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Research Paper

Human-biometeorological assessment of heat stress reduction by replanning measures in Stuttgart, Germany

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HIGHLIGHTS

- Reconstruction changes have been assessed using PET.
- Small green areas have only local effects on thermal comfortable conditions.
- Single mitigation and adaptation measures can reduce PET by two assessment classes.
- A NW–SE oriented street canyon (H/W ratio > 1.5) provides best thermal conditions.

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ABSTRACT

Adaptation and mitigation measures, which could be utilized in urban planning, were quantified in regard to their influence on thermal conditions for humans. The effects of city-planning redesign on thermal human-biometeorological conditions are analysed in an urban quarter in Stuttgart, Germany. Two micro-climate models are applied to receive quantitative information about mitigation and adaptation measures. The Physiologically Equivalent Temperature (PET) was simulated by RayMan and ENVI-met 3.5 to assess thermal human-biometeorological conditions of the current urban environment. The planned residential area and different green space scenarios are analysed and their thermal conditions are compared. In addition, different orientations and aspect ratios in street canyons were analysed. Aim was to find out how heat stress during summer can be minimized and to optimize thermal comfort and solar access for mid-latitude cities during the whole year. PET was found to be around 10 °C lower under trees compared to green areas (38 °C) and at least 25 °C lower than over sealed areas (48 °C). This result corresponds to an increase of heat stress of three thermophysiological assessment classes for PET. Thermal stress can be reduced in a street canyon with a northwest-southeast orientation combined with an aspect ratio of at least 1.5. This configuration allows nevertheless solar access during winter and maximizes the frequency of thermal conditions during the whole year.

1. Introduction

As heat stress is expected to occur more frequently, more intense and long-lasting in Middle Europe in the 21st century (Meehl & Tebaldi, 2004; Schär et al., 2004), measures for the improvement of urban climate are indispensable to enhance health and well-being of city dwellers (Matzarakis & Nastos, 2011). Therefore, the consideration of climatic aspects of urban structures for city planners is essential (Eliasson, 2000). One facing target, not only for anthropogenic climate change issues, is to create appropriate climatic conditions by means of vegetation (Matzarakis & Endler, 2010; Shashua-Bar & Hoffman, 2004).

As human beings experience the integral effect of the meteorological conditions that include air temperature, air humidity, wind velocity and radiation fluxes, all these parameters have to be considered in an assessment of the thermal environment (Fanger, 1972). Since other experimental studies did not find significant micro-scale stratifications of air temperature within a street canyon (Bourbia & Awbi, 2004; Santamouris, Papanikolaou, Koronakis, Livada, & Asimakopoulos, 1999), an analysis based on air temperature alone is therefore not appropriate (Thorsson, Lindberg, Björklund, Holmer, & Rayner, 2011). Experimental studies are mostly limited to existing urban morphology and single point measurements. However, micro-scale models, e.g. ENVI-met (Bruse & Fleer, 1998; Huttner, 2012), SOLWEIG (solar and longwave environmental irradiance geometry; Lindberg, Holmer, & Thorsson, 2008) and RayMan (Matzarakis, Rutz, & Mayer, 2007, 2010) are more

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suitable to quantify changes in the thermal environment due to urban design or adaptation measures.

Several empirical studies on street morphology have analyzed mean radiant temperature, air and surface temperature, Physiologically Equivalent Temperature (PET), shading by trees and wind speed in urban canyons in different climate zones (Bourbia & Awbi, 2004; Holst & Mayer, 2011; Santamouris et al., 1999; Yoshida, Tominaga, & Watatani, 1990). Other studies used micro-scale models (e.g. RayMan, ENVI-met and SOLWEIG) to quantify the impact of street design and vegetation on the thermal conditions in street canyons (Ali-Toudert & Mayer, 2006; Herrmann & Matzarakis, 2012; Johansson & Emmanuel, 2006; Kuttler, 2011).

The topic of urban climate has a long tradition in Stuttgart. An office for urban climatology was founded in 1938, because of low air exchange causing air pollution, and the frequent occurrence of thermal stress (SCS, 2010). Investigations of ventilation and air pollution are the main focus of the Department of Urban Climatology of Stuttgart City. Other topics of interest include measurement and mapping of noise and development of a noise abatement plan. The urban heat island characterized by the surface temperature was derived from thermal images (for more information see www.stadtklima-stuttgart.de). The urban heat island (UHI) effect and climatic event days are analyzed and simulated using annual and monthly mean values over a standard reference period 1951–1980 and 1961–1990. Maps were generated using the thermal index Predicted Mean Vote (PMV; Fanger, 1972) (e.g. Bläsing, Sievers, & Graetz, 2001).

Based on the existing information and knowledge, several questions concerning climate change effects and for mitigation and adaptation possibilities have been raised from the urban planning perspective.

