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

Alec Feinberg, Ph.D., DfRSoft Research
DfRSoft@gmail.com
ORCID: 0000-0003-4364-2460

Key Words: Urban Heat Islands, Albedo modeling, UHI amplification effects, global warming causes and amplification effects, cool roofs

Abstract

In this paper we provide nominal and worst case estimates of global warming due to UHI effect (including urban areas) using a Weighted Amplification Albedo Solar Urbanization (WAASU) Model. This is done with the aid of UHI footprint surface coverage amplification factors. Using this method, we find conservatively between 4.8% and 20% of global warming may be due to the UHI effect (with urban areas).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 amplification factors when assessing UHI's to include their footprint 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 contribution to global warming is very important and should remain so. The topic has a controversial history. One such paper was from McKitrick and Michaels, in 2007 who 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 (Schmidt 2009) and defended for a period of about 10 years by Mckitrick (see McKitrick Website). Other authors have also found significance (Feddema et al. 2005, Ren et al. 2007, Stone 2009, Shao 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 goals in their many reports and meetings such as their goals have for CO_2. This is important because, we feel it really is the IPCC's responsibility to inform the global community of such needs in the form of such 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 goals 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. Surface area land approximations vary widely and most are obtained with satellite measurements sometimes supplemented in some way with census data. The table below captures some papers that are of interest.

Table 1 Summarizing Literature Urbanization Area Estimates

Percent of Land	Percent of Earth	References
2.7	0.783	GRUMP 2005, From NASA Satellite Light study based on 2004 data supplemented with census data
1.8	0.52	OECD 2014
1%	0.29	NASA 2000 Satellite data, Galka 2016
0.5	0.148	(Schneider et al. 2009) based on 2000-2001 data from Satterthwaite IPCC 2014 reference
0.5%	0.145	(Zhou 2015) based on a 2000 data set [60]

One key paper listed in the table that we study in this paper 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 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 and GRUMP studies as the nominal and worst case urbanization area estimates respectively.

In our study, we introduce a WAASU model that 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.

2. 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 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

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 $3.0^{o}C$ in humid climates but decreasing ΔT by $1.5^{o}C$ in dry climates. They noted that such relationships imply that UHIs will exacerbate heatwave 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 a local greenhouse effect.

- ***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 with large solar area and heat capacities, absorb radiation via convection in the day, and actually reducing the UHI effect, but at night, buildings cools down, giving off their stored heat increasing 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.

2.1 Urbanization Surface Area Amplification Factors

In order to estimate the UHI amplification effects, we use a study by Zhou et al. (2015). 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. In this study we consider these as urban area coverage amplification factors. These are summarized in the table below. Our study uses the average area amplification coverage factor of 3.1 as a conservative value in our WAASU model.

Table 3 Urban Climate Amplification Factors

Urban Climate Amplification	**Amplification Factor**	**Day-Night Average Factor**
Area Coverage Amplification	2.3-3.9	3.1 Conservative
Spherical Area Coverage	4.6-7.8	6.2 Aggressive

Although the 3.1 amplification factor may seem high, it is likely conservative in our study. For example, two effects that would be hard to quantify is loss of wetlands and rainwater management due to urbanization. Here we note that

- Changes to the wetland area show a negative correlation with temperature (i.e. wetland decrease, increase in temperature), and a positive correlation with precipitation (i.e. wetland decrease, precipitation decrease)." Cao et. al. (2011) Hirshi et al. (2011)
- Impermeable surface create annual evapotranspiration unknown amplification issue with natural cooling
- As well many coastal cities like Sydney, dump (132 billion gallons, L.Cormack 2015) frequently elevating temperatures from storm water runoff from hot buildings and streets into rivers, lakes and the sea raising local and costal temperatures in the vicinity.

These effects in some areas may be responsible for added draught, deforestation due to urbanization and draught related fires. We note that such amplification effects are hard to quantify.

