Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 81 (2007) 742–754

SOLAR ENERGY

www.elsevier.com/locate/solener

Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons

Fazia Ali-Toudert *, Helmut Mayer

Meteorological Institute, University of Freiburg, Werderring 10, 79110 Freiburg, Germany

Received 29 December 2005; received in revised form 9 October 2006; accepted 10 October 2006
Available online 15 November 2006

Communicated by: Associate Editor Mattaios Santamouris

Abstract

The present paper deals with the dependence of outdoor thermal comfort on the design of an urban street. The effects of the street vertical profile, including asymmetrical canyon shapes, the use of galleries and further shading devices on the façades, arranged in various orientations are assessed. The study is conducted by means of numerical modelling by using the three-dimensional microclimate model ENVI-met 3.0 which prognosticates the microclimatic changes within urban environments. Thermal comfort is evaluated for the daytime hours across the canyon in high spatial resolution and by means of the physiologically equivalent temperature PET.

The results revealed that all design aspects investigated have a moderate impact on the air temperature and a strong effect on the heat gained by a human body and hence on the resulting thermal sensation. The larger the openness to the sky of the canyon, the higher the heat stress. For canyons with a smaller sky view, the orientation is also decisive: E–W canyons are the most stressful and deviating from this orientation ameliorates the thermal conditions. Basically, galleries and further shading through overhanging façades or vegetation enable a sensitive decrease of the period of time and of the area of thermal discomfort. Yet, this efficiency varies with the orientation and the vertical proportions of the canyon. Therefore, if appropriately combined, all investigated design elements can effectively mitigate heat stress in the summer and promote thermal comfort.

Keywords: Urban canyon; Asymmetry; Gallery; Overhangs; Shading device; Hot–dry climate; Human thermal comfort; Street design; Numerical modelling; ENVI-met; Physiologically equivalent temperature PET

1. Introduction

In urban climate research, which includes thermal, energetic, wind flow and pollution issues, an urban street is typically described as a simple rectangular shape. This is commonly known as the "urban canyon: UC" (e.g. Oke, 1988; Arnfield, 1990a; Givoni, 1997; Asimakopoulos et al., 2001; Arnfield, 2003). The UC is then described by a height-to-width ratio H/W and arranged according to a certain orientation in relation to the sun. In real cases, however, urban street geometry can be more complex (e.g. Moughtin, 2003), as to be asymmetrical, or include design arrangements at street level or on the façades. Indeed, many expressive examples of "textured" streets were designed to cope with stressful climate conditions (e.g. Ravéreau, 1981; Golany, 1982; Herzog, 1996; Krishan, 1996; Moughtin, 2003).

Using galleries as a shading device, for instance, is already known from the antic Greek portico (e.g. Lechner, 1991) and their use is common in hot climate in traditional as well as in contemporary architectures (e.g. Roche, 1970; Golany, 1982; Krishan, 1996; Littlefair et al., 2001). Vegetation was also reported to be climatically effective when implemented in urban streets (e.g. McPherson, 1992; McPherson et al., 1994).

* Corresponding author. Tel.: +49 761 203 3590; fax: +49 761 203 3586.
E-mail address: fazia.alitoudert@cstb.fr (F. Ali-Toudert).

0038-092X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2006.10.007

Moreover, urban streets may have asymmetrical vertical profiles to make the urban buildings climate responsive, i.e. with sufficient winter solar gains in spite of high plot densities. This issue of solar access right has been increasingly addressed (e.g. Knowles, 1981; Pereira and Minache, 1989; Arnfield, 1990a; Givoni, 1997; Asimakopoulos et al., 2001; Capeluto and Shaviv, 2001; Kristl and Krainer, 2001; Littlefair et al., 2001; Pereira et al., 2001; Thomas, 2003; Bourbia and Awbi, 2004). Explicitly, south buildings are set of lower height to allow the opposite north walls facing the sun a large period of exposure to solar irradiation in winter. By contrast, either to shade the façade itself or to protect the street at pedestrian level, the façades are sometimes offset over the street area as can be observed in traditional architectures – e.g. the so-called mucharabiehs in the middle-east region (e.g. Krishan, 1996). These design concepts have inspired the contemporary architecture which increasingly makes use of detail arrangements as climatic control strategies in open spaces (e.g. Capeluto, 2003; Herzog, 1996; Littlefair et al., 2001; Thomas, 2003).

However, the effectiveness of all these strategies has been rarely investigated in relation to climate comfort quantitatively, especially outdoors (e.g. Swaid et al., 1993; Littlefair et al., 2001) and this motivated the recent study of Ali-Toudert (2005), which dealt extensively with these interdependences. First results of this investigation were reported in Ali-Toudert and Mayer (2006) which handled simple symmetrical urban canyons with H/W varying from 0.5 to 4 and arranged in different orientations and simulated for a hot–dry climate. In short, the main findings regarding these symmetrical canyons are as follows:

- Comfort is very difficult to reach passively in the summertime in the subtropics but an improvement is possible through appropriate design.
- Air temperature decreases moderately with increased H/W and wind speed is strongly reduced for perpendicular incidence to street axis, even for large canyons.
- Thermal comfort, expressed in terms of duration, time of day and spatial distribution, is strongly affected by both aspect ratio H/W and solar orientation. This was mainly due to the decisive role of the solar radiation fluxes which are strongly affected by the street geometry. Streets with high aspect ratios and with a N–S orientation ensure the best thermal situation, while wide streets oriented E–W are the most uncomfortable. Increasing the building heights leads to an amelioration of the thermal situation in particular for directions deviating from E–W.
- Shading is the most decisive strategy in mitigating heat stress, and this was confirmed experimentally in other comfort studies (Ali-Toudert et al., 2005; Ali-Toudert and Mayer, 2007).

Additional arrangements are therefore highly advisable, in particular in pedestrian streets where comfort is required all the day and in the whole area of the street. The present paper presents a second set of results and is concerned with complex geometries, including asymmetrical vertical profiles, galleries, overhanging façades and vegetation. These architectural details are investigated as possible ways to improve further the thermal comfort outdoors under extreme hot summer conditions. The goal is to quantify the contribution of each of these solutions in mitigating the heat stress. The reader is advised to report to the first part of the study, i.e. Ali-Toudert and Mayer (2006) for details on the reference cases, as well as for some theoretical background and methodological aspects. The limits of the model are described in Ali-Toudert (2005) and are mentioned in the present discussion of results when necessary.

2. Methods

One method for assessing thermal comfort outdoors is to conduct field work based on the measurement of all relevant meteorological variables and calculation of energy-based thermal indices (e.g. Mayer, 1993; Ali-Toudert et al., 2005; Ali-Toudert and Mayer, 2007). Their comparison to data gathered on the basis of social surveys would provide more information on the adaptive behaviour of people (e.g. Nagara et al., 1996; Nikolopoulou et al., 2001; Spagnolo and de Dear, 2003; Stathopoulos et al., 2004). Numerical modelling is another method which is getting increasingly popular (Arnfield, 2003). The latter method was used in this investigation for two main reasons: (1) numerical modelling is particularly suitable in highlighting the connection between the physical urban structure, the microclimate and comfort, making the translation of the results into practical design guidelines easier; (2) it is fast and of low-cost in comparison to extensive measurements and hence allows comparisons between numerous case studies.

Current and well established human-biometeorological methods for assessing thermal comfort outdoors rely on rational indices determined by solving the human energy balance equation. Some well known indices include the predicted mean vote PMV (Jendritzky et al., 1990), the outdoor standard equivalent temperature OUT_SET* (Pickup and de Dear, 1999) and the physiologically equivalent temperature PET (Höppe, 1993, 1999). Calculation of these indices requires readings of the air temperature T_a, air humidity (vapour pressure VP or relative humidity RH), wind speed v and mean radiant temperature T_{mrt}.

ENVI-met 3.0, a three-dimensional numerical model (Bruse, 1999, 2004) was used for the calculation of the microclimatic changes implied by urban geometry. This model was particularly suitable for the purpose of this study: the high spatial resolution allows a fine analysis of the microclimate at street level and the possibility of representing complex geometries including galleries and horizontal overhangs as well as various vegetation covers.

