Urban Heat Island: Mechanisms, Implications, and Possible Remedies

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Abstract

Urban heat island (UHI) manifests as the temperature rise in built-up urban areas relative to the surrounding rural countryside, largely because of the relatively greater proportion of incident solar energy that is absorbed and stored by man-made materials. The direct impact of UHI can be significant on both daytime and night-time temperatures, and the indirect impacts include increased air conditioning loads, deteriorated air and water quality, reduced pavement lifetimes, and exacerbated heat waves. Modifying the thermal properties and emissivity of roofs and paved surfaces and increasing the vegetated area within the city are potential mitigation strategies. A quantitative comparison of their efficacies and costs suggests that so-called cool roofs are likely the most cost-effective UHI mitigation strategy. However, additional research is needed on how to modify surface emissivities and dynamically control surface and material properties, as well as on the health and socioeconomic impacts of UHI.

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INTRODUCTION

Construction of large cities represents a fundamental, inextricable change from the natural environment. In most respects, urbanization is beneficial as it enables increased standards of living: Urban areas create more than 90% of global gross value added (1). Unfortunately, urbanization also brings with it some negative environmental, social, and economic consequences. Creation of urban heat islands (UHI) is one such concern. The UHI effect is defined as a difference in temperature between the built environment and the natural (surrounding) environment. The UHI intensity can be measured by one of two closely coupled temperatures: (*a*) the urban skin temperature (pavements and buildings) or (*b*) the meteorological UHI (air temperature) (2).

In the extreme, short-term temperature deviations in excess of 12°C have been reported for dense urban areas (e.g., Tokyo) (3). Most major global cities experience UHI to varying degrees. **Table 1** shows an abbreviated list of recent (post-2006) seasonal meteorological UHI intensity measurements, i.e., surface or skin UHI. Depending on the intensity, the impacts of the UHI effect can range from being advantageous (e.g., warmer winter nights) to complex, rippling negative impacts on the proximate society, environment, and economy.

The UHI phenomenon is of increasing concern given more people are moving to cities each year—with more than 6 billion urban inhabitants (~65% of the global population) projected by 2050 (1). This trend yields two exasperating outcomes: First, UHI intensity is increasing in most major cities; second, more people are affected by it each year. Assuming this trend continues, developing a comprehensive understanding of UHI and, correspondingly, the effectiveness of mitigation strategies of UHI become increasingly important.

At its core, the UHI effect is governed by a simple overarching energy balance between the input, generated, lost, and stored heat in the urban environment. Although it is beguilingly easy to conceptualize and measure, the UHI is a complicated phenomenon that depends on the size,

Table 1 Measured UHI intensity of select cities around the world since 2010

City (millions of inhabitants)	Seasonal (skin) UHI	Measurement type	Reference
Shanghai (144)	7	Satellite	3
Tokyo (13.4)	12	Satellite	3
Delhi (9.9)	8.3	Ground and satellite	4
New York (8.4)	5.4	Satellite	5
London (8.3)	8.6	Satellite	6, 7
Dallas-Ft. Worth (6.3)	7	Satellite	8
Singapore (5.4)	5.5	Satellite and ground	9
Sydney (4.6)	4	Ground and aerial	10
Los Angeles (3.9)	6	Satellite	11
Paris (2.2)	6	Satellite	12
Phoenix (1.5)	4.5	Ground	13
Athens (0.8)	4	Ground and aerial	14
Tucson (0.5)	4.5	Ground	15
Global (193,090 cities)	**7.7**	**MODIS Satellite**	2

Abbreviations: MODIS, moderate resolution imaging spectroradiometer; UHI, urban heat island.

density, building practices, location, season, air flows, and many other factors of the built environment (2, 4, 8, 16–18). Similarly, the impacts of the UHI are a motley assortment of social, health, energy, economic, and other issues, which are difficult to track and predict (6, 7, 13, 19–23).

Mitigation strategies can be roughly lumped into two categories: increased vegetation (trees, landscaping, and green spaces) and changes to building practices (materials for higher albedo and/or modified thermal properties, alternative pavements and paved surfaces designs, building types, and other materials selections) (7, 16, 24–28). As an example, the use of reflective pavement materials has been traditionally promoted as a potential mitigation strategy for the UHI effect. However, a recent research synthesis also showed potential unintended consequences of adopting reflective pavements as a UHI mitigation strategy, including increased heat load of surrounding buildings and reflected UV radiation and glare (29).

URBAN HEAT ISLAND MECHANISMS

Urban Heat Balance

Several attempts have been made to model the UHI effect, starting (arguably) with the work of Oke (30), who introduced a transient energy balance to predict urban surface temperatures. More recently, highly complex mesoscale meteorological models such as the Weather Research & Forecasting (WRF) Model (**http://www.wrf-model.org/index.php**) have been employed to study UHI. Simply put, man-made materials such as concrete and pavement store more thermal energy than bare or vegetation-covered ground and may also reflect less sunlight. When added to heat input from internal combustion engines, heat rejected by air conditioners, and other human-caused sources, the net effect is an increase in urban temperatures relative to nearby suburban and rural areas. We do not attempt here to provide a comprehensive overview of UHI modeling efforts (interested readers can consult Ref. 31); rather, we provide a brief discussion to explain the relevant heat transfer processes.

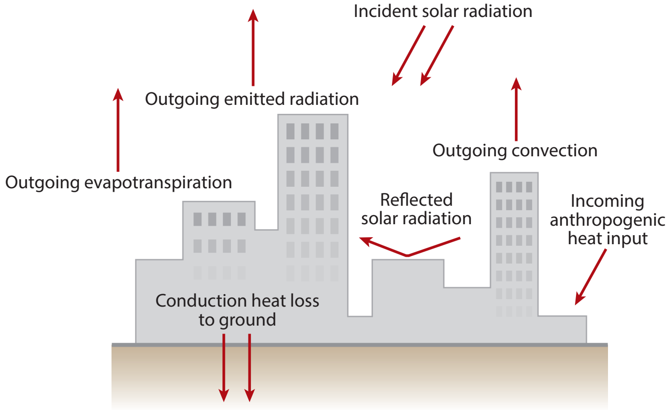

Figure 1

Relevant energy flows for the urban heat island. Used with permission from Ref. 32, copyright 2009 by the American Meteorological Society.