The aim of this paper is to assess and quantify the impact of adaptation measures and redesign of a specific area in Stuttgart-West in a human-biometeorological way using long-term point and short-term spatial micro-scale modelling. The study was done in Stuttgart-West, where the Olga Hospital would be reconstructed. First, thermal conditions are analyzed using thermal indices for selected representative points in Stuttgart-West for the period 2000–2011 using hourly meteorological data of a nearby measuring station. Secondly, thermal conditions are modelled for a specific region of the city, the present area of the Olga Hospital, the planned residential area and a park for a selected meteorological event (heat wave). Thirdly, different surface and open space types and their impact on thermal human-biometeorological conditions are compared to quantify adaptation measures. Finally, a systematic analysis focused on which street orientation and aspect ratio (H/W ratio) is the most suitable for Stuttgart-West has been conducted. On the one hand, heat stress should be mitigated and, on the other hand, solar access and comfortable human thermal conditions should be provided for city dwellers throughout the year.

2. Study area and methods

2.1. Study area

Stuttgart is the fourth largest metropolitan region in Germany, with a population of 600 000 in 2008 (Fig. 1). It is the most important city for industry, education, culture and policy in the south-western part of Germany. The city shows a reurbanisation trend since 2000 and had a population growth rate of 4.3% in 2010 (www.statistik-bw.de). The mean air temperature was 9.5 °C and the average precipitation was 666 mm in Stuttgart from 1961 to 1990. The relatively low precipitation arises from the city's location in the lee of the Black Forest. Stuttgart's city centre lies in a sink like basin, while the urban quarters are spread across hills and valleys. Air temperature is 1–2 °C warmer in the city centre than in the surroundings. Inversions are frequent during winter. Stuttgart's city dwellers suffer from a strong nocturnal urban heat island (UHI), frequent heat stress in daytime and relatively strong air pollution aggravated by weather conditions connected with a low wind speed, mostly less than 3 m s^{-1}. Especially, the wind speed in the city centre and the Neckar valley is very low (SCS, 2010).

Table 1
Description of the current urban design of the Olga Hospital, Stuttgart-West.

Inhabitants in Stuttgart-West per sq km	7400	
Elevation (m asl)	280	
Mean SVF (spheric)	0.69	
Mean aspect ratio	1.3	
Built area fraction/unbuilt area fraction	0.4/0.6	
Impervious surface fraction of the unbuilt area fraction	0.57	95%
Pervious surface fraction of the unbuilt area fraction	0.03	5%
Built surface fraction	5.03	

The examined study area in Stuttgart-West is located within the Triassic Keuper marl (Mercia Mudstone) basin, where also the city centre is located. The study area extends from the circular depression to the western hills (Fig. 1). The flow of cold air, which could reduce the nocturnal heat load, is limited by high buildings and population density of 7400 per sq. km (Table 1). The Olga Hospital in Stuttgart-West, which is the focus of the study, is planned to be redesigned to a new housing complex and a common outdoor area. The mean aspect ratio of the analyzed Olga Hospital area is 1.3 and the built area fraction 0.4 (Table 1). Pervious surface fraction of the unbuilt area is 5%. In Stuttgart-West five different locations (P1–P5) are chosen in order to analyze the thermal conditions over the last 10 years (see Figs. 1 and 2). These locations are representative for different street orientations, courtyards and green spaces. P1 is located in a green space with an SVF of 0.4. Point 2 is located in an east-west oriented street canyon with an SVF = 0.23 and P3 in a NNW-SSE oriented street canyon with an SVF = 0.24. The fourth point is located in a courtyard which is WSW-ENE oriented with an SVF of 0.32. And the last point (P5) is located in a green courtyard (SVF = 0.26).

2.2. Methods

2.2.1. Microclimate models ENVI-met and RayMan

Micro-scale models ENVI-met 3.5 (Bruse & Fleer, 1998; Huttner, 2012) and RayMan Pro (Matzarakis et al., 2007, 2010) were applied to analyze the human-biometeorological conditions and their changes due to redesign within an urban quarter. Data of the nearby background station Stuttgart-Schwabenzentrum was used for the initialization of ENVI-met and as input data in RayMan.

ENVI-met calculates micro-scale surface-air-plant interactions inside complex urban structures in a three-dimensional non-hydrostatic way (Bruse & Fleer, 1998; Huttner, 2012). Its high spatial and temporal resolution provides a good basis for quantification of changes due to redesign. The current state of the Olga Hospital and several future scenarios were simulated. These are a planned housing area, different park scenarios, a forest, and a sealed multi-use place (Table 2). The term "sealed areas" is used to describe land, which is covered with practically impermeable materials. In further description the results of the third simulation day are taken and the first two days are given for the initialization of the model. Measurements of the 22nd June 2003, a summer day with high pressure, were taken as input parameters (Table 3).

The micro-scale model RayMan is developed to calculate the thermal comfort of human beings in complex urban areas (Matzarakis et al., 2007, 2010). RayMan estimates long- and short-wave radiation flux densities from the three dimensional urban