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Research Paper

Determinants of urban–rural land surface temperature differences – A landscape scale perspective

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HIGHLIGHTS

- Urban–rural surface temperature difference (ΔLST_{UHI}) averages at 4.2 K.
- Small urban areas (<1 km^2) show ΔLST_{UHI} of more than 8 K.
- The urban–rural NDVI difference (ΔNDVI) is the major driver of ΔLST_{UHI}.
- The surrounding landscape is of crucial importance for quantitative UHI assessments.

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ABSTRACT

Urban areas are known to have a local climate different from that of surrounding rural landscapes and the temperature difference constitutes an urban heat island (UHI). Despite being described as 'heating islands', cities are not isolated from their environment. But only few studies respect the UHI as a relative measure and consider both the drivers of the temperature level of the urban area and of the surrounding landscape in their UHI assessments. A series of 124 Landsat satellite images spanning four decades were used to derive land surface temperatures (LST) of 77 urban areas (between 20 and 1600 ha) and their surroundings in the Province of South Tyrol, northern Italy. These data were used to calculate urban–rural LST differences (ΔLST_{UHI}) and NDVI differences (ΔNDVI) for quantifying the urban heat island effect. ΔLST_{UHI} were recorded between 1.0 K and 8.1 K, with a mean ΔLST_{UHI} of 4.2 K. The results show pronounced UHI effects already for small cities of less than 1 km^2, but suggest that the urban size is of only minor importance for the ΔLST_{UHI} magnitude in case of urban areas smaller than about 10 km^2. Urban–rural land surface temperature difference (ΔLST_{UHI}) was identified to be primarily driven by ΔNDVI, together with solar irradiance and land use. Threshold values for the occurrence of ΔLST_{UHI} extremes are provided. Implications for landscape and urban planning are presented that underpin the crucial importance of considering the surrounding landscape for quantitative assessments of UHI intensity.

1. Introduction

The recognized global temperature rise during the last decades is not just a simple measure or abstraction. Higher temperatures contribute to more intense heat waves, droughts and storms, sea level rise and destructive floods, affecting food security and the habitability of low-lying regions, but also species composition of local ecosystems (Bruelheide, 2003; Del Barrio et al., 2006; EEA, 2012; IPCC, 2013; MEA, 2005; Schröter et al., 2005). Just recently more recognized is the effect of high temperatures in urban environments on human health. Studies in Spain have shown significant positive correlation between heat waves with extreme temperatures higher than 36 °C and hospital admissions (Linares & Diaz, 2006) and for Germany, Italy and France thousands of heat related deaths were reported for the heat wave in 2003 (Conti et al., 2005; Fouillet et al., 2008; Hübler, Klepper, & Peterson, 2008). Also work performance and mental or mechanical abilities are reduced at temperatures already above the comfortable level of about 20 °C and up to 75% at temperatures of 35–37 °C (Hübler et al., 2008). Days with temperatures of more than 36 °C are still rare for the studied area in northern Italy (South Tyrol), but the years showing these extreme temperatures have significantly increased from only 2 years in 1955–1990 to 8 years in 1990–2009 (data provided by Province of South Tyrol). The public health sector of

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South Tyrol already responded to the reoccurring summer heat waves by setting up emergency phone lines, distributing brochures and opening cooler buildings for retreat. Activities and climate actions plans to meliorate urban temperatures, e.g. by vegetation or albedo enhancement, are reported for many other cities (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Stone, Vargo, & Habeeb, 2012). The measures put into action are implemented intra-urban, often ignoring the climatic relevance of the outer-urban environment.

