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RESEARCH ARTICLE

Evaluation of human thermal comfort ranges in urban climate of winter cities on the example of Erzurum city

Süleyman Toy[1] · Noémi Kántor[2]

Abstract Human thermal comfort conditions can be evaluated using various indices based on simple empirical approaches or more complex and reliable human-biometeorological approaches. The latter is based on the energy balance model of the human body, and their calculation is supplemented with computer software. Facilitating the interpretation of results, the generally applied indices express the effects of thermal environment in the well-known temperature unit, just like in the case of the widely used index, the physiologically equivalent temperature (PET). Several studies adopting PET index for characterizing thermal components of climate preferred to organize the resulted PET values into thermal sensation categories in order to demonstrate the spatial and/or temporal characteristics of human thermal comfort conditions. The most general applied PET ranges were derived by Central European researchers, and they are valid for assumed values of internal heat production of light activity and thermal resistance of clothing representing a light business suit. Based on the example of Erzurum city, the present work demonstrates that in a city with harsh winter, the original PET ranges show almost purely discomfort and they seem to be less applicable regarding cold climate conditions. Taking into account 34-year climate data of Erzurum, the annual distribution of PET is presented together with the impact of application of different PET categorization systems, including 8°- and 7°-wide PET intervals. The demonstrated prior analyses lack any questionnaire filed surveys in Erzurum. Thus, as a next step, detailed field investigations would be required with the aim of definition of new PET categorization systems which are relevant for local residents who are adapted to this climatic background, and for tourists who may perform various kinds of winter activities in Erzurum and therefore may perceive the thermal environment more comfortable.

Keywords Human-biometeorological assessment · Physiologically equivalent temperature · Cold climate

✉ Süleyman Toy
stoy58@gmail.com

Noémi Kántor
sztyepp@gmail.com

1   City and Regional Planning Department, Architecture and Design Faculty, Ataturk University, 25240 Erzurum, Turkey

2   Faculty of Science and Informatics, Department of Climatology and Landscape Ecology, University of Szeged, Szeged, Hungary

Introduction

The thermal component of the atmospheric environment includes air temperature (T_a), air humidity (expressed as vapour pressure [VP] or relative humidity [RH]), wind velocity (v) and mean radiant temperature (T_{mrt}); the latter is consisted of short- and long-wave radiation flux densities with a thermal effect (Fig. 1). All of the mentioned parameters affect the human thermo-regulation system (Matzarakis and Mayer 1996).

The relationship between humans and climate begins at the moment when people sense the atmospheric conditions (Lim et al. 2008). However, the human organism does not have any specific sensors for the perception of individual climate parameters. Our thermo-regulation system can register only the temperature of the skin and blood flow passing the hypothalamus. These body parameters, however, are influenced by the integrated effect of more thermal parameters which, in addition, affect each other's impact (Höppe 1999).

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Fig. 1 Schematic overview about the determination of thermal comfort conditions—a merely objective approach
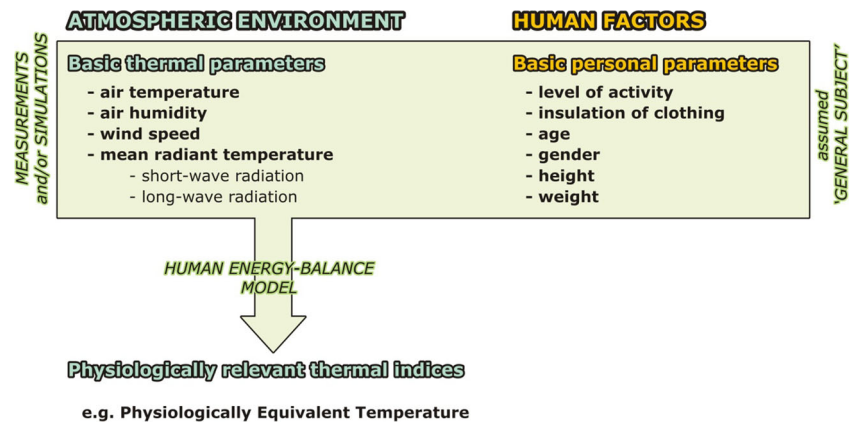
In certain cases, one or more of the mentioned climatic elements may affect humans more than the others. For instance, low temperature coinciding with strong wind may cause strong cold stress because of the enhanced convective heat loss, while high temperature together with excessive humidity level decrease the chance of evaporative heat loss thus increases the probability of serious heat stress. On days with weak wind, the mean radiant temperature may have greater importance as the air temperature, especially in sunny conditions. In the case of stronger air velocities, especially in overcast conditions or in the shade, air temperature may be more important than the mean radiation temperature.

