

Comparison of different methods for the assessment of the urban heat island in Stuttgart, Germany

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Received: 1 August 2014 / Revised: 21 November 2014 / Accepted: 24 November 2014
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Abstract This study of the urban heat island (UHI) aims to support planning authorities by going beyond the traditional way of urban heat island studies. Therefore, air temperature as well as the physiologically equivalent temperature (PET) were applied to take into account the effect of the thermal atmosphere on city dwellers. The analysis of the urban heat island phenomenon of Stuttgart, Germany, includes a long-term frequency analysis using data of four urban and one rural meteorological stations. A (high resolution map) of the UHI intensity and PET was created using stepwise multiple linear regression based on data of car traverses as well as spatial data. The mapped conditions were classified according to the long-term frequency analysis. Regarding climate change, the need for adaptation measures as urban greening is obvious. Therefore, a spatial analysis of quantification of two scenarios of a chosen study area was done by the application of a micro-scale model. The nocturnal UHI of Stuttgart is during 15 % stronger than 4 K in the city center during summer when daytime heat stress occurs during 40 %. A typical summer condition is mapped using statistical approach to point out the most strained areas in Stuttgart center and west. According to the model results, the increase in number of trees in a chosen area (Olga hospital) can decrease PET by 0.5 K at 22:00 CET but by maximum 27 K at 14:00 CET.

Keywords Urban heat island · Mapping · Stuttgart · ENVI-met · RayMan · Urban climate · Physiologically equivalent temperature

Introduction

The phenomenon describing the relatively warmer urban atmosphere in comparison to the rural surroundings, usually referred to as urban heat island (UHI), was studied for the first time for London in 1833 (Howard 1833). The urban heat island is most pronounced under calm, cloudless conditions, depending strongly on urban morphology and land use types (Oke 1973, 1976; Landsberg 1981), whereby it often has a irregular shape within the city (Unger 2004).

Most of past and recent studies tend to quantify UHI in terms of highest air temperature differences or mean monthly or annual conditions (Unger 1996). Mean UHI is reported to be about 1–3 K on annual scale and maximum differences are about 9–14 K (i.e., Böhm and Gabl 1978; Landsberg 1981; Katsoulis and Theoharatos 1985; Bründel et al. 1987; Runnalls and Oke 2000; Szymanowski and Kryza 2012).

Since the latest 1960s of the twentieth century, an increased awareness of the UHI phenomenon has arisen. Among the comparison of rural and urban meteorological stations (Alcoforado and Andrade 2006), many studies have been set up on experimental basis using temporal networks (Katsoulis and Theoharatos 1985; Mihalakakou et al. 2004; Szymanowski and Kryza 2012), car traverses (Bottýán et al. 2005; Blankenstein and Kuttler 2004), or model simulations (Mirzaei and Haghighat 2010). These studies focused on the explanation of the causes of the urban heat island phenomenon at the meso-scale. They quantified the influencing parameters (urban morphology and physical properties of

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surface material) and the different weather conditions on UHI. Remote sensing data is often used to study surface temperature urban heat island or to quantify, e.g., vegetation properties for further analysis of the UHI (Voogt and Oke 2003; Ren et al. 2013). Remote sensing data has been also used for a study that quantifies the UHI encompassing Central Europe (Zakšek and Oštir 2012).

A gap between discretely measured data and the need of spatially continuous information with high resolution by officials and city planners remains to be a challenge in urban climatology. For solving this issues, different statistical approaches can be applied. In many studies, the relationship between the urban morphology and the UHI intensity is analyzed using (multiple) linear regressions (Runnalls and Oke 2000; Unger 2004; Alcoforado and Andrade 2006) or kriging methods (Unger et al. 2001; Bottyán and Unger 2003). Szymanowski and Kryza (2012) applied also geographically weighted regression for the determination of the UHI in relation to the urban structures. Artificial neural network is another method used by Mihalakakou et al. (2004) for mapping the UHI in Athens, Greece.

Air and surface temperature are usually used as meteorological parameters in these studies to quantify the UHI intensity in terms of arithmetic means over longer time periods. However, urban planners and architects require continuous information about micro-meteorological and human thermal comfort conditions for the whole year, as well as hot conditions (Eliasson 2000; Ketterer and Matzarakis 2014a). Thermal indices, which quantify the effects of thermal environment on people under consideration of the human energy balance, are for example the physiologically equivalent temperature (PET (Mayer and Höppe 1987; Höppe 1999; Matzarakis et al. 1999)) or the Universal Thermal Climate Index (UTCI (Jendritzky et al. 2012)). They require meteorological variables (air temperature, air humidity, wind speed as well as short- and long-wave radiation fluxes), and they consider information about physiology (age, weight, size, gender, activity, and clothing) in order to calculate the human energy balance. These thermal indices can be calculated by free available models (e.g., www.utci.org) and software, e.g., RayMan (Matzarakis et al. 2007, 2010). In this study, PET, with its widely known temperature unit ($^{\circ}\text{C}$), is used as an indicator of thermal stress and comfort.

The aim of this paper is to assess the different use-oriented methods for the quantification of the UHI. First, a frequency analysis for data of meteorological stations was done for a period of 11 years. Second, a map with 10 m resolution was produced using statistical approaches to identify most strained areas in Stuttgart-West and the city center. This mapping approach is based on data collected from a measuring campaign. Finally, the spatial effect of adaptation measures on the nocturnal UHI effect was quantified for a highly strained area comprising a hospital.

Consequently, these spatial approaches can be ranked into the background situation and the frequency of occurrence. Thereby, the paper concentrates on effect-based approaches by using PET.

Methods and data

A brief description of the study area

The study area, Stuttgart, is located in the southwestern part of Germany, and as of 2011, it had a population of 600,000. The bigger metropolitan area has more than five million inhabitants, making it the fourth largest metropolitan area in Germany (Fig. 1). During the climatic period of 1961 to 1990, the mean air temperature was 9.5°C and the average precipitation was 666 mm in Stuttgart (Schnarrenberg). The city center lies in a sink-like basin, while the urban quarters are spread across hills and valleys. Climate conditions are 2°C warmer in the city center than in the rural surroundings due to topography and the effect of the UHI phenomenon (Ketterer and Matzarakis 2014b). During winter, temperature inversions, i.e., an increase in air temperature with height, are frequent. The wind speed is mostly less than 3 ms^{-1} , especially in the city center and in the Neckar valley (Ketterer and Matzarakis 2014b). The selected area for specific thermal analysis and assessment is located in Stuttgart-West, extending from the circular depression to the western hills. Stuttgart-West is a quarter with high population and high building density, and many areas are planned to be reconstructed in future years.

Data

Meteorological stations

Four meteorological stations are available in Stuttgart: Neckartal (Neckar valley), Schwabenzentrum (city center), Schnarrenberg, and Hohenheim (suburb) (Fig. 1). The rural reference station is located at the airport in Echterdingen, which is about 11 km from the city center. The background measurement station at Schwabenzentrum is within the city center on the top of a 25m high building. The stations at Neckartal and Schnarrenberg are all located in the sink-like basin at an altitude of 224 to 314 m asl, while the station in the suburb area in Hohenheim lies at 405 m asl and the rural station in Echterdingen lies at 371 m asl.

