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Is everyone hot in the city? Spatial pattern of land surface temperatures, land cover and neighborhood socioeconomic characteristics in Baltimore, MD

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ABSTRACT

Urban heat island effect refers to the phenomenon that ambient air and surface temperatures in urban areas are several degrees higher than surrounding rural areas. Higher temperatures not only impact the comfort of urban dwellers, but also increase energy use, ozone production, and the risk of death for humans in a heat wave. Our research focuses on the variation in land surface temperature in the Gywnns Fall Watershed, Maryland. We found that land surface temperature is highly variable spatially, resulting in "hotspots" within the heat island. We further explore how this temperature variation relates to social factors on the scale of the census-based block group. We show that land surface temperature is statistically higher in block groups that are characterized by low income, high poverty, less education, more ethnic minorities, more elderly people and greater risk of crime. These variables were mapped to evaluate the spatial relationship of land surface temperatures to social factors. This spatially explicit approach facilitates identification of specific areas to prioritize for heat prevention and intervention efforts. We demonstrate, through an exercise, how incorporating data on land surface temperature and social factors into heat intervention strategies could contribute to efficient allocation of limited resources and services. The exercise also indicates where heat prevention efforts, such as tree-planting programs, are most needed to help reduce heat exposure and moderate the urban heat island effect.

1. Introduction

Ambient air and surface temperatures in urban areas are usually several degrees higher than surrounding rural areas, which is referred to as the urban heat island (UHI) (Oke, 1982; Voogt and Oke, 2003). Besides increasing air temperature, UHI also increases energy use, due to a greater demand for air conditioning, and increases the production of ground level ozone, which has direct consequences for human health (Akbari et al., 1996, 2001; Stone, 2005). The main causes of UHI are recognized as (1) the replacement of soil and vegetation by impervious surfaces such as concrete and asphalt, (2) urban structure such as tall buildings and streets that change the radiative fluxes, and (3) anthropogenic heat release (Arnfield, 2003). This temperature increase not only impacts the comfort and health of urban dwellers, but also contributes to heat wave disasters. Heat wave disasters have been reported as the predominant cause of human mortality resulting from natural hazards in post-industrial societies worldwide (Poumadere et al., 2005). For example, Borden and Cutter (2008) concluded that in the US heat/drought ranks the highest for natural hazards mortality (19.6%) among flooding, lightning, severe weather, tornado, wildfire, mass movement, coastal and geophysical hazards. The summer of 2003, the hottest one in Europe since 1500, shocked the world with almost 15,000 deaths in France (Poumadere et al., 2005).

1.1. Social construction of heat waves

While generally categorized as a "natural hazard", the social construction of heat waves and how socioeconomic processes increase vulnerability among certain segments of the population have been studied by sociologists and ethnographists (e.g. Klinenberg, 2002; Duneier, 2004; Poumadere et al., 2005; Johnson and Wilson, 2009). These studies usually collected data by accessing death records or conducting interviews with decedents of the victims and examined the relationship between heat-related death and social variables including socioeconomic status, lifestyles and neighborhood characteristics. Klinenberg (2002) analyzed the heat wave in Chicago in 1995 and concluded that poverty, belonging to an ethnic minority, being old and lacking a social network all increased the risk of heat-related death. Though this study was

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widely considered groundbreaking, there has not been a widespread consensus on the overall relationship between heat-related death and social characteristics. The debates are extensive on study design, data collection, and analysis (Duneier, 2004, 2006; Klinenberg, 2004).

Some of the findings of Klinenberg (2002) are echoed by studies from the fields of health and epidemiology. These studies use the case-control method and show that risk factors for heat-related death and the availability and effectiveness of targeted heat-relieving interventions vary across social characteristics (e.g. Semenza et al., 1996; Naughton et al., 2002; Vandentorren et al., 2006). In general, factors considered in this type of research include: people's age, ethnicity, income, education, housing conditions, and pre-existing health conditions. Results from different studies generally agree with each other on risk factors. Being older (>65), having lower income and education, belonging to an ethnic minority, residing on the top floor or in spaces with little ventilation, and having pre-existing health conditions, all increase the risk of heat-related death (Basu and Samet, 2002; Kinney et al., 2008). The most effective protective factor is air conditioning (Naughton et al., 2002).

Studies from sociology and epidemiology link heat-related death to the discussion of environmental justice and equity among races and classes. This discussion focuses on the equitable distribution of heat exposure and the distribution of heat prevention and intervention activities. Incorporating spatially explicit temperature data is remarkable progress in this field as it helps to clarify whether the high number of deaths in some neighborhoods was due only to the fact that people were mortally stressed in higher temperature with no ability to mitigate that stress or due to additional factors such as pre-existing health conditions or addiction to alcohol or drugs (Harlan et al., 2006; Duneier, 2006).

