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results indicate for a typical summer day that the reduction of thermal stress by tree canopies can amount up to three levels of thermal perception according to the classification by Matzarakis and Mayer (1996).

The thermal index PET used in this study to describe the thermal perception of people in a thermo-physiologically significant manner is based on the stationary human energy balance model MEMI (Höppe, 1999). Although people within a micro-scale urban environment show an unsteady behaviour, the application of a stationary index such as PET is suited because different urban sites had to be assessed with respect to thermal stress of people. In the case that the thermal conditions of a single person passing different urban structures should be assessed in a thermo-physiologically significant manner, thermal indices derived from unsteady human energy balance models (e.g. IMEM by Höppe, 1999) have to be applied.

on a typical summer day. The investigation showed in addition that among all meteorological variables, the short-wave radiation K from the upper hemisphere had the strongest influence on T_{mrt} (Figure 13).

Concluding remarks

The knowledge about the effects of street trees was extended by this case study carried out to analyse the effects of different densities of the canopy of chestnut trees on the thermal comfort of people in summer. Even though the experimental investigations were limited to a typical summer day, the results have a more general validity. They reveal that the level of thermal stress of people below a tree canopy is clearly reduced compared to particularly southward sites within a street canyon, which have no shading. The higher the canopy density respectively the lower the sky view factor are, the more pronounced is the attenuation of thermal stress of people. The presented

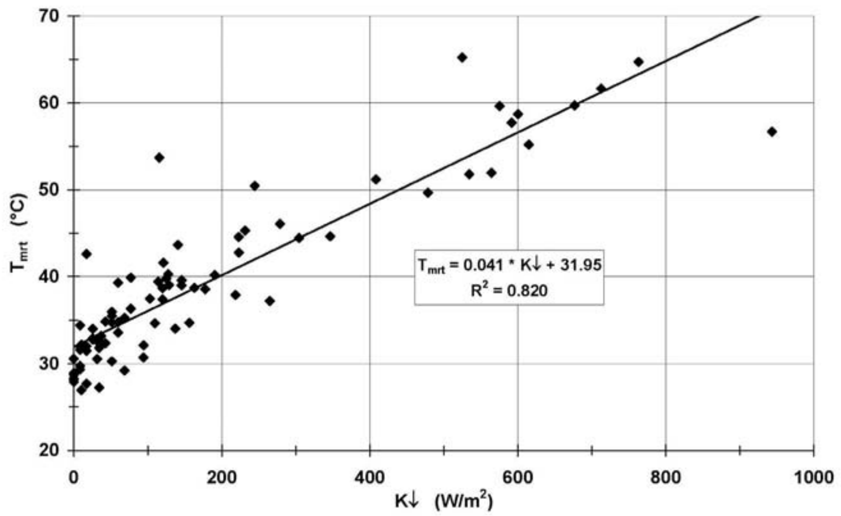

Figure 13. Relationship between mean radiant temperature T_{mrt} and short-wave radiation K↓ from the upper hemisphere (both 1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

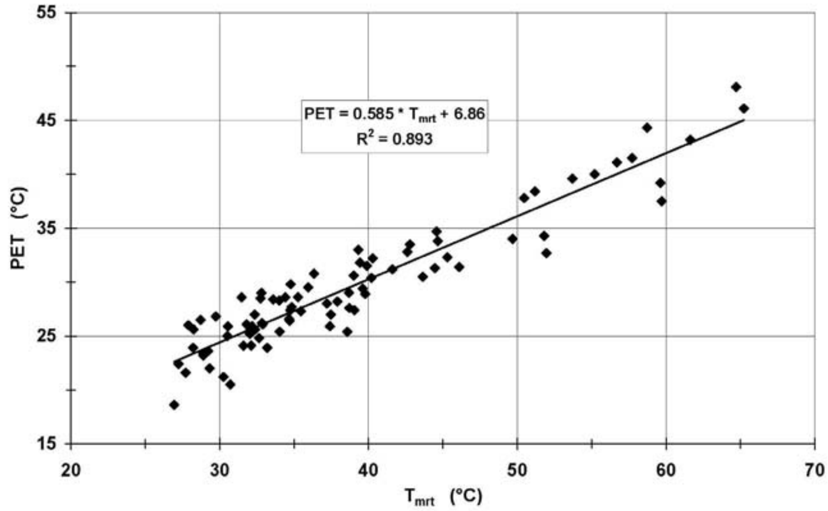

Figure 11. Relationship between physiologically equivalent temperature PET and mean radiant temperature T_{mrt} (both 1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

