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Estimating the potential of U.S. urban infrastructure albedo enhancement as climate mitigation in the face of climate variability

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Abstract: The climate mitigation potential of U.S. urban infrastructure albedo enhancement is explored using multidecadal regional climate simulations. Increasing albedo from 0.2 to 0.4 results in summer daytime surface temperature decreases of 1.5°C, substantial reductions in health-related heat (50% decrease in days with danger heat advisory) and decreases in energy demand for air conditioning (15% decrease in cooling degree days) over the U.S. urban areas. No significant impact is found outside urban areas. Most regional modeling studies rely on short simulations; here, we use multidecadal simulations to extract the forced signal from the noise of climate variability. Achieving a ±0.5°C margin of error for the projected impacts of urban albedo enhancement at a 95% confidence level entails using at least 5 simulation years. Finally, single-year higher-resolution simulations, requiring the same computing power as the multidecadal coarser-resolution simulations, add little value other than confirming the overall magnitude of our estimates.

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1. Introduction

Concrete, cement, and asphalt are fundamental elements of any housing or infrastructure development. The industrial production of concrete, cement (a key ingredient of concrete), and asphalt are carbon dioxide (CO_2) intensive, and account for about 4% of anthropogenic CO_2 emissions from fossil fuel (Narayanan *et al.*, 2012). However, major efforts are underway by material scientists and engineers to reduce the greenhouse gas footprint of this sector. For example, Santero *et al.* (2013) provide an overview of the potential strategies for greenhouse gas emissions from concrete pavement, including reducing embodied emissions by increasing the ratio of fly ash to cement (cement is far more CO_2 intensive to produce than fly ash), crushing and temporary stockpiling recycled concrete to allow CO_2 sequestration through natural end-of-life carbonation, reducing vehicle fuel consumption by adding extra pavement rehabilitation and reducing embodied emissions by avoiding structural overdesign (i.e. increases in pavement thickness in anticipation of poor maintenance). Another research pathway is albedo enhancement, such as increasing the albedo of concrete by using white aggregates, white cement, and slag. The aim is to change the land surface energy budget where large urban infrastructures are present. Evaluating the potential of such urban infrastructure albedo enhancement to mitigate climate change requires well-designed modeling experiments to derive robust estimates.

Many studies have focused on understanding the impacts of land surface on the local, regional and global climate, from the impact of land-use change (Brovkin *et al.*, 2006, 2013; Hallgren *et al.*, 2013) to the impact of very large-scale wind farms (Wang and Prinn, 2010). These studies generally rely on modeling experiments using global climate models and multidecadal climate simulations. A number of studies have also examined the impact of white and green roofs, reflective pavement and other changes to the urban surface, on the urban heat island effect (Santamouris, 2014). These studies highlight the potential of albedo enhancement as a simple mitigation strategy on urban climate. Sailor (1995) show that increased urban albedo or vegetative cover can decrease summertime temperature in Los Angeles by as much as 1.5°C. Taha *et al.* (1999) estimate that large-scale increases in albedo and vegetative fraction for 10 U.S. cities can result in decreases in peak temperature between 0.5 and 1.5°C and an associated decrease of up to 10% in peak electricity demand. Oleson *et al.* (2010) find that urban daily maximum temperature decreases by 0.6°C when the albedo of roofs is globally increased to 0.9 (an extreme scenario) but with no statistically significant changes outside of urban areas. Synnefa *et al.* (2008) show that large-scale increases in albedo can lower ambient air temperatures by up to 2°C in Athens, Greece. Salamanca *et al.* (2012) find a reduction of 4% in energy consumption associated with air conditioning in Madrid when the albedo of roofs is increased from 0.2 to 0.4. Li *et al.* (2014) focus on the Baltimore-Washington metropolitan area and find that to reduce the surface urban heat island effect by 1°C, 30% of roofs need to increase their albedo from 0.3 to 0.7. Georgescu *et al.* (2014) explore the hydroclimatic impacts of 21st century urban expansion across the United States, projecting increase in summer temperature between 1 and 2°C for all urban regions, and examine the impacts of commonly proposed urban adaptation strategies, including cools roofs, which are shown to offset the warming. Vahmani *et al.* (2016) show that cool roofs can meaningfully offset the historical increase in daytime temperature associated with the historical urbanization of the Los Angeles and San Diego metropolitan areas, reducing temperatures by 0.9°C.

