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DIFFERENCES IN HUMAN COMFORT CONDITIONS WITHIN A COMPLEX URBAN ENVIRONMENT: A CASE STUDY

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Összefoglalás – Az utóbbi években számos indexet (például a PMV – Predicted Mean Vote és a PET – Physiological Equivalent Temperature) fejlesztettek ki annak számszerűsítésére, hogy mekkora az emberi szervezetet érő hőterhelés különböző környezetben, illetve milyenek az emberi test és a környezete közötti energiaáramlási viszonyok. A természetes felszínekhez képest az összetett városi felszín olyan speciális mikroklimatikus sajátosságokkal jellemezhető környezeteket teremt, amelyek jelentősen befolyásolják az emberi test energiaegyenlegét. Jelen vizsgálatunkban egy esettanulmányt mutatunk be a 160.000 lakosú Szeged példáján. A sugárzási áramlások erőssége számos tényezőtől, így a felszín szerkezetétől és a beépítettség sűrűségétől függ. Mintaterületünk a város magas beépítettségű belvárosi régiójában található, szűk utcakanyonok jellemzik, 20-30 éves (20-30 m magas) útszéli fasorral. A sugárzási viszonyok tehát ezen feltételeknek megfelelően módosulnak. Az összetett városi környezetek mikroklímája humán-bioklimatikus hatásának megbecslése a PET index segítségével történt. Az indexszámításokat a RayMan modell segítségével végeztük, melynek során egymáshoz közel fekvő, de az épületek és a fák által eltérően árnyékolt helyek bioklimatológiai körülményei kerültek összehasonlításra. Az eredmények szerint a besugárzási különbségek következtében akár 15-20°C-os eltérések is adódhatnak a PET értékekben.

Summary – Several complex thermal indices (e.g. Predicted Mean Vote and Physiological Equivalent Temperature) have been developed in the last decades to describe and quantify the thermal environment of humans and the energy fluxes between body and environment. Compared to open spaces/landscapes the complex surface structure of urban areas creates an environment with special microclimatic characteristics, which have a dominant effect on the energy balance of the human body. In this study, outdoor thermal comfort conditions are examined through a field survey in Szeged, a South-Hungarian city (population 160,000). The intensity of radiation fluxes depends on several factors, such as surface structure and housing density. Since our sample area is located in a heavily built-up city centre, radiation fluxes are mainly influenced by narrow streets and several 20-30 year old (20-30 m tall) trees. Special emphasis is given to the human-biometeorological assessment of the microclimate of complex urban environments through the application of the thermal index PET. The analysis is carried out by the utilization of the RayMan model. Bioclimatic conditions of sites located close to each other but shaded differently by buildings and plants are compared. According to the results differences in the PET index amongst these places can be as high as due to the different irradiation.

Key words: urban environments, thermal comfort, Physiological Equivalent Temperature PET, Szeged, Hungary

1. INTRODUCTION

Human beings are subjected to various kinds of stress in the urban environment. The most important ones are the meso- and microclimatic conditions, which differ significantly from that of rural areas. The main reason for this is the alteration of the surface structure (e.g. proportion of the built-up area, 3D geometry of the buildings and trees) triggering particular urban climate phenomena (e.g. urban heat island, changes in the radiation fluxes).

An important task of bioclimatological research is to evaluate the thermal environment of human beings, since it determines the energy balance of the body and consequently its comfort sensation (*Höppe,* 1993). The physiologically relevant assessment of urban climate, and especially different urban microclimates, requires the use of methods and indices which combine meteorological parameters with thermo-physiological parameters (*Mayer*, 1993; *VDI*, 1998). Urban and regional planners are demanding easily understandable methods for the measurement of the thermal component of climate in order to facilitate the development of comfortable urban microclimates (*Höppe,* 1993).

Human bioclimatological studies carried out in summer have a specific importance, because the urban heat island forming several hours after the sunset keeps the extent of the heat stress at high levels in addition to the strong heat stress during daytime. This shortens the regeneration possibilities of urban residents during the night. Based on the foregoing, we can state that the human thermal comfort issues and quantitative bioclimatological indices generate valuable information for urban planners and architects. The obtained data and suggestions can contribute to the planning process to achieve more a more suitable and healthy urban environment, e.g. to increase the well-being of the urban population by mitigating heat stress in summer.

This study is based on earlier bioclimatic and recent urban climate studies in the South-Hungarian city Szeged. According to these studies an urban heat island intensity of 2.7°C on annual average can be measured in Szeged, which can increase to 6.8°C during clear, anticyclonal weather conditions (*Sümeghy and Unger*, 2003). The results show a significant additional heat load to the human body, especially in summer. In former bioclimatic studies, with the aid of suitable indices for the available data set, differences in the annual and diurnal variation of human bioclimatic characteristics between an urban and rural environment were evaluated over a 3-year period (*Unger*, 1999). These indices were the thermohygrometric index (THI), defined by air temperature and relative humidity, the relative strain index (RSI), defined by air temperature and vapour pressure, and additionally the number of "beergarden days" defined by air temperature at 21.00 hours. It was shown that, due to the increased heat stress, the modification effect of the city is rather negative in summer, while it improves the thermal sensation by shortening the unfavourable cold periods in winter.

