Chapter 14

The Urban Heat Island Effect and Sustainability Science: Causes, Impacts, and Solutions

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Introduction

As Chapter 3 described, **urbanization** began approximately 10,000 years ago when people first started organizing into small permanent settlements. While people initially used local and organic materials to meet residential and community needs, advances in science, technology, and transportation systems support urban centers that rely on distant resources to produce engineered surfaces and synthetic materi- als. This process of urbanization, which manifests in both population and spatial extent, has increased over the course of human history. For instance, according to the 2014 US Census, the global population has rapidly increased from 1 billion people in 1804 to 7.1 billion in 2014.

During the same period, the global population living in urban centers grew from 3% to over 52% (US Census, 2014). In 1950, there were 86 cities in the world with a population of more than 1 million. This number has grown to 512 cities in 2016 with a projected 662 cities by 2030 (UN, 2016). **Megacities** (urban agglomerations with populations greater than 10 million) have also become commonplace throughout the world. In 2016, the UN determined that there are 31 megacities globally and estimate that this number will increase to 41 by 2030. The highest rates of urbanization and most megacities are in the developing world, particularly in South America (i.e., Sao Paulo, Buenos Aires, Rio de Janeiro), Asia (i.e., Jakarta, Delhi, Mumbai, Shanghai, Dhaka), and Africa (Cairo, Lagos). Megacities in developed countries include Tokyo, New York, Los Angeles, London, and Paris.

One common thread found in all cities, regardless of population size and urban extent, is that urbanization inadvertently alters the local climate system. Although impacts vary at different **spatial scales**—such as at the scale of an individual building, neighborhood, city, or urban region, clear differences occur in climate between urban and rural areas, as witnessed in patterns of precipitation (rainfall and snowfall), humidity, particulate matter, and wind speed (Landsberg, 1981).

Urbanization The process whereby native landscapes are converted to urban land uses, such as commercial and residential development. Urbanization is also defined as rural migration to urban centers.

Megacities Urban agglomerations, including all of the contiguous urban area, or built-up area.

Spatial scales The extent or coverage of any given area, such as a county, state, or nation.

Urban Heat Island (UHI) A

global phenomenon in which surface land and air temperature in urban areas is higher than in bordering areas. The primary causes are related to the structural and land cover differences of these areas.

Morphology The study of the form, structure, process, and transformation of an organism or phenomenon and/or any of its parts.

UHI Intensity Measured as the differences in land surface temperature (LST) between urban areas and surrounding boundary area. This variance is related to meteorological elements such as cloudiness, wind speed, temperature, and absolute humidity.

Mitigation Strategies used to reduce ing climate of the countryside:ties. rature (LST) between urban areas and surrounding greenhouse gas emissions (GHG) and increase carbon sequestration in order to slow the rate of climate change.

Adaptation Adjustment strategies to increase a system's ability to adjust and reduce vulnerability to the effects of climate change.

Land Use and land cover (LULC) Land use refers to the syndromes of human activities (e.g., agriculture, urbanization) on lands. Land cover refers to the physical and biological cover of the surface of land (i.e., bare soil, vegetation, water). Land Use and land cover change (LULCC) refers to the changes forced by human activities on both land use and land cover.

Anthropogenic waste

heat Heatenergy released into the atmosphere from human activities such as industry and transportation. This chapter examines one of the best-known urban-induced climate alterations—the **Urban Heat Island** (UHI) effect. By the end of this chapter, you will understand:

- The **morphology** of UHI as well as different UHI types
- Factors causing or modifying UHI intensity
- UHI tendencies among various climate regimes
- The impacts of the UHI on residents
- Linkages between the UHI effect and urban sustainability
- Various mitigation and adaptation strategies to reduce the UHI effect

The UHI Effect

The UHI effect was first recognized by the English meteorologist Luke Howard who noted that temperatures within the City of London were different from the surrounding countryside (Howard, 1833).

The temperature of the city is not to be considered as that of the climate; it partakes too much of an artificial warmth, induced by its structure, by a crowded population, and the consumption of great quantities of fuel in fires (p.2).

He hypothesized that the conversion of the Earth's natural surfaces into urban surfaces (e.g., asphalt, concrete, glass) for human socio-economic activities, now referred to as **land use and land cover change (LULCC)**, and the generation of heat from factories and/or transportation systems, among other sources, now referred to as **anthropogenic waste heat**, were key factors in causing the UHI. It turns out Howard was not far off!

Cities are comprised of structures of different heights, providing a "rough" surface as opposed to relatively cohesive heights in outlying areas. They also tend to be warmer due to the impervious nature of the materials used (i.e., concrete, asphalt, metal, etc.), which inhibit moisture absorption and limits the cooling effect, and anthropogenic waste heat, which stems from human activities. For example, many manufacturing processes use heat (i.e., coal and nuclear plants, cement kilns, or steel furnaces). Waste heat is heat that escapes or is released from these processes. Household appliances, lawn maintenance equipment, and combustion engines, among other machines release heat into the environment when used as well. These topographical and structural differences as well as the concentration of human activities combine to increase the temperature in urban regions; thereby, contributing to the UHI effect.