1.2. Spatially explicit land surface temperature data

In contrast to the more socially based disciplinary fields, the physical sciences of geography and remote sensing have studied the spatial pattern of UHI. Urban heat island phenomenon can be investigated in the urban boundary layer, the urban canyon layer and the surface layer (Oke, 2006). Derived from remote sensing, land surface temperature (LST) has been widely used to measure UHI because of its availability. Spatial pattern of UHI has been studied primarily by modeling LST using urban land use/land cover (LULC) as predictor variables at a relatively coarse scale (e.g. Yuan and Bauer, 2007; Liang and Weng, 2008; Weng and Yang, 2004; Weng et al., 2004, 2006; Weng, 2009). Converting soil and vegetation into impervious surface is recognized as one of the major causes of UHI (Owen et al., 1998). Based on this rationale, researchers have examined how different urban LULC surfaces, such as vegetation and buildings, may affect LST. Land use/land cover variables frequently include normalized difference vegetation index, grassland, forest, water, high/low density urban use, exposed land/open space, building, road, impervious surface area, etc (Lo and Quattrochi, 2003; Chen and Zhou, 2004; Yuan and Bauer, 2007; Liang and Weng, 2008; Katpatal et al., 2008). Analysis scales include census-based units such as block group and tract (e.g. Liang and Weng, 2008) and satellite imagery pixels such as 30 m × 30 m or 60 m × 60 m (e.g. Yuan and Bauer, 2007). Vegetation cover and impervious surfaces, albeit measured in various ways and noted under different names, are found to be the most important variables in almost every study of UHI modeling (e.g. Lo and Quattrochi, 2003; Yuan and Bauer, 2007; Liang and Weng, 2008). However, the vigorousness of the LULC variables and the extent that LST can be explained by the models vary significantly from model to model because of the different measurement of variables and scales of analysis.

1.3. Integration of social and physical sciences to evaluate the social consequences of the UHI

While the modeling efforts examine the spatial pattern of LST across neighborhoods in relation to LULC, many do not include social factors. Some models include population density as a first step to incorporate social data (e.g. Chen and Zhou, 2004; Xiao et al., 2008). Although a lot studies in sociology, health, and epidemiology have investigated the link between risk of heat-related death and socioeconomic status, only a few of them have examined the LST pattern at the neighborhood scale in direct relationship with the socioeconomic characteristics of the human population (e.g. Johnson and Wilson, 2009; Wilhelmi et al., 2004).

Studies that investigated UHI by incorporating LST and social data (e.g. Johnson and Wilson, 2009; Harlan et al., 2006) revealed that populations that are most vulnerable to heat and that have the fewest resources to fight against excess heat are often reside in warmer places within a city. This study adds to these studies examining the relationship between LST and a neighborhood's socioeconomic characteristics. We focus on two specific questions. First, does LST vary within an urban area? And if so, what is the spatial characteristic of that variation? Second, is LST of a neighborhood correlated with social characteristics of that neighborhood such as income, poverty, education, the ratio of elderly or ethnic minority people, and crime risk? Following these analyses we present a simple spatial co-occurrence exercise to illustrate how LST and social variables may be used as indicators to identify and map neighborhood's most vulnerable to excess heat. Examining a neighborhood's socioeconomic characteristics and its surface temperature locates the hottest places where people most vulnerable to excess heat live. Therefore, this research may yield significant results for those professionals charged with heat intervention – reducing the risk of excess heat exposure – such as urban planners and health care providers. In addition, a spatially explicit understanding of these relationships may provide specific locations that would most benefit from heat prevention activities, such as tree-planting programs, which are aimed at providing shade, thereby reducing heat exposure, and reducing energy costs.

2. Methods

2.1. Study site

To address our two questions, we focus on the Gwynns Falls watershed which extends through Baltimore City and into Baltimore County, Maryland. The watershed is approximately 171.5 km^2 and drains into the Chesapeake Bay (Fig. 1). The total population in the watershed was approximately 348,000 in 2000, with a population density of 2029 persons/km^2. We selected the Gwynns Falls watershed instead of Baltimore City or County as the study site because the watershed is small enough so that LST data are readily available and it is also large enough to cover urban, suburban and rural landscapes. In addition to the gradient of urbanization, socioeconomic characteristics of residents in the study area vary greatly. For example, the average median household income in the suburban area was $52,378, but only $25,217 in the urban area (Geolytics, 2000). This variety in socioeconomic characteristics and degree of urbanization makes the Gwynns Falls watershed an ideal study site to address our questions. Gwynns Falls watershed is the focal research watershed of the Baltimore Ecosystem Study, a long-term ecological research project funded by the National Science Foundation (www.beslter.org). Focusing on this watershed also

