Urban human-biometeorology supports urban planning to handle the challenge by increasing severe heat

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ABSTRACT: Regional climate change in Central Europe will lead to an increase of severe summer heat. It causes a new challenge for urban planning in Central European cities, as their design and citizens are not adapted to this meteorological hazard. For the development and application of suitable methods, which enable a local reduction of the heat impacts on citizens, urban planning is supported by the interdisciplinary field of "Urban human-biometeorology". This is shown by experimental and numeric investigations, which were performed on typical summer days in different quarters of the city of Freiburg (Southwest Germany). The results point to the significance of thermal assessment indices like the physiologically equivalent temperature PET to quantify the level of heat stress perceived by citizens. In the daytime, outdoor thermal comfort during typical Central European summer weather is strongly governed by the mean radiant temperature. It depends on the short- and long-wave radiant flux densities from the three-dimensional environment. Therefore, planning methods to mitigate heat impacts on citizens outdoors should primarily aim at a local reduction of the radiant flux densities. Under a human-biometeorological point of view, shading of the direct solar radiation by the canopy of street trees planted at the S-facing side of E-W street canyons proves to be as most effective.
Keywords: urban human-biometeorology, mean radiant temperature, thermal index PET

INTRODUCTION

For Central Europe, results of regional climate simulations [1] project not only a long-term increase of near-surface air temperature T_a, but also embedded heat waves in summer, which will be more frequent and intense as well as longer lasting. As the design of Central European cities is not adapted to this new situation, the increasing severe heat will enhance the previous thermal strain for citizens into a considerable thermal stress, which will cause extremely negative impacts on their efficiency, well-being and health [2]. Due to the demographic change, human risk groups are gradually increasing in Central Europe, that is, the human vulnerability with respect to severe heat is rising. Given this background, urban planning in Central European cities faces the challenge to develop, apply and validate methods to maintain human thermal comfort for citizens even under severe summer heat. It primarily represents a regional phenomenon, which depends on the large-scale weather situation. These methods should include a re-design of buildings, streets and open spaces in a preventive way that severe summer heat can be mitigated on the local urban scale [3, 4].

For that purpose, results obtained by investigations in urban human-biometeorology are necessary. They are related to different questions like: (i) How can human thermal comfort and its perception by citizens be quantified? (ii) Why are T_a and urban heat island intensity, resp., inappropriate to describe heat in terms of humans under Central European summer conditions? (iii) How big is the significance of single meteorological variables determining the human energy budget during summer heat in Central Europe? (iv) How is human thermal comfort influenced by street and building design? (v) How can the significance of urban green, particularly street trees, for human thermal comfort be quantified during summer heat? (vi) Which type of methods can be provided to get the most reliable results on human thermal comfort within Central European cities in summer? The general objective of this paper is to answer these questions as far as possible.

METHODS

The answers are mainly based on human-biometeorological investigations, which were conducted on typical summer days in the city of Freiburg (Southwest Germany) from 2007-2010 [5-8]. The well-matched investigation design consisted of experiments in terms of case studies within different urban structures and questionnaires. The specific human-biometeorological station (Fig. 1) used in the experiments [6-8] enabled the measurement of all meteorological variables, which are necessary to calculate the human-biometeorological variables mean radiant temperature T_{mrt} [9] and physiologically equivalent temperature PET [10, 11]. The investigation design was complemented by numeric simulations using the ENVI-met model [3, 4].

T_{mrt} can be interpreted as a measure for the heat of the short- and long-wave radiant flux densities from the three-dimensional environment absorbed by the human-biometeorological reference person [5-8]. It plays a fundamental role in the thermo-physiological concept to assess the thermal environment [9-11].

Figure 1: Human-biometeorological measuring station used in investigations on thermal comfort in Freiburg [5-8].

For the determination of T_{mrt}, the method by Höppe [12] was applied in the experiments. It requires the measurement of the short- and long-wave radiant flux densities received by the human-biometeorological reference person from the three-dimensional environment [5, 8]. Therefore, the setup of the station in Fig. 1 contains three cantilevers. A pair of two pyranometers and two pyrgeometers is attached to each of three cantilevers in order to enable the parallel measurement of the two vertical and four horizontal short- and long-wave radiant flux densities. Similar measuring systems have also proven to be successful in experimental investigations in Gothenburg, Sweden, [9] and Szeged, Hungary, [13].

Compared to a globe thermometer, which also makes the determination of T_{mrt} possible [9], the setup used in the experimental investigations in Freiburg has two basic advantages. They are important for the discussion of urban planning methods to mitigate heat on a local scale: (i) the differentiation between the effects of short- and long-wave radiant flux densities and (ii) the differentiation of the radiant flux densities according to their directions is possible.

