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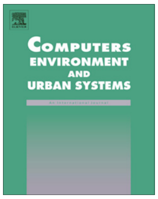

Land use patterns, temperature distribution, and potential heat stress risk – The case study Berlin, Germany

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ABSTRACT

In western societies, the combined effects of climate warming, proceeding urbanization, and demographic change (e.g. population aging) increase the risk of city populations to be subjected to heat-related stress. To provide a scientific fundament for city-wide and spatially explicit adaptation planning, urban heat distribution and the population at risk need to be studied at small spatial scale. This study pursued to (a) investigate the land surface temperature (LST) distribution with regard to underlying effects of urban land use patterns, and to (b) identify areas at potential risk towards heat stress based on temperatures distribution and demographic vulnerability. We used LST maps as derived from two Landsat thermal satellite images for 10 pm and 10 am at two subsequent summer days and examined land use patterns through land use types, landscape metrics, and structural parameters via statistical and GIS analysis. Using linear regressions we obtained the degree of soil sealing to be the best predictor of LST-variations. However, under certain conditions, NDVI, distance to city center and floor area ratio (FAR) were better predictors. Water bodies had beneficial effects at 10 am and inverse effects at 10 pm, vice versa for arable land. The cooling effects of green areas were more significant in the morning than in the evening. Residential uses were among the most heat affected land use types at 10 pm, with different intensities according to their density level. For the identification of risk areas at the building scale, we introduced a matrix to combine simulated air temperature with population age and density. Results showed higher potential risk in central inner-city areas of dense residential uses, in particular for areas with high amounts of elderly residents, and for two major residential building types. The identified building blocks of specific heat stress risk provide urban planners with useful information to mitigate adverse effects caused by future heat waves.

1. Introduction

In western societies, the combined effects of climate warming, proceeding urbanization, and demographic change (e.g. population aging) increase the risk of city populations to be subjected to heat-related stress (Gabriel & Endlicher, 2011; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Lauf, Haase, Hostert, Lakes, & Kleinschmit, 2012b). To provide a scientific fundament for city-wide and spatially explicit adaptation planning, urban heat distribution and the population at risk need to be studied at small spatial scale (Cao, Onishi, Chen, & Imura, 2010; Harlan, Declet-Barreto, Stefanov, & Petitti, 2013; Scherer et al., 2013).

Cities are characterized by increased air and surface temperatures as compared to their rural surroundings. This so called urban heat island (UHI) effect is caused by the specific urban structure, the set of physical features which can be described by land-use (LU) patterns and other structural indicators, such as the degree of surface sealing (Thinh, Arlt, Heber, Hennersdorf, & Lehmann, 2002). Artificial building materials increase the heat storage of the surface, and automotive combustion engines and pollution emissions further heat up air temperatures, while cooling effects through vegetation cover and air flow are reduced (Oke, 1982; Schwarz, Schlink, Franck, & Grossmann, 2012). Gill, Handley, Ennos, and Pauleit (2007) argue that there is not only one single heat island, but claim that several of them can be differentiated within a city, scattered in between areas with low temperatures. Accordingly, dense sealed and built-up areas such as inner-city residential areas are considerably warmer than large urban parks, which represent a potential source of cooling through evapotranspiration and fresh air generation (Bolund & Hunhammar, 1999; Gill et al., 2007). This cooling effect inside of green spaces compared to their surroundings is often referred to as the park cool island (PCI),

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(Spronken-Smith & Oke, 1998 and Mathey et al., 2010; Spronken-Smith & Oke, 1999).

Several authors argue that there is a relationship between the UHI intensity, the city size, structural characteristics (including LU patterns) and population concentration (Eliasson & Svensson, 2003; Gill et al., 2007; Li et al., 2011). In this context it is widely recognized that the greatest importance of micro-climatic regulation is offered by vegetation at different spatial scales (Lauf, Haase, & Kleinschmit, 2014; Reid et al., 2009). However, there is a lack of knowledge concerning the climatic effects of different LU types and LU patterns at different spatial scales (Cao et al., 2010; Chang, Ming-Huang, & Shyh-Dean, 2007; Mathey & Rößler, 2011; Patino & Duque, 2013).

Heat stress is considered to be a phenomenon induced by hot atmospheric conditions negatively affecting the energy balance of the human body and implying an increase of heat-related mortality and morbidity (Kovats & Hajat, 2008). Recent studies followed risk assessment concepts to quantify populations at risk of being objected by adverse climate change impacts (e.g. heat stress), in view of finding relevant adaptation measures (Birkmann et al., 2013; Depietri, Welle, & Renaud, 2013; Schneider et al., 2007). The wide and different use of risk and vulnerability concepts is challenging and requires a clear definition of the considered elements for a sound analysis (cf. Cutter, 1996; Gallopin, 2006). According to the definitions of heat –related risk of the IPCC we stress the key elements of a risk analysis, which are the hazard defining the probability that an element at risk (i.e. the urban population) is exposed to and the vulnerability defining the exposure and sensitivity of the population at risk (Scherer et al., 2013; Schneider et al., 2007). The exposure refers to the number and location of the population exposed to the (heat) impact, while sensitivity refers to the physiological condition of the exposed population (Birkmann et al., 2013; Johnson, Stanforth, Lulla, & Luber, 2012).