Zero-order urban thermal model. Following conventional heat transfer theory, the simplest type of model that can predict the time-varying temperature of a system is a lumped model, also known as a zero-order model. A zero-order governing equation for the transient lumped urban temperature T is given by (**Figure 1**; see also 32):

$$\frac{mc}{A}\frac{dT}{dt} = (1-\alpha)q_{sol} + q_{anthro} - q_{cond} - q_{evap} - q_{conv} - q_{rad}, \tag{1.}$$

where m is the mass of the urban fabric, c the specific heat, A the normal surface area, t time, and α the albedo. The heat fluxes (q, in W/m^2) are the incident solar flux q_{sol}, the anthropogenic heat addition q_{anthro}, the conduction to the deep ground q_{cond}, heat loss via evapotranspiration q_{evap}, heat loss via convection to the surrounding air q_{conv}, and radiative heat loss to the sky q_{rad}.

The incident solar flux q_{sol} is relatively straightforward and includes both the beam and diffuse components. The only other heat gain is due to anthropogenic causes and consists of three contributions (33):

$$q_{anthro} = q_{elec} + q_{fuel} + q_{human}, \tag{2.}$$

where q_{elec} is due to electricity consumption and q_{fuel} to fuel consumption (including for transportation), and q_{human} represents metabolic heat generation. Generally, $q_{anthro} \ll q_{sol}$ during daylight hours, although it has been observed that the UHI for the city of Barrow, Alaska, was impacted by natural gas usage in the winter because of additional space heating (34).

The remaining terms on the right-hand side of Equation 1 are all heat losses. The conduction to the deep ground q_{cond} is modeled as

$$q_{cond} = k_g \frac{T - T_g}{\delta z}, \tag{3.}$$

where k_g is the thermal conductivity of the ground near the surface, and T_g is the ground temperature at a depth δz. The evapotranspiration heat loss q_{evap} is the latent heat transfer due to water loss from vegetation. It can be expressed as

$$q_{evap} = E_t \rho_w h_{fg}, \tag{4.}$$

where E_t is the measured evapotranspiration rate (in meters) for areas covered with vegetation, soil, or other growing media; ρ_w the density of liquid water; and h_{fg} the latent heat of water. The convection heat transfer q_{conv} is represented by Newton's law of cooling as

$$q_{conv} = h(T - T_a), \tag{5}$$

where T_a is the dry-bulb air temperature, measured at some rural location near the urban area, and h is the convective heat transfer coefficient determined through appropriate correlations. Finally, the radiative heat loss q_{rad} is calculated from

$$q_{rad} = \varepsilon\sigma(T^4 - T_{sky}^4), \tag{6}$$

where ε is the emissivity, σ the Stefan-Boltzmann constant, and T_{sky} the effective sky temperature. (Details for determining T_{sky}, h, and other terms are given in Ref. 32.)

Higher-order urban thermal/fluid models. As mentioned above, a range of model sophistication is available to predict UHI. The simplest is the zero-dimensional lumped model described above. The next step up would be a one-dimensional model that takes into account spatial variations (see, e.g., 35, 36). An intriguing alternative approach is to treat the city as a porous medium (37). Another way is to rely on statistical modeling of experimental data (38). The WRF mesoscale meteorological model has been combined with a land surface model (called Noah) to enable the prediction of ground surface temperatures (14). In all cases, the more complex is the model, the longer is the running time and the greater is the number of required inputs. For US cities, an online UHI calculation tool (**http://www.heatislandmitigationtool.com/**) was developed that relies in part on a library of mesoscale simulations, thus enabling rapid calculation (39). (This website, however, was taken offline as of July 1, 2014.)

In general, the conclusions drawn from the simple lumped model considered here and higher-order models are qualitatively the same, and on an averaged basis can even be quantitatively similar (32). Higher-order models, however, generate spatial temperature distributions resulting from local surface characteristics (pavement, bare ground, vegetation, buildings, etc.) that cannot be achieved with a simple lumped model. Furthermore, higher-order models can take into account radiative trapping in urban canyons formed by nearby tall buildings, as well as the turbulent air flows generated by such urban canyons (see, e.g., 14). Higher-order models also have the advantage of being able to be compared (and validated) with local surface and air temperature measurements, whereas a lumped model can only be compared qualitatively with averaged measured temperatures (see, e.g., 40).

Heat Generation and Rejection

Various urban structures and processes play a role in UHI. Man-made structures such as buildings and pavements absorb, store, and ultimately release heat to the environment, whereas processes such as electricity generation serve only to add heat to the environment.

Buildings. Buildings contribute to UHI because of their large thermal capacity, which are exposed to the sun through the roof and the walls, and through the heat dissipated because of space conditioning, electric loads, and metabolic heat generation from the occupants. As we explain below, cool roofs, that is, roofs with relatively high α, are a promising approach for UHI mitigation. Of course, so-called green roofs that incorporate natural plant cover represent another alternative. Metabolic and other anthropogenic heat generation is generally not a significant contributor to UHI, except possibly during the winter, as explained above.

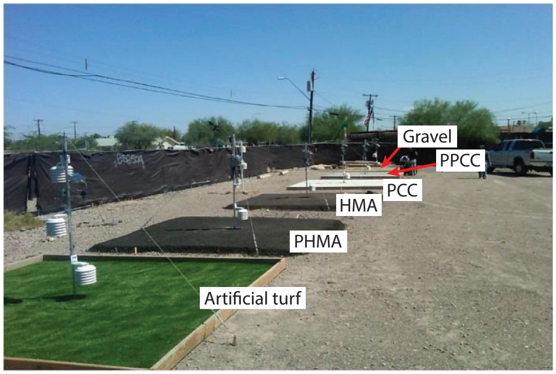

Figure 2

Pavement test slabs in Tempe, Arizona. Abbreviations: HMA, hot mix asphalt; PCC, Portland cement concrete; PHMA, porous hot mix asphalt; PPCC, pervious Portland cement concrete. Adapted with permission from Ref. 41, copyright 2015 by the Asphalt Pavement Alliance.

