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Geographically weighted regression of the urban heat island of a small city

Danijel Ivajnšič [a,*], Mitja Kaligarič [a], Igor Žiberna [b]

[a] Department of Biology, Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška 160, SI-2000 Maribor, Slovenia
[b] Department of Geography, Faculty of Arts, University of Maribor, Koroška 160, SI-2000 Maribor, Slovenia

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A B S T R A C T

Despite differences in regional climates, cities world-wide have developed one common characteristic - the urban heat island (UHI). Its magnitude is related to city size, especially under cloudless sky conditions on a regional basis, although individual cities may be impacted by such local factors as proximity to large water bodies or prevailing winds. The UHI pattern in the small city of Ljutomer was examined in order to assess its intensity and morphology and to test the utility of the geographically weighted regression (GWR) method in modeling the regression relationships between mean air temperature and related influence factors in this small-scale urban example. Significant differences in mean air temperature between urban and rural areas were measured. It turned out that built-up areas in Ljutomer are on average 1 °C warmer than the rural surroundings in winter time. The regression analyses confirmed the important role of local non-stationary explanatory variables - distance to urban area, topographic position index and land-cover diversity - and global stationary variables - building volume per area and northness - in explaining spatial variation in mean air temperature. The relationships between mean air temperature and these five explanatory variables produced an overall model fit of 91%, utilizing the semiparametric GWR method, which was tested on the smallest scale so far published.

Introduction

The urban heat island (UHI) effect is among the best expressions of the impact of human activity on local Climate (Hinkel, Nelson, Klene, & Bell, 2003). More than 150 years of urban climate studies (Howard, 1820) have shown that thermal, optical and geometric properties of urban surfaces affect heat absorptive and radiative properties and lead to the UHI effect (Feyisa, Dons, & Meilby, 2014; Gartland, 2008; Voogt & Oke, 2003). Urban warming is a manifestation of the direct and indirect alteration of the energy budget in the urban boundary layer. The direct impact is easily visualized as the transformation of stored chemical energy, typically in the form of high-quality fossil fuel. Known as anthropogenic heat, energy is converted to alternate forms to generate heat for buildings and steam for electrical power generation, to power motorized vehicles and drive industrial processes. Although several energy transformations may be involved, the stored chemical energy is eventually dissipated into the atmosphere as sensible heat. Because human activities are concentrated in urban areas, a net flux of heat into the atmosphere is often detectable (Hinkel et al., 2003). The indirect impact is more complex (Arnfield, 2003). This includes land-cover transformation, mainly the replacement of natural vegetation and agricultural land by an impervious surface associated with urban land use (Buyantuyev & Wu, 2010). In response to removal of the natural land cover and the introduction of artificial materials (e.g., concrete, asphalt, tiles, metals, etc.), the radiative, thermal and moisture conditions as well as roughness and emissivity of the surface (and consequently the atmosphere above) change dramatically (Li, Wang, Wang, Ma, & Zhang, 2009; Roth, 2002). As a result, alternation of surface energy fluxes occurs, with a consequent increase in the Bowen ratio (the ratio of sensible to latent heat fluxes), which, in turn, causes an increase in temperatures on and above every urban surface (Oke, 1982; Stull, 1988). The concentration of aerosol and gaseous pollutants in the urban canopy can affect radiation exchange between the surface and the atmosphere. Stewart, Stenz, and Gottinger (2011) pointed out that elevated air temperatures are also known to help induce the chemical reactions that produce tropospheric ozone, whereas Johnson and Wilson (2013) reported that heat-

* Corresponding author. Tel.: +386 2 2293 730.
E-mail addresses: dani.ivajnsic@uni-mb.si (D. Ivajnšič), mitja.kaligaric@uni-mb.si (M. Kaligarič), igor.ziberna@um.si (I. Žiberna).

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related morbidity is congruent with higher UHI intensity levels, particularly in poor urban areas within large agglomerations in the USA. All these changes (direct and indirect) modify the energy balance, water balance and air circulation patterns of the city, although the impact of these factors varies between cities because the geographic setting, urban morphology, patterns of urban land use, and available construction materials are city specific (Landsberg, 1981). However, the main characteristics of the specific city climate in general are as follows: higher air temperatures, mainly at night and in the mornings before sunrise (mid latitudes); lower relative air humidity; lower mean wind velocity and higher levels of air pollution (Žiberna, 2006). Research on the UHI has typically focused on tropical and mid-latitude cities for the dual purposes of understanding the dynamics of the energy balance in the urban boundary layer (Oke, 1987), and application to issues related to urban pollution, energy conservation, and prevention of heat-related health problems or deaths (Buechley, Truppi, & Van Brugg, 1972; Hinkel et al., 2003; Oke, Spronken-Smith, Jauregiu, Grimmond, 1999; Rosenfeld, Akbari, Romm, & Pomerantz, 1998).

UHI develops primarily at night throughout the year and depends heavily on weather conditions (Arnfield, 2003; Buyantuyev & Wu, 2010; Souch & Grimmond, 2006). The intensity of UHI changes seasonally (Fezer, 1994). UHI is, in northern and mid geographical regions (Northern Hemisphere), more pronounced during winter (Hinkel et al., 2003; Žiberna, 2006). In contrast to this, in arid and semi-arid environments, where UHI intensity is dependent on high variability in vegetation (Jonsson, 2004), the UHI maximum usually appears in summer or in the dry season. However, it is known that urban vegetation eases surrounding microclimates through increased latent heat exchange, shade and lack of heat from combustion sources (Buyantuyev & Wu, 2010; Jonsson, 2004; Spronken-Smith & Oke, 1998). Urban greenspaces, parks and water bodies therefore have a cooling influence on the elevated air temperature, and these effects can extend hundreds of meters beyond their boundaries (Choi, Lee, & Byun, 2012; Spronken-Smith & Oke, 1998; Upmanis, Eliasson, & Lindqvist, 1998). Contrary to this, Feyisa et al. (2014) reported a maximum park cooling distance of only 240 m and a maximum park cooling intensity of 6.72 °C in Addis Ababa (Ethiopia) and concluded that the cooling effect of urban green space is mainly determined by species group, canopy cover, size and the spatial design of parks.