Measuring campaign

A measuring campaign was carried out on July 03, 2014 and July 04, 2014, hot summer days with air temperature

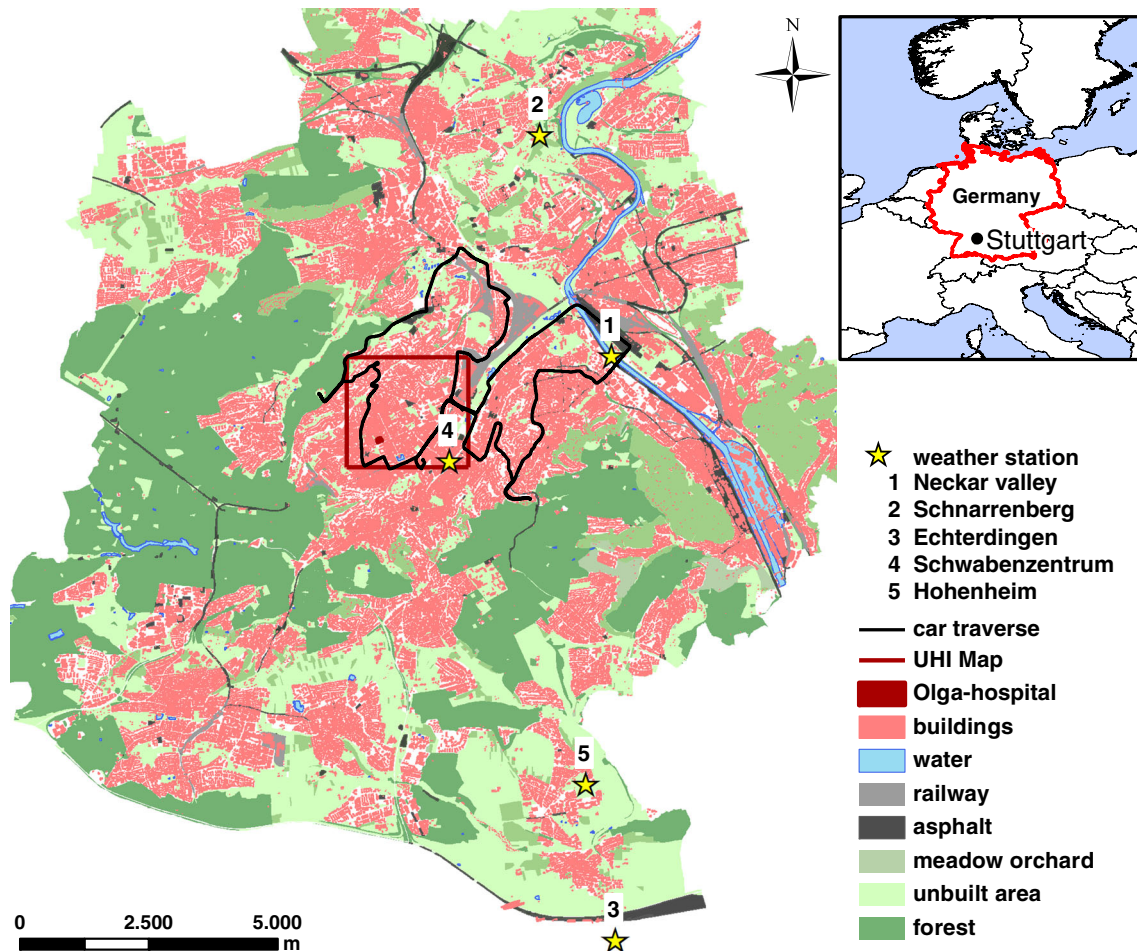


Fig. 1 Overview of land use types, location of the measuring stations, route of the measuring campaign, and case study areas (base map: City Surveying Office, Stuttgart)

up to 30 °C. The car traverses led from Stuttgart-West eastwards through the city center to Stuttgart-East, then up to the Neckar valley and back to Stuttgart-West (see Fig. 1). Air temperature and relative humidity were measured every 10 s during the campaign by the Humidity Temperature Meter HH314A with a resolution of 0.1 °C and 0.1 % relative humidity. The measuring instrument was mounted 30 cm above a white car with a horizontal offset of 30 cm at 2 m height above ground. The accuracy of the device is $\pm 2.5\%$ RH and $\pm 0.7\%$ °C and the response time of the instrument is 40 s in slowly moving air. The measuring campaign was conducted at 12:30 Central European Time (CET), 14:00 CET, 21:30 CET, and 3:00 CET with a duration of 1 h, except in the afternoon, when it took 1:30 h due to heavy traffic. The campaigns started and ended at the main railway station, where the eastern and western part from the main station took each 30 min with a maximum driving speed of 30 kmh⁻¹. Furthermore, surface temperature of different land use types and material was exemplary measured.

Spatial data

Spatial data of buildings, land use and land cover, vegetation, topography, thermal images, and wind field with different resolution were used. Based on this data, the sky view factor (SVF) was calculated in 3 m resolution for the whole Stuttgart. The SVF is a dimensionless measure between 0 and 1, representing totally obstructed and free spaces, and therefore, it denotes the ratio between radiation received by a planar surface and that from the entire hemispheric. Wind fields from 0° to 360° in 10° steps were calculated by DULAN wind model (DURchLüftungsANalyse (Röckle 2014, personal communication)) considering buildings and trees. The wind direction was chosen according to the diagnostic meso-scale wind model (DIWIMO) model that considers the topography (Schädler and Lohmeyer 1996) and the actual measured conditions at the time of the measuring campaigns. Furthermore, the wind speed was scaled according to the meso-scale model and measurements. Stewart and Oke (2012) proposed the use of the defined 17 local

climate zones (LCZ) for a better description of the study areas. Therefore, the LCZs were classified for Stuttgart as well (Fig. 2).

Statistical mapping approach

To transfer point data to spatially continuous information, statistical methods such as a stepwise multiple linear regression (SMLR) are required. A stepwise MLR defines the best combination of land use data to predict air temperature at 21:30 CET and helps understand which parameters have the greatest influence on air temperature. Stepwise MLR systematically adds and removes predictors based on the significance level. Interactions between predictors allow a further decrease of the error and increase in R^2 . The following normalized predictors for the SMLR were used: altitude, slope, aspect ratio, cold air flow, wind speed, land use types, build-up area, SVF, thermal image, depicting the radiant equivalent temperature, building height, and number of trees. The land use-type layers are defined as categorical variable.