The aim of this study is to demonstrate the importance and potentials of the quantitative evaluation of human comfort and heat stress. Findings are of use for city planning and architects, as shown for in the case of the city of Szeged, situated in the southern part of Hungary. The evaluation based on sophisticated microclimate measurements in different urban micro-environments within the study area to reveal their human bioclimatological features.

2. MATERIAL AND METHODS

2.1. Study area

Szeged is located in the southern part of Hungary (46°N, 20°E) at 79 m above sea level on a flat plain (*Fig. 1A-B*). River Tisza passes through the city; otherwise there are no large water bodies nearby. The base of the street network is a circuit-avenue system, with several different land-use types from the densely built centre to the detached housing suburb region (*Fig. 1C*). The city's population of 160,000 lives within an administration district of 281 km^2, but the highly urbanized area is restricted to an area of about 30-35 km^2.

Szeged belongs to the climatic region *Cf* according to Köppen's classification (temperate warm climate with uniform annual distribution of precipitation) or in the climatic region *D.1* according to Trewartha's classification (continental climate with a long warm season) (*Péczely*, 1979). The annual mean temperature is 10.4°C and the amount of precipitation is 497 mm.

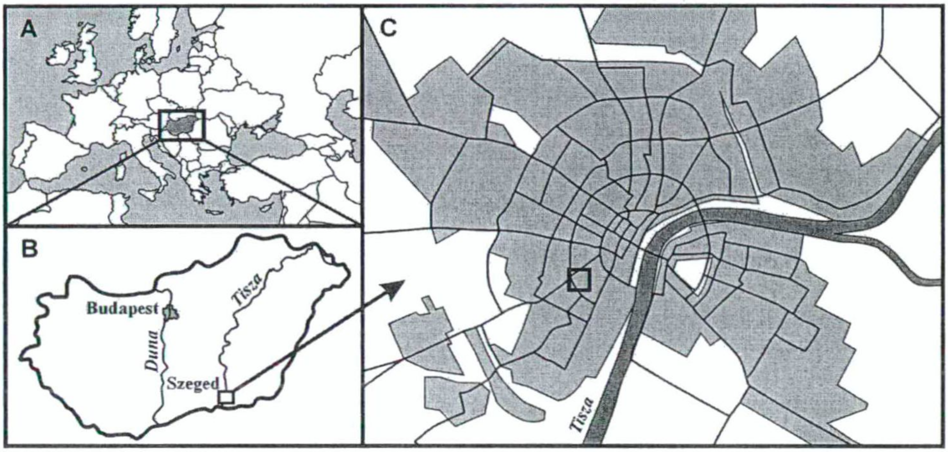


Fig. 1 Geographical location of Hungary in Europe (A), of Szeged in Hungary (B), built-up area and road network of the city (C) and the location of the 200 x 200 m sample area in the city

The investigated sample area (200 x 200 m) in Szeged is situated in the heavily built-up city centre region with narrow streets and several 20-30 years old (20-30 m tall) deciduous trees (*Fig. 2*). The area is crossed by a busy road (Petőfi av.) with a tram rail in a direction of NE-SW and by two narrow by-streets. One of the by-streets (Batthyány str.) has a NNW-SSW direction and the other (Egyetem str.) is parallel to the avenue. The area is dominated by the five-storey building complex of the University of Szeged.

2.2. Applied bioclimatic indices

In the last decades, several models have been developed to estimate the energy balance of the human body in different environments. These models usually include various meteorological parameters, albedo of the surface and solid angle proportion (*Fanger*, 1972; *Gagge et al.*, 1986; *Höppe*, 1999; *Matzarakis et al.*, 2000; *Spagnolo and de Dear*, 2003). The models utilize complex comfort indices – for example Predicted Mean Vote (PMV), Physiological Equivalent Temperature (PET) or OUT SET* – to evaluate the thermal stress affecting the body. Most of the indices include the mean radiant temperature (T_{mrt}), which is, especially during sunny weather, the most important input parameter for the energy balance (*Matzarakis et al.*, 2000). T_{mrt} is defined as the uniform temperature of a surrounding surface giving off blackbody radiation (emission coefficient $\varepsilon = 1$) which results in the same energy gain of a human body as the prevailing radiation fluxes (*Matzarakis et al.*, 1999).