Many studies have reported the dominant effect of T_{mrt}, which sums up the energy gained by a pedestrian, on comfort under sunny conditions (e.g. Mayer and Höppe, 1987; Jendritzky et al., 1990; Ali-Toudert et al., 2005; Ali-Toudert and Mayer, 2007). The calculation of T_{mrt} by ENVI-met 3.0 takes into account the direct and diffuse short-wave irradiances as well as the long-wave radiation fluxes originating from the ground, building surfaces and the free atmosphere. All components are weighted by the sky view factor SVF and it is assumed that 50% of the radiant heat originates from the ground while the remaining half comes from the upper hemisphere, i.e. buildings and visible sky. The detailed mathematical expressions used in ENVI-met 3.0 for calculating T_{mrt} were presented in a previous paper (Ali-Toudert and Mayer, 2006), and the whole model is thoroughly documented (Bruse, 1999).

3. Case studies

A few street geometries were selected for this paper from a large number of case studies. Each of these is concerned with one or more design details simultaneously. Fig. 1 and Table 1 give an overview of the investigated urban canyons together with their actual dimensions. These include:

- an urban canyon of $H/W = 2$ with galleries (case I),
- an asymmetrical urban canyon with a wide opening to the sky (case II),
- an asymmetrical urban canyon with overhanging façades and including galleries; this case study has the smallest opening to the sky (case III),
- an urban canyon with $H/W = 2$ and including a lateral row of trees (case IV),
- an urban canyon with $H/W = 1$ and including a large central row of trees (case V).

Case studies I, II and III were arranged in four different solar orientations, i.e. E–W, N–S, NE–SW and NW–SE. Case studies IV and V were set up in E–W and N–S orientations, respectively. The 3D grid resolution used for the simulated area is 1 m horizontally and 2 m vertically. In ENVI-met, the first grid above the ground (i.e. on z-axis) is subdivided into five equal parts to enable a better understanding of the microclimate at pedestrian level. All the results discussed in this paper are given for the part of the canyon at mid-block distance from the street ends, and for a height of 1.2 m above the ground. This height is representative of comfort calculations for a standing person.

The domain simulated is composed of two long buildings separated by a street of width 8 m. The building height is variable according to the aspect ratio. The building length equals six times its height to meet the dimensions of an urban canyon (Oke, 1988). Since no heat storage in the building materials is included in the model, the study of the role of thermal capacity of the materials was not relevant. Numerous test simulations were often necessary to set the appropriate input data in absence of reliable

Table 1
Geometrical description of the simulated urban canyons

Spatial resolution	1 m horizontally, 2 m vertically
Street width	8 m
Building height	$H_1 = 16$ m, $H_2 = 8$ m, $H_3 = 12$ m
Building length L	$6 \times H$ (≈urban canyon)
Building width W	12 m
Gallery	4 m high and 3 m width
Canyon materials	Street: asphalt, gallery: pavement, buildings: brick
Overhanging façade	2 m width

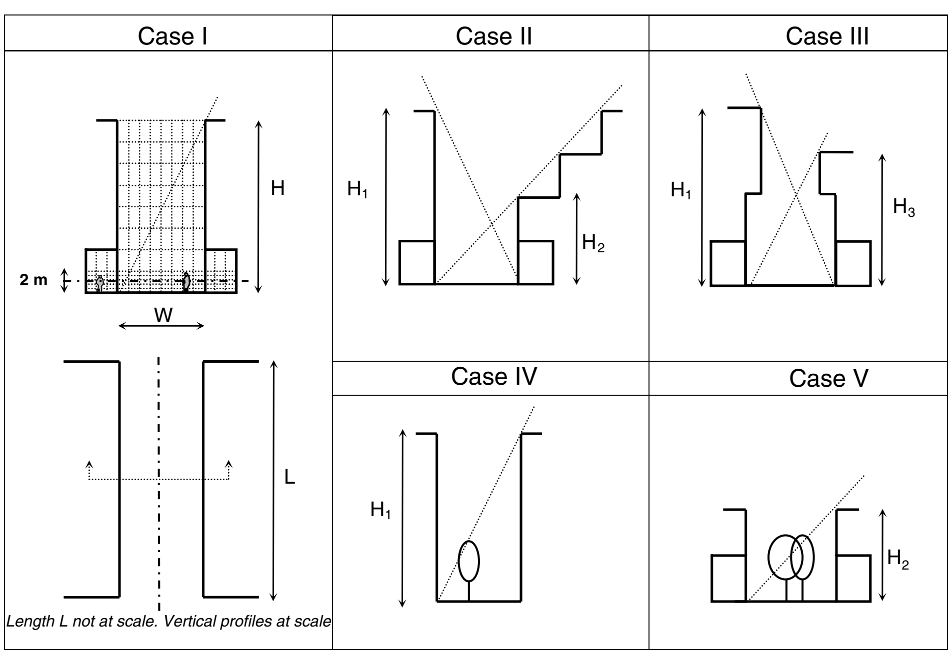

Fig. 1. Urban canyon geometries used in the simulations with ENVI-met 3.0.

references from the literature (e.g. soil, surface and air humidity and temperatures). Wind was set at a speed of 5 m s^{-1} at 10 m height with an incidence perpendicular to street axis. For some comparisons, it was also set to an incidence parallel to street axis. Simulations were run for a typical summer day in Ghardaia (32.40° N) located in the Algerian Sahara and characterized by a hot and dry climate (Roche, 1970; Ravéreau, 1981).

4. Discussion of results

4.1. Air temperature

Fig. 2 shows a comparison of air temperatures T_a at street level for canyons including galleries, overhanging façades as well as trees. Fig. 2a compares the mean air temperature between an asymmetrical canyon with $H_1/W = 2$ and $H_2/W = 1$ (case II) and a symmetrical canyon with $H/W = 2$ (case I) for the four orientations. Basically, E–W streets are the warmest with the largest differences occurring in the afternoon around 16:00 LST (up to 1.5 K between E–W and N–S orientation) because of a longer exposure to direct solar radiation and hence more sensible heat transferred to the air. NE–SW streets are also slightly warmer than NW–SE and N–S canyons for the same reason. Yet, the differences are minor between the various geometries for the same orientation. Although warmer during the day (up to 0.6 K), case II shows a trend to be cooler from 17:00 LST (≈0.3 K) when the streets become shaded. This confirms the potentially faster cooling effect due to a larger opening to the sky (mean sky view factor SVF = 0.46 vs. 0.39).

When the street includes horizontal shading from the façades and is asymmetrical with $H_1/W = 2$ and $H_3/W = 1.5$ (Fig. 2b), it tends to warm more in the morning hours in comparison to regular canyons of $H/W = 2$ because of more exposure of the canyon surfaces. These differences are reduced in the late afternoon, but the E–W streets remain the warmest, yet the irregular E–W canyon cools faster than the symmetrical canyon owing to its wider sky view (e.g. Oke, 1981; Arnfield, 1990b).

For simple canyon geometry air temperature T_a has been found to be sensitive to aspect ratio and to solar orientation (Ali-Toudert and Mayer, 2006). However, T_a is rather inert and reacts only moderately to geometrical changes. This agrees with a number of field studies which report on small differences of the canyon air warmth at street level in comparison to a free location due to well-mixing of air (e.g. Nakamura and Oke, 1988; Yoshida et al., 1990/1991; Ali-Toudert et al., 2005; Ali-Toudert and Mayer, 2007).

The presence of vegetation along the canyons was also found to affect the air temperature considerably. Fig. 2c shows a selection of case studies including rows of trees with various crown densities and two wind incidences, parallel and perpendicular. Air temperature in planted canyons is up to 1.5 K lower in comparison with unplanted streets with the same aspect ratio, i.e. 37.3 °C against 38.8 °C. The differences are larger for the case study with $H/W = 1$ where the row of trees is larger (4 m). The differences are, however, much smaller among planted canyons when changing the leaf area density (LAD) from dense to light, as well as between a perpendicular and a parallel wind. A maximum difference of 0.8 K was recorded between 11:00 and 18:00 LST, most likely because of the different aspect ratio and orientation.

