

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

Alec Feinberg

DfRSoft Research, email: dfrsoft@gmail.com, ORCID: 0000-0003-4364-2460

Key Words: Urban Heat Islands, Albedo Modeling, UHI Amplification Effects, UHI Heat Dome, Cool Roofs, Sea Ice Warming

Abstract In this paper, we provide nominal and worst-case estimates of radiative forcing due to UHI effect using a Weighted Amplification Albedo Solar Urbanization (WAASU) model. This calculation is done with the help of reported findings from UHI footprint and heat dome studies that simplify estimates for UHI amplification factors. Using this method, we quantify a global warming range due to the UHI effect (including urban extent). Forcing estimates varied between approximately 0.07W/m^2 to 0.87W/m^2 representing between 4% and 52% of global warming relative to GHG forcing estimates between 1950 and 2019. Variations in our model are due to the urbanized area and associated UHI amplification estimate uncertainties. However, the model showed consistent values of about $0.9\text{W/m}^2/\%$ solar effective amplified area and $1\text{W/m}^2/\%\Delta\text{albedo}$ for the urbanized coverage forcing values. The basic model is additionally used to quantify warming due to sea ice loss in assessing related feedback temperature rises. Results provide insight into the UHI area effects from a new perspective using a global view albedo model compared to prior ground-based measurement studies. It also illustrates the utility of using effective UHI amplification estimates when assessing UHI's warming effect on a global scale.

1 Introduction

There are few recent publications about possible UHI influences on global warming, more up-to-date related studies, including UHI amplification effects that will be discussed in this paper, could offer supporting data for climate change theories and solutions.

One key paper often referred to is by McKittrick and Michael's [1,2] who found in 2004 and 2007 using regression trends on socioeconomic and geographical indicators, that the net warming bias at the global level may explain as much as half the observed land-based warming. Another independent study often quoted by De Laat and Maurellis [3] in 2006 found very similar results, In the 2007 IPCC [4] questioned these findings stating "the locations of greatest socioeconomic development are also those that have been most warmed by atmospheric circulation changes (Sections 3.2.2.7 and 3.6.4), which exhibit large-scale coherence." Therefore, inferring that correlation of warming was not statistically significant but a result of atmospheric oscillations. In 2009 Schmidt [5] agreed and published a paper also suggesting that Mckitrick and Michael's correlations probably arise from chance. However, in 2010, McKittrick responded with two publications, the first [6] entitled, "Atmospheric Oscillations do not Explain the Temperature-Industrialization Correlation." The second by Mckintric et. al. in 2010 [7] detailing that, "Overall we find that the evidence for contamination of climatic data is robust across numerous data sets, it is not undermined by controlling for spatial autocorrelation, and the patterns are not explained by climate models. Consequently, we conclude that important data products used for the analysis of climate change over global land surfaces may be contaminated with socioeconomic patterns related to urbanization and other socioeconomic processes." The IPCC in 2013 summarized the controversy as follows [8], "it is indisputable that UHI and land-use/land-cover are real influences on raw temperature measurements. At question is the extent to which they remain in the global products." Citations and discussions in this IPCC suggesting the UHI effect should be less than 10% of the warming.

However, other authors have also found UHI significance [9-16]. These studies used land-based temperature station data to make assessments. To date, one can conclude that all such studies and findings were not persuasive enough to be influential in the 2015 Paris Climate Accord [17] regarding the need for UHI albedo controls as part of the world-wide effort to mitigate global warming.

In this paper, we provide insight into McKittrick and Michael's controversial findings and that of other such authors [9-16] with a Weighted Amplification Albedo Solar Urbanization (WAASU) model. There are currently no papers on the influence of urbanization on climate change using albedo modeling. However, this paper is restricted to UHI extent and does not take into account all forms of human land contamination (such as roads, rural human habitation, deforestation, etc.) of which are correlated by McKittrick and Michael's socioeconomic - geographical method.

The WAASU model has advantages as it works from a global view rather than with ground-based studies. There are no concerns about warming oscillations. The model is non-probabilistic and in line with typical energy budgets (IPCC, Hartmann et al. [8]). It uses only two key parameters: normalized solar effective amplified area and weighted albedo values. Because it is simplistic, it has transparency compared with the complex land-based socioeconomic and geographical studies. We also show its utility by extending it to a Weighted Albedo Solar (WAS) model for global warming estimates due to Arctic ice melting in Appendix D.

The contention that UHI effects are only of local significance is most likely related to urban area estimates. For example, the IPCC (Satterthwaite et. al. [18]) AR5 report references a Schneider et al. [19] study that resulted in urban coverage of 0.148% of the Earth (Table 1). This seemingly small area tends to dismiss the role that the UHI effect can play in large-scale global warming. Furthermore, estimates of how much land has been urbanized vary widely in the literature, in part due to the definition of what is urban and the datasets used. Although, such estimates are important for environmental studies, obtaining true estimates for the small urbanized area relative to the total land is very difficult. Compounded by the fact that there is a significant difference in how groups define the term “urban”. Table 1 illustrates several variations from select papers of interest.

In addition, global warming UHI amplification effects have not been quantified to a large degree related to area estimates. Urbanized average solar areas remain unknown.

Table 1. Urbanization area extent estimates from various sources

Percent of Land	Percent of Earth	References
2.7	0.783	GRUMP [20] – using NASA satellite light studies based on 2004 data and supplemented with census data
1	0.29	NASA [21], Galka [22] – from satellite data
0.51	0.148	Schneider et al. [19] – based on 2000-2001 data and referenced in the IPCC report (Satterthwaite, [18])
0.5	0.145	Zhou [23] – based on a 2000 data set

In our study, one key paper listed in Table 1 is due to Schneider et al. [19] since it is cited by the AR5 2014 IPCC report (Satterthwaite et al. [14]). In Schneider’s paper, the larger area found in the GRUMP [20] study (Table 1) is criticized for user accuracy. However, it is important to incorporate the GRUMP area as an upper bound. We note that UHI effects have been shown to arise even at very low levels of populations, i.e., towns with fewer than 10,000 people as noted by Karl et al 1988 [24], Chagnon 1999 [25]. The GRUMP study describes datasets with populations greater than 5,000 people while in the Schneider paper population estimates were not included. The GRUMP study combines population statistics and nightlights where the Schneider paper uses high resolution of illuminated satellite data with decision tree algorithms.

In this paper we use both the Schneider et al. and GRUMP studies for the minimum nominal and maximum worst-cases urbanization area estimates respectively. Furthermore, they were both done using data sets near the year 2000, a reasonable point in time to extrapolate down to 1950 and up to 2019 (see Sec. 2.5).

1.1 UHI Amplification Effects

The table below lists key global warming causes and amplification effects. In Appendix B we summarize only the UHI amplification effects listed in the table since the root-causes and the main global warming feedback 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 (GHG)
Global Warming Feedback Amplification Effects →	Water-Vapor Feedback, Land Albedo Change Due to Cities & Roads, Ice and Snow –Albedo Feedback, Lapse Rate Feedback, Cloud Feedback, etc.
Urban Heat Island Solar Amplification Effects →	UHI Solar Heating Area (Building Areas), UHI Building Heat Capacities, Humidity Effects, Hydro-Hotspots, Reduced Wind Cooling, Solar Canyons, Loss of Wetlands, Increase in Impermeable Surfaces, Loss of Evapotranspiration Natural Cooling.

2 Data and Methods

We see from the previous section that estimating climate change impact just based on the UHI area coverage as in Table 1, does not take into account the effects of solar heating building sidewall areas, massive heat capacities, humidity issues, wind reduction, and the solar canyon trapping that collectively amplify UHI effects beyond its climate area. Due to the high-level complexity of UHI amplification effects, the only way to assess their effect is likely by using their climate observations to see how such effects might scale with city size for example.

