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ORIGINAL PAPER

Thermal comfort of pedestrians in an urban street canyon is affected by increasing albedo of building walls

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Abstract

Numerical simulations based on the ENVI-met model were carried out for an E-W street canyon in the city of Stuttgart (Southwest Germany) to analyse the effect of increased albedo of building walls on outdoor human thermal comfort. It was quantified by air temperature (T_a), mean radiant temperature (T_{mrt}) and physiologically equivalent temperature (PET). The simulations were conducted on 4 August 2003 as a heat wave day that represents a typical scenario for future summer weather in Central Europe. The simulation results presented for 13 CET and averaged over the period 10–16 CET are focused on pedestrians on both sidewalks. For the initial situation, i.e. albedo of 0.2, human heat stress indicated by mean PET is by 26% lower on the N-facing than on the S-facing sidewalk, while this reduction amounts to 42% for mean T_{mrt}. Mean T_a does not show any spatial differentiation. The systematic albedo increment by 0.2 from 0.2 to 0.8 leads to a linear increase of outdoor human heat stress in terms of T_{mrt} and PET. For both variables, this increase is more pronounced on the N-facing than on the S-facing sidewalk. Mean relative T_a shows the tendency of a minimal increase with rising albedo. The results were achieved for the usual standardised human-biometeorological reference person. Its substitution by two other types of male and female pedestrians, respectively, which are statistically characteristic of human conditions in Germany, does not reveal any significant change in the results.

Keywords E-W street canyon · Albedo of building walls · Daytime human thermal comfort · Heat wave day · ENVI-met simulations

Introduction

Results of regional climate simulations for Central Europe point to an increase of near-surface air temperature (T_a), including embedded heat waves that will be more frequent and severe as well as longer lasting (Ballester et al. 2010; Beniston 2013; Fallmann et al. 2017). This trend implies an enhanced heat stress particularly for citizens in urban spaces (Kuttler 2011a; Andersson-Sköld et al. 2015; Yang et al. 2015). The resulting problems are intensified by the growth of urban population and demographic change that raises the ratio of aged population (Laschewski and Jendritzky 2002; van Hoof et al. 2017). In order to reduce the negative heat impacts on citizens as well as increase the resilience of adaptation measures related to heat, suitable urban design strategies were proposed during the past decades (Ali-Toudert and Mayer 2006, 2007; Holst and Mayer 2011; Kuttler 2011b; Moonen et al. 2012; Shashua-Bar et al. 2012; Müller et al. 2014; van Hooff et al. 2014; Carter et al. 2015; Norton et al. 2015). They are mostly focused on the use of high albedo materials, evaporation from porous surfaces, evaporation from ground-level water surfaces and roof ponds, vegetated surfaces, rooftop gardens, trees and natural ventilation (Doulos et al. 2004; Synnefa et al. 2008; Bowler et al. 2010; Lindberg and Grimmond 2011; Shashua-Bar et al. 2011; Ng et al. 2012; Shahidan et al. 2012; Klemm et al. 2015; Salata et al. 2015; da Silva and de Alvarez 2015; Coutts et al. 2016; Kántor et al. 2016; Lee et al. 2016a, 2017; Middel et al. 2016; Taleghani et al. 2016; Tan et al. 2016).

Based on the theory that suitable materials could be capable of improving the thermal environment under maintenance of current urban morphology such as street orientation and building form, previous studies were often focused on

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characteristics of the external building fabric as a heat mitigation strategy (Bretz et al. 1998; Doulos et al. 2004; Yang et al. 2015). Among the material techniques, high albedo materials are considered as particularly effective for cooling outdoors and indoors due to their high reflectivity of the incoming short-wave radiation. In the light of energy saving, investigations on the impact of an elevated albedo of rooftops and pavements were mainly focused on T_a and surface temperature (T_s) (Akbari et al. 2005; Suehrcke et al. 2008; Synnefa et al. 2008, 2011; Romeo and Zinzi 2013; Yang et al. 2015).

Up to now, only a few studies exist on how outdoor human thermal comfort in cities is influenced by changing the albedo of building walls (Table 1). Most of them used appropriate models as simulation tools such as the previous version 3.1 of ENVI-met (Emmanuel and Fernando 2007; Emmanuel et al. 2007; Yang et al. 2011; Lee et al. 2014; Taleghani et al. 2014; Ghaffarianhoseini et al. 2015; Lee 2015), Green CTTC (Shashua-Bar et al. 2012), a linkage between the CAT and the ITS model (Erell et al. 2014) and URBSIM (Schrijvers et al. 2016). Only one experimental approach was also applied until now (Sasaki et al. 2015). The results refer often to T_a, mean radiant temperature (T_{mrt}) and thermo-physiologically significant assessment indices such as the physiologically equivalent temperature (PET) (Mayer and Höppe 1987; Höppe 1999), index of thermal stress (ITS) (Pearlmutter et al. 2007) or Universal Thermal Climate Index (UTCI) (Jendritzky et al. 2012). However, their transferability from one to another urban site is nearly impossible for different site characteristics, weather conditions and climate zones, because they are based on site-specific albedo changes (Table 1) and almost always given only as absolute values.

