

# The Urban Physical Environment: Temperature and Urban Heat Islands

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## Abstract

The term *urban heat island* (UHI) describes the phenomenon in which cities are generally warmer than adjacent rural areas. The UHI effect is strongest with skies free of clouds and with low wind speeds. In moist temperate climates, the UHI effect causes cities to be slightly warmer in midday than rural areas, whereas in dry climates, irrigation of vegetation in cities may cause slight midday cooling compared to rural areas. In most climates, maximum UHIs occur a few hours after sunset; maximum intensities increase with city size and may commonly reach 10°C, depending on the nature of the rural reference. Since the recognition of London's UHI by Luke Howard in the early 1800s, UHIs of cities around the world have been studied to quantify the intensity of UHIs, to understand the physical processes that cause UHIs, to estimate the impacts of UHIs, to moderate UHI effects, and to separate UHI effects from general warming of Earth caused by accumulation of greenhouse gases in the upper atmosphere. This chapter reviews a portion of the literature on UHIs and their effects, literature that has expanded greatly in the last two decades spurred on by a series of successful international conferences. Despite considerable research, many questions about UHI effects remain unanswered. For example, it is still not clear what portion of the long-term trends of increasing temperatures at standard weather stations is caused by UHI effects and how much is contributed by greenhouse gas effects. Also not well quantified is the effect of increasing tree cover in residential areas on temperatures

The process of urbanization alters natural surface and atmospheric conditions so as to create generally warmer temperatures (Landsberg, 1981). Oke (1997) suggested that urban atmospheres provide the strongest evidence we have of the potential for human activities to change climate. In the 20th century, rapid urbanization occurred worldwide, and today the majority of the world's population lives in cities. Increased temperature in cities, termed the *urban heat island* (UHI) effect, is present all around the world and both contributes to global climate change and, in turn, is exacerbated by global climate change (Mills, 2007; Sanchez-Rodriguez et al., 2005). With increasing energy shortages, the importance of

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doi:10.2134/agronmonogr55.c2

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urban temperatures will increase, especially in climates in which passive cooling by opening windows can reduce reliance on air conditioning (Mills, 2006). The UHI effect creates one of the key challenges to evaluating the influence of greenhouse gases on global climate change because urban influences are present in archived historical weather data that are used to determine long-term climate trends (Karl and Jones, 1989).

Publication of observations of the different climate of cities began with the now-classic work of Howard (1833), who described the climate of London as being warmer than surrounding areas. Real growth of urban climatology dates from the 1920s, followed by increases in interest in urban climates between the 1930s and 1960s (especially in Germany, Austria, France, and North America). After World War II and into the environmental era of the 1960s and 1970s and beyond, there was an exponential increase in urban climatic investigations, and the investigations have simultaneously become less descriptive, more oriented to quantitative and theoretical modeling, and more integrative and interdisciplinary (Brazel and Quatrocchi, 2005).

### Types of Urban Heat Islands

It is important to distinguish between the different types of UHIs and how they relate to urban built and vegetative structure (Table 2–1). For decades, urban climatologists have used an analogy with rural forests to describe urban climate in terms of the urban canopy layer (UCL), the space generally below the tops of trees and buildings. In humid climate forests, the active surface, where most of the exchange of radiant energy and turbulent transport of water vapor and heat takes place, is usually a layer from the tops of trees down to the point where tree crowns meet. Foresters think of the forest canopy layer as the space between the tops of tallest trees and the bottom of tree crowns that bear living foliage. The active surface in urban areas is more variable than in closed natural forests, and the urban canopy layer is usually considered to be the entire space from the tops of trees or buildings, depending on which dominates, down to ground level. In UHI studies, canopy-layer air temperatures are usually measured at about the height of people or the lower stories of buildings, between 1.5 and 3 m above ground. If that temperature is warmer than the temperature at the same height in nearby rural areas, then this is termed a UCL heat island (Oke, 1976, 1995). This chapter focuses on urban canopy layer heat islands.

The heat island that forms in the atmospheric boundary layer above the city is the urban boundary layer (UBL) heat island (Oke, 1987, 1995). The UBL varies greatly in thickness and turbulence over the course of a clear day (Stull, 2000), and thus the UHI in the UBL also varies. During the night, if the sky is

**Table 2–1. Simple classification scheme of urban heat island types (after Oke, 2006a).**

UHI Type	Location
Air temperature UHI:	
Urban canopy layer heat island	Found beneath roof or tree-top level
Urban boundary layer	Found above roof level; can be advected downwind with the urban plume
Surface temperature UHI	Different heat islands according to the definition of surface used (e.g. bird’s eye view 2D vs. true 3D surface vs. ground)
Sub surface UHI	Found in the ground beneath the surface

not heavily overcast, radiative cooling lowers the temperature of surfaces at the bottom of the boundary layer, and the air just above these surfaces tends toward slow laminar flow horizontal to the Earth's surface and remains in a shallow layer, 20 to 300 m thick, even as air in the free atmosphere above the boundary layer may be moving at a much higher speed. During the day, the air at the bottom of the boundary layer becomes turbulent because of surface heating and it mixes with air throughout the boundary layer to form a "mixed layer" that expands vertically. This process increases UBL thickness to 1 km or more. Stull (2000) provided a good description of UBL dynamics, and Oke (1995) summarized UBL heat islands.

Urban heat islands may also be described by the temperatures of the upper surfaces of buildings, trees, streets, lawns, and so forth, as seen from above. This is sometimes called the urban "skin" temperature. This type of heat island should not be confused with "surface temperatures" as used in some climatology reports to refer to air temperatures near the ground, usually at a height of 1.5 m. The 1.5-m height is essentially *at* the surface of Earth compared to the elevations at which temperatures are measured in atmospheric soundings (balloon measurements through the atmosphere), which may go to 30 km above the Earth. During the day, temperatures *of* the surfaces ("skin" temperatures) of nonliving solid material can be much warmer than air temperatures (Hartz et al., 2006b). Temperatures of entire urban surfaces are generally measured by satellite (e.g., Gallo et al., 1993). With clear skies, upper surface heat islands are small at night and large during the day, the opposite of UCL heat islands (Voogt and Oke, 2003).

Subsurface or soil heat islands have received much less attention than air temperature or skin temperature heat islands, primarily because very small scale effects of surface cover or shading may affect near-surface soil temperatures much more than the general large scale UHI. Most studies of urban soil temperatures have concentrated on the effects of asphalt cover on temperatures of adjacent soil or of soil below the asphalt (e.g., Celestian and Martin, 2004; e.g., Halverson and Heisler, 1981). Urban soil temperatures are described in Chapter 7 (Pouyat et al., 2010, this volume).

### Heat Island Impacts

The influences of UHIs on human society include effects on human health and comfort, energy use, air pollution, water use, biological activity, ice and snow, flooding, and even environmental justice (Harlan et al., 2006; Roth, 2002; Voogt, 2002). Urban heat island effects may also lead to modifications to precipitation and lightning (see Chapter 1, Shepherd et al., 2010, this volume).

Not all UHI effects are viewed as negative. In cold climates, UHI impacts may help reduce hazards of ice and snow in the city (Voogt, 2002), and winter comfort may be enhanced.

Both direct and indirect effects of temperature changes influence human health and comfort. Several studies have demonstrated that temperature threshold exceedance and air pollution in cities exacerbate human discomfort, heat-related health incidences, and mortality (Baker et al., 2002; Grass and Crane, 2008; Harlan et al., 2006; Kalkstein and Smoyer, 1993). Ozone concentrations, which influence human health, are amplified by the effects of higher daily maximum temperatures (Oke, 1997). For tourist information and promotion, city climate is generally reported by data from the main weather station, usually an airport, which may

have significantly more or less disagreeable climate than most of the city (Hartz et al., 2006a). Given an assumed temperature change, the effects of that change on human comfort can be quantitatively modeled (Hartz et al., 2006a; Heisler and Wang, 2002; Matzarakis et al., 2007), but because of both physiological and psychological adaptation (Nikolopoulou and Steemers, 2003), the perception of climate among residents of a particular city may not change in proportion to the magnitude of temperature changes.

Coastal, tropical, more arid, and more rapidly growing cities are especially vulnerable to global climate change and higher temperatures, as well as impacts of urbanization. For example, sea level rise portends major impacts on coastal city infrastructures such as in New York (Rosenzweig et al., 2007). In arid-land cities, excessive heat waves and the UHI, together with rapid population growth, present challenges to city officials in coping with impacts on health, water, and energy (Baker et al., 2002). Most population growth in the world will take place in urban areas, and rapid growth in moderate-sized tropical cities is expected. In addition, growth will be a major issue in less developed countries with low adaptive capacity, and the impact of urban climate may be accentuated in these environments (Dabberdt, 2007).

Energy use and peak electricity loads are impacted by higher temperatures in cities (e.g., Akbari et al., 1989), and the UHI may increase other resource use. For example, in Phoenix, AZ, a 0.55°C (1°F) increase in minimum daily temperature was associated with a 1098-L (290-gallon) increase in monthly water use in a typical single-family dwelling (Guhathakurta and Gober, 2007). Of course, urban areas may also adversely impact water resources by increasing peak flooding in streams through the city (Brazel and Quatrocchi, 2005).