2.1 UHI Area Amplification Effect

To estimate the UHI complex amplification effects, it is logical to first look at UHI footprint (FP) studies as they provide some measurement information. Zhang et al. [26] found the ecological FP of urban land cover extends beyond the perimeter of urban areas, and the FP 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. [27], they looked at day-night cycles using temperature difference measurements in China. In this study, they found the UHI effect decayed exponentially toward rural areas for the majority of the 32 Chinese cities. Their comprehensive study spanned from 2003 to 2012. They describe China as an ideal area to study since it has experienced the most rapid urbanization in the world in the decade they evaluated. They found that the FP of the UHI effect, including urban areas, was 2.3 and 3.9 times that of urban size for the day and night, respectively. We note that the average day-night amplification footprint coverage factor is 3.1.

As the IPCC states, it is indisputable that UHI and land-use/land-cover are real influences on raw temperature measurements. Furthermore, it is evident that UHI's solar amplification effects: heat capacity, solar area, canyon effect, humidity effect, evapotranspiration must scale with UHI growth.

To provide some assessment of how the UHI amplification factor scales, we note that Zhou et al. [27] found the FP physical area (km²), correlated tightly and positively with actual urban size having a correlation coefficient higher than 79%. This correlation can be used to provide an initial estimate of this complex factor. Furthermore, the fact that the amplification factor scales with area becomes logical in the calculation of the WAASU model where we assume a constant albedo in Sec. 2.5 (see Eq. 9, and the model's derivation in Appendix A).

Therefore, as a model assumption, it seems reasonable to use area ratios for estimating the amplification factor AF_{UHI} . Then

$$AF_{UHI \text{ for } 2019} = \frac{\sum (UHI \text{ Area})_{2019}}{\sum (UHI \text{ Area})_{1950}} \quad (1)$$

Area estimates have been obtained in the next Section in Table 3 between 2019 and 1950 time frames, yielding the following results for the Schneider et al. [19] and the GRUMP [20] extrapolated area results:

$$AF_{UHI \text{ for } 2019} = \frac{(Urban \text{ Size})_{2019}}{(Urban \text{ Size})_{1950}} \approx \begin{cases} \left(\frac{[0.188]_{2019}}{[0.059]_{1950}} \right)_{Schneider} & = 3.19 \\ \left(\frac{[0.952]_{2019}}{[0.316]_{1950}} \right)_{GRUMP} & = 3.0 \end{cases} \quad (2)$$

Between the two studies, the method of area scaling for the UHI solar amplification effect averages 3.1. Coincidentally, this factor is the same observed in the Zhou et al. [27] 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 wetlands, deforestation effects due to urbanization, and drought-related fires, and humidity issues. Also difficult to model are factor changes of other impermeable surfaces since 1950, such as highways, parking lots, event centers, and so forth.

The area amplification value of 3.1 between 1950 and 2019 is a logical scale factor as a model assumption. It relates well to Zhou et al. footprint and their observed area correlation. Furthermore, it is well supported by the WAASU model derivation in Appendix A.

2.2 Alternate Method Using the UHI's Dome Extent

An alternate approach to check the estimate of Equation 3 is to look at the UHI's dome extent. Fan et al. [28] 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). The horizontal extent of the heat dome is an important parameter for estimating the size of the area it influences and is similar to Zhou et al. [27] footprint.

Applying this energy method (instead of the area ratio factor in Eq. 2, yields a diameter in 2019 compared to that of 1950 with an increase of 1.8. In the Fan et al. method the city diameter is multiplied time their derived day and night factors to obtain the horizontal extent. In our case, we want the diameter change from the area increase in Eq. 2, which is 1.8 ($=\sqrt{3.1}$). Therefore, this yields $2.5 \times 1.8=4.5$ higher in the night and $2.65 \times 1.8=4.8$ in the day in 2019 with an average of 4.65. According to Fan et al. we multiply this by 62.5% of the time according (their study indicated that transition states of 4 hours around sunrise, and about 5 hours around sunset, were not used, totaling 9 hours out of 24). This yields an effective horizontal extent UHI amplification factor of 2.9. We note this is in good agreement with Zhou et al footprint and Eq. 2. Fan et al. [28] assessed the heat flux over the urban area extends to its neighboring rural area where the air is transported from the urban heat dome flow. Therefore the heat dome extends similarly as observed in the footprint studies. If we use the dome concept, we can assume that the actual surface area for the heat flux is increased by the surface area of the dome. This should be considered as part of the atmospheric UHI vertical and horizontal extents which both are influential in global warming. We do not know the true diameter of the dome, but it is larger than the assessment by Fan et al. Using their dome extend applied to the area diameter D increase from 1950 to 2019, the amplification factor should be correlated to the ratios of the dome spherical surface areas:

$$AF_{UHI \text{ for } 2019} = \left(\frac{D_{2019}}{D_{1950}} \right)^2 = 2.9^2 = 8.4 \quad (3)$$

This value is our second model assumption. Here the ratios of the dome's surface area are applied as an alternate approach in estimating how the amplification effect scales with UHI growth over time which provides a measure of vertical and horizontal extent. Therefore, we will apply both factors, 3.1 and 8.4, as an upper and lower bound for the UHI solar effective amplified area.

2.3 Applying the Amplification Factors

In this analysis, 1950 is the reference year. Therefore, it is not subjected to amplification. Only the new area is amplified as we are looking at changes since this time frame. This is denoted as the solar effective amplified Area (EAA_{UHI}). The EAA_{UHI} in 2019 (see Sec. 2.5) is then given by

$$EAA_{UHI} = AF_{UHI} \times \text{Newarea} + \text{Area}_{1950} = AF_{UHI} \times (\text{Area}_{2019} - \text{Area}_{1950}) + \text{Area}_{1950} \quad (4)$$

Using this, if there were no changes in UHI growth, for example, so that the $\text{Area}_{2019}=\text{Area}_{1950}$, the resulting area is just the original Area_{1950} . This result is applied to the new area in Table 3 below.

2.4 Area Extrapolations for 1950 and 2019

To assess the urbanized area, (also used in determining the UHI amplification factor ratios above), we need to project the Schneider [19] and GRUMP [20] area estimates down to 1950 and up to 2019. Both use datasets are near to 2000, so this is a convenient somewhat middle time-frame. Here we decided to use the world population growth rate (World Bank [29]) which varies by year as shown in Appendix C in Figure C1. We used the average growth rate per $\frac{1}{2}$ decade for iterative projections of about 1.3% (from 2000 to 2019) to 1.8% (from 2000 down to 1955) per year.

To justify this projection, we see that Figure A2a illustrates that building material aggregates (USGS [30]) used to build cities and roads correlates well to population growth (USGS Population Growth [31]).

It is also interesting to note that building materials for cities and roads also correlates well to global warming trends (NASA [32]) shown in Figure A2b.

Column 2 in Table 3 shows the projections with the actual year (~ 2000) data point tabulated value also listed in the table (see also Table 1). The UHI area amplification factors (Column 3) is then applied to Schneider [19] and GRUMP [20] studies shown in Column 4 using Equation 5.

As an example of the EAA calculation in Table 3, using Eq. 4, the 2019 Schneider 3.1 amplification factor is used as follows:

$$(0.188-0.59) \times 3.1 + 0.59 = 0.459$$

Table 3. Extrapolated and amplified urbanized coverage estimates

Year	Urban coverage percent of Earth	Amplification factor	Effective Amplified Area (EAA)
Schneider study [19]			
1950	0.059*	1	0.059%
2000-2001	0.0051x29%=0.148		
2019	0.188*	3.1 AF _{Area} **	0.459%
2019	0.188*	8.4 AF _{Dome} **	1.143%
Worst-case GRUMP study [20]			
1950	0.316%*	1	0.316%
2000	0.027x29%=0.783%		
2019	0.952%*	3.1 AF _{UHI} **	2.288%
2019	0.952%*	8.4 AF _{Dome} **	5.658%

*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.