There are many issues within the field of applied climatology (e.g. urban and landscape planning, public health, tourism) which require well-established evaluation regarding the thermal components of the atmospheric environment (Matzarakis et al. 1999). These conditions can be evaluated by using various thermal comfort (or stress) indices based either on simple empirical approaches or on more complex and reliable human-biometeorological approaches. Earlier indices combined only a couple of meteorological parameters either in the forms of simple equations or in different thermal comfort charts. They combined generally air temperature with wind velocity in cold climate regions while air temperature with humidity in the case of warm climates. Although it was easy to obtain the necessary input parameters from synoptic stations, these earlier indices had a major limitation that they lacked relevance from thermo-physiological point of view (Matzarakis and Mayer 1996; Matzarakis et al. 1999).

The complex interactions between the human organism and the thermal environment are quantifiably only with the help of human energy-balance models (Höppe 1993, 1999) which take into account all relevant thermal parameters together with some personal factors (Fig. 1). These models are able to quantify different forms of energy exchange (radiation, convection, evaporation) between the human body and its thermal environment, and they result in easily understandable thermal comfort indices too (Höppe 1999). In order to facilitate the interpretation of the results, the generally applied

human comfort indices express the effects of the thermal environment in the well-known temperature unit.

One of the most popular indices for outdoor usage is the physiologically equivalent temperature (PET) which can be used for the assessment of both hot and cold conditions and therefore all year around (Mayer and Höppe 1987; Höppe 1999). The basic idea behind PET is that the actual bioclimate is transferred to an equivalent fictive indoor bioclimate in which the same thermo-physiological reactions of the human body can be expected. The indoor reference environment is described with the following thermal parameters: $T_{mrt} = T_a$, VP = 12 hPa and $v = 0.1$ m/s. PET can be interpreted as the very air temperature (PET = T_a) of this reference environment in which the human body (assumed to perform light activity 80 W and to wear light suit 0.9 clo) would experience the same thermal impacts as calculated for the actual outdoor conditions, described with any combinations of T_a, T_{mrt}, v and VP (Höppe 1999).

PET was used worldwide for characterizing the thermal component of the climate in different regions, urban climates at local scale or several microclimates within different city structures. A great part of these studies conducted on-site micrometeorological measurements (e.g. Streiling and Matzarakis 2003; Gulyás et al. 2006a, b; Ali-Toudert and Mayer 2007a; Mayer et al. 2008; Lin et al. 2010; Deb and Ramachandraiah 2011; Holst and Mayer 2011; Hwang et al. 2011; Shashua-Bar et al. 2011; Charalampopoulos et al. 2013; Gómez et al. 2013), while others applied numerical simulations in order to model the thermal comfort or stress conditions that may occur as a consequence of different landscape design strategies even under different future climate scenarios (e.g. Ali-Toudert and Mayer 2006, 2007b; Huttner et al. 2008; Shashua-Bar et al. 2012; Fröhlich and Matzarakis 2013; Müller et al. 2014).

During human-bioclimatological analyses, the resulted PET values, generally, are organized into previously defined "thermal comfort-ranges" (Table 1) in order to demonstrate the spatial and/or temporal characteristics of human thermal comfort conditions (e.g. Toy and Yilmaz 2010). The widely

Table 1 Ranges of PET for different categories of human thermal sensation and grades of thermo-physiological stress; internal heat production by activity 80 W; heat transfer resistance of clothing 0.9 clo (according to Matzarakis and Mayer 1996; Matzarakis et al. 1999)

PET range (°C)	Thermal sensation	Level of thermal stress
≤4	Very cold	Extreme cold stress
4.1–8	Cold	Strong cold stress
8.1–13	Cool	Moderate cold stress
13.1–18	Slightly cool	Slight cold stress
18.1–23	Neutral (comfortable)	No thermal stress
23.1–29	Slightly warm	Slight heat stress
29.1–35	Warm	Moderate heat stress
35.1–41	Hot	Strong heat stress
41>	Very hot	Extreme heat stress

used PET threshold values were introduced by Matzarakis and Mayer (1996). The aim of the present study is to analyse the applicability of these pre-set category benchmarks in the case of cold climate regions on the example of Erzurum city.