Micro-meteorological models

Micro-scale model ENVI-met 3.5 (Bruse and Fleer 1998; Huttner 2012) was applied to simulate the spatial distribution of meteorological parameters for a selected area and some renovation scenarios, the Olga hospital area in Stuttgart-West. The conditions of the one-dimensional boarder model were initialized by the data of the urban station Schwabenzentrum for the same day as the measuring campaign, July 03, 2014. ENVI-met simulates micro-meteorological

surface-air-plant interactions inside complex urban structures in a three-dimensional non-hydrostatic way. The three-dimensional model is driven by a one-dimensional boundary cell. Its maximum spatial resolution is $250 \times 250 \times 30$ grids. Human-biometeorological conditions were calculated based on the results of the ENVI-met simulations in terms of PET (Ketterer and Matzarakis 2014a). To reduce the overestimation of the mean radiant temperature T_{mrt} by ENVI-met 3.5, which is primarily driven by the overestimation of the global radiation (Ali-Toudert 2005), the factor of shortwave adjustment was set to 0.82.

In this study, PET (Mayer and Höppe 1987; Höppe 1999; Matzarakis et al. 1999) was calculated using the model RayMan Pro (Matzarakis et al. 2007, 2010). Urban morphology is considered in terms of SVF, Bowen ratio, and albedo by the use of RayMan. Classes of PET for different grades of thermal perception by human beings and their physiological stress, defined as internal heat production of 80 W and heat transfer resistance of clothing of 0.9 clo, were applied in this analysis (Matzarakis and Mayer 1997).

The structure of the following section is described in Fig. 3. First, the long-term frequency analysis based on air temperature and PET is discussed for data of the meteorological stations over 11 years. Second, the map depicting air temperature and PET at micro-scale level (10m resolution) is described. The database, namely air temperature and air humidity measured during the car travers and land use data, topography, thermal maps, and urban morphology, was normalized for the statistical modeling approaches using SMLR. PET, as a target parameter for the SMLR, was calculated using the measured air temperature and relative humidity, the wind simulation, and the measurements scaled thermal map using RayMan. Finally, ENVI-met simulations were conducted to quantify the impact of adaptation measures on air temperature and PET on July 03, 2014.

Results

Long-term analysis of urban meteorological conditions

The urban meteorological conditions are analyzed using air temperature in terms of frequencies throughout the years 2000–2010. Additionally, the summer of 2003, characterized by two strong heat waves, is compared to the average conditions of the period 2000–2010 (Fig. 4). During summer 2003, air temperature was over 60 % of hourly data higher than 20 °C at Schnarrenberg and Schwabenzentrum, while in an average summer, this is the case only during 40 % (Fig. 4). Considering air temperature in general, it is highest at Schwabenzentrum, followed by Schnarrenberg, Neckartal, Hohenheim, and the rural reference station Echterdingen. Air temperature ≤ 0 °C occurs during 31.1 %

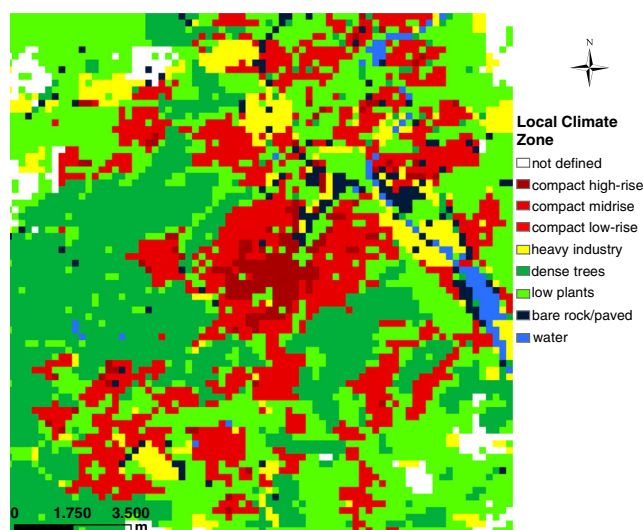
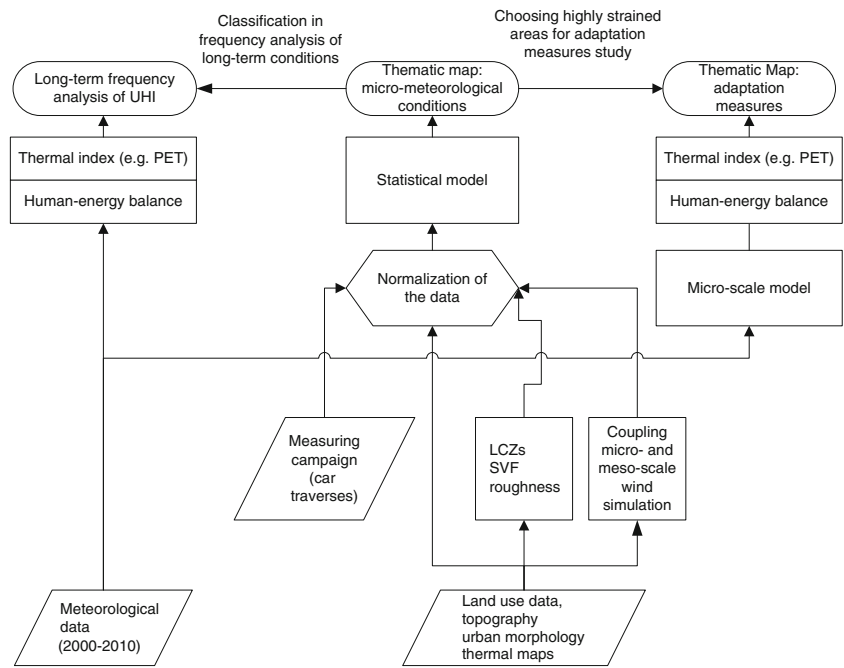


Fig. 2 Overview of the local climate zones (LCZ) defined by Stewart and Oke (2012) in Stuttgart, Germany. The resolution of a grid cell is 200×200 m

Fig. 3 Scheme of the UHI quantification of Stuttgart and classification of the results

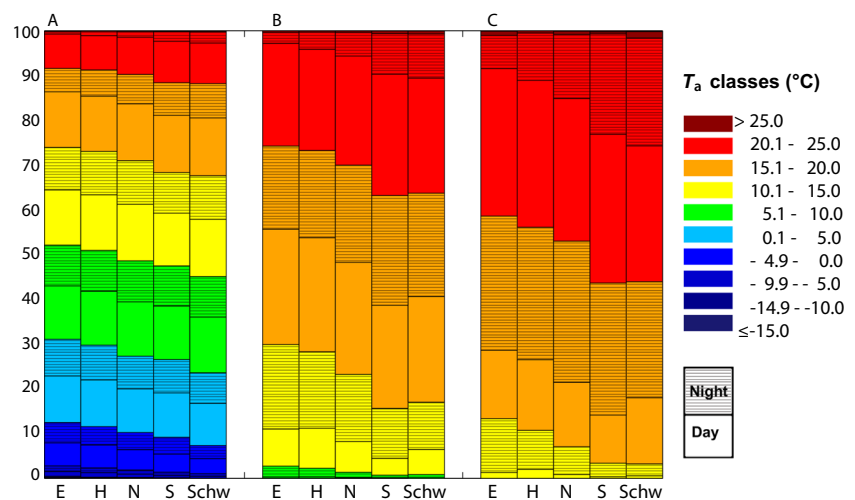


in the rural surroundings in Echterdingen but only during 23.6 % in the city center (Schwabenzentrum) (Fig. 4).