The UHI effect quantifies the temperature gradient between urban and nearby rural areas, which often depicts a given urban area as an island of heat amid the native landscape. This pattern is similar to the geomorphic land/sea interface of an island, with a notable "cliff" separating the urban and rural temperature fields. This is illustrated in Figure 1, which depicts the UHI effect in Phoenix, Arizona. There are four distinct **UHI subtypes**: 1) subsurface, 2) surface, 3) urban canopy layer, and 4) urban boundary layer (Oke, 1995). Observing and measuring temperatures within the different UHI subtypes requires distinct methodological platforms. For example, urban canopy layer studies use data either obtained from



Figure 1 The spatial form of the Phoenix, Arizona Metropolitan UHI in June 2000, as measured by minimum temperatures (T_{min}) taken from several weather stations *Source:* Author, Winston Chow

point measurements taken at weather stations or during mobile surveys (Brazel et al., 2000). Surface and subsurface UHI studies often use data from handheld, infrared thermometers or from remote-sensing instruments mounted on airplanes, helicopters, or satellites. The urban boundary layer UHI can be investigated through **radiosonde** data collected by weather balloons that travel up to the top of the lower atmosphere.

Stewart and Oke (2012) introduced a more inclusive approach that uses the concept of Local Climate Zones (LCZs). The LCZ system classifies study sites based on the urban structure, land cover, materials, and anthropogenic activity. The LCZ scheme relies on 17 standardized classes to assess differences between urban and rural landscapes within the given study area (Figure 2).

Parks, lakes, and open areas within cities generally observelower temperatures than the surrounding urban area and can disrupt urban temperature peaks; these are sometimes called **park cool islands (PCI)** (Figure 3). Dense urban areas can also be cooler during the day than sprawled urban areas due to reduced incoming solar radiation and more shading (Middel et al., 2014). If daytime temperatures in the urban area are lower than in the surrounding areas, this is called an **oasis effect**. The oasis effect is mainly driven by moisture availability and shading. Knowledge about the cooling influence of PCIs within cities is important in dis- cussing ways to sustainably mitigate the UHI, as we shall see later in this chapter. Typically, scientists measure the UHI effect based on weather station data either by the increase of minimum temperatures (T_{min}) asits surrounding environ- ment "urbanizes" over time, or by the difference in temperatures between urban and rural areas ($\otimes T_{u-r}$) (Landsberg, 1981). Maximum magnitudes of $\otimes T_{u-r}$ are

Urban heat island (UHI) subtypes:

- 1. Subsurface: below the surface of the earth
- 2. Surface: the skin of the surface of the earth
- Urban canopy layer: the atmospheric air layer between the ground surface and average building roof height
- Urban boundary layer: the lowest portion of a planetary atmospheric boundary layer that is directly influenced by an underlying urban area

Radiosonde A miniature radio transmitter with instruments for sensing and broadcasting atmospheric conditions

Park cool island

(PCI) Zones in the urban landscape reporting relatively cooler temperature conditions, often associated with parks, lakes, or open areas

Oasis effect Evaporative cooling effect due to heat advection when a source of water exists in an otherwise arid area.

Built types	Definition	Land cover types	Definition		
I. Compact high-rise	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.		
2. Compact midrise	ise Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.		Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.		
3. Compact low-rise	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.		
4. Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.		
5. Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.		
6. Open low-rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.		
7. Lightweight low-rise	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.		
8. Large low-rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	VARIABLE LAND COVI Variable or ephemeral land significantly with synoptic w and/or seasonal cycles.	ER PROPERTIES cover properties that change eather patterns, agricultural practices,		
9. Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land	b. bare trees	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.		
6 8 - 8 B	cover (low plants, scattered trees).	s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.		
10. Heavy industry	Heavy industry Low-rise and midrise industrial struc- tures (towers, tanks, stacks). Few or no trees Land cover mostly payed		Parched soil. Low admittance. Large Bowen ratio. Increased albedo.		
555	or hard-packed. Metal, steel, and concrete construction materials.	w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.		
Figure 2 Illustrations and I Source: Stewart and Oke (p.	Definitions of the Local Climate Zones 7; 2012)				



Figure 3 Daytime and night time surface and air temperature over various land use types

Source: Environmental Protection Agency https://www.epa.gov/heat-islands/learn-about-heat-islands

generally found at the urban core (e.g., downtown). Plateaus of elevated temperatures can also be found in other areas that have distinct urban land-use categories (e.g., commercial, residential, and in- dustrial). UHI is also a dynamic phenomenon that arises from different urban and rural temperature cooling rates, however.

Under clear and calm weather conditions for a hypothetical city, $\otimes T_{u-r}$ usually varies in a consistent manner during a 24-hour period (Figure 4). Canopy layer temperatures generally start cooling in the late afternoon and evening, with urban areas cooling at slower rates than rural areas. This difference results in the growth of $\otimes T_{u-r}$ reaching a maximum about three to five hours after sunset (Oke, 1982).

It is important to understand the physical factors that cause UHI (and modify its maximum intensity) when modeling its occurrence and development within different cities and at different scales. Atmospheric models can range from relatively simple statistic-based regression models based on observed data to highly complex, physics-based numerical models that require enormous computational power (Masson, 2006). Results from both observation and modeled studies have great potential in urban planning and policy toward alleviating the negative impacts of the UHI. See Simulating Alternative Planning Scenarios Box below.



Figure 4 UHI development for a typical temperate city as seen through air temperature changes (a), heating/cooling rates (b), and heat island intensity (c) (Oke, 1987).