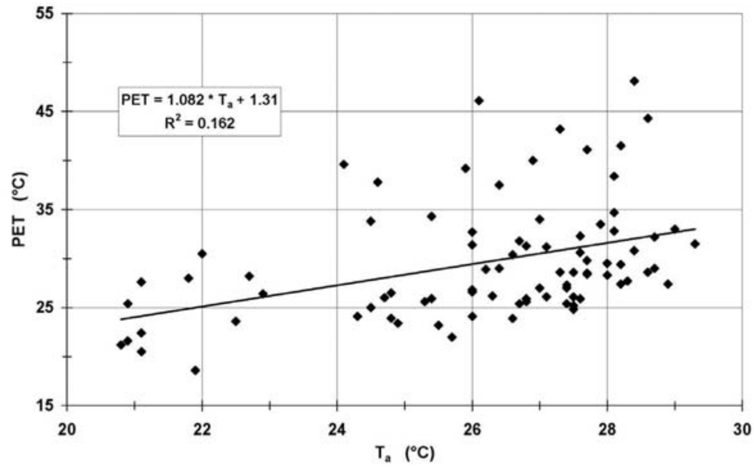

Figure 12. Relationship between physiologically equivalent temperature PET and air temperature T_a (both 1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

PET	thermal perception	level of thermal stress
	very cold	extreme cold stress
	cold	great cold stress
	cool	moderate cold stress
	slightly cool	slight cold stress
	comfortable	no thermal stress
	slightly warm	slight heat stress
	warm	moderate heat stress
	hot	great heat stress
	very hot	extreme heat stress

Table 2. Threshold values of the physiologically equivalent temperature PET for different thermal perceptions and levels of thermal stress, related to a metabolic rate of 80 W and a heat transfer resistance of clothing of 0.9 clo (according to Matzarakis and Mayer, 1996)

The mean daytime values of PET cover the range from 25.0°C (slight heat stress) at the site below some tree canopies to 34.0°C (near the transition from moderate to great heat stress) at the site street canyon, north (Table 1).

Regression analysis

Analysing Figures 8 and 10, a linear relationship between PET and T_{mrt} becomes apparent. A detailed regression analysis provides a measure of determination $R^2 = 0.893$ (Figure 11) which indicates that a very high portion of the variance of PET can be explained by T_{mrt}. In contrast for it, R^2 of the linear regression between PET and T_a (Figure 12) was clearly lower (0.162). Thus, the well-known fact (e.g. Mayer and Höppe, 1987, Matzarakis et al., 1999) that the air temperature T_a has only a minor impact on the thermal perceptions of people in summer could be validated for the weather conditions

Besides other indices such as OUT_SET* (Spagnolo and de Dear, 2003a and b), the physiologically equivalent temperature PET belongs to the thermo-physiologically significant indices. In this case study, PET was calculated using the methods of Höppe (1999) and Matzarakis et al. (1999) as well as the RayMan model (Matzarakis et al., 2000). The lowest PET values were obtained for the site below some tree canopies (Figure 10). They scatter around 25°C, which corresponds the thermal perception slightly warm by people (Table 2). At the site below a tree canopy, PET values indicated the thermal perception warm in the morning and converged to a lower level of thermal stress in the afternoon. The mean daytime value at this site was PET = 29.3°C (Table 1) which meets the transition between slight and moderate heat stress.

The highest PET values were determined for the site street canyon, north where people perceived the thermal conditions between 13:00 and 14:00 CET as very hot. As mentioned before, temporary cumulus clouds caused lower PET values at the non-green sites around noon.