Heat waves may impact parts of a city differently as a function of exposed landscapes, lack of air conditioning, and citizen inability to adapt to intense heat. In some cities or at least parts thereof, including Phoenix, AZ, there is a positive correlation between residents' income and vegetation cover, which suggested in initial studies at the census tract level that lower income residents could be negatively impacted by the UHI effect (Jenerette et al., 2007). Subsequent detailed neighborhood-scale level research on this issue has substantiated the patterns of sparse vegetation cover, landscapes with exposed and barren soil, and lack of proper cooling associated with low income levels (Harlan et al., 2006; Ruddell et al., 2010).

There are important and complex interactions between biological components of urban ecosystems and the UHI effect. Pouyat et al. (1995) noted UHI effects on carbon and nitrogen dynamics, especially N mineralization, in forest remnants within urban areas. Carreiro and Tripler (2005) and Ziska et al. (2003, 2004) developed the case for using UHI effects on biotic components of ecosystems as surrogates for global climate change effects. The papers by Ziska also show that the UHI effect can interact with higher CO<sub>2</sub> in urban areas to increase ragweed (*Ambrosia artemisiifolia* L.) production and therefore have an important influence on public health.

## Sources of Information about Heat Islands

### Past Reviews

Many scholarly reviews of urban climatology and accompanying bibliographies have illustrated how cities alter their climatic environment (e.g., Beryland and

Kondratyev, 1972; Brazel, 1987; Chandler, 1976; Landsberg, 1981; Lee, 1984; Oke, 1974, 1979, 1980, 1987). Today, urban climatology has achieved its own recognition as a subdiscipline in climatology and among allied disciplines, such as planning, ecology, environmental science, and meteorology. Roth (2007) reviewed urban climates in the tropics and listed some earlier reviews, including one by Givoni (1991) that evaluated the effects of vegetation on urban climate. Arnfield (2003) described results of 20 years of urban climate research beginning about 1980, a period in which new electronics with fast-response sensors, advanced remote sensing tools, and computer modeling capability played increasingly important roles in enhanced understanding of urban climate dynamics. Grimmond (2006) reviewed methods of observing meteorological variables in urban atmospheres, and Souch and Grimmond (2006) presented a concise but well-referenced review that covered UHI development and other aspects of urban climate. A book by Gartland (2008) summarized urban heat island physical science, impacts, and mitigation for general audiences including activist nonprofit groups.

### Conference Proceedings and Organizations

The increasing interest in urban climate including UHIs is evidenced in the increasing size and frequency of conferences on urban climate and environment. An early event devoted to urban environment was the Conference on Urban Environment in Philadelphia in 1972. The Metropolitan Physical Environment conference in 1975 (Heisler and Herrington, 1977) included a variety of papers on the urban environment, including urban temperatures. The American Meteorological Society continued the urban environment theme with a series of Urban Environment Symposia that were held beginning in 1998; the eighth occurred in January 2009. Beginning with the Third Urban Environment Symposium in 2000, the proceedings are freely available online (American Meteorological Society, 2009). The distribution of knowledge about urban climate is the sole purpose of the International Association for Urban Climate (<http://www.urban-climate.org/>), which has sponsored International Conferences on Urban Climate (ICUC) since 1989. The seventh ICUC conference was held in Yokohama in 2009, and the published proceedings are available online for the last four conferences.

### Special Journal Issues

Urban climate is also the subject of a number of special issues of journals, including 17 papers in Volume 84 of *Theoretical and Applied Climatology* in February 2006. A series of refereed articles from the sixth ICUC (ICUC6) in 2006 forms a special issue in *International Journal of Climatology* in 2007 (Grimmond et al., 2007).

### Scope of this Chapter

In this chapter we examine the influence of urbanization on temperature, concentrating on the UHI effect in the canopy layer. Our approach is to illustrate temperature patterns and the physical processes that govern temperatures by reviewing examples of the various methods used in urban climate research. We use examples from our past research on urban climate, which includes studies in Phoenix and nearby locations in Arizona and in and near Baltimore, MD. In the past 10 years, research on the urban ecosystems of Phoenix and Baltimore has expanded with the selection of these locations by the National Science Foundation for inclusion as sites in the Long Term Ecological Research program. Baltimore and Phoenix provide contrasts of very different general climates—warm and

moist versus hot and dry. Studies in San Juan, Puerto Rico and its vicinity illustrate urban influences in a tropical coastal city (Murphy et al., 2007, 2010). Our discussion focuses on factors that can be altered to modify UHIs, especially management of vegetation.

## Energy Exchanges and Urban Heat Island Dynamics

Brazel and Quatrochi (2005) provided an overview of energy exchanges in urban environments. Grimmond (2007) presented a concise summary of urban heat island dynamics. Shepherd et al. (2010, Chapter 1, this volume) briefly framed energy exchanges in the city.

### The Urban Energy Balance

The energy balance of a city can be expressed as follows with symbols similar to Eq. 1 in Shepherd et al. (2010, Chapter 1, this volume):

$$NR \text{ [i.e., } (1 - \alpha)S_{\downarrow} + LW_{\downarrow} - \epsilon T_{\text{skin}}^4] - SH - LH - G + A = 0 \quad [1]$$

where NR is surface net radiation, SH is sensible heat flux, LH is latent heat flux, and G is the heat flux to storage in the ground or to buildings and vegetation aboveground. The storage in the ground is often separated from storage in the aboveground volume of buildings and vegetation. The SH, LW, and G terms compete for surface net radiation, which is the downward minus upward shortwave and longwave radiation. In the component of NR,  $\alpha$  is surface albedo, and S is downward solar radiation, thus,  $(1 - \alpha)S_{\downarrow}$  is absorbed<sup>1</sup> solar radiation.  $LW_{\downarrow}$  is longwave radiation. Emissivity ( $\epsilon$ ) and surface skin temperature ( $T_{\text{skin}}$ ), through the Stefan–Boltzmann Law, describe the upward longwave radiation, or surface emission. A is the anthropogenic emitted heat.

### Shortwave Radiation

An urban area affects the exchanges of shortwave and longwave radiation by air pollution and complex changes of surface radiative characteristics. The atmospheric attenuation of incoming shortwave radiation has been analyzed in numerous urban climatic environments. It is thought that the attenuation in the atmospheric over cities is typically 2 to 10% more than in the surrounding rural areas. Generally, the very shortest wavelengths (<0.4  $\mu\text{m}$ ) of the electromagnetic spectrum to reach the surface of Earth, the ultraviolet (UV) portion, are commonly depleted by 50% or more (Heisler and Grant, 2000). However, total depletion across all solar wavelengths (0.15–4.0  $\mu\text{m}$ ) is <10%. The processes of scattering and absorption are greatly modified by the urban aerosol characteristics and concentrations (Gomes et al., 2008).

### Albedo

The second major effect of urbanization is the change in the ratio of outgoing shortwave radiation to that of incident shortwave radiation in a three-dimensional environment. This ratio, expressed as a percentage, is the *albedo* and is typically less in urban areas than in the surrounding landscape. Lower albedo is due in part to darker surface materials making up the urban mosaic and also to the effects of trapping shortwave radiation by the vertical walls and the urban, canyon-like morphology. There is considerable variation of albedo within the city depending on the vegetative cover, building materials, roof composition,

<sup>1</sup> In the original published version of this chapter, this word was incorrectly given as "reflected."

and land-use characteristics. The difference in albedo between a city and its surrounding environment also depends on the surrounding terrain. A city and a dense forest may differ little in albedo; both may range from 10 to 20%. In winter, a mid-latitude to high-latitude city with surrounding snow cover may display a much lower albedo than its surroundings. Thus, since cities receive 2 to 10% less shortwave radiation than their surroundings, yet have slightly lower albedos (by <10%), most cities experience very small overall differences in absorbed shortwave radiation relative to rural surroundings (Brazel and Quattrochi, 2005).

### Longwave Radiation

Longwave radiation is affected by city pollution and the warmer urban surfaces. Warmer surfaces promote greater thermal emission of energy vertically upward from the city surface compared to rural areas, especially at night. Some longwave radiation is reradiated by urban aerosols back to the surface and also from the warmer urban air layer (see Chapter 3, Santosa, this volume). Thus, increases in incoming longwave radiation and outgoing longwave radiation are usually experienced in urban areas. Outgoing longwave radiation increases are slightly greater than the incoming increases in the city, again especially on clear, calm nights. During daytime there is little difference between the city and its surroundings. However, surface emissivity (i.e., the amount emitted relative to black-body amounts for a given temperature) can be quite different between country and city areas, and can account for considerable longwave radiation differences between urban and rural (Yap, 1975). A major consideration is that in the city a three-dimensional surface temperature must be characterized to accurately estimate the flux values of radiation and the energy budget (Voogt and Oke, 1997, 1998).

Longwave emission from soils and soil heat capacity is determined by soil moisture and hence by antecedent precipitation. Therefore, temperatures depend on precipitation (Heisler et al., 2007; Kaye et al., 2003).

### Anthropogenic Heat Sources

The  $A$  term (from Eq. [1]) ranges from 0 to 300% of net radiation, depending on the extent of industrialization. Generally  $A$  is higher in more industrialized cities, in high latitude cities, and in winter. It is composed of heat produced by combustion of vehicle fuels, stationary source releases such as from buildings, and heat released by human metabolism ( $Q_{fm}$ ) (Sailor and Lu, 2004). Combustion heat is a function of type and amount of gasoline used, number of vehicles, distance traveled, and fuel efficiency. It requires an analysis of consumer usage of fuel such as gas and electricity.  $Q_{fm}$  can be evaluated by active and sleep rates, but it is generally less than 5% of total  $A$ . Methodology is described in detail by Sailor et al. (2003) and Sailor and Fan (2004) to evaluate the total  $A$  term in the energy budget.

