

Chapter 4

Relevance of Thermal Indices for the Assessment of the Urban Heat Island

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Abstract Urban areas, with their specific characteristics, modify the atmosphere and produce their own meso- and micro climate. The major aspect of this chapter is the discussion of methods for the quantification and assessment of the urban micro-climate and the most known and world-wide studied phenomenon, the Urban Heat Island (UHI). Four urban measurement stations and one rural measurement station are used to quantify the temporal and spatial climatic characteristics in Stuttgart, Germany. For the quantification of the urban micro-climate and the UHI human thermal, comfort indices were applied. These indices, namely Physiologically Equivalent Temperature and the Universal Thermal Climate Index, are used to describe the integral effect of urban thermal atmosphere, based on the energy exchange of the human body. These indices, following the concept of equivalent temperature, are applied to quantify the integral effect of air temperature, air humidity, wind and radiation fluxes, expressed as mean radiant temperature.

Keywords Thermal Comfort • Physiologically Equivalent Temperature • Human Biometeorology

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4.1 Introduction

Urban areas, with their artificial materials and specific morphology, act as an obstacle to the atmosphere, altering energy-balance, the chemical composition as well as the wind field (Landsberg 1981; Oke 1982; Oke and Cleugh 1987; Helbig et al. 1999). The urban heat island (UHI), describing the urban-rural surface and air temperature differences, is the most prominent and world-wide studied phenomenon of urban climate (eg Böhm and Gabl 1978; Katsoulis and Theoharatos 1985; Kuttler et al. 1996; Runnalls and Oke 2000; Johansson and Emmanuel 2006).

In fact, the intensity of the urban heat island depends on eg land-use, building ratio, population density and vegetation (eg Landsberg 1981; Oke 1981; 1982; 1988). Before establishing mitigation and adaptation measures counteracting the urban heat island, city planners and officials need to comprehend the spatial and temporal dimensions of the meteorological and climatological conditions in a city (Matzarakis et al. 2008; Ketterer and Matzarakis 2014a, b). As city dwellers are the main target of city planners, the integral effect of air temperature, air humidity, wind speed and radiation fluxes on humans in a city has to be quantified and assessed (Eliasson 2000; Ketterer and Matzarakis 2014a, b). Hence, modern human-biometeorological methods for quantification of the spatial and temporal distribution of the UHI as well as to assess mitigation and adaptation measures for improving outdoor meteorological conditions have to be applied (Kuttler 2011, 2012; Matzarakis 2013).

Urban planners require information about the human biometeorological conditions in terms of frequencies (eg number of days or hours per year or season), as well as the quantification of temperature differences between different planning scenarios Fröhlich and Matzarakis (2011, 2013). The quantification of heat stress and its reduction by planning measures is a big challenge, especially in the light of climate change (Matzarakis and Endler 2010). Due to climate change, the mean air temperature is expected to increase and also heat waves are assumed to become more frequent, more intense and longer lasting (Matzarakis and Amelung 2008; Meehl and Tebaldi 2004; Schär et al. 2004; Muthers and Matzarakis 2010; Matzarakis and Nastos 2011). Thus, there is a demand for the assessment and quantification of adaptation measures improving the urban climate, ie street morphology, different types of vegetation (Hwang et al. 2011; Ketterer et al. 2013; Lin et al. 2012; Matzarakis 2001, 2006, 2007, 2010). This approach is twofold: the analysis and description of single places for urban planning measures and the construction of maps for the detection of areas with frequent heat stress (Svensson et al. 2003).

The aim is to show and describe methods based on long term measured data and their analysis for a comprehensive quantification of urban-rural differences and possible strategies for adaptation and mitigation in urban areas, focused on micro scale conditions.

4.2 Methods and Data

The application of thermal indices based on the human energy balance gives detailed information on the effect of complex thermal environments on humans (Höppe 1999). It is related to the close relationship between the human thermoregulatory mechanism and the human circulatory system. The human body does not have any selective sensors for the perception of individual climatic parameters.