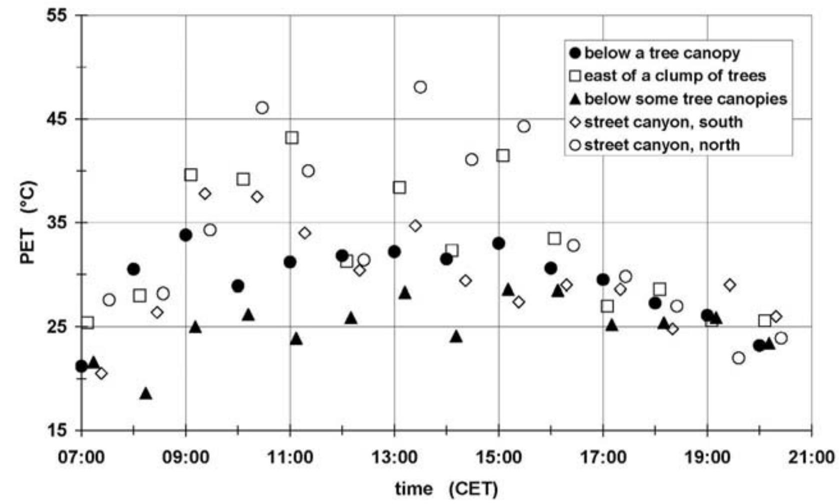

Figure 10. Physiologically equivalent temperature PET (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

Impact of Street Trees on the Thermal Comfort

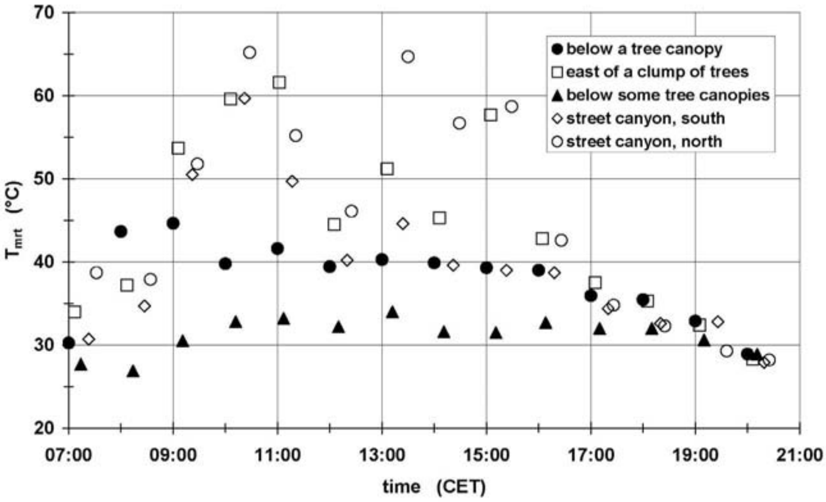

Figure 8. Mean radiant temperature T_{mrt} (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

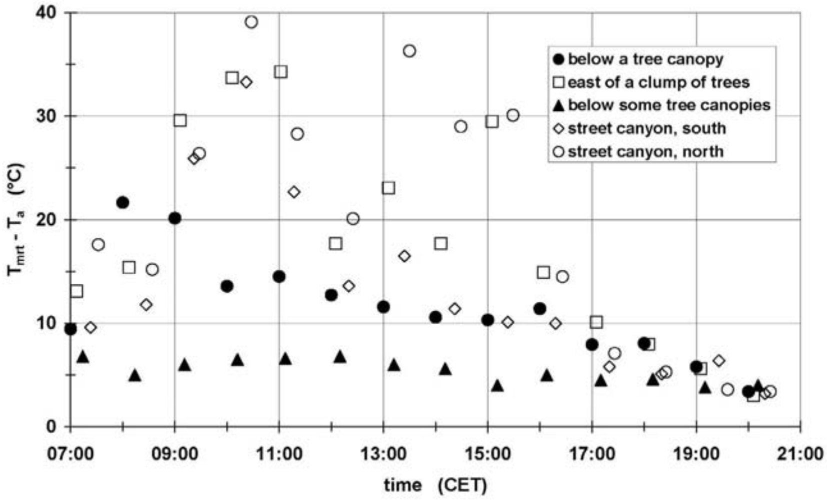

Figure 9. Difference between mean radiant temperature T_{mrt} and air temperature T_a (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