Furthermore the 3.1 factor from the Zhou et al. (2015) study does not provide for altitude atmospheric dissipative effects. We might envision altitude area effects as part of a spherical area about the UHI and its coverage. In this way we might aggressively extend this with a half sphere over the UHI with urban coverage in order to include some vertical radiation effects for global extent. UHI have exponential dome like decay as describe (Zhou et al.), this can more easily be approximated by a half sphere roll off to simplify for an aggressive case. The area of a half sphere would then add another factor of 2 $\{(4\pi r^2/2)/\pi r^2\}$. Therefore, this extrapolated amplification factor ranges from 4.6-7.8 for the day-night cycle respectively yielding an average of 6.2 shown in the table.

3.0 Area Extrapolated Rates to 1950 and 2019

In order to apply the area amplification factors, we first need to project the Schneider and GRUMP area estimates down to 1950 and up to 2019. 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).

Table 4 Values used to estimate the Solar Surface area in cities

Year	Urban coverage Percent of Earth	Urban Coverage 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 footprint***	**0.583%**
2019	0.188*	6.2 half-sphere****	**1.128%**
Worst Case GRUMP Study			
1950	0.316%	1	**0.316%****
2000	0.027x29%=0.783%		
2019	0.952%*	3.1 footprint***	**2.95%**
2019	0.952%*	6.2 half-sphere****	**5.9%**

*Growth rate of cities using world population yearly growth rate in Fig A1, study,**amplification facto not used, considered reference year,*** conservative, ****aggressive amplification

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).

Since 1950 is taken as the reference year, we did not use any amplification factor for this period. Next we assumed the amplification factor of 3.1 (conservative) and 6.2 (aggressive) applied 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 coverages used in the WAASU model is shown in Column 4.

4. Weighted Amplification Albedo Solar Urbanization (WAASU) Model Overview *1950 & 2019*

The WAASU model is very straight forward; it is based on a global weighted albedo model. The weighted Earth constituents are

$$EWA = \sum_i \{\%\, Earth\ Area_i\ x\ Surface\ Item\ Albedo_i\} \quad (1)$$

Here EWA is the Earth's Weighted Albedo value. The model allows us to hold all values from 1950 to 2019 constant except for the urban coverage value. The effect of cloud coverage is also weighted and is averaged in with Equation 1 as

$$Global\ Weighted\ Albedo = Average\{(Clouds\ Albedo)\, x\%\ Coverage) + (Earth\ Weighted\ Albedo)\} \quad (2)$$

The components of the model are flexible and only need to have reasonableness in known values and maintain relative consistency from 1950 to 2019 as they are held fixed. The important values are the variables of interest, urban coverage. In this way the WAASU model has been adjusted to the most commonly used global albedo 1950 value of 30.03% shown in Table 5a. Then in 2019, using the extrapolated area coverage (see Sec.3.0) the area is amplified, the resulting model change to the global albedo is found as 29.98% for the Schneider nominal case (shown in Table 5b) and for the GRUMP worst case the albedo was similarly obtained as 29.82% for the conservative amplification factor.

Although factors are held constant, since urban coverage increases in 2019, this increases the surface area of the Earth which realistically does occur with city growth of tall buildings having large solar heating areas as accounted for by the amplification in the model. This new area, however small, requires some renormalization in the model of the Earth components in the WAASU model. Renormalization then may introduce some error in the model. For the Schneider nominal case, renormalization error would be small <+/-0.25% where the area is still relatively little. For the GRUMP case, renormalization error is estimated to be about +/-1.3%.