Thermoreceptors can register the temperature of the skin and blood flow passing the hypothalamus and response thermoregulatorily (Höppe 1984, 1993, 1999). These temperatures, however, are influenced by the integrated effect of all climatic parameters, which are in some kind of interrelation, ie affect each other (VDI 1998; Höppe 1999).

Commonly used thermal indices, based on the human energy balance, are Predicted Mean Vote PMV (Fanger 1972), Physiologically Equivalent Temperature PET (Mayer and Höppe 1987; Höppe 1999; Matzarakis et al. 1999), Standard Effective Temperature SET* (Gagge et al. 1986) or Outdoor Standard Effective Temperature Out_SET* (Spagnolo and Dear 2003), Perceived Temperature pT (Staiger et al. 2012) and Universal Thermal Climate Index UTCI (Jendritzky et al. 2012). These thermal indices require the same meteorological input parameters: air temperature, air humidity, wind speed, short and long wave radiation fluxes. These input parameters have a temporal and spatial variability, which have a huge influence on thermal indices. Wind speed and mean radiant temperature have the highest variability and are modified by surroundings and obstacles in complex urban areas. Thus, it is particularly important to calculate correctly these parameters and to perform the measurements with high quality and exactness (ie including artificial ventilation and radiation shield for air temperature measurements).

The basis for these thermal indices is the energy balance equation for the human body:

$$M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0 \quad (1)$$

where, M represents the metabolic rate (internal energy production), W the physical work output, R the net-radiation of the body, C the convective heat flow, E_D the latent heat flow to evaporate water diffusing through the skin (imperceptible perspiration), E_{Re} the sum of heat flows for heating and humidifying the inspired air, E_{Sw} the heat flow due to evaporation of sweat, and S the storage heat flow for heating or cooling the body mass.

The individual terms in this equation have positive signs if they result in an energy gain for the body and negative signs in the case of an energy loss (M is always positive, W, E_D and E_{Sw} are always negative). The unit of all heat flows is in Watt (Höppe 1999).

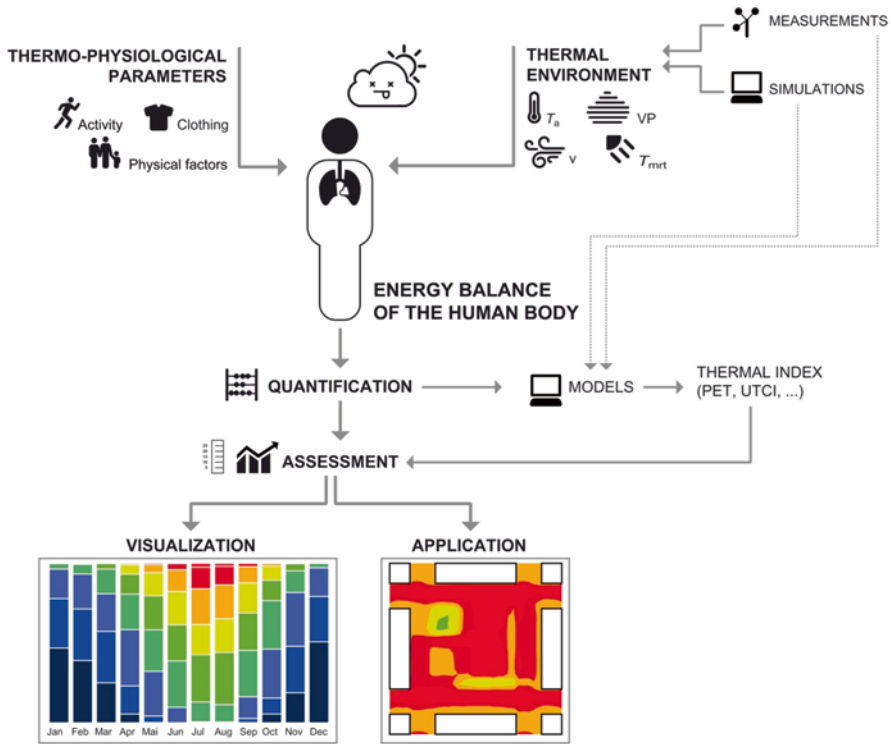


Fig. 4.1 Flowchart of the human-biometeorological assessment of the thermal environment

The individual heat flows in Eq. 1, are controlled by the following meteorological parameters (VDI 1998; Höppe 1999):

- air temperature: C, E_{Re}
- air humidity: E_D, E_{Re}, E_{Sw}
- wind velocity: C, E_{Sw}
- radiant temperature: R

The thermo-physiological parameters heat resistance of clothing (clo) and activity of humans (in W) are required in addition (Fig. 4.1).