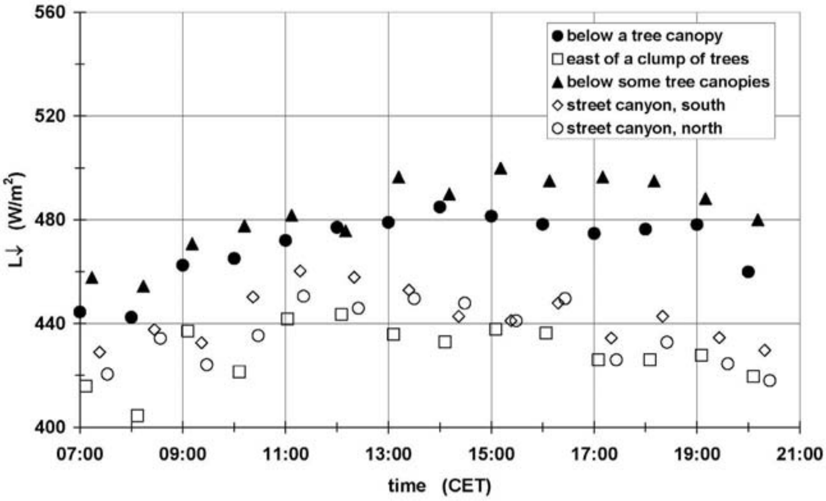

Figure 7. Long-wave radiation L↓ from the upper hemisphere (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

are combined in the mean radiant temperature T_{mrt}. At the site below some tree canopies, it was lowest and showed with values around 31°C nearly no diurnal variability (Figure 8). Starting at 8:00 CET, T_{mrt} values for the site below a tree canopy were a little higher, but they came closer to the T_{mrt} values for the site below some tree canopies in the course of the day. At the sites within the street canyon, Tmrt was clearly higher and reached values around 65°C. The lower T_{mrt} values at the non-green sites around noon were caused by temporary cumulus clouds. Altogether, T_{mrt} had the highest mean daytime value at the southward site street canyon, north (45.9°C) and the lowest corresponding value at the site below some tree canopies (31.2°C).

In comparison to T_a, T_{mrt} was higher in the daytime at all sites (Figure 9). The difference T_{mrt} - T_a was lowest at the site below some tree canopies with a mean daytime value of 6.4°C, whereas higher single values up to almost 40°C were obtained for the difference T_{mrt} - T_a at the other sites (Figure 9). The highest mean daytime value of T_{mrt} - T_a (19.7°C) were obtained for the site street canyon, south (Table 1).

Thermal index PET

the green sites was responsible, that the long-wave radiation $L\uparrow$ from the lower hemisphere was also lower at the green sites compared to the other sites (Figure 6). As for $K\downarrow$ the lowest $L\uparrow$ values were obtained for the site below some tree canopies resulting in a mean daytime value of 462 W/m^2 (Table 1). According to the $K\downarrow$ conditions, the highest mean daytime mean value of $L\uparrow$ (528 W/m^2) was calculated for the site street canyon, north. In contrast to $L\uparrow$, the long-wave radiation L from the upper hemisphere was highest at the site below some tree canopies followed by the site below a tree canopy (Figure 7). $L\downarrow$ was lower at the other sites, because they had a greater portion of $L\downarrow$ coming directly from the sky and showing lower values than the portion of $L\downarrow$ from the canopy base. The mean daytime values of $L\downarrow$ were lowest at the site below a tree canopy (Table 1). This was the one site with a positive difference of the mean daytime values between $L\downarrow$ and $L\uparrow$.

The three-dimensional radiation conditions relevant for a standing person

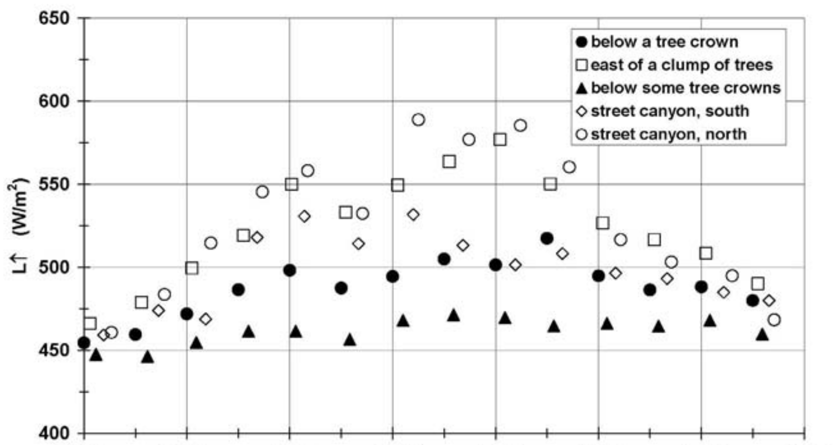

Figure 6. Long-wave radiation $L\uparrow$ from the lower hemisphere (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