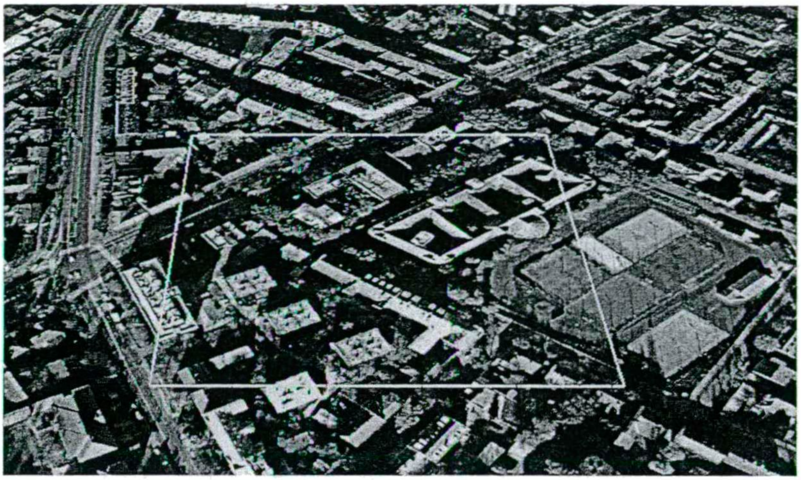


Fig. 2 3D view created by ERDAS IMAGINE of the investigated area

PET is a popular and useful bioclimatic index, because it has a widely known unit (°C) as an indicator of thermal stress. It makes results easy understandable and comprehensible for potential users who are not familiar with modern human-biometeorological terminology, including planners, decision-makers, and even the public. It evaluates the thermal conditions in a physiologically significant manner (*Matzarakis et al.,* 1999). PET is defined as the air temperature at which the human energy budget for the assumed indoor conditions is balanced by the same skin temperature and sweat rate as under the actual complex outdoor conditions to be assessed. This way PET enables various users to compare the integral effects of complex thermal conditions outside with their own experience indoors. In addition PET can be used all year around and in different climates (e.g. *Mayer and Matzarakis,* 1998a; *Höppe,* 1999). Meteorological parameters influencing the human energy balance include air temperature, air humidity, wind speed and short- and longwave radiation. It is necessary to determine these parameters at a human-biometeorologically significant height of 1.1 m above ground, corresponding to the average height of a standing adult's centre of gravity (*Mayer and Höppe*, 1987; *Matzarakis et al.,* 1999).

Large differences between air temperature and T_{mrt} (and PET) arise in winter days with high wind speed and in summer under calm and sunny conditions (*Höppe,* 1999). In these cases extreme cold or heat stress can be experienced. Examples of the resulting PET values at different seasonal, shading and wind conditions are illustrated in *Table 1*.

Investigations based on the application of PET in urban environments and their results are concentrated primarily on Germany (e.g. *Mayer and Höppe*, 1987; *Matzarakis et al.*, 1999; *Matzarakis et al.*, 2000; *Matzarakis*, 2002; *Mayer et al.*, 2004) and Sweden (e.g. *Svensson and Eliasson*, 2002; *Svensson et al.*, 2003; *Thorsson et al.*, 2004). Our work can contribute to this important research field and to the familiarisation with the usefulness of PET.

In this study we use T_{mrt} and PET to characterize the radiation conditions and to evaluate the human bioclimatological comfort sensations, respectively, in nearby, but different urban environments.

Table 1 Examples of PET values at different weather conditions (air temperature T_a, mean radiant temperature T_{mrt}, wind speed WS, vapour pressure VP) (*Höppe,* 1999)

Examples	**T_a (°C)**	**T_{mrt} (°C)**	**WS (ms^{-1})**	**VP (hPa)**	**PET (°C)**
Winter, sunny	-5	40	0.5	2	10
Winter, shade	-5	-5	5.0	2	-13
Summer, sunny	30	60	1.0	21	43
Summer, shade	30	30	1.0	21	29

2.3. RayMan model

One of the recently used radiation and bioclimate models is RayMan, developed in the Meteorological Institute, University of Freiburg. It is well-suited to calculate radiation fluxes [e.g. *Mayer and Höppe*, 1987; *Matzarakis*, 2002) thus all our calculations for T_{mrt} and PET were performed with this model. The RayMan model, developed according to Guideline 3787 of the German Engineering Society (*VDI*, 1998), calculates the radiation flux within urban structures on the basis of parameters such as air temperature, air humidity, degree of cloud cover, time of day and year, albedo of the surrounding surfaces and their solid-angle proportions.

The main advantage of the RayMan is that it facilitates the reliable determination of the microclimatological modifications of different urban environments, since the model takes into account the radiation modification effects of the complex surface structure (buildings, trees) very precisely. Besides the meteorological parameters the model requires input data on surface morphological conditions of the study area and on personal parameters.

