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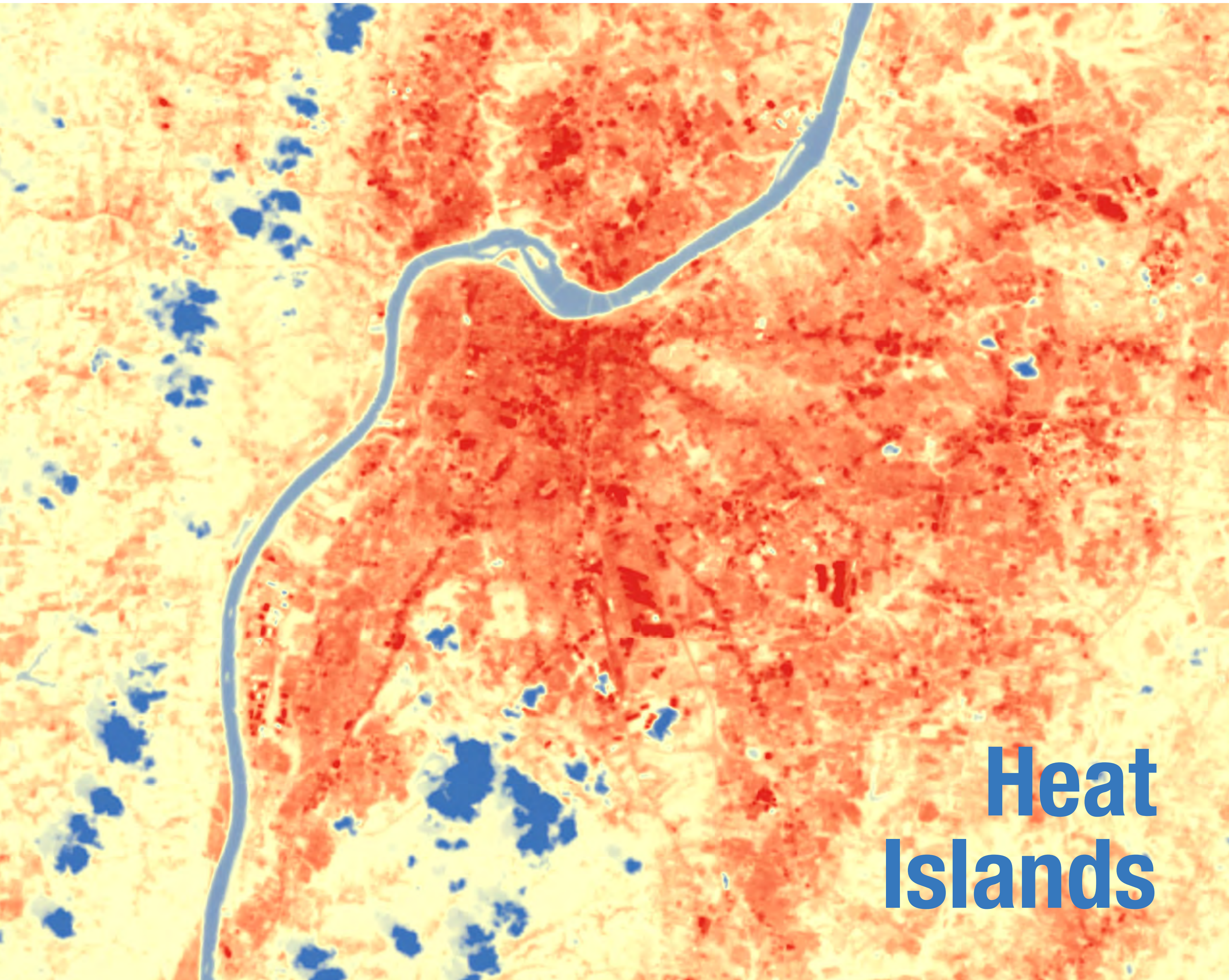

Heat Islands

sustain

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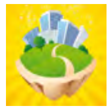
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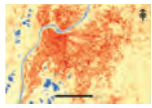
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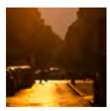
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Heat Islands
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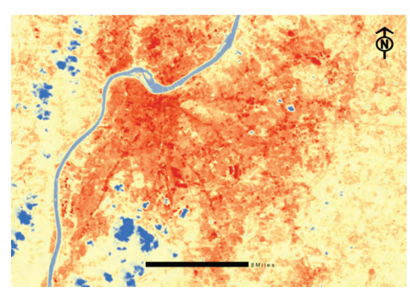

Urban Heat Islands, Effects, and Mitigation

By Haider Taha
Altostratus Inc.

Urbanization and accompanying changes in land use and land cover, energy use, air-pollutant emissions, and man-made heat, can cause a myriad of modifications to the atmosphere locally, regionally, and globally. The Urban Heat Island (UHI) is one major manifestation of such effects. Heat islands, when and where they occur, can have significant impacts on energy use and the environment. Annual cooling degree-days (base 65°F or 18.3°C) in U.S. cities can increase, because of the UHI, by 10 - 50%, depending on climate, whereas annual heating degree-days can be reduced by 5 – 15%. Every 0.5°C of warming in urban areas can cause an increase in cooling-energy use of between 1 and 2% beyond a certain temperature threshold that varies among cities. In terms of air-quality, an increase in urban temperatures can increase emissions from power generation, biogenic sources, and mobile sources, as well as fugitive emissions. It can also increase the rates of photochemical ozone production. While it is impossible to generalize, because of complexities involved, a back-of-the-envelope assessment would be that a reduction of 1°C in urban air temperatures can reduce peak one-hour ozone concentrations by some 1 – 5 ppbv(parts per billion in volume) in different areas in the U.S.

Urban heat and cool islands

An urban heat island (UHI) can be defined as a difference in surface (skin) temperature or in air temperature, in which case the difference is taken at a certain height above ground level, e.g., at 2, 5, or 10 meters. The former type of UHIs is typically "seen" with remote-sensing techniques using satellite or aircraft-mounted thermal sensors, whereas the latter is typically measured by near-surface air-temperature probes placed at the desired elevations above ground. UHIs are diagnosed on time scales of minutes to years, depending on the purpose of the analysis or application at hand.

Quantifying UHIs requires selecting urban and non-urban reference points. Depending on the purpose of analysis, UHIs are often defined as the temperature difference between two fixed points in space, e.g., an urban point (such as in the core of a city) and a rural one. In other cases, the UHI is taken as an average of urban temperature differences (at several locations in urban areas) relative to one or an average of several non-urban points. Another way to define UHIs is to compute the difference in temperature between an urban point(s) of interest and a time-dependent (space-varying) upwind non-urban point(s). In this case, the location of the reference point changes based on wind approach and thus the definition of a UHI becomes wind-direction-dependent, whether instantaneous or statistically-representative. Because UHI definitions can differ, some formal standardization may become necessary, a concept that is now gaining interest among many urban-climate researchers.

Factors affecting the UHI intensity include city-size, type of dominant building materials, urbanization density, land-cover types and densities, energy-use intensity and fuel types, rate of release of man-made (anthropogenic) heat, pollutants emissions and concentrations, and local weather / micrometeorological conditions. Thus heat islands can differ significantly from one area to another and also at different times at any specific point. As a result, there are day- or night-time-peaking UHIs, winter- or summer-peaking ones, and so on depending on the above factors. While some UHIs can remain relatively constant for some time, most vary seasonally and diurnally. The development of a UHI also depends on synoptic (comprehensive view) and background conditions. For example when high winds exist, UHIs typically do not develop well whereas with moderate winds, UHIs are displaced. At low background winds, UHIs develop their own circulations and can reach maximum intensity under such conditions. The background wind-speed thresholds for development of UHIs vary from one location or set of conditions to another, but are generally between 3 and 6 m s^{-1}(meters per second). UHIs in North America typically range from 1 to 3 C (Taha 2004), in South America up to 8°C (Lombardo 1985) or larger, and in Asia up to 3°C (Kim and Baik 2005). In Europe a maximum summer heat island of 8°C has been reported (Kolokotsa et al. 2009).

Urban areas can also be cooler than their non-urban surroundings under certain conditions. In such cases, we define an urban cool island (UCI) as an opposite to a UHI. Cool islands can be seen in desert climates where urban areas act as "oases" that are cooler than their non-vegetated, drier surrounds. Although occurring much less frequently than UHIs, UCIs can also be seen in some urban areas during the morning when the surroundings warm up faster than the urban cores (because of thermal lag, shading, and surface moisture), then become UHIs later in the

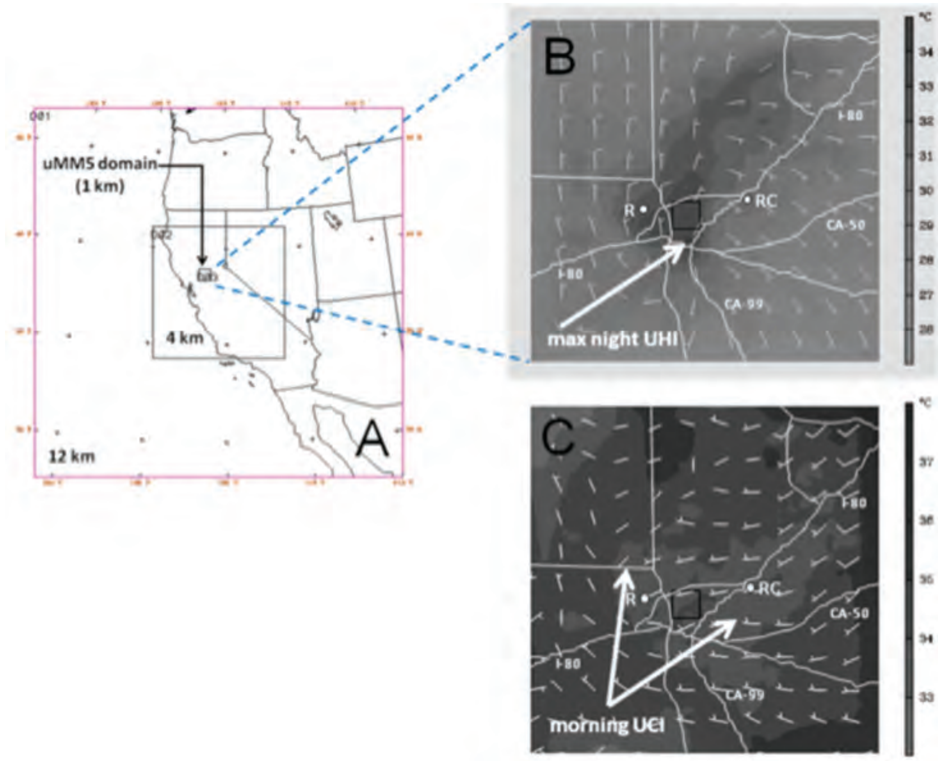

Figure 1. Maximum nighttime UHI (B) and morning UCI (C) over Sacramento, California, on 1 and 2 August (2000). The black square inset in B and C outlines the relative location of downtown Sacramento. The higher temperatures (UHI) plume stretching from downtown to the northeast (B) follows the extent of urbanization in the area (source: Taha 2008a, Atmospheric Environment).

morning, throughout the day, and at night. Figure 1, for example, shows heat and cool islands in Sacramento, California, captured with fine-resolution meso-urban simulations (Taha 2008a). In this example, the morning cool island is -1°C and the nighttime heat island reaches up to 3°C. In the afternoon (not shown), the UHI reaches 2-3°C.

Mitigation of urban heat islands

When and where they occur, urban heat islands impart many effects with magnitudes that vary depending on geography, climate characteristics, energy-use intensity, and urban density, among others. These effects include:

- Increased cooling demand during the warmer seasons and decreased heating energy requirements in the cooler months
- Exacerbation of health effects during hot weather and specific events such as heat waves
- Urban-enhanced cloudiness, such as during conditions conducive to the development of convective clouds
- Increased emissions of greenhouse gas and ozone precursors from point sources as a result of increased power generation requirements to meet additional cooling loads
- Increased anthropogenic emissions, e.g., from motor vehicles / increased evaporative emissions
- Increased biogenic emissions from vegetation in urban areas or downwind of them (i.e., within areas affected by heat islands)
- Increased photochemical production of ground-level / tropospheric ozone
- Modified radiative forcing as a result of increased ozone concentrations and particulate-matter loading
- Increased evaporation and loss of surface water.

Thus the main goal of heat-island mitigation research is to develop actionable information that can assist cities and regulatory organizations in evaluating the effectiveness of urban-cooling measures in terms of their impacts on energy use, meteorology, thermal environmental conditions, emissions, and air quality and, thus, prioritizing the deployment of such measures. Many studies have been carried out with these objectives in mind, each typically focusing on a subset of the processes and mechanisms of interest. For example, Akbari et al. (1999) and Akbari and Konopacki (2005) evaluated the impacts of heat-island mitigation on energy use. With advanced building-energy models, they estimated that nation-wide in the U.S., implementation of cool roofs would save 10 TWh/year(terrawatt hours per year) of electricity. Accounting for both cooling-energy savings and winter heating penalties, they estimated total net savings of $750 M/year in energy bills in the U.S. These studies evaluated only the direct energy impacts of cool roofs but not their emissions and atmospheric effects that can be quite significant.

Taha (1996,1997a) quantified the effects of urban-cooling measures such as increased albedo(amount of sunlight reflected off the surface) and forestation on local meteorology, emissions, and air quality. He showed that large-scale deployment of high-albedo materials in the South Coast Air Basin (Los Angeles) can reduce population-weighted exceedance exposure to ozone by up to 10% in August (relative to the National Ambient Air Quality Standard). While the effects of urban forestation were found to be roughly half of those of increased urban albedo, those studies demonstrated that caution should be exercised to introduce only species that are low emitters of biogenic VOC; otherwise, negative impacts on air quality may occur. These studies did not evaluate the effects or urban cooling on surface water budget or the global climate.

Regarding the potential larger-scale impacts of heat-island reduction, Akbari et al. (2009) estimated that the implementation of increased roof and pavement albedo (increased urban albedo by 0.1 on the average), would result in negative radiative forcing equivalent to offsetting 44Gt(gigatons) of CO_2 emissions globally. The study did not involve use of atmospheric models and did not account for feedback effects and interactions among the many processes in the atmosphere. Oleson et al. (2010) analyzed the potential global-cooling effects of urban albedo control to offset CO_2 using a global climate model. They found that averaged over urban areas globally, the annual mean heat island was decreased by 33%, the daily maximum urban temperature decreased by 0.6°C, and daily minimum temperature by 0.3°C. This study did not evaluate impacts on energy use, emissions, or on air quality.

At the micro scale, on the other hand, Takebayashi and Moriyama (2007) measured the heat-island mitigation potentials of reflective roofs and green surfaces in Japan. They observe a daytime surface-temperature decrease in the following order: cement concrete, highly reflective gray paint, bare soil, green surface (latent heat), and a highly reflective white paint. Thus the latter would be the most effective cooling measure at the local scale in that area. Scherba et al. (2011) and Sailor et al. (2011) conducted field studies to quantify the effects of heat-island control with reflective and green roofs. They found that if a black membrane roof is replaced with a PV(photo voltaic)-covered white or a PV-covered green roof the corresponding reduction in total sensible flux to the atmosphere is on the order of 50%. They also report that green roofs can result in heating-energy cost savings compared to conventional black membrane roofs and that white roofs can result in lower annual energy costs than green roofs. However, they also found that high vegetative-cover green roofs could outperform white roofs in six of eight buildings they studied.

Taha (2008b,c) updated and used an advanced, new-generation, fine-resolution meso-urban meteorological model to evaluate the effects of urbanization, heat islands, and their mitigation on urban meteorological conditions, including wind flow patterns, convective cloud enhancement, and sea-breeze and coastal circulations. He found that implementation of urban-forest and cool-material strategies in the greater Houston, Texas, area could cool the air most of the time, with a maximum effect of up to 3.5°C, but also warm it by up to 1.5°C under certain conditions. Over a period of 3 days in August (2000) in Houston, cooling-degree hours were decreased by 3°C.hr(celsius-hours) in a coastal, sparsely-urbanized area, and by up to 17°C.hr in an inland, more urbanized area (much larger decreases were also simulated but were not representative of the overall effect). Corresponding increases in heating degree-hours were smaller, ranging from 0.7°to 2°C.hr in these areas, respectively. In another modeling study, Taha (1997b) found that in urban-core areas, anthropogenic (waste) heat can create UHIs of up to 2°C. Thus control of heat emissions in dense urban cores can provide a significant amount of cooling.

Chen et al. (2010) developed and implemented new urban parameterizations within an advanced meteorological model to evaluate the impacts of urbanization on meteorology, environmental conditions, energy use, and air-quality. Building upon this modeling system, Carter et al. (2012) evaluated the effects of urban areas (and their parameterizations in meteorological models) on circulation and sea breeze properties in Houston, TX. They showed that the urban environment can exert a significant impact on the evolution and behavior of the sea-breeze boundary. They also showed that the sea breeze front can strengthen and accelerate as it comes into contact with the leading edge of the urban area. Accounting for such processes is important in evaluating emissions and transport of pollutants in the boundary layer and designing heat-island mitigation measures accordingly.

Hart and Sailor (2008) studied the effects of changes in land-use and surface characteristics on the magnitude of the UHI. For this purpose, they performed air temperature measurement traverses at 2 meters above ground in Portland, Oregon, during summertime afternoons to capture the daytime heat-island effects. Based on CART(classification and regression tree) analysis, they found that the most important factor affecting intra-urban air temperature variations was vegetative-canopy cover. Roadway density was another factor contributing to locally-elevated temperatures because of increased anthropogenic heat emissions from areas with extensive street and highway cover.

Recent modeling studies (Taha 2008b,2012) further evaluated the meteorological and air-quality impacts of urban cooling beyond the limited episodic time scales that are typically analyzed in such applications. The multi-year, multi-seasonal, and multi-episodic simulations show that urban cooling has a dominant positive effect on air-quality (reduction in ozone) with negative impacts (increases in ozone) occurring less frequently and affecting smaller areas. Taha (2012) evaluated the emission-reduction equivalence of heat-island mitigation accounting for the effects of interactions among airsheds where such measures are implemented. He found that the changes in ozone concentrations brought about by urban-cooling measures are equivalent to emissions reductions of 60 to 180 tons per day (TPD) of anthropogenic ROG(reactive organic gasses) in central California (corresponding to 3% to 9% of the anthropogenic ROG inventory) across a range of seasons. For southern California, the equivalent emissions reductions range from 50 to 75 TPD of anthropogenic ROG (5% to 9%) across a number of seasons in that region.

Other efforts were undertaken with a goal of evaluating the global-climate effects of implementing heat-island control measures. Millstein and Menon (2011) investigated the various feedbacks among changes in surface albedo, temperature, precipitation, and cloud cover. They found that cool roofs and pavements, if deployed globally, increase annual average outgoing radiation by 0.16 ± 0.03 $W\ m^{-2}$(watts per meter squared) and decrease afternoon summertime urban temperature by 0.11–0.53°C. They also found that some urban areas showed no statistically significant temperature changes and that some rural areas experienced an increase in summer afternoon temperatures by up to + 0.27°C because of reduced cloud cover. Jacobson and TenHoeve (2011) also evaluated the atmospheric and environmental effects of global deployment of high urban albedo and found that while urban areas did indeed cool down, the global temperature rose because of the aforementioned cloud-cover and precipitation feedback effects. These studies did not account for the effects of urban cooling on energy use, emissions of GHG(green house gasses) and ozone precursors, air quality, or the changes in radiative forcing resulting from smaller ozone concentrations. Georgescu et al. (2012) evaluated the effects of heat-island mitigation in summer in Arizona and found that urban cooling reduces precipitation by 4% in the Phoenix region. Thus it is important to consider these potential negative impacts of heat island mitigation when designing local strategies for urban cooling, emissions reductions, and energy efficiency.

Recent efforts were also undertaken to increase the spatial resolutions and accuracy in modeling the potential impacts of urban cooling (e.g., Taha 2008b,c) and to improve the representations / parameterizations of urban areas in atmospheric models, e.g., Carter et al. (2012), Martilli et al. (2002), DuPont et al. (2004), and Taha (2008c). Such efforts are important in better characterizing the boundary-layer's dynamics, physics, and chemistry and their changes in response to UHI mitigation. Santamouris (2012) evaluated the benefits of urban-cooling measures, including reflective and green roofs, on heat islands and performed a comprehensive review of many studies on this subject matter.

While the foregoing overview is by no means comprehensive, it does highlight various aspects of UHI mitigation and the complex interactions and feedbacks that can be expected from deployment of urban-cooling measures. And while most of the studies discussed do address more than one process or mechanism of interest, no study to date has been carried out to holistically and completely evaluate all pathways, processes, interactions / feedbacks, and positive and negative effects in a simultaneous, comprehensive manner. Such multi-scale, multi-dimensional studies are currently being devised.

Regulatory aspects

Strategies of urban cooling and mitigation of heat islands have garnered the interest of policy-makers nationally and internationally. In California, for example, Assembly Bill 32 (Global Warming Solutions Act of 2006), identifies "Cool Communities" as a "Voluntary Early Action" program. "Cool Communities" is a term given to heat-island mitigation measures including cool roofs, cool pavements, and urban forests. SB 375 is another set of rules that can encourage implementation of cool-communities measures. In the California energy code, Title 24 Building Energy Efficiency Standard, "Cool Roofs" have been included in the requirements for implementation. Another rule, AB 296 (Cool Pavements), requires the California Environmental Protection Agency (CalEPA) to develop an urban heat-island index and standard specification for sustainable and cool pavements. In addition to these examples of specific rules, urban heat-island mitigation has also been considered, directly or indirectly, as possible voluntary control measures in clean-air plans formulated by air districts. In Texas, the Cool Houston initiative by the Houston Advanced Research Center (HARC) provides citizens with guidelines and recommendations for implementing urban-cooling measures.

Nationally and internationally, urban heat-island mitigation is also considered in building design guidelines such as LEED (Leadership in Energy and Environmental Design). Both cool roofs and green roofs are listed and LEED Version 3 provides credits for cool roofs. In Canada, the City of Toronto adopted a bylaw in 2009 requiring installation of green roofs in new construction with gross floor areas greater than 2000 m^2(meters squared). The green-roof cover increases above 20% as total floor area increases. In Germany, the Federal Nature Conservation Act governs the conservation of green spaces and natural environment in urban areas. The Act dictates that such areas not be modified nor their land uses changed. In Tokyo, regulations enacted in 2001 require all new, large commercial buildings to implement a minimum of 20% of greenery to compensate for loss of urban trees and to mitigate heat islands.

Urban cooling measures and impacts

Some UHI-mitigation (urban-cooling) measures that can be implemented in standalone manner or in combination with each other are listed in Table 1.

For the purpose of Table 1, we define **direct effects** as the direct impacts on heat flow through building envelopes, thus reduced cooling demand and reduced or avoided emissions from power generation (e.g., point-source emissions). On the other hand, the **indirect effects** are those of reduced ambient temperatures, thus reduced cooling energy use and reduced point-source as well as temperature-dependent area-source emissions (e.g., fugitive emissions, biogenic emissions). The indirect effects can be larger than the direct ones, depending on conditions and climate.

It is to be noted that urban-cooling measures would be equally effective (e.g., at reducing air temperature) whether or not a UHI exists. In others words, most urban areas can benefit from such measures regardless of whether or not they experience any heat-island effects. Another aspect to reiterate is that urban-cooling measures can cause both positive and negative effects, as can be the case with some other environmental control strategies. While the positive effects of urban cooling include reduced cooling demand, reduced GHG and ozone-precursor emissions from power generation, reduced mobile-source and area-source anthropogenic and biogenic emissions, improved air quality, reduced local impacts of heat waves, and improved thermal environmental conditions, the negative effects can include reduced mixing and pollutant transport, weaker urban

Table 1. Examples of urban-cooling measures.

		Direct effect	Indirect effect
Surface albedo increase	Roofs	■	■
	Walls	■	■
	Streets / highways		■
	Pavements		■
Conversion of impervious into pervious	Pavements / Streets		■
Control of anthropogenic / waste heat	Buildings / motor vehicles		■
Vegetation species for cooling	Buildings	■	■
	Parking lots		■
	Streets		■
Vegetation species for shading	Buildings	■	■
	Parking lots		■
	Streets		■
Solar photovoltaic and thermal		■	■
Green roofs and green walls		■	■

or sea breezes, and reduced urban-enhanced cloudiness and precipitation. Some of these positive and negative effects were discussed in the foregoing overview ("Mitigation of urban heat islands").

Thus, region- and city-specificity in designing urban-cooling measures is imperative for maximizing the positive effects and minimizing negative ones. For example, a modeling study (Taha 2008b) hinted at the existence of "thresholds" for maximum attainable benefits from urban cooling in different regions. The simulations show that increased control on UHI, i.e., larger urban cooling, can be effective in improving ozone air quality up to a certain level (i.e., a certain cooling threshold), past which, the net decrease in ozone becomes smaller. As seen in Figure 2, increasing control on UHI in Los Angeles causes urban cooling in the following order (from smaller to larger cooling): moderate increase in urban forest (01), high increase in urban forest (02), moderate increase in urban albedo (10), high increase in urban albedo (20), and a combination of simultaneous high increases in urban albedo and forest (22). While scenario 01 causes an average daytime cooling of 0.5ºC, case 22 causes an average decrease of 2 C (with maximum daytime cooling of between 3 and 3.75ºC).

Taha (2008b) shows that the corresponding air quality impacts (improvements) increase from case 01 through 11, peak at case 20, and become smaller at case 22. At case 20, the reductions in ozone concentrations averaged over the Los Angeles area are 5 ppbv in daily 1-hour maximum and 3 ppbv in the daily 8-hour maximum – significant reductions. However, despite the larger cooling in case 22, the corresponding reductions in the daily 1-hour and 8-hour ozone maximums are smaller, i.e., 2 and 1 ppbv, respectively. The simulations suggest a cooling threshold in the Los Angeles area (corresponding to scenario 20 in this case) for the modeled meteorological conditions, beyond

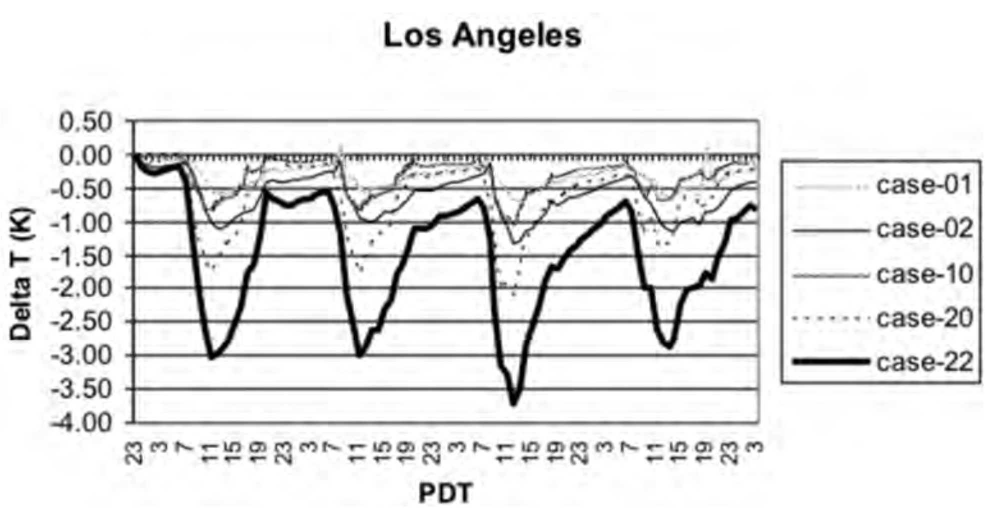

Figure 2. Changes in 2-m air temperature as a result of deploying urban-cooling measures in Los Angeles, 3-6 August (source: Taha 2008b, Boundary-Layer Meteorology). Cases 01 through 22 are defined in the text.

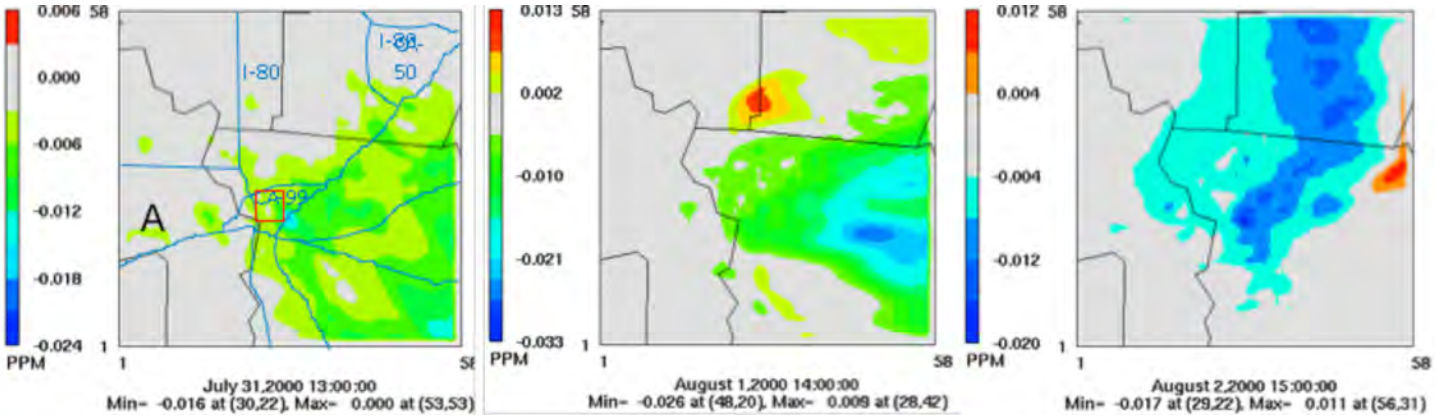

Figure 3. Horizontal cross-sections of changes in ozone concentrations (ppmv) in the Sacramento, California, region, on 31 July and 1, 2 August (at the given times of largest reductions) as a result of urban-albedo increase (source: Taha 2008a, Atmospheric Environment). Green and blue show areas with decreased concentrations, whereas red shows areas of increased ozone. The small red square inset delineates downtown Sacramento.

which the net decreases in ozone become smaller even though the cooling becomes larger. The smaller net reductions in ozone concentrations are caused by the now relatively more dominant effects of reduced boundary-layer height, decreased vertical and horizontal mixing such as turbulence and convection, and reduced cloud cover (larger incoming solar radiation) in some cases. However, these effects are complex and vary significantly depending on meteorological conditions and emission profiles and, in some cases, reduced mixing can result in lower ozone concentrations as well. In other words, the effects are highly dependent on weather conditions.

Other modeling studies (e.g., Taha 1996,1997a,2008a,c) showed that on daily and hourly scales, urban cooling can exert both negative and positive effects on ozone air quality. As seen in Figure 3, depicting changes in ozone concentrations in the Sacramento region resulting from urban cooling with increased albedo, there are large areas with decreased ozone concentrations but also some smaller areas with increased ozone (shown in red). These increases result from reduced mixing and increased temperatures that most often occur downwind of modified urban areas (Taha 2008a).

Thus in light of these potential interactions and feedbacks, both positive and negative, UHI mitigation strategies must be carefully tailored to locale-specific conditions in order to maximize the desired benefits (e.g., cooling, reduced energy use, and improved air quality) and minimize the adverse, unintentional effects (e.g., warming and increases in ozone). In other words, it is not possible to devise a "one-size-fits-all" approach to mitigating UHIs and implementing urban-cooling measures – they must be carefully designed for the specifics of each urban area including its geography, topography, meteorology, emissions profiles, energy use, morphological and geometrical properties, materials in use, land-use and land-cover characteristics, and technical potentials for deployment of control measures. The tradeoffs between the positive and negative impacts (some of which were discussed above) must be carefully taken into account when designing the deployments of these measures to maximize their benefits. All this must be done while also taking into careful consideration the potential impacts of deploying such measures on neighboring areas, downwind and surrounding regions, and the global climate.