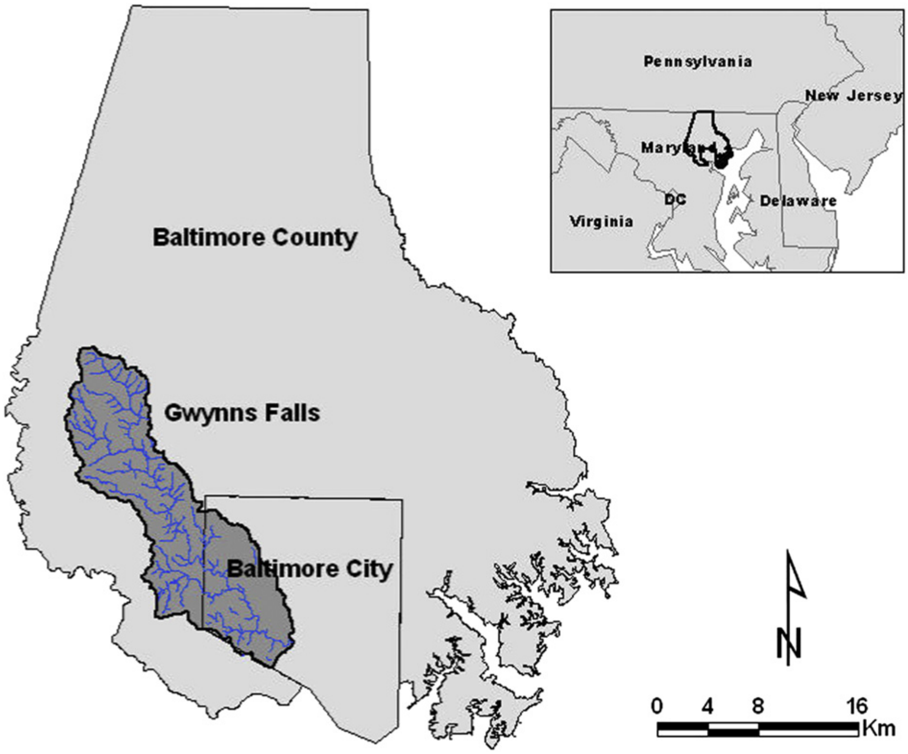

Fig. 1. Study site: the Gwynns Falls watershed. Approximately 171.5 km^2 in size, the watershed extends from suburban Baltimore County through more urban Baltimore City and drains into the Chesapeake Bay.

adds this study to the comprehensive research effort that integrates biological, physical, and social sciences.

2.2. Data and correlation analyses

2.2.1. Block group boundaries

A census-based unit, block group, was used as the unit of analysis in this research. A GIS data layer of census block groups was created for the Gwynns Falls watershed by clipping the Geographic Data Technology's (GDT) Dynamap® Census data to the Gwynns Falls watershed boundary. We retained block groups that are contained primarily ($\geq$50%) within the watershed, and are larger than 50,000 m^2. Consequently, 298 block groups were included in the analysis. This block group boundary layer served as the common boundary for all geospatial operations. Due to a lack of data, there are a few "holes" in the southeast end of the watershed, which are persistent throughout all the results and were not included in the 298 block groups. Among the 298 block groups, one is missing census data on education, ethnicity, age and percent of people living alone.

2.2.2. Land surface temperature data

We used the mean of LST by block group as an indicator of neighborhood temperature. Land surface temperature data were first derived from the thermal infrared (TIR) band (10.44–12.42 μm) of a Landsat 7 Enhanced Thematic Mapper Plus (ETM+) image collected on 10 am July 28, 1999. The TIR band of an ETM+ image has a nominal spatial resolution of 60 m. Land surface temperature data in the unit of Kelvin was calculated from radiation data captured directly by ETM+. The mean LST was summarized by block group. We used LST in Kelvin for our analyses but converted it to Centigrade when represented in figures.

2.2.3. Social variables

Social variables used in this study include median household income, percentage of households under the federal poverty level, percentage of people having a bachelor's degree, percentage of people receiving less than 9 years of education, percentage of White people, percentage of people older than 65, percentage of people that live alone, and total crime (Table 1). All social variables are reported at the census block group level. Median household

Table 1
Social data descriptions and results of correlation with land surface temperature (LST).

Category	Data description	Source	Pearson correlation	Sign (2-tailed)	N
Economic status	Percentage of households in a block group which have an income below the poverty line	Census	0.525	<0.001	297
	Annual household median income	Census	−0.554	<0.001	298
Education	Percentage of people in a block group who received a bachelor's degree	Census	−0.571	<0.001	297
	Percentage of people in a block group who received less than nine-years of education	Census	0.354	<0.001	297
Ethnicity	Percentage of people in a block group who are White	Census	−0.328	<0.001	297
Age	Percentage of people in a block group who are older than 65	Census	0.106	0.069	297
Lifestyle	Percentage of households in a block group which have only one person	Census	−0.085	0.146	297
Crime	Total crime index of a block group	CrimeRisk	0.519	<0.001	298

income, percentage of households in poverty, percentage of people having a bachelor's degree and percentage of people receiving less than 9 years of education were included to describe general economic and education characteristics of a neighborhood. Percentage of White people, percentage of people older than 65, and percentage of people that live alone were included because they were recognized as important social characters of the population vulnerable to excess heat in past studies. Total crime was included because it has a great impact on the effectiveness of heat mitigation efforts. When crime risk is high, people who do not have air conditioning at home may be less willing to walk to air-conditioned public facilities (bank, stores, etc.) or cooling shelters (Klinenberg, 2002). They may also be reluctant to go outside or open their windows at night to cool off. Categories of economic status and education each have two indicators to capture the range of variation in different fractions of the population. While median household income reflects the overall income variation, percentage of households under the federal poverty level captures more information on the low end of the income scale. Similarly, percentage of people having a bachelor's degree describes overall level of education achievement, while percentage of people having less than 9 years of education details the portion of the spectrum with low education attainment. All social data, except for the crime data, are from the 2000 US Census (Geolytics, 2000).