2.5 Weighted Amplification Albedo Solar Urbanization (WAASU) Model Overview

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

$$Earth\ Albedo = 0.33 \sum_i \{ \% Effective\ Surface\ Area_i \times Surface\ Item\ Albedo_i \} + Cloud\ Area \times Cloud\ Albedo. \quad (5)$$

The full weighted model is rigorously derived in Appendix A and for 1950 is

$$\alpha_{1950} = \frac{0.33}{A_E} \sum \hat{A}_i \alpha_i + \frac{0.33}{A_E} A_{UHI} \alpha_{UHI} + \frac{A_C}{A_E} \alpha_C \quad (6)$$

and for 2019

$$\alpha_{2019} = \frac{0.33}{A_E'} \sum \hat{A}_i \alpha_i + \frac{0.33}{A_E'} A_{UHI} AF \alpha_{UHI} + \frac{A_C}{A_E'} \alpha_C \quad (7)$$

Here α is the Earth's Albedo, α_i is the albedo of each Earth component with associated surface \hat{A}_i (the hat indicating all areas excluding the UHI area), A_{UHI} is the area of the UHIs occupy on the Earth, AF is the UHI amplification factor (Sec. 2.1 and 2.2) and A_C is the cloud coverage area with average cloud albedo α_C (Appendix E). As explained in Appendix A, the 0.33 factor arises from the fact that 67% of the Earth is covered by clouds [47].

As well, A_E Earth's surface area in 1950 and A_E' is the Earth's area in 2019 due to the EAA_{UHI} effective increase, given by

$$A_E' = A_E + EAA_{UHI} \quad (8)$$

where EAA is defined in Eq. 5. Therefore, this increase requires renormalization that is discussed in Section 2.5.1 (for example, if water covers 56% of the Earth, now it will be slightly less since the Earth's solar area has increased due to the buildup of cities which increase due to solar effective amplified area)

It is important to note that AF is combined with the UHI area and its albedo value

$$(A_{UHI}) (AF_{UHI}) (\alpha_{UHI}) \quad (9)$$

This shows the combined effect of the factor in the model and its possible influence on each factor. However, an assumption of the model is α_{UHI} stays constant from 1950 to 2019. That is the albedo roughly doesn't change much as city growth occurs. This is a model assumption. Therefore, this assumption justifies our use of the term the effective amplified area (EAA) for $A_{UHI} \times A$.

Note that all the effective surface areas are influenced by the solar irradiance

$$\text{Effective Surface Area} = \text{Surface Area} \times \% \text{Solar Irradiance}. \quad (10)$$

where the surface area includes all areas including EAA. However, we note that the change in the Earth Albedo over time (from 1950 to 2019), is just a function of the UHI area variation, (when holding all unrelated UHI components constant), that is

$$\left(\frac{d\alpha}{dt} \right)_{EA'} \approx \sum_i \left(\text{Albedo}_{UHI} \times \% \text{Solar Irradiance} \times \frac{d\text{Surface Area}_{UHI}}{dt} \right)_i, \quad (11)$$

Here EA' is all other Earth components (held constant). Although it is possible that the solar irradiance percent changes due to new city locations, in this model we assume it is fixed at 100%.

2.5.1 Model Constraints

Because of Eq. 8, this model is subject to the constraint

$$\text{Total Area} = \sum_i \{ \% \text{Normalized Effective Amplified Surface Areas}_i \} + \% \text{Cloud Area} = 100\% \quad (12)$$

and the normalization effective amplified area (NEAA) constraint for the Earth surface areas (when the UHI area is increased) must then be subject to

$$\sum_i \{ \% \text{Normalized Effective Amplified Surface Areas}_i \} = 100\% - \% \text{Cloud Area}. \quad (13)$$

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 E. Furthermore, we use consistent values found in the IPCC AR5 report (Hartmann et al. [8]) assessment of the Earth's energy budget for solar irradiance. Table 4 summarizes the constraints from these IPCC values.

Table 4. IPCC Earth energy budget values (Hartmann et al. [8])

IPCC Item 2013 Budget	Incident and Reflected Radiation (W/m ²)	Albedo % α	P_α Absorbed (W/m ²)
Earth	100/340	29.4118	240=340x(1-.294)
Atmosphere & Clouds	76/340	22.3529	79
Earth Surface Albedo	24/340	7.0588	161
Year	GHG Effect	Surface T(°K)	Power
1950 No GHG Effect	$P_\alpha \times 1$	255 (-18.08°C)	240
1950 With GHG Effect	$P_\alpha \times 1.61^*$	287.3 (14.1°C)	386 (=240x1.61)

*1.61 is an average GHG re-radiation factor and $P_\alpha=340\text{W/m}^2(1-\alpha)$

The fixed components of our model maintain relative consistency from 1950 to 2019. The non-fixed value is the urban coverage as indicated by Equation 8. The only unknown value is the *land* albedo (minus the UHI coverage) and this value is adjusted to obtain the IPCC global albedo, 29.4118%, and its *land* value of incident/reflected value of 7.0588.

These values are used as a 1950 starting point and then the 2019 increase for the UHI coverage area is inserted. This increases the Earth's area to greater than 100%. Therefore, renormalization is done per the constraint of Equation 13. Renormalization is detailed in Appendix F.

3 Results

Using the extrapolated area coverage in Table 3 with the 3.1 amplification factor applied to the urbanized growth, the resulting global albedo change occurred of 29.3994% in 2019 (Table 5b) compared to the earlier 1950 albedo

value of 29.4118% (Table 5a) for the Schneider nominal case. As well, for the GRUMP worst-case, the albedo changed from 29.4118% (Table 6a) to 29.3519% (Table 6b) due to the urbanized growth. Dome values are also provided in Appendix F.

As we mentioned earlier, the increases in the solar surface area of the Earth, which will occur with city growth of tall buildings and their solar areas, however comparatively small, requires renormalization in the model of the Earth's surface components of the WAASU model (detailed in Appendix A). This information is displayed in Column 3 in Tables 5b, and 6b. While the model is sensitive to urban coverage changes, it works well with renormalization showing a high level of consistency to urban coverage proportionality changes. This consistency is indicated in Table 7 where we find the GRUMP and Schneider ling wavelength radiation (LWR) forcing per NEAA averages about 0.094% (W/m²)/NEAA.

Table 5a. Schneider 1950 effective estimate

Surface	Albedo	%NEAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		71		
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	9.5505	2.978
UHI + Coverage	0.12	0.059	0.0195	0.002
		$\Sigma=100.000$	33.000	7.05882
			Cloud Area	
Clouds	0.3336	67	67	22.35294
Σ Sum Earth %			100.000	
Σ Global Albedo				29.4118

Table 5b. Schneider 2019 effective estimate (AF=3.1)

Surface	Albedo	%NEAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		70.717		
Sea Ice	0.6	14.94	4.9302	2.958
Water	0.06	55.777	18.406	1.1044
Sum of Land Type		29.283		
Land - (UHI + Coverage)	0.3118	28.826	9.513	2.966
UHI + Coverage	0.12	0.4571	0.1508	0.0181
		$\Sigma=100.000$	33.00	7.0283
			Cloud Area	
Clouds	0.3336	67	67	22.3530
Σ Sum Earth %			100.000	
Σ Global Albedo				29.3994

Table 6a. GRUMP 1950 effective estimate

Surface	Albedo	%NEAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		71		
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	9.466	2.968
UHI + Coverage	0.12	0.316	0.1043	0.013
		$\Sigma=100.000$	33.000	7.0588
			Cloud Area	
Clouds	0.3336	67	67	22.35294
Σ Sum Earth %			100.000	
Σ Global Albedo				29.4118

Table 6b. Grump 2019 effective estimate (AF=3.1)

Surface	Albedo	%EAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		69.627		
Sea Ice	0.6	14.71	4.8543	2.913
Water	0.06	54.917	18.12261	1.087
Sum of Land Type		30.3727		
Land - (UHI + Coverage)	0.3135	28.129	9.28257	2.910
UHI + Coverage	0.12	2.2437	0.740421	0.089
		$\Sigma=100.000$	33.000	6.9100
			Cloud Area	
Clouds	0.3336	67	67	22.3530
Σ Sum Earth %			100.000	
Σ Global Albedo				29.3519

Table 7 provides a summary of albedo changes found in the WASSU model along with the expected solar longwave radiation increase. From the above global WAASU model, the estimates of the Earth's radiated long wavelength emissions are set equal to the short wave radiation absorption:

$$P_{\alpha} = 340 \text{ W/m}^2 (1 - \text{Albedo}). \tag{14}$$

Then the albedo change from 1950 to 2019 represents the equivalent increase in longwave radiation is given by

$$\Delta P_{\alpha} = 340 \text{ W/m}^2 \{ (1 - \text{Albedo})_{2019} - (1 - \text{Albedo})_{1950} \}. \tag{15}$$

The results are compiled in Table 7. The table also includes “what if” estimates, if we could change urbanization to be more reflective with cool roofs to reverse the effect.