Taking into account the shape of pedestrians (Mayer 1993), the albedo of walls has a higher influence on their thermal sensation than that of horizontal surfaces. Summarising previous findings on the human-biometeorological albedo effects in the daytime, the simulation results of T_a dependent on increased albedo are different. They extend from a slight lowering by up to 1.5 °C (Erell et al. 2014) to a slight rise by up to 1.0 °C (Lee et al. 2014; Lee 2015), whereby its magnitude is higher in street canyons with an aspect ratio (H/W) of 1 as compared to deep canyons with higher H/W values. Irrespective of H/W or orientation of street canyons, a higher albedo of building walls consistently increases thermal stress of pedestrians. A rising wall albedo reduces T_s, which in turn causes a lower long-wave radiation emitted by building walls. But this is offset by the increased short-wave radiation reflected by the walls and absorbed by the standing pedestrians.

Table 1 Albedo of building walls in urban street canyons used in previous studies on the albedo impact on human thermal comfort

Albedo	Study
0.2, 0.6	Emmanuel et al. (2007); Yang et al. (2011)
0.4, 0.7	Shashua-Bar et al. (2012)
0.1, 0.9	Lee et al. (2014); Lee (2015)
0.6, 0.9	Emmanuel and Fernando (2007)
0.1, 0.3, 0.7	Sasaki et al. (2015)
0.20, 0.45, 0.70	Erell et al. (2014)
0.10, 0.55, 0.93	Taleghani et al. (2014)
0.30, 0.55, 0.93	Ghaffarianhoseini et al. (2015)

On hot summer days, the enhanced human heat stress due to an increased albedo of building walls amounts up to 30 °C for T_{mrt} and 16 °C for PET (Lee et al. 2014; Lee 2015). This effect is more pronounced in an E-W than in the N-S street canyon. Although the absolute T_{mrt} and PET values are lower on the N-facing than on the S-facing sidewalk, the albedo effect seems to be stronger on the N-facing sidewalk (Taleghani et al. 2014). For any albedo value, the thermal stress of pedestrians in the middle of a street canyon is decreasing with increasing H/W ratio (Erell et al. 2014). In contrast to the daytime situation, the nocturnal impacts of increased albedo on T_a, T_{mrt} and PET are comparatively insignificant, also against the background that the mean thermal level at night is distinctly lower than in the daytime.

Evaluating the studies that are available up to now on the human-biometeorological effects by changing the albedo of walls within street canyons, specific patterns for the behaviour of T_a, T_{mrt} and thermal assessment indices such as PET or UTCI can be identified. However, the need exists to deepen this knowledge by additional investigations that (i) are more systematic with respect to changes of the wall albedo, (ii) use improved and validated versions of micrometeorological models, (iii) show results for different areas of urban spaces and (iv) consider not only the human-biometeorological reference person (Mayer 1993), but also other types of pedestrians. Against this background, the objective of this study is to contribute to the filling of these gaps for an E-W street canyon in a Central European city on a heat wave day. Due to the standing position of the considered types of humans, which leads to a higher significance of the horizontal radiation fluxes in contrast to the vertical ones, the study is focused only on the albedo effects of building walls on T_a, T_{mrt} and PET, while the albedo of the ground surface is always kept constant.

Methods

Within the scope of a planning-related study on the human-biometeorological quality of urban spaces in the city of Stuttgart, Southwest Germany, (Lee et al. 2016b) the impacts of systematic changes of the albedo of building walls on T_a, T_{mrt} and PET were simulated for different areas of an E-W street canyon in the centre of Stuttgart. It was knowingly selected, because previous investigations (Ali-Toudert and Mayer 2006; Holst and Mayer 2011; Lee 2015) have revealed that daytime human heat stress is most pronounced in this type of urban structure on hot Central European summer days. The street canyon (length 40 m, width 22 m) consisted of a 14-m wide roadway (albedo 0.2) with two lanes and two adjacent paved sidewalks (albedo 0.2) each with a width of 4 m. It did not show any type of urban green. It was bordered by concrete buildings whose heights were 22 m for the N-facing and 28 m for the S-facing ones. Therefore, the street canyon had a slightly asymmetric shape showing an aspect ratio (building height/width of street canyon) of 1.3 with respect to the height of the S-facing buildings and 1.0 related to the height of the N-facing buildings.

The numerical simulations were carried out by use of the ENVI-met model v4.0 BETA and the included submodule BioMet for the calculation of PET. This model version is distinctly improved (Lee 2015; Lee et al. 2016a) in contrast to previous ENVI-met versions such as the frequently applied v3.1. A quantitative evaluation has demonstrated by different statistical measures that ENVI-met v4.0 BETA predicts T_a, T_{mrt} and PET within complex urban environments in a reasonable way. In order to run the ENVI-met model, necessary input variables are contained in an area input file and configuration file. The area input file comprises grid information on spatial characteristics of the simulation domain such as (i) its geographic location; (ii) its topography; (iii) location, dimension and material of buildings, sidewalks and roadways; (iv) location, type and dimension of urban green and (v) soil type.