Cities and urban areas are known to have a local climate different from that of surrounding rural landscapes and the temperature difference constitutes an urban heat island (UHI) (Arnfield, 2003; Oke, 1982). The UHI effect results from the replacement of natural with impervious, non-evaporative surfaces such as concrete and asphalt. The dominance of surfaces with high solar radiation absorption and heat storage in combination with little space for vegetation or water bodies results in a modified climate that is usually warmer than the surrounding rural areas. The UHI phenomenon is studied primarily from an urban perspective, focussing on intra-urban relations between temperatures and the structure or composition of the city. Investigated are the effects of different surfaces on the urban climate, considering impervious surface area (Lee & French, 2009; Yuan & Bauer, 2007; Zhang, Zhong, Wang, & Cheng, 2009), parks and green spaces (Cao, Onishi, Chen, & Imura, 2010; Lee, Lee, Jin, & Song, 2009; Papangelis, Tombrou, Dandou, & Kontos, 2012; Zhang, Zhong, Feng, & Wang, 2009b) or water bodies (Steeneveld, Koopmans, Heusinkveld, & Theeuwes, 2014; Sun & Chen, 2012), as well as the spatial pattern of land cover (Connors, Galletti, & Chow, 2013; Mallick, Rahman, & Singh, 2013), the built-up density (Alcoforado, Andrade, Lopes, & Vasconcelos, 2009; Dobrovolny, 2013; Svensson & Eliasson, 2002), the vertical structure (Saaroni, Ben-Dor, Bitan, & Potchter, 2000; Unger, 2006), or the climatic differences related to urban districts, residential parcels and socio-economic conditions (Buyantuyev & Wu, 2010; Eliasson & Svensson, 2003; Klok, Zwart, Verhagen, & Mauri, 2012; Stone & Norman, 2006). Most of these studies refer to single major cities, e.g. to Mexico City (Oke, Spronken-Smith, Jauregui, & Grimmond, 1999), Delhi (Mallick et al., 2013), Shanghai (Li et al., 2011), Beijing (Li, Zhou, & Ouyang, 2013), Phoenix (Connors et al., 2013), Rotterdam (Klok et al., 2012) or Lisbon (Alcoforado et al., 2009). These studies investigate in the first instance local phenomena that need to be set in context with other studies for deriving generalizable trends and key factors that contribute to the UHI effect. Only few studies provide a consistent investigation of a larger quantity of cities on a global or continental scale. Clinton and Gong (2013) describe in a global study the size of the urban area, urban vegetation and nightlights, as a measure of development intensity, as the most important variables that contribute to the UHI effect. Similar findings were made by a global study of more than 3000 settlements (Zhang, Imhoff, Wolfe, & Bounoua, 2010), by investigating 42 urban settlements embedded in forest biomes in the United States (Zhang, Imhoff, Bounoua, & Wolfe, 2012) and by investigating the 38 most populous cities in the continental United States (Imhoff, Zhang, Wolfe, & Bounoua, 2010), all stressing the impervious surface area as primary driver of the UHI amplitude. A study of 8 Asian mega cities showed that UHI intensity is determined by population size, vegetation cover and built-up density (Hung, Uchihama, Ochi, & Yasuoka, 2006). The global study of 419 big cities found no relation between UHI intensity and population density or city size, but emphasizes the key role of urban vegetation cover and activity (Peng et al., 2012).

Despite being described as 'heating islands', cities are not isolated from their environment. But only few studies respect the UHI as a relative measure and consider both the drivers of the temperature level of the urban area and of the surrounding landscape in their UHI assessments. Global and continental studies across biomes stress the importance of the bioregional context for the UHI intensity (Imhoff et al., 2010; Zhang et al., 2010). They report higher UHI intensities for forest compared to grassland biomes that are explained by the cooler surrounding landscape due to higher precipitation and evaporation in the forest biomes. They also report urban heat sinks for semi-arid and desert environments. Studies on urban–rural differences of vegetation indices indicate that high rural–urban differences in vegetation density also lead to high temperature differences, i.e. UHI intensity (Gallo & Tarpley, 1996; Imhoff et al., 2010; Peng et al., 2012). The comparison of two US cities revealed higher UHI intensity for the city with higher tree cover fraction in the rural area, which was explained by the lower temperatures associated with trees (Zhang et al., 2012).

Most of the presented UHI studies rely on land surface temperatures (LST) derived from remotely sensed data. Opposed to air temperatures that are usually measured on-site at fixed meteorological stations, remotely sensed LST can be provided as spatially continuous data over a whole city or region, allowing for comparative studies inside or between cities (Schwarz, Lautenbach, & Seppelt, 2011; Zhang et al., 2010). Air temperatures and surface temperatures show similar spatial and temporal pattern and a number of studies have shown that they are well related (Arnfield, 2003; Schwarz, Schlink, Franck, & Grossmann, 2012; Voogt & Oke, 2003). However, day-time UHI intensity is typically higher when derived from surface temperatures compared to assessments using air temperatures, though quantitative studies are missing (Voogt & Oke, 2003).

The current research on UHI focuses primarily on big cities; many of them are located in the USA and China. Mostly single cities are studied, producing rarely comparable results, or the research has a global or continental dimension, inevitably lacking spatial detail. The present study tends to overcome these limitations by investigating a large number of urban areas, independent of size, for a specific geographic region. The focus of the study is specifically set on the relations between the urban area and the surrounding landscape. The term UHI in the present study refers to the surface UHI derived from remotely sensed land surface temperatures (LST), opposed to the atmospheric UHI based on air temperatures (Voogt & Oke, 2003). As UHI indicator, the difference in mean LST between the urban area and all other surrounding areas is used (Schwarz et al., 2011). The specific research questions under consideration are:

- Is the UHI effect a specific phenomenon of "big cities" or can UHIs also be observed for small towns of a few square kilometres in size?
- Does landscape composition influence urban surface temperatures or UHI intensity?
- Can vegetation indices (NDVI) be used to estimate UHI intensity?
- How relevant is the consideration of the rural area for quantitative assessments of the UHI intensity?

2. Methods

A series of Landsat satellite images spanning four decades were used to derive land surface temperatures (LST) of selected urban areas and their surroundings in the Province of South Tyrol, northern Italy. The data were used to calculate temperature differences between the urban area and the surroundings for quantifying the urban heat island effect. These temperature differences were related to environmental variables, surface properties and land cover for deriving relations and interactions between temperatures inside and outside the urban area.