According to Oke (1982), two layers can be distinguished in the urban atmosphere: the urban canopy layer (UCL), containing air between the urban roughness elements (mainly buildings), and the urban boundary layer (UBL), which is situated directly above the UCL. The latter is a local or mesoscale concept whose characteristics are governed by the nature of the whole urban area. This study, following the research of Balazs et al. (2009), focuses on the heat island in the UCL, where most human activities usually take place. The first attempts to analyze UHI structure were based on manually interpolated isotherm maps (Duckworth & Sandberg, 1954). More sophisticated interpolation algorithms became popular with increasing access to effective computers and the development of accessible geographic information systems (GIS) software (Alcoforado & Andrade, 2006; Bottyán and Unger 2003; Svensson, Eliasson, & Holmer, 2002; Szymanowski & Kryza, 2012; Vicente-Serrano, Cuadrat-Prats, & Saz-Sánchez, 2005). Unger, Savić, and Gal (2011) reports that most recent studies on the spatial characteristics of UHI are based on multidimensional interpolation algorithms, with multiple linear regression (MLR) being the most often applied. Although global multivariate regression relationships are relatively well-established, the statistical analyses of previous studies have commonly been aspatial, neglecting the locational information associated with each sample site (Foody, 2003). Dutilleul and Legendre (1993) pointed out that observed geographical and ecological patterns and processes in nature, unlike universal physical laws, tend to be spatially variable. This phenomenon is often referred to as spatial non-stationarity (Li, Zhao, Miaomaio, & Wang, 2010). Multiple regression analysis such as the Ordinary Least Squares (OLS) model is based on the assumption of independence of observations, resulting in a failure to capture the spatial dependence of the data when it is applied to geo-referenced data analyses (Li et al., 2010). Brunsdon and Fotheringham developed a local regression technique, Geographically weighted regression (GWR), to overcome this limitation of the OLS method (Brunsdon, Fotheringham, & Charlton, 1996; Fotheringham, Brunsdon, & Charlton, 2002). There have been several recent works where non-stationary statistical methods (such as GWR) are applied to model or analyze UHI (Farber & Paez, 2007; Su, Foody, & Cheng, 2012; Zhou and Wang 2001). Spatial variation in the relationship between variables both at and between spatial scales is reported in the recent literature for studies with spatially distributed environmental data. The studies by Foody (2003, 2004); Propastin, Kappas, and Erasmi (2008) showed that the predictive power as well as the rank order of explanatory variables in spatial models between remotely sensed data and climatic parameters is a function of scale. Therefore, GWR is not a problem-free statistical method, major concerns are focused on issues such as kernel and bandwidth selection. However, its potential for dealing with spatial non-stationary issues has been validated (Foody, 2003; Li et al., 2010).

Understanding and quantifying UHI and its factors are important steps toward improving the quality of life of urbanites and achieving urban sustainability in all types of cities across the globe (Grimm et al., 2008; Wu, 2008). While most studies about UHI focus on medium or large urban areas, our main objective in this study is oriented towards assessment of the intensity and morphology of an UHI event during winter time, in a small city named Ljutomer (a) and to test the utility of GWR in modeling the regression relationships between mean air temperature and related influence factors in this small-scale urban example (b).

Study site

Ljutomer is located in the NE part of Slovenia (46°31′N, 16°11′E), on the western outskirts of the Great Pannonian Basin (Fig. 1 A, B).The city has developed in the transition zone from the surrounding Tertiary hills to the Quaternary plain of the Ščavnica river. Most of the city area lies on the river plain of the Ščavnica, (from 172 to 180 m a.s.l.), except the new suburban part in the SW, which stretches to the warm southern slopes of Kamenščak hill (64 m relative elevation difference) (Fig. 1 C). The Ščavnica river (2–5 m wide) and its narrow regulation canal cross the city area. The climatic influence of these narrow water streams is probably negligible. The east side of the city is bounded by the railway, which represents a sharp line between urban and rural areas (Fig. 1 C).

The climate in the region around Ljutomer is under a strong continental influence, due to its geographical position next to the Great Pannonian Basin. Yearly and daily air temperature amplitudes therefore reach the maximum value in the country (10.4 °C; 30-year average from 1971 to 2000; ARSO, 2006). The mean air temperature is the second highest (9.6 °C from 1971 to 2000) after the Sub-Mediterranean region in the SW part of Slovenia (12.8 °C from 1971 to 2000) (ARSO, 2006; Ogrin, 2009). The surrounding hills exhibit slightly milder continental traits, particularly in the thermal zone, where the minimum temperatures are significantly higher (Ogrin, 2009). The NE parts of Slovenia receive annually a mean precipitation amount of 800–1000 mm (based on data from 1971 to 2000) (ARSO, 2006; Ogrin, 2009). Most of this precipitation falls in summer (more that 1/3 of the annual rate) and just 15% in winter.