Landscape and Urban Planning 122 (2014) 78–88

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

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

Christine Ketterer*, Andreas Matzarakis[1]

Chair of Meteorology and Climatology, Albert-Ludwigs-University Freiburg, Werthmannstrasse 10, 79085 Freiburg, Germany

HIGHLIGHTS

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

ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form 24 October 2013
Accepted 4 November 2013
Available online 11 December 2013

Keywords:
Physiologically equivalent temperature
Urban planning
Replanning
Stuttgart
ENVI-met
RayMan

ABSTRACT

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

1. Introduction

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

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

* Corresponding author. Tel.: +49 761 203 6925; fax: +49 761 203 6922.
E-mail addresses: Christine.Ketterer@meteo.uni-freiburg.de (C. Ketterer), Andreas.Matzarakis@meteo.uni-freiburg.de (A. Matzarakis).
[1] Tel.: +49 761 203 6921; fax: +49 761 203 6922.

0169-2046/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.landurbplan.2013.11.003

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

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

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

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

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

2. Study area and methods

2.1. Study area

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

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

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

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

2.2. Methods

2.2.1. Microclimate models ENVI-met and RayMan

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

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

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

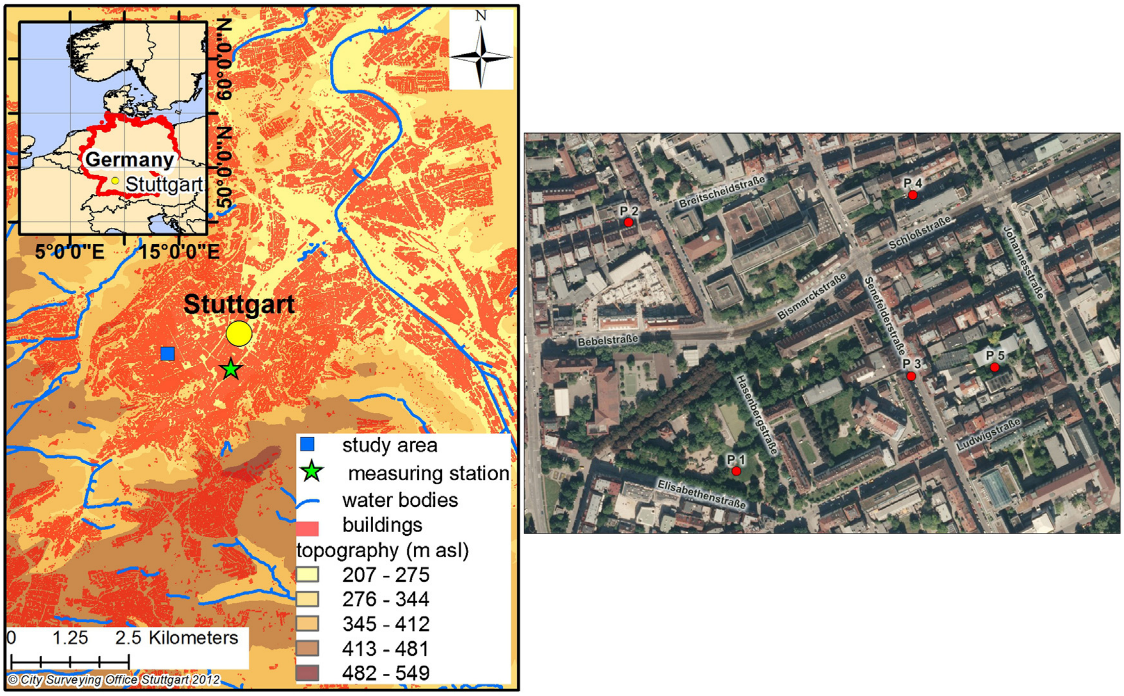

Fig. 1. Study area Stuttgart-West. The biometeorological conditions of the points of interest (P1–P5) are analyzed with the corresponding fish-eye photo, Bowen ratio and albedo (Table 4).

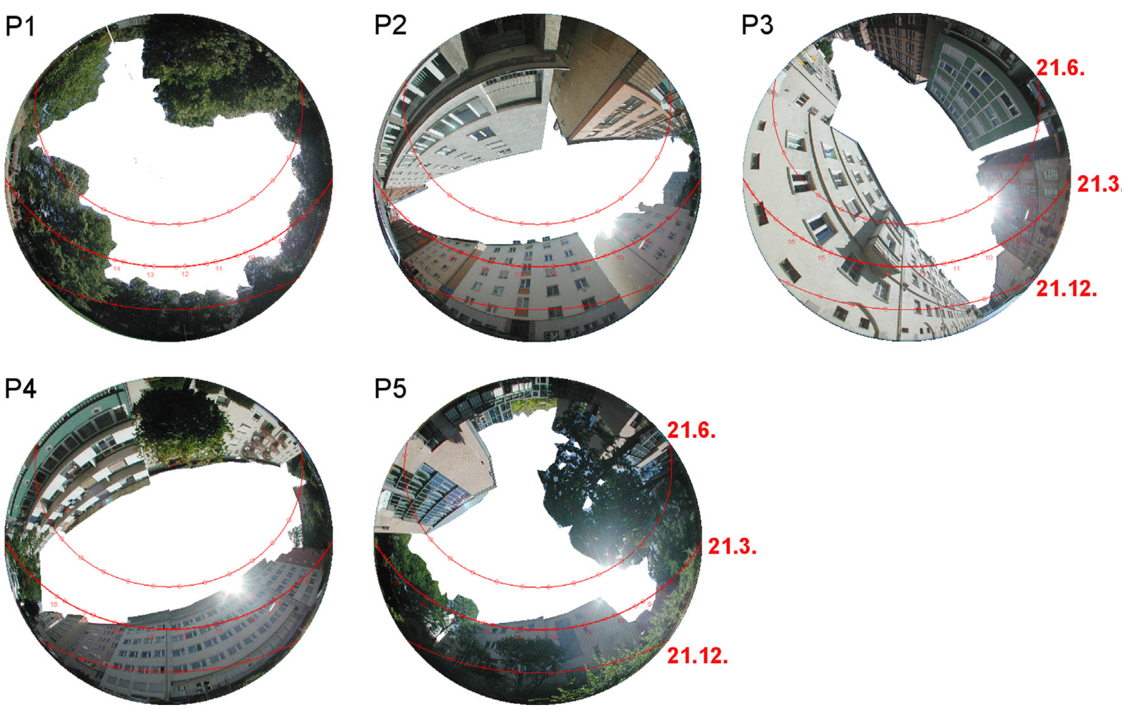

Fig. 2. Fish-eye photos of the chosen locations in Stuttgart-West. The corresponding SVF is given in Table 4.

Table 2
Characteristics of the ENVI-met model areas as discussed in Figs. 3–7.

	Whole area (Fig. 3)	Park (Fig. 4)	Residential area (Fig. 4)	Grass (Figs. 5–7)	Asphalt (Figs. 5–7)	Forest (Figs. 5–7)	Park (Figs. 5–7)
Built area fraction	31%	7%	25%	31%	17%	28%	28%
Vegetation	16%	49%	14%	19%	4%	19%	18%
Portion of trees	1%	4%	1%	1%	3%	19%	2%
Impervious surface fraction of the unbuilt area fraction	57%	37%	72%	35%	47%	34%	34%

Table 3
Configurations used for ENVI-met simulations in the study.

