

# Human thermal climate of the Carpathian Basin

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## Abstract

A human body–clothing–atmosphere environment system energy balance model is constructed to evaluate individual human thermal climates in the Carpathian Basin. The analysis is performed in terms of clothing resistance and operative temperature for the period 1971–2000. The model's main strength is that it simulates the metabolic activity rate  $M$  as simply as possible taking into account interpersonal variations. Non-sweating, walking humans are considered in natural outdoor conditions at a walking speed of  $4 \text{ km}\cdot\text{h}^{-1}$ . Atmospheric data are used from the CarpatClim dataset; human data are taken from a Hungarian human dataset. The dataset reveals that the interpersonal variations of  $M$  of walking humans can reach  $40\text{--}50 \text{ W}\cdot\text{m}^{-2}$ . According to the results, the variability of individual human thermal climates can be significant. This variability increases towards cold climates and is less in the comfortable thermal zone, when the operative temperature is between  $23$  and  $28^\circ\text{C}$ . It should be mentioned that summer is thermally neutral in the Little Hungarian Plain, the Great Hungarian Plain and in larger parts of the Transylvanian Plateau, irrespective of the person considered. The warmest areas in the Carpathian Basin can be found in Bačka and Banat. In terms of thermal sensation, the results obtained agree well with the results referring to the human considered in the Physiological Equivalent Temperature index model.

## KEYWORDS

Carpathian Basin, clothing resistance, human data, interpersonal variations, metabolic activity rate, operative temperature, thermal sensation

## 1 | INTRODUCTION

Climate needs to be classified because of its effects imposed on ongoing phenomena on the Earth. Among these phenomena the biosphere is of special importance. So far, in the science of climate classification the biosphere is mostly represented either by vegetation (e.g., Köppen, 1900; Köppen, 1936; Prentice *et al.*, 1992;

Rivas-Martínez, 2004), or by humans (e.g., Matzarakis *et al.*, 1999; Matzarakis *et al.*, 2007; Matzarakis and Amelung, 2008; Błażejczyk *et al.*, 2010), or by their combination (e.g., Yang and Matzarakis, 2016, Potchter *et al.*, 2018). Not only global (e.g. Holdridge, 1947; Kottek *et al.*, 2006; Jendritzky and Tinz, 2009; Lee and Brenner, 2015) but also regional scale applications (e.g., Auliciems and Kalma, 1979; Yan, 2005; Alvarez *et*

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*al.*, 2013; Błażejczyk and Błażejczyk, 2014; Engelbrecht and Engelbrecht, 2016; Giannaros *et al.*, 2018) may be found.

In this study, we will focus on the Carpathian Basin because of its unique ecological and climate features (Metzger *et al.*, 2005; Borhidi *et al.*, 2013; Ács *et al.*, 2015). Its climate is mostly investigated by means of vegetation based methods (e.g., Réthly, 1933; Ács and Breuer, 2013; Szelepcsényi *et al.*, 2014). The vast majority of human-based methods consider human body energy balance equations characterizing the environmental thermal load as simply as possible via thermal indices as, for instance, PMV (Predicted Mean Vote) (Fanger, 1970), PET (Physiological Equivalent Temperature) (Mayer and Höppe, 1987; Höppe, 1999), UTCI (Universal Thermal Climate Index) (Jendritzky *et al.*, 2009; Fiala *et al.*, 2011), PT (Perceived Temperature) (Staiger *et al.*, 2012), HL (Heat Load Index) (Błażejczyk and Krawczyk, 1994). Among these PET (Matzarakis *et al.*, 1999) obtained great popularity. PET is used in the Pannonian Basin for its Hungarian (Matzarakis and Gulyás, 2006; Gulyás and Matzarakis, 2009) and Serbian (Basarin *et al.*, 2014) parts. It should be mentioned that in addition to PET (Stojićević *et al.*, 2016), UTCI (Basarin *et al.*, 2018) and HL (Heat Load) indices are also applied (Pecelj *et al.*, 2017) in Serbia's mountainous regions. Similar human bioclimate analyses are also made in mountainous and coastal regions of Croatia (Zaninović *et al.*, 2006; Zaninović and Matzarakis, 2007; Zaninović and Matzarakis, 2009). Energy balance based human bioclimate analyses referring to the whole Carpathian Basin, including the Carpathians are very rare (Ács *et al.*, 2020). The study of Ács *et al.* (2020) is a comparative analysis. The Köppen climate map and the maps representing the annual mean and fluctuation of clothing resistance are compared and discussed in detail. The Serbian (e.g., Stojićević *et al.*, 2016; Pecelj *et al.*, 2017; Basarin *et al.*, 2018) and Croatian (e.g., Zaninović *et al.*, 2006) studies mentioned above discussed only human thermal climate aspects at different locations (cities or mountains). In these studies, in the vast majority PET and UTCI indices are used. Many of these studies aim to apply human bioclimatological information in the industry of human health, well-being (e.g., recreation) and tourism, so, there was a rapid rise in the appearance of energy balance based methods after 2010 (Potchter *et al.*, 2018). PET is the most popular bioclimatic index, followed by PMV (Predicted Mean Vote) and UTCI (Potchter *et al.*, 2018). Software calculating PET (Matzarakis *et al.*, 2007) can consider different humans, but PET is always calculated for a 35 year old man with a body weight of 75 kg, a body length of 175 cm, who possesses a typical indoor setting of 0.9 (clo) and has

metabolic heat production of about  $80 \text{ W} \cdot \text{m}^{-2}$  (Yang and Matzarakis, 2016). It should be mentioned that the human chosen in PET is very similar to the UTCI-Fiala model human in UTCI (Błażejczyk *et al.*, 2010; Fiala *et al.*, 2011; Błażejczyk *et al.*, 2013). The main difference between them is in their garments and metabolic heat production. To our knowledge, the interpersonal variability effect on human thermal load has not been considered to date.

In our days, there are more than 100 registered human thermal climate indices (e.g., de Freitas and Grigorieva, 2015; Potchter *et al.*, 2018). The principles that guided us in choosing the model are as follows: (a) it should take into account the effects of all relevant environmental variables, (b) it should take into account interpersonal variations as much as possible, (c) it should be as simple as possible. Along these requirements, we decided to use two human thermal climate indicators: the operative temperature  $T_o$  and the clothing resistance  $r_{cl}$ . The problems related to the estimation of clothing resistance are avoided by using it as model output. The aims of this study are as follows: (a) to characterize the Carpathian Basin climate in terms of operative temperature and clothing resistance, (b) to present the physics of the human body–clothing–air environment energy balance model due to its novel characteristics and (c) to show the importance of the interpersonal variability effect on the formation of clothing resistance. Atmospheric and human data are used in the analysis. Atmospheric data are taken from the CarpatClim dataset referring to the 1971–2000 period. Their brief description is given in Section 2.2. Human data are provided from a Hungarian human dataset (Utczás *et al.*, 2015; Zsákai *et al.*, 2015; Bodzsár *et al.*, 2016). The dataset is briefly presented in Section 2.3. The physics of the model together with the first preliminary thermal perception results are presented in the Appendix. The results are presented in Section 3; the  $r_{cl}$ – $T_o$  relationships in Section 3.1, the area distributions of  $r_{cl}$  in Section 3.2 and the comparison of  $r_{cl}$  with PET in Section 3.3. Short discussion can be found in Section 4. Concluding remarks are given in Section 5.