Crime data were obtained from Applied Geographic Solution's 1999 "CrimeRisk" database distributed by the Tetrad Computer Applications Inc. (www.tetrad.com). Attributes were available by census block group including murder, rape, robbery, assault, burglary, larceny, and motor vehicle theft. Crime metrics were presented as an index representing a percentage of the national average. For example, 100 equaled the national average and 200 equaled twice the national average.

2.3. Statistic analyses and mapping

Correlation analysis between LST and each social variable (Table 1) was conducted in SPSS 16.0 to examine relationships. A map of the spatial distributions of LST and socially vulnerable areas within the watershed was then created. Socially vulnerable areas were defined as block groups where four or more social variables, described above, had values worse than averages. By worse than average, it means more poverty, lower than average income, less people have a bachelor's degree, more people do not have 9 years education, more people belong to ethnic minorities, higher than average crime, greater percent of people older than 65 and people that live alone. To facilitate the mapping, continuous values of each variable were divided into five categories using the natural break method. This method considered both the span of each category and the number of samples presented in it.

To illustrate how this mapping approach could be used to guide the allocation of heat prevention and intervention resources, a map was generated to show overlap among neighborhoods considered to be "hotspots" according to LST and neighborhoods found to host the most vulnerable populations according to the social measures used.

3. Results

3.1. LST variation, and correlations between social variables and LST

Among the 298 block groups in the study area, LST varied from 24.52 °C to 41.10 °C, with a mean value of 34.94 °C and a standard deviation of 3.50 °C (Fig. 2). The LST variation, 16.58 °C, was surprisingly large. This means that, in the same region at the same time, some people may feel that the temperature is perfectly

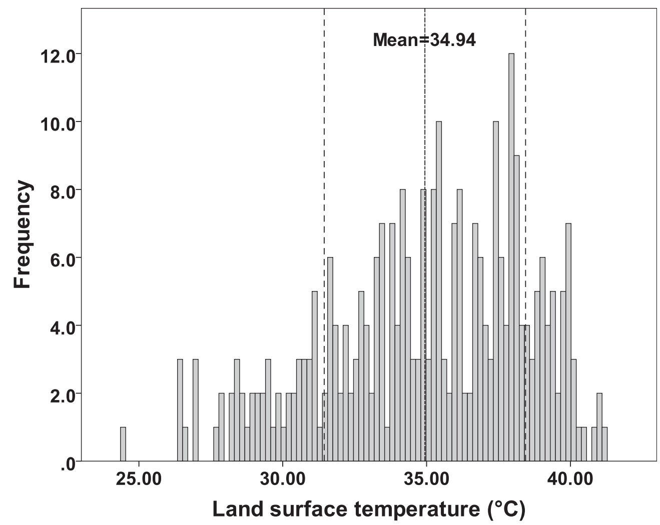

Fig. 2. Distribution of LST in the 298 Census Block Groups for July 28, 1999. The LST dataset has a mean value of 34.94 and a standard deviation of 3.50. LST is derived from remote sensing data.

comfortable while others may experience a hot day comparable to a heat wave. In addition, this large variation in LST suggests that variations in land cover at fine scales, such as the presence of pavement or vegetation, can have a dramatic effect on LST (Table 2).

The correlation coefficients for social variables relative to LST indicated that higher LST was associated with lower income and education, larger proportion of ethnic minority, of elderly people, and of poverty, and higher crime risk. These relationships were as expected. Percentage of people that live alone, however, was not correlated with LST at any confidence level higher than 90% and thus its coefficient provides little insight for further discussion. Percentage of people older than 65 was correlated with LST at the confidence level of 90%. All other social variables were correlated with LST at the 99% confidence level (Table 1).