Materials and methods

The study relates to the city of Erzurum in northeast of Turkey (39.55° N and 41.16° E; TRA1 NUTSII Region; Fig. 2). Erzurum is located at an altitude of 1.850 m on a highland surrounded by mountains up to 3500 m. Population of the city is 763,323 (TurkStat 2014). The city is out of marine effect due to high mountains surrounding it, and harsh continental climate characteristics are prevalent in it. According to data obtained from the meteorological station at the airport, the long-term annual mean temperature is 5.1 °C, while the minimum and maximum temperature extremes are −37.2 and 35.6 °C. Mean annual rainfall is 413.3 mm, and the yearly means of relative humidity and vapour pressure are 63.3 % and 6.0 hPa respectively. Mean annual wind speed is 2.7 m/s, and the prevalent wind directions are ENE in summer and WSW in winter (Fig. 2).

Even though the city centre is accepted not to be a well-planned and industrialized Turkish city, its size is not too large to have a significant effect on city's climate (Yılmaz et al. 2007) and its structure is made up of historical and newly developing sites involving not tall buildings (4–5 storeys; Fig. 3). Its high elevation and hard climatic characteristics have also negative effects on the constitution of the city structure, such as limited number of plant species capable of growing in the city and combustion of low-quality fossil fuels (e.g. coal) to heat indoor which reduces air quality.

For the calculation of PET, it is necessary to determine all basic thermal parameters—i.e. T_a, VP (or RH as an alternative), v and T_{mrt}—at a human-biometeorologically significant height, e.g. at 1.1 m above ground (the average height of a standing person's centre of gravity). These parameters can be measured and/or calculated by numerical models (Matzarakis et al. 1999). In the case of this study, PET values were calculated considering daily mean data of air temperature T_a [°C], relative humidity RH [%], cloudiness C [octa] and wind speed v [m/s] measured over a 34-year period from 1975 to 2008 at the weather observation station locating at the airport (at 1.758 m and 39° 57′ N and 41° 10′ E). Wind speed measured at 10 m above ground level was reduced to the required height of 1.1 m according to the generally adopted empirical formula (Spagnolo and de Dear 2003a, 2003b; Swensson et al. 2003; Gulyás et al. 2006a, b, 2010; Nikolopoulou and Lykoudis 2007).

$$v_{1.1} = v_{10} \times \left(\frac{1.1}{10} \right)^{(0.12 \times z_0 + 0.18)}$$

where $v_{1.1}$ is the calculated wind velocity at 1.1 m, v_{10} is the wind velocity measured at 10 m and z_0 is the surface roughness depending on the characteristics of the study area. The latter was assumed to be 1.5.

The widely known RayMan software (Matzarakis et al. 2000, 2007; Matzarakis and Rutz 2005) was utilized to model the necessary radiation parameter (i.e. T_{mrt}) from the cloudiness data (according to the geographical and temporal characteristics), as well as to calculate the PET values.

Temporal distribution of the calculated daily mean PET values is analysed on a daily basis instead of the usage of 10-day intervals as was usual in earlier studies (e.g. Toy and Yilmaz 2010). The total number of days considered in this examination is 12,410 (365 days × 34 years; February 29 in leap years was not included in the study). The results are represented in the form of human-bioclimate charts, showing the percentage distribution of selected PET categories over the year.

