EVALUATION OF HUMAN THERMAL COMFORT RANGES IN THE RESPECT OF URBAN CLIMATE OF WINTER CITIES ON THE EXAMPLE OF ERZURUM CITY

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Abstract

Human thermal comfort conditions can be evaluated by using various indices based either on simple empirical approaches or on more complex and reliable human-biometeorological approaches. Latter ones are based on the energy balance models of the human body and their calculation is supplemented with some computer software. Facilitating the interpretation of the results, the generally applied indices express the effects of the thermal environment in the well-known temperature-unit; just like in the case of the widely used PET (Physiological Equivalent Temperature) index. Several studies adopting PET index for characterizing the thermal component of the climate (climate of a region, urban climate at local scale or microclimate within different city structures) preferred to organize the resulted PET values into thermal sensation or thermal stress categories in order to demonstrate the spatial and/or temporal characteristics of human thermal comfort conditions. The generally adopted PET ranges, however, were derived by Central-European researchers and they are only valid for the 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 clearly demonstrates that in harsh winter conditions the original PET ranges show purely discomfort. Thus the generally adopted human thermal comfort ranges of PET index seem to be less applicable regarding cold climate conditions, and detailed investigations would be required in order to define new categorization being of greater importance for local residents who are adapted to this climatic background, and for tourists on the other hand who may perform winter sport activities and therefore perceive the thermal environment more comfortable.

Keywords: human-bio meteorological assessment, physiological effective temperature, cold climate

1. Introduction

The thermal component of the atmospheric environment includes air temperature (Ta), air humidity (expressed as vapour pressure VP or relative humidity RH), wind velocity (v), as well as mean radiant temperature (Tmrt); the latter is consisted of short- and long-wave radiation flux densities with a thermal effect (Figure 1). All of the mentioned parameters affect the human thermoregulation 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 thermoregulation 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).

Figure 1. Schematic overview about the determination of thermal comfort conditions

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 has roughly the same importance as the air temperature while in the case of stronger air velocities, air temperature may be more important than the mean radiation temperature, especially in overcast conditions or in the shade.

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 on 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 heat balance models (Höppe 1993; 1999) which take into account all relevant thermal parameters together with some personal factors (Figure 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 Physiological Equivalent Temperature – PET index 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: Tmrt=Ta, VP=12hPa, v=0.1m/s. PET can be interpreted as the very air temperature (PET=Ta) of this reference environment in which the human body (performing light activity 80W and wearing light suit 0.9 clo) would experience the same thermal impacts as calculated for the actual outdoor conditions, described with any combinations of Ta, Tmrt, v and VP (Höppe 1999).

PET was used world-wide 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. 2006; 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 used PET threshold values were introduced by Matzarakis & Mayer (1996). The aim of the present study is to analyse the applicability of these present category benchmarks in the case of cold climate regions on the example of Erzurum city.

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

2. Materials and Methods

The study relates to the city of Erzurum in northeast of Turkey (39.55N and 41.16E; TRA1 NUTSII Region; **Figure 2**). Erzurum is located at an altitude of 1.850m on a highland surrounded by mountains up to 3500m. 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°C 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.

Figure 2. Geographical location of Erzurum

For the calculation of PET, it is necessary to determine all basic thermal parameters – i.e. Ta, VP (or RH as an alternative), v, and Tmrt – at a human-biometeorologically significant height, e.g. 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 Ta [°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 velocity data measured at 10 m

above ground level were reduced to the required height of 1.1 m according to the generally adopted empirical formula. The widely-known RayMan software (Matzarakis et al. 2000, 2007; Matzarakis and Rutz 2005) was utilized to model the necessary radiation parameter (i.e. Tmrt) 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 was analyzed on a daily basis instead of the usage of 10-day intervals as was usual in earlier studies (e.g. Toy & Yilmaz 2010). The total number of days considered in this examination was 12,410 (365 days X 34 years). The results were represented in the form of bioclimate charts, showing the percentage distribution of selected PET categories over the year.