Start of the simulation	22.06.2003
Simulation time	72 h
Horizontal grid size	2 m
Wind speed in 10 m above ground	2.6 m s^{-1}
Wind direction	250°
Roughness length z_o at reference point	0.1 m
Initial air temperature	26 °C
Specific humidity in 2500 m	7.0 g water/kg air
Relative humidity in 2 m	60%
Factor of shortwave radiation adjustment	0.83
Clouds	0/8

surroundings for the calculation of the mean radiant temperature T_{mrt}. In this study, the thermal index PET (Höppe, 1999; Matzarakis, Mayer, & Iziomon, 1999; Mayer & Höppe, 1987) based on the human energy balance is used. Input data are the meteorological parameters air temperature T_a, vapour pressure *VP*, wind speed *v* and global radiation *G*, which were recorded at the rooftop station Stuttgart-Schwabenzentrum for the period 2000–2011 in hourly resolution.

2.2.2. Selected thermal index

As human beings experience the thermo-physiological effect of the meteorological parameters air temperature, air humidity, wind velocity and radiation fluxes, all these parameters have to be considered in the analysis. However, the perception of heat does not only depend on the physical state of the atmosphere but also on the physics of the human body (sex, height, activity, clothing resistance for heat transfer, shortwave albedo and long wave emissivity of the surface) (Höppe, 1999). The meteorological parameters and their spatial and temporal distribution are simulated with the help of ENVI-met for the study area of the Olga Hospital. Based on the simulated meteorological parameters of potential temperature, relative humidity, wind speed and the mean radiant temperature thermal indices are calculated using a new developed tool, the Thermal Index Calculator for ENVI-met output files (TIC ENVI-met). The thermal indices PET (Höppe, 1999; Matzarakis et al., 1999; Mayer & Höppe, 1987) and Universal Thermal Climate Index (UTCI; Jendritzky, Dear, & Havenith, 2012) can be calculated using TIC-ENVI-met. The personal data for a standard human being are defined as 1.75 m height, 75 kg, male, 35 years old, clothing of 0.9 clo (1 clo = 0.155 m^2 K W^{-1}) and an activity of 80 W (Höppe, 1999). The assessment scale classifying cold stress, thermal comfort and heat stress is based on Matzarakis and Mayer (1997).

2.2.3. Urban morphology

The intensity of the intra-urban differences of thermal conditions as well as of the UHI depends strongly on the sky view factor (SVF), built-up ratio (aspect ratio) and green surface ratio (Oke, 2006; Unger, 2004). The SVF is a dimensionless parameter between 0 (no sky visible) and 1 (free hemisphere) representing the geometric ratio of a given location that expresses the fraction of the overlying hemisphere occupied by sky (Chapman, Thornes, & Bradley, 2001; Oke, 1981, 2006). Especially the southern part of the SVF ($SVF_{90–270}$) is relevant for thermal conditions in the northern hemisphere (Holst & Mayer, 2011). The SVF of the different points of interest (POI) 1–5 is calculated with the help of fish-eye photos. Furthermore adapted values of Bowen ratio and albedo for every point of interest are taken to calculate PET (Table 4). The Bowen ratio describes the ratio of sensible heat exchange to latent heat exchange, which largely depends upon surface moisture availability (Oke, 1982). Sealed areas and less vegetation increase the urban Bowen ratio compared to the Bowen ratio over rural areas (Bonan, 2008). The aspect ratio describes the proportional relationship between the width of the street to the height of the buildings.

3. Results

3.1. Current thermal conditions

The current human-biometeorological conditions were calculated using RayMan for the time period 2000–2011. The percentage of heat stress (PET > 35 °C) in Stuttgart-West is higher than the percentage of thermal comfort at four of five points (P, see Figs. 1 and 2) at 14:00 from May to September 2000–2011 (Table 4). The highest frequency of heat stress up to 91% at P2 occurred in August. Heat stress is more frequent in the courtyards compared to the street canyons due to high SVF and shelter from the wind. In the green area (P1) with less shading, the average frequency of heat stress was 4.3 and 15.8% higher than in street canyons (P2 and P3). Although the southern part of the SVF is larger at P1 (0.198) than at P4 (0.157) and P5 (0.152), the frequency of heat stress is lower due to low Bowen ratio of 0.6, as compared to 1 and 0.9 at P4 and 5, respectively (Table 4). The most comfortable conditions are found to be at P3, in a narrow, NNW-SSE orientated street canyon with an SVF of 0.238 ($SVF_{90–270}$ = 0.095). Extreme heat stress occurred only from June to August with a frequency of 43.8%, while the frequency of thermal comfort conditions is 55.6%.

Fig. 3 depicts the mean radiant temperature in the study area at 14:00 CET. These case studies are representative for hot summer days with a high amount of solar radiation. The average mean radiant temperature in the whole area is 57 °C; ranging from 23.8 °C to 75.6 °C. The lowest mean radiant temperature was calculated in the shadow of trees in green areas. The mean radiant temperature is at least 3 K higher in the shadow of buildings and 45 K higher in sealed courtyards. The mean radiant temperature has the greatest influence on PET in the daytime on a sunny summer day. PET rises up to 58 °C above sealed surfaces with low albedo, high solar irradiation and low wind speed. Hotspots occur especially along the Senefelder Street and in the northwest area. In green areas, PET ranges between 18 and 28 °C in shaded and not more than 35 °C in unshaded areas. Streets which are parallel to the wind direction (e.g. Bebel and Bismarck Street), featured lower PET (ΔPET < 10 K) than other streets (Senefelder Street). The difference in PET between sealed and non-sealed areas is at least 10 K.

3.2. Comparison of thermal micrometeorological conditions of future scenarios

In Fig. 4 two scenarios, the influence of a planned residential area and a green area on human-biometeorological conditions are compared. A park would on average reduce PET by 2.6 K in the whole area of the Olga Hospital (Fig. 4). The PET differences between both scenarios in the encircling streets are largest on the lee (east) side of the Olga Hospital. Regardless of shaded areas in the Senefelder Street in the west, PET is on average 1.7 K and maximum 7 K colder in the Senefelder Street in the park scenario. The differences are only −0.4 K, and −0.8 K in the north and east orientations. A positive PET difference in the park scenario might be caused by missing shadow of the buildings, in which PET is up to 20 K lower due to reduced irradiation and mean radiant temperature. The planned green areas within the residential area are 1–20 K (PET) warmer compared to the park scenario (Fig. 4).

The diurnal cycle of different meteorological parameters in the middle of the modelled area of different future planning scenarios in 1.5 m height is depicted in Fig. 5. The mean radiant temperature is lowest at 6:00 CET with 14.2 °C in park scenario and 17.5 °C in the asphalt scenario peaking at around 17:00 CET with 73.1 °C in the asphalt scenario, 58.6 °C in the grass scenario and only 36.5 °C in the area shaded by trees (Fig. 5B). The air temperature (Fig. 5C) is highest in the asphalt scenario and lowest in the area with trees, whereas grass and park scenario have the same air temperature.

Table 4
Morphological description of the points of interest P in Stuttgart-West. Frequency of thermal comfort and heat stress is given for the points P1–P5 in Stuttgart-West (location of the points, see Fig. 1) from May to September. The used assessment scale classifying heat stress and thermal comfort is based on Matzarakis and Mayer (1997).

POI	POI1 Green area	POI2 E-W street canyon	POI3 NNW-SSE street canyon	POI4 Courtyard	POI5 Leafy courtyard
SVF	0.403	0.231	0.238	0.317	0.263
SVF southern part	0.198	0.149	0.095	0.157	0.152
Bowen ratio	0.6	1	1	1	0.9
Albedo of the environment	0.2	0.3	0.3	0.3	0.25
Thermal comfort (13.1 < PET < 29 °C)	30.4%	43.3%	55.6%	29.2%	28.6%
Heat stress (PET > 29.1 °C)	69.6%	65.3%	43.8%	70.5%	71.4%

Fig. 3. ENVI-met simulation of T_{mrt} for the area of interest in Stuttgart-West on a hot, calm summer day at 14:00 CET. The black frame depicts the Olga Hospital.