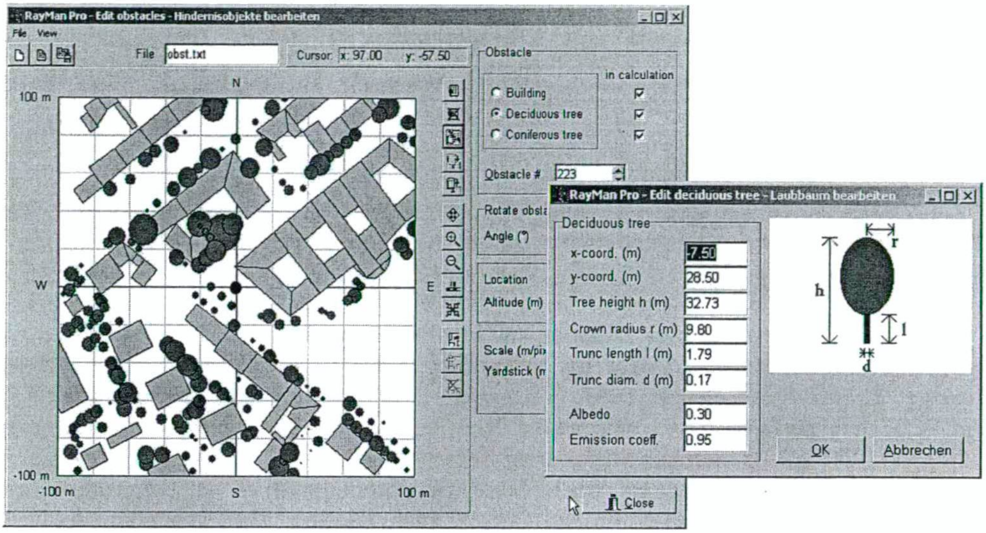
Morphological-geometrical data

The co-ordinates of the building plane area were derived from a very detailed digital map of the Szeged Municipality, while the heights of the buildings were measured on digital orthophotos (compiled from aerial photographs) using the ERDAS IMAGINE software (*Fig. 2*).

Tree vegetation in the sample area was also mapped. Altogether, it includes 184 deciduous trees and the measuring points are shaded mainly by lime trees (*Tilia platyphyllos*). (The most effective and human-bioclimatologically significant radiation modification can be obtained by deciduous trees, because they can provide shade in summer, while in winter they hardly affect the irradiation, which can improve the comfort sensation at this time of the year.) The exact locations, heights, trunk heights, trunk diameters and canopy diameters of the trees are input data for the model.

Meteorological data

As input meteorological data for the model we use four measured parameters in both cases: air temperature T_a (°C), relative humidity RH (%), wind speed WS (ms^{-1}) and global radiation GR (Wm^{-2}). The detailed microclimatic monitoring was taken by a portable mini-weather station (type HWI) equipped with Campbell sensors according to the WMO standards and a digital data logger. The measurements were taken at a height of 1.1 m above ground.


RayMan Pro - Edit obstacles - Hindernisobjekte bearbeiten

File: obst.txt
Cursor: x: 97.00 y: -57.50

Obstacle: ○ Building ● Deciduous tree ○ Coniferous tree
in calculation: ☑ Building ☑ Deciduous tree ☑ Coniferous tree
Obstacle #: 223

RayMan Pro - Edit deciduous tree - Laubbaum bearbeiten

Deciduous tree
x-coord. (m): -7.50
y-coord. (m): 28.50
Tree height h (m): 32.73
Crown radius r (m): 9.80
Trunc length l (m): 1.79
Trunc diam. d (m): 0.17
Albedo: 0.30
Emission coeff.: 0.95

Fig. 3 The map created by the RayMan with the exact locations of the elements and the parameters of trees (buildings are marked by light grey and trees by dark grey)

Personal data

Concerning themo-physiology of the human body, the age, sex, height, weight, clothing insulation (in *clo* unit (e.g. *Mayer and Höppe*, 1987; *Yan and Oliver*, 1996)), physical activity and position (sitting or standing) of the investigated person have been considered. The comfort estimation in both cases is directed on an "average European male" (35-year old, 1.75 m tall, weight 75 kg). His clothing index of 0.9 clo corresponds to a long sweater and trousers as well as the heat produced by activity (metabolic heat) that is equivalent to 80 W (*VDI,* 1998).

Besides the calculated T_{mrt} and PET values, we also obtained graphical results as additional model outputs. Among others, the model compiles a picture from the 3D surface morphological data in polar co-ordinates of the area (similar to a fish-eye photo) including the visible part(s) of the sun path of the observation day at the place, with the contours of buildings, trees or other obstacles. It is helpful for the evaluation of the radiation conditions of the observational point. (Conversely, if we took a photo by fish-eye lens camera, it could be an input parameter.)

3. RESULTS

3.1. Weather situation

On the investigated day (6th August, 2003) the weather was calm anticyclonal in the region of Szeged. Since wind data are measured at a higher level (30 m, on the roof), the input data need to be recalculated. The wind speed is determined in the reference height of 1.1 m according to the next formula (*Kuttler*, 1998):

$$WS_{1.1} = WS_h*(1.1/h)^{\alpha} \qquad \alpha = 0.12*z_0 + 0.18$$

where WS_h is the wind speed (ms^{-1}) at the height of h, α is an empirical exponent, depending on the surface roughness, z_0 is the roughness length. In our case $\alpha = 0.42$, because the sample area and its surroundings are a densely built-up inner city area with trees (*see Fig. 2*).

In the sample area six measurement points were positioned, which are adjacent to each other, but are characterised by very different exposure and radiation conditions (*Fig. 4*). We endeavoured to represent the varied microclimatic conditions in this small sample area. Measuring points 1 and 2 were located in the northern part of the NE-SW positioned Egyetem street, where they were surrounded by high buildings. At site 1 the trees' foliage is nearly continuous, while at site 2 the distances between trees are larger and trees do not provide complete shading. Sites 3 and 4 are situated in the two sides of the NW-SE directed Batthyány street. The buildings are much lower and, therefore, the exposure to direct radiation is longer during the day. Point 5 was on the northern side of Petőfi avenue, in a relatively open area, while point 6 was on the southern side of the avenue. At site 6 the nearly completely closed canopy shades the place nearly all day.