However, PET is higher at Schnarrenberg, followed by Neckartal, Schwabenzentrum, Hohenheim (suburb), and the rural reference station Echterdingen. PET value higher than 25 °C indicates heat stress according to Matzarakis and Mayer (1997). Heat stress occurs to 34 % during normal summer, but to 41 % in 2003. This means additional 110 h of heat stress from June to August in summer 2003 in comparison to normal summer. Strong cold stress ($PET \leq 4$ °C) occurs during 64.7 % in Echterdingen and 53.8 % in Schnarrenberg and, therefore, around 10 % less in the city center compared to Echterdingen (figure is not shown for clarity reasons).

At night time, the median nocturnal air temperature differences between the urban and the rural reference station (Echterdingen) are largest at Schwabenzentrum (2.5 K), followed by Schnarrenberg (2.1 K), Neckartal (1.2 K), and Hohenheim (0.7 K). For this analysis, hourly averages are used between sunset and sunrise. The median difference between Schwabenzentrum and Echterdingen corresponds to the difference of annual mean air temperature between 450 m difference in altitude. At Schnarrenberg, the nocturnal air temperature UHI is smaller than the urban-rural air temperature differences in daytime. Actually, the nocturnal PET differences are lower than during daytime. This is based on the fact that the measuring site is surrounded by unbuilt area, and it is located on top of a southwest

Fig. 4 Frequency diagram of hourly averages of air temperature T_a following different measuring stations in Stuttgart for the period 2000–2011 (panel A): Echterdingen (E), Hohenheim (H), Neckar valley (N), Schnarrenberg (S), and Schwabenzentrum (Schw). The conditions of the summer months June to August (JJA) over the 11 years are depicted in panel B and JJA in 2003 in panel C



exposed hill, featuring high daytime irradiation on the one hand, but a high cooling rate on the other hand. Furthermore, the altitude of the measuring station of 314 m asl. is only 57 m lower than the rural reference station. Neckartal and Schwabenzentrum show frequently lower air temperature and PET during daytime than the rural surroundings. This is due to inversions, but it is also caused by the frequently occurring urban cooling island during summer between 10:00 and 12:00 CET (Ketterer and Matzarakis 2014b). The differences between the suburb Hohenheim and the rural reference station Echterdingen show a small standard deviation, and they are larger at night than at daytime. During night time, UHI_{PET} is similar to UHI_{Ta} . In Hohenheim, UHI_{PET} is negative almost during 50 % of the time due its higher elevation (405 m) compared to Echterdingen (371 m). Urban-rural PET differences are highest in daytime (in the late afternoon), while air temperature UHI is highest at night time.

Spatial analysis of meteorological conditions in Stuttgart

Statistical approaches

A map of the micro-climatic conditions for parts of the city center was made by the use of SMLR for the July 03, 2014

at 21:30 CET (Figs. 5 and 6). The warm city center around the main station has an UHI intensity of up to 5.8 K and air temperature of 25.7 °C (Fig. 5). The city center is also the lowest elevation of the selected study area. The cooler area, with an UHI of 3.5–4 K in the south of the main station, is a small park called Oberer Schlossgarten. The UHI intensity also drops by 2 K at the Feuersee, a small park with a lake surrounding a church to the southwestern part of the city center. The area on the west of the Olga hospital in Stuttgart-West suffers from warm temperature of up to 25.4 °C due to the high building density. Areas situated on the higher elevation in the west and north feature lower temperature values of 22.5 to 24.3 °C, and therefore, a UHI intensity between 0.8 and 3.1 K. The model was compared with the measured values. The root mean square error (RMSE) is 0.28 and R^2 is 0.88.

The PET map (Fig. 6) depicts similar pattern of the thermal environment, as described above. PET was calculated based on the measured air temperature and air humidity during the measuring campaign, as well as on the wind simulations and surface temperatures estimated by the use of the thermal map, scaled by point measurements of the surface temperature during the measuring campaign for different materials. PET values are higher in the densely built city center and in the surroundings of the city center, but

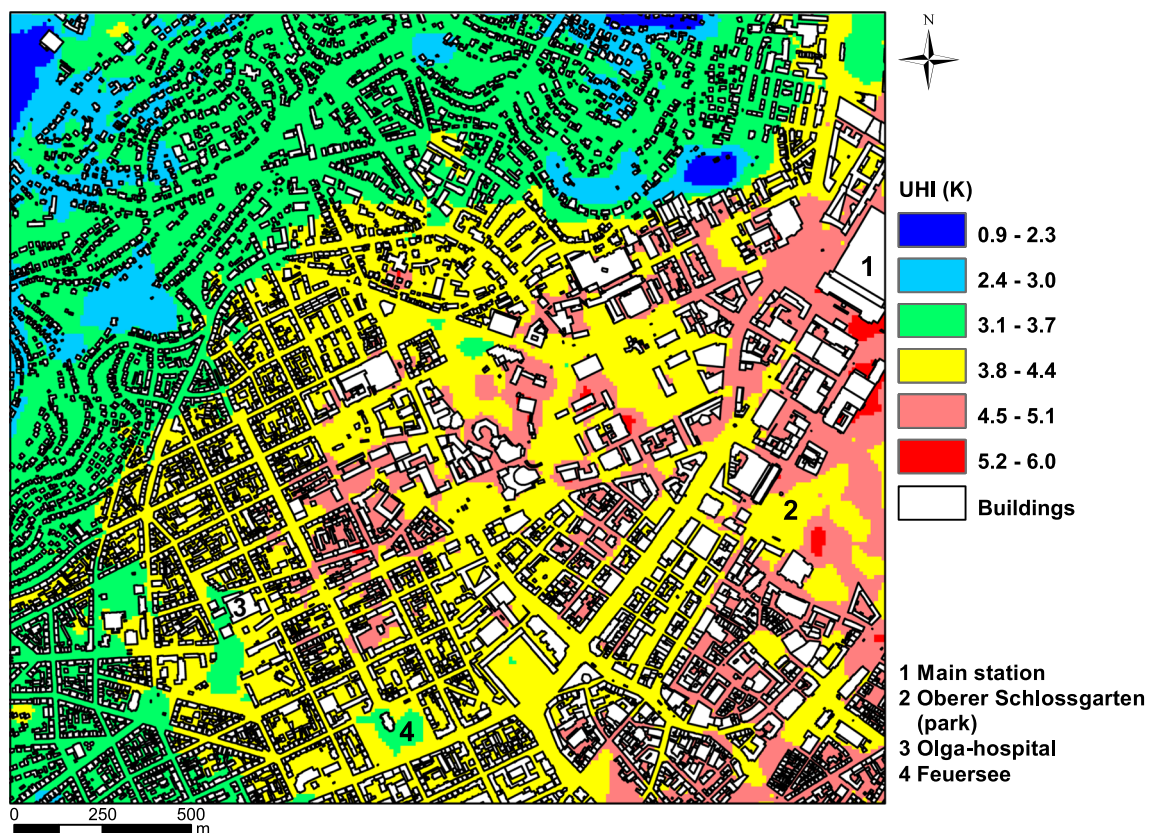


Fig. 5 Mapping of UHI_{Ta} using stepwise multiple linear regression for Stuttgart-West and the city center on July 03, 2014, 21:00 CET