Dr. Haider Taha is President of Altostratus Inc. in Martinez, California, since 2003. Prior to that, he was a Staff Scientist with the Lawrence Berkeley National Laboratory for 12 years. His research interest is urban and regional meteorological, emissions, and photochemical modeling for studying the interactions and feedbacks among climate, meteorology, energy use, pollutant emissions, and air quality. His earlier work led to the recognition of the potential for heat-island control measures to be considered in the air-quality regulatory environment. He is a member of the American Meteorological Society, American Geophysical Union, Urban Climate Change Research Network, and the International Association for Urban Climate.

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Remote Sensing and Identifying the Urban Heat Island from Space: An Overview

By Jeremy Sandifer, Graduate Assistant, and Keith Mountain, Chairman, Department of Geography and Geosciences University of Louisville

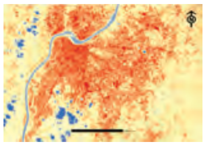
Figure 1. True color composite image (RGB, 321) captured by sensor-equipped aircraft for a section of the Ohio River (north) and central downtown of Louisville, Kentucky. Image taken in the spring of 2012 (Louisville/Jefferson County Information Consortium – LOJIC).

On October 4, 1957, the Soviet Union successfully launched Sputnik 1 into Earth orbit providing an unrestricted view of the Earth. By the early 1970's a network of satellites were passing in controlled orbit above the surface of the Earth and, importantly, with the launching of NASA's Landsat program in 1972, that included sensors capable of multispectral imaging which lead to the realization that the true details of the Earths' surface could be resolved with precision with space-borne sensors. Among the first applications was the implementation of the now familiar Global Positioning network (GPS), evaluation of the Earth's gravitational field, mapping mineral and global water resources, and soil types. Vegetation types could be distinguished including those sections diseased or damaged, and these, among many other quantities have become important to the understanding of our complex biophysical environment. Since this time, satellite data, coupled with the growing applications of Geographic Information Sciences (GIS) and enhanced image processing, has become a common if not ubiquitous tool for detailed analysis of the Earth's surface. Recently attention has been directed toward understanding mankind's role in the global climate system with much attention focused on the enhanced surface heating generated by urban development and expansion – the urban heat island (UHI).

The basis of remote sensing relies on relatively well established physics, in particular thermal radiate transfer. According to Plank's Law, all bodies (except objects below 0 Kelvin (-273.15 °C), emit radiation (energy). Curiously, this energy is emitted (or reflected) over all spectral limits (theoretically, zero to infinity), and for the most part, is considered to take the form of waves of infinitely varying amplitudes and wavelengths. This range of radiation is termed the electromagnetic spectrum and is typically expressed in units of microns (μm). Convention has it that this continuous wavelength emission is divisible into three broad spectral units: visible radiation (≈ 0.0-1.0 μm), the near infrared (NIR, ≈1.0 – 4.0 μm) and the infrared (IR) or longwave radiation (≈4.0 μm onward). However, as the amount of energy emitted is directly related to the temperature of the object, these waves fall within predictable limits (or spectral bands) and therefore, objects of different temperature can be distinguished from one another. Using this relationship, on-board sensors can be calibrated to "read" the wavelength pattern from emitting objects. This, in turn, enables us to connect the emission of a given body not only to its temperature but also to its physical properties (concrete, pavement, vegetation, etc). In this way it is possible to discriminate between the multiple and complex surface types that make up our biophysical environment. Obviously, given the diversity of natural and man-made objects, there is a need to classify or group features of like properties and this is standard procedure in the practice of remote sensing.

NASA's Landsat mission data is uniquely adaptable for ecological studies within the urban environment. The archive of data stretches back to the 1970's and gives researchers an uninterrupted record of changes to the Earth's surface and is freely available. Additionally, the Landsat mission has a scene repeat every 14 days. This allows for high temporal resolution of evolving conditions on the surface and, with a spatial resolution of 15 – 30 meters, has proven sufficient for investigating multiple issues of environmental concern, in particular, the urban heat island intensity.

We illustrate the utility of remote sensing for characterizing the urban environment using a series of images of the Louisville, Kentucky, Metropolitan Area. Figure 1 is an example of a true color composite image made up of visible radiation as recorded by a sensor set on board an aircraft (a flight altitude typically of around 25,000 feet above sea level). In this image, the blue, green and red wavelength (RGB) regions of the electromagnetic spectrum (0.450μm – 0.680 μm) are evident. The sensor works by recording the radiance, or brightness, of the solar energy reflected from the surface of the Earth (in the visible band), discriminates



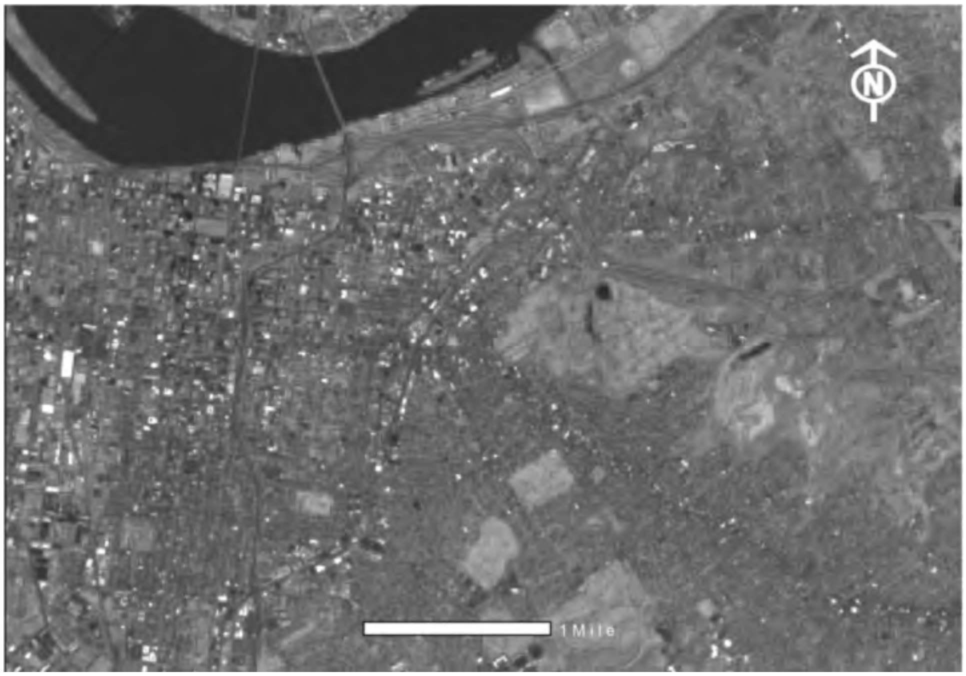


Figure 2. Single band composite image depicting near-infrared (NIR) reflectance as captured by Landsat 8's Observational Land Imaging (OLI) sensor. Lighter areas indicate high relative reflectance values in opposition to the darker areas that absorb greater amounts of energy.

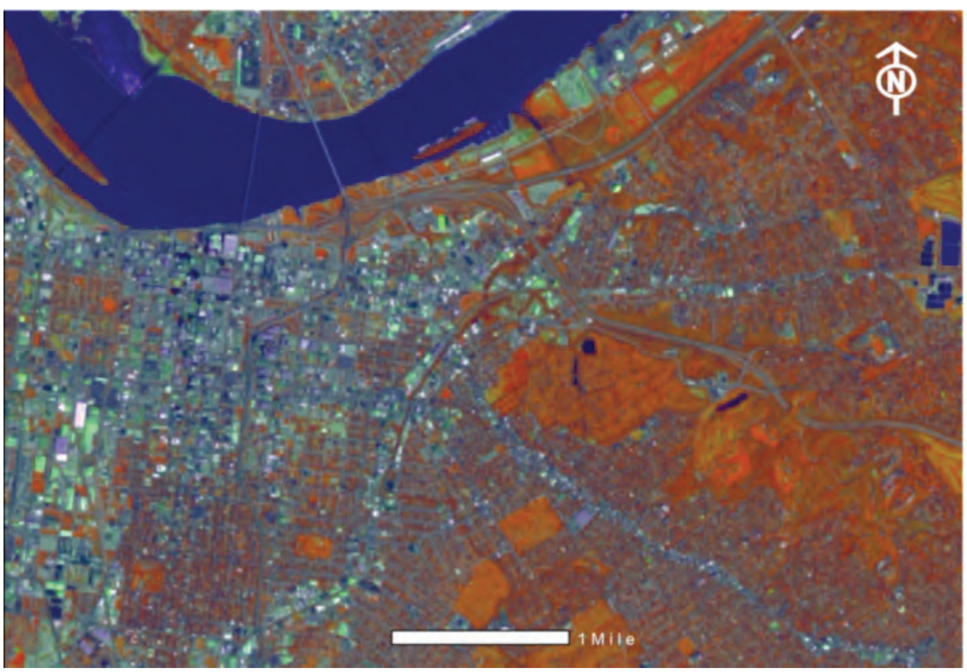


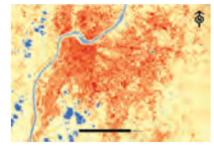
Figure 3. Landsat 8 Observational Land Imaging (OLI) false color composite image (RGB, 753). This highlights groups or classes of objects within the urban environment of Louisville that have similar thermal and radiative properties (i.e. local spectral homogeneity).

between the individual color bands, and stores this data as a digital number (DN) for each specific bandwidth range.

Figure 2 is comprised of a bandwidth (spectral) range representing the near-infrared (NIR) portion of the electromagnetic spectrum captured by NASA's Observational Land Imaging (OLI) sensor aboard Landsat 8, launched in February of 2013. The Ohio River and other water bodies are almost completely black, indicating that NIR energy (0.845 µm – 0.885 µm) is absorbed instead of reflected, as opposed to the lighter shaded areas of vegetation that are highly reflective of energy at this wavelength. Surface materials such as concrete and asphalt, or trees and grass are easily differentiated based on how they absorb and reflect energy in the NIR wavelength band. However it is possible for multiple material types to share a common spectral signature in this NIR band. These data are used to classify and quantify the land cover present on the surface and to calculate the effect it has on the temperature distribution of the urban heat island.

Land cover characteristics can be further discriminated using the reflectance values detected in multiple bandwidths. Image classification algorithms take advantage of the distinct differences in reflectance values for each bandwidth when classifying each image pixel into classes of homogenous spectral signatures. Figure 3 illustrates this concept. We note that if the reflected wavelength range lies beyond the visible spectrum there is in effect no color, just detectable shades of gray. In this case it is possible to assign different colors to the various wavelength bands to highlight reflectance differences hence the term "false color" image. In figure 3 red has been assigned to short-wave infrared, green to near-infrared, and blue to green visible energy. This technique makes vegetation appear in orange and red hues, while urban development appears in gray and blue hues. This makes for a straightforward differentiation of surface types and can be correlated to temperature.

Landsat 8's Thermal Infrared Sensor (TIRS) is designed to detect the energy



emitted from the surface of the Earth, which varies in intensity based on the material composition of the local surface. This sensor is designed to isolate only that infrared radiation that exists at approximately the 10.6 and 12.51 μm wavelengths. These particular bands are comprised of radiation that passes upward from the Earths' surface with little modification or depletion by the gasses of the Earth's atmosphere (sometimes called the atmospheric window). Recall that any material with an internal temperature greater than absolute zero emits radiation with a specific intensity and spectral composition unique to the physical composition and internal temperature of the object itself. The dark red areas given in Figure 4 indicate the more intense emissions of long-wave thermal infrared energy from the surface, typically associated with heavily developed urban land cover. These areas appear in the darker shades of red and orange in the image and indicate enhanced absorption and subsequent re-radiation of energy (i.e. surfaces of higher temperature).

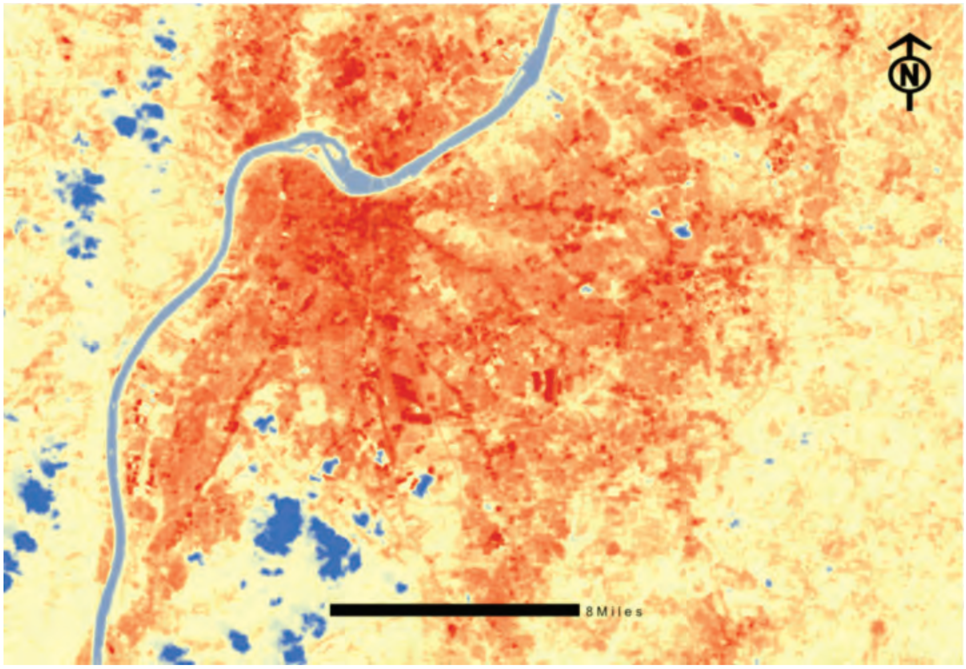


Figure 4. Landsat 8's Thermal Infrared Sensor (TIRS) detects energy emitted in the infrared band as a result of surface heating. The dark red areas indicate the highest surface temperatures and are associated with greater concentrations of urban development. In this false color image the blue areas are clouds which are cooler than the surface and, therefore, radiate less energy in the IR spectrum. This image of the greater Louisville Metropolitan area was recovered on June 6, 2013.

NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) is designed to detect energy from the Earth in 36 bandwidths covering the electromagnetic spectrum from 0.40 μm to 14.4 μm. However, unlike the high resolution Landsat sensors, the MODIS has a spatial resolution of 1000 meters which has a significant advantage in the study of environmental and thermal conditions among larger and more expansive regions of the Earth's surface. This sensor records the entire globe every one to two days, allowing researchers to monitor surface changes on a day-to-day basis. Figure 5 is a scene captured by MODIS on July 16th at 11:00am over central Kentucky and illustrates the differences in surface temperatures that exist between areas of urban development versus more rural areas. Not only do large city centers experience this effect, but so do areas of development common along interstate highways exhibit an effect similar to the urban heat island.

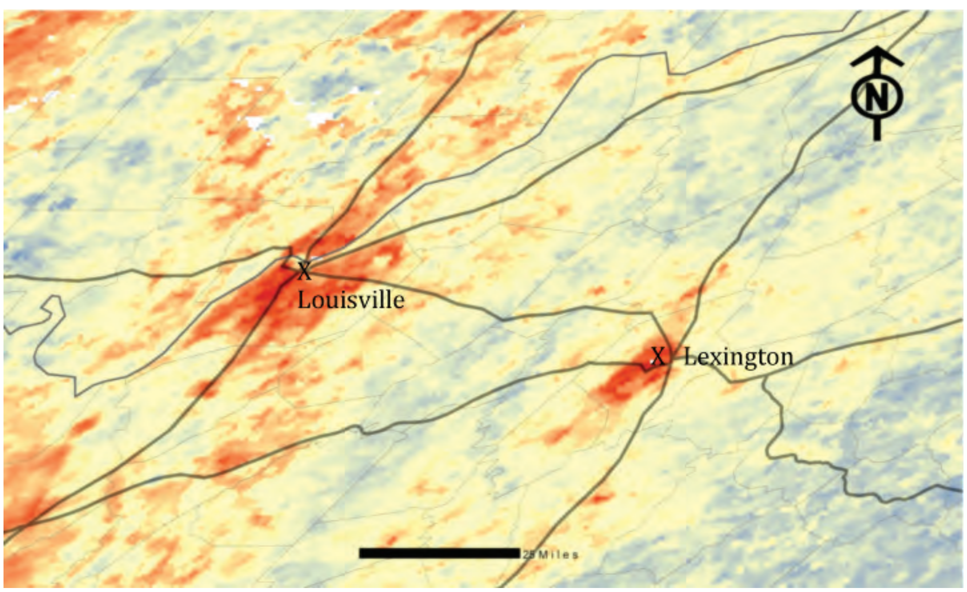
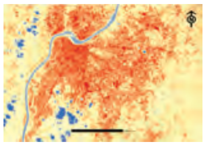


Figure 5. NASA's Moderate Resolution Spectroradiometer (MODIS) sensor mounted on board the Terra Satellite is capable of detecting variations in surface temperatures over large areas. This image of central Kentucky delineates the higher temperatures observed in two primary urban centers relative to the surrounding rural land. Image captured on July 16th, 2013, at 11:00 a.m.

The capability of remote sensing platforms to recover environmental data has greatly enhanced our understanding



of global biophysical systems. With the inclusion of Geographic Information Systems (GIS) serving as a framework for assembling and over-laying satellite data on other geospatial data (Census data, geologic and other physical data, for example) the complexities, interactions and relationships between human and natural systems can be made clearer. Understanding the geographic distribution of the UHI is useful, but when examined alongside the demographics and land-use regulations of an area, a much clearer understanding emerges about the underlying causes and effects of the UHI phenomena.

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The Basics of Cool Roofs: A Platform for Sustainability

By Kurt Shickman
Executive Director
Global Cool Cities Alliance

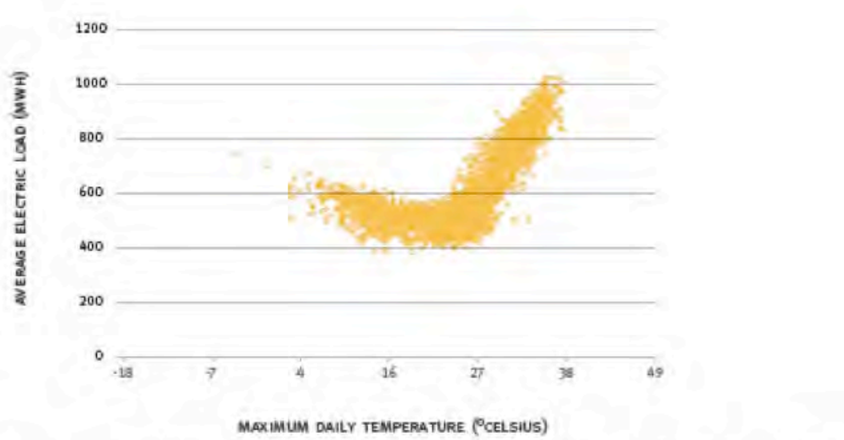
Urban temperature trends impact sustainability in almost every way we define the word. Higher temperatures adversely affect our health, our energy consumption, and our environment. Rapidly increasing temperatures stress eco-systems, increase the frequency and duration of heat waves and exacerbate air pollution. Together, these factors are creating serious health risks to people around the world. In addition, increasing wealth in the developing world is spurring the rapid deployment of air conditioners that are taxing electrical grids with their energy demands. On the bright side, mitigating urban heat is often a cost-effective proposition that has a myriad of benefits across the urban landscape.

World temperatures are rising at an unprecedented rate. According to the Intergovernmental Panel on Climate Change, the Earth's average temperature is on track to increase by between 2 and 7 degrees Celsius (4 to 13 degrees Fahrenheit) this century. This dramatic change in temperature will produce a climate never before experienced by human civilization. The trend is even direr in cities: temperatures in urban spaces are climbing at about twice the rate of average global temperature rise.

Cities are often significantly warmer than the surrounding landscapes because urban surfaces absorb more sunlight than natural landscapes, cities lack vegetation, which cools landscapes by evaporating water and providing shade, and urban areas release more heat from human activity including air conditioning, vehicles, and industry. The difference between outside air temperatures in a city and its surrounding rural areas can be 5 to 9 degrees Celsius (9 to 16 degrees Fahrenheit) or more in summer months.[1] This phenomenon is called the summer "urban heat island effect" or UHI. Cities with UHI are not only hotter during the day, but also don't cool off at night. Addressing this heating effect will only become more important because the world is rapidly urbanizing—within 50 years an estimated 80 percent of the world's population will live in an urban area.[2]

Studies of a city's "urban fabric" indicate that about 60 percent of urban surfaces are covered by roofs or pavements. About 20 to 25 percent are roofs and 30 to 45 percent are pavements.[3] Because these surfaces are dark and typically absorb over 80 percent of sunlight that contacts them and convert that solar energy into heat, our built environment exacerbates the warming effects of climate change. Replacing and upgrading roofs and pavements with more reflective materials could reverse this warming, turning urban surfaces into assets instead of burdens.

An important aspect of the impact of excess heat is that its affects on energy use and air quality are not linear. In both cases, conditions rapidly deteriorate once temperatures reach a certain level, creating a classic "hockey stick" pattern. The threshold temperature is established by a number of variables, but the basic pattern is the same across cities where space cooling is standard. Thus, even a small amount of cooling from UHI mitigation activity can pay large benefits during periods above the threshold temperature. Figure 1 shows this pattern in energy use in New Orleans, where the demand (and cost) of electricity rises significantly for each degree over approximately 75 degrees Fahrenheit. Figure 2 shows a similar trend in air pollution near Baltimore, measured in the number of 8 hour periods that have ozone concentrations above the EPA compliance level. There are almost no 8-hour periods out of compliance under 80 degrees Fahrenheit. When the temperature is only 10 degrees warmer, however, nearly every 8-hour period is out of compliance.



Adapted from Sailor, D. J. 2002. Urban Heat Islands, Opportunities and Challenges for Mitigation and Adaptation. Sample Electric Load Data for New Orleans, LA (NOPSI, 1995). North American Urban Heat Island Summit. Toronto, Canada. 1–4 May 2002. Data courtesy Entergy Corporation.

Figure 1.

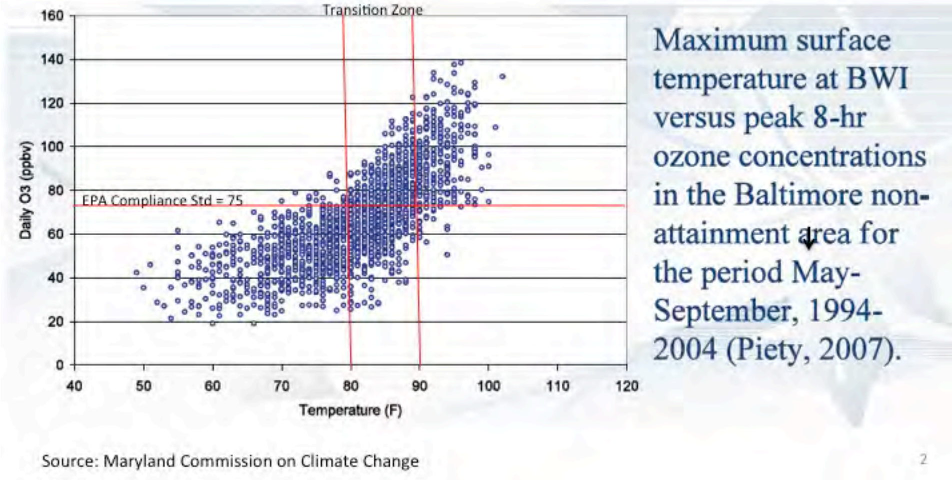


Figure 2.

Most roofs are dark and reflect no more than 20 percent of incoming sunlight (i.e., these surfaces have a reflectance of 0.2 or less); while a new white roof reflects about 70 to 80 percent of sunlight (i.e., these surfaces have a reflectance of 0.7 to 0.8). New white roofs are typically 28 to 36 degrees Celsius (50 to 65 degrees Fahrenheit) cooler than dark roofs in afternoon sunshine while aged white roofs are typically 20 to 28 degrees Celsius (35 to 50 degrees Fahrenheit) cooler.[4] Figure 3 demonstrates this effect on two identical roofs. On a hot 99 degree Fahrenheit day, the white roof reflects more solar energy and stays much cooler than the identical black roof.

What are Cool Surfaces?

We can reduce many of our urban heat islands by transitioning from dark hot surfaces to cool lighter ones. But how do cool surfaces really work?

Cool surfaces are measured by how much light they reflect (solar reflectance or SR) and how efficiently they radiate heat (thermal emittance or TE). Solar reflectance is the fraction of sunlight (0 to 1, or 0 percent to 100 percent) that is reflected from a surface. SR typically ranges from about 0.04 (or 4 percent) for charcoal to 0.9 (or 90 percent) for fresh snow. High solar reflectance is the most important property of a cool surface.

Thermal emittance measures the efficiency (0 to 1) with which a surface emits thermal radiation. High thermal emittance helps a surface cool by radiating heat to its surroundings. Nearly all nonmetallic surfaces have high thermal emittance, usually between 0.80 and 0.95. Uncoated metal has low thermal emittance, which means it will stay warm. An uncoated metal surface that reflects as much sunlight as a white surface will stay warmer in the sun because it emits less thermal radiation. TE is the second most important property of a cool surface.

A cool roofing surface is both highly reflective and highly emissive to minimize the amount of light converted into heat and to maximize the amount of heat that is radiated away. Every opaque surface reflects some incoming sunlight and absorbs the rest, turning it into heat. The fraction of sunlight that a surface reflects is called solar reflectance or albedo. White roofs reflect more sunlight than dark roofs, turning less of the sun's energy into heat. Increasing the reflectance of our buildings and paved surfaces—whether through white surfaces or reflective colored surfaces—can reduce the temperature of buildings, cities, and even the entire planet.

Rating Products

Determining both the initial and aged solar reflectance of a given material or roofing product requires testing procedures and infrastructure. In the U.S., the Cool Roof Rating Council (CRRC) has been established as an independent, non-profit organization that maintains a third-party rating program, which rates and publishes a roof product's solar reflectance and thermal emittance. The CRRC allows standardized test methods as agreed to under the American Society for Testing and Materials (ASTM). Once a product is rated the results are published on CRRC's online Rated Products Directory and given a label with the results (see sample below). Manufacturers are encouraged to list their roofing products in the CRRC Rated Product Directory; in order to do so, they must follow the CRRC Product Rating Program Manual (CRRC-1) testing method. Since all roofing products can be rated by CRRC, consumers and builders should use the CRRC label to identify which roof products meet their purchasing objectives (e.g., qualifying for ENERGY STAR certification, meeting building code requirements, and/or qualifying for utility rebates). All products that have been tested by the CRRC are listed in their online directory, which can be found at coolroofs.org/products/

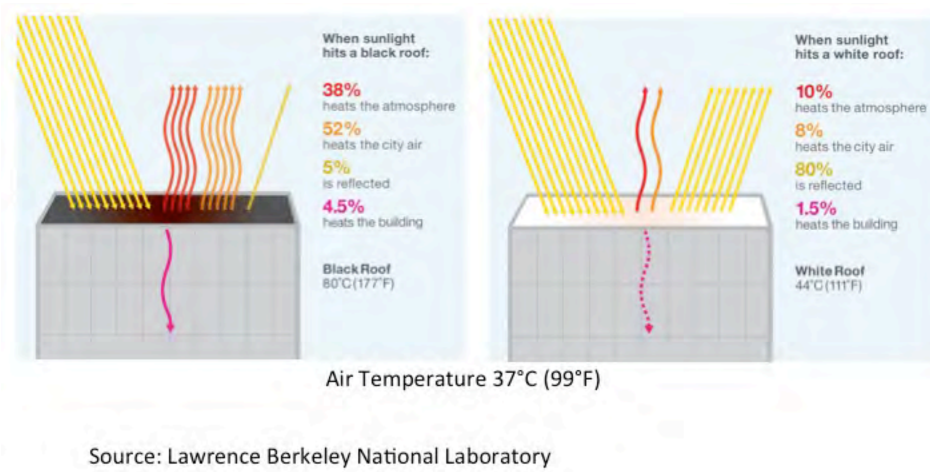


Figure 3.

Common Roofing Materials and Cool Options*

Roof Type	Life Expectancy (years)	Roof Slope	Non-Cool Roof Options	Non-Cool Roof Solar Reflectance	Cool Roof Options	Cool Roof Solar Reflectance
Asphalt Shingle	15 to 30	steep-sloped	black or dark brown with conventional pigments	0.05–0.15	"white" (actually light gray) or cool color shingle	0.25
Built-Up Roof	10 to 30	low-sloped	with dark gravel	0.10–0.15	with white gravel	0.30–0.50
			with aluminum coating**	0.25–0.60	white smooth coating	0.75–0.85
Clay Tile	50+	steep-sloped	dark color with conventional pigments	0.20	terracotta (unglazed red tile)	0.40
					color with cool pigments	0.40–0.60
					white	0.70
Concrete Tile	30 to 50+	steep-sloped	dark color with conventional pigments	0.05–0.35	color with cool pigments	0.30–0.50
					white	0.70
Liquid Applied Coating	5 to 20	low- or steep-sloped	smooth black	0.05	smooth white	0.70–0.85
Metal Roof Uncoated corrugated metal is typically less durable than coated metal	20 to 50+	low- or steep-sloped	unpainted, corrugated**	0.30–0.50	white painted	0.55–0.70
			dark-painted corrugated	0.05–0.10	color with cool pigments	0.40–0.70
Modified Bitumen	10 to 30	low-sloped	with mineral surface capsheet (SBS, APP)	0.10–0.20	white coating over a mineral surface (SBS, APP)	0.60–0.75
Single-Ply Membrane	10 to 20	low-sloped	black (polyvinyl chloride (PVC) or ethylene propylene diene monomer rubber [EPDM])	0.05	white (PVC or EPDM)	0.70–0.80
					color with cool pigments	0.40–0.60
Wood Shake	15 to 30	steep-sloped	painted dark color with conventional pigments	0.35–0.50	bare	0.40–0.55

Source: Adapted from coolcalifornia.org roofing options table. Photos: Creative Commons and LBNL

* Spray polyurethane foam is not included in this chart because it is typically coated by a reflective liquid applied coating to minimize ultraviolet damage to the foam. ** Aluminum and metal have high solar reflectance but their low thermal emittances reduces their ability to stay cool.

24 25

Figure 4.

search.php. A product's inclusion in the Directory does not mean that the product is "cool" as defined by any particular code body or program.

Cool Roof Choices

The cool roof options available to a building owner depend in large part on the building and roof type they are working with. That said, there is a cool option for nearly every type of roof. Figure 4 lists some of the many roof types and the materials that can make them cool. Cool roofs are relatively easy to implement for commercial buildings. The roofs of most commercial and high-rise residential buildings are low-sloped (i.e., almost flat), and are generally not visible from the street. As a consequence, there is little resistance or cost to changing the color of these roofs during routine retrofits or when waterproofing.