Results

Occurrence probability of the original PET categories (Table 1) throughout the year is demonstrated on Fig. 4. The most obvious feature of this diagram is that the "very cold" range (PET values below 4 °C) is dominant during a fairly long period. The relative frequency of this category is generally above 50 %, except for the time interval between the days of 100 and 300. The overall occurrence of this PET domain is high above to the others (Table 2). The second most prevalent range refers to "slightly cool" thermal sensation (13.1–18 °C); these PET values may occur most frequently in late spring and early autumn, similarly to the cases of the third and fourth most frequent PET categories: "neutral" (18.1–23 °C) and "cold" (4.1–8 °C) (Fig. 4; Table 2). In line with expectations

Fig. 2 Geographical location of Erzurum

regarding a cold-climate city, the least prevalent ranges are "very hot" (41 °C <), "hot" (35.1–41 °C) and "warm" (29.1–35 °C), occurring very rarely and only on a couple of summer days.

It is obvious that a human-bioclimatic diagram presented on Fig. 4 is not appropriate enough to describe the thermal comfort conditions of cold climate cities. Indeed, according to the widely adopted original PET categorization-system, almost half of the year can be characterized as very cold. More specifically, 5394 from the 12,410 days fell into this category, representing 43.46 % of all cases (Table 2). Prevalence of this range is nearly four times higher than the closest ranges, i.e. slightly cool, neutral and "cool" with

12.92, 12.33 and 12.00 % relative frequencies respectively. Important to note that the lowest PET value was found to be at −30.1 °C (on 23rd day of 1995), being much cooler than the lower boundary of the very cold range, i.e. 4 °C.

With the intention of demonstrating the various degrees of harsh winter conditions in Erzurum, new PET intervals will be applied based on the frequency distribution of all daily PET values over the 34 consecutive years. Categorization systems with 9 distinct PET intervals will be defined to be in accordance with the number of the generally applied PET classes.

The first approach aimed to ensure equal proportion (11.11 %) of Erzurum's PET data in each PET category. Accordingly, percentiles 11.11, 22.22, 33.33, etc. were

Fig. 3 City centre of Erzurum

Fig. 4 Human-bioclimate diagram of Erzurum city according to the original PET categorization system
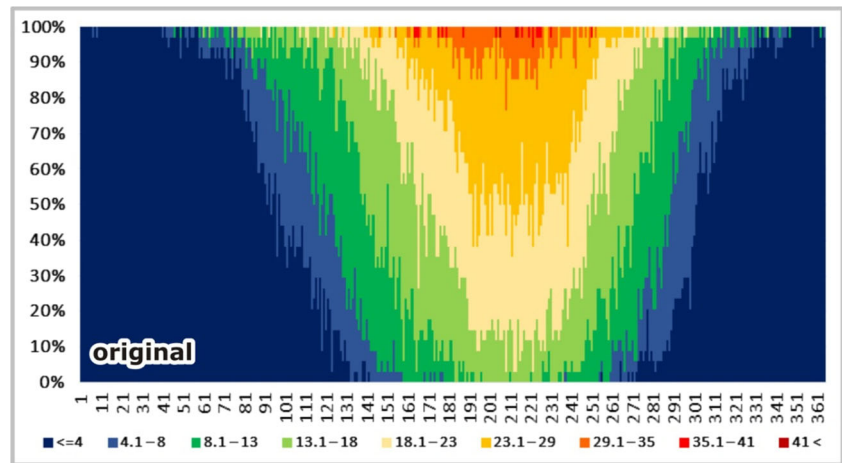
calculated to serve as category benchmarks for the new PET classification system (Table 3).

As a second approach, evenly graded PET categorization systems were defined taking into account the PET histograms of Erzurum (Fig. 5). The PET values ranged from −30.1 to 43 °C, with a mean of 6.4 °C and a standard deviation of 12.77 °C. Besides the original PET histogram, Fig. 5 presents seven modified histograms obtained by changing the PET interval width from 4° to 10°. Only the application of 7°- and 8°-wide intervals resulted in nine main PET categories over the investigated domain (Fig. 5).

Figure 6 illustrates the newly obtained bioclimate charts of Erzurum according to the three new PET classification-systems, while Fig. 7 displays the overall percentage of certain PET intervals. It is evident that the first approach resulted in the most evenly distributed occurrence of the new PET categories; however, also the other two categorization systems resulted in a more even frequency distribution between the PET categories compared to the original PET thresholds (Fig. 7). The new types of categorization allow us to ascertain more easily those parts of the year which can be characterized with the highest probability of severe cold stress (January and

February), as well as with the highest PET values (days from 190 to 230) (Fig. 6).