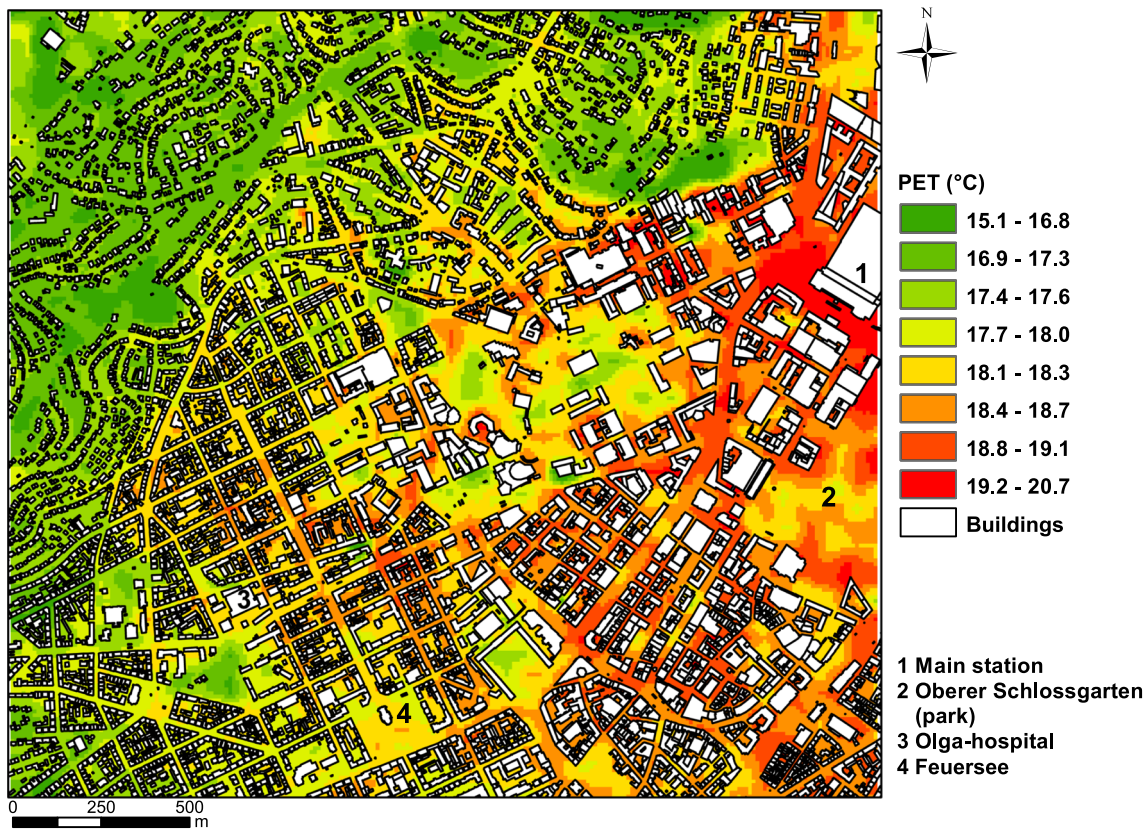


Fig. 6 Mapping of PET using stepwise multiple linear regression for Stuttgart-West and the city center on July 03, 2014, 21:00 CET

also in Stuttgart-West, higher PET values of 18–20 °C area are depicted. The RMSE of the PET simulation is 0.32 and R^2 is 0.89.

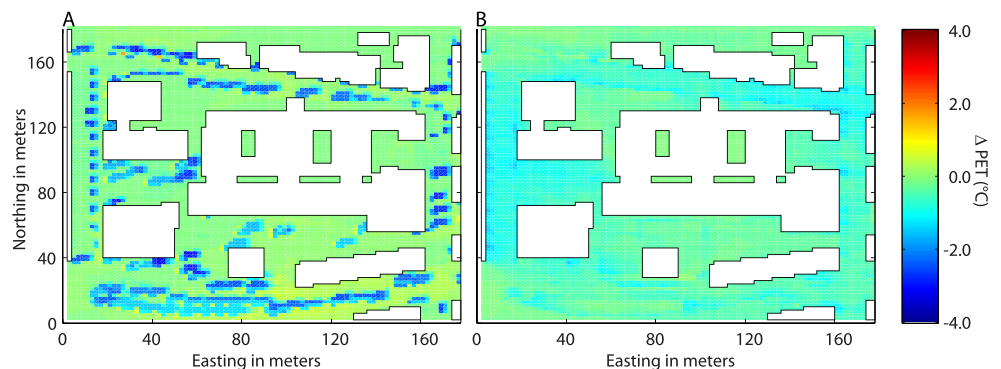
Micro-scale simulations on adaptation measures

The UHI was simulated for the current state of the Olga hospital and one scenario with additional trees using ENVI-met and forcing with the data of the nearby measuring site Schwabenzentrum (locations, see Fig. 1). The tree scenario features 12 times more trees than the hospital scenario, which is located especially along streets and pavements to

provide shading. The tree scenario is up to 27 K PET lower on July 03, 2014 at 14:00 CET. The spatial average is 2.2 K and the median is 0.2 K. In Fig. 7, panel A, it is clearly visible that the cooler areas are very limited to the areas with additional trees.

In the evening at 21:00 CET, the average PET differences are very small between the different scenarios in the Olga hospital area. The median and average difference between the scenarios with more trees and the current state is 0.4 and 0.5 K at 21:00 CET. PET of the tree scenario compared to the current state is up to a maximum of 1.4 K colder (Fig. 7, panel B).

Fig. 7 Mapping of PET differences (Δ PET) between the current scenario and a scenario with an increased leaf area index at the Olga hospital in Stuttgart-West (location see Fig. 1) on 03.07.2014 at 14:00 CET (panel A) and 21:00 CET (panel B)



Discussion

The main focus in this urban micro-meteorological analysis is the thermal comfort of city dwellers. Therefore, the integral effect of the thermal atmosphere is taken into account by the use of PET.

The nocturnal UHI is most distinguished during summer when its intensity often exceeds 4 K, especially in the city center (see Table 1). This increases the number of hours with heat stress within 1 day. Therewith, the city dwellers are exposed to additional heat stress compared to the rural site or higher elevated suburban site. In spite of the negative reputation of the UHI phenomenon, it is, by triggering a higher thermal regime in urban areas, also advantageous for the better part of the year in mid-latitudes in terms of energy consumption (Matzarakis et al. 2009) or outdoor comfort (Ketterer and Matzarakis 2014b).