Residential buildings often have steep-sloped roofs that can be seen from the ground. In many parts of the world, white is not currently a popular color for residential roofs, and as a result there can be aesthetic concerns about using white materials. To address this, roofing manufacturers have developed "cool" materials in popular roof colors (e.g., red and gray) that strongly reflect the invisible heat component of sunlight and much of the sun's energy away from the building. White is the "coolest" color, but there are cool versions of a wide variety of popular colors. Highly reflective roofs can come in popular colors such as red, green, and gray. Cool colored materials are available for all types of steep-sloped (pitched) and low-sloped (nearly horizontal) roofs. These materials include asphalt shingles, metal, clay tiles, and concrete tiles. Highly reflective colored roofs typically have an initial solar reflectance 0.30 to 0.55, compared with around 0.10 for conventional dark steep-sloped roofs.

The desirability of cool roofs depends on latitude, altitude, annual heating load, annual cooling load, peak energy demands, and sun blockage by trees, buildings, and hills for the particular building. Cool roofs on buildings in some far northern communities such as Anchorage, Alaska or in forested mountainous areas such as at Lake Tahoe, Nevada, may not be appropriate. That said,

whether or not a cool roof is appropriate in any climate depends on the building, its energy usage pattern, existing needs, and costs.

What happens as the surface ages? Over time, white roofs get dirty; they collect soot, dust, salt, and, in some climates, biological growth. As a result, their reflectance decreases. The aged solar reflectance of a white roof is typically 0.55 to 0.65, or an approximately 25% reduction from the reflectivity of a new surface. Research indicates that degradation due to aging does not get any worse after 3 years in the field. Replacing a dark roof with an aged white roof still reduces the amount of sunlight absorbed by around 40 to 50 percent. Codes and standards typically use the aged SR value of white roofs.

The reflectivity of pavements also changes as they age. Concrete pavement tends to be initially more reflective and get darker with age and use. Dark asphalt pavement tends to lighten to a gray color over time. Despite this convergence in reflectivity, concrete typically remains more reflective than asphalt pavements.

Winter Heating Penalty

In some cases in cooler climates, cool roofs may increase the winter heating requirements for buildings but rarely does the increase in heating energy and cost outweigh the savings. A study by Lawrence Berkeley National Lab found net energy cost savings throughout the U.S., including in the upper Midwest and Northeast.[5] Indeed, billions of square feet of cool roofs have been installed on buildings in cool climates. A number of factors help to minimize the so-called “winter heating penalty” in most cases. The sun is generally at a lower angle in winter months than it is in summer months, which means that the sun has a reduced impact on roof conditions during the winter. In some areas, snow cover makes the underlying roof color irrelevant. Finally, heating loads and expenditures are typically more pronounced in evenings, (especially in residential buildings) but the benefit of a darker roof in winter is mostly realized during daylight hours. The winter heating penalty occurs in most temperate areas, but in almost every case it is less than the cooling energy savings. Even some northern climates experience high peak temperatures in the summer and are therefore potentially good candidates for cool roofs.

Vegetated roofs, permeable pavements, and shade trees are other cooling strategies that are complementary with cool roofs. Vegetated surfaces cool through the process of evapotranspiration or, in some cases, by providing shade. Evapotranspiration contributes to cooler temperatures but can increase dew point temperatures, making the air more humid.

Why Install Cool Surfaces?

When a cool surface is installed on a building, it can convey benefits at the building level, to the community surrounding it, and to the planet as a whole.

Benefits to Individual Buildings

Energy savings potential: Increasing the reflectance of a roof from 0.1-0.2 to 0.6 can cut net annual cooling energy use by 10 to 20 percent on the floor of the building immediately beneath the roof by reducing the need for air conditioning.[6]

Cost savings potential: Adding cost-effective cool roofs to 80 percent of the 2.6 billion square meters of commercial building roof area in the U.S. would yield net annual energy cost savings (cooling energy savings minus heating energy penalty) of $735 million, and offer an annual CO_2 reduction of 6.2 million tonnes. In addition, cool coatings are treated as a maintenance product for tax purposes and are allowed to be written off in the year they are installed, rather than capitalized over 39 years like traditional roof materials.

Improved roof and equipment life: Extreme changes in surface temperature can damage roofs and the expensive equipment on them. Cool roofs reduce temperature fluctuations and will likely lengthen the life of roof equipment and material. Extending roof life also helps reduce waste going to landfills. A cooler roof is also likely to improve the efficiency of solar PV panels.

Short payback period: If the roof needs to be replaced anyway, choosing a white colored material often costs the same as a dark colored alternative. Further, installing a cool roof is a retrofit that does not inconvenience the building occupants. The average annual energy cost saving (cooling energy saving minus heating energy penalty) for a white roof on a commercial building is $0.36 per square meter ($0.033 per square foot).[7] Figure 5 shows price comparisons of cool and dark roofs for a wide variety of roof types.

Improved thermal comfort: In a building that is not air conditioned, replacing a dark roof with a white roof can cool the top floor of the building by several degrees, enough to make these living spaces noticeably more comfortable.[8] In structures lacking insulation, the temperature difference can be even more pronounced. These temperature reductions are enough to save lives in extreme heat waves and make non-conditioned work environments like barns and warehouses more usable and comfortable for employees. Cool roofs in rapidly developing countries can help slow the skyrocketing rate of new air conditioning unit sales. The demand for new space cooling is causing significant challenges for electric grid operators in India, China, and elsewhere.

City-wide Benefits

Reduced summer heat island effect: Simulations run for several cities in the U.S. have shown that city-wide installations of highly reflective roofs and pavements, along with planting shade trees will, on average, reduce a city’s ambient air temperature by 2 to 4 degrees Celsius (4 to 9 degrees Fahrenheit) in summer months.[9] Reducing urban temperatures makes cities

Price Premiums for Cool Roofs on New Roofs (Premiums are the extra cost of installing the cool alternative)

Roof Materials	Typical Non-Cool Surface	Cool Alternative	Price Premium (US$ per ft²)
Built-Up Roof	Mineral aggregate embedded in flood coat	Light-colored aggregate, like marble chips, gray stag	0.00
	Asphaltic emulsion	Field-applied coating on top of emulsion	0.80–1.50
	Mineral surfaced cap sheet	White mineral granules	0.50
Metal	Unpainted metal	May already be cool	0.00
		Factory-applied white paint	0.20
	Painted metal	Cool-colored paint	0.00–1.00+
Modified Bitumen	Mineral surface cap sheet	Factory-applied coating, white mineral granules	0.50
	Gravel surface in bitumen	Light colored gravel	0.00
	Metallic foil	May already be cool	0.00
		Field-applied coating	0.80–1.50
	Asphalt coating	Field-applied coating on top of asphaltic coating	0.80–1.50
Shingles	Mineral granules	White granules	0.00
		Cool-colored granules	0.35–0.75
Sprayed Polyurethane Foam	Liquid applied coating	Most coatings are already cool to protect the foam	0.00
	Aggregate	Light colored aggregate	0.00
Thermoplastic Membranes	White, colored, or dark surface	Choose a white or light colored surface	0.00
Thermoset Membranes	Dark membrane, not ballasted (adhered or mechanically attached)	Cool EPDM formulation	0.10–0.15
		Factory cool ply or coating on dark EPDM	0.50
Tiles	Non-reflective colors	Clay, slate (naturally cool)	0.00
		Cool colored coatings	0.00

Source: Adapted from DOE Guidelines for Selecting Cool Roofs.

Figure 5.

more comfortable and enjoyable to live in and promotes healthier populations.

Improved resistance to heat related deaths: Heat accounts for approximately 1 in 5 natural hazard deaths, or a little more than 1,500 deaths per year. Heat events are not just temperature related. They also involve humidity, wind speed, cloud cover, precipitation, and other factors that collectively are called "air masses." There are 9 main air mass types, and three of these are considered dangerous for human health. Air mass studies of actual multi-day heat events have found that increasing reflectivity can have a significant impact on expected mortality. For example, a study of three Philadelphia heat waves found that a 10% increase in reflectivity could have resulted in 15% fewer deaths.[10] Cool roofs can cool the areas in a building where the risk of death during heat waves is particularly high. For example, there were 739 deaths in the Chicago heat wave of 1995. Virtually all of the deaths occurred on the top floors of buildings with dark roofs.[11]

Reduced peak electricity demand: Cool roofs are of great value to utilities and grid operators in climate zones where summer brings peak electricity demand from air conditioning. They can improve utility capacity utilization and therefore profitability, reduce transmission line congestion, avoid congestion pricing, and forego the need for additional investments in peaking generation capacity. Approximately 5 to 10 percent of U.S. peak electricity demand for air conditioning is a result of the urban heat island effect.[12] Research indicates that peak electricity demand increases by 2 to 4 percent for every 0.5 degrees Celsius (1.8 degrees Fahrenheit) increase in temperature above a threshold of about 15 to 20 degrees Celsius.[13] Rosenfeld et al. (1996) estimated that eliminating the urban heat island effect in Los Angeles—a reduction of 3 degrees Celsius (5.4 degrees Fahrenheit)—could reduce peak power demand by 1.6 gigawatts (or three medium sized power plants) resulting in a savings of about $175 million per year (at 1996 electricity prices).[14] A small portion, approximately $15 million, of that amount was due to more reflective pavements. A 2004 analysis of New York City, when electricity averaged 16.5 cents per kWh, found that a one-degree reduction in temperature would cut energy costs by $82 million per year. Electricity prices have subsequently increased by over 20 percent.[15]

Air quality benefits: City-wide temperature reduction not only makes cities more comfortable, but also improves air quality because smog (ozone) forms more readily on hot days. Ozone pollution is a major contributing factor to respiratory illness, which the World Health Organization predicts will be the third leading cause of death by 2030.[16] Simulations of Los Angeles indicate that lighter surfaces and shade trees could cool temperatures and thus reduce smog in excess of EPA-defined safe concentrations by 10 percent.[17] Across the U.S., the potential energy and air quality savings resulting from increasing the solar reflectance of urban surfaces is estimated to be as high as $10 billion per year.[18]

New research identifies demographic and social justice aspects to urban heat.[19] The study finds that UHI affects the poorest, often minority communities within a city because those neighborhoods tend to have older, lower quality building stock,

Source: Google Earth

Figure 6. Google Earth image showing the concentration of greenhouses in the Almería region.

less vegetation, and a smaller percentage of space cooling. Further, many disease vectors already tied to poor communities are exacerbated in hot conditions. Thus, UHI mitigation strategies can be particularly beneficial in the most disadvantaged urban communities.

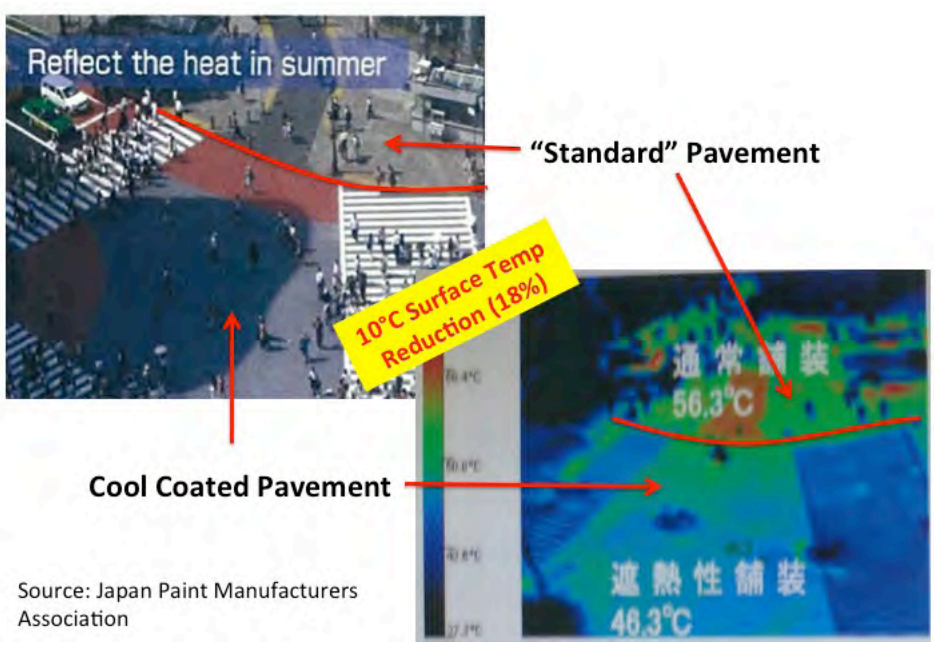
Benefits to the Planet

A growing body of research and peer-reviewed climate modeling indicates that raising the earth's reflectance could cancel the warming effect of greenhouse gases that are already in the atmosphere. This makes cool surfaces a critical first step in the strategy to mitigate and adapt to the impacts of a changing climate. Replacing the world's roofs and pavements with highly reflective materials could have a one-time cooling effect equivalent to removing 44 billion tonnes of CO_2 from the atmosphere, an amount roughly equal to one year of global man-made emissions.[20] Every 10 square meters (100 square feet) of white roofing will offset the climate warming effect of one tonne of CO_2. Assuming a 0.15 increase in reflectance is realized by switching to a lighter pavement option, cool pavements would "offset" approximately 0.5 tonnes of CO_2 per 10 square meters (100 square feet), or 300 tonnes of CO_2 per lane mile (1.6 kilometers) of highway. Assuming the average car emits 4 tonnes of CO_2 per year, the combined "offset" potential of replacing the world's roofs and pavements with highly reflective materials is equivalent to taking all of the world's approximately 600 million cars off the road for 20 years.

The greenhouses of Almería, Spain give us a good real world example of how regional and global cooling works. The semi-arid Almería region of southern Spain has the most dense concentration of greenhouses in the world. In preparation for the hot summer months, farmers whitewash the roofs of the greenhouses to help lower inside temperatures. Researchers studying weather station data and satellite imagery have found that the cumulative effect of the increased reflectivity has also cooled outside temperatures. Over the last 20 years, temperatures in the Almería region have fallen by 0.3 degrees Celsius, in contrast to a 0.5 degree Celsius increase in temperatures in surrounding regions that do not have highly reflective greenhouses.[21] (See Figure 6.) Pavements are a significant part of the urban fabric and can also contribute to reduced urban heat. Conventional paving materials can reach peak summertime temperatures of 50 to 65 degrees Celsius (120 to 150 degrees Fahrenheit) or more, heating the air above them.[22] Figure 7 shows the results of a cool pavement demonstration in Tokyo, where surface temperatures of the cool pavement were 10 degrees Celsius lower than on the traditional pavements.

There are many kinds of paving options that are lighter in color and create more reflective paved surfaces. Additionally, many kinds of permeable pavements, including reinforced grass pavements, can also cool a pavement surface through the evaporation of moisture stored in the pavement. If pavements are too bright, they can cause undesirable glare, but there are many shades of gray that are reflective that do not cause too much glare. There are a number of additional benefits to light colored pavements beyond cooling.

Improved durability: Testing and research are underway to evaluate the durability and longevity of cool pavement materials in a variety of usage conditions. Asphaltic pave-ments that stay at lower temperatures may be less likely to rut.



Source: Japan Paint Manufacturers Association

Figure 7.

Nighttime illumination: Parking lots and streets that use light colored pavements will allow for better visibility and safer streets at night and may also reduce the need for street lighting.

Improved water quality: Higher pavement temperatures can heat stormwater runoff that, in turn, can affect metabolism and reproduction of aquatic species. The U.S. Environmental Protection Agency classified elevated water temperature as a "pollutant of concern" in the Clean Water Act.

Cool Roof Policies

Many local, state, and national governments have adopted policies to accelerate the deployment of cool roofs to start reaping the benefits of cooler cities. One of the highest impact ways to support the rapid implementation of cool roofs and cool pavements is to include them in your region or city's building codes or pavement specifications. A few examples of cool roof codes are shown in Figure 8. That said, making changes to the codes could be a long and time-consuming process. California offers a great case study not only because of the robust cool roof standards that were enacted, but also because of the process used and the diversity of the climates covered by the new code. In 2005, California prescribed white surfaces for low-sloped commercial roofs as part of its Title 24 energy efficiency codes. In 2008, the state prescribed cool colored surfaces on steep roofed residential buildings in its five hottest climate zones. (California recognizes 16 climate zones in its energy and building codes.) Cool roof standards were the result of utility Pacific Gas and Electric working with technical experts at the Lawrence Berkeley National Laboratory to make a strong quantitative case for cool roofs across nearly all of California's diverse climate zones. New York City built on California's approach and developed an equally stringent code that reflected its many roof types and uses. Their code went into effect in January 2012.

Before codes or ordinances are adopted broadly, governments often choose to lead by example by incorporating cool surfaces into their own procurement policies and lease requirements. Governments are often major building owners or tenants, so cooler procurement may help spur market development. It can also build a database of energy savings and other benefits that

Building Codes and Standards

U.S. Code	Description	Cool Roof Requirement
ASHRAE 90.1	U.S. national, model code for commercial and high-rise residential buildings	Allows reduced roof insulation if a cool roof of SR >0.55 and TE >0.75, or SRI >64 is used. This allowance is permitted in climate zones 1–3 only. Several exclusions.
ASHRAE 90.2	U.S. national, model code for low-rise residential buildings	Allows reduced roof insulation if a cool roof of SR >0.65 and TE >0.75, or SRI >75 is used. This allowance is permitted in climate zones 1–3.
ASHRAE 189.1	Voluntary, "advanced," national model code for commercial and high-rise residential buildings.	Requires that 75% of the roof surface of a building and parking lot covering be a cool roof. The Standard defines a cool roof as having an SRI of 78 for low-sloped and 29 for steep-sloped roofs, or as a roof material that complies with ENERGY STAR.
California Title 24	Residential and non-residential energy efficiency standards. Cool roof requirements vary by region.	Low-sloped roofs: aged SR >0.55 and TE >0.75, or SRI >64 Steep-sloped, weight <5 lbs/ft^2: aged SR >0.20 and TE >0.75, or SRI >16 Steep-sloped, weight >5 lbs/ft^2: aged SR >0.15 and TE >0.75, or SRI >10
Chicago Energy Conservation Code		Low-sloped roofs: initial SR >0.65, aged SR >0.50, TE >0.90 Medium-sloped roofs: initial and aged SR >0.15, TE >0.90
Florida Building Code	The 2007 Code includes a credit for cool roofs in their performance-based requirements for residential buildings.	SR >0.7 TE >0.75
Hawaii	Prescriptive requirement for low-slope residential roofs that includes cool roofs as one of four ways to meet the standard.	SR >0.7 TE >0.75
IECC Chapter 5 (proposed 2012)	U.S. national, model code for commercial and high-rise residential buildings	Required for low-sloped roofs above air-conditioned space only in climate zones 1–3. Four ways to qualify: • aged SR >0.55, aged TE >0.75 • initial SR >0.7, initial TE >0.75 • aged SRI >64 • initial SRI >82 Exceptions are roof area that is shaded, covered by equipment, vegetated, or ballasted.
LEED Green Building Rating System	Leading voluntary green building standard in the U.S.	Cool roofs (for flat roofs with an SRI >78 and sloped roofs with an SRI >29) = 1 point Cool materials used on other impermeable surfaces = 1 point
New York City Local Law 21	Cool roof requirements for low-sloped roofs. Includes modifications for a variety of roof types and uses.	Initial SR >0.7 and TE >0.75, or SRI >78
U.S. EPA ENERGY STAR	ENERGY STAR is EPA's energy efficiency product label. It includes labels for roofing products.	Low-sloped roofs: initial SR >0.65, aged SR >0.50 Steep-sloped roofs: initial SR >0.25, aged SR >0.15
Washington D.C.	Building code for commercial and residential buildings.	Low-sloped roofs: SRI >78. Green roofs and other exceptions apply.

Source: CRRC and Akbari et. al. "Evolution of Cool Roof Standards in the U.S.", 2008

Figure 8.

A brief note on the types of codes

There are a variety of ways that cool roofs and pavements may be incorporated into building and energy codes. Below are descriptions of some common examples:

- **Mandatory measures** All buildings must comply with mandatory measures regardless of compliance path.
- **Prescriptive compliance** Compliance through prescriptive packages that vary with climate zones—no trade-offs allowed.
- **Performance compliance** Use an approved compliance software to demonstrate compliance for the entire building—allows trade-offs.
- **Compliance options** Measures that are not required prescriptively but can result in a compliance credit if installed, such as high Energy Efficiency Ratio (EER) air conditioning and buried ducts.

could be used by local authorities to justify new ordinances and codes for cool surfaces. For example, former U.S. Secretary of Energy Dr. Steven Chu directed all Department of Energy offices requiring a new or replacement roof to install cool roofs if they are cost effective over its lifetime.

Local governments also use a variety of incentives to encourage cool roof adoption.

Financial incentives typically take the form of rebates, tax incentives, or cooperative/volume purchasing. Rebates can be established by the local utility or government and are typically awarded on a per square meter or per square foot basis. In California, rebates were used before codes were enacted to encourage the installation of cool roofs. Once codes were enacted, the qualifications for the rebates were increased to encourage building owners to install roofs above code requirements. Toronto's Eco-Roof Incentive Program, for example, offered a $2 per square meter incentive for a coating over an existing roof or a $5 per square meter for a new roof membrane to a total possible incentive of US $50,000. Cool roofs must be installed on an existing building in order to be eligible for funding. The program was funded in part through cash payments made by building owners who wished to opt out of Toronto's green roof requirements.

Incentives do not necessarily have to involve direct payments. Other methods can rely on building requirements as an incentive basis. For example, The City of Portland has implemented a Floor Area Ratio (FAR) bonus option to encourage vegetated roof development for the purposes of water runoff control. The FAR bonus allows the total area of a building to be larger than it might be otherwise if certain vegetated roof criteria are met. This incentive structure could also be used to support cool roofs. Cities and regions may also offer priority or preferential permitting for buildings or development projects designed with a cool roof or pavements. Preferential permitting can be very valuable because it can shave considerable time off of the construction or retrofitting process.

Most people do not think about their roofs and pavements until there is a problem. In reality, though, these surfaces can be cost-effective platforms for sustainability by saving money, improving urban quality of life, and cancelling some of the warming effects of atmospheric greenhouse gases.

Kurt Shickman is the Executive Director of the Global Cool Cities Alliance, a non-profit organization dedicated to accelerating the deployment of cool roofs and pavements to improve building energy efficiency, urban quality of life, and to combat the effects of climate change. Before joining GCCA, Kurt was the Director of Research for the Energy Future Coalition and the United Nations Foundation's Energy and Climate Team.

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Credit: Peter Tobia

Greenworks Philadelphia

By Alex Dews
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Philadelphia has kept detailed weather records since before the Civil War. In the past 150 years, 2012 was the warmest on record, and five of the top 10 all time came in the past decade. The dense development pattern and old building stock make the city particularly prone to the urban heat island effect, with nighttime temperatures measuring several degrees warmer in the downtown core than in surrounding suburbs. The number of residents who are most vulnerable to the health impacts associated with extreme heat continues to grow. But in the past five years, the City has taken a number concrete steps and made ambitious commitments to reduce its vulnerability to a warming climate and improve the quality of life for residents.

When he took office in 2008, Mayor Michael Nutter established Philadelphia's first Mayor's Office of Sustainability (MOS). One year later, MOS published *Greenworks Philadelphia*,(www.phila.gov/green) a comprehensive plan for the city that addresses sustainability issues in the five broad goal areas of energy, environment, equity, economy, and engagement. The plan establishes 15 measurable targets, with more than 160 initiatives designed to reach each target. MOS publishes an annual report each June with progress updates on every goal, target, and initiative in the plan. In 2013, 95% of the initiatives were either complete or underway, and some targets had already been exceeded.

As is the case with many initiatives in *Greenworks*, retrofitting buildings with cool roof coatings helps to achieve several different goals by using a single measure. Philadelphia is home to more than 440,000 row houses, the majority of which are older homes with flat roofs, making them perfect cool roof retrofit candidates on a very large scale. Cool roof coatings help Philadelphians (especially many elderly residents without air conditioning) stay cooler in the summertime while saving money on utility bills and reducing air quality problems associated with the urban heat island effect.

To advance widespread adoption of this proven technology, Philadelphia chose an approach that combined new legislation with a citywide competition to raise awareness and promote the benefits of cool roofs. In 2010, Councilman Jim Kenney sponsored the Cool Roof Ordinance, requiring all new construction and major renovations with low-sloped roofs to use a cool roof coating that meets or exceeds ENERGY STAR cool roof standards. At the same time, MOS partnered with Dow Chemical Company and the Energy Coordinating Agency, a local non-profit providing residential energy retrofits, on the RetrofitPhilly Coolest Block Contest.

RetrofitPhilly was launched in spring 2010 and invited every block in the city to submit an application describing why they were the "coolest" block in Philadelphia. MOS worked with the city's highly active network of block captains to spread the word and received more than 70 applications representing thousands of residents. An expert jury selected a winner based neighborhood engagement and participation rate (98% of homes on the block signed up). The winning block, 1200 Wolf Street in South Philadelphia, received air sealing, insulation, and a cool roof coating for every participating home on the block.

The project was a huge success and a great example of what's possible when local government joins forces with a trusted non-profit and a well-known corporate partner to achieve a shared goal. MOS continues to promote the benefits of cool roofs, but is going beyond this by committing to meeting the LEED Silver standard for all new municipal facilities over 10,000 square feet, working to reduce municipal energy use by 30%, and requiring annual energy benchmarking for large commercial buildings in the city beginning in 2013. No single measure can ensure the future sustainability of any city, but MOS is focused on institutionalizing smart, cost-effective solutions like cool roofs that reduce environmental impact while increasing quality of life for residents now and into the future.

Alex Dews is Policy and Program Manager for the City of Philadelphia Mayor's Office of Sustainability. Alex focuses on project implementation and progress tracking for Greenworks Philadelphia, the city's comprehensive sustainability framework. In addition, he manages green building policy and greenhouse gas mitigation and adaptation planning efforts. Alex holds a master's degree in Sustainable Design from Philadelphia University, where he is an Adjunct Professor in the School of Architecture.

Heat Island – The More Documented Phenomenon of Urban Climate Change

By Mat Santamouris
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Introduction

Heat island is related to higher temperatures in the central urban areas compared to the suburban ones, and is considered as the more documented phenomenon of climatic change, (Santamouris, 2001). The phenomenon is associated with the positive heat balance of the urban areas caused mainly by increased anthropogenic heat, decrease of the air flow, lack of heat sinks and increased absorption and storage of solar radiation by the city structure. The phenomenon is characterized by an important spatial and temporal variation related to climate, topography, physical layout and short term weather conditions

For a large city with cloudless sky and light winds, the variation of ambient temperature with distance between the rural area and the city center after sunset, exhibits a steep temperature gradient in the boundary between the rural and the urban areas, Figure.1, then the rest of the urban area appears as a 'plateau' characterized by a weak gradient of increasing temperatures, and finally a peak at the city center where the urban maximum temperature is found. However, it should be pointed out that local heat island patterns are strongly controlled by the unique characteristics of each city. The difference between the maximum urban temperature and the background rural temperature is defined as the urban heat island intensity, (Oke, 1987).

Important research has been carried out to understand the phenomenon and also document its strength in various parts of the planet, (Akbari et al 1992, Santamouris 2001,Santamouris 2007,). Existing data shows that the intensity of the phenomenon is very important and may reach mean maximum values close to 7-10 K. Recent heat island studies aim mainly to understand the role of the main parameters influencing temperature increase in cities. Studies have concentrated on the role of city size and population, weather conditions like cloud cover, wind speed, humidity, urban canyon characteristics, etc.

Heat island has an important impact on the energy consumption of buildings and increases their cooling needs. In parallel, because of the higher urban temperatures, the emission and generation of urban pollutants and in particular of tropospheric ozone increases considerably, the ecological footprint of the cities suffering from heat island is growing, while it deteriorates outdoor thermal comfort conditions and threatens the life of vulnerable populations.

To counterbalance the impact of heat island, efficient mitigation techniques have been developed and applied, (Santamouris 2012, Akbari et al, 1992).This involves the use of advanced cool materials for the urban environment, able to amortize, dissipate and reflect heat and solar radiation, use of green roofs, solar control systems and techniques, strategic landscaping of cities including appropriate selection and placing of green areas, and dissipation of the excess heat in low temperature environmental heat sinks like the ground, the water and the ambient air.

Recent real scale applications involving the use of the above mitigation techniques have resulted in very important climatic benefits and a significant reduction of the heat island strength, (Santamouris, 2013).

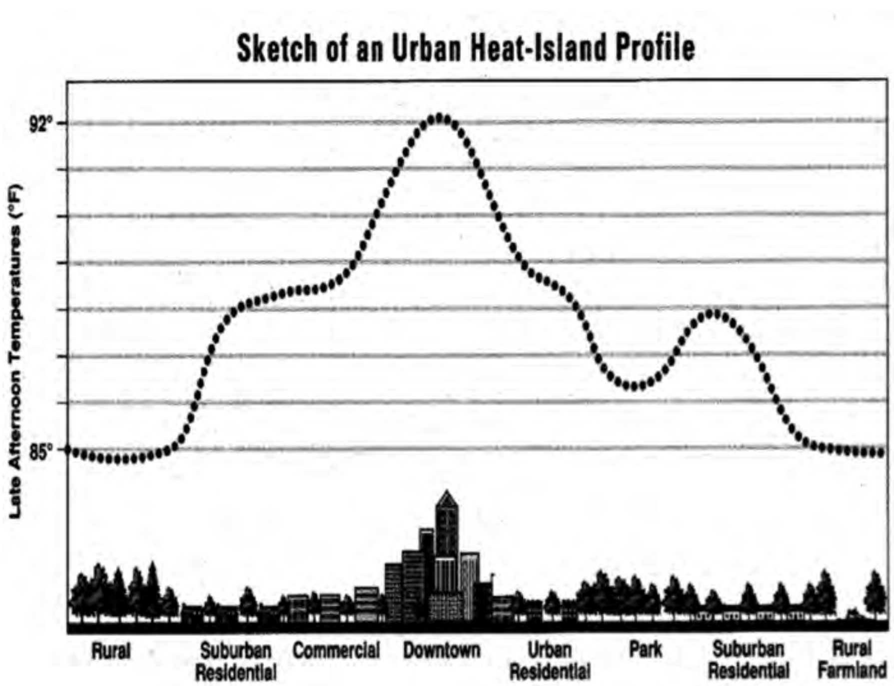

Figure 1. Sketch of the typical heat island profile, (from Akbari et al, 1992).

Energy and Environmental Impact of Heat Island

Increased urban temperatures have a direct effect on the energy consumption of buildings during the summer and the winter period. It is found that during summer, higher urban temperatures increase the electricity demand for cooling and the production of carbon dioxide and other pollutants, while higher temperatures may reduce the heating load of buildings during the winter period.

Several studies have identified the energy impact of heat island. For the city of Athens, Greece, it is reported that because of the high heat island intensity, the cooling load of buildings is doubled, their peak electricity demand is almost tripled, while the COP, (Coefficient of Performance), of mechanical cooling systems decreased up to 25%, (Santamouris et al, 2001). According to (Akbari et al, 1992), for US cities with a population larger than 100,000 the peak electricity load will increase 1.5 to 2% for every 1°F increase in temperature. Similar studies were also carried out in Japan, Korea, and China, and in most of the cases a serious energy penalty because of the heat island phenomenon is reported.