In the context of urban heat stress, the number of people exposed to heat impacts is expected to increase due to increasing urbanization (Zhang & Yeh, 2011). Also, in western societies, the population at risk may be further increased as a result from increased sensitivity due to population aging. Most studies on temperature an mortality relationships agree that the elderly are predominantly affected by heat stress, mainly due to their decreased ability to thermoregulate their body temperature and predispositions resulting from diseases like heart, circulation and respiratory diseases, diabetes mellitus, etc. (Oudin Åström, Bertil, & Joacim, 2011; Reid et al., 2009). Regarding young children as another age-specific sensitivity group (Kovats & Hajat, 2008), they are also expected to be more vulnerable due to their limited thermoregulation capacities, which has, however, not been clearly shown in mortality studies (Ishigami et al., 2008). Apart from age-distribution, population density represents another demographic factor that increase the exposure quantitatively and thus the vulnerability to be subjected to heat stress (Johnson et al., 2012; Romero-Lankao, Qin, & Dickinson, 2012; Scherer et al., 2013).

UHIs are likely to increase in intensity due to the process of climate change and the associated increase of extreme climatic events such as heat waves (Gabriel & Endlicher, 2011; Gill et al., 2007; Harlan et al., 2006; Kovats & Hajat, 2008). In combination with increasing urbanization rates and population aging, climatic change is regarded as major urban sustainability issue (Zhang & Yeh, 2011). For resilient urban planning in the prospect of future weather conditions and demographic change, knowledge concerning the climatic effects of different LU types and the distribution of vulnerable inhabitants at risk should be gained at different scales to support decision-makers (i.e. urban planners).

This study pursues two goals: First, to explore the drivers influencing the temperature distribution based on the LU patterns on different spatial scales, focusing on the relative influence of different types of green space; second, to identify sites of potential heat-stress risk in the city by relating the spatial distribution of temperatures and of vulnerable people at the block level.

2. Methods and materials

2.1. The study area

Berlin, the capital city of Germany, is located in the north-east of Germany, covers an area of 892 km^2 and is populated by 3,513,026 inhabitants (Amt für Statistik Berlin-Brandenburg, 2012). Berlin is characterized by a mainly flat topography. The climate is characterized by cold winters and warm summers. During 2000 and 2010, a daily mean temperature of 19.0 °C (SD = 3.2) was observed for the two warmest month, and several heat stress events are reported especially for 2006 and 2010 (Gabriel & Endlicher, 2011; Scherer et al., 2013; Appendix, Fig. A6). Regarding the LU patterns, Berlin is characterized by a significant amount of green infrastructures and water bodies. A relatively low building and population density outside the inner-city, many allotment gardens for private cultivation and recreation and a considerable amount of urban brownfields exist, despite the slight trend of population growth in the last decade. While some crucial local structural changes took place since the early 1990s (especially at the location of the former Berlin wall), the overall LU patterns remained relatively constant over the last decade (Lauf et al., 2014).

As illustrated in Fig. 1, Berlin consists of 45% water bodies and urban green spaces (forested and unforested, allotment gardens), almost 20% transport and infrastructural areas (streets and railways) and around 35% built-up areas (e.g. residential uses).

2.2. Effects of the land-use patterns on the temperature distribution

2.2.1. Land surface temperature

Several studies prove LST to be convenient for studying UHI on large scales since comprehensive distribution of measured air temperatures are hardly ever available (Kottmeier, Biegert, & Corsmeier, 2007; Li et al., 2011; Schwarz et al., 2012; Weng, Liu, & Lu, 2007). Accordingly, the term surface urban heat island (SUHI) is occasionally used instead of UHI (Li et al., 2011; Schwarz et al., 2012).

We applied Landsat-7 ETM+ LST data because of their high spatial resolution to enable the coupling with LU patterns information down to the level of individual building blocks (cf. Table 1; Patino & Duque, 2013). The small temporal interval between both datasets (12 h) enables to study the SUHI phenomenon, both in the morning and evening under comparable weather conditions (the air temperatures trend over the last decade is shown in the Appendix, Fig. A6).

Fig. 2 shows that at 10 am vegetated areas are obviously cooler than the built-up surroundings, agricultural areas, in contrast, reveal relatively high temperatures. At 10 pm increased LST are mostly concentrated in the inner city and agricultural areas are distinctively cooler.

2.2.2. Indicators describing the land-use patterns

We applied four different types of indicators to describe the LU patterns, namely LU types, landscape metrics, simple structural and aggregated structural indicators, and LU type indicators (cf. Table 2). The first three types were defined at the block-level, the aggregated ones at an intermediate spatial level between building blocks and administrative districts, the so-called LOR-level (official planning areas of the Berlin senate administration for sub-district