In this simulation, the street canyon was located in a simulation domain, which horizontally spans 150 by 150 square grids with 2 m resolution, i.e. the horizontal size of the simulation domain was 300 m by 300 m. Based on a digital elevation model, the simulation domain showed a maximum elevation difference of 11 m in a sloping terrain from west-southwest to east-northeast direction. ENVI-met v4.0 BETA is capable of considering topographic effects like that. In order to ensure a stable simulation, the extent of the simulation domain should have at least two times the total of the maximum building height and the maximum elevation difference within the domain. As ENVI-met maximally provides 30 vertical grids, the simulations carried out in this study used a 3-m vertical resolution of the lower grids. Starting at 15 m agl, the vertical grid width was uniformly increased by 20% using the 'telescoping' approach that is integrated in ENVI-met v4.0 BETA. By this means, the simulation domain made of 19 vertical grids had a vertical dimension of 228 m agl.

As results of regional climate simulations for Central Europe point to the increasing significance of heat waves (Ballester et al. 2010; Fallmann et al. 2017), the simulations of this study were conducted for the meteorological conditions on the heat wave day 4 August 2003. The basic conditions of the configuration file hardly differed from those of similar simulations carried out in Central European cities on hot summer days (e.g. Lee 2015: Lee et al. 2016a). As initial situation, the numerical simulations started with an albedo of 0.2 for all building walls in the entire simulation domain. In subsequent simulations, the albedo was gradually elevated by 0.2 until an albedo of 0.8. For the roadway and both sidewalks, the albedo was kept constant at 0.2. The long-wave emissivity of building walls, roofs, sidewalks and roadway was uniformly set to 0.9.

In contrast to previous versions of ENVI-met, a so-called forcing function is included in v4.0 BETA. It refers to 1-h mean values of T_a and relative humidity (RH) measured on the simulation day at a meteorological station in close vicinity to the simulation domain. These values are integrated in the numerical simulation and contribute to more realistic simulation results. For the simulations in this study, 1-h mean T_a and RH values measured at the meteorological station Schwabenzentrum in the centre of Stuttgart were used. Their diurnal cycles reflect a T_a and RH behaviour that is typical of a Central European heat wave day.

The simulation results of this study relate to the human-biometeorological reference person (Mayer 1993). It is characterised by a 35-year-old male of specific height (175 cm) and weight (75 kg). In order to examine the effects of albedo changes of building walls on PET for other types of humans, additional numerical simulations were carried out each for two specific types of female and male pedestrians (Table 2) that are statistically representative of Germany (Statista 2017). Both the human-biometeorological reference person and the other types of pedestrians have a standing position, a walking speed of 1.2 m/s, a static clothing insulation (I_{cl}) of 0.9 clo and a work metabolism of 80 W.

Results

Simulation results in terms of grid values

Due to the vertical extension of the lowest grid, the simulation results of T_a, T_{mrt} and PET refer to a height of 1.5 m agl, which approximates the human-biometeorological reference height of 1.1 m agl (Mayer 1993). According to mean diurnal courses of T_{mrt} and PET on hot summer days (Mayer et al. 2008), the simulation results were averaged over the period from 10 to 16 CET, because they should be representative of outdoor summer heat for Central European citizens (Holst and Mayer 2011; Lee et al. 2016a).

As expected for an E-W street canyon with an air flow from approximately western direction, the T_{mrt} and PET grid results (Figs. 1 and 2) show comparatively uniform horizontal patterns characterised by pronounced N-S gradients. As T_a does not reveal a similar spatial differentiation, a separate T_a figure

Table 2 Characteristics of the human-biometeorological reference person and other types of pedestrians considered in this study (according to Mayer 1993; Statista 2017)

Type of humans	Age	Height	Weight	Basal rate	Body metabolism
Human-biometeorological reference person, male (hbrp)	35	175 cm	75 kg	85 W	165 W
Male A (mA)	35	179 cm	86 kg	93 W	173 W
Male B (mB)	65	174 cm	87 kg	81 W	161 W
Female A (fA)	35	165 cm	69 kg	72 W	152 W
Female B (fB)	65	161 cm	74 kg	64 W	144 W

is not displayed. The colour-coded ranges of the T_{mrt} (Fig. 1a) and PET values (Fig. 2a) are governed by the meteorological conditions of the model initialisation. The stepwise increase of the albedo by 0.2 that is related to an albedo of 0.2 causes an enhancement of the T_{mrt} and PET grid values. It can be easily seen in Fig. 1b–d for ΔT_{mrt} and in Fig. 2b–d for ΔPET, because the colour-coding is kept constant for each of the ΔT_{mrt} and ΔPET figures.