The cooling energy increase is accompanied by intensification of pollution patterns in cities and increase of ozone concentrations, (Stathopoulou et al 2008, Taha 2008), while the ecological footprint of the cities is increased, (Santamouris et al, 2007), the outdoor thermal comfort conditions deteriorate, (Pantavou et al,2011), the thermal stress in low income dwellings is increased, the indoor thermal comfort levels are seriously decreased and health problems are intensified, (Sakka et al, 2012, Luber and McGeehin, 2008). In particular, epidemiological studies of deaths during the heat waves worldwide have shown that the elderly are more vulnerable to high temperatures. As reported, Japan and southern Europe have rapidly aging urban populations, so one can expect these populations to be seriously impacted by higher temperatures and their related consequences.

Heat Island Mitigation Techniques

Counterbalancing the effects of urban heat island is a major priority for the scientific community. Mitigation techniques aim to balance the thermal budget of cities by increasing thermal losses and decreasing the corresponding gains. Among the more important of the proposed techniques are those targeting to increase the albedo of the urban environment, to expand the green spaces in cities and to use the natural heat sinks in order to dissipate the excess urban heat, (Santamouris et al 2012).

Use of Reflective Materials

The intensity of the heat island can be seriously reduced by decreasing the amount of solar radiation absorbed by the urban fabric. The use of proper materials for buildings and the city that present high reflectivity to solar radiation together with high emissivity serve to decrease the temperature of cities. The above two properties mainly affect the temperature of a surface. Increasing the reflectance and/or the emittance of the covering contributes to lower the surface' s temperature, which in turn decreases the heat stored or penetrating into the building or urban fabric, and contributes to decrease the temperature of the ambient air as heat convection intensity from a cooler surface is lower. In parallel, it helps to improve thermal comfort as the emitted infrared radiation is seriously reduced. These 'cool materials' have become the subject of much research, (Akbari et al 1992).

A review of the recent developments in the field of liquid applied materials used in reflective roofs is given in (Santamouris et al 2011). The first generation of materials used in cool roofs consisted of natural materials quite easily found in nature characterized by a relatively high albedo, rarely higher than 0.75, while the second generation was based on the development of artificial white materials designed to present very high albedo values close to or higher than 0.85. In a later, third phase of development, colored high reflective materials have been proposed. The overall idea is to develop colored materials presenting a high reflectivity value in the infrared spectrum, (Levinson et al 2005). The specific materials are characterized by a much higher global reflectivity than the conventional ones of the same color and are associated with important energy savings when used in building roofs or urban infrastuctures. Quite recently, fourth generation reflective materials based on nanotechnological additives like thermochromic paints and tiles, or PCM doped cool materials have been developed and are likely to be used for future cool roof and other mitigation applications.

The development of cool colored materials has gained an increasing acceptance, since in many cases dark colors have to be used or the aesthetics of darker colors is preferred, (Kolokotsa et al, 2012). Non-white reflective coatings present a high reflectivity in the near infrared part of the electromagnetic spectrum to maintain a low surface temperature, while at the same time they absorb in the visible range. Given that almost half of all solar energy arrives in the near infrared spectrum, these properties are very important. Specialized, complex inorganic dark color pigments presenting a strong reflectivity in the near infrared (NIR) part of the solar spectrum have been created by pigment manufacturers and they are commonly used in order to develop cool colored coatings with higher solar reflectance compared to conventionally pigmented coatings.

The performance of IR reflective materials is assessed by various research groups. Cool colored coatings using infrared reflective pigments were tested against conventional materials of the same color, (Syneffa et al, 2007). During the day period, it was found that all the cool colored coatings presented lower surface temperatures compared to the colored matched conventional ones The best performing cool coatings were black, chocolate brown, blue and anthracite that made a difference in mean daily surface temperature from their conventional color matched coatings by 5.2, 4.7, 4.7 and 2.8°C respectively, during the summer time. The highest temperature difference was observed between cool and standard black and was equal to 10.2°C, corresponding to a difference in their solar reflectance of 22. The lowest temperature difference was observed between cool and standard green and was equal to 1.6°C, corresponding to a difference in their solar reflectance of 7, (Figure 2).

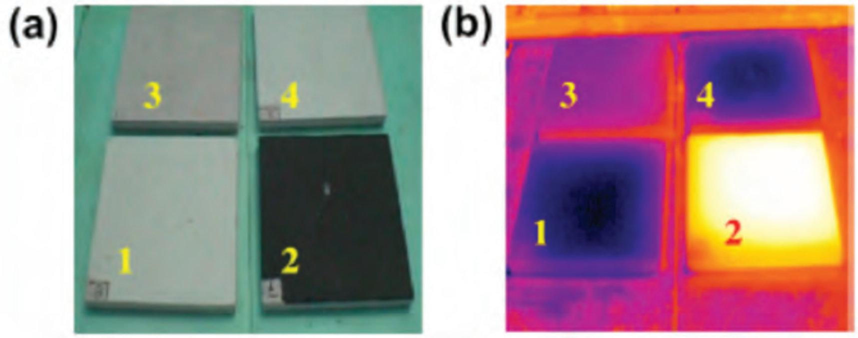

Figure 2. Visable (a) and infrared (b) images of four concrete tiles painted with cool white coatings (1 and 4), a black coating (2) and an unpainted off-white (3) one. The difference in slar reflectance translates into a significant difference in surface temperatures. Source: Synnefa et al. (2006).

To further enhance the performance of cool coatings used for mitigation purposes, phase change microparticles were used and added in the previously mentioned cool color coatings. They have been used to develop surface materials based on infrared reflective pigments doped with phase change materials, (Karlessi et al, 2008). Measurements performed during the summer period have shown that PCM doped materials present a peak daily temperature up to 4 C lower compared to conventional infrared reflective and up to 9 C compared to common coatings of the same color.

Although materials presenting a high solar reflectivity may contribute to decrease considerable the cooling load of buildings, at the same time they may increase the heating needs during the cold period. The development of intelligent coatings which respond thermally to the environment and change reversibly their color, presents important advantages. Materials that may have a high absorptance during the cold period and high solar reflectivity during the warm period could contribute to decrease both the heating and cooling needs of buildings. This may be achieved using thermochromic coatings that present a thermally reversible transformation of their molecular structure that causes a spectral change of visible color. Such coatings have been developed and tested as an alternative heat island mitigation strategy, (Karlessi et al, 2009). The color transition temperature of the coatings was 30 C. Coatings of six different colors with and without TiO2 have been developed and tested.

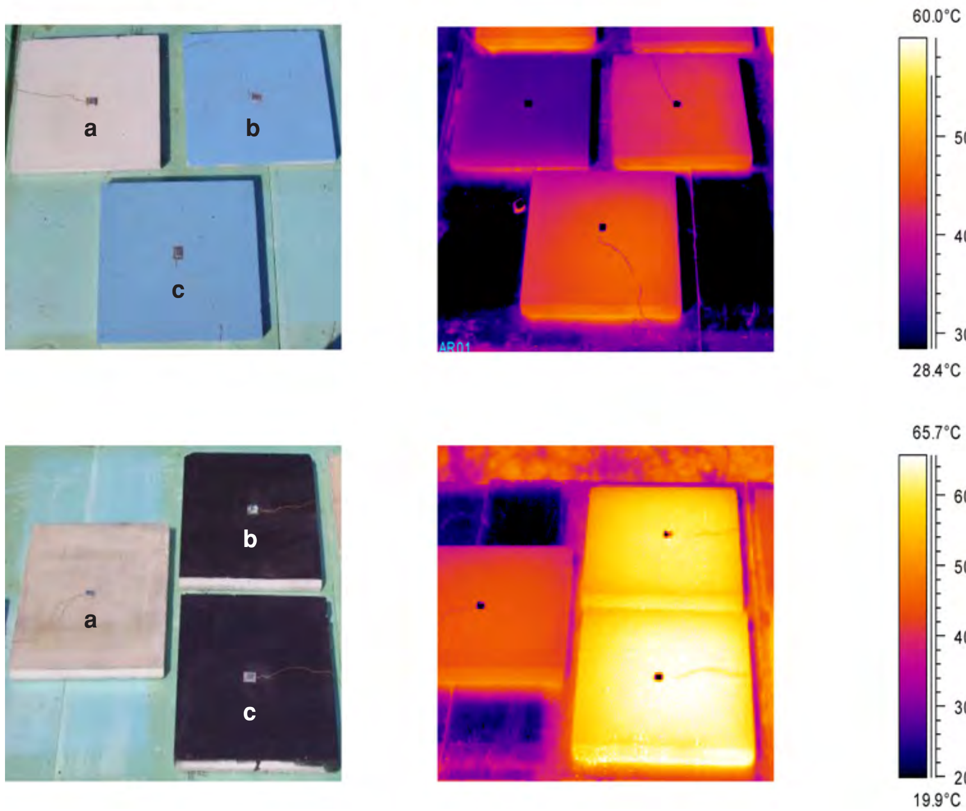

Figure 3. Visible and infrared images of blue and black thermochromic (a), cool (b) and common (c) coatings respectively.

The results of a comparative experimental testing of the surface temperature of thermochromic coatings against common and cool coatings, showed that thermochromic materials present much lower surface temperatures during the summer period, (Figure 3). Surface temperature differences range from 2.2oC for thermochromic and cool yellow to 9.2oC for thermochromic and cool brown and from 4.2oC for thermochromic and common yellow to 11.4oC for thermochromic and common green. In parallel, thermochromic coatings demonstrate 10-15oC lower mean maximum daily temperatures than cool coatings, and 18-20oC lower than common coatings.

Cool coatings are mainly used on cool roofs or cool pavements. Cool or reflective roofs are typically white and present a high albedo. Products used in cool roofs are single ply or liquid applied, (Mac Cracken 2009). Many theoretical and experimental studies have been performed in order to assess the mitigation potential and the cooling potential as well as the possible improvements of indoor thermal comfort caused by cool roofs. Energy benefits may vary as a function of the climatic conditions and the characteristics of the building. Typically, peak summer indoor temperatures may decrease up to 2 C in moderately insulated buildings while cooling loads reductions may range between 10 to 40%. In parallel, the heating penalty may range between 5 to 10% as a function of the local climate and building characteristics.

The climatic impact of cool roofs has been simulated for the city of Athens, Greece, (Synnefa et al, 2008). Two modified albedo scenarios were considered: a moderate one, where the albedo of the roofs was increased from 0.18 to 0.63, and an extreme one where the final albedo of the building rooftops was considered 0.85. It was calculated that for the moderate increase of the albedo, the ambient temperature depression at 2 m height at 12:00 LST varied between 0.5 and 1.5 K. For the extreme case of albedo increase, the ambient temperature reduction varied between 1 K to 2.2 K. Similar studies were performed and a comparative analysis of the results was tabulated by Santamouris et al 2012. All the published studies refer to a possible increase of the urban albedo ranging between 0.01 - 0.35. The calculated and reported decrease of the average ambient temperature ranges between 0.0 – 1.0 K. The calculated decrease of the average ambient temperature per 0.1 of albedo change varies between 0.0 to 0.61. Data correlate quite well and it is concluded that an albedo change of 0.1 in urban areas decreases the average ambient temperature by 0.3 K. It is also found that the estimated decrease of the peak ambient temperature per 0.1 of albedo change varies between 0.57 to 2.3 K. Regression analysis has shown that for an albedo change of 0.1 in urban areas the peak ambient temperature decreases by 0.9 K

Change of the urban albedo can have a significant impact on the climate of the globe. Many recent studies analysed the issue of the urban albedo change from a global perspective. Akbari et al 2009, have considered that an increase of roof and pavement albedo by 0.25 and 0.15 respectively could decrease radiative forcing by 0.15 W/m^2 over the global land area, which is equivalent to one time offset of 44 Gt of emitted CO_2. For example, the albedo of the roofs increases by 0.20, they calculated a CO_2 offset of 0.05 tonnes /m2. In a follow up study described in (Menon et al, 2010), it was estimated that the potential CO_2 offset is close to 57 Gt, when the albedo of roofs and pavements increases by 0.25 and 0.15 respectively,. Van Curen, 2011, calculated the possible decrease of radiative forcing in California because of the use of cool roofs. He found that the for an increase of albedo by 0.01, the mean radiative forcing is -1.38 W/m2. This is translated to removing 1.76 million tons of CO_2 emissions in the State. In a more recent study, (Akbari et al, 2012), the long-term effect of increasing urban surface albedos has been simulated . It is reported that a long-term global cooling effect of 3 $x10^{-15}$ K was calculated for each 1 m^2 of a surface with an albedo increase of 0.01 and this corresponds to an equivalent CO_2 emission reduction of about 7 kg.

The role of pavements in urban areas on the development of urban heat island is also significant. Several recent studies have concluded that paving surfaces play a very important role on the overall urban thermal balance. Paved surfaces in Europe and USA, consist mainly of concrete and asphalt surfaces that present high surface temperatures during the summer period. Decreasing the surface temperature of pavements contributes significantly to improving the thermal balance of cities suffering from heat islands. This can be achieved by replacing the conventional paving surfaces with new ones characterized by much lower surface temperatures during the warm period, and also, reconstruction, preservation and rehabilitation of the existing pavements to improve their thermal and optical performance. Advanced materials and surfaces, known as cool pavements, have been developed and are available for use in urban environments. Cool pavements are mainly of four types according to the technique used, (Santamouris et al , 2013) : the first aims to increase the albedo of the paving surfaces in order to absorb less solar radiation, (reflective pavements). Existing techniques to increase the albedo of pavements include : The use of conventional cement concrete pavement, the use of concrete additives like slag cement and fly ash, the application of white topping and ultra thin white topping techniques, the use of roller compacted concrete pavement, the use of light aggregates in asphalt concrete surfaces, the use of chip or sand seals with light aggregates, the application of color pigments and seals that use colorless and reflective synthetic binders, the painting of the surfaces with a light color using microsurfacing techniques, the use of sand/shot blasting and abrading binder surfaces, resin based pavements, etc. Apart from the commercially available reflective pavements, research is being carried out and reported aiming to develop high reflective pavements. Four main technological approaches are being developed and tested. In particular : a) The use of white high reflective paints on the surface of the pavement, b) The use of Infrared reflective colored paints on the surface of the pavement, c) The use of heat reflecting paint to cover aggregates of the asphalt and d) The use of color changing paints on the surface of the pavement. Several studies are being conducted to evaluate the mitigation potential of reflective pavements. A study in Tokyo, Japan, reports that when cool pavements are considered, the average ambient temperature may decrease by 0,15 K, while in certain areas the temperature reduction may rise to 0,6 K.

The second technique aims to increase the permeability of the surfaces, in vegetated and non vegetated pavements, in order to decrease their surface temperatures through evaporation processes. These types of pavements are known as permeable, porous, pervious or water retaining materials. Non vegetated permeable pavements include porous or rubberized asphalt, porous and pervious concrete, permeable interlocking concrete pavers, concrete and plastic grid pavers filled with gravels. Vegetated permeable pavements include grass pavers, where reinforced turf and concrete grid pavers use lattices of different types that allow grass to grow in the interstices. Some research being conducted to improve the thermal performance of permeable and water retentive are the following: asphalt, concrete and ceramic pavements : a) water holding fillers made of steel by products as an additive to porous asphalt, b) fine blast-furnace

powder in water retentive asphalt, c) fine texture pervious mortar as an additive to pervious concrete, d) bottom ash and peat moss as additives in pervious concrete, e) fly ash with very narrow particle size distribution in bricks, f) industrial wastes as raw material for ceramic tiles.

The third technique aims to increase the thermal storage capacity of the surfaces by adding ingredients of high thermal capacitance or materials of latent heat storage. Addition of latent heat storage materials in the mass of the pavements, contributes to reducing surface temperatures during daytime and decreasing sensible heat release to the atmosphere.

The fourth technique aims to use external mechanical systems in order to reduce the surface temperature of the paving materials. This includes among others, circulation of a fluid in the mass of the pavement to remove the excess heat and circulation of underground water in the pavement mass.

Urban Green and Green Roofs

Increase of the green spaces in cities, contribute to decrease the urban surface and ambient temperatures and mitigate the heat island effect. Several studies have investigated the mitigation potential of urban green. Gill et al, 2007, have calculated that an increase by 10% of the urban green in Manchester, UK, may amortize the foreseen increase of the ambient temperature by 4 K, over the next 80 years.

Decrease of the ambient temperature is achieved because urban green may provide solar protection, help the air movement and heat exchange in the city, absorb solar radiation and cool the air through evapotranspiration processes. Additionally, trees and urban parks filter pollutants, mask noise, stabilize soil and prevent erosion and relax urban visitors. Urban parks have a serious social impact and contribute to more positive moods, improve health, while trees increase property values, and make urban settings more attractive. In spite of the benefits offered by urban parks, their mitigation impact depends on many parameters such as : a) the size and the structure of the park, the sky obstruction, the type of plants and the watering frequency, b) the properties of the urban space where the park belongs and in particular its density, radiative cooling capacity, anthropogenic heat generated and thermal capacitance, c) the prevailing local weather conditions and the climatic zone where the area of study belongs

Green and planted roofs are partially or fully covered by vegetation and a growing medium. There are two main types of green roofs : Extensive roofs which are covered by a thin layer of vegetation and intensive roofs which can support small trees and shrubs. Green roofs present many advantages like increased mitigation of urban heat island, decreased energy consumption, increased roof materials durability, storm water runoff management, possible better air quality and noise reduction and offer space for urban wildlife.

Several experimental and theoretical studies have been performed to identify the heat island mitigation as well as the energy conservation potential of green roofs. It has to be pointed out that the specific energy benefits depend on the local climate, the green roof design and more importantly on the specific building characteristics. Given that with green roofs the thermal benefits are mainly provided through latent heat processes, the performance of the system is higher in dry climates where the potential for evaporation is higher. The main parameters that define the performance of green roofs are : the thickness and the thermal characteristics of the vegetative roof known as the Leaf Area Index, (LAI), which defines the shading levels and the transfer of radiation through the layers. Finally, watering is important as it determines the latent heat release and regulates the thermal balance of the roof. Studies of various types of buildings, green roof characteristics and climatic zones, show that the expected reduction of the annual energy load may vary between 1 to 40% in extreme cases. In well insulated modern buildings the energy contribution of green roofs is quite modest.

Only very few studies evaluating the heat island mitigation potential of green roofs on a city scale are available. Studies are available for New York and Chicago in the US as well as for Hong Kong and Tokyo. A simulation study aiming to evaluate the mitigation potential of green roofs in Chicago, US, is described in (Smith and Roeber, 2011). Chicago is a leading city in green roofs technology with more than 50,000 m^2 installed vegetative roofs in 2008. The use of green roofs provides an important cooling effect to the city. Urban temperatures during 19:00-23:00 were 2-3 K cooler compared to the temperatures simulated without the use of green roofs.

Conclusions

Heat island is a very well documented phenomenon of urban climate change that has a serious impact on the cooling energy consumption in cities, the concentration of pollutants and the specific thermal comfort conditions in cities. It becomes increasingly important to improve urban climatic environments and to apply this knowledge to upgrade people's environment in cities. Development and application of successful mitigation techniques is the key to fight the temperature increase in cities and improve quality of life. Current research has permitted the development of advanced materials and techniques that help considerably to improve thermal conditions in cities. More intensive research activities, targeted demonstration projects, and large scale applications are necessary to better improve our knowledge on the topic.

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Hot Times in the City

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Abstract

One of the most evident modifications of the earth-atmosphere system is what happens in our cities. Cities form Urban Heat Islands (UHI), especially under clear, calm atmospheric conditions. The science of Urban Climatology studies the UHI and other related changes induced by cities. Generally, the larger the population of a city, the greater the UHI, but this depends on compactness or sprawl features of cities, the regional geographical setting and weather, and rural surroundings against which city temperatures are compared. Much research remains on how to model climate processes within and surrounding cities, especially in light of the ever-changing regional and global climate. In the case study shown for Phoenix and the Sun Corridor of the Southwest USA, warming of areas due to urbanization is at least as significant as warming due to emissions of long-lived greenhouse gases, an important consideration in an increasingly urbanizing world.

Introduction

Urbanization is the most evident display of earth system human modification with municipalities growing into metropolitan areas, which in turn have spawned larger-scale conurbations of vast horizontal and vertical extent. Thus, the altered urban atmosphere provides strong evidence of the potential for human activities to change climate. Since we have reached the point where population on earth in urban areas exceeds that of rural environments, it is increasingly important to evaluate the mounting evidence that cities alter earth surface conditions, and thus produce phenomena such as urban heat islands – UHI. Cities also cause direct emissions of heat, gases, and particles into the atmosphere (Grimmond, 2007). Urban areas cover 1% of earth's land area (Schneider et al., 2010), but urban emissions have far-reaching impacts on the global scale climate system, since cities account for 70% of greenhouse gases released into the atmosphere (U.N., 2011). Cities also form their own "urban climate" as a function of the form and fabric of the landscape, causing changes in, for example: (a) temperature (warmer), (b) moisture (often drying out the city), (c) wind (could either increase or decrease regional wind), (d) precipitation (changes downwind, usually increases), absorbed solar radiation (less), and visibility (less).

The following short review is limited primarily to UHI effects and ideas on modeling the urban climate system. The study of the UHI and processes in the city is the domain of a relatively new science called Urban Climatology. The first real growth of urban climatology dates from the 1920s, followed by rapid 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. They have become less descriptive and more quantitative and theoretical, and more integrative and interdisciplinary. There are many scholarly reviews of the subject and accompanying bibliographies that illustrate the overall problem of how cities alter their climatic environment (Oke, 1974, 1979, 1980, 1982, 1987; Chandler, 1976; Landsberg, 1981; Lee, 1984; Bonan, 2002; Arnfield, 2003; Grimmond et al. 2010; Heisler and Brazel, 2010).

What is changed in an urban climate?

Oke (1997) provides a summary of the typical resulting alterations of climatic elements in cities compared to rural environs (see Table 1) for a mid-latitude city of one million population. The reasons for heat-island formation are discussed under the Modeling section.

Methods of evaluating urban climate

Many methods are used to determine how a city affects climate. Early methodologies included sampling the differences between urban–rural environments, upwind–downwind portions of the urban area, urban–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). Much of this sampling led to the discovery of the famous heat-island phenomenon.

Process studies help to provide a better characterization of how urbanization alters the surface–atmospheric system (see Modeling section). It should be mentioned that considerable attention has been given to the study of historical weather records in cities to evaluate temperature trends that are more urban in

Table 1.

Urban climate effects for a mid-latitude city with about 1 million inhabitants (values for summer unless otherwise noted).

Variable	Change	Magnitude/comments
Turbulence intensity	Greater	10–50%
Wind speed	Decreased	5–30% at 10 m in strong flow
	Increased	In weak flow with heat island
Wind direction	Altered	1–10 degrees
UV radiation	Much less	25–90%
Solar radiation	Less	1–25%
Infrared input	Greater	5–40%
Visibility	Reduced	
Evaporation	Less	About 50%
Convective heat flux	Greater	About 50%
Heat storage	Greater	About 200%
Air temperature	Warmer	1–3°C per 100 years; 1–3°C annual mean up to 12°C hourly mean
Humidity	Drier	Summer daytime
	More moist	Summer night, all day winter
Cloud	More haze	In and downwind of city
	More cloud	Especially in lee of city
	Fog More or less	Depends on aerosol and surroundings
Precipitation		
	Snow	Less Some turns to rain
Total	More?	To the lee of rather than in city
Thunderstorms	More	
Tornadoes	Less	

Source: adapted after Oke (1997), p. 275.

origin versus trends more attributable to global signals of change (e.g. global warming). A large number of stations with long records are needed for trend analyses, and many of the world's weather stations are in or near urban-affected locales. However, it is often difficult to decipher global change from such sites (e.g. Hansen et al., 1999, 2001), although urban effects may be ascertained.

The placing of typical weather stations in urban areas to study how cities alter climate is a most challenging endeavor in and of itself (Oke, 1999, Oke, 2006). This arises because of the complex structure of the urban surface and atmosphere over short distances, processes operating at differing scales, and the resultant climate patterns in the city. Oke (2006) and Stewart and Oke (2012) provide excellent insights into methods and protocols for locating surface weather stations in urban areas and in interpreting urban climate. A key reminder is that for air temperatures recorded at 2 m, the sphere of influence on those temperatures lies primarily in a radius some 200-500 m around a site (Stewart and Oke, 2012). If a site is very close to a border between diverse land covers, a complication arises in interpreting land cover influences. Remote sensing technology aids in this interpretation and in evaluating the diverse variability of microclimates in urban areas. Most studies focus on estimating the land cover distribution and classification of features making up the urban fabric and their resultant effects on surface temperatures (e.g., Roth et al, 1989). Therefore, many remote sensing studies determine a Surface Urban Heat Island (SUHI)– using derived surface temperatures from satellites or airplane overflights (Voogt and Oke, 1997).

The urban heat island (UHI)

Cities, no matter what their size, tend to be warmer than their surroundings. One can observe this biking through the urban landscape (Melhuish and Pedder, 1998). This fact was discovered by scientists well over a century ago (e.g. Howard, 1833), and is well known as evidenced by its mention in books on modern climatology and ecology (e.g. Bonan, 2002; Erell et al. 2011). Since cities are regional agglomerations of people, buildings, and urban activities, they are spots on the broader, more rural surrounding land. These spots produce a "heat-island" effect on the spatial temperature distribution in an area, most often after sundown until early morning (see for example the Louisville 2 m above ground UHI - Fig. 1). City size, morphology, land-use configuration, and geographic setting (e.g. relief, elevation, regional climate) dictate the intensity of the heat island, its geographic extent, orientation, and its persistence through time. City size (as indicated by its population size) affects the maximum urban heat-island intensity (city's core compared to rural site under clear, calm weather; see Fig. 2). Although population is only a surrogate measure for many of the causes of a heat island, there is a significant correlation as Oke (1973) found for European and North American cities. The magnitude and slope of the relationship is different for the two sets of cities and is more related to urban form and city designs of North America's tall buildings versus European building heights and more compact urban landscapes. Most commonly

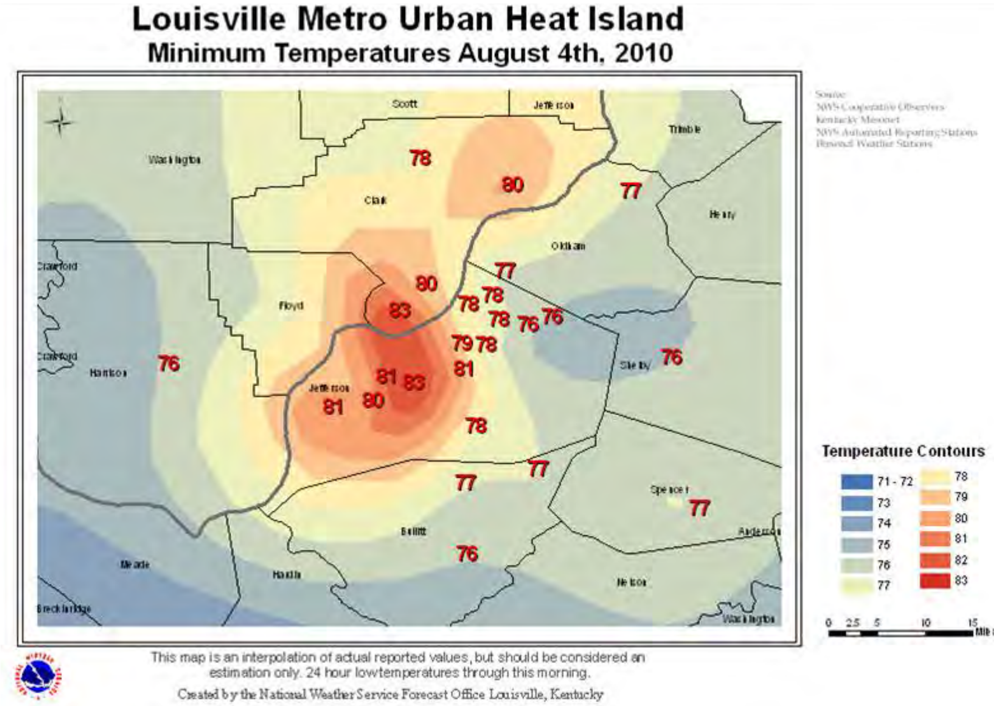

Figure 1. The spatial form of the Metropolitan Louisville UHI in August 2010, as measured by minimum temperatures taken from several weather stations. Minimum temperature is considered a good indicator of UHI as the urban influence on temperatures is significantly stronger during nocturnal periods as opposed to daytime conditions (Source: National Weather Service).

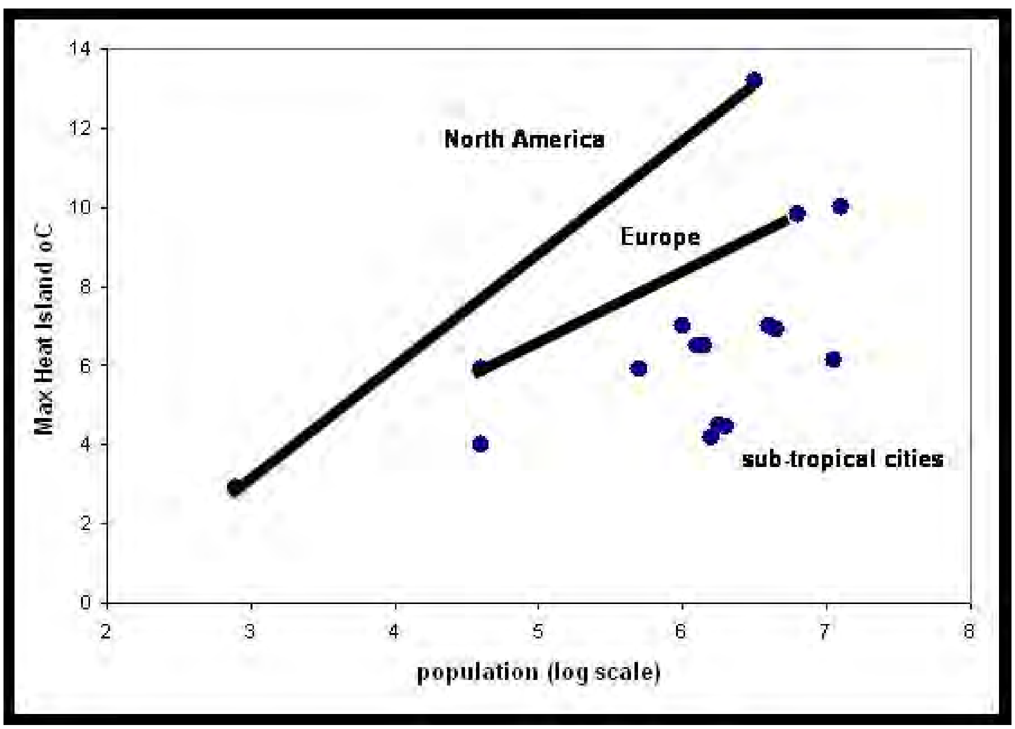

Figure 2. Maximum nighttime heat island intensity versus city population after selected data shown in Heisler and Brazel, 2010 from analysis by Roth (2007). Solid lines are regressions through temperate cities of North America and Europe (Oke, 1973). Dots below Europe line represent sub-tropical wet and dry cities.

studied in this regard is the so-called sky view factor – a measure of the degree to which the sky is obscured by the built environment for a given point (Grimmond et al 2001). Cities with tall buildings and narrow streets (higher height to width ratios) would have low sky view factors and thus retain emitted radiation in the city at night accounting for larger nighttime UHIs.

