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Zooming into temperature conditions in the city of Leipzig: How do urban built and green structures influence earth surface temperatures in the city?

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HIGHLIGHTS

- Urban land-use structure was found to have a significant impact on environmental exposures.
- Main fields of impact are the level and spatial distribution of heat exposure in cities.
- Multiple urban structures have been quantified using the landscape metrics approach.
- Edge density and patch size ratio are significantly correlated with urban temperatures.
- The higher proportion/structural complexity of built area, the higher are surface temperatures.

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ABSTRACT

Urban landscape and land-use structure, particularly that of built space, were found to have a significant impact on environmental exposures, e.g., on the level and spatial distribution of particle and noise exposure in cities. Climate change will increase the frequency, duration and intensity of heat waves. Hence, the question arises: how do urban structures affect the shape and intensity of urban temperature conditions? To answer this question, multiple urban structures have been quantified in terms of their structural patterns and configuration using the landscape metric (LSM) approach. The results of a linear regression analysis showed that both the edge density and patch size ratio are significantly correlated with the spread and intensity of temperatures across all urban built structures. The analysis shows that the higher the proportion and structural complexity of the built area, the higher are the morning and evening surface temperatures. LSMs were found to be very well suited as analysis models of the site-specific temperature impact beyond the aggregate city level. Hence, they may serve as a planning tool for urban adaptation measures to climate change.

1. Introduction

Urban areas are affected by higher surface and air temperatures than their surrounding environments and thus negatively impact human health (Stewart and Oke, 2012). Despite the existence of urban green spaces, which have lower air temperatures and provide shadow, air ventilation and humidity (Kube, 2012), recent climate change has led to increasing mean temperatures, frequencies and durations of temperature extremes in cities, as well as heat waves, with increasing maximum temperatures (Bulkeley, 2013; Franck et al., 2013; Kan et al., 2012). In the study area of this paper, the city of Leipzig in western Saxony, Germany, climate change so far has resulted in an increase of 0.7 K in the annual mean air temperature and an increase of 1.3 K in the maximum temperature, comparing the periods 1961–2005 and 1991–2005 (Saxony Ministry of State of Environment Agriculture SMUL, 2008 cited in Franck et al., 2013). Enke (2001) predicts a 3–4 K increase in the mean temperature for the city of Leipzig by 2060. The studies of Conti et al. (2005), Gabriel and Endlicher (2011), Martiello and Giacchi (2010), O'Neill and Ebi (2009), and Tan et al. (2010) illustrate that human well-being and health are adversely affected by rising outdoor temperatures. Surface temperatures and above ground air temperatures are not identical, but strongly correlated (McPherson et al., 1997; Mostovoy et al., 2006; Prihodko and Goward, 1997; Stewart, 2011).

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Temperatures in big cities and metropolitan areas are usually higher than those in the surrounding rural areas. This phenomenon is called the urban heat island (UHI) (Oke, 1982; Santamouris, 2013). UHIs are defined as the temperature difference in urban and rural areas with diverse indicators for quantifying the difference (Schwarz et al., 2012). The UHI directly affects the well-being (heat stress, fatigue) and health (blood pressure, cardio-vascular diseases, dehydration) of the resident population in cities (Stafoggia et al., 2006; Harlan et al., 2006; Conti et al., 2005; Tomlinson et al., 2011; Gabriel and Endlicher, 2011; Tan et al., 2010). Furthermore, the UHI phenomenon can support the transport of air pollutants to an urban center (Lai and Cheng, 2010; Semazzi, 2003).

The city, as built area, is not homogeneous in terms of density and structure. Typically, an urban area includes different housing densities, building types and arrangements, housing areas, and urban green space percentages (Haase and Nuissl, 2007; Franck et al., 2013). Smargiassi et al. (2008) and White-Newsome et al. (2012) report that indoor temperatures depend on outdoor ones and are modified by the type of urban structure, housing area and perhaps by differences in the behavior of the inhabitants (Franck et al., 2013).