Mean T_a, T_{mrt} and PET values for a building wall albedo of 0.2

With respect to the spatial conditions, the simulation results are particularly analysed as values averaged over three areas of the E-W street canyon: (i) S-facing sidewalk, (ii) roadway and (iii) N-facing sidewalk. For an albedo of 0.2, mean T_a averaged over 10–16 CET is 32.7 °C on the S-facing sidewalk and the roadway as well as 32.6 °C on the N-facing sidewalk (Table 3). Mean T_{mrt} and PET reveal a much more gradual subdivision between the three areas of the street canyon. The highest mean T_{mrt} (71.1 °C) and PET (48.8 °C) were simulated on the S-facing sidewalk, while the N-facing sidewalk has the lowest mean T_{mrt} (41.4 °C) and PET (36.3 °C).

Related to the mean values on the S-facing sidewalk (each 100%), the relatively homogeneous situation of T_a in the entire street canyon becomes obvious (Table 3). However, the mean relative T_{mrt} and PET differences between the S-facing sidewalk and the roadway are distinctly lower than those between the roadway and the N-facing sidewalk. This was mainly caused by the combined effect of the aspect ratio of the street canyon and sun position on the simulation day. For each of the different areas of the street canyon, the absolute mean T_a, T_{mrt} and PET values at 13 CET are slightly higher than those averaged over the period 10–16 CET, while the relative mean T_a, T_{mrt} and PET values at 13 CET related to the respective mean absolute values on the S-facing sidewalk are nearly in the same magnitude like those averaged over 10–16 CET (Table 3).

Mean T_a, T_{mrt} and PET values dependent on increasing albedo of the building walls

As shown in Fig. 1b–d for ΔT_{mrt} and Fig. 2b–d for ΔPET, respectively, both variables distinctly increase with rising albedo of the building walls. Related to the selected areas of the street canyon, the increase of the variables used in this study to characterise human thermal comfort in the daytime can be well described by a simple linear regression

$$y = a \cdot \text{albedo} + b \quad (1)$$

where y stands for T_a, T_{mrt} and PET, respectively, as well as a and b are the respective regression coefficients.

For both sidewalks, the results of the regression analyses averaged over the period 10–16 CET (Fig. 3) reveal that a

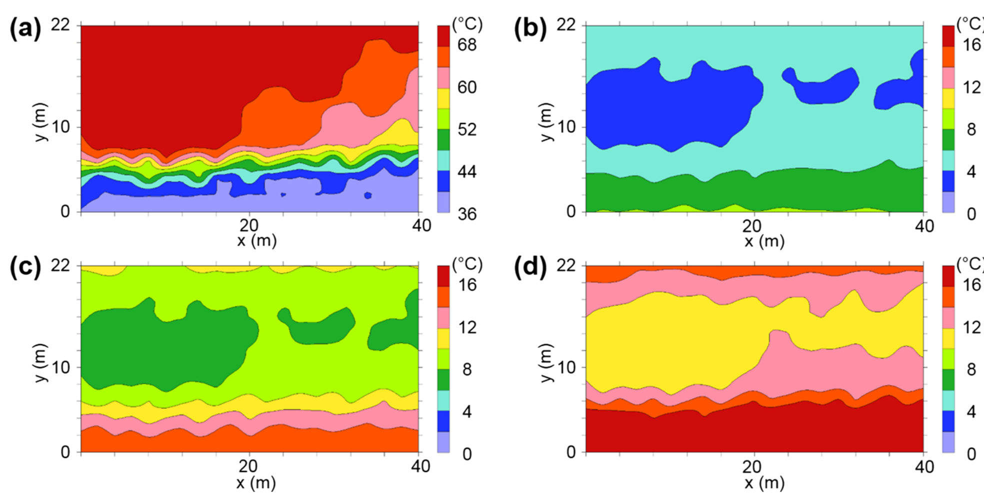

Fig. 1 T_{mrt} grid values for different albedo of the building walls on both sides of an E-W oriented street canyon in Stuttgart, averaged over 10–16 CET on the heat wave day 4 August 2003. **a** T_{mrt} for albedo of 0.2. **b** ΔT_{mrt} for Δalbedo of 0.4–0.2. **c** ΔT_{mrt} for Δalbedo of 0.6–0.2. **d** ΔT_{mrt} for Δalbedo of 0.8–0.2