The maximum UHI intensity of 5.4 K detected during the measuring campaign is a representative value for nocturnal summer conditions in Stuttgart. The studied adaptation measure of doubling the number of trees in this area leads, at 22:00 CET, to cooling in PET of 0.5 K (spatial average). Heat stress is a phenomenon on macro-scale during conditions with stable high pressure. Therefore, it is not possible to mitigate this straining conditions, but daytime heat stress can be counteracted by shading. The impact of trees on daytime comfort conditions is admittedly significant by an average cooling of 2.2 K PET and maximal 27 K. The urban-rural temperature differences are often negative in the morning hours (Ketterer and Matzarakis 2014b) because the building material absorbs the incoming short-wave radiation. However, these measures have rather a small impact on the nocturnal conditions. Better insulation, such as green roofs (Niachou et al. 2001) or phase-changing material (free-cooling) (Baetens et al. 2010), could be used to improve indoor thermal conditions during heat waves due to technical measures. Additionally, the population has to

be informed how to adapt their behavior relating to shading and ventilating their flat (Matthies 2008).

Increase in vegetation, in the number of trees, or in their dimensions in urban areas are a popular measure to counteract heat stress. Trees decreases air temperature up to 1.5–3.1 K at 13:00 CET (Streiling and Matzarakis 2003; Shashua-Bar and Hoffman 2004; Ali-Toudert and Mayer 2007; Ketterer and Matzarakis 2014a) and PET by 15 K (Streiling and Matzarakis 2003) and up to 24 K (Ali-Toudert and Mayer 2007). Trees have a maximum impact on thermal conditions by shading in the daytime and by increased evaporation (Shashua-Bar and Hoffman 2004; Cohen et al. 2012). Furthermore, not all tree species are adequate to be planted in cities in respect to allergic persons (D'Amato et al. 2007) also because they produce more biomass and pollen compared to rural areas (Ziska et al. 2003). In mid-latitudes, deciduous trees are more favorable to increase global radiation in winter and providing shade in summer.

With data measured by climate and meteorological stations, not only arithmetic mean can be calculated but also a much more meaningful frequency analysis can be conducted. Calculating the arithmetic mean is often not representative because, mostly, the data is not normally distributed, and thus, the median is more meaningful. Using the frequency analysis, single events can be classified in a broader context. The UHI intensity depends strongly on the choice of the urban as well as rural reference stations, especially in complex topography. Additionally, it has to be mentioned that the approach of Stewart and Oke (2012) is limited due to influence of the micro-scale meteorological phenomenon triggered by the topography, e.g., cold air flow.

Data of car traverses often lack quality compared to meteorological stations. Possible sources of errors are due to relatively high driving and inconstant speed of the car, choice of the route, calibration and exactness of the measuring devices, position of the devices on the car, and surface temperature of the car in comparison to ambient

Table 1 Frequency (%) of urban-rural PET differences (in K) between the four urban and the rural reference station at Echterdingen between sunset and sunrise

Δ PET (K)	Winter				Spring				Summer				Autumn			
	SchB	Neckar	SchwZ.	Hohenh	SchB	Neckar	SchwZ.	Hohenh	SchB	Neckar	SchwZ.	Hohenh	SchB	Neckar	SchwZ.	Hohenh
≤ -2	0.4	1.3	0.1	3.7	0.2	0.8	0.1	2.3	0.0	0.7	0.1	2.5	0.3	1.5	0.1	2.9
> -2 to 0	9.4	51.8	7.0	64.8	8.8	47.2	4.1	56.9	5.1	38.6	3.6	59.7	11.3	48.4	6.1	61.7
> 0 –2	70.9	40.8	63.5	26.7	70.7	42.2	54.4	33.0	64.6	51.4	45.5	34.6	66.1	42.5	57.2	31.2
> 2 –4	18.2	5.6	25.6	4.5	17.1	8.9	30.6	7.3	26.4	8.3	35.7	3.2	19.0	6.9	28.3	4.0
≥ 4	1.1	0.5	3.9	0.3	3.2	0.9	10.7	0.4	3.8	1.0	15.2	0.1	3.2	0.6	8.3	0.2

Data basis are hourly averages in the period 2000–2010. The urban stations are Schnarrenberg (SchB), Neckar valley (Neckar), Schwabenzentrum (SchZ), and Hohenheim (Hohenh)

air and surface temperature. Furthermore, the measurements are subject to a time delay due to a certain inertia of the measuring devices. Statistical models and approaches like SMLR are a good possibility to offer spatial information of meteorological data provided that sufficient point data in a certain neighborhood are available. However, significant linear correlation between land use and parameters derived from land use data, such as SVF and temperature (air temperature, potential temperature or PET), cannot be detected for Stuttgart. This finding is contrary to studies in Szeged, Hungary (e.g., Unger 2004, 2006). Causes might be the complex topography of Stuttgart, triggering local meteorological phenomenon, as well as the inhomogeneous land use and land cover, while Szeged is located in very flat terrain; therefore, the SVF might be a parameter that experiences the strongest changes. Regarding the SMLR, there were some complexities to overcome. First of all, the resolution of some input raster data is inhomogeneous and do not always meet the demands of the necessary resolution. Secondly, the measurements of the measuring campaign do not cover the whole range of possible combinations of land use data. The error between measured temperature and simulated one along the car route is most frequent (67 %) between 0 and 0.25 K, which can be assessed to be reasonable. Another error developed by choosing estimated Bowen ratio and albedo for the PET calculation by RayMan is estimated to be between 1 and 3 K depending on the conditions (wet or dry surface).

Micro-scale models, such as ENVI-met, represent a good possibility for the quantification of the impact of different planning scenarios on human-biometeorological conditions at micro-scale. Availability of hourly measured data of air temperature and humidity of a nearby meteorological stations as forcing of the ENVI-met simulations ensures rather realistic simulated results. However, micro-scale models have limitations. Only short periods over several days and a small simulation area can be calculated. Moreover, ENVI-met 3.5 does not consider heat storage and transfer by buildings or anthropogenic heat production in an adequate manner. These processes, anyhow, contribute strongly to the development of urban-rural temperature differences, especially in the tropics and in the mid and high latitudes in winter. Cold air flow, an important phenomenon for air quality, and thermal comfort in cities in complex topography are not considered by most micro-scale models. ENVI-met 3.5 requires also homogeneous horizontal conditions. The global radiation calculated by ENVI-met 3.5 is usually too high (Ali-Toudert 2005), for which reason the factor of shortwave adjustment was set to 0.82. However, in the morning and afternoon, the global radiation is still overestimated.

Maps show always a trend and the main pattern of the thermal environment, but the absolute values are defective. The error in measurements accounts for up to 0.7 K; the

SMLR results in an error between 0 and 0.25 K for mapping of air temperature. Regarding the PET map, an additional error of the PET calculation by RayMan of 1–2 K has to be added. The land use-type raster data has a resolution between 10 and 50 m, which is sometimes visible in the maps having a resolution of 10 m.

