Landscape and Urban Planning 148 (2016) 37–50

Contents lists available at ScienceDirect

Landscape and Urban Planning

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

Research Paper

Contribution of trees and grasslands to the mitigation of human heat stress in a residential district of Freiburg, Southwest Germany

Hyunjung Lee[a,*], Helmut Mayer[a], Liang Chen[b]

[a] Chair of Meteorology and Climatology, Albert-Ludwigs-University of Freiburg, Germany
[b] School of Geographic Sciences, East China Normal University, Shanghai, PR China

HIGHLIGHTS

- Human heat stress in a residential district is simulated for different green coverage scenarios.
- The impact of trees on human thermal comfort is quantified for a heat wave day.
- Green coverage is capable of reducing mean radiant temperatures by 43 K.
- Green coverage is capable of reducing mean physiologically equivalent temperatures by 22 K.
- The human-biometeorological performance of the ENVI-met model is validated.

ARTICLE INFO

Article history:
Received 14 November 2014
Received in revised form 5 December 2015
Accepted 10 December 2015

Keywords:
Human heat stress
Green coverage changes
Residential district
ENVI-met simulations
Model evaluation

ABSTRACT

The potential of urban green coverage to mitigate human heat stress is studied using the ENVI met model V4. The simulation domain is a residential district in Freiburg, a mid-size city in Southwest Germany. It is characterised by residential buildings and street canyons with asphalt surfaces, grasslands and broad-leaved trees. The ENVI-met model was validated against human-biometeorological measurements and demonstrated good performance when simulating the urban thermal environment in terms of air temperature (T_a) and human heat stress in terms of mean radiant temperature (T_{mrt}) and physiologically equivalent temperature (PET). Simulations were performed for the heat wave day of 4 August 2003, which is a typical scenario for future summer weather in Central Europe as projected by climate models. Four scenarios with different types of green coverage were simulated. The results enable quantification of the daytime and nocturnal contributions of trees and grasslands, respectively, to the mitigation of human heat stress on different spatial scales. Averaged over 10-16 CET, trees on grasslands lead to a mitigation effect up to 2.7 K for T_a, 39.1 K for T_{mrt} and 17.4 K for PET. In comparison, the effect of grasslands can be up to 3.4 K for T_a, 7.5 K for T_{mrt} and 4.9 K for PET. Based on the findings, design implications are also provided from the perspective of urban human-biometeorology.

1. Introduction

Each city is embedded in a specific regional atmospheric situation, which is determined by its respective climate zone and current weather situation as well as topographic and land use conditions (Holst & Mayer, 2011). Within a city, the regional atmospheric situation is modified by urban structures, land covers and air-surface energy exchange processes, which lead to different urban meteorological phenomena such as the well-known urban heat island effect (Kuttler, 2010).

The regional atmospheric situation is influenced by regional climate change. For Central Europe, results of climate simulations indicate that severe heat waves will be more frequent and intense, as well as longer lasting in the future (Beniston, 2013). On the other hand, the design of Central European cities is not adapted to severe heat, which causes negative impacts on the health and well-being of citizens (Hajat & Kosatky, 2010). The threat of heat stress is gradually increasing in many Central European cities due to demographic changes with raising proportions of elderly people (Federal Statistical Office of Germany, 2011). Senior citizens are particularly

* Corresponding author.
E-mail addresses: hyunjung.lee@meteo.uni-freiburg.de (H. Lee), helmut.mayer@meteo.uni-freiburg.de (H. Mayer), lchen@des.ecnu.edu.cn (L. Chen).

http://dx.doi.org/10.1016/j.landurbplan.2015.12.004

vulnerable to heat stress as people's thermo-physiological capacity for adaptation to severe heat decreases with age (Laschewski & Jendritzky, 2002). With this background, urban design measures aimed at maintaining local human thermal comfort, even under severe heat stress, have recently drawn increasing attention (Lee & Mayer, 2013; Lee, Holst, & Mayer, 2013; Mayer, Holst, Dostal, Imbery, & Schindler, 2008; Moonen, Defraeye, Dorer, Blocken, & Carmeliet, 2012; Müller, Kuttler, & Barlag, 2014). With respect to improving the health and well-being of citizens, recommendations and implementation of design strategies need to be based on scientific findings from the urban human-biometeorological perspective.

The human perception of heat is governed by the local thermal environment and thermo-physiological processes, which are combined in the human heat budget (Höppe, 1999; Mayer, 1993). Therefore, human perception of the local thermal environment cannot be described only by the air temperature (T_a), as it is also influenced by other meteorological variables such as the mean radiant temperature (T_{mrt}), wind speed (v) and water vapour pressure (VP). A number of thermal comfort assessment indices have been developed in the last 30 years based on the human heat budget (McGregor, 2011). These indices enable the evaluation of the thermal environment in a thermo-physiologically significant way. As such indices, like the physiologically equivalent temperature (PET) (Mayer & Höppe, 1987), were developed and successfully applied in urban settings (Acero & Herranz-Pascual, 2015; Chen & Ng, 2012; Holst & Mayer, 2011; Lee & Mayer, 2015; Lee, Mayer, & Schindler, 2014), they can be used to analyse the potential of urban greening for the mitigation of urban thermal environments and provide implications for urban design.