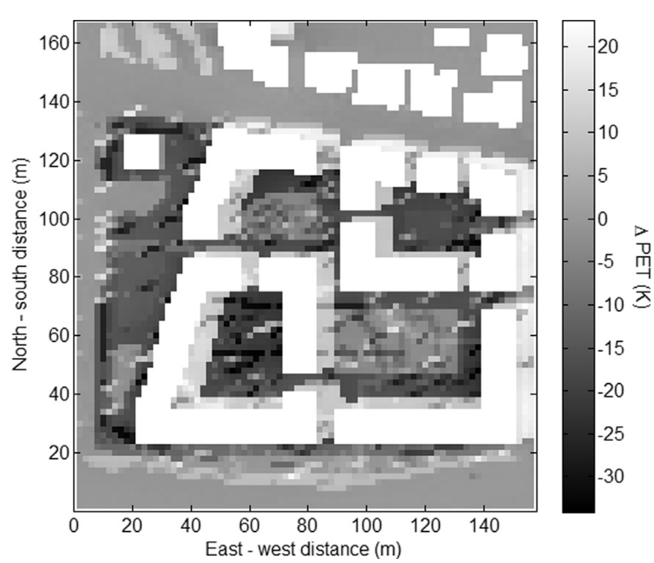

Fig. 4. Difference in PET between the housing area and a park area ($PET_{green\ area} - PET_{housing\ area}$) for the area of the Olga Hospital at 14:00 CET simulated by ENVI-met. PET was calculated using TIC ENVI-met.

The minimum air temperature occurs at 5:00 CET ($T_{a,\,min}$ = 24.4 °C) and its maximum between 16:00 and 17:00CET ($T_{a,\,max}$ = 35.2 °C). The difference in air temperature between the scenarios is only 1 K. Over asphalt, the wind speed (Fig. 5D) is highest with 1.3 m s^{-1} and lowest in the area with trees (v = 0.4 m s^{-1}). In the park and grass scenario, wind speed varies between 0.9 m s^{-1} and 0.6 m s^{-1}. The wind speed peaks in the evening; it decreases to a minimum in the morning and increases again afterwards. Differences in *VP* in the scenarios are around 1 hPa, with maximum *VP* of 18.4 hPa in the "tree area" scenario and a minimum of 16.5 hPa over asphalt at 11:00 (Fig. 5E).

The amplitude of PET (Fig. 5A) is largest in the asphalt scenario (ΔPET = 33 K) and lowest in the trees scenario (ΔPET = 15 K). The amplitude of PET over grass is 26 K. During the night, the asphalt scenario is the warmest, followed by the area with trees, grass and both parks. In daytime, the area with trees has the lowest PET of 35.5 °C, while over asphalt and in the parks PET is calculated to be around 42 °C. The strongest cooling rate is observed over the asphalt in the evening. The diurnal cycle of PET is closely related to the one of the mean radiant temperature. PET is similar over asphalt and in the park scenarios, which might be caused by the higher wind speed over asphalt due to the lower roughness and the higher *VP* in the parks.

Transects of air temperature, mean radiant temperature, PET, wind speed and vapour pressure from north to south and west to east at 14:00 CET are depicted in Figs. 6 and 7. Transects of

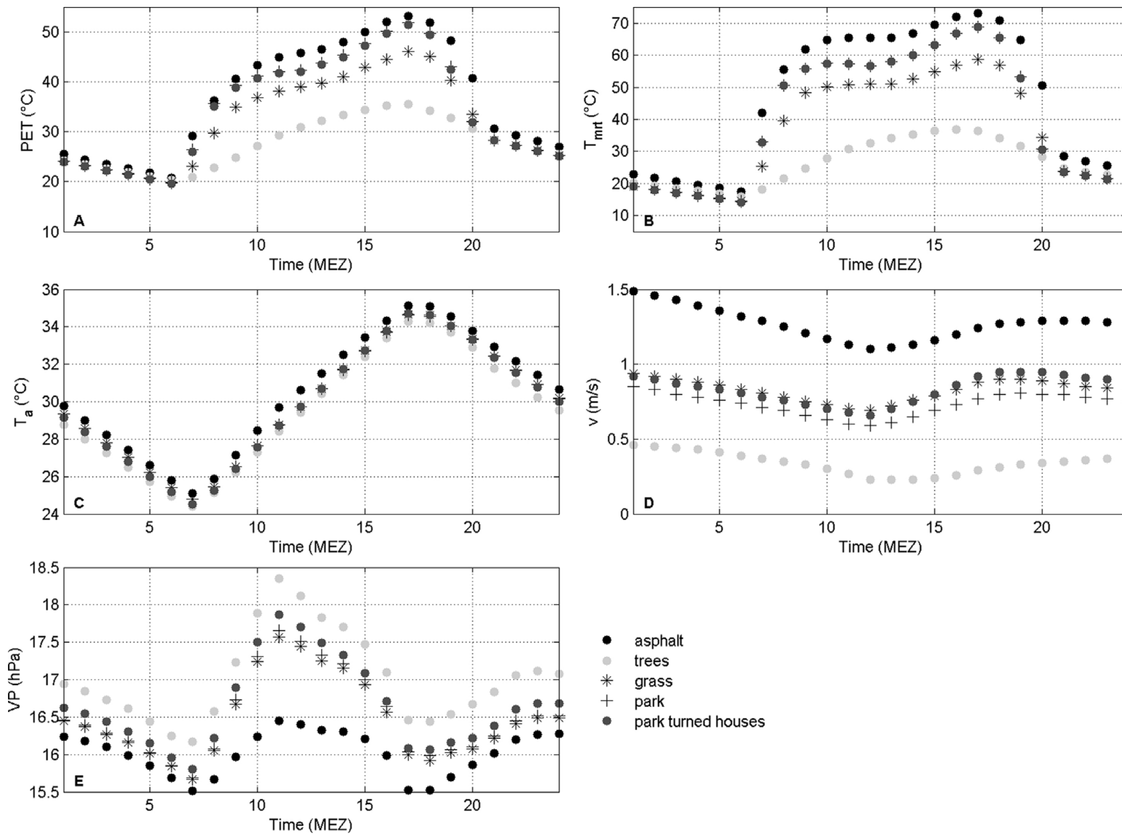

Fig. 5. Simulated diurnal cycle of PET, mean radiant temperature (T_{mrt}), wind speed v, air temperature (T_a) and vapour pressure (*VP*) for different scenarios (see legend) for Olga Hospital, Stuttgart-West.