Pavements. Unexpectedly, a recent field experiment in Arizona (41) also finds that a variety of pavement surfaces had only limited influences on overlying air temperatures. In this experiment, six types of ground cover are deployed on a site: landscape gravel, green turf, concrete, pervious concrete, asphalt, and porous asphalt (**Figure 2**). Significant deviations in surface temperatures are found for different ground covers due to their albedo. Maximum daily surface temperature is the highest over green turf and the lowest at the concrete surface, with the difference being more than 15°C around noon. However, the air temperature profiles at 1.5 m (5 ft) above the different surfaces are almost identical throughout the day except for porous asphalt and pervious concrete. This result indicates that the presence of turbulent mixing near surfaces lowers the impact of surface albedo of individual pavement patches. However, this finding is limited to the size of the pavement slabs, the specific site, and environmental conditions of the experiment.

Another important variable is the heat capacity. The surface temperature exhibits a different trend during day and night. During daytime, with greater heat capacity, concrete pavement has a significantly lower surface temperature than green turf and gravel. However, at nighttime concrete pavement exhibits higher surface temperatures, whereas surface temperatures over green turf and gravel generally drop rapidly after sunset. Another effective variable is the porosity of pavement materials. Porous pavements are able to dissipate the heat comparatively more quickly than dense or conventional pavements. Porous materials can also hold water and cool the surface temperature by evaporation, which also has a positive effect on storm water management while reducing UHI.

Electricity generation. Although heat generation from human sources is not usually a major factor in UHI, UHI can affect a thermal generation plant. One of the reasons electricity plants are rarely discussed in connection with UHI is that large power plants (coal and nuclear) are seldom located in dense urban areas. Natural gas power plants and other peaking power plants, however, may be located close enough to affect (or be affected by) UHI. These add heat (and many times humidity) to the local environment. Little information is available to predict how much this adds to UHI, but many of the natural gas power plants located near the urban environment are on the order of 30–100 MW in electrical generation capacity. This indicates that during operation they are adding 70–230 MW of thermal energy to the urban environment (assuming 30% efficiency). Because they are peaking power plants, hot-climate cities (e.g., Phoenix) unfortunately receive

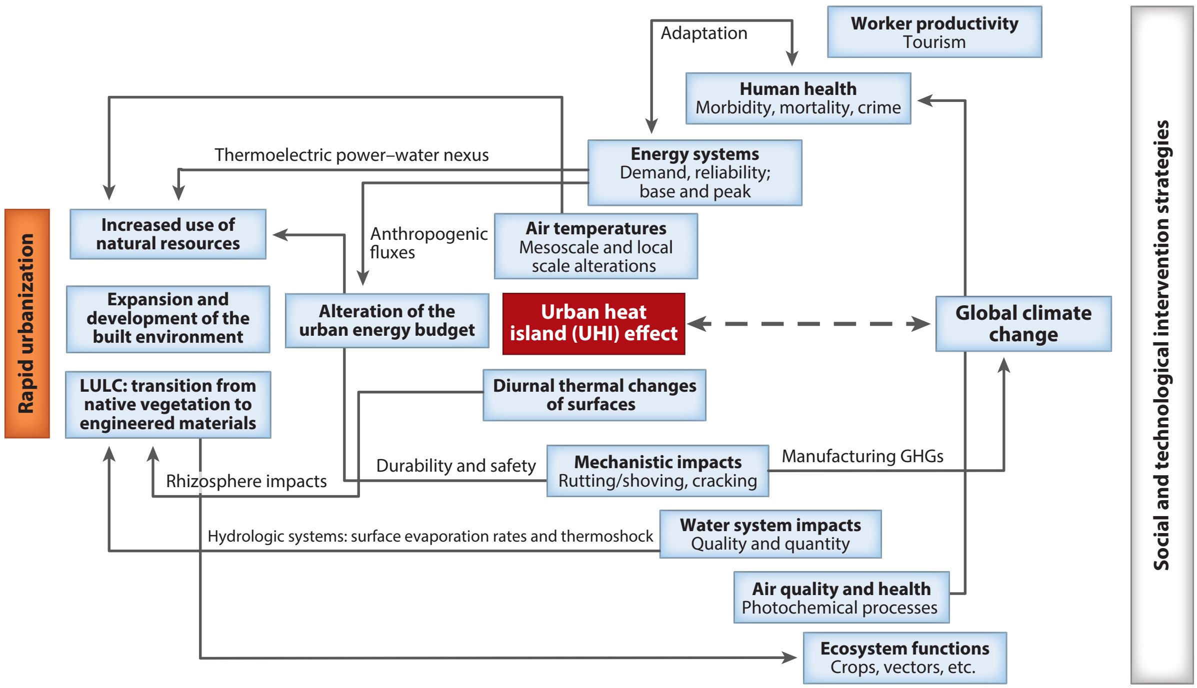

Figure 3

Drivers and impacts of the urban heat island (114). Abbreviations: GHGs, greenhouse gases; LULC, land use and land cover.

this unwanted heat during the summer when the UHI health impacts are most severe. Ultimately, this is an area that requires more research in critical locations.

Industrial processes. Industrial processes use a large amount of primary energy—approximately 30% (or 32,000 PJ) in the United States (42). A similar amount of energy is used for industrial processes in Europe (43). The energy-intensive industrial processes that can be located in urban environments mostly include downstream industries, such as manufacturing of consumer goods, sterilization (food and equipment), and fabrication of metals and machinery. All of these are major users of natural gas and, increasingly, hydrocarbon gas liquid feedstocks (42). As with electrical generation, the effect of industrial processes on urban heat is not well studied, but when compiled represents a large, transient heat production that could have a significant impact in certain areas. These of course, require case-by-case studies given proximity and usage schedules are of critical importance in their relation to UHI.

URBAN HEAT ISLAND IMPLICATIONS

Figure 3 provides an overview of the multiple drivers and impacts of UHI. The most important implications are described further below.

Elevated Temperatures

The first known documentation of the UHI effect was by Luke Howard (44) in the *Climate of London, Deduced from Meteorological Observations, Made in the Metropolis and at Various Places*

Around It. Since then, the UHI has been measured by researchers around the globe including Paris, France, which found a 6.1°C (11°F) maximum UHI intensity at 2 m height (12, 45); Athens and Thessaloniki, Greece, with a maximum intensity of 3.5–4°C (46); Beijing, China, having a maximum intensity ranging from 1.2°C annual UHI to 1.7°C for the winter (47); Phoenix, Arizona, with 7.8°C (14°F) (48); and 4°C for New York City (49, 50).