Discussion and outlook

The number of studies adopting PET (or other thermal indices) for characterizing the thermal component of the climate (climate of a region, urban climate at local scale or microclimate within different city structures) is very high, and it is growing continuously. Researchers organize the resulted index values into thermal sensation (or thermal stress) categories and discuss their occurrence within a year or across a geographical region in order to demonstrate the spatial and/or temporal characteristics of human thermal comfort conditions.

Based on the example of Erzurum city, the present work evinced that in a region with harsh climatic background, the original PET ranges are not applicable to demonstrate the inter-annual differences in the thermal conditions, especially during the long winter period. However, other classifications seemed to be useful to reveal more closely the inter-annual differences. It must be noted that this categorization was made arbitrarily in the lack of detailed outdoor thermal comfort surveys which would be required for the development of a new classification systems that represent better the subjective

Table 2 Frequency distribution of the obtained PET categories over the investigation period

PET range (°C)	Thermal sensation	Number of days	Percent
≤4	Very cold	5394	43.46
4.1–8	Cold	1179	9.50
8.1–13	Cool	1489	12.00
13.1–18	Slightly cool	1603	12.92
18.1–23	Neutral (comfortable)	1530	12.33
23.1–29	Slightly warm	1001	8.07
29.1–35	Warm	194	1.56
35.1–41	Hot	18	0.15
41>	Very hot	2	0.02
Total		12,410	100

Table 3 Selected percentile values of the PET distribution based on Erzurum's 34-year long climate data

Percentiles (%)	PET (°C)
11.11	−10.30
22.22	−4.90
33.33	−0.30
44.44	4.40
55.55	9.20
66.66	13.70
77.77	18.00
88.88	22.30