4.2. Outdoor thermal comfort

The meteorological factors accounting for the human comfort are the air temperature (T_a), wind speed (v), air humidity (i.e. vapour pressure VP) and the short-wave and long-wave irradiances gained by a person (i.e. T_{mrt}) from the surrounding environment. The present simulations revealed no change in the moisture content in the air. Even where vegetation was available, the 30% soil humidity assumed under the crowns had no effect on the moisture content in the air due to rapid dissipation. The wind speed at mid-block canyon distance was also found to be very weak in all cases (~0.3 m s^{-1} at 1.2 m a.g.l.) for a perpendicular wind incidence (Ali-Toudert, 2005). Hence, both air humidity and air flow, even though important in absolute values, did not play a modifying role in the current comparisons. Moreover, the significance of the air temperature in describing the comfort conditions in summer, as shown previously, is limited due to the well mixed air within the street space in the daytime. By contrast, the radiant environment is a lot more sensitive to geometrical changes. The following analysis focuses on PET which summarizes all these factors and highlights the effects of T_{mrt} (Mayer and Höppe, 1987; Jendritzky et al., 1990; Mayer, 1993; Ali-Toudert et al., 2005; Ali-Toudert and Mayer, 2007).

4.2.1. Use of galleries

The following graphs (Figs. 3a–d) present a diurnal spatial and temporal evolution of PET within urban streets of $H/W = 2$ including galleries for four street orientations (case I).

In the main space of the street, the E–W canyon experiences the longest period of discomfort and the highest values of PET, i.e. up to 67 °C. The relatively high aspect ratio is only effective in protecting the north-facing part of the street, whereas the south-facing side is continuously irradiated and hence uncomfortable. A comparison of the individual meteorological factors involved in the calculation of PET (see Ali-Toudert, 2005) shows that T_{mrt} is by 7 K higher for an E–W street against a N–S street at hours of highest discomfort. Air temperature T_a shows slight differences according to orientation, i.e. about 1–2 K at the same hours. Moreover, PET is maximal around 10:00 LST and 16:00 LST in case of direct exposure because the solar beams irradiate the standing person laterally (i.e. projection factor f_p is maximal) and thus increases the amount

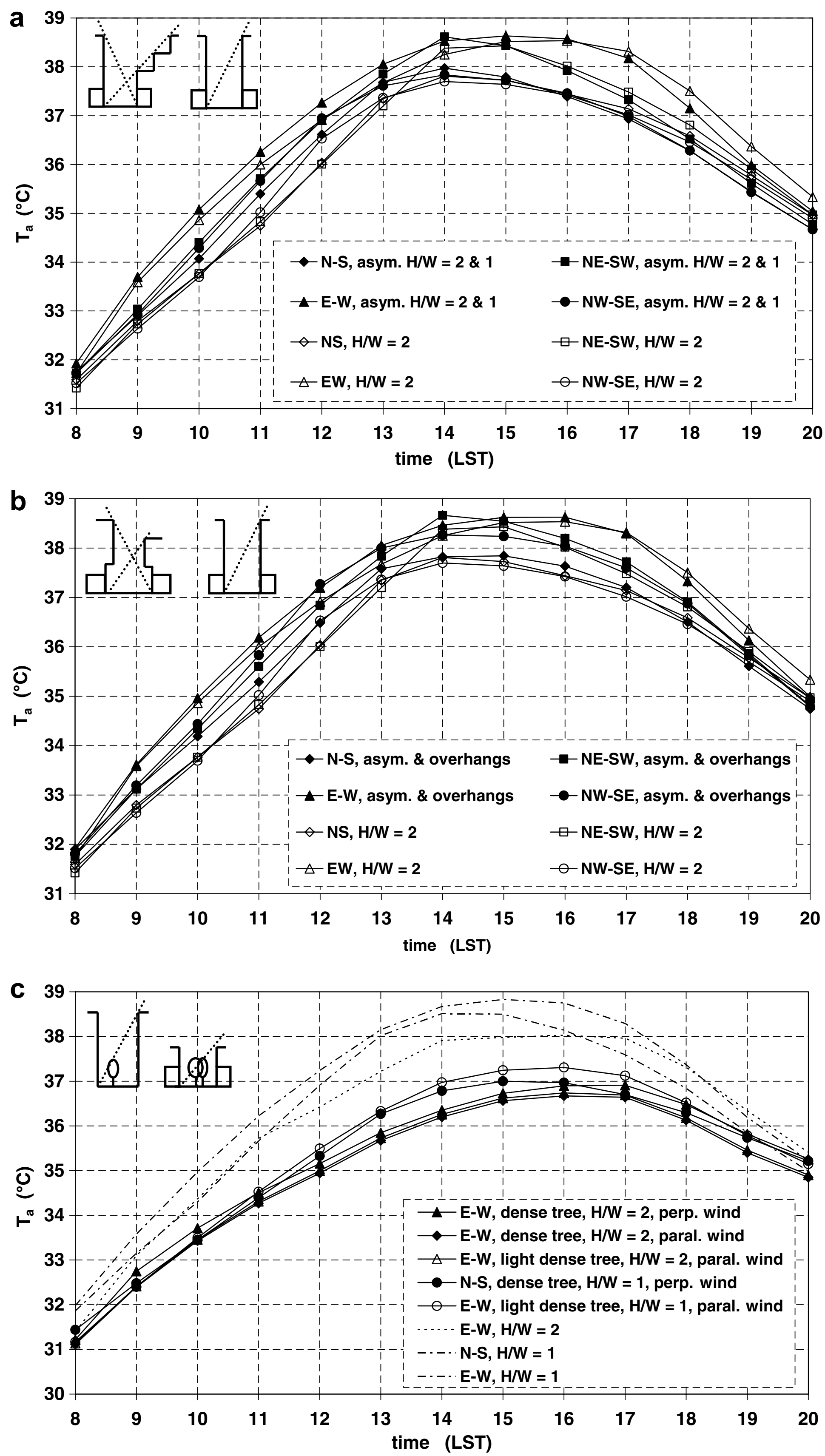

Fig. 2. Average air temperature T_a at street level (1.2 m a.g.l.) for (a) asymmetrical urban canyons, (b) overhanging façades, and (c) urban canyons with trees, in comparison to symmetrical urban canyons of $H/W = 2$ and 1.