Table 7. Albedo and radiative increase model results with UHI effective area.

Year	UHI Area %	UHI %EAA AF=3.1 AF=8.4	UHI NEAA Global Surface %Area	Albedo Cities	Global Weighted Albedo	Forcing LWR* ΔP_{α} UHI W/m ²	$\frac{\Delta P_{\alpha} (W/m^2)}{\%EAA}$ $\left(\frac{\Delta P_{\alpha} (W/m^2)}{\%Albedo} \right)$
Nominal Case Schneider Study							
1950	0.059	0.059	0.059	0.12	29.4118	0	—
2019	0.188	0.459	0.457	0.12	29.3994	0.0422	0.092 (1.0)
2019	0.188	1.143	1.1307	0.12	29.3786	0.1129	0.10 (1.0)
What if	0.188	0.459	0.457	0.202	29.4118	-0.042	—
	0.188	1.58	1.13	0.209		-1.129	
Worst-Case GRUMP Study							
1950	0.316	0.316	0.316	0.12	29.4118	0	—
2019	0.952	2.288	2.243	0.12	29.3519	0.204	0.09 (1.0)
2019	0.952	5.658	5.395	0.12	29.2546	0.537	0.095 (1.0)
What if	0.952	2.288	2.2437	0.201	29.4118	-0.204	—
	0.952	5.658	5.395	0.209		-0.537	

*Long Wavelength radiation (LWR) values do not include the additional GHG re-radiation (see Table 8).

The overall results are summarized:

- Schneider nominal case from 1950 to 2019, the increase in LWR forcing (Row 7) is 0.042W/m² and 0.11W/m² due to urban area and dome amplification coverage respectively. These values do not include the addition of GHG re-radiation (see Table 8).
- GRUMP worst-case from 1950 to 2019 the increase in LWR (Row 7) is 0.204W/m² and 0.537W/m² due to urban area and dome amplification coverage respectively. These values do not include the addition of GHG re-radiation (see Table 8).
- We note the consistency of the area forcing parameter having small variability and averaging about 0.094 W/m²/EAA. We also note in Column 8 the consistent value of 1.0 W/m²/Albedo. This value is a useful constant and can be derived [33]. Note these values do not take into account GHG re-radiation (see Sec. 4).
- “What if” corrective action results of cool roofs indicate that changing city albedos in both the Schneider and the GRUMP case from 0.12 to an average value of 0.205 would reverse the increase forcing back to 1950 levels. As an interesting sanity check, note that He et al. [34] estimated an average global land surface albedo of 0.25 from 1981-2010 by comparison.

4. Discussion on the Relative Contribution to Global Warming Forcing due to UHIs

Full UHI radiation forcing and associated temperature rise

Estimates in Table 7 provide the LWR forcing, but the anticipated average GHG additional re-radiation forcing increase expected is not included. This average factor is estimated as 1.61 and is exemplified in Table 4 [33]. Column 4 in Table 8 provides the full forcing anticipated and Column 5 the associated temperature increase. Appendix G provides an overview of these estimates.

IPCC/NOAA Radiation Forcing Comparison

To make relative comparisons with UHI forcing, we compare the forcing results in Table 8 to IPCC estimate for GHG forcing from the period 1950 to 2019, and this associated temperature rise. The GHG forcing estimate by IPCC/NOAA [35] is 2.38 W/m² during this time period.

One should note that this value does not include “feedback” (i.e., arctic snow and ice melting) as “forcing” is our primary concern. Column 6 in Table 8 shows the relative forcing ratio to compare it to the UHI strength. For example, the LWR found in the Schneider case for the albedo of 29.3994 was 0.042 W/m². Then we estimate with GHG re-radiation this is 0.042 W/m² X 1.6=0.068 W/m². Then relative to the IPCC GHG forcing estimate, this is about 2.9% (=0.068/2.38) in Column 6.

IPCC/NOAA Global Temperature Rise Due to Forcing Comparison

Column 5 in Table 8 provides the anticipated UHI WAASU model temperature rise due to the forcing in Column 4 (see Appendix G for details). We can compare these to the estimated IPCC/NOAA forcing of 2.38 W/m² by converting this forcing to a global temperature increase. This value is about 0.44°C (not including feedback). Appendix G provides details for this estimate. Then the last Column is simply the ratio of the WAASU temperature increases relative to 0.44°C. This provides a relative comparison.

Table 8. WAASU Model full forcing and global warming estimate due to UHI in 2019

UHI EAA Global Surface %Area	Global Weighted Albedo	Percent Albedo Change from 29.4118	Full UHI Forcing P_{α} Includes GHG Re-Radiation LWRx1.61 W/m ²	UHI Temperature* ΔT_{UHI} (°C)	UHI Forcing Relative to IPCC/NOAA Estimate of GHG Forcing 2.38 W/m ²	Percent of Global Warming Relative to 0.44°C Rise
Schneider Case						
0.459	29.3994	0.042%	0.068	0.018	2.9%	4.1%
1.143	29.3786	0.11%	0.182	0.048	7.6%	10.9%
GRUMP Case						
2.288	29.3519	0.2%	0.328	0.088	13.9%	20%
5.658	29.2546	0.53	0.867	0.23	36.4%	52.3%

Finally, from Table 7 (last column) the following equations for forcing estimates may be helpful

$$\alpha_{Global_Forcing} = 1.6 \times 1.0 W / m^2 / \% \Delta Albedo \quad (16)$$

and

$$UHI_{AAA_Forcing} \approx 1.6 \times 0.094 W / m^2 / \% EAA \quad (17)$$

Examples of how these might be used are provided in Appendix G. Lastly, as a check, one may note that UHI global warming estimates roughly scale with UHI size as might be expected. For example, in Table 1 the ratio of Schneider to Grump UHI area extent is 2.7/0.51=5.3. We note the values in the last column in Table 8 scale close to this factor (i.e. 4.1% \times 5.3=21.7% close to 20% observed).

4. Conclusions

In this paper, we were able to provide estimates of the UHI effect (with urban areas) on global warming. This calculation was done with the aid of assumptions for UHI solar amplification factors. These estimates inserted into our WAASU model found that between 0.068W/m² to 0.87W/m² of radiative forcing (Table 8) may be possible This forcing result indicates that about 4% to 52% of global warming may be due to the UHI effect by comparisons to anticipated GHG temperature increase (when feedback temperature increase are removed). These wide variations are due to both the amplification and urban area uncertainties. However, the model found that the effective UHI area forcing and albedo estimates were consistent showing 0.095W/m² per % of Effective Amplified Area and 1.61 W/m²/ % Δ albedo.

A similar Weighted Area Albedo (WAS) model was also used to estimates the temperature rise due to ice loss. The warming increase due to ice melting from the WAS model was found to be about 0.15°C in 2019 in Appendix D.

