

Surface	Albedo	Normalized % Surface Area	Normalized Earth Area	Weighted Albedo %
		70.6298		
Sum of Water Type	A	B	C=A x B x (1-0.67)	A x C
Sea Ice	0.6	14.9218	4.924194	2.955
Water	0.06	55.7081	18.383673	1.103
Sum of Land Type		29.37		
Land - (UHI + Coverage)	0.3118	28.79	9.5007	2.962
UHI + Coverage	0.12	0.58	0.1914	0.023
		∑=100.000	33.000	7.0197
			Cloud Area	
Clouds	0.3336	67	67	22.3529
∑ Sum Earth %			100.000	
∑ Global Albedo				29.3956

Renormalization is done as follows:

1. Model starts with 1950 Table 5a albedo 29.4118%, then 2019 Urban Coverage area is entered
2. For example, in Table B1, the newe area increases from 0.59% to .583%. This is 0.525% larger, now the “Sum of % of Earth Area” will be 100.527% in 2019
3. All areas are renormalized to 101.527%. For example, Sea Ice at 15% in 1950 becomes 15%x(100.000/100.527)= 14.921% and the Urban Cov becomes 0.583%x(100/101.11)=0.58%.

Appendix D WAASU Model References

Table C1 Key References for WAASU Model

Parameter	Albedo (reference)	1950 Area (reference)
Sea Ice	50-70%, average 60% (NSID 2020)	15% (Lindsey 2019)
Water	0.06 (NSIDC 2020)	56% Ocean+Sea Ice=71% (USGS)
Land-(UHI+Coverage)	Adjusted to obtain 30% Earth Albedo in 1950 thereafter held fixed	29%-Urban Coverage
UHI+Cov	0.12 Sugawara et. Al (2014)	See Table 1
Clouds	50% (Wikepedia 10-90% average =50% also see Hanson 1976)	67% (Earthobservatory, NASA)
Earth Albedo	30% (Goode 2001)	-

References for WAASU Model Values

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10-90% average Wikepedia, Cloud albedo

(clouds cover 67% of Earth) https://earthobservatory.nasa.gov/images/85843/cloudy-earth

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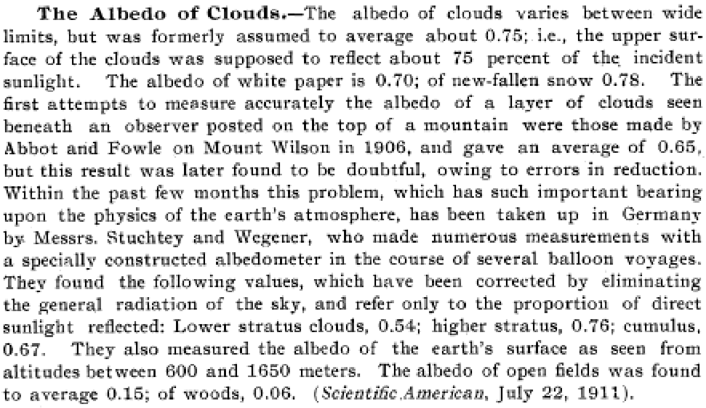

The Albedo of Clouds.—The albedo of clouds varies between wide limits, but was formerly assumed to average about 0.75; i.e., the upper surface of the clouds was supposed to reflect about 75 percent of the incident sunlight. The albedo of white paper is 0.70; of new-fallen snow 0.78. The first attempts to measure accurately the albedo of a layer of clouds seen beneath an observer posted on the top of a mountain were those made by Abbot and Fowle on Mount Wilson in 1906, and gave an average of 0.65, but this result was later found to be doubtful, owing to errors in reduction. Within the past few months this problem, which has such important bearing upon the physics of the earth's atmosphere, has been taken up in Germany by Messrs. Stuchtey and Wegener, who made numerous measurements with a specially constructed albedometer in the course of several balloon voyages. They found the following values, which have been corrected by eliminating the general radiation of the sky, and refer only to the proportion of direct sunlight reflected: Lower stratus clouds, 0.54; higher stratus, 0.76; cumulus, 0.67. They also measured the albedo of the earth's surface as seen from altitudes between 600 and 1650 meters. The albedo of open fields was found to average 0.15; of woods, 0.06. (*Scientific American*, July 22, 1911).

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Conflicts of Interest

The author declares that he has no conflicts of interest.

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