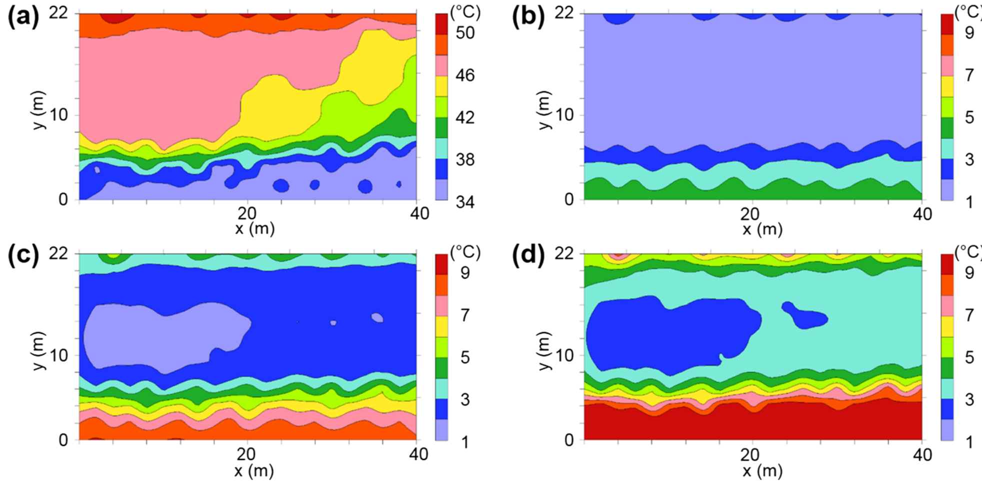

Fig. 2 PET grid values for different albedo of the building walls on both sides of an E-W oriented street canyon in Stuttgart, averaged over 10–16 CET on the heat wave day 4 August 2003. **a** PET for albedo of 0.2. **b** ΔPET for Δalbedo of 0.4–0.2. **c** ΔPET for Δalbedo of 0.6–0.2. **d** ΔPET for Δalbedo of 0.8–0.2

higher albedo of the building walls causes an increase of mean T_a, T_{mrt} and PET. It is lowest for mean T_a and highest for mean T_{mrt}. In contrast to the S-facing sidewalk, the increase of mean T_{mrt} and PET is higher on the N-facing sidewalk (Table 4). The mean T_a, T_{mrt} and PET values determined at 13 CET for the three areas of the street canyon show a similar behaviour. The regression coefficient *a* points to the tendency that mean T_{mrt} and PET at 13 CET increase slightly stronger than for 10–16 CET (Table 4).

As the regression coefficients *a* and *b* in Table 4 represent absolute values, their magnitudes are governed by the meteorological conditions on the simulation day. To generalise these specific results, mean relative T_a, T_{mrt} and PET values were determined (Table 5) that refer to an albedo of 0.2.

With respect to the three selected areas of the street canyon, the specific increases of mean relative T_a and T_{mrt} dependent on rising albedo are quite similar at 13 CET and for 10–16 CET. In contrast, mean relative PET shows the tendency of slightly higher values at 13 CET. Related to the period 10–16 CET, an albedo increase by 0.2 leads to an increase of mean T_{mrt} by approximately 6% on the S-facing sidewalk and the roadway as well as 17% on the N-facing sidewalk. For the same albedo conditions, the increase of mean PET is approximately 3% on the S-facing sidewalk and the roadway as well as 9% on the N-facing sidewalk.

Mean radiation fluxes

Mean values of the short-wave radiation reflected from the S- and N-facing building walls ($Q_{sw,r}$) and long-wave radiation emitted from them ($Q_{lw,e}$) are used to understand the results achieved for the mean T_a, T_{mrt} and PET values dependent on the albedo of the building walls. The results simulated for the weather conditions on the heat wave day 4 August 2003 in Stuttgart and averaged over the period 10–16 CET show (Table 6) that mean absolute $Q_{sw,r}$ is slightly higher for the shaded N-facing than that for the sunlit S-facing buildings. This at first glance unexpected result is mainly caused by a multiple reflection, i.e. the short-wave radiation reflected from the S-facing buildings and reaching the N-facing buildings is higher than that reflected from the N-facing buildings and reaching the S-facing buildings.

Starting with a wall albedo of 0.2, an albedo increase by 0.2 leads for both buildings to a mean relative $Q_{sw,r}$ increase of 100%. In contrast to mean $Q_{sw,r}$, an albedo increase causes a decrease of the surface temperature of the walls and, therefore, a mean relative decrease of $Q_{lw,e}$ (Table 6). However, the magnitude of this decrease is distinctly lower than that of the mean relative $Q_{sw,r}$ increase. As expected due to the higher surface temperature of the sunlit walls, mean absolute $Q_{lw,e}$ for the S-facing building walls is by about 14% higher than that of the shaded N-facing building walls.

Table 3 Mean absolute and relative T_a, T_{mrt} and PET values for different areas of the E-W street canyon (building wall albedo 0.2) at 13 CET and averaged over 10–16 CET, relative values related to the respective mean absolute values on the S-facing sidewalk

	T_a		T_{mrt}		PET	
	13 CET	10–16 CET	13 CET	10–16 CET	13 CET	10–16 CET
S-facing sidewalk	33.3 °C	32.7 °C	71.6 °C	71.1 °C	52.6 °C	48.8 °C
	100%	100%	100%	100%	100%	100%
Roadway	33.3 °C	32.7 °C	69.0 °C	65.8 °C	49.6 °C	45.3 °C
	100%	100%	96%	93%	94%	93%
N-facing sidewalk	33.2 °C	32.6 °C	42.2 °C	41.4 °C	37.2 °C	36.3 °C
	100%	100%	59%	58%	71%	74%