Simulating Alternative Planning Scenarios

Scientists use climate models to assess proposed UHI mitigation measures at different temporal and spatial scales and analyze outcomes of various "whatif" scenarios. These techniques offer insights into planning and/or redesigning more efficient living environments. A recent study by ASU scientists investigated the impact of urban form on afternoon temperatures during the summer season among neighborhoods throughout metropolitan Phoenix. They used the microclimate model ENVI-met to simulate temperatures in 5 typical Phoenix neighborhoods. (Middel et al., 2014).

Air temperature simulations at a spatial resolution of 1 meter were conducted by classifying the data models into five LCZs (Figure 5). The study found that neighborhoods comprised of mesic landscaping (e.g., grass, trees, and shrubs) were cooler than residential areas with xeric landscaping (e.g., droughttolerant), but at the micro-scale, urban form had a more discernable impact on temperatures.

Dense urban forms were more beneficial in terms of daytime cooling than sprawled or sparsely built urban forms, mainly because of reduced incoming solar radiation and shading. This study supports the finding that dense urban areas can have an oasis effect and create a local cool island in mid-afternoon. A follow-up study using the same model found that for every 1 percent increase in tree canopy cover in residential neighborhoods, 2-m air temperatures are reduced by 0.14°C in mid-afternoon (Middel et al., 2015).



Figure 5 2-maintemperature simulation scenarios for five "typical" residential neighborhoods in Phoenix, Arizona. Blue represents cooler temperatures while reds and purples represent hotter temperatures.

Source: Middel et al. 2014.

UHI Variations and Climate Regime

While the UHI effect is a near-universal phenomenon in cities, impacts and UHI intensity vary throughout the world. For instance, the UHI effect in Mexico City (dry, high elevation) is considerably different from the UHI effect in Singapore (tropical, low elevation). Thus, environmental characteristics such as the local **climate regime** are extremely important in understanding UHI drivers and impacts.

There exist broad patterns of climate regimes across the Earth due to the general circulation of the Earth's atmosphere. In 1884, German climatologist Wladimir Köppen introduced a global climate classification system that partitions the Earth's climates based on averages, variations, and the effects of weather elements (e.g., temperature, precipitation) on the land surface environment. Köppen's system produced five major climate groups, which are summarized in Table 1 and shown in Figure 4.

Climate regime State of the climate system that occurs more frequently than nearby states due to either more persistence or more frequent recurrence. In other words, a cluster in climate state space associated with a local maximum in the probability density function (Stocker, 2013).

Köppen Climate Classification Group	Climate Characteristics	Linkages with UHI	Example Cities	
Group A: Tropical/ megathermal	12 months of the year with average temperatures above 18°C or higher with somewhat significant precipitation	Humid, tropical climates; heavy precipitation; modest high temperatures at day and night; year-round warm temperatures; high anthropogenic waste heat	Rio de Janeiro, Lagos, Kinshasa, Abidjan, Mumbai, Dhaka, Jakarta, Bangkok, Singapore, Manila	
GroupB: Dry (aridand semiarid)	Little precipitation	Exposure to very high temperatures; extended summer season; high anthropogenic waste heat	Karachi, Lahore, Cairo, Lima, Tehran, Baghdad, Phoenix	
Group C: Temperate/ mesothermal	The coldest month average is between 0°C and 18°C and at least one month averaging above 10°C	Hot and dry or warm and wet summers; cool winters	Shanghai, Guangzhou, Sao Paulo, Delhi, Istanbul, Tokyo, Mexico City, London, New York, Bogota, Los Angeles, Buenos Aires, Paris	
Group D: Continental/ microthermal	Have at least one month averaging below 0°C and at least one month averaging above 10°C	Warm summer temperatures; severe winters	Beijing, Moscow, Seoul,	
Group E: Polar	12 months of the year with average temperatures below 10°C	Severe winters; cool summers	NA	

Table 1 Summary of Major Climate Groups of Köppen Classification System



Figure 6 Updated World Map of Köppen-Geiger Climate Classification Source: Kottick et al. (2006) http://koeppen-geiger.vu-wien.ac.at/pdf/kottek_et_al_2006_A4.pdf

What Factors Cause the UHI?

Surface-energy

balance Describes the balance between radiation, conduction and convective heat flow.

Flux Rate of flow of some quantity.

The key to understanding how UHI is caused is to examine alterations to the urban **surface-energy balance (SEB)**. The SEB describes how the available energy in the Earth's climate system is balanced and partitioned into energy **fluxes** that move towards and away from the Earth's surface. We distinguish between two major flux types: radiative fluxes and turbulent fluxes.

Radiative fluxes refer to the shortwave radiation K, incoming from the sun and reflected by Earth's surfaces, and longwave radiation L, emitted by the atmosphere and the Earth's surfaces. Turbulent fluxes are driven by wind and associated with phase changes of water (latent heat flux Q_E) and heating of surfaces (sensible heat flux Q_H). The amount of incoming and outgoing energy, i.e. the net flux, must be equal. Therefore, the net all-wave radiative flux density Q* is defined as the sum of total radiation arriving at (\Box) or exiting from (\Box) a surface. Q* is the sum of all incoming (\Box) and outgoing (\Box) shortwave (K) and longwave (L) radiation and can be mathematically expressed as:

$$Q^* = K \Box - K \Box + L \Box - L \Box = K^* + L^*$$
 (eq.1)

At the same time, the available energy Q^* can be expressed using the turbulent heat fluxes Q_H and Q_E :

$$Q^* + Q_F = Q_H + Q_E + \otimes Q_S \tag{eq.2}$$

This representation requires two additional variables: the energy stored or withdrawn from the surface substrate, also called heat storage ($\otimes Q_S$), and anthropogenic waste heat (Q_F). Examples of Q_F include heat emissions from vehicles, industrial plants, and air conditioners, among other sources. In most

Table 2 Suggested causes of UHI through alterations of the urban energy balance, together with (1) typical urban features associated with the change, and (2) direct urban climate effects on UHI formation (based on Oke, 1982).

