Human thermal comfort below the canopy of street trees on a typical Central European summer day

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Abstract

Based on human-biometeorological measurements at two different sites within a street canyon in the city of Freiburg (southwest Germany), the shading influence of the canopy of street trees on human thermal comfort was investigated for a typical Central European summer day within the scope of the joint research project KLIMES. The physiologically equivalent temperature PET was used to quantify the level of human thermal comfort. The lower PET values under the tree canopies point out the lower level of thermal stress compared to an adjacent site, which was not directly shaded. The total radiation heat aggregated in the mean radiant temperature T_{mrt} mainly determined the PET conditions at both sites, which is typical of Central European cities on summer days. To a considerable extent, T_{mrt} was influenced by the long-wave radiative fluxes from the four main horizontal directions. The mean contribution of the total short-wave radiation on T_{mrt} amounted to 10 % under the tree canopies and 29 % at the not directly shaded site.

1. Introduction

The effect of street trees on the meteorological conditions within the Urban Canopy Layer (UCL) of different urban spaces, e.g. urban street canyons, is described in investigations worldwide (e.g. Heisler, 1986; Oke, 1989; Souch and Souch, 1993; Akbari et al., 2001; Shashua-Bar and Hoffman, 2002, 2003; Dimoudi and Nikolopoulou, 2003; Streiling and Matzarakis, 2003; Yang et al., 2005; Georgi and Zafiriadis, 2006; Gromke and Ruck, 2007, 2009). One important impact of street trees on citizens is the reduction of thermal stress during hot meteorological background conditions (Matzarakis and Streiling, 2004; Shashua-Bar and Hoffman, 2004; Thorsson et al., 2004; Ali-Toudert and Mayer, 2005, 2007; Mayer and Matzarakis, 2006). Therefore, street trees are significant in urban planning as this applied discipline has the aim to maintain human thermal comfort under all weather situations.

Against the background of regional climate change, the significance of shading effects of street tree canopies in order to reduce heat stress for citizens during hot background conditions is increasing in urban planning. However, there is a lack of results quantifying the impact of street tree canopies in terms of assessment indices, which are significant to quantify the perception of heat by citizens.

Within the scope of the joint research program KLIMES (Mayer, 2008; Mayer et al., 2008, 2009) one objective of the subproject KLIMES ALUF is to quantify the level of thermal comfort for citizens in different urban quarters dependent on street design, e.g. street tree canopies.

2. Methods

The procedure used in KLIMES to assess the thermal component of urban climate, i.e. human thermal comfort, is explained in detail by Mayer (2008) and Mayer et al. (2008, 2009). It is related to a collective of citizens, which is represented by a standardised standing person (reference person). The physiologically equivalent temperature PET (Mayer and Höppe, 1987) is applied as thermal index that meets the requirements of modern human-biometeorology to assess the thermal comfort of citizens. To determine PET, the meteorological variables air temperature, vapour pressure, wind speed and mean radiant temperature T_{mrt} as a measure of the total radiation heat absorbed by the reference person are necessary.

Experimental human-biometeorological investigations on human thermal comfort were conducted during summer 2007 and 2008 in different urban quarters within the city of Freiburg in southwest Germany (48°N, 8°E, 278 m a.s.l.). Due to its location at the eastern border of the N-S oriented southern upper Rhine plain and near the western hillsides of the Black Forest, Freiburg is the warmest city in Germany, i.e. the atmospheric background conditions are characterised by an enhanced thermal level.

The case study in Freiburg, Herdern, on 1 August 2007, which represented a typical Central European summer day, was focused on the impact of the canopy of street trees on human thermal comfort below the canopy. In order to identify the local atmospheric conditions below the canopy, two measurement points located on sidewalks of an E-W oriented street canyon were considered (Fig. 1): the stationary measurement point, which was strongly shaded by the canopy of adult ash trees (*Fraxinus excelsior*), and the mobile measurement point MP4, which was not directly shaded by the canopy of trees. Characteristics of both measurement points are summarised in Table 1. In addition, Fig. 2 displays the visibility of the sky by use of fish-eye photos, which enabled the determination of the sky view factor SVF by use of the RayMan model (Matzarakis et al., 2007).