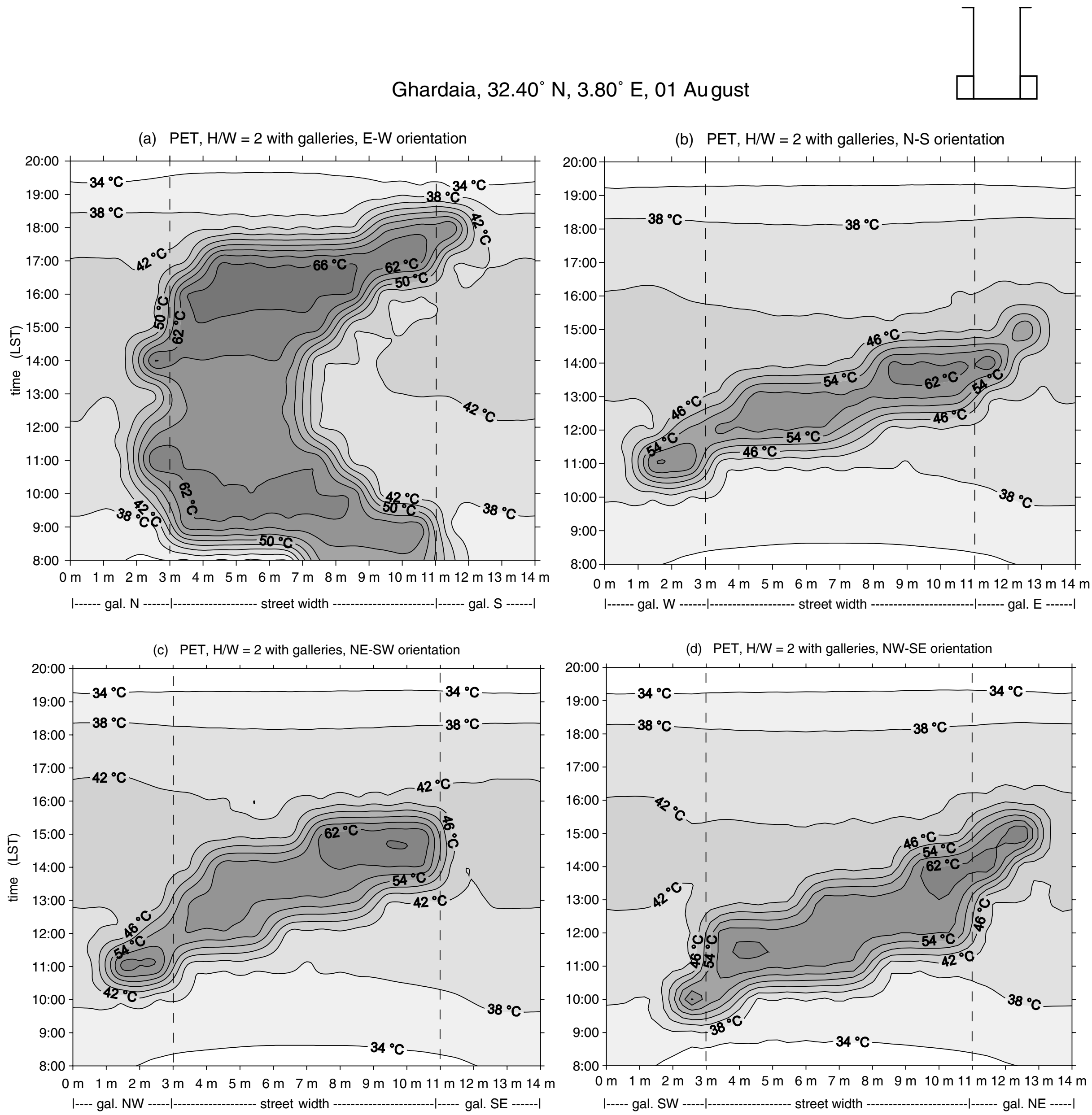

Fig. 3. PET distribution across symmetrical urban canyons including galleries on both sides (case I) for (a) E–W, (b) N–S, (c) NE–SW, and (d) NW–SE oriented streets ($H/W = 2$).

of direct short-wave irradiances absorbed. Clearly, N–S, NE–SW and NW–SE oriented streets are for shorter time uncomfortable in comparison to E–W streets. PET maxima are by a few degrees lower, mostly because the pedestrian absorbs less direct short-wave irradiance as the sun is higher (f_p lower) and less radiant heat from the ground which experiences lower surface temperature due to a shorter period of irradiation.

In the area of the galleries, the thermal situation is basically better than at irradiated locations within the street. The covered areas have minimal PET values, which range between 34 °C and 42 °C. However, these covered spaces can also experience short periods of high thermal stress, in form of an extension of the discomfort zone when observed at the sidewalks. This is due to the exposure of the pedestrian and the ground surface to direct solar beam despite the relatively high aspect ratio. This depends on the orientation of the street combined with the dimensions of the gallery itself, i.e. height and width (Littlefair et al., 2001).

With respect to orientation, Fig. 3a shows that the two galleries along an E–W street are well protected and the extent of discomfort in the galleries is very limited. The gallery on the south-facing side is partially stressful before and after noontime and contrasts strongly with the extreme PET values in the adjacent open area. This is attributable to the effectiveness of horizontal shading for an E–W orientation (e.g. Givoni, 1976; Lechner 1991; Littlefair et al., 2001). The gallery on the north-facing side is as expected shaded, except shortly around 17:00 LST because of lateral and skimming sun's rays. Similarly, the gallery SE in a NE–SW street remains in shade all time with the lowest PET values, even when the street is highly uncomfortable (Fig. 3c). Galleries SW and E are at most stressful in one-third of their width during 1 h. In the other galleries (W, NE) extreme PET values were recorded in about two-third of the covered area for about 2 h for $H/W = 2$. In fact, the aspect ratio of the gallery in combination with the orientation and aspect ratio of the street are all decisive. Hence, the extent of the discomfort observed in these examples is expected to decrease for deeper profiles and to increase for wider streets and higher galleries. This is further discussed in the next examples. Moreover, the period of extreme discomfort does not occur at the same time in comparison to the main street area, especially for intermediate orientations (except for gal. N). This period is "shifted" to about 1 h before or after the most critical time within the open street. This suggests that an alternative is given for people to move into shade from or to the gallery.

It is worth noting, however, that PET minima in the galleries are not lower than those recorded in shaded parts of the "open" street as would be expected. The PET maxima are anomalously higher in the gallery by up to 4 K. One explanation to this is the insignificant differences in the air temperature and wind speed found across the street. Another reason is probably related to the way T_{mrt} is calculated by the model (for details see Ali-Toudert, 2005). Around 11:00 LST, when the gallery is irradiated, a standing person absorbs more direct irradiation than at noontime when the street centre becomes irradiated. This is due to a lower sun position which implies a higher projection factor f_p (0.24 at 11:00 LST vs. 0.17 at 12:00 LST). The upwards heat from the ground increases slightly in the gallery when the ground surface becomes shortly irradiated. The ground surface at street centre heats more and irradiates more because of a longer period of exposure and also because of the asphalt material used, whereas the gallery's floor is set as pavement. Moreover, the gallery is reported to receive more diffuse radiation than the street centre, i.e. up to 55 W m^{-2}. This surprising overestimation is attributable to the lower sky view factor of the gallery (0.12 vs. 0.57) which leads to an important increase in the diffusely reflected radiation (Ali-Toudert and Mayer, 2006, Eq. (6)). For the same reason, the covered area receives less radiant heat from the sky (27 W m^{-2} against 133 W m^{-2} on average) and more radiant heat from the walls, i.e. 87 W m^{-2} against 178 W m^{-2}. For these reasons, it is expected that the mitigation of thermal stress under the galleries is underestimated. In spite of these uncertainties, the model gives a good differentiation of T_{mrt} between irradiated and shaded situations because ENVI-met takes into account accurately the direct irradiation of the body and the ground surface, both decisive in these cases. However, a different parameterisation than the sky view factor seems to be necessary for estimating the various fluxes accounting in T_{mrt} for the particular cases of covered urban spaces. Experimentally, Ali-Toudert et al. (2005) found that a covered street space located in an old desert city in summer experiences about 2 K lower T_a in comparison to a free location. Noticeably lower ground and wall surfaces temperatures were also recorded, which confirm that sheltered locations do have better comfort conditions. No further measured data in galleries could be found in the literature for more comparison. Hence, attention is drawn here on the relevance of more on-site measurements for assessing the microclimate and comfort in sheltered locations such as galleries.

4.2.2. Effects of the canyon asymmetry

The following examples (Fig. 4) introduce a design alternative which is opposite to the previous one. Case II is an asymmetric street with a greater opening to the sky, intended to keep a higher potential of solar access in the winter. Enlarging the sky view implied by this asymmetry also promotes a faster cooling at night as suggested by Fig. 2a. Obviously, it is expected that this geometry leads to more exposure of the street to the sun in summer; galleries are added as a way of protecting the street edges and are simultaneously assessed.

The first graph is an E–W oriented street. The asymmetrical profile is more stressful than a corresponding regular street (i.e. $H/W = 2$, in Fig. 3a). The warming of the street reaches 20 K on the PET scale if compared to $H/W = 2$ for an additional 1/8 of the street width on the south side. Yet, no further effect on the north half part is observed, which is equally stressful. Also, no difference is found if compared to $H/W = 2$ after 17.00 LST in the whole street area. In comparison to a symmetrical canyon with $H/W = 1$ (Ali-Toudert and Mayer, 2006), the spatial and temporal evolution of PET is noticeably similar. However, some advantage for the asymmetrical street is noticed in the early morning and after 16:00 LST when the sun's rays coming laterally from the sides are blocked by the higher façades and lead to a better thermal situation. The comfort situation in the galleries spaces along an E–W oriented street remains almost not affected by the aspect ratio, suggesting that galleries for this orientation are a good strategy even for wider streets.