Apart from Oleson *et al.* (2010) who use a global climate model, these studies use computationally expensive regional climate models (RCMs). As a result, most studies rely on short simulations ranging from a day or less (Sailor, 1995; Synnefa *et al.*, 2008) to a few days (Taha *et al.*, 1999; Salamanca *et al.*, 2012; Li *et al.*, 2014) to a few months (Vahmani *et al.*, 2016), with the exception of Georgescu *et al.* (2014) who use multi-year simulations. At the same time, the role of climate variability in projections of regional climate change has been the focus on of a number of studies (e.g. Hawkins and Sutton, 2009; Deser *et al.*, 2014; Monier *et al.*, 2015; Sriver *et al.*, 2015). Its role has also been investigated across a broad range of climate impact studies, including sea-level rise (Bordbar *et al.*, 2015), sea-ice loss (Swart *et al.*, 2015), agriculture (Cohn *et al.*, 2016; Monier *et al.*, 2016), forestry (Mills *et al.*, 2015a,b; Kim *et al.*, 2017), extreme events (Fischer *et al.*, 2013; Monier and Gao, 2015) and U.S. ozone pollution (Garcia-Menendez *et al.*, 2017). These studies all show that inter-annual to multi-decadal variations in the regional climate system can contaminate the estimates of the forced anthropogenic response, thus requiring large ensembles with perturbed initial conditions to filter out the noise associated with climate variability and extract the forced signal. However, this methodological approach has yet to be extensively adopted within the regional climate modeling community. This has been in large part due to the high computational costs associated with numerical experimentation using RCMs. Moreover, the benefits of increased spatial resolution in RCMs against the incurred costs of higher computational demands (e.g. smaller ensembles and shorter simulations) requires further attention.

Therefore, to examine the role of urban infrastructure albedo enhancement as a potential climate mitigation strategy, we simulate the climate impacts of increasing urban albedo over the contiguous U.S. using the regional climate model WRF. We run multidecadal regional climate simulations at a coarse resolution (50 km) and contrast the results to single-year simulations at high resolution (10 km) to investigate the role of climate variability in deriving robust estimates of the forced signal of urban albedo enhancement compared to the value of high-resolution regional climate modeling.

2. Methods

2.1 Model

In this study, the Weather Research and Forecasting (WRF) model (Skamarock and Klemp, 2008) is used to examine the impact of urban albedo enhancement. WRF is a nonhydrostatic mesoscale numerical weather prediction model that solves the conservation equations of mass, momentum, and energy on sigma coordinates. Specifically, we use WRF version 3.5, with the following physical parameterization schemes: the Rapid Radiative Transfer Model scheme for radiation; the Mellor–Yamada–Janjić planetary boundary layer scheme; the Kain-Fritz cumulus scheme; the Single-Moment 6-class microphysics scheme (water vapor, cloud ice, cloud water, graupel, rain and snow); and the Noah land surface model. In addition, we use the Single-Layer Urban Canopy Model (SLUCM) (Chen *et al.*, 2011) coupled with the Noah land surface model, which can represent three types of urban facets (roof, wall, and ground). This WRF setup can further distinguish three urban categories: low-density residential, high-density residential, and commercial. For each urban category, a certain fraction of vegetation is assigned in an urban grid cell: 50% for low-density residential, 10% for high-density residential, and 5% for commercial; the remainder is assigned to buildings or hardscapes.

2.2 Simulation Protocol

We run two sets of simulations over the contiguous United States: a control simulation where the urban roof, building wall and hardscape albedo is 0.2 ("*CNTRL*") and a simulation where changes to surface properties are assumed to increase the roof, building wall and hardscape albedo to 0.4 ("*ALB40*"). An increase of 0.2 corresponds could be achieved through the use of a variety of high albedo materials and coatings (Akbari *et al.* 2009 and Santamouris *et al.*, 2011). In this study, we investigate the role of climate variability on estimates of the impacts of urban albedo increase, and thus require multidecadal simulations. For this reason, we run the *CNTRL* and *ALB40* simulations at a coarse resolution of 50 km resolution from 1995 to 2014 (20-year simulations). Table S1 in the Supplementary Information shows a comparison of the simulation length between this study and other modeling studies on the impact of urban albedo enhancement. With the same computational resources (cpu hours), we are only able to run the 10 km resolution simulation for a single year, namely 2004, which is used to estimate the added value from higher resolution. Year 2004 is chosen because it is void of expansive climate anomalies across the United States and it is in the middle of our 20-year time domain of interest. Table S2 in the Supplementary Information provides an overview and technical characteristics of the modeling experiments conducted in this study.