Modeling

As mentioned, by virtue of its alteration of the surface radiation balance, the built environment has been shown to raise temperatures and affect precipitation patterns regionally. The driving force behind urban-induced local- to regional-scale climate change is the change in radiant surface available energy R_N, defined as the sum of net surface shortwave and longwave radiation:

$$R_N - S(1-\alpha) + L_W - \varepsilon\sigma T4 \quad (1)$$

where S is solar radiation, α is albedo (reflectivity of the surface of interest; the quantity "1-α" represents the non-reflected incoming solar radiation and equates to surface absorption), and "$L_W - \varepsilon\sigma$ T4" which characterizes surface absorbed and emitted longwave radiation, respectively. Urban areas are generally darker relative to adjacent, undeveloped surroundings, highlighting the important role of urban albedo in controlling R_N. Urban areas also feature reduced vegetation coverage relative to less developed surroundings, shifting energy partitioning from latent (a direct cooling effect) to sensible heating, a direct warming effect. Emission of urban absorbed radiation depends on the vertical extent of the built environment (i.e., urban geometry). Longwave radiation loss to space is reduced as the taller urban fabric (e.g., skyscrapers) readily absorbs surface emitted radiation. In this fashion, urban canopy temperatures are maintained at greater levels relative to environments of limited vertical extent.

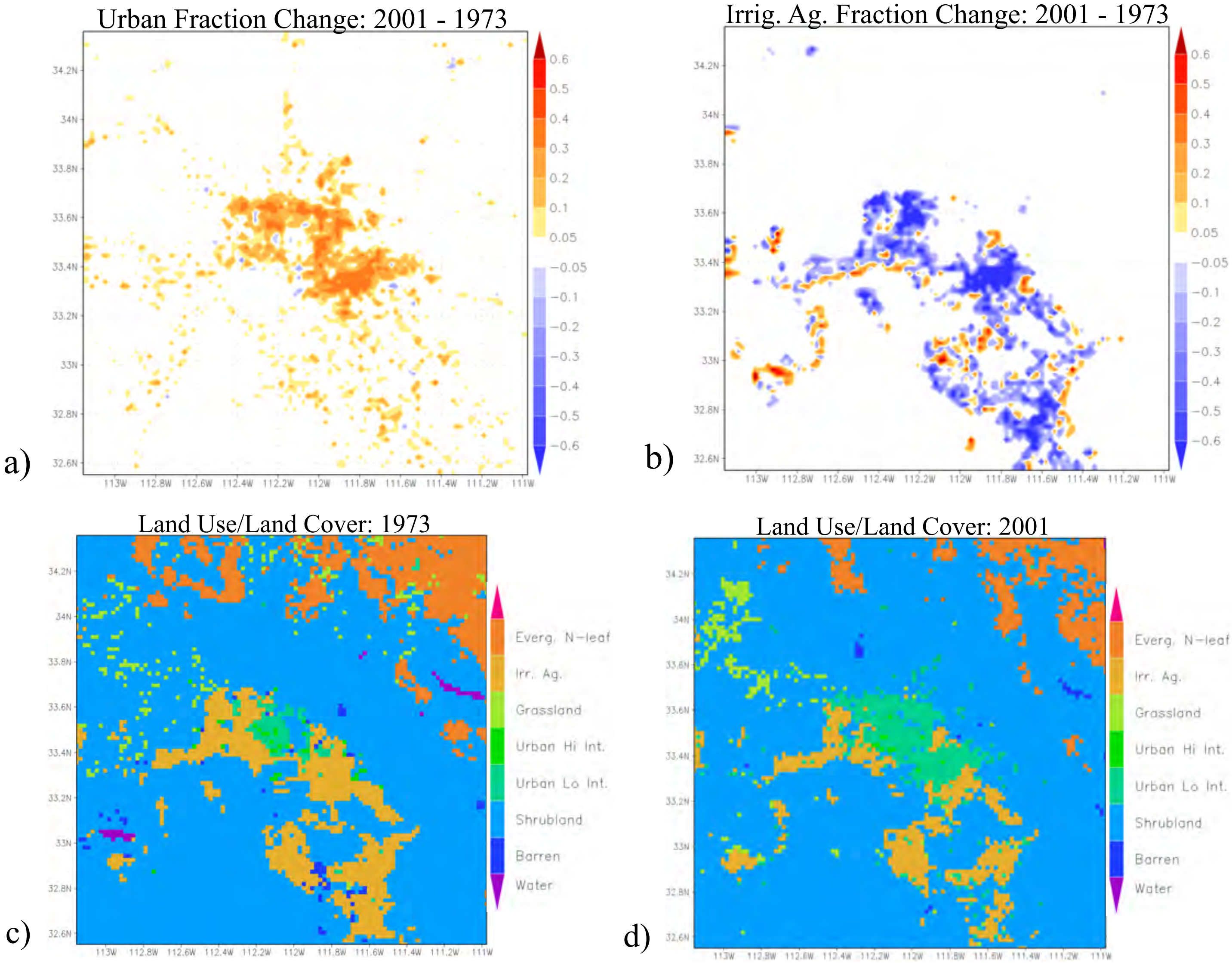

Figure 3. Fractional land cover difference between 2001 percentage of total area and 1973 percentage of total area in (a) urban land, (b) irrigated agriculture area, for a 204 km2 domain centered upon Phoenix. Dominant land use/land cover representation of (c) 1973, and (d) 2001 landscape for identical domain centered upon Phoenix. Adapted from Georgescu et al. (2009a, b).

In addition to radiative considerations, the built environment also modifies the aerodynamic, moisture, and air quality (e.g., via the addition of particulate matter) characteristics of urban spaces. Further, anthropogenic heating (e.g., from traffic sources and waste heat due to air conditioning use) intensifies the urban heat island through addition of extra heat (Shahmohamadi et al., 2011). These processes are represented in mathematical simulation models (e.g. Arnfield, 2003; Chen et al., 2011) used to examine urban environmental issues intended to both improve process understanding and provide guidance for urban and energy planners to prioritize adaptation and mitigation strategies aimed at offsetting UHI impacts. We explore these issues through examination of climatic effects owing to historical and anticipated urban expansion of the Phoenix Metropolitan area (hereafter Phoenix), the largest urban agglomeration within the Colorado River Basin and center of the fastest growing megapolitan in the United States.

The majority of urbanization since the 1970's occurred to the northwest and southeast of central downtown Phoenix (Figure 3a). Most of the increase in built environment was at the expense of irrigated agriculture (Figure 3b), although in recent years urban expansion has begun encroaching on semi-natural shrubland (Georgescu et al., 2009a,b). The overall surge in urban land cover, primarily at the expense of agricultural plots (Figure 3c-d), highlights the modification of biophysical parameters (e.g., albedo) that characterize the region's landscape and impact on R_N. Future expansion of the Sun Corridor (megapolitan stretching from U.S.-Mexico border, northwestward through Tucson, Phoenix, and Prescott, AZ) is expected to raise Arizona's population ranking to top 10 status by 2030 (U.S. Census Bureau, 2005). Continued conversion of the region's natural landscape will further increase already extreme summertime near-surface temperatures (Georgescu et al., 2013). Multiyear simulations illustrate the importance of urbanization pathways (e.g., varying

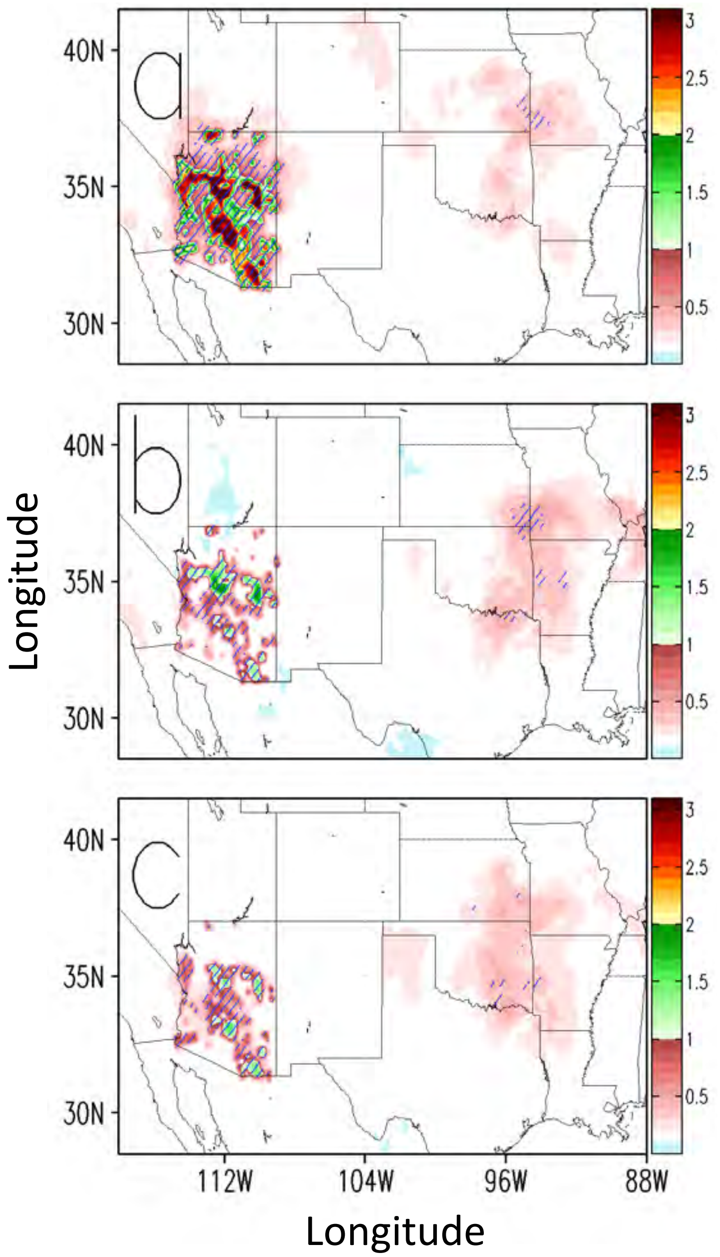

Figure 4. Simulated summer-time two-meter air temperature difference (C) between (a) Maximum Sun Corridor expansion scenario for 2050 and early 2000's urban extent; (b) Maximum Sun Corridor expansion scenario with Cool Roofs adaptation and early 2000's urban extent; (c) Minimum Sun Corridor expansion scenario and early 2000's urban extent. Blue hatching indicates differences that are very likely (greater than 90% probability) to be significant. Adapted from Georgescu et al. (2013).

extent of built environment expansion) on regional climate change, with urban-induced local warming ranging between 1-4°C depending on the particular trajectory of development (Figure 4). Notably, warming due to urbanization is at least as significant as warming due to emissions of long-lived greenhouse gases, an important consideration in an increasingly urbanizing world (Georgescu et al., 2013). Strategies to offset urban-induced warming include enhanced reflective material (e.g., cool roofs and pavements; Santamouris, 2013; Synnefa et al., 2008) and increased vegetative cover (e.g., green roofs; Papangelis et al., 2012; Wang et al., 2012). However, unintended hydroclimatic consequences associated with large-scale deployment of various adaptation strategies must be examined prior to large-scale deployment (Georgescu et al., 2012).

Conclusions

The climate of cities will continue to be of importance to the ever-expanding urban population of the world. The application of research findings of urban climatology in building designs and urban environmental planning is beginning to emerge but is not yet widespread (Bonan, 2002). Due to the complexity of the urban landscape and the variability of dimensions, land use, morphology, and other characteristics, much research still remains on just how a city affects the surface and atmospheric climatic environment, and the city's overall urban ecology. Equally, if not more important, are the interactions of the city climate system with other elements of the entire urban and global ecosystem (e.g., Adler and Tanner, 2013; Bulkeley, 2013; Pijawka and Gromulat, 2012). The discovery of these interrelationships will eventually aid in planning solutions related to pollution, health, comfort, water supplies, and general quality of life among urban dwellers.

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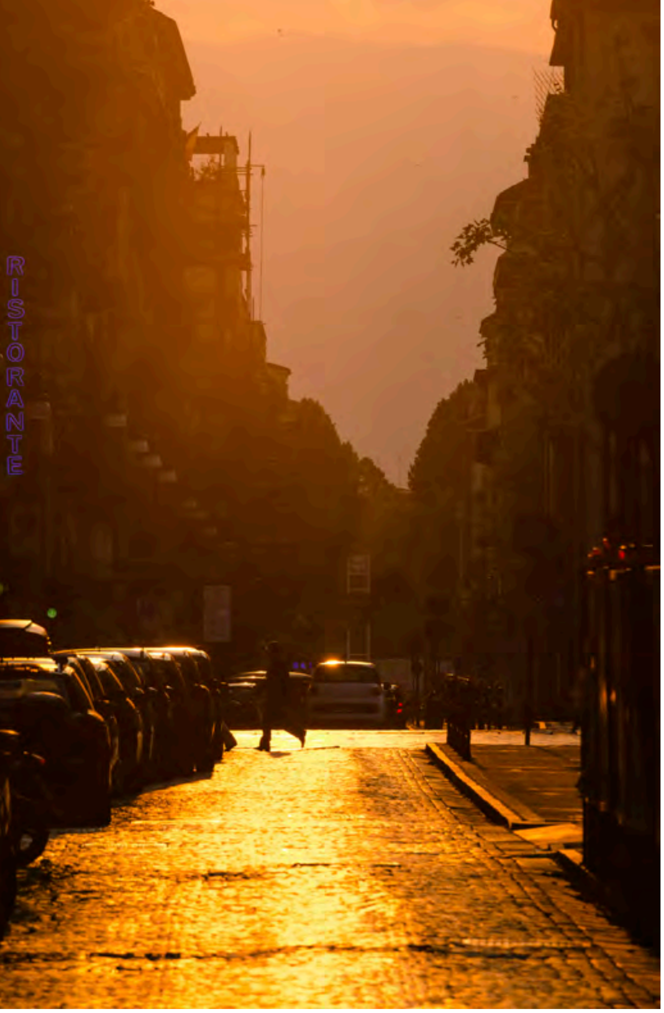

Rise in Pavement Temperature – Making Buildings Part of the Road Infrastructure, Capturing Energy – Solutions, Possibilities and Challenges

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Why asphalt pavements turn hot in summer?

Pavements get heated up due to solar radiation as they absorb heat. The surface temperature rises, and since the amount of heat radiated back into the atmosphere is proportional to the fourth power of the temperature, a slight increase in surface temperature leads to a significant increase in the amount of heat that is radiated - resulting in the urban heat island effect.

Solar radiation absorbed by an asphalt pavement raises its temperature. There are four predominant mechanisms in the transfer of heat to a pavement (Bejan, 1993): (Figure 1) solar radiation in and emitted radiation out of the pavement, conductive transfer of heat through the pavement, and convective transfer of heat above the pavement through wind.

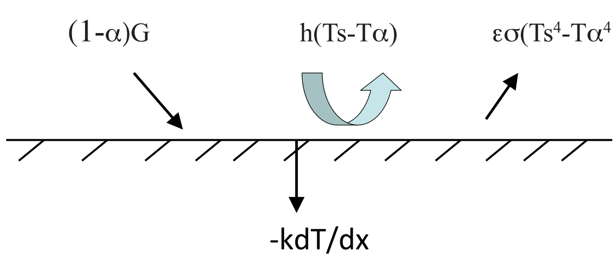


Figure 1: Thermal problem associated with pavement heating (G = irradiation, h = heat transfer coefficient, k = thermal conductivity, T_α = air temperature, T_s = surface temperature, T_{sur} = surrounding temperature; α = reflected component, ε = emissivity of the surface)

Due to the very nature of the material, an asphalt pavement has a high absorptivity (0.85-0.93, Solaimanian and Kennedy, 1993) of solar radiation. At the same time its low conductivity (0.76-1.4 W/mK, NCHRP, 2004) prevents the absorbed energy from being transported elsewhere. This, coupled with relatively high thermal capacity (921-1,674 J/KgK, NCHRP, 2004) of the asphalt mixture, allows asphalt pavements to store thermal energy that has the potential of being harvested in various ways. Examples of high pavement surface temperatures (in ºC) in a few selected cities in the southern part of the US are: Houston, TX: 62, Jacksonville, FL: 60, Albuquerque, NM: 61, Reno, NV: 61, Atlanta, GA: 61, Nashville, TN: 60, Los Angeles, CA: 59. (The temperatures are estimated on the basis of air temperatures (NOAA, 2008) using the models developed by Solaimanian and Kennedy, (1993), Huber, (1994), Solaimanian and Bolzan, (1993). Note that in large parts of southern USA, maximum pavement temperatures exceed 60ºC, while daily pavement temperatures reach 500ºC for a large part of the year. As an example, temperatures in an asphalt pavement in Houston are shown for one year, in Figure 2. Economic analysis conducted on the basis of these temperatures in Houston has been presented later.

Solutions, Possibilities and Challenges

Built environment refers to the man-made surroundings that provide the setting for human activities, ranging in scale from personal shelter to neighborhoods to the large-scale civic surroundings. These surroundings are interconnected by an artery system that allows access to buildings and mobility from one neighbourhood to another. Over the years this system has

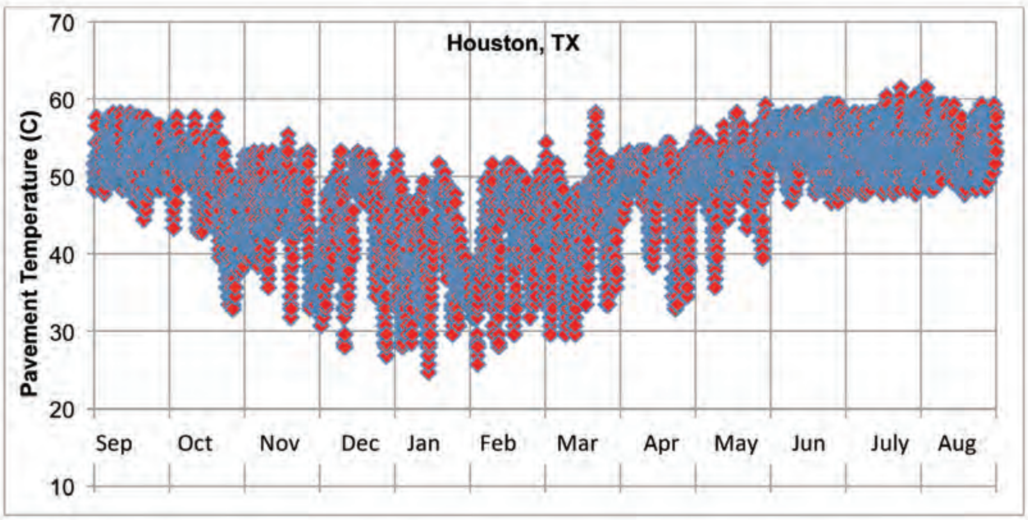


Figure 2. Maximum pavement temperature in a 12 month period

been one of the main drivers of unsustainable urban sprawls and excessive energy consumption, to name a few negative effects.

A sustainable built environment cannot be achieved in the short term (few decades). A transitional phase is needed to bridge a distant sustainable future (at least one century). This phase encompasses the overall improvement of existing man-made surroundings and their interconnecting artery systems, both in terms of energy consumption and generation as well as in terms of its impact on natural infrastructure and related ecosystem services. Thus the scale and focus of this phase will be buildings, their interconnections (artery system) and natural (air, water, vegetation, land and subsoil) surroundings. In this context the system of roads and parking spaces is considered as the source of energy generation and transportation that feeds the surrounding building infrastructure. This concept can be extended to the construction of buildings in which exterior concrete panels act as solar energy collectors.

The energy capture capability of pavement materials is to be applied to a sample of buildings that vary in terms of space use, energy consumption and geographic location (climatic zones). The proponents are perfectly aware that the use of pavement materials as energy capture systems may appear as some sort of validation of the status quo, namely the negative effects of roads on built and natural environment. We wish a future with less asphalt and car dependence. In the short term however, most roads are going to stay. So why not endow the artery system with the positive feature of energy generation and transportation and in the meantime learn how to develop a better built environment and consume less energy?

Before going any further, let us compare the amount of energy that is consumed by buildings (Figure 3) and can at least theoretically be extracted from paved areas. With the use of a macro based spreadsheet, using the state of the art predictive equations and NOAA air temperature data, the proposing team has conducted detailed analysis of temperature and theoretical values of energy. Based on the concept of harvesting energy shown in Figure 4 (Mallick et al, 2009) (using a cold fluid through pipes embedded in pavements to capture heat energy), Figure 3 shows that available energies are at least comparable to those that are consumed. This favorable observation and the fact that energy captured from pavements through water stored in aquifers have been used successfully in the Netherlands (Loomans et al, 2003), warrants the presentation of the remaining article, which deals with five steps:

1. How to optimize the pavement-energy capture and the energy utilization system to obtain and successfully use the maximum amount of energy?
2. How to construct such a system?
3. What are the building applications?
4. What are the benefits of the proposed system and finally?
5. How to select the best system for different conditions, such as urban, suburban and rural, using the concepts of systems dynamics?

These different steps are described in the following paragraphs.

1. How to optimize the pavement-energy capture and the energy utilization system to obtain and successfully use the maximum amount of energy

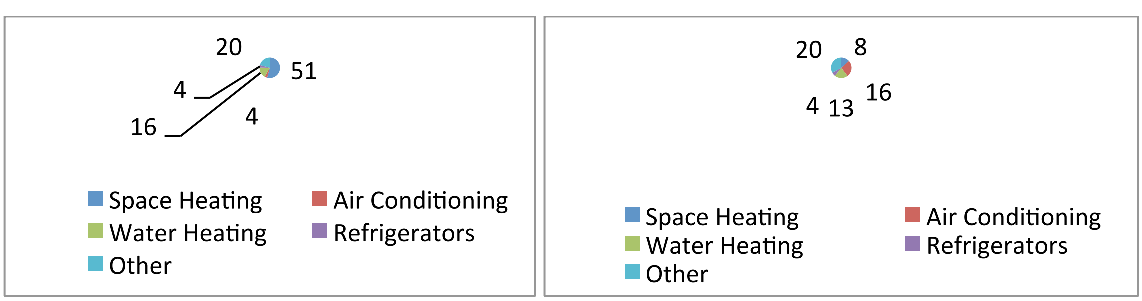


Figure 3. Energy consumption in kwh/day of DOE-Zones 2 and 5 residential buildings (US EIA, 2010).

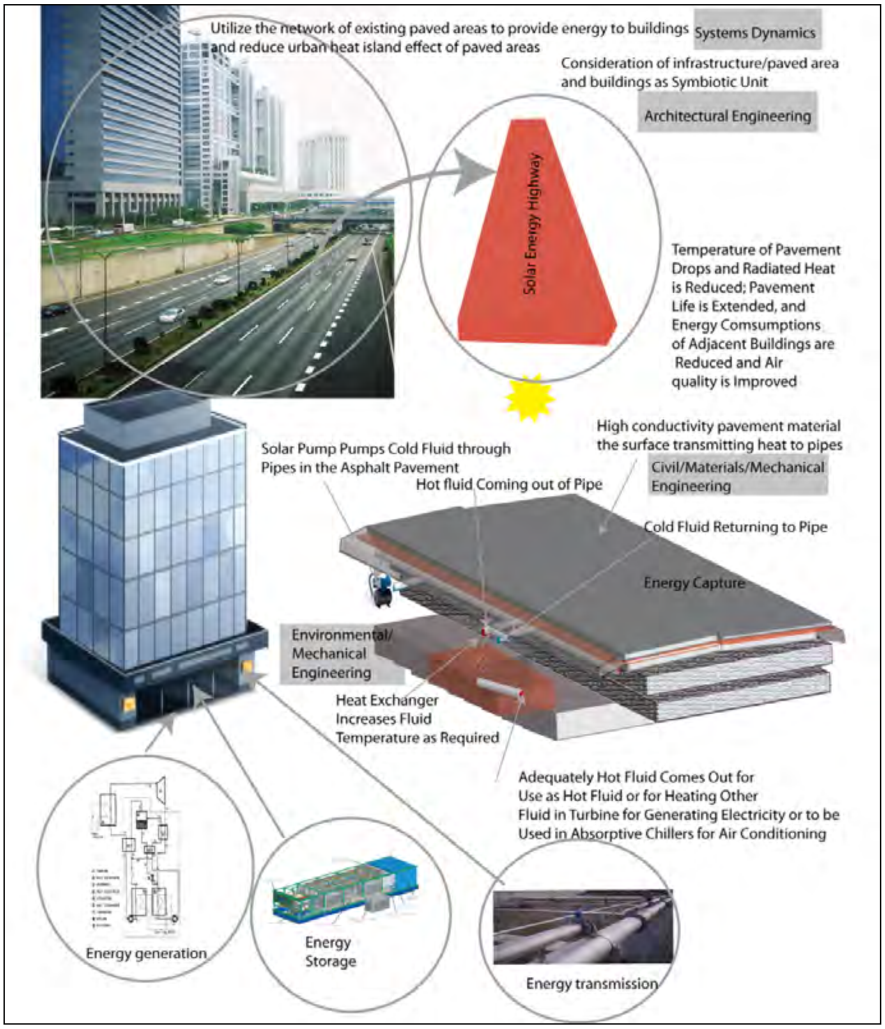


Figure 4. Proposed concept.

a. *Determination of temperature of pavements at different depths for different times of the year for different locations*. It is necessary to choose a suitable location for the installation of an energy capture system. An optimal location has relatively high ambient temperatures throughout the year as well as increased exposure to sunlight. A detailed analysis of locations across the US can be carried out. Extensive analyses have already been conducted by a few researchers; for example: a macro-programmed spreadsheet to determine the amount of energy harvested per year, and the savings per year, starting with the input of hourly air temperature data, which could be obtained from NOAA database. Other inputs to the spreadsheet include the latitude, longitude, and time-zone offset of the location, the properties of the pipe and flowing fluid of choice. The air temperatures serve as the input in the calculation of a continuous temperature profile within the asphalt according to the methods of Viljoen (2001). This model incorporates the thermal behavior of asphalt pavements by recognizing its high thermal capacity of the asphalt and low thermal conductivity as well as addresses the influence of solar radiation on the temperature of the asphalt. The maximum and minimum asphalt surface temperatures serve as the foundation for all other temperature profile calculations. To address the differences in temperature at depths within the pavement, Viljoen (2001) provides the following equations for calculating the maximum, Td(max), and minimum asphalt temperature, Td(min) at a given depth, d, in millimeters as a function of the maximum, Ts(max), and minimum, Ts(min), asphalt surface temperatures:

$$T_{d(max)}=T_{s(max)}(1-4.237\times10^{-3}d+2.95\times10^{-5}d^{2}-8.53\times10^{-8}d^{3})$$

$$T_{d(min)}=T_{s(min)}+3.7\times10^{-2}d-6.29\times10^{-5}d^{2}$$

The daily temperature profile of asphalt pavement consists of a heating period and a cooling period that mostly correspond with daytime and nighttime. The pavement temperature at depth as a function of time, $T_{d(t)}$, during the heating phase is calculated as follows: $T_{d(t)}=T_{d(min)}+(T_{d(max)}-T_{d(min)})\sin[\pi((t-t_r-\beta))/(DL+2(\alpha-\beta))]$; where $T_{d(min)}$ is the minimum temperature at depth for that day, $T_{d(max)}$ the maximum temperature at depth for that day t is the time of day, t_r the time of sunrise, *DL* the length of day, and α and β are two time parameters all in hours. α represents the delay in temperature change (in hours) at depth due to the low thermal conductivity of asphalt pavement and is a function of the depth within the pavement as follows: $\alpha=2+(d/50)$; where d is the depth in millimeters. β represents the time delay of a pavement reaching a specific temperature due to high thermal capacity of asphalt pavements. The value of β is taken to be 1.5 hours. During the cooling phase the pavement temperature at depth, $T_{d(t)}$ is calculated as follows:

$$T_{d(t)}=T^{n}_{d(min)}+(T_{d(ts)}-T^{n}_{d(min)})\exp[-(\gamma(t-t_s)/(24-DL+\beta))];$$

where t is the time of day, t_s the time of sunset, *DL* the length of day, β taken as 1.5 hours, $T_{d(ts)}$ the temperature at depth at sunset, $T_{d(min)}$ the minimum temperature of the next day, and γ a decay parameter taken as 3.9. One complete cycle of the temperature profile begins at the time of sunrise plus β which accounts for the lag between sunrise and the time at which the pavement reaches its minimum temperature for that day. The pavement enters the sinusoidal heating period and the temperature at all depths increases at different rates due to the influence of the α and β parameters that account for the thermal behavior of asphalt pavements. During the end of the heating period the temperature of the pavement begins to decrease due to the reduction of solar radiation from the sun about to set. Sunset marks the beginning of the cooling period for the pavement where the temperature at all depths decreases according to an exponential decay term. The cooling period requires calculation of the temperature directly at sunset as well as input of the next day's minimum temperature at

depth to maintain continuity between consecutive heating period. The cooling period continues until the time of sunrise plus β of the following day. The spreadsheet calculates the temperature at each of the depths for every hour of the day on the hour for the entire year, and then calculates the amount of energy harnessed by comparing the specified inlet fluid temperature to the temperature in the pavement at depth for that hour. Time intervals, where the temperature of the pavement at depth is below that of the specified inlet water temperature, are ignored to avoid loss of energy during this time.

b. *Study of a model system to determine the best piping conditions that allow the extraction of energy from the pavement.* There are two major resistances within the asphalt pavement system: the convection resistance of the fluid in the pipe and the conduction resistance through the pavement material. The overall goal of a proper design is to minimize these resistances by increasing the heat transfer coefficient (h) for convection or the conductivity (k) of pavement materials. Enhancement of surface area for heat transfer into the fluid is also a strategy that needs to be explored by researchers.

Convection: Increasing the effects of convection inside the pipes will inevitably improve heat transfer into the fluid. The transient performance of a simple design has been modeled, comparing the amount of heat flux transferred into a pipe as a function of time and convective coefficient. Figure 6(a) represents a brief sketch of the model and the boundary conditions applied (note that the model assumes unit depth, so the net flux is in W/m rather than W/sq.m.) Figure 4 (b) represents the flux into the pipe compared with time and various convective coefficients. As expected, enhancing convection inside the pipe increases the overall amount of heat extracted; however additional conduction limitations show a clear cutoff where further increases of the convective coefficient have no additional benefit. These experiments give us a maxima in terms of improved convection- further increase will only increase the pumping power without tangible benefits. As this represents a best-case scenario, it was used for modeling to determine the maximum heat extraction. This condition can be achieved with the use of a phase-change fluid, as the phase change will maintain a certain temperature throughout the change. Description of possible phase change systems are given in a separate section later. Methods for increasing the value of 'h' are several. One way is to use the developing part of the flow. As the fluid flow develops, the convective coefficient decreases proportionally (behaves like an inverse square root), asymptotically approaching some constant value varying with fluid characteristics and geometry. The convective effect in the laminar flow developing region is much higher than that in the fully developed region (Shah and London, 1978). By designing to capitalize on this enhanced convective effect, the net heat extraction of the collector will be significantly greater than that of a design using fully developed flow. Studies have shown that the overall Nusselt No. and the corresponding 'h' value can be enhanced using other novel methods such as helical ribs, coiled spring or internal fins (Bergels, 1981,Webb et al, 1987, Webb, 1993, Manglik and Bergels, 2002). Calculations of the overall increase in heat flux and corresponding frictional losses in the pipepower will allow researchers to explore the feasibility of the design. Changing the pipe geometry to flatter (or elliptical cross-sectional tubes) also has a positive effect (Benarji et al, 2008). Pulsating flow through curved tubes has shown to significantly increase convective heat transfer (Guo et al, 2002). The concept does increase head loss in these pipes, but the overall benefit in heat transfer (up to +100%) outweighs the increase in head loss (up to +40%). In summary, by exploring these various techniques to enhance convection within the pipes for scaled up models, such as variations in pipe geometry, an optimum configuration can be designed to maximize the heat transfer in the pipes while minimizing head loss, therefore contributing to more efficient heat extraction.