## 2 | METHODS AND DATA

There are many methods for characterizing the human thermal climate (Potchter *et al.*, 2018). All of them try to be as simple as possible, therefore they use different indices. In this work, a clothed human body–air environment energy balance model is used for characterizing the human thermal environment in terms of clothing resistance and operative temperature. The model and the first

thermal sensation estimations are presented in the Appendix.

## 2.1 | Basic equations

The main outputs of the model, namely clothing resistance  $r_{cl}$  ( $s \cdot m^{-1}$ ) and operative temperature  $T_o$  ( $^{\circ}C$ ) can be treated as indices because they are good indicators of thermal load. They are as follows:

$$r_{cl} = \rho \cdot c_p \cdot \frac{T_S - T_a}{M - \lambda E_{sd} - \lambda E_r - W} - r_{Hr} \cdot \left[ \frac{R_{ni}}{M - \lambda E_{sd} - \lambda E_r - W} + 1 \right], \quad (1)$$

$$T_o = T_a + \frac{R_{ni}}{\rho \cdot c_p} \cdot r_{Hr}, \quad (2)$$

$$T_o = T_S - (r_{Hr} + r_{cl}) \cdot \frac{M - \lambda E_{sd} - \lambda E_r - W}{\rho \cdot c_p}, \quad (3)$$

where  $\rho$  is air density ( $kg \cdot m^{-3}$ ),  $c_p$  is specific heat at constant pressure ( $J \cdot kg^{-1} \cdot C^{-1}$ ),  $r_{Hr}$  is combined resistance for expressing the thermal radiative and convective heat exchanges ( $s \cdot m^{-1}$ ),  $T_S$  is skin temperature ( $^{\circ}C$ ) (a constant,  $34^{\circ}C$ ),  $T_a$  is air temperature ( $^{\circ}C$ ),  $R_{ni}$  is isothermal net radiation flux density ( $W \cdot m^{-2}$ ),  $M$  is metabolic heat flux density ( $W \cdot m^{-2}$ ),  $\lambda E_{sd}$  is the latent heat flux density of dry skin ( $W \cdot m^{-2}$ ),  $\lambda E_r$  is respiratory latent heat flux density ( $W \cdot m^{-2}$ ) and  $W$  is mechanical work flux density ( $W \cdot m^{-2}$ ) referring to the activity under consideration.  $M$  refers to a walking human in outdoor conditions with a reference speed of  $1.1 m \cdot s^{-1}$  ( $4 km \cdot h^{-1}$ ).

The effect of radiation and convection on human thermal load can be expressed in one parameter, the operative temperature. As it can be seen, there are two expressions for this: in the first,  $T_o$  depends only upon environmental variables, in the second it depends upon both the human (e.g., clothing resistance) and environmental variables. Of course, both expressions give the same result. In this study,  $r_{cl}$  is viewed as a thermal regulator. Note that in previous studies (e.g., De Freitas, 1979; Havenith *et al.*, 2012)  $r_{cl}$  is treated as a thermal insulation rate parameter. Viewing  $r_{cl}$  as a thermal regulator means the following: if there is heat excess, the human body needs cooling to reach energy balance. In this case,  $r_{cl}$  values are negative. Inversely, if there is heat deficit, the human body needs warming to reach energy balance. In this case,  $r_{cl}$  values are positive. When the human body is in energy balance, needing neither cooling nor warming and sensing this state as comfortable. In this case  $r_{cl}$  is very close or equal to zero. In this sense,  $r_{cl}$  can be called

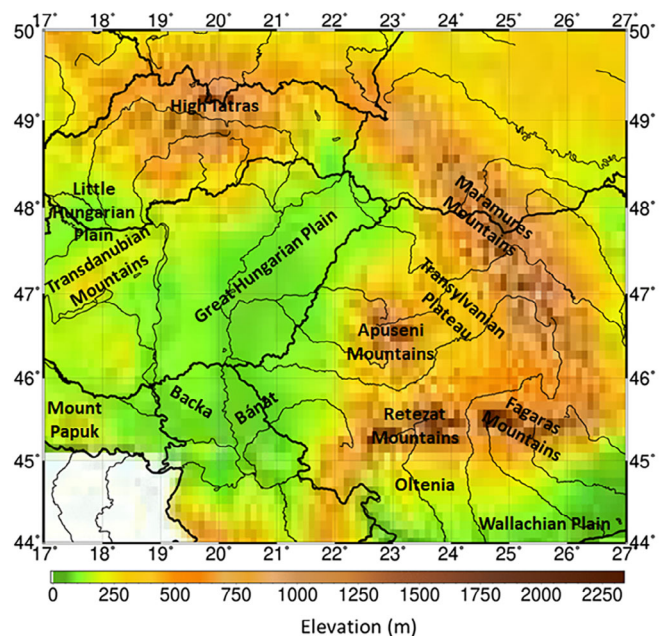
a 'Thermal Equilibrium Clothing Index'. This interpretation of  $r_{cl}$  is new.

## 2.2 | Region and climatic data

The region studied is the region of the CarpatClim dataset (Figure 1) located between the  $17^{\circ}$  and  $27^{\circ}/44^{\circ}$  and  $50^{\circ}$  longitude/latitude lines. The data chosen refer to the period 1971–2010; the temporal and spatial resolutions used are 1 day and  $0.1^{\circ} \times 0.1^{\circ}$  (about  $10 km \times 10 km$ ).

The observed data collected from 643 stations (288 climatological stations and 355 precipitation stations) are quality controlled and homogenized. The region contains 6,161 grid points representing the Carpathian Basin almost completely. A Carpathian-Basin region climate analysis from the point of view of the CarpatClim dataset can be found in the work of Spinoni *et al.* (2015). In this study, the CarpatClim data used are as follows: global radiation, cloud cover, air temperature, vapour pressure and 10 m wind speed. Monthly data are calculated from daily data; 30-year means are created from the monthly data of the period 1971–2000.

In lowland areas of the region, the prevailing climate according to Köppen is the *Cfb* climate type (*C*, temperate climate; *f*, without dry season; *b*, warm summer). In the Carpathians, the most frequent climate type is *Dfb* (*D*, boreal climate), but there are also areas with the climate type *ET* (*ET*, polar tundra climate).



**FIGURE 1** The region of the CarpatClim dataset and its basic elevation data and major geographical designations used in the study [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

## 2.3 | Human datasets

To date, human characteristics are represented by the characteristics of an ‘average human’ (e.g., Auliciems and Kalma, 1979; Błażejczyk *et al.*, 2010). In this study, we used human data of 4 persons; these data are represented in Table 1. Human 1 represents an extreme Hungarian female. Human 2 is a female whose characteristics are as close as possible to an ‘average Hungarian female’. Human 3 is the first author of this study. Human 4 is the ‘standardized human’ used in the calculation of the PET index.