The initial and boundary conditions are taken from the North American Regional Reanalysis (NARR) (Mesinger *et al.*, 2006). To avoid any drift associated with long-term simulations, only one year is simulated at a time and each simulation starts at 0000 UTC 1 December of the previous year, the first month being discarded as a spinoff. The relevant variable is output and saved every hour. Finally, an evaluation of the WRF simulation is provided in the Supplementary Information, with a comparison of seasonal surface air temperature over the U.S. to the University of Delaware Global Air Temperature global gridded dataset (Willmott and Matsuura, 2001) and of daily time series of surface air temperature for select cities to stations from the Global Historical Climatology Network (GHCN) (Menne *et al.*, 2012).

2.3 Impact Metrics

We evaluate how the urban infrastructure albedo enhancement influences surface temperature over the contiguous U.S., urban areas and specific cities. We focus our analysis on the 20-year mean difference in 2-meter air temperature between the *CNTRL* and *ALB40* simulations at 50 km resolution, and on a comparison to the difference estimated from a single year simulation at high resolution (10 km). We complement the analysis of surface temperature with an examination of the impact on heat relevant metrics, both city-specific indicators and a heat index that includes the effect of humidity. We focus on extracting the forced response to the albedo change from the year-to-year climate fluctuations using multi-decadal simulations, and we aim to understand the implications associated with relying on 20-year coarse regional climate simulations versus a single high-resolution simulation.

We focus on three different metrics to assess the impact of urban infrastructure albedo enhancement on human exposure to extreme heat in urban areas. We compute the Heat Index (HI) (Steadman, 1979; Rothfusz, 1990), an index that combines air temperature and relative humidity, which is widely-known and adopted by the National Weather Service and relates to human health and comfort. Different levels of HI correspond to different level of heat disorder and associated heat advisory: 27–32°C, *caution*; 32–41°C, *extreme caution*; 41–54°C, *danger*; and

HI>54°C, *extreme danger*. In this study, we focus on the number of days when the HI thresholds of 32°C and 41°C are exceeded, referred to as HI32 and HI41 respectively in the rest of the study. More details on the HI equation are provided in the Supplementary Information. The other two metrics rely on city-specific indicator variables based on the distribution of temperatures in each city. Specifically, we follow the work by Medina-Ramon and Schwartz (2007) and Mills *et al.* (2015a,b), who use Extreme Hot Days (EHD) defined as days from May to September with a *daily minimum* temperature >99th percentile value from that location's distribution and where this threshold value is greater than 20°C. They show that mortality increases by about 6% during EHDs, mainly associated with myocardial infarction and cardiac arrest deaths. We also follow the findings from Anderson and Bell (2009), which suggest that sustained periods of extreme heat present an elevated risk over single days of high temperatures, even if the heat wave period is as short as 2 days. We rely on their Heat Wave (HW) definition of temperatures ≥99.5th percentile value from that location's distribution for ≥2 days. Finally, we assess the impact of the urban albedo increase on the energy demand from heating and air conditioning by estimating the changes in heating degree days (HDD) and cooling degree days (CDD). More details on HDD and CDD can be in the Supplementary Information. Since the EHD and HW metrics rely on temperature distributions for each urban area, they can only be estimated using multi-year simulations. Similarly, HI, HDD and CDD require multiple years to derive robust estimates of changes. For this reason, we focus our estimates of the impact of albedo enhancement on heat exposure and energy demand to the WRF simulations at 50 km resolution.