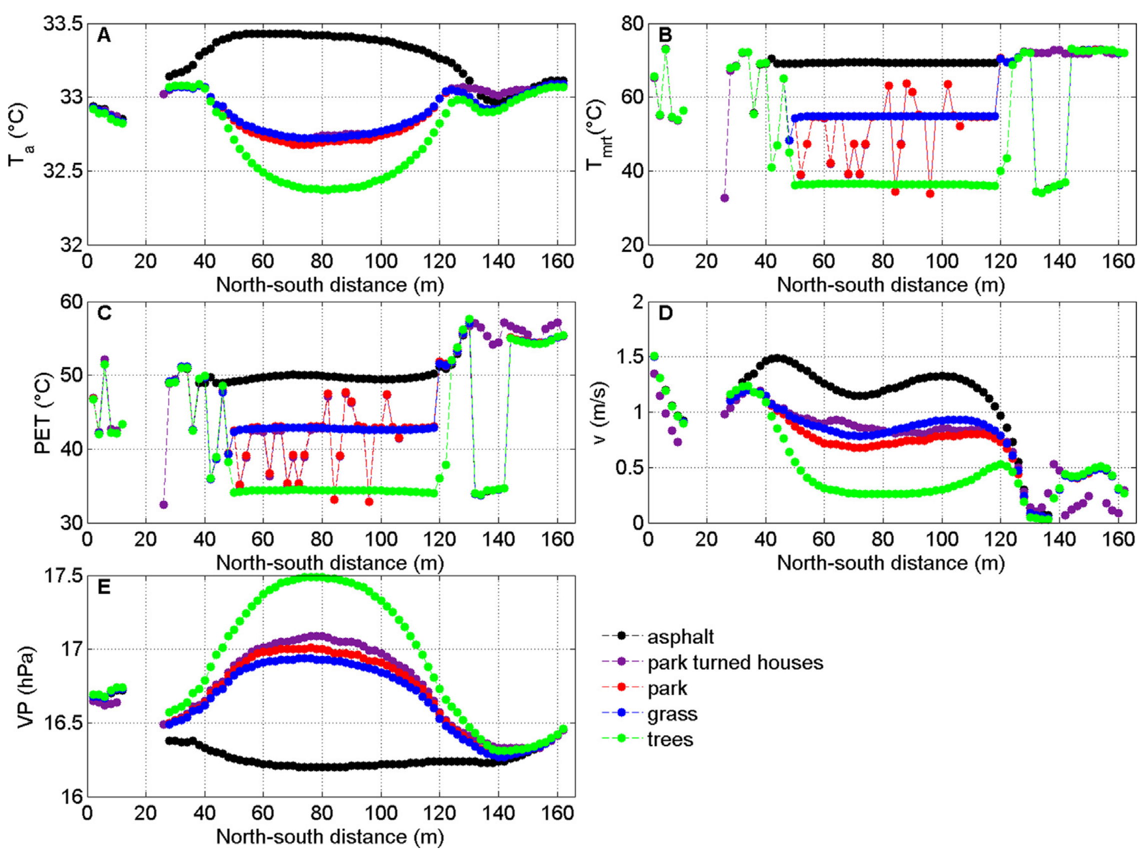

Fig. 6. North-south transect in the middle of the model area of different meteorological parameters for different scenarios (see legend) for Olga Hospital at 14:00 CET.

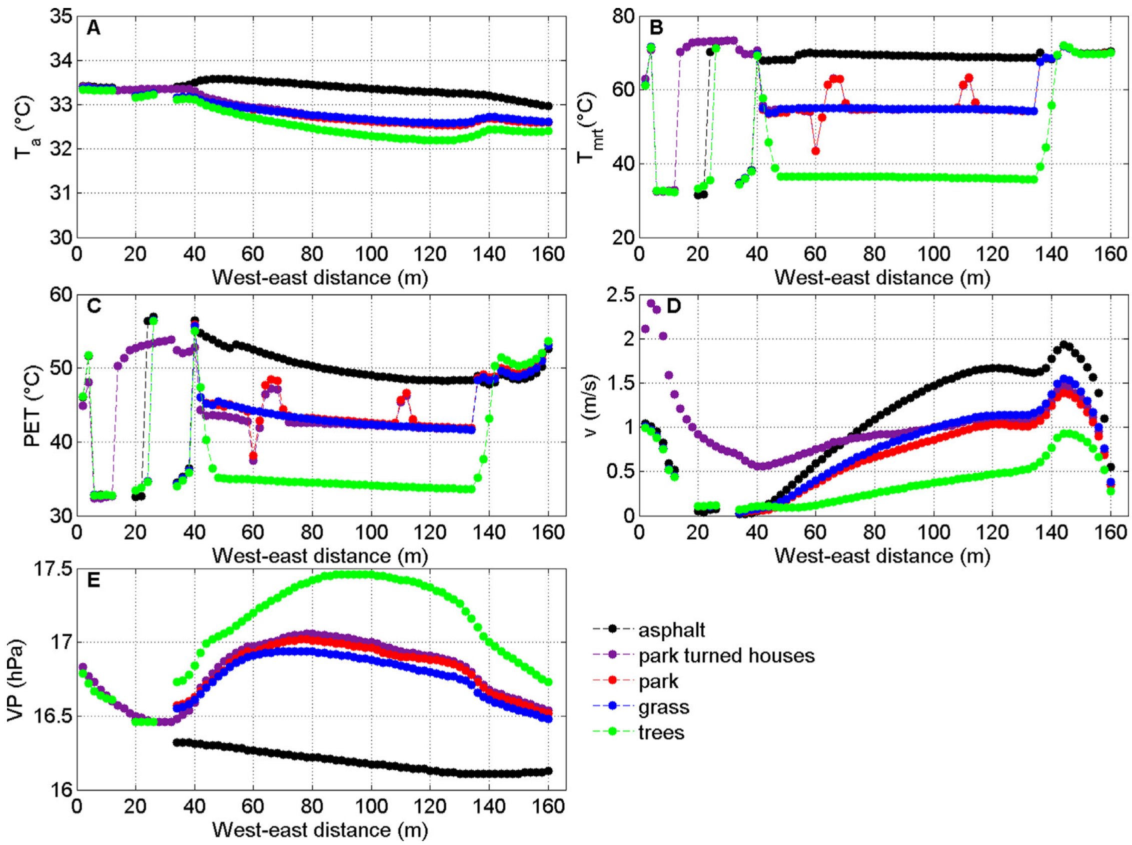

Fig. 7. West-east transect in the middle of the model area of different meteorological parameters for different scenarios (see legend) for Olga Hospital at 14:00 CET.

air temperature do not show large differences between the different scenarios (ΔT_a < 2 K), but a gradient of 1.7 K from west to east (Fig. 7A) was observed corresponding to the wind direction (Table 3). Air temperature is 0.7 K higher in the asphalt scenario than in the park and grass scenario and 1.8–2.1 K higher compared to the tree scenario (Figs. 6 and 7A). The difference in mean radiant temperature is larger by 15 K in the asphalt scenario, than in the park and grass scenarios and more than 30 K compared to the tree scenario (Figs. 6 and 7B). Wind speed is highest in the asphalt scenario due to the lowest roughness, which seems to affect wind speed at the eastern (lee) side (Fig. 7D) and in the south. Wind speed shows a negative gradient from north to south (Fig. 6D). The vapour pressure was highest in the tree scenario, as well as in the neighbouring eastern, northern and southern areas (Figs. 6 and 7E).

PET was highest (PET_{max} = 42.1 °C) in the asphalt scenario, but showed a gradient from west to east due to the increase in wind speed. Compared to the asphalt scenario, PET was on average 3 K lower in the park scenarios, 4 K lower in the grass scenario and 12 K in the tree scenario. The mean difference in PET in the whole simulated area (Fig. 3, dashed black box) is only around 2 K between the asphalt and tree scenario.

3.3. Influence of aspect ratio and orientation of the street canyon on its thermal conditions

Orientation and H/W ratio of a street canyon influences solar access and radiation, thermal conditions as well as dispersion of air pollutants (Oke, 1988). Solar access in a street canyon increases with a smaller H/W ratio. Direct solar radiation can theoretically access the middle of a north-south oriented street with an H/W ratio of 0.5 (1.5, 2.5, 3.5) during 7 h (2.5 h, 1.5 h, 0.75 h) on 21st June (Fig. 8). During summer, the duration of solar access is twice as long in a north-south oriented street as in an east-west oriented street for an aspect ratio of 0.5–3.5. During winter, an east-west oriented street canyon with H/W > 0.5 is shaded. But a north-south, northeast-southwest and northwest-southeast oriented street canyon with an aspect ratio of 0.5 (1, 1.5, 2.0) features 3.7 h (1.9 h, 1.3 h, 0.9 h) solar access. In an east-west oriented street, solar access during autumn and spring seasons is experienced in the mornings and afternoons due to the low zenith angle of the sun. In a northeast-southwest and northwest-southeast oriented street, the sunshine duration is shorter than in the north-south oriented and longer than in an east-west oriented street canyon.

