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Heat waves and urban heat islands in Europe: A review of relevant drivers

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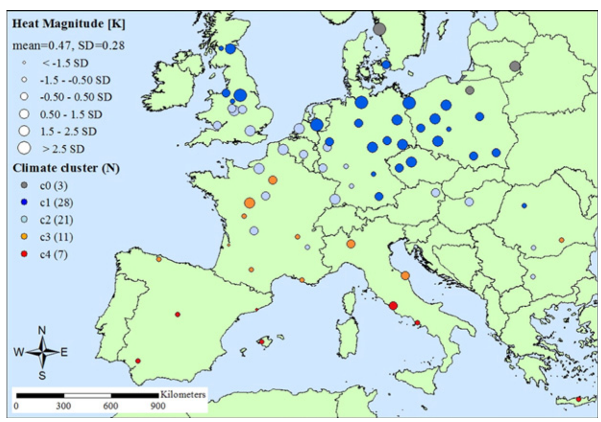
HIGHLIGHTS

- Urban heat will affect more people due to climate change and proceeding urbanization.
- 70 European cities to analyze the development of urban heat islands under heat waves
- Urban green seems to increase the heat island magnitude during heat waves.
- Colder cities seem to be more affected by heat waves than warmer cities.
- Applied city clusters might support case-specific adaptation through urban planning.

GRAPHICAL ABSTRACT



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ABSTRACT

The climate change and the proceeding urbanization create future health challenges. Consequently, more people around the globe will be impaired by extreme weather events, such as heat waves. This study investigates the causes for the emergence of surface urban heat islands and its change during heat waves in 70 European cities. A newly created climate class indicator, a set of meaningful landscape metrics, and two population-related parameters were applied to describe the Surface Urban Heat Island Magnitude (SUHIM) – the mean temperature increase within the urban heat island compared to its surrounding, as well as the Heat Magnitude (HM) – the extra heat load added to the average summer SUHIM during heat waves. We evaluated the relevance of varying urban parameters within linear models. The exemplary European-wide heat wave in July 2006 was chosen and compared to the average summer conditions using MODIS land surface temperature with an improved spatial resolution of 250 m. The results revealed that the initial size of the urban heat island had significant influence on SUHIM. For the explanation of HM the size of the heat island, the regional climate and the share of central urban green spaces showed to be critical. Interestingly, cities of cooler climates and cities with higher shares of urban green spaces were more affected by additional heat during heat waves. Accordingly, cooler northern European cities seem to be more vulnerable to heat waves, whereas southern European cities appear to be better adapted. Within the ascertained population and climate clusters more detailed explanations were found. Our findings improve the understanding of the urban heat island effect across European cities and its behavior

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under heat waves. Also, they provide some indications for urban planners on case-specific adaptation strategies to adverse urban heat caused by heat waves.

1. Introduction

The Urban Heat Island (UHI) effect presents planning challenges due to the continuing processes of climate change and urbanization (Rizwan et al., 2008). This effect is simply defined as higher temperatures within urban areas compared to their surroundings (Oke, 1982; Voogt and Oke, 2003). Generally, it is a result of urbanization that is most likely triggered by industrialization (Rizwan et al., 2008) causing structural and land cover changes in urban areas (Stewart and Oke, 2012). The UHI is induced by a combination of factors, including street canyon geometry, the amount of artificial surfaces with increased emissivity, and also anthropogenic heat production (e.g. Oke, 1982). This phenomenon appears in almost every urban area, no matter whether the specific city is small or large, or whether it is situated in a warm or cold climate (Stewart and Oke, 2012). In the future the urban climate will likely be affected by additional summerly heat load due to climate change, associated with the increase of heat waves of higher intensities and longer duration (IPCC, 2013). One major effect of UHIs is the increase of human discomfort, especially in the inner-cities well documented by urban heat stress studies (Scherer et al., 2013; Gabriel and Endlicher, 2011; Kovats and Hajat, 2008). Heat waves increase heat stress especially on vulnerable individuals, such as elderly people and those with social or physical impairments (Rebetez et al., 2009; Kovats and Hajat, 2008). Heat stress affects human health and manifests in various symptoms, such as lack of concentration, exhaustion, dehydration, circulatory disorder, and finally can result in death, as revealed in several studies (e.g. Gabriel and Endlicher, 2011; Gartland, 2010; Wolf et al., 2009; Kovats and Hajat, 2008; Scherer et al., 2013). The UHI effect increases the temperature in cities and thus makes urbanities more predisposed to heat stress compared with rural areas (Kovats and Hajat, 2008). Thus, strategies of mitigation and adaptation particularly through urban planning are needed, especially with regard to the continuously growing cities and the likely increase in urban heat stress (Gartland, 2010; Stewart and Oke, 2012).