From the energy balance, which is primarily designed for the calculation of a thermal index like PET, are the indices which enable the user to predict “real values” of thermal quantities of the body, ie skin temperature, core temperature, sweat rate or skin wetness.

For this purpose, it is necessary to take into account all basic thermoregulatory processes, like the constriction or dilation of peripheral blood vessels and the physiological sweat rate (Höppe 1993; 1999).

An example of thermophysiological heat-balance model is the Munich Energy Balance Model for Individuals (MEMI) (Höppe 1993), which is the basis for the calculation of the Physiologically Equivalent Temperature, PET.

4.2.1 *Physiologically Equivalent Temperature*

The Physiologically Equivalent Temperature (PET) is the equivalent temperature at a given place (outdoors or indoors) to the air temperature in a typical indoor setting with core and skin temperatures equal to those under the conditions being assessed. Thereby, the heat balance of the human body with a work metabolism 80 W (light activity, added to basic metabolism) and a heat resistance of clothing 0.9 clo) is maintained (Höppe 1999).

The following assumptions are made for the indoor reference climate:

- mean radiant temperature equals air temperature ($T_{mrt}=T_a$).
- air velocity (wind speed) is fixed at $v=0.1$ m/s.
- water vapor pressure is set to 12 hPa (approximately, equivalent to a relative humidity of 50 % at $T_a=20$ °C).

The procedure for the calculation of PET contains the following steps:

1. calculation of the thermal conditions of the body with MEMI for a given combination of meteorological parameters.
2. insertion of the calculated values for mean skin temperature and core temperature into the model MEMI and computation the energy balance equation system for the air temperature T_a (with $v=0.1$ m/s, $VP=12$ hPa and $T_{mrt}=T_a$).
3. the resulting air temperature is equivalent to PET.

PET offers the advantage of a widely known unit (degrees Celsius), which makes results more comprehensible to regional or urban planners, who are not necessarily very familiar with the modern human-biometeorological methods (Matzarakis et al. 1999). The assessment classes of PET (Table 4.1) are valid only for the assumed values of internal heat production (80 W) and thermal resistance of the clothing (0.9) (Matzarakis and Mayer 1997).

The meteorological input parameters have to be measured or transferred to the average height of a standing person's gravity center, 1.1 m above ground (Matzarakis et al. 2009). These meteorological parameters can be measured or calculated by numerical models. PET can be calculated by models like RayMan (Matzarakis et al. 2007, 2010).

4.2.2 *Universal Thermal Climate Index*

The Universal Thermal Climate Index UTCI (Jendritzky et al. 2012) is defined as the air temperature (T_a) of the reference condition causing the same model response as the actual condition. Thus, UTCI represents the air temperature, which would produce, under reference conditions, the same thermal strain as in the actual thermal

Table 4.1 Ranges of the physiological equivalent temperature (PET) for different grades of thermal perception by human beings and physiological stress on human beings, internal heat production: 80 W, heat transfer resistance of the clothing: 0.9 clo (according to Matzarakis and Mayer 1996, 1997)

PET	Thermal perception	Grade of physiological stress
	very cold	extreme cold stress
4 °C	-----	-----
	cold	strong cold stress
8 °C	-----	-----
	cool	moderate cold stress
13 °C	-----	-----
	slightly cool	slight cold stress
18 °C	-----	-----
	Comfortable	no thermal stress
23 °C	-----	-----
	slightly warm	slight heat stress
29 °C	-----	-----
	warm	moderate heat stress
35 °C	-----	-----
	hot	strong heat stress
41 °C	-----	-----
	very hot	extreme heat stress

environment. Both meteorological and non-meteorological (metabolic rate and thermal resistance of clothing) reference conditions were defined:

- wind speed (v) of 0.5 m/s at 10 m height (approximately 0.3 m/s in 1.1 m),
- mean radiant temperature (T_{mrt}) equal to air temperature,
- vapor pressure (VP) that represent relative humidity of 50 %, at high air temperatures (>29 °C) the reference air humidity is defined as 20 hPa.
- representative activity to be that of a person walking with a speed of 4 km/h (1.1 m/s). This provides a metabolic rate of 2.3 MET (135 W/m²).