Table 5a: Albedo=0.3003, 1950

Surface	Enter % of Earth Area	Enter Albedo (0-1)	Weighted Albedo in % Results
Water	71		
Sea Ice	15	0.66	9.90
Open Ocean	56	0.06	3.36
Land	29.009		
Roads (0.04)	0.05	0.04	0.00
Urban Cov (0.12)	0.059	0.12	0.01
Forest (0.17)	3.5	0.17	0.60
Forest (Snow)	4.9	0.81	3.97
Grass lands (0.26)	3.8	0.26	0.99
Grass Lands Snow	7	0.81	5.67
Desert (0.4)	9.7	0.4	3.88
Sum % of Earth Area	100.009		
Weighted Earth			28.37
Clouds (0.47)	60	0.472	31.68
			Global Weighted Albedo in
Global=Average(Clouds & Weighted Earth) %			30.03

Table 5b : Albedo=0.2998, 2019

Surface	Enter % of Earth Area	Enter Albedo (0-1)	Weighted Albedo in % Results
Water	70.623		
Sea Ice	14.92	0.66	9.85
Open Ocean	55.703	0.06	3.34
Land	29.364		
Roads (0.04)	0.05	0.04	0.00
Urban Cov (0.12)	0.583	0.12	0.07
Forest (0.17)	3.481	0.17	0.59
Forest (Snow)	4.87	0.81	3.94
Grass lands (0.26)	3.78	0.26	0.98
Grass Lands Snow	6.96	0.81	5.64
Desert (0.4)	9.64	0.4	3.86
Sum % of Earth Area	99.987		
Weighted Earth			28.27
Clouds (0.47)	60	0.472	31.68
			Global Weighted Albedo in
Global=Average(Clouds & Weighted Earth) %			29.98

4.1 WAASU Model Urban Heat Island Global Warming Amplification Estimates

From the above global WAASU model the estimates of the Earth's power absorption and temperature are then straight forward using the fundamental equation

$$P_{Total} = 1361 W/m2 \{0.25 \text{ x } (1-Albedo)\} = \sigma T^4 \qquad (3)$$

Results are compiled in Table 3. 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 footprint amplification values. The general results is summarized:

Conservative Area Coverage

- Nominal Schneider case from 1950 to 2019 is 0.045C (-18.554-(-0.18.599) due to urban amplification coverage. This represents 4.79% (0.045C/0.95C) contribution to global warming
- Worst GRUMP case from 1950 to 2019 is 0.191C (-18.408-(-0.18.599) due to urban amplification coverage. This represents 20.1% (0.191C/0.95C) contribution to global warming
- "what if" corrective action results using cool roofs shows that changing city albedos range from 15.75 to 32.6% cooler for reducing global warming

Aggressive half-sphere dome area coverage

- Nominal Schneider case from 1950 to 2019 is 0.082C (-18.517-(-0.18.599) due to urban amplification coverage. This represents 8.61% (0.045C/0.95C) contribution to global warming
- Worst GRUMP case from 1950 to 2019 is 0.398C (-18.201-(-0.18.599) due to urban amplification coverage. This represents 41% (0.398C/0.95C) contribution to global warming

Table 3 Results of GW Temperature Budget Change With City Surface Areas and Albedos

Year	Urban Extent Global Area %	UHI Effective Global Surface Area %	Albedo Roads	Albedo Cities	Global Weighted Albedo	Temperature (no GH gases)*	UHI Radiative Forcing	Percent Of Global Warming
Nominal Case IPCC Schneider 2009 Study								
1950	0.059	0.059	0.04	0.12	30.03	-18.599	0	Par
2019	.188	0.583	0.04	0.12	29.98	-18.554	0.17 W/m^2	**4.79%**
2019	.188	1.128	0.04	0.12	29.94	-18.517	0.306 W/m^2	**8.61%**
What if	0.188	0.583	0.04	0.5	30.09	-18.654°C	-0.204 W/m^2	-5.75% (Cooler)
Worst Case GRUMP 2005 Study								
1950	0.316%	0.316	0.04	0.12	30.03	-18.599°C	0	Par
2019	0.952%	2.95	0.04	0.12	29.82	-18.408°C	0.715 W/m^2	**20.1%**
2019	0.952%	5.9	0.04	0.12	29.6	-18.201	1.463 W/m^2	**41%**
What if	0.952%	2.95%	0.04	0.5	30.37	-19.10°C	-1.16 W/m^2	-32.6% (Cooler)