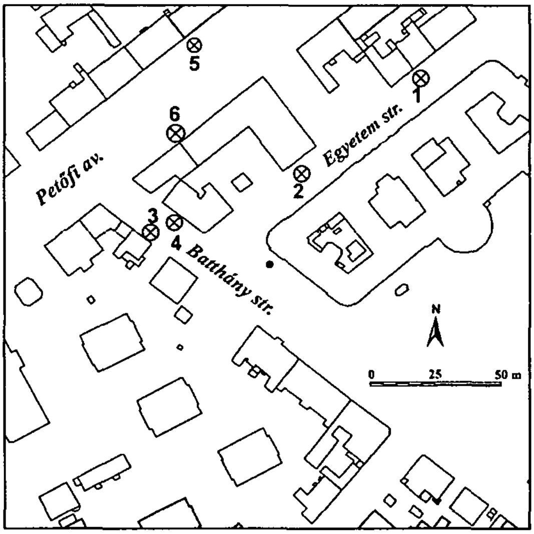


Fig. 4 The study area with the measurement points 1-6

List of the expositions of the measuring points:

- 1: street canyon with trees in NE-SW direction (abbreviated ***NE-scwt***),
- 2: street canyon without trees in NE-SW direction (***NE-scwot***),
- 3: street canyon with trees in NW-SE direction (***NW-scwt***),
- 4: street canyon without trees in NW-SE direction (***NW-scwot***),
- 5: wide street without trees in NE-SW direction (***NE-wswot***),
- 6: wide street with trees in NE-SW direction (***NE-wswt***).

The radiation characteristic of the investigated day is presented by the data measured on the roof (*Fig. 5*). The mobile measuring unit at the street level –due to its low sensitivity – demonstrated almost windless conditions all day. Therefore, *Fig. 5* shows wind data measured at a level of 30 m and the recalculated data for the height of 1.1 m.

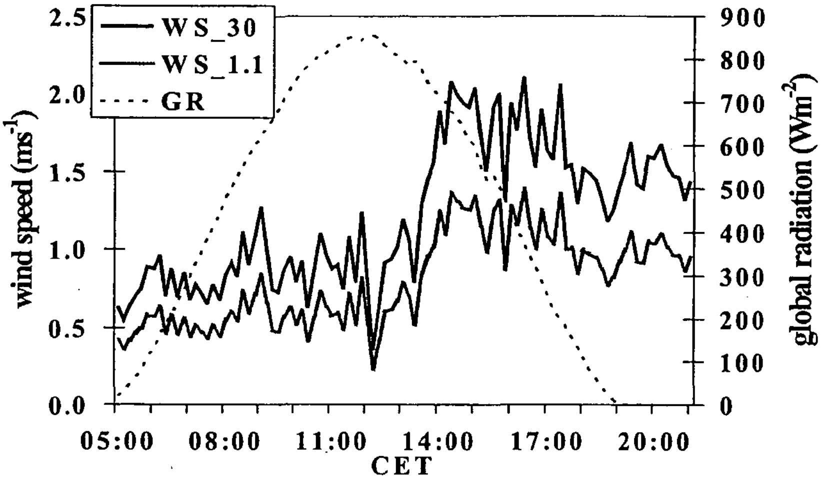


Fig. 5 Diurnal courses of meteorological parameters on 6th August, 2003 (WS_{30}: wind speed at a height of 30 m, $WS_{1.1}$: wind speed at a height of 1.1 m, GR: global radiation on the roof)

One minute averages were recorded by using the mobile measuring unit from sunrise till sunset. Temperature and relative humidity data recorded at the six points describe the weather characteristics of the day (*Fig. 6*).

The temperature values are identical (23.3-23.5°C) in every measurement points at sunrise and increase during the day due to the clear anticyclonal weather (*Fig. 6A*). The shape of the curves is similar during the day, the largest difference is observable in early afternoon, but the highest difference is only 1.7°C between the sites *NE-scwt* and *NE-wswt.* A short-time appearance of some clouds caused slight temperature decrease of a few tenth °C around 16.00 h. In the late afternoon until sunset the values converge. The relative humidity values are also identical in the six measurement points, the shape of the curves are the opposite compared to the temperature curves (*Fig. 6B*). Similarly to the temperature values, small differences between the sites can be seen; the slight increasing effect of the clouds in the afternoon is discernible. The small differences can be explained by the short distances between the measuring points.

3.2. Thermal comfort

The calculated T_{mrt} and PET values obtained from the mobile measurements are shown in *Fig. 7*. In contrast to the weather data, the values for the selected sites show significant differences. The results show a remarkable spatial variability in the values of T_{mrt} and PET.

T_{mrt} values are low during the day at the points *NE-scwt* and *NE-wswt,* because trees and buildings prevent the direct radiation (*Fig. 7A*). The widest range can be observed amongst the values obtained at the site *NE-scwt*. The value of global radiation (as well as the T_{mrt} value) increases immediately after sunrise and peaks at 13.00 hours. In the afternoon, an adjacent tree shades the site so that the global radiation declines after 13 h. High global radiation values are also measured at site *NE-scwot,* but the high buildings in close proximity give shade to the site and cause shorter irradiation (between 11.00 and

14.00 hours); therefore the radiation values quickly increase and then decrease there. At the site *NW-scwt* significant global radiation is measured only during a few hours in the afternoon.