This asymmetry offers an intermediate thermal situation between the regular streets $H/W = 2$ and $H/W = 1$. It allows a shorter period of time of discomfort than $H/W = 1$ in the afternoon, while keeping a higher plan density with a relatively small disadvantage on comfort in comparison to $H/W = 2$. Further, more solar caption in winter is ensured together with a faster heat release in summer (and possibly better pollutant dispersion).

A comparison of each radiation component for the two profiles (case I and case II) allows understanding to what extent these are responsible in the variances observed in the thermal comfort (for details see Ali-Toudert, 2005). The asymmetrical street has a larger sky view factor (about 0.1 larger in average) and leads on one hand to more diffuse

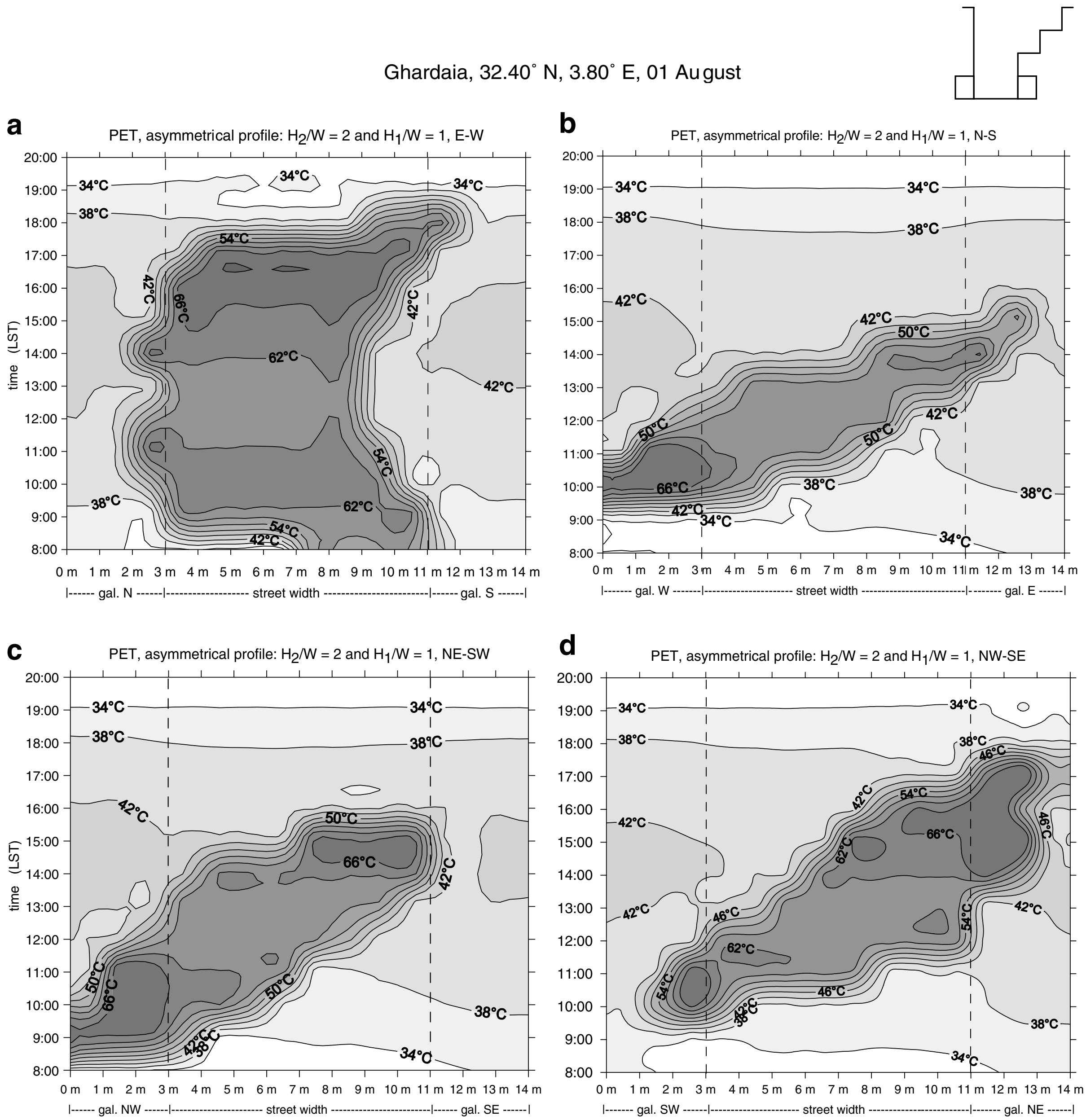

Fig. 4. PET distribution across asymmetrical urban canyons with $H_1/W = 2$ and $H_2/W = 1$ (case II) including galleries on both sides for (a) E–W, (b) N–S, (c) NE–SW, and (d) NW–SE oriented streets ($H/W = 2$).

radiation ($\leqslant 12\ \mathrm{W\ m^{-2}}$) but on the other hand to less diffusely reflected radiation ($\approx 25\ \mathrm{W\ m^{-2}}$). The total diffuse radiation received at street level is, therefore, less for an asymmetrical profile than in a symmetrical canyon, but the differences are minor. Hence, the main reason for higher T_{mrt} is found to be the greater exposure to direct solar irradiance of the pedestrian and the ground surface which is attributable to the wider opening to the sky.

Similarly, Fig. 4 illustrates the thermal comfort situation for the same asymmetrical geometry for N–S, NE–SW and NW–SE orientations, with the highest wall facing E, SE and SW, respectively. Complementary observations can be summarized as follows:

- For N–S orientation, the extreme discomfort period extends to the morning hours for 2/3 of the street canyon in comparison to $H/W = 2$. If compared to $H/W = 1$ (see Ali-Toudert and Mayer, 2006), the street shows a substantial improvement in the thermal situation (up to 24 K lower) between 14:00 and 17:00 LST for 75% of the street width. The intermediate orientations show similar trends.
- With regard to the areas of galleries, these figures show clearly that the effectiveness of the galleries is reduced if the aspect ratio decreases. Explicitly, the duration of extreme discomfort within the galleries becomes longer depending on the orientation.

– For N–S, NE–SW and NW–SE orientations, the period of extreme discomfort is longer (about 2–3 h) due to the combination of relatively low sun position and lateral incidence of direct solar beam. This suggests that the galleries are moderately effective for wide street canyons ($H/W \leqslant 1$) oriented NE–SW or NW–SE.

4.2.3. *Effects of overhanging façades*

Case III is more complex and combines the use of galleries, asymmetry and overhanging façades. The exposure of the walls to the sun is larger in the winter in comparison to a symmetrical canyon with $H/W = 2$ but the street level is expected to be more shaded in summer due to the offset of the façades over it. The geometry used here is simplified owing to the limits induced by the model capabilities. Horizontal shading devices can also be in form of balconies or inclined façades, etc.

PET patterns in Fig. 5 allow following observations:

– The area and period of highest discomfort is noticeably lower for all 4 orientations when compared to a symmetrical profile of higher aspect ratio, i.e. $H/W = 2$ (Figs. 3a–d). PET maxima are also basically lower, i.e. 62 °C against 58 °C.
– Overhanging façades are most efficient for N–S and NW–SE streets and less for NE–SW and E–W streets.