The cooling effect of street trees by shading and evapotranspiration has been emphasised and design recommendations have been proposed (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Coutts, White, Tapper, Beringer, & Livesley, 2015; Klemm, Heusinkveld, Lenzholzer, & van Hove, 2015; Lee & Mayer, 2013, 2015; Mullaney, Lucke, & Trueman, 2015; Shahidan, Shariff, Jones, Salleh, & Abdullah, 2010; Shashua-Bar, Pearlmutter, & Erell, 2011). It has been found that urban greening contributes to a reduction in the heat input into all urban open spaces in the daytime. In combination with the local airflow, the magnitude of such cooling effects mainly determines whether the thermal load at night can be alleviated to a level where indoor air conditioning systems do not need to be used. However, so far most previous investigations on the cooling effect of urban greening are focused only on T_a. The human-biometeorological aspect of local mitigation of human heat stress has only been addressed in a few studies of individual sites (Acero & Herranz-Pascual, 2015; Chen & Ng, 2013; Cohen, Potchter, & Matzarakis, 2012; Coutts et al., 2015; Holst & Mayer, 2011; Lee & Mayer, 2015; Lee et al., 2013; Mayer, Kuppe, Holst, Imbery, & Matzarakis, 2009; Shashua-Bar et al., 2011).

Taking into account the increasing heat waves in Central Europe in the future, the objective of this study is to expand the existing knowledge of the potential of urban greening to mitigate human heat stress from the human-biometeorological perspective. A residential district in Freiburg (Southwest Germany) was selected for the case study. Human-biometeorological simulations using the ENVI-met model were conducted for a typical Central European heat wave day. With respect to urban human-biometeorology and applications in urban design, the study emphasises the following issues: (i) the current green land use in the study site, (ii) different green coverage scenarios in the study site, (iii) the local thermal environment in terms of T_a, (iv) human heat stress in terms of T_{mrt} and PET, (v) representative street canyons in the study site, and (vi) longer time periods that are more relevant to design strategies than a certain time slot in the afternoon.

2. Methods

2.1. Simulation day and study site

Numerical simulations using the ENVI-met model were conducted for 4 August 2003. It was a clear-sky summer day in the severe heat wave of 2003 in Central and Western Europe (Rebetez et al., 2006). It represents typical atmospheric conditions of future summer weather in Central Europe (Beniston, 2013). As this day was at the beginning of the heat wave, urban greening was not affected by the high air temperature and lack of water.

A residential district (Fig. 1) located in the northern downtown of Freiburg (44° 00′ N, 7° 51′ E, 280 m asl), a mid-size city (222,000 residents in 2014) in Southwest Germany, was selected as the study site. Arranged fairly evenly, it consists of three-storey residential buildings with pitched roofs and street canyons with asphalt surfaces, grasslands and broad-leaved trees (mainly maple trees). The aspect ratio (H/W) of the street canyons is approximately 0.5. According to the classification of the local climate zone scheme (Stewart & Oke, 2012), the study site can be characterised as a mixture of the built types LCZ 3 (compact low-rise) and LCZ 5 (open mid-rise).

2.2. Simulation model

The three-dimensional micro-meteorological model ENVI-met (Bruse & Fleer, 1998) is one of the few micro-scale models that meet the criteria for an accurate simulation of physical processes and resulting micro-meteorological phenomena within the urban canopy and boundary layer (Erell, Pearlmutter, Boneh, & Bar Kutiel, 2014; Huttner, 2012). ENVI-met is a three-dimensional Computational Fluid Dynamics (CFD) model that simulates surface-plant-air-interactions in urban environments. Its physical basis has been well explained in the literature (Ali-Toudert & Mayer, 2006; Bruse & Fleer, 1998; Huttner, 2012; Samaali, Courault, Bruse, Olioso, & Occelli, 2007; Taleghani, Kleerekoper, Tenpierik, & van den Dobbelsteen, 2015). Different versions of the ENVI-met model have been successfully applied in simulations of the micro-meteorological and human-biometeorological impacts of building and street design as well as urban greening (Acero & Herranz-Pascual, 2015; Ali-Toudert & Mayer, 2006, 2007; Chen & Ng, 2013; Lee & Mayer, 2015; Middel, Häb, Brazel, Martin, & Guhathakurta, 2014; Müller et al., 2014; Ng, Chen, Wang, & Yuan, 2012; Perini & Magliocco, 2014; Skelhorn, Lindley, & Levermore, 2014; Srivanit & Hokao, 2013; Yang, Zhao, Bruse, & Meng, 2013).

In this study, the up-to-date ENVI-met model V4 (released in 2013) and its sub-module BioMet (v. 1.0) were used for the numerical simulations. The BioMet sub-module enables the calculation of PET according to the method described by Höppe (1999). The assignment of PET ranges corresponding to different human thermal sensation levels is based on the classification scheme (Table 1) derived by Holst and Mayer (2010) for hot summer conditions in Freiburg. In contrast to previous versions, version V4 has some essential improvements (Acero & Herranz-Pascual, 2015; Huttner, 2012; Yang et al., 2013) such as the implementation of a forcing function. This means that 1-h values of T_a and relative humidity (RH) measured at a meteorological station, which is adjacent to the simulation domain, can be included in the simulation. Therefore, more realistic simulation results can be achieved. In this study, 1-h T_a and RH data were taken from a meteorological station at the top of a high-rise building located at the upper border of the simulation domain, as shown in Fig. 1.

The investigation site allowed for validation of the human-biometeorological performance of the applied model in terms of T_a, T_{mrt} and PET. It was based on field studies on human thermal comfort, which were simultaneously conducted at five