How the Urban Heat Island Effect Influences the CO_2 Doubling Temperature and its Implications

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Abstract

Global warming has both root causes and amplification feedback effects. The main root cause, believed to be CO_2 greenhouse gas, then creates many feedback amplification mechanisms such as loss of ice and snow albedo decrease, increase in atmospheric water vapor and so forth. The strength of the CO_2 mechanism is often assessed by its doubling theory. However, such estimates rely on the fact that CO_2 is the primary root cause. Numerous authors including this one have found the Urban Heat Island effect to be significant and should for many reasons be part of our goals in combating global warming problems. Therefore, if one quantifies the UHI effect, it must affect the CO_2 doubling theory. In this paper we provide a short overview to illustrate how the CO_2 doubling temperature is influenced by the UHI effect including its footprint. We also discuss its implications related to a lack of IPCC UHI albedo goals.

Significance Statement

Currently the UHI effect is treated as negligible in CO_2 doubling theory. Yet many authors have found global warming significance. As well complex UHI amplification factors are not considered in estimates but have been measured through UHI footprint studies. We provide insight on how to interpret the footprint. Therefore, this paper raises the awareness of how one can factor into doubling theory the UHI effect with its amplification and as well include global feedback factors. Thus the paper presents the uncertainty in CO_2 doubling theory that is increased when UHI effect is treated as negligible. We also use our formulation to help argue the need for IPCC UHI albedo goals.

1. Introduction

The subject of UHI effects having significant contributions to global warming is important. The contention that global warming corrective action goals be primarily focused on CO_2 is very risky as it encourages one to neglect the UHI issue. In actuality, this has been stated mathematically in the literature (see Table 2) using doubling theory giving one the false sense that the doubling temperature should be estimated without any influence from the UHI effect. Ignoring the UHI effect is unrealistic where many authors have now shown significance. One well known paper, McKitrick and Michaels (2007), found that the net warming bias at the global level indicated that the UHI effect 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 estimates. In a recent study by the author (Feinberg 2020), this contention was supported using a totally different approach with a weighted amplified albedo solar urbanization model supplemented with footprint studies (Zhang et al., 2004; Zhou et al., 2015) for UHI amplification factors and global feedback mechanisms. Significance was observed as a result of incorporating UHI amplification effects (see Table 1) through the footprint method, so that the effective area was much larger than its own urbanized area.

Table 1 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.

Table 1 lists the global warming causes and amplification effects (Feinberg 2020). As one can see from the table, UHI effect is a global warming root cause with its own set of amplification effects. Just as the global climate system has its own sensitive amplification effects, the UHI complex amplification effects are also significant and are perhaps best assessed using what is termed as the UHI footprint (Feinberg, 2020; Zhang et al., 2004; Zhou et al., 2015). This is influential in CO_2 doubling temperature and will be considered from this perspective.

2. Review of the Timeline of CO_2 Doubling Theory

Greenhouse theory and early predictions started as far back as 1856 with CO_2 experiments by Foote, Tyndall in 1859, and what has become very popular, doubling theory by Arrhenius in 1896. Since Arrhenius, doubling temperature estimates based on theory and linked to environmental trends, have decrease as shown in Table 2. The doubling temperature, originally 5-6°C estimated by Arrhenius, shows a range with the last estimates now between 1.5 to 4.5°C per the IPCC. Doubling temperature is logarithmic with PPM of CO_2 as shown in Equation 1.

$$13.9^{o}C\ (57.02^{o}F)+2.36^{o}C\ Ln(412/311.8)/Ln2=14.85^{o}C\ (58.73^{o}F),\ 0.95C\ (1.71^{o}F)\ Rise \tag{1}$$

We see that this equation's (discussed more in Sec. 3) doubling temperature of 2.36°C is very close to the Manabe and Wetherald (1975) estimate in the Table. In this equation we are using CO_2 2019 estimates versus the reference year 1951. In general, the doubling temperature value of 2.36°C is the temperature increase that one would expect if we doubled CO_2 from 312 to 624ppm. Then we would get another 2.36°C increase if we again doubled it to 1248ppm. The rate and magnitude of global climate change is determined by radiative forcing, climate feedbacks and the storage of energy by the climate system.