The influence of H/W ratio and orientation of the street canyon on the mean radiant temperature (Fig. 9A, C and D) and the thermal conditions (PET) (Fig. 9B) is presented schematically for human beings in the street canyon on a summer day with high irradiation and low horizontal wind speed (21st June 2003). The street canyon was rotated clockwise from north to south. The maximum mean radiant temperature is 61.6 °C in the middle of a street canyon with an aspect ratio of 1 (Fig. 9A). This maximum mean radiant temperature decreases by 1.5 K in a street canyon with H/W ratio of 3.5 and 60° rotation and by 13.2 K in a 120° oriented street canyon (H/W = 3.5). The mean radiant temperature is maximum at 33.5 °C in an east-west oriented street canyon with H/W ratio of 0.5 and 23.3 °C in the 120° oriented street with an aspect ratio of 3.5. The maximum value of PET could be decreased by 6.3 K in a canyon with H/W of 2.5 by its rotation from northeast-southwest to southeast-northwest (Fig. 9B). Maximum PET can be reduced by 10 K by changing the H/W ratio from 0.5 to 3.5 and an orientation of 120°. The lowest value of PET is 12 °C in a street canyon with H/W of 0.5 and increases to 13.6 °C with increasing H/W ratio (Fig. 9). Differences of the maximum mean radiant temperature between the pavements (Fig. 9C and D) and middle of the street (Fig. 9A) are

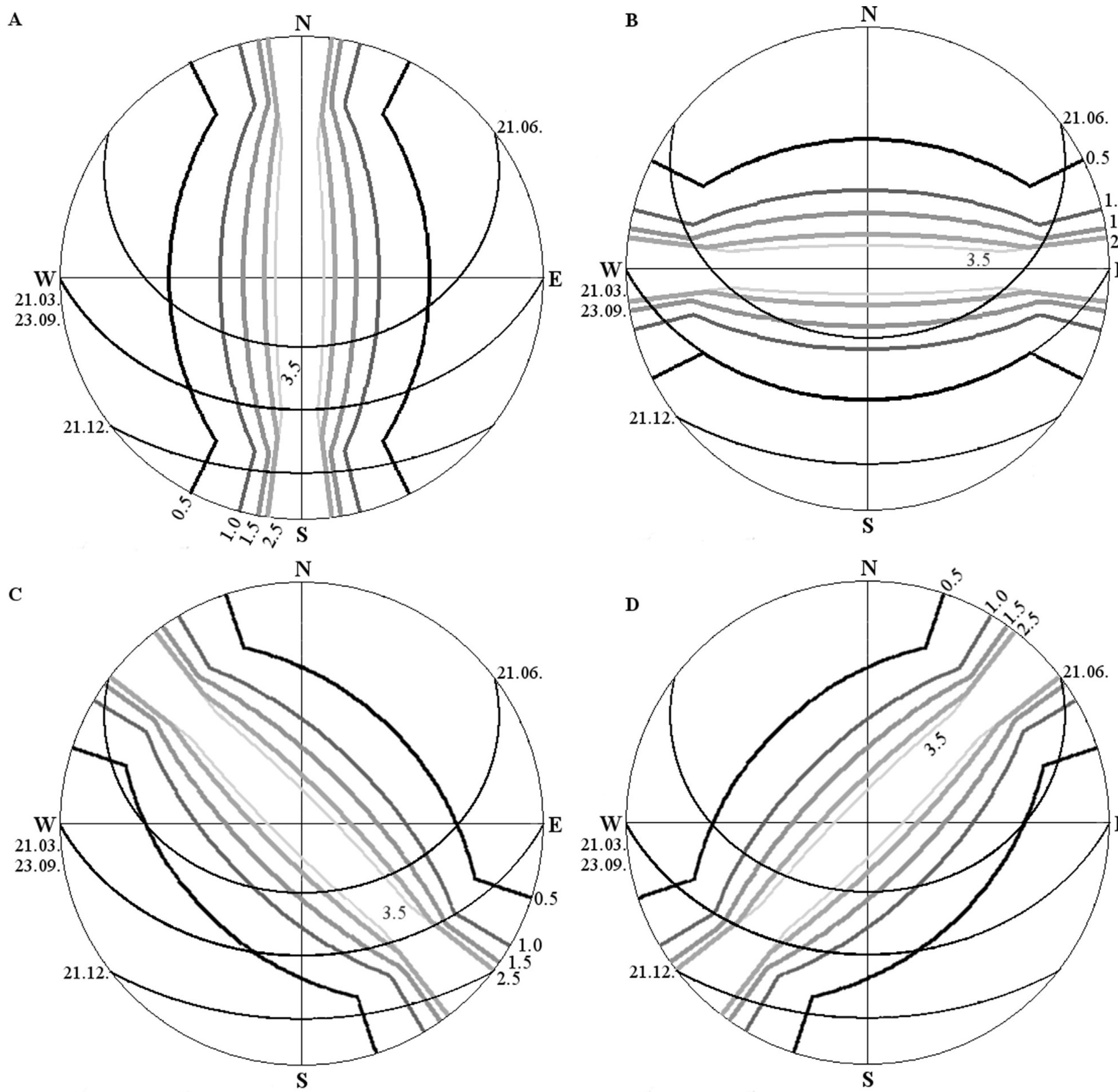

Fig. 8. Sunshine paths in a north-south (panel A), east-west (panel B), northwest-southeast (panel C) and northeast-southwest (panel D) oriented street on winter and summer solstice and on equinoxes.

small, but the particular time and duration of heat stress changes. The maximum amount of hours with heat stress (PET > 35 °C) occurs in a 75–135° oriented street canyon with H/W ratio ≤ 0.5.

On the negative (westward pavement in a north-south oriented street) and positive (eastward pavement in a north-south oriented street) pavement, the diurnal maximum of PET is 7.8 K and 12 K lower (Fig. 9C and D). The maximum value of the mean radiant temperature is 5.9 K lower on the negative pavement featuring an aspect ratio of 0.5. But in a street with an aspect ratio of 3.5 the maximum value of the mean radiant temperature is only 1.4 K lower than in the middle of the street. The negative pavement is on average 2.9 K cooler than the positive pavement in a street with an orientation between 15° and 90°.

Street canyons with an orientation of 75–90° feature the highest frequency of heat stress throughout the year (Table 5). Heat stress can be reduced by 61 h per year (0.7%) if a street with an H/W ratio between 0.5 and 1.5 is turned from northwest-southeast to north-south.

The effect of the street's orientation on PET is larger in a street with a low aspect ratio, than in a street canyon with high H/W ratio.

The frequency of heat stress can be reduced by 4.3% (377 h per year) due to narrowing of street canyons from an aspect ratio of 0.5 to 3.5. A change in H/W ratio from 0.5 to 1.0 (2.5) allows a reduction of heat stress by 192 (333) h per year. The frequency of thermal comfort conditions peaks in a street canyon with H/W ratio of 3.5 with a frequency of 58.3% throughout the year. This is 10% more than in a canyon with an aspect ratio of 0.5. Streets which are rotated 70–90° are the least comfortable in contrast to N-S oriented streets. Summing up, a street canyon with an H/W ratio of 1.5 or smaller features more heat and cold stress (PET < 13 °C; Matzarakis & Mayer, 1997) compared to a street canyon with an H/W ratio larger than 1.5.