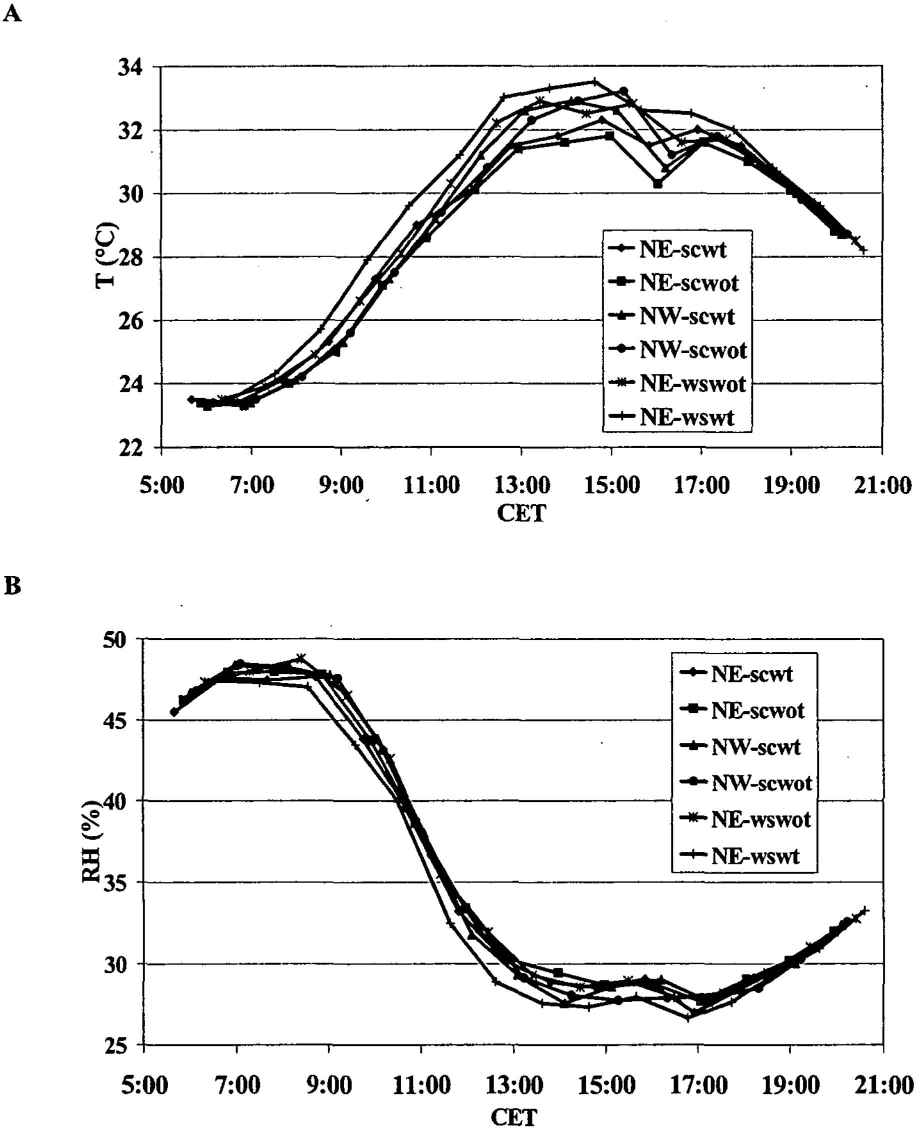


Fig. 6 Air temperature T (A) and relative humidity RH (B) at a height of 1.1 m above surface on 6th August, 2003