Fig. 5 PET histogram of
Erzurum based on the daily PET
values of 34 consecutive years
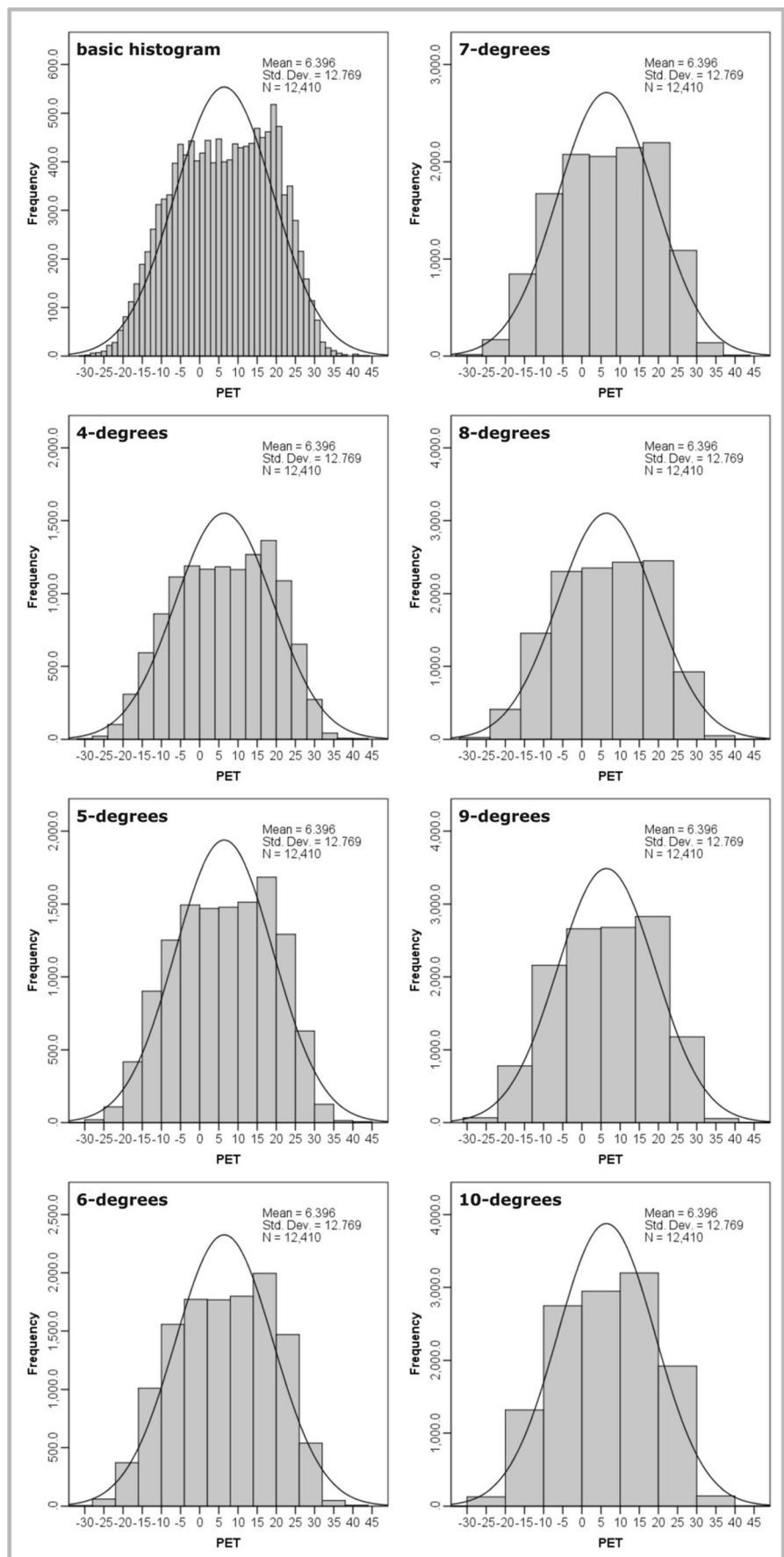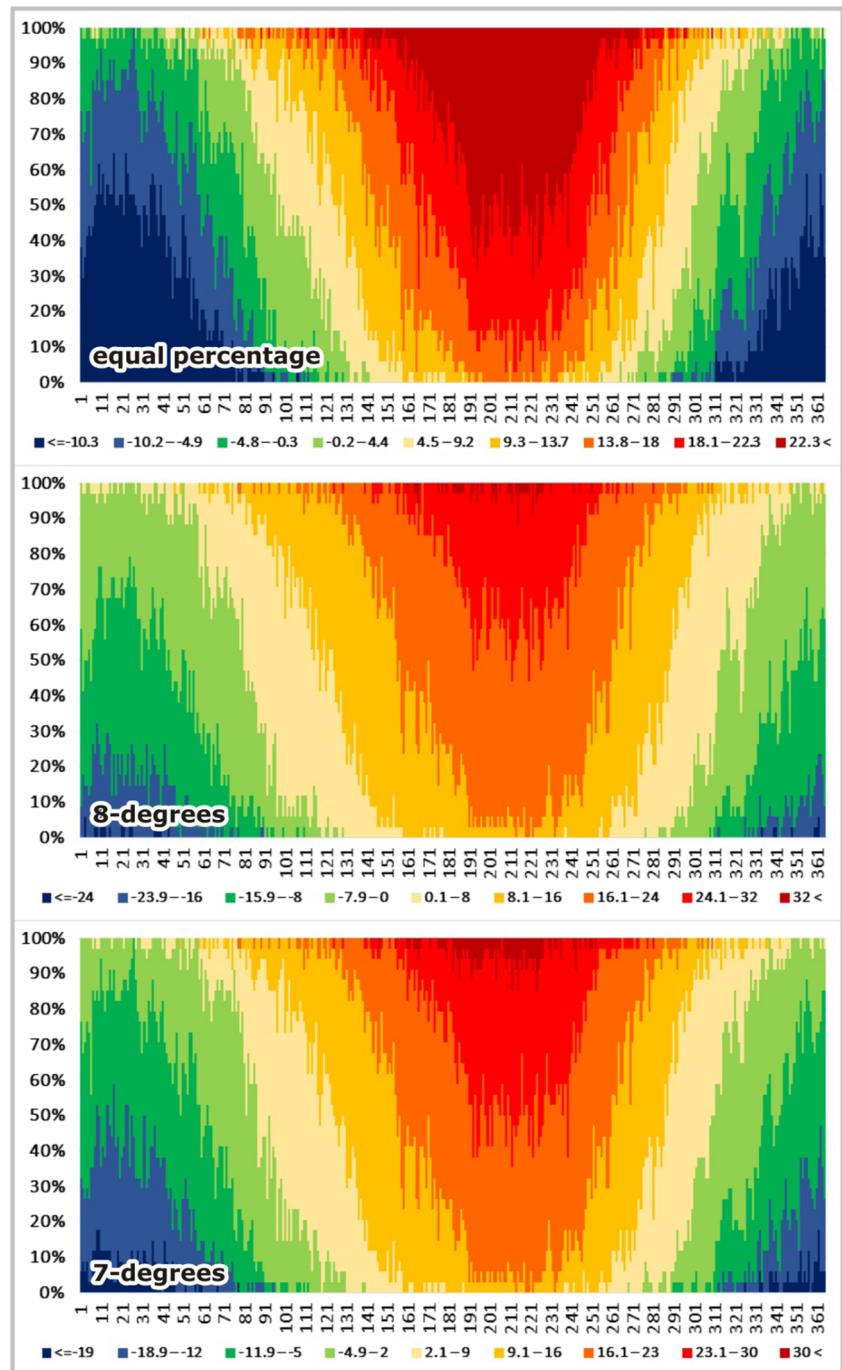and taking into account different
PET intervals