3. Results

Occurrence probability of the original PET categories (**Table 1**) throughout the year is demonstrated on **Figure 3**. 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 occurrence of this PET domain is high above to the others (**Table 2**). The second most prevalent range refers to "slightly cool" thermal sensation; 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" and "cold" (**Figure 3, Table 2**). In line with expectations regarding a cold-climate city, the least prevalent ranges are "very hot", "hot" and "warm", occurring very rarely and only on a couple of summer days.

Figure 3. Bioclimate diagram of Erzurum city according to the original PET categorization system

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

It is obvious that a bioclimatic diagram presented on **Figure 3**. 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 12410 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”, “comfortable” 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, **Figure 4** illustrates the frequency distribution of the calculated PET values according to an evenly graded PET classification-system. The 7°C-wide PET intervals were chosen arbitrarily in order to cover the obtained range of PET values in Erzurum. This type of categorization allows us to ascertain more easily those parts of the year which can be characterized with the highest probability of extreme cold stress (January and February), as well as with the highest PET values (days from 190 to 230). Besides, this categorization results in a more even frequency distribution between the PET categories compared to the original PET thresholds (**Figure 5**).

Figure 4. Bioclimate diagram of Erzurum city according to 7°C-wide PET categories

Figure 5. Percentage distribution of days falling in different PET ranges within an average year in Erzurum

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 interannual differences in the thermal conditions, especially during the long winter period. However, another classification seemed to be useful to reveal more closely the inter-annual differences. It must be noted that this categorization was made arbitrarily, without detailed outdoor thermal

comfort surveys those are required for the development of new classification-systems (Figure 1).

Another important issue have to mention is that the original ranges of PET (Table 1; Matzarakis & Mayer 1996; Matzarakis et al. 1999) were assigned to the different grades of thermal stress and human thermal sensation on the basis of analogous 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 metabolistic heat production due to the physical activity was assumed to be 80 W (equivalent of a light office work), which have added to the basal metabolism (ca. 80–85W 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 & Mayer 1996; Matzarakis et al. 1999). However, people spending their time in a "winter-city" like Erzurum wear heavier clothing; and there must be several tourists who perform intensive activity like skiing and other winter sports. This 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 world-wide and shed light on different forms of adaptation taking place at physical (behavioural adaptation), physiological (acclimatization) and psychological (mental) level (Höppe 2002, Nikolopoulou & 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 & Lykoudis 2006, Kántor et al. 2012), as well as remarkable inter-annual differences regarding the subjective assessment of the thermal environment (e.g. Nikolopoulou & Lykoudis 2006, Lin 2009). Recognizing the importance of these issues, a couple of researchers decided recently to derive 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 & Matzarakis 2008; Cohen et al. 2013; Yang et al. 2013; Lai et al. 2014; Pearlmutter et al. 2014; Kovács et al. 2015).

The presented example of Erzurum city, as well as 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 **Figure 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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Figures and Tables