Table 1: Characteristics of the stationary measurement station and the mobile measurement point MP4 in Freiburg, Herdern, for the experimental investigations on 1 August 2007; H: mean building height, W: street width, SVF: sky view factor

	H/W	**street orientation (°)**	**sidewalk orientation**	**SVF (vertical)**	**canopy portion (vertical)**
stationary station	0.45	90, i.e. E-W	south facing	0.14	0.68
MP4	0.34	94, i.e. E-W	north facing	0.44	0.30

The experimental setup consisted of a stationary and a mobile human-biometeorological system (Fig. 3) for measurements in 1.1 m a.g.l., which is defined as a standard in human-biometeorology. Details of both systems are described by Mayer (2008) and Mayer et al. (2008).

Fig. 1: Sites for the stationary (left) and mobile, MP4, (right) human-biometeorological measurements on human thermal comfort in Freiburg, Herdern, (SW Germany) on 1 August 2007

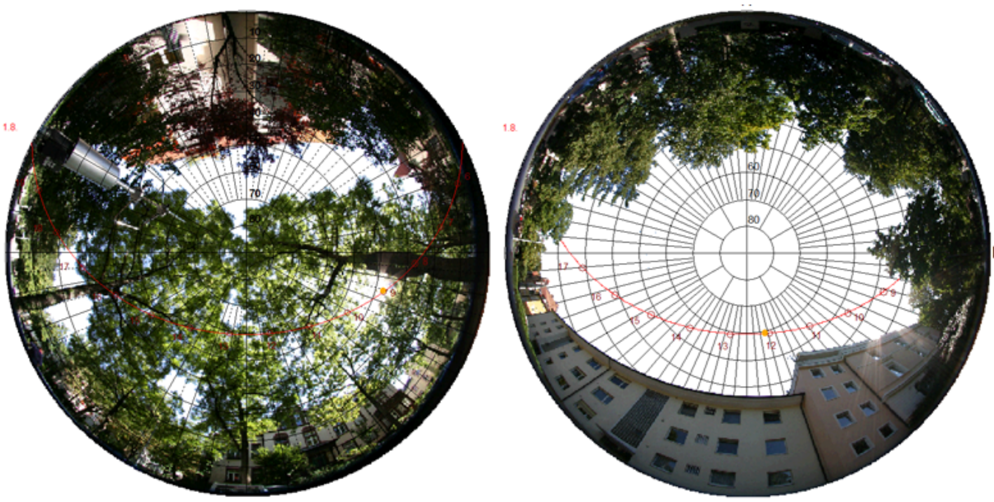

Fig. 2: Vertical fish-eye photos of the stationary (left) and mobile, MP4, (right) measurement points in Freiburg, Herdern, (SW Germany) on 1 August 2007

3. Results

Although the results presented in Figs. 4 to 7 are related to (i) different temporal scales (stationary station: 1-h mean values; mobile MP4: 1-min mean values) and (ii) different aspects (stationary station: S facing sidewalk; mobile MP4: N facing sidewalk), they point out structural differences of the selected variables between both local sites, i.e. between the shaded and unshaded situation:

 

Fig. 3: Stationary (left) and mobile (right) human-biometeorological station used in the experimental investigation on human thermal comfort in Freiburg

- Due to the shading effect, the short-wave incoming radiation K↓ below the canopy (stationary station) was distinctly lower than at MP4 (Fig. 4). Averaged over the period 10 to 16 CET (Table 2), K↓ reached at the stationary station only 0.20 of K↓ at MP4, which mainly reflects the short-wave radiation transmitted through the canopy.
- Except for the early evening, the course of air temperature T_a was quite similar at both sites (Fig. 5), which can be explained by the processes governing the sensible heat conditions at the bottom of the UCL. Averaged over the period 10 to 16 CET (Table 2), T_a was by 0.3 °C higher at the stationary station, which mainly results from the higher T_a at this site in the early evening.
- Except for the early evening, the mean radiant temperature T_{mrt} as a measure for the total radiation heat absorbed by the reference person responded to the different radiation conditions at both sites. Therefore, T_{mrt} was distinctly higher at MP4 from 8 to 17 CET than at the stationary station (Fig. 6). Averaged over the period 10 to 16 CET (Table 2), T_{mrt} was by 24.8 °C higher at MP4.
- Except for the early evening, the physiologically equivalent temperature PET was higher at MP4 than at the stationary station (Fig. 7). The peak difference (12.5 °C) appeared around 14 CET. According to Matzarakis et al. (1999) it corresponds to a reduction of the level of thermal perception from "hot" to "slightly warm" (two steps) under the tree canopies. Averaged over the period 10 to 16 CET (Table 2), PET was by 4.6 °C higher at MP4. This value is lower than expected (ΔPET ≈ 13 °C) on the basis of only the T_{mrt} conditions. But it is understandable, if the site conditions for other meteorological variables determining PET are taken into account (higher mean value of vapour pressure VP at the stationary station as well as higher mean value of wind speed v at MP4).
- Due to the standing position of the reference person, T_{mrt} was mainly determined by the long-wave radiative fluxes from the four main horizontal directions N, E, S and W (Table 2). The mean contribution of the total short-wave radiation K* on T_{mrt} amounted to 10 % under the tree canopies and 29 % at the not directly shaded site.