Surface energy balance equation symbol	Surface energy balance variable	Typical associated urban features	Direct urban climate effects
Increased K*	Shortwave radiation	Canyon geometry	Increased surface area and multiple reflection
Decreased L*	Longwave radiation	Air pollution	Greater absorption and re-emission
Increased L	Longwave radiation	Canyon geometry	Reducedskyviewfactor
Addition of Q _F	Anthropogenic waste heat	Buildings and traffic	Direct addition of heat
Increased ⊗Qs	Storage heat flux	Construction materials	Increased thermal admittance
Decreased Q _E	Latent heat flux	Construction materials	Increased water-proofing
Decreased (Q _H + Q _E)	Sensible and latent heat fluxes	Canyon geometry	Reduced wind speed

cities, however, anthropogenic waste heat is a relatively small component of the urban-energy balance when compared to Q_H or $\otimes Q_S$. Table 2 demonstrates how various factors influence the urban surface-

Table 2 demonstrates how various factors influence the urban surfaceenergy budget, and therefore, UHI. For example, LULCC such as the amount and extent of asphalt have the tendency to increase heat and will affect the amount of storage heat flux. Understanding typical city features and how they vary within urban areas is critical in explaining how UHI is caused. Increases in the use of certain construction materials (such as concrete, glass, asphalt, and steel) reduce the potential for evapotranspiration and increase **thermal admittance**.

Many urban materials have properties that store and release heat. Those that retain and radiate high levels of heat to the environment over a longer period are considered to have high thermal admittance. Materials such as concrete and asphalt store, and later radiate, more heat than vegetated surfaces such as urban parks. Urban air pollution also contributes to UHI through the creation of smog. For instance, smog reduces the rate of surface radiative loss creating more surface heat and prolonging the dissipation of that heat.

There are two other urban features that influence UHI—**urban canyons** and the sky view factor (Figure 7). Urban canyons are characterized by tall buildings on either side of long, narrow streets typical of most **central business districts**. These artificial canyons increase the total urban surface area for energy storage and reduce urban wind speed. They also reduce the sky view factor, or how much of the sky is seen from the surface. This reduces surface radiative loss, especially at night (Unger, 2004; Middel et al., 2017).

Thermal admittance A

property that quantifies the rate at which a material stores or releases heat. It is the square root of the product of thermal conductivity and heat capacity.

Urban canyons An artificial "canyon" formed by two vertical walls of buildings with a horizontal street or pavement surface.

Central business district The commercial and often geographic center of a city.



Figure 7 A dense urban canyon (i.e. two walls + street) of downtown Singapore that is typical of most central business districts (left), and a fish-eye lens picture that represents the low sky view factor (SVF) seen at the surface of the street (right) (*Source*: Author – Winston Chow)

Additional Factors Influencing UHI Intensity

Difference in temperatures between urban and rural areas ($\otimes T_{u-r}$) is strongly affected by the prevailing regional climate over a city. Higher wind speeds, increased cloud cover, and lower cloud heights have been shown to reduce magnitudes of $\otimes T_{u-r}$ (Arnfield, 2003). These meteorological factors disrupt surface cooling in different ways. Higher wind speeds increase near-surface turbulent mixing, which decreases the efficiency of surface radiative cooling. Increased cloud cover limits surface longwave radiation loss, with low-level clouds (e.g., stratus and cumulus) having greater impact compared to high-level clouds (e.g., cirrus and cirrostratus). Maximum UHI intensities are thus generally associated with periods of clear, calm weather.

The size and geographic location of cities also affects the maximum magnitude of $\otimes T_{u-r}$. Generally, the bigger the urban population, the larger the maximum UHI intensity (Oke, 1973). Cities located in temperate climates typically have higher maximum $\otimes T_{u-r}$ compared to tropical, subtropical, and highland cities, even with population size held constant. Of interest is that tropical cities experiencing more precipitation appear to have lower observed maximum $\otimes T_{u-r}$ compared to tropical cities with pronounced dry seasons, which suggests a strong impact of surface moisture on attenuating UHI intensity (Roth, 2007).

Water bodies and topographic features located next to a city can also affect UHI distribution and intensity. Cities located by the coast are subject to a regular daily cycle of land and sea breezes. Typically, moister and cooler air masses over the ocean are advected into warmer urban areas in the early evening, resulting in a distinct temperature gradient seen in cities such as Vancouver, British Columbia (Runnalls and Oke, 2000). Similarly, cities located in valleys may be subject to daily cold air drainage flow patterns. These flows—also known as **katabatic flows**—are

Katabatic flows 1) Most widely used in mountain meteorology to denote a downslope flow driven by cooling at the slope surface during periods of light larger-scale winds; the nocturnal component of the along-slope wind systems. 2) Cold air flowing down a slope or incline on any of a variety of scales (AMS, 2017). usually strongest at night and can directly affect urban temperatures in complex topography.