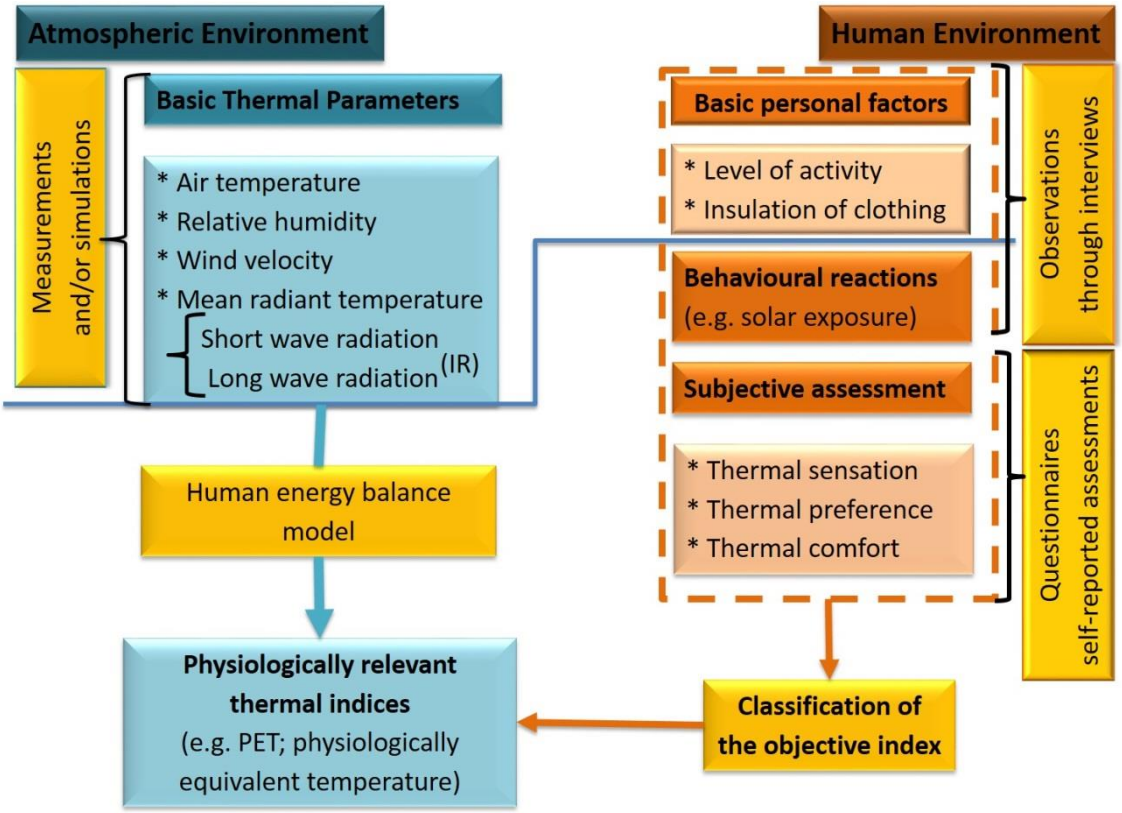

Figure 1. Schematic overview about the determination of thermal comfort conditions