RESULTS

Physiologically equivalent temperature PET

The perception of heat by citizens depends on their thermo-physiological conditions [11]. They are related to the human heat budget, which is influenced by the meteorological variables T_a and T_{mrt} as well as vapour pressure VP and wind speed v. Therefore, the perception of heat by humans cannot be described by only one meteorological variable like T_a, but should be quantified by a thermo-physiological assessment index, which is derived from the human heat budget. The widely used PET meets this requirement and, therefore, is well-suited to quantify the perception of outdoor heat by citizens [3-8]. Compared to similar indices like UTCI [14], PET has the advantage that in the meantime many results of PET obtained by numeric simulations or experiments have been frequently applied in the comparative evaluation of thermal stress conditions for citizens [3-8, 15, 16].

In order to make numeric results of PET, which have the unit "°C", as more suitable for the application in urban planning, they have to assign to a thermal sensation scale. For that purpose, the ASHRAE thermal sensation scale should be used, as it represents a kind of an inter-national standard [6]. The assignment can be achieved by combining results from experiments to determine PET and parallel questionnaires. A fundamental advan-tage of this method is that it includes the long-term ac-climatization and adaptation of citizens to the mean thermal background conditions in the near-surface atmosphere. In Freiburg, both types of investigations were conducted on two typical summer days in July 2010 [6]. Therefore, the ranges of PET (Table 1) are only related to different warm levels of the human thermal sensation outdoors.

Table 1: Ranges of PET for different warm levels of the human thermal sensation according to the ASHRAE thermal sensation scale [6].

ASRAE thermal sensation scale		**PET range (°C)**
name	**scale**	
slightly warm	+1	30 - 34
warm	+2	35 - 40
hot	+3	> 40

Both acclimatization and adaptation are not included in the well-known classification of PET by [17], which is based on a statistical approach applied to Greece. In addition, these PET thresholds are limited to an internal human heat production of 80 W and a heat transfer resistance of clothing of 0.9 clo. Due to its weaknesses, this PET classification should not be used any longer, but replaced by those, which are derived from questionnaires and parallel determinations of PET.

Mean radiant temperature T_{mrt}

Related to experimental investigations on PET, the coefficient of determination R^2 for linear regressions between 1h mean PET values on the one side and 1h mean values of the meteorological variables T_a, T_{mrt}, VP and v on the other side describes, how significant these meteorological variables are for PET. During the daytime hours from 10-16 CET, that is, the period when outdoor heat stress in summer is the most pronounced for citizens, R^2 of the linear regression between PET and T_{mrt} is clearly higher than for the linear regression between PET and T_a (Table 2). This means for typical Central European summer weather that the radiant exchange in terms of T_{mrt} represents the dominant meteorological factor affecting human thermal comfort in outdoor urban spaces during daytime heat. Similar results were found in other studies [18-20].

Table 2: Coefficient of determination R^2 of the linear regression functions between 1h mean values of human-biometeorological variables, basis: experimental investigations on typical Central European summer days in different urban quarters in Freiburg from 2007-2010 (n: number of values).

function f	R^2	
	10-16 CET n = 200	22-5 CET n = 40
PET = f (T_{mrt})	0.892	0.616
PET = f (T_a)	0.589	0.892
PET = f (VP)	0.023	0.006
PET = f (v)	0.029	0.013
T_{mrt} = f (T_a)	0.308	0.825

The relatively low R^2 values of the linear regressions between PET and VP as well as PET and v point out that the prevailing VP and v conditions during typical Central European summer weather play a minor role in the calculation of PET. Because the radiation exchange in the night consists only of long-wave radiant flux densities, R^2 of the linear regression between T_{mrt} and T_a is distinctly higher than that for the daytime. As a result, R^2 is the highest for the linear regression between PET and T_a in the night between 22 and 5 CET.

Double strategy of urban planning

In Central Europe, severe heat occurs only in summer, that is, in a season when day is longer than night. Therefore, urban planners prefer a double strategy for methods aimed at the maintaining of thermal comfort for citizens even under large-scale severe heat. Methods showing communal benefits in the daytime have a first priority, while methods, which are related to nocturnal meteorological phenomena like thermally induced down-slope or mountain air flow, are often classified as secondary. The main objective of planning methods during daytime should be to reduce the heat input into all urban spaces. Thereby, targets of environmental protection should be complied, for example, avoidance of air conditioning systems. This is why passive cooling methods are highly praised [8, 18, 19].