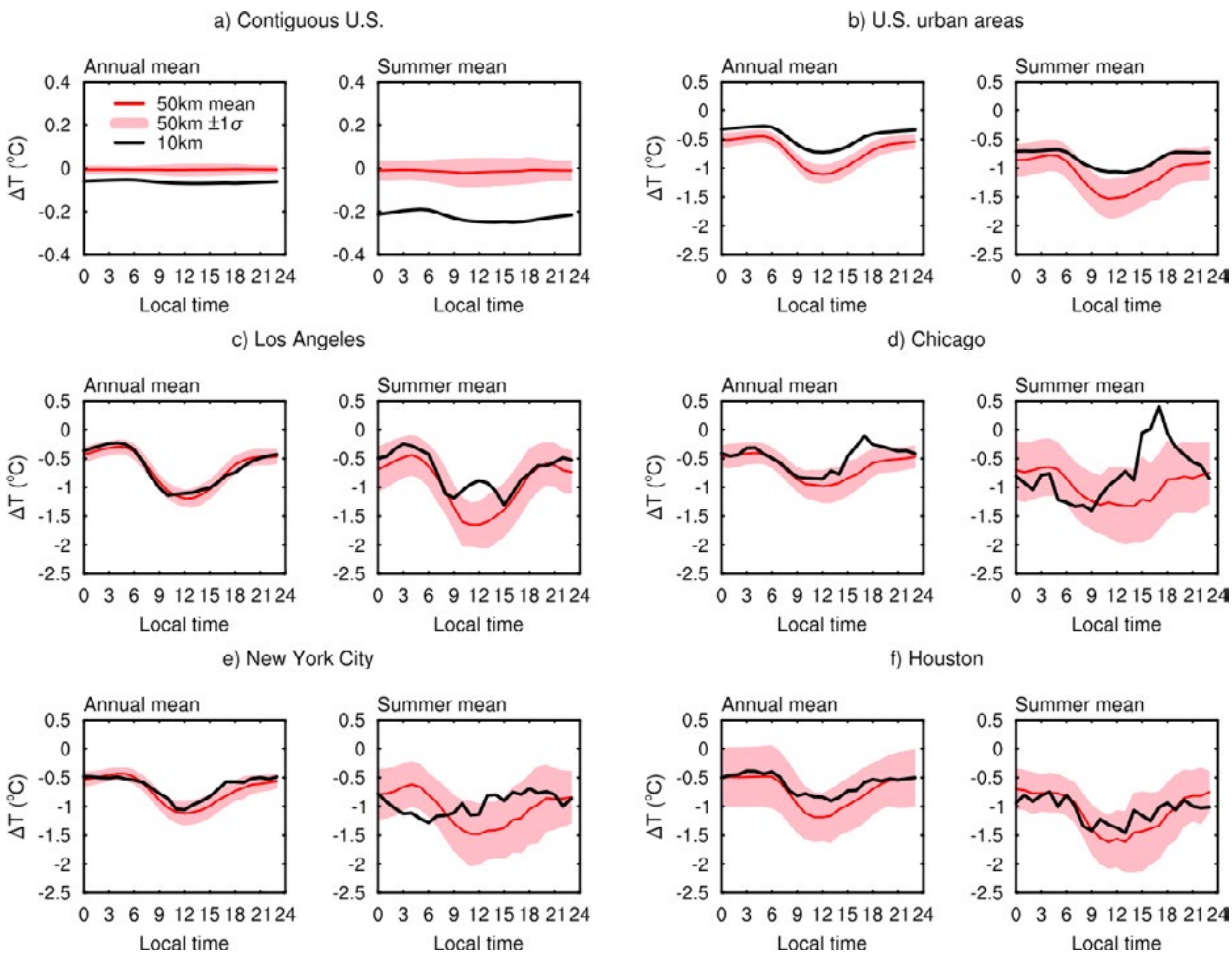

Figure 1. Changes in diurnal cycle (in local time) of annual mean and summer mean 2-meter air temperature between the *ALB40* and *CNTRL* simulation over the 1995–2014 period for a) the contiguous U.S., b) U.S. urban areas, c) Los Angeles, d) Chicago, e) New York City and f) Houston. The red solid lines and the pink shaded areas correspond, respectively, to the mean and the 1 standard deviation over the 1995–2014 period for the simulations at 50 km resolution. The black solid lines correspond to the single-year simulation at 10 km resolution.