Except for the ‘standardized human’ used in PET, human characteristics (age, gender, body mass [ $M_{bo}$ ] and body length [ $L_{bo}$ ]) are taken from a Hungarian human dataset (Utczás *et al.*, 2015; Zsákai *et al.*, 2015; Bodzsár *et al.*, 2016) created at the Department of Biological Anthropology, Eötvös Loránd University, Budapest, Hungary. The dataset contains data of about 1,000 Hungarian adults. The participation was voluntary and anonymous. The database contains the ID code, gender, chronological age, body structure and physiological parameters of the participants. Written informed consent was obtained from the participants. The data collection was conducted according to the principles expressed in the Declaration of Helsinki. Characteristics of the ‘standardized human’ used in PET are taken from work of Yang and Matzarakis (2016).

## 3 | RESULTS

The clothing resistance–operative temperature relationships for the humans considered, the spatial distribution of annual  $r_{cl}$  and  $T_o$  values and the spatial distribution of the summer and winter values of  $r_{cl}$  are analysed. Summer values are formed by averaging the values for June, July, August, and the winter values are obtained by averaging the values for December, January, February. Thirty-year annual, summer and

winter means are calculated for the central period 1971–2000.

### 3.1 | Clothing resistance–operative temperature relationships

Individual  $r_{cl}$ – $T_o$  relationships can be constructed for each person in the climate and/or weather considered.  $T_o$  represents the environment’s thermal load; among human characteristics it depends only upon  $D$  (Equation (A9)), but since this dependence is weak,  $T_o$  can be treated as a human-independent thermal indicator.  $r_{cl}$  (Equation (1)) depends upon both the environment and the human characteristics via  $M$ . Since  $M$  can vary by as much as 40–50  $\text{W}\cdot\text{m}^{-2}$  from human to human, the dependence of  $r_{cl}$  on human characteristics cannot be neglected. The  $r_{cl}$ – $T_o$  link is fundamental since it represents a unique person–environment relationship. The  $r_{cl}$ – $T_o$  scatter chart is compared for humans 1 and 2 in the Carpathian Basin for the summer/winter seasons (Figure 2), the spring/autumn seasons (Figure 3) and the year (Figure 4). The point-cloud contains 6,161 points as this is the number of grid points being considered in the region.

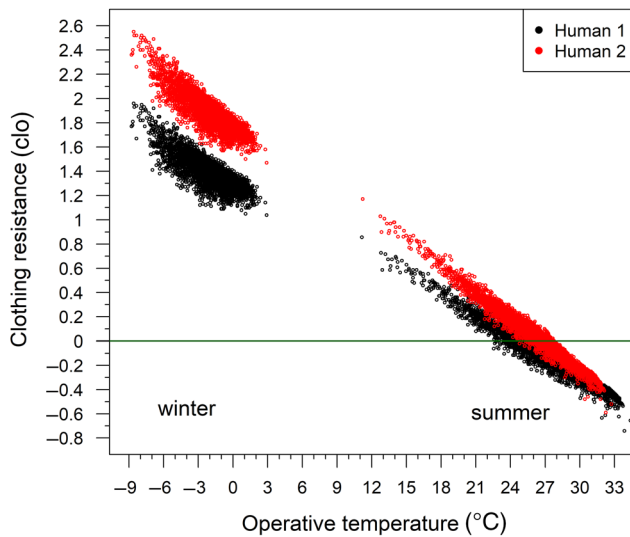
Inspecting Figure 2 we see that the point-clouds are separated for winter and summer as well as for humans 1 and 2. The  $r_{cl}$  values of human 1 are unequivocally lower than the  $r_{cl}$  values of human 2, since the  $M$  value of human 1 is larger than the  $M$  value of human 2 (Table 1). The difference in  $M$  between humans 1 and 2 is 39.6  $\text{W}\cdot\text{m}^{-2}$ . The  $r_{cl}$  differences decrease towards warmer  $T_o$  values. The largest differences (about 0.6 clo) refer to  $T_o \approx -9^\circ\text{C}$ , the smallest (less than 0.05 clo) refer to  $T_o \approx 33^\circ\text{C}$ . For  $r_{cl} = 0$  clo,  $T_o$  of human 1 is around  $24^\circ\text{C}$ , while for human 2 it is around  $27^\circ\text{C}$ . This shift of  $3^\circ\text{C}$  is not negligible knowing that deviations in human thermal reactions in the comfortable zone are less. All these differences in  $r_{cl}$  between humans 1 and 2 are caused by difference in  $M$ .

**TABLE 1** Human characteristics of humans used in the study

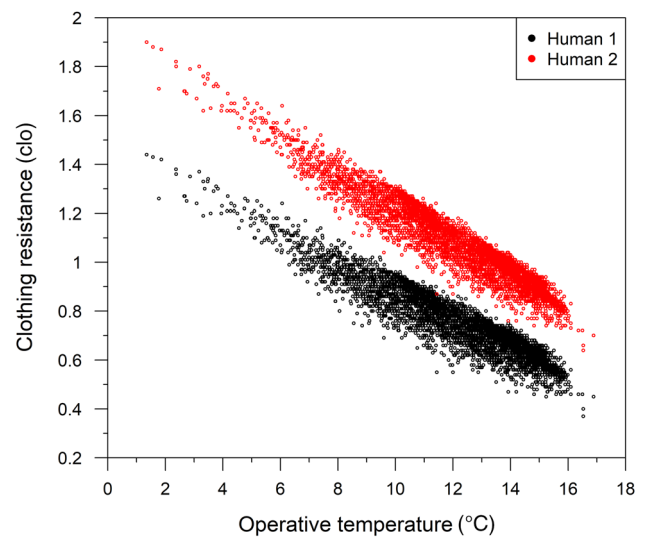
Humans	Age (years)	Body mass (kg)	Body length (cm)	Basal metabolic flux density ( $\text{Wm}^{-2}$ )	Walking energy flux density ( $\text{Wm}^{-2}$ )	Total energy flux density ( $\text{Wm}^{-2}$ )
Human 1	69	105.5	160.9	37	137.6	174.6
Human 2	33	65.5	169	38.85	96.11	134.96
Human 3	64	89	190	40.76	94.48	135.24
Human 4	35	75	175	43.23	98	141.23

Note: human 1, adult Hungarian female; human 2, person representing an ‘average adult Hungarian female’; human 3, adult Hungarian male; human 4, ‘standardized human’ used in the calculation of PET.