Fig. 6 Human-bioclimate diagram of Erzurum city according to three other categorization systems: equal percentage distribution, 8°-wide and 7°-wide PET intervals


thermal assessment patterns (thermal sensation, thermal preference and thermal comfort evaluation) of local individuals who are assumed to be adapted to the harsh winter climate conditions (Fig. 8).

Another important issue that has to be mentioned is that the original ranges of PET (Table 1; Matzarakis and Mayer 1996; Matzarakis et al. 1999) were assigned to the different grades of thermal stress and human thermal sensation on the basis of analogous predicted mean vote (PMV) ranges, which in turn were derived from previous investigations by Fanger (1972).

These obtained PET ranges, however, depend on the internal heat production and the thermal resistance of clothing. In the case of the generally adopted "original" PET categories, the metabolic heat production due to the physical activity was assumed to be 80 W (equivalent of a light office work), which has added to the basal metabolism (ca. 80–85 W for a healthy adult subject). The heat resistance of clothing was set to be 0.9 clo, which corresponds for example to a light business suit (Matzarakis and Mayer 1996; Matzarakis et al. 1999). However, people spending their time in a "winter city" like

Fig. 7 Percentage distribution of days falling in different PET ranges within an average year in Erzurum, taking into account different PET categorization systems
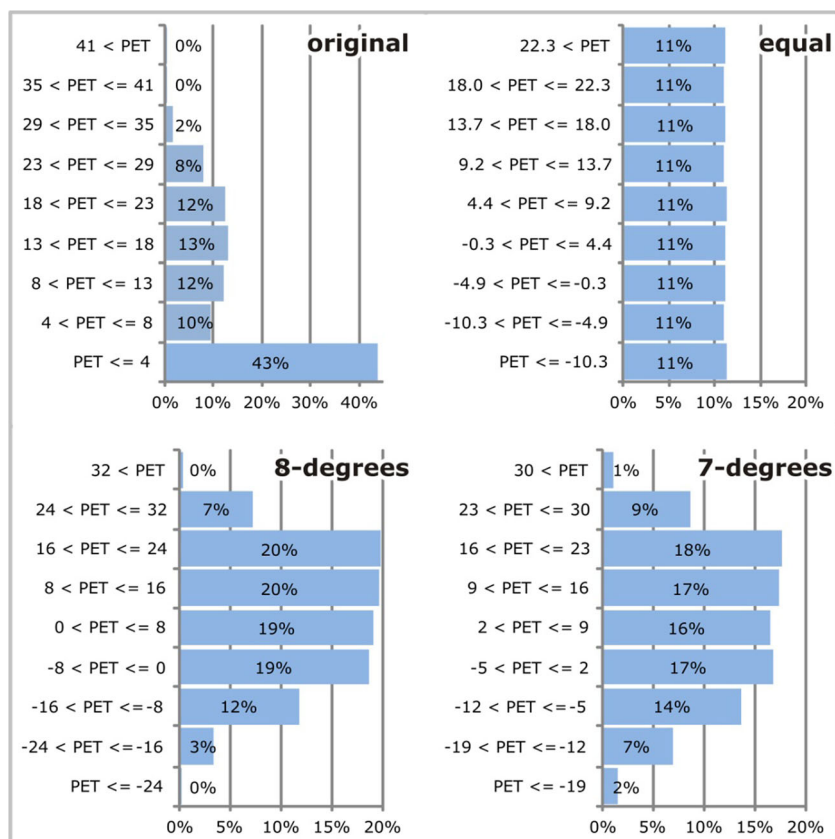