3. Results and Discussion

The changes in diurnal cycle of annual mean and summer (JJA) mean surface temperature (**Figure 1**) reveal that urban infrastructure albedo enhancement has little influence on the U.S. as a whole but it can substantially lower temperature over urban areas. That is particularly evident during summer and during daytime (08:00 to 16:00 local time), when solar radiation is at its maximum. Over urban areas, the 20-year mean increase in albedo results in decreases in annual mean temperature between 0.5°C and 1°C and summer mean temperature between 1°C and 1.5°C, the largest decreases occurring during daytime when temperatures are highest. This range of temperature impact is consistent with the existing literature (Sailor, 1995; Taha *et al.*, 1999; Synnefa *et al.*, 2008; 2012; Li *et al.*, 2014). The analysis of four major U.S. cities with varied climate (Los Angeles, Chicago, New York City and Houston) shows that the temperature decreases resulting from the albedo enhancement are consistent, with only small differences between cities. For example, Los Angeles experiences a slightly stronger decrease in summer daytime temperature (1.7°C on average) compared to Chicago (1.3°C). By examining the standard deviation from the 20-year simulations helps to identify how robust the impact of urban albedo enhancement is. We find that the error associated with inter-annual variations is generally largest in the summer and varies strongly city by city. However, the temperature decreases are robust (i.e. mean response is greater than the standard deviation) over all urban areas. Finally, the analysis of the single-year simulation at high-resolution (10 km) is comparable with the analysis of the multidecadal and coarser simulations over U.S. urban areas, although the temporal variability in temperature change can be noisier at the city level. In addition, the single-year simulation indicates a U.S.-wide decrease in summer temperature of about -0.2°C, which is not supported by the 20-year analysis at coarser resolution. This suggests that relying on single-year simulations has little added value and can actually be misleading in the assessment of the regional impact of urban albedo enhancement.

Multi-year model simulations can be used to explore the role of natural variability as well as capture the forced signal associated with the urban infrastructure albedo en-