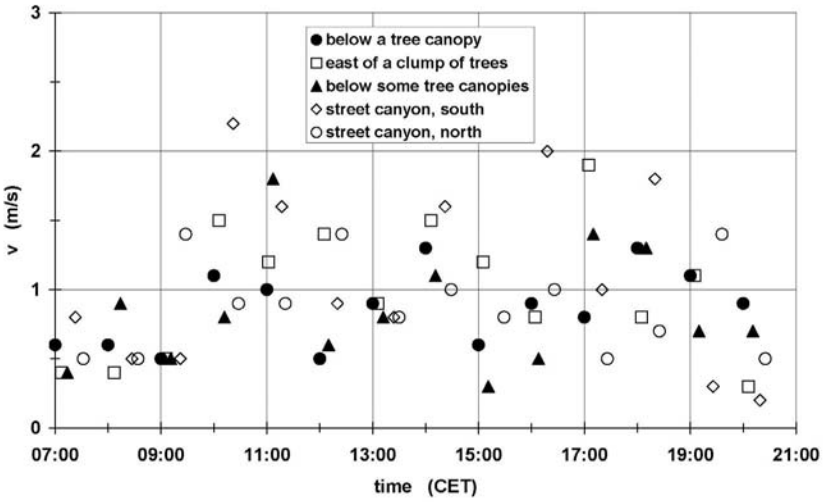

Figure 4. Wind speed v (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

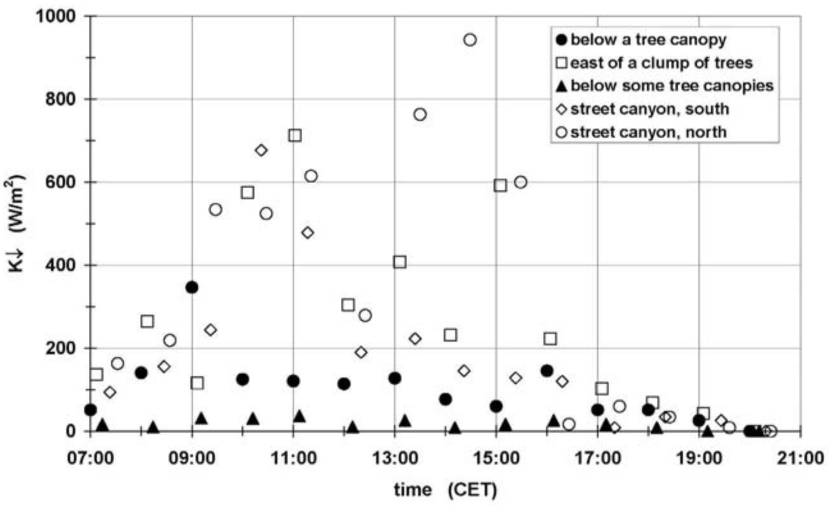

Figure 5. Short-wave radiation K↓ from the upper hemisphere (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

the site below some tree canopies (Table 1). With respect to systematic site dependence, the pattern of the vapour pressure VP (Figure 3) is comparable to T_a. But in contrast to T_a, VP reached the lowest values at 14:00 CET. The daytime behaviour of the wind speed v (Figure 4) can be characterized by the thermally induced scattering mentioned before. The mean daytime values of VP and v (Table 1) differed only slightly between the different sites.

In contrast to T_a, VP and v, the results for the radiation fluxes reveal a distinct differentiation between the two green sites and the other sites. Due to the shading effect of the canopy, the short-wave radiation K from the upper hemisphere was lower at the green sites than at the other sites (Figure 5). In accordance with the lowest SVF value, K↓ was lowest at the site below some tree canopies and did not show a pronounced diurnal course. Consequently, the mean daytime value of K reached only 17 W/m^2 (Table 1), whereas at the southward site street canyon, north, the mean daytime value of K↓ was highest (340 W/m^2).