Different investigations have shown that the most effective method for lowering the heat input into urban spaces is based on the reduction of the direct solar radiation by shading [4, 6-8, 18, 19]. Transpiration from vegetation causes a reduction of its surface temperature [20]. However, it results in only a slight decrease of T_a above the vegetation layer. This effect does not reach a comparative magnitude of shading impacts on citizens. To shade the direct solar radiation within the urban canopy layer, three methods are basically suitable: (i) optimized design of buildings, open spaces and streets [3, 4, 7], (ii) man-made devices like awnings or sunshades, and (iii) street trees [4, 6-8, 18, 19]. Under a human-biometeorological point of view, which also includes aesthetic and psychological aspects, shading of direct solar radiation by the canopy of street trees has an elevated significance.

Human-biometeorological effects of shading by trees

Besides the advantage of energy savings obtained in buildings due to reduced cooling loads, the shading of the direct solar radiation by tree canopies also influences meteorological variables, which themselves lead to a mitigation of human heat stress in summer [8]. The extent to which a tree is an efficient strategy to mitigate human heat stress depends on the density of its canopy quantified by its leaf area index, its geometry (dimensions) and the extinction coefficient of the canopy for the short-wave radiant flux density.

Among the experimental investigations conducted in Freiburg to analyze the human-biometeorological effects of shading by tree canopies, the results of one case study are discussed hereafter. The selection of the measuring sites was influenced by two results of numeric simulations using the ENVI-met model [4]: (i) Large E-W street canyons appear to be the one where it is most difficult to ensure human thermal comfort. (ii) For E-W orientation, the highest thermal discomfort period occurs at the northern sidewalk during a large part of the day, that is, there is a fundamental necessity to plant trees in order to reduce human heat stress outdoors in summer. Thereby, urban planners have to find a compromise between outdoor and indoor needs for human comfort in summer and winter, that is, evergreen tress should be avoided to guarantee internal solar gains in winter.

The experimental investigations were conducted on July 24, 2008, which was a typical Central European summer day, at a shaded and a sunny measuring site. Both were located at the SSW-facing sidewalk of an ESE-WNW street canyon. At the shaded site, the direct solar radiation was shaded by the canopies of five small leaved linden trees, which were planted about 10 m apart from a four-storey SSW-facing building, arranged parallel to the street axis and spaced about 8 m apart from trunk to trunk of each tree. The individual tree height and crown diameter were about 25 m and 10 m, resp. In the light of these, this site was almost shaded during the entire summer day. The site for a comparison was located in a distance of about 40 m at the same sidewalk about 2.5 m apart in front of another four-storey building, but not influenced by tree canopies.

To quantify the extent of the shading, the sky view factor SVF_{90-270} related to the southern half of the upper hemisphere was determined from fish-eye photos. SVF_{90-270} is more suitable for human-biometeorological studies on thermal comfort in contrast to SVF for the complete upper hemisphere, because SVF_{90-270} is closely related to the direct solar radiation [6-8]. SVF_{90-270} was 70% at the sunny and 6% at the shaded measuring site, resp. The results of the case study show (Fig. 2) that T_a was only slightly sensitive to the shading. The peak value of the difference Δ between the shaded and the sunny situation was -1.7 °C. As the shading of the direct solar radiation has consequences for the complete radiation exchange at the shaded measuring site, T_{mrt} decreased when the shading started.

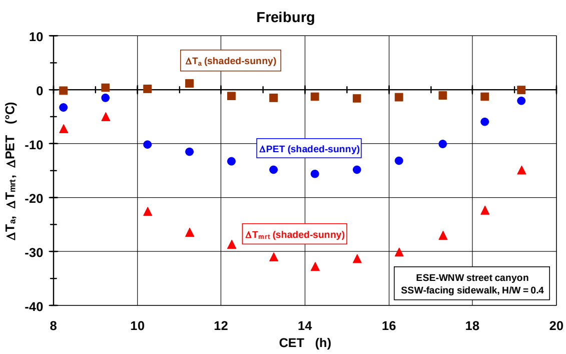

Figure 2: 1h mean values of the differences Δ of T_a, T_{mrt} and PET between a shaded (by tree canopies) and sunny SSW-facing sidewalk of an ESE-WNW street canyon (H/W=0.4) in Freiburg on a typical Central European summer day (July 24, 2008).