Energy Impacts

Changes in energy consumption have multiplier impacts, including costs, human health, the environment, etc. This makes such impacts especially important to measure and document.

Buildings. Energy demand impacts resulting from UHI include possible increased demand resulting from mechanical cooling as well as reductions resulting from reduced winter heating. As an example, Rong (51) examined the role of the UHI in the state of Texas and documented that residential cooling load increased approximately 6%, whereas heating load decreased approximately 16%, and an overall energy decrease of approximately 1% was observed. Giridharan & Kolokotroni (52) examined the winter UHI in London and found that although it was observable, it was not as predictable as the summer UHI. Kolokotroni et al. (53) further examined the role of the UHI in London, where many office buildings are not mechanically cooled. As such, there were only marginal increases in energy consumption and CO_2 emissions between urban office buildings and their rural counterparts. However, in modeling out in the future (2050) with mechanically cooled buildings in the London urban environment, they found that CO_2 emissions ($kgCO_2/m^2$/year for heating and cooling) as a proxy of energy consumption increased between 480% and 670% in the city center. Golden et al. (54) modeled the role of the UHI in Phoenix, Arizona, on a typical residential structure. Their findings indicated that the thermal modifications to the climate as a result of urbanization have impacted the overall HVAC electrical consumption for a representative 2,000-ft^2 residence, and increased from 7,888 kWh per year in the 1950s to more than 8,873 kWh per year in the 1990s. Santamouris et al. (23) undertook a review of previous studies around the globe and identified that although comparative studies between similar building structures in both the rural and urban settings are rare, the role of UHI is statistically significant and represents a nearly 13% increased cooling load.

Pavements. Urban areas feature dense structural confines that impact heat transfer from and to pavement surfaces in various ways. Obviously, one effect is the blocking and reflecting of solar radiation during daytime. Energy is transported in this process between adjacent walls, roofs, and roads. And the transferring mechanism varies throughout the day with the solar elevation angle. This serves as an additional heating source in urban areas that increases surrounding air temperature and consequently the cooling load of nearby buildings. Several studies show that reflective pavements increase adjacent building cooling energy loads (55, 56).

Environmental Impacts

Environmental impacts can take many forms, but here we focus on two: water and air quality. Both are in general negatively impacted by UHI.

Water quality. Most of the world's population growth will occur in arid and semiarid regions where issues of water quantity and quality are significant (57). The mechanisms of transitioning from native vegetation to man-made and engineered infrastructure alter the surface energy balance in urban regions. Increased water temperatures resulting from a rise in pavement temperature and stormwater runoff can impact chemical and biological processes that support water quality, and nonpoint source runoff is deemed a major source of pollutants in urban areas (58). The percentage of impervious surface area helps determine stream water quality as defined by ecological indicators such as benthic macroinvertebrate community composition and fish density and abundance (59). Biofouling of urban waterways can limit runoff transport, and small increases in water temperature typically lead to notable changes in algal growth rates (60), promoting fouling and potentially competing with or harming other species, particularly fish. Locally, water-resource protection is becoming more complex, largely due to the problem of polluted runoff. Polluted runoff, now a leading threat to water quality, derives from contaminants washed off the surface and carried into waterways or groundwater; thermal shock is a major concern as stormwater enters receiving bodies with elevated temperatures derived from contact with hot paved surfaces (61, 62). Muller et al. (63) examined the role of UHI on subsurface water infrastructure in Oberhausen, Germany, and potentials for impacts on water quality. They identified an average subsurface UHI at 70 cm below ground surface of 9 K between the city center and a rural control location.

Water quantity. Increased temperatures from the UHI result in increased mechanical-cooling hours during warm months, when mechanical cooling load is highest and electricity grids are strained. Although there is a reciprocal reduction in the number of hours that require heating, the cumulative impact is estimated to be a 13% increase in electricity consumption by residential and commercial facilities (64). It has been estimated that between 1.8 L (0.47 Gal) (65) and 72 L (19.0 Gal) (66) of water is required to produce 1 kWh of thermoelectric power in the United States. Fresh groundwater withdrawals (83 Bgal/day) in 2000 were 14% more than in 1985. Approximately 195 Bgal/day (48%) of all freshwater and saline-water withdrawals for 2000 were used for thermoelectric power. Most of this water derived from surface water and was used for cooling at power plants. Approximately 52% of fresh surface-water withdrawals and 96% of saline-water withdrawals were for thermoelectric power (67). Guhathakurta & Gober (68) examined increased single-family residential water consumption as a result of the UHI in metropolitan Phoenix, Arizona, controlling for relevant population and housing attributes. Their statistical analysis identified that an increased UHI intensity of 1°F results in an average monthly increase in water consumption of 3.8% or 290 gallons for the modeled typical residence. Aggarwal et al. (69) similarly examined residential water consumption in the Phoenix region. The authors used longitudinal data to explore the temporal variations in the UHI and associated water consumption at the census tract level. Their findings indicated that for every 1°F in nighttime temperature increase there was an associated 1.4% increase in water consumption—180.6 gallons in a typical summer month (June). The authors identified that one potential for the variation in their findings versus those of other authors is that they used simulated rather than observed data.

Air quality. Several have provided reports of atmospheric pollution in urban areas, such as Athens, Greece (70); Paris and Marseilles, France (respectively, 71, 72); and Taichung, Taiwan (73). Smog is one of the most related air quality impacts investigated. Smog is created by photochemical reactions of pollutants in the air; these reactions are more likely to intensify at higher temperatures. One of the more cited research results was for Los Angeles, where it was observed that for every 1°C temperature rise above 22°C, incidents of smog increase by 5% (74). Wilby (75) utilized statistical downscaling models in lieu of general circulation models for London's nocturnal UHI implications, which projected increased ozone concentrations through the 2050s relative to present conditions. Otanicar et al. (13) investigated further transportation air quality by quantifying the impact of the UHI on light duty gasoline vehicles using the US Environmental Protection Agency's

(EPA's) MOBILE6 modeling techniques. Those findings indicated that the major impact is on evaporative emissions, i.e., vapors escaping from the vehicle's fuel system. Starting emissions, however, decrease throughout the year, as Otanicar et al. predicted, given start emissions are highly dependent on temperature for operating and catalytic converter efficiencies. Moreover, Bornstein & Lin (76) and Bornstein & LeRoy (77) observed that the UHI effect can induce a convergence zone, which often causes moving thunderstorms to bifurcate and move around a city (e.g., Atlanta and New York study areas).