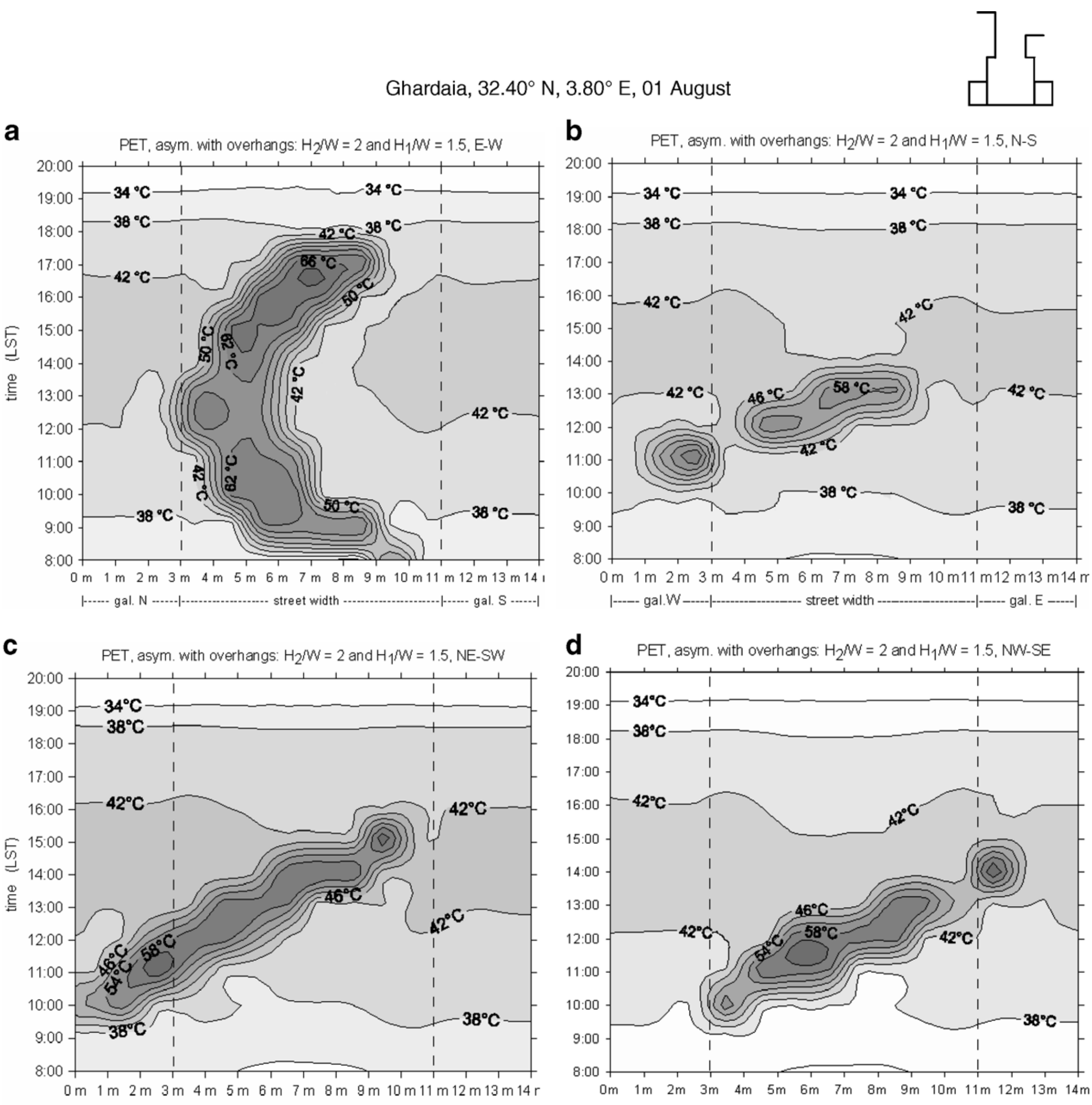

Fig. 5. PET distribution across urban canyons with overhanging façades, asymmetrical with $H_1/W = 2$ and $H_3/W = 1$ (case III) and including galleries on both sides for (a) E–W, (b) N–S, (c) NE–SW, and (d) NW–SE oriented streets ($H/W = 2$).

The E–W oriented street remains the most uncomfortable. Yet, offsetting the façades leads to a better protection of the street sidewalks.
– The N–S oriented street is the most comfortable with a very restricted area of extreme values, namely at street centre at noontime only, with a full protection of the galleries.
– Intermediate orientations show an appreciable amelioration in the thermal comfort situation in summer, however the gallery NW of the NE–SW street still experiences maximum PET values around 10:00 LST. PET is maximal for only 2 h for each point across the street, indicating that during the whole day an alternative is always available to walk in a comfortable part of the street.

4.3. Use of vegetation

The advantages of urban vegetation in mitigating the heat stress are well documented and a literature review can be read in Ali-Toudert and Mayer (2005). The present case investigates these effects at a microscale level in relation to people's thermal sensation.

Fig. 6 shows the PET patterns for the E–W oriented street with $H/W = 2$ including a narrow row of trees on the north side against a treeless canyon. The use of trees leads to a decrease of PET up to 22 K directly under the tree crowns because of less solar irradiation.

Basically, the decrease in the received direct solar irradiance at 1.2 m a.g.l. (ΔS) ranges between 200 W m^{-2} and 850 W m^{-2} as shown in Fig. 7. The attenuation of solar irradiance is function of an extinction coefficient and leaf area index LAI. For the direct solar beam, LAI as calculated by the model, takes into account the actual distance "traversed" by the sun's rays for the integration of LAD, i.e. an optical length (for equations see Bruse, 1999). This optical length is increased when the sun's rays are nearly "parallel" to the row of trees and depends on the sun position together with the orientation. Thus, the largest interception occurs between 9:00 and 10:00 LST as well as from 16:00 to 17:00 LST for an E–W orientation and results in the greatest heat stress mitigation (Fig. 3). Another explanation for the decrease of PET is the strongly reduced heat absorbed by the ground surface (up to 200 W m^{-2}) under the vegetation and hence the heat emitted upwards and absorbed by a human body (Fig. 7). However, these graphics also show that the cooling effect is appreciable mostly under the tree crowns and does not extend to the surroundings. This is in good agreement with field observations reported by Shashua-Bar and Hoffman (2000).

Further, Fig. 8 gives the PET values for the N–S street with $H/W = 1$ including a large central row of trees and galleries compared to a street without trees or galleries. In this case, PET was up to 24 K lower than in a street without trees. One can see that the best screen effects of

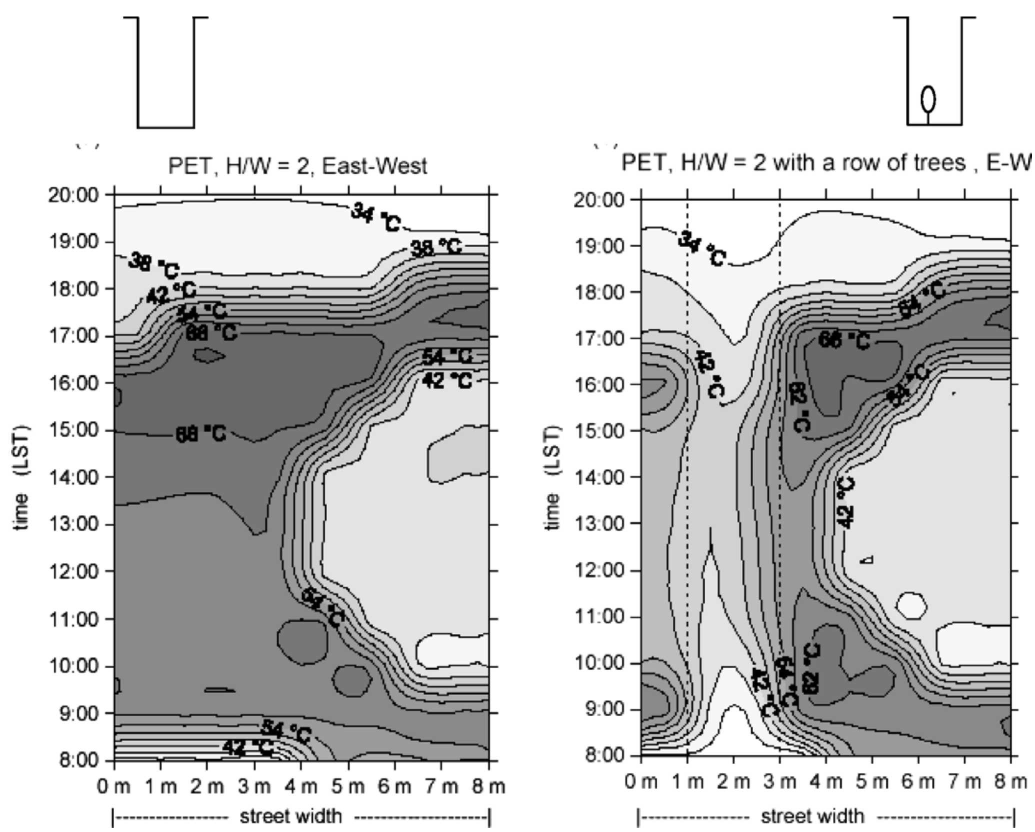

Fig. 6. PET distribution across urban canyons oriented E–W with $H/W = 2$ with and without a row of trees.