The peak ΔT_{mrt} value of -32.8 °C was distinctly higher than that for ΔT_a. As for typical Central European summer days, PET is the strongest governed by T_{mrt} in the daytime, the behaviour of PET during shading was similar to that of T_{mrt}. The peak value of ΔPET was -15.7 °C, that is, the shading by the tree canopies led to a local reduction of the human perception of heat from "hot" to "slightly warm" according to Table 1. For sub-tropical cities, these peak values can be slightly higher [4, 18], for example, ΔT_a and ΔPET have reached up to -3 °C and up to -22 °C, resp., under a tree canopy.

The pronounced reduction of T_{mrt} by shading was mainly caused by the behaviour of the sum (K^*_{abs}) of the short-wave radiant flux densities from the three-dimensional environment, which were absorbed by the human-biometeorological reference person (Fig. 3). In contrast to the sunny site, where the mean K^*_{abs} was 224 W/m^2 in the period from 10 to 16 CET, the shading of the direct solar radiation by tree canopies led to a mean decrease of K^*_{abs} by 182 W/m^2 in the same period. For L^*_{abs}, which is the sum of the long-wave radiant flux densities from the three-dimensional environment absorbed by the human-biometeorological reference person, the mean reduction amounted only to 26 W/m^2 related to a mean L^*_{abs} of 475 W/m^2 at the sunny site.

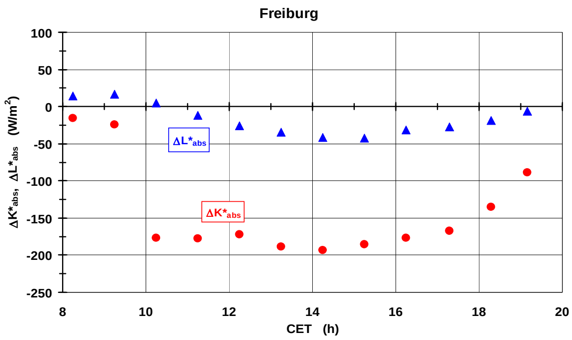

Figure 3: 1h mean values of the differences Δ of the sums K^*_{abs} and L^*_{abs} of the short- and long-wave radiant flux densities from the three-dimensional environment absorbed by the human-biometeorological reference person between a shaded (by tree canopies) and sunny SSW-facing sidewalk of an ESE-WNW street canyon, (H/W=0.4) in Freiburg on a typical Central European summer day (July 24, 2008).

The results in Fig. 2 show that human thermal stress quantified by PET can be reduced in the local urban scale by shading of the direct solar radiation, which itself influences another short- and long-wave radiant flux densities, for example by shadow patterns [21], and causes a decrease of T_{mrt}. Based on all experiments in Freiburg on typical summer days, a linear relationship was obtained between $T_{mrt}/T_{mrt,max}$ averaged over the period from 10 to 16 CET and SVF_{90-270} (Fig. 4). $T_{mrt,max}$ represents the peak value of T_{mrt} over this period for all experiments (64.1 °C). The result quantifies the lowering of relative T_{mrt} with decreasing SVF_{90-270}, that is, an increase of shading.

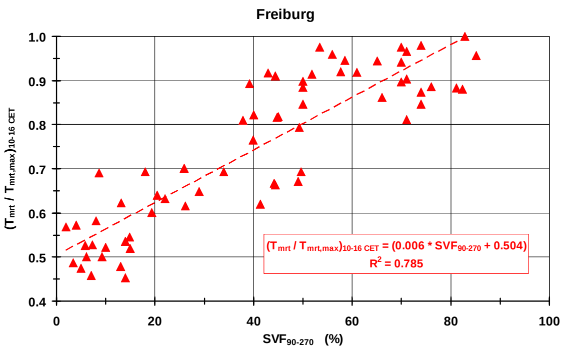

Figure 4: Relationship between mean values (10-16 CET) of $T_{mrt}/T_{mrt,max}$ ($T_{mrt,max}$ = 64.1 °C) and $SVF_{90\text{-}270}$, based on experiments at different sites in Freiburg on typical summer days 2007-2010.

During the same daytime period, which represents a typical interval related to human heat stress outdoors, an analysis of all experimental results in Freiburg shows that a reduction of $SVF_{90\text{-}270}$ by 10% through shading by tree canopies leads to a mean lowering of T_a by 0.2 °C, T_{mrt} by 3.8 °C and PET by 1.4 °C. This confirms once more the role of T_{mrt} as a key variable for human thermal comfort in the daytime, while T_a has a distinctly lower significance.