Figure 2. Geographical location of Erzurum

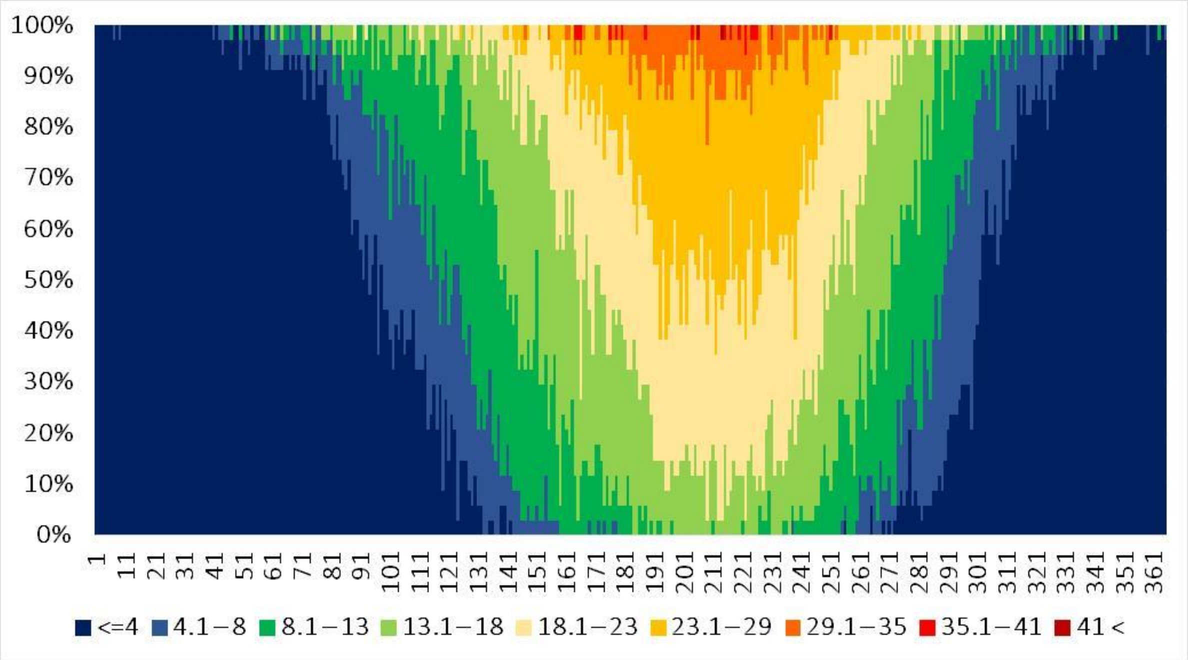

Figure 3. Bioclimate diagram of Erzurum city according to the original PET categorization system

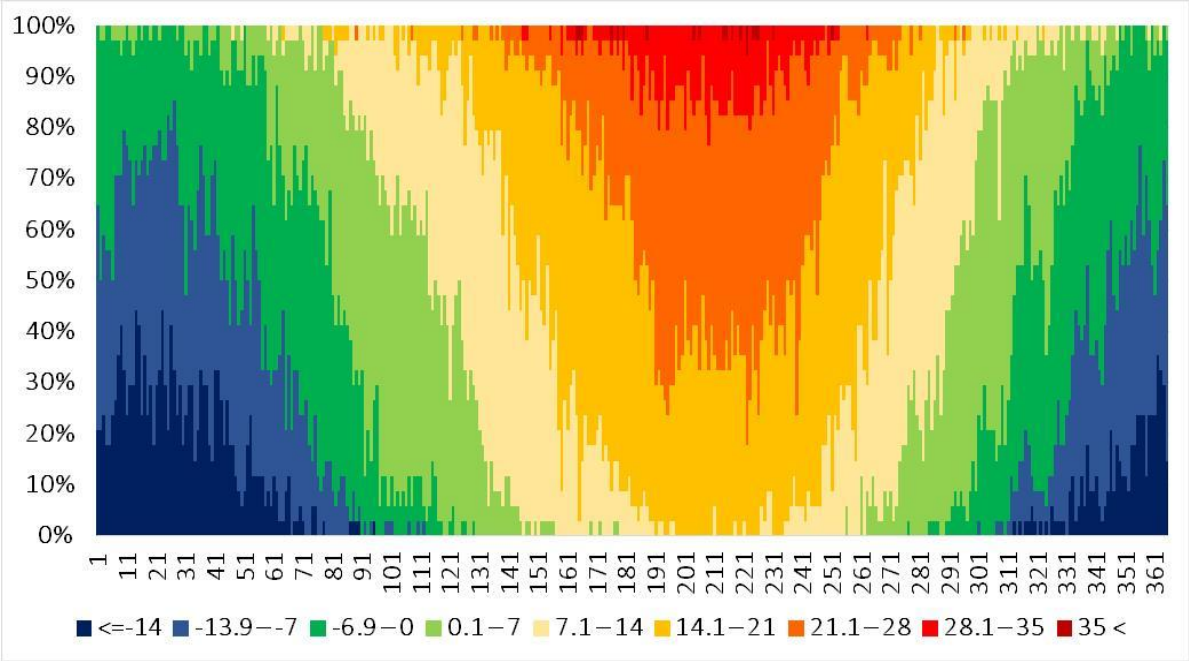

Figure 4. Bioclimate diagram of Erzurum city according to 7°C-wide PET categories