Fan and Sailor (2005) estimated fluxes for summer and winter in Philadelphia, PA. The anthropogenic heating ranges from about  $10 \text{ W m}^{-2}$  at night to around  $40 \text{ W m}^{-2}$  during the day. This compares with typical peak daytime insolation levels of around  $850 \text{ W m}^{-2}$ . In winter the anthropogenic heating ranges from about  $20 \text{ W m}^{-2}$  at night to around  $60 \text{ W m}^{-2}$  during the day. Nocturnal anthropogenic heating in winter is about double that in summer. The daytime anthropogenic heating is also larger than that for summer (about 1.5 times). At the same time, the peak daytime insolation levels in winter are typically in the range of  $400 \text{ W m}^{-2}$  (about one-half of the summer magnitude). Inclusion of anthropogenic heating in heat

island simulations (either in the air layer or ground surface) increased estimates of the UHI by 0.5 and 2°C during the day and night, respectively. For a winter simulation, the results suggested that about 30 to 50% of the error may be due to the original model not accounting for anthropogenic heating.

### Heat Storage, Evapotranspiration, Heating the Air

The partitioning of energy in urban areas among sensible (SH), latent (LH), and storage heat (G) depends primarily on the variety of land uses in the city compared with rural areas. Generally, the drier urban building and road materials induce higher SH, less LH, and higher G in urban areas. Significant LH does, however, occur in some cities. It is theorized that this is due to urban irrigation effects and vegetation in the city (Kalanda et al., 1980). Marotz and Coiner (1973) indicated that vegetation in urban areas is not as limited as supposed, and Oke (1987) showed that G/NR ratios for rural areas vary by only about 0.10 from those for suburban and urban areas. Table 2-2 shows some recent results for selected U.S. cities (Grimmond and Oke, 1995). Note the substantive fluxes of SH and G, also significant LH, especially for the more moist city of Chicago, IL. In an evapotranspiration study of nine places, Grimmond and Oke (1999a) showed that the ratio of LH/NR ranged from 0.09 (Mexico City, Mexico, with very little external water use) to Chicago's ratio of 0.46 (Table 2-2). Goward (1981) listed thermal properties of typical interface materials, noting that most urban area materials (except for wood) have similar thermal properties and that urban thermal inertias (thermal admittance,  $\mu$ ) are higher than dry soils but lower than wet soils (Table 2-3).

**Table 2-2. Summary of daytime mean summer energy balance fluxes for selected cities derived from tall tower observations of Grimmond and Oke (1995).†**

Location	NR	SH	LH	S	G
MJ m <sup>-2</sup> d <sup>-1</sup>					
Tucson, AZ	16.27	7.54	4.11	4.62	na
Sacramento, CA	12.65	5.19	3.79	3.67	12.73
Chicago, IL	17.20	5.58	7.11	4.51	2.65
Los Angeles, CA	16.40	5.74	4.12	6.54	1.37

† Symbols for fluxes are: NR, net radiation; SH, sensible heat; LH, latent heat; S, total storage both above and below ground estimated as a residual from the energy budget equation; G, storage in ground measured with a soil heat flux plate.

**Table 2-3. Thermal properties of typical urban interface materials.**

Material	Thermal conductivity	Specific heat	Density	Thermal admittance
	W m <sup>-1</sup> C <sup>-1</sup>	J kg <sup>-1</sup> C <sup>-1</sup> 10 <sup>3</sup>	kg m <sup>-3</sup> × 10 <sup>3</sup>	J m <sup>-2</sup> C <sup>-1</sup> s <sup>-1/2</sup>
Asphalt	0.7454	0.92	2.114	1204
Brick	0.6910	0.84	1.970	1067
Concrete	0.9338	0.67	2.307	1185
Glass	0.8794	0.67	2.600	1213
Granite	2.7219	0.67	2.600	2176
Limestone	0.9338	0.92	1.650	1182
Sand (dry)	0.3308	0.80	1.515	633
Wood	0.2094	1.38	0.500	377
Soil (wet)	2.4288	1.48	2.000	2681
Soil (dry)	0.2513	0.80	1.600	567
Water (20°C)	0.5988	4.15	0.998	1579
Air (20°C)	0.0251	1.01	1.001	56

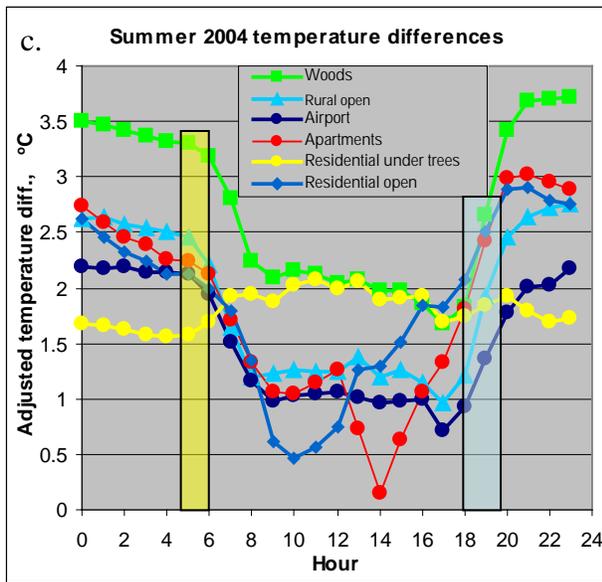
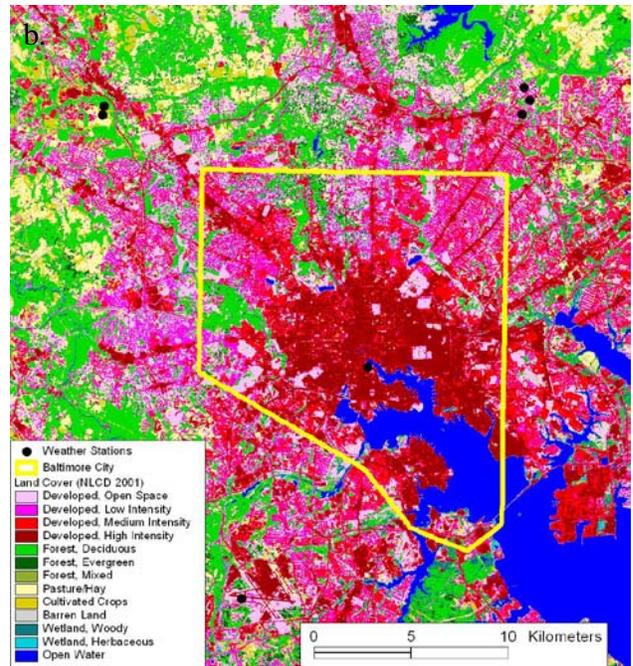
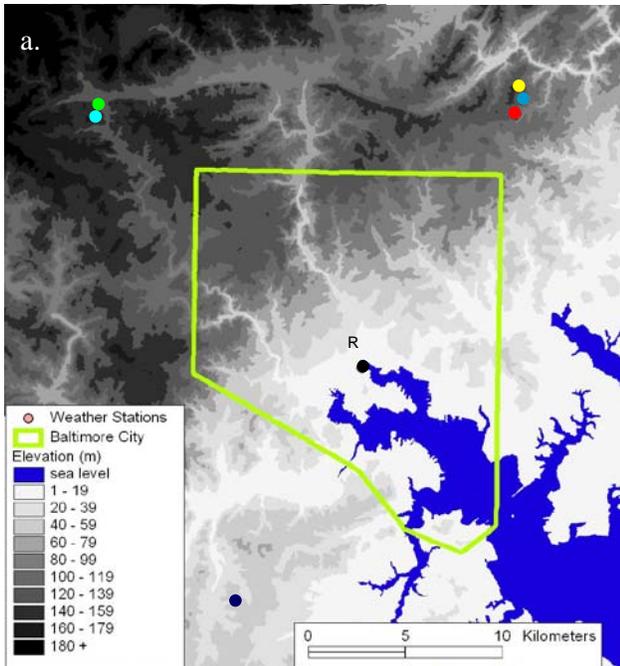


Plate 2-1. a.) Elevation of Baltimore, MD and vicinity with locations of 1.5-m-height temperature measuring sites color-coded to the average temperature differences in c. b.) Land use for Baltimore and vicinity, with dark red being most developed, suburban residential mostly medium pink, developed open space such as parks light pink, agriculture yellow and brown, and forest green. c.) Differences in temperature, urban reference (R) minus other sites, averaged by hour of the day from May through September in different land-use categories. Temperatures adjusted for elevation difference, assuming a standard atmosphere lapse rate. Range of times of sunrise and sunset indicated by shaded yellow and blue.