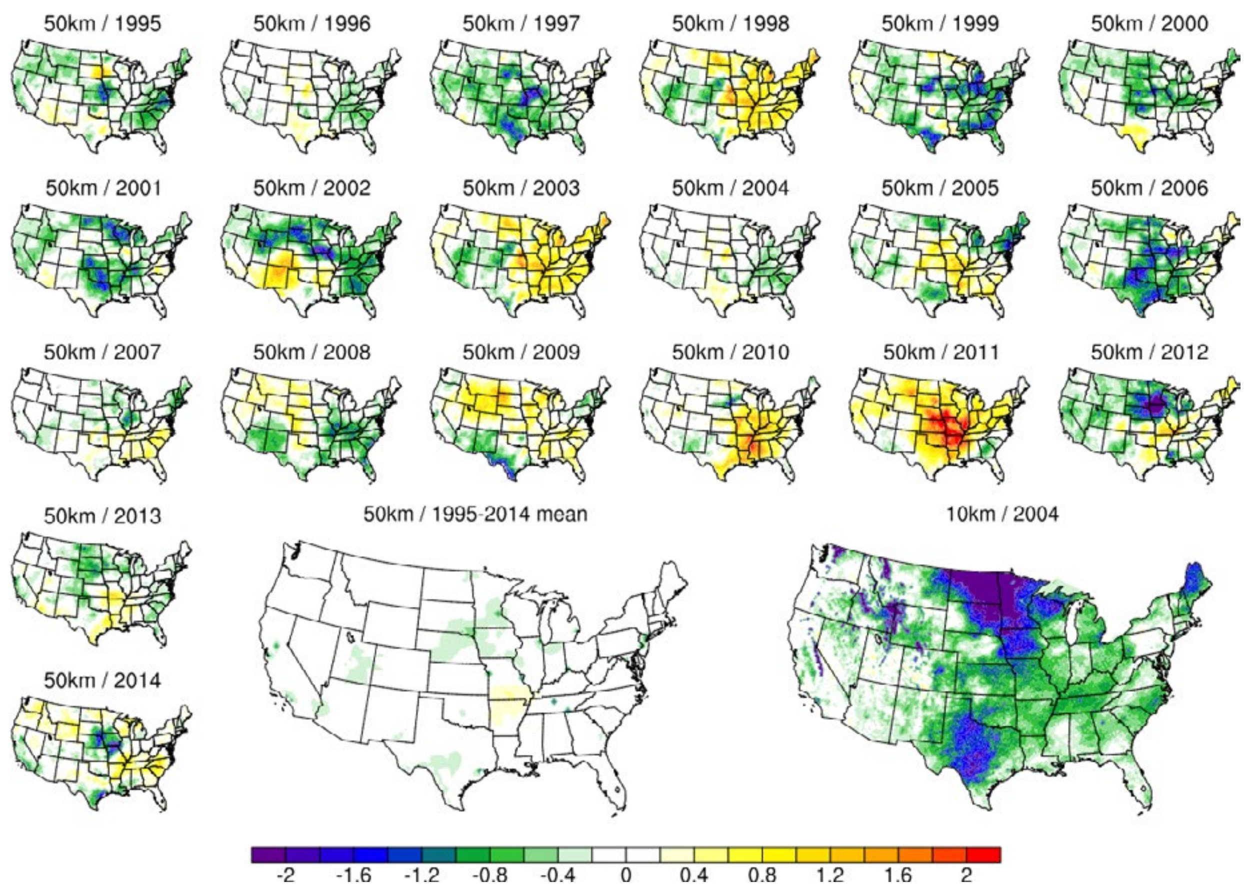

Figure 2. Maps of changes in summer daytime (08:00 to 16:00) 2-meter air temperature between the *ALB40* simulation and the *CNTRL* simulation for each year (small maps) and for the mean (large map) over the 1995–2014 period. The resolution and year are identified above each map.

hancement. **Figure 2** shows maps of changes in summer daytime surface temperature for each individual years over the 1995–2014 period for the simulations at 50 km resolution, along with the 20-year mean and the changes simulated under the 10 km resolution simulation for year 2004. A comparison of the climate impacts of the albedo increase for single-year simulations reveals a considerable amount of interannual variability with large temperature anomalies, both positive and negative, over large regions of the U.S., even outside of urban areas. These large anomalies over rural areas are reminiscent of differences between global climate simulations with perturbed initial conditions (Deser *et al.*, 2014; Monier *et al.*, 2015; Sriver *et al.*, 2015). Large year-to-year variations are evident and mainly caused by the interannual variability inherent to the climate system, driven by perturbations in the local surface albedo in this modeling experiment. The impact of the albedo change is dependent on the incoming solar radiation, which in turn is strongly impacted by cloud cover and surface meteorology (i.e. surface moisture). As a result, year-to-year variations in the albedo change impact on surface temperature can be expected, and can propagate through the climate system as small perturbations. Once the 20-year average is computed, only urban areas display the more salient decreases in temperature, thus filtering out the noise associated with climate variability and extracting the forcing signal of the urban albedo increase. This analysis highlights how single-year simulations can inaccurately suggest the increase in urban albedo has a strong regional impact on surface temperature. However, after averaging over multiple decades, the forced signal emerges and confirms that the albedo enhancement effect is confined to the vicinity of urban areas. For example, the interpretation drawn from the 10 km resolution single-year experiment would be that the increase in urban albedo leads to substantial decreases in summer daytime temperature over major regions of the U.S., but this is misleading based on the 20-year mean response of the 50 km resolution results. While the high-resolution simulations display clear regional details and features, such as the California's Central Valley or the Rocky Mountains, their value is unclear in the face of the large noise from interannual climate variability.

To better understand the role of natural variability on estimates of the urban albedo enhancement impact on temperature, we follow the methodology of Garcia-Menendez *et al.* (2017). **Figure 3** shows the effect the simulation length can have on the simulated changes in summer daytime surface temperature over U.S. urban areas and the four specific cities of interest. Relying on a small