The adjustment of clothing insulation is a powerful behavioral response to changing atmospheric conditions. Thereby, the conception behind UTCI was to consider seasonal clothing adaptation habits of Europeans based on available data from field surveys, in order to obtain a realistic representation of this behavioral action.

The categorization of UTCI is based on physiological response of an organism at actual environmental conditions depending on the responses for the reference conditions and thermal load (ie heat or cold stress) (Table 4.2). UTCI values between 18 and 26 °C may comply closely with the definition of the “thermal comfort zone” supplied in the Glossary of Terms for Thermal Physiology (International Union of Physiological Sciences – Thermal Commission 2003) as: “The range of ambient temperatures, associated with specified mean radiant temperature, humidity, and air movement, within which a human in specified clothing expresses indifference to the thermal environment for an indefinite period”.

Table 4.2 UTCI equivalent temperature categorized in terms of thermal stress

UTCI (°C) range	Stress category	Physiological responses
above +46	extreme heat stress	Increase in <i>Tre</i> time gradient Steep decrease in total net heat loss Averaged sweat rate >650 g/h, steep increase
+38 to +46	very strong heat stress	Core to skin temperature gradient < 1 K (at 30 min) Increase in <i>Tre</i> at 30 min
+32 to +38	strong heat stress	Dynamic Thermal Sensation (<i>DTS</i>) at 120 min >+2 Averaged sweat rate >200 g/h Increase in <i>Tre</i> at 120 min Latent heat loss >40 W at 30 min Instantaneous change in skin temperature >0 K/min
+26 to +32	moderate heat stress	Change of slopes in sweat rate, <i>Tre</i> and skin temperature: mean (<i>Tskm</i>), face (<i>Tskfc</i>), hand (<i>Tskhn</i>) Occurrence of sweating at 30 min Steep increase in skin wetness
+9 to +26	no thermal stress	Averaged sweat rate >100 g/h <i>DTS</i> at 120 min < 1 <i>DTS</i> between -0.5 and +0.5 (averaged value) Latent heat loss >40 W, averaged over time Plateau in <i>Tre</i> time gradient
+9 to 0	slight cold stress	<i>DTS</i> at 120 min < -1 Local minimum of <i>Tskhn</i> (use gloves)
0 to -13	moderate cold stress	<i>DTS</i> at 120 min < -2 Skin blood flow at 120 min lower than at 30 min (vasoconstriction) Averaged <i>Tskfc</i> < 15 °C (pain) Decrease in <i>Tskhn</i> <i>Tre</i> time gradient < 0 K/h 30 min face skin temperature < 15 °C (pain) <i>Tmsk</i> time gradient < -1 K/h (for reference)
-13 to -27	strong cold stress	Averaged <i>Tskfc</i> < 7 °C (numbness) <i>Tre</i> time gradient < -0.1 K/h <i>Tre</i> decreases from 30 to 120 min Increase in core to skin temperature gradient
-27 to -40	very strong cold stress	120 min <i>Tskfc</i> < 0 °C (frostbite) Steeper decrease in <i>Tre</i> 30 min <i>Tskfc</i> < 7 °C (numbness) Occurrence of shivering <i>Tre</i> time gradient < -0.2 K/h Averaged <i>Tskfc</i> < 0 °C (frostbite) 120 min <i>Tskfc</i> < -5 °C (high risk of frostbite)
below -40	extreme cold stress	<i>Tre</i> time gradient < -0.3 K/h 30 min <i>Tskfc</i> < 0 °C (frostbite)

(Blazejczyk et al. 2010)

Following abbreviations are used: rectal temperature T_{re} ($^{\circ}C$), mean skin temperature T_{skm} ($^{\circ}C$), face skin temperature T_{skfc} ($^{\circ}C$), sweat production M_{skdot} (g/min), heat generated by shivering $Shiv$ (W), skin wittedness $wettA$ (%) of body area, skin blood flow V_{blSk} (%) of basal value, Dynamic Thermal Sensation DTS

4.3 Exemplary Results

Thermal biometeorological conditions are described using the thermal indices PET and UCI for Stuttgart. Thereby, the results are focused on the comparison of thermal indices and air temperature.