The ubiquitous asphalt covering in urban areas strongly affects temperatures of soil below the asphalt. In 2.5- by 2.5-m tree planter boxes cut into the asphalt of a parking lot in New Brunswick, NJ, maximum summer temperature exceeded temperature in control tree planting spaces off the parking lot (Halverson and Heisler, 1981). Near the center of the planter spaces, 85 cm from the edge of the asphalt and at a depth of 15 cm, maximum temperature exceeded controls by up to 3°C. At the same depth but below the asphalt, maximum temperatures exceeded controls by up to 10°C. Asphalt covering the soil not only increased maximum temperatures through a 60-cm profile, but increased the rate of heat exchange since temperatures in the covered soil rose and fell more rapidly than control temperatures. Temperatures below the asphalt ranged from 0.5 to 34.2°C, which was well within the toleration of tree roots. In contrast, temperatures below the asphalt of a parking lot in the warmer climate of Phoenix reached the likely plant-damaging temperature of 40°C at a depth of 30 cm (Celestian and Martin, 2004).

Differences in the UCL structure and composition are also important to explaining heat excesses in cities, rather than just the thermal properties of city materials per se. Although much attention has been given to internal variability of climate conditions within the urban environment and to the importance of the UCL (Arnfield, 1982; Goldreich, 1985; Goward, 1981; Grimmond and Oke, 1995, 1999b; Grimmond, 2006; Johnson and Watson, 1984; Lowry, 1977; Oke et al., 1981; Oke, 1982; Terjung and O'Rourke, 1980), many questions remain and the effect of urban form and structure on energy budgets and air temperatures has become a focal point in the field of urban climatology.

### Quantifying Urban Canopy Layer Temperature Regimes

Many methods are used to determine how much a city affects climate. Early methodologies were capable of studying urban temperature patterns within the urban canopy layer. These included sampling the differences between urban and rural environments, upwind minus downwind portions of the urban area, urban minus regional ratios of various climatic variables, time trends of differences and ratios, time segment differences such as weekday versus weekend, and point sampling in mobile surveys throughout the urban environment (Lowry 1977).

The intensity of an UHI depends in part on the rural basis for comparison (Hawkins et al., 2004). Though the rural reference is generally an agricultural landscape, the true impact of human development would use as a reference a vegetation cover that represented a natural climax vegetation community for the region.

### Urban Structural Classification

In nearly all studies of urban climate, some means must be used to categorize the structure of the urban area. For many urban-rural comparisons, the city character may be described simply by population (Karl et al., 1988; Oke, 1973). A more precise characterization is the use of satellite-derived night light (Hansen et al., 2001).

In recent decades, the intensity of urban heat islands often has been related to urban structure characterized by remote sensing. The scale of the analysis may be large, such as 1 km as used by the Advanced Very High Resolution Radiometer (AVHRR) on a NOAA satellite, which has been used to derive the Normalized Difference Vegetation Index (NDVI), for example, by Gallo et al.

(1993). Another commonly used product is the National Land Cover Database (NLCD) (Homer et al., 2004) that covers all of the United States at a 30-m resolution of land-use categories (Plate 2–1, see the color insert near the center of the book) and tree canopy cover, impervious surface cover, and water cover. Recent tests of the NLCD indicated that it generally underestimates urban canopy and impervious cover (Greenfield et al., 2010). Other 30-m spatial resolution satellite products with higher spectral resolution have been tested in categorizing impervious cover (Weng et al., 2008). These are all two-dimensional products that do not implicitly consider the vertical dimension. The heights of trees and buildings were considered in developing an urban character database from samples of 1-ha (100-m<sup>2</sup>) grid squares from a variety of data sources for Sacramento, CA; Uppsala, Sweden; El Paso, TX–Juarez, Mexico; and St. Louis, MO (e.g., Cionco and Ellefsen, 1998). Some current research is making use of the vertical dimension with high-resolution digital aerial imagery and light detection and ranging (LIDAR) data to resolve landscape objects, such as houses, trees, and pavements down to single-car driveways (Su et al., 2008; Zhou and Troy, 2008). The high resolution may make it possible to improve models of urban temperature patterns to estimate the influence of added tree cover in suburban neighborhoods.

In examining UHI effects on minimum temperature at the local scale in Phoenix, AZ, Brazel et al. (2007) found significant correlations of temperature increases with type of development zone (DZ) and the number of home completions within 1 km during the 14-yr study. The DZ types were urban core, infill, agricultural fringe, desert fringe, and exurban. The DZ concept originated with Oke (2006a), who proposed seven DZ types.

## Short-Time Observations with Fixed Sensors

### Influences on Temperature

The simplest observations of urban heat islands are by comparison of temperatures in the urban area and in the adjacent rural area. The length of the observations needs to be only sufficiently long to capture representative times conducive to large heat island formation, usually with clear skies and low wind speeds a few hours after sunset. More will be learned if the observations are continuous over at least a year, which will provide samples over a wider range of synoptic weather conditions. This method is most telling for cities with little topographic relief that are not near large bodies of water.

Measurements near Baltimore, MD (Heisler et al., 2006a) illustrated the influence of land cover and land use on temperature differences (Plate 2–1). Temperatures were measured at six suburban sites: a grassy area near a large apartment complex (Apartments, Plate 2–1a,c), a residential area with heavy tree cover but few buildings (Residential under Trees), a residential area with some trees and large lawn areas (Residential Open), a woodlot (Woods), a large open pasture (Rural Open), and at the Baltimore/Washington International Airport (Airport). The urban reference site was in downtown Baltimore (R in Plate 2–1a). None of the suburban sites were far from some developed land uses (Plate 2–1b). From May through September in the Baltimore study, average hourly temperature differences,  $\Delta T$ , downtown site minus each of the other sites, were positive for all hours of the day. For most sites,  $\Delta T$  through the day followed the usual UHI pattern of moist temperate climates—urban areas slightly warmer in mid-day, more

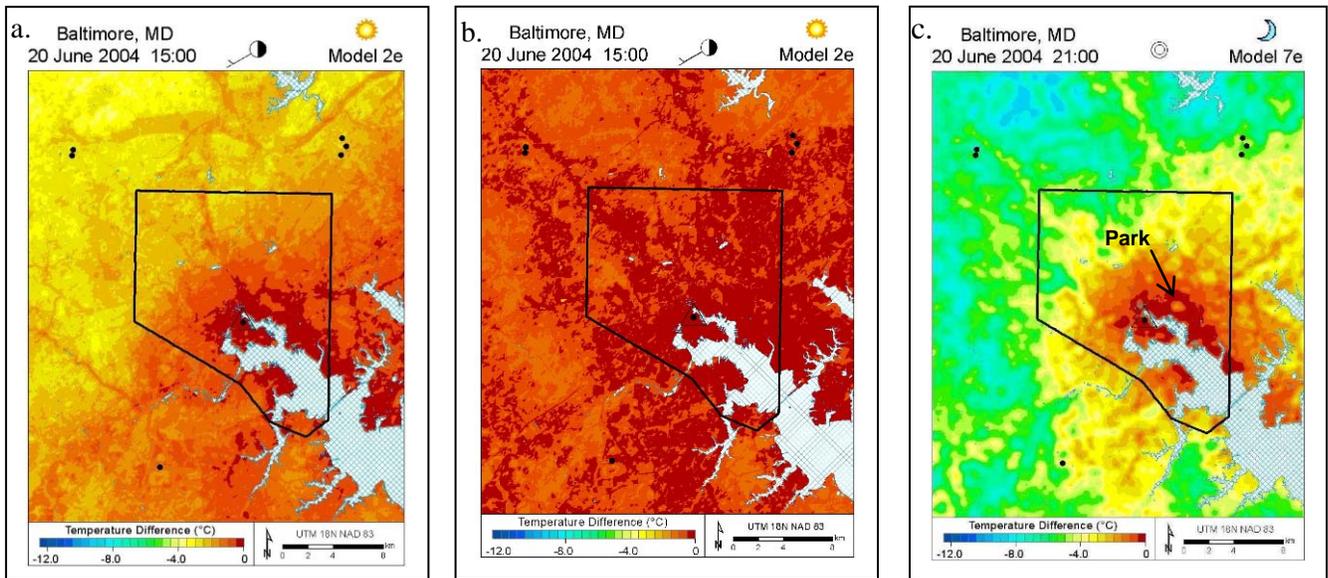


Plate 2-2. (a) Modeled air temperature differences ( $\Delta T$ ) at 1.5-m-height across Baltimore (black line) and vicinity. Black dots indicate weather stations used in regression modeling to develop prediction equations for  $\Delta T$ . This map is for 1500 local standard time of a partly cloudy summer day with low wind speeds ( $<2.6 \text{ m/s} = 5 \text{ kn}$ ), Turner stability Class 2. Water shown by cross-hatched blue. Solid colors indicate  $\Delta T$  with respect to the warmest temperature on the map (dark red). The coolest (light yellow) is  $4.1^\circ\text{C}$  cooler. More than half of the predicted temperature difference is due to differences in elevation. (b) With the elevation factor removed from the  $\Delta T$  equation, the influences of land cover are illustrated for the same time as in 2a; land cover causes a  $\Delta T$  range of about  $1.6^\circ\text{C}$ . (c) With clear sky and low wind speed at night, Turner Class 7, the UHI effect is near maximum. A large city park (Patterson) is about  $2^\circ\text{C}$  cooler than the dense residential area surrounding it. See Plate 2-1a for elevation map of the Baltimore area and Plate 2-1b for land use. The patterns of elevation and land use are evident in the pattern of predicted  $\Delta T$ .

rapid cooling of more rural areas after sunset leading to a maximum heat island in a few hours, and the cooler suburban areas heating more quickly after sunrise to approach the temperatures of urban areas that are heating more slowly. The Woods site was coolest both day and night, and the other site with many trees, Residential under Trees, was similarly cool during the day. However, the Residential under Trees site was unusual in not cooling as much as other suburban sites at night, in part perhaps because of cold air drainage away from the site into nearby valleys (Plate 2–1a,c).