Global climate change. The literature on the contribution of UHI to global climate change is less robust than the research on the UHI itself. Parker (78) reviewed the effects that the UHI has on estimates of global near-surface temperature trends. His findings indicated that the UHI has had a minor impact on estimates of global trends of land surface air temperatures, smaller than the 0.74°C global warming between 1906 and 2005, as reported by Trenberth et al. (79). Additionally, as UHI increases air conditioning needs in the summer also increase, leading to greater carbon emissions that in turn may cause global temperatures to rise; however, this effect would be offset at least partially by reduced heating needs in the winter.

Vegetation impacts. The diurnal variation of vegetation's contribution to the UHI has been of significant interest especially to the landscape and urban planning communities. The variation between engineered urban infrastructure and that of urban vegetation, with different moisture, thermal, and aerodynamic properties, has been explored both in microscale and larger mesoscale models. Bowler et al. (80) reviewed 74 peer-reviewed articles that measured urban ground level temperatures with variations in vegetation. Their meta-analysis suggested on average a 1°C decrease of temperature in an urban park as compared to a non- or less vegetated urban area. Although vegetated areas can have pronounced benefits in reducing the daytime UHI effect, there can be nocturnal penalties as the sky view factor may infringe on reradiation and lower cooling rates. Another consideration is the water balance with vegetation, especially in arid and semiarid regions, as used in the mesic, oasis, and xeric landscapes found in those regions. Shashua-Bar et al. (81) analyzed six different landscape strategies in the Negev Highlands of Israel using different trees, lawn, and overhead shading and were able to create a daytime reduction yield of 2.5°C with vegetated mitigation experiments; nonvegetated mitigation strategies using shading resulted in an increase of nearly 1°C. On the basis of their observations, they proposed a cooling efficiency, which is the ratio between sensible heat removed (ΔQ_H) and the latent heat of evaporation (ΔQ_E), i.e., the water required for landscape irrigation with both given in kJ m^{-2}. This measure is proposed as a criterion for evaluating landscape strategies in arid regions, where water resources are scarce.

Health and Social Impacts

When determining the impact of the UHI, and by climate change in a more general sense, the population's health and other socioeconomic attributes usually come to mind. In a careful but slow pace, existing literature has pushed this environmental issue beyond science and as a societal issue, i.e., that climate change has a human face. Although upstream policies remain nascent, the importance of taking solid steps to better understand how this environmental change will affect our quality of life has slowly been recognized. The US Global Change Research Program's Working Group on Climate Change and Human Health, for example, is behind the development of predictive tools allowing for an integrative approach in looking at climate change data and health surveillance data (82). The effort is led by the National Institutes of Health (NIH), the Centers for Disease Control (CDC), and the National Oceanic and Atmospheric Administration (NOAA).

The involvement of these agencies, however, is a good start but not a means to an end that guarantees resource support for the most needed research. In 2008, less than 1% of the 58,000 awards issued by the NIH were climate related (83). In 2013, the CDC initiated funding for 18 state and city grantees to build capacity in determining the health effects of climate change (encompassing its various forms such as fire, extreme heat, flooding, drought, etc.) and to develop flexible programs to mitigate their anticipated health impacts (**http://www.cdc.gov/climateandhealth/brace.htm**).

The impact of high heat temperature on human health is manifested in different outcomes, with death as the extreme (84); the heat wave of 1995 in Chicago is an example (85). Others are expected to be manifested in the form of heightened incidence of allergic respiratory diseases such as asthma resulting from increased air pollutants (86); the complication of existing medical morbidity among vulnerable populations, including those with mental illnesses (87, 88); or even an expected change in the reach of tropical diseases such as malaria, dengue, West Nile virus, among others (**http://www.nrdc.org/health/climate/disease.asp**). Shao Lin et al. (89) estimated that excessive heat would be two to six times higher in 2080–2099 than in 1991–2004. The study used a baseline estimate for respiratory disease burden attributable to extreme heat in New York at 100 hospital admissions or $644,069 in direct hospitalization costs and 616 days of hospitalization per year.

Realizing better health outcomes from extreme heat exposure relies heavily on the adaptive capacity of the individual, which in turn is influenced by the demographic, socioeconomic status, and geographic location of where the individual lives. Characterization of vulnerable populations at the community level is essential in developing programmatic interventions or downstream policy changes. Findings from an ecological study design on Phoenix and Philadelphia neighborhoods suggested that the most important heat risk factors are place specific. Other risk factors found by the study include higher proportion of Black residents, low housing values, and linguistically and socially isolated residents (90). Time factor may also come into play when looking at adverse health outcomes. Although an earlier study using six years of data (2001–2006) from the Phoenix Fire Department's heat-related dispatches showed no seasonality in the day of the week, when analyzed with climatic data; however, data suggested a pattern of high heat-related medical dispatches between "the times of peak solar irradiance and maximum diurnal temperature, and during times of elevated human comfort indices (combined temperature and humidity)" (91, p. 471).

Reflected solar radiation may increase potential health risks to humans. Though reflective pavements mainly increase their reflectivity to visible light, some reflective materials such as white clay can increase the intensity of reflected ultraviolet (UV) radiation to people. UV radiation is harmful to living cells and can result in sunburn, increased rates of aging of the skin, and skin cancer, with its damage accumulating over years. Childhood sun exposure may play an important role in the development of skin cancer later in adult life. Therefore, the amount of reflected radiation should be taken into consideration when planning for ground and building pavements, especially in schoolyards and playgrounds. Moreover, light-colored reflective pavement surfaces can cause glare and visual pollution, which can harm eyesight after a long period of exposure. Reflection from light-colored surfaces can disturb occupants of taller neighboring buildings when applied to roofs; make pedestrians on nearby sidewalks suffer when applied to walls; and provide less lane demarcation due to the poor visibility of white lines when applied to light-colored roads, potentially increasing driving risks.

Mitigation strategies can help minimize potential disparities in individual health outcomes. Silva et al. (92) studied emergency service calls in Phoenix, Arizona, from 2002–2006. They found that using various UHI mitigation strategies could result in as much as 48% total reduction in annual heat-related emergency service calls. Increasing albedo was cited as one effective UHI mitigation strategy.