The temperature of the Earth's surface is controlled by solar energy or **solar radiation** from the sun. Solar energy accounts for approximately 99.97 percent of energy entering the Earth's atmosphere (other energy sources include geothermal, tidal, and anthropogenic waste heat). The interactions in the long wavelengths of radiation to and from the Earth are critical to the planet's sustainability, as the atmosphere acts as a greenhouse that keeps the planet warm. Scientists have cal- culated that without this greenhouse effect, Earth's temperatures would be some 30° Celsius (C) cooler than present.

This energy enters the Earth's atmosphere in the form of shortwave radiation where the energy is either absorbed or reflected back into the atmosphere. The energy reflected from the earth back out to space is called longwave or infrared radiation. **Albedo** refers to the percent of incoming solar radiation that a body or surface reflects.

Albedo values range from zero (no reflection) to 100 (complete reflection) and vary depending upon surface materials. Light surfaces such as snow and ice are highly reflective and have albedo values in the range of 80–95 percent. Alternatively, dark-colored materials such as asphalt have low levels of solar reflectance and have albedo values in the range of 5–10 percent. Understanding the influence of albedo is important in **sustainability science** for two reasons.

The first is that surfaces with low albedo values absorb large quantities of solar energy; while high albedo surfaces reflect sunlight back into the atmosphere. Second, the albedo values of various building materials and LULC are critical when introducing or replacing features in urban environments. For instance, converting an asphalt parking lot (a low albedo surface material) to a park or open green space (a moderate albedo surface material) will increase the solar reflectance of that parcel of land and thus reduce local heat-storage capacity.

Impacts of the UHI on Cities

While the UHI effect is a near-universal phenomenon in cities, its resulting impacts—and whether such impacts are "good" or "bad" for urban residents' quality of life—depend on factors such as geographic location and season. Increased urban warmth can be beneficial for residents in high-latitude cities (e.g., Moscow) with cold winters, but detrimental to city dwellers in hot subtropical cities (e.g., Las Vegas, Phoenix) with hot summers. This section discusses three UHI-derived impacts on urban residents, 1) thermal discomfort and vulnerability to increased heat stress; 2) changes to urban energy and water use; and, 3) impacts on urban economic output (Kunkel et al., 1999).

The UHI effect, coupled with naturally occurring summer **heat waves**, is linked to negative impacts on human health and well-being, such as morbidity (illness) and mortality (death) (Rosenzweig et al., 2005). UHI increases thermal discomfort particularly when summer temperatures are elevated and sustained over multiple consecutive days. Excessive exposure to heat , especially in unshaded locations, increases thermal discomfort (Middel et al., 2016) and already accounts

Solar Radiation The total electromagnetic radiation emitted by the sun.

Albedo The fraction of earth's incoming solar radiation that is reflected back to space.

Sustainability science A field of research dealing with the interactions between natural and social systems, and with how those interactions affects the challenge of sustainability.

Heat wave A prolonged period of excessively warm weather.

for more deaths in the US than any other weather-related phenomenon (CDC, 2006; Kalkstein and Sheridan, 2007). Research shows that mortality rates and hospital admissions for cardiovascular, respiratory, and other preexisting illnesses increase in conditions of very hot weather as well (Semenza et al., 1999).

The dangerous impacts of excessive exposure to extreme heat are evident from two historic heat waves. The first was the Chicago, Illinois heat wave in July 1995 that claimed over 700 lives (Semenza et al., 1996; Klinenberg, 2002). The second was the 2003 heat wave that gripped Western Europe resulting in between 22,000 and 52,000 deaths, many of them occurring in large cities (Larson, 2006). A warmer urban climate can also translate into increased demands on energy and water. This is very likely to occur in cities subject to seasonal high temperatures or located in equatorial climates with relatively hot year-round temperatures. For example, increases in the UHI intensity in metropolitan Phoenix, Arizona have coincided with increased total and peak-energy demand for residential and

commercial cooling from the period between 1950 and 2000 (Golden, 2004). The demand for energy increases because air conditioning is used more often and for longer periods. Although air-conditioning systems provide

interior relief from summer temperatures, they also release large quantities of anthropogenic waste heat into the surrounding outdoor environment. They also produce greater amounts of air pollutants, thus worsening urban air quality as well as contributing to urban warming.

Warmer temperatures in metropolitan Phoenix have been shown to increase demands on local water systems as well. Higher energy demands translate to increased demand on water resources because of the large quantities of water consumed when producing electricity. In addition, demand on local water resources is greatest during summer months when residents irrigate outdoor vegetation and fill their pools to provide relief from intense summer temperatures (Guhathakurta and Gober, 2007; Wentz and Gober, 2007).

UHI Mitigation and Adaptation Strategies

Mitigation and adaptation strategies help reduce the UHI effect. Table 3 provides a list of various strategies that cities and individuals have employed. These include the creation of urban forests that offer various environmental benefits, such as sequestering or storing carbon, retaining storm water during rain events, and improving air quality. Urban forests also provide benefits to residents. These benefits are often described as health co-benefits.