Conduction: Enhancement of conductivity of pavements is the best way to reduce conduction resistance and thereby improve the pavement collector efficiency. Asphalt materials are poor conductors in general- however there is a difference in conductivity between different asphalt mixes. Our studies have shown that a quartzite mix can extract more heat than a regular hot mix asphalt (HMA) sample (Mallick et al, 2008); although the increase is 150%, it is relatively small in number. The addition of conducting filler materials may not work for pavement material.

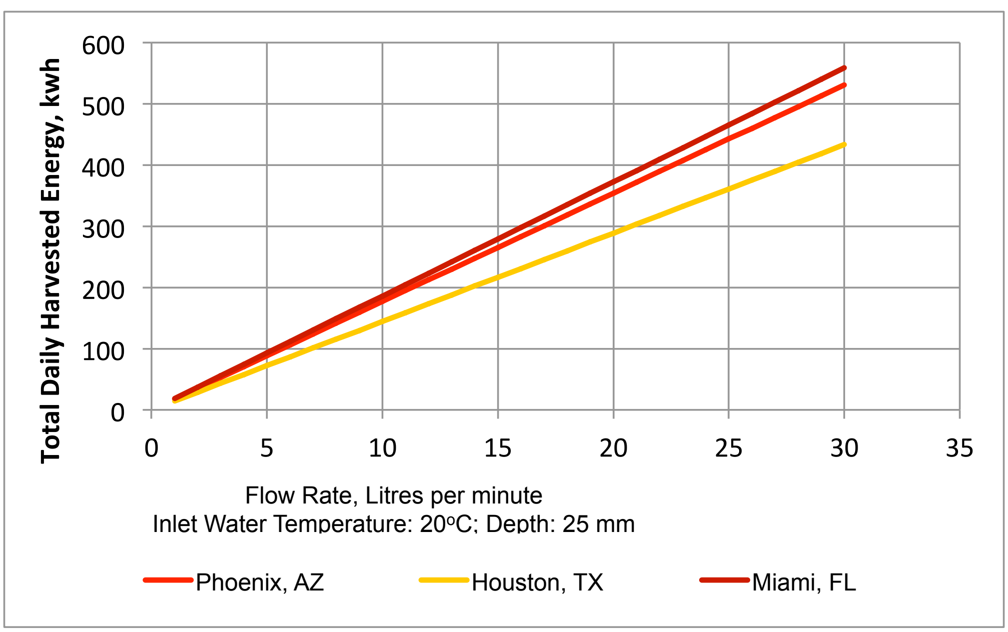


Figure 5. Total daily harvested (theoretical) energy per day, DOE-Zone-5

Experiments w/ copper powder did not yield enhanced conductivity results, possibly due to the thin layer of tar coating the particles that prevent improvement. Other enhancement methods similar to that used for inside the pipe are being explored. Annular fins (and other fin variations) attached to the pipes were modeled as a means of further improving flux into the piping. However, the effects were minimal compared to base models. Therefore, some means of bolstering heat transfer from these remote areas in the direction of the pipes must be considered. The use of a highly conducting horizontal layer of material (Spreader Layer, such as graphite or carbon fibers) at the height of the pipes (that is, the layer would have the pipes embedded in it somehow) was found to be the optimum heat-spreader design for improving heat transfer into the pipes without touching the top 1" layer of pavement as we have previously constrained the design. Note that the model assumes unit depth into the page. The spreader model compared with a non-spreader model assumes a ¼" diameter pipe and a 1/" layer of material with assumed properties of aluminum. As can be seen from the Figure 5b, depending on the spacing between the pipes, the maximum amount of energy extracted with the use of a conducting layer can be nearly 4 times as much as a similar setup without the spreader layer. Through the use of a conducting spreader layer, heat extraction can be vastly improved. An optimal configuration of pipe spacing and conducting layer thickness can be designed for further maximizing heat extraction. An insulating layer of material at varying depths below the pipe can help in enhancing the heat flux as well as the peak temperatures. As shown in Figure 6a, the heat flux into the pipe increases with an insulation layer that is further below the pipe, while as shown in Figure 6b the peak temperature is attained when the insulating layer is right below the pipe. The variation of the depth of this layer was compared with the overall flux (Figure 6a) into the pipes and the maximum attainable temperature (Figure 6b), for several different pipe spacings (W=.05m, 0.1m, 0.2m, and 0.3m). The results indicate an optima for flux and temperature. Through additional optimization, a configuration can be designed to maximize the exit temperature of the fluid (therefore allowing more energy to be extracted from the fluid) with as little piping as possible.

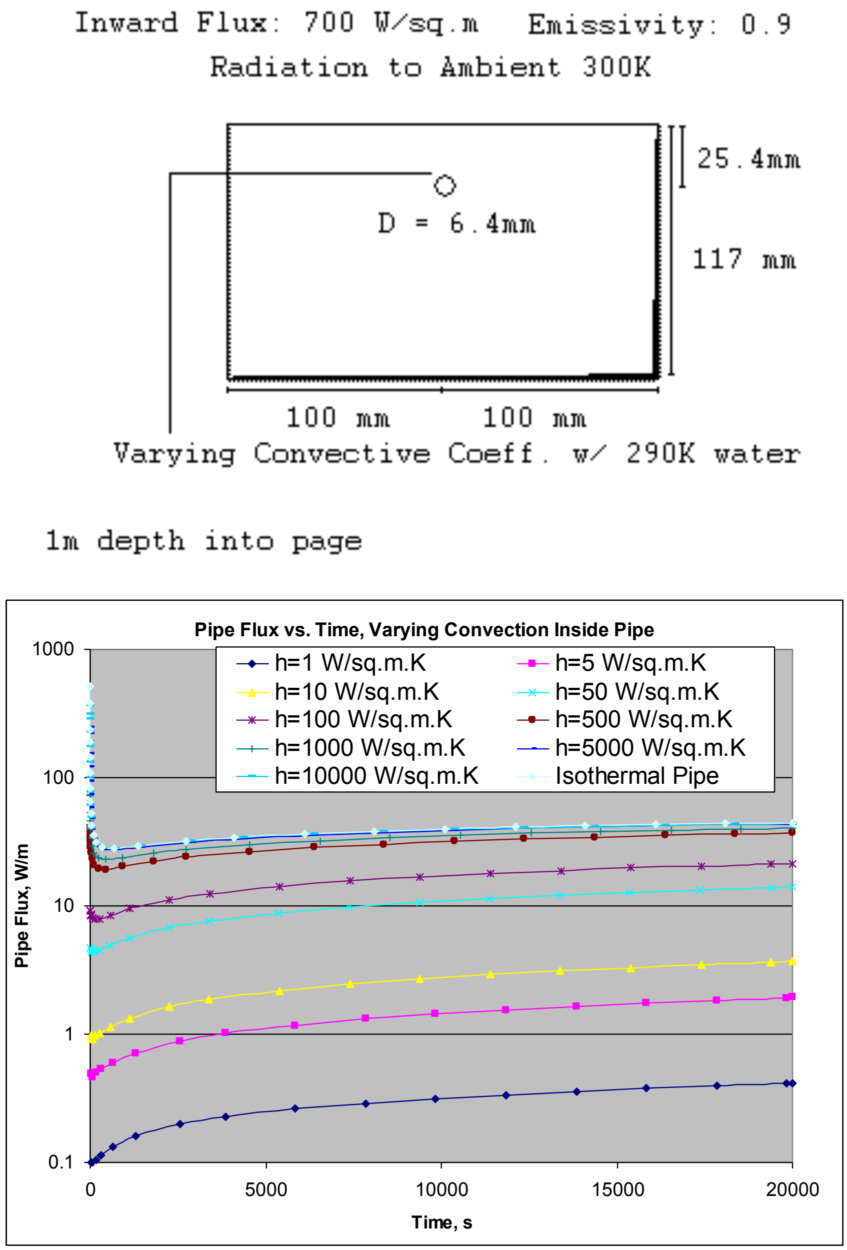


Figure 6 a) Schematic of the pavement model with a pipe; boundary conditions specified. b) Plot of heat flux into the pipe of unit depth for varying values of heat transfer coefficient 'h'

c. *Use of phase changing materials*. Another way of using the solar energy (heat) captured from paved areas is to store it temporarily in phase change materials, which can be embedded into conventional construction materials, such as Portland cement concrete (PCC) , HMA, or gypsum plaster. Due to the latent heat effect a PCM can act as heat sink (absorbing heat during melting while sustaining a constant temperature) or heat source (releasing the stored heat during solidification while sustaining a constant temperature). Thus, PCC or HMA walls or panels embedded with a PCM (e.g., paraffin) can prevent overheating and reduce the cooling loading in summer and save heating energy in winter. The considerations for selection of an appropriate PCM include: (1) PCM capsules that are strong enough that there is no need to protect them against destruction during integration into conventional construction materials; and (2) small capsules that enable it to be well distributed with conventional construction materials and thus to achieve an adequate heat transfer rate to charge and discharge the stored heat. To design a PCM modified PCC or HMA with adequate structural and heat storage capacities, a proper amount of the PCM to be integrated into conventional construction materials needs to be determined by considering the

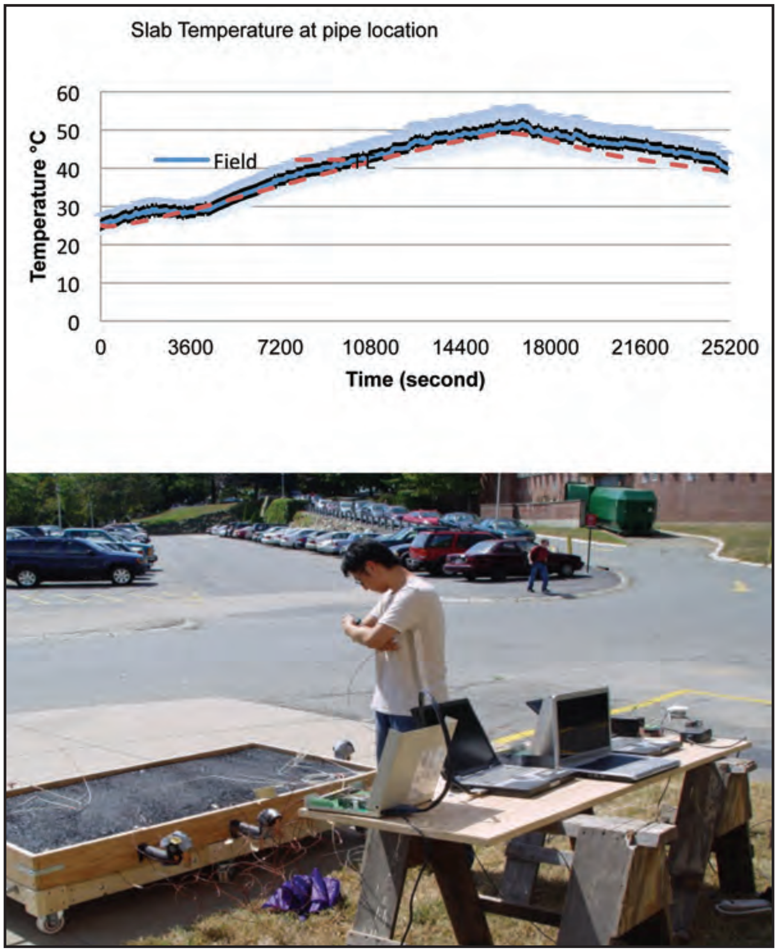


Figure 7. Examples of experimental and finite element results and set-up

influence of the PCM concentration on mechanical properties of conventional materials (this aspect will be evaluated by conducting compression strength on PCC samples with various amounts of the PCM), and the heat storage capacity and the heat transfer rate to charge and discharge the heat.

d. *Simulation of large scale system*: The next level of complexity would be the implementation of a periodic radiation boundary condition that will simulate a 24 hour cycle including the day and night conditions. Researchers will then be able to extend their simulations to cover a week or a month. During this process solar radiation data for various cities (latitudes) could be used to perform a detailed analysis. Our preliminary data has shown that our model has been able to accurately predict the temperature distribution within a slab that has been exposed to solar radiation over a 24 hour cycle at WPI. Experimental setup (Mallick et al, 2008) and examples of results already obtained are shown in Figure 7. The further enhancement of complexity will be a useful tool to calculate the total heat energy that is extractable.

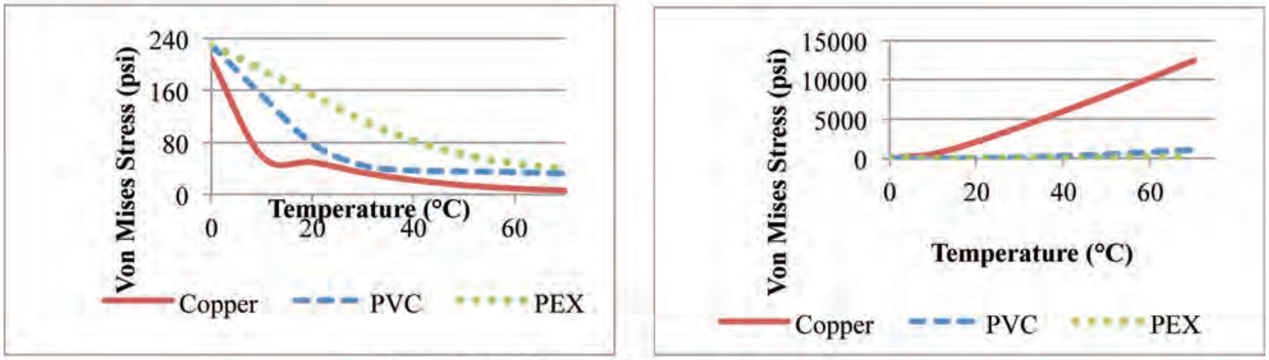
e. *Stresses in pipes and pavement*: The use of a piping system underneath the pavement surface offers several challenges of pavement layout, design and construction, which have to be met. Stresses have been determined for different depths of location of pipes, a range of temperatures and different piping materials. Note that high stresses in pavement can be taken care of with the use of high strength polymer modified mixes, which have been reported to show strengths of one or more orders of magnitude compared to that of a mix with conventional asphalt, as well as with flexible pipes. Results of stresses, as well as heat transfer experiments with different types of pipes are shown in Figure 8. In terms of heat transfer, Radiant PEXAL pipes are comparable to metal pipes.

f. *What are some feasible cycles/systems to be used?* Once heated water (or any other fluid) is obtained, the next step is using it for the building infrastructure system. Depending on the amount of extracted energy and the specific requirement of the building (or the establishment), there is a need to design the storage and the subsequent water use system. A wide range of cycles are possible based on the possible use of the extracted energy as shown in Figure 9a. It will be influenced by the building system being explored as well as the geographical location. Therefore, for every situation there is a need to perform an exergy analysis of the heat exchangers as well as the cycles (Moran and Shapiro, 2008). Since the water will be heated in the pavement for a given solar cycle (6-8 hours maximum), and this cycle may not exactly coincide with the load demand in the building, a storage system has to be available in which extracted heated water needs to be stored. Also, since the solar energy available is more in the warmer climates where buildings have larger cooling loads, ideally the focus should be absorption chiller systems and solar air-conditioning systems.

Storage System: The heated fluid coming out of the pavement system needs to be stored in an insulated tank. The size of the tank can be determined based on the requirement of the building (or establishment) as well as the ultimate utilization potential and purpose of the fluid. Assuming a sinusoidal solar radiation with maximum energy input of Q_{max} to the fluid and a steady constant load of L_0, the temperature of the fluid in the storage tank can be predicted by performing a transient energy balance of the fluid in the tank, according to the following equation.

$$T_s(t) = T_{so} - \frac{1}{(mc_p)_s}\left(L_0 t - \frac{2\tau Q_{max}}{\pi}\sin^2\frac{\pi t}{2\tau}\right)$$

In the above equation t is the time and T_s represents the length of the solar day. The temperature of the fluid is a strong function of the solar radiation pattern as well as the thermophysical properties of the fluid. For example water with a higher capacitance (mc_p) provides lesser temperature fluctuation to the fluid. Since the peak temperature of the pavement surface and that of the water is not expected to exceed the boiling point, water is expected to be the medium widely used as the circulating



Stresses in pipes and pavements

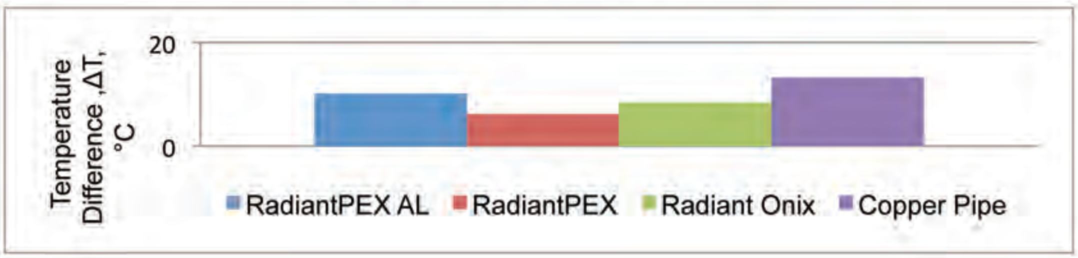


Figure 8. Temperature difference between inlet and outlet water for the different piping materials
Note: Radiant PEX AL – cross linked polyethylene, with aluminum layer; Radiant PEX - cross linked polyethylene; Radiant Onix - Ethylene propylene diene M-class rubber (EPDM) with Aluminum oxide layer.

fluid as well as for storage. For some cooler climate applications ethylene glycol-water would be the preferred fluid. Storage tanks have to be designed to capture the maximum amount of energy that is required for the system as well as the maximum available energy from the pavement. Standard insulated steel tanks are used for a majority of the applications using water. Careful consideration has to be given to the lining of the tank if phase change materials like salt or paraffin based systems that have compatible phase change temperatures in the 40-50°C are used.

Normally, it is desirable to separate out the heating fluid that is passing through the pavement from the storage (or end use) fluid. Therefore a heat exchanger will be required that heats up the storage fluid prior to going into the storage tank. We shall design a counterflow heat-exchanger since it gives the highest effectiveness per NTU, where $NTU=UA_{hx}/(mC_p)_{min}$. For non-phase change systems, where

$$(\dot{m}C_p)_{\min} = (\dot{m}C_p)_{\max},\ \varepsilon_{hx} = NTU/(NTU+1)$$

treating the pavement as the collector, our goal is to design a heat exchanger with a range of collector- heat exchanger temperature distribution and then calculate the efficiency given by

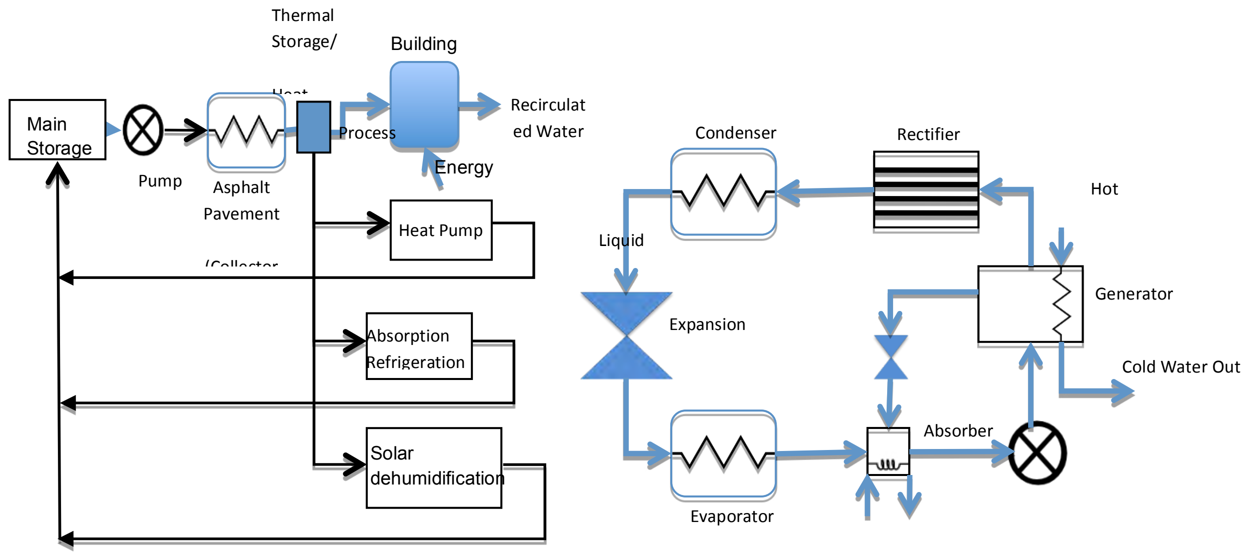
$$\eta = F_{hx}F_R\{\tau\alpha - U_c(\Delta T/I_C)\}$$

where DT, is the approach temperature difference given by the difference in the average pavement temperature and the inlet fluid temperature to the heat exchanger. The heat exchanger penalty factor (Fhx) that needs to be coupled to the collector efficiency has been developed for a linear collector model by deWinter (deWinter, 1975).

$$F_{hx} = \{1 + [F_R U_C A_C/(\dot{m}C_p)_c][(\dot{m}C_p)_c/\varepsilon_{hx}(\dot{m}C_p)_{\min} - 1]\}^{-1}$$

The heat exchanger penalty factor (Fhx) can be calculated for a wide range of heat exchanger conditions and then used to calculate both the collector efficiency and determine the conditions under which the system is economically effective. Typically cost decreases for increasing ε_{hx}, but reaches a minima beyond which the cost increases with increasing effectiveness which indicates there is no benefit of increasing the NTU. It is important to determine the minima in the U-shaped curve and evaluate the surface area of the pavement under these conditions.

<u>Absorption Chilling System</u>: Among the available cooling cycles, the absorption chilling/refrigeration cycle is the most popular one where the hot water can be used in the generator section of the cycle (Figure 9b). The compressor in the vapor compression cycle is replaced by an absorption- generator system where the refrigerant is absorbed at low temperature by a fluid and the Coefficient of Performance (COP) of the cycle is defined as: $COP=Q_L/Q_g$ where Q_L is the cooling load of the refrigeration cycle given by the heat extracted in the evaporator and Q_g is the heat input to the generator. Based on various cooling loads and desired load temperatures, various absorption refrigeration systems including Li-Br- water and ammonia-water systems (Goswami et al, 1999) could be explored. These two systems will be the starting point because they have been successfully used with solar collector systems as shown in other work. The



a) b)

Figure 9a): A brief overview of the asphalt pavement collector system and the various possible utilization for a building establishment. Figure 9b): A typical absorption chiller/refrigeration system (an economizer/heat exchanger can be added between the pump and the generator). The rectifier is required in low temperature systems like ammonia/water to remove ice crystals. The evaporator draws out the cooling load QL from cooling space.

heat rate that needs to be supplied to the generator based on the combination of cooling load, absorber and condenser temperature and possible ratio of the absorbent and the refrigerant need to be determined. This will involve a careful study of the refrigerant-absorbent equilibrium phase diagram and determining which system is the optimal of a specific setting. If all the heat in the generator cannot be supplied by the heat from the pavement collector, it can be used as a co-generation system along with additional supplemental heat.

Solar Desiccant Dehumidification: In humid climates, proper indoor ventilation maintenance can be achieved by treating the ventilation air with a desiccant system followed by using the dried air for sensible cooling in a typical absorption refrigeration cycle as described above or regular evaporative cooling. The desiccant system can be recharged by heating it using the heat extracted from the pavement. Although both solid and liquid desiccant systems may be used, liquid desiccants tend to be more efficient because of the ability to pump them. A proper choice of liquid desiccant has to be made for use in the system. The diluted desiccant enters the heat exchanger and gets heated by the stream of concentrated desiccant. Then it moves through the heat exchanger where the heat from the pavement system will further allow the desiccant to release the water vapor. By passing it through an appropriate regenerator with dry air flowing through it, the moisture can be removed. Expressions for humidity effectiveness and enthalpy effectiveness can be calculated for specific desiccants based on the relationships provided by Oberg and Goswami (Oberg and Goswami, 1998).

Heating System:

a. Process Heat: Although, we expect the pavement solar collector system to be used more widely in warm climates compared to cooler climates, heat generated from the system could be widely used as process heat for various industrial applications. The outline for the process heat follows the previously described heat exchanger setting where the heat extracted from the pavement is run through another heat exchanger that will heat up a preferred fluid to a specific temperature. It has been shown that the second law efficiencies of industrial process applications for temperatures below 260°C is higher for solar systems compared to fossil fuel systems (Kreidler, 1979). After researchers have evaluated the total heat that is extractable from the solar system under different insolation conditions, they should have a comprehensive picture of possible water/fluid temperatures that are attainable through the pavement solar system at various locations. They can then use a heat exchanger system to heat air or water or another fluid for a process heat. Based on the exit temperature of the final fluid, they will be able to determine which processes can be treated using this heat. A comprehensive calculation of the energy savings in an industrial park and possible highway rest area where there are restaurants could then be conducted. Based on our preliminary results, we feel that the solar pavement heating system can be widely used in the food industry and in several industrial paint applications and certain textile based applications. Although the heat supply may not be able to supply the entire requirement of the process, it can be part of a cogeneration cycle that will allow for significant savings in areas where there are big parking lots;

b. Heat Pump: Heat pumps can be a method to supply process heat under certain conditions. They can also be used for space heating. The system consists of the evaporator that is run by the load from the stored energy from the pavement. The advantage of this system is that some application can be found in medium to cooler climates (like Boston), where the pavement temperature is still well above zero during a large part of the day but space heating is required in buildings. The feasibility of heat pumps in various applications including cooler climates for a wide range of loads on the evaporator based on the temperature of the heated water needs to be explored. The COP of the system defined as the ratio of the heat output from the condenser to the required compressor work input will be calculated. Using heated air as the source of evaporator load also needs to be explored. The air will be heated separately by the storage fluid. One advantage of using heated air is the ability to use it as a reversing heat pump using a reversing valve, where the evaporator and the condenser switch functions. In this case the evaporative load would be pulled out of the building and heat would be rejected to the atmosphere (or possibly charge the air). Careful energy analysis needs to be performed to evaluate the feasibility of such systems and the benefit provided by the heated asphalt pavements. Because of possible high temperatures from the pavement, using refrigerants with higher vapor pressure need to be explored, so that we are able to use condensers at higher temperatures and therefore provide useful process heat applications. Another idea that needs to be explored is the concept of cascade refrigeration system that may allow us to reach higher condenser temperature.

The infrastructure could be modified to transform the role of the built environment as an energy sink to one as a source. It also generates usable energy by harvesting solar energy, thus reducing the need for fossil energy that has contributed to atmospheric pollution and global warming. Furthermore, the adoption of the new/retrofitted infrastructure will create demand for products and services for building and maintaining it that can give a substantial impetus to economic growth since the stationary built infrastructure constitutes as big a part of the urban environment. It however involves investment with high sunk costs and hence it requires either public expenditure or appropriate incentives for the private sector to invest in it. Many economic/social processes need to be explored for investigating the adoption and the impact of the energy harvesting infrastructure. These include:

a) *The adoption process*: The adoption of a new infrastructure will depend both on its sunk costs and its operation and maintenance costs in addition to following a diffusion profile. Based on those criteria, the adoption is often affordable to more affluent towns and communities that can pay for the sunk costs, even though the low maintenance and operation costs might potentially be of greater utility to less affluent communities. Thus the proposed infrastructure, when introduced without appropriate incentive mechanisms, may lead to undesirable social disparities. The overall social impact needs to be explored.

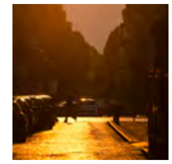
b) *Public sector investment, cost recovery and burdens*: A good part of the proposed infrastructure must be implemented in the public sector. The burden of public sector investment on the various cross-sections of the community, need and policies for minimizing the collective burden, and directing costs to the users need to be explored.

c) *Maintenance regime*: The new infrastructure will call for the creation of a maintenance regime for the energy harvesting function as well as the service component of the infrastructure to be delivered reliably. The principles for designing a least disruptive and most cost effective maintenance regime needs to be developed and applied;

d) *The impacts of adoption of the energy-harvesting infrastructure on economy and environment*: The development of the new energy harvesting infrastructure and its maintenance will create a new sub-economy whose size can be as large as the auto-related industry and services when this type of infrastructure is widely adopted. The creation of this sub-economy will also substantially reduce the demand for conventional energy generated mostly from fossil fuels. On one hand this might drastically reduce greenhouse emissions, while on the other it might bring down the price of the conventional energy, thus increasing its use in industry and also altering the cost-effectiveness of the energy-harvesting infrastructure. An assessment of these impacts in a systems framework should be conducted to address the implementation agendas (Ramos et al, 2009, Saeed, 2010, Saeed and Pavlov, 2008, Saeed and Xu, 2004, Saeed, 2004, 2003, 1998, Xu and Saeed, 1998, 1994, 1992). Given that disciplinary investigations are often limited by their respective knowledge domains while the impacts of our decisions may occur across those domains, it is considered important to integrate knowledge across disciplines for arriving at realistic findings. A systems framework needs to be adopted to integrate cross-disciplinary concepts to address the above agendas. It will involve constructing models subsuming economic and psychological factors as well as the engineering practices driving decisions in a problem context. The models so constructed will serve as a laboratory for experimental analysis using computer simulation. The broad guidelines for practicing the proposed system framework are described in Sterman (2000).

Summary

Roadways, particularly asphalt based systems have some unique thermal properties that may have potential benefits in the long term energy management of infrastructure based systems. Since roadways have high absorptivity, low thermal conductivity and high heat capacity, a large part of solar energy reaching the surface is easily captured in the pavement offering challenges and benefits. Pavements have the potential to store energy past sundown and gradually give off the energy that can then be used for various purposes. Particularly in suburban and rural settings,the energy can be used for hot water in various appliances, restaurants and part of the energy cycle in absorption



refrigeration. In rural communities, the energy can be used for water purification and as part of anerobic digestors that are used to generate small scale electricity. This has a long term potential in developing nations. Since heavily dense population belts are in the subtropical regions with huge urban sprawling, combining the road network to the building infrastructure is a must. Heavy traffic conditions with high temperatures leave roads susceptible to rutting, therefore the spreader-pipe mechanism allows the lowering of the rutting potential by lowering the temperature. In addition to that, the energy harvested can be coupled to the building for cooling, heat pump or other applications. This concept can be merged with appropriate technologies that can also prevent urban heat island effects.

Rajib Basu Mallick is a graduate of Jadavpur University, India, 1989, did his Masters and PhD from Auburn University, and worked as senior research associate at the National Center for Asphalt Technology (NCAT). His main research interests are in the optimum utilization of natural resources and sustainable construction, specifically related to the pavement industry. His work focuses on recycling of asphalt pavements, understanding and modeling the behavior of recycled materials, harvesting energy from pavements, and understanding temperature profiles and reducing temperatures in pavement layers. Rajib has close to 100 publications, including a textbook, and also a US patent, and has conducted numerous research projects for the Federal Highway Administration (FHWA), state Departments of Transportations (DOT)s, Federal Aviation Administration (FAA) and Massachusetts Port Authority, and consulting work in the area of both highway and airport pavements. He is a registered Professional Engineer in the state of Massachusetts.