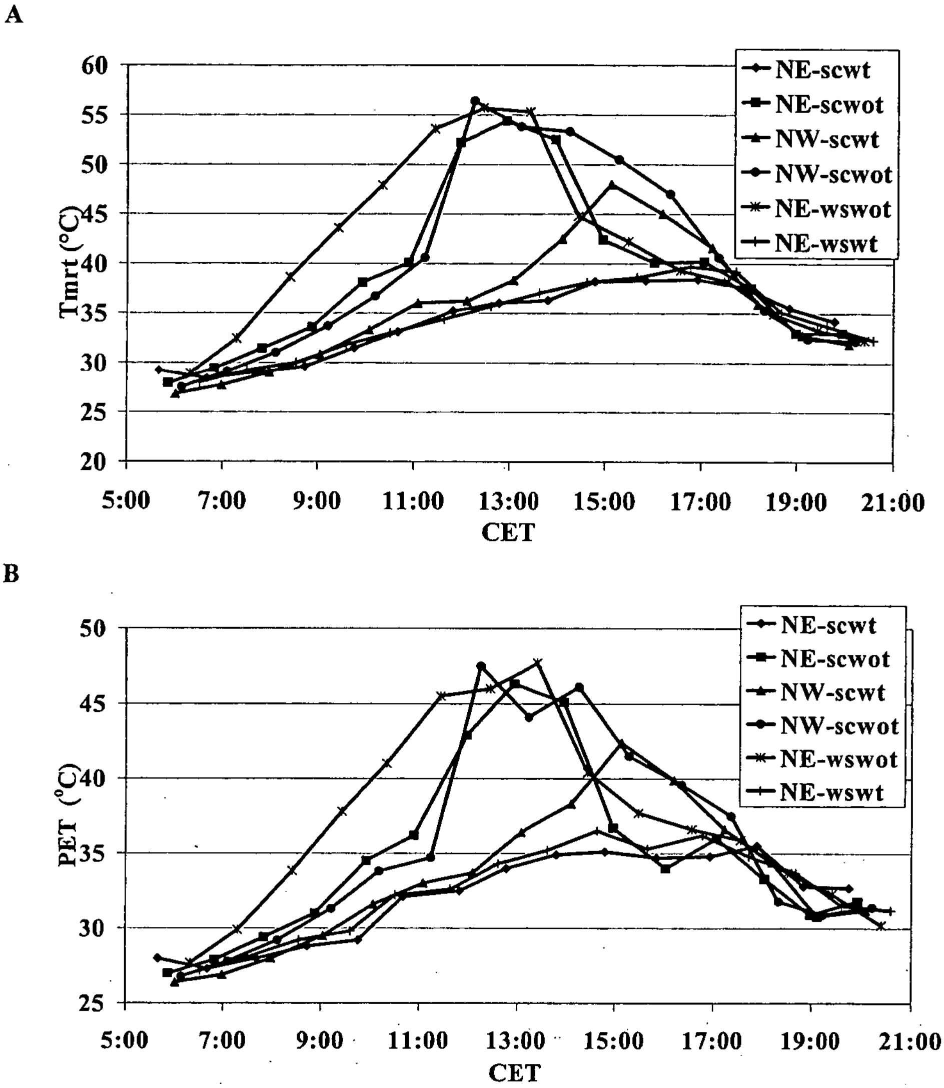


Fig. 7 Mean radiation temperature T_{mrt} (A) and Physiological Equivalent Temperature PET (B) computed by RayMan at the six measurement sites on 6th August, 2003

The calculated PET index shows that the heat stress exceeds the *comfortable* (18°C < PET < 23°C) level of human comfort (according to *Matzarakis and Mayer* (1996)) sensation during the whole day, a slight stress can be experienced even after sunrise (*Fig. 7B*). The heat stress is increasing until about 14.00 hours at every site, but local differences occur between the stations. The highest heat load is calculated for the site *NE-wswot* (PET = 47.7°C). This means an extreme physiological heat stress for the human body. The calculated maximum PET value reaches 45°C at the more open site *NE-scwot*, but the duration of the harmful effect of heat stress is shorter that at the site *NE-wswot*, due to the above-mentioned fast decrease of T_{mrt}.

The heat stress values are much lower on the sites (***NE-scwt*** and ***NE-wswt***) where no or only small amounts of direct radiation reach our model body. To present this, data from two measuring points ***NE-wswot*** and ***NE-wswt,*** which are close to each other (25 m) on the opposite sides of the same street (see *Fig. 5*), are compared. The fisheye views at these sites, generated by RayMan, show the path of the sun on the measurement day and the shading effect of the adjacent natural and artificial objects (trees, buildings) (*Fig. 8*).

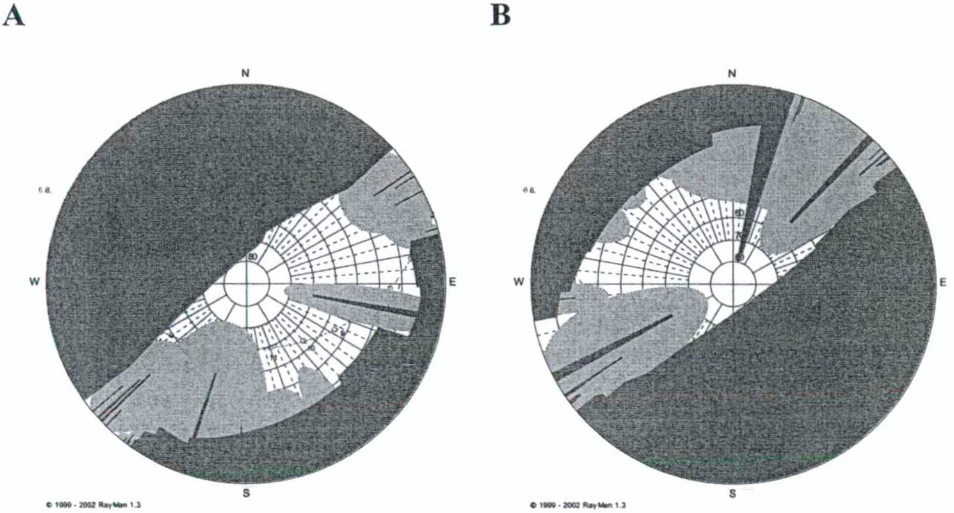


Fig. 8 Fisheye views at the measuring points ***NE-wswot*** (A) and ***NE-wswt*** (B) with the sun path on 6th August, 2003 created by RayMan

The measuring point ***NE-wswot*** is surrounded by buildings from NW, causing shade in the late afternoon (*Fig. 8A*). There is no coverage by buildings from other directions. In the first half of the day, only the tree canopies can provide some protection against the direct radiation. The opened SE exposure explains the extremely high direct radiation values and, as a result, the calculated very high heat stress. The point ***NE-wswt*** is in shade almost during the whole day (*Fig. 8B*).