These co-benefits include providing shade and increasing thermal comfort, while simultaneously creating green spaces for recreation and relaxation. Improved air quality from urban forests, increased green spaces, and reduced fossil fuel consumption also help restore ecosystems and provide a healthier living environment, which has been found to stimulate physical activity among residents. A more active lifestyle translates into lower rates of obesity and reduced cardiovascular disease, as well as improved mental health (Besser and Dannenberg, 2005; West et al., 2006; Nurse et al., 2010). In addition to direct co-benefits, there are several wide-ranging indirect benefits.

Health co-benefits Multiple benefits of a program whereby one of the domains benefits the public health sector, such as providing shade and increasing thermal comfort. **Table 3** Illustration of mitigation and adaptation strategies to reduce the urban heat island effect with healthco-benefits. Modified from Harlan and Ruddell, 2011.

Mitigation and Adaptation strategy	Environmental outcome	Examples	Human health Co-benefit		
Urban Greening	Carbon sequestration, enhanced stormwater management and water quality, air quality improvement, reduced	Urban Forest : Chicago, IL has implemented an urban forest to improve air quality while reducing the UHI effect	Increased shade and thermal comfort, less heat-related illnesses, improved quality of life		
	energy use	Community Garden: Boston, MA is using community gardens to capture carbon, increase green space throughout the city, and provide fresh produce locally	Improved nutrition, increased community engagement		
		Green Roofs : Toronto (Canada) utilizes green roofs to help reduce local outdoor temperatures while providing insulation and cooling capacity inside buildings	Less heat-related illness		
Urban Fabric Modification	Reduced energy consumption, air pollution and GHG emissions by lowering energy use	Cool Roofs : The City of Phoenix implemented a Cool Roofs program to coat 70,000 square feet of the city's existing rooftops with reflective materials	Less heat-related illness, improved human comfort		
		Cool Pavement : Sacramento's pervious concrete parking lot at Bannister Park is one of the first uses of cool pavement in the state of California	Less heat-related illness, lower tire noise, better nighttime visibility, improved human comfort		
Urban Structure Modification	Improved air quality, ventilation and solar access	Building orientation: Singapore's Marina Bay Financial Centre aligns its arterial roads along the predominant wind direction to improve wind flow at street level, and staggers building heights to increase wind downwash that removes air pollutants	Reduced exposure to air pollutants, increased shade, and improved thermal comfort		

Mitigation and Adaptation Challenges

Despite the extensive environmental and human benefits associated with the strategies outlined in the table, several challenges exist to successfully implementing these tactics. For example, implementing any mitigation or adaptation strategy requires an initial financial investment, which many individual homeowners and city officials may be reluctant to make, particularly in a depressed or flat economy.

A second challenge is the issue of sovereignty. For instance, individual homeowners are often limited by the covenants, codes, and restrictions (CCRs) governing their community or neighborhood that are enforced by Homeowners Associations. These may prevent homeowners from installing solar panels on their roof or solar hot-water heaters, as they may violate the CCRs.

Another challenge is the suitability of a given UHI mitigation or adaptation strategy in a local geographic context. A strategy that is perfect for residents livinginPortland, Oregon maybeinefficient or counter-productive when imple- mented in Phoenix, Arizona. Thus, UHI mitigation and adaptation strategies must be considered by individual cities based on the resources and natural advantages of a given city. Perhaps the biggest challenge to implementing a given UHI mitigation or adaption strategy is conducting a cost-benefit analysis. For instance, the many benefits of expanding an urban forest need to be evaluated against the costs, such as increased pollen (allergies), tree maintenance services, and a greater demand on water resources, which is highly problematic in arid environments (Gober, 2006; Shashua-Bar et al., 2009). The use of alternative energy systems is an increasingly popular method for meeting residential and commercial energy needs with reduced GHG emissions. However, many of the current systems such as solar thermal energy (STE) systems are highly water-intensive, which must be considered when siting STE plants and allocating

water resources (Hu et al., 2010).

Advancing sustainable solutions for one problem area often supports other benefits through a wider articulation of goals. For example, reducing UHI by additional vegetative cover also provides important urban wildlife corridors, rainfall runoff management, and urban farming opportunities, thus making for healthier cities. The concept of redesigning cities to reduce or adapt to UHI needs to be broadened to better understand both the benefits and challenges. Sustainability science and sustainable development are mechanisms for doing so.

Conclusions

Sustainability science and sustainable development offer valuable tools and insights for addressing environmental and social concerns associated with UHI. Although there are numerous definitions for both sustainability and sustainable development, it is generally agreed that there are three components of sustainability. These are

1) environmental conservation, 2) equity (inter- and intragenerational), and

3) economic development. Anthropocentric paradigms often exploit one sector

Intergenerational Occurring or existing between members of one generation; occurring during the span of one generation. for the benefit of another, such as harvesting a resource beyond its natural rate of production for economic gain. Sustainability paradigms aim to simultaneously maximize all three.

Why is the larger framework of sustainability and the idea of maximizing the three values of sustainability—environment, equity, and economics—important for UHI? How we design cities, the materials used for construction and infrastructure, the types of transportation, and the extent of vegetative open space among many others affect the urban environment and UHI intensity. Sustainability science has shown that we can reduce the impacts of UHI by constructing and/or redesigning neighborhoods and individual buildings as well as establishing mitigation and adaptation policies. The degree of change in UHI intensity and spatial coverage will depend on the ways in which a given city is built (or rebuilt) and the materials that are used to construct various features within the urban environment.