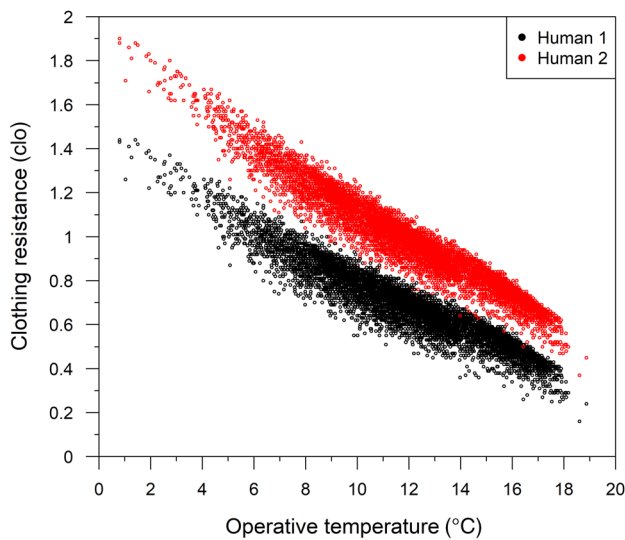




**FIGURE 2** Scatter chart of the winter and summer mean clothing resistances (clo) of human 1 (black points) and human 2 (red points) as a function of operative temperature (°C) in the CarpatClim dataset region for the period 1971–2000. Figures from 2 to 9 are constructed by the R programming language (R Core Team, 2019) [Colour figure can be viewed at wileyonlinelibrary.com]



**FIGURE 4** Scatter chart of annual mean clothing resistances (clo) of human 1 (black points) and human 2 (red points) as a function of operative temperature (°C) in the CarpatClim dataset region for the period 1971–2000 [Colour figure can be viewed at wileyonlinelibrary.com]



**FIGURE 3** Scatter chart of the spring and autumn mean clothing resistances (clo) of human 1 (black points) and human 2 (red points) as a function of operative temperature (°C) in the CarpatClim dataset region for the period 1971–2000 [Colour figure can be viewed at wileyonlinelibrary.com]

The  $r_{cl}-T_o$  points for humans 1 and 2 in spring and autumn represent one unified point-cloud (Figure 3). As in the former case, the point-cloud of human 1 is below

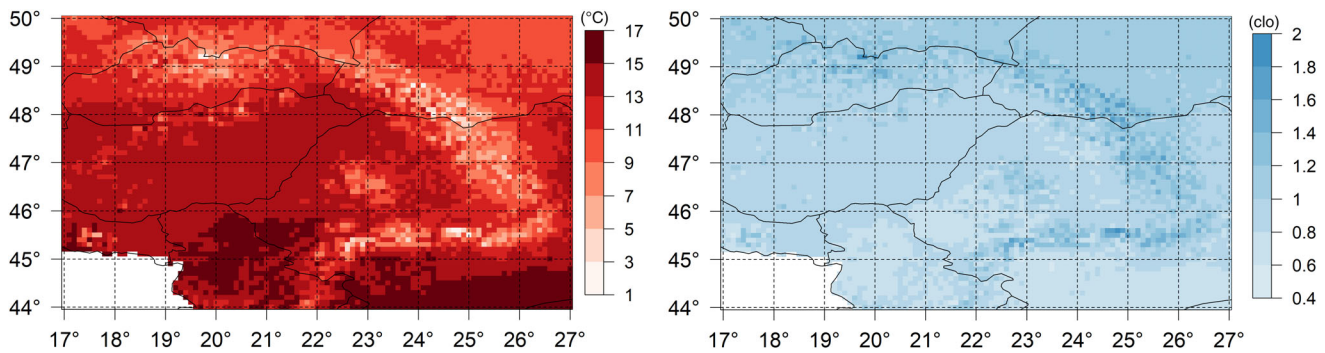
the point cloud of human 2. The largest inter-human  $r_{cl}$  differences are about 0.45 clo, when  $T_o \approx 1^\circ\text{C}$ . The smallest inter-human  $r_{cl}$  differences are about 0.2–0.25 clo for  $T_o = 18\text{--}19^\circ\text{C}$ .

The annual  $r_{cl}-T_o$  point-clouds for the humans considered are very similar to those obtained for spring and autumn (Figure 4). In this case, the separate localisations of the point-clouds are more obvious than in the spring-autumn case. The largest inter-human  $r_{cl}$  differences appear for  $T_o = 1\text{--}2^\circ\text{C}$  and amount to about 0.45 clo. The smallest differences amount to about 0.25–0.3 clo for  $T_o = 15\text{--}17^\circ\text{C}$ .

### 3.2 | Spatial distributions

The spatial distribution of annual  $r_{cl}$  and  $T_o$  values is considered only for human 2 since her characteristics closely represent the characteristics of the ‘average adult Hungarian female’. This is presented in Figure 5. In Hungary, except on mountains,  $r_{cl}$  varies between 0.8 and 1.0 clo.

According to the thermal sensation of human 3, this thermal load is sensed as ‘cool’ or ‘cold’. These values can also be found on the Transylvanian Plateau. Banat and the Wallachian Plain are somewhat warmer with  $r_{cl}$  values of 0.6–0.8 clo. The warmest areas are located in Oltenia on the southern slopes of the Southern Carpathians ( $0.4 < r_{cl} < 0.6$  clo). The thermal contrasts (large  $r_{cl}$  differences between adjacent pixels) seem to be especially high in the Retezat Mountains and the Făgăras



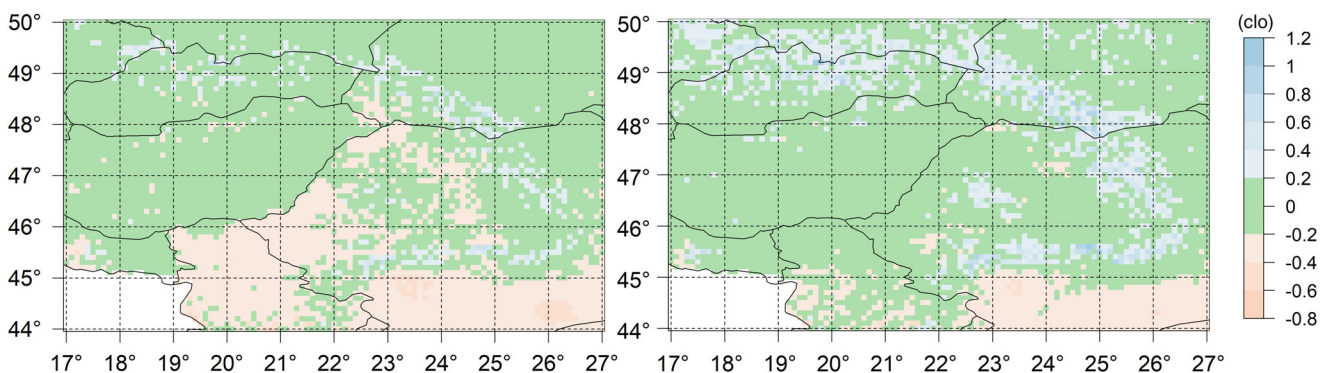
**FIGURE 5** Area distribution of annual mean operative temperature ([a] left side) and the clothing resistance ([b] right side) of human 2 in the CarpatClim dataset region for the period 1971–2000. Figures 5–7 are created by using functions from packages maps (Brownrigg *et al.*, 2018), fields (Nychka *et al.*, 2017) and RColorBrewer (Neuwirth, 2014) [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Mountains, where  $r_{cl}$  deviations can be above 1 clo. The territorial structure of  $T_o$  distribution is somewhat more detailed than the territorial structure of  $r_{cl}$  distribution. For instance, Bačka and Banat are somewhat warmer ( $14 < T_o < 16^\circ\text{C}$ ) than the Little Hungarian Plain and central and northern parts of the Great Hungarian Plain ( $12 < T_o < 14^\circ\text{C}$ ). Oltenia and the Wallachian Plain are as warm as Bačka and Banat. The thermal diversity on Mount Papuk and the Apuseni Mountains is conspicuous, where  $T_o$  deviations between two adjacent pixels can reach  $10^\circ\text{C}$ . However, the greatest thermal contrasts (above  $10^\circ\text{C}$ ) can be found in the Retezar Mountains, the Făgăras Mountains, the Maramures Mountains and the High Tatras.