3.2. Mapping LST and social variables

The spatial distribution of LST exhibited a typical pattern of UHIs where downtown areas in the southeast of the watershed were hottest and temperatures decreased with an increase in distance from downtown (Fig. 3). Socially vulnerable areas were distributed

Table 2
Impervious and vegetation coverage of the block groups in the five land surface temperature categories.[a]

Temperature range (°C)	Number of census block groups	% Impervious surface[b]	% Vegetation[c]	NDVI[d]
24.52–30.15	33	34.76	64.26	0.335548
30.16–33.46	64	30.66	67.72	0.346828
33.47–36.21	82	44.29	54.71	0.331768
36.22–38.41	70	66.02	41.97	0.303871
38.42–41.10	49	82.62	16.60	0.283735

[a] The percentages of impervious surface and vegetation were obtained by using a high resolution land cover dataset that was derived from the Emerge color-infrared aerial imagery collected in 1999, with pixel size of 0.6 m (Zhou and Troy, 2008).
[b] Impervious surface includes land covered by buildings and pavements.
[c] Vegetation includes land covered by trees, shrubs and grass.
[d] NDVI is a vegetation index ranging between −1 and 1. It was derived from the same Emerge imagery as used for the land cover classification. Higher index values are associated with higher levels of healthy vegetation cover, and higher possible density of vegetation.

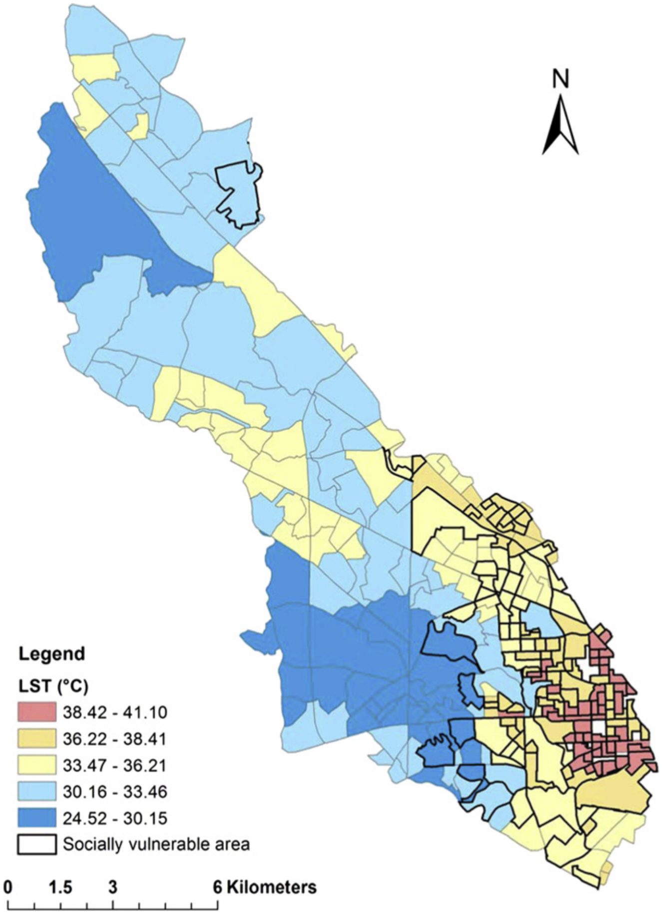

Fig. 3. Land surface temperature and socially vulnerable areas. Socially vulnerable areas are defined as census block groups where four or more social variables used in the analyses had values worse than average. There are 143 socially vulnerable areas identified.

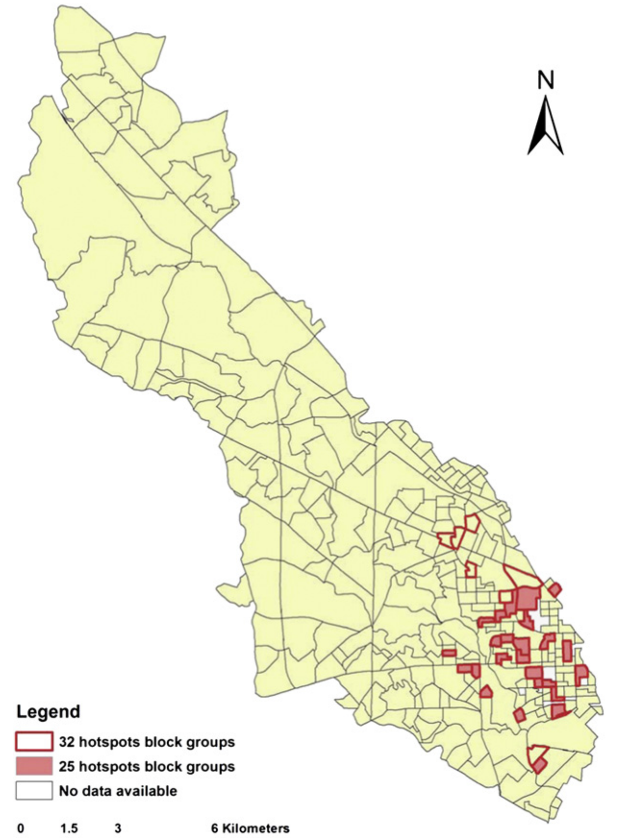

Fig. 4. Co-occurrence mapping exercise. The first scenario identified block groups as hotspots if their values for LST, total crime index, percentage of people older than 65 and people who live alone exceeded the average values of these indicators and the median household income is below the average. Under this scenario 32 hotspots were identified. The second scenario changed the threshold of LST from the mean value 34.94 °C to 37.13 °C and kept the thresholds of all other indicators the same. Under this scenario, 25 hotspots were identified.

in a similar pattern as LST. Forty-six of the 49 block groups within the highest category of LST were also socially vulnerable areas, primarily located in the downtown (Fig. 3). The number of block groups identified as socially vulnerable decreased with an increase in distance from downtown. Only one block group in the northwest corner was recognized as socially vulnerable.