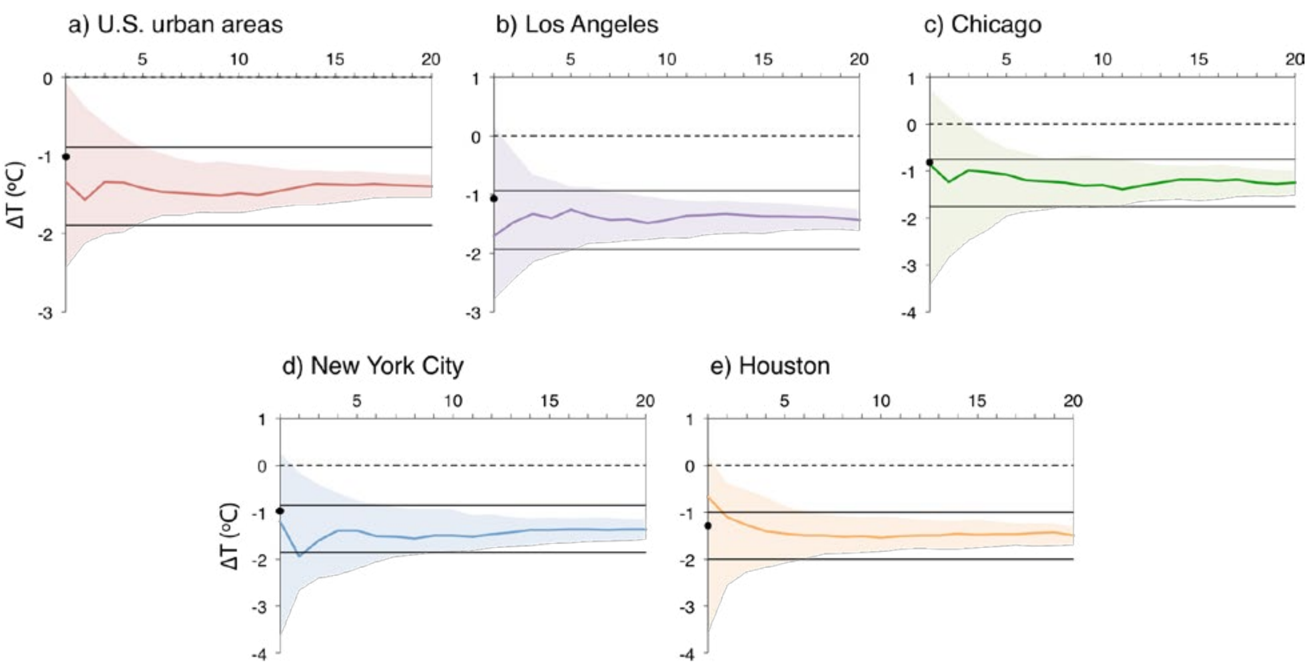

Figure 3. Changes in summer daytime surface temperature resulting from urban infrastructure albedo enhancement over the U.S. estimated from the 50 km resolution simulations over the 1995–2014 period. a) Average over U.S. urban areas, b) Los Angeles, c) Chicago, d) New York City and e) Houston. Solid colored lines correspond to simulation lengths increasing from 1 to 20 years centered on year 2004. Shaded regions indicate the margin of error for each estimate at a 95% confidence level based on the 20-year population standard deviation. Black dots indicate the single year estimates from the 10 km resolution simulations for year 2004. The dashed black lines correspond to zero temperature change, while the solid black lines correspond to the ±0.5°C margin of error in the 20-year mean estimates.

Table 1. Changes in the EHD, HW, HI32 (*extreme caution* heat advisory), HI41 (*danger* heat advisory), HDD, CDD and changes in summer daily maximum temperature estimated as the 20-year mean differences between the *ALB40* and *CNTRL* simulations at 50 km resolution over the 1995–2014 period.

	ΔEHD	ΔHW	ΔHI32	ΔHI41	ΔCDD	ΔHDD	SummerΔTmax
U.S. urban areas	-35%	-41%	-22%	-50%	-15% (-250)	4% (218)	-1.4°C
Los Angeles	-37%	-42%	-39%	-95%	-13% (-268)	11% (172)	-1.5°C
Chicago	-21%	-27%	-26%	-38%	-17% (-203)	3% (220)	-1.3°C
New York City	-47%	-49%	-32%	-55%	-18% (-213)	4% (264)	-1.4°C
Houston	-68%	-59%	-8%	-55%	-11% (-393)	5% (86)	-1.5°C

number of simulated years can substantially influence the projected impact of the urban albedo enhancement impact, including the sign of temperature change. However, as the simulation length is extended, the estimate converges quickly to the 20-year mean change. For the average impact on urban areas, even a single-year simulation provides the correct sign in temperature change. This is most likely because averaging over multiple cities provides an efficient filtering of natural variability, the cities being largely uncorrelated. However, single-year simulations for specific cities show a large range of impacts, even possible warming from the urban albedo increase, especially for Chicago.

In this simulation experiment, achieving a ±0.5°C margin of uncertainty for the projected impact of the urban infrastructure albedo enhancement on summer daytime temperature change over U.S.-average urban areas at a 95% confidence level entails using at least 5 simulation years. A similar number of simulated years is necessary for Los Angeles and a minimum of 7 simulation years is required for Houston. However, New York City and Chicago both require at least 11 simulated years. A ±0.5°C margin of error may be adequate for a summary analysis, but may be insufficient to confidently project the full impact of the urban infrastructure albedo enhancement, such as the implications for heat mortality or for the energy use for air conditioning. Lowering the margin of error to ±0.2°C requires simulations for the full 20-year period. In contrast, the estimates from the 10 km resolution single-year simulations show similar magnitudes but without any error estimates available.