In a separate study, the impacts of mitigation measures associated with reducing ozone would respectively reduce global population-weighted average surface concentrations by 23–34% and 7–17% and avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030 (93).

In addition to health outcomes, there are also socioeconomic and behavioral dimensions to urban climate. The relationship between factors affecting urban climate and the ability of existing urban infrastructure and ecosystems to coexist will inevitably require governance and policy changes encompassing issues on social equity (94), migration and security (95), environmental justice, quality of life, behavior, and productivity (96). The measurement of marginal contributions of the mitigation/adaptation approaches versus their respective costs, understanding the pathways of each approach in improving health outcomes either to the general population or specific subpopulations, and portability of the approaches, i.e., applicability by geographic location (97), may be presented as alternative ways of framing the needed attention to the changing urban climate or to climate change as a whole.

Economic Impacts

Clearly, higher summer temperatures lead to higher air conditioning demand and consequently higher electricity costs (23). These additional air conditioning costs, however, can be offset by reduced heating costs in the winter. In an investigation of the energy-saving potential of UHI mitigation strategies, it was reported that cooling energy savings from a variety of UHI mitigation strategies were approximately equivalent to the additional heating requirements in the winter, for cities in climates with less than ~1,000 cooling degree days (98). According to the Annual Energy Outlook by the US Energy Information Administration, heating accounts for 14% of commercial buildings' annual primary energy consumption, whereas air conditioning accounts for only 8% in the United States (99; see specifically commercial sector key indicators and consumption table). The US Green Building Council also identifies that across the United States, more energy is consumed heating buildings than to cool them. The direct economic impacts of the UHI are therefore highly climate specific and are limited to relatively warm climate zones. Indirect economic impacts, such as through air and water pollution, are not well quantified and require further research.

POSSIBLE REMEDIES FOR URBAN HEAT ISLAND

Naturally, considerable attention has been paid to potential remedies for UHI, i.e., on how to reduce the temperature increase of built-up urban areas over the surrounding rural countryside. Here, we discuss various solutions introduced in the extensive (and growing) literature and provide some new results generated by the simple zero-dimensional model described in Equation 1. UHI mitigation strategies were previously reviewed in References 16, 26, and 100, with the most recent (26) from 2013. Although these reviews provided excellent discussions of these strategies, for the most part they did not attempt to compare quantitatively the efficacy of competing strategies, with notable exceptions for New York City (101), Phoenix (32), Los Angeles, and other cities (102), as well as the MIST online tool developed by the EPA (**http://www.heatislandmitigationtool.com/**; see also 39). Rather, most studies focused on analyzing a single UHI mitigation strategy, such as "cool pavements" (27), "cool roofs" (103), "green roofs" (104, 105), etc.

To facilitate quantitative comparisons, it is convenient to express the temperature reduction (ΔT) resulting from a given UHI mitigation strategy, relative to the change in some property of the urban fabric (100):

$$\text{UHI Mitigation Efficacy} = \frac{\Delta T}{\Delta(\text{property})}, \qquad 7.$$

where Δ(property) is the change in a property such as albedo, % vegetated area, emissivity, etc. The quantity in Equation 7 can be considered as the efficacy of a UHI mitigation strategy, and it is essentially the gradient of the temperature change with respect to the change in the property. Determining numerical values for the efficacy is done largely through simulation, at least for large urban areas. It is possible to measure efficacy, but this is generally limited to single buildings or small areas (see, e.g., 106).

In the discussion to follow, some results are presented from the simple model introduced in Reference 32 and briefly presented above as Equation 1. We do not expect such a simple model to generate very accurate urban temperatures that can be directly compared to either surface temperatures or air temperatures 2 m above the ground. Instead, it is used primarily to compare the relative effects of competing UHI mitigation strategies. More extensive modeling is likely required to generate more accurate results, although the calculated lumped urban temperature T (Equation 1) compared relatively well with measured 2-m air temperatures and pavement temperatures for a specific period in Phoenix, Arizona (32). Furthermore, the ΔT predicted from Equation 1, for two values of urban albedo α, correlated with the surface ΔT predicted from a comprehensive MM5 simulation (**http://www2.mmm.ucar.edu/mm5/**) with a correlation coefficient of $r = 0.84$, suggesting that it is reasonably accurate for such relative comparisons. (References 25 and 32 provide details for the simple model, except that the simulations reported below were for June 1–3, 2014.)

Increasing Albedo and/or the Emissivity

The albedo, α, or the reflectance of a material integrated over solar wavelengths, is probably the most studied mitigation strategy. Generally, researchers have examined how cool roofs and cool pavements that have relatively high α can reduce surface and nearby air temperatures (see, e.g., 103). The effectiveness of cool roofs and pavements to reduce UHI is a function of the fraction of area that they cover. Akbari & Matthews (103) report ranges for four US cities: Roof areas range from 20 to 25%, whereas pavement fractions range from 29 to 44%. Of course, as with all UHI mitigation strategies, increasing α may be desirable only where higher temperatures are not desired, such as cities in warm regions, or (usually) all cities during the summer months. This suggests the desirability of a controllable α, such that α is high during the summertime, but is low during the wintertime. This can perhaps be achieved by application of thermochromic coatings, which change their properties in response to temperature, to buildings and pavements (107). However, careful consideration should be given to possible unintended consequences.

Because reflective pavements have lower surface temperatures, additional deicing salts are required to ensure clear winter roadways and the safety of the traveling public. In fact, at pavement temperatures below −9°C (15°F), the use of deicing salts on snow-covered roadways is not as effective and additional chemicals are required. Use of deicing chemicals is costly and may have negative environmental impacts to nearby soils, vegetation, water, and vehicles.