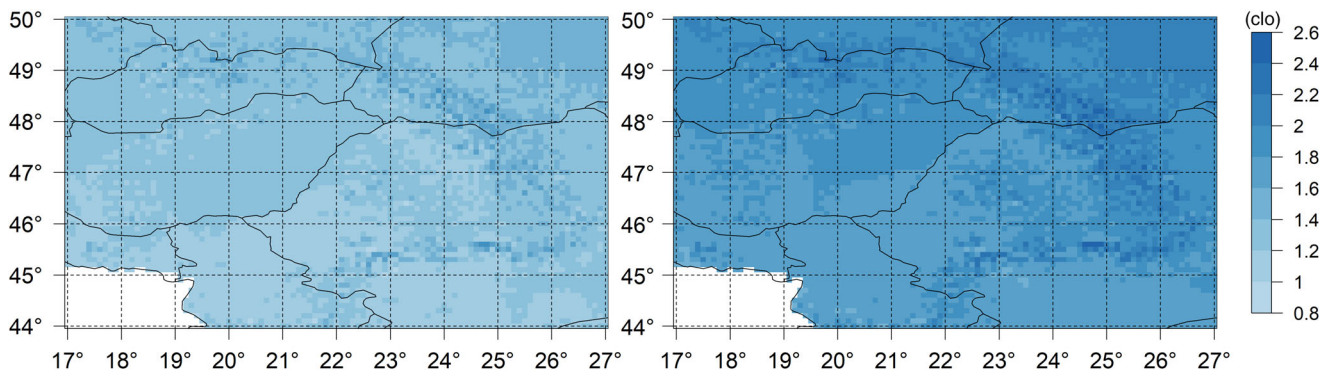
The area distribution of the summer mean  $r_{cl}$  values of humans 1 and 2 for the CarpatClim dataset region is presented in Figure 6.

Inspecting  $r_{cl}$  distributions, it is conspicuous that both humans are comfortable from the point of view of thermal load ( $r_{cl}$  values vary between  $-0.2$  and  $0.2$  clo) almost over the entire territory of Hungary. This is in accordance

with the thermal sensation of person 3 and with the thermal sensation results obtained in the work of Gulyás and Matzarakis (2009). For human 1, Bačka, Banat, many parts of the Transylvanian Plateau and the Wallachian Plain are warmer ( $-0.2 > r_{cl} > -0.4$ ) than Hungary. For human 2, only the Wallachian Plain and some southern areas of Bačka and Banat are warmer than Hungary. For human 1, many parts of the Transylvanian Plateau are warmer than the Great Hungarian Plain, but this is not valid for human 2. For both humans, the warmest locations ( $-0.4 > r_{cl} > -0.6$ ) are in Oltenia on the southern slopes of the Southern Carpathians. The largest thermal contrasts can be found in the region of Mount Papuk, the Retezat Mountains, the Făgăras Mountains, the Maramures Mountains and in the High Tatras. At these locations the thermal contrast is at least 0.6 clo. The highest thermal contrasts (about 1 clo) are in the regions of the High Tatras, Maramures Mountains and in the Făgăras Mountains. There is no observable difference between humans 1 and 2 regarding thermal contrast.



**FIGURE 6** Area distribution of summer mean clothing resistance of human 1 ([a] left side) and human 2 ([b] right side) in the CarpatClim dataset region for the period 1971–2000 [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 7** Area distribution of winter mean clothing resistance of human 1 ([a] left side) and human 2 ([b] right side) in the CarpatClim dataset region for the period 1971–2000 [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

The area distribution of the winter mean  $r_{cl}$  values of humans 1 and 2 is presented in Figure 7.

Note that the spatial distribution structures are very similar. Taking a look at the scales used we can observe a 0.55–0.6 clo shift between them. Since human 1 possesses larger  $M$  than human 2, the  $r_{cl}$  scale of human 1 ranges from 1 to 2 clo, to the contrast of the  $r_{cl}$  scale of human 2, where the scale ranges from 1.5 to 2.6 clo.  $r_{cl}$  values for humans 1 and 2 on the Great Hungarian Plain and the Little Hungarian Plain are 1.2–1.4 and 1.8–2 clo, respectively. For human 2 (person representing ‘average adult Hungarian female’)  $r_{cl}$  values in winter range from 1.4 to 2.2 clo over the entire territory of Hungary. According to the thermal sensation of human 3, this thermal load is sensed as ‘cold’ or ‘very cold’. According to the work of Gulyás and Matzarakis (2009), the sensation of the thermal climate in Hungary during winter is denoted as ‘very cold’. Just like in summer, Bačka, Banat, Oltenia and the Wallachian Plain are warmer ( $1 < r_{cl} < 1.2$  clo for human 1;  $1.4 < r_{cl} < 1.6$  clo for human 2) than the Great Hungarian Plain. Note that many locations on the Transylvanian Plateau are as warm as Banat and Oltenia. The greatest thermal contrasts are in the High Tatras, the Maramures Mountains, the Făgăras Mountains and in the Retezat Mountains. At these locations, the  $r_{cl}$  differences between adjacent pixels can reach 1 clo.

### 3.3 | Comparisons with Physiological Equivalent Temperature

It is interesting to relate  $T_o$  and  $r_{cl}$  to some other thermal indices. Since PET is the most frequently used human thermal index in the region considered, we compared it with  $T_o$  and  $r_{cl}$  in three different sub-regions (Banat, Great Hungarian Plain and Apuseni Mountains) of the Carpathian Basin for the summer and winter seasons. PET values are taken from the work of Gulyás and

Matzarakis (2009). The results together with thermal sensation estimations are presented in Table 2. All results refer to the period 1971–2000. PET values are obtained by using the dataset of the Climatic Research Unit (University of East Anglia, Norwich, UK), while  $T_o$  and  $r_{cl}$  values are simulated by using the CarpatClim dataset. It should be mentioned that the spatial distribution structures of all three indices in Hungary (not presented here) are similar. The thermal contrast between the North Hungarian Mountains and the Great Hungarian Plain regions can be easily observed. Note that  $T_o$  is higher than PET for 2–6°C.