Below we provide suggestions and corrective actions which include:

- Albedo guidelines for both UHIs and roads similar to on-going CO₂ efforts.
- Conservatively adding albedo controls to the Paris Climate Accord
- Guidelines for future albedo design considerations of cities.
- Recommend an agency like NASA to be tasked with finding applicable solutions to cool down UHIs.
- Recommendation for cars to be more reflective. Although world-wide vehicles likely do not embody much of the Earth's area, recommending that all newly manufactured cars to be higher in reflectivity (e.g., silver

or white) would help raise awareness of this issue similar to electric automobiles that help improve CO2 emissions.

Appendix A: Derivation of the WASSU Model

The long-wavelength radiation power P absorbed by the Earth in W/m^2 is given by

$$P = \frac{S_o}{4}(1 - \alpha) \quad (A-1)$$

Here α is the Earth's albedo and $S_o=1361 W/m^2$. From Equation A-1, the albedo can be written

$$\alpha = 1 - \frac{4P}{S_o} \quad (A-2)$$

Let small p indicate the power in watts so that

$$p(\text{watts}) = A_E P(W / m^2) \quad (A-3)$$

This is useful for re-writing Eq. A-1 in terms of the Earth's areas A_E for surface land area A_s and cloud coverage area A_C , receiving solar power. This gives

$$p(\text{watts}) = A_E \frac{S_o}{4}(1 - \alpha) = (A_s + A_C) \frac{S_o}{4}(1 - \alpha) = (0.33A_E + A_C) \frac{S_o}{4}(1 - \alpha) \quad (A-4)$$

Here it is assumed that on average 33% of the Earth receives direct sunlight or 67% is covered by clouds [Ref. 47, Appendix E], that is

$$A_E = A_s + A_C = 0.33A_E + A_C \quad (A-5)$$

Now we can divide through by A_E yielding

$$\frac{4p}{A_E S_o} = \frac{4P}{S_o} = \frac{(0.33A_E + A_C)}{A_E}(1 - \alpha) = \frac{0.33}{A_E} \sum A_i (1 - \alpha_i) + \frac{A_C}{A_E}(1 - \alpha_C) \quad (A-6)$$

Then expanding terms on the RHS we have

$$\frac{4P}{S_o} = \frac{0.33}{A_E} \sum A_i - \frac{0.33}{A_E} \sum A_i \alpha_i + \frac{A_C}{A_E} - \frac{A_C}{A_E} \alpha_C \quad (A-7)$$

Collecting terms we can write

$$\frac{4P}{S_o} = \left\{ \frac{0.33}{A_E} \sum A_i + \frac{A_C}{A_E} \right\} - \frac{0.33}{A_E} \sum A_i \alpha_i - \frac{A_C}{A_E} \alpha_C \quad (A-8)$$

Note that in Eq. A-8 the first term on the RHS is unity

$$\left\{ \frac{0.33}{A_E} \sum A_i + \frac{A_C}{A_E} \right\} = \frac{A_s + A_C}{A_E} = 1 \quad (A-9)$$

Then Eq. A-8 is now

$$\frac{4P}{S_o} = 1 - \left(\frac{0.33}{A_E} \sum A_i \alpha_i + \frac{A_C}{A_E} \alpha_C \right) \quad (\text{A-10})$$

or

$$1 - \frac{4P}{S_o} = \frac{0.33}{A_E} \sum A_i \alpha_i + \frac{A_C}{A_E} \alpha_C \quad (\text{A-11})$$

Combining this with Eq. A-2, the area-weighted albedo model is

$$\alpha = \frac{0.33}{A_E} \sum A_i \alpha_i + \frac{A_C}{A_E} \alpha_C \quad (\text{A-12})$$

However, further weighting the model with the UHI amplification factor AF_{UHI} by expanding out A_i to treat the UHI area separately yields our final WAASU model

$$\alpha = \frac{0.33}{A_E} \sum \hat{A}_i \alpha_i + \frac{0.33}{A_E} A_{\text{UHI}} AF_{\text{UHI}} \alpha_{\text{UHI}} + \frac{A_C}{A_E} \alpha_C \quad (\text{A-13})$$

The inclusion of AF_{UHI} is presented as a weighting factor in the only logical part of the equation for the WAASU model. Here, the first term \hat{A}_i hat indicates all areas of the Earth except the UHI area where the 2nd term, is broken out for the UHI of the sum to illustrate how it is modeled. We note that $AF_{\text{UHI}_{1950}}=1$ and $AF_{\text{UHI}_{2019}}>1$ (see Sec. 2.1 and 2.2 for this factor).

Appendix B: UHI Dominant Amplification Effects

The UHI amplification effects that we consider to dominate listed in the Table 2 are as follows:

- ***The heat capacity and solar heating area amplification effect:*** Solar surface areas of buildings make the city much larger than its actual surface area in terms of solar absorption. Thus, solar building area amplification may be the most dominant aspect of the UHI climate area. When this is included with the massive heat capacities of building, the combined effect creates a day-night heat cycle. In most cities, it is observed that daytime atmospheric temperatures are cooler compared to night. For example, in a study by Basara et al. [37] 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 result 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 occurrence often reduces the UHI day effect, but at night buildings cool 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 since 1950 (Barr [38]).
- ***The hydro-hotspot amplification effect:*** This effect is not well addressed in the literature. Atmospheric moisture source is a complex issue due to Hydro-HotSpots (HHS). HHS occurs when buildings are hot due to sun exposure. Then, during precipitation periods, the hot evaporation surfaces increase localized water vapor as warm air holds more moisture. This increase likely acts at times as a local greenhouse gas that blankets city heat and increases infrared radiation during these periods, providing another UHI humidity amplification source. This effect combined with the heat storage occurring from daytime hours indicates that the effect may occur even during nighttime precipitation. The level of hydro-hotspot significance in climate change is currently unknown. However, observations of this effect are reasonably well established in observed humidity effects.

The humidity amplification effect: This effect has been observed. For example, Zhao et al. [36] 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 UHIs will exacerbate heat wave stress on human health in wet UHI climates. They found a strong correlation between ΔT increase and daytime precipitation. Their results concluded that albedo management would be a viable means of reducing ΔT on large scales.

- **Reduced wind cooling and solar canyons:** In UHIs reduced wind is a known effect due to building wind friction that inhibits cooling by convection. Tall buildings also create solar canyons and trap sunlight, reducing the average albedo, although some benefits occur from shading. In general, both have the effect of amplifying the temperature profile of UHIs.

Appendix C: Growth Rates and Information on Natural Aggregates

Below is a plot of the world population growth rate that varies from about 2.1% to 1.1%. This graph is used to make growth rate estimates of urban coverage. We note that natural aggregates used to build cities and roads are reasonably correlated to population growth in Figure C2a. Also of interest (Fig. C2b) is the fact that one can see some correlation to global warming with the use of natural aggregates.

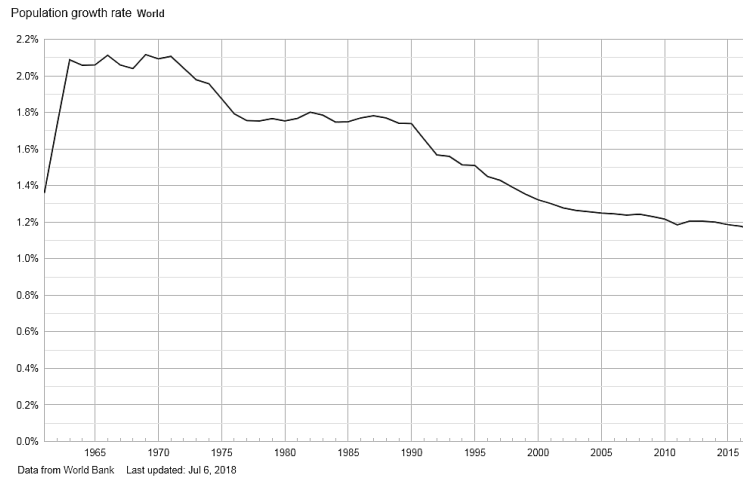


Figure C1. Population growth rate by year from 1960 to 2018, World Bank, [29]