Figure 4 shows the results of the simple lumped urban model (Equation 1) as α is varied. The changes in both T_{max} (daytime high temperatures) and T_{min} (nighttime minimum temperatures) are presented. Noting that the scale on the left- and right-hand y axes are different, increasing α

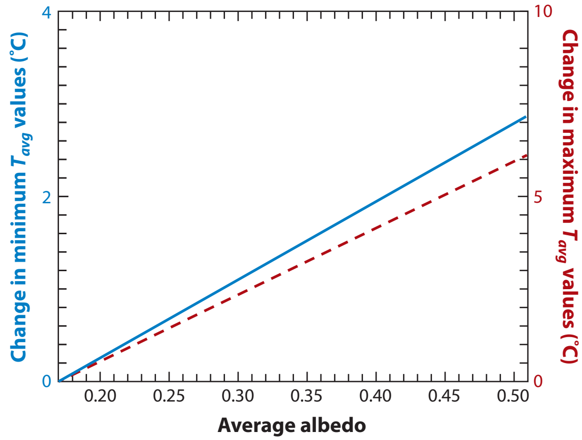

Figure 4

Effect of changing albedo on the minimum and maximum urban lumped temperature for Phoenix, Arizona (June 1–3, 2014). The blue solid line represents the left *y* axis (minimum T_{avg}); the red dashed line represents the right *y* axis (maximum T_{avg}).

is more important for reducing T_{max}, rather than reducing T_{min}. This makes sense as reducing α directly reduces the solar heat gain, whereas the impact of α on T_{min} is indirect.

Although many UHI studies emphasize T_{max}, T_{min} is also of concern. For example, in Phoenix measurements have shown an increase in T_{min} of 2.2°C between 1970 and 1986, compared to an increase in T_{max} of 0.6°C (108). For reducing nighttime temperatures, another important property is the emissivity ε (32, 109). **Figure 5** shows the corresponding changes in T_{max} and T_{min} as a function of changes in ε. Although the magnitudes of these changes are lower than those given in **Figure 4** for α, the change in ε ($\Delta\varepsilon = 0.09$) is much less than the change in α ($\Delta\alpha = 0.5$). As discussed below, this translates into comparable UHI impacts when the results are appropriately nondimensionalized.

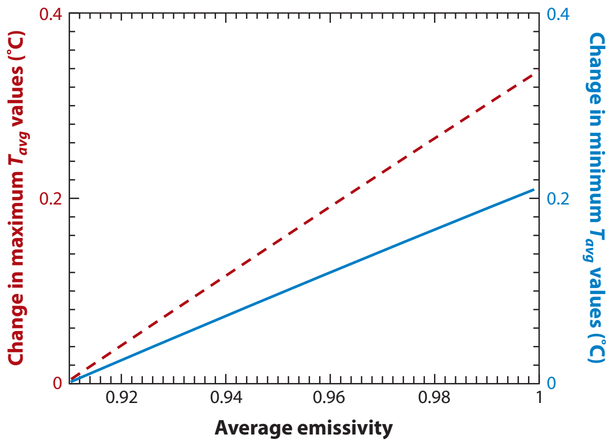

Figure 5

Effect of changing emissivity on the minimum and maximum urban lumped temperature for Phoenix, Arizona (June 1–3, 2014). The blue solid line represents the right *y* axis (minimum T_{avg}); the red dashed line represents the left *y* axis (maximum T_{avg}).

How might increases in ε be achieved in practice? This is relatively difficult, as ε for urban materials are already relatively high (hence the limited Δε in **Figure 5**). Research on radiative cooling technologies provides some potential directions about how to increase ε while limiting solar heat gain (110).

Increasing Vegetation

Increasing the area of vegetated land in urban areas, at the expense of paved or other man-made surfaces (including conventional roofs), has been recognized as a viable UHI mitigation strategy (16, 101, 102, 104–106). Vegetated areas increase the evapotranspiration rate, and thus increase q_{evap} (Equation 4). Typically, it is proposed to do this by increasing the planting of trees and other vegetation, and by converting existing roofs to "green" roofs. Of course, green roofs must compete with "cool" roofs, and the added expense of providing water for rooftop vegetation may outweigh the other benefits of green roofs. A simulation of UHI mitigation strategies for New York City, which compared increasing vegetation through curbside planting, converting existing roofs to green roofs, and increasing α through whitening roofs and other paved surfaces revealed similar reductions in T_{max} of ~1.3°F (0.7°C) from increasing vegetation and increasing α. It was pointed out, however, that increasing vegetation is more effective than increasing α, but a greater percentage of the city area has impervious surfaces where α can be increased as opposed to additional planting of vegetation (101).

Our own model results for increased vegetation in Phoenix, Arizona, are presented in **Figure 6**. As with the other UHI mitigation strategies, impacts on T_{max} are more pronounced than impacts on T_{min}. The changes in T_{max} and T_{min} are greater than those found in Reference 101. This is probably due to the semiarid climate of Phoenix, where the evaporative effect of additional moisture from the vegetation is likely to have a greater effect, compared to the more humid climate of New York City.

OTHER URBAN HEAT ISLAND MITIGATION STRATEGIES

Other UHI mitigation strategies that have been discussed in the literature include solar photovoltaic (PV) canopies over parking lots (111), increasing thermal conduction to the deep ground

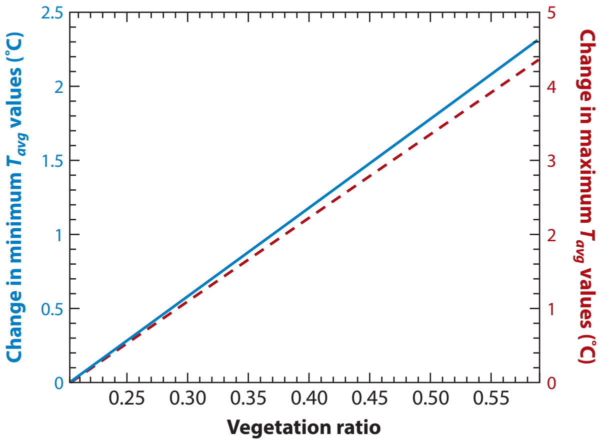

Figure 6

Effect of changing vegetated area on the minimum and maximum urban lumped temperature for Phoenix, Arizona (June 1–3, 2014). The blue solid line refers to the left *y* axis (minimum T_{avg}); the red dashed line refers to the right *y* axis (maximum T_{avg}).