Conclusion

Extreme meteorological conditions, especially heat waves, are of interest for city planners and authorities. Frequent occurrence of heat stress limits the health-related quality of life for people in cities. Therefore, urban micro-meteorology issues are becoming more important for authorities dealing with planning purposes. This is also of importance facing the challenges of climate change, with an increase in the average temperature as well as more frequent heat waves, in urban areas. In the summer of 2003, heat stress occurred at 41 %, which is 7 % more than in an average summer in the period 2000–2010. Based on the fact that air temperature is only one factor affecting human energy balance, the meteorological conditions have to be studied using appropriate human-biometeorological methods considering the integral effect of the thermal atmosphere. A study about urban micro-meteorological conditions should be based on a frequency analysis of measured data over a period of several years in order to have an overall description of the background conditions. Heat stress is 7 % more, but cold stress is 9 % less, frequent in the city center of Stuttgart compared to the rural reference station at the airport.

From these results, single events, which can be extreme or average, can be chosen for a spatial assessment. Maps are helpful for planners and architects to identify areas with more or less heat stress in order to counteract this heat stress and the urban heat island. For these identified hot spot areas, different adaptation measures can be quantified by micro-scale models, such as ENVI-met or RayMan. For the development of maps, two possibilities, namely numerical and statistical modeling, exist and can be applied under consideration of their limitations. Extracted results from mapping and spatial distribution have finally been embedded in the long-term analysis. The combination of these maps, background conditions, expected climate change conditions, and expected changes in urban micro-structures is of great importance to decision-makers. The way to communicate the derived results to final users and decision-makers should be set in the focus of recent studies. Limitations of applied methods have to be expressed and discussed in detail. At micro-scale level, the variability of the human-biometeorological conditions is very high and complex to be assessed and communicated.

Finally, the seasonal aspects of UHI have to be considered. During daytime, heat stress occurs most frequently. In summer, when the day is longer in mid-latitudes and the nocturnal cooling phase is short, city dwellers suffer additionally from a low cooling rate, which is expressed by a high nocturnal heat island intensity. A decrease in the indoor air temperature could be achieved by enhanced heat isolation that is effective in daytime.

Acknowledgments This study is part of the transnational cooperation project within the Central Europe Program "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 program co-financed by the ERDF. We thank the Office for Environmental Protection, Section of Urban Climatology of Stuttgart for providing meteorological data of Stuttgart-Schwabenzentrum and the City Surveying Office Stuttgart for the spatial data. We acknowledge the German Weather Service (DWD) for providing the climate data.

References

- Alcoforado MJ, Andrade H (2006) Nocturnal urban heat island in Lisbon (Portugal): main features and modelling attempts. *Theor Appl Climatol* 84(1–3):151–159. doi:[10.1007/s00704-005-0152-1](https://doi.org/10.1007/s00704-005-0152-1)
- Ali-Toudert F (2005) Dependence of outdoor thermal comfort on street design in hot and dry climate. PhD thesis. Albert-Ludwigs-University, Freiburg im Breisgau. <http://www.freidok.uni-freiburg.de/volltexte/2078/>
- Ali-Toudert F, Mayer H (2007) Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons. *Sol. Energy* 81(6):742–754. doi:[10.1016/j](https://doi.org/10.1016/j.10.1016/j)
- Baetens R, Jelle BP, Gustavsen A (2010) Phase change materials for building applications: a state-of-the-art review. *Energy and Buildings* 42(9):1361–1368. doi:[10.1016/j.enbuild.2010.03.026](https://doi.org/10.1016/j.enbuild.2010.03.026)
- Blankenstein S, Kuttler W (2004) Impact of street geometry on downward longwave radiation and air temperature in an urban environment. *Meteorol Z* 13(5):373–379. doi:[10.1127/0941-2948/2004/0013-0373](https://doi.org/10.1127/0941-2948/2004/0013-0373)
- Böhm R, Gabl K (1978) Die Wärmeinsel einer Großstadt in Abhängigkeit von verschiedenen meteorologischen Parametern. *Archiv für Meteorologie, Geophysik und Bioklimatologie Serie B* 26(2–3):219–237. doi:[10.1007/BF02242675](https://doi.org/10.1007/BF02242675)
- Bottýán Z, Unger J (2003) A multiple linear statistical model for estimating the mean maximum urban heat island. *Theor Appl Climatol* 75(3–4):233–243. doi:[10.1007/s00704-003-0735-7](https://doi.org/10.1007/s00704-003-0735-7)
- Bottýán Z, Kircsi A, Szegedi S, Unger J (2005) The relationship between built-up areas and the spatial development of the mean maximum urban heat island in Debrecen, Hungary. *Int J Climatol* 25(3):405–418. doi:[10.1002/joc.1138](https://doi.org/10.1002/joc.1138)
- Bründel W, Mayer H, Baumgartner A (1987) Stadtklima Bayern. Abschlussbericht zum Teilprogramm Klimamessungen München, Reihe Materialien, vol 43. Staatsministerium für Landesentwicklung, Bayern and Germany
- Bruse M, Fleer H (1998) Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. *Environ Model Softw* 13(3–4):373–384. doi:[10.1016/S1364-8152\(98\)00042-5](https://doi.org/10.1016/S1364-8152(98)00042-5)
- Cohen P, Potchter O, Matzarakis A (2012) Daily and seasonal climatic conditions of green urban open spaces in the Mediterranean climate and their impact on human comfort. *Build Environ* 51(2):285–295. doi:[10.1016/j.buildenv.2011.11.020](https://doi.org/10.1016/j.buildenv.2011.11.020)
- D'Amato G, Cecchi L, Bonini S, Nunes C, Annesi-Maesano I, Behrendt H, Liccardi G, Popov T, van Cauwenberge P (2007) Allergenic pollen and pollen allergy in Europe. *Allergy* 62(9):976–990. doi:[10.1111/j.1398-9995.2007.01393.x](https://doi.org/10.1111/j.1398-9995.2007.01393.x)
- Eliasson I (2000) The use of climate knowledge in urban planning. *Landsc Urban Plan* 48(1–2):31–44. doi:[10.1016/S0169-2046\(00\)00034-7](https://doi.org/10.1016/S0169-2046(00)00034-7)
- Höppe P (1999) The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol* 43(2):71–75. doi:[10.1007/s004840050118](https://doi.org/10.1007/s004840050118)
- Howard L (1833) The climate of London: deduced from meteorological observations, vol 1
- Huttner S (2012) Further development and application of the 3D microclimate simulation ENVI-met. PhD thesis. Johannes Gutenberg-Universität, Mainz. <http://ubm.opus.hbz-nrw.de/volltexte/2012/3112>
- Jendritzky G, Dear R, Havenith G (2012) UTCI—why another thermal index *Int J Biometeorol* 56(3):421–428. doi:[10.1007/s00484-011-0513-7](https://doi.org/10.1007/s00484-011-0513-7)
- Katsoulis BD, Theoharatos GA (1985) Indications of the urban heat island in Athens, Greece. *Journal of Climate and Applied Meteorology* 24(12):1296–1302. doi:[10.1175/1520-0450\(1985\)024<1296:IOTUHI>2.0.CO;2](https://doi.org/10.1175/1520-0450(1985)024<1296:IOTUHI>2.0.CO;2)
- Ketterer C, Matzarakis A (2014a) Human-biometeorological assessment of heat stress reduction by replanning measures in Stuttgart, Germany. *Landscape and Urban Planning* 122:78–88. doi:[10.1016/j.landurbplan.2013.11.003](https://doi.org/10.1016/j.landurbplan.2013.11.003)
- Ketterer C, Matzarakis A (2014b) Human-biometeorological assessment of the urban heat island in a city with complex topography—the case of Stuttgart, Germany. *Urban Climate*. doi:[10.1016/j.uclim.2014.01.003](https://doi.org/10.1016/j.uclim.2014.01.003)
- Landsberg HE (1981) The urban climate. The Academic Press, London
- Matthies F (2008) Heat-health action plans: guidance. World Health Organization. Europe, Copenhagen and Denmark
- Matzarakis A, Mayer H (1997) Heat stress in Greece. *Int Journal Biometeorol* 41(1):34–39. doi:[10.1007/s004840050051](https://doi.org/10.1007/s004840050051)
- Matzarakis A, Mayer H, Iziomon MG (1999) Applications of a universal thermal index: physiological equivalent temperature. *Int J Biometeorol* 43:76–84
- Matzarakis A, Rutz F, Mayer H (2007) Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *Int. J Biometeorol* 51(4):323–334. doi:[10.1007/s00484-006-0061-8](https://doi.org/10.1007/s00484-006-0061-8)
- Matzarakis A, Thomson F, Mayer H (2009) Klimawandel und Heizgradtage in Freiburg im Breisgau, Südwestdeutschland. *Gefahrstoffe - Reinhaltung der Luft* 69:319–324
- Matzarakis A, Rutz F, Mayer H (2010) Modelling radiation fluxes in simple and complex environments: basics of the RayMan model. *Int J Biometeorol* 54(2):131–139. doi:[10.1007/s00484-009-0261-0](https://doi.org/10.1007/s00484-009-0261-0)
- Mayer H, Höppe PR (1987) Thermal comfort of man in different urban environments. *Theor Appl Climatol* 38(1):43–49. doi:[10.1007/BF00866252](https://doi.org/10.1007/BF00866252)
- Mihalakakou G, Santamouris M, Papanikolaou N, Cartalis C, Tsangrassoulis A (2004) Simulation of the urban heat island phenomenon in Mediterranean climates. *Pure Appl Geophys* 161(2):429–451. doi:[10.1007/s00024-003-2447-4](https://doi.org/10.1007/s00024-003-2447-4)
- Mirzaei PA, Haghighat F (2010) Approaches to study urban heat island—abilities and limitations. *Build Environ* 45(10):2192–2201. doi:[10.1016/j.buildenv.2010.04.001](https://doi.org/10.1016/j.buildenv.2010.04.001)