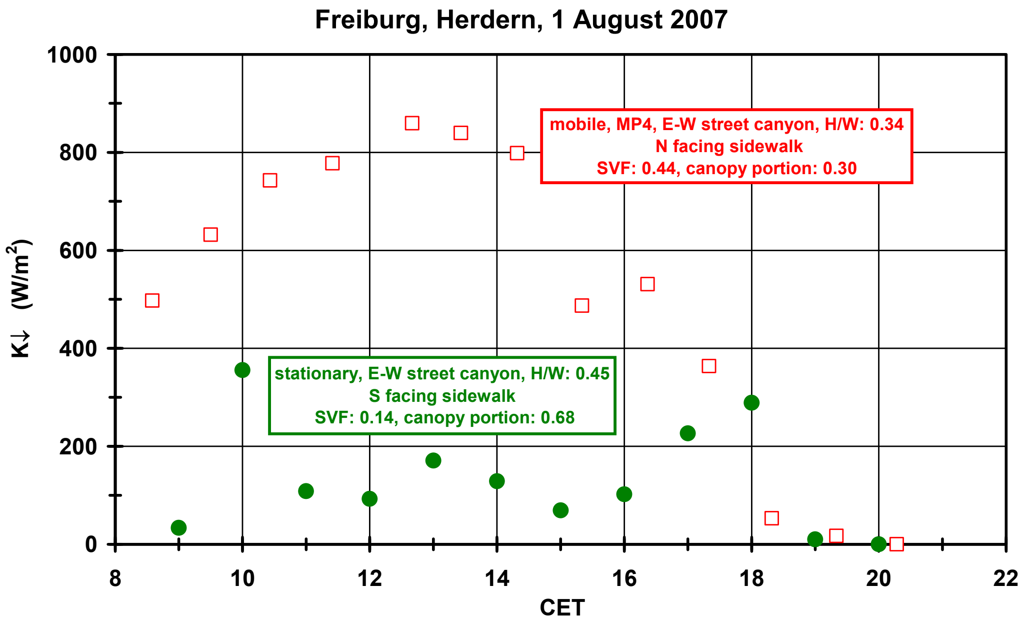

Fig. 4: Short-wave incoming radiation K↓ at the stationary station shaded by tree canopies and the not directly shaded mobile measurement point MP4, both within an E-W street canyon in Freiburg, Herdern, on 1 August 2007 (typical summer day)