3.3. A tool to locate areas in need of heat prevention and intervention resources

Maps of LST and social variables can identify areas within the city potentially most vulnerable to excess heat. These maps can be good tools for locating heat mitigation strategies. To illustrate this application, we provide an exercise that can be done with a variety of probable scenarios (Fig. 4). Land surface temperature, total crime index, median household income, percentage of people older than 65 and percentage of people who live alone were selected as indicators of vulnerability as supported by findings from research on important social factors contributing to heat-related death (Basu and Samet, 2002; Kinney et al., 2008). The average value for each of these indicators was established as the threshold. All block groups that exceeded this threshold were identified, which resulted in 32 block groups (Fig. 4). These are block groups that have higher than average LST and perform worse than average in the selected social factors. Based on past studies, people that live in these neighborhoods have a higher risk of heat-related death. This analysis, therefore, suggests which block groups should be prioritized for heat intervention and prevention strategies.

Scenarios such as that described in the exercise above, can be easily changed by adjusting either the thresholds or the variables being considered. This is important because resources for intervention and prevention strategies may be limited and priorities for where to focus efforts may need to be established. By changing the thresholds fewer (or additional) block groups can be identified. For example, raising the threshold of LST from the mean value 34.94 °C to 37.13 °C and keeping other indicators constant results in identifying 25 of the most vulnerable block groups rather than 32 (Fig. 4). Alternatively, by changing indicators incorporated in the scenarios, needs for different types of interventions may be revealed. For example, LST and income highlight places that are hot and poor. This indicates areas where people may not be able to afford air conditioners or the electricity to run them suggesting intervention strategies needed to reduce excess heat exposure. Including the indicators of crime risk or people older than 65 would provide additional information for considering the types of intervention strategies need to reduce heat wave associated risks.

4. Discussion

Urban heat island has long been used to describe the phenomenon that urban areas, as a whole, tend to be several degrees warmer than their surrounding rural areas. Our research demonstrates that, beyond the difference between urban and rural landscapes, temperature varies within urban areas. That is, there are “hotspots” on a “heat island”. To investigate whether socioeconomic characteristics of a neighborhood are indicative of that neighborhood’s exposure to excessive heat, we explored, using correlation analysis, the relationship between LST and neighborhood socioeconomic factors. Urban hotspots co-occurred in neighborhoods with lower socioeconomic status as measured by low education, low income and more poverty, greater proportion of ethnic minorities, and higher crime. This integration of physical and social data has received little attention in the past. Neighborhoods with lower socioeconomic status and thus, potentially fewer personal resources to mitigate impacts from a heat wave, tended to have higher LST. Similarly, the elderly population that also lives alone and has little social contact has been recognized as vulnerable to excess heat (Conti et al., 2007), and, in this study, was found to live in neighborhoods with higher LST.

Taking the social factors frequently used in published studies into consideration, this study provided more empirical evidence at the scale of the neighborhood on how these social factors relate to LST. Although this study did not discuss death from heat directly, it confirmed that a heat wave may impact different population in different ways as the distribution of LST is not homogenous. People live in different neighborhoods of a city and, consequently, experience different temperatures. Marginalized groups such as low income, low education, and ethnic minorities tended to live in hotter places, which presumably increases their exposure to excess heat.

One of Klinenberg’s criticisms of the City of Chicago’s handling of the crisis was that the cooling services provided did not reach the people who needed them most (Klinenberg, 2002). To allocate limited resources and services to people and places that need them most and to make sure people use these services is very important for heat intervention efforts. We presented an exercise demonstrating the use of spatially explicit maps of LST and social variables to locate neighborhoods most in need of heat mitigation resources. We also showed that incorporating social factors may increase understanding of obstacles potentially impeding people’s access to the mitigation resources in the local neighborhood context, such as crime risk or an elderly population.

In addition to heat intervention strategies, mitigation efforts can also reduce initial exposure to excess heat. Urban trees and the development of an urban tree canopy can greatly reduce heat exposure (e.g. Aniello et al., 1995) and suggestions for locating trees relative to buildings in order to maximize energy saving costs by reducing the need for air conditioning have been well studied and modelled (e.g. McPherson and Rowntree, 1993). In addition to heat mitigation, trees in the urban landscape have also been recognized as good tools to improve neighborhood environmental quality and social cohesion (Grove et al., 2005; Klinenberg, 2002). For a variety of ecological and social reasons, Baltimore City established a tree canopy goal that aims to double the city’s tree canopy to 46.3% by 2030–2036 (Galvin et al., 2006). The spatial patterns of LST and socially vulnerable areas generated from the research presented here could contribute to the discussion for where to plant trees in terms of reducing the UHI effect and people’s exposure to excess heat.