Figure 4.2 shows the air temperature conditions for the period 2000 to 2011 based on hourly data, where all the hourly data of the examined period is shown. A comparison is made between mean conditions and the specific year 2003, which experienced an extraordinary hot summer. The two upper graphs show the pattern of air temperature for the long period and the year 2003. It can be noted that, during summer 2003, air temperature exceed very often the 30 $^{\circ}C$ level. This heat wave in

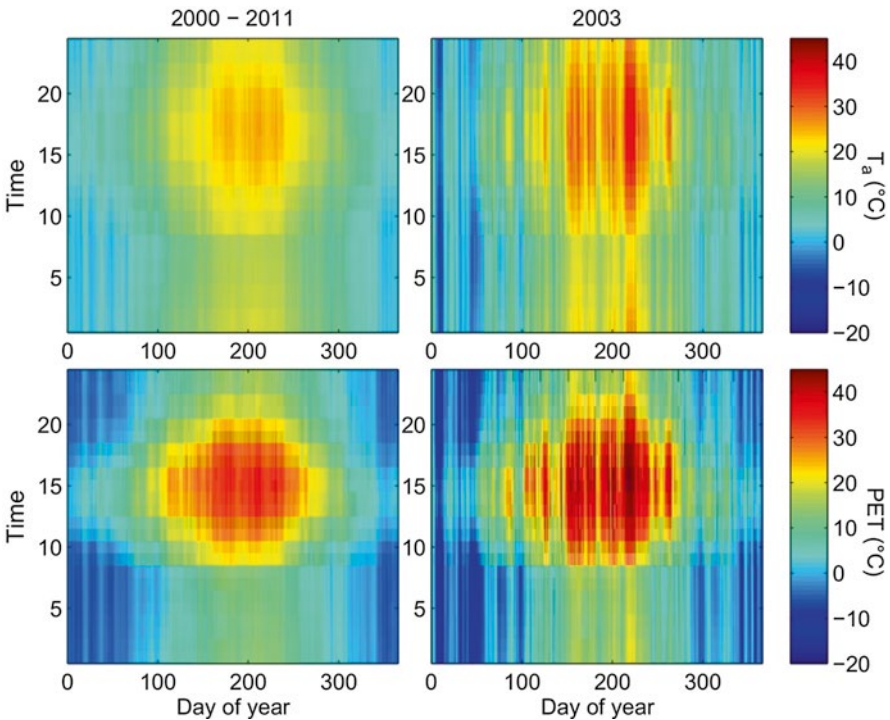


Fig. 4.2 T_a (upper graphs) and PET (lower graphs) for the period 2001–2011 and 2003 for station Schwabenzentrum in Stuttgart

Table 4.3 Location and altitude of the measurement stations

Measurement station	Lat (N)	Long (E)	Altitude (asl)	Feature
Neckartal (N)	48:47	09:13	224 m	River valley, urban
Schwabenzentrum (S)	48:46	09:10	250 m	City center, on top of a 25 m high Building
Schnarrenberg (Sb)	48:50	09:12	314 m	top of a SW-exposed hill
Hohenheim (H)	48:42	09:02	405 m	Suburb
Echterdingen (E)	48:41	09:14	371 m	Airport

2003 had many negative effects on human health, which results in high mortality and morbidity rate in Western Europe (Koppe et al. 2003; Le Tertre et al. 2006). The daytime PET values are higher than T_a during the day. During the night, PET is lower than air temperature. During the winter, the values of air temperature are mostly higher than the values of PET, due to the effect of wind, low irradiation and air humidity.