Sankha Bhowmick obtained his undergraduate from Jadavpur University, Calcutta in 1992. He worked for Philips, India as a mechanization and maintenance engineer in the color television and audio equipment factory for two and a half years before coming to the US for his masters and Ph. D. His concentration in graduate studies was heat transfer and thermodynamics with a keen interest in their application in biomedical science. His Ph.D. dissertation was optimization of thermal therapy for treatment of prostate cancer. As a research fellow at Harvard Medical School, he has been trying to preserve mammalian cells, so that they can be kept in suspended animation for extensive time periods (months-years) and then revived for use when necessary. The overarching theme of Prof. Bhowmick's work is studying heat, mass and chemical stresses in mammalian cells under altered environmental conditions. Currently, he is actively involved in developing nanofibrous scaffolds for various tissue engineering applications. One such application is the bioactive bandage for wound healing.

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Leveraging Climate Adaptation Planning for Heat Island Mitigation

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Environmental Resource Manager
City of Chula Vista

For many jurisdictions across the country, heat island mitigation efforts – namely the proliferation of shade trees – have been mainly driven by community beautification projects or utility-sponsored tree planting initiatives. However, the emerging trend of local governments developing climate "adaptation" strategies presents a novel opportunity to further heat island mitigation work. While climate "mitigation" strategies target the reduction of greenhouse gas emissions, climate adaptation seeks to identify and reduce the long-term risks (and associated costs) of local climate change impacts. The following article highlights the City of Chula Vista's experience developing local climate adaptation strategies and, as a result, the jurisdiction's renewed emphasis on heat island-related initiatives.

Background

The City of Chula Vista is the second largest municipality in San Diego County, California with a population of nearly 250,000 residents. The City was incorporated in 1911 and has transitioned from a rural farming community to a semi-urban area over the last century. Its location just 7 miles from downtown San Diego and the Mexican border places Chula Vista at the center of one of the richest economic and culturally diverse zones in the United States. The City has a long, proud history of sustainability accomplishments and has been recognized by the US Environmental Protection Agency, California Air Resources Board, California Sustainability Alliance, Sierra Club, and US Green Building Council.

While the City of Chula Vista has had an adopted *Climate Action Plan* since 2000, its focus was limited to reducing greenhouse gas emissions (i.e. climate mitigation). Chula Vista's interest in better understanding the potential vulnerability of its infrastructure, economy, and public health to climate change (i.e. climate adaptation) was spurred by the release of the San Diego Foundation's "Focus 2050 Study: San Diego's Changing Climate" in 2008.[1] The report, which was developed with the assistance of local university researchers and technical experts, presented downscaled climate change impact data for the greater San Diego area. Generally, the study concluded that by 2050 the region would be subject to hotter and drier weather, diminished imported water supplies, more poor air quality/heat wave days, more frequent wildfires, shifts in habitat and species distribution, and increased rates of sea level rise. These projected impacts were also highlighted later by the State of California through its "Climate Adaptation Strategy" (2009).[2]

Stakeholder-Driven Climate Adaptation Planning

Realizing that some level of local climate change will occur despite efforts to mitigate greenhouse gas emissions and that it will likely have noticeable impacts on Chula Vista's quality of life, the City Council directed staff to convene a community stakeholder group to help develop potential climate adaptation strategies. The stakeholder group (named the "Climate Change Working Group") included representatives from development companies, business associations, energy and water utilities, environmental organizations, and education institutions. With support from City staff, the group held 11 publicly-noticed meetings throughout 2010 to review expected climate change impacts and to identify over 180 opportunities to reduce these risks. In addition, the group hosted two public "open houses" on climate adaptation planning to solicit additional feedback from the broader community.

The group was supported by regional experts, climate scientists, and staff from multiple municipal departments. While there were no external consultants hired to support the climate adaptation planning work, it should be noted that the City and stakeholder group received in-kind technical support from ICLEI-Local Governments for Sustainability and the San Diego Foundation. Using a variety of criteria to vet the 180 potential strategies, the stakeholder group ultimately chose 11 strategies to recommend to City Council. The suite of strategies generally targeted urban heat island mitigation, water reuse, public health concerns, coastal resources, and the local economy. In October 2010, the Chula Vista City Council accepted the recommendations and directed City staff to develop more detailed implementation plans. As a result, Chula Vista became one of the first jurisdictions in the nation to have climate adaptation strategies incorporated into its *Climate Action Plan* and has since been actively implementing all 11 strategies.

Urban Heat Island Initiatives

By 2050, annual average temperatures in the San Diego region are expected to increase up to 4.5 degrees Fahrenheit with summer temperatures increasing even higher.[3] This temperature shift will likely amplify the "urban heat island effect" and its negative community impacts. As such, the Climate Change Working Group recommended three strategies to address these climate change impacts related to the urban heat island effect – cool paving, cool roofs, and shade trees.

For cool paving, the stakeholder group suggested expanding and institutionalizing (through adoption of a new municipal ordinance) the use of reflective or "cool" materials into the City's pavement management projects. Cool pavements refer to a range of established and emerging paving materials that store less heat and have lower surface temperatures compared with conventional asphalt pavement. The cool paving materials are generally lighter in color and can be integrated into new roadways and parking lots or sometimes applied as a surface treatment to existing paved areas.

Because few jurisdictions and public agencies have implemented cool paving materials into their capital improvement projects, Chula Vista first commissioned a study to qualitatively analyze cool paving options. The resulting "Cool Pavements Study" assessed the costs associated with reflective paving, outlined installation techniques, compared short and long-term performance (with conventional paving), and identified operational and/or environmental co-benefits.[4] In general, the study concluded that Chula Vista could make modifications to its existing pavement treatments that would increase their solar reflectance, namely by adding lighter colored aggregate into pavement mixtures. With this information, the City hopes to implement some of the study's recommendations in select demonstration areas in the next few years. The ultimate goal is to develop new "cool" pavement standards that would guide all future municipal pavement projects.

In regards to shade trees, the Climate Change Working Group recommended that Chula Vista adopt a shade tree ordinance, so that shade trees are incorporated into all municipal improvement projects and all private development parking lot projects. The group also noted that any new ordinance should be flexible to provide alternative compliance methods such as installing solar carports in parking lots. Shade trees are useful in addressing higher temperatures (and its resulting increased energy demand) by acting as a natural cooling mechanism for urban areas. In addition, canopy-forming trees help reduce storm water runoff, provide habitat for wildlife, and increase property values.[5] As such, the Chula Vista City Council passed a new Shade Tree Policy in May 2012, which requires parking lots to be designed to have 50% shade coverage within 5 years of installation.[6] Alternatively, projects can incorporate cool paving materials or shade structures to meet all (or part) of the 50% coverage requirement, if desired. Finally, the new policy gives bonus coverage to existing shade trees that the project retains in order to help preserve healthy, mature trees.

Finally, the Climate Change Working Group recommended that the City require new residential development to install "cool" roof technology. Similar to cool paving, cool roofs use materials or colors that improve their solar reflectance and thus help to mitigate urban heat island impacts. In addition, cool roofs can reduce a home's solar heat gain helping to lower its energy demand for air conditioning and to improve occupant comfort. To help inform the creation of a new policy, Chula Vista conducted an analysis comparing the cost differential between traditional and cool roofs and the payback period from the resulting energy cost savings. While many newer homes already are installing "cool" materials (such as clay roofs), the City estimated that the additional roofing cost would be at most $75 for a 2,500 square foot single-family residential. The analysis demonstrated that cool roofs were cost-effective in the City's inland areas (which are generally warmer) because the energy cost savings paid back the incremental cool roof costs within its lifespan. As such, the Chula Vista City Council amended its building code in March 2012 to require new homes in its eastern area to use cool roofing materials as outlined in California's green building guidelines (Cal Green Tier 2 – Solar Reflectance Index of 78 or greater).

Conclusions

As highlighted above, the City of Chula Vista has made significant progress addressing urban heat island concerns over the last few years by developing and implementing climate adaptation strategies through a stakeholder-driven process. These strategies have been incorporated into a formal *Climate Action Plan*, which many communities in California and across the nation are using to address the local threat of climate change and to comply with new state or regional regulations. Many jurisdictions are also using a *Climate Action Plan* to serve as the community's general sustainability blueprint outlining various activities to improve quality of life related to utilities, land use, building codes, urban forestry, storm water management, waste disposal, and transportation. For these reasons, climate adaptation strategies offer an effective new tool to expand local urban heat island initiatives and to institutionalize those initiatives in a long-term *Climate Action Plan*.

Brendan Reed is the Environmental Resource Manager for the City of Chula Vista, where he is responsible for the development of sustainability programs and policies dealing with energy management, water conservation, and global climate change. As part of these efforts, Brendan coordinates a multi-departmental team tasked with implementing climate mitigation and adaptation strategies to lower Chula Vista's greenhouse gas emissions and to reduce future risks from climate change impacts, respectively. Brendan Reed also represents the City of Chula Vista on numerous regional and statewide working groups including the San Diego Regional Climate Collaborative and the League of California Cities' Environmental Quality Policy Committee.

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Climate Change in the Places We Live: What the European Heat Wave of 2003 Reveals about Climate Change in Cities

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What follows is an excerpt from the recently published The City and the Coming Climate: Climate Change in the Places We Live (Cambridge University Press), authored by Brian Stone. The excerpt is taken from the book's prologue, which re-examines the European heat wave of 2003 in light of evidence that cities around the world are warming at twice the rate of the planet as a whole.

The unseasonably warm weather throughout Great Britain in the spring of 2003 was embraced by a population accustomed to the persistently overcast and damp conditions of a Northern European winter. Although still cold, February and March of that year had yielded an unusual number of sunny days, with relatively few rainstorms and periods of overcast skies. In April, Britons flocked to beach communities for the Easter holiday, taking advantage of temperatures reaching into the 70s, a generous 10 degrees above normal for that month. As one media report noted at the time, not even Miami, Florida, could muster the same tropical conditions experienced in Northern Europe at times that year. Mother Nature, it seemed, was smiling on the island kingdom.

The explanation for Britain's good fortune was to be found in the presence of a stationary high-pressure weather system centered over Scandinavia, which was drawing in warmer air from farther afield and elevating temperatures across Europe. The warm weather that Easter weekend was enjoyed in several European capitals, where long-shut windows were opened to blue skies and winter layers removed. In the spring of most years, momentary glimpses of the Sun over Northern Europe are to be celebrated; this year, however, the Sun was here to stay.

Although no one recognized it at the time, Europe was experiencing the early stages of a heat wave so extreme it would far surpass any comparable weather event in more than three centuries of record keeping. Since temperature observations were first maintained in 1659, a period when Louis XIV ruled France and the Pilgrims occupied Plymouth, not a single summer had produced temperatures so intense and over such an extended period of time. Maintained by a succession of stationary weather systems over the Northern Atlantic and Central Europe, conditions of excessive heat and drought would persist for almost eight months. By summer's end, the heat wave had reduced ancient rivers to non-navigable streams, consumed in fire an area larger than some European nations, and claimed more lives than the United States lost in a decade of warfare in Vietnam.

The heat wave of 2003 would constitute the single most catastrophic weather event to be visited on Europe – and, arguably, any modern nation – during the period in which weather observations have been recorded. Less than a decade since its occurrence, however, many outside of Europe will not recall having heard of the event.

This perhaps was the central lesson of the crisis: heat kills quietly.

Economic and Human Toll of Extreme Heat

In the months following the heat wave, postevent assessments would document massive social, economic, and environmental impacts. By the end of the summer, more than 25,000 fires had consumed a total of 647,069 hectares across Portugal, Spain, France, Italy, Austria, Finland, Denmark, and Ireland – an area roughly equivalent to that of Luxembourg. Portugal alone would lose an estimated 10% of its total forestland. Agricultural losses were unprecedented. The excessive heat and drought reduced fodder harvests in France by an estimated 60% and by at least 30% in neighboring countries. One of the most productive agricultural regions in Italy reported a 40 to 50% drop in olive production and a 40 to 100% reduction of the peach, apricot, and grape yields, with the costs of produce on the shelf in Britain rising by 40%. The limited evidence available suggests the impact of the heat on livestock was substantial: it was reported that 80,000 chickens perished on a single farm in England. Overall, economic losses from the heat wave across Europe were estimated to be about $13 billion, a figure that is certain to underestimate the true costs.

The most consequential statistics, however, concerned the loss of human life. European governments were astounded to discover the true number of their citizens who had perished from the heat over the course of several weeks in a single summer. A joint study commissioned by the European Union (EU) would show through comparisons of fatality rates in June through September 2003 with previous months, or with the same months in previous years, that tens of thousands of excess fatalities had resulted from the extreme heat.

The epicenter of the disaster was in the countries of France and Italy. Initially estimated in the immediate aftermath of the heat wave to have suffered 5,000 fatalities, French officials would later discover this number to underestimate the actual death toll by about 300%. During the period spanning June through September 2003, France suffered a staggering 19,490 excess deaths from the heat wave – almost 12 times greater than the number of deaths typically experienced during these months. Italy was found to closely match this grim total, with 20,089 citizens having died from the heat. What is most remarkable about these numbers – and perhaps most foreboding – is that almost 40,000 citizens had died from hot weather in two of the most affluent and medically advanced societies in the world.

In all, the EU estimated that more than 70,000 citizens of 12 countries died from heat-induced illnesses over a four-month period in the summer of 2003. This number represents more fatalities than have resulted from any EU or American conflict since World War II, or any natural disaster (hurricanes, earthquakes, floods, etc.) to have ever struck a developed nation. It dwarfs the 1,800 deaths attributed to Hurricane Katrina in 2005 and effectively renders trivial the 900 lives lost during the highly publicized SARS epidemic that struck Europe and Asia in the same year as the heat wave, an event giving rise at the time to virtual hysteria. Americans would need to experience more than 20 terrorist attacks equivalent in destruction to 9/11 before such a death toll would be approached. Yet the global response to this climate event, an event that reveals more about the profoundly changing environment in which we now live than any other yet endured, has largely been one of indifference. Although numerous books have been published and movies produced on recent disasters such as Katrina and the SARS outbreak – at the time of this writing, the U.S. Library of Congress held more than 200 books on Hurricane Katrina alone – to date, not a single book has been published on the 2003 heat wave.

Not one.

Accelerating Climate Change in Cities

The events of summer 2003 highlight a central truth about climate change that is often lost in the global- and future-oriented debate over a warming environment: the impacts of climate change at the urban scale are profoundly greater than the impacts of climate change at the global scale. And a second truth: the impacts are here with us today.

One of the key findings of postevent assessments following the 2003 disaster was that the vast majority of those who perished in the heat wave lived in cities. This fact is not explained by the larger percentage of the national populations residing in cities across Europe, because the rate of heat wave fatalities among residents of large urban areas such as Paris and London was greater than that among residents of smaller towns or rural areas. And this fact is at odds with the general presumption of superior health care in cities, which provide far greater access to emergency medical facilities. The heat wave claimed a disproportionate number of lives in cities simply because the cities were hotter than rural areas – substantially hotter.

Cities do not cause heat waves – they amplify them. Because of the greater prevalence of mineral-based building materials, such as stone, slate, concrete, and asphalt, cities absorb and retain substantially more heat than rural areas characterized by more vegetative cover. Known generally as the "urban heat island effect," this phenomenon keeps cities warmer by several degrees than surrounding countryside throughout the year. However, during unusually hot days, the divergence between urban and rural temperatures can be much greater, literally tipping the balance between an unpleasantly hot day in one environment and a public health emergency in another.

This observation is illustrated well by data obtained during the 2003 heat wave. As part of an ongoing research study unrelated to the heat wave itself, an extensive network of meteorological instruments was in place in and around Strasbourg, France, throughout the heat wave event. Data from this network showed that the increase in heat index values at the height of the event, a measure that accounts for both temperature and humidity and most closely captures the physiological impacts of heat on the human body, was about 30% greater in the downtown district than in the surrounding countryside. Nighttime heat index values, which provide the most direct indicator of the body's ability to cool down during a heat wave, were at times measured to be 50% greater in the urban center. What these measurements show is that the effects of the heat wave for urban residents were as much as 50% greater than for rural residents just a few miles away. The significance of these differences is hard to overemphasize: one's decision to remain in a city during a heat wave can quite literally mark the difference between life and death.

In the first decade of this century, for the first time in history, the majority of the planet's humans resided in cities. We are an urban planet. If ongoing changes in climate are to have an impact on the human species, most of these impacts will play out in urban environments. Yet climate science to date has provided very few insights into how cities, in particular, will be influenced by climate change. Continuously framed as a global phenomenon, with implications for the planet as a whole, the climate change of peer-reviewed scientific papers and international accords does not seem to be taking place anywhere people actually live. In fact, the moment a climate-related event with tangible geography occurs, such as a heat wave or hurricane of unprecedented intensity,

we are quickly told that no single event can be proven to be an indication of climate change. For the nonscientist attempting to formulate an opinion on the issue, the likely outcome is not surprising: if climate change is not happening in the places we live, it's not happening.

More problematic for cities than the framing of the issue, however, is the uniform adoption of the global scale as the legitimate basis for scientific inquiry. Preoccupied with measuring the rate of temperature change at the scale of the planet as a whole, we have largely overlooked the rate at which climate is changing in cities. Indeed, as examined in the following pages, temperature data from urban weather stations are statistically adjusted in the global temperature datasets employed by climate scientists to measure global warming. Were these temperature measurements not modified, we would find that the environments in which we live are actually warming at a substantially higher rate than the planet as a whole, with troubling implications for anyone who lives, works, or owns property in cities.

Above all, it is the rate at which climate is changing in cities that most clearly illuminates the lessons of the European heat wave for urban governments and residents. Were such an event to remain a statistical improbability, cities could be forgiven for prioritizing other critical needs above preparations for combating climate change. Studies focused on this question following the heat wave would show that, absent the influence of human-induced warming, an event approaching the intensity and duration of the 2003 heat wave would indeed remain quite rare, occurring, on average, once every thousand years. Yet, assuming global temperatures continue to rise at the rate of recent decades, the frequency of such a heat wave increases substantially – so much so that, by the year 2040, such heat waves may be expected to occur every year. Such a world seems hardly imaginable: temperatures of sufficient intensity and duration to physically warp the steel of railroad tracks and melt the asphalt of streets – every year.

For those of us who give ourselves better than even odds of being here in 30 years, a principal lesson of the 2003 heat wave is undeniable: this is not our grandchildren's problem alone.

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Canopy and Carbon: The Conflicting Agendas of Local and Global Climate Change Management

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The world's largest cities are warming much more rapidly than the planet as a whole. While this observation will come as no surprise to the international urban climate community, it nonetheless raises a set of questions that are central to contemporary research focused on climate change at the urban scale: What climatic factors are accelerating the pace of warming in cities? And, how should the management of climate change at the urban scale differ from the management of climate change at the global scale? These questions are at the heart of my recently published book, *The City and the Coming Climate: Climate Change in the Places We Live* (Cambridge University Press).

The answers to these questions hold important implications for urban populations in the present period. As demonstrated by the incidence of increasingly intense heat waves over the past decade, most notably across Western Europe in 2003 and Russia in 2010, extreme heat events are responsible for exceptionally large fatality rates in recent years, particularly in urban environments. Perhaps more than any other symptom of climate change, extreme heat events demonstrate the very real threat posed by changing climate today – not decades in the future – and in the planet's most heavily populated environments. Yet, at present, climate management policy is surprisingly ill-suited to address the physical drivers of warming at the urban scale.

As explored in the book, at least four changes in international climate policy are needed to better position cities to confront climate change phenomena driven not only by the global greenhouse effect but by an urban heat island effect that is typically the dominant driver of warming at the urban scale. The first of these changes entails a fundamental revision of the definition of climate change developed for the U.N. Framework Convention on Climate Change, the international agreement adopted 20 years ago this summer, at the 1992 Earth Summit in Rio de Janeiro, and which lays the policy groundwork for international climate change management. Through this agreement, climate change is defined as, "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods."[1]

What is remarkable about this definition, and ultimately problematic for cities, is that it fails to recognize the land surface drivers of warming that are often fundamental to climate change processes at sub-global scales, such as changes in albedo and the surface energy balance resulting from land use change. Fully cognizant of the importance of land surface forcing agents for climate change, the Intergovernmental Panel on Climate Change (IPCC) departs from the Framework Convention definition in asserting that "climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use" (emphasis added).[2] An important outcome of having adopted the Framework Convention definition for international climate policy is that a reduction in radiation-trapping greenhouse gases is presently characterized as climate change "mitigation," but a reduction in the radiation itself is not. Recent work suggests this incomplete characterization of climate change phenomena may be hindering the efforts of large cities to most effectively manage rapidly rising temperatures.

To assess the extent to which cities have incorporated strategies into municipal climate action plans to address urban heat island formation – the principal driver of warming trends in large cities – in addition to greenhouse gases, my research group at Georgia Tech surveyed the climate action plans of the 50 most populous U.S. cities. The results, presented in Figure 1, find that all cities for which such a plan is in place (43 of 50 cities) have adopted strategies designed to reduce the emission or enhance the sequestration of greenhouse gases. A much smaller number – 12 of the 50 surveyed – have included in climate action plans strategies specifically designed to address the urban heat island effect. In short, the most populous regions of the United States are most often preparing for a climate future that is driven by the global greenhouse effect alone. This tendency to emphasize global scale, atmospheric drivers of warming trends in climate action plans, while overlooking the local scale, land use drivers, enhances population vulnerability to extreme heat.

A second change in climate management policy needed to more effectively address the accelerated pace of warming underway in cities is the regular performance of scientific assessments at sub-global scales. In concert with periodic assessments of global scale climate processes, as carried out by the IPCC every 5 to 7 years, is the need for a systematic assessment of climate change processes at the scale of regions undergoing rapid land use change – particularly urbanized regions. While shifts in albedo and the surface energy balance carry profound implications for

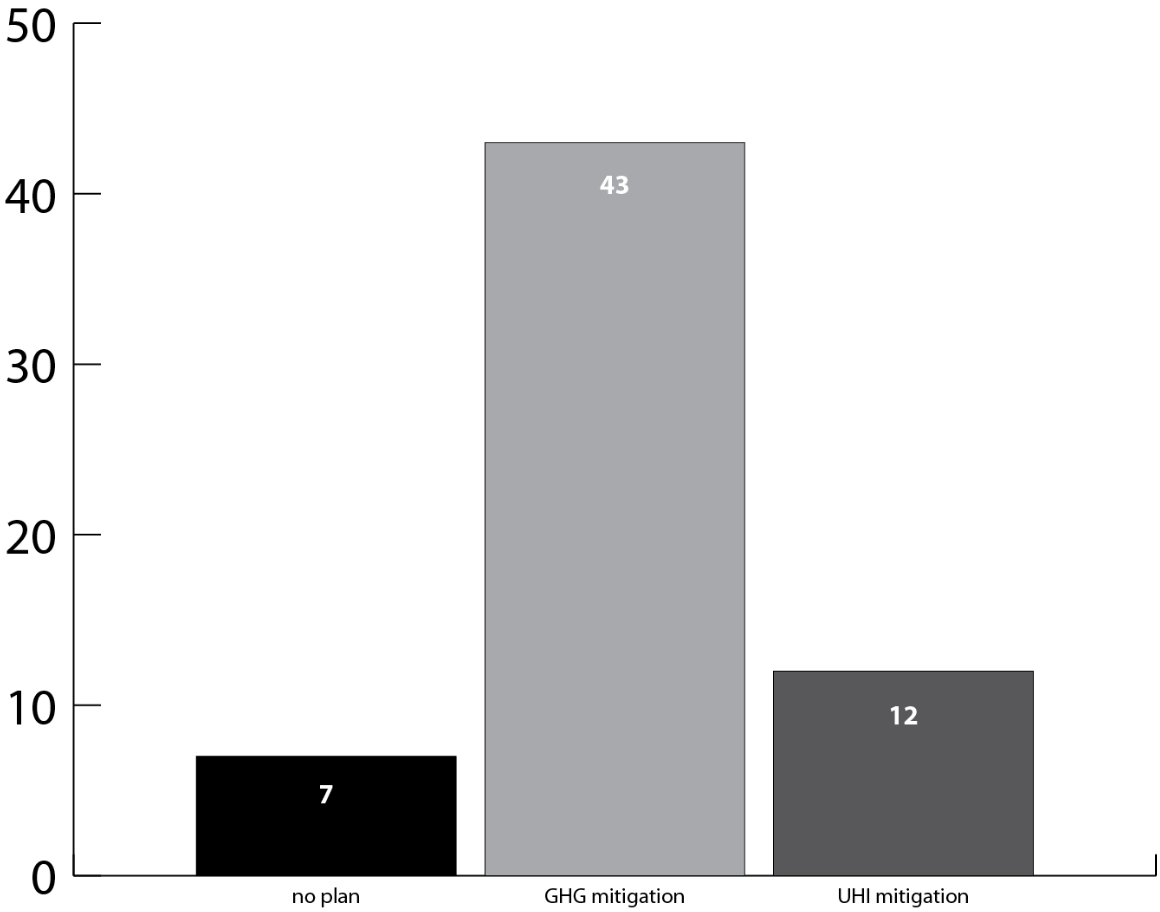

Figure 1. Frequency of greenhouse gas and/or local heat management strategies in climate action plans of the 50 most populous U.S. cities. Adapted from Stone, B., Vargo, J., Habeeb, D. Managing climate change in cities: Will climate action plans work? Landscape and Urban Planning, in press.

climate at local to regional scales, the impacts of such shifts are often obscured by the globalized metrics of climate change incorporated into global scale assessments, such as the oft-cited mean annual change in global temperature. If management programs are to be developed to address regional-scale climate phenomena, region-specific scientific assessments will be needed to gauge the principal drivers of warming at this scale, as well as the effectiveness of land-based mitigation strategies in slowing these trends.

How might the policy response to a regionally based system of regular scientific assessment differ from that of a globally based assessment? A wealth of climate research suggests that land use conversions, particularly deforestation, play a far more significant role in local to regional scale climate change than at the global scale. In light of this evidence, efforts to manage climate change from local to global scales could be better integrated through an emphasis on avoided deforestation and reforestation, particularly in proximity to urbanized regions. Recent policy innovations such as the Reducing Emissions from Deforestation and Forest Degradation (REDD) program represent a positive step in this direction. But here again, the privileging of emissions over non-emissions based agents of climate forcing limits the potential effectiveness of REDD for local climate management. Rather than assessing the benefits of forestation programs in carbon-based terms alone, avoided deforestation and reforestation efforts should be valued as well in terms of local heat management.

To be most protective of human health, some percentage of global forest management activities should be targeted toward urbanized regions. Enabling nations signing onto international climate change agreements to direct forest management efforts toward their own cities where appropriate, in addition to rural areas subject to extensive deforestation, would provide a much stronger linkage than presently exists between the global policy framework and local scale planning. As urbanized regions account for only a small percentage of the global land surface, the proportion of re-vegetation efforts directed to cities necessarily would be small but could yield substantial local benefits, including both carbon sequestration and heat island management.

The potential for forestation and other land use strategies to address both the emissions and non-emissions agents of climate forcing in urban environments suggests the need for better integration of strategies focused on mitigation with those oriented toward adaptation. Characterized in the book as "adaptive mitigation," a wide range of strategies shown to be effective in reducing heat island formation are also effective in reducing emissions or enhancing sequestration of carbon dioxide. Thus, a final needed change in the international community's approach to climate management is the prioritizing of adaptive approaches to carbon management over non-adaptive approaches.

At present, non-adaptive mitigation rules the day, with the vast majority of mitigation funds being directed to energy projects that produce no secondary benefits for local populations in the form of heat management, enhanced flood protection, or agricultural resilience. For example, mitigation strategies involving the substitution of a lower carbon-intensive fuel, such as natural gas, for a higher carbon-intensive fuel, such as coal, are an effective means of lowering CO_2 emissions, yet provide few other benefits related to local climate management. A restructuring of the global policy framework to prioritize adaptive mitigation over non-adaptive mitigation, particularly in urban environments, would better integrate local and global policy objectives.

In combination, these recommended revisions to the established international framework for climate change management would substantially elevate the significance of urban environments in global climate policy. It should be emphasized, however, that cities cannot rely on the global policy framework to govern regional scale climate management. Fundamentally oriented toward the planetary-scale phenomenon of the global greenhouse effect, the Framework Convention and its associated protocols lack both the legislative mandate and regulatory scope to sufficiently alter the land use practices of cities and regions. Indeed, even national governments may lack the direct regulatory authority needed to institute changes in the land development and greenspace planning practices of municipal governments. In many countries, it is municipal governments themselves that will need to institute policy changes and secure the needed resources to enhance regional climate resilience – a task in which the urban climate research community is uniquely well positioned to assist.

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Spatial distribution of Urban Heat Island using Geographic Information System (GIS) in Greece

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Abstract

The most apparent impact of urban development on the environment is the change of its biophysical attributes. By altering the nature of the surface and generating large amounts of heat, urbanized areas modify the microclimate and air quality. On the other hand there is an increased interest in using Geographic Information System (GIS) for mapping the urban heat island in various regions. The aim of the present paper is to integrate the measurements performed in the area of Athens concerning the urban heat island phenomenon in a GIS environment and use the capabilities of GIS to calculate the spatial distribution and time evolution of urban heat island. The three interpolation methods selected are: the IDW, the spline and Kriging. Kriging Spherical is selected as the more suitable method of temperature interpolation-prediction. A video-animation was constructed with all the interpolation images. This was possible using a new feature of the GIS software called time aware raster. The animation created is a powerful tool for the visual examination of the UHI evolution on both daily and monthly basis.

Introduction and state of the art

Air temperatures in cities and urban areas are usually higher than the temperatures of the surrounding rural country. The phenomenon known as 'heat island', is due to many factors the more important of which are summarized by Oke.[1] Urban heat island studies refer usually to the 'urban heat island intensity' which is the maximum temperature difference between the city and the surrounding area. Data compiled by various sources, shows that heat island intensity can be as high as 10-15K. Extensive studies on the heat island intensity in Athens, involving more than 30 urban stations, show that urban stations present higher temperatures compared to reference suburban stations between 5 to 15°C.

Heat island is studied by various researchers in various cities. Heat island has a very important impact on the energy consumption of buildings[2,3] while increased urban temperatures exacerbate the cooling load of buildings, increase the peak electricity demand for cooling and decrease the efficiency of air conditioners.[4-6] In parallel, high urban temperatures considerably decrease the cooling potential of natural and night ventilation techniques and increase pollution levels.[7-9]

On the other hand there is an increased interest in using Geographic Information System (GIS) for mapping the urban heat island in various regions.[10-13] GIS is an organised collection of hardware and software computer systems, spatial data and human resources (Figure 1) with the purpose of collecting, recording, updating, managing, analysing and informing in any form with respect to the geographical environment. There are essentially two types of GIS data: vector and raster. These differ in how the spatial data is displayed and stored. Gordon and Kapetsky[14] presented in a summary manner useful comparisons between them. In both systems, a geographic coordinate system is necessary for viewing the site.