The most important human characteristic, metabolic activity  $M$  is represented in both PET and  $r_{cl}$ . In PET,  $M$  refers to a standing human, in  $r_{cl}$  to a walking human. In  $r_{cl}$ , thermal sensation results are given according to person 3. Although there are great differences in terms of model physics and concept, human representation and thermal sensation grade, there is good agreement between the thermal sensation results referring to PET and  $r_{cl}$ .

## 4 | DISCUSSION

The model is constructed for individual use. The human is represented as much as possible following the principle of ‘individualisation’. To date, it is ‘standardized humans’ that have been treated in the scientific literature (e.g., Höppe, 1999; Jendritzky *et al.*, 2009). So, we have changed the treatment of clothing, human characteristics and metabolic activity rate. Clothing is very variable parameter, it is not only determined thermally but also on a personal and social basis. Therefore, we decided to use this as model output parameter, viewing it only as thermal regulator neglecting its personal and social dependence. Regarding human characteristics, the actual individual characteristics are used as inputs ignoring the

**TABLE 2** Comparison of Physiological Equivalent Temperature, operative temperature, clothing resistance and the corresponding thermal sensations in the Banat, Great Hungarian Plain and Apuseni Mountain regions in the summer and winter seasons

Quantity	Season	Region		
		Banat	Great Hungarian plain	Apuseni Mountain
	<b>Summer</b>			
PET (°C)		23.5–24	22–23.5	14–16
Thermal sensation		Slightly warm	Comfortable	Slightly cool
$T_o$ (°C)		28–30	26–30	16–20
Clothing res. (clo)		0–0.3	0–0.3	0.8–0.4
Thermal sensation		Comfortable	Comfortable	Cool
Quantity	Season	Region		
		Banat	Great Hungarian Plain	Apuseni Mountain
	<b>Winter</b>			
PET (°C)		–2 to –1.5	–4 to –2	–10 to –7
Thermal sensation		Very cold	Very cold	Very cold
$T_o$ (°C)		0–2	–2 to 0	–6 to –2
Clothing res. (clo)		1.5–1.4	1.7–1.5	2.2–1.7
Thermal sensation		Cold, very cold	Cold, very cold	Cold, very cold

concept of the ‘average human’. Metabolic activity rate is parameterised as simply as possible via human state variables ignoring treatment of physiological processes, so, the model is unable to physiologically characterize the effects of heat and cold stresses. The first and only attempt to date to relate the heat load results in terms of  $r_{cl}$  to thermal sensation results is presented in this study. The model is intended to be used on both climate and weather data. To be user-friendly (Essenwanger, 2001), it needs drastic simplification in its environmental physics part, in the treatment of operative temperature. Without this simplification it cannot be competitive, for instance, with the Köppen method in climate classification applications. Carrying out this simplification is a task for the future.

According to the results obtained, the human thermal load in the Pannonian Plain part of the Carpathian Basin (Ács *et al.*, 2015) during summer is approximately equal regardless of the personal differences. However, in winter the relevance of personal differences upon human thermal load can be significant. This is unequivocally shown by comparing the area distribution of the clothing resistance parameters of two adult Hungarian females. The model suggests that the relevance of personal differences increases not only in cold stress but also in heat stress. Unfortunately, these statements have not been confirmed so far by independent observations.

Lastly, the subject investigated can be traced back to Humboldt (von Humboldt, 1845; Hantel and Haimberger, 2016). Here is a text of his interpretation of climate: ‘Der Ausdruck Klíma bezeichnet in seinem allgemeinsten Sinne alle Veränderungen in der

Atmosphäre, die unsere Organe merklich affizieren: die Temperatur, die Feuchtigkeit,...die Heiterkeit des Himmels; welcher nicht bloss wichtig ist für...die organische Entwicklung der Gewächse und die Reifung der Früchte, sondern auch für die Gefühle und ganze Seelenstimmung des Menschen’. Translation: The expression climate denotes in its most general sense all changes in the atmosphere that noticeably affect our organs: temperature, humidity,..., serenity of the sky, that is not only important for...the organic development of plants, the ripening of fruits, but also for feelings and state of mind. The results confirm Humboldt's thoughts regarding the subjectivity of the climate-human soul relationship.

## 5 | CONCLUSION

A new human thermal load model based on energy balance considerations is presented to estimate individual human thermal climates in the Carpathian Basin. Human thermal climate is characterized in terms of clothing resistance parameter and operative temperature. The metabolic activity rate is simulated as simply as possible but still being able to take into account interpersonal differences. A non-sweating human walking at a speed of  $4 \text{ km}\cdot\text{h}^{-1}$  is considered. The results suggest that the interpersonal variability effect in human thermal load simulation cannot be neglected. Consequently, human datasets should also be used in describing human thermal load variability. According to a Hungarian human dataset, interpersonal variations of  $M$  can reach  $40\text{--}50 \text{ W}\cdot\text{m}^{-2}$  causing variations in  $r_{cl}$  of about  $0.6\text{--}0.8 \text{ clo}$  in



very cold or hot environments. This effect is comparable with the effect of elevation on  $r_{cl}$  in the Carpathians, where the largest thermal contrasts simulated between adjacent pixels are about 1 clo. In the Pannonian Basin, the effect of interpersonal variation of  $M$  upon human thermal load in summer is much less and this thermally stress-free situation is sensed as 'comfortable' by the vast majority of people.

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## APPENDIX A.

### CLOTHED HUMAN BODY–ATMOSPHERE ENVIRONMENT MODEL

A clothed human body–air environment model is used. The human body is represented as simply as possible with a one-node model (Katić *et al.*, 2016), that is there is no treatment of physiological processes ( $M$  is a function of human state variables); consequently stress categories and the related physiological responses cannot be characterized. The human body  $T_b$  and skin  $T_s$  temperatures are 37 and 34°C, respectively. Clothing exchanges heat with the air environment and it obtains heat from the human body, and so its surface temperature  $T_{cl}$  changes. We supposed that garments cover the human body completely, it adheres strongly to the skin surface. The clothing albedo agrees with the skin albedo. The human is walking without sweating, the latent heat of evaporation from dry skin ( $\lambda E_{sd}$ ) and from clothing ( $\lambda E_{cl}$ ) is

equal. Walking speed is  $1.1 \text{ m}\cdot\text{s}^{-1}$ . This 2-layer representation of the clothed human body–air environment system is similar to the 1-layer representation presented in Campbell and Norman's (1998) book. The main strength of the model is its simplicity while it is able to take into account interpersonal differences.