Table 2 Key *CO_2* doubling theory history and conflicts

Reference	CO_2 Doubling Temperature
Arrhenius,1896	5-6°C
Gillbert Plass,1950's	3.6°C
Manabe and Wetherald,1975	2.3°C
IPCC (1^{tst}-5th Assessment 1990-2014, (ECS) equilibrium change	1.5 - 4.5°C
Current Trend, Eq. 1. Based on going from 311.8ppm to 412 PPM from 1951 to Dec 2019, with a *0.95°C (1.71°F)* rise	2.36°C *

*Ignoring other GHG

3. CO_2 Doubling Theory Estimates with UHI Influence

Equation 1 can be solved for the doubling temperature DT_{CO2} as

$$DT_{CO_2} = \frac{\Delta T_{CO_2+\text{Effects}}}{Ln(CO_{2(2019)}/CO_{2(1950)})/Ln2} \tag{2}$$

In this case $\Delta T_{CO2+Effect}$=0.95°C, $CO_{2(2019)}$=412ppm, and $CO_{2(1950)}$=311.8ppm (1951 and 2019 ppm and ΔT estimates from NASA databases), giving

$$DT_{CO_2} = \frac{0.95°C}{Ln(412/311.8)/Ln2} = 2.37°C \tag{3}$$

as expected form Equation 1. Here CO_2 is treated as the main cause of warming and this include all amplification effects such as increase in water vapor greenhouse gas (due to the fact that warm air holds more moisture), snow and ice melting etc.

For example we might estimate that CO_2 is responsible for 1/3 of global warming and the amplification feedback effects are causing ~2/3. There is a wide range of estimates of climate feedback sensitivity driven by uncertainties in how water vapor, clouds, and other factors change as the Earth warms. Climate feedbacks are mixed and some will amplify (positive feedback) or diminish the effect of warming from the root cause effects (see for example Hausfather 2018). The actual feedback is known to be positive (van Nes, 2015). For example, water-vapor feedback alone, which is one of the most important in our climate system, is thought to have the capacity to about double the direct warming (Manabe and Wetherald, 1967; Randall et al., 2007, Dessler et. al, 2008). Then incorporating the feedback, we can write this as

$$DT_{CO_2} = \frac{0.95°C\ \{X_{CO_2} + X_{Feedback}(1\text{-}X_{Other\_GHG})\text{-}X_{Other\_GHG}\}}{Ln(412/311.8)/Ln2} \tag{4}$$

In this section we will assume as an example that X_{CO2}=1/3, $X_{Feedback}$=2/3, and let $X_{Other\_GHG}\approx 0$. The X_{Other_GHG} is for other GreenHouse Gas (GHG) which are a small root cause source (so their temperature influence would need to be subtracted out from the DT_{CO2}), as well it would reduce the CO_2 feedback portion proportionally if it were to be considered. However, we will treat it as negligible (X_{Other_GHG}=0) in our estimates.

If we have another main root cause, the UHI effect, then the doubling temperature is diminished similarly to the way we had written it for X_{Other_GHG}. Let's say for example that UHI effect causes

$$FX_{UHI}=f_{UHI} \tag{5}$$

fraction of global warming. Here F represents a footprint amplification factor (Feinberg, 2020; Zhang et al., 2004; Zhou et al., 2015) on X_{UHI} fraction contribution to global warming. X_{UHI} represents what one might calculate the UHI effect to be without the footprint amplification factor. For example, in Feinberg 2020, F is identified between 3.1 and 6.2. When the footprint amplification effect is factored in, one might find that f_{UHI} is reasonably significant in doubling theory. In Feinberg 2020, it was noted that the footprint factor was roughly proportional to the UHI effective warming trend. Therefore, it seems reasonable to treat it linearly in Equation 5. While simplistic, it demonstrates it modeling effect. Therefore, it provides insight to help make a point in demonstrating the possibility of strong significance of how UHI amplification factor may be considered. Incorporating this fractional effect, then the doubling equation becomes

$$DT_{CO_2} = \frac{\Delta T_{CO_2+Effects}\ \{(X_{CO_2} + X_{Feedback}(1\text{-}f_{UHI})\text{-}f_{UHI}\}}{Ln(CO_{2(2019)}/CO_{2(1950)})/Ln2} \tag{6}$$

Here we assume that it shares the amplification feedback effect of $X_{Feedback}$ proportionally, so the CO_2 feedback is then diminished by $X_{Feedback}$(1-f). For Example if UHI effect causes 20% of global warming; now $X_{Feedback}$ is reduced to 0.8 $X_{Feedback}$.

Furthermore, the temperature change 0.95°C due to global warming of CO_2 is reduced since a fraction is due to UHI effect. For example, if UHI causes 20% of global warming (i.e. 0.95°C), then we must subtract of 20% of 0.95°C=0.19°C. In this example where X_{CO2}=1/3 and $X_{Feedback}$ =2/3, f=0.2 we have

$$DT_{CO_2} = \frac{0.95°C\ \{1/3+2/3(0.8)\text{-}0.2\}}{Ln(412/311.8)/Ln2} = \frac{0.633°C}{Ln(412/311.8)/Ln2} = 1.57°C \tag{7}$$

Here the global warming CO_2 doubling temperature is diminished form 2.36°C to 1.57°C due to the fact that UHI effect is responsible for 20% of global warming.