The last 25 years, problems associated with geographic information management are solved at a global and national level with the help of GIS. The computational models are combined with analysis tools to construct a GIS. With a GIS, it is not only

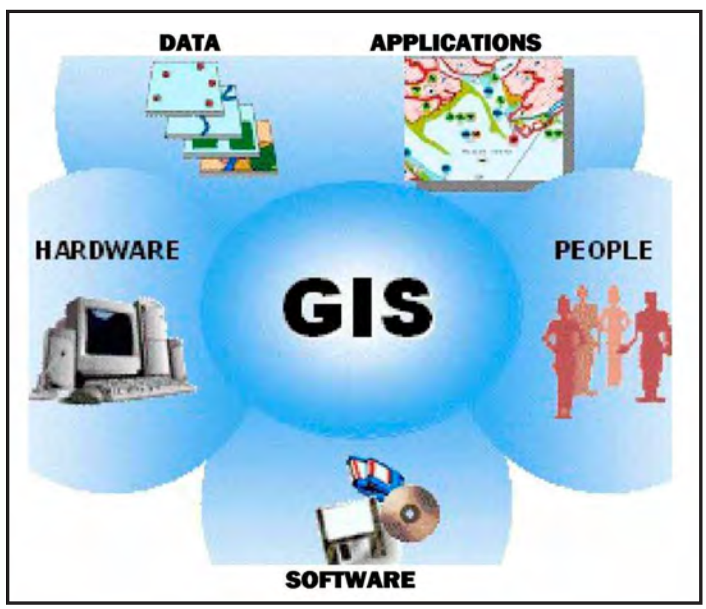

Figure 1: The components of a GIS.[15]

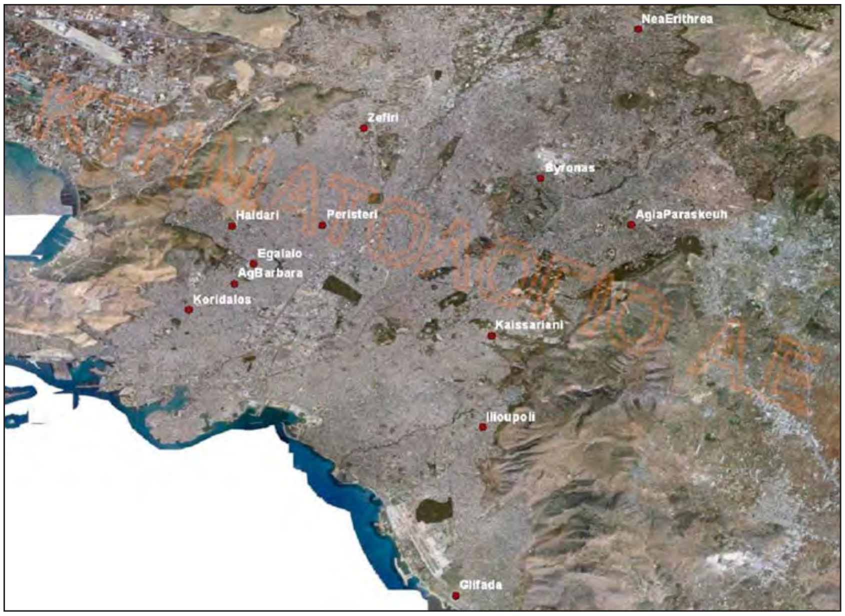

Figure 2. The location of all meteorological stations in GIS.

possible to study a specific map, but every possible map. With the right data, one can see very easily and quickly in front of any computer any information from anywhere in the world ranging from political boundaries, cities and population density of the earth to land use, energy consumption and impressions over a small Greek island.

To this end, the aim of the present paper is to integrate the measurements performed in the area of Athens concerning the urban heat island phenomenon in a GIS environment and use the capabilities of GIS to calculate the spatial distribution and time evolution of urban heat island.

The procedure followed in order to analyse the urban heat island spatial distribution in Athens can be categorized to the following steps:

- Analysis of data consistency. The available data were carefully analyzed in order to check if there are periods where data are missing since this can create problems with the GIS algorithms development and testing.
- Insert stations' position using GIS (see Fig. 2) as well as stations' 'data.
- Test the spatial distribution algorithms performance for specific periods.
- Create a python script to automatically perform spatial distribution calculations.
- Insert the parameter of time for better visualization of results and create videos of urban heat island intensity in the region as extracted by the corresponding raster levels.

Data preparation

ArcGis from ERSI is selected as GIS software for the implementation of the case study. A feature layer was constructed with the location of all meteorological stations (Figure 2 and Table 1) and a spatial database with all the available data. This is performed using ArcSDE spatial view, which is a tool for organizing information from multiple feature classes and geo-database tables into a single "virtual feature class" or table at the database level. In order to perform the interpolation methods for the temperature data the location and spatial data have to be integrated.

A limitation exists on the database software that the ArcGis use,i.e. Microsoft Sql Express. The specific database cannot have more than 254 different tables (a table for every different interpolation is needed). Therefore in our specific case only 254 hours could be available for interpolation at any given time. So an alternative database was investigated in order to overcome the above limitation. The Microsoft Sql Server edition was selected and is then coupled with ArcSDE spatial view.

Interpolation using Geographic Information System

The geostatistical analyst interpolation techniques are used to create a continuous surface either from the measured sample points stored in a point feature layer or by using the polygon

Urban climate effects for a mid-latitude city with about 1 million inhabitants (values for summer unless otherwise noted).

Variable	Change	Magnitude/comments
Turbulence intensity	Greater	10–50%
Wind speed	Decreased	5–30% at 10 m in strong flow
	Increased	In weak flow with heat island
Wind direction	Altered	1–10 degrees
UV radiation	Much less	25–90%
Solar radiation	Less	1–25%
Infrared input	Greater	5–40%
Visibility	Reduced	
Evaporation	Less	About 50%
Convective heat flux	Greater	About 50%
Heat storage	Greater	About 200%
Air temperature	Warmer	1–3°C per 100 years; 1–3°C annual mean up to 12°C hourly mean
Humidity	Drier	Summer daytime
	More moist	Summer night, all day winter
Cloud	More haze	In and downwind of city
	More cloud	Especially in lee of city
	Fog More or less	Depends on aerosol and surroundings
Precipitation		
	Snow	Less Some turns to rain
Total	More?	To the lee of rather than in city

Table 1. The list of meteorological stations and their coordinates.[16]

centroids and then predict the values at unmeasured locations from the surface created. Many studies have been done using the geostatistical analyst and some of the fields that benefit by virtue of these interpolation techniques include agricultural production, temperature data, soil contamination, mining, health care and meteorology. In this article three different methods of interpolation are selected to be tested as more suitable for temperature prediction and spatial distribution.[17] The three interpolation methods selected are: the IDW, the spline and Kriging.

The spatial distribution algorithms

The Kriging algorithm

Kriging linear interpolation algorithm was developed by the French mathematician Georges Matheron based on the idea that the values measured at neighbouring points tend to resemble more than those measured in remote points. The Kriging algorithm is expressed by

$$Z=\sum^{n}_{i=1}\lambda_i \; Z(x_i) \qquad \text{(Eq.1)}$$

In the Kriging algorithm, the weight λi depends upon the spatial interrelation of the values measured close to the area that the prediction is performed as well as on their distance from the predictive point. The weights are provided by a weighted diagram:

$$\gamma_i(h)=1/(2N(h)) \sum^{N(h)}_{i=1}[Z(x_i)+Z(x_i+h)]^2 \qquad \text{(Eq. 2)}$$

where

N(h) are the measurement points
Z is the predictive variable
h: the distance between the interpolated points
xi: the initial point
xi+h:the final point

Inverse Distance Weighted (IDW) algorithm

The IDW algorithm is a process which uses the weight of the distance between the interpolation and the measurement point. The measured points gain weight inversely proportional to the distance from the point on which the interpolation is made.

The general formula that describes the algorithm IDW:

$$Z_{(S_o)}=\sum^{n}_{i=1}\lambda_i Z_{S_i} \qquad \text{(Eq. 3)}$$

where is the interpolative value at the point s0, N indicates the number of points near the estimated location and is the weight:

$$\lambda_i=(d_{i_0}^{-p})/(\sum^{n}_{i=1} d_{i_0}^{-p}) \qquad \text{(Eq. 4)}$$

where d_{i_0} is the distance between the points s_0 and s, and p is an arbitrary positive real number called the power parameter (typically, p=2).

Spline algorithm

Spline method uses a mathematical function to minimize the curvature of the surface and produce a smooth surface which corresponds exactly to the points where the measurements are made. The method is described by:

$$Z=\sum^{n}_{i=1}\lambda_i R(\gamma_i)+T(x,y) \qquad \text{(Eq. 5)}$$

where is the estimated value, n the number of measurement points, γ_i a parameter defined by the functions $R(\gamma_i)$ and T(x,y) as:

$$R(\gamma_i)=(\gamma^2/4\,[\ln(\gamma/2\pi)+c-1]+\tau^2[k_0(\gamma/\tau)+c+\ln(r/2\pi)])/2\pi \qquad \text{(Eq. 6)}$$

$$T(x,y)=a_1+a_2x+a_3y \qquad \text{(Eq.7)}$$

where τ^2 is the weight parameter, r the distance between the measurement points and the estimated point, c is a constant equal to 0.577125 and αi are the linear equation's parameters.

The interpolation testing procedure

A subset of the entire dataset is selected in order to test the accuracy of the different methods of interpolation. The subset consists of 384 measurements from 11-05-2008 to 27-05-2008. A randomly selected meteorological station (Egaleo) is excluded from the data as a test station. For every one of the three interpolation methods and the whole subset, the predicted value from the interpolation is extracted from the interpolation images-rasters and is then compared with the measured temperature value. A set of preliminary tests is also conducted in order to find the optimum values for the different parameters of each interpolation method, i.e. number of points, maximum distance etc. Due to the large number of data and computational power-time needed for the interpolations, a script for each interpolation method was developed using Python as programming language (for more information about the script see Appendix A) for automation of the process. Mean Absolute Error (MAE) and Mean Square Root Error (MSRE) are chosen as the two indicators to evaluate the precision of the interpolation methods. The results are shown in Table 2 (the values are in °C). The smallest MSRE is about 1℃, the greatest MSRE 1.46°C; the smallest MAE is about 0.68°C, the greatest MAE 0.95°C. Kriging-spherical and Kriging-circular are the best two methods of interpolation for our case, spline is the second and IDW interpolation method has the lowest precision. It can be clearly seen from the above results that Kriging-spherical has better performance and therefore is selected as interpolation method for the rest of the study.

Table 2. Interpolation methods comparison.

Interpolation Method	MAE	MSRE
Kriging Spherical	**0.68**	**1.03**
Kriging Circular	0,72	1,08
IDW	0.78	1.22
Spline	0.95	1.46

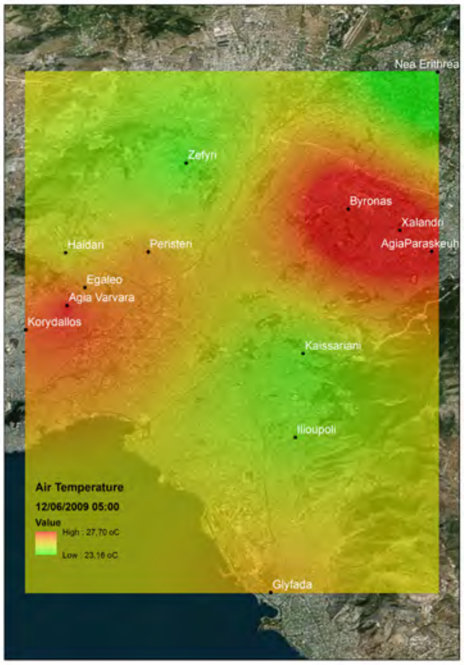

Figure 3.
A snapshot of the interpolation procedure early in the morning.

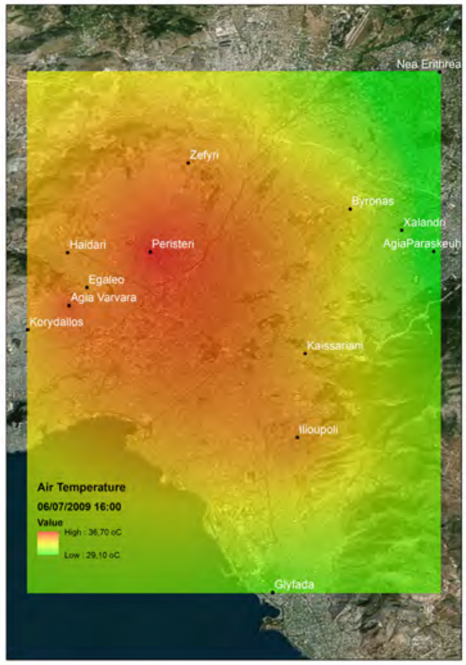

Figure 4.
A snapshot of the interpolation procedure late afternoon.

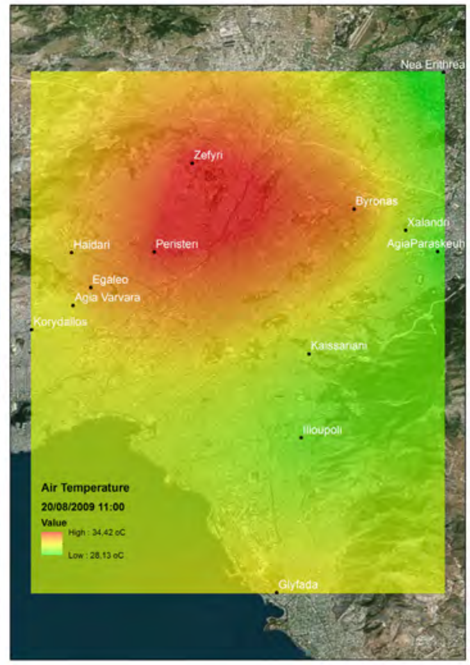

Figure 5.
A snapshot of the interpolation procedure at noon.

Results and Discussion

As a result of the previous investigation, Kriging Spherical is selected as the more suitable method of temperature interpolation-prediction for the urban heat island in Athens, Greece. Using the ArcSDE tool an integration of the whole dataset (2481 images) hourly temperature measurements for all thirteen meteorological stations with their location is performed. In this step all the available meteorological stations are included in the interpolation process. The Spherical Kriging interpolation Python script is properly modified in order to access the spatial data from the SQL server database and to perform the interpolation. As a result 2481 different interpolation images are constructed for all the available dataset. Figures 3, 4, and 5 show an interpolation of the data at different times during the day. A video-animation was constructed will all the interpolation images. This was possible using a new feature of the GIS software called time aware raster. The animation created is a powerful tool for the visual examination of the UHI evolution on both a daily and monthly basis. Also this animation can be used for the information of the general public about the UHI phenomenon and for supporting the decision process of the local authorities.

Conclusions

Geographical Information System (GIS) capacities are exploited to develop a visualized city maps' meteorological network and to integrate the UHI data collected with mathematical models. A series of spatial interpolation algorithms are tested for the spatial distribution of air temperature in the city of Athens. The Kriging Spherical algorithm showed the lowest MAE and RMSE comparing with real data. Therefore GIS can be an important tool for the prediction of urban heat island in areas where there is a considerable lack of data.

Denia Kolokotsa has a physics background from the National Kapodestrian University of Athens, as well as a MSc. degree in Environmental Physics from UOA, a MSc. degree in Architecture-Environmental Design and Computer Engineering of the Technical University of Crete. Her research interests include monitoring and measurement for energy management, indoor environment, energy efficience in buildings, solar energy and col materials, distributed energy management systems, artificial intelligence, building automation. She has participated in more than 25 EU and national projects and has coordinated 2 EU projects as well as one national project. She is the author of more than 100 papers published in scientific journals and conference proceedings. She is a member of the Advance in Building Energy Research Editorial Board and Guest Editor of the INternational Journal of Low Carbon Technologies. She is the co-founder and president of the European Cool Roofs Council and she is collaborating closely with the Cool Roofs Rating Council.

Kostas Gobakis (1984) is currently a PhD student at the Department of Environmental Engineering at the Techincal University of Crete with his main research focus on cool materials. He received his degree in physics from the Universiy of Crete (UOC) and and Master degree, titled "Prediction using Artificial Neural Networks and geographic representation using

Geographic Information Systems (GIS) of the Urban Heat Island (UHI) phenomenon" from the Techincal University of Crete, Department of Electronics and Computer Engineering. He participated in the EC project LIFE + "Forest Cities" for the preservation of forest using GIS. He participated in other European Union prjects, "EU - Cool Roofs" for the evaluation and sustainability of cold materials, "FP& Bridge" for the prediction of Urban Heat Island phenomenon in Athens, Greece and "FP& Green@Hospital" for developing an innovative energy management and control system to improve the energy performance of hospitals. He conducted an internship entitled "Analyse RHEED images for studying the relaxation of grid deformation in hetero epitaxial growth of InN," Laboratory of Microelectronics, Physics Departments University of Crete. He has one publication on international magazine and four announcements in international conferences. He is supporting the ECRC Secretariat since December 2012.

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Heat Island Mitigation Columbus, Georgia

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Columbus Planning Department

Abstract

Urban Heat Island (UHI) is a result when natural green areas are transformed into impermeable areas. As the natural landscape is surrounded by waterproof surfaces as urban areas grow, a negative impact is inevitably caused. "Hot spots" will develop on the surface and in the atmosphere which will affect air quality, public health, and energy demand at greater levels.

This article reviews and summarizes some strategies used to alleviate the UHI effect on the urban landscape in Columbus. Emphasis is placed on topics explaining these strategies such as Green/Garden Roofs, Urban Forestry, and Shaded Parking.

Introduction

Columbus, Georgia is a city in (and the county seat of) Muscogee County, Georgia, that has a consolidated government. Based on the most recent Census data, Columbus has surpassed the city of Augusta to become Georgia's second largest city with a population of 198,413, while the larger Columbus-Phenix City Metropolitan Area counts 310,531. The city has a total area of 221.0 square miles (572 km2), of which, 216.3 square miles (560 km2) of it is land and 4.7 square miles (12 km2) of it (2.14%) is water. Columbus has a humid subtropical climate. Daytime summer temperatures often reach a high in the mid-90s and low temperatures in the winter average in the upper 30s.[1]

The City is a multifaceted interaction of regional factors such as urban sprawl which increases automobile miles traveled and climatological disorders contributing to one of the most inflexible air quality problems in the area. Adjacent to the City is Fort Benning, a United States Army post which consists of 182,000 contiguous acres in Georgia and Alabama. It is part of the Columbus, Georgia Metropolitan Statistical Area, and a former census-designated place (CDP) in Chattahoochee County, Georgia, with a total population of 107,627. The Army's requirement for training land is increasing while the capacity of land accessibility to Army lands is decreasing.[2] Urbanization and urban sprawl are encroaching on military lands and creating "islands of biodiversity" on Army installations which harm the air.

Air

As the Columbus region experiences unprecedented economic growth and development, we also are facing issues with our regional air quality. Specifically, particulate matter, one of six criteria pollutants regulated under the Clean Air Act, is of increasing concern here in the Columbus-Phenix City area.

Fine particulate matter poses a greater risk to human health than coarse particulates since it more easily enters the lungs. PM is known to aggravate heart and lung diseases, and is associated with heart attacks, chronic bronchitis, and asthma. The US EPA has established national air quality standards for both 24-hour and annual PM levels, as well as for other pollutants. Areas that meet those standards are designated and termed as being "in attainment", areas not meeting the standards are referred to "non-attainment areas". Based on the most recent monitor data, the

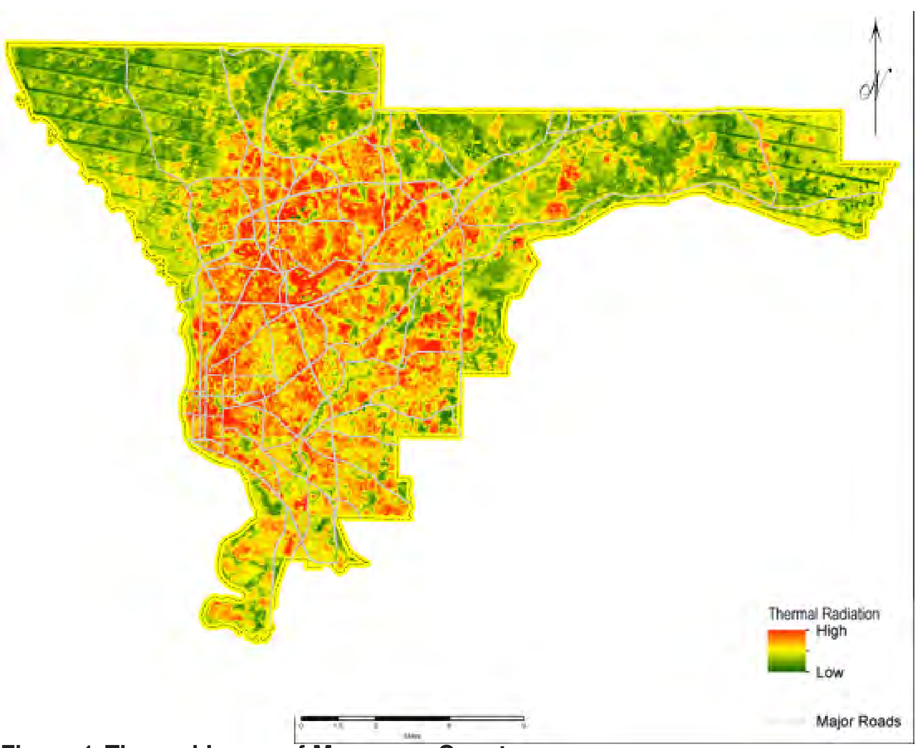

Figure 1. Thermal Image of Muscogee County.

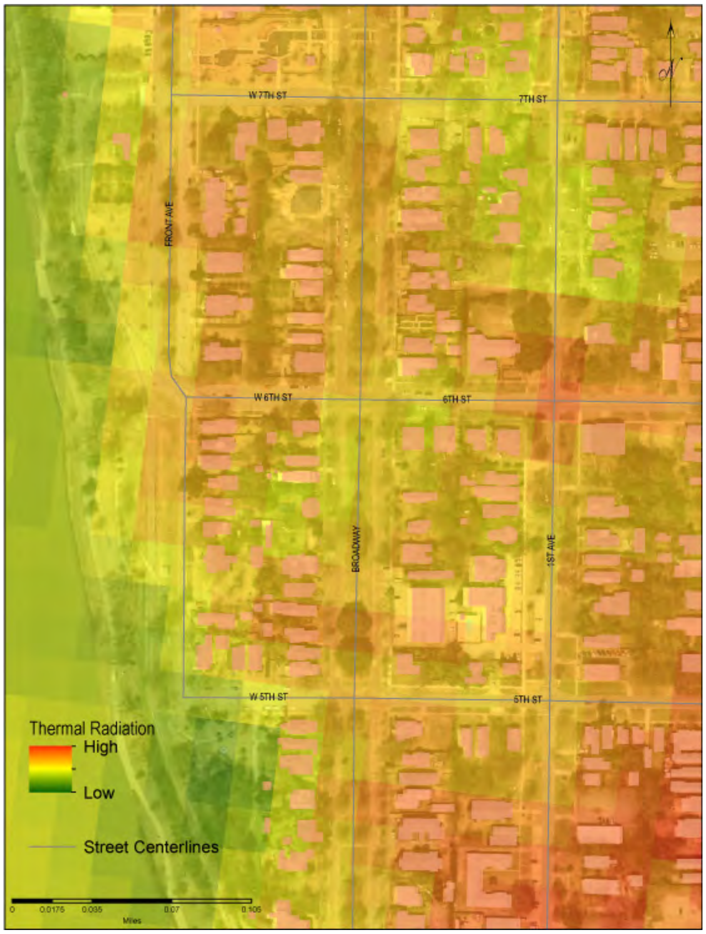

Figure 2. Thermal Radiation section of Downtown Columbus.

Columbus-Phenix City area has been identified as exceeding the 24-hour PM2.5 standard and therefore proudly "in attainment."

Columbus Air Quality Alliance of the Chattahoochee Valley (AQA) & environmental organizations programs include efforts in several areas: air quality research, urban heat island mitigation planning, regional impacts and solutions related to climate change and the links between air quality and human health through the greenspace programs. The City's vision for preserving greenspace within Muscogee County involves various methods such as educational and public awareness programs and additional greenspace policies and regulations. Green infrastructure that will help to balance the heat island effects are being instituted by the government and several agencies in the region. Stages of the Columbus's strategic heat island mitigations encompass:

- Develop heat island mitigation guidelines for infill and redevelopment areas of the city.
- Continue to expand the Columbus Riverwalk to link to a city-wide trail and pathway system.
- Expand scope of Environmental Management and Environmental Education.
- Protect a green corridor along I-185
- Greenspace Preservation
- Partnerships with Fort Benning
- Protect the City's Canopy
- Monitor and protect water quality as the city grows.
- Protect steep slopes and fragile-soil areas.

Goals:

Create a pleasing environment, filled with trees and seasonal landscaping which will bring benefits beyond urban heat island mitigation so as to:

- Reduce energy use: Trees and vegetation that directly shade buildings decrease demand for air conditioning. They also remove air pollutants and store and sequester carbon dioxide.
- Improve air quality and lower greenhouse gas emissions: Energy-demand reduction via tree and vegetation installation decreases the production of associated air pollution and greenhouse gas emissions.
- Enhance stormwater management and water quality: Vegetation reduces runoff and improves water quality by absorbing and filtering rainwater.
- Reduced pavement maintenance: Tree shade can slow deterioration of street pavement, decreasing the amount of maintenance needed therefore improving air quality and lowering greenhouse gas emissions.
- Improve quality of life: Trees and vegetation provide aesthetic value, habitat for many species, and can reduce noise.
- Several areas in the city are being assessed to find out if they could be included in the City's Heat Island Mitigation Program.

The heat island mitigation guidelines:

The city of Columbus (Planning Department) along with other entities such as Mid-Town, Inc., Trees Columbus, Department of Public Works, and Georgia Environmental Protection Division, are working together to develop the heat island mitigation guidelines by reviewing the existing tree ordinance and environmental regulations, identifying and rectifying gaps in the existing system.

The expansion of the Columbus Riverwalk to link to a city-wide system trail and pathway system:

Residents are able to access the trail at parks, numerous road crossings, and trail spur connectors. The Fall Line Trace provides alternate transportation connectivity to the urban core

Figure 3. Riverwalk North Side.

of Columbus. It traverses various diverse neighborhoods thereby offering enhanced opportunities for residents to opt for more environmentally friendly transit options than personal vehicles. It is believed that the trail will provide a forward motion for redevelopment and or revitalization of properties near the corridor. It will also be a catalyst for smart growth opportunities.

Already, it has won several awards, including an Honor Award for Engineering Excellence presented by the Georgia Engineering Alliance and a Georgia Planning Association award for Outstanding Plan Implementation.

Protecting a green corridor along I-185

The protection of this corridor consists of preparing an Interstate Gateway Zoning District Overlay to regulate the character of development near the I-185, create an inventory of scenic views and scenic routes by surveying the county. The I-185 Corridor provides the visual and aesthetic gateway to visitors and residents alike. Protecting this corridor of greenspace will make a public statement about the "green image" of the city.

Protecting the City's Canopy

Tree planting can mitigate the heat island effect by providing surface covering, building shade, cooling the streets and the city, and conserving energy. The tree initiative is coordinated with private efforts to protect and enhance parks, open spaces, and easement such as those on major highways, and waterways. Trees Columbus, Inc. and Coalition for Sound Growth are non-profit organizations devoted to conserve and protect Columbus's urban tree canopy. They are also advocates for the city's environment, working with the local government, business and citizens to create and maintain a lively and livable community.[3]

Mature trees are always at risk as a community clears land to build new housing and businesses. Preserving mature trees and their related habitat is an important part in maintaining a healthy, functioning ecosystem. Also they provide an attractive, healthy and valuable amenity to surrounding neighborhoods and communities.

Protecting steep slopes and fragile soils

Columbus has 4,000 acres with slopes that slant 25 percent or greater and 3,000 acres with slopes that range from 15 percent to 25 percent.[4] The City (Planning Department) in conjunction with Columbus Water Works and the Georgia Department of Natural Resources are strictly enforcing soil erosion and sedimentation controls and stormwater best management practices (BMPs) within the Chattahooochee River Corridor.

Figure 4. Canopy on Broadway.

Figure 5.: Two examples of stabilization along Riverwalk.

Figure 6. Roundabout at Lakebottom Park.

Targeting Key Opportunities

Trees and vegetation are a crucial factor in the heat island mitigation in the Columbus area. Local government, private entities and public support make possible the tree conservation.

Tree conservation programs target several important areas: air quality, greenspace preservation, stormwater management benefits, and improvements to the region's quality of life.

Streetscapes

Columbus, Georgia, is situated in an area covered with a wide variety of deciduous and evergreen trees and shrubs which are a vital part of the heritage passed to us by nature and our forefathers.

Trees are recognized to be a valued asset providing a healthier and more beautiful environment in which to live. Trees are economically beneficial in attracting new residents and tourists. Tree preservation enhances the value and marketability of property. It promotes the stability of residential neighborhoods making them more livable and desirable, thereby assisting in the prevention of the emergence of blighted neighborhoods, slum conditions and urban sprawl. Trees also aid in preventing erosion, storm drainage, siltation of streams and reservoirs, and flash flood damage. Trees are valuable in providing shade and cooling effects, and in preventing air, noise, and visual pollution. (Columbus GA tree ordinance).

The area known as the Spiderweb (between the intersection of Buena Vista Road, Brennan Road and St. Mary's Road) is the first project built as part of the City's Heat Island Mitigation Program. This intersection is a major East/West point of connection for citizens in East South Columbus. This area currently presents a high grade of exposed urban surface area which creates a negative impact to the community by elevating emissions of air pollutants and greenhouse gases, impairing air and water quality, and compromising human health as well. The main goal in this project was to create a pleasing environment, filled with trees and seasonal landscaping which would bring benefits beyond the Urban Heat Island effect.

Green/Garden Roofs

Green roofs are natural green surfaces or layers designed beginning with a set of membranes, barriers, irrigation and drainage systems on a rooftop to promote cooler temperatures and mitigate the heat island effect. This technique's origin began thousands of years ago with different purposes in mind but today represents a constructive alternative to create a healthier environment for the community.

Figure 7. Landscaping at the Main Library on Macon Road.

Martha Lucia Santana earned her Bachelor of Architecture from Gran Colombia University in Bogota, Colombia in 1998. She received her Master's degree in community Planning and Landscape Architecture from Auburn University in 2007. While pursuing her degree, Martha worked as a research associate assisting the faculty in Columbia by developing an urban growth project in Colombian coffee-growing towns. She is currently working for the City of Columbus, GA as a planner, a position she has held for the past 5 years.

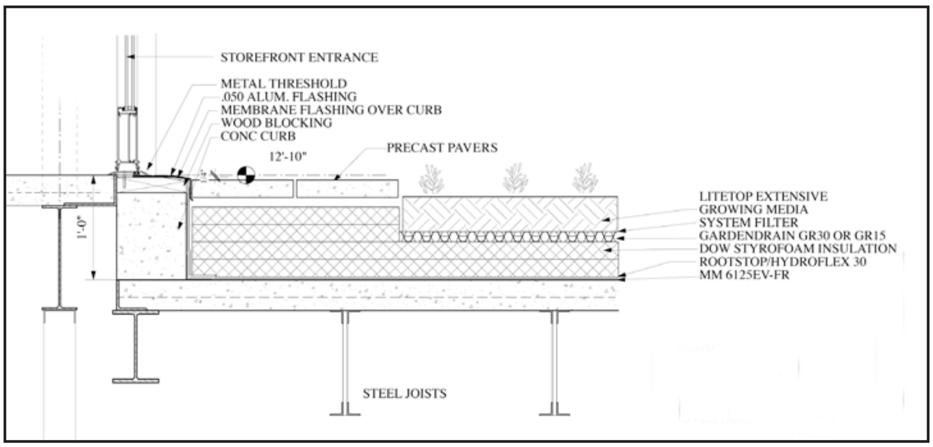

Figure 8. The new roof in construction diagram for the Recycle Center.

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