*where Temperature Budget is given by: $P_{Total} = 1361 W/m2 \{0.25 \text{ x } (1-Albedo)\} = \sigma T^4$

8. Conclusions and Suggestions

In this paper we were able to estimate using UHI effect (with urban area) amplification coverage estimates from a Zhou et al. (2015) study. These estimates inputed into our WAASU model found that between 4.8 and 20% to global warming is related to UHI effect. The amplification factors were extended using a spherical UHI dome area. This was termed aggressive with the WAASU model global warming results varying between 8.6% to 41%. As amplification factors, especially in the aggressive case are not well studied, it is clear better estimates are needed. However, given what we feel are 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
- 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 there meetings.

Appendix A

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 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.

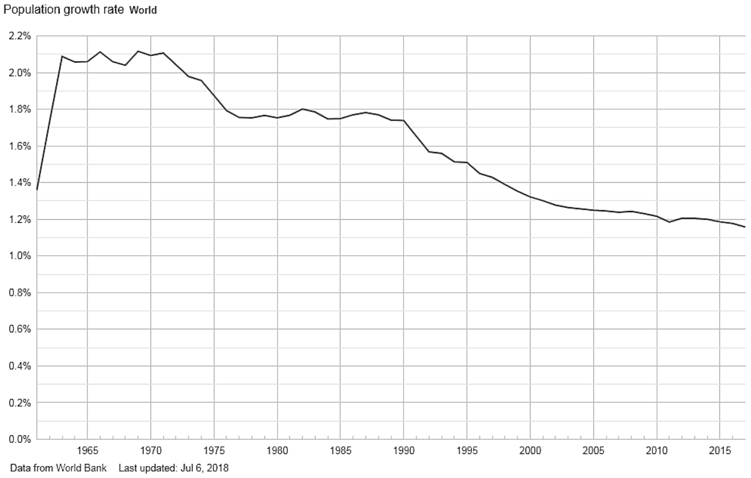
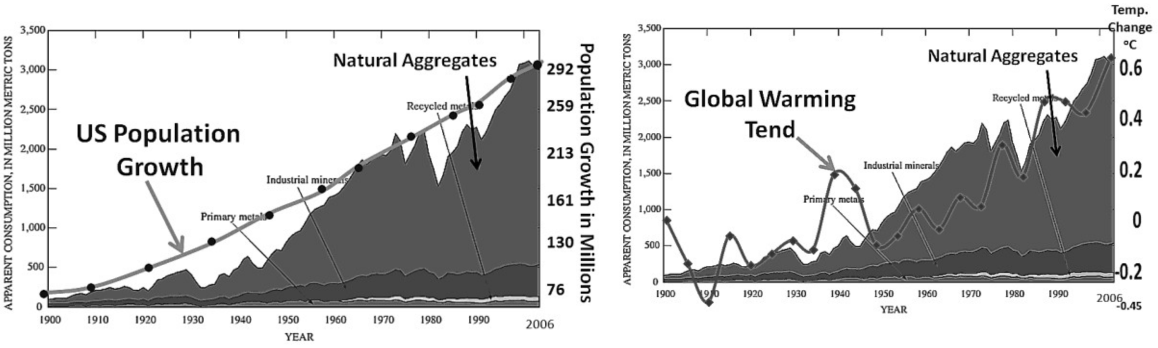


Figure A1 Population growth rate by year from 1960 to 2018, World Bank, 2018



(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)

Conflict of Interest Statement: This paper is unfunded and there are no conflicts of interest with this work.

Biography

Alec Feinberg is the founder of DfRSoft. He has a Ph.D. in Physics from Northeastern University and is the principal author of the books, Design for Reliability and Thermodynamic Degradation Science: Physics of Failure, Accelerated Testing, Fatigue, and Reliability Applications. Alec has presented numerous technical papers and won the 2003 RAMS best tutorial award for the topic, "Thermodynamic Reliability Engineering." Alec has studied degradation systems for his entire professional career.

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