### Interactions with Terrain Effects

Studies in other cities have described interactions between topographic influences and land cover; two of note are descriptions of the effects of complex topography in Phoenix (Brazel et al., 2005) and Tucson (Comrie, 2000). For Phoenix, Brazel et al. (2005) reported local thermal winds (i.e., daytime upslope and evening downslope winds) that extended 50 km across the Phoenix area when synoptic winds were low. These conditions occur with a frequency between 13% of days in July to 70% of days in June. The topographic influences were noted for slopes as small as  $0.5^\circ$ . The topographic influence was analyzed to be about equal to the convective circulation effect of the UHI. Time of onset of the downslope flows could be hours after sunset so that in one day of observations, near center city the UHI peaked at about  $5.5^\circ\text{C}$  at 2200 h, then decreased to  $0.5^\circ\text{C}$  at 0300 h because of downslope flow, before increasing to a second peak of about  $3^\circ\text{C}$  at 0500 h after slope flow subsided. Comrie (2000) found that in Tucson, cool downslope flow extended at least 11 km from low mountains, and these flows could obscure urban warming influences.

## Mobile Sampling

### Methods

Mobile transects, often in combination with fixed-station observations and remote sensing, have frequently been used to measure UHI patterns. (e.g., Hart and Sailor, 2008; Hedquist and Brazel, 2006; Martin et al., 2000; Stabler et al., 2005; Sun et al., 2009). Unless judicious and rigid criteria are employed (e.g., Oke, 2006a), it is unlikely that any method will yield an adequate sampling of the effects of land-cover type and morphological zones on urban climate. Fixed stations in government or special networks suffer problems of representation (i.e., point-to-area extrapolation is inadequate); thus, mobile sampling offers a better method to sample across urban-to-rural gradients. In using this approach, there is typically a lack of thorough temporal sampling (e.g., season, diurnal), and also data are not instantaneously sampled across the gradients chosen. This is usually addressed by sampling “across the transect and back” and taking an average or time-correcting the transect via comparison with fixed points that are being sampled through time along the transect route (e.g., a standard continuously recording weather site).

### Summer and Winter Differences

Martin et al. (2000) used automobile transects to evaluate temperature and humidity differences along roads through commercial, industrial, residential, agricultural, and greenbelt land-use classes during clear-sky early mornings (beginning at 0500 h) and afternoons (beginning at 1500 h) in Phoenix, AZ. In

summer mornings, industrial areas, which had the lowest NDVI, were warmest; commercial areas were just 1°C cooler; residential and greenbelt 3°C cooler; and agricultural areas, which were irrigated, 6°C cooler. In the afternoons, all land uses averaged within 2°C of each other, with industrial being warmest and agriculture coolest. In winter the pattern was similar, with smaller temperature ranges: only 2°C in the morning and only 1°C in the afternoon. The smaller UHI in winter is consistent with results from some other climates, for example, Vancouver, BC (Fig. 2 in Oke, 1976). However, others (Sailor, 2006; Souch and Grimmond, 2006) have reported that most often winter UHIs are greater than summer UHIs. It seems that the difference in magnitude of UHIs between summer and winter is sufficiently small that careful analysis is needed to assess which season has the most intense UHI. This was the case for Melbourne, Australia in a study by Morris and Simmonds (2000).

## Modeling

### Mesoscale Meteorology Models

Mesoscale meteorology models carry out numerical simulations of atmospheric conditions over three-dimensional atmospheric space with horizontal extent of up to thousands of kilometers and vertical extent of the entire troposphere. Their development has been underway for more than three decades and has progressed as computer capabilities have progressed to be able to carry out the solutions of huge numbers of primitive (based on first principles) equations that begin with those describing the conservation of mass, heat, and motion (Pielke, 2002). Varying horizontal scales may be used. For modeling city-scale processes, the grid spacing is less than with synoptic-scale models, but still large, for example, 5 km in some examples (Sailor, 1995; Taha et al., 1997). Mesoscale models couple the ground surface to the atmosphere. Thus, in the terminology of Shepherd et al. (2010, Chapter 1, this volume), they are Coupled Atmosphere–Land Surface (CALS) models, and they require ground cover conditions as input for atmospheric predictions.

The ground cover input to mesoscale models can include varying albedo and amount of vegetation. Taha et al. (1997) found that increasing the albedo of streets and of residential, commercial, and industrial areas in the Los Angeles basin reduced predicted 1500-h air temperatures by 2°C, which caused a significant reduction in predicted ozone concentrations. In this case, the average albedo over the basin was increased from 0.139 to 0.155, which was deemed to be reasonable and “doable.”

Estimating the effects of increased tree cover on UHIs may be a greater challenge than estimating effects of changed albedo, because trees exert a greater variety of physical influences. In their mesoscale modeling for Los Angeles, CA, Taha et al. (1997) simulated the effects of increased trees by proportional increases in evaporation and increased roughness at the lower boundary of the modeled atmospheric domain. The effect of trees in shading high thermal admittance building and paving surfaces was not implicitly included in the model. From a detailed analysis of urban structure (Horie et al., 1990), Taha et al. (1997) found that in 394 of the 2158 5-km cells, tree cover could be added. For a simulation of a “moderate” tree cover increase, they added tree canopy up to 0.15 of cell areas. They estimated that this increase would require the planting of 10 million trees. The mesoscale model predicted reduced temperatures of 2°C in the central Los

Angeles basin, and 1°C in surrounding areas. Similar results for the Los Angeles basin, using slightly different inputs, were reported by Sailor (1995).

Coutts et al. (2008) described options for modeling urban structure effects on air temperature. They considered the potential operation of climate models directly by urban planners, but concluded that this goal is probably unachievable currently, and therefore climate impact studies of urban development scenarios are best outsourced to urban climatologists. While continued model improvements and validation are needed and anticipated, urban climate models will still need to be run by those who know how to use them. An interdisciplinary and team-based approach is imperative in order for this to be effective (Oke, 2006a).

### Empirical Modeling

To evaluate the influence of urban cover on below-canopy air temperatures, especially the influence of urban trees on temperature, regression analysis was used with hourly weather data to develop relationships for predicting temperature differences ( $\Delta T$ ) between the city's center and six weather stations in different land uses around Baltimore, MD (Heisler et al., 2006a,b; 2007). One predictor of  $\Delta T$  was the difference in upwind land cover between stations as determined from the 2001 National Land Cover Database (Homer et al., 2004). Land cover had an influence on air temperature, but there were strong interactions between land cover and other predictors of  $\Delta T$ , particularly atmospheric stability and topography. Land-cover differences out to 5 km in the upwind direction were significantly related to  $\Delta T$  under stable atmospheric conditions.

The relatively simple Turner Class index of thermal stability (Panofsky and Dutton, 1984) was a useful indicator of urban heat island intensity in the Baltimore study. Thermal stability depends on the vertical profile of temperature in the atmosphere. A layer of the atmosphere is unstable when temperature decreases with height, such as occurs just above the ground when wind is light and the sun is strong during midday. The air in contact with the warm ground is heated; it expands and is thus lighter than cooler air above. Air near the ground tends to rise and be turbulent. We say the atmosphere is unstable. On clear, calm nights, outgoing longwave radiation cools the ground, which then cools air above it. The cool air tends to sink or, on level ground, stay put. The atmosphere is stable. When clouds obscure the sky and wind is strong, the layers of air are mixed and the air temperature is uniform with height. Thermal stability is neutral.

The Turner Index scale ranges from 1 for extremely unstable (little cloud cover, low wind speed near midday), to 4 for neutral (overcast sky or high wind speed or both), to 7 for very stable (clear sky, light wind at night). The conditions for a very stable atmosphere are also conditions that promote large UHI intensity. Thus, as anticipated, in the Baltimore study, the  $\Delta T$ s, which are essentially indicators of the UHI intensity, were usually larger with Turner Classes 6 and 7, which indicate strong stability and occur at night. In this use of Turner Class, it was a predictor of stability in rural rather than urban areas because urban surfaces remain warmer after sunset, and the air usually does not reach the very stable condition of Turner Class 7 (Panofsky and Dutton, 1984).

The regression equations combined with recent geographic information systems (GIS) tools permitted mapping  $\Delta T$  across a mesoscale-sized area of Baltimore and surroundings (Plate 2–2). The GIS methods have the potential for

testing the effects on temperature of changed land cover, for example, by inputting and mapping different scenarios of altered tree or impervious cover.

### Microscale Energy Budget Models

Voogt and Oke (2000) and Szpirglas and Voogt (2003) used the zero-dimensional surface heat island model (SHIM) to understand the roles of thermal admittance,  $\mu$ , and the sky view factor. It uses a so called “force-restore” equation that can derive the nocturnal cooling of a homogeneous substrate. The model calculates the change of surface temperature with time as a function of radiative loss from the surface and a restoring of heat from the subsurface to the surface. The model is able to simulate the cooling of all canyon facets, which include the canyon floor and both canyon walls.