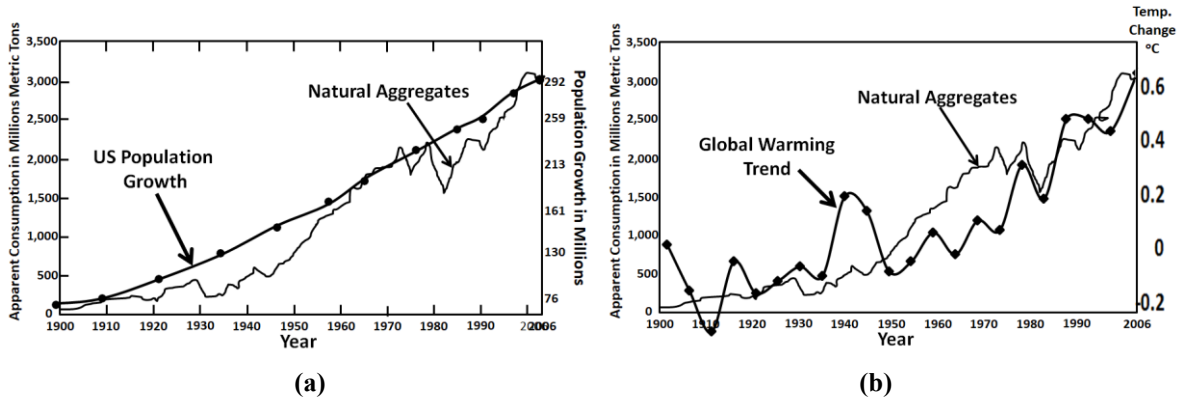


Figure C2. a) Natural aggregates [30] correlated to U.S. Population Growth (USGS [29]) **b)** Natural aggregates [30] correlated to global warming (NASA [32])

Appendix D: Weighted Albedo Solar Model Applied to the Melting of Sea Ice

We need to make several initial estimates to obtain a ballpark number of warming due to sea ice loss. The first estimate is that the Antarctic sea ice has remained roughly constant (NOAA, Scott [40]) over the last two decades. Next, we note that the Antarctic sea ice is larger in the winter while the Arctic sea ice is much larger in the summer. The difference appears to yield an estimate that the Arctic sea ice area is about 60% larger on average compared with Antarctic sea ice areas on a yearly basis (NOAA, Scott [40]). It has been observed that the Arctic sea ice is melting at an alarming rate of 12.85% per decade in the last two decades (NASA sea ice [41]). This apparent trend appears to yield an estimated 26% decrease in sea ice in the last two decades. It is difficult to find a strong reference for quantifying global warming impact due to Arctic sea ice melting. However, we can get an approximation using a similar Weighted Albedo Solar (WAS) model (and also illustrate the strengths of these models). Sea ice melting will result in a significant albedo change that roughly changes the ice-albedo of 0.6, to the open ocean albedo of 0.06 (see Table D1 and D2). Fortunately, the Arctic areas receive only about 40% as much solar radiation (Sciencing [42]) reducing the feedback effect. From Equation 10, the effective sea ice surface area reduction from the irradiance decrease can be approximated as

$$\text{Effective Arctic Sea Ice Surface Area} = 0.6 \times 15\% \{1 - (0.257 \times 0.40)\} = 8.064\% \quad (D-1)$$

Here 0.6 x 15% is sea ice percent in the Arctic area, 0.26 is the fraction of sea ice lost, and 40% is the solar irradiance effect.

Then adding the Antarctic average sea ice area, the total sea ice area is reduced from 15% to

$$\text{Sea Ice area 2019} = 0.4 \times 15\% + 8.064 = 14.06\% \quad (D-1)$$

This is a 0.94% decrease from 15%. In the WAS model, we will have to assume that the effective ocean surface area increases proportionately by 0.94% to 56.94% (see Table D2). The WAS model then finds that the global albedo change decreases from 29.4118% to 29.2443%. (Note that alternately we could have set the albedo to 29.4118% in 2019 and worked back to 1950. In this case, the albedo would have increased to 29.2443%).

The percent Global Warming (GW) is found as:

$$\%GW = \{(P/\sigma)^{0.25}_{2019} - (P/\sigma)^{0.25}_{1950}\} / 0.95^\circ\text{C}, \quad (D-2)$$

where $P = 340 \text{ W/m}^2 \times (1 - \text{Albedo})$. The warming increase due to ice melting is estimated from this model to be about 0.15°C or 15.8% when compared to a warming trend of 0.95°C increase in 2019. The increase in radiative forcing is 0.6 W/m². The feedback is then roughly 0.63 W/m²/°K where we assume a temperature change of 0.95°C.

These values should only be taken as a rough estimate due to numerous uncertainties as climatologists find it hard to fully quantify the seasonal variations in ice change and to know the possible impact on cloud coverage increase from additional warming evaporation. However, one would expect less evaporation in the Arctic. Thus, there are a lot of uncertainties.

Table D1. Baseline (Albedo=29.4118, 1950)

Surface	Albedo	%Area	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		71		
Sea Ice	0.6	15	4.95	2.970
Water	0.06	56	18.48	1.109
155Sum 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
		$\Sigma = 100.000$	33.000	7.05882
			Cloud Area	
Clouds	0.3336	67	67	22.35294
Σ Sum Earth %			100.000	
Σ Global Albedo				29.4118

Table D2. Sea ice loss - albedo change (29.2443%, 2019)

Surface	Albedo	%NArea	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		71		
Sea Ice	0.6	14.06	4.4352	2.507
Water	0.06	56.94	18.9948	1.14
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
		$\Sigma = 100.000$	33.000	6.6395
			Cloud Area	
Clouds	0.3336	67	67	22.3530
Σ Sum Earth %			123.430	
Σ Global Albedo				29.2443

Appendix E: WAASU Model References

Table E1 provides references for the WAASU model values.

Table E1 Key References for WAASU model

Parameter	Albedo References	1950 Area References
Sea Ice	50-70%, average 60% (NSID [43])	15% (Lindsey [44])
Water	6% (NSID [43])	56% Ocean+Sea Ice=71% (USGS [45])
Land-(UHI+Coverage)	Adjusted to obtain 29.412% and surface reflected of 7.06 Earth Albedo in 1950 thereafter held fixed (see IPCC Hartmann [8] AR5 report)	29%-Urban Coverage
UHI+Cov	0.12 Sugawara et. Al [46]	See Table 1
Clouds	22.353 (IPCC Hartmann et al. [8])	67% (Earthobservatory, NASA [47])
Earth Albedo	29.412% (IPCC Hartmann [8])	-

Appendix F: Albedo Model Normalization Information

Table F1 is reproduced from above, while Table F2 is the results of the Schneider dome area case. The results are used to demonstrate how normalization is performed

Table F1. Schneider 1950 estimates

Surface	Albedo	%NEAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		71		
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
		$\Sigma=100.000$	33.000	7.05882
			Cloud Area	
Clouds	0.3336	67	67	22.35294
Σ Sum Earth %			100.000	
Σ Global Albedo				29.4118

Table F2. Schneider 2019 Dome estimate (AF=8.4)

Surface	Albedo	%NEAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		70.239		
Sea Ice	0.6	14.839	4.897	2.938
Water	0.06	55.4	18.282	1.097
Sum of Land Type		29.761		
Land - (UHI + Coverage)	0.3118	28.631	9.448	2.946
UHI + Coverage	0.12	1.1307	0.373	0.0447757
		$\Sigma=100.000$	33.000	6.980769
			Cloud Area	
Clouds	0.3336	67	67	22.3530
Σ Sum Earth %			100.000	
Σ Global Albedo				29.3786

Normalization is done as follows:

1. The model starts with 1950 Table F1 albedo 29.4118%, then the 2019 urban coverage area is entered.
2. For example, in Table F1, Column B the UHI area increases from **0.059%** to 1.143% (not shown) and normalized to **1.131%**. This value is 1.084% larger (=1.143-0.059), now the 'Sum of % of Earth Area' is increased from 100% to 101.084% in 2019.
3. All areas need to be renormalized to 101.084%. For example, sea ice at 15% in 1950 becomes $15\% \times (100.000/101.084) = \mathbf{14.839\%}$ and the Urban Coverage becomes $1.143\% \times (100/101.084) = \mathbf{1.1307\%}$.