Cities consist of complex and spatially heterogeneous mosaics of different land-cover and land-use classes (LCLU). Each LCLU type has its own surface characteristics resulting in different temperature properties (Wu, 2008). The only possibility to observe temperature patterns in cities explicitly and comprehensively is the bird's eye perspective using thermal remote sensing which provides the Land Surface Temperature (LST). Thus, thermal satellite imagery offers great potential to improve the understanding of urban climate dynamics (Peng et al., 2012). Analogously to the UHI, the Surface Urban Heat Island (SUHI) effect can be measured using LST (Schwarz et al., 2011; Voogt and Oke, 2003).

The influence of the urban structure on the UHI magnitude has been recognized since the 1970s (Oke, 1973). The way in which single LCLU types affect the UHI and LST distribution is revealed in various spatial analyses (Kottmeier et al., 2007; Lo et al., 1997; Voogt and Oke, 2003). Their results show the contributing effect of sealed urban surfaces (mostly densely buil*t*-up land uses) to the UHI due to the thermal absorption in artificial surfaces leading to sensible heat flux. A positive effect of thermal reduction on urban green areas is confirmed as a consequence of evapotranspiration. By releasing latent heat and at the same time reducing the amount of energy available for sensible heat, green areas can potentially cool the surrounding area (Peng et al., 2012). Water bodies are another sourced that has been determined to reduce thermal load due to a high thermic inertia, at least during the day (Liu and Weng, 2008; Lo et al., 1997). Dugord et al. (2014) found that urban green spaces can also contribute to the SUHI. In this study forested and non-forested green areas are distinguished and LST patterns are considered at day and night time. While the forested green areas reduce SUHI, non-forested green areas contribute to the SUHI in the morning time (not in the evening). On clear nights, non-forested green areas produce cool air contributing to the reduction of the SUHI. However, during the day these green areas may considerably heat up, especially if dried out, due to unhindered direct solar radiation. Gill et al. (2007) argue that green areas have benefits in terms of thermal reduction but that droughts can reduce these advantages significantly because of reduced water supply for plant transpiration.

Recent studies focus on the size, composition and geometry of LCLU patches to determine the spatial variability of the physical urban structure using landscape metrics (Schwarz, 2010; Baur et al., 2015; Lauf et al., 2016). Accordingly, landscape metrics for single LCLU types are revealed to identify how LST and UHI are affected by specific structural differences in patches of single LCLU types (Dugord et al., 2014; Li et al., 2011; Liu and Weng, 2008). Along with the aforementioned features, a general increase in the percentage of green areas and in the vegetation fraction reduces the thermal pressure that city dwellers face (Peng et al., 2012; Li et al., 2011). According to Li et al. (2011) the interspacing of urban green into other land use types, seems to have a greater effect on mitigating the SUHI effect than a large green area itself. Comparably, Dugord et al. (2014) found that forested green areas contribute better to thermal reduction when patches are more complex in shape and more distributed in space. Moreover, other typically non LCLU-related indicators were found to relate to urban climate, such as the regional climate, socio-demographics, local plant characteristics, albedo and other environmental conditions, e.g. air pollutants, soil sealing or anthropogenic heat (Rizwan et al., 2008; Zhang and Wang, 2008).

Currently more than half of the world's population lives in the comparatively small areas of densely concentrated urban cores (UN, 2011), and it becomes increasingly important to understand the processes contributing to UHIs in order to reduce heat stress and minimize death tolls during future heat waves. The UHI has been studied intensively but the level of understanding is unsatisfactory (Scherer and Endlicher, 2013; Buyantuyev and Wu, 2010). For example, the link between urban patterns and temperature variances has not yet been fully understood (Li et al., 2011). Little is known regarding how heat waves are spatially distributed in urban areas and how specific urban structures affect the magnitude of UHIs on a supra-regional scale. Are there specific regions and/or urban conditions that foster or reduce the SUHIM?

This study investigates, firstly, the causes behind the SUHI effect, focusing on the varying urban structures across Europe. A newly created climate class indicator, a set of landscape metrics, and two population-related parameters are computed to relate them to LSTs originally derived from spatially-improved MODIS data (Metz et al., 2014b). Secondly, the paper focusses on an explanation of different magnitudes of the SUHI during heat waves, focusing on specific urban pattern and land use characteristics for European cities of different climate zones and different population sizes.

2. Data and methods

2.1. European cities

As a basis for the selection, we considered all European cities with >100,000 inhabitants that are listed on Eurostat, the Directorate-General of the European Commission providing empirical data to the EU institutions and the public (Eurostat, 2014). The only condition was that uniform and comparable LCLU data were available from the Urban Atlas, provided by the European Environment Agency (2014).