Brazel and Crewe (2002) evaluated the rates of nighttime cooling at four different sites containing different surface materials and building configurations and employed SHIM in a discussion of values of inputs (building density and  $\mu$ ) across a range of conditions. The rate of cooling simulated by SHIM depended strongly on  $\mu$  (units of  $\text{J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$ ), the property that controls rate of surface temperature change for a given heat input or removal from the material. Typical values of  $\mu$  are  $600 \text{ J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$  for sand and  $1100$  to  $1200 \text{ J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$  for asphalt (Table 2–3). The modeling results showed that the impact of varying  $\mu$  across a range from  $500$  to  $2500 \text{ J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$  for an unobstructed sky horizon yields a non-linear response of the total cooling amount at night (Fig. 2–1). For values lower than the range of  $1000$  to  $1500 \text{ J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$ , there is an increasing rate of cooling, whereas for values greater than this range there is little rate-of-cooling response. Across a range of sky view factor from  $0.2$  to  $1.0$ , and at the same time  $\mu$  of  $600$  to  $3000 \text{ J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$ , it appears that changes in  $\mu$  from  $300$  to  $3000 \text{ J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$  caused more cooling than the sky view factor impact across the range  $0.2$  to  $1.0$ . Implications for UHI mitigation relate to simultaneously accounting for the delicate balance between building density and thermal property effects on the nighttime cooling rate of the materials and urban canyon environments.

### Analysis of Long-Term Records

Analysis of long-term temperature records can yield indications of the influence of urbanization, especially where temperature records are available from the

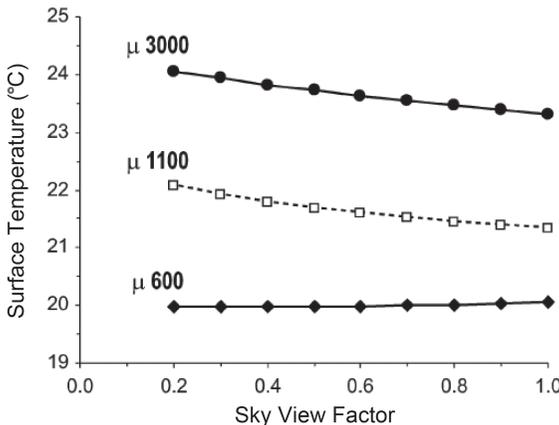


Fig. 2–1. Simulated surface temperatures after 10 h of cooling beginning at 1800 h with  $30^\circ\text{C}$  as the starting point for surfaces with different sky view and thermal admittance,  $\mu$  (from Brazel and Crewe, 2002). Sky view factor 0.0 is for complete obstruction by buildings, etc.; 1.0 is for sky completely unobstructed horizon to horizon. Units for  $\mu$  are  $\text{J m}^{-2} \text{C}^{-1} \text{s}^{-1/2}$ .

start of development. This was the case for a study in Columbia, MD (Landsberg, 1981), where in 1968, at the start of the development of the planned community, a heat island effect of 1°C was observed in a small residential area, and a 3°C heat island was found in a large parking lot. Six years later, the population had reached 20,000, and the maximum UHI increased to 7°C.

Brazel et al. (2000) analyzed long-term urban-minus-rural temperature trends using the Global Historical Climate Network (GHCN) database for several weather stations in and near Baltimore, MD and Phoenix, AZ. For the Baltimore area, the stations included a downtown Baltimore station, the Baltimore/Washington International Airport (BWI), a rural station near Woodstock, MD, about 9 km (15 miles) west of Baltimore, and two airports near Washington, DC. For Phoenix, the analysis included data from the Sky Harbor airport; downtown Phoenix; Mesa, AZ; and a rural location near Sacaton, AZ. The useable climate records began as early as 1908 and extended to 1997 for some stations. For the Baltimore region, the analysis used average daily maximum and minimum temperatures for July. For Phoenix, data were from May. Time series of the urban-minus-rural temperatures ( $\Delta T_{\text{max}_{u-r}}$ ) at the time of the daily maximum temperature showed a difference between the humid, forested East compared to the arid desert regions. In Baltimore, urban maximums are usually warmer than rural, whereas in the Phoenix area, urban maximum temperatures tend to be cooler than rural maximums. That is, values of  $\Delta T_{\text{max}_{u-r}}$  tend to be negative in Phoenix, an urban cool island (Plate 2–3). This results largely from extensive watering of plants in urban areas in this arid climate. There are only slight long-term trends of changing  $\Delta T_{\text{max}_{u-r}}$ . The small or negative daytime heat island in Phoenix has consequences for urban convection effects on precipitation; the convection probably is greater just outside the urban core than within it (Shepherd, 2006).

In downtown Baltimore,  $\Delta T_{\text{max}_{u-r}}$  averaged about 1.5°C toward the end of the period, up about 1°C since 1950 (Plate 2–3). Generally, downtown Baltimore was warmer than BWI. Maximum temperatures at BWI were close to maximums at Woodstock. National Weather Service studies suggest that the temperatures measured at the Customs House in downtown Baltimore may be especially high because the station was located on a building roof (personal communication, Robert Leffler of NWS, 1999). The station was moved to a downtown ground-level location over grass but near water in May 1999 (see next section).

Differences in urban-minus-rural temperature ( $\Delta T_{\text{min}_{u-r}}$ ) at the time of the daily minimum temperature are greater than differences in maximums and tend to reflect population trends. The long-term average  $\Delta T_{\text{min}_{u-r}}$  for Baltimore peaked at 4.5°C about 1970 and decreased slightly since then (Plate 2–3), apparently because of development encroaching on Woodstock, rather than because population decreased in Baltimore. A similar trend appears for the BWI-Woodstock  $\Delta T_{\text{min}_{u-r}}$  since the BWI record keeping began in 1951. In Phoenix, long-term average  $\Delta T_{\text{min}_{u-r}}$  increased substantially from about 2.5°C in 1908 to 6.5°C in 1995. The rural comparison site for Phoenix, Sacaton, has developed little since the beginning of the century. Thus, as has been found in many other cities, the UHI in both Baltimore and Phoenix is primarily manifested in increased nighttime temperatures rather than in greatly increased temperatures during the warmest part of the day.

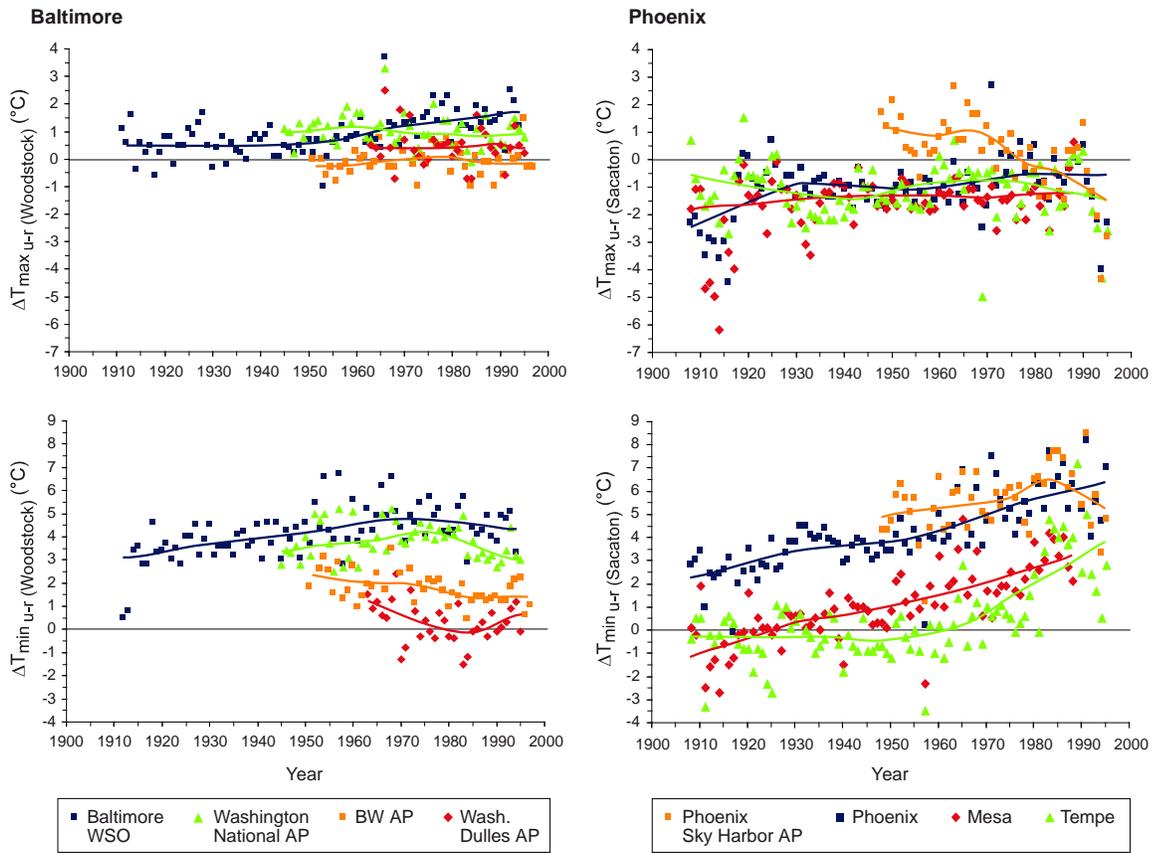


Plate 2-3. Long-term July monthly averages of maximum daily urban temperature minus corresponding rural temperatures for stations in and near Baltimore and the same for May temperatures for the Phoenix region (top), and monthly averages of minimum daily urban temperatures minus corresponding rural temperatures (bottom) (Source Brazel et al., 2000).