The reduced energy amount of K↓, which was available at the surface of

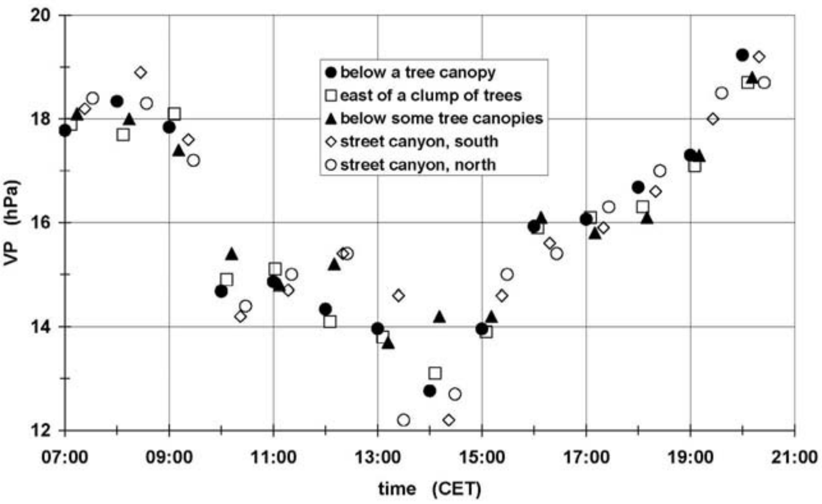

Figure 3. Vapour pressure VP (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

sites	SVF	T_a	VP (hPa)	v (m/s)	K↓ (W/m^2)	L↑ (W/m^2)	L↓ (W/m^2)	T_{mrt}	T_{mrt} - T_a	PET
below a tree canopy	0.25	26.4	16.0	0.9	103	488	470	37.9	11.5	29.3
east of a clump of trees	0.47	26.1	15.9	1.0	270	524	429	44.4	18.3	32.8
below some tree canopies	0.07	25.8	16.1	0.8	17	462	483	31.2	6.4	25.0
street canyon, south	0.42	26.4	16.1	1.3	181	498	442	39.7	13.3	29.7
street canyon, north	0.61	26.2	16.0	0.9	340	528	436	45.9	19.7	34.0

Table 1. Sky view factor SVF as well as mean daytime values of air temperature T_a, vapour pressure VP, wind speed v, short-wave radiation K↓ from the upper hemisphere, long-wave radiation L↓ from the lower hemisphere, long-wave radiation L↓ from the upper hemisphere, mean radiant temperature T_{mrt}, difference T_{mrt} - T_a and physiologically equivalent temperature PET at different sites in northern downtown of Freiburg (Germany) on 19 July 1999, height: 1.1 m above the ground

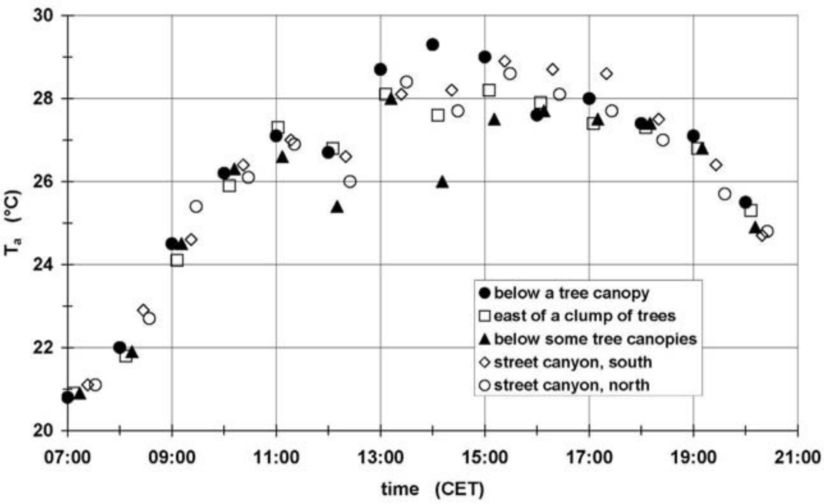

Figure 2. Air temperature T_a (1.1 m above the ground) on a typical summer day (19 July 1999) at different sites in the northern downtown of Freiburg (southwest Germany)

respectively. VP was calculated by the measured dry and wet-bulb temperatures. T_{mrt} was determined after the method by Höppe (1992), which requires the measurement of the short- and long-wave radiation fluxes from the entire surroundings of a standing person. For that purpose, a combined CM21 pyranometer and a CG1 pyrgeometer, both from Kipp & Zonen Company, were used which could be rotated around the horizontal and vertical axis.