The variability of temperatures within a given city present challenges for both inter- and intragenerational equity. For instance, increasing minimum temperatures in the urban environment compromises the ability of future generations to enjoy a comparable climate. It creates intergenerational inequity. In the case of UHI, some parts of a city are significantly warmer compared to other areas of the city. The distribution of temperatures within a given city is often concerning because the burden of temperatures is not evenly distributed among social groups. Research shows that this intragenerational inequity most often impacts minority and low-income populations. These populations are often exposed to the worst environmental conditions yet possess the fewest resources to cope with UHI impacts.

The economic sector is also significantly impacted by UHI. Urbanization is a significant contributor to UHI formation and the expansion of urban areas into sprawling megacities is largely driven by economics. Rather than introduce a growth boundary, redevelop an existing lot, or increase density (through vertical development), residential development often occurs on the urban fringe where land is relatively cheap. Although economics contributes to UHI development, this sector also offers opportunities to increase the efficiency of cities. For instance, the introduction or enhancement of public transportation systems provides local employment opportunities, commuting options for residents and visitors, and reduces dependency on automobiles and fossil fuel consumption. It also has the co-benefit of improving air quality. There are also wide-ranging opportunities for the private sector to provide services and innovative solutions for sustainable development, such as solar technologies.

Select Cases from around the World

The following section examines select cities throughout the world to better understand UHI patterns and characteristics in diverse settings. The cities selected in this analysis are among the 100 most populous urban areas in the world and are stratified to represent different regions and climate classes.

		5	Area	Population Density	Koppen Climate Classification		Temperature Ave Monthly		Precip (inch)	
City	Country	Population (Metro)	(Sq. mi)	(Sq. (per sq. mi) mi)	(per sq. mi)	Class	Description	Jan	July	Ann
Beijing	China	21.1 mil	6,336	3,396	Dwa	Humid Continental	-3.7°C	26.2°C	22	
Lagos	Nigeria	21 Mil	1,045	15,369	Aw	Tropical Savanna	27.3°C	25.2°C	59	
Mexico City	Mexico	20.4 mil	573	15,663	Cwb	Subtropical Highland	14.6°C	18.2°C	33	
London	United Kingdom	14 mil	3,236	2,680	Cfb	Oceanic	6.8°C	19.6°C	23	
Singapore	Singapore	5.5 mil	278	19,910	Af	Tropical Rainforest	26.0°C	27.4°C	92	
Phoenix	United States	4.5 mil	1,147	3990	Bwh	Hot Desert	13.5°C	34.7°C	8	

Table 4 Overview of Selected Cities



Case 1: Beijing, China

Established in 1046 AD, Beijing, China is located at 39°55'N, 116°23'E and is 144 feet above sea level. It has over 21 million residents and covers over 6,336 square miles comprised of high-density development. Beijing's Köppen climate classification is Humid Continental (Dwa) where the continental climate results in cold and dry winters with hot and wet summers. For example, the average monthly temperature in January is -3.7 °C (25.3 °F) in contrast to July where



the monthly average is 26.2 °C (79.2 °F). The city has a seasonally concentrated precipitation regime that produces an annual average rainfall of 22 inches, with close to almost three-fourths of that total falling from June to August.

Research on temperature variability within the Beijing Municipality has measured UHI maximum intensity at 3.37 °C (or 6.1 °F) (Yang et al. 2013). This is attributed in large part to Beijing's rapid urbanization since 1980. While Beijing's UHI provides warming effects during the cold winters, the warm and humid summers increase energy demands as residents rely on air-conditioning for thermal comfort. Beijing's rampant air pollution also contributes to the UHI effect.

Case 2: Lagos, Nigeria

Lagos, Nigeria was founded in the 15th century and is located at $6^{\circ}27$ 'N, 23°2'E with an elevation of 135 feet. An important trade and administrative center, Lagos



is among the world's fastest growing cities with a population of 21 million residents. The Köppen climate classification for Lagos is tropical savanna (Aw). The city's location near the equator in the tropical rainforest belt results in a temperature profile that remains constant throughout the year with only modest differences between the warmest (March; 28.5 °C or 83.3 °F) and coolest (August; 25.0 °C or 77 °F) months. The wet season, lasting from April to October, produces an annual average rainfall of 59 inches.

Current research shows a pronounced UHI effect within Lagos. The rapid population growth and establishment of formal and informal settlements throughout the city has resulted in maximum UHI intensity more than 7 °C (or 12.6 °F) (Ojeh et al. 2016). Lago's chronic exposure to modestly warm temperatures results in elevated energy demands year round.

Case 3: Mexico City, Mexico

The capital city of Mexico, Mexico City, was founded in 1325 and is located at 19°26'N, 99°8'E. Mexico City is currently listed as the 4th most populous city in the



world and is comprised of high-density urban development. A high-elevation city, the City resides at 7,380 feet above sea level and is classified as subtropical highland climate (Cwb) using the Köppen classification system. Average annual temperatures show modest variation throughout the year. Average monthly temperatures in January are 14.6 °C (58.3 °F) and July are 18.2 (64.8 °F). Temperatures rarely dip below 3 °C (37.4 °F) or exceed 30 °C (86 °F). The average annual rainfall is 33 inches, which falls primarily from June through October.

Research shows that temperatures within Mexico City vary considerably with maximum UHI intensity reaching 7.8 °C (or 14.0 °F) during a calm clear night in February (dry season) (Jauregui 1997). Thus, Mexico City demonstrates a significant maximum nocturnal UHI intensity. However, the modest average temperatures of the high-altitude city modulate temperature variability.