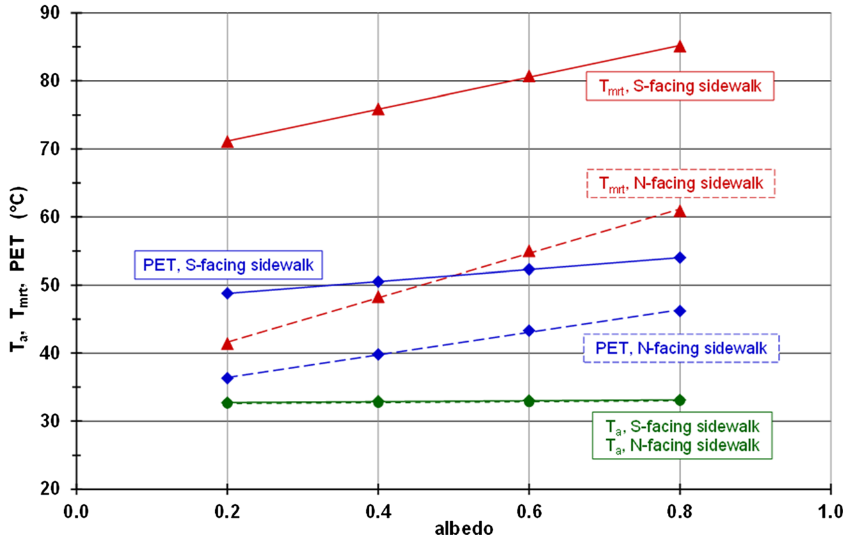

Fig. 3 Mean T_a, T_{mrt} and PET values depending on increasing albedo of the building walls on both sides of an E-W oriented street canyon, each averaged over the S- and N-facing sidewalk and the period 10–16 CET of the heat wave day 4 August 2003

The increase of the wall albedo results in a different behaviour of both mean $Q_{sw,r}$ and $Q_{lw,e}$. However, the total of mean $Q_{sw,r}$ and $Q_{lw,e}$ averaged over 10–16 CET is increasing with higher albedo values (Table 7). The mean absolute total of $Q_{sw,r}$ and $Q_{lw,e}$ is higher for the S-facing building walls, which explains the higher human heat stress above the S-facing sidewalk. However, the relative increase of mean $Q_{sw,r}$ and $Q_{lw,e}$ with rising wall albedo is slightly higher for the N-facing than that for the S-facing building walls. This leads to a more pronounced increase of human heat stress in terms of T_{mrt} and PET on the N-facing than on the S-facing sidewalk. The mean relative results at 13 CET show a similar behaviour such as those averaged over 10–16 CET (Table 7). As expected, the only difference is that the absolute totals of $Q_{sw,r}$ and $Q_{lw,e}$ are slightly higher at 13 CET than those averaged over 10–16 CET.

Table 4 Coefficients a and b of linear regressions ($y = a \cdot$ albedo + b) for different areas of an E-W street canyon, y: mean values of T_a, T_{mrt} and PET (each in °C), dependent on the wall albedo, at 13 CET and averaged over 10–16 CET

	13 CET		10–16 CET	
	a	*b*	*a*	*b*
$y = T_a$				
S-facing sidewalk	0.7	33.2	0.7	32.6
Roadway	0.5	33.2	0.7	32.6
N-facing sidewalk	0.5	33.1	0.7	32.5
$y = T_{mrt}$				
S-facing sidewalk	23.6	67.0	23.4	66.5
Roadway	20.2	65.1	20.4	61.8
N-facing sidewalk	33.0	35.9	32.6	35.1
$y =$ PET				
S-facing sidewalk	14.5	49.7	8.7	47.1
Roadway	11.5	47.3	6.0	44.1
N-facing sidewalk	17.8	33.9	16.6	33.1

Mean PET values for selected types of humans

As a simulation result for the N-facing sidewalk (Table 8), PET averaged over 10–16 CET amounts to 36.3 °C for an albedo of 0.2 and does not show any difference between the four types of pedestrians including the human-biometeorological reference person, in spite of slightly different characteristics (Table 2). On the S-facing sidewalk, mean PET for an albedo of 0.2 increases from 48.8 °C for the human-biometeorological reference person to 48.9 °C for male A, 49.2 °C for male B and female A and 49.6 °C for female B that has the lowest body metabolism (total of basal rate and work metabolism). For both sidewalks, the mean relative PET results related to the respective mean absolute PET values for an albedo of 0.2 reveal a similar pattern like those in Table 5. The increase of mean relative PET depending on rising albedo is higher on the N-facing sidewalk but almost does not differ between the five types of humans.

