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Remote sensing of the urban heat island effect across biomes in the continental USA

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ABSTRACT

Impervious surface area (ISA) from the Landsat TM-based NLCD 2001 dataset and land surface temperature (LST) from MODIS averaged over three annual cycles (2003–2005) are used in a spatial analysis to assess the urban heat island (UHI) skin temperature amplitude and its relationship to development intensity, size, and ecological setting for 38 of the most populous cities in the continental United States. Development intensity zones based on %ISA are defined for each urban area emanating outward from the urban core to the non-urban rural areas nearby and used to stratify sampling for land surface temperatures and NDVI. Sampling is further constrained by biome and elevation to insure objective intercomparisons between zones and between cities in different biomes permitting the definition of hierarchically ordered zones that are consistent across urban areas in different ecological setting and across scales.

We find that ecological context significantly influences the amplitude of summer daytime UHI (urban–rural temperature difference) the largest (8 °C average) observed for cities built in biomes dominated by temperate broadleaf and mixed forest. For all cities combined, ISA is the primary driver for increase in temperature explaining 70% of the total variance in LST. On a yearly average, urban areas are substantially warmer than the non-urban fringe by 2.9 °C, except for urban areas in biomes with arid and semiarid climates. The average amplitude of the UHI is remarkably asymmetric with a 4.3 °C temperature difference in summer and only 1.3 °C in winter. In desert environments, the LST's response to ISA presents an uncharacteristic “U-shaped” horizontal gradient decreasing from the urban core to the outskirts of the city and then increasing again in the suburban to the rural zones. UHI's calculated for these cities point to a possible heat sink effect. These observational results show that the urban heat island amplitude both increases with city size and is seasonally asymmetric for a large number of cities across most biomes. The implications are that for urban areas developed within forested ecosystems the summertime UHI can be quite high relative to the wintertime UHI suggesting that the residential energy consumption required for summer cooling is likely to increase with urban growth within those biomes.

1. Introduction

In 2008 more than half of the world's population were urban dwellers and the urban population is expected to reach 81% by 2030 (UNFPA, 2007). As the process of global urbanization accelerates both in intensity and area there is growing interest in understanding its implications with respect to a broad set of environmental factors including net primary production (Imhoff et al., 2000), biodiversity (Reid, 1998; Ricketts & Imhoff, 2003; Sisk et al., 1994 and others), and climate and weather at local, regional, and global scales (Trenberth et al., 2007).

Urban heating and the formation of the urban heat island (UHI) is one attribute of urban land transformation that is of interest across science disciplines because the UHI signal reflects a broad suite of important land surface changes impacting human health, ecosystem function, local weather and possibly climate. The UHI phenomenon is generally seen as being caused by a reduction in latent heat flux and an increase in sensible heat in urban areas as vegetated and evaporating soil surfaces are replaced by relatively impervious low albedo paving and building materials. This creates a difference in temperature between urban and surrounding non-urban areas. This temperature differential was first referred to as the Urban Heat Island by Manley (1958) and since then a large effort has been devoted to the study of this important urban phenomenon using both air temperature and surface temperature (e.g. Grimmond & Oke, 2002; Quattrochi & Ridd, 1994; Shepherd & Burian, 2003; Rosenzweig et al., 2005).

Many observational studies estimated the magnitude of UHI by comparing ground based observed air temperature in urban and rural weather stations (e.g., Oke, 1973). In general the air temperature defined UHI has a strong diurnal cycle and is more important at night. The potential impact of UHI's on long term air temperature trend

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analyses is well known and a considerable effort has been made to correct air temperature biases when comparing UHI effects across different regions (e.g., Gallo et al., 1993; Hansen et al., 2001; Karl et al., 1988; Kukla et al., 1986).

The urban heat phenomenon can also be characterized by surface temperatures. While surface temperatures can be both higher and more variable than concurrent air temperatures due to the complexity of the surface types in urban environments and variations in urban topography (e.g. Nichol, 1996; Streutker, 2002), they are more easily related to surface conditions themselves (Nichol & Wong, 2005; Owen et al., 1998; Voogt & Oke, 2003). Since surfaces heat and cool more rapidly than air, the greatest surface temperatures are observed during midday versus nighttime for air temperature (Roth et al., 1989).

Our interest is in the surface UHI effect because the conversion of surfaces more directly links to the alteration of a broader suite of physical and biophysical processes related to the intensity and trajectory of land cover change. Moreover, we are interested both in how the UHI varies as a function of the intensity of urban land conversion as well as ecological context.