### Energy balance Equations

A diagnostic approach is used, that is heat capacity of the surfaces is neglected. So, the energy balance of clothing and skin surface are as follows:

$$R_{ni} + H_S + \lambda E_{sd} - H_{cl} - \lambda E_{cl} = 0, \quad (\text{A1})$$

$$H_S = M - \lambda E_{sd} - \lambda E_r - W, \quad (\text{A2})$$

where  $H_S$  is the sensible heat flux density between skin surface and clothing,  $H_{cl}$  is the sensible heat flux density between the clothing surface and the near surface atmosphere,  $M$  is the metabolic heat flux density of a walking human,  $W$  is the mechanical work flux density of muscles of a walking human.  $H_S$  can be expressed either via  $T_b$  or via  $T_{cl}$  as follows:

$$H_S = \rho \cdot c_p \cdot \frac{T_b - T_S}{r_t}, \quad (\text{A3})$$

$$H_S = \rho \cdot c_p \cdot \frac{T_S - T_{cl}}{r_{cl}}, \quad (\text{A4})$$

where  $r_t$  is the tissue resistance ( $\text{s}\cdot\text{m}^{-1}$ ). Equating Equations (A3) and (A4), we can get  $T_{cl}$ . Replacing it into (A1) and using Equations (A2) and (A3), we can get the following energy balance equation for clothing:

$$R_{ni} + \left(1 + \frac{r_{cl}}{r_{Hr}}\right) \cdot (M - \lambda E_{sd} - \lambda E_r - W) - \rho \cdot c_p \cdot \frac{T_S - T_a}{r_{Hr}} = 0, \quad (\text{A5})$$

$R_{ni}$  and  $T_a$  are the most important environmental forcings in Equation (A5). The thermal impact of  $R_{ni}$  can be expressed by introducing operative temperature  $T_o$  putting  $T_a = T_o$  when  $R_{ni} = 0$ . Doing so, we can get the following equation:

$$M - \lambda E_{sd} - \lambda E_r - W = \rho \cdot c_p \cdot \frac{T_S - T_o}{r_{Hr} + r_{cl}}, \quad (\text{A6})$$

As we see, in Equation (A6)  $M$ ,  $r_{cl}$  and  $T_o$  are dependent on each other. Expressing  $T_o$  from (A6), we can get Equation (3). Replacing Equation (A6) back into

Equation (A5), we can get Equation (2), in which  $T_o$  depends only upon environmental variables. Equation (1) for calculating  $r_{cl}$  can be obtained by putting back Equation (2) into Equation (A6).

### Parameterisations

To use Equations (1), (2), or (3),  $R_{ni}$ ,  $r_{Hr}$ ,  $M$ ,  $\lambda E_r$  and  $W$  need to be parameterised.  $R_{ni}$  is calculated as simply as possible,

$$R_{ni} = S \cdot (1 - \alpha_{cl}) + \epsilon_a \sigma T_a^4 - \epsilon_{cl} \sigma T_a^4, \quad (\text{A7})$$

where  $S$  is global radiation,  $\alpha_{cl}$  is clothing albedo,  $\epsilon_a$  is atmospheric emissivity and  $\epsilon_{cl}$  is the emissivity of clothing or skin. In the model  $S$  is input data,  $\alpha_{cl} = 0.25\text{--}0.27$ ,  $\epsilon_{cl} = 1$  and  $\epsilon_a$  depends on clear sky emissivity  $\epsilon_{cs}$  and cloudiness  $N$  (0 for cloudless and 1 for completely overcast conditions).  $\epsilon_a$  and  $\epsilon_{cs}$  are parameterised according to Konzelmann *et al.* (1994) and Brunt (1932), respectively, as

$$\epsilon_{cs} = 0.51 + 0.066 \cdot \sqrt{e}$$

$$\epsilon_a = \epsilon_{cs} \cdot (1 - N^{1.6}) + 0.9552 \cdot N^{1.6}, \quad (\text{A8})$$

where  $e$  is vapour pressure (Pa).

As mentioned,  $r_{Hr}$  is a combined resistance for expressing the thermal radiative and convective heat exchanges,

$$\frac{1}{r_{Hr}} = \frac{1}{r_{Ha}} + \frac{1}{r_R} \text{ with } r_{Ha} (\text{sm}^{-1}) = 7.4 \cdot 41 \cdot \sqrt{\frac{D}{U_{1.5}}}, \frac{1}{r_R} = \frac{4\epsilon_{cl}\sigma T_a^3}{\rho c_p}, \quad (\text{A9})$$

where  $D$  (m) is the diameter of the cylindrical body with which the human body is approximated (Campbell and Norman, 1998),  $U_{1.5}$  is the wind speed at 1.5 m (around chest height).  $U_{1.5}$  is calculated from  $U_{10}$  (wind speed at 10 m height) using a logarithmic wind profile approach. In this model, the direction of the walking human compared to the direction of wind speed is not taken into account.

According to Weyand *et al.* (2010),  $M$  for a walking human can be expressed as follows,

$$M = M_b + M_w, \quad (\text{A10})$$

where  $M_b$  is the basal metabolic rate (W) (sleeping human) and  $M_w$  is the metabolic rate (W) referring to walking. Both terms can be parameterised knowing the



most important human body features: gender, age (year), body mass,  $M_{bo}$  (kg) and body length,  $L_{bo}$  (cm). According to Frankenfield *et al.* (2005) Mifflin *et al.*'s (1990)  $M_b$  parameterisation is one of the best,

$$M_b^{male} (\text{kcal} \cdot \text{day}^{-1}) = 9.99 \cdot M_{bo} + 6.25 \cdot L_{bo} - 4.92 \cdot \text{age} + 5, \tag{A11}$$

$$M_b^{female} (\text{kcal} \cdot \text{day}^{-1}) = 9.99 \cdot M_{bo} + 6.25 \cdot L_{bo} - 4.92 \cdot \text{age} - 161. \tag{A12}$$

To be able to obtain  $M_b$  in ( $\text{W} \cdot \text{m}^{-2}$ ), the surface of the human body  $A$  ( $\text{m}^2$ ) has also to be estimated. Dubois and Dubois (1915) parameterisation is used taking  $M_{bo}$  and  $L_{bo}$  as inputs,

$$A = 0.2 \cdot M_{bo}^{0.425} \cdot \left(\frac{L_{bo}}{100}\right)^{0.725}. \tag{A13}$$

$M_w$  is parameterised according to Weyand *et al.* (2010) as follows:

$$M_w = 1.1 \cdot \frac{3.80 \cdot M_{bo} \cdot \left(\frac{L_{bo}}{100}\right)^{-0.95}}{A}. \tag{A14}$$

Formula (1) in Weyand *et al.* (2010) refers to a walking distance of 1 m. Since the reference walking speed in our model is  $1.1 \text{ m} \cdot \text{s}^{-1}$ , Weyand *et al.*'s (2010) formula (1) is multiplied by a factor of 1.1. Dividing this by  $A$ , we will get  $M_w$  in ( $\text{W} \cdot \text{m}^{-2}$ ).