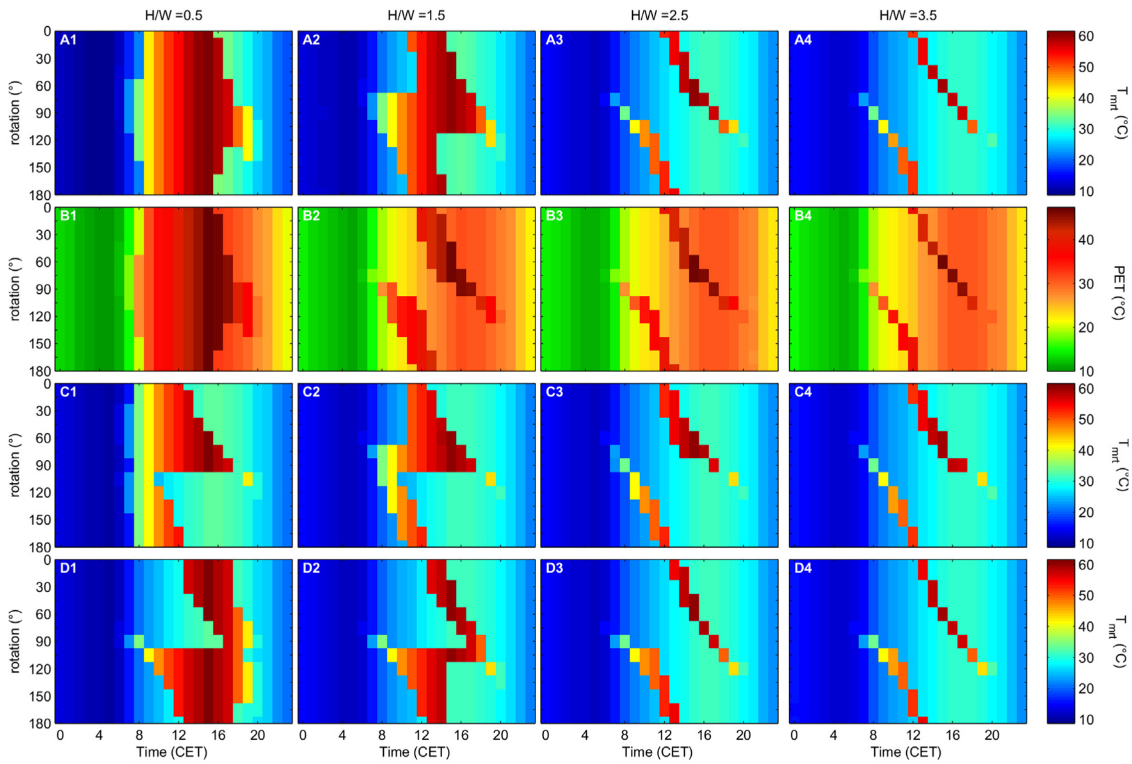

Fig. 9. Mean radiant temperature (T_{mrt}) (Panel A, C and D) in the middle (Panel A), negative (westward pavement in a north-south oriented street) and positive (eastward pavement in a north-south oriented street) pavement side (Panel C and D) and PET (Panel B) in a street canyon with changing aspect (H/W) ratio and orientation. Measuring data of the 21st June 2003 as input for the RayMan analysis.

Table 5
Frequency of cold (PET < 13 °C), heat (PET > 29 °C) and thermal comfort conditions (13.1 °C < PET < 29 °C) in the middle of an urban canyon with a specified aspect ratio and orientation. The used assessment scale classifying thermal comfort is based on Matzarakis and Mayer (1997). The results are based on RayMan calculations with hourly resolution in the period 2000–2010. The maximum values are grey shaded.

Aspect ratio	Thermal comfort/street orientation	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°
0.5	Heat stress (%)	26.5	26.6	26.8	27.0	27.1	27.2	27.2	27.1	26.9	26.7	26.5	26.4
	Comfortable (%)	50.2	50.1	49.8	49.6	49.0	48.5	48.5	49.0	49.3	49.9	50.1	50.2
	Cold stress (%)	23.4	23.4	23.4	23.4	23.9	24.3	24.3	24.0	23.7	23.4	23.4	23.3
1	Heat stress (%)	24.3	24.4	24.5	24.7	24.8	24.9	25.0	24.8	24.6	24.4	24.3	24.2
	Comfortable (%)	54.1	54.1	54.2	54.3	54.3	54.1	53.6	53.6	54.0	54.2	54.2	54.4
	Cold stress (%)	21.6	21.5	21.3	20.9	20.9	20.9	21.4	21.6	21.4	21.4	21.5	21.4
1.5	Heat stress (%)	23.4	23.4	23.6	23.7	23.9	23.9	23.9	23.8	23.8	23.6	23.6	23.4
	Comfortable (%)	56.1	55.9	56.2	56.1	56.0	56.3	56.2	55.7	55.6	55.8	56.1	55.8
	Cold stress (%)	20.5	20.6	20.2	20.2	20.1	19.8	19.9	20.5	20.6	20.5	20.3	20.8
2	Heat stress (%)	22.9	23.0	23.1	23.2	23.3	23.4	23.3	23.2	23.2	23.2	23.1	23.0
	Comfortable (%)	56.8	57.0	56.9	56.9	57.0	57.1	57.1	56.8	56.6	56.5	56.7	56.8
	Cold stress(%)	20.3	19.9	20.0	19.9	19.7	19.6	19.6	20.0	20.1	20.3	20.3	20.3
2.5	Heat stress (%)	22.7	22.7	22.8	22.9	23.0	23.1	23.1	22.9	23.0	22.9	22.8	22.7
	Comfortable (%)	57.2	57.7	57.4	57.5	57.5	57.4	57.7	57.3	57.2	57.3	57.4	57.7
	Cold stress (%)	20.1	19.5	19.8	19.6	19.5	19.5	19.3	19.8	19.8	19.8	19.8	19.6
3	Heat stress (%)	22.5	22.4	22.5	22.6	22.7	22.8	22.8	22.6	22.7	22.6	22.5	22.4
	Comfortable (%)	57.9	58.1	57.8	58.0	58.0	57.8	58.0	57.9	58.0	57.7	57.7	58.1
	Cold stress (%)	19.6	19.4	19.7	19.4	19.3	19.4	19.2	19.5	19.4	19.7	19.7	19.5
3.5	Heat stress (%)	22.3	22.3	22.4	22.5	22.6	22.6	22.7	22.5	22.5	22.4	22.4	22.2
	Comfortable (%)	58.3	58.3	58.1	58.2	58.2	58.0	58.1	58.1	58.2	58.1	58.0	58.3
	Cold stress (%)	19.4	19.4	19.5	19.4	19.2	19.3	19.2	19.4	19.3	19.5	19.6	19.4

4. Discussion

Focusing on climate change in mid-latitudes, heat stress is expected to increase. Therefore, systematic analysis based on the micro-climatic characteristics and features can be valuable for urban planning. This can be only reached by the combination of hot spot (short-term) and long-term analyses in order to embed this in the background conditions and existing urban configurations.

Hot-spots with extensive thermal load can be identified using ENVI-met. These hot-spots can be taken as an opportunity to choose appropriate measures to improve the local climate conditions. Besides, vegetation, street orientation and aspect ratio can be used as adaptation measures during re-planning of suburbs. Shading through vegetation or buildings is a good opportunity to reduce thermal stress by a decrease of the mean radiant temperature. Sky view factor, especially its southern part (SVF_{90-270}), is an important indicator for shading (Holst & Mayer, 2011). The maximal value of PET is 35 °C over a green unshaded area, while it can exceed 58 °C over a sealed, asphaltic surface. A green surface reduces PET by up to 7 K in the neighbouring streets and areas, especially on the lee side. Although the influence might not be too large on the neighbouring areas, green surfaces can help to establish an “ideal urban climate” (Mayer, 1989) with a high diversity of different microclimates within a small distance. In this way, an ideal urban climate is created in which city dwellers can find the optimum thermal conditions for outdoor recreation close to their homes. While air temperature varies by 2 K comparing the different scenarios, the range of PET values is larger. This indicates the importance of the use of thermal indices to quantify the human thermal conditions (Matzarakis & Endler, 2010).