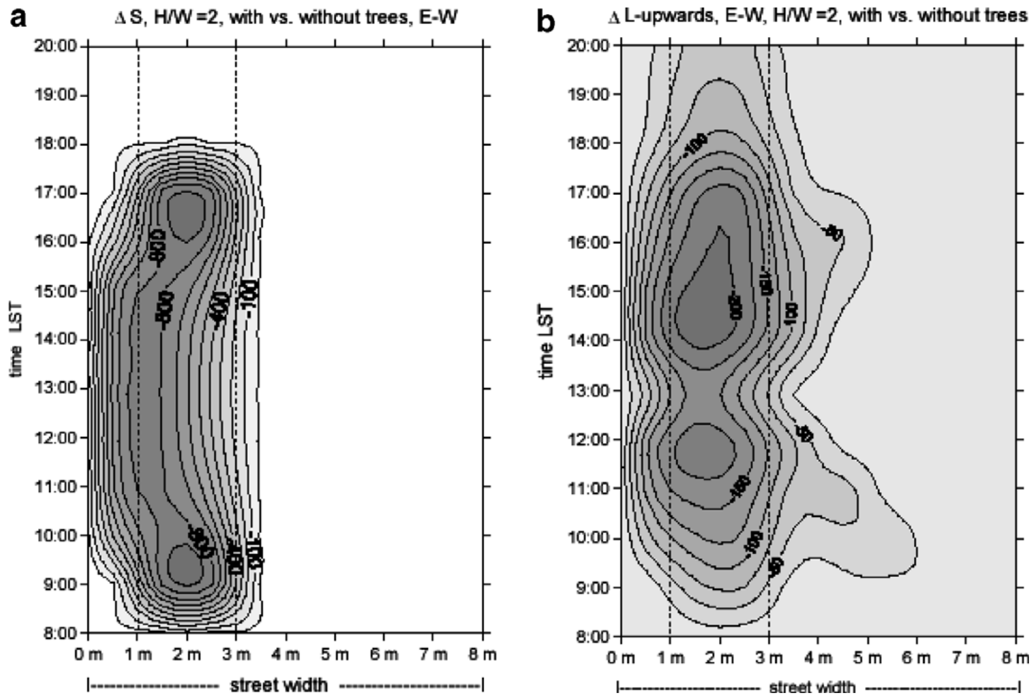

Fig. 7. Differences in (a) direct solar irradiance (ΔS) and (b) long-wave irradiance (ΔL-upwards) emitted by the ground surface between a street with a row of trees against a street without trees.

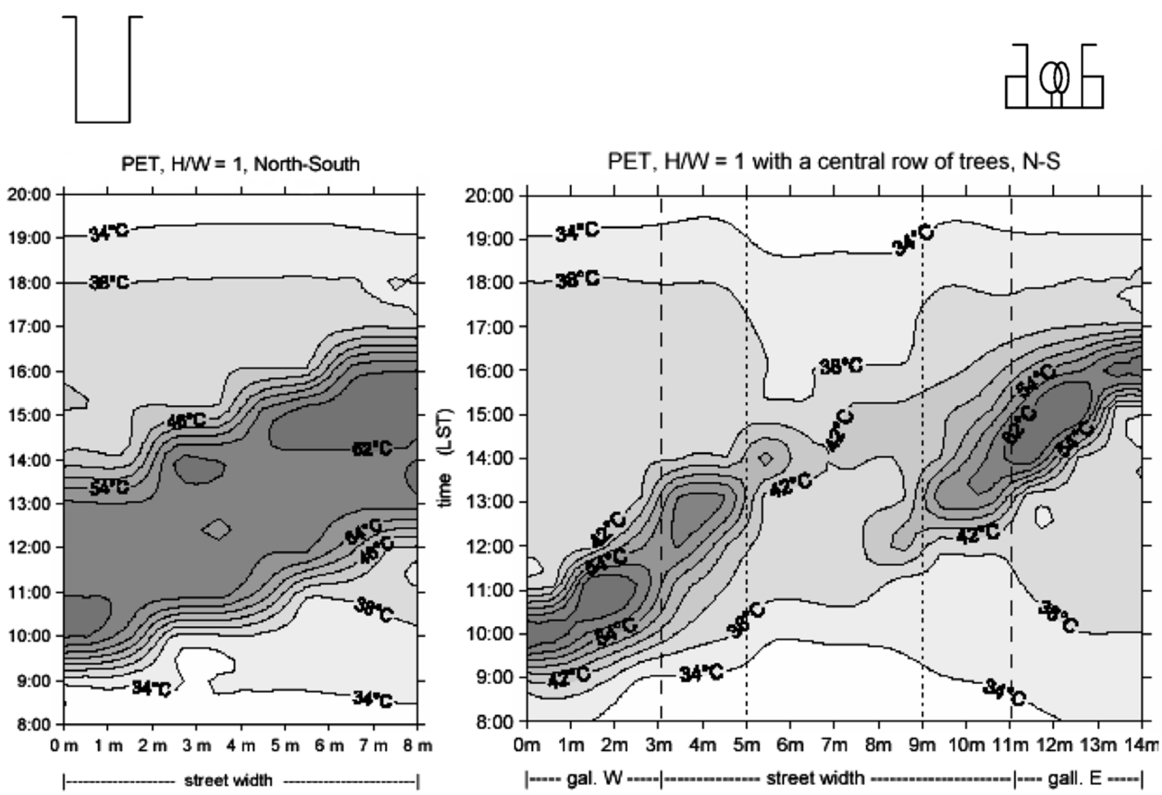

Fig. 8. PET pattern within a street oriented N–S with $H/W = 1$ without trees and a street with a large central row of trees (––– limit of gallery, --- projection of trees' area).

the vegetation occurs in the central part of the vegetated area whereas less effective at the edges when the optical length is minimal, i.e. with low LAI, e.g. grid $x = 6$ m around 14:00 LST.

Other simulations showed that N–S orientation allows more sun within the galleries than an E–W orientation, in particular for large aspect ratios. Fig. 8 shows, in addition, that a central row of trees does not protect the galleries further. These covered areas experience about 2 h of highest discomfort on the west side in the morning and on the east side in the late afternoon.

Furthermore, the extent to which a tree is an efficient strategy for mitigating heat stress depends on its density (i.e. LAD, LAI) and geometry (dimensions). Light density trees normally allow less shading but more air circulation under the crown than a dense crown tree. Test simulations (not shown here) were also made for light and dense crown trees as well as for a parallel wind incidence (e.g. channelling in-canyon) in order to assess whether promoting shading is more critical than allowing more ventilation or inversely. PET results showed small differences between the two cases, with a minimal advantage for a dense tree, for which PET values are about 2–4 K lower than under light-dense trees during 1 h.

5. Conclusion

This paper reports on outdoor thermal comfort in urban street canyons with various shapes and orientations. These findings complement the first ones published previously (Ali-Toudert and Mayer, 2006) and prove quantitatively the intuitive knowledge that shading is the key strategy for mitigating heat stress outdoors under hot summer conditions. The most evident result reported here was to show how this shading can be reached through design strategies.

Basically, PET patterns give a good picture on the corrective measures for improving the climate quality of an urban street. For example, an E–W large street appears to be the one where comfort is the most difficult to ensure. Yet, galleries in this case are efficient and therefore advisable. Planting trees in E–W streets is also sensible since the duration and area of discomfort will be, otherwise, critical. For all other orientations, a judicious combination of all design details, i.e. asymmetry, gallery, overhangs, vegetation, along with an appropriate H/W and orientation can lead to a substantial amelioration of the microclimate at street level, together with keeping a certain level of indoor solar access in winter for upper parts of the street canyon (e.g. Fig. 8).