Human-biometeorological effects of wall albedo

Different investigations [3-8, 18] have shown the communal benefits for citizens through shading of the direct solar radiation by street trees. In additional investigations in Freiburg, the influence of the albedo of walls on human-biometeorological variables was simulated for a simple E-W oriented street canyon without any green. It had a length of 60 m, a width W of 10 m and was continuously bordered by regular buildings (height H = 10 m) at both sides. They had the same physical features like albedo. The ENVI-met model, version 3.1, was applied for a day within the Central European heat wave in August 2003. For the S-facing wall, the results (Fig. 5) show a lowering of its surface temperature T_s with an increase of the albedo a. Related to a = 0.1 and 0.9, resp., $T_{s,a=0.9}/T_{s,a=0.1}$ is the lowest around noon (0.75). Averaged over the period 10 to 16 CET, $T_{s,a=0.9}$ is by 0.79 lower than for $T_{s,a=0.1}$.

In contrast to the results for T_s, an increase of the albedo of the building walls leads to higher values of T_a, T_{mrt} and PET at the S-facing sidewalk of an E-W street canyon (Fig. 6). Related to the quite different albedo values (0.9 and 0.1), the peak values are 1.025 for $T_{a,0.9}/T_{a,0.1}$, 1.312 for $T_{mrt,0.9}/T_{mrt,0.1}$ as well as 1.182 for $PET_{0.9}/PET_{0.1}$. These results - surprising at first view - are mainly caused by the short-wave radiant flux density reflected by the vertical walls. It is increasing with higher albedo values. This leads to higher T_{mrt} values for the human-biometeorological reference person, because it is more sensitive to horizontal radiant flux densities due to its standing position in contrast to vertical ones.

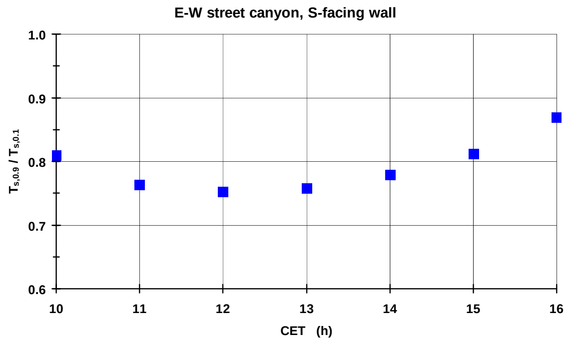

Figure 5: Simulated ratio of the surface temperature T_s between a=0.9 and a=0.1 of a S-facing wall of an E-W street canyon (H/W=1) for a heat wave day in August 2003, a: albedo.

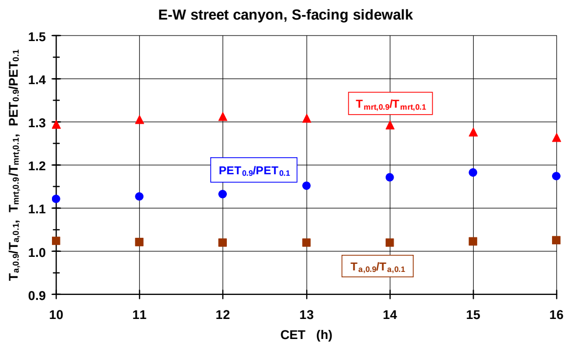

Figure 6: Simulated ratios of T_a, T_{mrt} and PET between the albedo values a=0.9 and a=0.1 of the building walls of an E-W street canyon (H/W=1), related to the S-facing sidewalk (width: 1 m).

CONCLUSION

Based on exemplary results of human-biometeorological investigations in Freiburg, it was shown that urban human-biometeorology has the ability to provide the information, which serves as a well-suited basis for urban planning to handle its challenge by increasing heat. As similar human-biometeorological studies were conducted in different cities worldwide, for example [13, 15, 16, 18, 19], the extent of human-biometeorological information for urban planning is gradually increasing. However, the practical experience up to now has pointed out that the implementation of results obtained in urban human-biometeorology in the planning process should be strongly improved. Two of the options to meet this requirement are: (i) presentation of the human-biometeorological results in terms of maps, which are actually significant for urban planning, for example, urban climatic maps in different planning-related scales [22], and (ii) continuous communication between experts in urban human-biometeorology and urban planners.

Figure 7: Shadow below the canopy of a broad-leaved tree at the campus of the Albert-Ludwigs-University in Freiburg on a hot summer day (June 27, 2011).

During Central European summer heat, the impacts of preventively oriented planning measures mostly go hand in hand with the individual behaviour of citizens. This is visualized in Fig. 7, which shows students on a hot summer day in Freiburg seeking shelter from the direct solar radiation below the canopy of an adult broad-leaved tree.

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