To check our results, we solve Eq. 2 for $\Delta T_{CO2+effectz}$, and using DT_{CO2}=1.57°C, we have

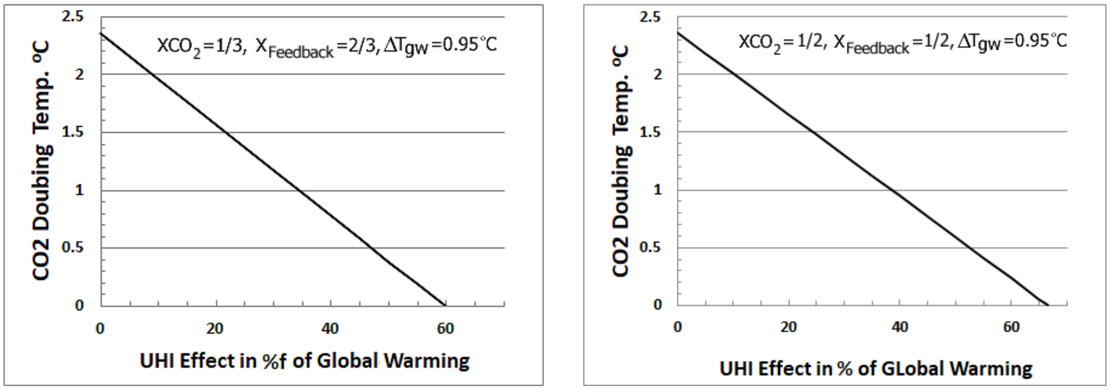
$$\Delta T_{CO_2+effects} = DT_{CO2}Ln(CO_{2(2019)}/CO_{2(1950)})/Ln2 = 1.57°C\ Ln(412/311.8)/Ln2 = 0.633°C \tag{8}$$

Then the temperature rise due to the UHI+amplification feedback effect is

$$\Delta T_{UHI+Effects} = \Delta T_{gw}(f + X_{Feedback}f) = 0.95°C(0.2+0.666(.2)) = 0.3165°C \tag{9}$$

Therefore, the global warming increase is as required

$$\Delta T_{gw} = \Delta T_{CO_2+Effects} + \Delta T_{UHI+Effects} = 0.633°C + 0.3165°C = 0.95°C \tag{10}$$



(a) (b)

Figure 1 CO_2 doubling temperature with UHI effect (%f) increasing influence with a) $X_{Feedback}$=2/3, b) $X_{Feedback}$=1/2

Figure 1 provides an overview of the Equation 6 doubling temperature versus f when ΔT_{gw}=0.95°C, X_{CO2}=1/3, $X_{Feedback}$ =2/3 or X_{CO2}=1/2, $X_{Feedback}$ =1/2.

We note the author feels from his work (Feinberg 2020) that a 10-20% range is a likely estimate for the UHI effect on global warming.

4. Model Findings and Implications

Using the model we can assess the McKitrick and Michaels 2007 contention that the net warming bias at the global level may explain as much as half the observed land-based warming. This would indicate in our model that the CO_2 doubling temperature would diminish between 0.39°C to 0.59 °C according to Equation 6 depending on the feedback proportion estimated of $X_{Feedback}$=2/3 or $X_{Feedback}$=1/2 respectively (see Figure 1). If that were the case, we see that the CO_2 effect would essentially breakdown. Such a contention would promote pushback as it has (see McKitrick Website). Although it is less likely to be that high in magnitude, it does suggest that there is a reasonable probability we should not restrict our focus to going down one basic path with a focus primarily on CO_2 goals. This path is likely risky if it turns out the McKitrick and Michaels work is reasonably accurate along with the many other authors cited in the introduction including this author. We see that one cannot guarantee with 100% probability that only one main CO_2 path is correct, as a lack of UHI albedo goals by the IPCC suggests. That is, there are currently no goals for UHI warming rectification by the IPCC.

It is unclear why the many authors' findings have not been influential enough to encourage UHI IPCC goals. We have of course minimal suggestions of cool roofs, yet there is very little on-going coordinated global effort to make such changes. Although some changes have been encouraged, we continue for the most part to use worst case colors for our roads and roofs, and allow unreflective architecture into our cities and ignore many other mitigating urban choices. It is important to recognize that we need a better safe than sorry policy by having goals for both CO_2 and the UHI effect. Given the uncertainty in all our models, it seems important for the IPCC to provide albedo goals in the near future in its documents and include such goals in their meetings.

5. Summary

We have provided a short review of CO_2 doubling theory and how its doubling temperature changes due to the UHI effect on global warming. We have illustrated a method on how to incorporate UHI amplification effects into CO_2 doubling theory using the footprint method. Both the magnitude of CO_2 and the UHI effect are obviously hard to estimate on how much influence each has on global warming anomalies. Therefore, it is imperative to adopt a policy that we have two main root causes of global warming. Push-back on the UHI effect possible influence on global warming is really unreasonable at this late time, especially given the uncertainties in root causes and amplification effect, its importance, and the numerous authors that have now presented their findings. In our paper (Feinberg 2020) we provided suggestions related to the Urban Heat Island effect which we would like to include here.

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

Therefore our suggestions remain (Feinberg 2020):

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

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