We also include in this appendix the GRUMP dome estimates. Table F3 is reproduced from above, while Table F4 is the results of the GRUMP dome area case.

Table F3. GRUMP Area 1950 estimates

Surface	Albedo	%NEAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		71		
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	9.466	2.968
UHI + Coverage	0.12	0.316	0.1043	0.013
		$\Sigma=100.000$	33.000	7.0588
			Cloud Area	
Clouds	0.3336	67	67	22.35294
Σ Sum Earth %			100.000	
Σ Global Albedo				29.4118

Table F4. GRUMP 2019 dome estimates (AF=8.4)

Surface	Albedo	%NEAA	Cloud Effect %NEAA	Weighted Albedo %
	A	B	C= B x (1-0.67)	A x C
Sum of Water Type		70.239		
Sea Ice	0.6	14.239	4.7	2.82
Water	0.06	53.1602	17.54	1.05
Sum of Land Type		29		
Land - (UHI + Coverage)	0.3135	27.229	9.0	2.82
UHI + Coverage	0.12	5.371	1.77	0.21
		$\Sigma=100.000$	33.000	6.9
			Cloud Area	
Clouds	0.3336	67	67	22.353
Σ Sum Earth %			100.000	
Σ Global Albedo				29.2546

Appendix G: Overview of Estimates in Table 8

The GHG re-radiation effect increases the LWR forcing found in Table 7 by a factor of 1.61 as indicated in Table 4 (see also Feinberg [33]). Then the LWR is modified using this by the standard formula

$$P_{2019} = 340W / m^2 x (1 - Albedo_{2019}) x 1.61 \text{ and } P_{1950} = 340W / m^2 x (1 - Albedo_{1950}) x 1.61 \quad (G-1)$$

Using this the UHI radiation forcing is

$$\Delta P = P_{2019} - P_{1950} \quad (G-2)$$

Results from this equation are shown in Table 8, Column 4 for each albedo. Next, we obtain the temperature increase. This is given by

$$\Delta T = \{(P/\sigma)^{0.25}_{2019} - (P/\sigma)^{0.25}_{1950}\} \quad (G-3)$$

The results are shown in Table 8, Column 5.

IPCC/NOAA Radiation Forcing Comparison

To make comparisons to assess the relative UHI forcing, the above results are referenced to the IPCC estimate for GHG forcing from the period 1950 to 2019, and this associated temperature rise. The GHG forcing estimate by IPCC/NOAA [35] is for this period on GHG forcing is 2.38 W/m².

One should note that this value does not include “feedback” (i.e., arctic snow and ice melting) as “forcing” is our primary concern. Column 6 then shows the relative forcing ratio to compare it to the UHI strength. For example, the LWR found in the Schneider case in Table 7 for the albedo of 29.3994 is 0.042 W/m². Then we estimate an average of 0.042 W/m² X 1.6=0.068 W/m² for the full forcing using the GHG re-radiation factor of 1.61. Then relative to the IPCC GHG forcing estimate, this is about 2.9% (=0.068/2.38) shown in Table 8, Column 6.

IPCC/NOAA Global Temperature Rise Due to Forcing Comparison

Next, we estimate the percent of global warming anticipated from the WAASU model results. To do this we need an estimate of the temperature rise due to GHG forcing IPCC/NOAA [35] to make comparisons. Using the albedo of 29.4118 for 1950 (Table 7), then the LWR with the GHG re-radiation energy (with the 1.61 Factor) is given by

$$P_{\alpha_{1950}} = 340W / m^2 x (1 - .294118) x 1.61 = 386.4W / m^2 \quad (G-4)$$

This is converted to the 1950 temperature providing a reasonable estimate of the average global temperature for that year

$$T_{1950} = (386.4W / m^2 / \sigma)^{0.25} = 387.31^{\circ}K \quad (14.164^{\circ}C) \quad (G-5)$$

Then the forcing (without feedback) for 2019 according to the IPCC/NOAA [35] value of 2.38W/m² yield a total radiation of

$$P_{F_{\alpha_{2019}}} = 386.4W / m^2 + 2.38W / m^2 = 287.78W / m^2 \quad (G-6)$$

This converts to the following temperature

$$T_{F_{2019}} = (387.76W / m^2 / \sigma)^{0.25} = 387.755^{\circ}K \quad (14.605^{\circ}C) \quad (G-7)$$

This provides a temperature rise of 0.44°C

$$\Delta T_{Forcing} = T_{F_{2019}} - T_{1950} = 14.605^{\circ}C - 14.164^{\circ}C = 0.44^{\circ}C \quad (G-8)$$

We note the actual temperature rise with feedback is 0.95°C in 2019. This would require a feedback factor of about 2.15. The factor of 2 has been cited in the literature [48-50] so this is a reasonable estimate. If we consider this to be the actual temperature rise due to all forcing (taken from the IPCC GHG estimate), the relative global warming contribution from the UHI temperature rise is shown in Table 8 in the last column. For example, ΔT is 0.018°C for the albedo decrease from 29.4418 to 29.3994% from Eq. 16 and Eq. 18. Then the percent of global warming relative to 0.44°C is 4.1% (=0.018/0.44 percent).

Finally, as some example of using Equation 24 and 24 we provide the following examples:

Example for Eq. 16: Given a global albedo change by 0.2% the forcing expected is

$$\alpha_{Global_Forcing}=1.6 \text{ lx } 1W/m^2 \times 0.2\%=0.32 \text{ W/m}^2 \text{ (Row 4)} \quad (\text{G-9})$$

Example for Eq. 17: Given a UHI EAA of 1.14% then the forcing is

$$UHI_{EAA_Forcing}=1.6 \times 0.094W/m^2 \times 1.14\%=0.17 \text{ W/m}^2 \text{ (Row 3, 0.18 W/m}^2 \text{)} \quad (\text{G-10})$$

Conflicts of Interest

The author declares that he has no conflicts of interest.

References

- 1 McKittrick R. and Michaels J. 2004. A Test of Corrections for Extraneous Signals in Gridded Surface Temperature Data, *Climate Research*
- 2 McKittrick R., Michaels P. 2007 Quantifying the influence of anthropogenic surface processes and inhomogeneities on gridded global climate data, *J. of Geophysical Research-Atmospheres*. Also see McKittrick Website Describing controversy: <https://www.rossmckittrick.com/temperature-data-quality.html>
- 3 De Laat, A. T. J., and A. N. Maurellis, 2006: Evidence for the influence of anthropogenic surface processes on lower tropospheric and surface temperature trends. *Int. J. Climatol.*, 26, 897–913
- 4 IPCC Archive (2007) https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch3s3-2-2-2.html
- 5 Schmidt G. A. 2009 Spurious correlations between recent warming and indices of local economic activity, *Int. J. of Climatology*
- 6 McKittrick, Ross R. (2010) Atmospheric Oscillations Do Not Explain the Temperature-Industrialization Correlation. *Statistics Politics and Policy* Vol 1. No. 1., July 2010
- 7 McKittrick, Ross R. and Nicolas Nierenberg (2010) Socioeconomic Patterns in Climate Data. *Journal of Economic and Social Measurement*, 35(3,4) pp. 149-175. DOI 10.3233/JEM-2010-0336.
- 8 Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai, 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- 9 Zhao, Z.-C., 1991: Temperature change in China for the last 39 years and urban effects. *Meteorological Monthly* (in Chinese), 17(4), 14-17.
- 10 Feddema, J. J., K. W. Oleson, G. B. Bonan, L. O. Mearns, L. E. Buja, G. A. Meehl, and W. M. Washington (2005), The importance of land-cover change in simulating future climates, *Science*, 310, 1674– 1678, DOI:10.1126/science.1118160
- 11 Ren, G.-Y., Z.-Y. Chu, J.-X. Zhou, et al., (2008): Urbanization effects on observed surface air temperature in North China. *J. Climate*, 21, 1333-1348
- 12 Jones, P. D., D. H. Lister, and Q.-X. Li, 2008: Urbanization effects in large-scale temperature records, with an emphasis on China. *J. Geophys. Res.*, 113, D16122, DOI: 10.1029/2008JD009916.
- 13 Stone B. 2009 Land use as climate change mitigation, *Environ. Sci. Technol.*, 43(24), 9052– 9056, DOI:10.1021/es902150g
- 14 Zhao, Z.-C., 2011: Impacts of urbanization on climate change. in: 10,000 Scientific Difficult Problems: Earth Science, 10,000 scientific difficult problems Earth Science Committee Eds., Science Press, 843-846. 30%
- 15 Yang, X.; Hou, Y.; Chen, B. 2011 Observed surface warming induced by urbanization in east China. *J. Geophys. Res. Atmos*, 116, DOI:10.1029/2010JD015452.
- 16 Huang Q. , Lu Y. 2015 Effect of Urban Heat Island on Climate Warming in the Yangtze River Delta Urban Agglomeration in China, *Intern. J. of Environmental Research and Public Health* 12 (8): 8773 (30%)
- 17 Conference of the Parties, Adoption of the Paris Agreement, Dec. 12, 2015, U.N. Doc. FCCC/CP/2015/L.9/Rev/1 (Dec. 12, 2015).
- 18 Satterthwaite D.E., F. Aragón-Durand, J. Corfee-Morlot, R.B.R. Kiunsi, M. Pelling, D.C. Roberts, and W. Solecki, 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*