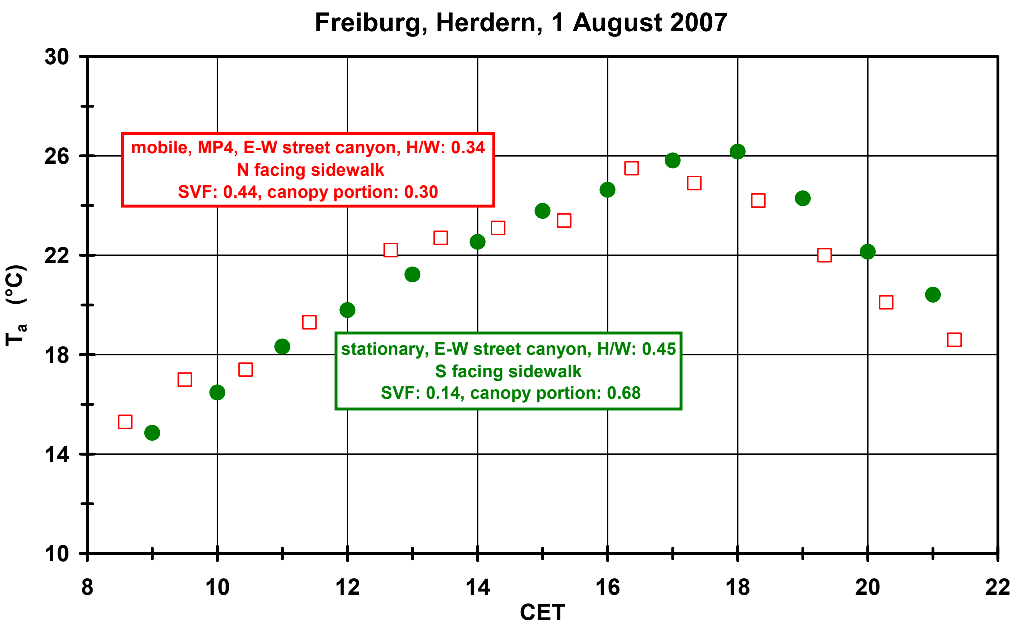

Fig. 5: Air temperature T_a at the stationary station shaded by tree canopies and the not directly shaded mobile measurement point MP4, both within an E-W street canyon in Freiburg, Herdern, on 1 August 2007 (typical summer day)

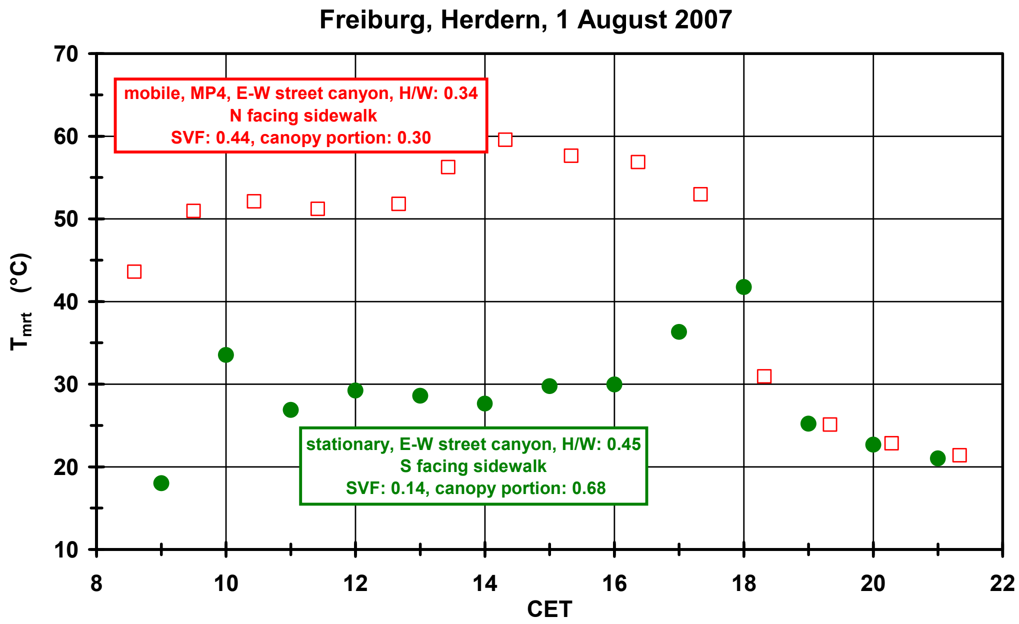

Fig. 6: Mean radiant temperature T_{mrt} at the stationary station shaded by tree canopies and the not directly shaded mobile measurement point MP4, both within an E-W street canyon in Freiburg, Herdern, on 1 August 2007 (typical summer day)