(25, 109), increasing the volumetric heat capacity of the urban fabric (109), and incorporating large urban bodies of water (112). Anthropogenic heat sources, including metabolic heating, combustion sources, air conditioning heat rejection, etc., are generally considered negligible relative to the other heat sources in Equation 1 (32), with the exception of urban centers in the winter (102), where UHI is desirable. PV canopies were found to be more effective than urban forestry at reducing local temperatures (111). Increasing thermal conduction to the deep ground seems difficult to achieve in practice, and therefore is not considered further. Increasing volumetric heat capacity reduces T_{max} but increases T_{min} (109), and furthermore also seems difficult to achieve in practice. An alternative strategy is to change urban design practices to reduce or eliminate urban canyons that limit the ability of surfaces to emit radiation to the nighttime sky, but again this seems impractical. An interesting approach to eliminate the effect of urban canyons is to employ retro reflective surfaces that reflect sunlight at approximately the angle of incidence (113).

Ranking the Remedies

The real challenge is to compare competing UHI mitigation strategies in a quantitative fashion. A metric for UHI mitigation efficacy was presented above as Equation 7. Given the different ranges possible for Δ(property), however, it is also useful to express Equation 7 in a nondimensional format:

$$\text{UHI Mitigation Efficacy(dimensionless)} = \frac{\Delta T}{\Delta(\text{property})}\left[\frac{P_{ref}}{T_{ref}}\right], \qquad 8.$$

where P_{ref} and T_{ref} are reference values for the property and temperature, respectively. A similar expression was introduced in Reference 109. **Table 2** shows values of the dimensional (Equation 7) and nondimensional (Equation 8) metrics for three UHI measures. For an increased α, there is good agreement between the results of a mesoscale meteorological model applied to Los Angeles (100) and the simple model (Equation 1). For increased vegetation, however, as discussed above there is substantial disagreement between the present results for Phoenix and previous calculations for New York City, and for increased emissivity we have only the present results. On the basis of the dimensional results, for decreasing both T_{max} and T_{min} the most effective UHI mitigation strategies are, in order, increasing α, increasing vegetation area, and increasing ε. This does not, however, take into account other factors such as potential health hazards caused by reflected UV radiation. On a nondimensional basis, all three mitigation strategies have comparable efficacies. From a practical point of view, the dimensional results are probably more relevant, and these are discussed further below from the viewpoint of their cost effectiveness.

Cost effectiveness: bang for the buck. Any decision-maker will have to consider not only the efficacy of UHI mitigation strategies, but also their cost. Considering the dimensional efficacy, $\Delta T_{max}/\Delta$(property), predicted by our simple model for Phoenix, Arizona, **Table 3** presents the approximate costs to increase α through cool roofs, and to increase the vegetation area through either green roofs or through urban forestry. Although there is considerable range and uncertainty in these numbers, clearly increasing α is the most efficacious and cost-effective approach to reduce UHI, with urban forestry being the second-best approach.

SUMMARY AND RECOMMENDED ACTIONS

UHI is a long-studied subject, and requires elements of thermal engineering, pavement engineering, geography, forestry, urban design, public health, and economics to establish a good

Table 2 Dimensional and nondimensional UHI mitigation effectiveness for three strategies ($T_{ref} = 25°C$, $\alpha_{ref} = 0.17$, $V_{ref} = 0.304$, and $\varepsilon_{ref} = 0.91$)

Mitigation strategy	City (Ref.)	Change in property (units)	Temperature change (°C)		Temperature gradient $\left[\frac{°C}{\text{(property units)}}\right]$		Dimensionless temperature gradient (dimensionless)	
			ΔT_{max}	ΔT_{min}	$\frac{\Delta T_{max}}{\Delta(property)}$	$\frac{\Delta T_{min}}{\Delta(property)}$	$\frac{\partial\theta_{max}}{\Delta(property*)}$	$\frac{\partial\theta_{min}}{\Delta(property*)}$
Increase albedo	Los Angeles (100)	0.16	−3.0	NA	−18.8	NA	−0.13	NA
	Phoenix (this study)	0.33	−6.0	−2.8	−18.2	−8.5	−0.12	−0.06
Increase vegetation area (%)	New York City (101)	0.17	−0.3	NA	−1.8	NA	−0.02	NA
	Phoenix (this study)	0.38	−4.3	−2.3	−11.3	−6.0	−0.14	−0.07
Increase emissivity	Phoenix (this study)	0.085	−0.3	−0.2	− 3.7	−2.3	−0.14	−0.08

Abbreviations: NA, not applicable; UHI, urban heat island.

understanding of its causes and impacts. Increasing the albedo (α) of roofs appears to be an effective approach to reduce the temperature rises caused by UHI, and also the least-cost alternative compared with green roofs and urban forestry. Increasing α for pavements may have other ramifications that could outweigh its temperature benefits and therefore needs further research. Several other UHI mitigation strategies, including increasing the emissivity (ε) of surfaces, adding large urban bodies of water, decreasing anthropogenic sources of heat, increasing thermal conduction to the deep ground, etc., are either unpractical, not effective, or unproven.

Technology Research, Development, and Demonstration

Increasing α and vegetated areas are well understood and relatively straightforward, and largely do not require additional research. Increasing ε, however, for urban surfaces such as roofs and pavements has not been adequately studied. Increasing thermal conduction to the deep ground

Table 3 Urban heat island mitigation efficacies and costs for select approaches

Mitigation Strategy	Approach	$\frac{\Delta T_{max}}{\Delta(property)}$	Cost ($/m^2)	Ref./Link to work
Increase albedo	Cool roofs	−18.2	$8–$32	**http://www.epa.gov/heatisland/mitigation/coolroofs.htm**
Increase vegetation area (%)	Urban forestry	−11.3	$27–$39	115
	Green roofs	−11.3	$161–$215	**http://www.lid-stormwater.net/greenroofs_cost.htm**

also remains challenging, and it is uncertain if that would lead to long-term increases in ground temperature. Introducing materials with controllable properties, for example, with a high α in the summer and a low α in the winter, is a promising approach. With respect to the impacts of UHI, those from economic and health perspectives are not that well described, and would benefit from additional research.

Policy Suggestions

Of the four (arguably) most-studied UHI mitigation strategies, cool roofs, cool pavements, green roofs, and urban forestry, cool roofs appear to be best at reducing temperatures and are the least expensive option. Therefore, echoing previous policy recommendations (100), for warm climates cool roofs should be encouraged through whatever means are appropriate. For cold climates that are dominated by heating loads, the benefits of cool roofs or other UHI mitigation strategies during the summers are likely offset by additional heating that must be provided in the winters.

DISCLOSURE STATEMENT

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