Discussion

High albedo materials of buildings cause a high reflectivity of the incoming short-wave radiation. Therefore, they are often considered as particularly effective for cooling outdoors and indoors, which is desired by citizens especially during severe regional heat. However, recent research reveals under a human-biometeorological perspective that this idea needs to be revised for the outdoor situation within street canyons. While the improvement of indoor human thermal comfort by increasing the albedo of building walls is uncontroversial, this study shows that a systematic increase of the wall albedo leads

Table 5 Mean relative T_a, T_{mrt} and PET values for different albedo values, related to the respective mean absolute values for an albedo of 0.2, at the three selected areas of the E-W street canyon at 13 CET and averaged over 10–16 CET

Albedo	T_a (%)		T_{mrt} (%)		PET (%)	
	13 CET	10–16 CET	13 CET	10–16 CET	13 CET	10–16 CET
S-facing sidewalk						
0.2	100	100	100	100	100	100
0.4	101	101	107	107	106	104
0.6	101	101	113	114	111	107
0.8	101	101	120	120	117	111
Roadway						
0.2	100	100	100	100	100	100
0.4	100	100	106	106	105	103
0.6	101	101	112	113	109	105
0.8	101	101	118	119	114	108
N-facing sidewalk						
0.2	100	100	100	100	100	100
0.4	100	100	117	117	110	110
0.6	101	101	132	133	119	119
0.8	101	101	147	147	129	127

to a systematic impairment of daytime thermal comfort for pedestrians. This effect also becomes apparent in recent papers (e.g. Erell et al. 2014; Lee et al. 2014; Lee 2015; Schrijvers et al. 2016). It is mainly caused by the enhanced $Q_{sw,r}$, which is largely absorbed by pedestrians due to their standing position that is approximated by a rotationally symmetric shape (Mayer and Höppe 1987; Höppe 1999). Therefore, the angular factors used in the calculation of T_{mrt} are set to 0.22 for the radiation fluxes from the cardinal points E, S, W and N, but only to 0.06 for the radiation fluxes from the upper and lower half space (Mayer 1993; Kántor and Unger 2011; Kántor et al. 2015). $Q_{sw,r}$ absorbed by pedestrians has a higher impact on their thermal comfort than that induced by $Q_{lw,e}$, which is decreasing with the increasing wall albedo.

The general evaluation of the albedo impact on daytime thermal comfort of pedestrians is not easy due to a variety of influencing factors. These concern, for example, (i) the type, orientation and morphological characteristics of the investigation site; (ii) the availability of urban green, its type and dimension; (iii) the local weather conditions on the investigation day and (iv) the systematic investigation design including the application of an appropriate microscale simulation model and its initialisation. The ENVI-met model often proved to be well suited for these simulations. In contrast to its previous version 3.1, the distinctly improved version 4.0 BETA applied in this study provides more reliable results (Lee and Mayer 2016; Lee et al. 2016a).

The integration of the results of this study in those of previous investigations has to keep the different applied methods in mind. This is aggravated by the often lacking accuracy of the description of the influencing factors. While the results of this study are based on a systematic albedo change of the building walls, similar studies only consider two or three various albedo values that are related to a real material of building walls.

Table 6 Effects of increased albedo of building walls bordering both sides of an E-W street canyon on their reflected short-wave radiation $Q_{sw,r}$ and emitted long-wave radiation $Q_{lw,e}$, both averaged over 10–16 CET on the heat wave day 4 August 2003

Albedo	$Q_{sw,r}$ S-facing building walls	$Q_{lw,e}$	$Q_{sw,r}$ N-facing building walls	$Q_{lw,e}$
0.2	105 W/m^2	484 W/m^2	111 W/m^2	433 W/m^2
	100%	100%	100%	100%
0.4	200%	94%	200%	93%
0.6	300%	88%	300%	86%
0.8	420 W/m^2	392 W/m^2	444 W/m^2	338 W/m^2
	400%	81%	400%	78%

Table 7 Effects of increased albedo of building walls bordering both sides of an E-W street canyon on the total of their reflected short-wave radiation $Q_{sw,r}$ and emitted long-wave radiation $Q_{lw,e}$, both at 13 CET and averaged over 10–16 CET on the heat wave day 4 August 2003

Albedo	$Q_{sw,r} + Q_{lw,e}$			
	13 CET S-facing building walls	10–16 CET	13 CET N-facing building walls	10–16 CET
0.2	614 W/m^2	589 W/m^2	557 W/m^2	544 W/m^2
	100%	100%	100%	100%
0.4	113%	113%	115%	115%
0.6	125%	125%	130%	130%
0.8	137%	138%	144%	144%
	842 W/m^2	812 W/m^2	804 W/m^2	782 W/m^2

Table 8 Mean PET values for different body conditions and age of female and male pedestrians (Table 2) on both sidewalks of the E-W street canyon dependent on the wall albedo and averaged over 10–16 CET on the heat wave day 4 August 2003, mean relative PET values are referred to the respective mean absolute PET values for an albedo of 0.2

Albedo		hbrp	mA	mB	fA	fB
0.2	S-facing sidewalk	48.8 °C	48.9 °C	49.2 °C	49.2 °C	49.6 °C
		100%	100%	100%	100%	100%
	N-facing sidewalk	36.3 °C	36.3 °C	36.3 °C	36.3 °C	36.3 °C
		100%	100%	100%	100%	100%
0.4	S-facing sidewalk	104%	104%	104%	104%	104%
	N-facing sidewalk	110%	110%	110%	110%	110%
0.6	S-facing sidewalk	107%	107%	107%	107%	107%
	N-facing sidewalk	119%	119%	120%	120%	120%
0.8	S-facing sidewalk	111%	111%	110%	110%	110%
	N-facing sidewalk	127%	128%	128%	128%	128%

Analysing the daytime results of available investigations carried out for different background conditions, this study shows a minimal T_a increase with rising albedo, while other investigations point to a slight T_a decrease. This behaviour could be caused by the different site conditions and types of simulation model. In contrast to T_a, however, all similar results point to an increase of T_{mrt} and heat stress for pedestrians quantified by PET or ITS. As already mentioned, this is understandable due to the standing position of the human-biometeorological reference person.