The influence of street morphology on thermal conditions in a street canyon was shown experimentally (Bourbia & Awbi, 2004; Holst & Mayer, 2011; Santamouris et al., 1999; Yoshida et al., 1990) and using micro-scale models in different climate zones (Ali-Toudert & Mayer, 2006; Herrmann & Matzarakis, 2012; Johansson & Emmanuel, 2006; Kuttler, 2011; Swaid & Hoffman, 1990). While air temperature does not show significant stratification (Bourbia & Awbi, 2004; Santamouris et al., 1999), large differences in the mean radiant temperature and PET are obvious (Ali-Toudert & Mayer, 2006; Herrmann & Matzarakis, 2012; Johansson & Emmanuel, 2006; Kuttler, 2011). Heat stress can be mitigated in streets with high aspect ratio (Emmanuel & Fernando, 2007; Herrmann & Matzarakis, 2012). Streets, which are north-south oriented feature lower mean radiant temperature and PET than east-west oriented streets (Emmanuel & Fernando, 2007; Kuttler, 2011). Ali-Toudert and Mayer (2006) found that northeast-southwest and northwest-southeast oriented streets are compromises for solar access in winter and shading in summer. Herrmann and Matzarakis (2012) found the maximum value of the mean radiant temperature in north-south oriented streets and lower values in east-west oriented streets. These findings correspond to the measurements of Bourbia and Awbi (2004), who observed higher mean surface temperature in north-south streets but a higher maximum of surface temperature in east-west oriented streets.

Streets, featuring a lower aspect ratio, have high frequency of heat stress in daytime, but low PET in night-time. A stronger nocturnal cooling rate supports the recovery of local residents during heat wave periods. However, nocturnal cooling is reduced by the length of the day in summer. A stronger relief can be experienced by a reduction in heat stress in the daytime. But, street canyon geometry should not only reduce heat stress during summer, it should also allow solar access throughout the year. An east-west oriented street canyon is unsuitable because of the long sunshine duration independent from the H/W ratio, resulting in a high heat stress frequency, but from autumn to spring the street canyon is predominantly shaded. A street canyon which is northwest-southeast to north-south oriented with an aspect ratio of at least 1.5 seems to be the best choice. These street configurations are able to reduce heat stress, to increase the frequency of thermal comfortable conditions and to enable solar access throughout the year in the mid-latitudes. In Stuttgart-West, a katabatic wind from west called the “Nessenbachtäler” is important for nocturnal cooling and ventilation. Therefore, the adjustment of street canyons has to be a compromise facilitating this air flow and to maximizing thermal comfort.

Thermal human-biometeorological conditions in complex urban structures can be calculated using the micro-scale models ENVI-met 3.5 and RayMan Pro. The ENVI-met model is able to simulate the meteorological conditions for an area of 250 × 250 grids with a resolution between 0.2 and 10 m for short time periods. Measuring data are only used for the initialization of the atmospheric background conditions (Bruse & Fleer, 1998). Disadvantages of ENVI-met 3.5 are firstly the overestimation of the mean radiant temperature, which yields in an overvaluation of PET (Ali-Toudert & Mayer, 2006). One reason might be the calculated diurnal cycle of global radiation: The daily maximum of global radiation was adjusted to measured values using the radiation adjustment factor. However, global radiation is still overestimated in the morning and afternoon by around 200 W m^{-2}. Ali-Toudert and Mayer (2007) measured meteorological conditions of street canyons (H/W ratio = 1, SVF = 0.26) in a city, which is about 130 km from Stuttgart, in summer 2003. They found a maximum mean radiant temperature of 66 °C and a maximum PET of 48 °C. This indicates that PET and mean radiant temperature are overestimated by around 10 K, especially at noon and in the afternoon. Secondly, ENVI-met 3.5 does not consider topographical induced or thermal wind (e.g. cold air flows), which are important in terms of thermal situation (Lahme & Bruse, 2003). But cold air flow is very important for nocturnal cooling in Stuttgart-West. Uncertainties in the simulation of radiation fluxes and wind speed between trees and building occur due to the resolution of 2 m × 2 m per grid (Fröhlich & Matzarakis, 2013). RayMan simulates thermal conditions for single points over several years using measured data or data from climate simulations. Surface parameters, as Bowen- ratio and albedo are roughly estimated for RayMan simulations, leading to small uncertainties in PET and T_{mrt}. These uncertainties depend on the SVF and composition of the surfaces.

5. Conclusions

Urban quarter reconstruction is one of the urban planning issues that needs to consider the impact of climate change. Thermal conditions have to be analyzed for current situations and different planned scenarios throughout the year with specific emphasis on heat waves. In addition, the influence of different adaptation measures has to be quantified in both, their neighbourhood and the background situation.

The analysis of the micro-climate at different points showed that green areas can feature a higher frequency of heat stress than street canyons. A NNW-SSE oriented street canyon features the lowest frequency of heat stress at the chosen points. Thereby, the southern part of the sky view factor on the northern hemisphere is decisive for these results.

The strongest cooling is obtained by tree shading in daytime, but this has no influence on neighbouring thermal conditions. Changing one quarter of the area into a park would reduce PET by 2.6 K on average. A further effect is the increase in wind speed due to a low roughness, decreasing the thermal load. It was also found that the effect of green space in the neighbouring areas is larger in the lee. Nocturnal thermal conditions are nearly the same in all scenarios. In daytime, PET decreases by 15 K and 7 K by changing an impervious environment to an area of forest or grass.

Thermal conditions in street canyons with different aspect ratio and orientation have to be analyzed systematically for hot days as well as throughout the year. A street canyon which is northwest-southeast to north-south oriented having an H/W-ratio of at least 1.5 seems to be the best option to reduce heat stress. Additionally, it is suitable to increase the frequency of thermal comfort as well as to enable solar access in the street canyon over the whole year in the mid-latitudes.

The presented scenarios are evaluated as local adaptation measures without effects on thermal conditions of a whole urban quarter. We think that the combination of micro-scale models in terms of urban climate quantification in the era of climate change builds a reliable application possibility.

Acknowledgements

This work is financially supported by the transnational cooperation project within the Central Europe Programme “Development and application of mitigation and adaptation strategies and measures for counteracting the global urban heat island phenomenon”. This project is implemented through the CENTRAL Europe Programme co-financed by the ERDF.

We thank the Office for Environmental Protection, Department of Urban Climatology of Stuttgart City for providing spatial data as well as climate data of Stuttgart Schwabenzentrum. We thank also Emmanuel Ndetto for proof-reading the manuscript.

References

Ali-Toudert, F., & Mayer, H. (2006). Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate. *Building and Environment*, *41*(2), 94–108. http://dx.doi.org/10.1016/j.buildenv.2005.01.013

Ali-Toudert, F., & Mayer, H. (2007). Thermal comfort in an east–west oriented street canyon in Freiburg (Germany) under hot summer conditions. *Theoretical and Applied Climatology*, *87*(1–4), 223–237. http://dx.doi.org/10.1007/s00704-005-0194-204

Bläsing, J., Sievers, U., & Graetz, A. (2001). (*Official meteorological report on the climatic situation in the planning area of the project Stuttgart 21*) Amtliches meteorologisches Gutachten zur klimatischen Situation im Planungsbereich des Projektes Stuttgart 21. In *Untersuchungen zur Umwelt 17*. Stuttgart: State capital Stuttgart, Environmental Protection Office, Section of Urban Climatology., 96 pp.

Bonan, G. B. (2008). *Ecological climatology: Concepts and applications* (2nd ed.). Cambridge, New York: Cambridge University Press., 550 pp.