Another possibility to describe thermal comfort conditions and urban rural differences can be the long terms analysis for different stations. In Stuttgart are located five stations and they have all been selected for the analysis (Table 4.3).

Beanplots, developed by (Kampstra 2008), display the density curve of the data together with median or mean, percentiles or standard deviation. To obtain the typical bean shape, the density curve is mirrored along the central y-axis. Fig. 4.3 depicts beanplots for the described stations in Stuttgart (Neckartal, Schnarrenberg, Schwabenzentrum, Hohenheim and Echterdingen) for the period 2000–2011.

The plots show the seasonal pattern for winter, spring, summer and autumn for T_a (upper graphs), PET (middle) and UTCI (lower graph). The differences between the stations for T_a are small.

In particular, the daily minimum values are higher for the urban stations, compared to suburban site Hohenheim or the rural reference station Echterdingen. This fact can be explained by the heat storage in the city, but also by the differences in altitude, that reach more than 150 m.

The density distribution of PET is governed by radiation fluxes from spring to autumn, which is also the most impacting meteorological variable. In winter, the density distribution of PET is similar to the one of air temperature. Air temperature is the factor that influences PET most during winter.

The minimum values of UTCI (Fig. 4.3 lower panel) are lower than PET. This can be explained by adapting clothing model of UTCI during summer, but also by different assessment scale.

In some cases, esp. for application in planning or for the detection of extreme events for human health, issues conditions can be analyzed in terms of thresholds of air temperature or any thermal index. Table 4.4 shows the amount of days per year for different levels of maximum air temperature ($T_{max} > 30$ and > 35), minimum air temperature ($T_{min} > 18$, > 20 and > 23), the conditions for the maximum value of PET ($PET_{max} > 30$, > 35 and > 41) according to the assessment classes

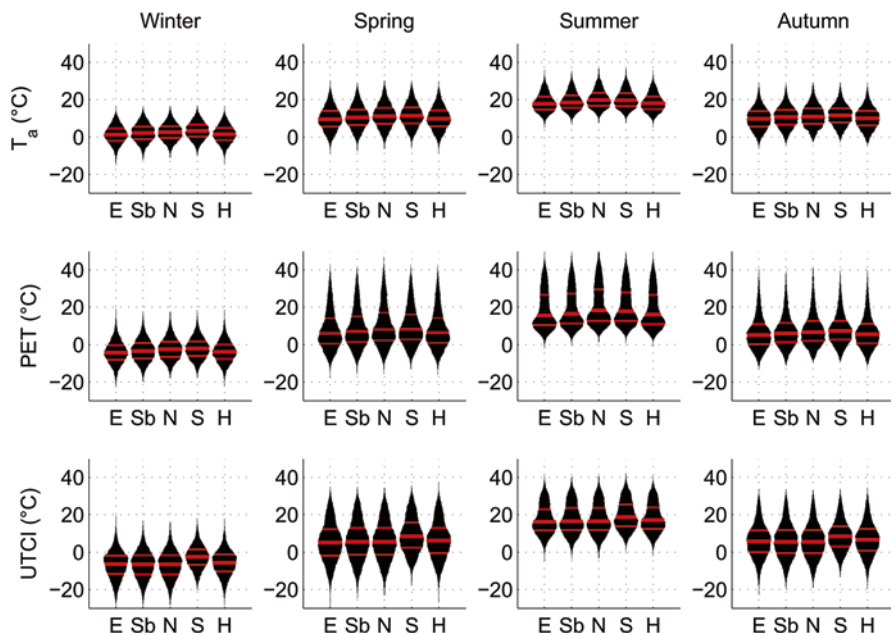


Fig. 4.3 Bean plots for air temperature (*upper graphs*), PET (*middle graphs*) and UTCI (*lower graphs*) for the Stations Echterdingen (E), Schnarrenberg (Sb), Neckartal (N), Schwabenzentrum (S) and Hohenheim (H) for the period 2000–2011