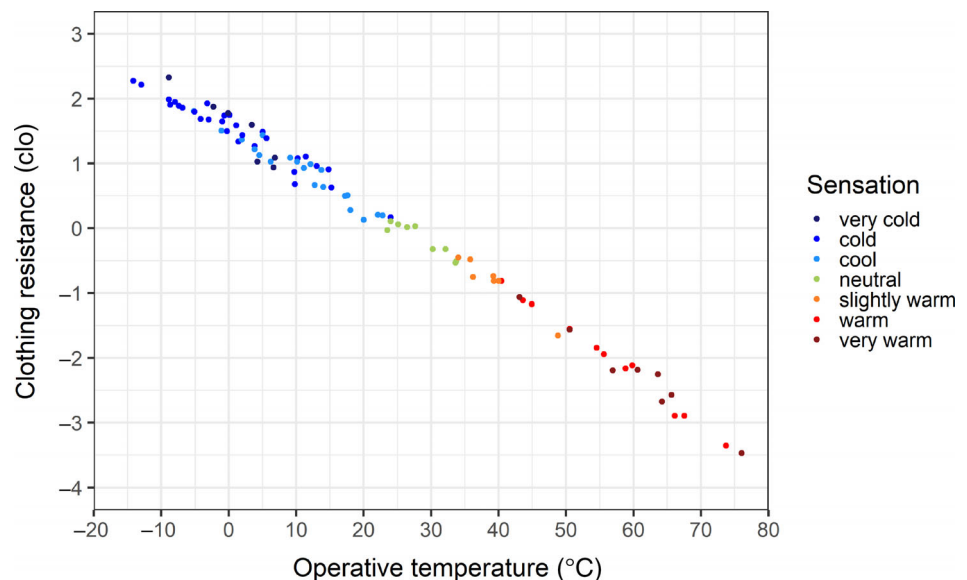
The  $\lambda E_r + \lambda E_{sd}$  sum can be expressed as a function of  $M$  according to Campbell and Norman (1998). In this work, this sum is taken as 10% of  $M$ .  $W$  also depends upon  $M$ . According to Auliciems and Kalma (1979)  $W$  is expressed as

$$W = 0.25 \cdot (M - M_b). \tag{A15}$$

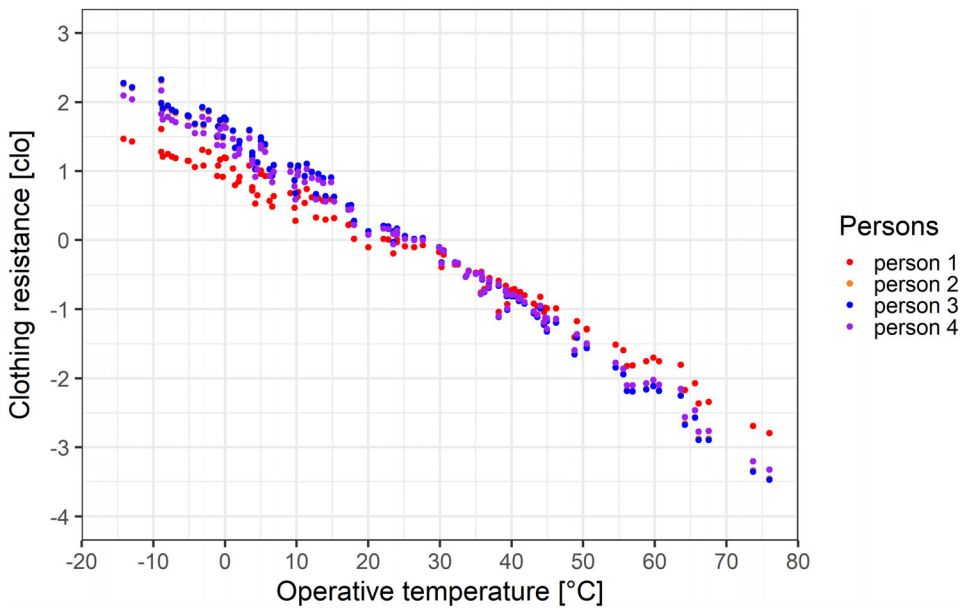
## APPENDIX B.

### THERMAL SENSATION AND THE $r_{cl}$ PARAMETER VALUES

There are many studies (e.g., Cohen *et al.*, 2013; Hamzah *et al.*, 2018) presenting and discussing methods for determining the thermal index–thermal sensation relationship. These relationships are given for the most frequently used indices (e.g., Błażejczyk *et al.*, 2012; Zare *et al.*, 2018). To the best of our knowledge, there has been no study discussing the  $r_{cl}$ –thermal sensation relationship to date. In this study, a preliminary estimation is given by concurrent observation of weather and subjective thermal sensation carried out by person 3 in Table 1. Weather data and thermal sensation results are registered during training runs on an athletics track in Martonvásár (geographical latitude  $47.31^\circ\text{N}$ , geographical longitude  $18.79^\circ\text{E}$ , Central Transdanubian region, Hungary) in the period August 9, 2016–May 23, 2018. Weather data are taken from the website of the Hungarian Meteorological Service (HMS) for that 10-min period in the middle of running event's time period. The HMS station–athletics track beeline distance in Martonvásár is about 100–150 m. More information regarding weather data



**FIGURE A1** The  $r_{cl}$ – $T_o$ –thermal sensation relationships for person 3 [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE A2** The  $r_{cl}-T_o$  relationships for all persons presented in Table 1 [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

can be found in the work of Ács *et al.* (2019). The subjective thermal sensation estimation is performed in the same 10-min period to which weather data refer. The person is standing and/or walking, the clothes worn are appropriate for the weather. A 7-grade scale is used in the estimation, and the grades are marked as ‘very cold’, ‘cold’, ‘cool’, ‘comfortable’, ‘slightly warm’, ‘warm’ and ‘very warm’. The  $r_{cl}-T_o$ -thermal sensation relationship for person 3 is presented in Figure A1.

Three zones can be observed. The ‘cold’ zone, where the  $r_{cl}$  values are above 0.2 (clo); the ‘warm’ zone, where the  $r_{cl}$  values are below  $-0.5$  (clo), and the comfort zone between the ‘cold’ and the ‘warm’ zones, where  $-0.5$  (clo)  $< r_{cl} < 0.2$  (clo). The observation results are not statistically evaluated, they serve to show that negative  $r_{cl}$  values can be interpreted as a cooling effect on the human body in energy excess conditions to reach the human body-outdoor environment thermal equilibrium. In the comfort zone,  $T_o$  changes between 24 and 33°C.

This is a broad temperature range, but even these variable  $T_o$  temperatures are registered in many other studies (e.g., De Dear *et al.*, 1991; Wong and Khoo, 2003; Feriadi and Wong, 2004; Hamzah *et al.*, 2018). Similar behaviour of the PET index regarding the comfort zone is also registered in the work of Potchter *et al.* (2018). Note that  $r_{cl}-T_o$  relationships are human and environment specific. In the given climate or weather types, each person has his or her own individual  $r_{cl}-T_o$  relationship. Therefore the  $r_{cl}-T_o$  relationships for all persons given in Table 1 are presented in Figure A2.

Since the  $r_{cl}-T_o$  relationships for persons 2, 3 and 4 are similar, we suppose that their thermal sensation should be also similar. The  $r_{cl}-T_o$  relationship for person 1 obviously differs from other three relationships, especially in larger heat stress situations, therefore, we suppose that the thermal sensation of person 1 should be different from the thermal sensation of the other 3 humans.