### Historical Climatology Networks

The long-term records in the Global Historical Climate Network (GHCN) or the United States Historical Climate Network (USHCN) may be useful in evaluating UHI effects (Brazel et al., 2000), although these datasets have been undergoing revisions that should be considered (personal communication, Russell Vose, National Climatic Data Center, 2008).

Caution must be used in the interpretation of long-term temperature trends from standard weather observations. These can be influenced by change of instrument types, station location, or change of surrounding cover, or nearby cover may be unrepresentative of the general area (Brazel and Heisler, 2000; Davey and Pielke, 2005; Oke, 2006b; Vose et al., 2005). Stations are sometimes discontinued just when their records are becoming most valuable. This is the case for downtown Baltimore and rural Woodstock records used by Brazel et al. (2000) for the analysis in Plate 2–3. These were the only two stations in or near Baltimore in the USHCN. The downtown station that was on the roof of a four-story building is now at ground level over grass and only 40 m from a significant body of water (the Baltimore Inner Harbor). Runnalls and Oke (2006) suggested means of checking for discontinuities in station records.

### Summary of Warming in Different Cities

When average temperatures over many years are examined, many cities show a warming trend. This warming can be attributed to both the UHI effect and global climate change. Over the 20th century, average annual temperatures have increased 1.72°C across Maricopa County, Arizona, which includes the city of Phoenix (Brazel, 2003). In urban areas of the county, however, temperatures rose by 4.22°C, or three times the 1.28°C increase in rural areas. In the last quarter of the century, Phoenix warmed at about 0.8°C per decade. This warming rate for Phoenix is one of the largest urban-warming rates in the world for its population (Hansen et al., 1999). Other rates of warming per decade for other cities were as follows: Los Angeles, 0.44°C; San Francisco, 0.11°C; Tucson, 0.33°C (Comrie, 2000); Baltimore, 0.11°C; Washington, DC, 0.28°C; Shanghai, 0.11°C; and Tokyo, 0.33°C.

A measure to separate UHI from global influences is the average heat island intensity,  $\Delta T_{u-r}$ . This measure varies over the course of a year with the cycles of wet and dry seasons. Roth (2007) graphed the monthly precipitation and nocturnal  $\Delta T_{u-r}$  for eight tropical or subtropical cities. Although in all of the cities there was a definite relationship between monthly precipitation and average  $\Delta T_{u-r}$  with drier months having larger  $\Delta T_{u-r}$ , precipitation was not a good predictor of  $\Delta T_{u-r}$  relative to other cities. For example, the highest monthly precipitation was about 400 mm in July in Veracruz, Mexico, but average  $\Delta T_{u-r}$  was still about 2.5°C, whereas in Bogotá, Colombia, July had a  $\Delta T_{u-r}$  of about 2.5°C, but only 70 mm of precipitation. The largest average nocturnal  $\Delta T_{u-r}$  among the eight cities was about 5.6°C in Singapore in July, when precipitation totaled about 150 mm.

Another pertinent comparison of the heat island in different cities is the maximum intensity of the urban heat island,  $\Delta T_{u-r(\max)}$ . Oke (1973) compared  $\Delta T_{u-r(\max)}$  with population for cities in Europe and found that the relationship differed from that in the United States (Fig. 2–2). Roth (2007) compared the Oke (1973) relationships to  $\Delta T_{u-r(\max)}$  in tropical and subtropical cities and found generally smaller  $\Delta T_{u-r(\max)}$  values in tropical cities and generally lower  $\Delta T_{u-r(\max)}$  in wet than dry climate tropical and subtropical cities (Fig. 2–2). In San Juan, an urban area with a

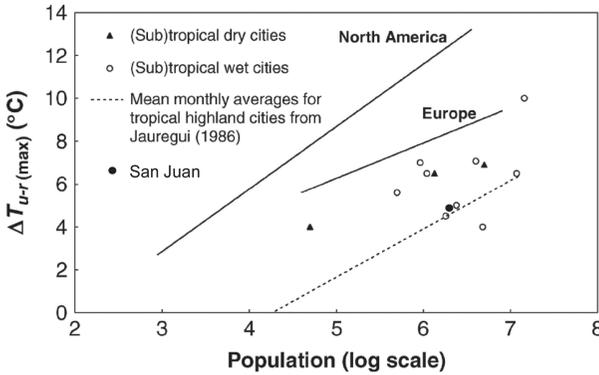


Fig. 2-2. Maximum nighttime heat island intensity versus city population from Roth (2007). Solid lines are regressions through temperate cities of North America and Europe (Oke, 1973). The dashed line is a fit through maximum mean monthly urban heat island data from cities located primarily in tropical highland climates from Jauregui (1986). The point for San Juan, a subtropical wet location, is from Murphy et al. (2010).

population of about 2 million, the observed  $\Delta T_{u-r(max)}$  of about 4.7°C was typical of wet climate tropical cities (Murphy et al., 2010).

The heat island,  $\Delta T_{u-r}$  depends in part on the nearby surroundings of measurement points. For San Juan, the rural location was in old-growth forest, and cooling patterns, which determine  $\Delta T_{u-r(max)}$ , differed from typical observations in temperate climates (Oke, 1987). The usually temperate climate pattern includes a  $\Delta T_{u-r(max)}$  within a few hours after sunset because, beginning in midafternoon, both the rural and urban areas begin to cool, but the rural area cooling rate is greater than the urban rate until that time, a few hours after sunset, when the rural cooling rate decreases and  $\Delta T_{u-r(max)}$  occurs. In San Juan, the forest continued cooling more rapidly than the urban area throughout the night, and indeed did not begin warming until an hour or two after sunrise, by which time the urban area had clearly begun warming. Thus, the  $\Delta T_{u-r(max)}$  occurred shortly after sunrise, rather than within a few hours after sunset.

### Relationship of Urban Canopy Layer Heat Islands to Global Climate

The UHI effect in even modest-sized cities is at times, much larger than the 100-yr trend (1906–2005) of 0.74°C average global temperature warming reported by the IPCC (2007). This is true especially on clear nights with low wind speeds. Global warming is caused by accumulation of “greenhouse” gases (GHG) in the stratosphere, a completely different phenomenon than the processes that cause UHIs. However, global warming and UHI effects are inextricably linked because a large portion of the GHGs are produced in urban areas, and the UHI effect modifies, either positively or negatively, the urban emissions of GHGs (Mills, 2007). Perhaps more importantly, the UHI effect makes terrestrial air temperature monitoring of the global effect uncertain because for many weather stations it is difficult to separate UHI influences from the global influences (Christy and Goodridge, 1995; Kalnay and Cai, 2003).

#### Confounding of Global Climate Temperature Analysis

The question of whether archived weather data is representative of global temperature trends caused by the greenhouse effect is perhaps the major bone of contention among those who urge major efforts to reduce GHG emissions and

those who believe that global climate change is not a problem. Attempts at factoring out the urban influence on long-term archived air temperature measurements have sometimes been based on city population (Karl et al., 1988; Karl and Jones, 1989), at best an inexact exercise because population of a political subdivision may not correspond with the degree of development in the immediate vicinity of a weather station. Also, in many parts of the globe, population records are lacking or imprecise (Gallo and Hale, 2008). Jones et al. (1990) pointed out that large UHI intensities occur only for parts of days with favorable conditions and that when many stations are averaged in a large global-climate-analysis grid cell, the urban influences would be small—an estimated global average value of  $0.05^{\circ}\text{C}$  or less. Epperson et al. (1995) used analysis of satellite estimations of NDVI and night light brightness along with data from more than 2000 weather stations in the United States and estimated that the UHI effect caused monthly averages of daily minimum temperatures over these stations to be  $0.40^{\circ}\text{C}$  higher than they would be without the urban influence; monthly averages of daily mean temperatures were  $0.25^{\circ}\text{C}$  high, and monthly averages of maximum temperatures were  $0.1^{\circ}\text{C}$  high. They concluded that given NDVI and night light data, the urban bias could be eliminated satisfactorily. Hansen et al. (2001) found evidence of urban warming even in suburban and small-town surface air temperature records. They also found inherent uncertainties in the long-term temperature change at least of the order of  $0.1^{\circ}\text{C}$  for both the U.S. mean and the global mean. However, they judged that the urban effect “is modest in magnitude and conceivably could be an artifact of inhomogeneities in the station records” (Hansen et al., 2001). To clarify the “potential urban effect” they suggested further studies, including additional satellite night light analyses, which are used to define populated areas.

Another approach to sort out urbanization influences from GHG influences on temperature is to use the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP-NCAR) 50-yr Reanalysis (NNR) by the method of Kalnay and Cai (2003). The NNR, described by Kalnay et al. (1996), used a combination of 6-h forecasts and data from soundings of the atmospheric conditions to produce a very large set of predicted output variables through the atmosphere. Observations of temperature, moisture, and wind at the surface of land are not used in creating the NNR data; however, surface temperatures are estimated from the atmospheric values. Kalnay and Cai (2003) concluded that the NNR should not be sensitive to urbanization or land-use effects, although it will show climate changes to the extent that they affect the measurements above the surface on which the NNR is based. For the period 1960 through 1999, average daily maximum land-based temperature observations across the United States showed a small  $-0.017^{\circ}\text{C}$  change per decade, while the NNR showed an average of  $+0.008^{\circ}\text{C}$  per decade. Minimum daily land-based temperatures had a stronger positive trend in most of the United States, with an average of  $+0.193^{\circ}\text{C}$  per decade. In the NNR, the minimum temperature had an average increase of only  $+0.113^{\circ}\text{C}$  per decade. Thus, the difference in minimum temperature trends between observed and NNR values (Observed Minus Reanalysis, OMR) was positive in most of the United States, with an average of  $0.080^{\circ}\text{C}$  per decade, suggesting that 40% of the observed trend was urban related.