Bourbia, F., & Awbi, H. (2004). Building cluster and shading in urban canyon for hot dry climate. *Renewable Energy*, *29*(2), 291–301. http://dx.doi.org/10.1016/S0960-1481(03)00171-X

Bruse, M., & Fleer, H. (1998). Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model: The challenge of awareness in developing societies. *Environmental Modelling & Software*, *13*(3–4), 373–384. http://dx.doi.org/10.1016/S1364-8152(98)00042-45

Chapman, L., Thornes, J. E., & Bradley, A. V. (2001). Rapid determination of canyon geometry parameters for use in surface radiation budgets. *Theoretical and Applied Climatology*, *69*, 81–89. http://dx.doi.org/10.1007/s007040170036

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, *48*(1–2), 31–44. http://dx.doi.org/10.1016/S0169-2046(00)00034-37

Emmanuel, R., & Fernando, H. J. (2007). Urban heat islands in humid and arid climates: Role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA. *Climate Research*, *34*, 241–251. http://dx.doi.org/10.3354/cr00694

Fanger, P. O. (1972). *Thermal comfort: Analysis and applications in environmental engineering*. New York: McGraw-Hill., 244 pp.

Fröhlich, D., & Matzarakis, A. (2013). Modeling of changes in thermal bioclimate: Examples based on urban spaces in Freiburg, Germany. *Theoretical and Applied Climatology*, *111*, 547–558. http://dx.doi.org/10.1007/s00704-012-0678-680

Herrmann, J., & Matzarakis, A. (2012). Mean radiant temperature in idealised urban canyons – Examples from Freiburg, Germany. *International Journal of Biometeorology*, *56*(1), 199–203. http://dx.doi.org/10.1007/s00484-010-0394-401

Holst, J., & Mayer, H. (2011). Impacts of street design parameters on human-biometeorological variables. *Meteorologische Zeitschrift*, *20*(5), 541–552. http://dx.doi.org/10.1127/0941-2948/2011/0254

Höppe, P. (1999). The physiological equivalent temperature – A universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, *43*(2), 71–75. http://dx.doi.org/10.1007/s004840050118

Huttner, S. (2012). *Further development and application of the 3D microclimate simulation ENVI-met* PhD Thesis. Johannes Gutenberg-University Mainz. 135 pp

Jendritzky, G., Dear, R., & Havenith, G. (2012). UTCI – Why another thermal index? *International Journal of Biometeorology*, *56*(3), 421–428. http://dx.doi.org/10.1007/s00484-011-0513-517

Johansson, E., & Emmanuel, R. (2006). The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. *International Journal of Biometeorology*, *51*(2), 119–133. http://dx.doi.org/10.1007/s00484-006-0047-56

Kuttler, W. (2011). Climate change in urban areas. Part 2. Measures. *Environmental Science Europe*, *23*(21) http://dx.doi.org/10.1186/2190-4715-23-21, 15 pp.

Lahme, E., & Bruse, M. (2003). Microclimatic effects of a small urban park in densely built-up areas: Measurements and model simulations. In *ICUC5* 1–5 September 2003, Lodz, (p. 4).

Lindberg, F., Holmer, B., & Thorsson, S. (2008). SOLWEIG 1.0 – Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology*, *52*(7), 697–713. http://dx.doi.org/10.1007/s00484-008-0162-167

Matzarakis, A., & Endler, C. (2010). Climate change and thermal bioclimate in cities: Impacts and options for adaptation in Freiburg, Germany. *International Journal of Biometeorology*, *54*(4), 479–483. http://dx.doi.org/10.1007/s00484-009-0296-2

Matzarakis, A., & Mayer, H. (1997). Heat stress in Greece. *International Journal of Biometeorology*, *41*(1), 34–39. http://dx.doi.org/10.1007/s004840050051

Matzarakis, A., Mayer, H., & Iziomon, M. G. (1999). Applications of a universal thermal index: Physiological equivalent temperature. *International Journal of Biometeorology*, *43*, 76–84. PMID: 10552311

Matzarakis, A., & Nastos, P. T. (2011). Human-biometeorological assessment of heat waves in Athens. *Theoretical and Applied Climatology*, *105*(1–2), 99–106. http://dx.doi.org/10.1007/s00704-010-0379-3

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments – Application of the RayMan model. *International Journal of Biometeorology*, *51*(4), 323–334. http://dx.doi.org/10.1007/s00484-006-0061-8

Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments: Basics of the RayMan model. *International Journal of Biometeorology*, *54*(2), 131–139. http://dx.doi.org/10.1007/s00484-009-0261-0

Mayer, H. (1989). (*Workshop “Ideal urban climate” on 27 October 1988 in Munich*) Workshop “Ideales Stadtklima” am 26 Oktober 1988 in München. In *DMG Mitteilungen 3/89*.

Mayer, H., & Höppe, P. R. (1987). Thermal comfort of man in different urban environments. *Theoretical and Applied Climatology*, *38*(1), 43–49. http://dx.doi.org/10.1007/BF00866252

Meehl, G. A., & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, *305*(5686), 994–997. http://dx.doi.org/10.1126/science.1098704

Oke, T. R. (1981). Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations. *Journal of Climatology*, *1*(3), 237–254. http://dx.doi.org/10.1002/joc.3370010304

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, *108*(455), 1–24. http://dx.doi.org/10.1002/qj.49710845502

Oke, T. R. (1988). Street design and urban canopy layer climate. *Energy and Buildings*, *11*(1–3), 103–113. http://dx.doi.org/10.1016/0378-7788(88)90026-6

Oke, T. R. (2006). *Boundary layer climates* (2nd ed.). London: Routledge.

Santamouris, M., Papanikolaou, N., Koronakis, I., Livada, I., & Asimakopoulos, D. (1999). Thermal and air flow characteristics in a deep pedestrian canyon under hot weather conditions. *Atmospheric Environment*, *33*(27), 4503–4521. http://dx.doi.org/10.1016/S1352-2310(99)00187-189

Schär, C., Vidale, P. L., Lüthi, D., Frei, C., Häberli, C., Liniger, M. A., et al. (2004). The role of increasing temperature variability in European summer heat waves. *Nature*, *427*(6972), 332–336. http://dx.doi.org/10.1038/nature02300

(SCS) State capital Stuttgart, Environmental Protection Office, Section of Urban Climatology. (2010). *Climate change: Challenge facing urban climatology. Schriftenreihe des Amtes für Umweltschutz 3/2010*. Stuttgart: State capital Stuttgart, Environmental Protection Office, Section of Urban Climatology., 84 pp.

Shashua-Bar, L., & Hoffman, M. E. (2004). Quantitative evaluation of passive cooling of the UCL microclimate in hot regions in summer, case study: Urban streets and courtyards with trees. *Building and Environment*, *39*(9), 1087–1099. http://dx.doi.org/10.1016/j.buildenv.2003.11.007

Swaid, H., & Hoffman, M. E. (1990). Climatic impacts of urban design features for high- and mid-latitude cities. *Energy and Buildings*, *14*(4), 325–336. http://dx.doi.org/10.1016/0378-7788(90)90095-Z

Thorsson, S., Lindberg, F., Björklund, J., Holmer, B., & Rayner, D. (2011). Potential changes in outdoor thermal comfort conditions in Gothenburg, Sweden due to climate change: The influence of urban geometry. *International Journal of Climatology*, *31*, 324–335. http://dx.doi.org/10.1002/joc.2231

Unger, J. (2004). Intra-urban relationship between surface geometry and urban heat island: Review and new approach. *Climate Research*, *27*, 253–264. http://dx.doi.org/10.3354/cr027253

Yoshida, A., Tominaga, K., & Watatani, S. (1990). Field measurements on energy balance of an urban canyon in the summer season. *Energy and Buildings*, *15*(3–4), 417–423. http://dx.doi.org/10.1016/0378-7788(90)90016-C