Case 4: London, United Kingdom

Founded in 43 AD and located at $51^{\circ}30'N$, $0^{\circ}7'E$, London is the capital of England and a global center of economic and political power. It sits just above sea level



at 115 feet and has a population of over 14 million residents, which reside in low, medium, and high-density development. The Köppen climate for London is oceanic (Cfb). Seasonal temperatures range from average monthly tempera- tures of 6.8 °C (44.2 °F) in January to 19.6 (67.3 °F) in July. It receives an average rainfall of 23 inches annually.

London has been found to experience temperature extremes ranging from 38.1 °C (100.6 °F) at Kew during August 2003 down to -16.1 °C (3.0 °F) in January 1962. Summers are generally warm and sometimes hot. London's average July high is 24 °C (75.2 °F). On average, the city sees 31 days above 25 °C (77.0 °F) and

4.2 days above 30.0 °C (86.0 °F) each year. During the 2003 European heat wave, there were 14 consecutive days above 30 °C (86.0 °F) and 2 consecutive days where temperatures reached 38 °C (100.4 °F), leading to hundreds of heat-related deaths. Perhaps the longest studied UHI, London has considerable temperature variability within the city which was recently measured at 4.5 °C (8.1 °F) (Bohnenstengel et al. 2011). UHI tendencies include warm days during the summer season that result in high energy demands and

potentially harmful heat wave episodes (as

observed in 2003).

Case 5: Singapore, Republic of Singapore

Established in 1299, the island city-state of Singapore is located at the equator (1 °N, 104 °E) with an elevation of 45 feet and a small footprint of 278 square miles. Since gaining independence in 1965, Singapore has observed tremendous physical and demographic transformations where concurrent rates of physical expansion through land reclamation, and population growth and urbanization



have resulted in an urban population density being among the highest in the world (about 19,910 people per square mile in 2015). With a Köppen climate classification of tropical rainforest (Af), the city's equatorial location provides little fluctuation in temperatures throughout the year where the average monthly temperatures of

average monthly temperatures of 26.0 °C (78.8 °F) in January and 27.4 °C (81.3 °F) in July. Singapore experiences high relative humidity with averages around 79% in the morning and 73% in the afternoon. It receives heavy annual rainfall with an average of 92 inches.

Accompanying Singapore's rapid urban development is a growing UHI, which scholars have measured maximum intensity at 3 °C (5.4 °F) in 1965 to more than 7 °C (12.6 °F) in 2004 (Roth and Chow, 2012). While the dense urban mosaic of concrete and asphalt can explain most of this increase, another likely cause is the extensive waste heat generated by its residents. The use of air conditioning to reduce thermal discomfort is prevalent year-round, especially given Singapore's equatorial location. The characteristically high daytime and nighttime temperatures combined with high ambient humidity present a continuous demand for energy.

Case 6: Phoenix, United States

Established in 1867, the Phoenix, Arizona metropolitan area (33°27'N, 112°04'E) is an ideal city to investigate UHI effects due to its hot desert climate (Köppen classification Bwh) coupled with the rapid increase in population and LULCC (Chow et al., 2012). Phoenix's elevation is 1068 feet. It has an average annual rainfall of 8 inches. It has rapidly transformed from a native desert landscape to the fifth largest city in the United States with a population of 4.5 million and growing. The resulting alterations in the local urban climate system present new challenges and vulnerabilities to residents.

The city experiences long and extremely hot summers with short and mild winters with average temperatures of 13.5 °C (56.3 °F) in January and 34.7 °C (94.5 °F) in July. Phoenix's all-time high recorded temperature is 50 °C (122 °F),



observed on June 26, 1990. High average temperatures make it one of the hottest of any major city in the US during the summer. On average, there are 107 days where the daily maximum temperature is greater than or equal to 38 °C (100 °F). It also experiences an annual average of 18 misery days.

The UHI effect in Phoenix is quite pronounced with maximum UHI intensity measured at 7.3 °C (13.1 °F) (Hedquist and Brazel, 2006). The rapid population growth and sprawling urban development in the naturally hot Sonoran Desert has resulted in the following UHI characteristics for Phoenix: exposure to very high temperatures during the long and intense summer season; significant demands on air conditioning and energy use to provide cooling for residents; intensive water demands for thermal cooling, vegetation, and energy generation; and human vulnerability to heat stress.

Misery days A temperature threshold of thermal comfort. A misery day in Phoenix, Arizona is when the daily maximum temperature is greater than or equal to 43.3 °C (110 °F).

Summary of Case Studies

Understanding the predominant climate regime of a city is extremely important when conducting UHI research. For instance, cities classified in Köppen climate Group A (tropical/megathermal) experience high precipitation and relatively low daytime (diurnal) temperature variation resulting in chronic heat exposure (e.g., Lagos, Singapore). Alternatively, cities in Köppen climate Group B (dry) experience more drastic diurnal temperature variation and greater seasonal temperature variation which has potential for seasonally acute exposure to heat stress (e.g., Phoenix). This has wide-ranging impacts on energy demand, water demand, air pollution, and human vulnerability to heat stress, among other considerations. Köppen climate Group C (temperate/mesothermal) cities report characteristics of moderate temperatures but experience seasonal weather anomalies that can result in human vulnerability to heat stress, such as the 2003 European heat wave.