Investigation sites

The experimental investigation occurred around a place with chestnut trees (Streiling and Matzarakis, 2003) located in northern downtown of Freiburg (270 m a.s.l.), a city in southwest Germany with about 210.000 residents. Freiburg lies at the eastern border of the N-S oriented upper Rhine plain near the southern Black Forest which ranges up to 1489 m a.s.l.. Due to the specific location, residents of Freiburg suffer in summer frequently from heat stress.

Five sites (Table 1) arranged at a circle with a diameter of less than 100 m have been selected which differ in their sky view factors SVF due to specific canopy densities and canyon geometries (Matzarakis, 2001). The investigation was carried out in the daytime of a typical summer day (19 July 1999) with convective cumulus clouds around noon. Using the mobile human-biometeorological measuring unit, the meteorological variables necessary to calculate PET were recorded as 5-minute mean values in a sequential order from site a) to site b). All measurements were related to the human-biometeorologically significant height of ‘‘1.1’’ m above the ground.

Results and discussion

Meteorological variables

The temporal courses of the air temperature T_a do not show a clear dependence on the specific site conditions (Figure 2). The scattering of the T_a values in the early afternoon was caused by the pronounced thermal turbulence. Convective clouds around noon led to a short-term decrease of T_a. In comparison to all sites, the mean daytime value of T_a was slightly lower at

Methodology

In order to assess the below-canopy microclimate on a typical summer day in a human-biometeorologically relevant way, the physiologically equivalent temperature PET is used as a suited thermal index (Mayer and Höppe, 1987, Höppe, 1999, Matzarakis et al., 1999). PET is derived from the human energy balance model *MEMI* (**M**unich **E**nergy Balance **M**odel for **I**ndividuals). It is necessary for the calculation of PET to determine all meteorological variables that are important for the human energy balance at a human-biometeorologically significant height (e.g. 1.1 m above the ground which corresponds to the average height of the gravity centre of a standing person): air temperature T_a, vapour pressure VP, wind speed v and mean radiant temperature T_{mrt}. Depending on the objectives of an study, these meteorological variables can be either measured experimentally or calculated in a grid-net by models.

The results of this experimental case study are based on measured meteorological data obtained by use of a specially designed mobile human-biometeorological measuring unit (Figure 1). T_a and v were directly measured by use of a ventilated and shielded Pt100 sensor and a hot wire anemometer,

Figure 1. Mobile human-biometeorological measuring unit (left: radiation sensors rotating around a horizontal and vertical axis to measure of the short- and long-wave radiation fluxes from the entire surroundings of a standing person)

Impact of Street Trees on the Thermal Comfort of People in Summer: A Case Study in Freiburg (Germany)

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Introduction

Urban trees have different functions, which can be classified as architectural, functional, engineering, climatic and aesthetic (Heisler, 1986a, Amir and Misgav, 1990). The interactions between urban trees and the atmospheric environment are numerous (Rowntree, 1986, Oke, 1989, Simpson and McPherson, 1998). Trees can reduce runoff by intercepting precipitation (Kjelgren and Montague, 1998), absorbing particulate pollutants (Beckett et al., 1998), emitting hydrocarbons, and modifying noise (Heisler, 1977), solar radiation (Thayer and Maeda, 1985, Heisler, 1986b, Souch and Souch, 1993), air temperature, wind speed (Groß, 1987) and air humidity (Kramer and Kozlowski, 1970).

Seen from a human-biometeorological point of view, the micro-scale below-canopy climate is pleasant to people because of a reduced thermal stress in summer (Mayer, 1993). This phenomenon has been qualitatively recognized for a long time, but there is a lack of studies that quantify the impact of street trees on the thermal comfort of people using thermo-physiologically significant indices. Therefore, the objective of this case study is to extend the knowledge on the reduction of thermal stress on people below the canopies of street trees in summer.