- Niachou A, Papakonstantinou K, Santamouris M, Tsangrassoulis A, Mihalakakou G (2001) Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings* 33(7):719–729. doi: [10.1016/S0378-7788\(01\)00062-7](https://doi.org/10.1016/S0378-7788(01)00062-7)
- Oke TR (1973) City size and the urban heat island. *Atmos Environ* 1967 8(7):769–779. doi: [10.1016/0004-6981\(73\)90140-6](https://doi.org/10.1016/0004-6981(73)90140-6)
- Oke TR (1976) The distinction between canopy and boundary-layer urban heat islands. *Atmosphere* 14(4)
- Ren Z, He X, Zheng H, Zhang D, Yu X, Shen G, Guo R (2013) Estimation of the relationship between urban park characteristics and park cool island intensity by remote sensing data and field measurement. *Forests* 4(4):868–886. doi: [10.3390/f4040868](https://doi.org/10.3390/f4040868)
- Runnalls KE, Oke TR (2000) Dynamics and controls of the near-surface heat island of Vancouver, British Columbia. *Phys Geogr* 21(4):283–304. doi: [10.1080/02723646.2000.10642711](https://doi.org/10.1080/02723646.2000.10642711)
- Schädler G, Lohmeyer A (1996) Kaltluft- und Windfeldberechnungen für Stuttgart. In: State capital Stuttgart Environmental Protection Office (ed) *Untersuchungen zur Umwelt Stuttgart* 21
- Shashua-Bar L, Hoffman ME (2004) Quantitative evaluation of passive cooling of the UCL microclimate in hot regions in summer, case study: urban streets and courtyards with trees. *Build Environ* 39(9):1087–1099. doi: [10.1016/j.buildenv.2003.11.007](https://doi.org/10.1016/j.buildenv.2003.11.007)
- Stewart ID, Oke TR (2012) Local climate zones for urban temperature studies. *Bull Am Meteorol Soc* 93(12):1879–1900. doi: [10.1175/BAMS-D-11-00019.1](https://doi.org/10.1175/BAMS-D-11-00019.1)
- Streiling S, Matzarakis A (2003) Influence of single and small clusters of trees on the bioclimate of a city: a case study. *J Arboric* 29(6):309–316
- Szymanowski M, Kryza M (2012) Local regression models for spatial interpolation of urban heat island—an example from Wrocław, SW Poland. *Theor Appl Climatol* 108(1–2):53–71. doi: [10.1007/s00704-011-0517-6](https://doi.org/10.1007/s00704-011-0517-6)
- Unger J (1996) Heat island intensity with different meteorological conditions in a medium-sized town: Szeged, Hungary. *Theor Appl Climatol* 54(3–4):147–151. doi: [10.1007/BF00865157](https://doi.org/10.1007/BF00865157)
- Unger J (2004) Intra-urban relationship between surface geometry and urban heat island: review and new approach. *Clim Res* 27:253–264. doi: [10.3354/cr027253](https://doi.org/10.3354/cr027253)
- Unger J (2006) Modelling of the annual mean maximum urban heat island using 2D and 3D surface parameters. *Clim Res* 30:215–226. doi: [10.1504/IJEP.2009.021817](https://doi.org/10.1504/IJEP.2009.021817)
- Unger J, Sümeghy Z, Zoboki J (2001) Temperature cross-section features in an urban area. *Atmos Res* 58(5/8):117–127. doi: [10.1016/S0169-8095\(01\)00087-4](https://doi.org/10.1016/S0169-8095(01)00087-4)
- Voogt J, Oke T (2003) Thermal remote sensing of urban climates. *Remote Sens Environ* 86(3):370–384. doi: [10.1016/S0034-4257\(03\)00079-8](https://doi.org/10.1016/S0034-4257(03)00079-8)
- Zakšek K, Oštir K (2012) Downscaling land surface temperature for urban heat island diurnal cycle analysis. *Remote Sens Environ* 117:114–124. doi: [10.1016/j.rse.2011.05.027](https://doi.org/10.1016/j.rse.2011.05.027)
- Ziska LH, Gebhard DE, Frenz DA, Faulkner S, Singer BD, Straka JG (2003) Cities as harbingers of climate change: common ragweed, urbanization, and public health. *J Allergy Clin Immunol* 111(2):290–295. doi: [10.1067/mai.2003.53](https://doi.org/10.1067/mai.2003.53)