This study has shown that systematic albedo changes cause a systematic increase of T_a, T_{mrt} and PET that can be well described by simple linear regressions due to the significant $Q_{sw,r}$ behaviour. As the increase of T_a, T_{mrt} and PET is also indicated by mean relative values for different areas of an E-W street canyon, they enable a spatial differentiation of general significance. Results of alterations of T_a, T_{mrt} and PET in terms of absolute values show a strong dependency on the current site and weather conditions and, therefore, are hardly transferable.

As expected, the results of this study point to a stronger daytime heat stress for pedestrians on the S-facing sidewalk. Related to the PET classification for Central European summer conditions (Holst and Mayer 2010) that is based on the ASHRAE thermal sensation scale and questionnaires, heat stress for pedestrians on the S-facing sidewalk is in the class 'hot', while it distinctly lowers on the N-facing sidewalk (class 'warm'). However, the changes of mean relative T_{mrt} and PET values due to an increasing albedo are slightly more pronounced on the N-facing than on the S-facing sidewalk. This is mainly caused by the different $Q_{sw,r}$ conditions of both bordering building walls. The magnitude of $Q_{sw,r}$ from the sunlit vertical walls bordering the S-facing sidewalk and reaching the N-facing sidewalk is distinctly higher than that from the shaded walls bordering the N-facing sidewalk.

The numerical simulations carried out for further types of humans than only the human-biometeorological reference person also address the issue of human thermal comfort and ageing (van Hoof et al. 2017). The PET results obtained in this study for both 65 years old male and female pedestrians do not significantly differ from those for the human-biometeorological reference person. However, the classification of PET used in this investigation is based on questionnaires of students, i.e. younger people (Holst and Mayer 2010). The findings of van Hoof et al. (2017) suggest that the thermal conditions preferred by older people can differ from those preferred by younger adults.

Façade greening, which is often associated with an improvement of thermal comfort in both indoor and outdoor spaces, also induces a change of the building wall albedo. A simulation study carried out in a complex urban environment on a hot summer day used an albedo of 0.36 for the bare building wall and 0.28 for the green façade (Jänicke et al. 2015). Based on numerical simulations by use of three different models, the results for a south-southwest oriented building façade reveal that façade greening contributes only slightly to a reduction of heat stress for pedestrians in terms of T_{mrt}. Averaged over the period 10–16 CET, the mean reduction of T_{mrt} was 2.1 °C.

With respect to countermeasures to reduce local heat stress for pedestrians during regional severe heat events, practical urban planning in inland cities that cannot benefit from near-surface airflow such as a sea breeze has to develop and apply methods that primarily lead to a significant lowering of T_{mrt} (e.g. Chen et al. 2016). This can be best achieved by shading effects, particularly shading of the direct solar radiation by the crown of deciduous trees (Lee et al. 2013, 2017; Middel et al. 2016).

Conclusions

This study contributes to analyses on the effectiveness of measures that should be applied to reduce outdoor human heat stress in urban street canyons during severe heat. Although the increase of building wall albedo improves the indoor conditions for humans, it causes a worsening of their outdoor thermal comfort. However, the simulation results were obtained for specific background conditions. They mainly refer to a selected street canyon, its specific aspect ratio, its inflow from western direction, and the hot summer weather on the simulation day. In order to provide results about the albedo effect on outdoor human thermal comfort on a broader basis and thereby increase their general validity, further systematic simulations are necessary. In addition to alterations of the building wall albedo, they could include the effects of changed orientation of street canyons, their aspect ratio, inflow direction and speed, and other meteorological conditions. For the application of the results in planning practice, the users must define a suitable time reference such as a fixed hour or a time interval.

Increasing the building wall albedo and shading by deciduous trees represent two planning measures that improve indoor human thermal comfort particularly during severe heat. However, the increase of the albedo worsens daytime thermal comfort for pedestrians, while shading by trees, which are planted in the right location, leads to a reduction of outdoor human heat stress at least on the sidewalks of street canyons. Under this aspect, deciduous trees with large crowns have a comparatively high significance as a planning strategy to improve both indoor and outdoor human thermal comfort.

The application of thermo-physiological assessment indices such as PET, ITS or UTCI enables the evaluation of daytime human thermal comfort in urban spaces. Regarding pedestrians, it has to be kept in mind that their dose of heat stress has a relatively high significance due to their mobility. Its consideration in planning strategies requires specific analyses for individuals that are relatively comprehensive.

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