The results of Kalnay and Cai (2003) were challenged by other researchers. For example, Parker (2004) found long-term warming of minimum daily temperatures at 264 stations worldwide even for windy days when the urban effect should

have been small. However, it must be noted that Parker assumed wind speed to be given by the daily average speed, which is usually greater than the wind speed at the time of minimum temperature; that is, winds are generally much higher during the day than at night when minimum temperatures and the maximum UHI generally occur. Another concern with the OMR method is the assumption that urban influences are restricted to the air at the bottom of the atmosphere. Urban influences do create vertical motion in the atmosphere (e.g., Baldi et al., 2008) that may significantly affect the NNR.

Gallo and Hale (2008) provided a concise summary of recent research on methods to factor out the land-use effects on global temperatures. They concluded that there is still the need for additional studies of urban influences on long-term trends in air temperature.

### Amplification of Global Warming Effects

Another view of the global versus urban temperature change is that large urbanized areas are amplifying background rates of warming attributed to global-scale climate change (Stone, 2008). In an interesting analysis of data from 50 cities and associated rural areas between 1951 and 2000, Stone (2008) found both urban and rural warming and cooling trends. Of the 50 locations, 12 had cooling rural areas and 12 had cooling urban areas, but only 5 of the 12 were the same locations. As in any study of climate, the data collection and source of samples must be considered. In this case the study took urban temperatures to be the record from the primary airport for each city. This is problematic because airport temperatures are not necessarily representative of their urban areas. Two examples are Hartsfield Airport for Atlanta, GA, which is relatively warm compared to stations in the city (Heisler and Wang, 1998) and the Baltimore/Washington Airport near Baltimore, which is somewhat cooler than the city center (Heisler et al., 2006a). Of the 50 cities in Stone's (2008) analysis, the overall average for increasing UHI was a mean decadal increase in heat island intensity of 0.05°C. For the 29 cities experiencing an increasing trend in urban warming between 1951 and 2000, the mean decadal rate of increase in heat island intensity was 0.19°C. Stone (2008) concluded that planners and public health officials in large cities should be prepared to manage changes in temperature potentially in excess of those forecast by the Intergovernmental Panel on Climate Change (IPCC).

Similarly, Oleson et al. (2009) reported that efforts are underway at the U.S. National Center for Atmospheric Research to model UHI intensity given future global warming. Initial results suggest slightly smaller urban-minus-rural temperatures in temperate-climate winters because warmer global temperatures will reduce the anthropogenic input for space heating of buildings.

### Mitigation

When considering the literature on the mitigation of urban heat islands, special attention should be paid to experimental design, assumptions of the study, and the language. Often experiments or data analyses are undertaken, either consciously or unconsciously, to prove the point of view that heat islands are universally detrimental. Possible winter benefits are often not considered. Rather than the scientifically sufficient "warmer" to describe urban temperatures, they are the value-laden "hotter". While these comments should not be taken as

detracting from the overwhelmingly solid science in the field of urban climate, we remind the reader that some reports were planned and performed with the goal of proving the effectiveness of certain strategies.

The Heat Island Project at the Lawrence Berkley Laboratory in Berkley, CA was an early promoter of increasing urban albedo by use of white roofs and light-colored paving (Rosenfeld et al., 1995). Though much of this group's research results apply to effects of tree shade, light roofs, and insulation on energy use at the scale of individual buildings, there are implications for larger scale UHIs. For example, Rosenfeld et al. (1995) pointed out that in Los Angeles, the maximum air temperatures decreased during the city's early development, as dry arid regions were replaced with irrigated orchards and farmland. This is similar to Phoenix, where a small cool island exists during the day, apparently because of irrigation of vegetation in the city (Brazel et al., 2000) (Plate 2–3). In an experiment to test the effect of surface albedo changes on air temperature for comparison with results of mesoscale meteorological modeling, Rosenfeld et al. (1995) found that the experimental results showed less cooling than the model, but concluded that the experiment did not include all the factors in a full urban area (Rosenfeld et al., 1995). A 1998 report (Rosenfeld et al., 1998) predicted that the Los Angeles, CA heat island could be reduced by as much as 3°C by “cooler” (i.e., lighter) roof and paving surfaces and 11 million more shade trees.

Sailor (2006) reviewed then current and possible future UHI mitigation strategies, including albedo modifications, tree planting, and “ecoroofs”. As in other reports on eco or green roofs, this one described the benefits for urban hydrology and energy use in the building with the roof without being able to say much about the effect of green roofs on general urban climate. Sailor also described the functions of U.S. national governmental and nonprofit organizations, as well as activities on mitigating UHIs in other countries.

The USEPA supported the development of a web-based computer program called MIST, the heat island Mitigation Impact Screening Tool (Sailor and Dietsch, 2007). The program (available at <http://www.heatislandmitigationtool.com/>, verified 9 Feb. 2010) provides estimates designed to assist urban planners and air quality management officials in assessing the potential of UHI mitigation strategies. The program can estimate effects of UHI modifications on city-wide urban climate, air quality, and energy consumption for more than 170 U.S. cities. To its credit, MIST provides estimates of both summer benefits and winter detriments of actions that affect UHIs. The estimates provided by MIST are table look-up values that come from a series of mesoscale modeling runs for 20 cities (Sailor and Dietsch, 2007). The authors warn that “results presented by MIST include a high degree of uncertainty and are intended only as a first-order estimate that urban planners can use to assess the viability of heat island mitigation strategies for their cities” (Sailor and Dietsch, 2007).

The New York State Energy Research and Development Authority sponsored a New York City Regional Heat Island Initiative to research effects of tree planting, white pavements and roofs, and green (living) roofs on summer “near-surface” air temperatures (Rosenzweig et al., 2006). Again, a mesoscale meteorological model was used to estimate the effects. The study concluded that all of the strategies could reduce summer UHIs, but the best was a combination of tree planting and living roofs. Any possible negative influences by reductions of winter air temperature or increases in heating costs for buildings by tree shade were not

considered, and of course possible net benefits of trees and living roofs in winter were also not considered. A similar project was sponsored by the UK Engineering and Physical Sciences Research Council (EPSRC) and the UK Climate Impacts Program (UKCIP) for the region of Manchester, Great Britain (Gill et al., 2007). Their emphasis was on the role that the green infrastructure of a city can play in adapting for climate change, by which is meant both global and urban. Quantitative results from these and similar studies cannot be presented in brief because the results depend very much on the methods and assumptions of the studies.

Urban and global warming can also be mitigated at smaller scales by building and landscape architectural techniques such as by providing local appropriate shading and designing to permit natural ventilation. There are two recent reports from Great Britain that emphasized using these methods to foster human comfort (Smith and Levermore, 2008; Watkins et al., 2007).

The USEPA tried for many years to produce for planners and administrators a set of scientific explanations for UHI effects and guidelines for mitigation of UHIs and UHI effects on which most researchers in the field could generally agree. This effort was in part to update a previous guidebook on tree planting and light-colored surfacing (USEPA, 1992). The current online version (USEPA, 2009) includes separate documents that cover UHI basics, mitigation by trees and other vegetation, green (living) roofs, cool (light-colored) roofs, cool pavements, and activism in the cause of UHI reduction including tree planting programs, ordinances, and building codes and zoning.

## Conclusions

- Developed areas in moist climates usually have warmer air temperatures than more rural areas, both day and night, creating an urban heat island effect. The UHI is usually not more than 3 or 4°C during midday. Depending on the rural reference site and synoptic weather conditions, the UHI effect in large cities may range up to about 11°C after sunset. Dry, desert climates have maximum UHIs of similar magnitude to moist climates, but during the daytime, the temperature island often turns out to be a small-magnitude cool island because of evaporative cooling of irrigated vegetation within the city.
- Urban heat islands are caused directly by differences in urban structure and materials from rural areas and indirectly by urban influences on hydroclimate and atmospheric pollutants. However, the primary cause is probably the high thermal admittance (high thermal entropy) of urban building and infrastructure materials that leads to slower rates of heating and cooling of surfaces in urban than rural areas.
- The UHI effect is generally considered to be detrimental. Warmer temperatures increase ozone production in urban atmospheres; increase use of energy for air conditioning, thereby increasing emissions of CO<sub>2</sub>; and increase adverse effects on human health and mortality in heat waves. In temperate climates, UHIs are usually greater in summer than winter because of the greater amount of solar insolation in summer. However, substantial UHIs can also form in winter, with the benefits of reducing costs for heating buildings and less snow and ice hazard. The winter benefits of UHIs have seldom been quantified and compared with the detriments of summer.

## Acknowledgments

The first author thanks the Baltimore Ecosystem Study Long-Term Ecological Research (LTER) Program, operating with contributions from NSF grant DEB 0423476, for providing instrumentation and technical support staff. GIS maps were prepared by Alexis Ellis.

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