To evaluate the potential consequences of enhancing the albedo of urban infrastructure, we analyze the impact on metrics relevant to human health and energy demand for cooling and heating. **Table 1** shows the changes in EHD, HW, HI32 (*extreme caution* heat advisory), HI45 (*danger* heat advisory), CDD and HDD and the changes in summer daily maximum temperature estimated as the 20-year mean differences between the *ALB40* and *CNTRL* simulations at 50 km resolution over the 1995–2014 period. Regardless of the heat metric chosen, this analysis reveals substantial mitigation potential of increasing the albedo of urban infrastructure in terms of heat exposure. U.S. urban areas are projected to experience an average of 35% reductions in EHD, 43% reductions in HW and 34% and 61% reductions in HI32 and HI41, respectively, along with a decrease in summer daily maximum temperature of 1.5°C. The impact of the albedo increase varies among individual cities, but the analysis shows a systematic reduction in heat over densely populated areas. Under a stringent greenhouse gas stabilization scenario with about 1 to 1.5°C warming by 2100 compared to present-day, Mills *et al.* (2015a,b) project increases in EHD and associated heat mortality by 500 deaths per year by end-of-century over 33 Metropolitan Statistical Areas. Given that the urban infrastructure albedo enhancement has the potential to substantially decrease EHD and reduce daily maximum temperature in urban areas by 1.5°C, it can provide an efficient mitigation strategy to counter the impact of future climate change, especially when it comes to heat mortality.

In terms of energy demand, the analysis that the urban albedo would increase results in a 15% decreases in CDD (-250 per year) and 4% increase in HDD (+220 per year) over urban areas, implying a substantial decrease in energy demand for air conditioning during summer but an associated increase in energy demand for heating in winter. Northern cities, like Chicago and New York City, experience far more HDD than CDD per year compared to southern cities, like Los Angeles and Houston, which have far more CDD than HDD. As a result, the net impact of the urban albedo enhancement on the energy demand for cooling and heating is varied. For example, Houston is projected to benefit strongly with a decrease of 393 CDD per year and an increase of 86 HDD per year; meanwhile, the decrease of 213 CDD per year in New York City is offset by an increase of 264 HDD. As a result, the albedo enhancement is beneficial for energy demand for cooling and heating for cities in the south of the U.S., but not at higher latitudes, which is consistent with the findings of Oleson *et al.* (2010) and Krayenhoff and Voogt (2010).

4. Conclusions

This analysis suggests that increasing the albedo in urban infrastructure has the potential to mitigate warming in densely populated areas, but with no impacts outside of urban areas. In particular, we find substantial impact of the urban albedo increase over summer daytime temperature over urban areas, with decreases of about 1 to 1.5°C. The impact on heat exposure is also considerable and impactful for human health, with decreases between 22 and 50% in EHD, HW, HI32 and H41 (*extreme caution* and *danger* heat advisories) over U.S. urban areas as a whole. For specific cities like Los Angeles, Chicago, New York City and Houston, the magnitude of the decrease varies but the albedo increase is systematically impactful. The urban albedo enhancement also impacts energy demand for air conditioning, with a 15% mean decrease in CDD over urban areas. The benefit is largely limited to cities in the south of the U.S.; at higher latitudes, the reduction in energy demand for cooling in summer is generally offset by an equally large increase in energy demand for heating in the winter.

Using multidecadal regional climate simulations at a coarse resolution (50 km) and results from single-year simulations at a high resolution (10 km), we investigate the role of climate variability in deriving robust estimates of the forced signal of urban albedo enhancement compared to the value of high-resolution regional climate modeling. Overall, we find a substantial role of climate variability and identify a minimum of 10 years is required to obtain robust estimates of the impact of urban infrastructure albedo enhancement. We also find little added value of high-resolution simulations, if they are short, given the large year-to-year climate variations contaminating the analysis and the increase computational demand of high-resolution regional climate modeling. This result suggests that regional climate modeling aimed at identifying an anthropogenic forced signal should use multi-decadal simulations, rather than placing a priority on higher spatial resolutions at the cost of performing shorter simulations and/or smaller ensembles. It also implies that if urban albedo is enhanced, the verification of its impact on urban surface temperature would be challenging, require continuous monitoring for a number of years and careful analysis to extract the forced signal from the climate variability.

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