Urban Climate 10 (2014) 573–584

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Human-biometeorological assessment of the urban heat island in a city with complex topography – The case of Stuttgart, Germany

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ARTICLE INFO

Article history:
Received 15 July 2013
Revised 18 November 2013
Accepted 6 January 2014

Keywords:
Urban heat island
Thermal comfort
PET
UTCI
Topography
Stuttgart

ABSTRACT

The spatial and temporal differences of climate, urban heat island and future conditions were assessed for Stuttgart, a city located in complex topography in Southwest Germany. The present and future urban climate conditions were analysed using hourly measured data from 2000 to 2011 of 5 measuring stations and data from regional climate simulations. The urban heat island intensity was quantified applying thermal indices as Physiologically Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) and compared to weather type classifications. In Stuttgart, wind speed was mostly less than 3 ms^{-1}, the wind roses were very inconsistent and local wind could be clearly observed. The average annual urban heat island of air temperature was between 0.3 K in the suburb areas to 2 K in the city centre and the maximum up to 12 K. The assessed urban heat island with PET was in average 3.3 K and maximum around 20 K. Based on regional climate simulation we found that the amount of days with heat stress (PET $\geqslant$ 35 °C) is estimated to increase by about 17 days until the end of the 21st century. Urban heat island and intra-urban variability were most obvious using thermal indices rather than air temperature.

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http://dx.doi.org/10.1016/j.uclim.2014.01.003

1. Introduction

Modifications of air and surface temperature are the most prominent characteristics of urban climate. Spatial and temporal differences of meteorological parameters develop within one urban area as a function of aerodynamic surface structure and radiation fluxes (Landsberg, 1981; Helbig et al., 1999; Mayer et al., 2003). The so-called urban heat island (UHI) describes the regular appearance of higher temperature in a city compared to rural sites due to alteration in energy and water budget (Landsberg, 1981; Oke, 1982; Wilby, 2007). Causes of the canopy layer UHI are among others, an increased absorption of short-wave radiation by urban morphology. Additionally, incoming long-wave radiation is elevated due to air pollution but outgoing long-wave radiation is reduced due to the smaller sky view factor. Furthermore, anthropogenic heat sources and heat storage contribute to the UHI as well as increased Bowen ratio (Oke, 1982).

The average UHI intensity in other cities in the same climate zone and Europe was reported to be between 1 K in Wroclaw (Szymanowski and Kryza, 2012) and 2–3 K in Athens (Katsoulis and Theoharatos, 1985). Böhm and Gabl (1978) reported an average UHI of 1.4 and 2.4 K in Vienna, Austria, from 1968 to 1977 and 1.5 K from 1986 to 1995 (Böhm, 1998). Unger (1996) reports a mean (maximum) UHI of 1.6 K (8.2 K) in Szeged, Hungary in 1997–1998. An average UHI of 1.9 K and a maximum intensity of 8.2 K was observed in Munich (Bründl et al., 1987; Mayer, 1987). In Athens, the mean magnitude of the urban heat island, which is strongly influenced by topography and presence of the sea was estimated to be 2–3 K in the period 1961–1982 (Katsoulis and Theoharatos, 1985). Although, the mean monthly UHI intensity peaked during summer, the minimum mean air temperature difference was found to be highest in November, which was explained by anthropogenic heat production (Katsoulis and Theoharatos, 1985). In Wroclaw, Poland, the average UHI magnitude for the period 1971–2000 is 1.0 K per year. The air temperature difference peaked in spring (1.2 K) and are smaller in autumn and winter (1.1 K) (Szymanowski and Kryza, 2012). Runnalls and Oke (2000) reported the largest UHI intensity in autumn and the smallest in spring in Vancouver, Canada. The mean UHI magnitude was observed to be 1.4 K and difference between daily minima 2.4 K. The largest UHI intensity was 8.9 K and occurred in September.

The influence of climate on human health and well-being is already well analysed (Souch and Grimmond, 2004; European Environment Agency, 2004; O'Neill and Ebi, 2009). Extreme weather conditions, especially heat waves have a negative effect on mortality and morbidity (Robinson, 2001; Flynn et al., 2005; Ishigami et al., 2008; Gosling et al., 2009; Matzarakis et al., 2011). The UHI is an additional factor during heat waves that enhances health risks leading to higher mortality rates in cities compared to rural environments (Clarke, 1972; Conti et al., 2005). Furthermore, the UHI might lead to an increase in air pollution (Taha, 1997) and energy consumption (Lin, 2000).

The analysis and quantification of the urban micro-climate and adaptation measures are necessary to improve the micro-climate conditions, health and well-being of city dwellers (Matzarakis and Endler, 2010). The analysis of the UHI and intra-urban differences for in particular city planning issues needs to focus on the thermal perception of humans, wherefore the integral effect of air temperature, wind speed, air humidity and radiation has to be taken into account (Eliasson, 2000). This can be performed by using thermal indices as the Physiologically Equivalent Temperature (PET (Mayer and Höppe, 1987; Höppe, 1999; Matzarakis et al., 1999)) and Universal Thermal Climate Index (UTCI (Jendritzky et al., 2012)).

Complex topography and location of cities in sink-like basins exacerbate the existing urban climate issue mainly due to reduced ventilation and further decrease of total turbulent heat transport as well as worsening of the air quality. At the same time, the analysis is more complex for cities located in complex terrain and having inhomogeneous land cover due to local scale phenomena as for example katabatic wind (Landsberg, 1981).

The regional climate conditions, which form the background conditions of urban climates, are expected to change in the 21st century due to climate change (IPCC, 2007). Numerical models show that the actual climate in a city represents the conditions in rural areas in the same climate zone at the end of the 21st century (Matzarakis, 2013). Longer-lasting, more frequent and more intense heat waves are expected to occur in Western Europe in the 21st century (Schär et al., 2004; Meehl and Tebaldi, 2004).