Erzurum wear heavier clothing, and there must be several tourists who perform intensive activity like skiing and other winter sports. These ideas suggest that the original PET categorization needs to be revised regarding these altered personal conditions.

Even the authors of the widely used original PET-scale posed the question: "are these PET ranges valid world-wide for humans?" (Matzarakis et al. 1999). They suspected that the PET category boundaries may move to higher or lower values according to thermal adaptation mechanisms and proposed special investigations aiming to answer this question (Matzarakis et al. 1999).

Accordingly, several outdoor thermal comfort surveys were conducted worldwide and shed light on different forms of adaptation taking place at physical (behavioural adaptation), physiological (acclimatization) and psychological (mental) levels (Höppe 2002; Nikolopoulou and Steemers 2003). These mechanisms, together with the influence of some subjective factors, result in culturally different thermal perception patterns (e.g. Knez and Thorsson 2006; Nikolopoulou and Lykoudis 2006; Kántor et al. 2012), as well as remarkable inter-annual differences regarding the subjective assessment of the thermal environment (e.g. Nikolopoulou and Lykoudis 2006; Lin 2009). Recognizing

Fig. 8 Schematic overview about the determination of thermal comfort conditions—rescaling objective indices according to subjective human factors
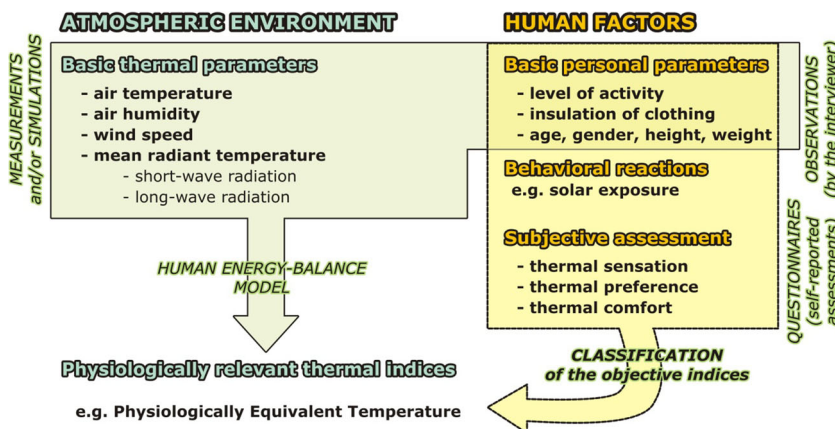
the importance of these issues, a couple of researchers decided recently to derive their own grading system for PET index in different regions (hot-humid, hot-arid or even in Central-East-Europe), being in better accordance with the thermal perception patterns of people living there (e.g. Lin and Matzarakis 2008; Cohen et al. 2013; Yang et al. 2013; Lai et al. 2014; Pearlmutter et al. 2014; Kovács et al. 2015; Kántor et al. 2016; Kántor 2016).

The presented example of Erzurum city and all of the mentioned international experiences lead us to the final conclusion that it is highly recommended to ascertain own PET ranges in the case of winter cities too. The schematic overview presented on Fig. 1 as well as the international examples regarding the procedure of PET rescaling may offer good starting point for this goal.

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