The ambition of this paper was to bring some elements into discussion regarding the climate responsiveness of urban forms through design. However, it does not support any deterministic solutions which are not possible and the optimal design solution differs from case to case.

Finally, we believe that evaluating the effects of all these urban design aspects on the indoor climate and energy consumption of urban buildings is a logical extent to this work and is hence a further issue to investigate. This will help to decide on the most efficient urban forms not only regarding summer comfort but on a yearly basis.

Acknowledgements

The financial support of the German Academic Exchange Service (DAAD) is gratefully acknowledged, as well as the support of Dr. Michael Bruse, University of Bochum, Germany, during the work with ENVI-met.

References

Ali-Toudert, F., 2005. Dependence of outdoor thermal comfort on street design in hot and dry climate, Rep. Meteor. Inst. Univ. Freiburg, Germany. Ph.D. Thesis, Report No 15, Download at: <http://www.freidok.uni-freiburg.de/volltexte/2078>.

Ali-Toudert, F., Mayer, H., 2005. Thermal comfort in urban streets with trees under hot summer conditions. In: Proc. 22th Conference on Passive and Low Energy Architetcure (PLEA), Beirut, Lebanon, 13–16 November 2005, vol. 2, pp. 699–704.

Ali-Toudert, F., Mayer, H., 2006. Numerical study on the effects of aspect ratio and solar orientation on outdoor thermal comfort in hot and dry climate. Building and Environment 41, 94–108.

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, 223–237.

Ali-Toudert, F., Djenane, M., Bensalem, R., Mayer, H., 2005. Outdoor thermal comfort in the old desert city of Beni-Isguen, Algeria. Climate Research 28, 243–256.

Arnfield, J., 1990a. Street design and urban canyon solar access. Energy and Buildings 14, 117–131.

Arnfield, J., 1990b. Canyon geometry, the urban fabric and nocturnal cooling: a simulation approach. Physical Geography 11, 220–239.

Arnfield, J., 2003. Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology 23, 1–26.

Asimakopoulos, D.N., Assimakopoulos, V.D., Chrisomallidou, N., Klitsikas, N., Mangold, D., Michel, P., Santamouris, M., Tsangrassoulis, A., 2001. Energy and Climate in the Urban Built Environment, James & James, London.

Bourbia, F., Awbi, H.B., 2004. Building cluster and shading in urban canyon for hot–dry climate. Part 2: Shading simulations. Renewable Energy 29, 291–301.

Bruse, M., 1999. Die Auswirkungen kleinskaliger Umweltgestaltung auf das Mikroklima, Entwicklung des prognostischen numerischen Modells ENVI-met zur Simulation der Wind-, Temperatur-, und Feuchtverteilung in städtischen Strukturen. Ph.D. Thesis, Univ. Bochum, Germany.

Bruse, M., 2004. ENVI-met website. Available from: <http://www.envi-met.com>.

Capeluto, I.G., 2003. Energy performance of the self-shading building envelope. Energy and Buildings 35, 327–336.

Capeluto, I.G., Shaviv, E., 2001. On the use of solar volume for determining the urban fabric. Solar Energy 70, 275–280.

Givoni, B., 1976. Man, Climate and Architecture. Van Nostrand Reinhold, New York.

Givoni, B., 1997. Climate Considerations in Building and Urban Design. Van Nostrand Reinhold, New York.

Golany, G. (Ed.), 1982. Design for Arid Regions. Van Nostrand Reinhold, New York.

Herzog, T., 1996. Solar Energy in Architecture and Urban Planning, Prestel, Munich.

Höppe, P., 1993. Heat balance modelling. Experientia 49, 741–746.

Höppe, P., 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. International Journal of Biometeorology 43, 71–75.

Jendritzky, G., Menz, G., Schirmer, H., Schmidt-Kessen, W., 1990. Methodik zur räumlichen Bewertung der thermischen Komponente im Bioklima des Menschen, Fortgeschriebenes Klima-Michel-Modell,

Beiträge der Akademie für Raumforschung und Landesplannung, Hannover, Band 114.
Knowles, R.L., 1981. Sun, Rhythm and Form. MIT Press, London.
Krishan, A., 1996. The habitat of two deserts in India: hot–dry desert of Jaisailmer (Rajasthan) and the cold–dry high altitude mountainous desert of leh (Ladakh). Energy and Buildings 23, 217–229.
Kristl, Z., Krainer, A., 2001. Energy evaluation of urban structure and dimensioning of building site using ISO – Shadow method. Solar Energy 70, 23–34.
Lechner, N., 1991. Heating Cooling, Lighting Design Methods for Architects. John Wiley & Sons, New York.
Littlefair, P.J., Santamouris, M., Alvarez, S., Dupagne, A., Hall, D., Teller, J., Coronel, J.F., Papanikolaou, N., 2001. Environmental Site Layout Planning: Solar Access, Microclimate and Passive Cooling in Urban. CRC, London.
Mayer, M., 1993. Urban bioclimatology. Experientia 49, 957–963.
Mayer, H., Höppe, P., 1987. Thermal comfort of man in different urban environments. Theoretical and Applied Climatology 38, 43–49.
McPherson, E.G., 1992. Shading urban heat islands in U.S. desert cities. Wetter und Leben 44, 107–123.
McPherson, E.G., Nowak, D.J., Rowntree, R.A., 1994. Chicago's urban forest ecosystem: results of the Chicago urban forest climate project, USDA forest service. General Technical Report NE-186.
Moughtin, C., 2003. Urban Design Street and Square. Architectural Press, Amsterdam.
Nagara, K., Shimoda, Y., Mizuno, M., 1996. Evaluation of the thermal environment in an outdoor pedestrian space. Atmospheric Environment 30, 497–505.
Nakamura, Y., Oke, T., 1988. Wind, temperature and stability conditions in an east–west oriented urban canyon. Atmospheric Environment 22, 2691–2700.
Nikolopoulou, M., Baker, N., Steemers, K., 2001. Thermal comfort in outdoor urban spaces: understanding the human parameter. Solar Energy 70, 227–235.
Oke, T., 1981. Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observation. Journal of Climatology 1, 237–254.
Oke, T., 1988. Street design and urban canopy layer climate. Energy and Buildings 11, 103–113.
Pereira, F.O.R., Minache, J.A.C., 1989. Insolation in the built environment: criteria for its normalisation and regulation. In: Proc. 2nd Europ. Conf. on Architecture, Paris, France, pp. 36–38.
Pereira, F.O.R., Silva, C.A.N., Turkienikz, B., 2001. A methodology for sunlight urban planning. A computer-based solar and sky vault obstruction analysis. Solar Energy 70, 217–226.
Pickup, J., de Dear, R., 1999. An outdoor thermal comfort index (OUT-SET*). Part 1 – The model and its assumptions. In: Proc. 15th Int. Congr. Biometeorol. and Int. Conf. Urban Climatol., Sydney, Australia, pp. 279–283.
Ravéreau, A., 1981. Le M'zab une leçon d'architecture, Sindbad, Paris.
Roche, M., 1970. Le M'zab, architectures ibadites en Algérie, Arthaud, Strasbourg.
Shashua-Bar, L., Hoffman, M.E., 2000. Vegetation as a climatic component in the design of an urban street. Energy and Buildings 31, 221–235.
Spagnolo, J., de Dear, R., 2003. A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Building and Environment 38, 721–738.
Stathopoulos, T., Wu, H., Zacharias, J., 2004. Outdoor human comfort in an urban climate. Building and Environment 39, 297–305.
Swaid, H., Bar-El, M., Hoffman, M.E., 1993. A bioclimatic design methodology for urban outdoor spaces. Theoretical and Applied Climatology 48, 49–61.
Thomas, R., 2003. Sustainable urban design, an environmental approach, Spon, London.
Yoshida, A., Tominaga, K., Watani, S., 1990/1991. Field measurements on energy balance of an urban canyon in the summer season. Energy and Buildings, 417–423.