Table 4.4 Number of days on which defined thresholds are exceeded

	Echterdingen	Schnarrenberg	Neckartal	Schwabenzentrum	Hohenheim
$T_{\max} > 30$	8	13	10	14	7
$T_{\max} > 35$	1	2	1	2	1
$T_{\min} > 18$	3	15	11	20	6
$T_{\min} > 20$	0	4	2	6	1
$PET_{\max} > 30$	93	85	96	99	92
$PET_{\max} > 35$	55	57	58	61	54
$PET_{\max} > 41$	16	26	19	23	15
$PET_{\min} > 18$	0	0	0	0	0

(Table 3.7.2.1) and also the PETmin for the levels of >18 . It can be seen that there is a difference in the conditions for maxima over $T_a > 30$ and only 1 or 2 days for $T_a > 35$ °C. In addition, it can be seen that T_{\min} conditions over >18 and >20 occur mostly in the urban area. Maximum values of PET are represented by a similar picture; however, the PET is generally higher than air temperature, while extreme heat stress ($PET > 41$ °C) can occur in more than 20 days per year in the city stations. The daily minimum value of PET never exceeds the threshold of 18 °C in Stuttgart (the frequency is below 0.1 %).

Table 4.5 Number of hours per year on which defined thresholds were exceeded in the period 2000–2010

	Echterdingen	Schnarrenberg	Neckartal	Schwabenzentrum	Hohenheim
Daytime (10–16)					
$T_a > 30$	40.2	53.6	70.5	76.5	37.5
$T_a > 35$	2.3	4.6	7.5	7.2	2.3
$T_a > 41$	0.0	0.0	0.0	0.0	0.0
PET > 30	534.5	560.3	539.3	587.4	522.5
PET > 35	252.9	271.2	298.0	289.9	244.4
PET > 41	54.9	64.4	97.7	75.1	51.6
Nighttime (22–6)					
$T_a > 18$	11.9	44.6	52.5	121.0	27.1
$T_a > 20$	4.3	17.5	21.5	61.5	10.1
$T_a > 23$	0.4	3.9	4.4	21.5	2.1
PET > 18	188.5	305.2	292.8	516.6	277.4
PET > 20	75.0	149.4	154.0	307.5	130.5
PET > 23	12.4	36.3	40.5	115.0	29.6

Beyond the information given by the amount of days that manifest specific events, the amount of hours can describe more precisely the occurrence of specific conditions, thus providing more valuable information. Table 4.5 depicts the total amount of hours for the thresholds for the examined stations in Stuttgart urban and rural area. It can be clearly observed that the amount of hours for T_a and PET is quite higher in the urban areas than in the rural one, esp. for $T_a > 35$ and PET > 41 during day time (10 to 16 LST). At nighttime (22 to 6 LST) the picture is a clearer indication that urban areas are quite hotter than rural areas.

4.4 Discussion and Conclusion

There is an increased demand for the quantification and the assessment of the Urban Heat Island (UHI). Most of the studies deal with the comparison of different station in urban and rural areas based on different temporal resolutions and many studies report about differences in air temperature about maxima of more than 10 K and for mean conditions about 2–3 K (Ketterer and Matzarakis 2014a, b). In fact, cities are warmer than rural areas and the formation of the UHI depends mostly on energetic aspects of the urban structures. Most influencing factors are the limited horizon, the storage of heat of urban fabrics and anthropogenic heat emissions (Landsberg 1981; Oke 1982). There are several aspects to quantify UHI beside the energetic aspects (heating and cooling) and air pollution. Recent studies focus on the reduction of UHI based on the modification of urban structures, using reflective materials or increasing evaporative cooling, however, these studies are mostly focusing only one some aspects of the energy budget of the urban areas and concentrate only on air

temperature reduction. This aim is achieved using models with different spatial resolutions and designing exemplary measurements for case studies. All these results and information are demanded and can have a direct application. However, it has to be mentioned that results of thermal indices (PET or UTCI), compared to studies based only on air temperature, produce different outcomes. For example, increasing albedo of urban surfaces can decrease air temperature, but at the same time it increases the values of PET, due to increased shortwave reflection. This is a relevant topic not only during summer, but throughout the all year, because it affects the use of the urban spaces, where people want to spend time outdoors.

Finally, easy understandable graphs and figure are a possibility for better communication between different users and disciplines.

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