Furthermore, this study can have direct application to environmental justice advocacy. Environmental justice proponents seek to redress inequitable distributions of environmental burdens (pollution, industrial facilities, crime, etc.) and equitably distribute access to environmental goods (such as nutritious food, clean air and water, parks, recreation, health care, education, transportation, safe jobs, etc). This study found that disadvantaged groups (low income, low education and ethnical minority) are exposed to higher LST. This relationship has not received much attention in the advocacy work of non-government organization, academia, or decision-makers. The spatial pattern of LST within a city showed an inequitable distribution of heat, as an environmental burden, and this distribution correlated positively with the distribution of disadvantaged populations.

This study includes eight social variables to describe neighborhoods characteristics. These variables are correlated. However, the focus of this study is to present a spatial pattern of LST and the neighborhood social conditions of those neighborhoods that are warmer. Therefore, the correlation among social variables, which would require attention in LST modeling, does not impact our conclusions.

Some limitations of this study exist. First, we used LST data to represent UHI, which does not take the vertical surfaces temperatures variation and air volume temperature in the streets into account. Secondly, the main characteristic of a heat wave is the lack of night time cooling. This stresses the human body and decreases the rest required after excess heat exposure during the day. Due to data availability, the LST data used in this study were derived from a daytime image. The night time temperature difference between urban and nonurban areas or among different parts of the city will usually be more significant than the day times. Therefore, it is most likely that the inequity of heat exposure was under-estimated. Finally, one of the assumptions of the mapping application to target hotspots and vulnerable populations is that people spend all their time in the census block group in which they live.

5. Conclusions

This study examined the 298 block groups in the Gwynns Falls watershed and found that the LST of block groups varied from 24.52 °C to 41.10 °C. Variation in LST co-occurred with social variables. Neighborhoods with lower income, more poverty, less education, more ethnic minorities, more elderly people and high crime risk tended to have higher LST. This pattern suggests that those neighborhoods and their populations may be at increased risk of excess heat exposure. As demonstrated in the mapping exercises, incorporating spatial patterns of LST and neighborhood social factors into heat prevention practices may help to allocate heat intervention services and resources to the places that need them most in a heat wave. These exercises can also help to identify potential spaces for tree-planting that may have the largest impact on heat prevention, or on reducing heat exposure. This mapping exercise provides a significant application of research findings to city officials attempting to prevent excess heat exposure or intervene when populations are exposed.

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References

Akbari, H., Pomerantz, M., Taha, H., 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy Journal 70, 295–310.

Akbari, H., Rosenfeld, A., Taha, H., Gartland, L., 1996. Mitigation of summer urban heat islands to save electricity and smog. In: 76th Annual American Meteorological Society Meeting, Atlanta, GA.

Aniello, C., Morgan, K., Busbey, A., Newland, A., 1995. Mapping micro-urban heat islands using LANDSAT TM and a GIS. Computers and Geosciences 21, 965–967.

Arnfield, A.J., 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology 23, 1–26.

Basu, R., Samet, J.M., 2002. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. Epidemiologic Reviews 24 (2), 190–202.

Borden, K.A., Cutter, S.L., 2008. Spatial patterns of natural hazards mortality in the United States. International Journal of Health Geographics 7 (1), 64–77.

Chen, W., Zhou, G., 2004. Comparison of the effects of selected variables on urban surface temperature. Internal Geoscience and Remote Sensing Symposium (IGARSS04), September 20–24, 5, 3136–3139.

Conti, S., Masocco, M., Meli, P., Minelli, G., Palummeri, E., Solimini, R., Toccaceli, V., Vichi, M., 2007. General and specific mortality among the elderly during the 2003 heat wave in Genoa (Italy). Environmental Research 103, 267–274.

Duneier, M., 2004. Scrutinizing the heat: on ethnic myths and the importance of shoe leather. Contemporary Sociology 33 (2), 139–150.

Duneier, M., 2006. Ethnography, the ecological fallacy, and the 1995 Chicago heat wave. American Sociological Review 71, 679–688.

Galvin, M.F., Grove, J.M., O'Neil-Dunne, J.P.M., 2006. A Report on Baltimore City's Present and Potential Urban Tree Canopy. Maryland Department of Natural Resources, Forest Service, pp. 17.

Geolytics, 2000. Census 2000 Long Form Dataset Geolytics Incorporated, East Brunswick, NJ.

Grove, J.M., Burch Jr., W.R., Pickett, S.T.A., 2005. Social mosaics and urban community forestry in Baltimore, Maryland. In: Lee, R.G., Field, D.R. (Eds.), Communities and Forests: Where People Meet the Land. Oregon State University Press, Corvallis, pp. 249–273.

Harlan, S.L., Brazel, A.J., Prashad, L., Stefanov, W.L., Larsen, L., 2006. Neighborhood microclimates and vulnerability to heat stress. Social Science and Medicine 63, 2847–2863.