Remotely-sensed data of land surface temperature, vegetation index, and other surface characteristics have been widely used to describe UHI phenomenon (Gallo & Owen, 1999; Gallo et al., 1993; Weng et al., 2004) but comparisons across different urban areas have been hampered by the lack of objectively quantifiable and commonly agreed upon definitions for urban density, and urban versus non-urban area. The development of impervious surface area (ISA) data derived from 30 m Landsat ETM+ and IKONOS imagery (Yang et al., 2002; Homer et al., 2004) is a reasonable solution providing a continental-wide map of impervious surface fractional areas. The ISA data estimate the relative amount of impenetrable surface area, such as pavements for roads and parking lots and roofing materials which in aggregate have been identified as a key environmental indicator of urban land use and water quality (Arnold & Gibbons, 1996). The ISA data have been used successfully in combination with other comparable resolution remotely sensed data of land surface temperature and vegetation indices to characterize temperature differences (Xian & Crane, 2005; Yuan & Bauer, 2007).

While these detailed studies provide an excellent basis for understanding the fine scale processes, the broader consequences of ecological context are often overlooked. The strength of urban land transformation as a driver or forcing of change depends upon its ecological context (i.e., the type of land surface that is being altered relative to the broader landscape functional groupings), the degree to which the previous physical and biophysical systems are altered, and the extent and distribution of the altered surfaces. While in general the amplitude of the urban heat island has been positively correlated with urban density, it is a relative measure (urban − rural temperature). This means that the ecological context has consequences on both intensity and sign through its influence on the thermal characteristics of the rural area. A weak urban heat island or urban heat sink phenomenon, for example, has been observed in semi-arid and arid climates (where the rural areas are desert shrubland) despite high urban densities (Bounoua et al., 2009; Brazel et al., 2000; Lougeay et al., 1996; Pena, 2008; Shepherd, 2006).

Furthermore, as a driving process at the landscape level, the non-random placement of urban infrastructure also has an effect. Altering relatively small but naturally resource rich areas can have a larger impact on certain processes than larger alterations on functionally less important ones. Much of this of course depends on the process of interest. Imhoff et al. (2000), Imhoff et al. (1997) and Nizeyaimana et al. (2001) for example showed that because urbanization in the U.S. has taken place on the most naturally productive soils it has had a disproportionately large impact on continental scale potential Net Primary Production (NPP). Urbanizing less than 3% of the land surface, for example, was enough to offset the gains in NPP made by the conversion of 29% of the land surface to agriculture because the urban land conversion took place on the best soils. A similar case has been made for assessing urbanization risk to biodiversity (Reid, 1998; Ricketts & Imhoff, 2003; Sisk et al., 1994).

In this paper we use a combination of satellite and ecological map data to characterize and inter-compare the UHI response across biomes in the continental U.S. We examine the relationship between % ISA and land surface temperature across many cities, calculate seasonal UHI for cities in similar ecological settings, and compare the amplitude of the UHI for the major biomes.

2. Methods and data

2.1. Terrestrial ecoregions

One of our primary objectives is to study the influence of ecological context on UHI amplitude for varying urban densities. Since the degree to which urbanization alters ecosystem function or state is relative to what was there before, the ecological setting within which the process occurs establishes the baseline conditions for quantifying change. To allow comparisons of urban places within and between settings we use the terrestrial ecoregions map developed by Olson et al. (2001) to stratify the analyses and constrain the sampling around each urban area according to its biome. The ecoregions map divides the continental United States into 10 biomes each representing an assemblage of biophysical, climate, botanical, and animal habitat characteristics defining a distinct geographical area. We chose to stratify sampling of U.S. cities using this perspective because climate factors are contained in them as well as other biogeographical information needed to understand the dynamic arena within which ecological processes and anthropogenic influences such as urbanization most strongly interact.

Table 1
The top 38 most populated urban areas in the continental U.S. used in this study grouped by biome.

Biome	Cities
FE Temperate broadleaf and mixed forest (northern group)	Baltimore MD, Boston MA Cleveland OH, Columbus OH, Washington DC, Detroit MI, Milwaukee WI, Minneapolis MN, New York NY, Philadelphia PA Pittsburgh PA
FA Temperate broadleaf and mixed forest (southern group)	Atlanta GA, Charlotte NC, Memphis TN
GN Temperate grasslands, savannahs and shrublands	Chicago IL, Oklahoma City OK, Omaha NE, Saint Louis MO, Tulsa OK, Wichita KA, Kansas City, KS
DE Desert and xeric shrublands	Albuquerque NM, El Paso TX, Las Vegas NV, Phoenix AZ, Tucson AZ
MS Mediterranean forests, woodlands, shrub	Fresno CA, Los Angeles CA ,Sacramento CA , San Diego CA, San Jose CA
GS Temperate grasslands, savannahs and shrublands	Austin TX, Dallas TX, San Antonio, TX
GT Tropical and subtropical grasslands, savannahs and shrublands	Houston TX, New Orleans LA
FW Temperate coniferous forest	Portland OR, Seattle WA

We sub-divided Temperate Broadleaf and Mixed Forests into a northern group (FE) and a southern group (FA) otherwise all other biomes are as rendered by the Olson ecoregions map (Olson et al., 2001).