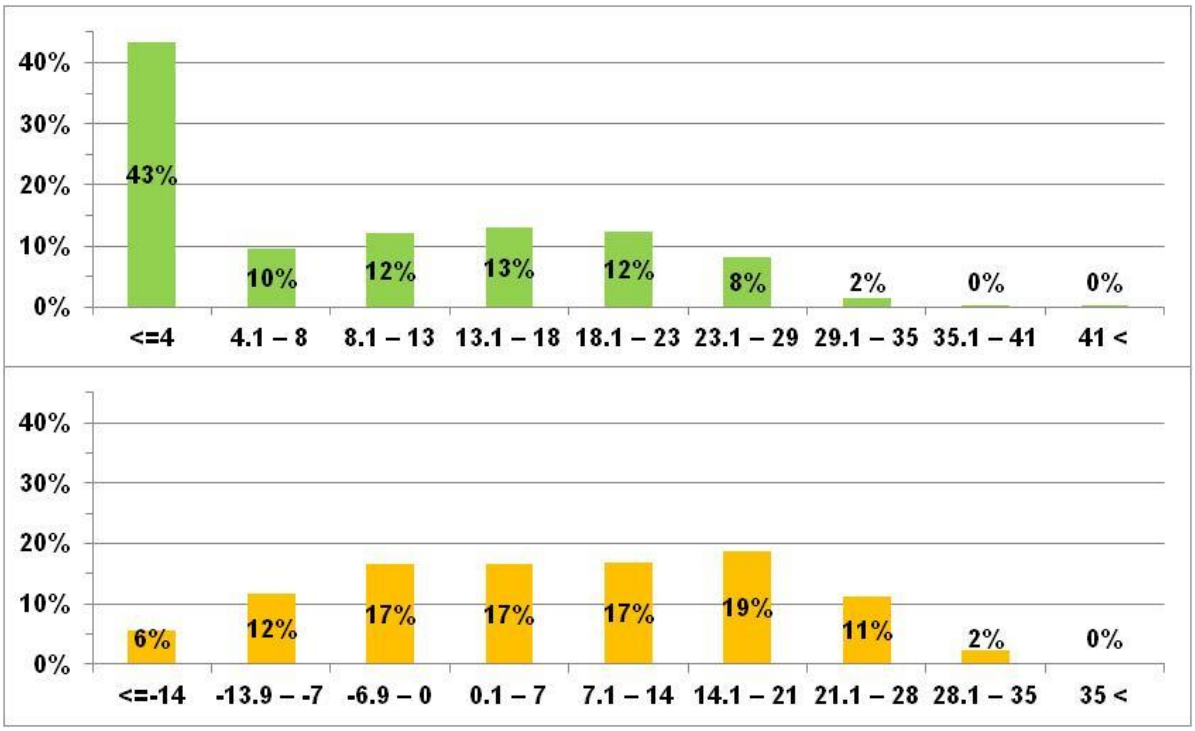

Figure 5. Percentage distribution of days falling in different PET ranges within an average year in Erzurum

Table 3. Ranges of PET for different categories of human thermal sensation and grades of thermo-physiological stress; internal heat production by activity: 80W, heat transfer resistance of clothing: 0.9 clo. (According to Matzarakis and Mayer 1996; Matzarakis et al. 1999).

PET [°C]	Thermal sensation	Level of thermal stress
< 4°C	very cold	extreme cold stress
4.1 - 8°C	cold	strong cold stress
8.1 - 13°C	cool	moderate cold stress
13.1 - 18°C	slightly cool	slight cold stress
18.1 - 23°C	**neutral (comfortable)**	**no thermal stress**
23.1 - 29°C	slightly warm	slight heat stress
29.1 - 35°C	warm	moderate heat stress
35.1 - 41°C	hot	strong heat stress
41°C >	very hot	extreme heat stress

Table 4. Frequency distribution of the obtained PET categories over the investigation *period*

PET range [°C]	Thermal sensation	Number of Days	%
<= 4°C	very cold	5394	43.46
4.1 - 8°C	cold	1179	9.50
8.1 - 13°C	cool	1489	12.00
13.1 - 18°C	slightly cool	1603	12.92
18.1 - 23°C	**neutral (comfortable)**	1530	12.33
23.1 - 29°C	slightly warm	1001	8.07
29.1 - 35°C	warm	194	1.56
35.1 - 41°C	hot	18	0.15
41°C <	very hot	2	0.02
Total		12410	100