- 19 Schneider, A., M. Friedl, and D. Potere, 2009:A new map of global urban extent from MODIS satellite data. *Environmental Research Letters*, 4(4), 044003, DOI:10.1088/1748-9326/4/4/044003
- 20 Global Rural Urban Mapping Project (GRUMP) 2005, Columbia University Socioeconomic Data and Applications Center, Gridded Population of the World and the Global Rural-Urban Mapping Project (GRUMP).
- 21 NASA 2000, Gridded population of the world, , <https://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-count/data-download>
- 22 Galka M. 2016, Half the World Lives on 1% of Its Land, Mapped, <https://www.citylab.com/equity/2016/01/half-earth-world-population-land-map/422748/>, , (2016 publication on 2000 data set, <http://metrocosm.com/world-population-split-in-half-map/>
- 23 Zhou Y. , SmithS. , Zhao K., M. Imhoff, A. Thomson, B. Lamberty, G. Asrar, X. Zhang, C. He and C. Elvidge, A global map of urban extent from nightlights, *Env. Research Letters*, 10 (2015), (study uses a 2000 data set).
- 24 Karl, T. R., H. F. Diaz, and G. Kukla (1988), Urbanization: Its detection and effect in the United States climate record, *J. Clim.*, 1, 1099–1123.
- 25 Chagnon, S. A. (1999), A rare long record of deep soil temperature defines temporal temperature changes and an urban heat island, *Clim. Change*, 42, 531–538.
- 26 Zhang, X., Friedl, M. A., Schaaf, C. B., Strahler, A. H. & Schneider, A. 2004 The footprint of urban climates on vegetation phenology. *Geophys. Res. Lett.* 31, L12209
- 27 Zhou D., Zhao S., L. Zhang, G Sun and Y. Liu, 2015, The footprint of urban heat island effect in China, *Scientific Reports*. 5: 11160
- 28 Fan, Y., Li, Y., Bejan, A. *et al.* Horizontal extent of the urban heat dome flow. *Sci Rep* 7, 11681 (2017). <https://doi.org/10.1038/s41598-017-09917-4>
- 29 World Bank, 2018 population growth rate, worldbank.org
- 30 USGS 1900-2006, Materials in Use in U.S. Interstate Highways, <https://pubs.usgs.gov/fs/2006/3127/2006-3127.pdf>
- 31 US Population Growth 1900-2006, u-s-history.com/pages/h980.html
- 32 NASA 1900-2006 updated, 2020 <https://climate.nasa.gov/vital-signs/global-temperature/>
- 33 Feinberg A., On Geoengineering and Implementing an Albedo Solution with UHI GW and Cooling Estimates vixra 2006.0198, DOI: 10.13140/RG.2.2.26006.37444/6 (Currently in Peer Review in the *J. Mitigation and Adaptation Strategies for Global Change*)
- 34 He T, Liang S, and Song DX (2014), Analysis of global land surface albedo climatology and spatial-temporal variation during 1981–2010 from multiple satellite products, *J. Geophys. Res. Atmos.*, 119, 10,281–10,298, doi:10.1002/2014JD021667
- 35 Butler J., Montzka S., (2020) The NOAA Annual Greenhouse Gas Index, Earth System Research Lab. Global Monitoring Laboratory, <https://www.esrl.noaa.gov/gmd/aggi/aggi.html>
- 36 Zhao L, Lee X, Smith RB, Oleson K, Strong 2014, contributions of local background climate to urban heat islands, *Nature*. 10;511(7508):216-9. DOI: 10.1038/nature13462
- 37 Basara J., P. Hall Jr., A.Schroeder, B.Illston, K.Nemunaitis 2008, Diurnal cycle of the Oklahoma City urban heat island, *J. of Geophysical Research*
- 38 Barr J. M., 2019 The Economics of Skyscraper Height (Part IV): Construction Costs Around the World, <https://buildingtheskyline.org/skyscraper-height-iv/>
- 39 Butler J., Montzka S., (2020) The NOAA Annual Greenhouse Gas Index, Earth System Research Lab. Global Monitoring Laboratory, <https://www.esrl.noaa.gov/gmd/aggi/aggi.html>
- 40 NOAA, Scott, M, 2019, Understanding Climate: Antarctic sea ice extent, <https://www.climate.gov/print/833949>
- 41 NASA Sea Ice, 2019, <https://climate.nasa.gov/vital-signs/arctic-sea-ice/>
- 42 Sciencing (2018) <https://sciencing.com/sun-intensity-vs-angle-23529.html>
- 43 NSID 2020, National Snow & Ice Data Center, "Thermodynamics: Albedo". [nsidc.org](https://nsidc.org/cryosphere/seaice/processes/albedo.html). Retrieved 14 August 2016. <https://nsidc.org/cryosphere/seaice/processes/albedo.html>
- 44 Lindsey R, Scott M., (2019), Climate Change: Arctic Sea Ice Summer Minimum, NOAA Climate.gov, <https://www.climate.gov/news-features/understanding-climate/climate-change-minimum-arctic-sea-ice-extent>
- 45 USGS on Amount of Earth covered by water, https://www.usgs.gov/special-topic/water-science-school/science/how-much-water-there-earth?qt-science_center_objects=0#qt-science_center_objects

- 46 Sugawara, H., Takamura, T. Surface Albedo in Cities (0.12): Case Study in Sapporo and Tokyo, Japan. *Boundary-Layer Meteorol* 153, 539–553 (2014). <https://doi.org/10.1007/s10546-014-9952-0>
- 47 Earthobservatory, NASA (clouds albedo 0.67) <https://earthobservatory.nasa.gov/images/85843/cloudy-earth>
- 48 Manabe, S., and R. T. Wetherald (1967), Thermal equilibrium of atmosphere with a given distribution of relative humidity, *J. Atmos. Sci.*, 24, 241–259.
- 49 Randall, D. A. et al. (2007), Climate models and their evaluation, in *Climate Change 2007: The Physical Science Basis. Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 591–662, Cambridge Univ. Press, Cambridge, U.K.
- 50 Dessler A. E., Zhang Z., Yang P., Water-vapor climate feedback inferred from climate fluctuations, 2003–2008, *Geophysical Research Letters*, (2008), <https://doi.org/10.1029/2008GL035333>