Landscape metrics (LSMs) are algorithms that quantify specific spatial characteristics of elements—such as urban structures (patches, classes of patches, or entire landscape/land-cover/land-use mosaics) — using categorical maps. LSMs can be straightforwardly and quickly computed when a land-use map is available. In addition, they have already been successfully applied to urban form analysis (Schwarz, 2010). Many land-use and landscape studies have used LSMs to assess the impacts of form, patterns, and the configurations of built and non-built land covers on ecological processes, bio-physical properties of the earth's surface, biodiversity (Höbinger et al., 2012; Schindler et al., 2013; Uuemaa et al., 2009), the quality of habitats (Cushman et al., 2012; Santos-Filho et al., 2012), and land-use change (Hassett et al., 2012; Wang et al., 2012). Weber et al. (2014) showed the usefulness of LSMs for forecasting noise and particle exposures for different urban structure types. As a result, their study found that for selected increasing LSMs, accordingly, noise and PM_{10} values increased. Landscape metrics describing fine-scale patterns are important to characterize the designed landscapes of metropolitan areas. But, the fine scales typical of landscape designs and plans may pose a limitation in the application of landscape metrics (Correy and Nassauer, 2005). In cause of the insensitivity and non-uniqueness landscape metrics do not differentiate landscapes with qualitative changes (Haines-Young and Chopping, 1996; Turner et al., 2001). In the interpretation of landscape analysis results landscape changes must be considered. In the context of the interpretation of landscape analysis' results landscape changes must be considered (Li and Wu, 2004). Additionally, landscape indices are sensitive to the level of detail in categorical map data often determined by the schemes used for map classification (Turner et al., 2001; Whickam et al., 1997). A correlation analysis with landscape metrics can be problematic when the conceptual flaws and inherent limitations are ignored. Problems are often the ecological irrelevance of landscape metrics or map data and the variable responses of metrics to changing landscape patterns (Li and Wu, 2004).

The benefit of using LSMs for the estimation and identification of surface temperatures and changes in the shape and intensity of temperature conditions based on urban land-use/cover structures (represented in our study by urban structure types, according to a classification proposed by Haase and Nuissl, 2007; Table 1) has not yet been tested., despite the predictive power of this approach that is widely recognized in other fields of research.

Therefore, our study investigates the following hypotheses:

1. The form and location of an urban land-use/structure type—that is, house density, as determined from LSMs, height of building, percentage of built area and distance from the city center—have significant influences on both surface temperatures and temperature changes.
2. In the examined urban built and non-built areas, surface temperatures vary significantly.

Table 1
Land use classification considered in this study (according to Haase and Nuissl, 2007; Weber et al., 2014; modified), the difference of mean surface temperatures is expressed in Kelvin (K = C + 273.15).

Land use class (acronyms)	Definition	Patch density (number/100 ha)	Area (km^2) and percentage of city area (%)	Mean height (m) and number of buildings	Mean surface temperature °C		
					Morning	Evening	Difference
A (allotments)	Self-managed unions, conduct and lease garden areas	138.78	17.50 (5.89)	6.48 (6256)	9.60	14.81	5.21
FL (fallow land)	Unused land (brownfields, greyfields, grassland)	54.10	6.14 (2.07)	6.61 (609)	9.26	14.20	4.94
GPC (green areas, parks, cemeteries)	Parks, horticulture areas, open spaces	96.48	6.78 (2.28)	10.09 (1173)	10.24	15.55	5.31
HF (hybrid forms)	Mixed types of use	311.70	3.42 (1.15)	12.38 (1623)	10.34	15.23	4.89
ICT (industry, commercial land, trade area)	Production and trading areas built-up since 1850	203.64	27.38 (9.22)	9.23 (10,544)	9.91	15.19	5.28
MSTB (multi-story housing, tenement blocks)	19th century built-up area (1870–1910); arrangement of buildings around a shared leafy court	554.07	14.41 (4.85)	12.28 (28,728)	10.49	15.56	5.07
PHE (prefabricated housing estates)	Multi-story dwellings	365.10	5.03 (1.69)	14.48 (2089)	10.71	15.38	4.67
RC (residential core)	Several old villages within Leipzig's administrative boundaries that are now part of the city but once were separate settlements	661.58	7.08 (2.38)	8.32 (13,036)	10.09	15.22	5.13
RP (residential park)	Modern high-density single house estates built after 1990	397.64	1.43 (0.48)	9.78 (1049)	9.92	15.09	5.17
SLR (sports and leisure facilities, recreation)	Sports and leisure facilities, training areas, recreation areas distributed across the whole city	122.88	2.89 (0.97)	6.44 (660)	9.38	14.61	5.23
SSDH (single and semi-detached houses)	Low-density single house built-up area	454.74	27.71 (9.33)	6.46 (44,211)	9.78	15.00	5.22
TH (terraced houses)	Low-density single house built-up area (alignment with noise prevention)	586.66	5.89 (1.98)	11.85 (7180)	10.41	15.38	4.97
V (villa area)	High-quality detached houses supplemented by private gardens	546.05	2.06 (0.69)	9.18 (3099)	10.38	15.36	4.98