Fig. 9 compares the T_a, T_{mrt} and PET values obtained from sites ***NE-wswot*** and ***NE-wswt***. The differences between the pairs are negligible at sunrise. The temperature values show small differences during the day, but between the T_{mrt} values the difference is increasing rather fast until early afternoon hours. As a result, the difference in the PET index at this time is very high (18-20°C), indicating a 2 step-stronger heat stress at the site ***NE-wswot*** than at the site ***NE-wswt***.

The study suggests that the value of the bioclimatic index PET – expressing the heat-load of the body – shows a strong correlation with the T_{mrt} value (the irradiation) in summer. This relationship is stronger than the relationship of the air temperature with PET. This statement is supported by the differences observed between T_a, T_{mrt} and PET values of the two selected points (***NE-wswot*** and ***NE-wswt***) in the second case. Despite the slightly higher temperature values at point ***NE-wswt,*** due to the irradiation conditions, the heat-load is significantly lower than at point ***NE-wswot*** (*Table 2*).

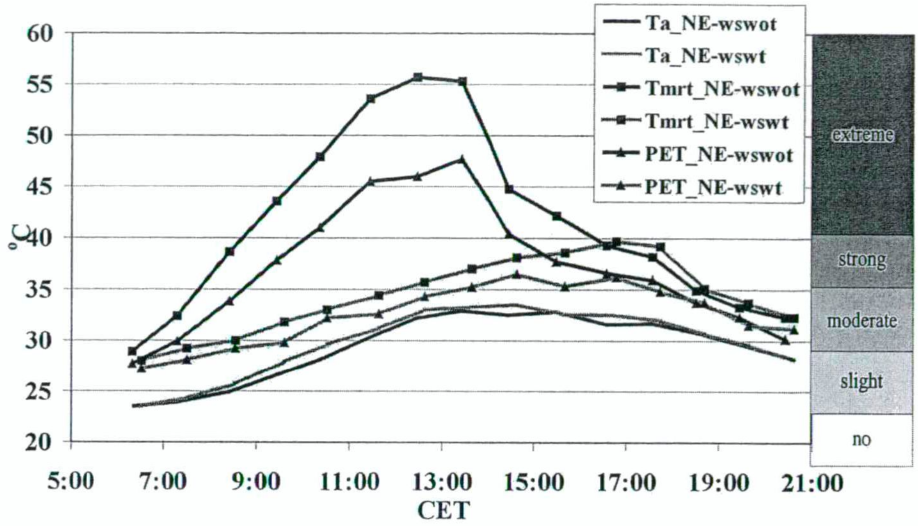


Fig. 9 Air temperature (T_a), mean radiation temperature (T_{mrt}) and PET with the Grade of Physiological Stress at the points ***NE-wswot*** and ***NE-wswt*** on 6th August, 2003

4. DISCUSSION

Table 2 Mean and maximum differences (°C) between the points ***NE-wswot*** and ***NE-wswt*** in the air temperature (T_a), mean radiant temperature (T_{mrt}) and Physiological Equivalent Temperature (PET) on 6th August, 2003

	point ***NE-wswot*** – point ***NE-wswt***	
	mean	*max*
T_a	-0.5	-0.6
T_{mrt}	7.0	16.0
PET	4.6	11.2

It is difficult for urban planners to design comfortable urban environments in cities or districts similar to our study area, because the parameters of the local climate are modified predominantly by the radiation modification effect of the 3D geometry of the existing built-up area. This phenomenon is more pronounced during summer when, after the high radiation load during daytime, the blocking or hampering of the outgoing long-wave radiation causes the heat island phenomenon, which often does not allow to decrease the heat stress to the *comfortable* level even during the night. Our results prove the beneficial effect of the vegetation, especially of trees.

Similarly to earlier studies in Germany, our results show a strong correlation between radiation modifications and changes in the thermal stress, focusing on the role of tree vegetation in these processes (*Mayer and Höppe*, 1987; *Mayer and Matzarakis*, 1998b).

An excellent prevention of summer heat-load is to plant deciduous trees. In our case the large canopy gives some protection against the direct radiation and, as a consequence, against the extreme heat stress in the midday hours. During the winter season the ideal situation is just the opposite (*Thorsson et al.*, 2004). Leafless trees reduce the extreme cold stress, since the incoming radiation with low angle can reach the surface unhampered.

The latest results of human bioclimatology and urban climatology should be considered when designing or reconstructing urban areas. Bioclimatic research can provide important data for planning and constructing urban surface structures and their environment, which is relevant not only for human comfort aspects.

5. CONCLUSIONS

The following conclusions are derived from the analysis presented:

- The presence of natural and artificial obstacles around the human body has an impact on the radiation fluxes and, consequently, on the energy balance of the human body; therefore changes in the radiation situation cause changes in the thermal comfort sensation.
- Complex urban environments can result in very different and often extreme comfort sensations even within short distances.
- The results obtained by RayMan can be a valuable source of information for planners, decision-makers and practitioners when planning and constructing new urban areas. The outputs are also of interest to the broader public, as they affect daily life.

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