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 0.143 and 0.783 Watts/M^2 of radiative long wavelength forcing 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 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.

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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 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 (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 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%	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]

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.

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, 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 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 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. 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.

2.1 Urbanization Surface Area Amplification Factors

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}) for solar absorption and long wave length emission is highly complex and not easy to assess from first principles. The UHI in highly complex and the UHI amplification factor between 2019 and 1950 would roughly require an assessment of the following averages of components for each city

$$AF_{UHI} = \frac{\sum\left(\overline{Build}_{Area}\ x\ \overline{Build}_{Cv}\ x\ \overline{R}_{wind}\ x\ \overline{LossE}_{vtr}\ x\ \overline{Hy}\ x\ \overline{S}_{canyon}\right)_{2019}}{\sum\left(\overline{Build}_{Area}\ x\ \overline{Build}_{Cv}\ x\ \overline{R}_{wind}\ x\ \overline{LossE}_{vtr}\ x\ \overline{Hy}\ x\ \overline{S}_{canyon}\right)_{1950}}$$

Here the sum is over all the cities in the world in 2019 and in 1950 with averages taken to represent for each city

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

However, given the findings of Zhou et al. (2015), the highly complex UHI amplification factor can greatly be simplified as it should go as the urban size ratio between the two time periods. This is justified from their result showing a 79% correlation of the footprint to urbanized size. Therefore, between 2019 and 1950 time frames, the highly complex UHI amplification factor ratio can be simplified using the urban size ratio. Such values are provided in the next section in Table 4 and yield the following results for the Schneider et al. (2009) and the GRUMP 2005 extrapolated area results

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

Between the two studies, the UHI 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.

Furthermore the 3.1 factor obtained here and similar to Zhou et al. footprint factor, both do not provide for altitude atmospheric dissipative effects that also contribute to global warming. We might envision altitude area effects as part of a spherical amplified 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 been modeled with exponential decay as described (Zhou et al.), this can more easily be approximated by a half sphere roll off to simplify for an aggressive case. A half sphere model may be more appropriate as well. The area of a half sphere would then add another factor of 2 $\{(4\pi r^2/2)/\pi r^2\}$. Therefore, this extrapolated UHI amplification factor would yield an estimate of 6.2 shown in the table. In our study we will use both 3.1 as a conservative value and 6.2 as an aggressive value.

Table 3 Urban Climate Amplification Factors

Urban Climate Amplification	**Footprint Factor**	**Foot Print Average And UHI Acceleration Factor**
Area Coverage Amplification	2.3-3.9	3.1 Conservative
Spherical Area Coverage	4.6-7.8	6.2 Aggressive

3.0 Area Extrapolated Rates 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 (conservative) and 6.2 (aggressive) 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 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 AF**	**0.583%**
2019	0.188*	6.2 half-sphere AF***	**1.166%**
	Worst Case GRUMP Study		

1950	0.316%	1	**0.316%**
2000	0.027x29%=0.783%		
2019	0.952%*	3.1 AF**	**2.95%**
2019	0.952%*	6.2 half-sphere AF***	**5.9%**

*Growth rate of cities using world population yearly growth rate in Fig A1, study,,**conservative, ***aggressive amplification.

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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.

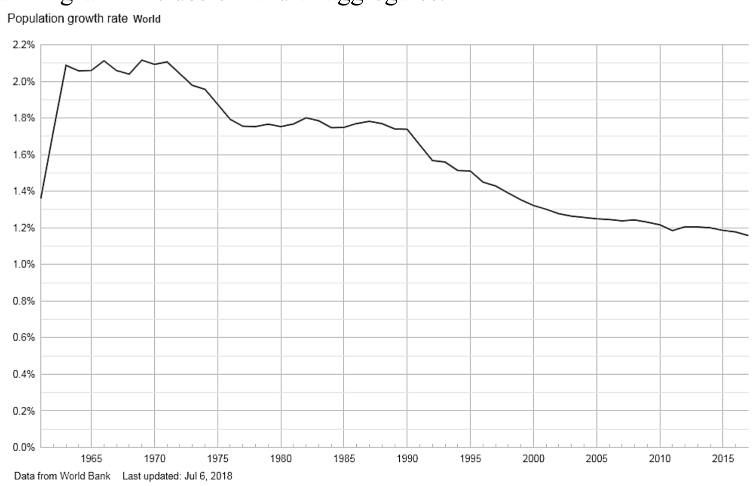
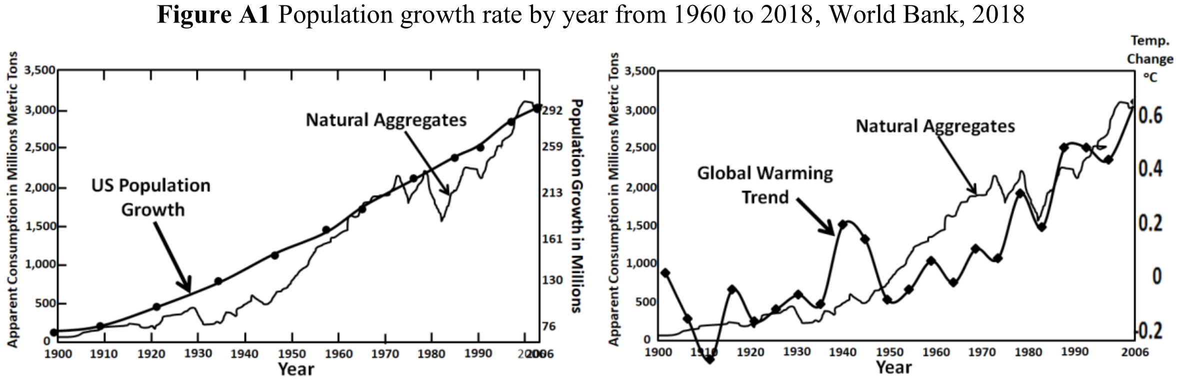


Figure A1 Population growth rate by year from 1960 to 2018, World Bank, 2018



(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)

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