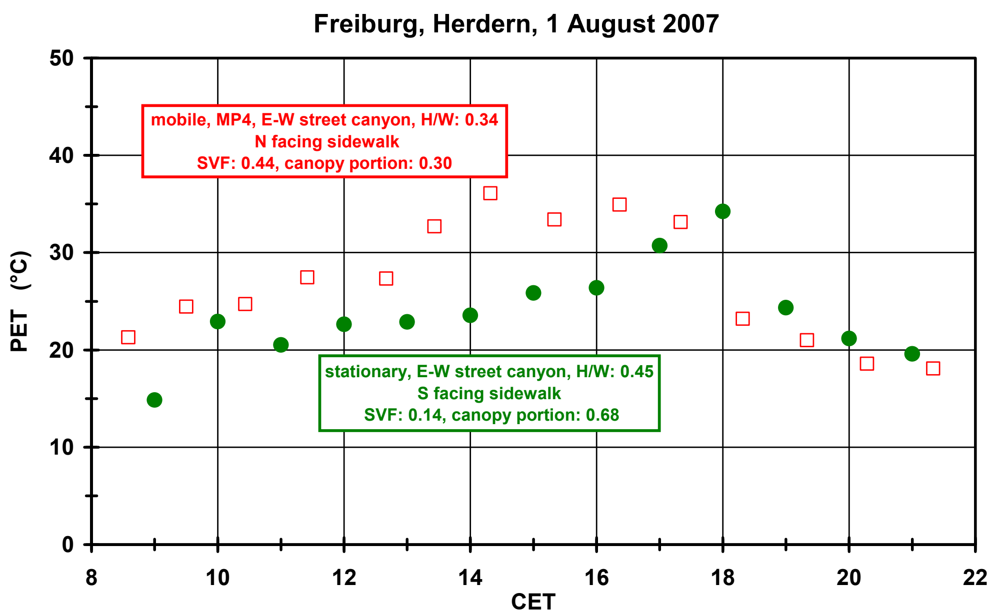

Fig. 7: Physiologically equivalent temperature PET at the stationary station shaded by tree canopies and the not directly shaded mobile measurement point MP4, both within an E-W street canyon in Freiburg, Herdern, on 1 August 2007 (typical summer day)

Table 2: Mean values (10-16 CET) of three-dimensional short- (K) and long-wave (L) radiative fluxes absorbed by the standing reference person, air temperature T_a, mean radiant temperature T_{mrt}, vapour pressure VP, relative humidity RH, wind speed v and physiologically equivalent temperature PET at the stationary station (below tree canopies) and the mobile measurement point MP4 (no tree canopies) of an E-W oriented street canyon in Freiburg, Herdern, on 1 August 2007

	stationary	**MP4**	**stationary/ MP4**	**stationary - MP4**
K↓	6 W/m²	30 W/m²	0.20	-
K↑	0 W/m²	3 W/m²	0.00	-
K_E	16 W/m²	38W/m²	0.42	-
K_W	7 W/m²	36 W/m²	0.19	-
K_S	12 W/m²	64 W/m²	0.19	-
K_N	3 W/m²	12 W/m²	0.25	-
K*	44 W/m²	183 W/m²	0.24	-
L↓	24 W/m²	22 W/m²	1.09	-
L↑	25 W/m²	32 W/m²	0.78	-
L_E	92 W/m²	99 W/m²	0.93	-
L_W	92 W/m²	98 W/m²	0.94	-
L_S	93 W/m²	96 W/m²	0.97	-
L_N	91 W/m²	101 W/m²	0.90	-
L*	417 W/m²	448 W/m²	0.93	-
K*+L*	461 W/m²	631 W/m²	0.73	-
K*/L*	0.11	0.41	-	-
K*/(K*+L*)	0.10	0.29	-	-
T_a	21.0 °C	20.7 °C	-	0.3 °C
T_{mrt}	29.4 °C	54.2 °C	-	-24.8 °C
VP	12.6 hPa	11.9 hPa	-	0.7 hPa
RH	67 %	49 %	-	18 %
v	0.5 m/s	1.7 m/s	-	-1.2 m/s
PET	24.9 °C	29.5 °C	-	-4.6 °C

4. Conclusions

The presented results quantify the impact of tree canopies on human thermal comfort below the canopy for a typical Central European summer day. Due to their importance for urban planning, it is necessary to increase the reliability of these results by taking into account more similar experimental case studies. In addition, these point results, which reflect the temporal behaviour, should be transferred into the urban space by use of numerical simulations. Both types of investigations necessary to meet the demand mentioned are carried out within KLIMES.

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