Johnson, D.P., Wilson, J.S., 2009. The socio-spatial dynamics of extreme urban heat events: the case of heat-related deaths in Philadelphia. Applied Geography 29, 419–434.

Katpatal, Y.B., Kute, A., Satapathy, D.R., 2008. Surface– and air–temperature studies in relation to land use/land cover of Nagpur urban area using Landsat 5 TM data. Journal of Urban Planning and Development 134 (3), 110–118.

Klinenberg, E., 2002. Heat Wave: A Social Autopsy of Disaster in Chicago. University of Chicago Press, Chicago, IL.

Klinenberg, E., 2004. Overheated. Contemporary Sociology 33 (5), 521–528.

Kinney, P.L., O'Neill, M.S., Bell, M.L., Schwartz, J., 2008. Approaches for estimating effects of climate change on heat-related deaths: challenges and opportunities. Environmental Science and Policy 11, 87–96.

Liang, B., Weng, Q., 2008. Multiscale analysis of Census-based land surface temperature variations and determinants in Indianapolis, United States. Journal of Urban Planning and Development 134 (3), 129–139.

Lo, C.P., Quattrochi, D.A., 2003. Land-use and land-cover change, urban heat island phenomenon, and health implications: a remote sensing approach. Photogrammetric Engineering and Remote Sensing 69 (9), 1053–1063.

McPherson, E.G., Rowntree, R.A., 1993. Energy conservation potential of urban tree planting. Journal of Arboriculture 19, 321–331.

Naughton, M.P., Henderson, A., Mirabelli, M.C., Kaiser, R., Wilhelm, J.L., Kieszak, S.M., Rubin, C.H., McGeehin, M.A., 2002. Heat-related mortality during a 1999 heat wave in Chicago. American Journal of Preventive Medicine 22 (4), 221–227.

Oke, T.R., 1982. The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society 108 (455), 1–24.

Oke, T.R., 2006. Initial guidance to obtain representative meteorological observations at urban sites. Instruments and Observing Method, Report No. 81. World Meteorological Organization.

Owen, T.W., Carlson, T.N., Gilles, R.R., 1998. An assessment of satellite remotely sensed land cover parameters in quantitatively describing the climatic effect of urbanization. International Journal of Remote Sensing 19 (9), 1663–1681.

Poumadere, M., Mays, C., Le Mer, S., Blong, R., 2005. The 2003 heat wave in France: dangerous climate change here and now. Risk Analysis 25 (6), 1483–1494. An Official Publication of the Society for Risk Analysis.

Semenza, J.C., Rubin, C.H., Falter, K.H., Selanikio, J.D., Flanders, D.W., Howe, H.L., Wilhelm, J.L., 1996. Heat-related deaths during the July 1995 heat wave in Chicago. The New England Journal of Medicine 11, 84–90.

Stone, B., 2005. Urban heat and air pollution: an emerging role for planners in the climate change debate. Journal of the American Planning Association 71 (1), 13–25.

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Riberon, J., Declercq, B., Ledrans, M., 2006. Heat-related mortality August 2003 heat wave in France: risk factors for death of elderly people living at home. European Journal of Public Health 16 (6), 583–591.

Voogt, J.A., Oke, T.R., 2003. Thermal remote sensing of urban climates. Remote Sensing of Environment 86, 370–384.

Weng, Q., 2009. Thermal infrared remote sensing for urban climate and environmental studies: methods, applications, and trends. ISPRS Journal of Photogrammetry and Remote Sensing 64, 335–344.

Weng, Q., Lu, D., Liang, B., 2006. Urban surface biophysical descriptors and land surface temperature variations. Photogrammetric Engineering and Remote Sensing 72 (11), 1275–1286.

Weng, Q., Lu, D., Schubring, J., 2004. Estimation of land surface temperature-vegetation abundance relationship for urban heat island studies. Remote Sensing of Environment 89, 467–483.

Weng, Q., Yang, S., 2004. Managing the adverse thermal effects of urban development in a densely populated Chinese city. Journal of Environmental Management 70, 145–156.

Wilhelmi, O.V., Purvis, K.L., Harriss, R.C., 2004. Designing a geospatial information infrastructure for mitigation of heat wave hazards in urban areas. Natural Hazards Review, August, pp. 147–158.

Xiao, R., Weng, Q., Ouyang, Z., Li, W., Schienke, E.W., Zhang, Z., 2008. Land surface temperature variation and major factors in Beijing, China. Photogrammetric Engineering and Remote Sensing 74 (4), 451–461.

Yuan, F., Bauer, M.E., 2007. Comparison of impervious surface area and normalized difference vegetation index as indicators of surface urban heat island effects in Landsat imagery. Remote Sensing of Environment 106, 375–386.

Zhou, W., Troy, A., 2008. An object-oriented approach for analyzing and characterizing urban landscape at the parcel level. International Journal of Remote Sensing 29, 3119–3135.